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The Maximum Speed of Surfers

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ABSTRACT

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As the peel angle of a breaking wave becomes more acute, a surfer must travel faster in order to stay ahead of the break point. At the critical limit of surfing, the board can go no faster, and the wave 'closes out'. In order to study the maximum speed that can be sustained on different waves, sequences of surfing recorded on videotape are subjected to kinematic analyses. Selecting twenty-nine sequences in which the surfer is judged to be moving as fast as possible, board speed is computed by dividing a visually estimated travel distance by an elapsed time, determined by counting frames of video. Breaker height is also estimated visually, and breaker type noted. An empirical, yet physically justified formula for the board speed is developed based upon breaker height (R^2 = 0.91). The video-derived model is verified against the limited amount of data collected by other means that are available in the literature. Breaker type is not found to have a direct influence on board speed.

ADDITIONAL INDEX WORDS: *Surfing, board-speed, breaking waves, videogrammetry.*

INTRODUCTION

In appraising a breaking wave for the purpose of recreational surfing, the maximum speed that can be sustained by a surfer on that particular wave must be greater than or equal to the speed of the point of incipient breaking. Otherwise, the breakpoint overtakes the surfer and the wave 'closes out'. Acknowledging the nascent work of WALKER (1974), these fundamental parameters herein are called the 'board speed' and the 'break rate', respectively. In the study of surfbreak, it is these two parameters which must be established, either by direct measurement or by computation. Although the break rate, P, could be estimated directly, *e.g.* using overhead airborne video, it typically has been computed from the expression:

$$P = \frac{c_b}{\sin(\alpha_b)} \qquad (1)$$

in which α_b is the peel angle, taken in plan view between the wave crest and the path of the breakpoint, and c_b is the wave celerity at breaking, as shown in Figure 1. WALKER (1974) measured the peel angle from aerial photographs, and computed the breaking wave celerity using:

$$c_b = 1.25\sqrt{gH_b} \qquad (2)$$

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in which g is gravity and H_b is the breaker height. DALLY (1990) noted that for the idealized case of plane waves and straight and parallel bottom contours, Snell's Law dictates that the peel rate given by (1) is predetermined in deep water.

With a fixed frame of reference, the 'effective' board speed, S_e, is rigorously defined as the magnitude of the projection of the velocity vector of the surfer, $\vec{V}_S$, onto the path of the breakpoint (which lies in the horizontal plane, see Figure 1). Consequently, in vector notation the effective board speed is expressed simply as:

$$S_e = \vec{V}_S \cdot \vec{\ell} \qquad (3)$$

where $\vec{\ell}$ is the unit vector that is tangent to the path of the breakpoint. By this definition, if the break rate (*i.e.* the speed of the breakpoint along its path) is persistently greater than the effective board speed, the breakpoint will overtake the surfer and the wave will close out, as stated above. On the other hand if the board speed is potentially faster than the break rate, the surfer must reduce his effective board speed, on average, by 'carving' or 'cutting back' in order to allow the breakpoint to catch up. During such maneuvers, and especially during the 'drop-in' at the beginning of the ride, the instantaneous, absolute speed of the surfer, $|\vec{V}_S|$, can be significantly faster than the break

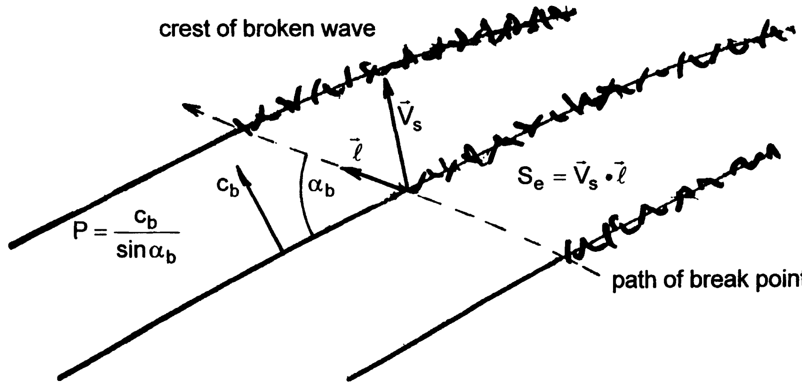

Figure 1. Definition sketch of board-speed parameters.

