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by

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LIMITATIONS ON THE CREATION OF CONTINUOUSLY SURFABLE WAVES GENERATED BY A PRESSURE SOURCE MOVING IN A CIRCULAR PATH

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ABSTRACT

In this paper, a novel idea to produce continuous breaking waves is discussed, whereby a pressure source is rotated within an annular wave pool. The concept was that the pressure source generates non-breaking waves that propagate inward to the inner ring of the annulus, where a sloping bathymetry (beach) triggers wave breaking. In order to refine the technique, research was conducted to better understand the mechanics of waves generated by a pressure source moving in a circular track in a constrained waterway, the transformation of these waves as they travel across the channel and the effect of the sloping beach on the wave quality for surfing.

The quality of the waves was defined in terms of wave height, speed and shape, with the desired aim to create plunging waves, known as "barrels", that are highly desired by surfers. Surfers also require a long steep crestline or "wall", to allow a full range of manoeuvres to be performed. Finally, the pool needed to be able to create waves suitable for surfers from beginner to expert level, defined in terms of both the wave height and angle between the wave break point angle and the beach, known a peel angle.

The primary novel outcome of the research conducted was to be able to design a pressure source that most efficiently imparted wave making energy into the water, and thus generated the largest possible waves whilst travelling at the required speed for surfing.

The major finding was that the design parameters are generally in competition, and to determine a balance of limiting values, the design parameters cannot be considered in isolation. Therefore, a set of empirical relationships between the design parameters were developed to allow the pool to be designed for a combination of desired wave height at the breakpoint, wave shape and given pool radius.

The limiting values for the parameters were determined experimentally, with the wave life-cycle from generation through transformation to wave breaking and dissipation used to focus the investigation. Scale model experiments were conducted in both linear and circular tracks. In addition to taking quantitative measurement of wave height and current formation, a method of qualitatively scoring the waves was developed to allow various pressure source shapes, operating conditions and bathymetries to be compared in terms of their suitability for surfing. The best quality waves were produced by a wedge-shaped wavedozer pressure source, such as the device detailed in Driscoll and Renilson [1].

Blockage, defined as the pressure source cross sectional area to channel cross-sectional area, was found to have a significant limitation on the generation of high quality waves suitable for surfing in a constrained waterway. Lateral wave decay, length and depth Froude Numbers also strongly influenced the waves during their life-cycle. Fundamentally, it was determined that only a very small range of design parameter values produce the desired high and shapely waves in the extremely constrained waterway under consideration.

NOMENCLATURE

κ	Blockage	$\frac{A_s}{A_c}$
∇	Volume displacement	
ξ	Wave breaking intensity	
ζ	Surface elevation	
ζ_{wp1}	Surface elevation measured close to the pressure source	
ω	Angular velocity	
λ_{beach}	Wavelength in deep water just before the beach	
A_c	Channel cross-sectional area	
A_s	Pressure source cross sectional area	
B	Pressure source beam	
$B*$	Normalised pressure source beam	$\frac{B}{R_0}$
c_p	Wave phase speed	
d	Draught	
$d*$	Normalised pressure source draught	$\frac{d}{h_0}$
Fr_h	Depth Froude number	
Fr_{h0}	Depth Froude number at R_0	
h_0	Water depth at R_0	
H_{beach}	Wave height at the start of the beach	
h_{beach}	Water depth at the start of the beach	
$H*$	Non-dimensionalised wave height	$\frac{H}{\sqrt[3]{\nabla}}$
LWL	Pressure source waterline length	
R	Radius	
R_0	Pool radius	
R_0	Beach radius	
s	Beach slope	
T	wave period	
u	Tangential component of the velocity (parallel with the pressure source line of travel)	
u_0	Pressure source velocity	
y	Lateral distance from R_0	
$y*$	Normalised lateral distance from R_0	$\frac{y}{R_0}$
y_{beach}	Lateral distance to the start of the beach	
$y_{beach}*$	Normalised lateral distance to the start of the beach	$\frac{y_{beach}}{R_0}$
Y_{beach}	Width of the beach	
WP	Wave probe	
Z_{beach}	Height of the beach	

INTRODUCTION

Surfing is fun. However, it is also extremely difficult to learn and master. This difficulty is no part helped by ever changing nature and short duration of the breaking waves; with the waves changing both day to day with the weather, and as the wave breaks on the shore. With the average wave breaking for less than 7 seconds, the surfer can only ride the waves for less than 8% of the time in the water [2]. Therefore, the dream of every surfer is for consistent, long lasting, high quality waves. This search concentrates surfers on to those areas of coastline that are exposed to regular surf, and with a bathymetry suitable to cause the wave to break in a consistent manner and provide a long ride.

Many surfers do not have the luxury of living near surf breaks, and must travel long distances in order to surf. Further, as coastal populations increase, and surfing becomes more popular, existing surf breaks become overcrowded, shortening their overall riding time even further. Surfers have responded by traveling to more distant and remote locations to chase uncrowded and better waves [2], even though this increases the cost of surfing and does not reduce crowding at their home breaks. Another solution has been to build artificial reefs in the ocean, however these still rely on the natural wave conditions. In this uncontrolled environment, the waves are affected by the constantly changing and potential adverse affects of the weather, including wave direction and period, wind (direction and strength), tide, and currents. A third solution is to generate waves in a controlled environment: the wave pool.

