UNIHI-SEAGRANT-TR-78-02

Beach and Surf Parameters in Hawaii

Franciscus Gerritsen

June 1978

The University of Hawaii Sea Grant College Program

$4.95

BEACH AND SURF PARAMETERS IN HAWAII

by

Franciscus Gerritsen

Final report on the Sea Grant project, Beach and Surf Parameters (R/OE-04); Franciscus Gerritsen, Principal Investigator; Sea Grant Years 04-06.

Sea Grant Technical Report
UNIHI-SEAGRANT-TR-78-02

June 1978

This publication reports on the result of research sponsored by the University of Hawaii Sea Grant College Program through Institutional Grant Nos. 2-35243 and 04-3-158-29 from NOAA Office of Sea Grant, Department of Commerce, with additional funds from the Hawaii State Legislature and the University of Hawaii. The US Government is authorized to produce and distribute reprints for governmental purposes notwithstanding any copyright notations that may appear hereon.

ABSTRACT

The beaches of Hawaii are used by tourists and residents alike and are therefore of tremendous social and economic importance. Most beaches are in excellent condition and need no measures of improvement. There are a few exceptions. The beach at Waikiki, for example, is in a relatively poor state because of continuous erosion and the presence of poorly designed structures.

This report describes the results of a three-year study of beach and surf parameters in Hawaii. Its aim is to obtain a better insight into the dynamic characteristics of beaches of the islands and into the physical processes that play a part in shaping the shoreline. The study builds on earlier studies and attempts to tie the various efforts together.

The study involves three classes of beaches: (1) primary beaches on the island of Oahu; (2) beaches on Oahu protected by headlands and/or subject to strong seasonal variations; and (3) beaches on the neighbor islands with special characteristics, e.g., cusps or natural offshore formations.

A chapter describing Hawaii's oceanic and coastal environment and their effect on the beaches of windward and leeward coasts is included.

In addition, this report presents the data collected during field studies, such as recordings of wave heights and periods, tides, current velocities and directions, beach profiles, and sand movements. Aerial and ground-level photographs from known elevations provided overall dimensional and descriptive data for the beaches. In addition, these photographs were used to prepare base maps, including traverse locations, for each site.

The field studies at Waikiki Beach represented a large portion of the total study effort. Situated on the leeward coast of the island of Oahu, Waikiki Beach is well protected from the dominant waves during tradewind conditions. Only infrequently the beach is affected by the southern swell, and it is during these conditions that changes in the beach are more significant. The study found the major cause of erosion to be a relatively strong rip current generated by southern swells.

The study on Haleiwa Beach was more limited in scope. Haleiwa Beach is situated on the north shore of the island of Oahu; and is subject to gradual erosion.

Waimea Bay Beach and Makaha Beach on the island of Oahu were other areas of study. It was found that heavy storms from the northwest during the winter months give rise to dynamic changes of these exposed beaches.

The study on Waimanalo Beach on the windward coast of Oahu, one of the finest beaches of the islands, showed that this beach is often characterized by the presence of beach cusps, which are wave-like formations on the shoreline. The behavior of beach cusps at Waimanalo and the role they play in shoreline processes are described. Because Waimanalo Beach is relatively stable, no improvements are necessary.

Incidental surveys of several beaches on the neighbor islands were conducted to gain information on specific characteristics, such as cuspate formations.

Other aspects of this report include dynamic beach behavior and stability of headland beaches. Of particular interest was the role that natural formations play in shoreline protection. By studying nature's way of stabilizing a beach, man can learn to do likewise.

In addition to describing the results of field studies, this report also gives suggestions for measures of improvement for the beaches at Waikiki and Haleiwa.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

Figure

LIST OF TABLES

Table

LIST OF PLATES

Plate

CHAPTER 1. INTRODUCTION

Beaches are a very significant part of Hawaii's physical environment. They are of great economic and social value and serve a variety of purposes, both recreational (tourism, surfing) and technical (coastal protection).

In the early 1970s, concern for the environment reached a culmination point. It was realized that for its protection and management a thorough understanding of environmental processes was necessary.

In the past, several studies have dealt with the beaches of Hawaii. A study by Moberly and Chamberlain (1964) was conducted for the state of Hawaii to obtain an inventory of Hawaii's beaches and their general characteristics. The study served as a prime source of information on Hawaii's beach systems. However, because this study had a broad base, it did not allow an in-depth analysis of the physical processes.

Campbell in 1972 added information to the Moberly and Chamberlain study by reporting on a re-survey of a number of selected beaches throughout the Hawaiian Islands and by comparing the results with previously established information. While he found that most beaches are relatively stable, a number of them were indeed eroding.

The beach at Waikiki was not included in the Moberly and Chamberlain survey, but was the subject of rather extensive studies by the US Army Corps of Engineers, Honolulu District (1963).

Despite these earlier studies, it was felt that the nature of beach and shore processes in the islands was not completely understood and that additional studies of beach and surf parameters would be needed. This study was therefore begun to better understand the nearshore processes of Hawaii's coastal zone. In 1970, the Hawaii State Legislature, recognizing the need for additional study, funded a surf parameters study. This effort was later supported by general funds of the state of Hawaii and integrated into the "Beach and Surf Parameters" project which was funded by Sea Grant for three years, 1971 to 1974.

The results of the surf parameters study were published in 1973 and 1974 (Kelly, 1973; Walker, 1974a).

The behavior of breaking waves is an essential parameter in the nearshore processes. Since information available in the literature on this subject shows serious gaps, a hydraulic model study was undertaken; both wave breaking on a straight beach and on a surf shoal were investigated. This part of the study has been published as a doctoral dissertation (Walker, 1974b). An additional model study was conducted to obtain a better understanding of the functioning of groins. The results were published in another doctoral dissertation, "On the Functional Design and Effectiveness of Groins in Coastal Protection" (Nayak, 1975).

This report does not include all material from these related studies, but essential information from them is used where appropriate.

CHAPTER 2. OBJECTIVES AND SCOPE

Objectives

The overall objectives of this study were as follows:

1. To identify characteristics of various dominant parameters in the coastal zone and their effect on beach stability

2. To determine general aspects of sand transport for selected beach areas

3. To evaluate beach cusp behavior for selected beaches

4. To study the influence of headlands and natural formations on beach stability

It was realized from the start that the study would be one of limited duration and scope, whereby it would be important to collect as much information as possible within the constraints of time and funding available. If a certain effort would require too much time and manpower in view of its overall results, a program adjustment was made. An example of this is the use of fluorescent sand tracing. Although the method was basically useful and provided insight into the process of littoral drift, its use was discontinued because of time constraints and the excessive manpower required. Instead, other methods, such as aerial photography and current measurements, were used to approach the problem.

Scope

The selection of sites for the study was based on one or more of the following criteria:

1. The importance of the beach in regard to its social and economic value

2. The need for data to assist in the planning and design of coastal protection or maintenance works

3. The existence of typical beach parameters or characteristic offshore conditions

4. The proximity of the site to the Manoa campus of the University of Hawaii or to the Look Laboratory of Oceanographic Engineering

For the purpose of this study, the beaches under investigation were grouped into three classes, with decreasing degree of study effort:

Class I--primary beaches on the island of Oahu. This group consists of Waikiki Beach on the leeward coast, Waimanalo Beach on the windward coast, and Haleiwa Beach on the north shore.

Class II--beaches on Oahu protected by headlands and/or subject to strong seasonal variations. This group is composed of Waimea Bay Beach, Kuilima Beach, Sandy Beach, and Makaha Beach.

Class III--beaches on the neighbor islands with special characteristics, e.g., cusps or natural offshore formations. The study of this group of beaches was the least thorough; it provided mostly general information. Included in this group are Hanalei Bay Beach, Poipu Beach, Port Allen Beach, and Barking Sands Beach on Kauai; Wailea Beach, Spreckelsville Beach, Baldwin Park Beach, and Puu Olai Beach on Maui; Hapuna Beach and Mauna Kea Beach on Hawaii; and Holupoe Beach on Lanai.

During the first two years of the study, efforts were concentrated on Class I beaches. Much attention was given to the beach at Waikiki, not only because of its convenient location as a study site, but also because of its great economic value to the state and the need for additional data for the planning and design of coastal improvements. Special attention was paid to current patterns under different conditions and their effect on sediment transport.

The beach at Waimanalo, on the windward side of the island of Oahu, is relatively stable, free from man-made structures, and frequently characterized by beach cusp formation. For these reasons Waimanalo Beach was selected as a site for a detailed cusp study.

On the north shore of the island of Oahu, the beaches are subject to severe wave attack during the winter months. Haleiwa Beach was selected as a study site because of its serious erosion problems, its importance as a recreational beach, and its proximity to Haleiwa Harbor.

During the third year of the study, the beaches of Class II and III were added to the program.

Figure 2.1 shows a map of the Hawaiian Islands with the location of the various study sites.

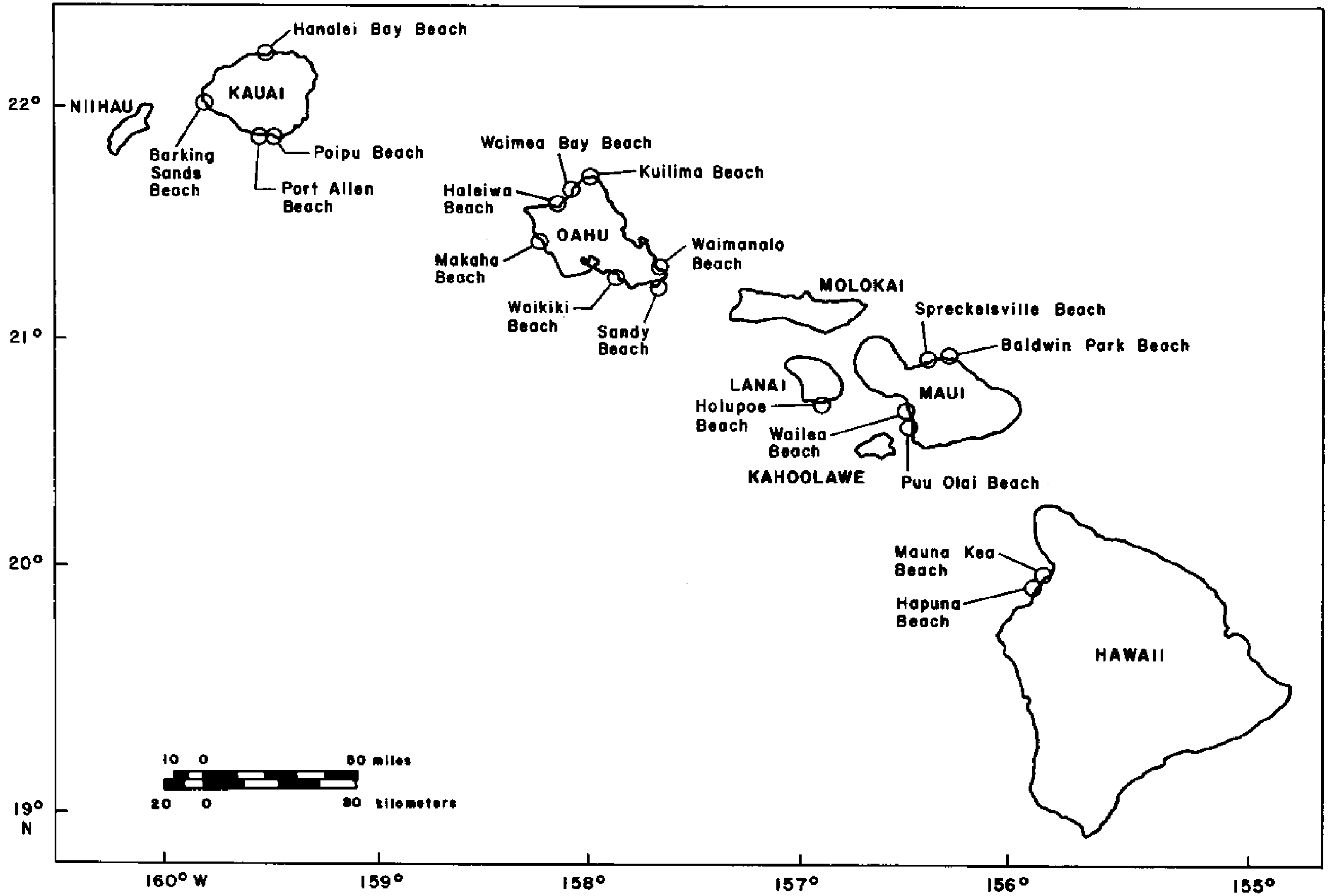


Figure 2.1. Map of the Hawaiian Islands showing the location of the beaches studied

CHAPTER 3. METHODOLOGY

General Procedures

The data collected during the field studies include recordings of wave heights and periods, tides, current velocities and directions, beach profiles, and sand movements. In addition, aerial and ground-level photographs and movies of the study sites were taken. Oblique aerials provided descriptive data concerning the coastal area involved. Vertical photographs from known elevations were used both to construct maps and to collect overall dimensional data on the beaches.

