Wave Wake Study:

HB4099 Motorboat Working Group

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AUSTRALIAN LEADER IN MARITIME TRAINING AND CONSULTANCY

Technical Report

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1.0 INTRODUCTION

In collaboration with the Oregon River Safety and Preservation Alliance (ORSPA), the Australian Maritime College (AMC) performed a series of full scale experiments on the Willamette River in which the wave wake from a range of different craft has been measured and analysed. The primary aim of the study was to acquire reliable wave wake data for typical speeds associated with wakesurfing, wakeboarding and water skiing activities in a scientific manner such that it can aid decision making processes.

2.0 BACKGROUND TO VESSEL WAVE WAKE

The waves generated by boats and ships (often referred to as 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. Researchers at the Australian Maritime College (AMC) were among the first to become involved in the field, with the assessment and monitoring of tourist vessels on the World Heritage listed Gordon River in remote south-west Tasmania – a project that continues to this day. The AMC's expertise expanded into the operation of high-speed commuter ferries, of which Australia was an early pioneer, plus various other commercial vessels and eventually to recreational craft.

The AMC team have had the benefit of ready access to a purpose-built hydrodynamic test basin for performing scale model wave wake experiments in a controlled environment, complemented by direct involvement in full scale wave wake trials on more than 60 different marine craft in a variety of different sites across Australia and the world. This has led to the acquisition of over ten thousand individual tests at model and full scale which has been used to create and validate a powerful wave wake predictor – a scalable, empirical predictor of wave wake properties based on vessel parameters, speed and water depth.

AMC researchers have published more than 30 peer-reviewed scientific articles and 50 technical reports on wave wake related topics and studies. A list of the published articles is available from AMC (2018).

The following background information has been provided to give readers who are new to the topic a basic understanding of some aspects that are important when attempting to assess the waves generated by many types of marine vessels, particularly those that operate in sheltered and confined waterways such as is found in the Willamette River's Newberg Pool, where the naturally occurring wind wave climate is low due to significantly reduced fetch:

- Naval architects and maritime engineers traditionally non-dimensionalise vessel speed using the length Froude number, Fr_L (Equation 1). Because water depth plays such a crucial role in the characteristics of the wave wake generated, it is also very important to consider the non-dimensional relationship between vessel speed and water depth, the depth Froude number, Fr_h (Equation 2).

Length Froude number

$$Fr_L = \frac{u}{\sqrt{gL}} \quad (1)$$

Depth Froude number

$$Fr_h = \frac{u}{\sqrt{gh}} \quad (2)$$

Where: u = vessel speed (m/s)
g = acceleration due to gravity (taken as 9.81 m/s)
L = waterline length of vessel (m)
h = water depth (m)

- For vessel wave wake studies, depth of water refers to that beneath the vessel's sailing line.
- In deep water, all vessels typically generate the largest waves when they travel at or around their displacement hull speed, which equates to length Froude numbers of $0.4 \le Fr_L \le 0.5$.
- The pattern of waves generated will change significantly depending on the water depth that the vessel is operating. The different wave patterns/zones are summarised in Figure 1 and briefly discussed below:
    - The well-known Kelvin wave pattern, consisting of both divergent and transverse waves, is generated at sub-critical speeds (Fr_h is less than approximately 0.75), where the water depth is considered to be 'deep'.
    - A depth Froude number of 1.0 is termed the critical speed and speeds leading up to this point are referred to as trans-critical speeds (approximately $0.75 \le Fr_h \le 1.0$). In this region, both the period and propagation angle of the leading divergent waves rapidly increase, as does the wave height.
    - Speeds in excess of depth Froude number of 1.0 are termed super-critical speeds, where a vessel's wave pattern changes again. These divergent waves will have relatively long periods, compared to the sub-critical wave pattern.
- It is well known and understood that at intermediate sub-critical depth Froude numbers the dominant waves of the Kelvin wave pattern will consist of a series of diverging waves along the cusp-locus line (which are dispersive in nature). This series of waves will start with a wave at the bow of the vessel followed by other waves arranged in such a way that each wave is stepped back behind the one in front in echelon and is of quite short length along its crest line. Thus, as the lateral distance from the vessel's sailing line increases it is likely that different waves will be measured. This is clearly the case in the example provided by the aerial photograph in Figure 2 where each of the white lines, representing longitudinal cuts of the wave pattern, cuts a different divergent wave (note that there are many more divergent waves than vertical lines displayed). These characteristics of sub-critical waves can result in notable scatter in measured wave heights in the field.
- In contrast, it can be much easier to identify the leading wave for super-critical vessel speeds (and high trans-critical speeds) as these waves have significantly longer crest lengths, making it a simpler task to track the same wave as it propagates away from the vessel's sailing line.
- Wave height can be significantly affected by hull design, but wave period is mostly unaffected. For example, two vessels of same length but significantly different displacement will generate waves of similar period, but the height of the heavier vessel's waves will very likely be greater, and hence be considerably more energetic.
- A vessels slenderness ratio (waterline length divided by the inverse cube of its displaced volume) is an excellent indicator of the waves generated by surface vessels. It is defined by Equation 3:

$$\text{Slenderness Ratio} = L/\nabla^{1/3} \qquad (3)$$

where L is the waterline length and ∇ is the displaced volume (in m^3), usually for design (full) load condition.

- When aiming to minimise vessel wave wake it is accepted practice to maximise the slenderness ratio - that is, make the vessel as long and light as practical. Minimising slenderness ratio is one way to increase wave height and energy.
- Wave height will decay with increasing lateral distance from the sailing line of the vessel. Wave period remains approximately constant over lateral distance (this does not necessarily apply close to the vessel, say within one-half boat-length, as the waves have generally not dispersed sufficiently).
- Wave period, although largely unaffected by changes to hull form, is dependent upon vessel length, vessel speed and water depth.

- The pattern (or train) of waves generated by marine vessels is very complex, consisting of many waves of varying height and period. These waves disperse as they propagate away from the sailing line of the vessel, as can be seen in Figure 3. Close to a vessel (say half a boat length), the wave pattern will appear to consist of only a few waves. It takes approximately one to two boat lengths for waves to disperse sufficiently such that the period of individual waves can be measured with certainty.
- Until relatively recently, it was common to assess vessel wave wake by quantifying the height and period of a *single* wave in the complex wave train, usually the highest. However, this has been proven to be inadequate, particularly when the vessel is operating in shallow water depths (trans-critical speeds and above). Given the complexity and dynamic nature of the complete wave train, it is considered impractical to attempt to assess each and every wave. The assessment methodology recommended by AMC is to identify and quantify up to three specifically defined waves in a wave train. This ensures that the waves possessing the greatest height, longest period and highest energy are always identified and assessed. The complex nature and large number of variables that influence vessel wave patterns means that there are occasions when all three (greatest height, period and energy) are represented by one, two or three individual waves. The three key waves are defined as follows:
    - Wave A – the leading diverging wave, which by definition, is the wave that will possess the longest period.
    - Wave B – the most significant (highest) wave following the leading wave (Wave A). The period will be shorter than the leading wave, but often not by a large margin, whereas the height is very often notably greater than the leading wave.
    - Wave C – it is common for a group of short period divergent waves to be generated and Wave C is defined as being the highest wave within this group. This wave always follows Waves A and B, hence will possess the shortest wave period of these three key waves.
- Note that the definitions of Waves A, B and C do not imply that only one wave of similar characteristics to each will be generated. Several waves of similar height and period to each representative wave may be present within each wave train. This is particularly the case with Waves B and C where multiple waves of similar period often occur as groups of 2 to 5 waves.
- Also of interest to most wave wake studies is the resultant wave energy (per unit crest width), which is proportional to both the square of wave height and wave period, so any change in either height or period will result in a significant change in wave energy.
- In recent years, when assessing vessel wave wake for comparative purposes, it has become common to calculate the energy in each key wave using Equation 4 (for each wavelength, per unit width of wave crest).

$$E = \frac{\rho g^2 H^2 T^2}{16\pi} \qquad (4)$$

Where: E = wave energy (J/m)
ρ = density of water (kg/m^3)
g = acceleration due to gravity (taken as 9.81 m/s)
H = wave height (m)
T = wave period (s)

A simplified version of this formula, for imperial units, is provided in Equation 5.

$$E = 40.97 H^2 T^2 \qquad (5)$$

Where: E = wave energy (lb.ft/ft)
H = wave height (ft)
T = wave period (s)

- The effect of slenderness ratio on the height of the maximum (highest) wave generated by a vessel is highlighted in Figure 4 where the wave height constant (vertical, y-axis) is plotted as a function of slenderness ratio (horizontal, x-axis). In this figure, it is clear that hull form has a significant influence on the height of the waves generated, with the wave height constant for all three key waves generally decreasing with an increase in slenderness ratio.

