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THE BORE PRODUCED BETWEEN THE HULLS OF A HIGH-SPEED CATAMARAN IN SHALLOW WATER

T Gourlay, Curtin University**, J Duffy,** Australian Maritime College and **A Forbes,** Austal Image, Australia

SUMMARY

An experimental investigation is made into the phenomenon of a bore wave produced between the hulls of a high-speed catamaran in shallow open water. The shape of this wave is analysed, along with the speed range over which it is likely to occur. Similarities are noticed with a monohull moving close to a wall, or on the centreline of a channel.

NOMENCLATURE

F_h	depth-based Froude number $U/\sqrt{gh}$
g	acceleration due to gravity
h	undisturbed water depth
η	free surface height above static waterline
S_{midships}	midships section area
S_0	channel cross-sectional area
U	ship speed
w_{cc}	distance between demi-hull centrelines

1. INTRODUCTION

In recent ship wake testing at the Australian Maritime College, it was noticed that a catamaran in shallow water produced a large breaking wave spanning between the hulls at certain speeds. Following this, the authors devised a testing program to carefully measure the properties of these waves.

The non-linear interaction of catamaran bow waves has been noticed [1] in deep water, where superposition of the hulls' bow waves causes localized breaking between the hulls. In shallow water, it has been noted that catamarans, like monohulls, may radiate solitons ahead of themselves at low supercritical speeds [2]. However in addition to these phenomena, there exists a range of speeds over which a large breaking wave spans almost uniformly between the two hulls of a catamaran in shallow water. It is this wave that is studied in this article.

An explanation for the two-dimensional nature of the breaking wave will be found by drawing an analogy with the case of a monohull in a narrow, shallow channel. In this case it has been found [3,4,5] that the hull will tend to radiate solitary waves ahead of itself when travelling at slightly supercritical speeds. At higher supercritical speeds these solitary waves begin to break, and may form a large breaking wave front [6] resembling a bore or hydraulic jump.

2. MODEL TESTS

Two hulls were selected for testing: a commercial displacement catamaran, the "Sorrento" (1:30 scale), and a generic slender catamaran with Series 64 demihulls [7]. Particulars of the models are shown in Table 1.

The scale model experiments were conducted in the Model Test Basin at the Australian Maritime College; this has length 35m and width 12m. The width of the basin, and the slenderness of the hulls, are such that the results should fairly well approximate open water. A water depth of 0.125m was used for all tests.

The model was towed at constant speed along the centreline of the basin, and was free to heave and pitch. Free surface height measurements were taken using three capacitance wave probes fixed in the basin, and close to the end of the run. Two of these wave probes were

	Sorrento	Series 64
Waterline length (m)	1.858	1.516
Demihull breadth (m)	0.133	0.139
Draught (m)	0.077	0.075
Demihull displacement (kg)	14.381	9.235
Distance between centrelines (m)	0.429	0.445
Midship cross-sectional area (m^2)	0.00931	0.00840

Table 1: Model particulars

Figure 1: Sorrento hull under way in shallow water, showing breaking wave between hulls and wave probe setup in the foreground

positioned between the hulls, so that the cross-bracing passed over the top of them (Figure 1). To achieve this, wave probes were made to the correct dimensions, and the cross-bracing was raised to provide sufficient clearance. One wave probe was positioned on the centreline between the hulls, and the other 90mm outboard (also between the hulls). The third wave probe was positioned at the same longitudinal position, but just outboard of one of the demihulls (400mm from the centreline for the Series 64 model, and 500mm from the centreline for the Sorrento model).

A speed range of 1.34 – 1.50 m/s was tested for the Sorrento hull, while a range of 1.28 – 1.40 m/s was tested for the Series 64 hull, all in increments of 0.02 m/s. Two runs were performed for each speed, and the bore heights were averaged over the two runs. The partly-random nature of whitewater in the breaking bore fronts produced surface fluctuations of around ± 3 mm in the bore height.

3. RESULTS

For both the Sorrento and Series 64 catamarans, bore waves were produced between the hulls over certain speed ranges. We shall quote speed in terms of the depth-based Froude number $F_h = U/\sqrt{gh}$, where U is the model speed, g is the acceleration due to gravity and h is the undisturbed water depth.

