International Journal of Maritime Engineering, Part A2 2006

CORRELATION OF PROTOTYPE AND MODEL SCALE WAVE WAKE CHARACTERISTICS FOR VESSELS OPERATING AT LOW FROUDE NUMBERS

G J Macfarlane, Australian Maritime College, Australia

SUMMARY

The paper summarises an experimental investigation into the correlation of model scale wave wake measurements against full scale trials results for a catamaran operating at low length Froude numbers.

Both full scale and 1/9th scale model experiments were conducted over the range of sub-critical length Froude numbers of approximately 0.1 to 0.3 (full scale speed range of 4 to 8 knots).

The results of the investigation confirm that a correlation factor of close to unity be applied when using model scale experimental data to predict full scale maximum wave heights for catamarans operating within such a speed range. It was also found that the scale model tests slightly over predict the period of the maximum wave, generally by around 5%. Consequently, it is expected that the energy of the maximum waves can also be accurately predicted from model scale data.

The paper also provides useful guidance notes for the conduct of full scale wave wake experiments.

NOMENCLATURE

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

1. INTRODUCTION

For over 20 years there have been concerns regarding environmental impacts from the wave wake generated by tourist cruise vessels operating within the narrow estuary of the lower Gordon River within the Tasmanian Wilderness World Heritage Area, [1, 2, 3]. As a result, various vessel operating criteria have been in force since 1989; for example, the adoption of the *75mm maximum wave height criterion* in 1998 effectively limited most commercial vessel operations to maximum speeds in the order of 6 knots. Vessel operations and river bank erosion continues to be closely monitored, [4].

A direct result of the introduction, and on-going revision, of vessel operating criteria is the development and introduction of new cruise vessels having hull forms specifically designed to minimise wave wake. Most commercial cruise vessels presently operating on the lower Gordon River are of similar catamaran form, locally referred to as the *Wanderer* class, named after the first vessel of its type which commenced operation in 1997. These catamarans typically have overall lengths between 25 to 32 metres and full load displacements between 50 to 75 tonnes. All are capable of maximum service speeds around 25 knots for traversing the approximately 40 kilometres of often rough water across Macquarie Harbour from their home port of Strahan to the mouth of the Gordon River.

Since 1998, all new commercial vessels proposed for operation on the lower Gordon River have been (and continue to be) evaluated against wash criteria by undertaking scale model experiments within a controlled environment. This has encouraged the development of so-called *low wash* hull forms as each vessel is accessed on its own merits in a consistent manner. The well known benefits of a high length-displacement ratio for minimising wave generation has also encouraged the use of lightweight materials in the construction of these vessels. In addition, benefits from varying a vessel's static trim have also been investigated using model scale tests and necessary modifications implemented prior to construction.

Although the licensing process described above generally appears to be having the desired effect with regard to vessels meeting a specified wash criteria, there still appears to be no known published data that deals with the correlation between model and full scale wave wake measurements, particularly for catamarans operating at low length Froude numbers, Fr.

There does exist small craft wash trials data 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 non-standard methodology, insufficient details provided, poor recording or over-simplification of results are common traits to be found. The International Towing Tank Conference recently indicated that there is a general lack of good physical wave wake data available for validation and/or correlation purposes, [5].

2. DESCRIPTION OF VESSEL AND MODEL

The test vessel is one of a number of similar type vessels presently used for commercial tourist operations on the lower Gordon River in Tasmania. 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 Figure 1.

Vessel Particular	*Full Scale*	*Model Scale*
Displacement (kg)	69,600	93.145
Length Overall (m)	29.0	3.222
Length Waterline (m)	25.36	2.818
Beam Overall (m)	8.51	0.946
Beam Demihull (m)	2.20	0.244
Demihull Spacing (m)	6.0	0.666
Draught Forward (m)	0.78	0.087
Draught Aft (m)	1.05	0.117
Model Scale Ratio	*9.0*	

Table 1 – Test Vessel Particulars

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 low length Froude numbers between $0.1 < Fr < 0.3$ (full scale speed range of 4 – 8 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 on the lower Gordon River in Southwest Tasmania. The controlled environment $1/9^{th}$ 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 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.

The testing methodology adopted for this study ensures that the results will not be 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. Quite 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 below, including some comments relating to the present study:

3.2 (a) Shoreline Types

As with previous 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 lower Gordon River site were conducted well away from the shoreline, so can be regarded as being independent of the shoreline type.

3.2 (b) 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 is considered to be deep. In the present study, shallow water effects are to be avoided as the resulting corrections increase analysis time and the likelihood of errors being introduced. In instances where the waterway under investigation is everywhere shallow, there is no option but to conduct shallow water tests and present the results accordingly.

The vessel's Fr_h should remain sub-critical (< 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.

The lower Gordon River test site has a relatively consistent depth of approximately 12 - 15 metres along the length of the course. Combined with the relatively low speeds of interest, the Fr_h are clearly sub-critical (< 0.4).

3.2 (c) Water Depth at Measurement Point

Besides the need for adequate depth along the sailing line, there must also be adequate depth at the measurement point.

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 wavelength.

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

For example, the T_{crit} at the shallowest point of concern in the present study (water depth of ~5.5 metres beneath one of the two wave probes) is approximately 2.5 seconds. The vast majority of wave periods measured were found to be below 2.0 seconds.

Lastly, wave shoaling should be avoided as it can influence wave elevation. 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 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 period and thus can essentially be ignored for most practical applications, [6]. As the focus of this study is on parameters surrounding the maximum waves (which have relatively short periods for small craft), the water depth at the measurement probes is considered quite adequate to avoid shoaling.

3.2 (d) 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 centreline of the vessel's track path and the location of the measurement point(s).

3.2 (e) Constant Vessel Speed

The wave wake field generated by any vessel will vary with vessel speed. The test vessel must be travelling 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 three boat lengths prior to passing the measurement point.

The operators of the test vessel on the lower Gordon River noted that during some of the slowest speed runs it was difficult to maintain a constant speed while also maintaining a straight course. This was believed to be primarily due to wind gusts and the need to maintain a sufficient speed in order to ensure safe manoeuverability of the vessel.

3.2 (f) Wave Probe Position

The wave probes must be positioned such that they are beyond any localised refraction caused by shallow water, or diffraction due to solid obstacles or irregular shoreline shape. Also, if an existing structure onto which the probes can be attached is not available, the water depth should not be so deep as to create practical set-up problems.

Two wave probes were set up at different longitudinal distances within the lower Gordon River 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 (g) Wave Probe Mounting Structure

Wave probes should be mounted on a sufficiently rigid structure such that it 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 which were considered sufficiently rigid to eliminate any notable movement during the conduct of the experiments.

3.2 (h) Bank Reflectivity

The wake of a passing vessel may take many seconds to pass completely by the measurement point. This is particularly so of high-speed, deep water wakes. 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 lower Gordon River test site due to offshore energy dissipation by submerged vegetation and irregular plan form and the positioning of the probes well outside any possible focal point for reflection.

3.2 (i) Interference

Minimisation 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.

Like 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 10 – 15 mm (approximately 10-30% of the maximum wave heights measured).

3.2 (j) Current

The general effect of current on the test results can be predicted, but it becomes very complicated when testing in shallow water where 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 travelling up-current and wave periods become longer. For the vessel travelling 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 the equivalent to travelling at that higher speed through the water with no current present.

The increase in period when travelling up-current is due to two effects. Firstly, the period may increase due to the higher speed through the water, as it would if the vessel travelled 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 travelling 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 travelling at 4 knots over the ground into a 2-knot current is travelling 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 travelling 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 the case at high speeds, the resulting wave data scatter is small.

