CHAPTER 151

RECREATIONAL SURFING ON HAWAIIAN REEFS

by

James R. Walker[1]

Robert Q. Palmer[2]

Joseph K. Kukea[3]

ABSTRACT

Recreational surfing has been studied in Hawaii to develop criteria for the preservation, enhancement and design of surf sites. The criteria will aid in planning compatible uses of the coastal zone. Surfing characteristics and wave transformations were studied in the field and related to ocean bottom features at prime surf sites. A small scale, three-dimensional, hydraulic model study was conducted to determine the effect that a given bottom feature had upon the surfing wave. A concept of a multiple-purpose surfing shoal to be compatible with several varied interests in the coastal zone was hypothesized from field, analytic, and model studies.

INTRODUCTION

Hawaii is the surfing mecca of the world. The ancient Hawaiians originated surfing, which has become a popular international sport. More than ten percent of the local population on Oahu surf (Anderson and Co, 1971). There are about 1,600 surf sites in Hawaii; however, many of these surf sites have good surfing conditions only under certain combinations of wind and wave conditions. Consequently, relatively few of these sites have good surfing conditions at a given time, and those sites with conditions conducive to surfing are generally overcrowded. The rapidly increasing popularity of surfing and the loss of surf sites due to construction projects contribute to the overcrowding of surf sites.

Overcrowding increases the frequency of injury and decreases enjoyment of the sport. Unlike skiing and golf, for which new recreational facilities may be built to meet the increased demand, surfing is confined

[1] Jr. Researcher, Dept. of Ocean Engineering, University of Hawaii

[2] Assoc. Researcher, Dept. of Ocean Engineering, University of Hawaii

[3] Grad. Student, Dept. of Ocean Engineering, University of Hawaii

to a limited number of natural surf sites, for given wind and wave conditions. Hence, an effort should be made to preserve and enhance these valuable natural surf sites and to develop design criteria for creation of multiple-purpose reefs.

ENVIRONMENT

There are eight major islands in the Hawaiian archipelago. All of the Islands have surf sites, however, Oahu, the island with the major population center, has the greatest number. This study was primarily conducted on the island of Oahu. Much of the bathymetry off Oahu is composed of fringing coral reef having ridges and sand-filled channels running seaward from shore. Surfing areas are generally found over the ridges, while the channels separate adjacent surf areas.

The stable coral and basalt reef formations, in contrast to sandy shoals, do not shift under wave attack. Stable shoals are conducive to the study of the surfing area because they induce relatively consistent wave transformations.

The location of some of the prime surf sites studied on Oahu are shown in Figure 1. The sites on the south shore, along the Ala Moana reef and at Queen's in Waikiki, have a fringing reef with steep seaward slopes to deep water. The north shore sites of Sunset, Pipeline, and Waimea are located in deeper water and generally have a flat, narrow shelf extending over a mile seaward from the 30-foot to the 60-foot depth contour. The bottom slopes on the leeward side, such as at Makaha, generally drop sharply to deep water. The shallow reefs on the windward side extend far seaward, then slope steeply to deep water.

In Hawaii, the northeasterly trade winds blow at ten to fifteen knots about 80 percent of the year. Local waves generated by the trade winds arrive at the windward coast with periods ranging from five to ten seconds and with breaker heights up to ten feet. Waves with similar characteristics occasionally occur on the southwestern shores during the winter months.

The big surf for which Hawaii is famous is due to waves generated by distant storms in the North Pacific, during the winter months, and in the Southern Hemisphere, during the summer months. These swell s break on island reefs far removed from their generating winds. Large, low pressure systems 1,000 to 2,000 miles northwest of the Islands generate surf on the northwestern shores with ten to fifteen second periods and with breaker heights up to 30 feet. The southern swell may be generated more than 5,000 miles from the Islands. These waves generally have periods of 14 to 20 seconds and breaker heights of three to 15 feet. The waves from the southern swell generally arrive in groups of three to five waves with very regular periods, characterized by ten to twenty minute intervals between groups.

Hawaii has a semi-diurnal tide with a mean daily range of two feet. Even this small tide range significantly influences the breaking wave characteristics at certain sites.

SURFING

Surfing is the sport of riding a breaking wave. Surfing is practiced using various forms of equipment, such as a board, a canoe, a sailboat, or even using no equipment, except perhaps fins, for body surfing. The most popular surfing form is board surfing and is the form referred to in this paper, although the basic techniques pertain to all surfing forms in general.

Surfing is generally performed at a specific location called a "surf site." A "surf site" is an area in which waves break in a consistent and desirable form under given conditions. The popularity of a surf site depends upon several variables, including the frequency of occurrence of breaker characteristics, wind, water surface conditions, proximity of the site to population centers, suitability for surfing under a wide range of wave conditions, access, and hazards.