Further information and discussion on the topic of vessel generated waves can be found in Macfarlane (2012).

To perform a rational assessment, especially when comparing the performance of differing craft and water sport activities, it is recommended that:

(1) a suitable benchmark be set. For the present study, it is suggested that this could be based on the characteristics of the waves generated by typical water ski boats and runabouts operating at speeds that are commonly used for water skiing and tubing activities;
(2) the investigation is limited to a select number of relevant variables that are representative of the intended vessel operations; and,
(3) the study considers all key waves in the generated wave profiles, but the direct comparison between differing craft focusses primarily on just the height and energy from the *maximum* wave.

3.0 FULL SCALE TRIALS, TEST SITE AND INSTRUMENTATION

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

There does exist small craft wave wake trials data available in the 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, poor recording or over-simplification of results are common traits to be found. 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.

The full scale trials for the present study were conducted between 7th and 10th August 2018 on a selected section of the Willamette River near Coalca Landing, Oregon City, Oregon, USA, as indicated in Figure 5. The site provided a relatively straight reach with a roughly constant water depth beneath the test vessel in the region of 40 feet. The water depth at the probe was confirmed as 15 feet. A cross-section of the river bathymetry at the measurement point is provided in Figure 6. The red circles on the water surface indicate the four lateral distances of 100, 200, 300 and 400 feet from the wave probe to the nominal track path of the test vessels. Buoys were deployed at appropriate locations to guide the boat operator to maintain a consistent distance/track path.

It is important to select a test site where the wave probe will not be subjected to boat-generated waves that reflect of the surrounding shore or any bluff structure as these reflected waves may contaminate the traces and lead to misleading results. For example, gently sloping beach-type banks are less reflective than levee-type banks. The site selected had a sufficiently non-reflective shore line, including considerable vegetation, resulting in minimal reflection.

Water surface elevation was measured using a single MK-VI salt/fresh water capacitance wave probe manufactured by Manly Hydraulics Laboratory. The signal from the wave probe was digitised and radio telemetered to a custom data acquisition unit which was located approximately 50 to 75 feet distant (set up on a stationary support vessel). Each run was recorded using a Dell laptop computer that was accessed by Labview acquisition software. The wave probe was calibrated both within the AMC laboratory and checked in situ. The calibration factors compare well against those obtained within laboratory conditions prior to departing and upon return to AMC.

At the commencement of each test session the wave probe and data acquisition equipment was set up on the test site. The wave probe was fixed to a vertical post that was driven into the river bed and supported by three equispaced ropes that were anchored to the river bed to minimise any lateral movement of the wave probe. 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. A photograph of the wave probe set-up is shown in Figure 7 (the umbrella was deployed to minimise direct sunlight on the yellow case that contains the wave probe power supply/signal transmitter).

4.0 TEST PROGRAM AND PROCEDURE

A systematic approach is highly recommended for any experimental campaign involving several variables. The test program undertaken involved various different craft, load conditions (including ballast options and number of passengers), lateral distance and boat speed. The marine craft used in this study and their respective load conditions are summarised in Table 1. The first eight cases listed in this table form the primary part of the planned test program. Case 9, the Centurion Ri217, was an incidental craft that provided two unscheduled wakesurfing runs past our wave probe at an estimated lateral distance of 350 feet. The actual ballast, passenger loading and speed are unknown. Case 10 refers to experimental data from a study performed in 2015, released by the Water Sports Industry Association (WSIA, 2018).

At the commencement of each run, the test vessel was accelerated to a nominal speed, achieved some distance prior to being perpendicular to the wave probes (typically 200 to 500 feet). Recording of the water surface elevation signal from the wave probe was triggered manually, dependent upon the lateral distance between the sailing line of the boat and the wave probe (nominal distances were 100, 200, 300 and 400 feet). This provided a baseline measurement of the ambient conditions prior to the arrival of the wake waves at the wave probe. The water surface elevation continued to be recorded until all significant waves generated by the passing boat had passed the wave probe (this generally lasted for approximately 60 to 120 seconds). The sample rate was set at 200 samples per second (200 Hz), which is more than adequate to clearly define each wave. Figure 8 shows a photograph taken during a typical run (R70) involving the 2015 Ski Nautique 200 at a speed of 12 mph and lateral distance of 100 feet. Yellow marker buoys used to guide the boat skipper to the desired lateral distance can be seen (these buoys were located using a hand-held GPS).

At the end of each run the test vessel paused until the waves generated had dissipated and conditions were considered calm enough for the next test run. The vessel then sailed past the wave probe in the opposite direction. Approximately 220 individual runs were performed.

Each test run has been individually analysed within an Excel macro worksheet, which imports the data file created during each test run and, from the discrete samples collected, plots a wave elevation time history. The macro then determines the characteristics of height and period of the maximum wave (and any other selected waves). Other quantities, such as wavelength, celerity, energy and power for the maximum wave can then be readily computed.

5.0 RESULTS

As previously noted, the large number of variables involved can lead to a huge amount of data to process, so a logical and considered approach is often necessary to achieve meaningful outcomes when comparing and presenting the wave wake performance of multiple vessels. This is the primary reason why it is recommended that the present study focusses on the *maximum* height and energy from each wave trace/run.

A typical wave elevation time series from one run is plotted in Figure 9. The Excel macro used to analyse each run determines the start of each successive wave by the change in wave elevation above the still water level from positive to negative (or vice versa) – this is the definition of a zero-crossing point. 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. The period of the maximum wave is obtained from the time between consecutive zero up-crossings (or down-crossings).

For this initial report, the analysed results are simply presented in the following sub-sections, with little or no discussion on the implications of the data.

Results for Wakesurfing Speeds: 10 to 12 mph

In Figure 10, maximum wave height is plotted as a function of lateral distance for several different cases at speeds of 10 to 12 mph, including all ballasted and unballasted wakesurfing craft and a fishing boat. Also included in this graph are two potential benchmark cases: a typical runabout operating at 22-24 mph and a ski boat operating at speeds around 30 to 32 mph.

Results extracted from publicly available data from the WSIA 2015 wake energy study have also been included in Figure 10. It is believed that five wave probes were deployed in this study, the first at a lateral distance from the test boat of 10 feet (where the maximum wave height was stated as being 27.8", beyond the limits of Figure 10), and the last probe a distance of 275 feet from the first (maximum wave height of 7.5"). Estimated maximum wave heights at the three intermediate probes are shown at lateral distances which assume the probes are equispaced.

Similarly, the energy of the maximum wave (for each wavelength, per unit width of wave crest) is plotted as a function of lateral distance for the same cases and speeds of 10 to 12 mph in Figure 11.

It was observed that the fishing boat (2004 Thunder Jet Alexis) generated notably higher waves at 10 mph than 12 mph, which is reflected in the results presented.

Results for Wakeboarding Speeds: 22 to 24 mph

The maximum wave height is plotted as a function of lateral distance for the wakesurfing craft and fishing boat at speeds of 22 to 24 mph in Figure 12. The same two potential benchmark cases have again been included. The energy of the maximum wave is plotted as a function of lateral distance for the same cases and speeds of 22 to 24 mph in Figure 13. Both ballasted and unballasted wakesurfing craft are presented as a single series as there was only a limited quantity of unballasted cases available at these speeds.