Mean current velocities of approximately 0.06 – 0.08m/s were measured near the vessel sailing line during the test sessions. These relatively low velocities should only have an effect on the slowest of test speeds and would otherwise simply appear as scatter in the test results. Thus, the test results presented here have not been corrected for current.

With the advent of low-cost Global Positioning Systems (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 the 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 present). However, it is likely that GPS units will be more prevalent and so speed limitations must reflect the worst-case condition, travelling up-current.

For the present study, vessel speed was obtained by measuring the time to travel a distance of 100m (between markers) and also by GPS. In general, the difference between the resulting speeds from these two methods varied by less than 3%. The vessel speeds presented in this paper are those derived from the time taken to travel the 100m distance and represent the vessel speed over ground (not through the water).

3.2 (k) 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, [7].

For the full scale experiments in the present study, water surface elevation was measured using two salt/fresh water capacitance wave probes with the signals from each wave probe radio telemetered to a custom data acquisition unit stationed approximately 25 to 40 metres 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 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 1.5% variation). The only notable difference between the calibrations was a zero shift, which was to be expected due to minor variations in river level during the course of each test session.

Recording of the water surface elevation signals from both wave probes was commenced well prior to the arrival of the test vessel so as 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, analogue to digital conversion resolution and sample rate. For the present study the wave probes had a resolution of approximately 1.0mm, analogue to digital conversion resolution was 12-bit and a sample rate of 100Hz 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).

3.2 (l) Lateral Distance Between Measurement Point and Vessel Sailing Line (y)

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 waves of differing wavelength superimposed. It takes approximately 2-3 boat lengths for waves to disperse sufficiently such that the period of individual waves can be measured with certainty, [8]. 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 a primary aim of the experiments is to investigate wave attenuation over distance then even larger lateral distances (for example, ten boat lengths), may be required, [9].

For the experiments on the lower Gordon River y = 50 metres as this is approximately equal to two boat lengths and ensures consistency with previous studies and wash criteria related to this region. It is understood that this distance was originally adopted within the lower Gordon River wave wake criteria for geomorphological purposes as it represents a reasonable ship – shore distance for vessels travelling near the middle of the river.

3.2 (m) Number of Test Runs

Due to many of the issues discussed above, 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, particularly for the lowest speeds where external influences resulted in the greatest degree of scatter in the results.

3.3 Model Scale Experiments

3.3(a) 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 35m long by 12m wide with an adjustable water depth between 0 and 1.0 metre. 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 carriage ran along two static guide cables spanning the length of the basin. For most applications the carriage 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 minimise wave reflections during calm water tests. A fixed wave absorber was located at the other end wall of the basin.

3.3 (b) 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 before and following the test program, with variations of less than 0.5%.

3.3 (c) Test Program

Two separate series of 1/9th scale model experiments were conducted. The first series of tests were conducted prior to construction of the vessel and formed part of the licensing process for commercial vessel operation on the lower Gordon River. Three different load conditions were investigated at this stage: light, mid and full load, however, these results have not been presented within this paper.

Following the conduct of the full scale trials on the lower Gordon River a further series of model scale experiments were conducted in order to more accurately represent 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 (a) Wave Elevation Time Histories

Repeatability is a key aim of any experimental study but is often an aspect 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 in Section 3.1), it should also be recalled that vessel generated waves vary with lateral distance due to dispersion, decay and interaction between the transverse and divergent wave systems, [8, 10]. 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 maximum wave height and related period.

An example of repeatability is shown in Figure 2 where the resulting wave elevation time histories for three different runs at the nominal Fr of 0.26 are shown. Note that time is plotted along the x-axis and wave surface elevation along the y-axis. It can be seen that the similarity between runs R38 and R40 is exceptionally good under the circumstances. However, the match is not so good for run R39, although this can still be considered acceptable. 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 +/- 2% and 4% respectively (approximately).

4.1 (b) Maximum Wave Height, Related Wave 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, [9, 10, 11]. These standard measures have been utilised in this study as together they may readily provide a numerically concise deep water description of the wave most likely to exceed any threshold of acceptable effect.

Consideration of either height or period in isolation from the other is only reasonable if vessel size and hull form are held constant. If not, then any regulatory benchmark requires use of both, so either of the similarly derived terms wave energy or power might be considered.

Wave power in the form of a wash rule has been adopted as the metric of regulation by Danish authorities and use of similar legal instruments has spread to Sweden and New Zealand [12] and is presently under consideration for the Gordon River.

Both wave power and wave energy have been shown to be useful indicators of erosion potential. Power is a measure of the wave energy expended over a given time whereas energy is a simple measure of the energy content of a particular wave. Wave power is a parameter commonly used in coastal engineering where coastal processes occur over long periods and therefore may be better characterised by a time-based parameter such as power. However, wave energy is often used when assessing the wash from a passing vessel as this can define a discrete event that has a definite start and finish, compared to naturally-occurring waves such as wind waves that are often better analysed over time.

For simplicity, wave energy (per metre crest length) is presented in this paper and can be calculated using Equation 2.

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

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, [13].

Figure 3 shows the maximum wave heights from all analysed test runs plotted as a function of Fr. A third order polynomial trendline has been fitted to the data (this resulted in a better fit than a second order trendline).

Also shown in Figure 3 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, [14].

As can be expected, a fair degree of scatter in the results is displayed.

The period of the maximum waves from all analysed test runs are plotted as a function of Fr in Figure 4. As for maximum wave height, a third order polynomial trendline and error bars (3.5%) have been fitted to the wave period data.

There is less scatter with the wave periods measured, which corresponds with a number of other studies involving wave wake measurements, [15, 16].

The resulting energy for each maximum wave can be calculated using Equation 2. This is plotted as a function of Fr in Figure 5.

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 and wind wave contamination were most likely the three greatest causes of data scatter.

4.2 Model Scale Data

Wave Elevation Time Histories

As discussed in Section 4.1, 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 Figure 6 where the resulting wave elevation time histories for two different runs at the nominal Fr of 0.20 are shown.
It is recommended that a repeat run be conducted at all speeds of interest, if even simply to confirm that good repeatability has been achieved (by producing plots such as that shown in Figure 6).

Repeatability alone is not an indicator that accurate wave wake measurements have been acquired. Factors such as those discussed in Section 3.2 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 challenge/limitation for undertaking wave wake experiments within conventional towing tanks due to their relative narrowness, [5, 8].

Maximum Wave Height and Related Wave Period and Energy
As for the full scale trials, the height and period of the maximum wave has been determined from each wave elevation time history.

The *corrected* maximum wave height is determined using the individual maximum wave heights from each of the six wave probes (placed at different lateral locations). It is well known that 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) in order to undertake an accurate assessment of the degree of wave decay over distance, and to minimise the influence of the wave system interaction, [8].

A single corrected maximum wave height at the specific location(s) of interest (y = 50 metres in this study) can be obtained by extracting the maximum wave height at each lateral location, provided the dispersion and decay rates of the divergent wave system is known. It has been shown that a good engineering approximation of the decay exponent for divergent waves is –1/3, [2, 8].

This corrected height is then considered to be representative of the divergent waves, with minimal influence from the transverse waves. For example, in Figure 7 maximum wave height is plotted as a function of lateral distance for a Fr of 0.18. The magnitude of the divergent component of the maximum wave at the lateral location of y = 50 metres is obtained using Equation 3 (shown by the line of best fit). More detail on the above analysis technique can be found in [8, 10 and 11].

$$H_m = \gamma . y^{-1/3} \qquad (3)$$

Note that γ (Gamma) is a constant (dependent upon vessel speed) and is obtained from the model test data.

Figure 8 shows the model scale test predictions for maximum wave height and the related wave period plotted as a function of Fr. Also shown are 5.0% error bars on the measurement of the wave height and 3.0% error bars on the measurement of 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.