The mechanics of surfing are first for the surfer to attain a position just seaward of the breaker zone. When a desirable wave approaches, the surfer paddles with the direction of wave advance, utilizing the force of gravity relative to the slope of the wave face to attain a velocity equal to the velocity of the wave. This is termed "catching a wave" and is shown schematically by the sequence in Figure 2. Once the wave is caught, the surfer assumes a standing or crouching position. The surfer then slides, or "drops," forward down the face of the wave from near the crest toward the trough, traveling at a velocity greater than that of the wave. During the drop, which takes from two seconds at Queen's in Waikiki on a three-foot wave to five seconds at Waimea Bay on a 15-foot breaker, the wave begins to break. The breaking then proceeds shoreward and laterally along the crest. After the acceleration experienced during the drop, the surfer initiates a turn to the right or to the left, escaping from the turbulent breaking region. The surfer maneuvers on the wave face in the vicinity of the junction of the unbroken wave and the breaking region, called the "peel," or "curl," by shifting his feet and weight to control the response of the surfboard. The surfer ends his ride when he "kicks out" back over the wave crest, or when he loses control of his board. If the surfer loses his board, it is transported by wind, wave, or current forces into the surfboard-recovery area. The surfer then must retrieve his board and return to the take-off area through the return zone. A schematic of these areas is shown in Figure 3.

WAVE TRANSFORMATIONS

Wave properties such as length, height, and asymmetry are modified as waves enter shallow water. The primary modifications influencing surfing are described by refraction, amplitude amplification, diffraction, and breaking. In addition, the incident wave system may induce secondary wave systems which influence the behavior of multiple breaking. Also, other non-linear effects such as breaking-wave-induced setup and currents influence the characteristics of surf sites and adjacent reefs and beaches.

Refraction plays two important roles in influencing the characteristics of a surf site. First, convergence of energy over a ridge, and divergence over a trough, result in wave height variations along the crest line. Secondly, refraction changes the direction of wave advance, tending to align the wave crest lines parallel with the bottom contours. The more closely aligned the crest lines and breaking depth contours become, the greater becomes the velocity that the surfer must attain to successfully ride the wave.

Wave height amplification due to shoaling water depths accounts for one of the most important wave transformations involved in forming the surfing wave. Over ridges, wave height is increased relative to wave height over the side channels. This amplitude differential induces waves to break along the channel edge, providing the peel where the wave is ridden. The amplification factor basically is dependent upon the water depth to wave length ratio, with the greater amplification factors found for the smaller ratios. Hence, the longer period waves are more sensitive to smaller depth variations and they break at a greater height relative to their deep water wave height. The longer period waves also tend to break in a more consistent pattern than do the shorter period waves.

Lateral transmission of wave energy induced by wave height variations along the crest line is not well understood. This effect, called diffraction, violates basic assumptions normally invoked in refraction analysis. Analytical description of wave benavior over shoals near the breaking region is therefore not reliable by conventional methods. Whalin (1970) has shown the degree of discrepency between refraction analysis and observed wave behavior in a convergence zone. Diffraction of water waves over a submerged shoal has been treated by Rao and Garrison (1970), but under non-breaking conditions. The primary influence of diffraction on surfing is to transmit wave energy laterally along the wave crest, thereby smoothing the response of the wave to the shoal. This suggests that the size and shape of the shoal are important factors in formation of a surfing wave.

In general, the most desirable surfing waves are those which break, although breaking is not a necessary condition for surfing. A condition for wave breaking occurs when the particle velocities of the wave crest equal the velocity of wave propagation (Stokes, 1847). Different wave theories predict this condition for breaking at different limits. The most commonly employed condition for breaking, due to McCowan (1894), is $H_b = 0.78d_b$, where H_b is the breaker height, and d_b is the breaking depth. Other investigators have employed various theories and have obtained different criteria for breaking, ranging from $H_b = 0.73d_b$ (Laitone, 1963) to $H_b = 1.0d_b$ (Dean, 1968).

Since wave theories are not generally valid near the breaker zone and the above criteria were developed for limiting waves traveling over a horizontal bottom, the reliability of the limits is questionable. Galvin (1969) reviewed data from several wave flume investigations and developed the following empirical relationships, which include the effect of beach slope, S: $d_b/H_b = 0.92$ when S is steeper than 14.3, and $d_b/H_b = 1.4 - 6.86/S$ when S is flatter than 14.3.

Breaker-type is also an important factor in surfing. Breaker-type is a classification of wave profile during breaking. Galvin (1968) studied movies of flume waves and derived the following expression for the breaker-type index, K: $K = H_b S/gT^2$, where g is the acceleration due to gravity, and T is the wave period. The suggested limits for breaker-type are: Surge when $K < 0.003$; Plunge when $0.003 \leq K \leq 0.068$; and Spill when $K > 0.068$. The most desirable surfing waves are those with breakertypes in the plunge-spill region.

The descriptions of wave behavior given above were developed for waves propagating over straight, laboratory slopes. These methods are difficult to apply to the composite slopes found over the complex coral reefs found in nature. Camfield and Street (1968) observed that wave transformations over composite slopes responded to the slopes some distance seaward of the breaker point. This finding was also observed during the course of the present study. Therefore, the slope one-half wave length seaward of the breaking point was employed in describing the characteristics of the surfing waves of this study.

