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Correlation of Prototype and Model-Scale Wave Wake Characteristics of a Catamaran

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This paper summarizes an experimental investigation into the correlation of model-scale wave wake measurements against full-scale trial results for a 24-meter long catamaran operating over a range of length Froude numbers. Both full-scale and 1/15th-scale model experiments were conducted over the range of length Froude numbers of approximately 0.3 to 1.0 (full-scale speed range of 6 to 28 knots). The water depth during the experiments was approximately 12 meters, with corresponding depth Froude numbers ranging from subcritical (~0.3), through a transcritical range (~0.8 to 1.1) into low supercritical speeds (up to ~1.3). The results of the investigation confirm that a correlation factor of close to unity be applied when using model-scale experimental data to predict the full-scale height and period of the maximum wave generated by similar catamarans operating within such speed ranges. Consequently, it is expected that the energy of the maximum waves can also be accurately predicted from model-scale data. This paper also provides useful guidance notes for the conduct of full-scale wave wake experiments and highlights some issues regarding the identification of the maximum wave(s) generated when vessels operate at trans and/or supercritical depth Froude numbers.

Keywords: wash; waves; wake; catamarans

1. Nomenclature

E = Energy per meter of wave crest length (J/m)
E_m = Energy of the maximum wave (J/m)
Fr = Length Froude number $[v(gL)^{-1/2}]$
Fr_h = Depth Froude number $[v(gh)^{-1/2}]$
g = Acceleration due to gravity (9.81 m/s^2)
h = Water depth (m)
H_w = Wave height (m)
H_m = Maximum wave height (m)
L = Waterline length (m)
N = Wave decay exponent
T_w = Wave period (s)
T_{crit} = Critical wave period (s)
T_m = Period of the maximum wave (s)
v = Vessel speed (m/s)
y = Lateral distance between vessel sailing line and measurement point (m)
γ = Constant
λ = Scale ratio
ρ = Density of water (kg/m^3)

Sheltered waterways have been used successfully for transportation and trade for thousands of years. However, the development of high-speed recreational and commercial vessels over the past 50 years has introduced a range of new issues. The waves generated by these vessels are often high and can have long periods, which can result in problems for other users of the waterway and to the environment, as has been well documented in recent years (Feldtmann 1997, Macfarlane & Cox 2007).

Although considerable research has been conducted into the prediction and effects from these waves over the past 20 or so years, there still appears to be little published data that deal with the correlation between model and full-scale wave wake measurements, particularly for catamarans operating over a range of length Froude numbers (Fr). The same could also be said for the validation of many numerical techniques used to predict the characteristics of vessel-generated waves.

Small craft wash trial data are available in professional literature, but almost all of it has little or no use in a detailed investigation. The lack of testing consistency, use of nonstandard methodology, insufficient details provided, poor recording, or oversimplification of results are common traits to be found. The International Towing Tank Conference (ITTC) recently indicated that there is a general lack of good physical wave wake data available for validation and/or correlation purposes (ITTC 2005a). One of the aims of this paper is to provide published experimental data suitable for the validation of numerical and/or experimental tools for managing wave wake issues.

The author recently published a study that dealt with the correlation between model- and full-scale wave wake measurements for catamarans operating at low Fr, 0.1 < Fr < 0.3 (Macfarlane 2006). This paper presents the results from a similar study, however, covering a much wider range of Fr, from approximately 0.3 up to 1.0. In addition, this paper discusses the complexities that arise in the analysis of data for vessel operations at trans and supercritical depth Froude numbers (Fr_h).

2. Description of vessel and model

The test vessel, *Wanderer II,* is one of a number of similar type vessels presently used for commercial tourist operations on the lower Gordon River in the island state of Tasmania,

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Australia. The main particulars of this vessel are presented in Table 1. The vessel displacement is based on that estimated using the fore and aft draughts measured at the time of the full-scale trials and referring to vessel specific hydrostatic data. The body plan of the test vessel is shown in Fig. 1.

3. Experimental program

3.1. General

The primary aim of the present study is to examine the relation between model- and full-scale wave wake characteristics and determine what correlation factor (if any) should be applied to results from scale model testing to accurately predict full-scale wave wake characteristics, concentrating on length Froude numbers between $0.3 < Fr < 1.0$ (full-scale speed range of 6 to 28 knots). The main task of the project involved the acquisition and analysis of high-quality data from both full-scale and model-scale experiments.

The full-scale tests were conducted in Macquarie Harbour in Southwest Tasmania over two separate sessions in January and May 1998. A photograph taken during the full-scale experiments can be seen in Fig. 2. A schematic showing the layout of the test site is shown in Fig. 3. The controlled environment 1/15th-scale model experiments were conducted within a model test basin at the Australian Maritime College in Launceston, Tasmania.

3.2. Full-scale experiments

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

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 discussed in this section, including some comments relating to the present study. Additional information about the importance of measurement techniques during full-scale trials is available in the guidelines developed by the PIANC (2003). The author encourages others to provide a similar level of detail whenever reporting or presenting experimental data of a similar nature.

Table 1 Test vessel particulars

Vessel Particular	Full Scale	Model Scale
Length overall (m)	24.0	1.600
Length waterline (m)	21.71	1.447
Beam overall (m)	8.00	0.533
Beam demihull (m)	2.26	0.151
Demihull spacing (m)	5.5	0.367
Displacement (kg)	55,000	15.898
Draught forward (m)	0.93	0.062
Draught aft (m)	0.95	0.063
Water depth (m)	~12	0.800
Length/depth ratio		~1.8
Model-scale ratio		15.0

3.2.1. Shoreline types. As with other similar studies, the test methodology was arranged to make it independent of the shoreline type, allowing direct comparison between results from other test programs conducted by the author. The tests at the Macquarie Harbour site were conducted well away from the shoreline and so can be regarded as being independent of the shoreline type.

3.2.2. Water depth at vessel sailing line. It is well known that there are fewer variables to account for with regard to vessel-generated waves when the water depth beneath the vessel is considered to be deep. For this to occur, the vessel's Fr_h must remain subcritical (<0.7). A vessel's wave wake field will alter with changes in governing parameters such as water depth and/or vessel speed, but the changes are not instantaneous and take several boat lengths to achieve a steady-state condition.

In instances where the waterway and vessel speeds under investigation result in transcritical (approximately $0.7 < Fr_h < 1.1$) and/or supercritical ($Fr_h > 1.1$) speeds, the conditions must be considered as being *shallow,* and the results must be analyzed and presented accordingly.

The Macquarie Harbour test site has a relatively consistent depth of approximately 12 to 15 meters along the length of the course. For the vessel speeds of interest, the Fr_h covers

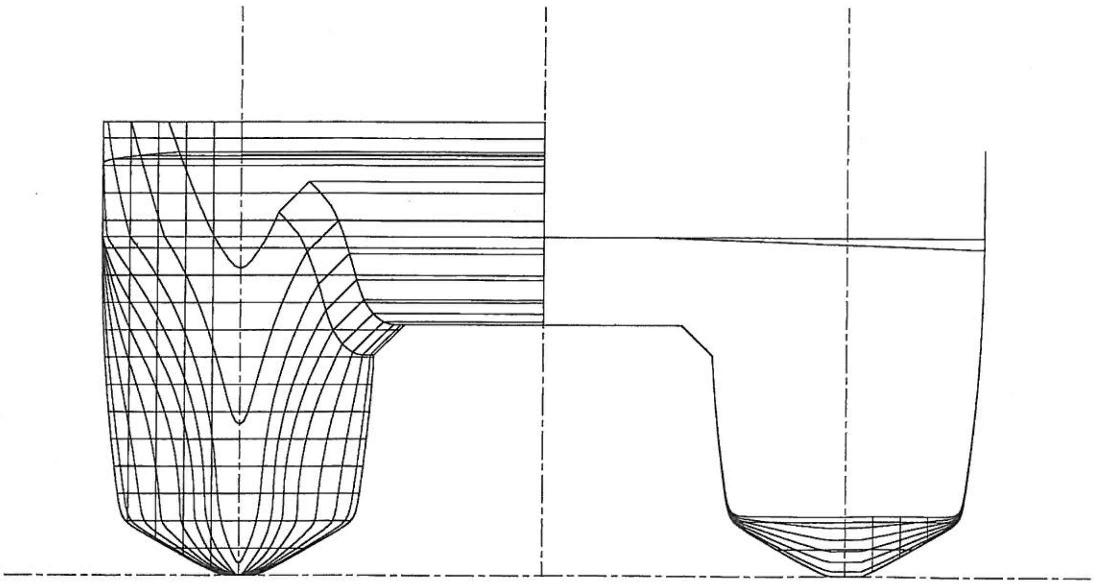

Fig. 1 Body plan of test vessel (permission to publish kindly provided by Incat Crowther Design)

