The Effects of Boat Waves on Sheltered Waterways – Thirty Years of Continuous Study

[1]Gregory Cox and Gregor Macfarlane
[1]Australian Maritime College, University of Tasmania, Launceston, Australia; gregory.cox@utas.edu.au

Abstract

The waves generated by boats and ships (termed wave wake, wake wash or simply wash) that operate within sheltered waterways or close to any shore, have received considerable attention over the past few decades. Although many various issues arise from the waves from vessel operations, such as damage to maritime structures and presenting a danger to other users of the waterways, it is erosion of surrounding shorelines that occurs most frequently and receives the most attention. Along with the interested parties, including those in vessel construction and operation through to regulation and monitoring, comes the inevitable and often overwhelming politics; the clash of public amenity, economics and environment.

The Australian Maritime College (AMC) first became involved in the field thirty years ago, with the assessment and monitoring of tourist vessels on the World Heritage listed Gordon River in Tasmania – a project that continues to this day. The AMC's expertise expanded into high-speed commuter ferries, of which Australia was an early pioneer, and eventually to recreational craft. A summary of past and present research is presented, which includes: deep water wave packet development and propagation; shallow water wake components and their relationship to deep water wakes; the distribution and intensity of erosive components within vessel wakes and the opportunities for, and limitations on, their mitigation through vessel design and operation.

Keywords: wave wake, wash, sheltered waterways, bank erosion.

1. Introduction

Prior to the introduction of high-speed passenger vessel services on sensitive waterways in Australia in the late 1980s, there were few wave wake studies conducted in this country. The earliest comprehensive report is that of Lesleighter [7], who studied recreational boating on the Hawkesbury River. The report is notable for two reasons: firstly, given the limited understanding at the time it remains one of the most insightful studies of small craft wave wake; secondly, the report does not have any references, probably because there were so few at that time. There had been studies undertaken in the USA in the 1950s but relating as much to commercial river traffic as recreational activities. Mass recreational boating was in its infancy at that time with the introduction to the rising post-war middle class of mass-produced fibreglass boats, low-cost engines, and cheap fuel.

Tourist services on the Gordon River in Tasmania were initially unregulated, allowing operators to transit the lower part of the river at high speed. Although the number of daily services was limited, it soon became apparent that shoreline erosion was evident at accelerating levels. The then newly established Australian Maritime College, and other institutions and regulatory bodies, undertook field work and vessel evaluation in the late 1980s. Von Krusenstierna [12] presents a comprehensive record of the depth of study undertaken. Since that time, the criteria regulating vessel services have evolved from a simple limiting wave height criterion to include more developed parameters such as wave energy. New vessels must undergo evaluation prior to an operating permit being approved. The Gordon River is continuously monitored as part of the government and industry commitment to protecting its World Heritage status.

Three maritime segments have continued interest in wave wake reporting. Recreational boating on inland waterways has increased the rate of shoreline erosion, particularly with the recent advent of activities such as wake surfing where design and operational measures are sought to actively increase wash height. This segment is troubling for regulators, as it generates little direct government revenue but is the most vocal. Passenger ferry services are increasingly seen as a means of alleviating congested roads, requiring inexpensive infrastructure and utilising natural pathways (waterways). Unfortunately, such services introduce a wave climate that sensitive waterways are often unable to accommodate, complicated by impacted shoreline developments owned by people with the means to oppose them. The third segment – large, high-speed coastal ferries (and mostly in Europe) – has been largely regulated to mitigate impacts [6]. The money associated with these services ensured action was swift.

The AMC's research in the field has been continuous since the 1980s. In this paper we review our present understanding of the science and introduce recent and ongoing research.

2. Wave Wake Dynamics.

The most common discord in wave wake studies is between the dynamics of the boat and the waves it generates. Unfortunately, it is still quite common for published reports to incorrectly differentiate between the two; [1] being an example.

Vessel dynamics are defined in terms of length Froude number, where $Fr_L = V/\sqrt{gL}$. The transverse waves, commonly referred to as stern waves, are the longest waves a vessel can generate. The maximum transverse wave height is reached at a length Froude number of 0.5, which is consistent for all vessels. Above this, the height reduces. A point is reached where the waves become too long for the vessel to generate them, even in deep water, and they die away somewhere before $Fr_L \sim 1.0$.