As the wave enters shallow water, the velocity of propagation decelerates. For wave lengths that are long compared to the water depth, the velocity of wave propagation, C, may be given by $C = \sqrt{gd}$ to the first approximation, and by $C = \sqrt{g(d + \eta)}$ to the second approximation, where is wave amplitude, and d is the still water depth. The second approximation appears to be more accurate; however it requires an <u>a priori</u> knowledge of η, which renders it more difficult to apply. The first approsimation may be used to predict the wave velocity in terms of breaker height by substituting $d_b = 1.28H_b$: $C = \sqrt{g(1.28)H_b}$. The expression indicates that the surfer must attain a greater velocity to catch larger waves and that the rides on larger waves tend to be faster than on smaller ones.

Non-linear effects, such as wave setup, induced currents, and energy decay, have important effects upon the surfing wave, as well as upon beach stability. A discussion of the relationship of these phenomena to surfing is given by Walker and Palmer (1971).

METHODS

Research methods involved primarily field observations of natural surf sites. Detailed bathymetric surveys of prime surf sites having desirable surfing characteristics were made. Water depths were measured using a recording echo sounder in water deeper than five feet and a sounding rod in depths of less than five feet. The bathymetric surveys were conducted during the season of calm seas. Wave transformations and surfing characteristics were observed and related to the bathymetry during the surfing season. Time-sequenced aerial photographs were taken, and their transparencies were projected over the bathymetric charts to study the wave transformations in relation to the bottom configuration. Land-based triangulation techniques were used to track surfer riding paths to supplement the aerial studies.

Field observations were supplemented with a 1:75 scale, three-dimensional, hydraulic model study. The model study was conducted to determine the influence of various shaol features on the surfing wave. The model basin, described by Fallon, et al (1971), had been built for a boat harbor entrance channel improvement study. This study was initiated by the surfing community, which was concerned over the possible loss of a surfing site. After the harbor study, shoal features, including size, depth, and seaward slope, were tested to determine their influence on breaking wave patterns. The shoals were constructed with model stones which represented 500-pound prototype basalt. Due to time limitations for use of the model, tests were restricted to a single wave condition having a 13.5-second period and six-foot breaker height. This condition is typical of summer surf at the test location. Model observations were primarily confined to observing changes in breaking wave patterns which were influenced by the various shoal configurations.

OBSERVATIONS

The characteristics of a dozen surf sites were studied in detail; however, Queen's in Waikiki was the subject to the most thorough study. Queen's was selected as a typical surf site and one from which an artificial surf site might be modeled. The bathymetry of Queen's, located in Waikiki Bay, is shown in Figure 4. The coral reef shoal is 300 feet wide and 600 feet long. It has a 150-foot wide, seven-foot deep sand-filled channel on the left side and a 16-foot deep hole on the right side. The shoal starts to form a ridge at 12-foot depth. A seven-foot deep trench on the shoreward side separates the surf shoal from the beach and seawall. Queen's is surfed by 20 to 50 people at a time on waves from two to eight feet high.

Figure 5 is the third of a sequence of aerial photographs taken at five-second intervals over Queen's. The breaking wave height was six feet and the period was 20 seconds. The crest lines showing the wave propagating over the shoal are superimposed over the bathymetry in Figure 6. The take-off, riding, end-of-ride, and board-recovery areas are labeled. The approximate path of the surfer is plotted, and the breaking region is crosshatched.

At position t = 0, the incident wave is slightly divergent due to the configuration of the bay in Waikiki. Upon traversing the shoal, the wave refracts and becomes convergent over the ridge comprising the Queen's shoal. Refraction and shoaling amplification increase the height rapidly over the 1:40 seaward slope, and the wave initially breaks in seven feet of water. The wave may be ridden to the left or the right. It should be noted that the breaking on the left generally follows the edge of the sand channel, and that the breaking on the right generally follows the 5.5-foot depth contour. The surfer maneuvers in the vicinity of the breaking region of the wave. This region, called the peel or curl, is outlined in the aerial photograph, Figure 5, by the white water patterns. Figure 7 illustrates a surfer riding in the peel. The rate of peel propagation along the wave crest line is termed the "peel-rate." The vector diagram in Figure 8 gives the relationship among the wave velocity, V_w, the velocity of the surfer, V_s, and the peel velocity, V_p. The included angle between the unbroken wave crest, along V_p, and the velocity of the surfer is termed the "peel-angle, α." At Queen's, in the above sequence, the peel-angle is 80 degrees to the left and 60 degrees to the right. The ride to the right is generally faster.

Peel-angle, breaker height, and breaker-type are important parameters defining the surfing wave. These characteristics are listed in Table 1 along with other observations made at study sites. Table 1 includes data taken from some of the most famous surf sites in the world. Pipeline is noted for its fast ride and hard, plunging breaker-type. Waimea Bay is noted for its large waves which are ridden by expert surfers. Queen's has small spilling waves ridden by average-skilled surfers. Figure 9 is a plot of peel-angle as a function of wave breaker height for observations listed in Table 1.