rate. However the effective board speed must in fact match the break rate P, on average, in order to have a successful ride. If the break rate increases on a given wave, the surfer has less time (and need) to cut back. In the critical limit, the surfer is moving move as fast as possible in order to stay ahead of the breakpoint and, at this condition, $\vec{V}_S$ and $\vec{\ell}$ are aligned and S_e equals $|\vec{V}_S|$ (which now equals P). Herein this limiting speed is called the maximum sustainable board speed, S.

In regard to maximum sustainable board speed, very little is known. WALKER (1974) made fourteen measurements of average surfer speeds (*i.e.* $\overline{|\vec{V}_S|}$, not S) at several popular surfing beaches in Hawaii by repeatedly triangulating the moving surfer's position using shore-based surveying instruments. However S, which determines the critical limit of surfing for each wave, was not studied directly. Because of the limited availability of his report, Walker's data for these fourteen rides (converted to S.I. units) are presented in Table 1. The ride with the fastest average surfer speed (11.6 m/s) was observed at Waimea; however, because of its large peel angle (80°) the speed was judged by Walker to be well below the maximum sustainable speed for a wave of that height (5.2 m). Only the four rides with the smallest peel angles (32°–40°) occurred under conditions close to his estimate of the surfable limit (rides 2a, 2b, 2c, and 7b). Even so, note that although the breaker height for the three rides at Ala Moana ranged from 1.8–3.0 m, the average surfer speeds estimated from the triangulation were all 9.1 m/s. Therefore, acknowledging the limitations of the triangulation method,

Table 1. *Surf site observations of* WALKER *(1974) and laboratory results of* HORNUNG *and* KILLEN *(1976).*

Data Point	Site	Local Bottom Slope	Wave Period (s)	Breaker Type	Peel Angle (degrees)	Breaker Height (m)	Average Surfer Speed (m/s)
1a	Queen's	1/40	12	Spill	60	1.2	5.5
1b	Queen's	1/40	20	Spill-Plunge	65	2.1	6.7
1c	Queen's	1/40	20	Spill-Plunge	55	1.8	6.4
1d	Queen's	1/40	20	Spill-Plunge	80	1.8	5.5
2a	Ala Moana	1/33	17	Plunge	35	1.8	9.1
2b	Ala Moana	1/20	20	Plunge	38	3.0	9.1
2c	Ala Moana	1/25	20	Plunge	32	2.7	9.1
3a	Lefts	1/30	20	Plunge	45	1.8	9.1
4a	Kewalo	1/37	17	Plunge-Spill	65	1.8	5.5
5a	Makaha	1/60	14	Spill	65	1.8	8.5
5b	Makaha	1/60	16	Spill	68	2.4	6.1
6a	Waimea	1/20	16	Plunge-Spill	80	5.2	11.6
7b	Pipeline	1/22	12	Hard Plunge	40	3.7	9.8
8b	Sunset	1/100	15	Plunge-Spill	65	4.6	10.1
hk	1/12 scale lab.	n/a	n/a	Plunge-Spill	42	0.18	2.24

it appears that of these three rides, only the ride with the smallest breaker height (2a) was truly at the maximum sustainable speed for that wave. For the ride at Pipeline (7b), although the surfer speed was slightly greater (9.8 m/s), the breaker height was double that of ride 2a, and so it is also doubtful that this ride truly occurred at the surfable limit.