The divergent waves, or bow waves, are either the same length or shorter than the transverse waves and are formed in packets. Vessels can generate several divergent systems that become superimposed in the far field. The divergent waves are the principal waves of concern, but transverse waves can be problematic in narrow waterways.

The magnitude of principal wake parameters can be related to the vessel and or its speed. Wave height is strongly a function of slenderness ratio; a non-dimensional relationship between length and displaced volume, such that $SR = L/\sqrt[3]{\nabla}$. The period of the transverse waves is a function only of vessel speed. The period of the divergent wave system is related to the vessel length and is the basis for scaling wave period from model to full scale.

When water depth is considered, vessel dynamics are defined in terms of depth Froude number, where $Fr_h = V/\sqrt{gh}$ at water depth h. The depth-critical speed is defined as a depth Froude number of unity.

2.1 Deep Water

Although regarded as the simpler of the two depth cases, it is more complex than what it appears. The waves generated are fully dispersive. Vessels generate multiple wave packets, some with periods that are similar. In the far field, the multiple packets disperse and therefore interact, complicating assessment of principal wave parameters. Figure 1 shows examples of this from model experiments, with the peculiarity that the waves of the second packet (stern divergent packet) are higher, which is peculiar to some monohulls. At slow speeds the packets take longer (and hence further) to interact due to their modest group celerity and so may be visible individually in the far field. At higher speeds, interaction is often underway close to the vessel.

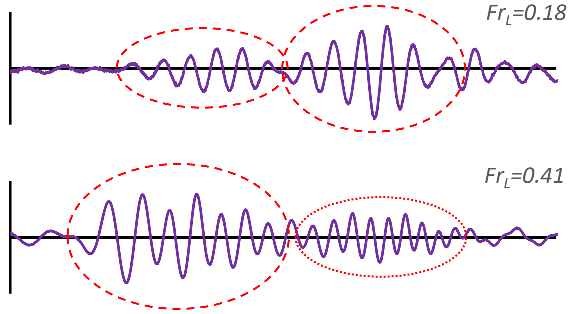

Figure 1 Deep water wave wake trace examples showing packet development. Waves are propagating right to left. The *upper figure*, at a slow speed, shows a bow and a stern packet. The maximum wave in each packet has the same period, hence the group celerities are the same. The *lower figure*, at higher speed, shows three packets. The left-most are the bow and stern packets superimposed, typified by oscillating crests and troughs. The right-most is a short period packet with slight height oscillation most likely caused by the transverse system. This packet is thought to be from a secondary hull feature such as the point of chine immersion.

As noted, the transverse wave system dies away at high speeds, though not to be confused with the depth super-critical condition where the transverse waves, which depend only on vessel speed, cannot exist. The lack of a transverse wave system at high speeds aids small craft wake analysis by removing one of the wave systems. Large craft rarely operate at speeds where the transverse system is depleted.

2.2 Shallow Water

This condition was considered the one full of unknowns. The vessel dynamics are affected by waterway depth and width restrictions, though as much a function of the waves generated as any hull dynamic interaction with the boundaries. Our present delineation of depth according to the wavelengths generated is shown in Table 1. The existence of the depth-critical speed of $\sqrt{gh}$ is well reported, and the depth trans-critical speed region of $0.75 < Fr_h \leq 1.25$ is to be avoided. What has not been well understood is the relationship between deep and shallow wakes, and what comprises the wake generated in shallow water.

Table 1 – Wavelength/Depth Relationships.

Condition	**$\lambda : h$ relationship**
Deep	$\lambda \leq 2h$
Practically Deep	$\lambda \leq 3.5h$
Transition	$3.5h < \lambda < 14h$
Practically Shallow	$\lambda \geq 14h$
Shallow	$\lambda \geq 16h$

Vessels generate divergent waves of significance with wavelengths in the order of the vessel length L. In that case, the highest divergent waves would begin to feel the bottom at $h/L < \sim 0.5$ and would be in transition at $h/L < \sim 0.28$. The very longest divergent waves are considered deep when $h \approx L$, which is the traditional definition of deep water for ship speed trials.