Wave pools are not a new concept. In 1934, the Wembley Swimming Pool in London was the first to thrill its visitors with small artificial waves. In 1966, the first indoor surfers rode waist-high waves in the Summerland wave pool in Tokyo, Japan [4]. Since then, more surf pools have been built around the world, receiving mixed reviews from surfers. The original linear wave pools, where the waves are generated at one end and travel to a beach at the other end, try to mimic naturally occurring waves with piston-driven paddles or similar mechanical devices. Such man-made waves are not very appealing to surfers as the rides are short, and the waves generally weak and poorly shaped.

Some manufacturers bend the pool around a curve to concentrate the swell, or shape the pool floor to improve the wave height [5]. Another method used to simulate surfing waves is to shoot a thin sheet of water over a wave shaped surface. However, this method does not provide an authentic surfing experience (a moving wave breaking along a shoreline) and, like the linear pools, generally only allows one rider at a time [6]. A third concept aims to draw an object though shallow water along a linear track creating waves in front of the object [7].

As the existing techniques generate the waves by moving large volumes of water, they are power intensive. Instead, the novel method discussed in this report more efficiently generates the waves by the pressure source imparting wave energy into water with minimal water movement.

Key deficiencies with these approaches involve both the lack of an authentic, scalable surfing wave motion of a moving wave breaking on a shoreline, the large power requirements to generate the waves and a limitation of a single rider being able to surf at one time, limiting the financial viability of the pool.

WEBBER WAVE POOL CONCEPT

In order to find the solution to these problems with current wave pool technology, a novel idea to produce continuous surfable breaking waves has been patented [8] by Liquid Time Pty Ltd, the Webber Wave Pool, whereby one or more pressure sources are rotated within an annular wave pool; Figure 1 and Figure 2. The pressure source is any object that disrupts the water surface, such as a ship-like hull or submerged body.

The inner ring of the annulus has a sloping bathymetry (i.e. a beach) to induce breaking of the waves (originating at the pressure sources), with the break point following the circular path around the central island at a given water depth at the breakpoint (h_{beach}) proportional to the wave height (H_{beach}); noting that for this analysis, the breakpoint was defined to be at the start of the beach. The quality of the waves generated by the pressure sources is critical for surfing, with the waves only breaking when triggered by the sloping bathymetry of the beach.

The design consists of multiple pressure sources travelling around the outer circumference of the pool whilst continually pushing wake waves towards the centre island where they are forced to break on the man-made beach due to the change in water depth. Should the pressure sources be symmetrical about their centre, allows the production waves in both the clockwise and anti-clockwise directions. Rotating the pressure sources clockwise will form left-handed waves and anti-clockwise will produce right-handed waves. An artist's impression of the concept and commercial applications are shown in Figure 1 and Figure 2 respectively.

It is intended that by providing a safe learning environment with repeatable wave conditions and long (unlimited) ride lengths, the overall surfing ability of the participants can quickly improve.

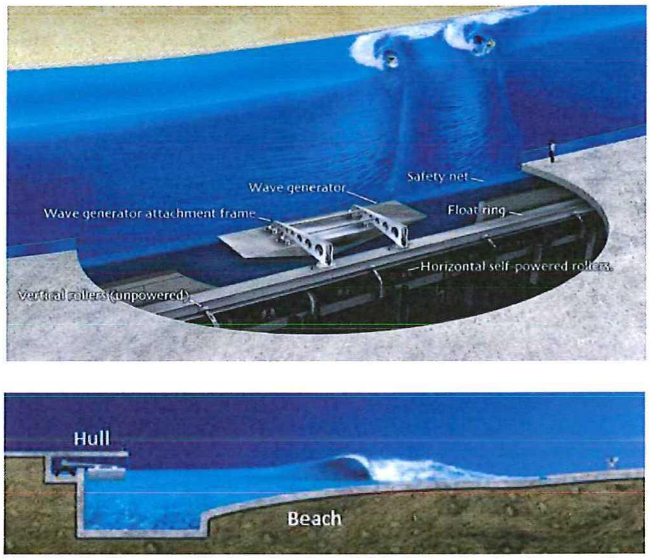

Figure 1. Concept design for the efficient method of generating continuously surfable breaking waves using moving pressure sources. (Reproduced with permission of Liquid Time Pty).

Figure 2. Artist's impression of the wave pool for a water park (Reproduced with permission of Liquid Time Pty Ltd).

FULL SCALE VALIDATION

The concept was proven, at least for a linear track, using a fishing vessel generating waves in a river estuary, where the vessel travelled in a straight line close to the bank. Figure 3 shows that one of the smaller waves generated by a moving pressure source waves can consistently surfed.

Figure 3. River testing such as that shown in this figure has proven that even the smallest of pressure source generated waves can be consistently surfed. (Reproduced with permission of Liquid Time Pty Ltd).