3.1 SORRENTO CATAMARAN

The Sorrento catamaran was seen to produce bore waves between the hulls in this water depth over the range $1.26 < F_h < 1.32$. At slightly lower Froude numbers, a bore wave was formed ahead of the model, similar to that produced by a monohull at similar Froude numbers in a wide tank or open water. At Froude numbers above this range, the bow waves between the hulls swept backwards at an angle, forming a standard supercritical wave pattern. Localized wave breaking still occurred where the bow waves from each hull met on the centreline.

In the bore-producing Froude number range, a large breaking wave was produced between the hulls, with its crest perpendicular to the direction of travel. This wave remained in a fixed longitudinal position relative to the ship. A profile view of the wave is shown in Figure 2.

The free surface elevation as a function of time, measured at each stationary wave probe, is shown in Figure 3 (same Froude number as Figure 2). The times at which the bow and stern pass the wave probes are also indicated, although these are approximate. Since the bore is steady with respect to the hull, this plot can also be

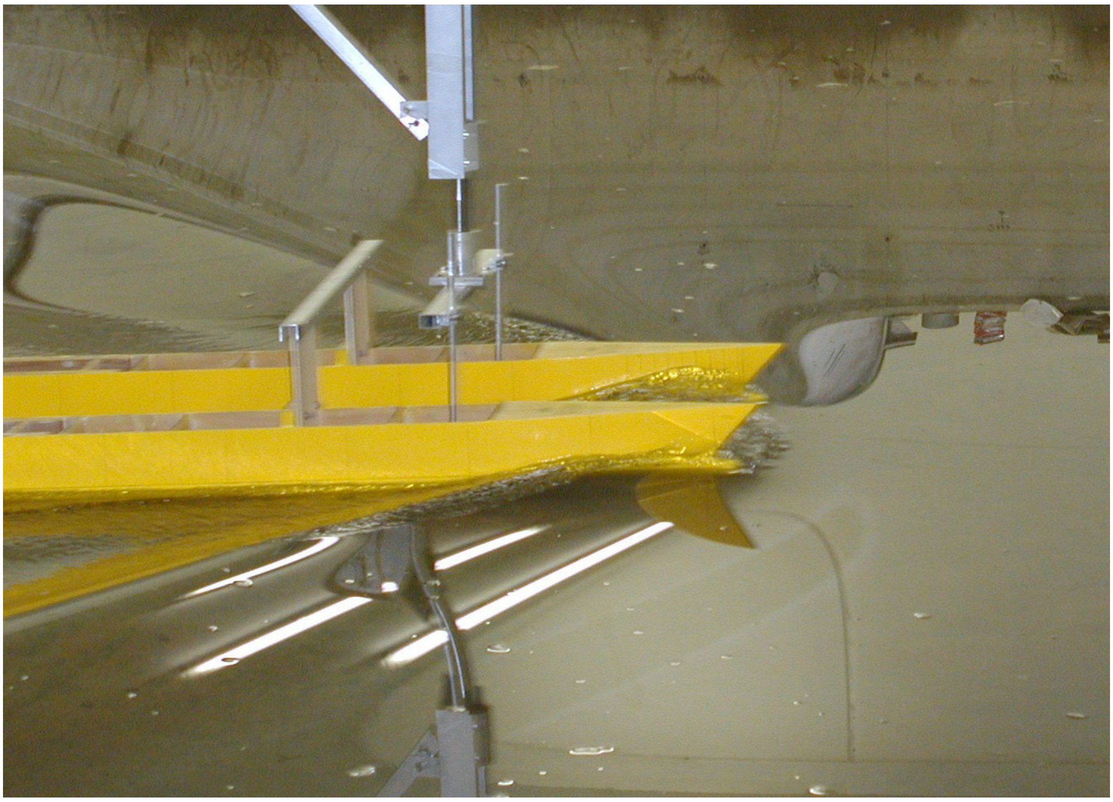

Figure 2: Profile view of Sorrento's bore wave at F_h = 1.32

thought of as describing the free surface height, as a function of longitudinal position along the ship, at a given instant in time.

Bearing in mind that all the wave probes are at the same longitudinal position, Figure 3 shows the uniformity of the bore wave between the centreline and offset wave probes between the hulls. Small differences were observed in all tests, due to the random nature of the surface irregularities in a breaking wave front.