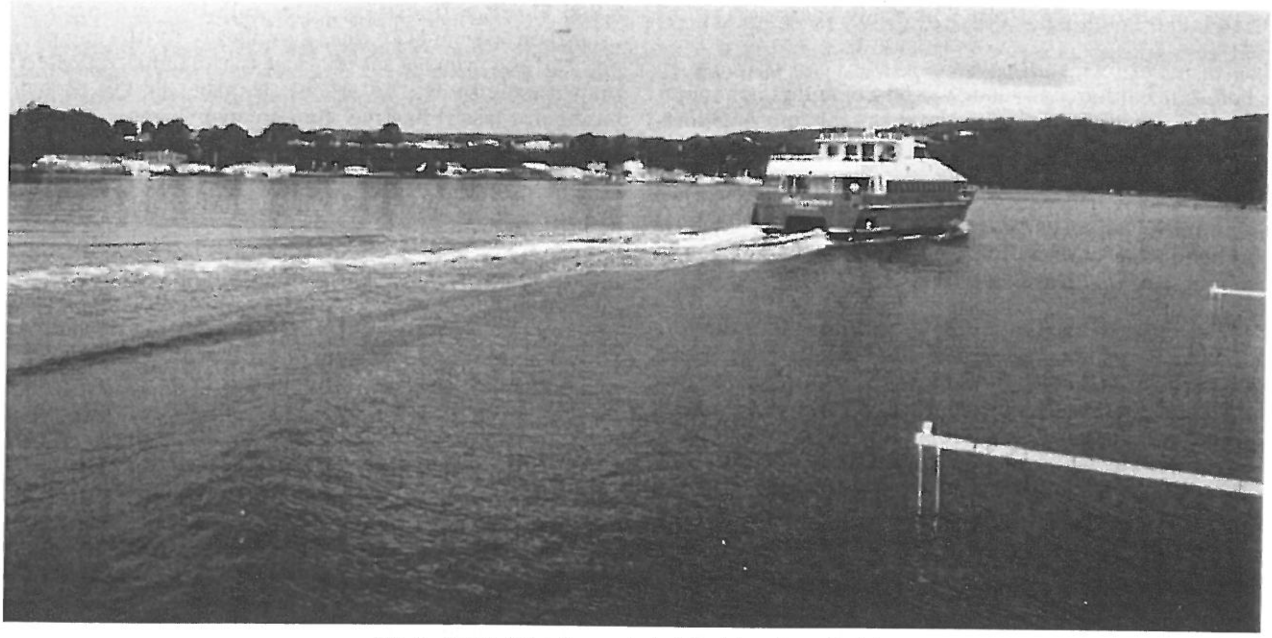

Fig. 2 Taken during the conduct of the full-scale wash trials

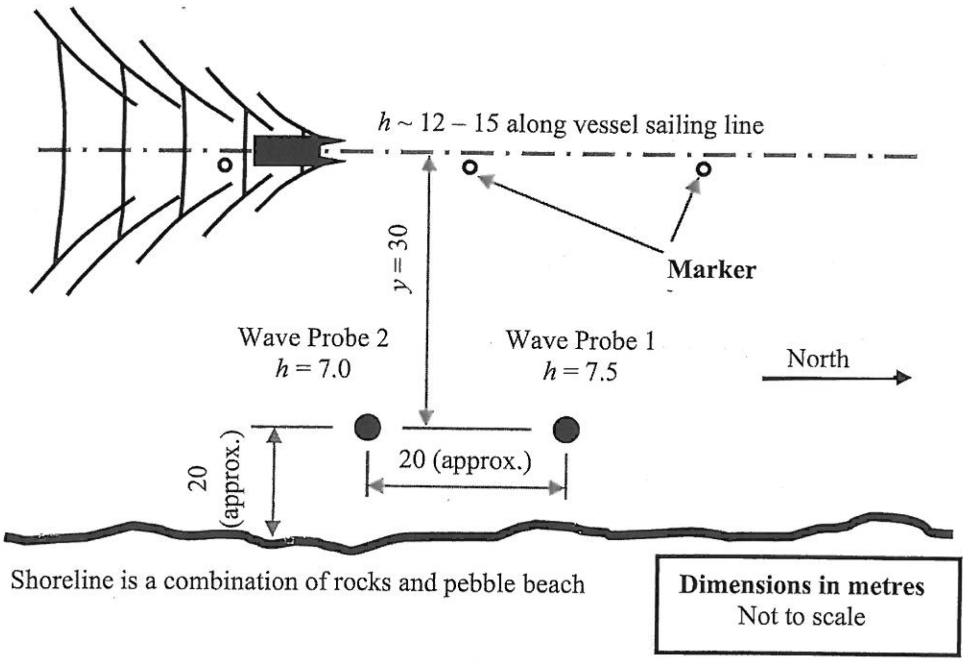

Fig. 3 Layout of test site on Macquarie Harbour

sub, trans, and supercritical speeds ($0.3 < Fr_h < 1.3$). Sorensen (1973) provides a clear description of how the wave patterns generated by a vessel change when traveling within these different speed regimes.

The fact that this study includes experiments at trans and supercritical Fr_h means that the results will be site specific to a degree, in that they should only be directly compared against results where the ratio of vessel length to water depth (L/h) is similar (see Table 1).

3.2.3. Water depth at measurement point. Besides the need to be aware of the depth along the sailing line, there must also be adequate depth at the measurement point(s).

Ideally, the water depth at the measurement point should be greater than half the length of the waves of interest. Equation (1) gives the relationship between water depth and critical period, above which water depth is shallower than half the wave length.

$$T_{crit} = \sqrt{\frac{4\pi h}{g}} \qquad (1)$$

For example, the T_{crit} at the shallowest point of concern in the present study (water depth of ~7.0 meters beneath one of the two wave probes) is approximately 3.0 seconds. The majority of wave periods measured were found to be between 3.0 and 5.0 seconds, highlighting the fact that the water depth will most likely have an influence on the waves, resulting in a degree of shoaling (USACERC 1984). This again results in the absolute measurements from this study being somewhat site specific.

As waves move into shallow water, they can increase in height before breaking. This is a period-dependent phenomenon—the longer-period waves shoaling the most. Short-period waves, such as wind waves, do not shoal much, if at all, before breaking. Any wave with less than approximately 2 seconds period will break virtually unchanged in height. Only minimal shoaling will occur for waves having periods less than about 3 seconds and thus can essentially be ignored for most practical applications (USACERC 1984).

3.2.4. Vessel sailing line. The sailing line must be straight, and vessels must adhere to that straight course during the approach to the measurement point. Wash is focused on the inside of a curved course and spread on the outside of a curved course. It is recommended that marker buoys (a minimum of two) be deployed to act as a guide to the sailing line, taking into consideration the required lateral distance between the centerline of the vessel's track path and the location of the measurement point(s).

3.2.5. Constant vessel speed. The wave wake field generated by any vessel will vary with vessel speed. The test vessel must be traveling at a steady-state speed for a considerable distance before reaching the measurement point and maintain this over the test course, for the wave field to also be considered steady. This distance will depend on the vessel speeds and lateral distance to the measurement point(s) of interest. This factor probably remains one of the single greatest causes of variation in field experiments on small craft. For the present study, the vessel operators aimed to reach the required steady-state speed a minimum distance of approximately six boat lengths prior to being adjacent to the measurement point.

With the advent of low-cost global positioning system (GPS), it is now often more cost effective to carry a GPS unit than to fit a speed log. The GPS will give vessel speed over the ground, whereas a speed log will give speed through the water. Technically, speed through the water is the most applicable measurement when a speed limit is applied to a waterway, as it correctly accounts for current (provided shallow water effects are not substantial). However, it is likely that GPS units will be more prevalent, and so speed limitations must reflect the worst-case condition, traveling up-current.

For the present study, vessel speed was obtained using an onboard GPS and represents the vessel speed over ground (not through the water).

3.2.6. Wave probe position. The wave probes must be positioned such that they are beyond any localized refraction caused by shallow water, or diffraction due to solid obstacles or irregular shoreline shape. Two wave probes were set up at different longitudinal distances within the Macquarie Harbour test site. It is believed that the effect from any local influence on the wave wake field was minimal for this series of experiments.

3.2.7. Wave probe mounting structure. Wave probes should be mounted such that the probe does not move when experiencing passing waves. If a wave probe is capable of moving laterally during field experiments, the resulting wave periods will be contaminated. Similarly, any vertical movement will result in variations in wave height.

For this series of experiments, both wave probes were rigidly mounted to sturdy beams extending out from solid timber pylons that were considered sufficiently rigid to eliminate any notable movement during the conduct of the experiments.

3.2.8. Bank reflectivity. The wake of a passing vessel may take many seconds to pass completely by the measurement point. If the probe is set too close to the bank, reflected waves may contaminate the traces. Gently sloping (beach-type) banks are less reflective than steeper forms.

Minimal reflection was experienced at the Macquarie Harbour test site due to an irregular plan form and the positioning of the probes well outside any possible focal point for reflection.

3.2.9. Interference. Minimization of the ambient wave background is another critical issue. Ideally, the test location must not be open to wind waves, uncontrolled incidental vessel wash, and excessive currents or water turbulence.

As in most field experiments, conditions were not ideal over the entire test session. Wind waves were present during some of the test runs; however, in the majority of cases the height of the ambient waves remained less than about 50 millimeters (approximately 5–15% of the maximum wave heights measured).

3.2.10. Current. The general effect of current on the test results can be predicted, but it can become complicated when testing in waterways that are restricted in either depth and/or width, particularly when the vessel operates close to the depth-critical speed. Generally, for a given speed over the ground (not through the water), wave heights increase when traveling up-current and wave periods become longer. For the vessel traveling up-current to achieve the same speed over the ground, it must travel at a faster speed through the water to counter the opposing current flow. The result is equivalent to traveling at that higher speed through the water with no current present.

The increase in period when traveling up-current is caused by two effects. Firstly, the period may increase due to the higher speed through the water, as it would if the vessel traveled faster in still water. Secondly, the propagation speed of the waves (relative to the earth fixed wave probe) has a current component, so the waves travel across the probe slower, creating an apparent increase in period. For the divergent waves, which propagate obliquely, the current effect on period is less than the transverse waves, which propagate parallel to the sailing line. This is further complicated if the vessel is traveling obliquely to the current itself, which is unlikely in a river environment. It should also be noted that current velocity is likely to vary at different positions within a river.

As an example, a vessel traveling at 4 knots over the ground into a 2 knot current is traveling at 6 knots through the water, so the wave parameters are representative of the 6 knot speed. If the vessel turns and travels at 4 knots over the ground with the 2 knot current, it effectively is traveling at 2 knots through the water and produces waves as such.

When the current velocity is a substantial fraction of the vessel speed, the wave results will be influenced. Similarly, when the current velocity is a small fraction of the vessel speed, as is often the case at high speeds, the resulting wave data scatter is small.

Negligible current was experienced during the test sessions at Macquarie Harbour.

3.2.11. Instrumentation. The correct use and calibration of appropriate instrumentation is of utmost importance to any experimental program. It is essential that instrumentation such as wave probes be calibrated and checked regularly as variations in conditions (such as water density, temperature, and salinity and air temperature) can drastically alter the accuracy of measured data (PIANC 2003).

For the full-scale experiments in the present study, water surface elevation was measured using two salt/fresh water capacitance wave probes with cables run back to a custom data acquisition unit stationed approximately 20 meters from the wave probes.

It is recommended that all wave probes be calibrated within the laboratory prior to and following each test session. It is often difficult to conduct comprehensive and accurate calibrations during on-site experiments; however, it is highly recommended that on-site checks at least be made at the start and on completion of each test session. The above procedure was adopted during the present study with good repeatability between the on-site and laboratory calibration factors (less than 2.0% variation). It should be noted that a zero shift can be expected during the course of a test session, usually due to minor variations in tide/river level.