APPROACHES

The main aim in designing a wave pool is to produce high quality surfable waves with the longest duration possible. The main constraint on the design is to produce the waves in the smallest space possible with a minimum amount of energy. To determine the design parameter values to generate the desired waves, three approaches were used: Empirical, numerical and experimental.

As the empirical analysis has simplifications and assumptions, experimental approach conducted both linear and circular scale model testing, with the limiting values for the design parameters established from the experimental results.

EMPIRICAL APPROACH

The first method was an empirical analysis to determine a series of empirical relationships between the design parameters. The empirical analysis combined existing relationship defining the effect of the pressure source shape and operating conditions, and bathymetry on the wave life cycle; from wave generation, through transformation to breaking and dissipation; Figure 4.

To allow the pool to be designed for a combination of H_{beach}, wave shape and pool radius (R_0,) the empirical analysis determined the relationships between the design parameters was developed. The pool bathymetry parameters, referred to in this paper, as shown in Figure 5. In conducting the empirical analysis, the waves will be assumed to break at y_{beach} with wave height of H_{beach}.

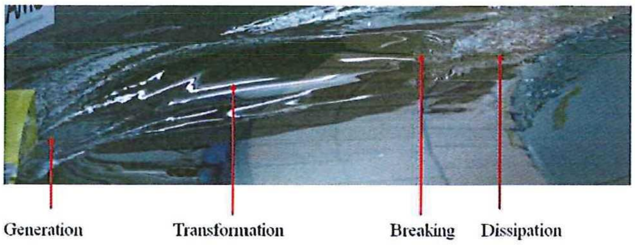

Figure 4. Wave life-cycle illustrated in the circular scale model at $Fr_{h0} = 0.975$ with $B^* = 275$mm, $d^* = 0.2$ and $h_0 = 250$mm. The model is travelling towards the camera.

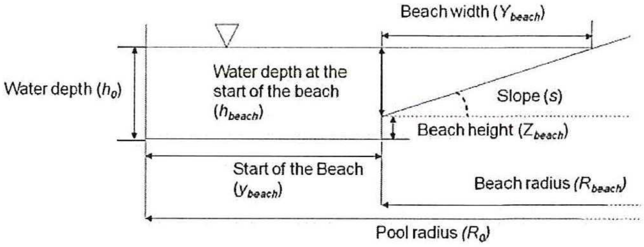

Figure 5. Bathymetry parameters

SURFING WAVES

To commence the empirical analysis; the first element of the work was to define the requirements of the wave pool from the end-user perspective, being the surfer. Key parameters were wave speed, breaking wave shape and wave height at the break point (H_{beach}).

WAVE SPEED FOR SURFING

The initial design parameter to be determined was the wave speed (c_p), for surfing, by considering two questions:

a. What is the design range of c_p for a surfing wave?

b. What is the minimum c_p for a wave to be surfable?

To determine c_p range for surfing, an initial analysis was conducted by a meta-analysis of existing surfing wave studies for mean c_p for different surf breaks around the world by Dally [55] and Hutt et. al. [38]. The average c_p of all observations was 6 m/s, with this value used as the initial design wave speed for the wave pool.

Field observations of surfing waves were conducted at Lorne Point, Victoria [3]. Lorne point was chosen as the waves break parallel with the shoreline, and with a desirable shape at small (less than 1m) wave heights. Thus, Lorne Point is considered a close representation of waves desired for the final wave pool.

To determine the minimum c_p that still produces surfable waves, the field observations were undertaken and analysed at

Lorne Point. The smallest surfable waves observed having h_{beach} = 0.5m with a wave period (T) = 3s, the minimum c_p was estimated as being 3m/s using shallow water estimate from Anthoni [4]. This observation was supported by Dally [5] and Hutt *et al.* [6], who observed a minimum c_p = 2m/s.

To translate the linear approximation to the case of a pressure source travelling in a circular track, it was observed that the waves travelled with the pressure source; that is the wave field was observed to have the same angular velocity (ω) as the pressure source. For the wave field to have the same ω as the pressure source at all radii, the tangential component of the velocity (parallel with the pressure source line of travel) (u) must be proportional to the radius (R).

WAVE HEIGHT

When talking about surf, the first question that surfers ask is "how big are the waves?" However the answer to this question is not straight forward, as surfers still cannot agree on how to measure wave height, where it is the wave face (on which the surfer rides) [7], the wave height in deep water before the wave breaks (that is measured using swell bouys and reported on weather reports), or some other measure.

In conducting the empirical analysis, the waves will be assumed to break at y_{beach} with wave height of H_{beach}. For a thrilling desirable ride, the wave must be large enough for the average surfer. As an initial design requirement, H_{beach} => 2m is desirable as it is overhead for the average height surfer (assumed as 1.75m), providing an exciting riding experience; Figure 6. Of course, smaller waves are also very enjoyable to ride, especially for less skilled surfers. Therefore, smaller diameter, cheaper wave pools that generate waves of H_{beach} < 2m may also be viable.