One additional source of information on maximum sustainable board speed is a laboratory study by HORNUNG and KILLEN (1976), in which an oblique hydraulic jump was created in a laboratory flume, to serve as a stationary breaking 'wave' for testing surfboard shapes. The authors were able to 'surf' 1/12 scale, free-floating model surfboards in the correct position just in front of the curl. The boards were proportionately weighted, and adopted their own equilibrium positions and orientations with respect to the wave face and flow. As also noted in Table 1, the speed of the free-stream flow was 2.24 m/s, the breaker height was 0.18 m, and the angle, in the horizontal plane, between the flow direction under the board and the wave crest (*i.e.* the equivalent peel angle) was nominally 42°.

The objective of the present study is to establish a functional relationship between maximum sustainable board speed and macro-properties of the breaking wave. As board speed is a function of the details of the wave-flow under the board, the size and shape of the board and fins, as well as the weight and position of the surfer, a theoretical relationship might conceivably be derived from basic principles of naval architecture and wave mechanics, or the problem studied at small scale in the laboratory using the oblique hydraulic jump of HORNUNG and KILLEN (1976). In this inaugural study however, estimates of maximum sustainable board speed were made using video of surfers in the prototype, and an empirical formula developed that relates board speed to breaker height.

VIDEO SELECTION AND ANALYSIS METHODS

The major source of data used in this study was a professionally shot surfing video entitled, "Wave Warriors III" (1988). This film, which documented mostly professional surfers in Hawaii, Australia, and California, was supplemented with video shot by the author of amateur surfers in Indialantic, Florida.

In selecting individual sequences from these videos to be analyzed, it follows from the discussion above that if the maximum board speed that can be maintained on a particular wave is greater than the wave's break rate, the surfer can take the time to make large turns and cut-backs. Therefore, in the videos, a surfer was judged to be moving at the maximum sustainable board speed for that wave if he was surfing a nearly direct line along the wave face. That is, he was not attempting any turns or acrobatics, and did not outrun the peel until 'kicking out' at the end of the ride. In regard to maximum speeds, it is noted that an accomplished surfer can 'pump' his board in order to increase the sustained speed beyond that otherwise provided by the wave. This skill, which is similar in concept to that of a skier who can increase his speed by 'skating' with his skis, is often used to accelerate on a section of wave whose shape is less than perfect (*i.e.* the wave is 'backing off'). In viewing the video, pumping is easily distinguished from carving and turning in that the up-and-down movement of the surfer working the board is confined to an excursion less than the length of the surfer's legs. Pumping was not being used in any of the critical-limit surfing sequences selected for this study.

Using these criteria, twenty-nine individual sequences from the two videos were identified for analysis. These sequences were all shot from shore-based, tripod-mounted cameras using telephoto lenses, with the photographer tracking the surfer. This maximized the size of the surfer in the viewfinder and allowed close examination of detail, while essentially eliminating any lens-induced distortion. Figures 2a–d present individual frames of video extracted from one of the sequences and serve to illustrate the videogrammetry methods described below.

Analysis of the video record relies upon establishing a length scale within each frame of video. As the only ordinary objects of fixed absolute size to appear in every frame are the surfer and the surfboard, it is necessary to use one of the two, although the exact dimensions of either are ordinarily unavailable. In general, surfboards typically range between 1.8–3.0 m in length, whereas surfers between 1.6–1.9 m tall. Also, in most of the sequences, the upright surfer is viewed in better perspective than the surfboard, and so it is best to use the surfer as the length scale. Consequently, assuming a value of 1.8 m for the height of an upright surfer, the size of the surfer on the video screen was then used to visually estimate the height of the wave at incipient breaking. For plunging breakers, incipient breaking was taken

Figure 2a–d. Example sequence of frames captured from video used in board-speed analysis. In (a), crouched surfer is estimated to be 1.4 m (4.5 ft) tall, and wave is estimated to be 2.4 m (8 ft) in height. In (d), during 'kick out', the board is estimated to be 1.8 m (6 ft) long. Six frames were counted between (a) and (c) for the board to cross the line of residual aeration, resulting in a speed estimate of 9.0 m/s (30 ft/s).

to be that section where the top of the wave first became vertical and started to turn over, in order to make an estimate of height that was consistent with that for spilling breakers. If the surfer was in a crouched position, the scaling length was reduced accordingly. These estimates were made to the nearest 0.3 m (1 ft) for waves less than 3 m (10 ft) in height, and to the nearest 0.6 m (2 ft) for larger waves. Breaker type, *i.e.* spilling or plunging, was also noted for each case.