6.0 REFERENCES

AMC, List of wave wake related publications by AMC personnel, https://amcstaff.utas.edu.au/maritime-engineering/wave-wake-predictor [accessed 26th August 2018]

Macfarlane, G.J., Marine vessel wave wake: focus on vessel operations within sheltered waterways, Doctor of Philosophy Thesis, Australian Maritime College, University of Tasmania, June 2012.

WSIA, Wave energy - leveraging data to fuel the stoke, https://www.wakeresponsibly.com/waveenergy.html [accessed 26th August 2018]

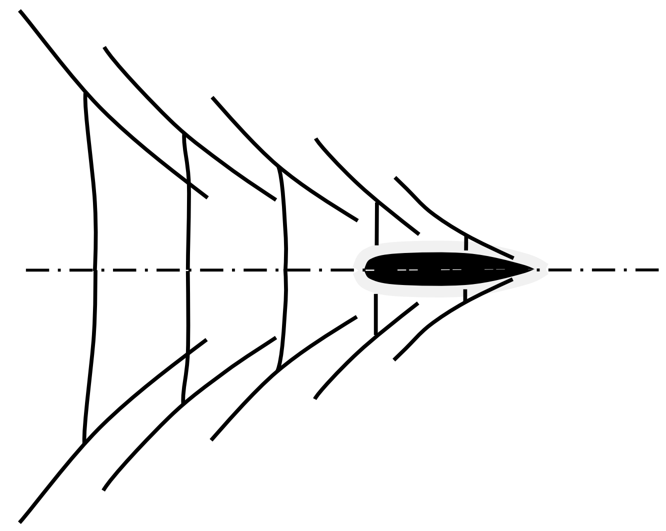
Table 1: Summary of test vessels and details

Case Number	Boat Description	Length LOA (feet)	Displacement						Comments
			Dry (lbs)	**Ballast Condition**	**Ballast** (lbs)	**No. PAX**	**PAX / Misc** (lbs)	**TOTAL** (lbs)	
1	2006 Malibu V-Ride	21'	3000	Ballasted	900	9	1620	5520	Systematic tests
2	2017 Nautique G21	21'6"	5500	Ballasted	2850	9	1620	9970	Systematic tests
3	2017 Nautique G21	21'6"	5500	No ballast	0	9	1620	7120	Systematic tests
4	2018 Axis T23	23'6"	4500	Ballasted	900	9	1620	7020	Systematic tests
5	2019 Axis T23	23'6"	4500	No ballast	0	9	1620	6120	Systematic tests
6	2004 Thunder Jet Alexis	21'	4100	N/A	0	6	1080	5180	Systematic tests
7	2015 Ski Nautique 200	20'	2850	N/A	0	6	1080	3930	Systematic tests
8	2008 Reinell Ski Boat	20'	2900	N/A	0	6	1080	3980	Systematic tests
9	2017 Centurion Ri217	21'7"	5350	Ballasted	4950	3	540	10840	Incidental craft
10	2015 Nautique G23	23'	5540	Ballasted	4250	2	360	10150	WSIA study

Sub-Critical (Kelvin waves)

$Fr_h < 0.75$

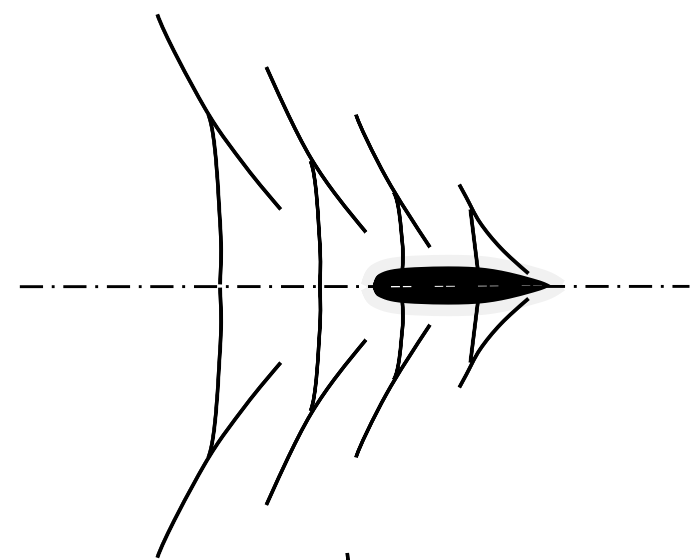
- Short-crested divergent waves
- Transverse waves present
- The well-known Kelvin deep water wave pattern



Trans-Critical

$0.75 < Fr_h < 1.0$

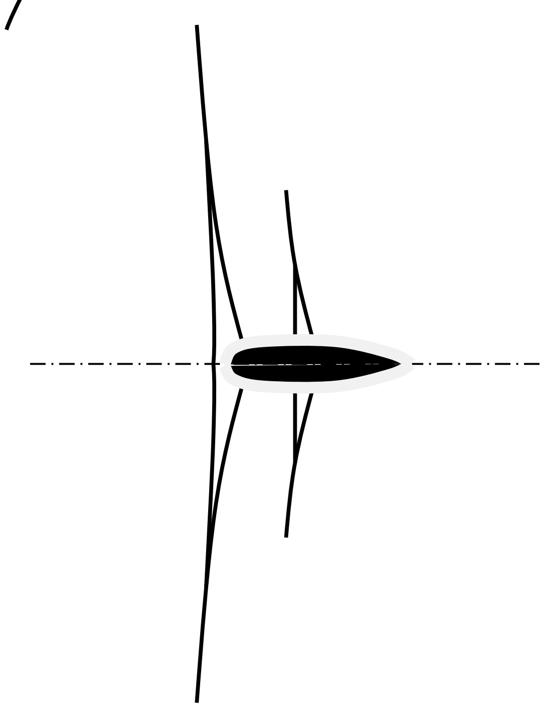
- Divergent wave angle increases
- Period of leading waves increases