Shallow water wave wake is characterised by long-crested waves. The leading wave is very weakly dispersive (but not fully non-dispersive), with dispersion slowly increasing through the trailing waves. Energy is condensed at the head of the wake. Figure 2 presents an example of the ratio of the energy of the first wave to the total wake energy in shallow water at a fixed lateral separation. If the water is shallow enough at the time of wake generation, the leading wave may account for almost all the wave wake energy.

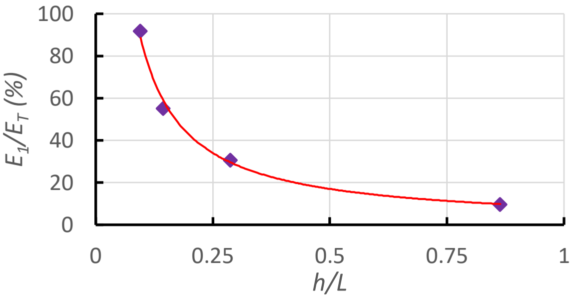

Figure 2 Ratio of energy of the first wave (E_1) and total wake energy (E_T) at a fixed lateral separation from model experiments as depth/length ratio reduces.

2.3 Small Craft

Recreational boating accounts for most of the wave wake studies but doesn't attract substantial funding because of its non-commercial nature devoid of direct government revenue. At least, that's been the historical attitude, though the shift in the modern political system and the rise of the "*I boat/fish/shoot and I vote*" crowd implies changing community priorities. The traditional approach against *soft targets* such as individual private boaters has been to control them with blanket restrictions, such as severe speed limits as are common or total bans such as that applied to the Gordon River system. Speed restrictions are sometimes applied with little regard to basic science and cause more harm than good. An example is the 8-knot speed zones reportedly used on parts of the Murray River [1], which would be useful for controlling the wash of the paddle steamers (both vessel length and water depth regimes) but would be the very worst condition for small craft.

Except in very shallow rivers, and almost too shallow for safe navigation, small craft wakes can be assessed as a deep-water condition. Wave periods less than about 3 s and water depths greater than about half the static waterline length don't warrant the extra effort of shallow water analysis. The AMC's past studies in SE Queensland [8] produced the two criteria approach which limited wave energy and wave period, with period related back to the vessel length. Small craft travelling at high speeds relative to length do not generate transverse waves and so the wake analysis is greatly simplified.

It is now generally accepted that certain recreational activities are (relatively) sustainable, provided they involve high-speed transit only. That includes water skiing. Problems arise where there is considerable manoeuvring, acceleration/deceleration, or activities that seek to maximise wake height by manipulating vessel speed and or weight.

A contentious activity embracing vessel wave wake over the past decade has not involved commercial vessels, but recreational wake sports [11]. The newer sports of wakeboarding and wakesurfing are creating the most concern, since both activities rely heavily on the waves generated by the tow boat. In wakeboarding, the waves are used as a launching ramp to perform manoeuvres and *tricks*, so the ideal wave is not necessarily large but must have a suitable steepness/slope. Wakesurfing requires the boat to generate a large wave that can be surfed without the aid of a tow rope. Wake boats are now deliberately designed to accommodate very large ballast tanks and other wake enhancing devices to maximise the size and shape of the waves generated.

Recent full-scale experiments by the AMC on ten typical craft, including the latest water skiing and wake boats, has confirmed that the energy of the maximum wave created by a modern wake boat at optimal speed (around 8 to 10 kn) can be an order of magnitude greater than those from water-skiing activities at much higher speeds. This study investigated the additional lateral distance required for the energy of the wakesurfing waves to reduce to the equivalent energy of those from water skiing. Not surprisingly, those who choose to wakesurf in populated areas or narrow waterways with sensitive banks are likely to receive vigorous complaints, something that is occurring increasingly on waterways around the world.

Invariably, the complications with small craft studies on inland waterways are the competing uses for the resource. The AMC's experience around Australia has been that recreational boating is often just a symptom of a wider problem and its restriction or prohibition only delays the inevitable. The Gordon River was an exception, largely because the rapid increase in recorded erosion was easily accredited to the newly introduced passenger vessels.

2.4 Large Craft

Large craft infers commercial (mostly passenger) vessels, characterised by shallow water wave wakes at the time of generation as opposed to deep water wakes transmuted. There are three conditions of interest: open, shallow water; channels restricted by width and depth; shallow coastal routes. The AMC has been most concerned with the first two;

the third has been the subject of considerable study in Europe in particular [6].