Recording the water surface elevation signals from both wave probes was commenced well prior to the arrival of the test vessel to provide a baseline noise measurement before the arrival of the wake waves at each of the wave probes.

There are a number of technical factors related to the instrumentation and data acquisition that should also be addressed to ensure good quality data is obtained. These include wave probe resolution, analog-to-digital conversion resolution, and sample rate. For the present study, the wave probes had a resolution of approximately 1.0 millimeters, analog-to-digital conversion resolution was 12 bit, and a sample rate of 20 Hz was adopted for all on-site experiments. The sample rate should be sufficiently high so as to allow clear definition of all waves of interest (both vessel and wind generated). The sample rate of 20 Hz for these tests (conducted in 1998) is now considered to be adequate, but relatively low when compared with recent practice, where a rate of 100 Hz is often adopted.

3.2.12. Lateral distance between measurement point and vessel sailing line. Dispersion can create difficulties when assessing wave traces obtained through the conduct of physical experiments. Where a wave trace is taken close to a vessel (within, say, half a boat length), the trace may appear to consist of only a few waves, when in fact these waves represent many more superimposed waves of differing wave length. It takes approximately two to three boat lengths for waves to disperse sufficiently such that the period of individual waves can be measured with certainty (Macfarlane 2002). Wave height is affected to a lesser degree.

Similarly, an overly large lateral distance between measurement point(s) and vessel sailing line (say, more than five boat lengths) can allow time for natural elements, such as wind and current, to influence the vessel generated waves. However, if the primary aim of the experiments is to investigate wave attenuation over distance, then even larger lateral distances (for example, 10 boat lengths), may be required.

For the experiments at Macquarie Harbour, the lateral distance between the wave probes and the vessel sailing line was just 30 meters ($y/L = 1.38$), which was just adequate. For more recent trials the y/L has generally been between 2.0 to 3.0.

3.2.13. Other vessel-related variables. Particulars such as the vessel's still water draught (fore and aft) and trim should be measured prior to and following each test session. Similarly, the use of any trim control devices during operation, such as trim flaps, stabilizers, or foils should be documented.

3.2.14. Number of test runs. Due to many of the issues discussed previously, it is recommended that multiple runs be conducted at each nominal vessel speed increment to ensure a sufficiently robust statistical database is acquired. This was achieved for the present study, with approximately 85 test runs conducted.

3.3. Model-scale experiments

3.3.1. Model scaling laws. As is the case with most scale models, those used in this study are geometrically similar, where the vertical and horizontal scales are the same, and they represent a true geometric reproduction of the prototype.

Similarly, for many problems involving water waves, inertia is the most predominant force in the system. This is why Froude scaling is used more extensively than any other for studies involving wave mechanics (Chakrabarti 1994). Many years of Froude scale modeling (through bodies such as the ITTC) has resulted in the development of a large background of experimental procedures and data reduction techniques.

Using Froude scaling, the wave height, wave length, and water depth scale linearly (as $1/\lambda$). Time and wave period scale as $1/\sqrt{\lambda}$.

3.3.2. Description of experimental facility. The facility used for the conduct of the model-scale experiments within a controlled environment was the Australian Maritime College's model test basin located on its campus in Launceston, Tasmania. The basin is 35 meters long by 12 meters wide with an adjustable water depth between 0 and 1.0 meters. This facility is ideally suited for conducting experimental research into the wash generated by marine craft, particularly when operating in shallow water depths.

The ship model was attached to a carriage that was towed using a dedicated winch system driven by an electric motor and gearbox and controlled by a digital speed control unit. The dynamometer allows the ship model freedom in pitch, heave, and roll. The variable speed towing mechanism is fitted with a fully automated braking system, programmable acceleration and deceleration ramps, and a pulse generator to supply an accurate chain of pulses related to drum speed in order to obtain an accurate recording of the actual model speed.

Removable wave absorbers can be positioned along each side wall and one end wall of the basin to minimize wave reflections during calm water tests. A fixed wave absorber was located at the other end wall of the basin. Additional details related to conducting wave wake measurements within this facility can be found in Robbins et al. (2007).

3.3.3. Instrumentation. Water surface elevation was measured using six capacitance-type wave probes positioned at various lateral locations relative to the model's sailing line. The wave probes were fully calibrated after being positioned in the basin, and calibration checks were made prior to commencing and following the completion of the test program, with variations of less than 0.5%.

3.3.4. Test program. The model-scale experiments were conducted following the full-scale trials at Macquarie Harbour to replicate the vessel displacement, draught, and static trim of the vessel during the full-scale trials. These details are provided in Table 1.

4. Presentation of data

4.1. Full-scale data

4.1.1. Wave elevation time histories. Repeatability is a key aim of any experimental study, but is often an aspect

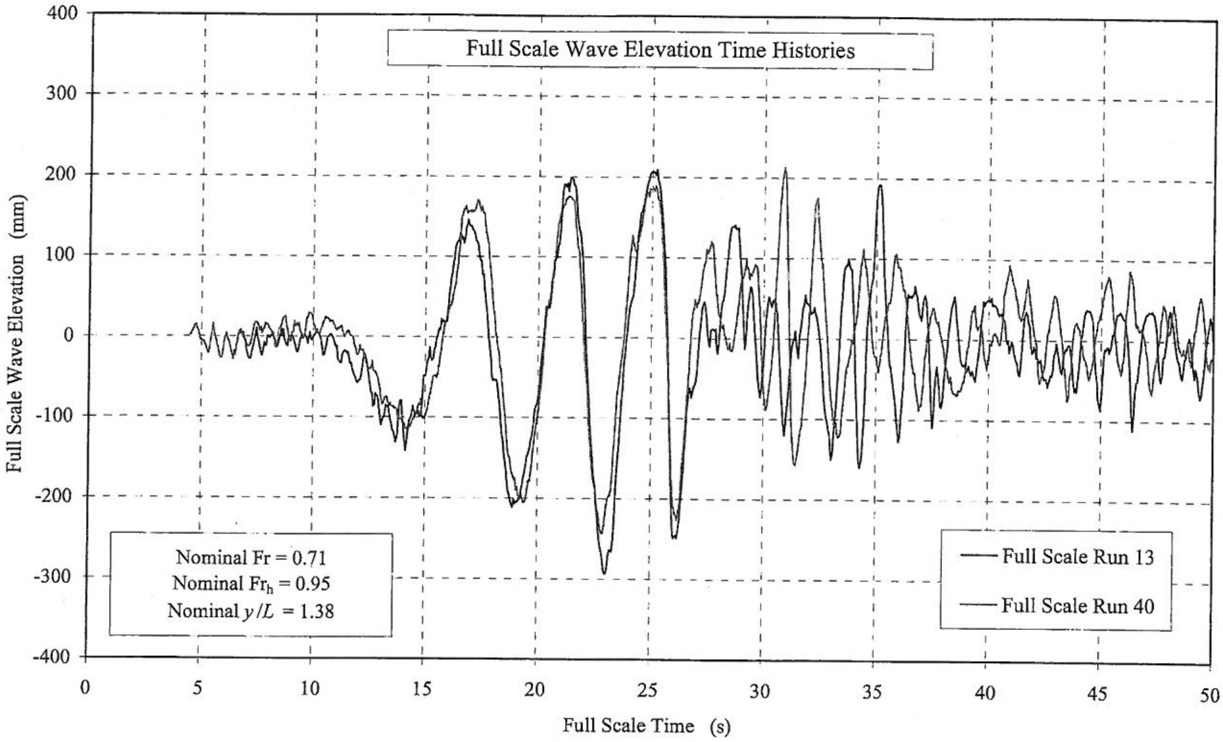

Fig. 4 Comparison of wave elevation time histories from full-scale trials

that can be difficult to achieve when directly comparing individual wave elevation time histories from data collected during full-scale trials. In addition to the vast number of factors that can vary whenever undertaking experiments in an uncontrolled environment (as discussed previously), it should also be recalled that subcritical vessel generated waves vary with lateral distance due to dispersion, decay, and interaction between the transverse and divergent wave systems (Macfarlane 2002, Macfarlane & Renilson 1999). Thus, it is almost impossible to obtain two wave elevation time histories from full-scale trials that can be considered the same. It is, however, expected that much better repeatability should be achievable for standard wave wake measures that can be extracted from time histories, such as the height of the maximum wave and its related period.

An example of repeatability from the full-scale tests is shown in Fig. 4, where the resulting wave elevation time histories for two different runs at the nominal Fr of 0.71 (Fr_h = 0.95) are shown. Note that time is plotted along the x-axis and water surface elevation along the y-axis. It can be seen that the similarity between runs R13 and R40 appears good under the circumstances, particularly when considering that these two runs were conducted in different test sessions 4 months apart. It should be noted that both the vessel speed and the lateral distance between the vessel sailing line and measurement point are nominal values, and an error analysis indicates that these values may vary by up to approximately ±2% and 4%, respectively.

4.1.2. Maximum wave height, period, and energy. There has been considerable discussion in recent years about the most appropriate measure(s) with which to quantify wave wake, particularly when shoreline erosion is a key concern. The height and period of the highest individual wave, commonly referred to as the *maximum* wave, appear to have emerged as the most appropriate and thus most frequently adopted (Macfarlane & Renilson 1999, 2000, Glamore et al. 2005). These standard measures have been used in this study, as together they readily provide a numerically concise description of the wave most likely to exceed any threshold of acceptable effect.

The height and period of the *maximum* wave are often used to determine the wave energy (per meter crest length) and can be calculated using:

$$E_m = \frac{\rho g^2 H_m^2 T_m^2}{16\pi} \quad (2)$$

The height and period of the maximum wave can be readily extracted from each wave elevation time history. The maximum wave height was obtained by combining the individual peak and trough amplitudes. The maximum wave height is defined as being the single greatest distance from a trough to a successive crest (or crest to trough) recorded anywhere within the sample, and the wave yielding this maximum height is termed the *maximum* wave.

The corresponding wave period data is usually related to the maximum wave. It is obtained from the zero-crossings at the start and end of the maximum wave. It should be noted that not all wake waves generated within a wave packet have the same period. This is especially true for wake waves generated at or near critical Fr_h and above (Whittaker et al. 2000).