3.2 SERIES 64 CATAMARAN

The Series 64 demihulls have smaller midship section area than those of the Sorrento, and the Series 64 catamaran was seen to produce bores over a lower range of Froude numbers ($1.17 < F_h < 1.21$). At Froude numbers slightly below this range, a non-breaking wave was formed between the hulls; this remained stationary relative to the model and resembled a solitary wave. At Froude numbers above this range, a standard supercritical wave pattern was formed, with only localized wave breaking where the bow waves meet on the centreline

An example free surface profile in the bore-producing Froude number range is shown in Figure 4 for the Series 64 catamaran. The breaking bore front shows a similar form to that produced by the Sorrento, and is almost perfectly uniform between the hulls. This uniformity continues all the way to the stern of the vessel.

3.3 COMPARING BORE HEIGHTS FOR BOTH HULLS

The bore height was seen to stay approximately constant with changing Froude number, and was similar between the two hull types, as shown in Figure 5. The bore height was around 0.53 - 0.56 times the water depth

4. DISCUSSION

4.1 ANALOGY OF A MONOHULL IN A CHANNEL

Comparisons can be drawn between the bore produced by a catamaran and that produced by a monohull in a channel. The centreline between the demihulls of a catamaran acts like a channel wall (neglecting wall friction), so that the flow past each demihull of a catamaran is similar to the case of that demihull moving by itself close to a channel wall. Correspondingly, soliton-type waves have been calculated and observed experimentally for a monohull moving close to a channel wall, in between the hull and the wall [8,9].

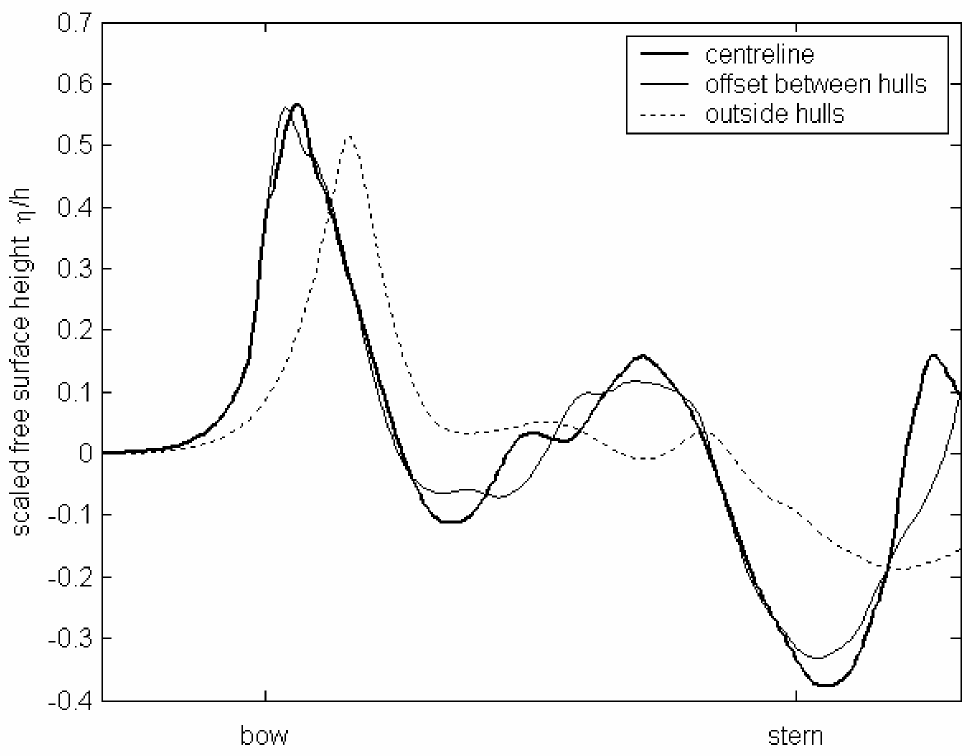

Figure 3: Free surface elevation for Sorrento hull at F_h = 1.32.