As noted, waterways are considered shallow when $h/L < 0.5$ due to the innate relationship between vessel length and the period of the divergent waves generated. That then creates a dilemma. If the depth Froude number-related operating range to avoid is $0.75 < Fr_h \leq 1.25$, it implies that $0.53 > Fr_L \geq 0.88$ at $h/L = 0.5$, with the limits reducing at the rate $\sqrt{2(h/L)}$ at depth/length ratios below that. At that shallow threshold condition of $h/L = 0.5$, the speed condition $Fr_L = 0.5$ is the very worst speed/length ratio for wave wake generation and $Fr_L \geq 0.88$ is impractical for most passenger vessels. The dependence of speed on installed power guides high-speed ferry length Froude numbers towards a range of $\sim 0.6 \leq Fr_L \leq \sim 0.9$. It is economics and or service scheduling (the timetable effectiveness of increased speed) that determine service speeds. Installed power P varies with speed V according to $P \propto V^n$, with the exponent $n \sim 2.5$ at higher speeds. Speed is expensive.

Figure 3 shows the relationship between h/L and Fr_L and delineates operation according to wave wake risk; seeking to avoid speeds where adverse vessel and depth dynamics combine. An additional area to avoid, where $0.45 < Fr_L < 0.55$ and wave resistance of all vessels naturally peaks, is also shown. Except at slow speeds, continuous high-speed operation at $h/L < 0.15$ is considered either highly problematic or untenable, except for very lightweight vessels or in very wide waterways (width $\geq 100L$, but subject to verification depending on slenderness ratio). When $h/L > 0.5$, deep water relationships are adequate.

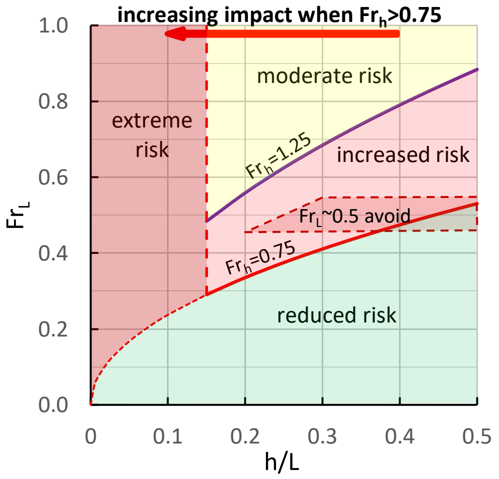

Figure 3 Vessel speed/length, and depth/length regime guidelines in terms of wave wake risk for $h/L \leq 0.5$.

When the waterway becomes restricted by width as well as depth and blockage (ratio of immersed hull cross-section to waterway cross-section) increases, high speeds are certainly impossible for larger craft. There is no black and white definition for what is considered *restricted*. Drawdown, which characterises the travelling depression abreast of the vessel, is noticeably deep up to 1L laterally and can be present several boatlengths abreast of the sailing line if the vessel's slenderness ratio is low (heavy for its length). Blockage effects above about 1% would be visible and above about 2% would be significant. The only consistent operating regime to avoid restricted channels problems that has been validated experimentally is to operate at $Fr_h < 0.75$, represented in Figure 3 below the left-most dashed line. The relationship $Fr_h = 0.75$ also marks the limit of *practically deep* (Table 1) for the transverse wave system, so it is more than just a notional value.

Very large, high-speed vessels on near coastal routes must avoid high speeds when $h/L < 0.15$; a navigation regime that becomes possible with larger craft due to the sub-linear relationship between vessel draft and length. The effects are particularly troublesome when the slenderness ratio is reduced, leading to the formation of leading waves that can transform into solitary waves given sufficient amplitude, time and shoaling water.

3. Wave Wake Criteria Development

Traditionally, the height of the highest (or maximum) wave has been the principal measure of wave wake intensity for both designers and regulators. There has never been a clear reason offered for its adoption, other than being the *big shiny thing* in the wake. Surprisingly, even though research has shown it to be an inconsistent and often misleading measure of erosion potential [2][8], it is still the most commonly used. When considered properly as one of several wave wake parameters, it does have a primary role but not an exclusive one.