The board speed during each sequence was determined in the following manner. In viewing the sequence, a 'stationary' object on the face of the wave was identified and used as a local point of reference. This object was usually a small patch of residual aeration left by a previous wave, which the board passed directly through in many cases. Using the freeze-frame mode of the video-player, the sequence was advanced until the tip of the surfboard was as close as possible to the reference point, or to an imaginary vertical line passing through the reference point. The number of frames required for the tail of the board to subsequently touch the reference line was then counted, and the result divided by 30 Hz (the frame exposure rate in real time) to produce an elapsed time. The assumed size for the surfer was used to estimate the length of the surfboard, and to refine the estimate of the distance traveled to account for the fact that the nose and tail often did not land exactly on the reference line. These estimates are believed to be accurate to the nearest 0.3 m (1 ft). Dividing the travel distance by the elapsed time produced the estimate of the board speed.

Referring to the sequence of video frames in Figures 2a–d as an example, firstly the crouched surfer in Figure 2a is estimated to be 1.4 m (4.6 ft) tall, and the plunging breaker is roughly 1.75 'crouched surfers' in height at the right-hand border of the frame, *i.e.* $H_b \cong 2.4$ m (8 ft). The line of aeration that is clearly visible at the nose of the board in Figure 2a is crossed (Figure 2b), and the tail of the board passes the line six frames later in Figure 2c. Figure 2d shows a frame captured during the kick-out in which the board is in good perspective. In relation to the size of the surfer in this frame, the board length is estimated to be 1.8 m

Table 2. *Results developed from photogrammetric analysis of surfing videos.*

Counter-time (min.:sec.)	Breaker Type	Breaker Height, H_b (m)	Travel Distance, δ (m)	Number of Frames, N	Computed Board Speed, and Error Range S (m/s)
Wave Warriors III					
2:42	Plunge	3.0	1.8	5	10.8 ± 0.9
2:46	Plunge	3.0	1.8	5	10.8 ± 0.9
3:46	Plunge	1.8	1.8	7	7.7 ± 0.7
4:06	Plunge	1.2	1.8	9	6.0 ± 0.5
4:25	Plunge	2.4	3.0	14	6.4 ± 0.3
4:50	Plunge	2.4	1.8	8	6.8 ± 0.6
5:01	Spill	1.2	1.8	9	6.0 ± 0.5
7:16	Plunge	3.0	1.8	5	10.8 ± 0.9
8:54	Plunge	3.0	1.8	5	10.8 ± 0.9
9:05	Plunge	2.4	1.8	6	9.0 ± 0.8
9:35	Plunge	1.2	1.8	10	5.4 ± 0.5
14:34	Spill	1.2	1.8	7	7.7 ± 0.7
16:58	Plunge	1.8	2.1	8	7.9 ± 0.6
17:50	Plunge	6.1	2.1	4	15.8 ± 1.1
18:51	Plunge	2.4	2.1	6	10.5 ± 0.8
25:19	Plunge	4.3	2.4	6	12.0 ± 0.8
25:21	Plunge	4.9	2.7	6	13.5 ± 0.8
26:27	Plunge	2.4	1.8	5	10.8 ± 0.9
27:52	Spill	1.2	1.8	8	6.8 ± 0.6
34:21	Plunge	9.1	3.0	5	18.0 ± 0.9
34:59	Plunge	9.1	3.0	5	18.0 ± 0.9
49:22	Spill	1.8	1.8	7	7.7 ± 0.7
51:54	Plunge	2.4	1.8	6	9.0 ± 0.8
54:59	Plunge	2.4	1.8	6	9.0 ± 0.8
56:00	Plunge	1.8	1.8	7	7.7 ± 0.7
Indialantic Local					
1:16	Spill	1.2	1.8	7	7.7 ± 0.7
5:08	Spill	1.2	1.8	7	7.7 ± 0.7
6:15	Spill	1.2	1.8	7	7.7 ± 0.7
8:30	Spill	1.2	1.8	8	6.8 ± 0.6

(6 ft) in length. Consequently, the estimated board speed is 9.0 m/s.