Figure 5 shows the maximum wave heights from all analyzed test runs plotted as a function of Fr. Also shown in Fig. 5 are 12% error bars on the measurement of the wave height and 2% error bars on vessel speed. These have been estimated by conducting an uncertainty analysis (ITTC 2005b). As can be expected, a fair degree of scatter in the results is displayed.

The period of the maximum waves from all analyzed test runs are plotted as a function of Fr in Fig. 6. As for maximum wave height, error bars (3.5%) have been fitted to the wave period data. There is less scatter with the wave periods measured, which corresponds with other studies involving wave wake measurements (Macfarlane 2006, Macfarlane & Cox 2004).

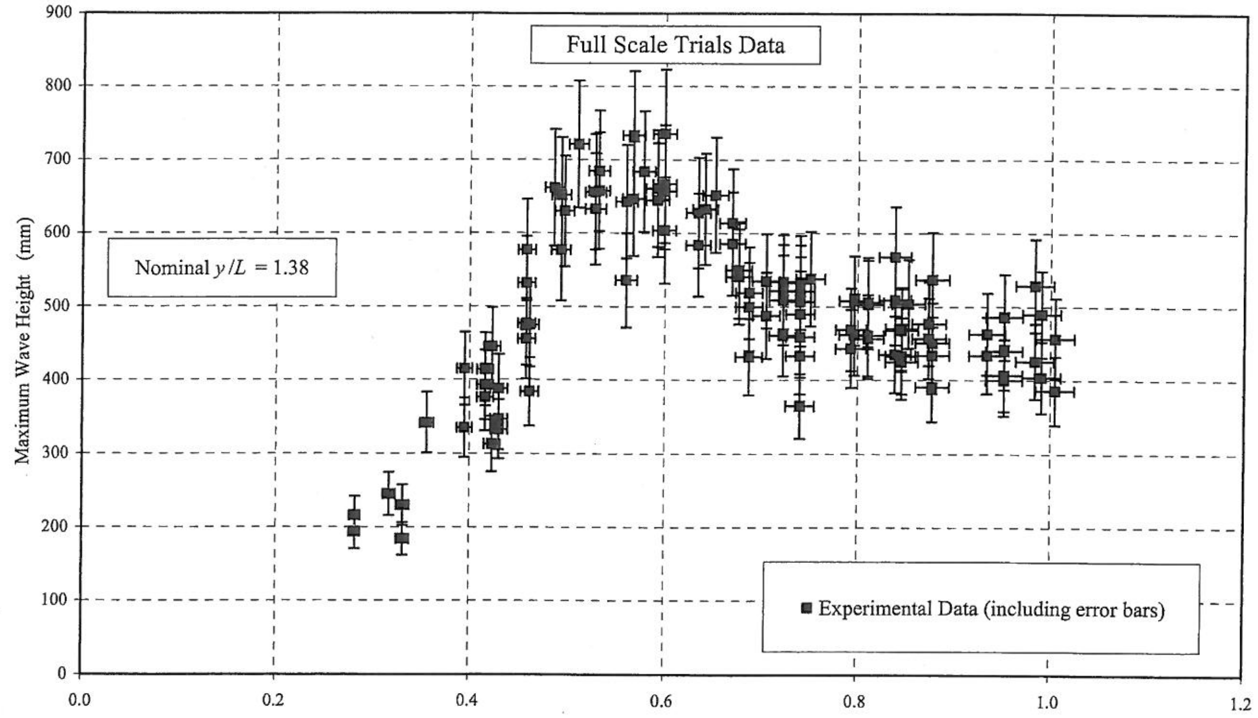

Fig. 5 Full-scale trials data. H_m as a function of Fr

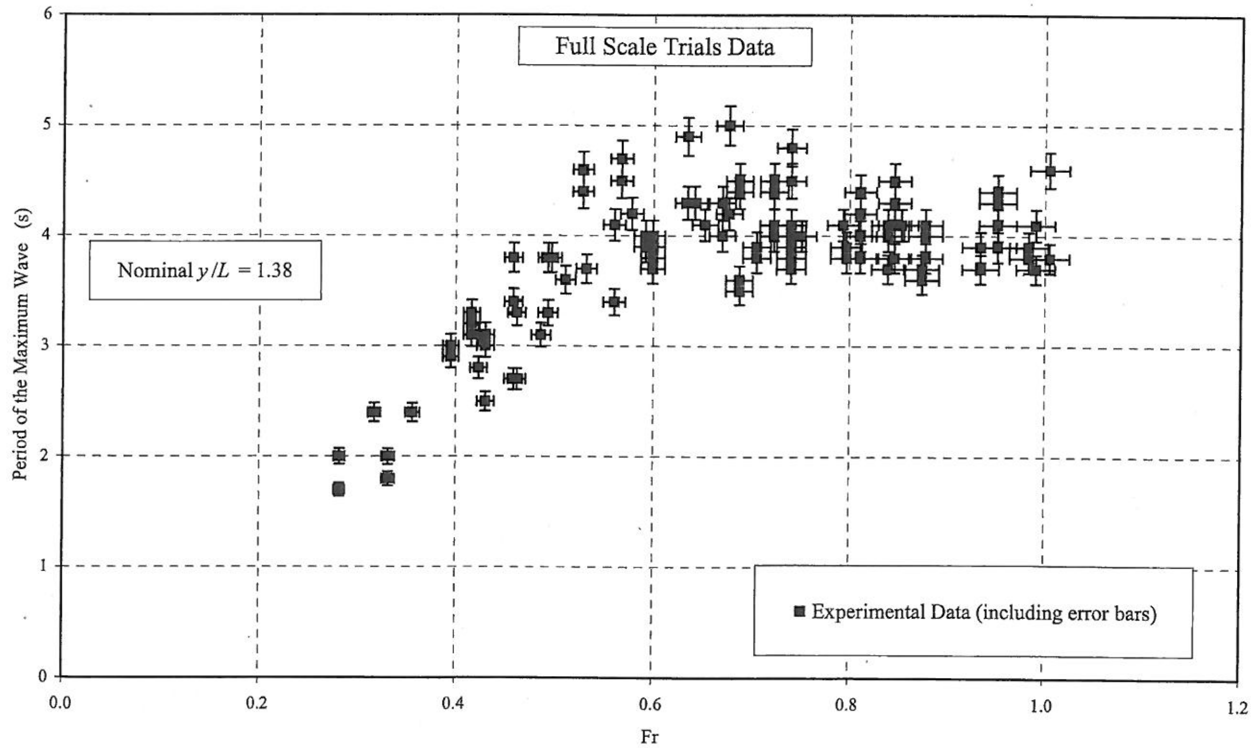

Fig. 6 Full-scale trials data. T_m as a function of Fr

The resulting energy for each maximum wave can be calculated using equation (2). This is plotted as a function of Fr in Fig. 7.

Full-scale testing is always subjected to external environmental influences such as wind waves and currents and can never yield the same degree of accuracy as model testing within a controlled environment. The measurement of speed, the attainment of a steady-state vessel operating condition, effects due to water depth and wind wave contamination were most likely the greatest causes of data scatter.

It is worth noting that even when the repeatability appears good on the surface, as seen in Fig. 4, there can still be relatively notable variations in the values for maximum wave height. For example, for the two runs presented in Fig. 4,

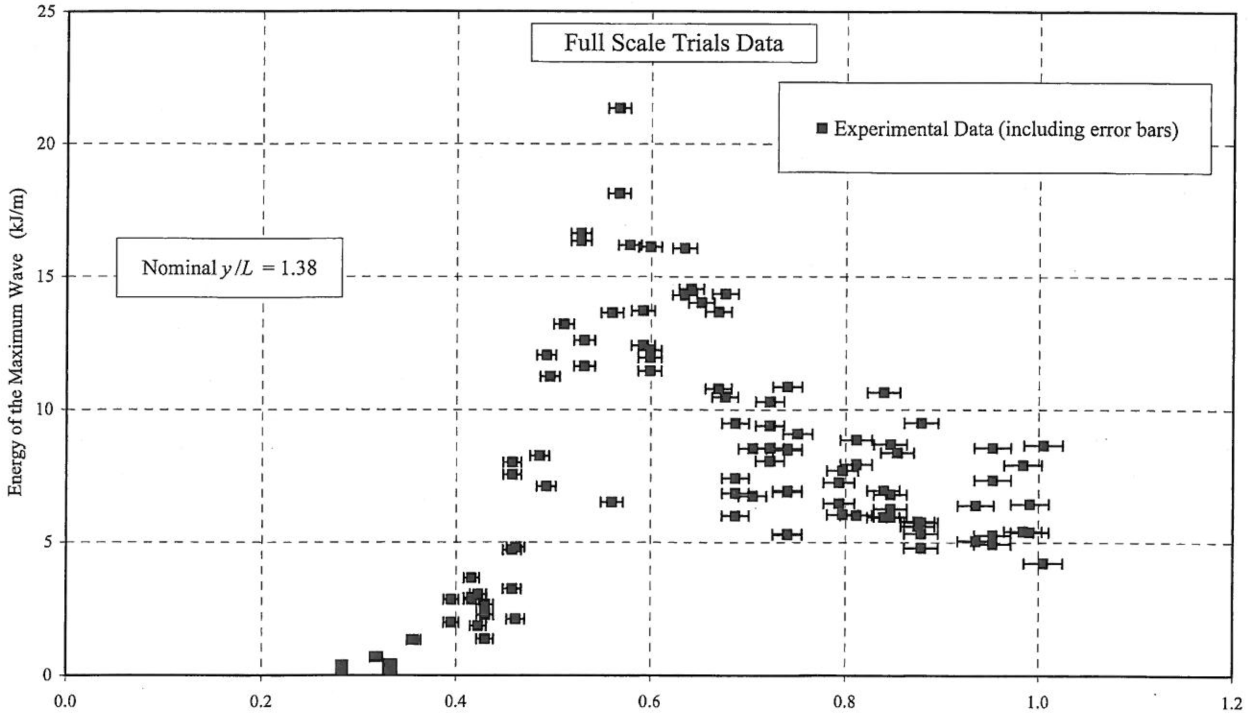

Fig. 7 Full-scale trials data. E_m as a function of Fr

values of 432 and 500 millimeters are extracted, which represents a 15% difference. In this example there is less than 5% difference in period of the maximum wave.