Based upon the observations of the skill level required to surf at the study sites, suggested conditions for surfable peel-angle are given in Figure 9. The peel-angle limit is also based upon the assumption that the velocity of a surfer is limited to about 40 feet per second or less over an extended length of ride. It is assumed that the surfer cannot successfully match the peel velocity for greater peel-angles for the given wave height. Also shown in Figure 9 are subjectively developed categorizations of surfer skill level to indicate the peel-angles and breaker heights preferred by surfers of different experience. It is emphasized that categories are not clearly differentiated from one another and there is considerable overlap. Figure 9 could be of benefit in selecting design criteria for an artificial surf site.

To the first approximation, the peel-angle may be related to the breaker height, and velocity of the surfer by the expression $\sin \alpha = \sqrt{gH_b B}/V_s$, where B is a breaker height coefficient, d_b/H_b. Using the McCowan breaking criteria, B = 1.28 in the preceding equations, isolines of surfer velocity, V_s, are plotted in Figure 9. The peel-angle is related to the included angle between incident wave crest line and the breaking depth contour. Hence, surfing velocities are related to the incident wave and bottom characteristics.

The preceding discussion pertains primarily to fluid-bottom interactions. The breaking properties of height and form of waves and the water surface conditions are significantly influenced by the wind. A surf site has the most desirable conditions with a component of wind of less than 15 knots opposing the direction of wave advance. Stronger opposing winds tend to interfere with the surfing by lifting the surfboard nose out of the water and roughening the water surface. A component of wind following the direction of wave advance tends to prematurely topple the wave crest and spoil the water surface conditions by generating local chop. It should be noted, however, that many popular surf sites exist with strong following winds. These sites generally exist only under the adverse wind condition which generates the surfing wave.

Several observations of wave behavior at surf sites have been made. One of these is the effect of finite height waves and wave breaking on the refraction of waves propagating over a surf shoal. Figure 10 traces the history of a wave crest propagating over the Queen's surf shoal. Observed wave orthogonals are drawn and compared with orthogonals computed by linear wave theory ray tracing techniques. It whould be noted that the calculated orthogonals indicate the presence of a caustic. The observed orthogonals start to converge, but, during the breaking process, the wave crest approaches the trough and a divergence is observed. This divergence may be attributed to several phenomena, including the finite wave height effect on wave velocity of propagation, the wave-induced current over the shoal, and the increase in wave crest velocity as the crest slides down the face of the wave toward the trough. This latter effect has been observed causing large breaking waves to diverge from a shoal into navigation channels rather than refract into the adjacent reef.

These phenomena render standard wave ray tracing techniques invalid in the breaking zone. This is normally implied, but often ignored in practice.

Several important observations were made in the model study which supplemented the field observations. Since some of the prototype surf sites were modeled, it was readily verified that the model reasonably duplicated the breaking wave patterns under the conditions tested. Given below are pertinent results of the testing of shoal features required to induce favorable surf.

The first test series involved moving the 15-foot depth contour 100 feet seaward to make a 15-foot deep shoal. Shoal widths of 100-, 200- and 400-foot widths were tested. No noticeable changes in the wave breaking patterns due to the presence of the shoal were observed. The next test series involved moving the ten-foot depth contour seaward 100 feet to make shoals of the same widths noted above. The effect of these shoals was to move the breaking depth seaward 50 feet. The next test series involved moving the eight-foot contour seaward by similar shoal increments. The primary influence of the eight-foot deep shoal was to move the breaking position seaward 70 feet. The width of these shoals did not have a noticeable effect except to create a wider breaking area.

The abrupt depth transitions used in formation of the shoals are not usually found in the prototype; therefore, a 1:30 slope was extended from the eight-foot deep shoal to the existing bottom. The primary effect of the slope was to move the breaker position seaward another 30 feet to the eight-foot contour. The seaward slope has an important function in the formation of the surfing wave. The slope reduces reflection, influences breaker-type, and if shaped properly, causes a convergent zone.

Excellent surfing conditions are commonly found on both sides of natural and man-made channels. Channels are important features of surf sites since they separate adjacent sites, induce smaller amplitude amplification factors relative to those over the shoal, and help refract the wave over the surf shoal. A series of four tests involving channels with widths of 50, 100, 200 and 300 feet was conducted. The shoal depth was eight feet, the channel depth was 15 feet, and the shoal was 200 feet long and 700 feet wide. The 50- and 100-foot wide channels did not induce the expected refraction or the desired amplitude amplification differential relative to that over the shoal required to produce a desirable surfing wave. In these cases, the wave broke completely across the channel. The 200- and 300-foot wide channels did induce a desirable surfing wave form.

MULTIPLE PURPOSE REEF CONCEPT

A general concept of a surf site has been hypothesized from field, analytic, and model observations. The bottom features required to produce the surf site features shown in Figure 3 are summarized in the following discussion and shown in Figure 11.

A seaward slope, in a ridge configuration, induces a convergence, influences the breaker type and height, and causes the wave to gradually increase in amplitude until it becomes a breaking wave. A flat seaward slope also causes the initial breaking to spread over a wide area, thereby allowing more people to surf the area. A steep transition from deep water to the breaker depth may produce a very hard, plunging wave whose amplitude and steepness increases so rapidly that the surfer cannot "catch" the wave. Such a condition occurs at the Makaha Bowl, where the depth shoals from 37 feet to 16 feet in less than 50 feet of wave travel distance. It is very difficult to catch a wave a this site at the peak.