WAVE SHAPE

The shape of the wave at the breakpoint is a critical element of the suitability of the wave for surfing. Galvin [8] and Battjes [9] found the wave will break in different breaker shapes dependent on the beach slope (s), H_{beach} and the wavelength in deep water just before the beach (λ_{beach}), where the wave crests parallel with the beach slope. Battjes [9] used the Iribarren number (ξ) (or surf similarity parameter) to describe the breaker type on the basis of previous results of Galvin [8]:

$$\xi = \frac{\tan(s)}{\sqrt{H_{beach}/\lambda_{beach}}} \qquad (1)$$

Battjes [9] found the range of values for ξ for the different wave breaker types, as detailed in Table 1.

Breaker type	ξ
Spilling	$\xi < 0.4$
Plunging	$0.4 <= \xi <= 2.0$
Surging / collapsing	$\xi > 2.0$

Table 1. Breaker type and ξ (from [9])

The types of breaker shapes were defined by Galvin [8] as:

a. **Spilling** breakers. These waves are surfable, however they are not the highest quality.

b. **Plunging** breakers. These waves are the highest quality waves.

c. **Collapsing** breakers. These waves are not surfable.

d. **Surging** breakers. These waves are not surfable.

For surfers, the ultimate experience is to ride inside a plunging "barreling" wave; Figure 6. Surfers routinely travel all over the world to ride "barrels" plunging waves as not all surfing breaks generate plunging waves, and due to the distribution of H_{beach} in a wave group (known in surfing as a "set" of waves) not every wave plunges. Therefore, to constantly generate plunging waves is the ultimate aim of the wave pool.

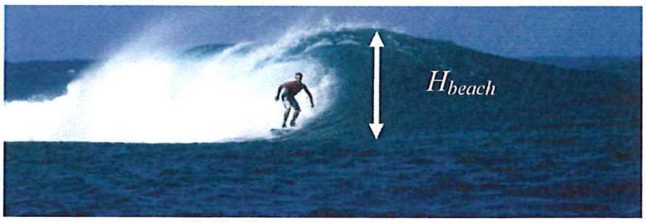

Figure 6. Surfer riding plunging wave of $H_{beach} \approx$ 2m.

WAVE WIDTH

The length of smooth, unbroken wave crest is defined as the usable "wall" width. As defined by Hartley [10], a wide steep wall is required to provide surfers sufficient vertical and lateral space to perform typical manoeuvres. An example of such a high quality wave is shown in Figure 7.

Mead *et. al.* [11] further associates the different parts of the breaking wave with the different manoeuvres .The 'pocket' is just in front of the barrel and is where the majority of the waves power is located. It forms the steepest part of the wave and thus is the section where surfers are able to generate the most speed. The 'shoulder' is where the wave is the least steep and generally surfers will struggle to generate speed whilst surfing on this section. Advanced surfers will often use a cutback manoeuvre to position themselves back in the pocket. The 'lip' is the uppermost point of the wave and can be used for powerful top-turns or aerials. The 'white water' is the broken part of the wave in which is generally avoided by surfers of a reasonable skill level. White water may be surfed by beginners while they are learning to stand up.

The wall width is nominally the distance between the outer wall and the break point, minus the pressure source beam. Further, a bow wash (breaking bow wave) is created as the pressure source travel, causing an area of turbulent water; termed the near-field region; Figure 8. This near field region is unsuitable for surfing and reduces the usable wall width.

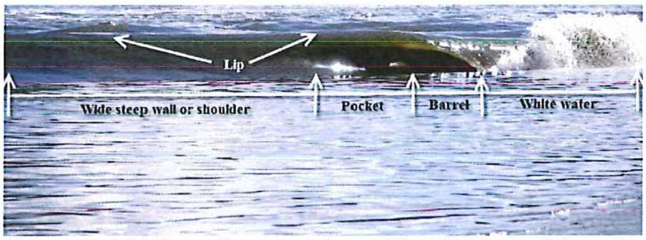

Figure 7. A high quality wave shape. The elements of the wave as described by Mead *et. al.* [11] are shown.

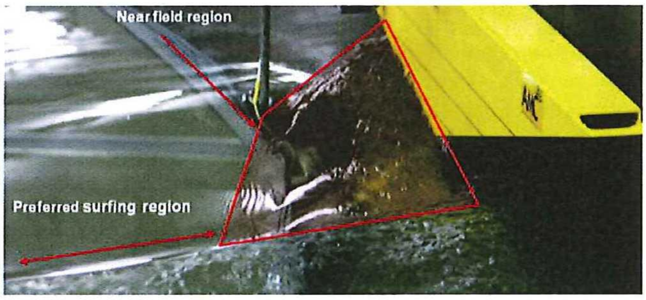

Figure 8. Example of near field effects for model 6.

NUMERICAL APPROACH

Once the set of empirical relationships between the design parameters were developed to allow the pool to be designed for a combination of desired H_{beach}, ξ and R_0, a numerical approach was undertaken using the *Michlet* linear potential flow model [12]. *Michlet* had the advantage of being able to efficiently model a large number of test conditions. An efficient modeling method was required to conduct an initial analysis of the waves generated by the pressure sources given the freedom to control many of the design parameters, including pressure source configuration (shape, length, beam, draught, and volume displacement), water depth, and pressure source speed.