RESULTS AND EMPIRICAL MODELING

Results of the analysis of the twenty-nine surfing sequences are presented in Table 2. Information presented includes: the counter-time at which the sequence began, the breaker type, the breaker height, the surfboard length/travel distance (δ), the number of frames (N) required for the board to pass the reference point, and the computed board speed. Twenty-one breakers were of the plunging type, and eight were spilling. The range in values for the parameters are:

Breaker height (H_b)	1.2–9.1 m
Travel distance (δ)	1.8–3.0 m
Number of frames (N)	4–14
Computed board speed (S)	5.4–18.0 m/s

In general terms, for fixed surfboard size/shape and surfer weight, one would expect the maximum sustainable speed to increase with breaker height, and to perhaps increase for plunging breakers as compared to spilling breakers. Figure 3 presents a plot of S versus H_b for the data from Table 2, and the expected trend of increasing board speed with increasing wave height is clearly evident. The R^2-correlation between observed S and H_b is 0.8968. Perhaps contrary to expectations, albeit limited in number the spilling breakers do not display a trend that is noticeably different from the plunging breakers.

The curve representing the best-fit empirical model of the form

$$S = A\,(H_b)^M \qquad (4)$$

is also presented in Figure 3 where, in m-s units, A is 6.03 and M is 0.4882. The R^2 correlation between measured and modeled values of S is

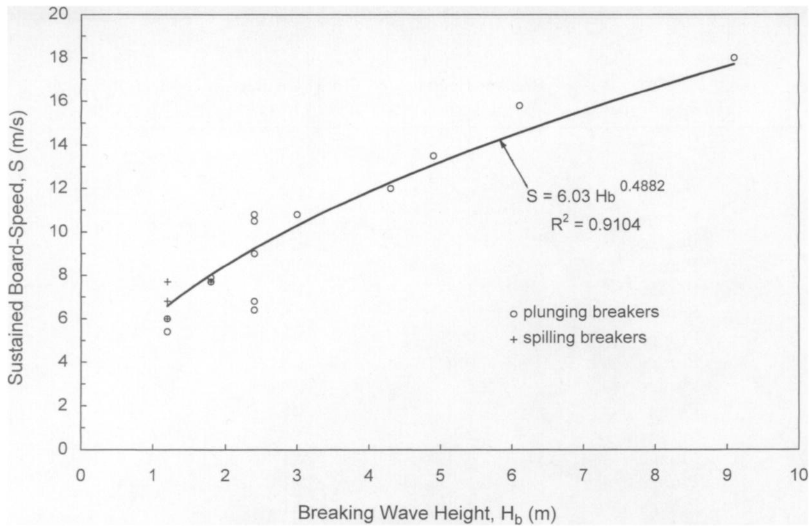

Figure 3. Maximum sustained board speed in comparison to breaker height, estimated from analysis of surfing videos (data in Table 2). Curve is best-fit power model.

0.9104. The correlation coefficient is 0.9542 and the standard error of estimate is 1.0216 m/s.

The fact that the best-fit power M of the breaker height in (4) is essentially 1/2 strongly supports the assertion that the problem is governed almost wholly by the Froude Number, and not by the Reynolds or Weber Numbers (see also HORNUNG and KILLEN, 1976). In other words, it is form drag that limits the speed of the surfboard and not viscous drag nor surface tension, and so the velocity scale should equal the square root of the length scale. Hence, a model of the form:

$$S = \beta \sqrt{gH_b} \qquad (5)$$

is adopted, for which the best-fit value of β is found to be 1.93. The R^2-correlation between S measured and S predicted from (5) is 0.9108. The correlation coefficient is 0.9543, and the standard error of estimate is 1.0198 m/s.