Side channels separate a surf site from adjacent sites, create differential amplitude amplification factors relative to the shoal, and enhance refraction. The channels provide an area for the surfers to gain access to the site without interfering with others surfing. Breaking wave-induced rip currents moving seaward are generally found in the side channels. The alignment of the side channel relative to the direction of wave advance helps to control the peel rate.

The shoal provides an area for the wave to break and dissipate energy. The shoal should be of variable depth to allow for incident waves with a wide range of characteristics to break in a form desirable for surfing. The shoal should be long enough to provide a ten- to 30-second ride. Longer riding areas increase surf site capacity.

The trench is perhaps the most ideal type of board-recovery area because it isolates the surf site from the beach, swimming area, and structures. The trench should be wide enough and deep enough to stop the wave from breaking and to reduce the velocity of the wave-induced current.

There are many variations of this surf site concept which are typical of many natural sites. For example, the basic concept shown in Figure 11 has surfing to both the left and right. However, many surf sites are located next to promontories where it appears that the shoal is a submerged projection of land. Makaha and Waimea have this configuration. The general concept is easily modified to describe this configuration by considering only half of the shoal. The other half of the shoal continues to rise above the water to the promontory.

In addition to surfing, other interests such as swimming, fishing, diving, boating, beach usage, land reclamation, and construction projects compete for usage of the coastal zone. Proper planning in the coastal zone could minimize conflicts and allow for several uses of the area. One such plan, which occurs naturally in some areas, is the "multiple-purpose reef." The plan incorporates an artificial reef designed according to the general surf shoal concept shown in Figure 11. The shoal would act as a submerged breakwater, dissipating wave energy by inducing the wave to break. The dissipation of energy would serve as an erosion control device, noted by Zwamborn, et al (1970), or to reduce the design wave at a structure. Natural shoals on the island of Maui have been observed to protect beaches from erosive wave action. The board-recovery trench would isolate the surf site from swimming areas, beaches, and structures. The side channels could be boat harbor entrance channels with return zones near the channel edge. If the shoal were made of coral, or were an artificial shoal made of rock or artificial concrete units, the voids would provide fish habitat. The shoal could be used as a diving area when the surf is down.

Surfing is an important recreation in many coastal zone communities. An effort should be made to preserve and enhance surf sites and to create new surf sites which would be compatible with other uses of the coastal zone. This investigation is only a first step in describing surfing characteristics. More intensive research is required to better define breaking wave behavior over complex bathymetry and on surfboard hydrodynamics.

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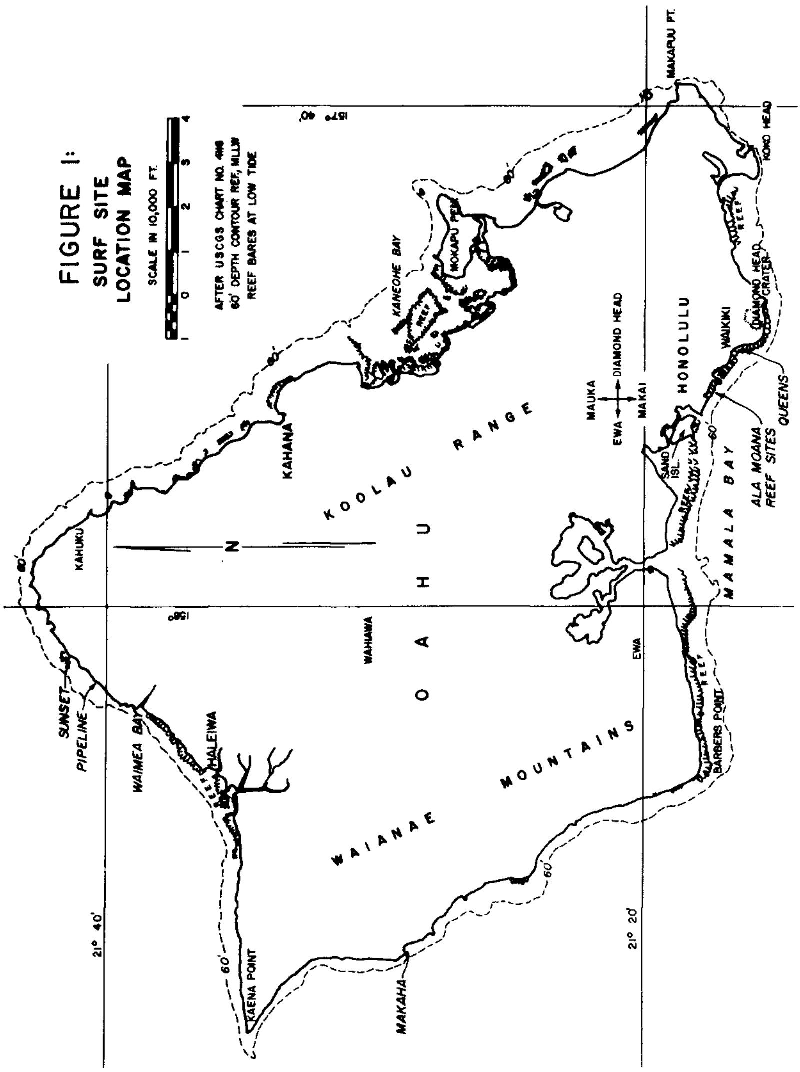