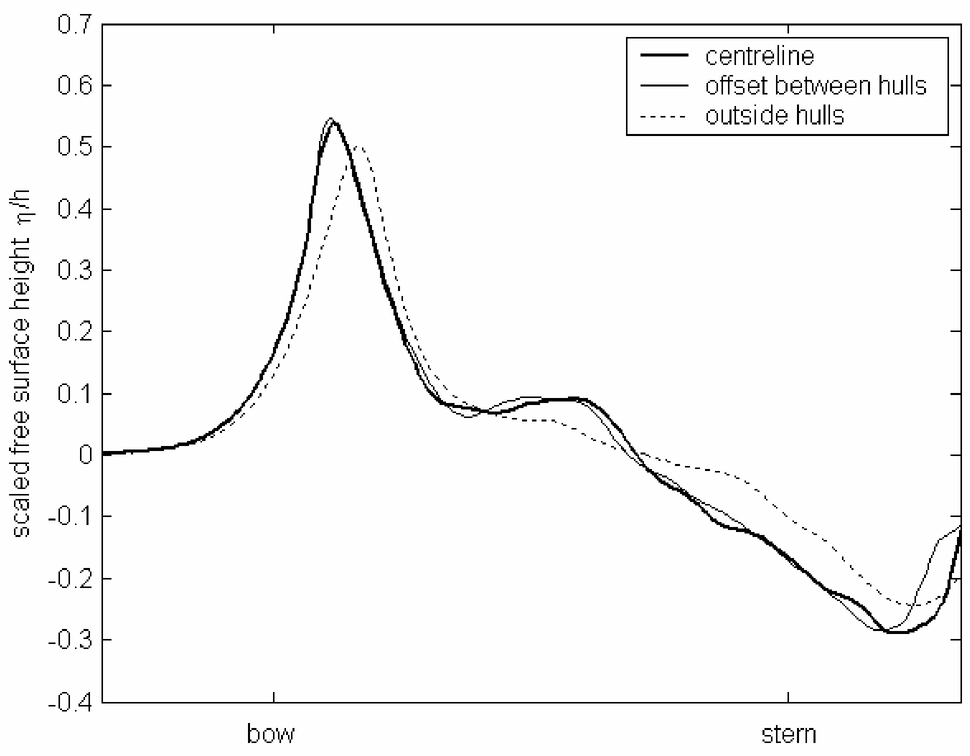

Figure 4: Free surface elevation for Series 64 hull at F_h = 1.17

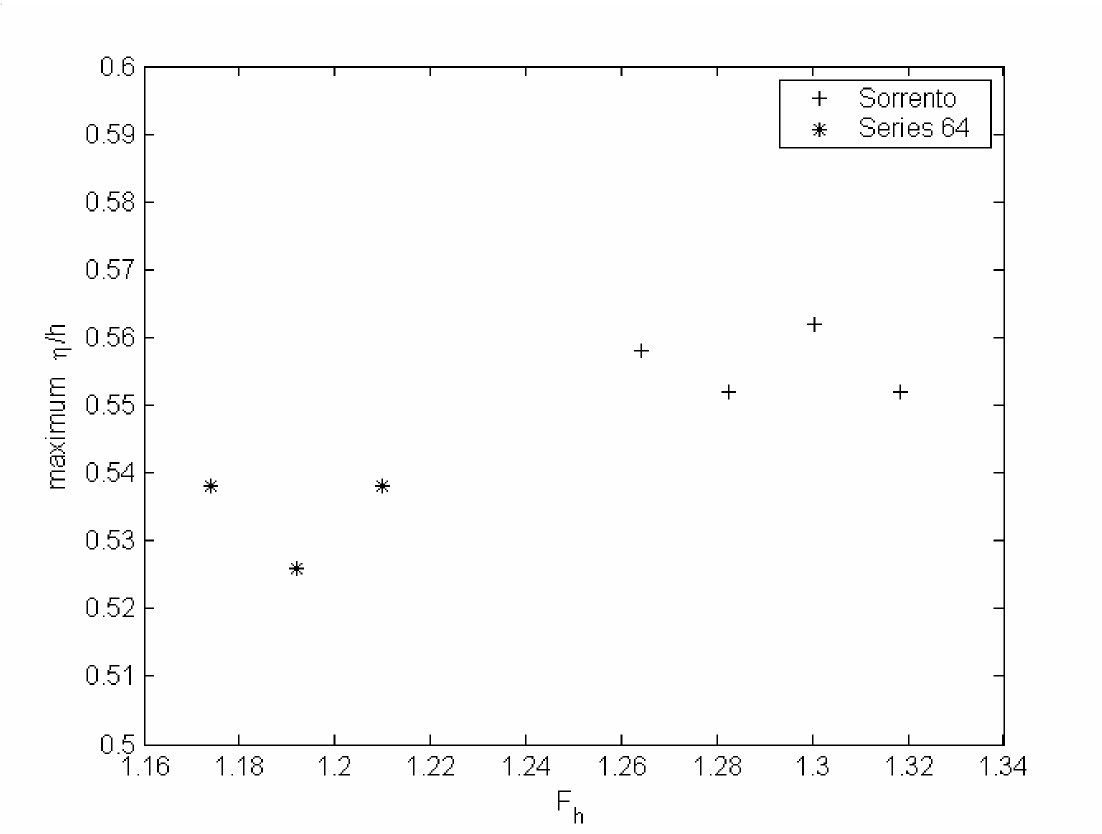

Figure 5: Measured bore height for both hulls at all speeds

If there were no cross flow beneath the demihulls and around the bows, the flow would be similar to that of a monohull moving along the centreline of a channel. Bore waves have been noticed in this case [6], with similar properties to those observed here. For example, for a monohull in a narrow, shallow channel, smooth solitons are observed to radiate periodically ahead of the ship at low supercritical Froude numbers, and start to break at $F_h = 1.1 - 1.2$ [4]. The wave produced between the catamaran demihulls in our experiments started to break at a similar Froude number.

Once the solitons produced by a monohull in a channel have broken, their crest height stays approximately constant at $\eta / h \approx 0.6$ as the Froude number increases [6]. Then, at a transition Froude number, the bore sweeps back from the bow at an angle, indicating the commencement of steady supercritical flow.

For our catamaran experiments, the height of the bore crest also stayed approximately constant with increasing Froude number for each model tested. In addition, there was a definite "transition" Froude number at which the bow wave between the hulls changed from a perpendicular, uniform bore to a swept-back wave coming from each hull.

4.2 AN EFFECTIVE "BLOCKAGE COEFFICIENT" FOR CATAMARANS IN SHALLOW WATER

Continuing the analogy of a monohull in a channel, it is possible to define an effective "blockage coefficient" for flow between the hulls of a catamaran in open water. For a monohull in a channel, the blockage coefficient is normally defined [10] as Blockage coefficient =

$$\frac{S_{\text{midships}}}{S_0}$$

Where

S_{midships} = midship section area

S_0 = channel cross-sectional area (to undisturbed waterline)

For a monohull travelling in a channel at transcritical speeds, the blockage coefficient is the important parameter governing the production of solitons [5] and bores [6].