Maximum wave height is generally increasing with increasing Fr, which is to be expected for the displacement speeds under investigation, [8]. However, there is a notable dip in the curve around Fr = 0.245. Given that a similar result appears at all six wave probes for all four load conditions undertaken at model scale (not all presented here), it can be assumed that this combination of L and Fr has resulted in a reduction in height of the maximum wave.

The resulting energy for each maximum wave, calculated using Equation 2, is also plotted as a function of Fr in Figure 8.

4.3 Comparison of Model and Full Scale Results

Wave Elevation Time Histories
As was shown in Figure 6, it is possible to obtain very similar wave wake traces from repeat runs within a controlled environment. In Section 4.1 it was explained that it is much more difficult to obtain good repeatability of wave wake traces from full scale trials due to the large number of variables involved, particularly due to ambient conditions, wave dispersion and the interaction between divergent and transverse wave systems. However, an example was presented in Figure 2 where two runs, at the nominal Fr of 0.26, were found to be exceptionally 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 Figure 9 (same nominal speed and lateral distance). As can be seen, 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. Such comparisons provide further support for the wave analysis technique utilising multiple laterally located waves probes, as described in Section 4.2, when attempting to determine a characteristic height of the maximum wave.

Maximum Wave Height

Figure 10 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 have been removed.

As can be seen, there is good agreement between the full scale measurements and the model scale predictions, particularly between $0.16 < Fr < 0.23$.

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 $0.1 < Fr < 0.3$.

Wave Period & Energy of the Maximum Wave

The full scale measured period of maximum waves are compared against those predicted from the model scale experiments in Figure 11, both plotted as functions of Fr.

As can be seen, there is good agreement between the full scale measurements, however, the model scale predictions tending to lie towards the upper bound of the full scale measurements for most of the speed range. Thus, it is suggested that a correlation factor of 0.95 may be applied when using model scale experimental data to predict the period of full scale maximum waves over this speed range.

Similarly, the energy of maximum waves measured during the full scale trials are compared against those predicted from the model scale experiments in Figure 12, 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 accurate, 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 appears to confirm this. Note that the above suggested correlation factor of 0.95 for model scale period has not been applied to the data presented in this figure.

5. CONCLUSIONS

The primary aim of this study was to examine the relationship between model and full scale wave wake characteristics and determine what correlation factor, if any, should be applied to results of model testing to accurately predict full scale wave wake characteristics, concentrating on a catamaran hull form operating at low length Froude numbers.

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 collected on the lower Gordon River, Tasmania. 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 for similar vessels operating within the range of $0.1 < Fr < 0.3$.

It was also found that the scale model tests slightly over predict the mean values of period of the maximum wave, generally by around 5%. Thus, it is suggested that a correlation factor of 0.95 may be applied when using model scale experimental data to predict the period of full scale maximum waves over this speed range.

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.

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

ACKNOWLEDGEMENTS

The work described in this report covers part of a research project funded by the Tasmanian Department of Primary Industry, Water & Environment. The author would like to acknowledge the following for their generous support:

- Jason Bradbury of the Land Conservation Branch, DPIWE, for initiating the study, securing funding and valuable input;
- Troy and Guy Grining of World Heritage Cruises for kindly providing their vessel and crew for the conduct of the full scale tests;
- Incat Crowther Design, the Tasmanian Parks & Wildlife Service, Martin Renilson and Greg Cox.

REFERENCES

1. von Krusenstierna, A., River Bank Erosion by Boat-Generated Waves on the Lower Gordon River, Tasmania, Master of Science Thesis, The University of Wollongong, NSW, 1990

2. Renilson, M. R. and Lenz, S., An Investigation into the Effect of Hull Form on the Wake Wave Generated by Low Speed Vessels, 22nd American Towing Tank Conference, pp. 424 – 429, August 1989

3. Bradbury, J., Cullen, P., Dixon, G. and Pemberton, M., Monitoring and Management of Streambank Erosion and Natural Revegetation of the Lower Gordon River, Tasmanian Wilderness World Heritage Area, Australia, Environmental Management Vol. 19, No. 2, New York, 1995 pp259-272.

4. Worboys, G., Lockwood, M. and De Lacy, T. (eds), Protected Area Management: Principles and Practice, Oxford University Press, 2005.

5. International Towing Tank Conference, Proceedings of the 24th International Towing Tank Conference, Volume 1, Report of the Resistance Committee, 2005.

6. U.S. Army Coastal Engineering Research Center, Shore Protection Manual, Volumes I and II, U.S. Government Printing Office, Washington, DC, 1984

7. Permanent International Association of Navigation Congresses, Guidelines for Managing Wake Wash from High-Speed Vessels, Report of Working Group 41, Maritime Navigation Commission, Brussels, 2003.

8. Macfarlane, G. J., The Measurement and Assessment of Sub-Critical Vessel Generated Waves, Master of Philosophy Thesis, Australian Maritime College, October 2002.

9. Glamore, W. C., Hudson, R. and Cox, R. J., Measurement and Analysis of Boat Wake Waves: Management Implications, Proceedings of the 17th Australasian Coastal and Ocean Engineering Conference, Adelaide, 20 – 23 September 2005.

10. Macfarlane, G. J. and Renilson, M.R., Wave Wake – A Rational Method for Assessment, Proceedings of the Royal Institution of Naval Architects International Conference on Coastal Ships and Inland Waterways, London, 17 & 18 February 1999.

11. Macfarlane, G. J. and Renilson, M.R., When is Low Wash Low Wash? An Investigation Using a Wave Wake Database, Proceedings of the Royal Institution of Naval Architects International Conference on Hydrodynamics of High Speed Craft - Wake Wash & Motions Control, London, United Kingdom, November 2000.

12. Croad, R. and Parnell, K. E., Proposed Controls on Shipping Activity in the Marlborough Sounds: A Review under S.32 of the Resource Management Act, Report to the Marlborough District Council, Opus International Consultants Limited and Auckland UniServices Limited, September 2002

13. Whittaker, T. J. T., Doyle, R. and Elsaesser, B., A study of the leading long period waves in fast ferry wash, Proceedings of the Royal Institution of Naval Architects International Conference on Hydrodynamics of High Speed Craft - Wake Wash & Motions Control, London, United Kingdom, November 2000.

14. International Towing Tank Conference, Recommended Procedures and Guidelines, Version 2005, Revision 03, 2005.

15. Macfarlane, G. J. and Cox, G., Vessel Wash Impacts on Bank Erosion – Noosa River Between Lake Cootharaba and Lake Cooroibah – Brisbane River Kookaburra Park to the Bremer River Junction, Refereed Report for the Moreton Bay Waterways and Catchments Partnership, AMC Search Report No. 01/G/18, May 2002.

16. Macfarlane, G. J. and Cox, G., Vessel Wash Impacts on Bank Erosion - Maroochy River, Refereed Report for the Moreton Bay Waterways and Catchments Partnership, AMC Search Report No. 04/G/18, December 2004.

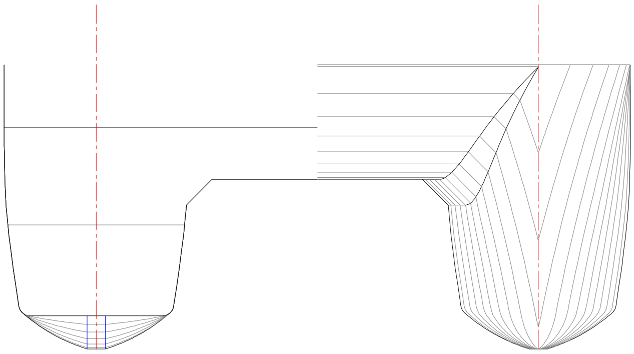

Figure 1: Body Plan of Test Vessel (permission to publish kindly provided by Incat Crowther Design).