FIGURE 1: SURF SITE LOCATION MAP

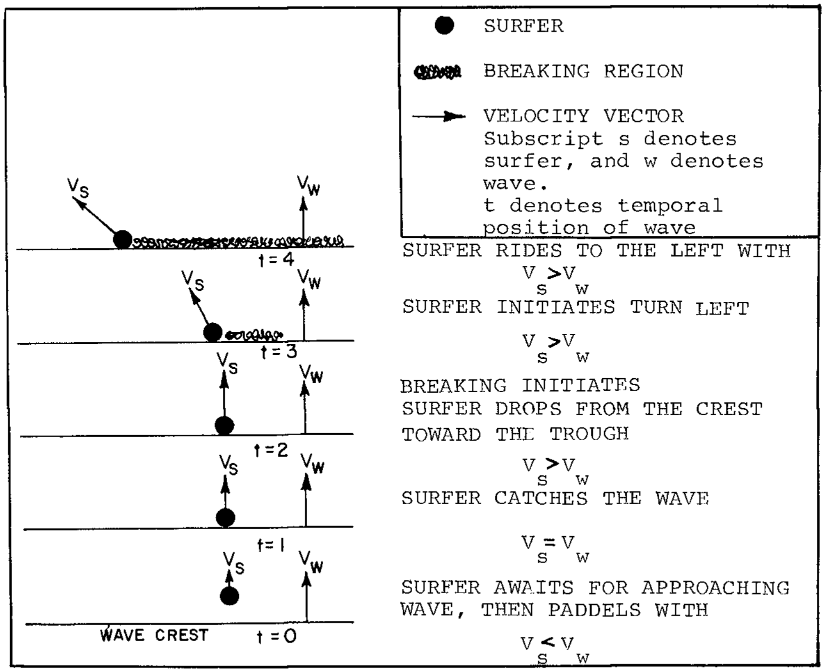

FIGURE 2: SURFING SEQUENCE SCHEMATIC

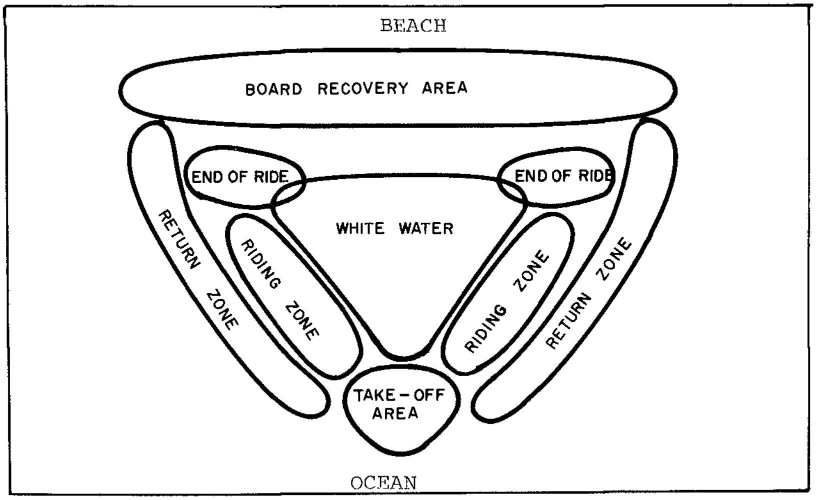

FIGURE 3: SCHEMATIC OF SURFING AREA

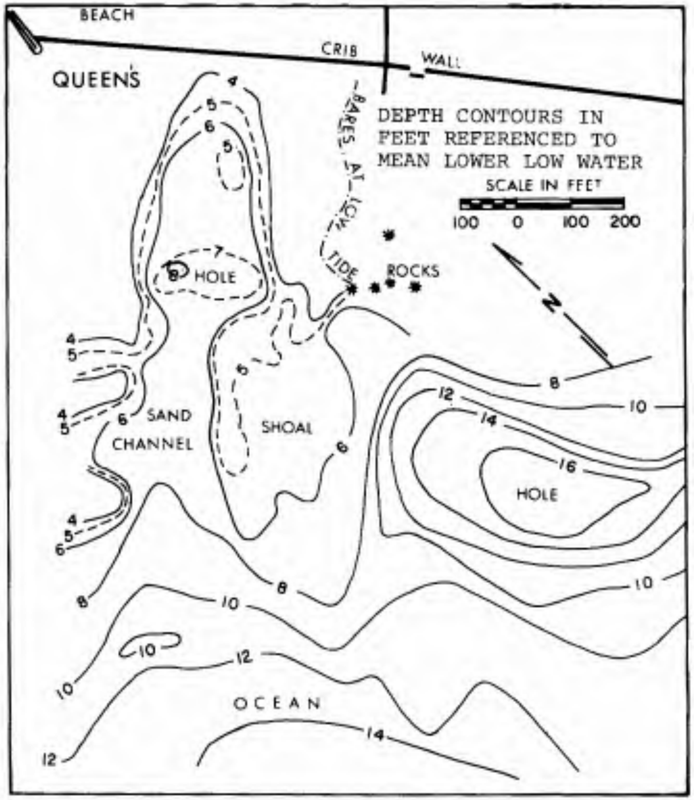

FIGURE 4: BATHYMETRY OF QUEEN'S SURF SITE

FIGURE 5: AERIAL PHOTOGRAPH THREE OF A SEQUENCE OF A SIX-FOOT HIGH BREAKER WITH A TWENTY SECOND PERIOD AT QUEEN'S IN WAIKIKI, APRIL 26,1972. THE TIDE ELEVATION WAS +1.0 FEET.

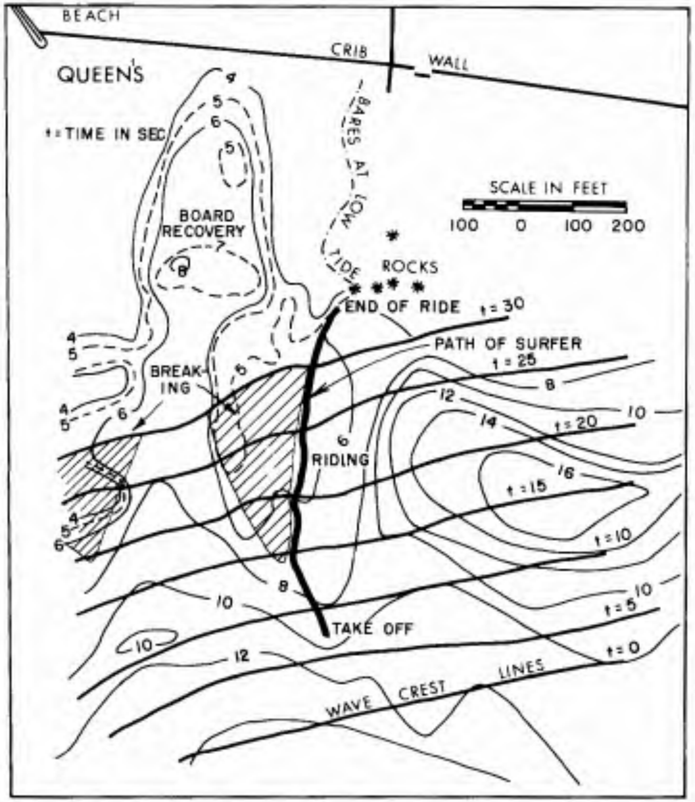

FIGURE 6: WAVE PROPAGATONG OVER QUEEN'S

FIGURE 7: SURFER RIDING IN THE "PEEL" ON AN EIGHT FOOT BREAKER AT ALA MOANA, JUNE 5, 1972.

TABLE 1: SURF SITE OBSERVATIONS