As detailed in Michell [13], the waves are created by a pressure source where there is a change in the beam in the streamwise direction; the component of a pressure source where the waterline is parallel (flat sided) does not contribute to wave making [14]. Therefore, the initial focus was on determining a pressure source design that has continually changing beam would efficiently generate waves. Examples of this design were the hyperbolic tangent waterline pressure sources, with waterline length (*LWL)* to beam (*B)* ratio of 1.3 and 1.75, used in initial investigation by Schipper [15] and Vries [16].

To provide experimental data to validate the ability to accurately predict the wave heights using *Michlet*, linear tow tank testing was conducted using three different pressure source models and combinations of speed, water depth and draught. However the *Michlet* model was not able to accurately predict the wave shape generated by the wide (non-thin) pressure sources. These early results were published by the authors [17] [18], with the work presented at a conferences [19] [20]and other venues.

A further numerical approach consider the effect of the wavedozer beam and entry angle on the generated wave height was conducted by Essen [21] using the *RAPID* non-linear potential flow model. Finally, a three dimensional Finite Volume Method (FVM) numerical approach to model the entire wave pool system with a beach in place to allow the breaking wave shape to be predicted is currently being undertaken by Javanmardi [22] using *ANSYS-CFX / FLUENT*, that solves the RANS equations with finite-volume approach and uses the volume of fluid technique to simulate the free-surface motion.

The authors changed the focus to the experimental approach, given the limitations of the potential flow numerical approaches and with the more complex FVM approach being undertaken by Javanmardi [22].

EXPERIMENTAL APPROACH

The third approach was devoted to a series of four experimental scale model experiments. The focus of the experimental approach was first to deal with the pressure source shape and the operating conditions to maximise the size and quality of the generated waves. Subsequently, the effects of the bathymetry on the wave transformation breaking and dissipation were examined.

The results were also used to determine of the design parameter limiting values for input to the empirical analysis, and to validate the author's Michlet predictions, Essen's *RAPID* predictions, and Javanmardi's FVM model [22].

Linear and circular scale models were built and tested at the Australian Maritime College (AMC). The linear testing was conducted in the 100m tow tank, with the circular scale model built in the Model Test Basin (MTB); Figure 9. Cameras and wave probes were used to record and exam the shape and development of the waves.

Figure 9. Circular scale model

PRESSURE SOURCES

Most studies into ship wave generation have focused on miminising the wave generation [23] [24] [25], thus reducing the ship wave resistance [26] [27], nuisance to other users of the waterway [28] and destructive wave-shore interaction [29]. Previous work by Macfarlane [26] and others has found that wave making increased with the beam to length ratio; that is a short, wide pressure source; Figure 10. A more efficient pressure source shape, being a wavedozer, was investigated by Standing [30], and further developed by Driscoll [1] and Renilson [31]. The wavedozer is also a very simple structure to form, essentially simply being an inclined flat plate. The initial wavedozer design is shown in Figure 11. The wavedozers used differed from those previously tested by Standing [30], Driscoll and Renilson [1] [31], that spanned the channel, where the wavedozer tested by the author had limited beam.

The pressure sources tested for different shapes and values of beam, draught, *LWL* and entry angle (α) (for the wavedozers) as detailed in Table 2. The pressure sources were configured so they were fixed in heave and trim.

Figure 10. Model 2 parabolic pressure source of 700mm length, 600mm beam, 500mm height.

Figure 11. The first wavedozer shape Model 3 tested. The direction of travel was from left to right.

Serial	Model Type.	Beam [mm]	*A* [deg]
Linear			
1	Parabolic	300	N/A
2	Parabolic	600	N/A
3	Wavedozer	300	14
Circular Series 1			
4	Wavedozer	176	14
5	Wavedozer	251	14
6	Wavedozer	176	14
7	Wavedozer	251	14
Circular Series 2			
8	Wavedozer	75	4 - 18
9	Wavedozer	175	14
10	Wavedozer	275	14
11	Wavedozer	150	14
Circular Series 3			
12	Wavedozer	275	7
13	Wavedozer	550	7

Table 2. Pressure sources tested in each series

QUALITATIVE ASSESSMENT

The next question surfers ask each other when checking the surfer is "how good is it". That is, for surfing, wave quality is as important, if not more important, than the wave height (H_{beach}). This question is again subjective, however, the wave quality can be broken down into a number of elements.

In addition to the wave shape (ξ), the wave quality is also determined by wall width, wave steepness and smoothness of the wave face. These qualities determine the type of manoeuvres that a surfer may do on the wave.

To support the qualitative assessment of the wave quality, the wave scoring system developed by the Association of Surfing Professions [32] was used, Table 3, with two examples of excellent waves shown in Figure 12. The judging criteria were clarified to allow for the steady state nature of the waves generated in the pool.