ERROR ANALYSIS

Although some scatter exists in the video-acquired data, the overall trend is certain and the empirical formula (5) is physically justified. The majority of the potential error in the video method lies with determining the wave height and the travel distance, which are both visually estimated relative to the approximated height of the surfer. Although the error in these estimates cannot be directly quantified, the resolution error can be assessed to some degree in the following manner. As noted above, it is believed that H_b is estimated to within $\pm$ 0.15 m for smaller waves, and $\pm$ 0.3 m for larger waves. In regard to computing S, travel distance (δ) is resolved to within $\pm$ 0.15 m and, due to the use of the freeze-frame mode of the video-player, N is a repeatable integer. Consequently, the actual board speed is bounded by:

$$S = \frac{30(\delta \pm 0.15\text{ m})}{N} \qquad (6)$$

indicating that the relative error is greater for short boards (δ small). From (6), the error range in board speed ($\pm$4.5/N, m/s) is noted in Table 2 for each sequence. The minimum resolution error is $\pm$ 0.3 m/s, and the maximum is $\pm$ 1.1 m/s.

Also of potential concern to the accuracy of this type of video analysis method is the effect of off-normal perspective on the length measurements, *i.e.* the fact that the line-of-sight of the camera may not be perpendicular to the object whose size is being estimated. Firstly however, it is noted that all estimates were made visually, and a practiced observer viewing familiar objects has some ability to intuitively compensate for perspective. In spite of the fact that the surfers in the sequences selected for analysis were typically moving across the camera's line of sight, the apparent

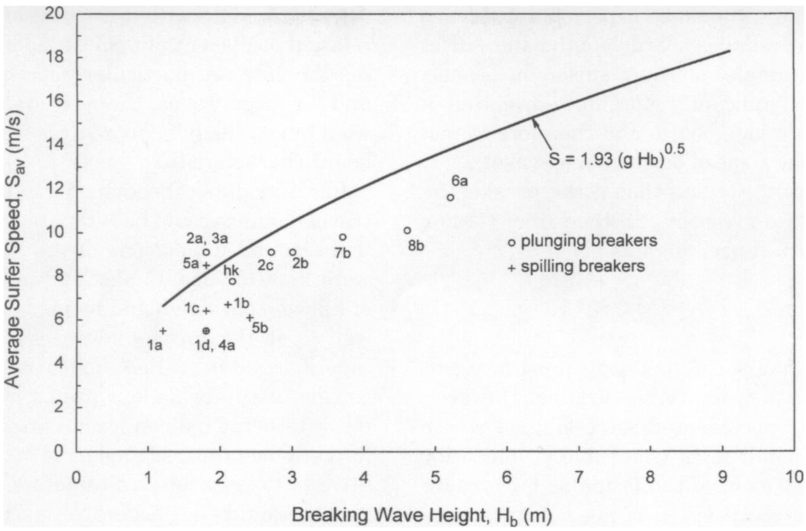

Figure 4. Surfer speed data (from Table 1) of WALKER (1974) and HORNUNG and KILLEN (1976) plotted against Equation 5. Most rides were slower than the maximum sustainable speed suggested by the results of the video analysis.

length of the board was sometimes greatly reduced by off-normal perspective in the horizontal plane (*e.g.* Figure 2a–c). However, one particularly strong feature of the videogrammetric method is that off-normal perspective does not affect the frame count N, as long as the view of the nose and tail of the board is unobstructed. Thus, if a reliable estimate of the true board length can be made elsewhere, say in a different frame with good perspective (*e.g.* Figure 2d), the board speed can be estimated even in those sequences with less-than-optimal perspective. Finally, with the shore-based camera located several hundred yards away from the surfer and at essentially the same elevation, neither the estimate of the height of the surfer nor the estimate of the breaker height should have been affected by off-normal perspective in the vertical plane.