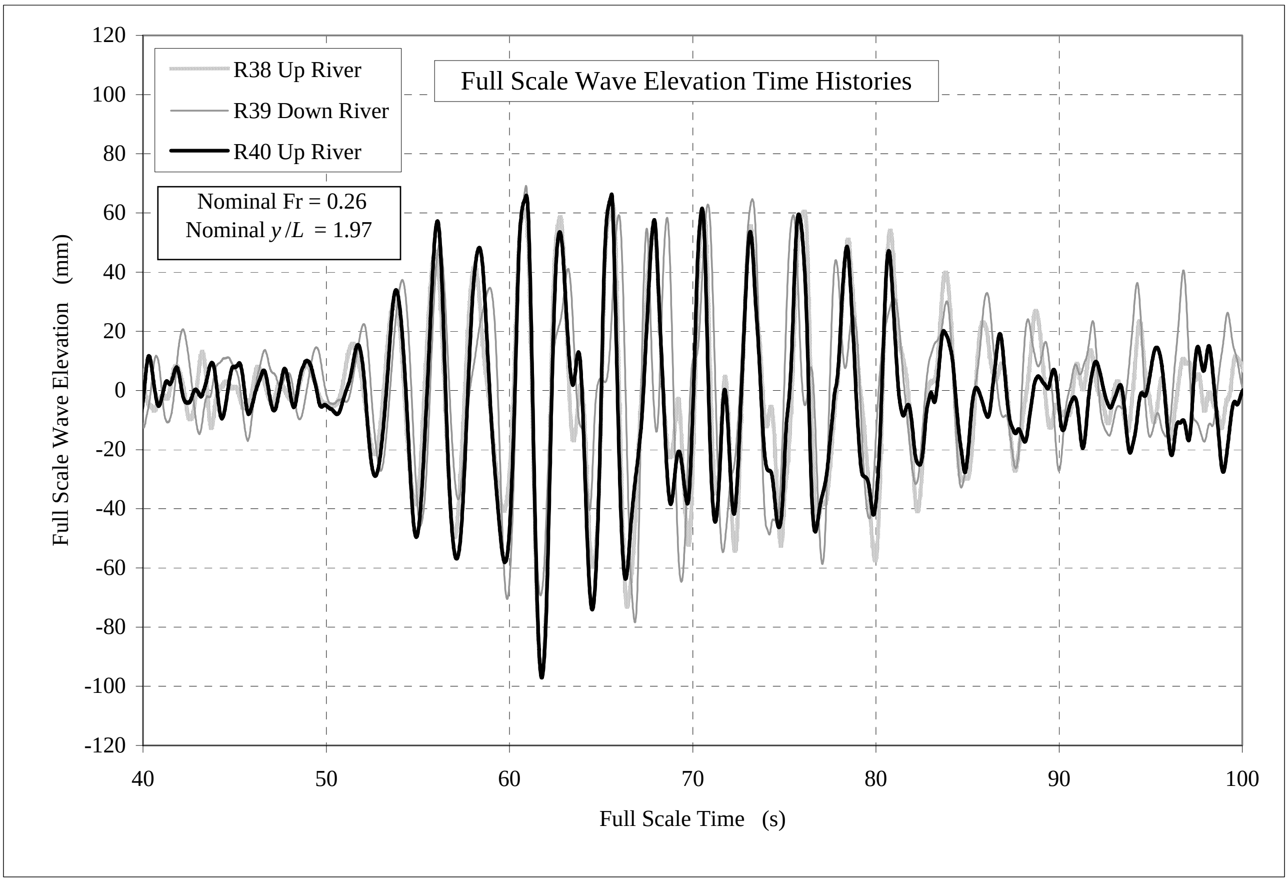

Figure 2: Comparison of wave elevation time histories from full scale trials.

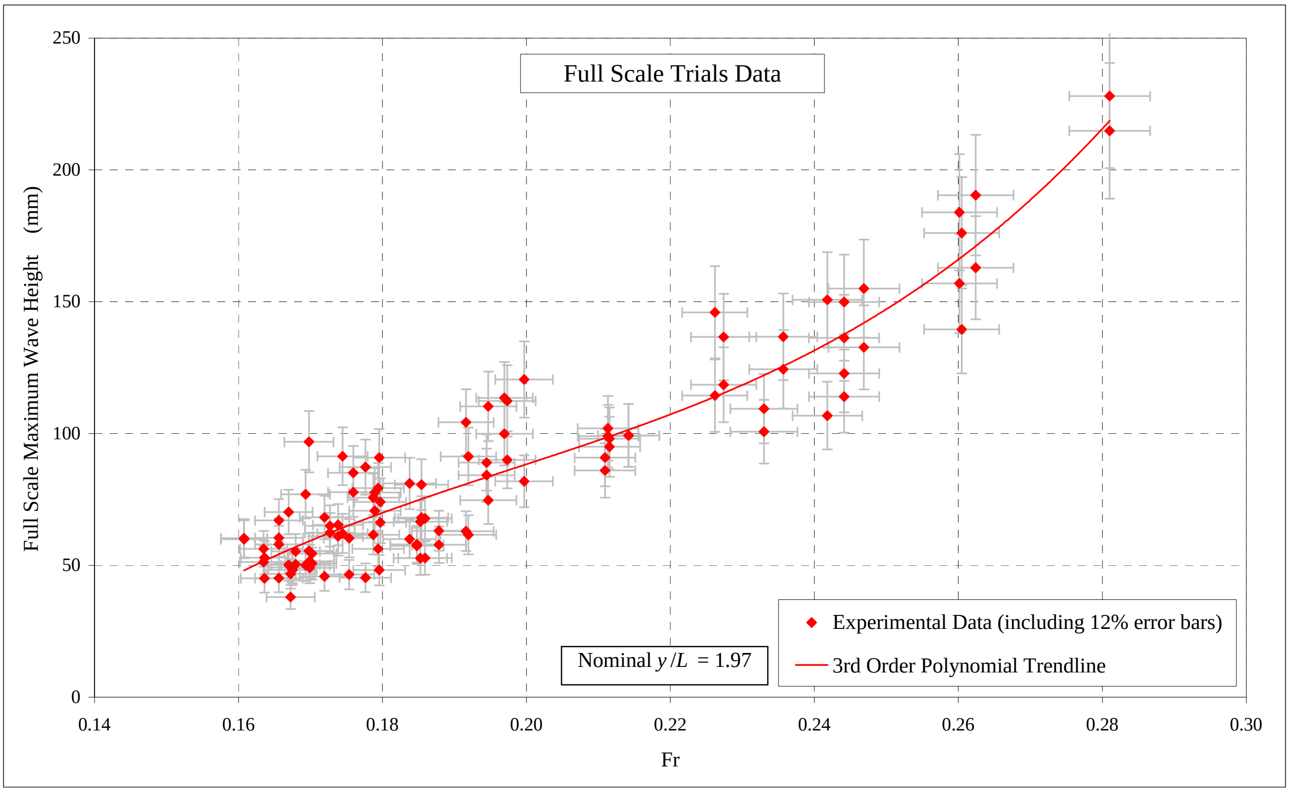

Figure 3: Full scale trials data - H_m as a function of Fr.