Critical

$Fr_h = 1.0$

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



Super-Critical

$Fr_h > 1.0$

- No transverse waves
- Long-crested divergent waves
- Long-period leading waves

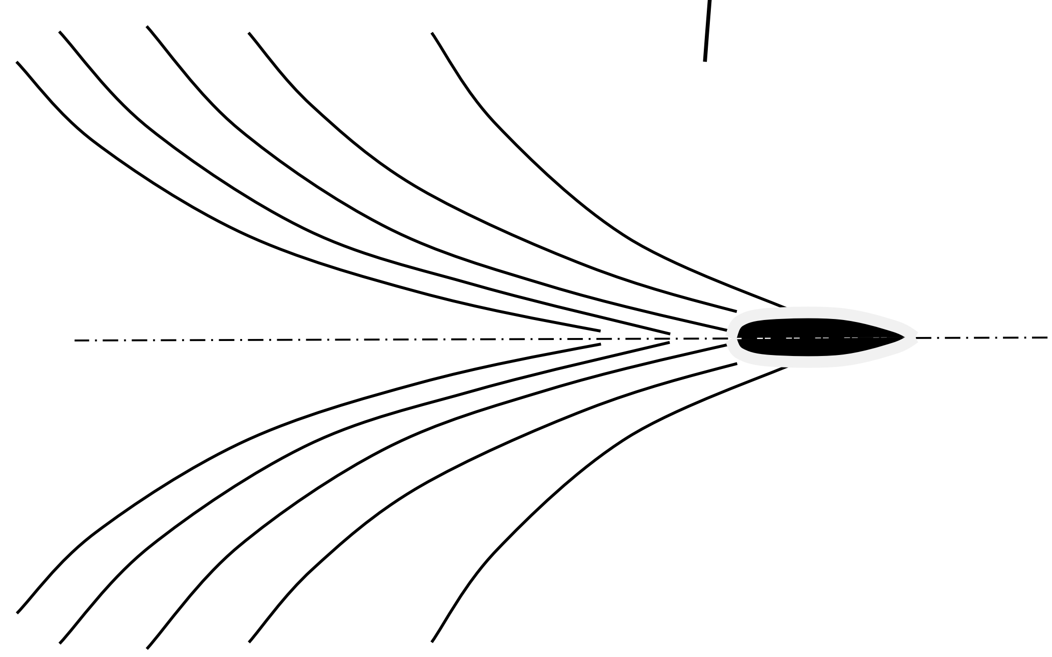


Figure 1 Vessel wave wake patterns

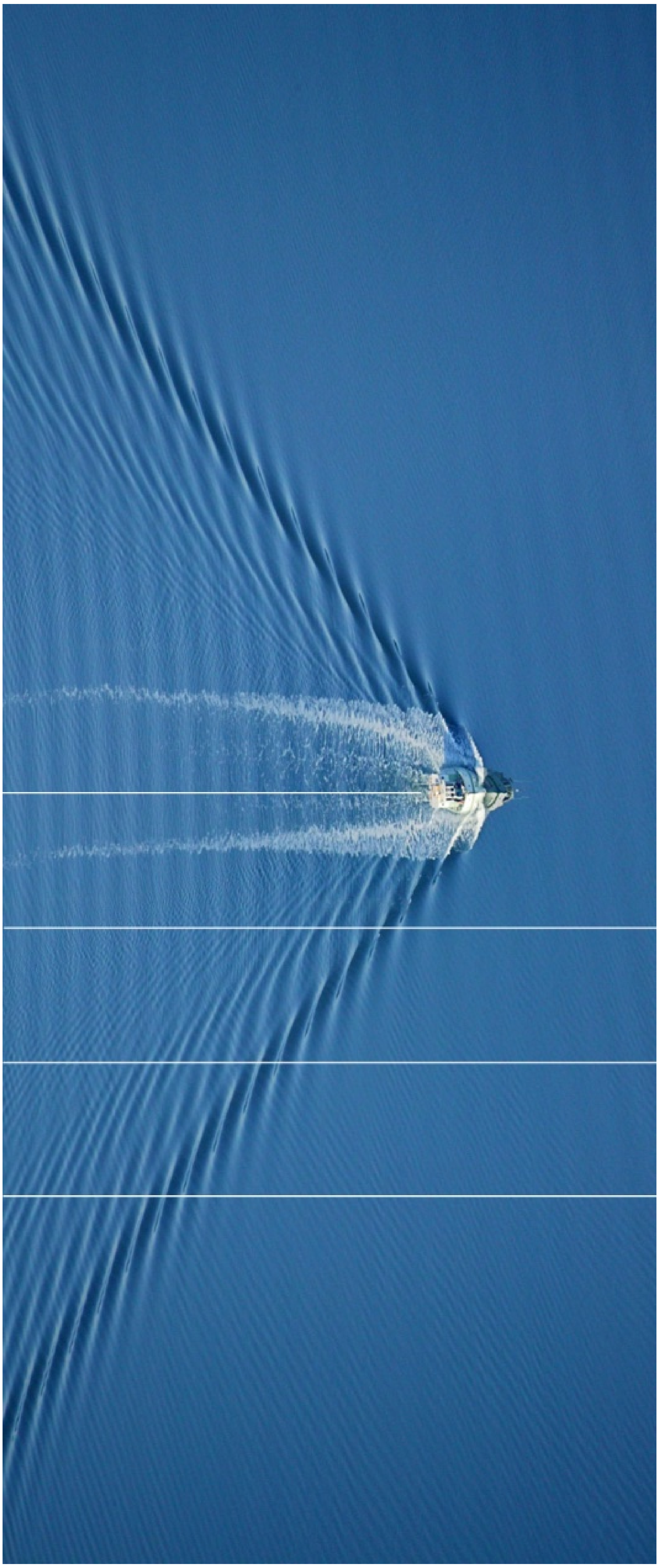


Figure 2 Aerial photograph of Kelvin wave pattern (Airview Aerial Photography)

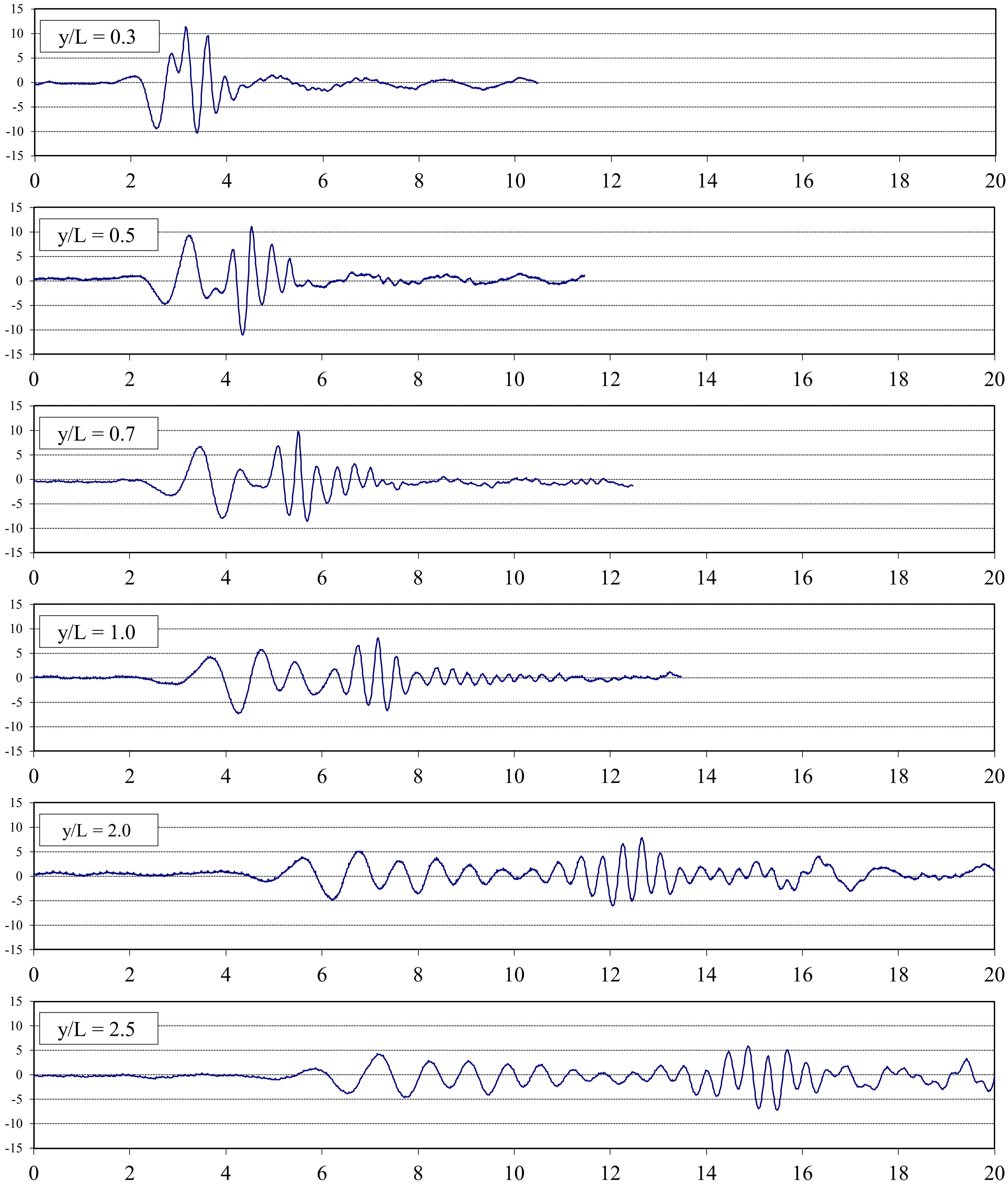


Figure 3 Deep water wave dispersion (various lateral wave probe positions)