DISCUSSION

The data from WALKER (1974) provided in Table 1 are plotted in Figure 4, along with the empirical model (5) developed above. Of the fourteen observations of board speed, all but three fall below the curve. This indicates that, overall, the rides did not take place at the critical limit of surfing. However, several of Walker's observations fall within the scatter of the S estimates of Figure 3. The one ride suspected of being truly at the surfable limit (2a) reassuringly falls slightly above the curve. However, rides 3a and 5a, which had peel angles of 45° and 65° respectively, also fall above the curve. The other rides judged by Walker to be close to the surfable limit (2b, 2c, and 7b) are below the curve, but 2c in particular is arguably within the scatter of the S estimates of Figure 3.

The single data point from the laboratory experiment of HORNUNG and KILLEN (1976) is also presented in Figure 2 (point 'hk'). In plotting this point, the measured values reported by Hornung and Killen have been Froude-scaled according to the 1/12 length scale of their experiment, with the wave height and free-stream speed becoming 2.16 m and 7.76 m/s respectively. The data point falls below, yet close to, the curve. Although the point falls within the scatter of the data used to develop (5), it is possible that the peel angle in the experiment (42°) may not have been critical. If so the model board, although sitting motionless on the face of the stationary wave, was actually riding lower on the face than it would if the peel angle were more acute. In addition it is noted that the free-stream speed in the flume has been taken as the board speed, whereas the fluid speed directly under the board (expected to be greater than the free-stream, but not provided by Hornung and Killen), might be more appropriate.

Regardless of the error in the estimates of maximum sustainable board speed, scatter in the data in Figures 3 and 4 should be expected due to variations in board shape, board length, and surfer weight. For example, a heavy surfer on a short board creates significantly more form-drag than a light surfer on a long board, and therefore cannot sustain as great a speed on the same wave.

It is interesting to note that if the breaker celerity was indeed given by (2), then from (1) and (5) a *single* critical peel angle is given by:

$$\sin \alpha_b \geq \frac{1.25}{\beta} \cong 0.6477 \qquad (7)$$

for $\beta = 1.93$. That is, the peel angle must be greater than 40° for a wave to be surfable. However, WALKER (1974) documented successful rides with peel angles as small as 32° (see Table 1), indicating that some refinement of the formulas for breaker celerity and/or board speed is needed. In a companion paper that applies (5) to stochastic modeling of surfing climate (DALLY, 2001), the prediction of c_b is enhanced by including the effects of bottom slope and wave period, resulting in a range of critical peel angles of 33°–50°.

CONCLUSIONS

The videogrammetric method described herein is a viable means of investigating maximum sustainable board speeds of surfers. The frame-by-frame scrutiny of a permanent videotape record facilitates careful, repeatable data reduction and analysis. Use of telephoto lenses in shooting the surfing sequences maximizes the size of the surfer and the surfboard, thereby enhancing resolution and accuracy. If commercially available surfing videos are used, the method is very inexpensive and robust as compared to possible methods for direct, in situ measurement of board speed in the field. The untapped source of data sitting on the shelves of video stores is potentially vast.

Equation (5), derived from the video data, appears to be a laudable first-attempt to model maximum sustainable board speed in relation to characteristics of the breaking wave. The relationship is physically justified by Froude scaling, and represents the data with a R^2 value of 0.91 and a correlation coefficient of 0.95. In addition to expanding the data set, particularly for spilling breakers and for large waves, the next step in refining (5) would most likely be to address surfer weight and board characteristics.

In future data collection efforts, wave height and travel distance could be estimated more accurately if the actual dimensions of the surfer and board were known. Also, in shooting new video, stripes of known spacing should be made on the board as well as on the surfer's lower legs, thereby adding 'rulers' to aid in scaling. Concurrent overhead-video, shot with a wide lens from a hovering helicopter or tethered balloon, would provide valuable information on the peel angle and surfer position relative to the shore-based camera. Of course, if distances could be accurately scaled from the overhead video, board speeds could be computed directly and used to verify the method developed herein.

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