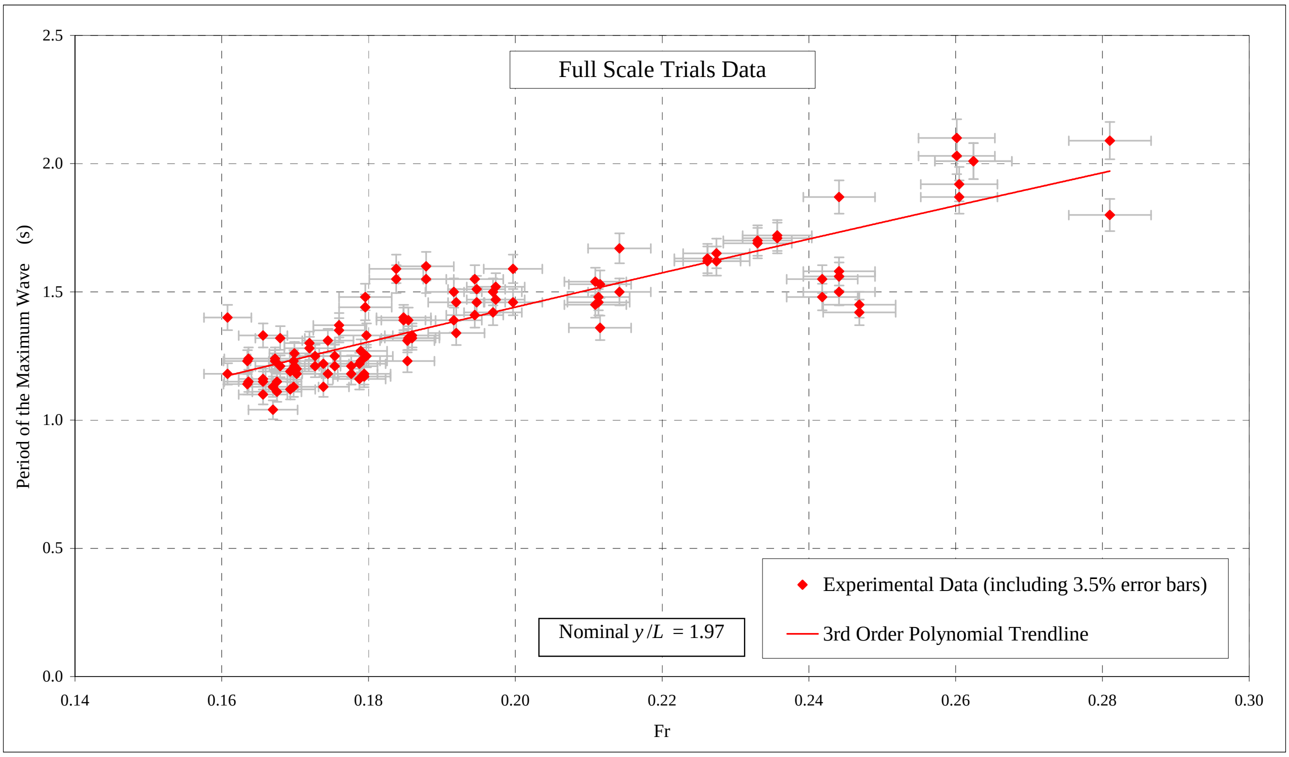

Figure 4: Full scale trials data – T_m as a function of Fr.

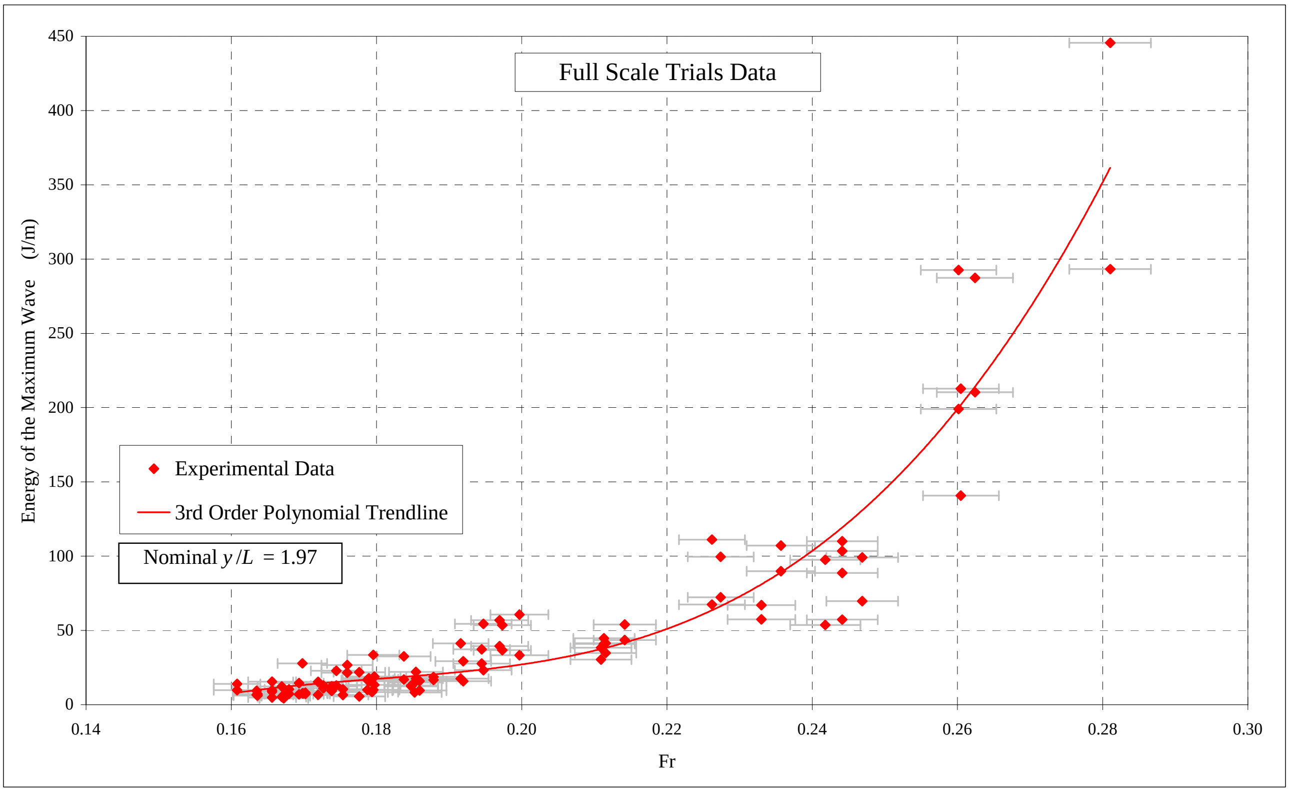

Figure 5: Full scale trials data – E_m as a function of Fr.