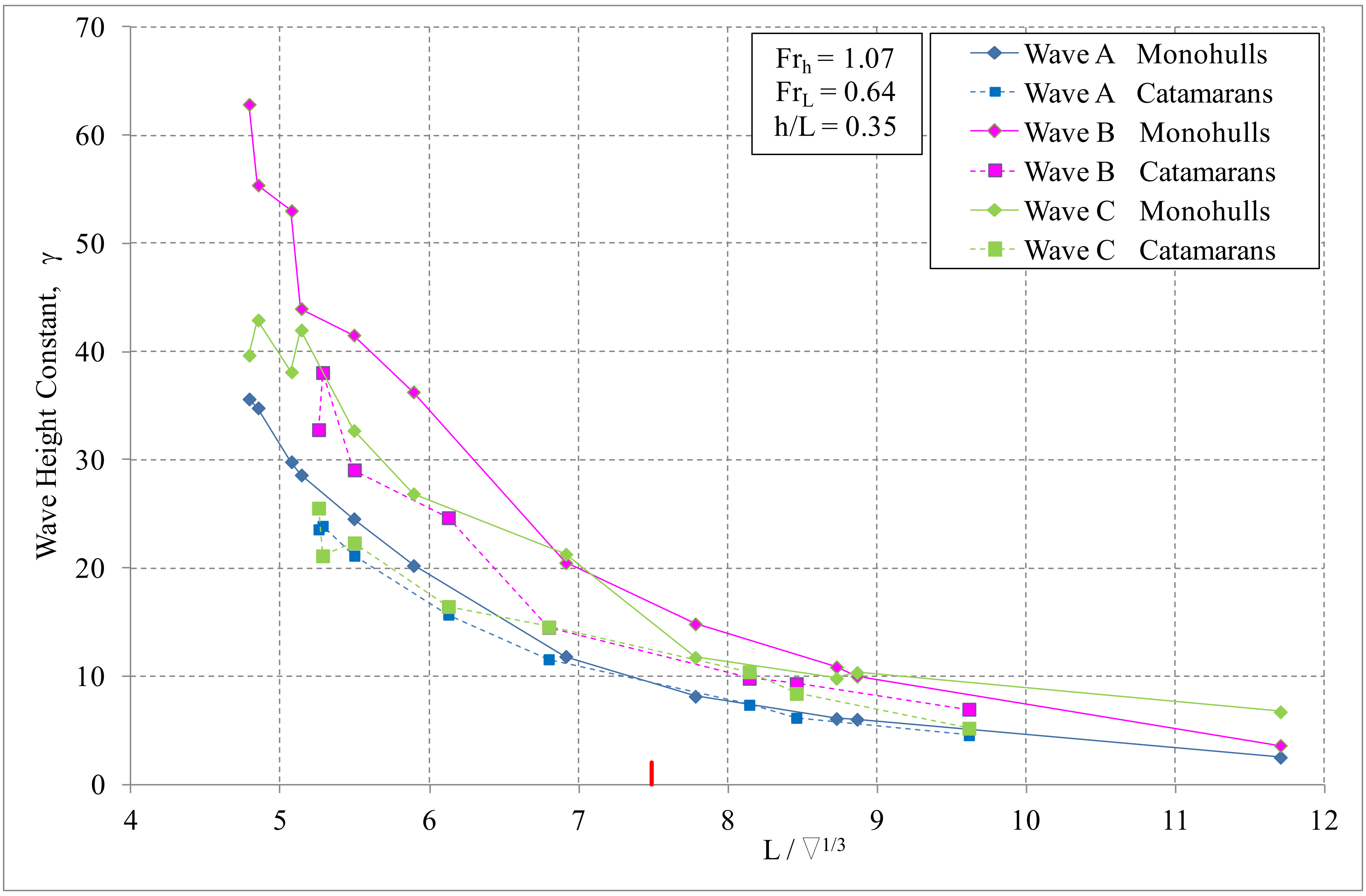


Figure 4 Example of the influence that slenderness ratio (L/ ∇$^{1/3}$) has on the maximum wave height constant

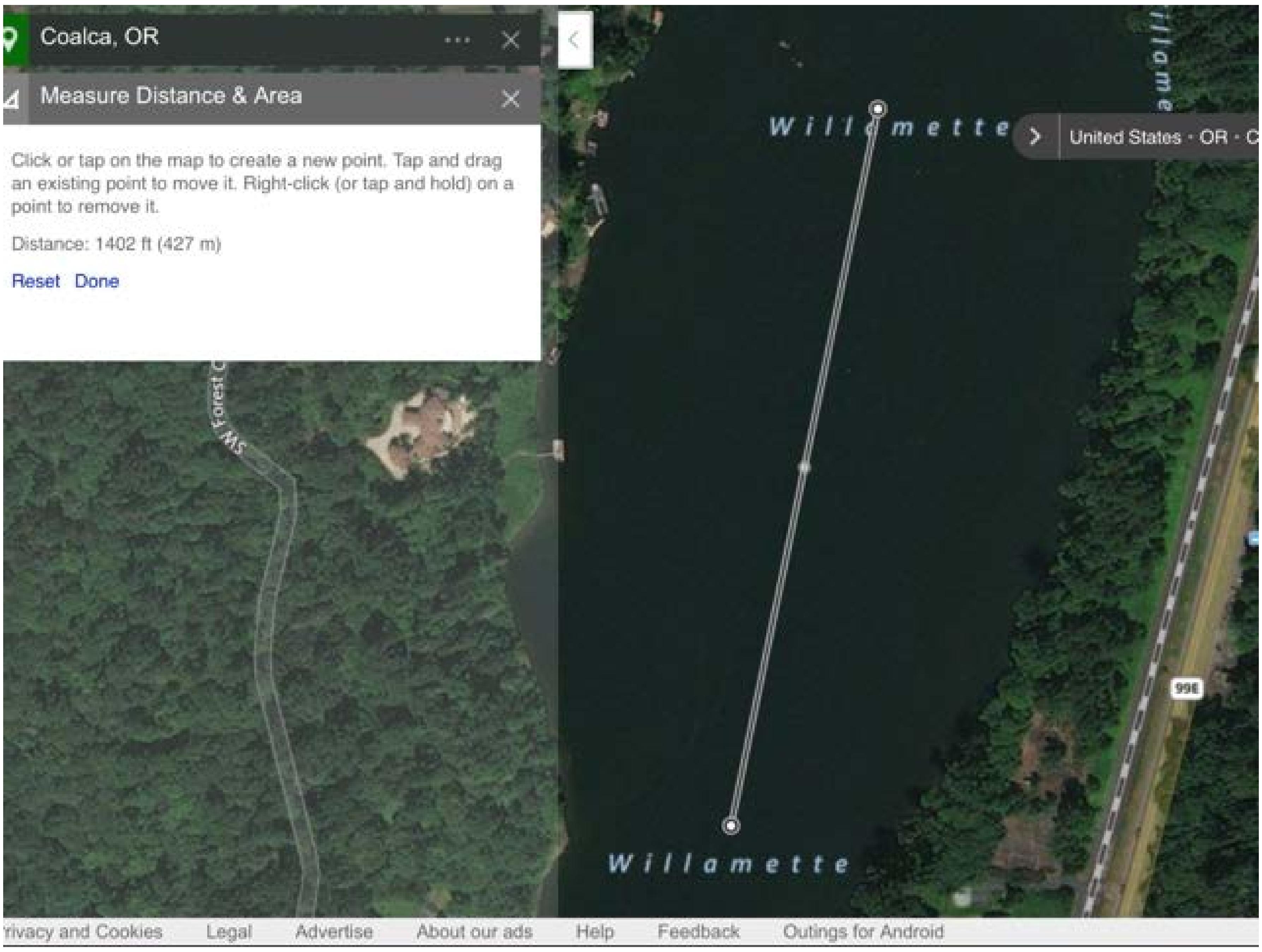


Figure 5 Location of the test site (from Google maps)