The reason for its usefulness is that it defines the wave packet envelope, which in turn characterises wave decay due to dispersion. Also, as the wave at the peak of the packet envelope, its period remains constant and defines the packet group celerity. The constancy of the period of the maximum wave has always been known, though never explained. The minor variance in measured period at different lateral separations can be explained by slight variations in the relative position of the maximum wave, alternately slightly before or after the packet envelope maximum.

When considering erosion thresholds, the maximum wave is singularly the parameter that defines all deep-water wake waves. Generally, if the maximum wave is below the sediment entrainment threshold, all waves in the wake would be below the threshold. Two conditions can complicate this. Firstly, if the erosion threshold is exceeded, and several waves may be capable of that, the maximum wave alone may not be an indication of how many waves exceed the threshold. Secondly, wakes generated in shallow water (super-critically) may not conform to this and a different approach is required.

The AMC has relied increasingly on multi-parameter criteria, including energy of the maximum wave and energy per unit wave height (E/H). As with wave height, energy alone is not always an indicator of wash intensity. It is not the quantity but the form in which it is delivered [2]. For that reason, we now believe that comparisons of annualised boat wave energy and wind wave energy are meaningless for comparing the impacts of different wave regimes.

Energy is a complex parameter. The degree to which the waterway is energised is directly related to the engine power and the fuel consumed. The energy may spread as the waves propagate, but it cannot disappear (internal and bottom friction aside, which are minor). Whatever energy is represented by the wave system must eventually be expended at the shore. Close to the vessel, the energy is contained in only a few large waves. At a distance, dispersion leads to the same energy shared across many more waves. Increased lateral separation is a technique used to mitigate wave wake impacts, but it works not by reducing total energy but by reducing the energy within individual waves. What it cannot do is reduce wave period. Also, in shallow water where dispersion is weak, the benefits of increased lateral separation are reduced, with energy retained in the leading waves.

In 2002 the AMC was involved with assessment of vessel wave wake impacts on rivers in S.E. Queensland and the development of operating criteria that could be applied to the (mostly) recreational traffic [8]. The extensive work of von Krusenstierna [12] on the Gordon River in the late 1980s was used to determine threshold conditions for sediment entrainment. That led to the first application of multiple operating criteria rather than reliance on a single measurement such as maximum wave height. Von Krusenstierna's erosion data were presented in the form of composite parameters; for instance, wave period was recorded as the average of the significant waves. The fundamental wave parameters could be recovered from the composite data with some confidence.

In terms of the parameter $H_m T_1^2$ (maximum wave height and period of the first wave), the plotted erosion rates fell into three distinct bands – low, medium and high. It was possible to define the upper bound of low erosion in terms of wave period energy at a particular distance from the sailing line. The period of the maximum wave, representing the wave packet envelope maximum and hence the group velocity, remains approximately constant at high speeds and can be correlated with vessel length. That gave the two-part operating criteria: the energy of the maximum wave had to be below the threshold, and the vessel length had to be shorter than an upper limit that determined the wave period.

The defined *low erosion* limit of 30 J/m wave energy at 23 m from the sailing line correlated closely with the figure derived independently for the Gordon River using a different approach. However, the method was only useful at high speeds where parameters such as the period of the maximum wave are relatively constant. At slow speeds, or for large vessels in shallow water, it did not apply.

As part of the on-going environmental monitoring of the Gordon River, a more complex and complete set of full-scale experiments were undertaken between 1997 and 2005, of which a subset of this unpublished work is presented here. The wakes of several vessels, including large tour vessels and small craft, were recorded at the same time as turbidity was recorded at two near-shore locations using infrared nephelometers. Of the 73 recorded vessel tests in this subset (two small craft; one monohull and one catamaran), all recorded periods (of the *maximum wave*) were less than *3 s*, with a period of *3 s* at the wave probe measurement depth of 4 m being at the limit of *practically deep*. The wave probe was located close to the nephelometers but far enough offshore to avoid reflections from the steep shorelines. Height attenuation was ignored. Shoaling was applied but made little difference at these short periods. Wave wake studies are inevitably a study of orders of magnitude and not small percentages.