4.2. Model-scale data

4.2.1. Wave elevation time histories. As discussed previously, repeatability is a key aim of any experimental study. Unlike full-scale trials, it should be possible to obtain excellent repeatability when conducting experiments within a controlled environment such as the AMC model test basin.

An example of the excellent repeatability that can be obtained during physical model experiments in a controlled environment is highlighted in Fig. 8 where the resulting wave elevation time histories for two different runs at Fr = 0.71

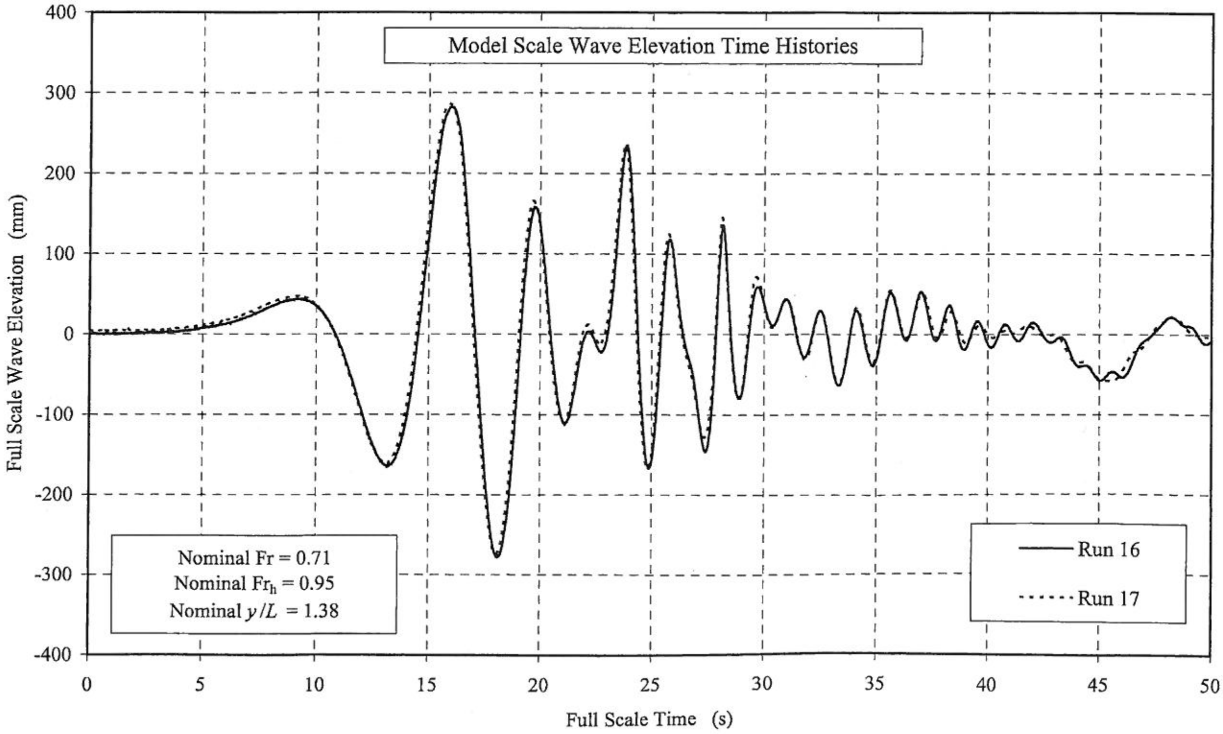

Fig. 8 Comparison of wave elevation time histories from model-scale tests, Fr = 0.71

are shown. Here the differences are so small it is difficult to distinguish between the two separate runs.

It is recommended that a repeat run be conducted at all speeds of interest, if simply to confirm that good repeatability has been achieved (by producing plots such as that shown in Fig. 8).

Repeatability alone is not an indicator that accurate wave wake measurements have been acquired. Factors such as those discussed previously are equally important during the conduct of model-scale experiments within a controlled environment as they are for full-scale on-site experiments. For example, it is possible to obtain repeatable wave wake traces that include waves generated prior to the ship model attaining the required constant speed and/or waves that are affected by reflected waves off test basin walls. This later problem has been acknowledged as a limitation for undertaking wave wake experiments within conventional towing tanks because of their relative narrowness (ITTC 2005a, Macfarlane 2002).

By looking at the wave elevation time history shown in Fig. 8, it can be seen that it is a straightforward task to identify the maximum wave, from which the height and period can be readily determined. However, when investigating waves generated by vessels operating at supercritical Fr_h it is likely that at least two distinct wave packets of different (nominal) wave period will be identifiable (Sorensen 1973, Whittaker et al. 2000). An example of this is shown in Fig. 9, where the wave elevation time history for a run at Fr = 0.85 is shown (Fr_h = 1.14).

In such cases it is not uncommon to find that the highest wave may occur within the second (or third) wave packet, but this wave will possess a much shorter wave period than those waves in the first packet. However, this highest wave is not necessarily the wave with the greatest energy. This honor is more likely to go to the smaller but notably longer wave in the first packet (as indicated in Fig. 9), recalling from equation (2) that both height and period are equally weighted when calculating wave energy.

This brings into question the precise definition as to which of these two (or perhaps more) waves should be considered as the *maximum* wave. For the present study, two maximum waves are considered for all supercritical Fr_h: those with the greatest *height* and the greatest *energy*, as indicated in the example given in Fig. 9.

4.2.2. Maximum wave height, period, and energy. It is well known that, for subcritical speeds, interference between the transverse and divergent wave systems will affect the wave heights measured at different distances from the vessels' sailing line. As a result, it is recommended that wave elevation time histories be obtained at many transverse locations (a minimum of five is recommended) to undertake an accurate assessment of the degree of wave decay over distance and to minimize the influence of the interaction between wave systems (Macfarlane 2002). It should also be noted that the rate that waves generated at subcritical speeds decay will vary from those at trans and supercritical speeds. The decay rate is also likely to vary with changes in vessel speed and water depth.

In Fig. 10 maximum wave height is plotted as a function of lateral distance for the Fr of 0.63. The curve of best fit through the experimental data is of the form of:

$$H_m = \gamma \cdot y^{-1/N} \tag{3}$$

Note that γ (gamma) is a constant (dependent on vessel speed) and is obtained from the model test data (Renilson & Lenz 1989, Macfarlane & Renilson 1999). For the two runs shown in Fig. 10 the decay exponent, N, equates to −0.36. It has been shown that a good engineering approximation of the decay exponent for subcritical divergent waves is −0.33; however, it has been shown to vary between −0.2 and −0.45 (Macfarlane 2002).

Figure 11 shows the model-scale predictions for maximum wave height and the related wave period plotted as a function of Fr. Also shown are 6.5% error bars on the measurement of the wave height and 3.0% error bars on the measurement of

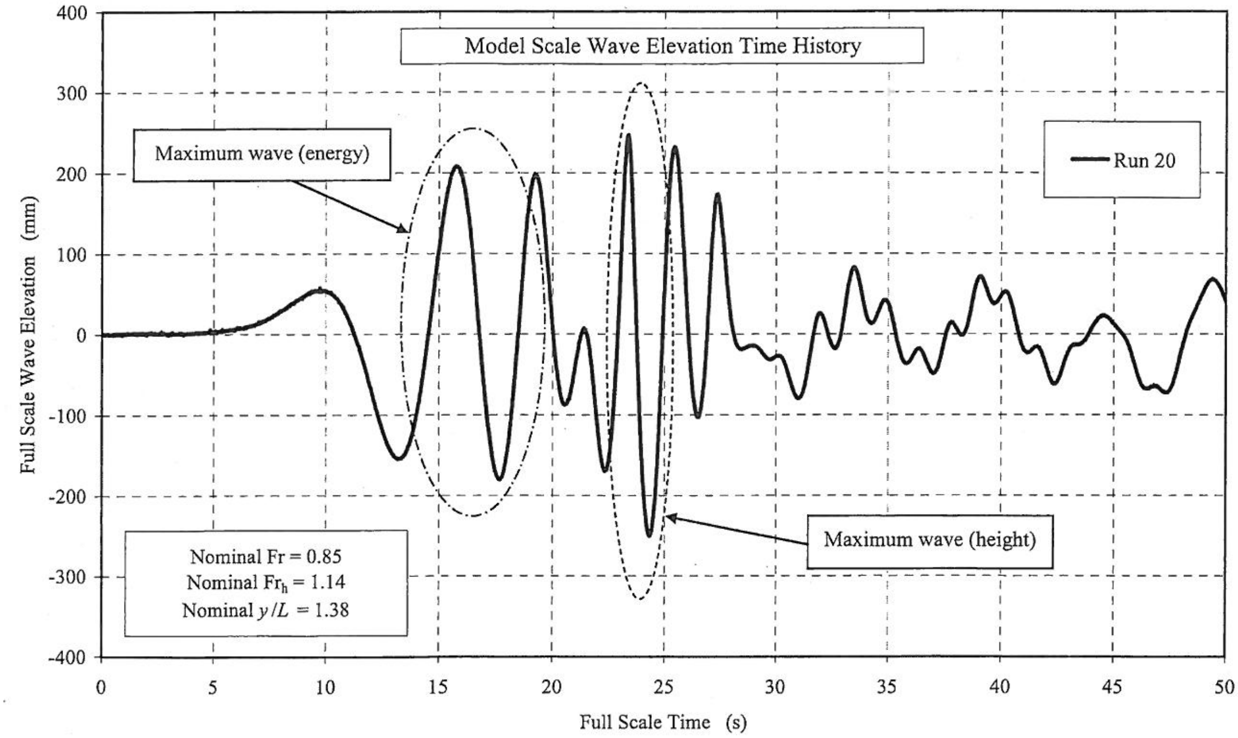

Fig. 9 Comparison of wave elevation time histories from model-scale tests, Fr = 0.85