Field surveys were conducted at all sites, but the extent of the measurements differed for each study site. The surveys were repeated at different time intervals.

The field studies at Waikiki Beach represented a large portion of the total study effort. Wave and tidal measurements were made. Surface and subsurface currents were measured using various techniques. Beach traverses were established for beach profile measurements. Sand samples were collected along beach traverses for analysis in the laboratory. Furthermore, a modest program of fluorescent tracing of sediment was carried out.

The study of Haleiwa Beach was more limited in scope. Emphasis was placed on recording beach profile measurements periodically in order to correlate profile changes with seasonal changes in wave climate. Currents were measured using varying techniques under different conditions.

In the study of Waimanalo, Kuilima, and other beaches, a base map was prepared from aerial photographs of the sites. Beach traverses were then established and scale maps of the sites were drawn from the photographs. The cuspate formation at Waimanalo Beach was studied in detail by taking profile measurements at short distances. Sand samples were taken at all traverses and subjected to sieve analysis. This general procedure was repeated periodically. Incidental surveys of some beaches on Oahu and on the neighbor islands were made to gain additional information on cuspate formation to be correlated with the Waimanalo Beach data and on the effect of natural formations on beach protection to be correlated with the Kuilima Beach data.

Methods of Measurement

The methods for measuring the physical parameters affecting the beaches are described individually with respect to the parameter in question. The data compiled on field surveys were recorded in field books and later analyzed and reduced to usable form.

Winds

During field surveys, wind speeds were measured by using a hand-held, rotor-type anemometer. Wind direction was recorded by the use of the vane on the anemometer.

Waves

Two pressure-type wave recorders were used to measure wave conditions at Waikiki Beach: the Hydro-Products Model 521 wave recorder and the N.B.A. Controls, Ltd. Model DNW-2 wave recorder. Both were bottom-mounted on fabricated steel frames placed at a depth of 50 ft to assure a non-breaking wave condition, whereby the depth to wavelength ratios were in the range of intermediate depth for most periods. The Hydro-Products Model 521 recorded significant wave height and period, plus tide on a Rustrak strip chart recorder. Unfortunately, due to a faulty seal, the 521 wave recorder was flooded and destroyed before useful data could be obtained. Measured pressures were converted to wave heights by applying a pressure response operator based on linear wave theory.

The N.B.A. DNW-2 was well suited for spectral analysis. It operated for 30 days at a sampling rate of two hours per day. A continuous voltage signal was magnetically imposed on a conventional tape cassette. On land, the cassette was played back through the surface unit to the digitizing computer of the Hawaii Institute of Geophysics. Table 3.1 gives monitoring and digitizing specifications. The digital data on computer tape were then run through a time series analysis program with the final output being a frequency spectrum. To find the significant wave height, H_s, a trapezoidal integration was carried out to determine the variance of the record, the latter assumingly related to H_s^2 by a factor of 16.

TABLE 3.1. MONITORING AND DIGITIZING SPECIFICATIONS FOR N.B.A. CONTROLS, LTD. MODEL DNW-2 WAVE RECORDER

Parameter	Specification
Monitoring	
Recording speed	0.0268 in./sec, 0.06 cm/sec
Range settings	6 m (height) 3 to 60 sec
Pressure range	0 to 50 psi which corresponds to a potentiometric change in resistance
	0 to 1,000Ω ± 10% with linearity of ± 1%
Center frequency	15 ± 5 Hz
Voltage range	-3 to +3 volts (for 6 m range)
Digitizing	
Playback speed	1.875 in./sec, 4.2 cm/sec
Play/record ratio	69.962:1
Sample rate	32 Hz
Low pass cutoff	1.6 Hz
High pass cutoff	None
Center frequency	1,050 ±350 Hz

Waves inside the breaker zone were measured by using Robert Shaw capacitance gages coupled with Rustrak strip chart recorders (Plate 3.1). The gages were mounted in the field during days of field operation. In addition to wave recording by instruments, visual observations during the field studies provided data on average breaker height, period, and direction. The wave period was averaged over 10 successive waves.

Plate 3.1. Robert Shaw capacitance gages measuring the height of waves in the surf zone

Currents

Currents are usually measured using dye and drogue paths. The dye was of the Rhodamine-B type and the drogues were X-shaped and suspended approximately 1 ft below the water surface by flotation devices. The paths of drogues and dye patches were determined by means of triangulation and time-lapse photography from high-rise apartments near the beach. Aerial photography was also used to determine the movement of dye patches.

At Waimanalo and Kuilima Beaches, the drogues consisted of partially submerged white plastic bottles weighted with sand.

Tides

Two Stevens tide gages (such as the one shown in Plate 3.2) were used. Each is a self-recording instrument that continuously records the water level by means of a weighted float-pully system connected to a clock-driven cylinder chart recorder.

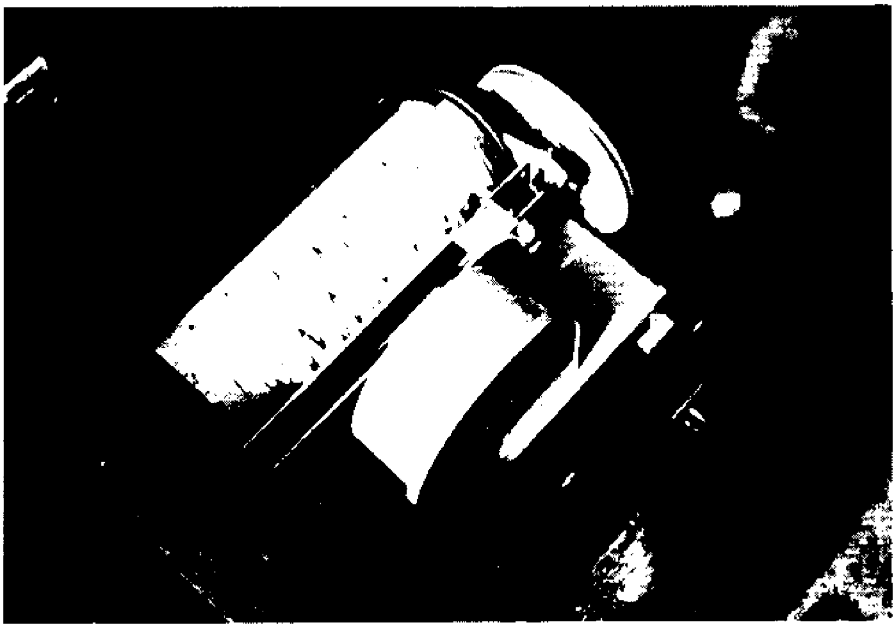


Plate 3.2. Stevens tide gage

Beach profiles

Beach profile measurements were taken at most of the study sites. Either nearby benchmarks or local landmarks were used as points of reference.

At Waikiki Beach, profile measurements were taken at two-month intervals, or more frequently if exceptional conditions occurred.

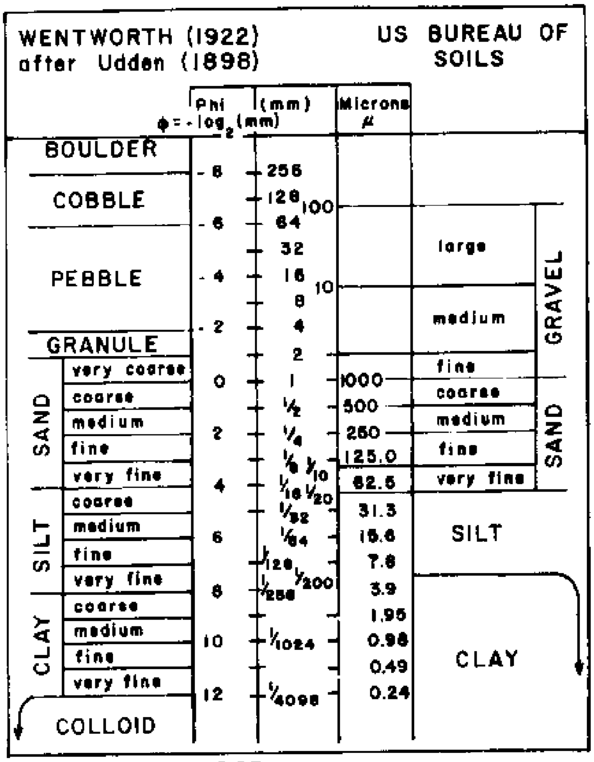
The average beach slope at MLLW (mean lower low water) was determined by examining sections 100 ft seaward and landward from the estimated MLLW line.

Sediment samples

Beach sediment samples were usually collected at the waterline and sometimes at 10 ft offshore, such as at Waikiki Beach. In some cusp studies, a number of samples were collected at various elevations to examine sediment variability over a cusp range.

After drying, the sediment samples were subjected to sieve analysis. This was accomplished by shaking the dried sample through a series of nested sieves for 10 minutes. After the shaking the weight of the sample in each sieve was recorded. This permitted the computation of the mean particle diameter, standard deviation, skewness, and kurtosis. These parameters are given in ϕ-units, where $\phi = -\log_2 D$ and D = particle diameter in millimeters.

Figure 3.1 and Table 3.2 give descriptive measures of size distribution and a classification of granular materials according to ϕ-units and microns (1 mm = 1,000 microns).



After Shepard, 1963

Figure 3.1. Comparison of various grain size scales

TABLE 3.2. DESCRIPTIVE MEASURES OF SIZE DISTRIBUTION

Measure	Nomenclature	Definition
Central Tendency	Phi Median Diameter	$Md\phi = \phi_{50}$ $= M_\phi - (\sigma\phi\alpha\phi)$
	1 Phi Mean Diameter	$M_\phi = \frac{1}{2}(\phi_{16} + \phi_{84})$ $= Md_\phi + (\sigma\phi\alpha\phi)$
Dispersion (Sorting)	2 Phi Deviation	$\sigma_\phi = \frac{1}{2}(\phi_{84} - \phi_{16})$
Skewness	3 Phi Skewness	$\alpha_\phi = \dfrac{M\phi - Md_\phi}{\sigma_\phi}$
Kurtosis (Peakedness)	4 Phi Kurtosis	$\beta_\phi = \dfrac{\frac{1}{2}(\phi_{95} - \phi_5) - \sigma\phi}{\sigma_\phi}$

After Shepard, 1963 (original source: Inman, 1952)

Cusps

The data collected at each site where cuspate features were found included the average length of a series of cusps (enabling the calculation of the mean cusp length and the standard deviation), beach profiles at the embayment and node of the cusp (allowing the determination of the beach slope), and sediment samples both at the node and embayment of each cusp. At Waimanalo Beach, profiles and sand samples were taken over cusp study sites.

CHAPTER 4. GENERAL DESCRIPTION OF HAWAII'S OCEANIC AND COASTAL ENVIRONMENT

This chapter examines the general nature of the oceanic and nearshore environment in the Hawaiian region. This information provides background in understanding the different characteristics of nearshore processes at sites of different exposure to winds, waves, tides, and currents.

Information on the environmental parameters in this report is limited in scope. For more detailed information, see Moberly and Chamberlain (1964) and St. Denis (1974).

Winds

In the Hawaiian Archipelago, winds can be classified into four different groups: tradewinds, kona winds, tropical storms, and tropical cyclones.

St. Denis (1974) made a distinction between winds and tropical storms or cyclones. Winds are characterized by the apparent absence of a core, whereas tropical storms and tropical cyclones are characterized by its apparent presence. The difference between tropical storms and cyclones is one of core temperature. The hot, rapidly rising air core accounts for the great intensity of the winds in a tropical cyclone.

The mechanics of a tropical cyclone are the same as for a hurricane which is the name of this phenomenon in the Caribbean, Gulf of Mexico, and western Atlantic. It is called a typhoon in eastern Asia, Japan, and the Philippines.

This report will only present wind information in a general form as one of the basic elements of environmental conditions.

Table 4.1 lists frequencies of occurrence for various wind directions and intensities at the Honolulu airport. An analysis of these hourly wind observations revealed that 67 percent of the time the wind directions are from the northeast to east. Other directions have a low percentage of occurrence, with frequencies of 0.6, 0.8, and 0.7 percent of the time for the directions west-southwest, west, and west-northwest, respectively.

Wind intensities are given as one-minute averages. Gust intensities are considerably higher than the one-minute averages for the same percentages of time. The expected long-term trend of the maximum value of the mean wind intensity for one-minute intervals, as computed by St. Denis (1974), is presented in Figure 4.1.