Data Pt	Site	Bottom Slope S	Breaker Height H_b (ft)	Wave Period T(sec)	Breaker Type Index	Surfer Velocity V_s (ft/sec)	Peel Angle α (degrees)	Breaker Type
1a	Queen's	40	4	12	0.035	18	60R	Spill
b	Queen's	40	7	20	0.022	22	65R	Spill-Plunge
c	Queen's	40	6	20	0.019	21	55R	Spill-Plunge
d	Queen's	40	6	20	0.019	18	80L	Spill-Plunge
2a	Ala Moana	33	6	17	0.021	30	35	Plunge
b	Ala Moana	20	10	20	0.015	30	38	Plunge
d	Ala Moana	25	9	20	0.017	30	32	Plunge
3a	Lefts	30	6	20	0.014	30	45	Plunge
4a	Kewalo	37	6	17	0.024	18	65	Plunge-Spill
5a	Makaha	60	6	14	0.057	28	65	Spill
b	Makaha	60	8	16	0.058	20	68	Spill
6a	Waimea	20	17	16	0.041	38	80	Plunge-Spill
7a	Pipeline	65	18	16	0.14	45*	35	Plunge
b	Pipeline	22	12	16	0.032	32	40	Hard Plunge
8a	Sunset	100	18	16	0.22	43*	40	Plunge-Spill
b	Sunset	100	15	16	0.18	33	65	Plunge-Spill