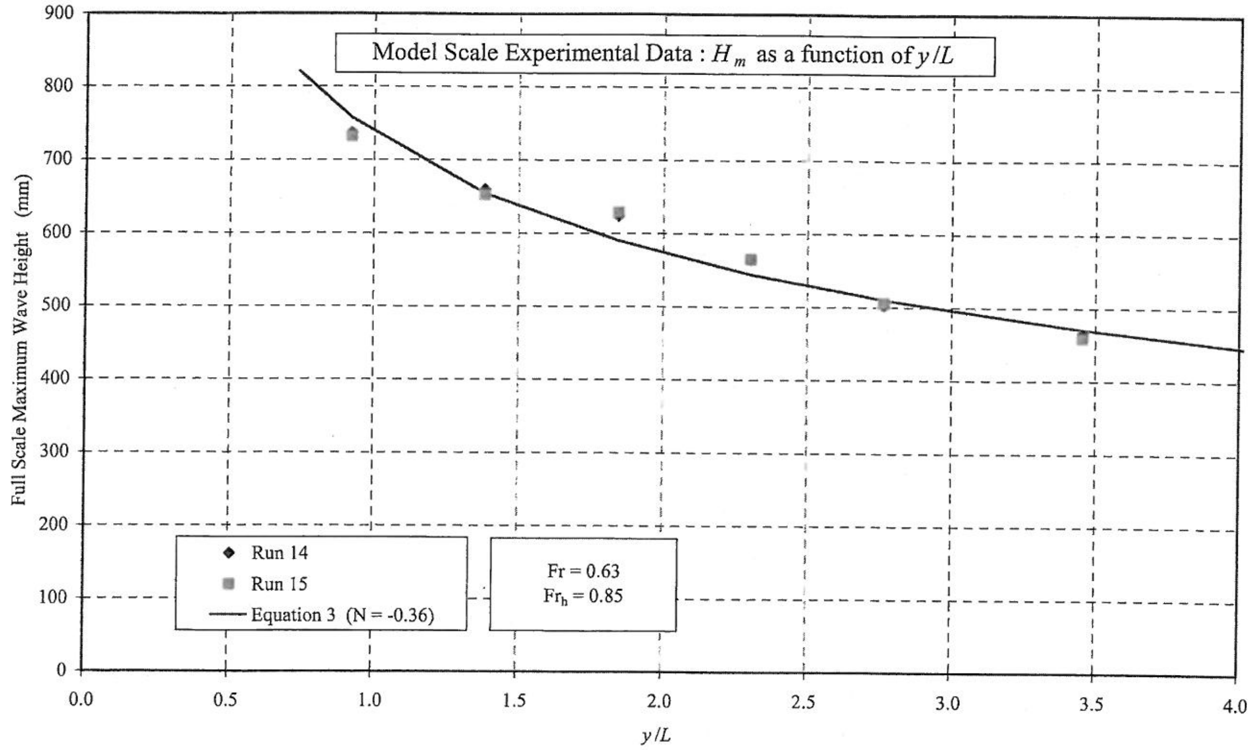

Fig. 10 Model-scale test results. H_m as a function of y/L

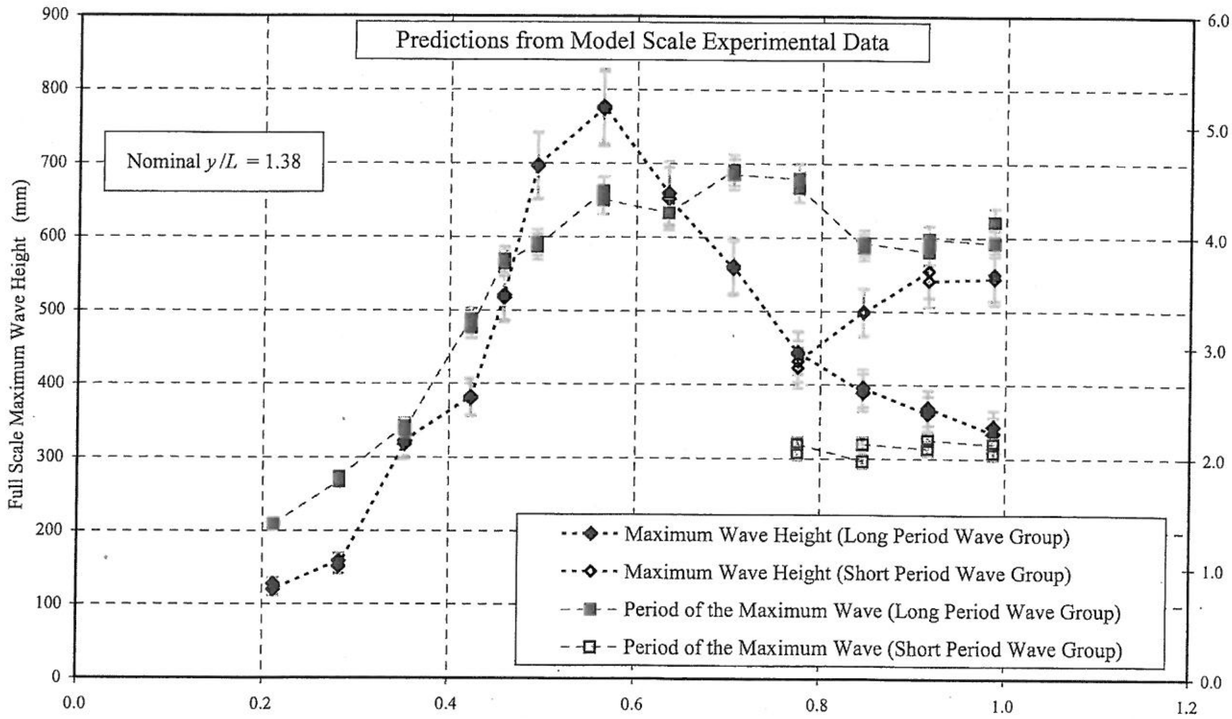

Fig. 11 Model-scale predictions. H_m and T_m as a function of Fr

wave period. Errors of less than 0.5% can be expected for model speed and lateral distance (y) within this controlled environment and hence have not been indicated in this figure.

As can be expected, maximum wave height increases with increasing Fr up until around the so-called "hump" (or "hull") speed of Fr = 0.5 where vessel wavemaking resistance is known to reach a peak. As the Fr increases further the maximum wave heights reduce.

For Fr of 0.78 and above, where in this case the Fr_h become supercritical, the maximum wave heights and related wave periods for the highest waves in both the long- and short-period wave packets have been presented in Fig. 11. For the long-period wave group, the period remains roughly constant at around 4 to 5 seconds, while the maximum wave height gradually continues to reduce. A different result is found for the short-period wave group where the height of the maximum wave increases, whereas the period is fairly constant but roughly only half that for the long-period wave group.

The resulting energy for each maximum wave, calculated using equation (2), is plotted as a function of Fr in Fig. 12. The dramatic increase in energy around the hull speed (~Fr = 0.5) is clearly evident. Also of note is the fact that the maximum wave in the long-period wave group consistently has a greater energy than the maximum wave in the short-period wave group, although the difference between them reduces with increasing Fr. Unfortunately, it is not possible to conclude from this series of data if this trend would continue such that the energy of the maximum wave in the short-period wave group exceeds that of the long-period wave group with a further increase in speed.

The results in Figs. 11 and 12 highlight how important it is to clearly define the maximum wave (or any similar measure) when quantifying waves generated at trans and supercritical depth Froude numbers. The author is presently involved in further research to better define the most suitable measure for such circumstances.

4.3. Comparison of model and full-scale results

4.3.1. Wave elevation time histories. As was shown in Fig. 8, it is possible to obtain similar wave wake traces from repeat runs within a controlled environment. It was explained in earlier sections that it is much more difficult to obtain good repeatability of wave wake traces from full-scale trials because of the large number of variables involved, particularly due to ambient conditions, wave dispersion, and the interaction between divergent and transverse wave systems. However, a typical example from the present study was presented in Fig. 4 where two runs, at the nominal Fr of 0.71, were found to be relatively good under the circumstances.

The wave elevation time histories from these two full-scale runs have been directly compared against the corresponding data from the model-scale tests in Fig. 13 (for a common nominal speed and lateral distance). A similar comparison is provided in Fig. 14 for the nominal Fr of 0.85.

As can be seen in Figs. 13 and 14, there are definite similarities between the model and full-scale traces, particularly with regard to the period of waves throughout the wave trace. As can be expected, there is some variation in the heights of each wave, presumably due to the reasons previously discussed.

4.3.2. Maximum wave height. Figure 15 compares the full-scale measured maximum wave heights against those predicted from the model-scale experiments, both plotted as a function of Fr. For clarity, all error bars previously displayed have been removed.

As can be seen, there is generally good agreement between the full-scale measurements and the model-scale predictions, particularly for speeds up to Fr = 0.5. For speeds 0.5 < Fr < 0.7 the model-scale predictions tend to be close to the upper edge of the full-scale data, suggesting that the model-scale predictions are slightly conservative. The predictions of maximum wave height for each of the two wave period groups for the supercritical speeds have been also been compared against the full-scale trials data in Fig. 15. Interestingly, the maximum wave height from the long-period waves appears to be close to the lower edge of the full-scale data, and those of the short-period waves are close to the upper edge. It may be possible that the apparent increase in scatter in the full-scale data around these supercritical speeds may be partly due to the similarity in wave heights between the two wave groups (as is evident in Fig. 14).