Kona winds and kona storms in Hawaii are from a southerly to south-westerly direction. They usually bring rainy weather with higher humidity.

Tropical cyclone tracks in the Hawaiian area are shown in Figure 4.2. Most cyclones in the vicinity of the Hawaiian Islands travel in a west-northwesterly to northerly direction. Two cyclones, Nina (1957) and Dot (1959), caused high wind intensities and high waves in Hawaiian waters.

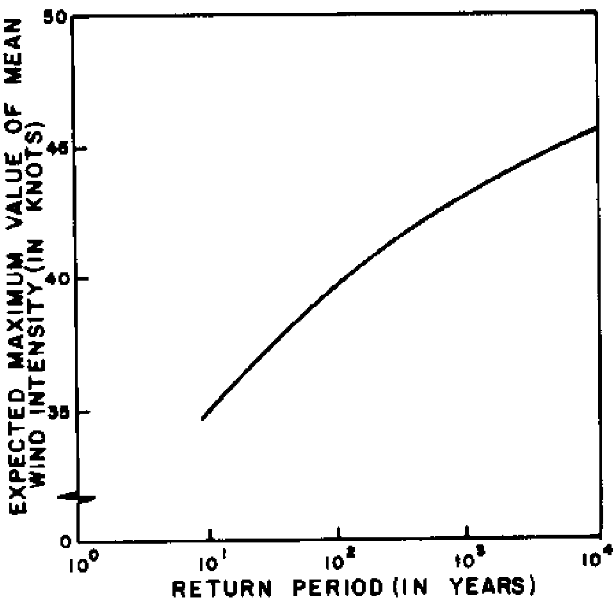
TABLE 4.1. PERCENTAGE OF FREQUENCY OF WIND DIRECTION AND INTENSITY FROM HOURLY OBSERVATIONS AT THE HONOLULU AIRPORT (ONE MINUTE AVERAGES)

Speed / Direction	1- 3	4 - 6	7 - 10	11 - 16	17 - 21	22 - 27	28 - 33	34 - 40	41 - 47	48 - 55	56	%	MEAN WIND SPEED
N	1.5	1.8	1.1	.3	.0	.0						4.8	5.7
NNE	.8	1.2	.9	.5	.1	.0						3.6	7.0
NE	1.2	2.9	6.4	7.8	2.7	.5	.0	.0	.0			21.5	11.2
ENE	.6	3.0	9.9	12.6	4.2	.6	.0	.0				30.9	11.8
E	.7	1.9	5.3	4.6	1.6	.2	.0					14.3	10.7
ESE	.2	.4	.6	.3	.1	.0	.0	.0	.0			1.5	8.9
SE	.2	.4	.8	.7	.1	.0	.0	.0				2.2	9.8
SSE	.1	.3	.8	.6	.2	.0	.0	.0	.0			2.2	10.1
S	.2	.6	1.3	.6	.1	.0	.0					2.9	9.0
SSW	.1	.2	.6	.3	.0	.0	.0					1.3	9.2
SW	.1	.2	.6	.3	.1	.0	.0					1.3	9.3
WSW	.1	.1	.2	.2	.1	.0	.0					.6	10.3
W	.2	.2	.2	.1	.0	.0	.0					.8	7.3
WNW	.2	.3	.1	.0	.0	.0	.0					.7	5.3
NW	1.4	1.6	.7	.1	.0	.0						3.9	5.1
NNW	.8	1.2	.6	.1	.0	.0	.0					2.8	5.5
VARBL													
CALM												4.7	
	8.3	16.4	30.1	29.3	9.4	1.5	.1	.0	.0			100.0	9.7

Total Number of Observations 224409

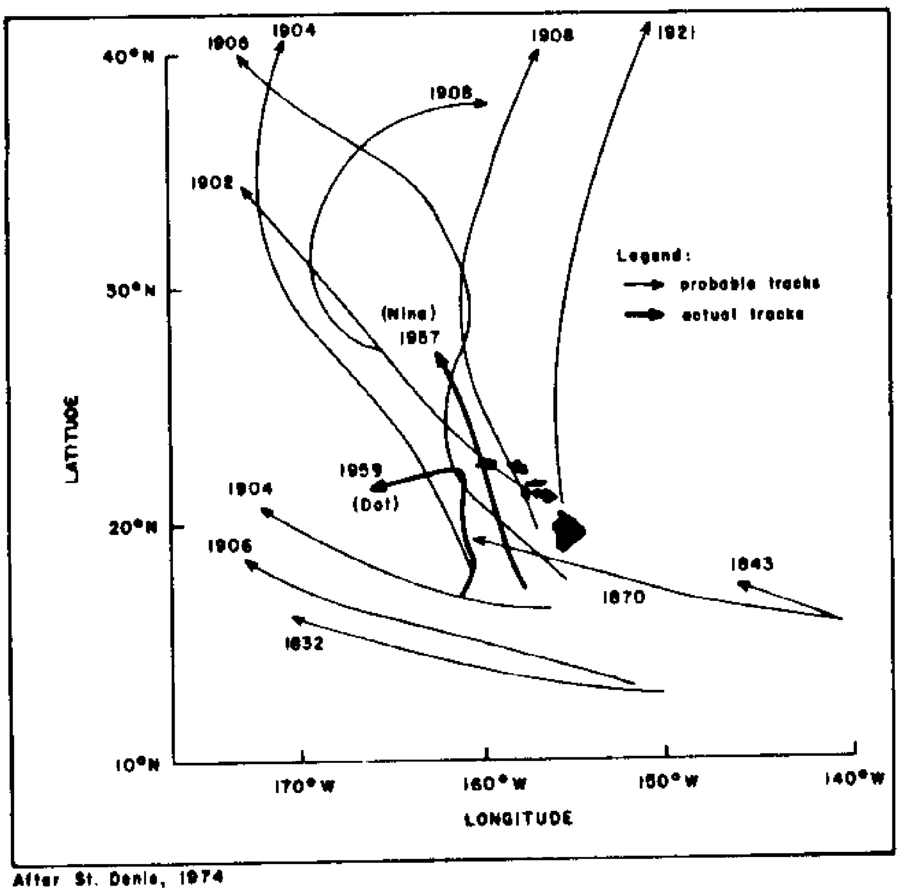
Note: Wind intensity is given in knots.

From St. Denis, 1974 (Original source: U.S. Air Force, Data Processing Division, Asheville, N.C. 28801)



After St. Denis, 1974

Figure 4.1. Long-term trend of the expected maxiumum value of mean wind intensity



After St. Denis, 1974

Figure 4.2. Tropical cyclone tracks in the Hawaiian area (1832-1959)

In 1976, cyclone Kate was on a collision course with the island of Hawaii but, due to a change in direction, did not affect the island.

Winds affect the direction and magnitude of surface currents in the ocean, as well as the currents in shallow coastal areas. Wind setup or storm surge is usually very much limited around the Hawaiian Islands due to the great depth of the ocean and the narrow width of the continental shelf. Its magnitude is usually less than 1.0 ft, except for the most extraordinary conditions.

Waves

The wave patterns in the region of the Hawaiian Islands are complex in nature; they are the results of local and distant storms and therefore are characterized as wind waves and swell.

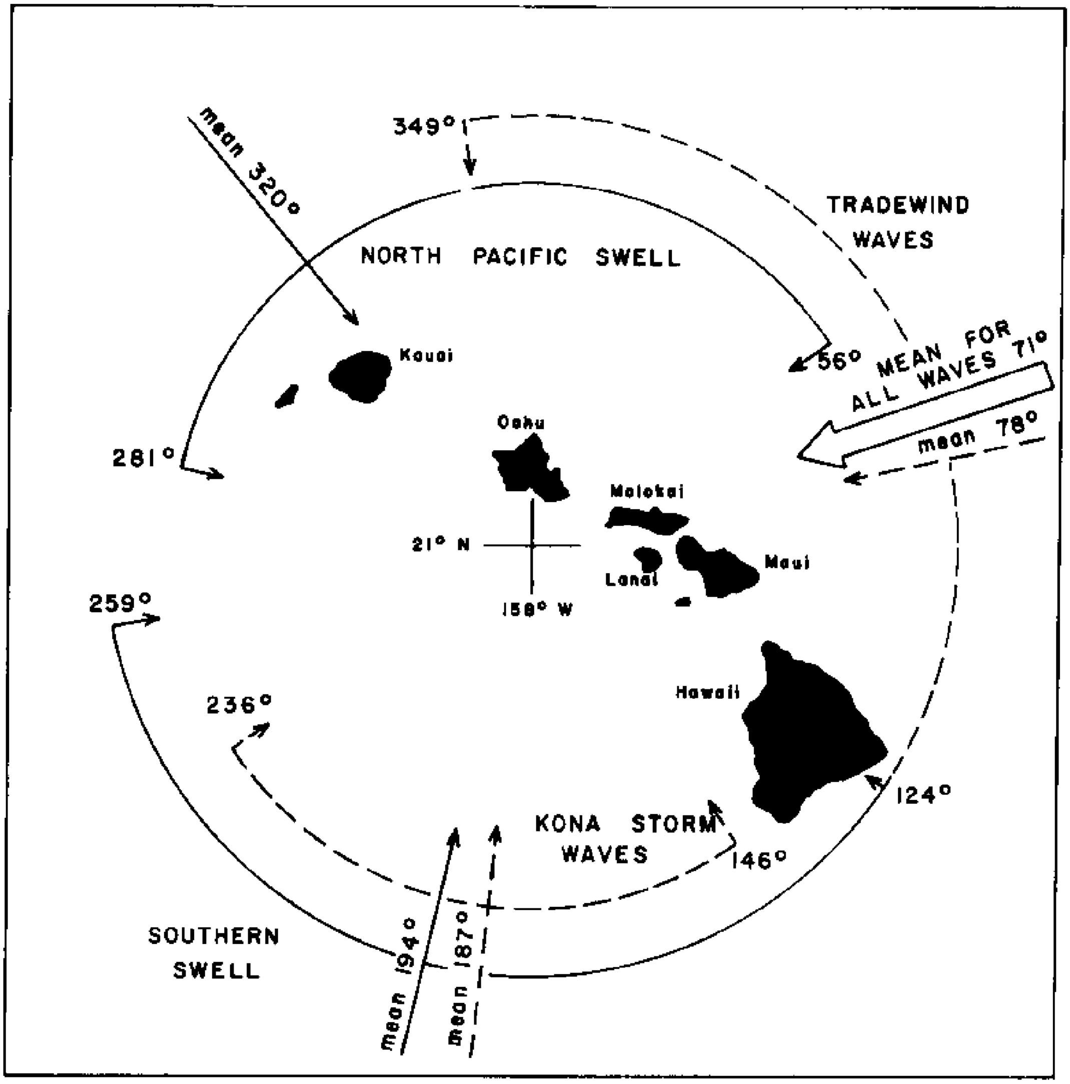
Basic data on wave conditions in the Hawaiian area are contained in two studies: a compilation by Homer (1964) and another by Ho and Sherretz (1969). These studies were based on wave observations in a few areas as well as on hindcasts. The analysis of the wave data gives rise to the classification of Hawaiian waves into five distinct categories: (1) tradewind waves, (2) North Pacific swell, (3) kona storm waves, (4) southern swell, and (5) cyclonic or hurricane waves. This classification was first suggested by Inman et al. (1963). A pattern for categories 1 through 4 was suggested by Moberly and Chamberlain (1964). Some results derived from the Homer (1964) and the Ho and Sherretz (1969) studies on Hawaiian waves are presented in Table 4.2; a diagram showing these dominant wave directions is presented in Figure 4.3. The characteristics of the various wave groups follow Figure 4.3.

TABLE 4.2. SOME RESULTS DERIVED FROM THE HOMER AND THE HO AND SHERRETZ STUDIES ON HAWAIIAN WAVES

Wave Type	Homer			Ho and Sherretz
	Expected Frequency of Occurrence (%)	Significant Height (ft)	Significant Period (sec)	Significant Height (ft)
Tradewind waves	75.3	4.79	8.63	
Kona storm waves	10.3	3.52	6.18	
Wind waves	85.6	4.31	11.45	
North Pacific swell	74.0	4.79	13.89	
Southern swell	53.0	2.60	13.07	
Swell	127.0*	4.53	13.55	
All waves	212.6*	6.25		4.69 Makapuu Pt. 4.69 Kilauea Pt.

*A frequency > 100% indicates that certain types are counted more than once.

After Homer, 1964



After St. Denis, 1974

Figure 4.3 Various types of waves that affect the Hawaiian Islands with their range and mean directions

Tradewind waves. These waves are generated by the prevailing northeasterly tradewinds. They occur about 75 percent of the time with an average significant wave height of 4.8 ft and a period of 8.6 sec. Significant wave heights greater than 12 ft may be expected 8.5 percent of the time.