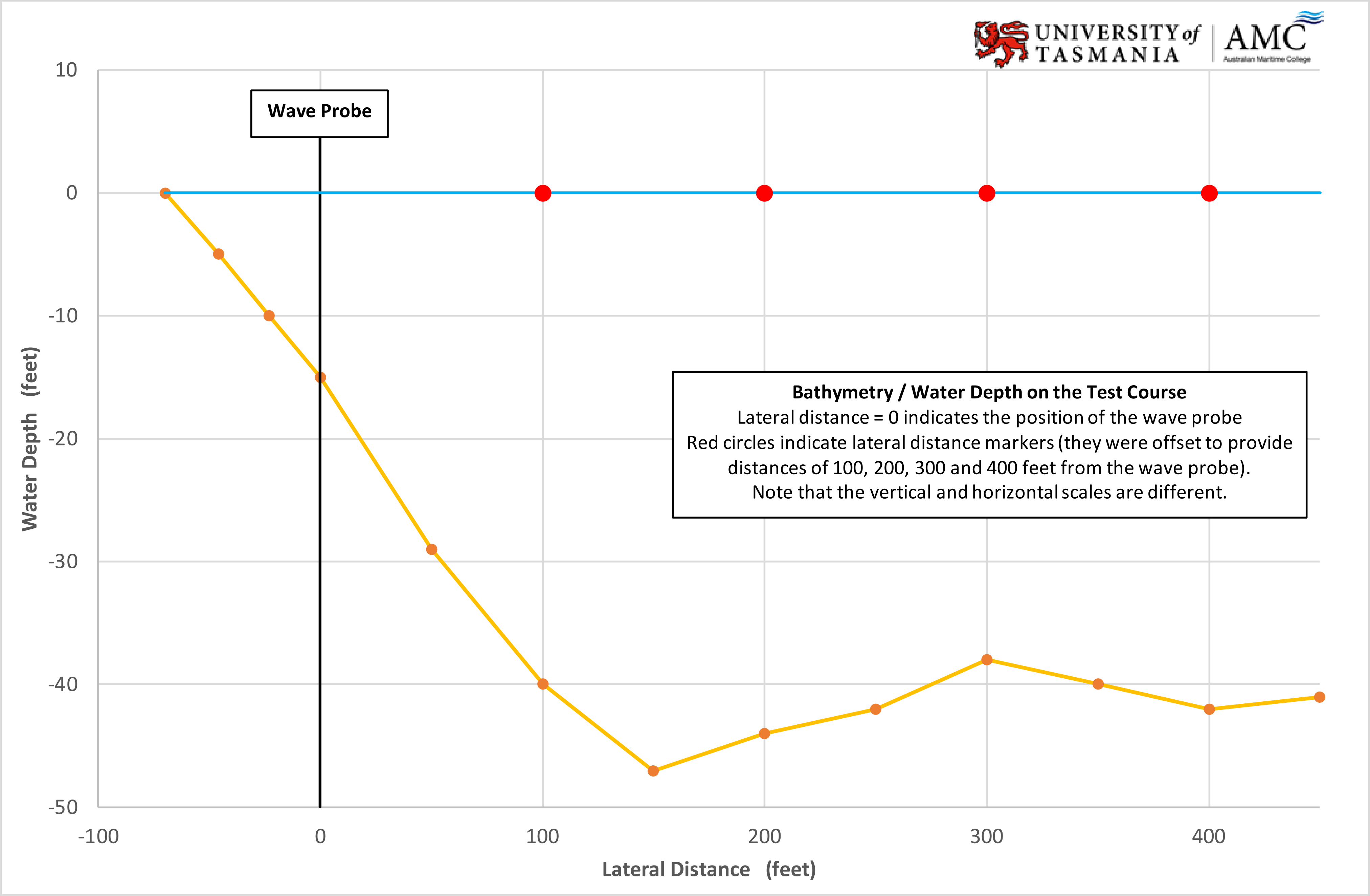


Figure 6 Cross-section of the test course showing water depth and lateral distances

Figure 7 Photograph of the wave probe set-up

Figure 8 Photograph of 2015 Ski Nautique 200 at a speed of 12 mph and lateral distance of 100 feet (Run R70)

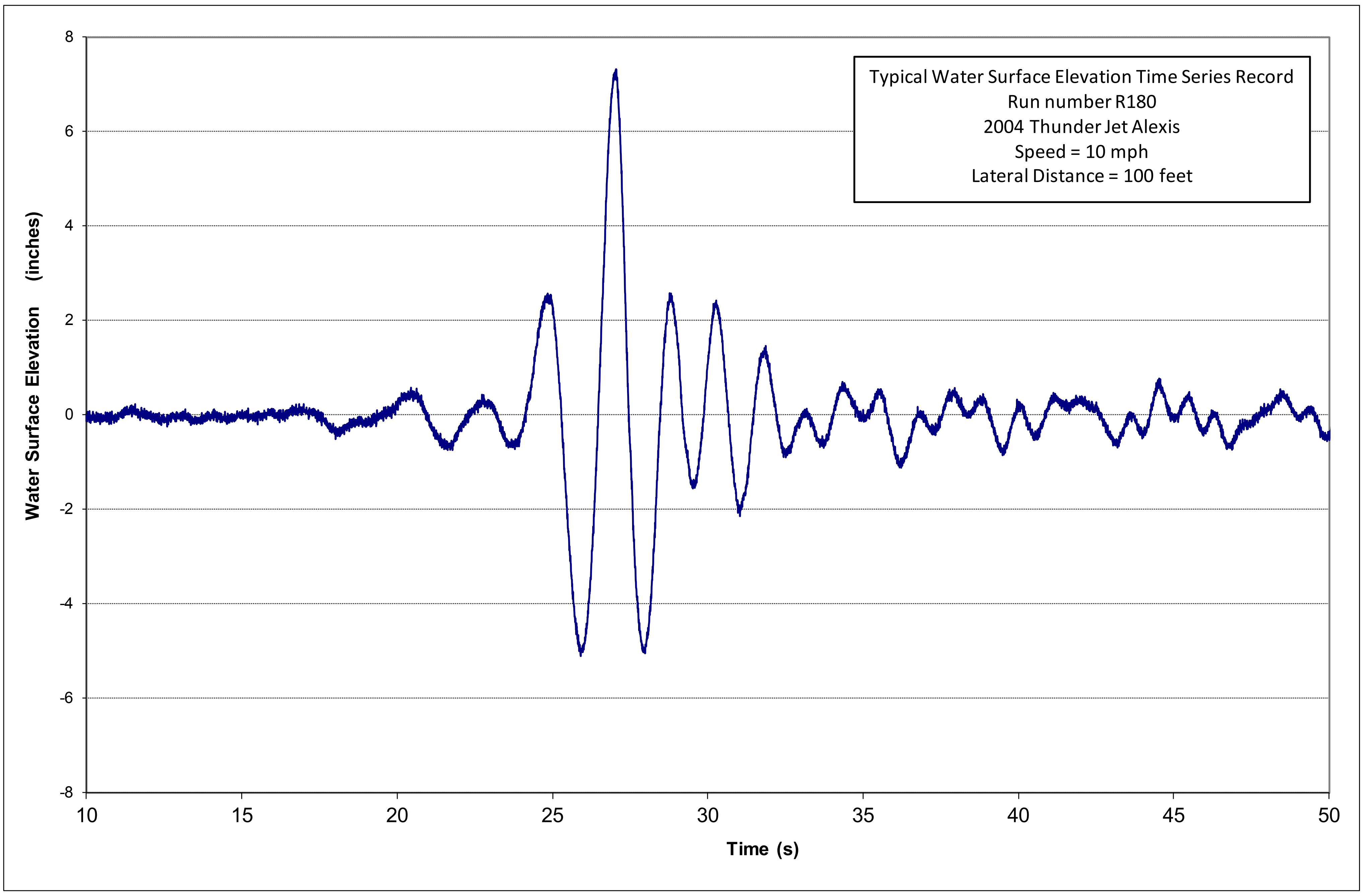


Figure 9 Example of a typical wave surface elevation time series: 2004 Thunder Jet Alexis at 10 mph (Run R180)