From these results it is concluded that a correlation factor close to unity should be applied when using model-scale experimental data to predict full-scale maximum wave heights for similar vessels operating within the speed range of 0.3 <

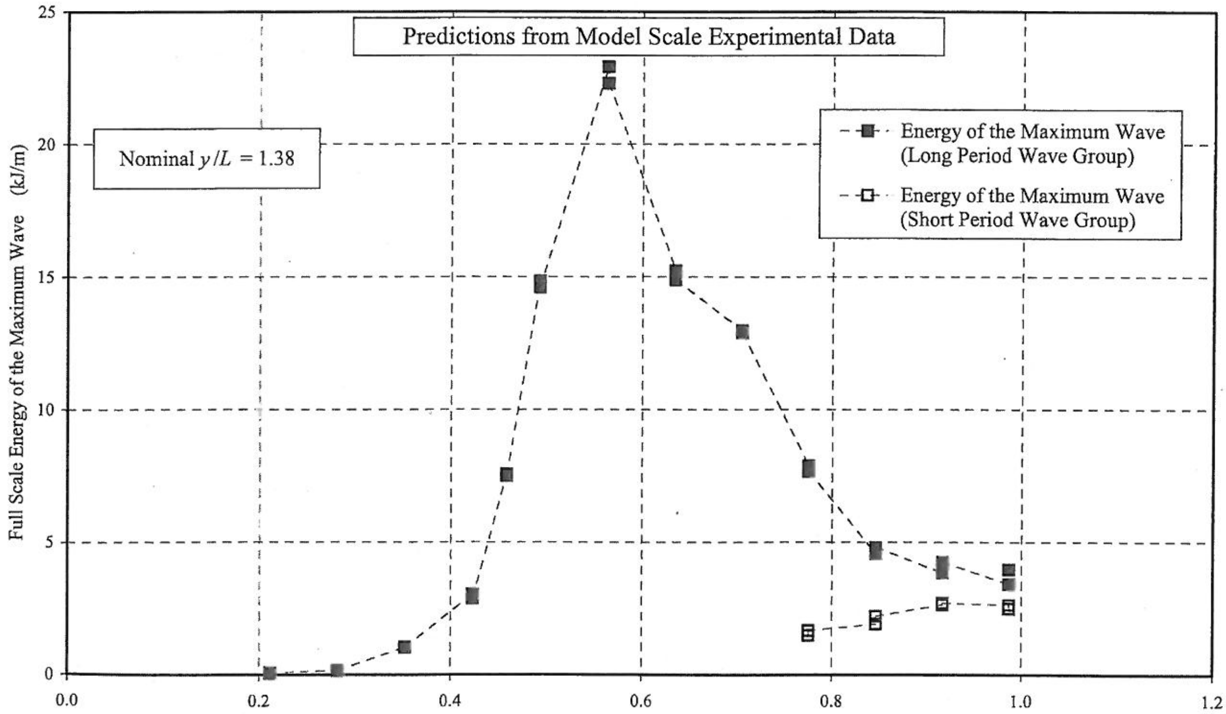

Fig. 12 Model-scale predictions. E_m as a function of Fr

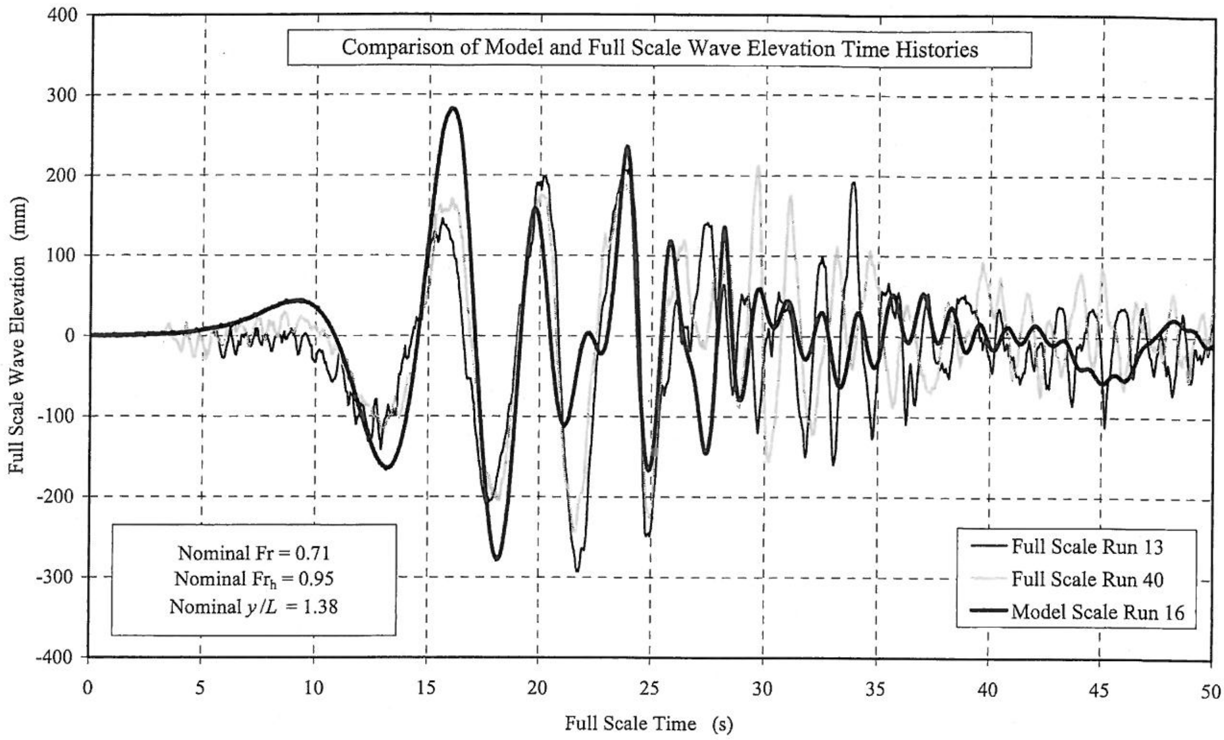

Fig. 13 Comparison of model-scale predictions with full-scale trials data. Wave elevation time histories, Fr = 0.71

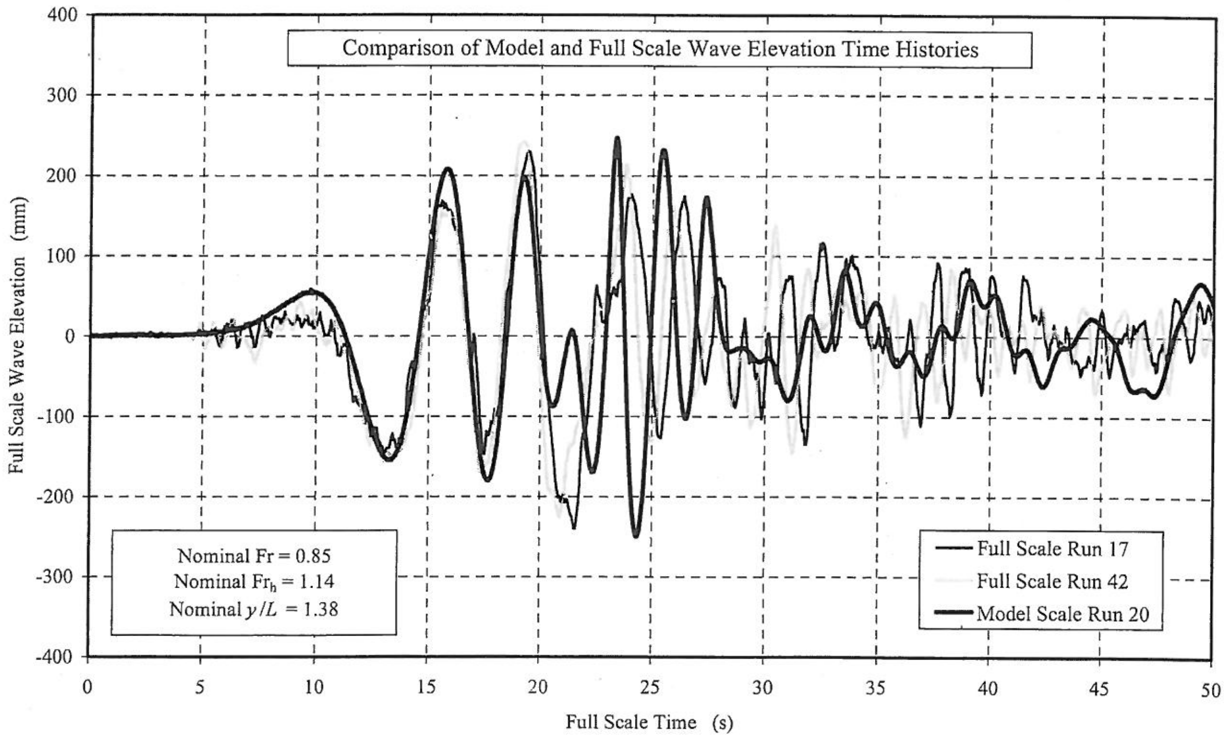

Fig. 14 Comparison of model-scale predictions with full-scale trials data. Wave elevation time histories, Fr = 0.85

Fr < 0.8, provided the Fr_h remains subcritical. It is possible that such a correlation factor may be conservative around Fr = 0.5.

It is more difficult to pinpoint a suitable correlation factor for the higher speed range of 0.8 < Fr < 1.0, most likely due to the difficulties discussed previously for trans and supercritical Fr_h. As a result, it is clear that close attention must be paid to the two (or more) distinct wave packets that are characteristic of vessel operation at such speeds.

4.3.3. Wave period of the maximum wave. The full-scale measured period of the maximum waves are compared against those predicted from the model-scale experiments in Fig. 16, both plotted as functions of Fr.

As can be seen, there is good agreement between the full-scale measurements and the model-scale predictions for the period of the highest wave in the long-period wave group. The poor correlation between the full-scale data and the model-scale predictions for the short-period waves suggests

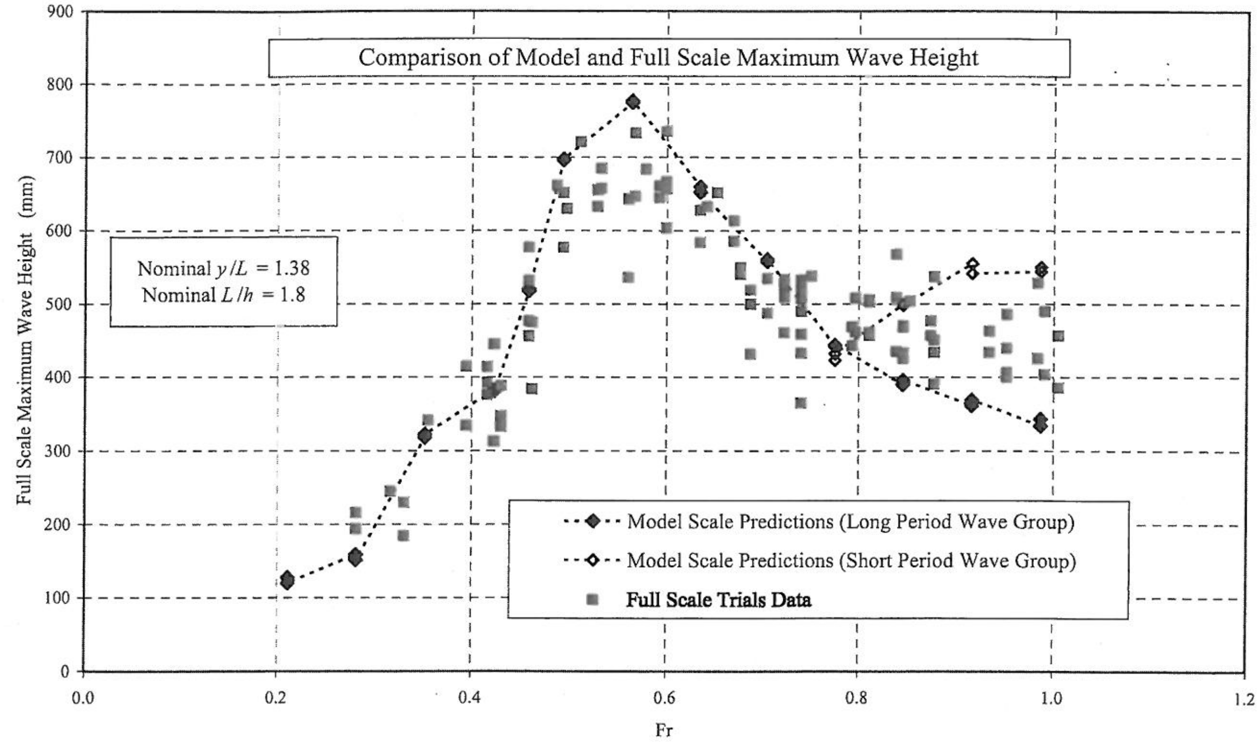

Fig. 15 Comparison of model-scale predictions with full-scale trials data. H_m as a function of Fr