* Wave not ridden, R= ride to the right, L= ride to the left

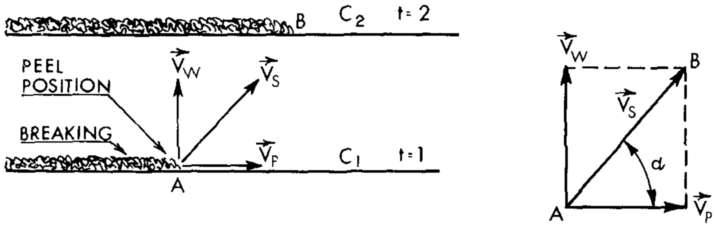

FIGURE 8: DIAGRAM SHOWING RELATION AMONG PEEL PARAMETERS

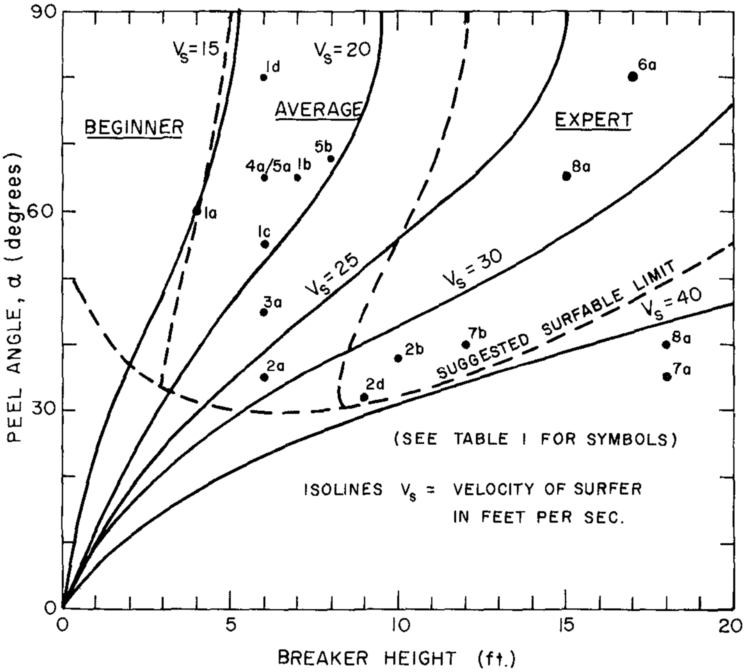

FIGURE 9: PEEL-ANGLE vs. BREAKER HEIGHT

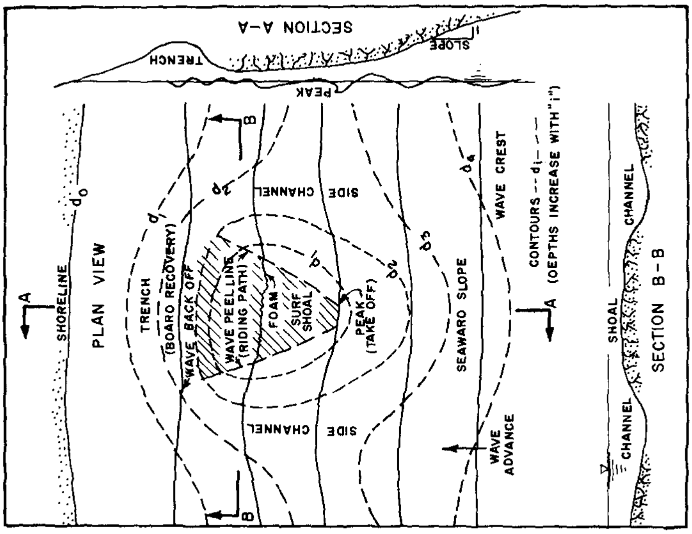

FIGURE 11: MULTIPLE-PURPOSE REEF CONCEPT

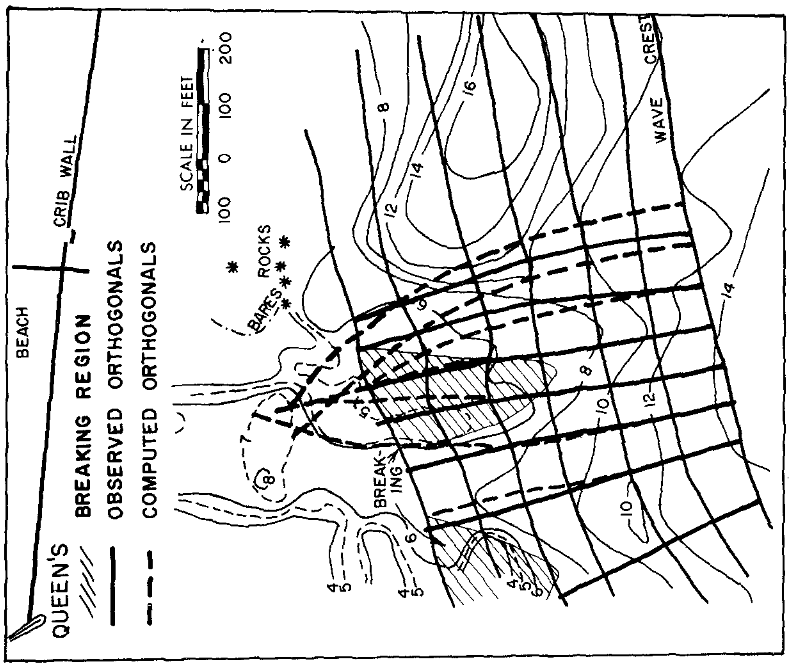

FIGURE 10: COMPARISION OF OBSERVED AND CALCULATED WAVE ORTHOGONALS