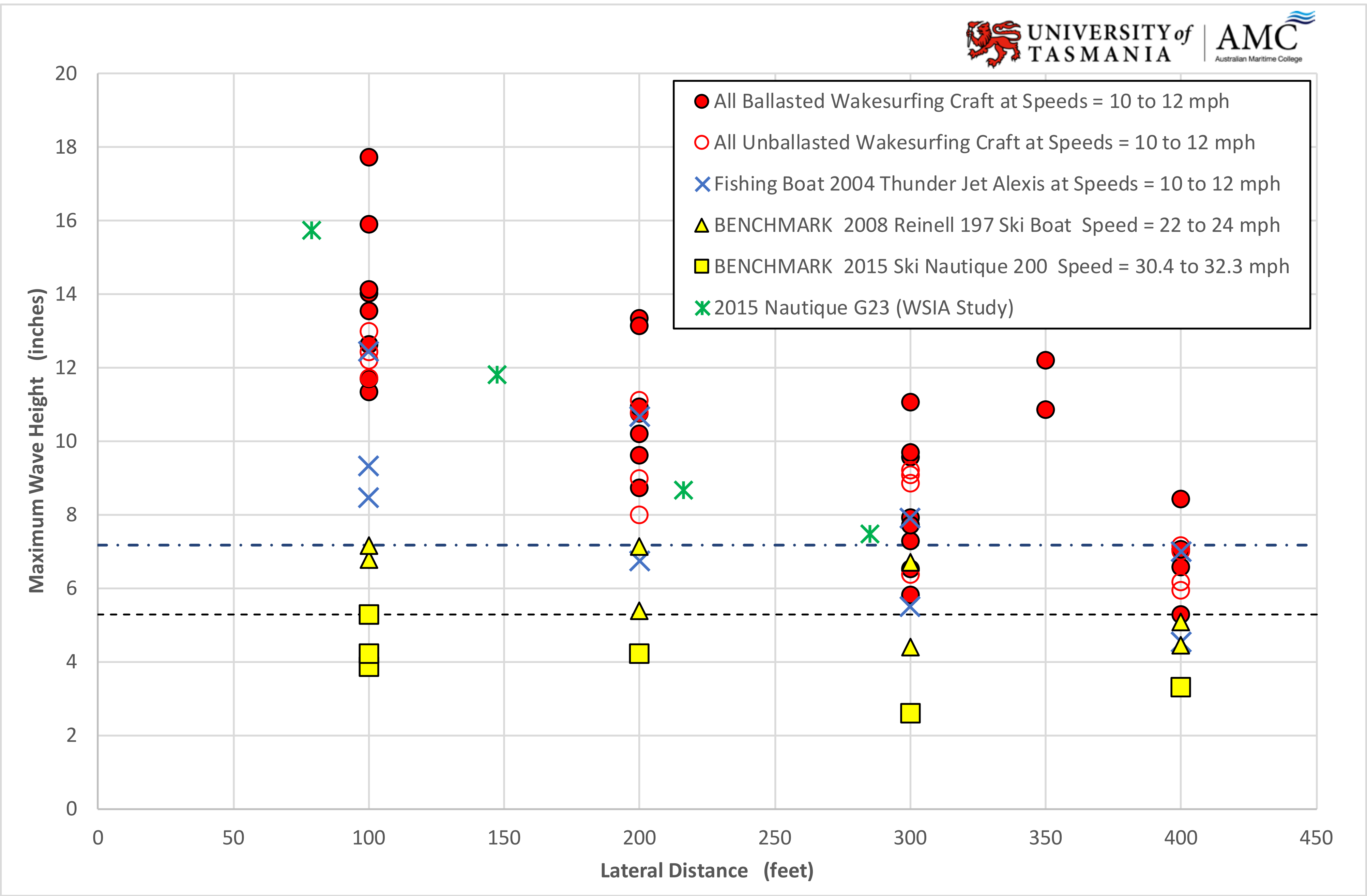


Figure 10 Maximum wave <u>height</u> as a function of lateral distance: <u>Wakesurfing</u>