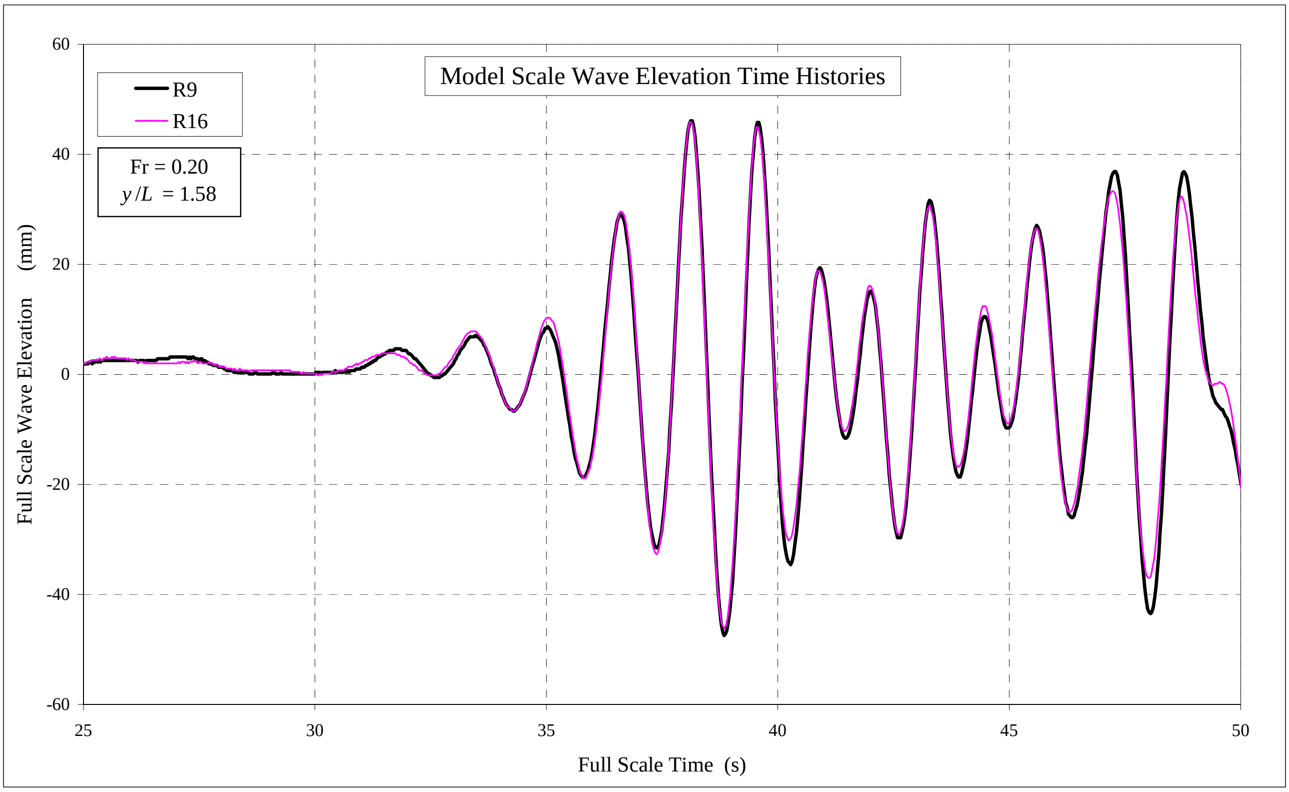

Figure 6: Comparison of wave elevation time histories from model scale tests.

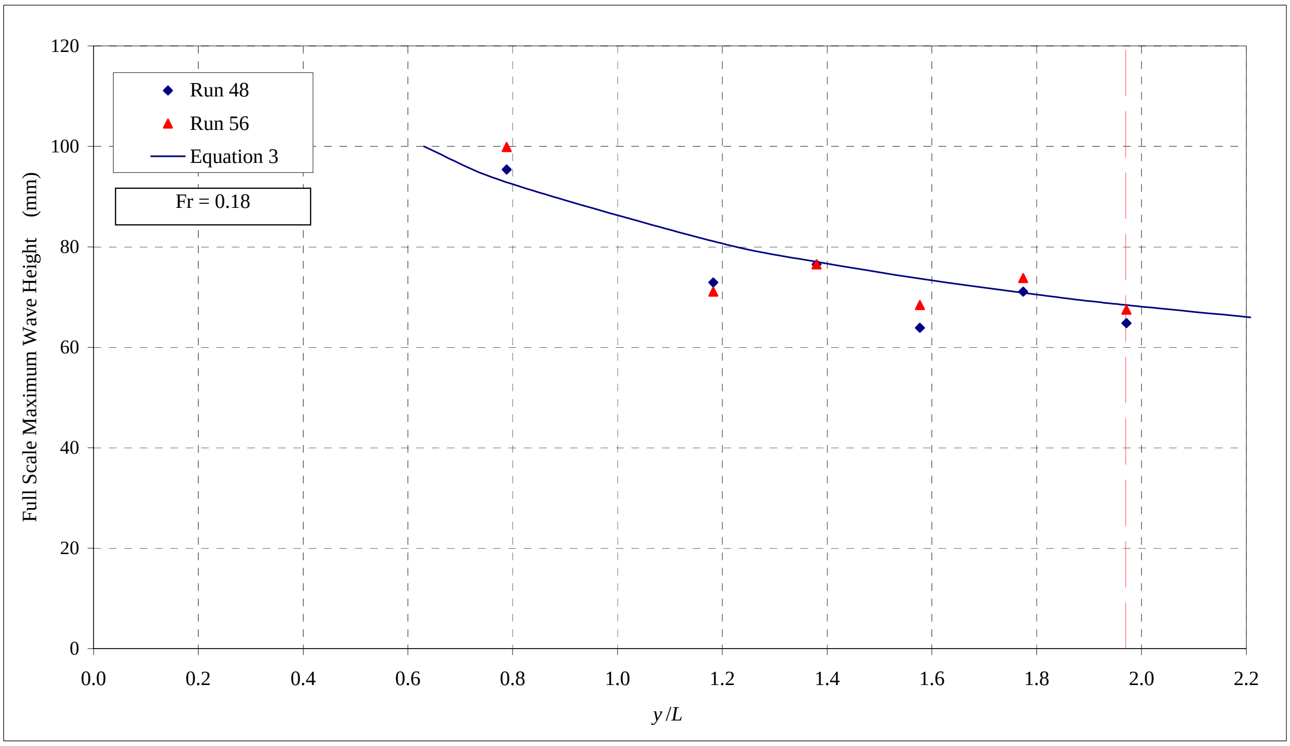

Figure 7: Model scale test results – H_m as a function of y/L.