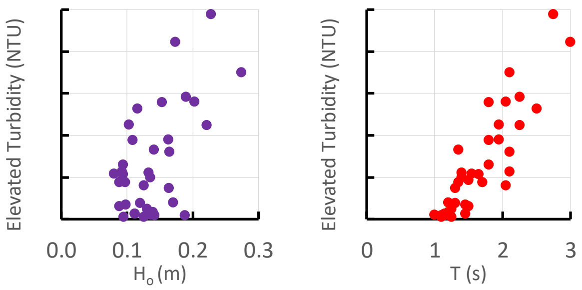

Figure 4 Elevated turbidity against measured deep-water maximum wave height (H_o) and period of the maximum wave (T) for the Gordon River data. Wave height exhibits an inconsistent, wide spread. Wave period has a more developed trend. Note the rapid increase in turbidity for little additional input, increasing steadily once turbid.

All the recorded wave parameters could therefore be considered as applicable in deep water. That was only possible in the full range of Gordon River experiments because the large vessels transited at slow speeds and the small vessels were incapable of creating long divergent waves, regardless of speed. Results in terms of height of the maximum wave and corresponding period against elevated turbidity are shown in Figure 4. As expected, they confirmed that wave height was a poor predictor of erosion potential. Analysis of composite parameters such as energy, power and HT^2 (energy per unit wave height in deep water) showed that HT^2 was a promising analogue of erosion potential [8][9].

4. Turbidity Thresholds and Erosion.

Von Krusenstierna [12] demonstrated that there were relationships between the incident waves and thresholds of sediment entrainment, though could not provide anything more than site-specific values. Using the developed equations of Komar and Miller [5] for sediment shear stress, a threshold curve was overlaid on the Gordon River turbidity data. The data was sub-divided into three groups, representing *no elevated turbidity (0-1 NTU)*, *threshold turbidity* (2-5 NTU) and *positive turbidity* (>5 NTU). The sensitivity of the nephelometer was 3 units. The results are shown in Figure 5 and exhibit a surprisingly accurate correlation between the predicted threshold and turbidity.

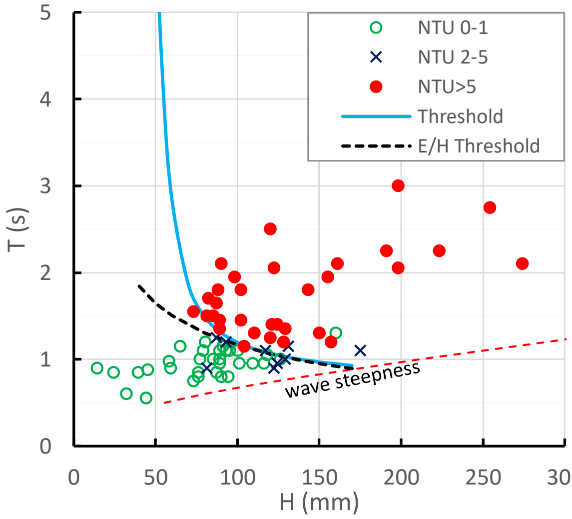

Figure 5 Comparison of Gordon River turbidity experiments against the predicted threshold and the E/H threshold derived from wave parameters.

There is close correlation between the threshold based on a constant *energy per unit wave height* (E/H) and the entrainment threshold, at least for shorter wavelengths. The threshold line of Figure 5 can be divided into two parts: the horizontal sector for short period, high waves and the vertical sector for long period, low waves. The analogue for the horizontal threshold sector is E/H. The analogue for the vertical threshold sector is wave runup. It can easily be shown that the maximum wave runup R_{max} is proportional to $\sqrt{E/H}$. Moreover, the shallow water Ursell number for a long wave in shallow water is also proportional to E/H.

Except in specific circumstances, it would be impractical to impose boating restrictions based on threshold values. It only worked on the Gordon River because of the severe restriction placed on vessel traffic and speeds (recreational boating is prohibited, and commercial tourist operations are licenced and monitored). The Noosa River study [8] recognised this and proposed *low erosion* limits.

A new measure of erosion prediction is proposed, based on the integration of accumulated excess bottom shear stress between the entrainment threshold and wave breaking. It would allow different vessels, routes and speeds to be ranked according to their propensity to entrain sediment, with entrainment used as an analogue of erosion. Work in this area is ongoing.