Score	Description	Requirements
0	No wave	Unrideable
0.0 - 1.9	Barely surfable	No turns. Spilling wave.
2.0 - 3.9	Fair	Simple turns. Spilling wave.
4.0 - 5.9	Average	Turns, smooth wave. Spilling wave.
6.0 - 7.9	Good	Plunging wave with smooth, steep wall
8.0 - 10.0	Excellent	Plunging wave with long, smooth, steep wall

Table 3. Wave scores

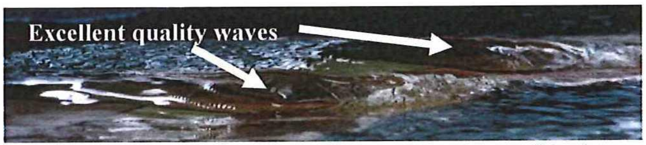

Figure 12. Examples of excellent waves generated in the circular scale model by model 10 with $d^* = 0.2$ in $h_0 = 250\text{mm}$ at $Fr_{h0} = 0.975$.

EXPERIMENTAL RESULTS

From the experimental results, a key parameter that related the wave life-cycle to the pressure shape, operating conditions and bathymetry was the blockage (κ) is defined as the pressure source cross sectional area (A_s) to channel cross-sectional area (A_c):

$$\kappa = \frac{A_s}{A_c} \tag{2}$$

Robbins *et al.* [33] investigated the effect of κ. on the formation of a soliton in a constrained channel. Robbins developed a plot of κ as a function of Fr_h; Figure 13. This was divided into:

a. *Sub-Critical Zone* with no / limited soliton formation and a divergent wave field.

b. *Critical Zone* with significant soliton formation.

c. *Super-Critical Zone* with no / limited soliton formation and super-critical wave field.

Robbins *et. al.* [33] observed that soliton forming *Critical* Zone extended with increased κ. Robbins *et. al.* [33] only tested at $\kappa < 0.02$. The authors of this paper extended Robbins' results to $\kappa <= 0.07$ by plotting the circular scale model series 3 results with and without a beach in place were plotted against Robbins *et. al.* theoretical criticality boundary; Figure 14. Conditions were determined to be in the *Critical Zone* when the non-dimension wave height (H^*) as a function of non-dimensional lateral distance (y^*) was less than condition 62 $\kappa \approx 0$; an example is shown in Figure 15 for condition 56 $\kappa = 0.07$.

Therefore, to maximise the wave height at the breakpoint (H_{beach}), the preference would be for blockage to be minimised; i.e. $\kappa \approx 0$. However, a beach is required to trigger the wave to break with the desired plunging shape. From Figure 14, the presence of the beach may allow conditions slightly within the *Critical Zone* to be used, limited to $\kappa <= 0.07$ and $Fr_{h0} < 1$.

It must be noted that by Robbins *et. al.* [33] and the present work differ:

a. **Pressure sources.** Robbins *et. al.* used a catamaran whilst the present work used wavedozers.

b. **Bathymetry.** Robbins *et. al.* used a rectangular channel with a constant water depth. The present work used sloping beaches.

For all conditions, a *bow wave* was generated in front of the pressure source, including for $\kappa \approx 0\%$; Figure 16. The *bow wave* is believed to be due to a combination of the two phenomena; a primary wave and / or a soliton. The formation of the *bow wave* resulted in less energy being available for the divergent waves, and therefore the reduced maximum ζ_{wp1} of the trailing divergent waves, as indicated by the reduction in divergent wave elevation for condition 56 with increasing soliton formation; Figure 16.

The bow wave / soliton was generally not steep enough to break, and therefore would not be used for surfing in this wave pool design. Therefore, the formation of the *bow wave* is a major limitation on the generation of surfable divergent waves, and was sought to be minimised.

The main outcome of the empirical approach was that the design parameters are in competition. Therefore, the values of the design parameters are carefully balanced to achieve the desired breaking wave shape and height. κ and associated soliton formation are found to have the greatest limitation on the generation of high quality waves suitable for surfing in a constrained waterway. However, a wide, shallow entry angle wavedozer was found to generate smooth high waves, which were able to be triggered to break with a plunging shape.

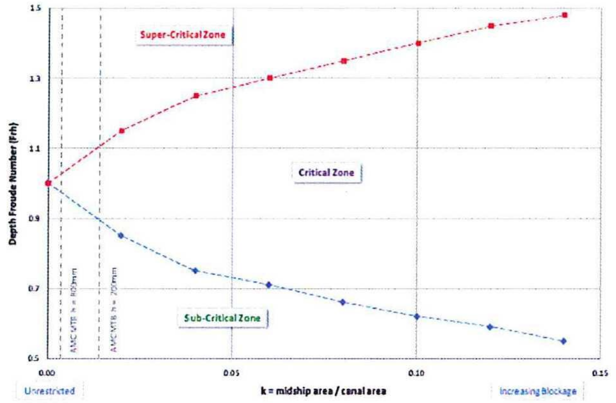

Figure 13. κ as a function of Fr_h from Robbins *et. al.* [33].