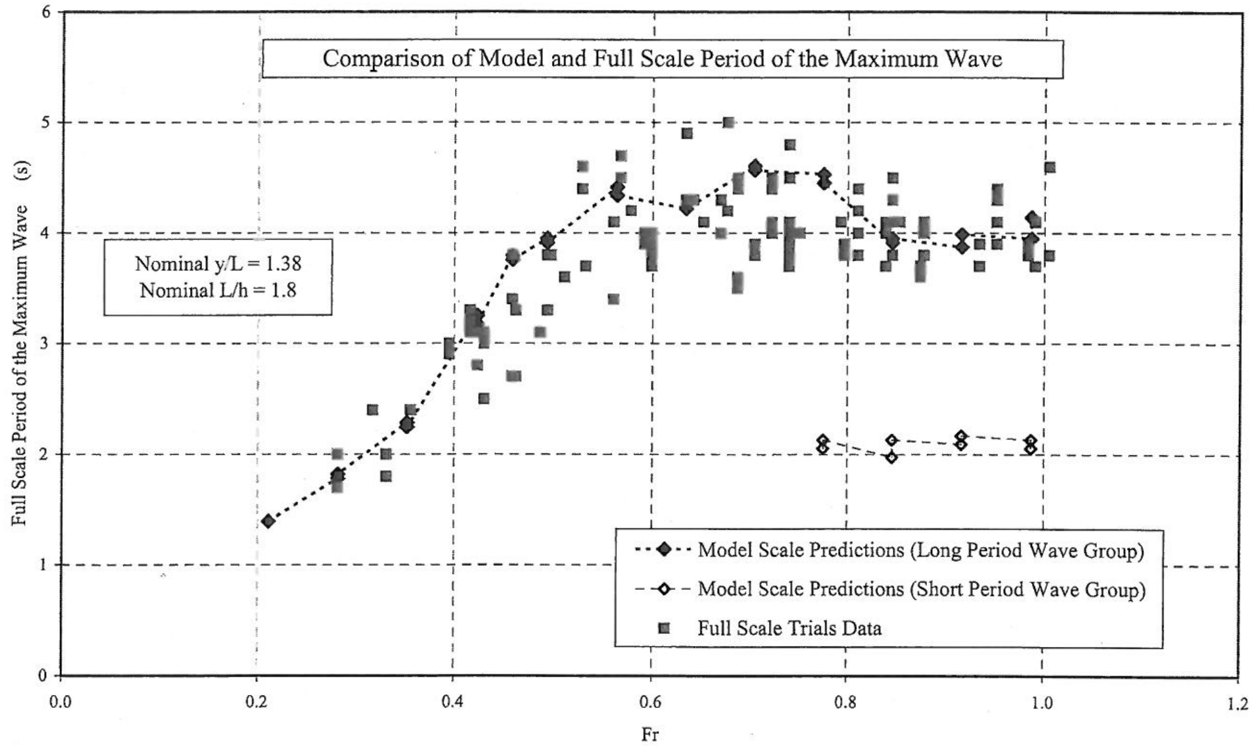

Fig. 16 Comparison of model-scale predictions with full-scale trials data. T_m as a function of Fr

that the longer-period waves were dominant during the full-scale trials within the uncontrolled environment. In reality, it is the longer-period waves that are generally of more interest to those concerned with the effects of vessel-generated waves.

Thus, it is suggested that a correlation factor close to unity may be applied when using model-scale experimental data to predict the period of full-scale maximum waves for the speed range of $0.3 < \mathrm{Fr} < 0.8$. This correlation factor may also be applicable at higher speeds, provided that the L/h ratios are similar, and it is the longer-period wave group that is assessed if the vessel is traveling at supercritical speeds.

4.3.4. Wave energy of the maximum wave. The energy of the maximum waves measured during the full-scale trials

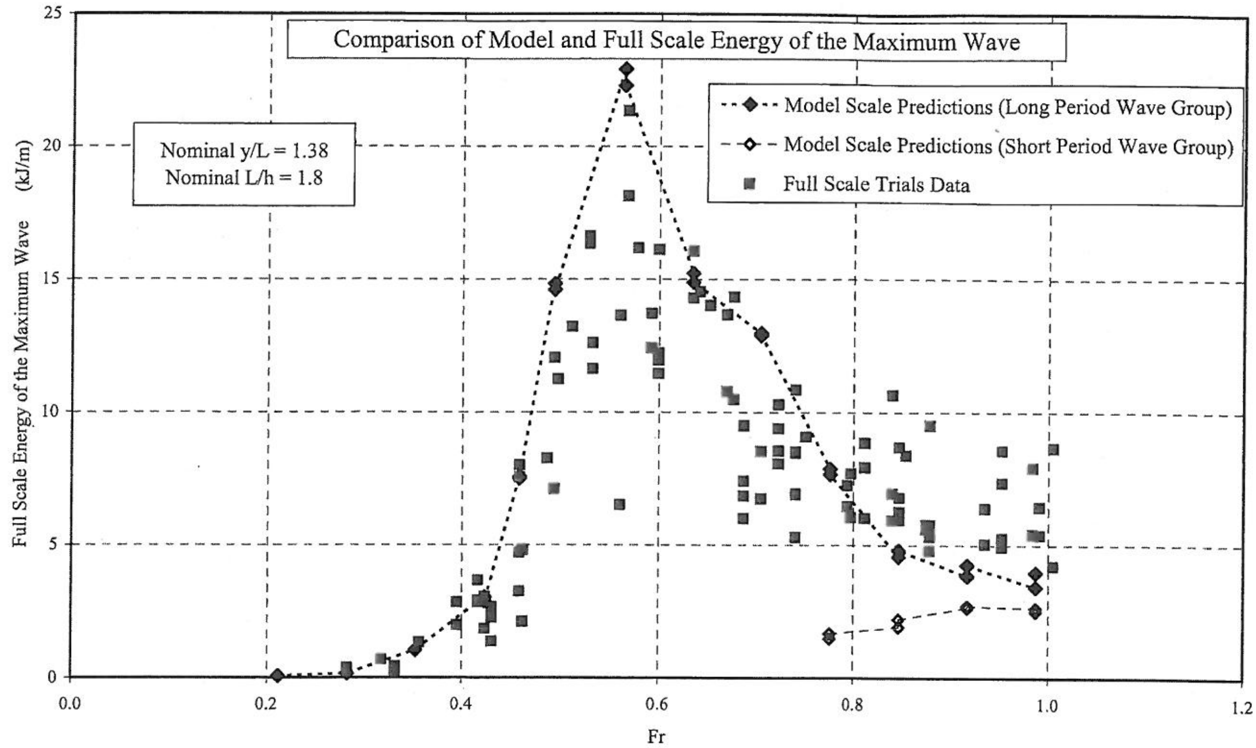

Fig. 17 Comparison of model-scale predictions with full-scale trials data. E_m as a function of Fr

are compared against those predicted from the model-scale experiments in Fig. 17, both plotted as functions of Fr. Given that the model-scale predictions of both maximum wave height and its related period have been shown to be reasonably representative of the full-scale measurements up to a Fr of 0.8, it is expected that the energy of the maximum wave (and also presumably wave power) can be accurately predicted from model-scale data. The data displayed in this figure generally appear to confirm this; however, the predictions are slightly conservative around the hull speed of Fr ~0.5, as was the case for the maximum wave height.

For speeds in excess of Fr = 0.8 the model-scale predictions for both the long- and short-period wave groups tend to underpredict the wave energy found from the full-scale trials. Further investigation into vessel generated waves at supercritical Fr_h is presently underway.

5. Conclusions

The primary aim of this study was to determine what correlation factor, if any, should be applied to results from scale model experimental data to accurately predict full-scale wave wake characteristics, concentrating on a catamaran hull form operating in the speed range of 0.3 < Fr < 1.0.

The results confirm that good correlation was found between the predictions from model-scale experiments within a controlled environment and a series of full-scale trials data up to the Fr of 0.8. Consequently, it is concluded that a correlation factor of close to unity be applied when using model-scale experimental data to predict full-scale maximum wave heights and related wave periods for similar vessels operating within the range of 0.3 < Fr < 0.8, provided the Fr_h remains subcritical. It is also recommended that the vessel length to water depth ratio be similar to that for the present study ($L/h \approx 1.8$).

Given that the model-scale predictions of both maximum wave height and its related period have been shown to fairly accurately match the full-scale measurements, it is expected that the energy (and power) of the maximum wave can also be fairly accurately predicted from model-scale data.

The uppermost vessel speeds of interest in this study (0.8 < Fr < 1.0) correspond to trans and low supercritical depth Froude numbers. It was found that close attention to the two (or more) distinct wave packets that are characteristic of operation at such speeds is warranted.

Finally, a number of recommendations for good practice when undertaking wave wake experiments have been suggested.

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MARINE TECHNOLOGY
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