North Pacific swell. The North Pacific swell develops from storm-generated waves over the North Pacific. This group of waves occurs 74 percent of the time and has an average significant wave height of 4.8 ft with a period of 13.9 sec. During the winter months in Hawaii, the waves in this group may reach up to 20 ft in height with periods of 20 sec and higher. Damage to the north shore of the islands has been extensive under these conditions. An example is the storm of December 1-4, 1969. The storm was located far to the northwest of the islands and had northwesterly winds of 45 to 60 miles per hour. High seas generated in that area reached the Hawaiian Islands as swell

18 to 20 ft high in the open ocean, causing high surf up to 30 to 40 ft (at times estimated even 45 to 50 ft high) along the north and west coasts of the islands (US Army Corps of Engineers, Honolulu District, 1970). Total damage to all the islands during this storm was estimated at $1.51 million. One person was swept away and drowned while watching the surf at Waimea Bay (Bottoms, 1970).

Kona storm waves. These waves are generated by local storms. They occur 10 percent of the time; their average significant wave height is 3.5 ft and their average period 6.2 sec. The higher waves in this group range between 10 and 16 ft in height and 8 and 10 sec in period.

Southern swell. This category of waves is generated by storms in the southern hemisphere. The waves arrive at the Hawaiian Archipelago as swell after having traveled over long distances. They are usually low in height but occasionally reach heights of over 12 ft (often in the spring). The waves occur 53 percent of the time from April to October. The average significant height is 2.6 ft with an average period of 13.1 sec.

Frequency distribution for waves of different groups, both regarding wave height and period, are presented in Figures 4.4 and 4.5.

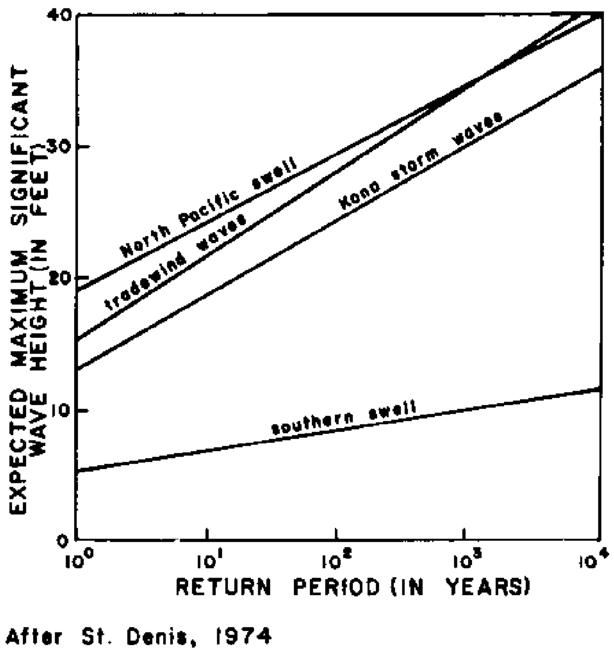


Figure 4.4. Long-term trend in the expected maximum value of significant wave heights based on the Homer compilation

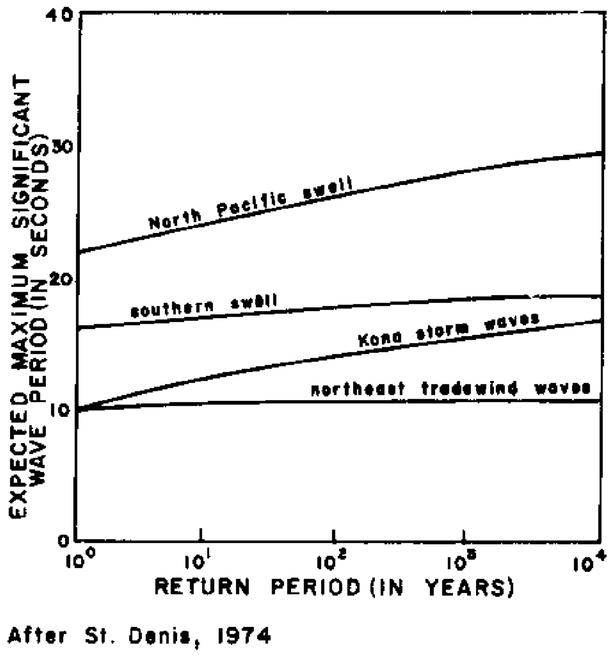
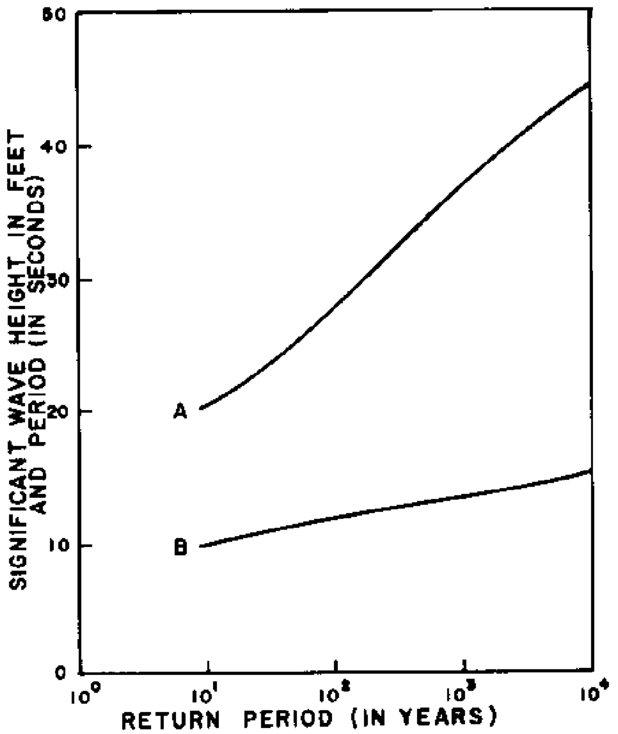


Figure 4.5. Long-term trend in the expected maximum value of significant wave periods based on the Homer compilation

Cyclonic or hurricane waves. Although tropical cyclones occur infrequently in Hawaiian waters, when they do occur, they generate high waves of great steepness. Since 1950, only five tropical cyclones have passed in the vicinity of the Hawaiian Islands. Damage to the beaches has been relatively insignificant, however. Computations by St. Denis (1974) showed that the expected maximum value of the significant wave height in a tropical cyclone in the Hawaiian area is 29 ft for a 100-year return period. The expected period for the same return interval is 12 sec. For the 10-year return period, the values are 21 ft and 10 sec, respectively (Figure 4.6). Although the effects of tropical cyclones on the tidal level are considerably less severe in Hawaii than on the Gulf and Atlantic coasts of the US mainland, their effect on the setup of the wind-generated waves certainly cannot be disregarded.



After St. Denis, 1974

Figure 4.6. Long-term trend in the expected maximum value of significant wave height, A, and period, B, at the radius of maximum wind of a Hawaiian cyclone, moving at an average speed of 10 knots

Tsunamis

Earlier in this report, it was mentioned that the effect of wind setup or storm surge on Hawaii is small because of the depth of the ocean and of the narrow width of the continental shelf. The same conditions, however, make the Hawaiian Islands vulnerable to the effect of tsunamis. Situated in the middle of the Pacific Ocean, the Hawaiian Islands are affected by tsunamis from widely differing generating areas around the Pacific, such as the Aleutian Islands, Chile, and the seas near Japan.

Damage by tsunamis has been significant in Hawaii over the years. The north and east sides of the islands particularly have been subject to heavy impact. Examples are the extensive damages to the Hilo area on the island of

Hawaii during the 1946 and 1960 tsunamis. The maximum run-up in the Hilo area during these two tsunamis was reported to be 26.6 ft and 34.4 ft, respectively (Pararas-Carayannis, 1969). The 1946 tsunami, which was generated in the Aleutian Islands, is considered the most destructive tsunami that ever hit the Hawaiian Islands, as far as loss of life and property is concerned. In the Hilo area, damage cost was $26 million, with 173 persons dead and 163 injured, and with 488 buildings demolished and 936 damaged.

Under certain conditions the tsunami assumes the characteristics of a breaking wave (bore) in shallow coastal areas and becomes particularly destructive, such as during the 1960 tsunami in Hilo. Information on the effect of tsunamis on beaches is limited, but the effect may be significant and may lead to large displacement of samd in the nearshore zone. The beach will gradually be restored to its original configuration if the sand from the beach is not lost into deep water.

In November 1975, a locally generated tsunami caused considerable damage on the island of Hawaii. It only required a short time for the locally generated tsunami to reach the islands; advanced warning could not be given.

Wave setup

In coastal regions, waves change their characteristics by refraction, diffraction, shoaling, and finally, breaking.

The process of wave breaking gives rise to a change of the mean water level in the breakerzone, called wave setup. The setup is defined as the wave-induced height of the mean level of the water surface above the undisturbed level.

On a sloping beach the value of the wave setup is approximately 1/4 of the wave height at breaking (Battjes, 1974.)

Outside the breakerzone there is a small lowering of the water table called set-down.

In shallow coastal areas and on coastal reefs the wave setup can be significant. It affects the mean water level, and also, because of this, design wave for coastal structures. In addition, it gives rise to considerable current activity if conditions are favorable.

The concept of wave setup, was independently developed by Longuet-Higgins and Stewart (1964), Lundgren (1963), and Dorrestein (1961).

Longuet-Higgins and Stewart introduced the term "radiationstress" in waves to which the wave setup is related. Radiationstress is defined as the contribution of the waves to the mean horizontal flux of horizontal momentum. It appears as a stress (force per unit length) in the vertically integrated equation of motion of the mean flow.

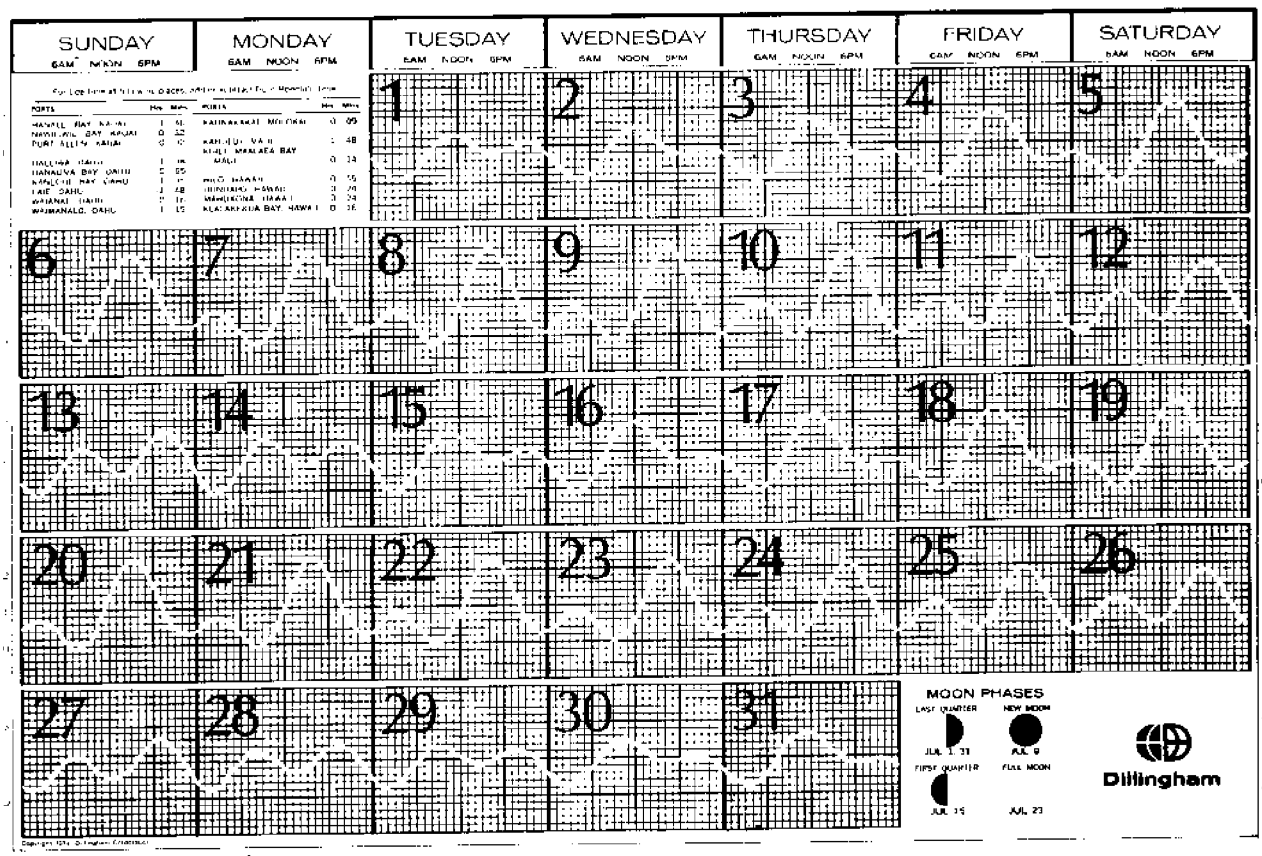
Recently other investigators (Battjes, 1974) have made significant contributions to the further development of the theory.