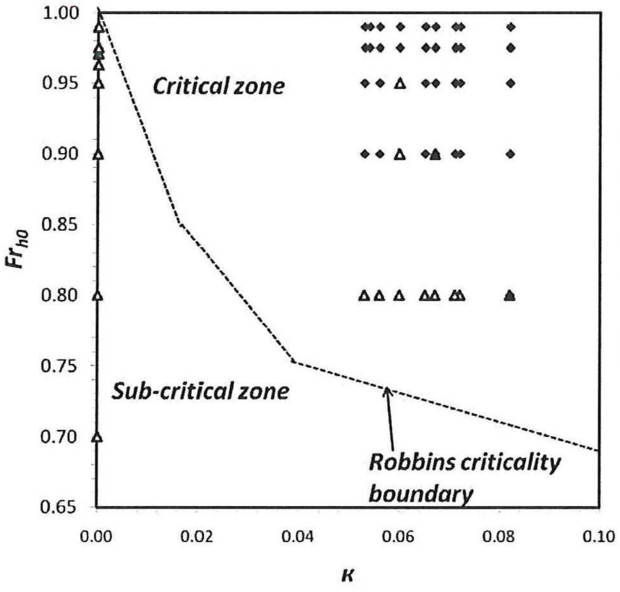

Figure 14. *Sub-Critical* (open triangles) and *Critical* (solid diamonds) configurations plotted against Robbins *et. al.* theoretical criticality boundary (adopted from Robbins *et. al.* [33]).

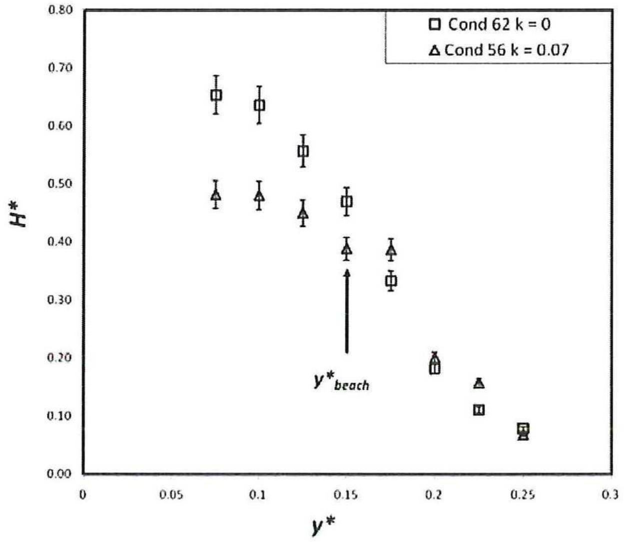

Figure 15. H^* as a function of y^* for different values of κ for model 12-02 with $d^* = 0.2$ in $h_0 = 250$mm at $Fr_{h0} = 0.95$; condition 62 $\kappa = 0$ and condition 56 $\kappa = 0.07$. The beach is in place at $y_{beach}^* = 0.15$ for condition 56.

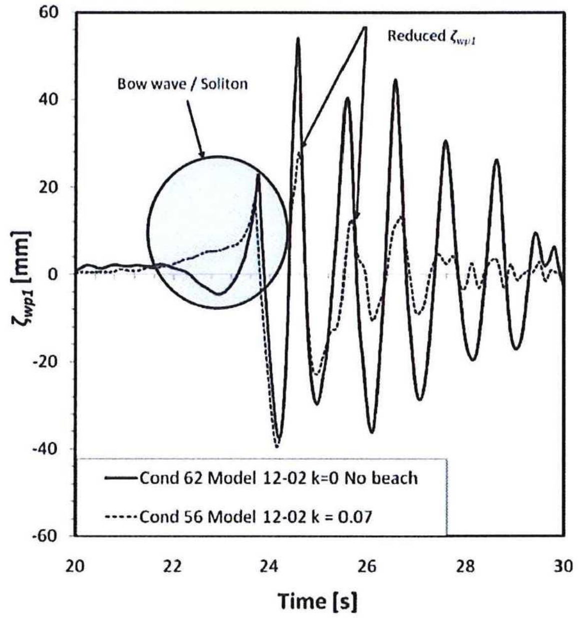

Figure 16. Time traces of ζ_{wp1} for model 12 for $\kappa \approx 0$ and $s = 16^{O}$ with $\kappa = 0.07$ at $Fr_{h0} = 0.95$ with $d^* = 0.2$ in $h_0 = 250$mm. Model 11-12 was time shifted to align with model 12-02. The pressure source bow passed the wave probe at time = 24.5 seconds.

POOL RADIUS (R_0)

Finally, in order to generate the maximum number of surfable waves, the commercial wave pool requires multiple pressure sources, without adverse wave interaction; that is, the water surface needed to calm sufficiently after the passing of one pressure source, prior to the second pressure source travelling through the same water so as not to affect the wave quality of the waves generated by second and subsequent pressure sources.

To determine the time required to allow the water surf to calm, by observation, non-adverse residual waves interaction was defined being when surface elevation, measured close to the pressure source (ζ_{wp1}), excited by the pressure source was less than 10% of the maximum ζ_{wp1} of the first wave generated. As an example, ζ_{wp1} of the first wave was 56mm at time = 30s; Figure 17. Therefore, the water is defined as being calm enough for the second pressure source to pass when ζ_{wp1} < 5.6mm; which occurs by time = 38s. With the second pressure source passing at time = 50s, the pressure sources should be able to be placed closer together.