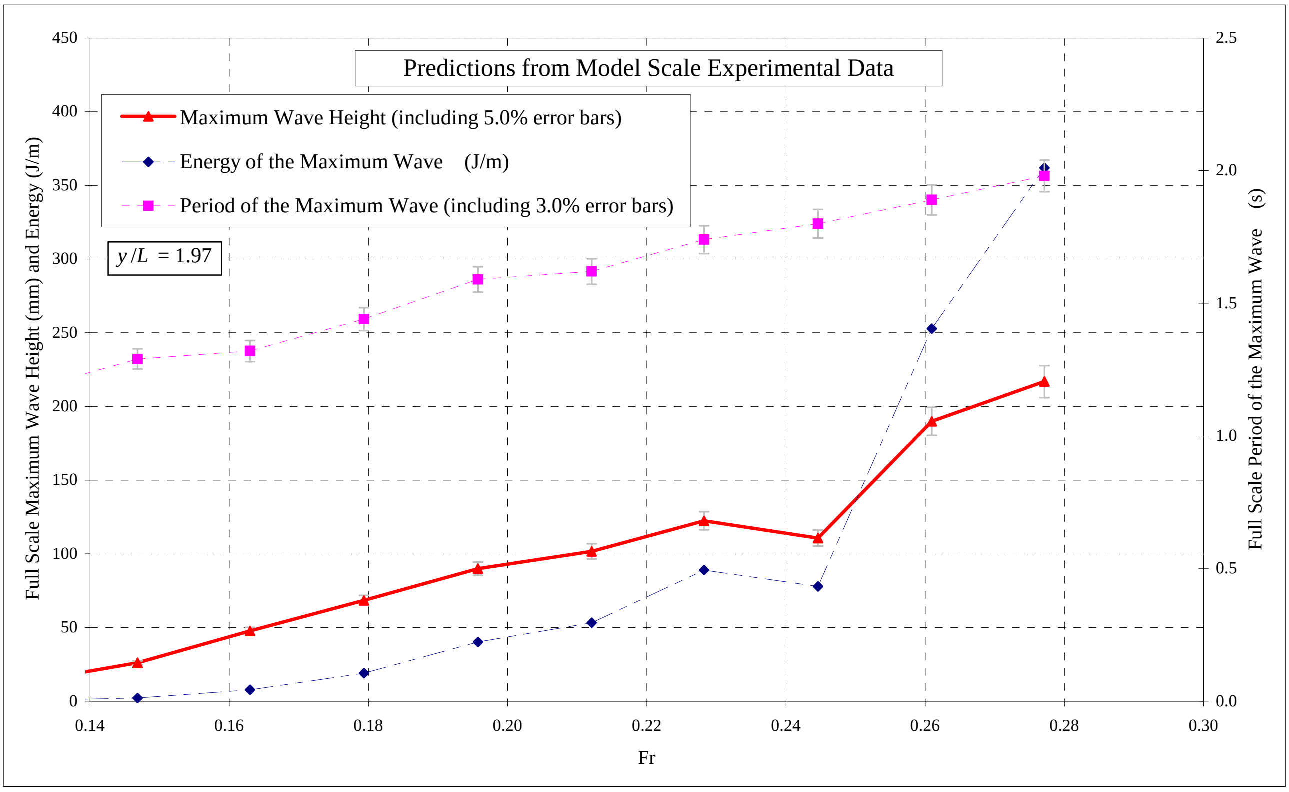

Figure 8: Model scale predictions – H_m, T_m and E_m as a function of Fr.

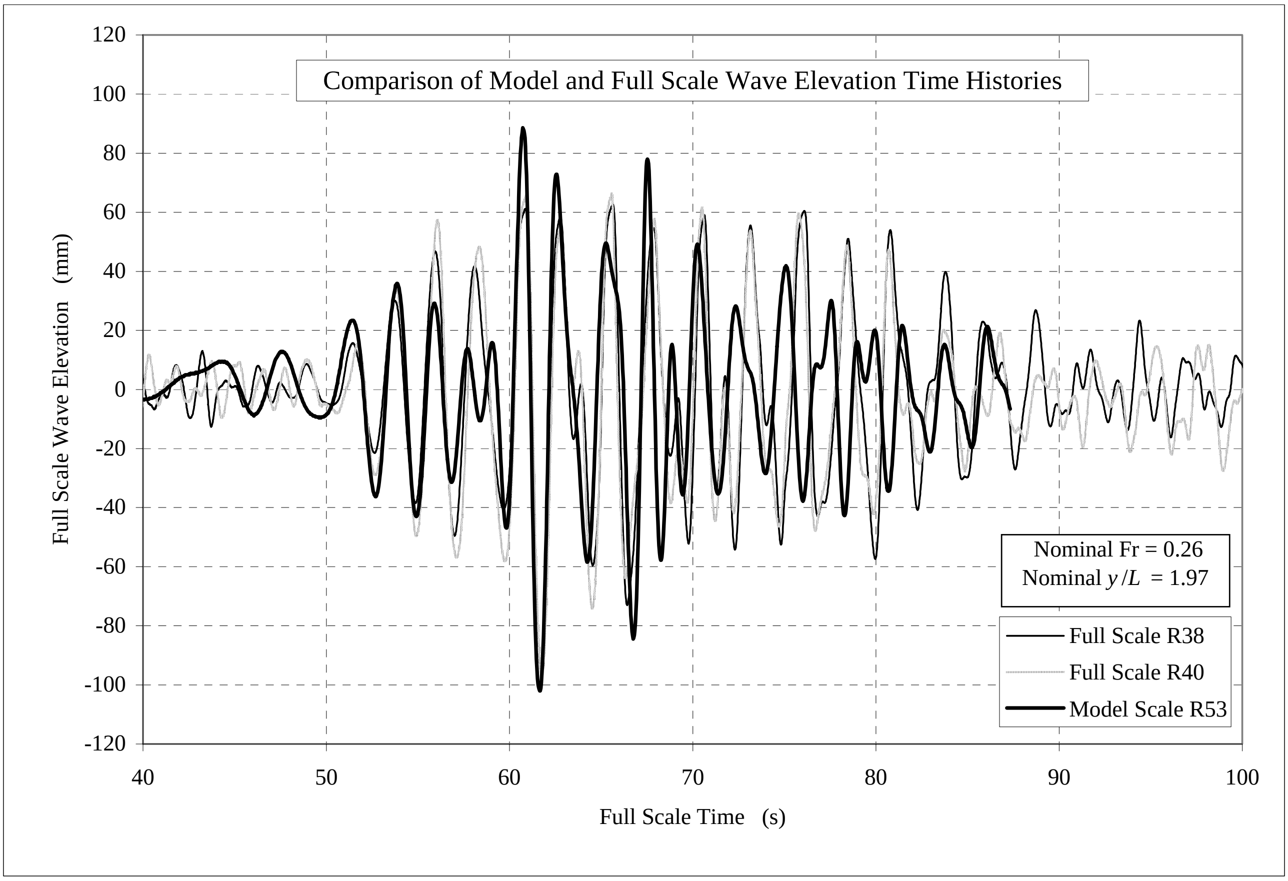

Figure 9: Comparison of model scale predictions with full scale trials data – wave elevation time histories.

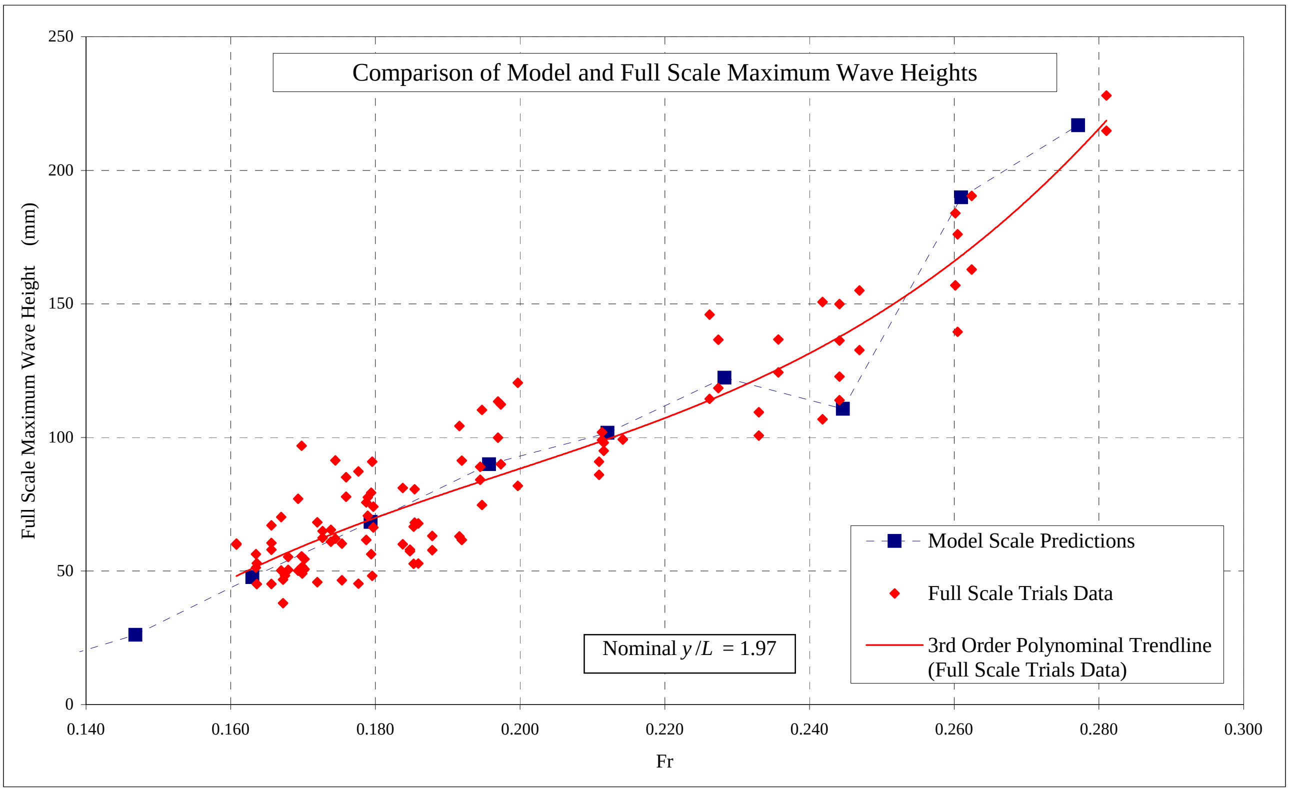

Figure 10: Comparison of model scale predictions with full scale trials data – H_m as a function of Fr.