5. Wave Height Decay

The rate of wave height decay has long been contentious. Decay is expressed as the power relationship $H = \gamma y^n$, where H is the wave height, γ is a vessel-dependent constant, y is the lateral separation, and n is the decay exponent. The early researchers, looking for a solution, took the work of Havelock [4] and adopted his approximated decay exponent values of -0.5 for the transverse system and -0.33 for the combined transverse and divergent systems at the Kelvin wedge. Unfortunately, the -0.33 value of the combined system was recast as the value for the divergent system [6], which technically it is not.

Empirically, the decay exponent of the highest wave varies from -0.2 to -0.45 [10]. Doctors and Day [3], in a comprehensive numerical study of three catamaran and three monohull variants, produced decay variations from -0.2 to -1.06 and focussed heavily on the latter as an example of a possible design solution without offering any overall interpretation of their results. The -1.06 exponent occurs over quite a narrow speed range (around 13 knots) which would not be considered a viable speed for commuter services. Moreover, the speed was consistent for all vessel length variants, inferring it was a function of the transverse wave system, which itself is a function only of speed. In the normal operating range of passenger vessels, $\sim 0.6 \leq Fr_L \leq \sim 0.9$, the decay exponent averaged about -0.33. At higher speeds, $Fr_L > \sim 1$, the decay rate calculated by Doctors and Day [3] reduced to -0.5. That is important. It is known that the transverse system dies away at high speeds in deep water, so the decay rate of the combined system would be that of only the remaining divergent system. Importantly, it is known that the decay exponent of a single, dispersive wave packet is -0.5.

Ongoing investigation suggests that the wave decay rate is a function of group celerity and the number of cycles the packet undergoes. In shallow water it is known that the decay rate decreases, which aligns with the group celerity relationship. Complicating this is the fact that all vessels produce multiple divergent wave packets, some of which have similar period profiles and so interact in the medium to far field. As a result, it is now believed that there will most likely never be a definitive understanding of wave height decay, and the only practical solutions are empirical relationships. In the absence of relevant data, a decay exponent of -0.33 is still preferred as a conservative approximation for the decay exponent, at least for high-speed craft.

6. Wave Wake Mitigation by Design

Contrary to popular belief, there is little that can be done to mitigate wave wake at high speeds ($Fr_L > 0.5$) by design [2][9]. The belief that reducing a vessel's wave resistance component is a solution is not wholly true. As noted, it's not necessarily the total energy of the wave that is the most important but the form in which it is delivered.

Vessel designers know that increasing length and reducing displacement (increasing slenderness ratio overall) reduces wave resistance. The historical focus on wave height alone as a measure of wave wake intensity led to high slenderness ratios in passenger vessels. However, the intimate relationship between vessel length and wave period saw the benefits of lower wave heights traded against increased wave periods. Wave height decays with distance as energy is spread throughout the dispersing packets and across more waves, but wave period remains constant.

In shallow water, where dispersion is weak, the total wake energy accumulates in the leading waves and requires increased distances to attenuate. The deteriorating h/L ratio of a longer hull also aggravates this shallow water effect (refer Figures 2 and 3).

For these reasons, we now believe that the most effective sheltered water passenger vessels would be those that are modest in length and capacity, as well as being lightweight by design. The requirement for modest passenger capacity would put further pressure on service viability, but it may be the key to sustainability. Catamarans are preferred for their practical design features such as stability, deck area and lightweight structures.

For small craft, the options are few. Their design is always a compromise between production cost and functionality. Vessels such as ski boats were traditionally designed with minimal freeboard and structure, shallow deadrise, and lightweight engines, to reduce the impact of the wake on the skier. The newer wake sports vessels seek to do the opposite. Apart from a reduction in weight, there is little that could be done to reduce small craft wave wake impacts by design – most control would come from regulation.

7. Conclusions

Thirty years on, there is no end in sight to the AMC's work in this field, and what looked to be a straightforward task has proved to be never-ending. Having gone a long way, time has been spent re-visiting fundamental beliefs and correcting them where necessary, many of which were the residues of shallow and opportunistic reporting that have proved difficult to expunge from the common literature. Present and future work is focussed heavily on quantifying wave wakes and their impacts, as well as developing the database of past test results.

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