A similar blockage coefficient can be defined for a catamaran travelling in open water, by considering the midship section area of each demi hull as a fraction of the cross-sectional area of the equivalent channel.

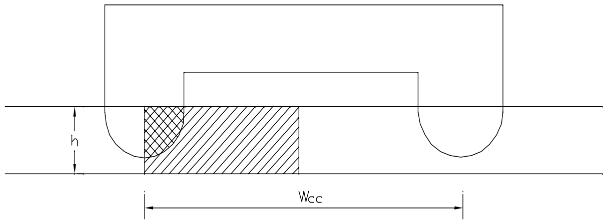

Figure 6: Blockage coefficient for a catamaran in shallow water

As shown in Figure 6, the suggested blockage coefficient is given by

Catamaran blockage coefficient

$$= \frac{S_{\text{midships}} / 2}{h w_{\text{cc}} / 2} = \frac{S_{\text{midships}}}{h w_{\text{cc}}}$$

This is the same blockage coefficient as if each demihull were travelling in a channel of width the same as the spacing between centrelines. For a catamaran, however, the blockage effect is only important between the hulls.

For our model tests, the blockage coefficients were 0.174 for the Sorrento hull and 0.140 for the Series 64 hull. As noted in [6], a high blockage coefficient for a monohull in a channel means that bores will be produced up to a larger Froude number. This trend was also true for the catamaran, with the low blockage coefficient (Series 64) case reaching steady supercritical flow at a lower Froude number. The Series 64 hull only produced bores over a small Froude number range, and it is probable that this block coefficient is close to the lower limit of bore production.

Therefore, based on these experiments, we expect that bores would only be produced for blockage coefficients of around 0.12 – 0.15 or larger. At lower blockage coefficients than this, a solitary wave may form between the hulls for depth Froude numbers slightly greater than 1, but steady supercritical flow will be reached before the solitary wave starts to break.

4.3 EFFECT OF CROSS-FLOW

The cross flow beneath and around the bows has an important effect on the form of the bore wave. Transverse flow beneath the demihulls of a catamaran is not just a shallow-water effect; model tests in deep water [11] indicated cross-flow velocities of 5-7% of the ship speed, being outwards near the bow and inwards near the stern.