In a current study by the author and his associates, the aspects of wave setup and wave attenuation on a shallow fringing reef are being investigated. In this study, measurements in the field and in the laboratory are used to verify the setup phenomenon and its related aspects.

Tides

Tides in the Hawaiian Archipelago are of the mixed semidiurnal type. The tidal hydrograph demonstrates a significant daily inequality in which there is a considerable difference in the elevation of successive high waters during spring tide and strong diurnal characteristics during neap tide. Figure 4.7 shows a monthly tidal chart for Honolulu Harbor, as reproduced from the Dillingham Corporation's tide calendar for 1975. At Honolulu Harbor the mean tidal range between lower low water and higher high water is 1.9 ft. The maximum tidal range measured was 4.2 ft, with the highest high tide recorded at 3.05 ft and the lowest tide at -1.15 ft. Tide reference level is 0.8 ft below mean sea level (MSL). Deviations from the astronomical tides may be caused by the effect of offshore and onshore winds during storms and by atmospheric pressure effects. Tsunamis may have a great effect on the water level near the coast for a short time (1 to 2 hours). Information on tides in Hawaiian waters is available from yearly predictions of the National Ocean Survey (1976).

JULY 1975 TIDE CHART



From Dillingham Corporation

Figure 4.7. July 1975 Tide Chart

Currents

Currents in the Hawaiian Archipelago are of a complex nature because of the plurality of causes. The following components may be distinguished: large-scale circulation, tidal currents, wind-induced currents, and wave-induced currents.

Large-scale circulation is mainly due to temperature and pressure differences over the Pacific Ocean. It forms the outward boundary condition for the nearshore circulation patterns in the vicinity of the Hawaiian Islands.

Tidal currents are due to the gravitational effects of the moon and the sun and are related to the vertical water level differences of the tides. Tidal currents are weak in the greater depths of the ocean but they become significant in shallow coastal areas. In the vicinity of the islands they account for 60 to 90 percent of the total current activity (St. Denis, 1974).

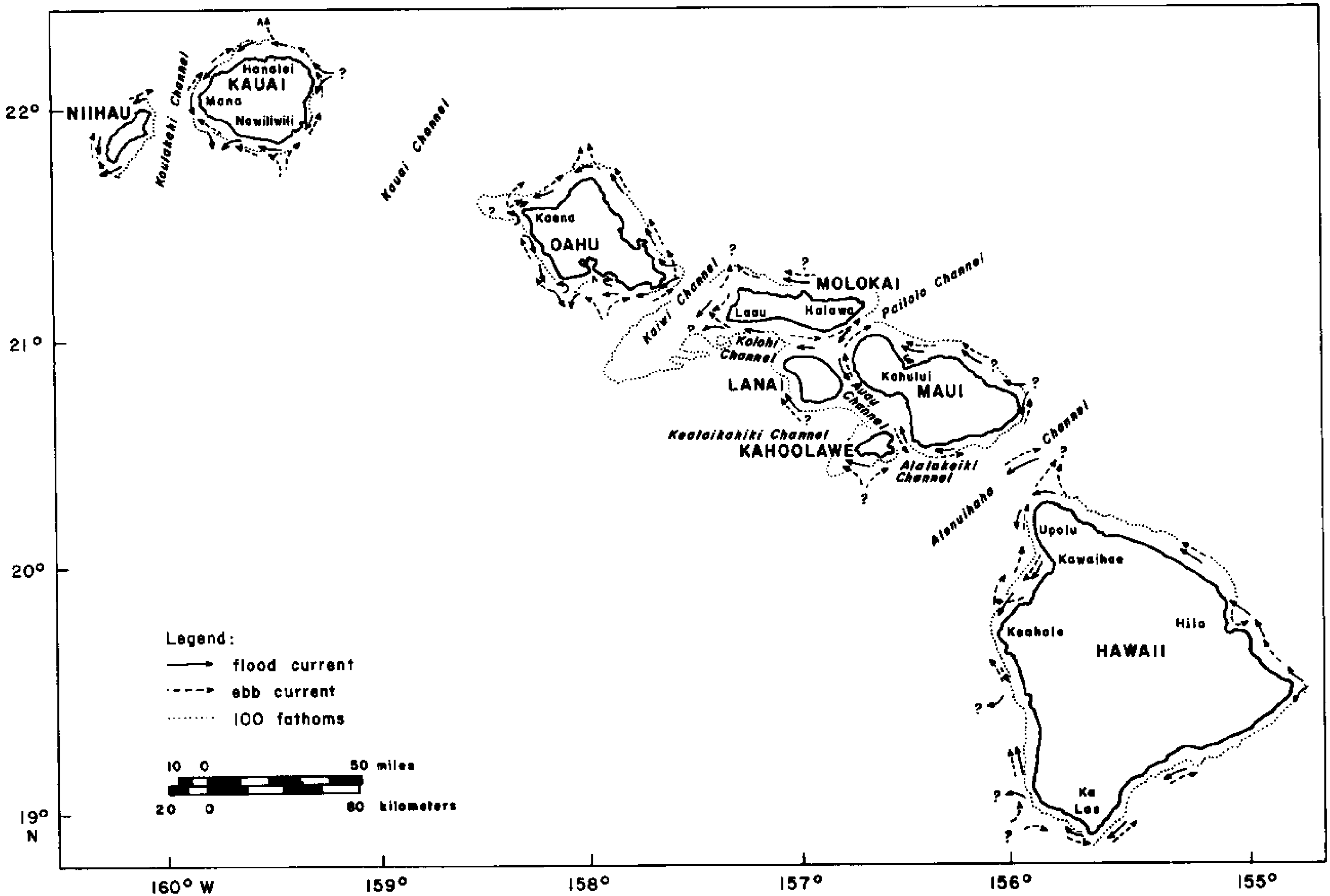
The effect of winds on current is different for deep and shallow water. In deep water it demonstrates itself as the Ekman drift, having a 45 degree clockwise direction from the wind at the surface of the ocean as a result of the Coriolis effect. At the surface the strength of the wind-induced current is about 2 percent of the wind speed; the current decreases exponentially in strength with increasing depth until it becomes virtually zero at the depth of $d = 12.6U_a$, where d is in meters and U_a is the mean wind speed in m sec^{-1}

In shallow water the direction of the wind-induced current is determined by the direction of the wind and the orientation of the coastline. The vertical current distribution is thereby affected by wind stress and bottom friction. The strength of the current is of the order of 2 to 3 percent of the wind speed.

Wind-induced currents are weak in the open ocean, but they may be strong in the coastal areas. Three types may be recognized: mass transport currents induced by the non-linearity of surface waves; rip currents which are directed from the coast seaward (Bowen and Inman, 1969; Noda, 1972); and longshore currents which run parallel to the coastline in the breaker zone (US Army Coastal Engineering Research Center, 1973).

Rip currents and longshore currents may at times be very strong (depending on the wave action) and contribute significantly to the sediment transport in the nearshore zone.

A generalized diagram of coastal currents around the Hawaiian Islands is shown in Figure 4.8 (Laevastu et al., 1964). The most probable current patterns around the island of Oahu for different seasons and tides are presented in Figures 4.9 and 4.10. Measurements of the currents at a station off Diamond Head by Wyrtki et al. (1969) show a strong dominance of the tidal currents in that area. Figure 4.11 shows the tidal current ellipses from the study by Wyrtki et al. (1969), with tidal current amplitudes as follows: semidiurnal 0.59 m sec^{-1} and diurnal 0.09 m sec^{-1}. As to the nature of the tidal currents, the following observations may be made: the semidiurnal tidal wave approaches the Hawaiian Islands from the northeast, with flood currents between the islands running from northeast to southwest and ebb currents running in the opposite direction.



After Laevastu et al., 1964

Figure 4.8 Generalized diagram of coastal currents around the Hawaiian Islands

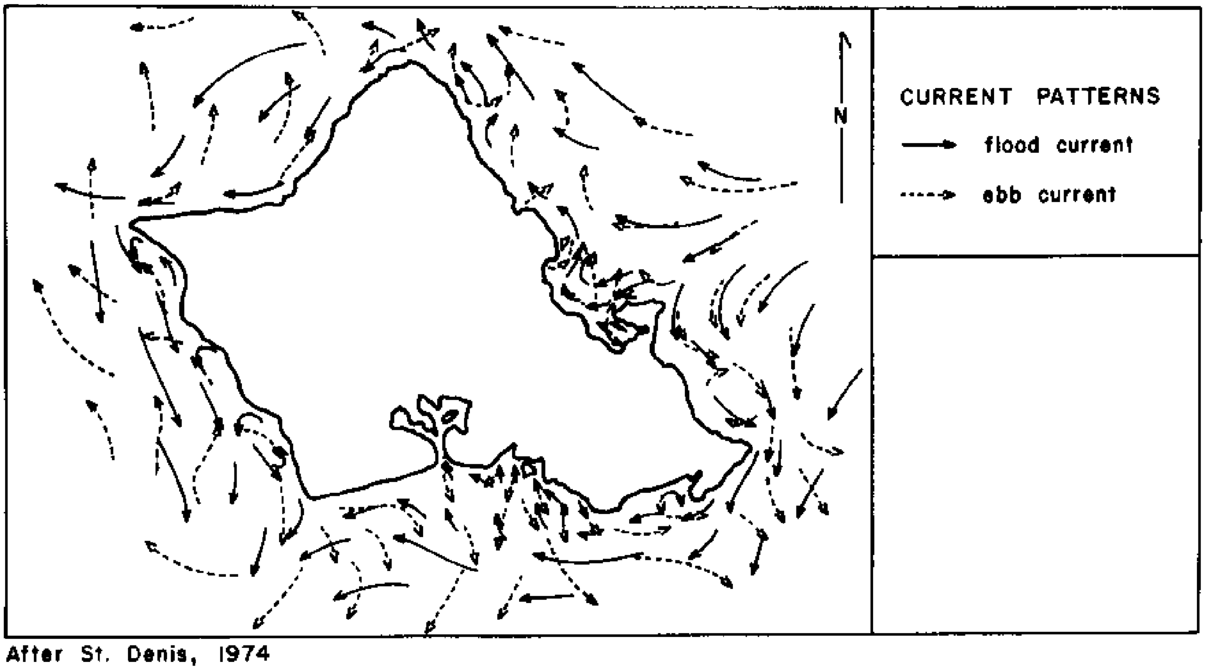


Figure 4.9. Most probable current patterns around Oahu (0 to 500 ft depth) during the months from October to March

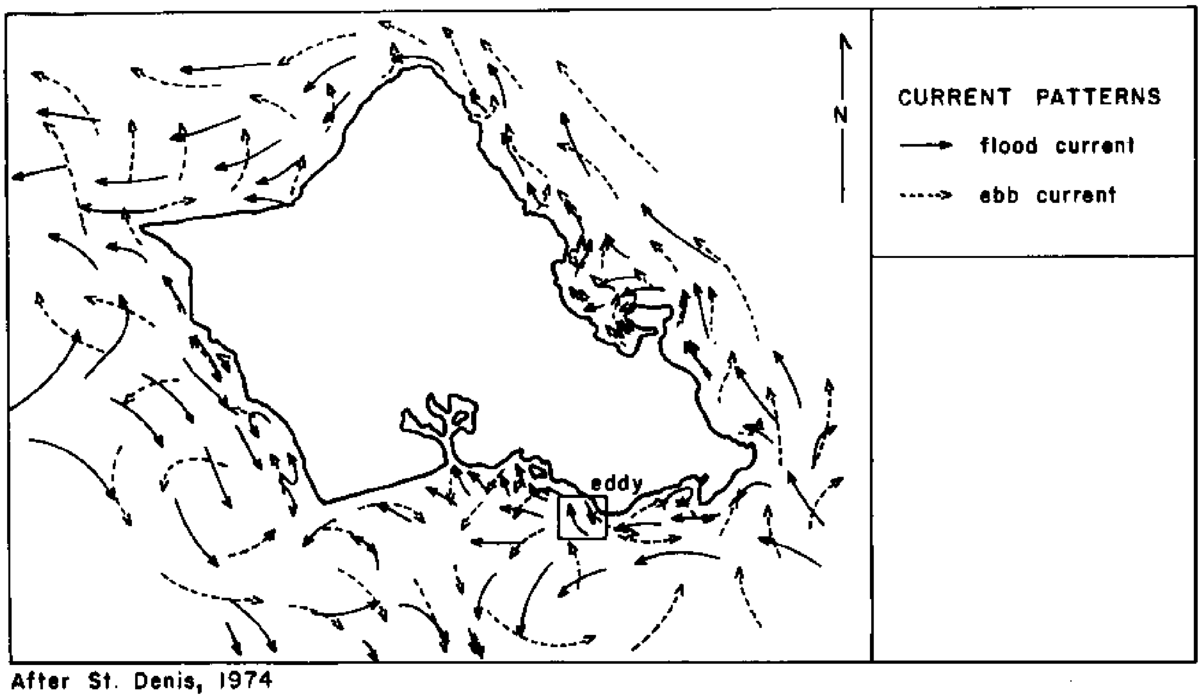
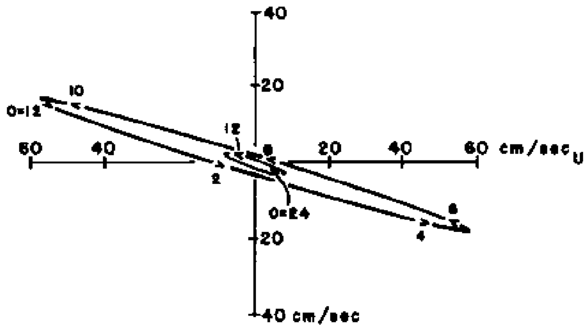