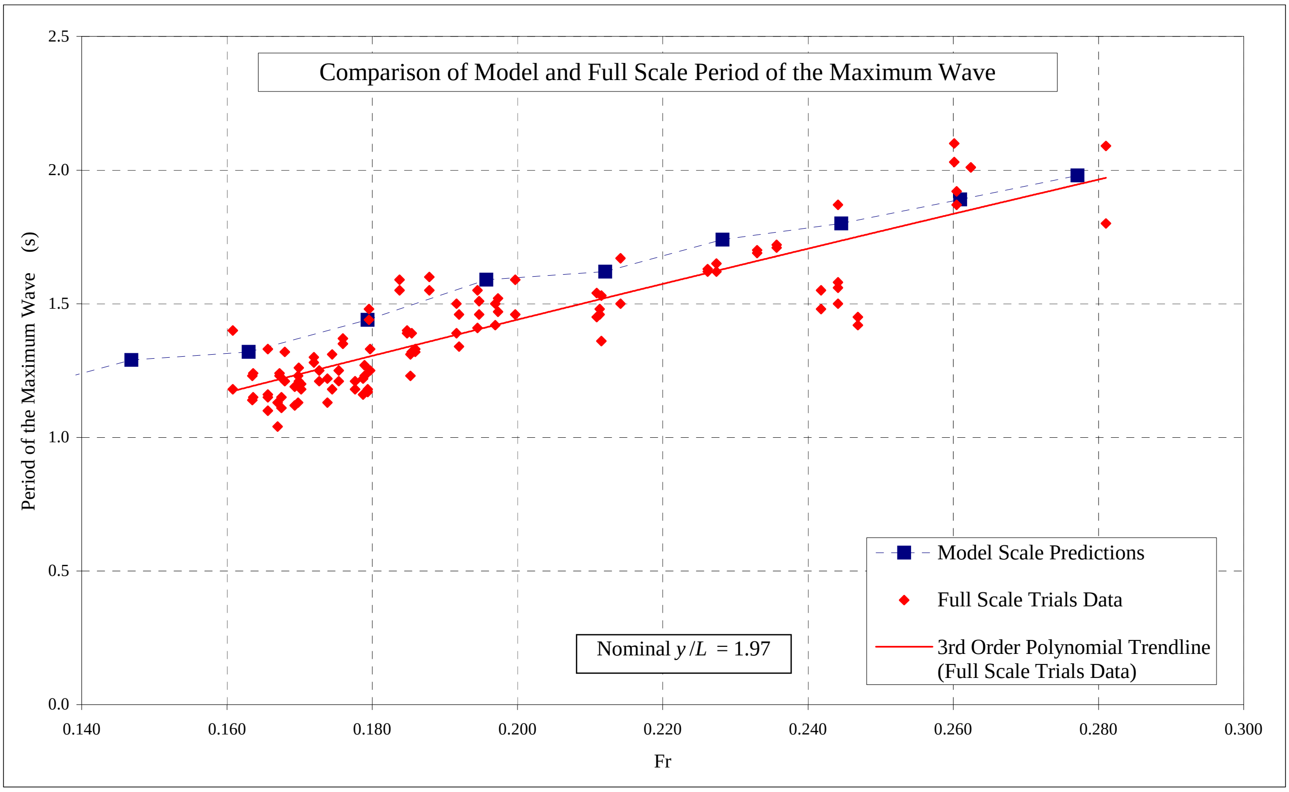

Figure 11: Comparison of model scale predictions with full scale trials data – T_m as a function of Fr.

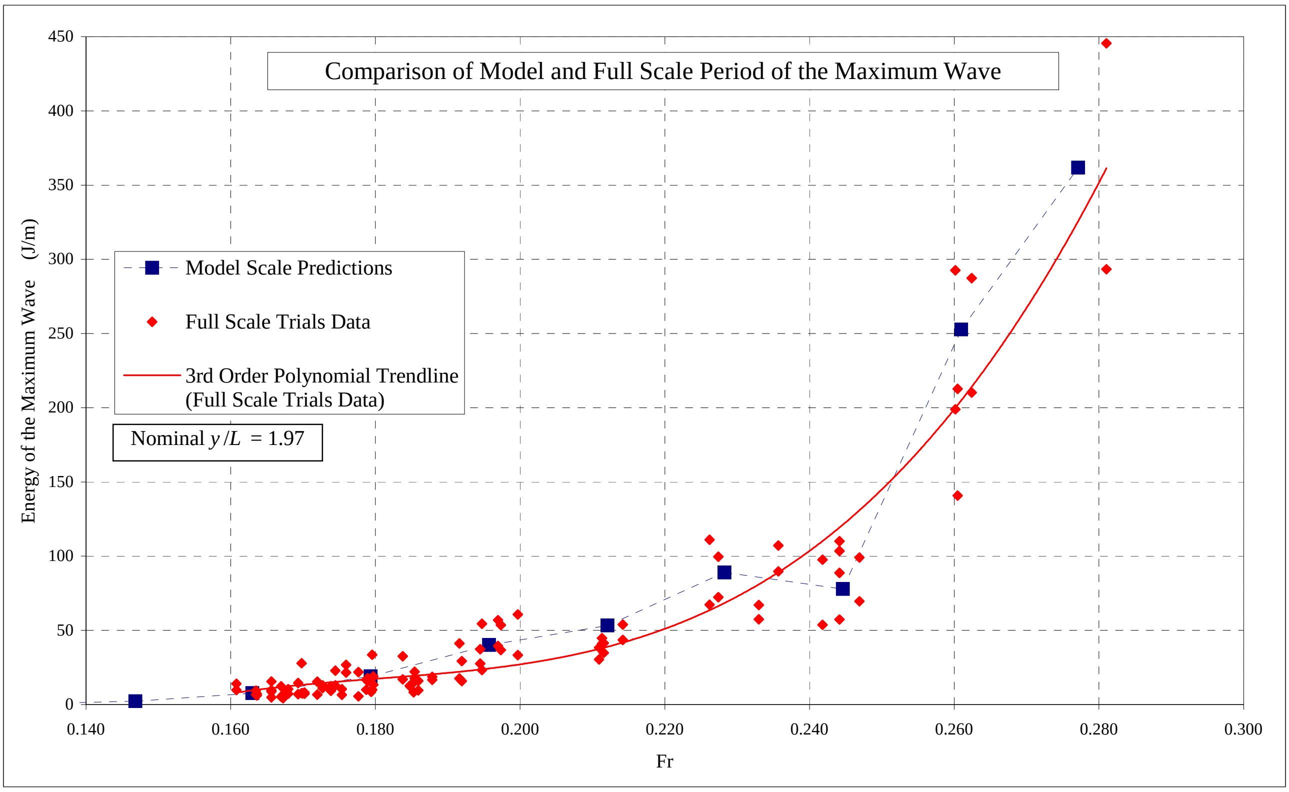

Figure 12: Comparison of model scale predictions with full scale trials data – E_{m} as a function of Fr.