As seen in the free surface plots of Figures 3 & 4, the free surface height outside the demihull bows is lower than between the demihulls. Therefore a generally higher pressure exists between the bows than outside, causing an outward cross-flow beneath the hulls. The increased underkeel clearance at the bow caused by the strong bow-up trim also allows more fluid to pass outwards beneath the hulls.

The outward fluid loss between the hulls means that the bore height is diminished as compared to the case where no cross-flow occurs. This explains the slightly smaller bore height ($\eta / h \approx 0.55$) of the catamaran, as compared to the symmetric case (with no cross-flow leakage) of a monohull in a channel ($\eta / h \approx 0.6$).

Another difference between a catamaran in open water and a monohull in a channel is that for a catamaran the bore tends to stay in a fixed position relative to the ship, while for a monohull in a channel it may travel faster and ahead of the ship [6]. Any tendency for catamaran bore waves to travel ahead of the ship in open water will be quashed when the bore tries to leave the bow, as significant flow leakage would occur around the bows.

Transverse flow leakage beneath and around the bows also has a profound effect on the transition Froude number at which bores stop being produced. For the port/starboard symmetric case with no cross-flow (such as a monohull moving along the centreline of a channel) the methods of [6] can be used to predict this transition, using the catamaran blockage coefficient defined above. Based on this formulation, transition should occur at $F_h = 1.83$ for the Sorrento hull and $F_h = 1.74$ for the Series 64 hull. The actual transition was seen to occur at $F_h = 1.34$ for the Sorrento hull and $F_h = 1.23$ for the Series 64 hull. We see that flow leakage beneath the hulls allows a steady supercritical wave pattern to occur between the hulls, when it would not otherwise be possible.

5. IMPLICATIONS FOR HIGH-SPEED CATAMARANS

The bore waves witnessed in these experiments only occur at transcritical speeds in very shallow water. Scaling the Sorrento results to full scale, for example, gives a catamaran of waterline length 55.7m and draught 2.3m, travelling in water of depth 3.75m (depth / draught ratio 1.62). When travelling at speeds between 14.9 and 15.6 knots, this vessel will produce a large bore wave between the hulls, of height 2.1m above the static waterline.

The implications of this bore wave would be as follows:

- A large hump in the resistance curve. Energy loss in the breaking bore front will cause a very large wave resistance at this speed. Breaking through the hump to higher supercritical speeds may not be achievable.

- Significant bow-up trim, caused by the elevated free surface height near the bow. This in turn will increase the grounding risk at the stern of the vessel. In the situation described, this vessel's stern would be very close to grounding.

Clearly, operating at even moderate speed at such a small depth/draught ratio is best avoided for passenger catamarans, so as not to risk grounding. It is also likely that these vessels may not be able to break through the resistance hump and into the stable supercritical speed range.

However, existing and proposed military high-speed catamarans may well need to travel at transcritical speeds in shallow water. For these vessels, overcoming the resistance hump and avoiding grounding are of paramount importance. Further research is required into the effect of bore waves on resistance, sinkage and trim.

6. CONCLUSIONS

Over a narrow transcritical speed range, a catamaran travelling in shallow water may produce a bore wave between its hulls. This wave lies perpendicular to the hulls, is of uniform height, and stays stationary at the bow of the vessel. It resembles a broken solitary wave, such as is produced by a monohull in channel, and its height is around 0.55 times the water depth.

Production of this bore wave depends largely on a blockage coefficient based on demihull midship area, spacing between centrelines, and water depth. This blockage coefficient, and the resulting description of the bore wave, are analogous to a monohull travelling along the centreline of a channel.

For blockage coefficients greater than around 0.12 – 0.15, a bore wave is likely to be produced at depth-based Froude numbers around 1.2. Higher blockage coefficients mean that bores are produced up to higher speeds. Lower blockage coefficients mean that a steady supercritical wave pattern will be reached before the bore is formed.

The bore's height and speed range are both slightly diminished as compared to the monohull case, most likely due to an outwards cross-flow beneath the demihull bows. This leakage dilutes the pressure between the demihulls and decreases the size of the resulting bore wave.

For catamarans that are able and required to travel at transcritical speeds in very shallow water, the bore waves described will have an important effect on resistance, trim and grounding risk. Further research is required to quantify these effects.

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