Figure 4.10. Most probable current patterns around Oahu (0 to 500 ft depth) during the months from March to October



After St. Denis, 1974 (Original source Wyrtki et al., 1969)

Figure 4.11. Tidal current ellipses for semidiurnal and diurnal components off Diamond Head, Oahu

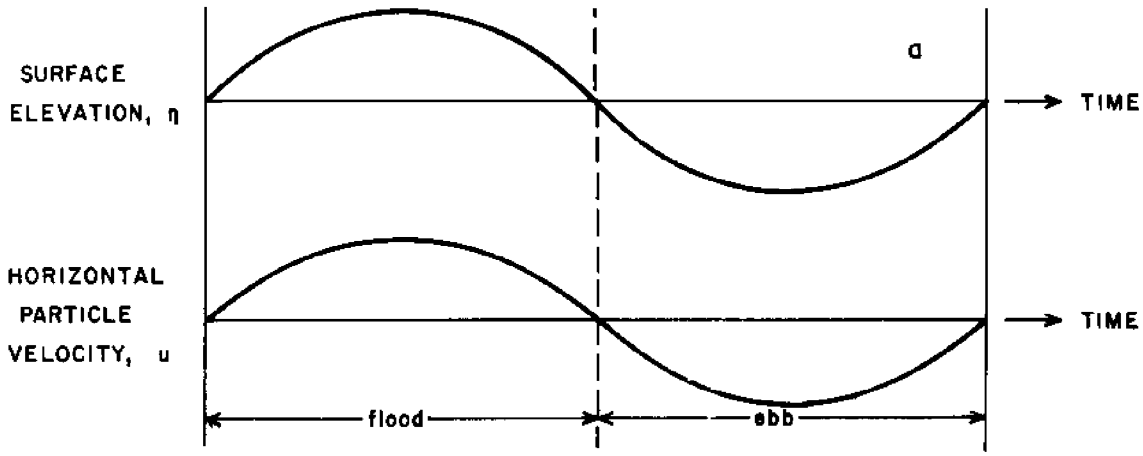
The definitions of flood and ebb currents need further clarification. In unrestricted open seas the tidal wave propagates as a progressive wave. In this case, the currents are in phase with the elevation of the water level as shown in Figure 4.12a. If friction is negligible, there is an agreement of phase between the tidal elevation and the tidal current; the maximum current occurring at the time of high water. Under these conditions flood currents are defined as the currents that flow in the direction of wave propagation. In enclosed bays such as Pearl Harbor, the tidal wave is reflected against the coastal boundary and a standing wave situation prevails. In this case, maximum currents occur between high and low tide with slack currents occurring near the times of high and low water (Figure 4.12b). The flood current is then defined as the inflowing current, the ebb current as the outflowing one.

In open bays, such as Mamala Bay and Waimanalo Bay, there usually is a mixed situation in which defining the flood and ebb currents is more complicated.

Beaches

In various ways, Hawaiian beaches differ from the beaches on the US mainland. These differences include the characteristics of the littoral drift, the source of the beach sand, and the presence of shallow offshore coral reefs.

Along US mainland beaches, the transport of sediment takes place in a relatively narrow zone parallel to the shoreline, usually over large distances along the shoreline. This transport pattern is interrupted by tidal inlets. In Hawaii, the transport mechanism is usually in the form of littoral cells in which transport perpendicular to the shoreline is significant. The offshore reefs cause the larger waves to break before reaching the coast and thus provide a protective mechanism for the shores and beaches. The reefs also act as a source for beach material.



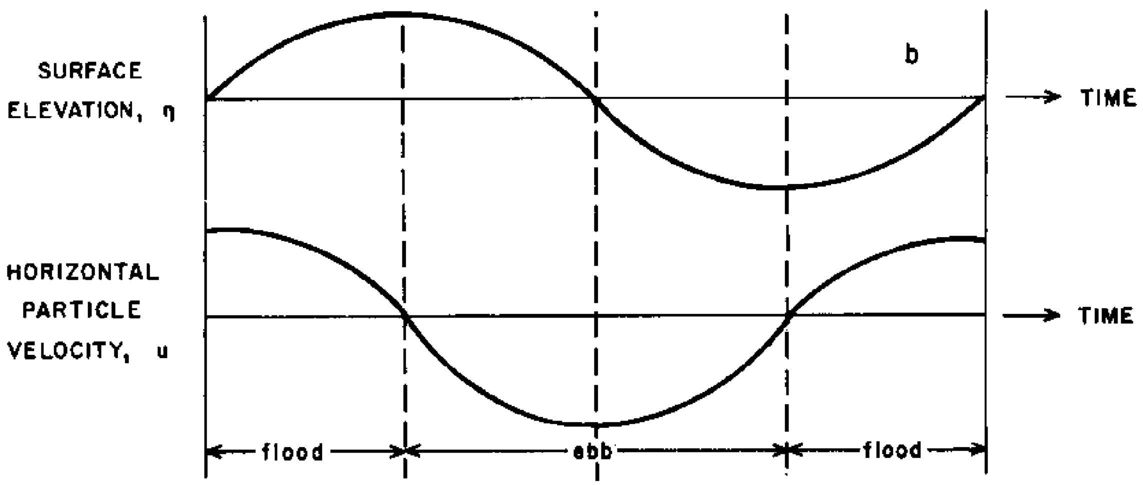


Figure 4.12. Phase relationship between tide and current for (a) a progressive wave and (b) a standing wave

While propagating over the reef, dissipation of wave energy takes place. After breaking, waves are often regenerated into waves of reduced height and shorter period. Thus, their effect on the beaches is less severe than on beaches subject to high wave exposure.

Because of their important function and the narrow width of the continental shelf, the reefs in Hawaii are in need of preservation. Where protective reefs do not exist, wave attack on the shoreline can be very severe.

Most island beaches have sand of medium grain size (0.2 to 0.6 mm). The windward beaches usually have smaller grains than the leeward beaches while coarse sand is also found on the exposed north and west coasts. The most important sources of beach sand are: coastal reefs, coastal streams and rivers, coastal erosion (e.g., weathering of beach rock), biochemical action, and volcanic action.

Unlike most mainland beaches that are made up of terrigenous material from river supplies, Hawaii's beaches for the larger part are made up of biogenous material from the reefs. Johannes (1971) reported that Chave et al. estimated the gross production of calcium carbonate by reef communities to average between 100 to 500 tons per acre per year. This production is used for the building and maintenance of the reef and nearby beaches.

In Hawaii, volcanic action is a source of land formation and beach sand production. This is a unique situation, which from time to time occurs on the island of Hawaii where black sand beaches are generated from lava (Cox et al., 1976).

Most beach sands are composite in nature. Light-colored calcareous grains sometimes mix with the darker-colored silicate grains of volcanic origin (Moberly and Chamberlain, 1964). Calcareous sands are composed of the remains of reef organisms. Foraminifera predominate in most island beaches and appear to be useful as natural tracers in the study of beach processes. By staining the foraminifera with Rose Bengal dye, it can be determined whether or not they have living protoplasm (Colburn, 1971). Coral fragments usually consititute only a minor portion of calcareous beach sands. Quartz is absent from most Hawaiian beaches; it is found in only a few areas.

CHAPTER 5. PRIMARY BEACHES ON OAHU

Results of measurements of three primary beaches on the island of Oahu--Waikiki Beach, Waimanalo Beach, and Haleiwa Beach--will be discussed in this chapter. A description of the various parts of Waikiki Beach and its history are included for background and clarification.

Waikiki Beach

Location and description

Waikiki Beach is located in Honolulu on the south shore of the island of Oahu and extends about 2.25 miles from the Ala Wai Yacht Harbor to Diamond Head (Figure 5.1). It is the major recreational beach both for the city's population and for tourists.

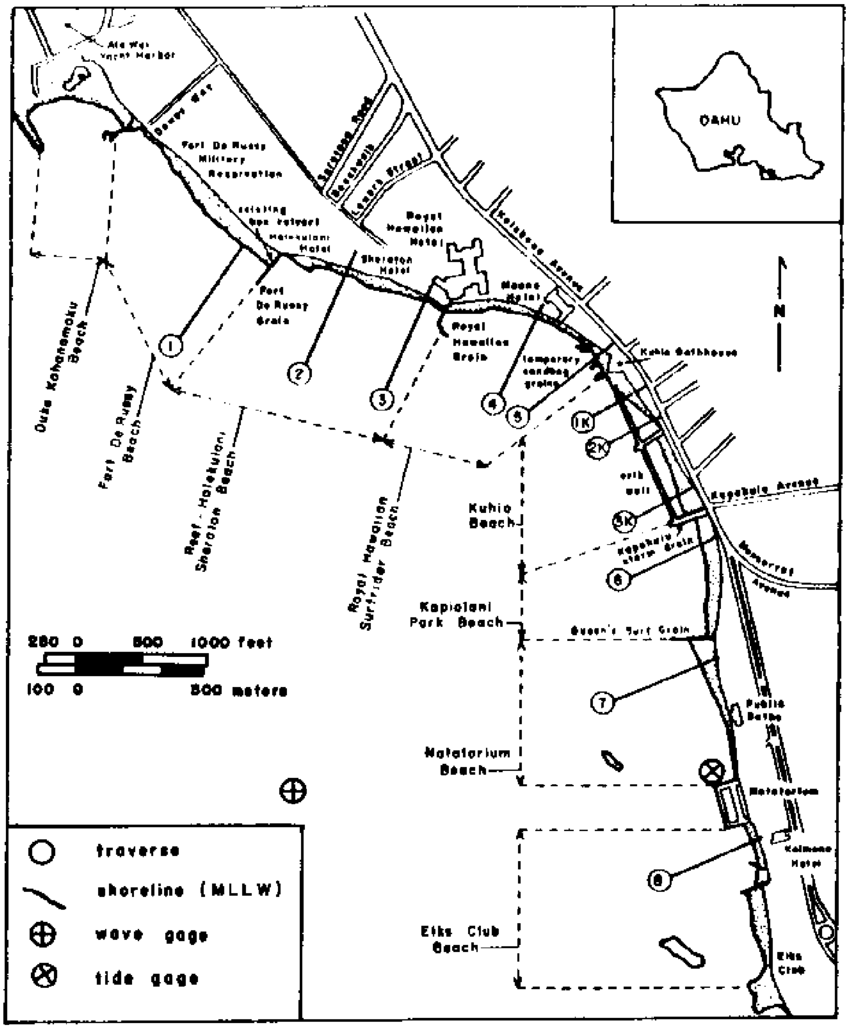


Figure 5.1. Waikiki Beach study area

For convenience, the beach at Waikiki was divided into eight sections with different characteristics. A short description of each of these sections follows.

Duke Kahanamoku Beach. This beach is located in the westernmost section and forms the transition between the Ala Wai Yacht Harbor area and the rest of Waikiki Beach. The 1,000-ft beach section is situated between two groins and has the characteristics of a headland beach. This beach was constructed in 1956 and has an offshore swimming area 150 ft wide and 7 ft deep.

Fort DeRussy Beach. This section has a length of 1,800 ft and extends along the Fort DeRussy military reservation. Immediately offshore, an area about 200 ft wide was dredged in 1917 for fill material. A portion of this area was later filled to -8 ft with material from dredged reef areas. In 1971 a beach widening project was carried out using crushed coral which gave the beach a hard and bright surface. After this project, the dry beach ranged in width from 150 to 200 ft. The east end of this section is marked by a 300-ft storm drain which is partly protected by a rubble mound and which acts as a groin.