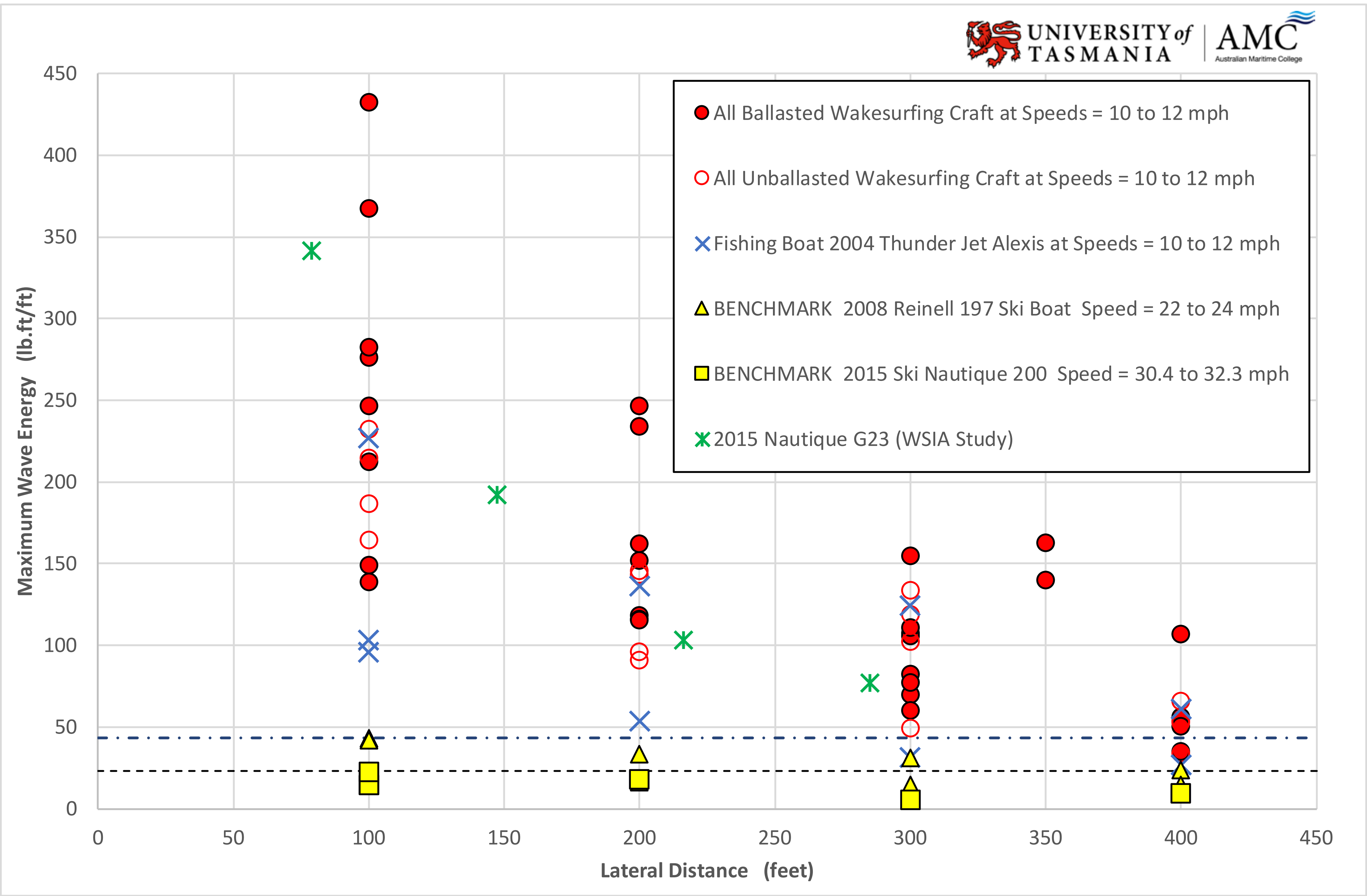


Figure 11 Maximum wave energy as a function of lateral distance: Wakesurfing

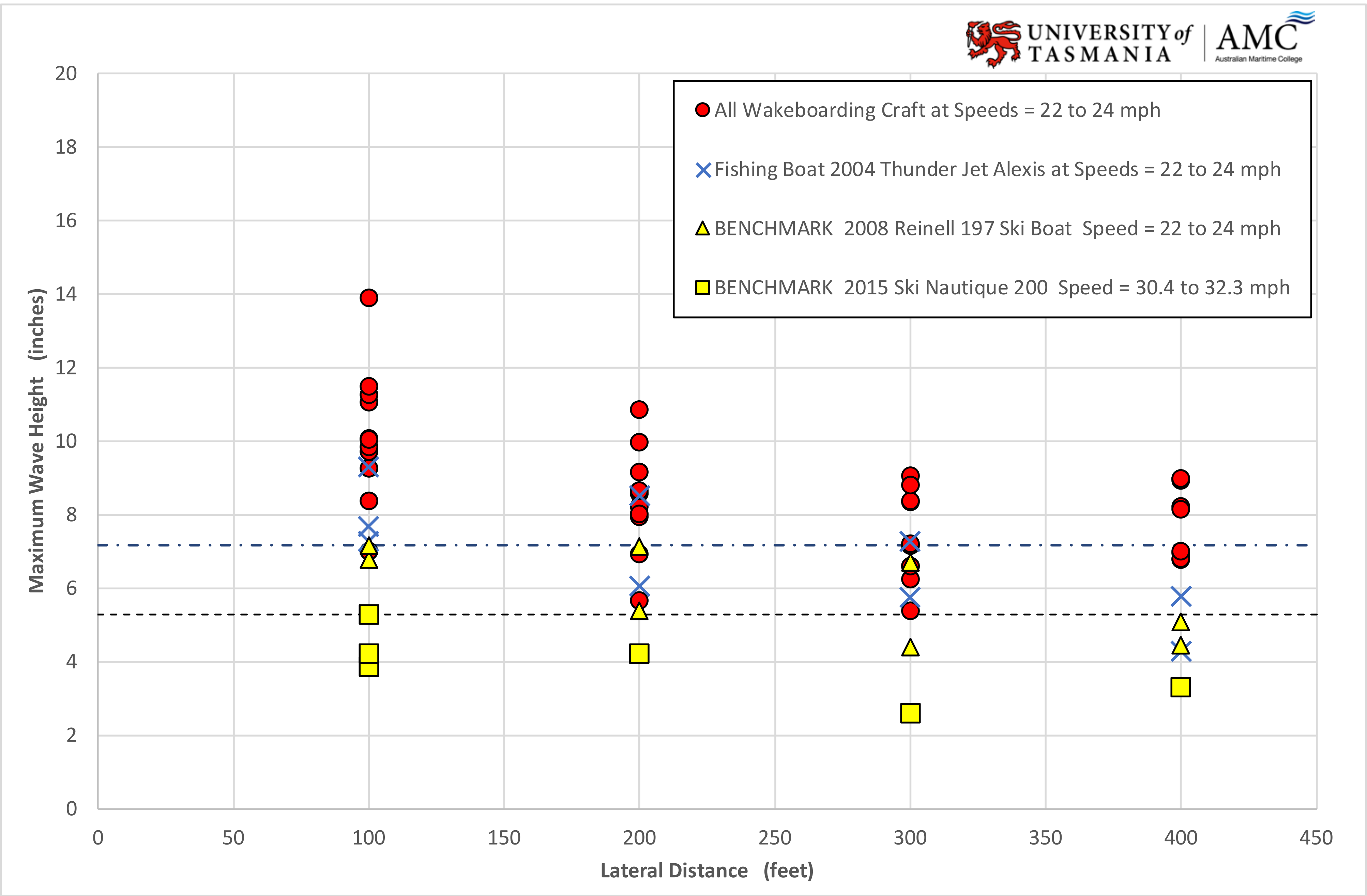


Figure 12 Maximum wave height as a function of lateral distance: Wakeboarding

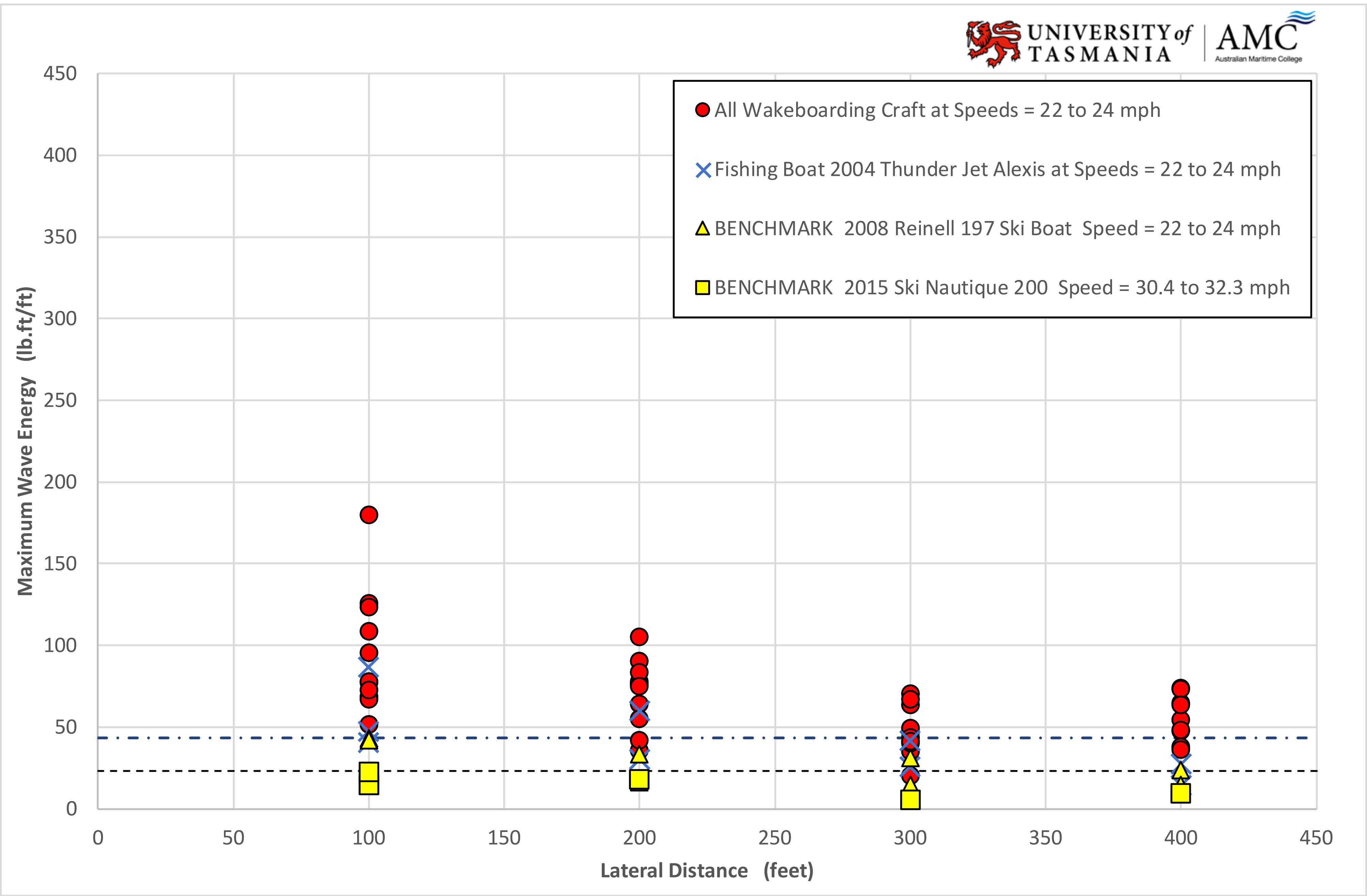


Figure 13 Maximum wave energy as a function of lateral distance: Wakeboarding