Therefore, along with pressure source speed (u_0), R_0 will determine the length of time for each pressure source to travel around the pool, and therefore the number of pressure sources that may be used in a single pool.

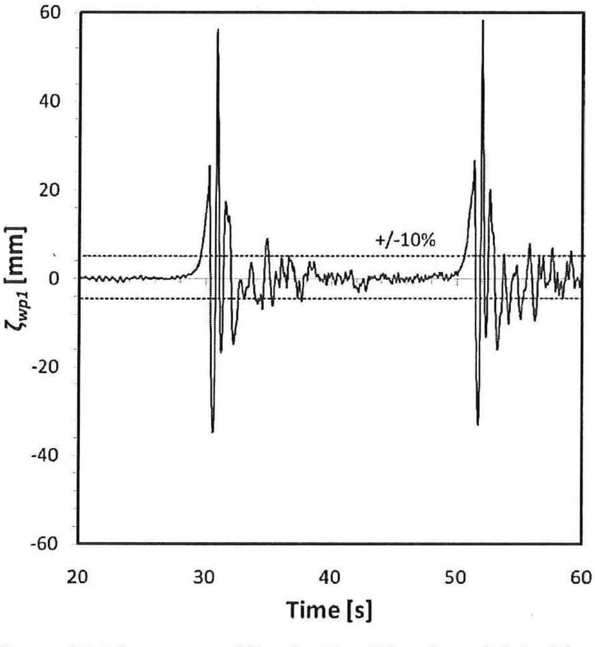

Figure 17. Time trace of ζ_{wp1} for Condition 6 model 5 with d^* = 0.2 in h_0 = 250mm at Fr_{h0} =0.95.

CONCLUDING REMARKS

The design of a circular wave pool concept has been produced by Webber Wave Pools and patented within Australia and Internationally. This design shows great promises to not only produce a unique facility for expanding the surfing industry but also to conduct significant research into repeatable breaking waves.

A key finding was that the pressure source shape, operating conditions and bathymetric design parameters were in competition. Therefore in order to generate high, plunging waves in the constrained channel, these design parameters could not be considered in isolation. It was found that the wave quality was extremely sensitive to changes in the design parameters.

Subsequently, a set of empirical relationships between the design parameters were determined to allow a pool to be designed for a combination of the desired height of the largest waves at the break point, a plunging wave shape in a given pool radius.

This work continued the research conducted by Robbins *et. al.* [33]. As detailed in Robbins *et. al.* [33], soliton formation is time dependent and specific to blockage. Robbins *et. al.* [33] advising that the wider (i.e. full scale) implications of these model test findings are potentially significant, with all previous wave measurements for *critical* values of Fr_h, will be time dependant (i.e. unsteady), especially in high blockage environments such as rivers or canals. However, facilities limitations (i.e. limited length tow tanks and test basins), may not allow sufficient time for the soliton to fully form or reach a steady state with a beach in position. Therefore, the circular track scale model may provide the facility to address this limitation.

However, sufficient results were obtained by the end the program to allow pressure source and bathymetry to be configured to produce two high quality plunging waves per pressure source. The present work dealt with determining a configuration that was sufficient to commericalise the patented design, and through the combination of the empirical analysis, this was achieved. The promise of making the perfect repeatable-surfable wave seems to be coming true.

Further work

Based on the work presented in this paper, a number of recommendations and suggestions for future work can be made.

Pool design steps

To design a full size pool, it is recommended to use the empirical relationships and design parameter values chosen from the experimental results.

The predicted design and the shape of the wave should then be confirmed using the *ANSYS-CFX / FLUENT* numerical model developed by Javanmardi [22]. The model allows the investigation of the wave shape, currents and forces on the pressure source throughout the water volume, and in far greater detail, than could be achieved experimentally. The model allows the visualisation of the three dimensional breaking wave shape, facilitating a qualitative assessment of the wave quality for surfing. This valuable data is not necessarily accessible by the experimental method due to the difficulty of measuring the breaking wave shape, especially once full scale pools are considered. The model has been validated against the current circular track scale model test results.

Experimental approach

The next circular track scale model should be used to validate the initial design predicted using the empirical relationships.

This work continued the research conducted by Robbins *et. al.* [33]. As detailed in Robbins *et. al.* [33], soliton formation is time dependent and specific to blockage. Robbins *et. al.* [33] advising that the wider (i.e. full scale) implications of these model test findings are potentially significant, with all previous wave measurements for *critical* values of Fr_h, will be time dependant (i.e. unsteady), especially in high blockage environments such as rivers or canals. However, facility limitations (i.e. limited length tow tanks and test basins), may not allow sufficient time for the soliton to fully form or reach a steady state with a beach in position. Therefore, the circular track scale model may provide the facility to address this limitation.

The results of this research may be also applied to other applications such as ship waves generated during manoeuvring (curved tracks) and operations in restricted waterways. Scientifically, the research provides a method to significantly extend the fundamental knowledge of wave mechanics.

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