Reef-Halekulani-Sheraton Beach. This beach section narrows from a width of about 100 ft at its west end to about 25 ft in front of the Halekulani Hotel, then widens near the Sheraton Hotel and narrows towards the east end. This beach section is subject to relatively large seasonal variations.

In front of the Halekulani Hotel the beach is sometimes completely submerged at high tide, due to the adverse effect of the seawall which was built too close to the waterline. The nearshore area is made up of a coral reef, except for a narrow sand channel off the Halekulani Hotel. A 350-ft long curved groin separates this section from the next.

Royal Hawaiian-Surfrider Beach. This curved beach section is stabilized by the curved groin at its west end. The width of the beach in this section is largest at the west end and smallest at the east. The predominant littoral drift in this section is clearly to the west. Near the east end in front of the Kuhio Beach bathhouse are three temporary sandbag groins which mark the end of this section. The nearshore and offshore areas of this section are sandy with some exposed coral reefs.

Kuhio Beach. This section extends from the sandbag groins to the Kapahulu storm drain which acts as a groin. Landward of this section there is a boulevard with a vertical seawall. About 250 ft offshore, a partially submerged offshore barrier 1,450 ft long offers protection against wave attack. The crest is at +1 ft along the northwest portion and at +3 ft along the southeast portion. In 1975 the northwest seawall was rebuilt to +3 ft. In 1972 a cooperative beach improvement project between the federal government and the state was carried out in this area. The project consisted of the placement of 82,200 cubic yards of beach fill, reconstruction and realignment of the seawall and the access to the beach, and reinforcement and lengthening of the existing groins. Outside the offshore wall, the reef extends to about 2,000 ft from shore, except in front of the storm drain where a partially filled submarine canyon is located.

Kapiolani Park Beach. This section runs from the Kapahulu groin to the Queen's Surf groin and is 1,360 ft long. The beach is narrow and its nourishment is adversely affected by the Queen's Surf groin.

Natatorium Beach. This beach extends from the Queen's Surf groin to the Natatorium and has a width of about 150 ft. Its north end is stabilized by the Queen's Surf groin. Near the Natatorium, the beach is very narrow and becomes completely submerged at high tide. Here wave reflection against the seawall has an adverse effect on the beach.

The Natatorium, a 100-m long seawater swimming pool, was built as a war memorial after World War I and its continued existence is under discussion.

Elks Club Beach. The southernmost section of Waikiki Beach extends from the Natatorium to the Elks Club. This beach is narrow but relatively stable and the nearshore area is a popular swimming area. In front of the Outrigger Canoe Club the beach was artificially widened and a groin built to help stabilize the beach. A wooden pier is located in front of the Kaimana Hotel and a 4.5-ft deep dredged channel permits access to the anchorage of the Outrigger Canoe Club.

Beach history

Most of the sand in the Waikiki Beach area has been brought in artificially during various beach improvement projects over the past years. Up until the latter part of the 19th century, Waikiki Beach was a narrow barrier beach in front of a swamp and lagoon. Dredging, filling, and construction changed the area into the most valuable piece of real estate in the state of Hawaii (Crane, 1972).

In the early 1900s, seawalls were built along the beach to protect the land. In a study on beach history, Crane (1972) referred to a report on the investigation of Waikiki Beach during 1926 by the Engineering Association of Hawaii in which it was concluded that seawalls were the primary cause of beach erosion. To restore and protect the beach, private and public owners of waterfront property constructed a variety of shore protection structures such as groins and offshore barriers in front of their property. These structures were often ill-designed, only partially effective, and never completely adequate to solve the problem. Currently, the adverse effects of vertical seawalls too close to the water's edge continue to play a part in the erosion problem.

Erosion and stabilization problems persist at Waikiki Beach today, but recent measures of improvement carried out by the federal government and the state in the Kuhio Beach area have improved the situation considerably. In order to evaluate the effectiveness of existing coastal protection structures as well as to help further planning, design, construction, and maintenance, it is necessary to have an adequate understanding of the complex nearshore processes.

The history of Kuhio Beach is particularly interesting from a coastal engineering point of view. In 1939, a 690-ft section of this beach was developed using artificial nourishment. The beach was subsequently eroded over the course of time. During the period 1951-57, the state of Hawaii, in conjunction with the federal government, placed 160,000 cubic yards of sand on the beach as part of the beach restoration project. The project further included the construction of an offshore breakwater and two groins. Two years after the initial construction, a rapid erosion of the beach necessitated further replacement of 18,750 cubic yards of sand. The most recent improvements were accomplished in 1973 and 1975. Improvements in 1972-73 consisted of the placement of 12,000 cubic yards of sand on the beach and of additional construction works, such as the renovation and beautification of the seawall east of Kapahulu groin and the building of two groins (Figure 5.2a). In 1975, additional work was carried out by improving the offshore breakwater and by further restoration of the beach, as well as adding 9,500 cubic yards of imported sand (Figure 5.2b). During the execution of recent projects, considerable erosion was experienced during periods of high waves.

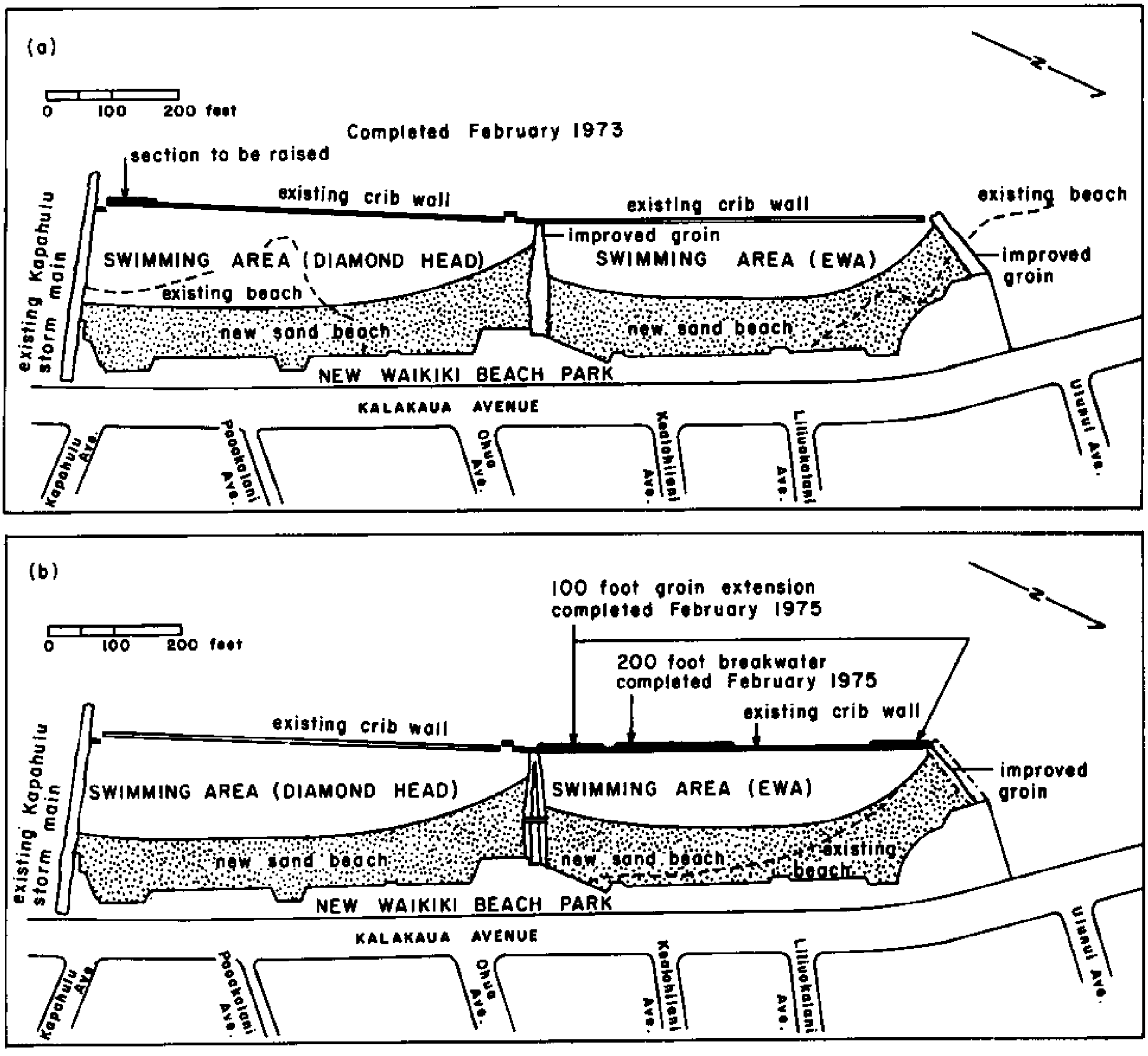


Figure 5.2. Kuhio Beach improvement plans: (a) 1973 and (b) 1975

Geomorphology

The beach at Waikiki lies on a coral reef that extends offshore to about one mile. In various locations the top of the coral reef can be seen near the surface of the water. This reef formation extends inland for about a mile, rising to several feet above sea level (US Army Corps of Engineers, 1963). The live reef in the Waikiki Beach area is most dominant on the outer reef slope west of the Royal Hawaiian Hotel (Chave and Tait, 1973).

The coral reef is considered the main natural source of sand nourishment for the beach. There is no indication of nourishment from deposits of sands brought down by the few streams that enter the ocean in this area.

Waikiki Beach was once a barrier beach with swamp and lagoon areas behind the beach. This swamp has been largely filled with dredged coral material. The coral shelf contains scattered pockets, ridges, coral heads, and reaches of sand over a wide area. A submarine canyon exists seaward from Kuhio Beach; it is the result of old freshwater flows from an inland watershed. The flow of fresh water is presently routed through the Ala Wai Canal and the canyon is gradually filling with sand. Further to the west, the Halekulani sand channel is also the result of the same mechanism.

Waves

The beach at Waikiki, situated on the south shore of Oahu, is affected by various types of waves. The tradewind waves reach Waikiki Beach after passing through the Molokai channel (Kaiwi Channel). They diffract and refract before they reach the Waikiki shoreline, causing their height to be considerably reduced.

Kona storm waves affect the Waikiki Beach area directly. During wave studies by the US Army Corps of Engineers from September 1948 to September 1949, the observed waves were from the south to southwest nearly 100 percent of the time, but predominantly from the south-southwest direction (US Army Corps of Engineers, 1963). A total of 869 observations of wave height, period, and direction were made during that period. The measurements were conducted by reading a 3-inch diameter graduated pipe set in 20 ft of water about 27,000 ft from the Moana Hotel. The average wave height was in the range of 1.5 to 2 ft during the 9-month period from September 1948 to June 1949 and 2 to 3 ft from June to September 1949. Wave heights greater than 4 ft occurred occasionally with a maximum observed value of 11 ft. Breaker height was usually 1 to 2 ft higher than the observed waves at the pole. Breakers higher than 6 ft were observed on eight different occasions. Wave periods ranged from 7 to 27 sec, with most periods between 10 and 18 sec.

During the period of observation by the US Army Corps of Engineers, a storm which was centered about 500 miles southwest of the Hawaiian Islands affected the Waikiki Beach area on January 14-18, 1949. Table 5.1 lists observed waves and wave conditions at Waikiki Beach during this storm when both erosion and deposition of sand were observed in various areas.

As the waves approach the shoreline from deep water, they become higher due to shoaling. However, as they travel over the gently sloping shelf, much

TABLE 5.1. STORM AND WAVE DATA, JANUARY 14-18, 1949

Date	U.S. Weather Bureau Data for Honolulu		Observations at Waikiki (10:00 Hawaiian Standard Time)						Open Sea Data Vicinity Hawaiian Islands*	
	Average Wind Direction	Average Wind Velocity (mph)	Wave Direction From	Average Wave Height (feet)	Height of Shore Breakers	Wave Period (seconds)	Wind Direction From	Wind Velocity (mph)	Wind Velocity (knots)	Wind Direction
Jan. 14	Southwest	6.2	Southwest	1.6	----	12	Southwest by south	4-7	10-15	South
Jan. 15	South	12.6	South	†4.1	----	10	South	13-18	8-14	South
Jan. 16	Southeast	#13.8	South	10.0	----	10	South	32-38	11-16	South
Jan. 17	Southeast	18.3	South	11.0	12.3	10	Southeast	19-24	12-13	South
Jan. 18	East	9.8	South by West	8.5	7.5	10	East-northeast	4-7	18-25	South

*Synoptic wave data
†Every 10th wave, 3-1/2 feet
#Fastest continuous mile of wind expressed in velocity: 41 mph. Gusts to 83 mph occurred this day.

From U.S. Army Corps of Engineers, Honolulu District, 1963.

of their energy is dissipated and even high waves at sea generate only moderate breakers on the shore.

Because of its location, the beach at Waikiki is almost entirely protected from the northern swell which has a negligible effect on the beach processes in the area. The opposite is true for the southern swell. The beach lies completely open to waves of this type which causes the greatest changes in beach configurations by transporting sediment in an offshore direction.

More study is needed to determine the adverse effects, if any, of the behavior of cyclonic waves in the Waikiki Beach area.

Wave refraction. Wave refraction plays a very important part in nearshore processes. Figures 5.3, 5.4, and 5.5 show the general characteristics of wave refraction for waves from southerly and easterly directions. Computed refraction coefficients for the southern swell give values of 0.64 and 0.77 for the locations shown in Figure 5.4. Tradewind waves from east-northeasterly directions pass through the Molokai channel and reach the Waikiki Beach area after diffraction and refraction. For this situation a refraction coefficient of 0.32 was found. Only a relatively small portion of this wave energy reaches the Waikiki shoreline and consequently the influence of the tradewind waves on the nearshore processes in this region is small. The shallow coastal reef between the Natatorium and the Queen's Surf groin has a strong protective effect on the beach in that area. Along the western edge of this shallow reef, waves usually reform and break, as may be seen in Plate 5.1.

The submarine canyon in the Kuhio Beach area has two effects on the approaching waves: it permits the higher waves to approach closer to the shore in that area than at the adjacent reef and it induces additional refraction near the shoreline. This in turn results in erosion of sand from the shore near the canyon forming a concave bench with the point of deepest erosion in the vicinity of the canyon.

Wave observations during the course of this study. Measurements were made in the Waikiki Beach area and at a nearby offshore station near Kewalo Basin as follows:

1. Wave measurements with self-contained pressure sensors off Waikiki Beach at 50 ft depth

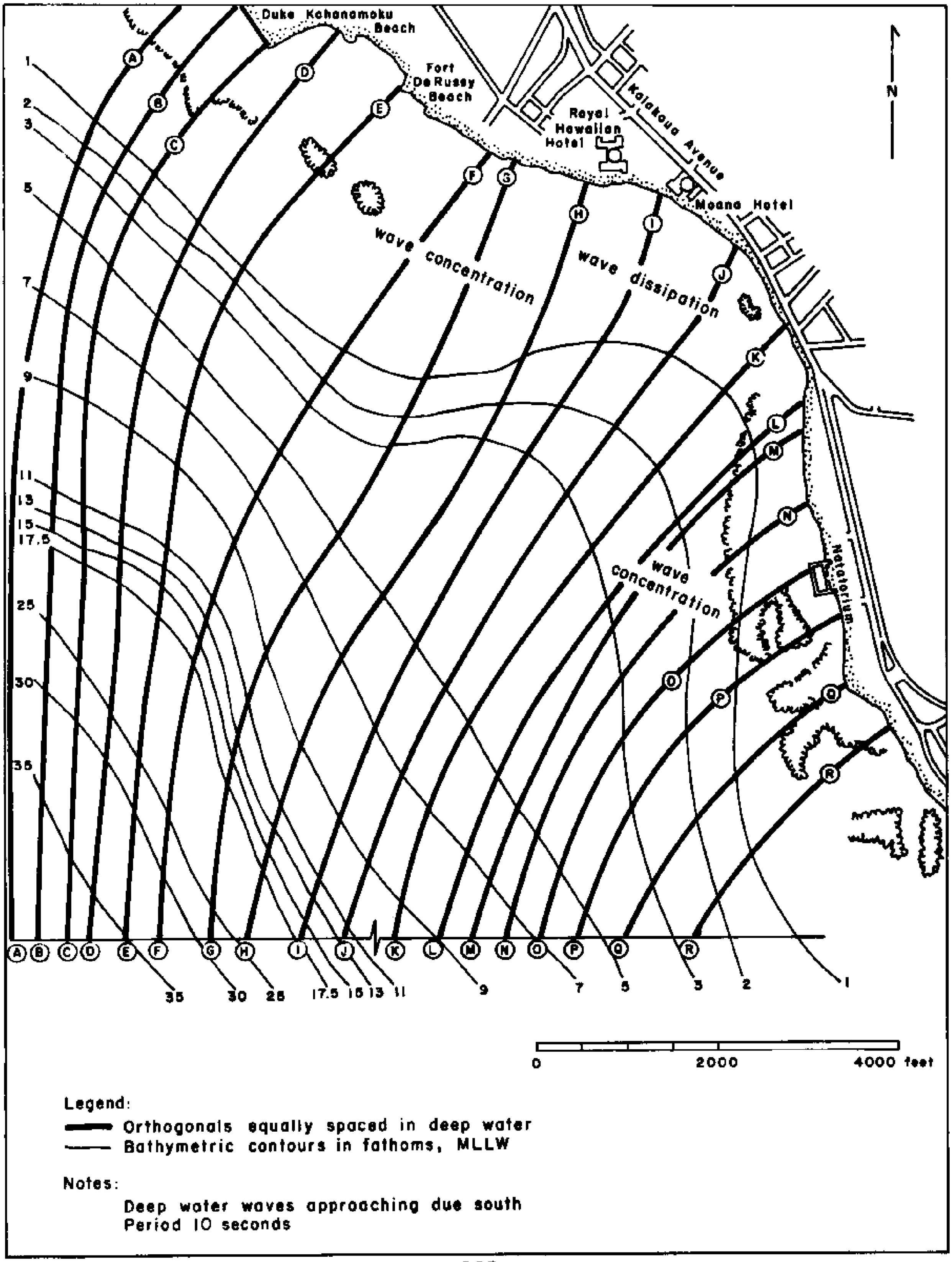
2. Wave measurements with a pressure sensor off Kewalo Basin about 2 miles northwest of the center of Waikiki Beach in about 40 ft of water. The sensor was connected to shore with a cable (Figure 5.6).

3. Visual observations of surf conditions during field investigations

The data obtained were used for the following types of analysis:

1. Wave height spectra for wave conditions at the offshore station at Waikiki Beach

2. Comparison between wave conditions at Waikiki Beach and Kewalo Basin



After U.S. Army Engineers District Honolulu, 1963

Figure 5.3. Wave refraction diagram, southerly waves at Waikiki Beach, Oahu

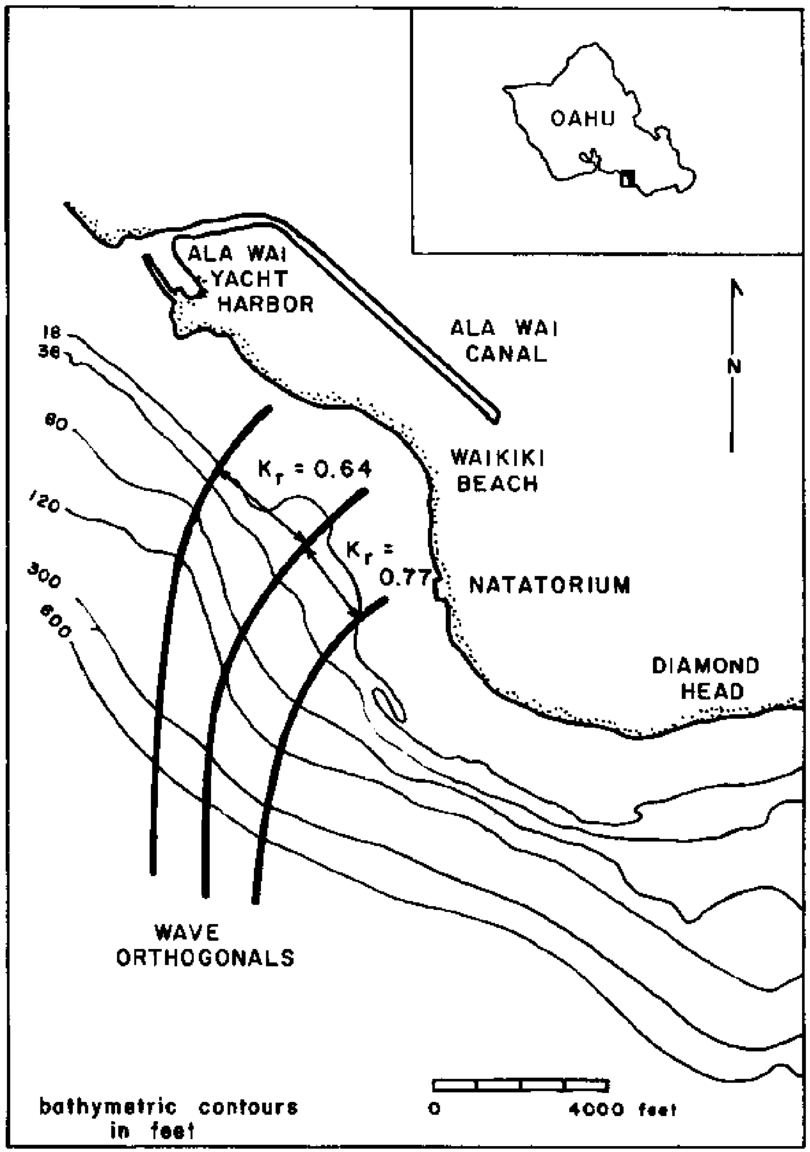


Figure 5.4. Refraction of 15-second southern swell at Waikiki Beach, Oahu

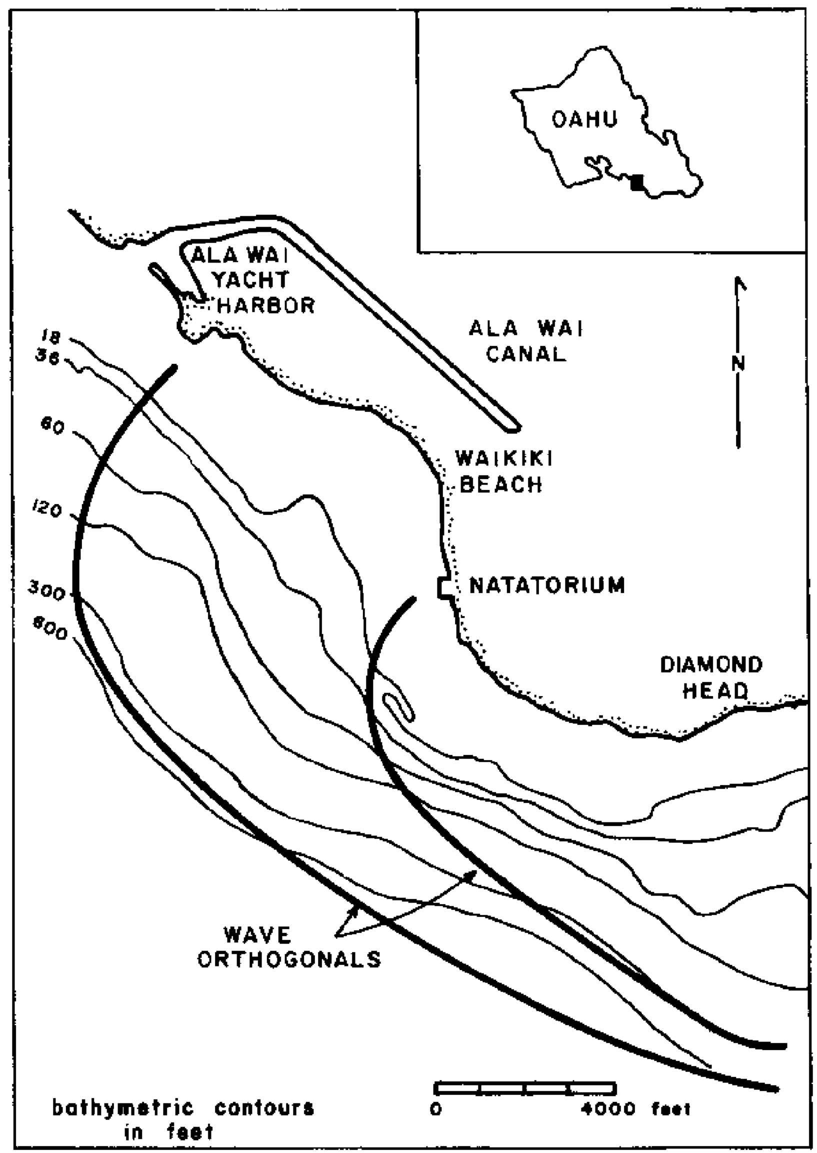


Figure 5.5. Refraction of 8-second tradewind wave at Waikiki Beach, Oahu

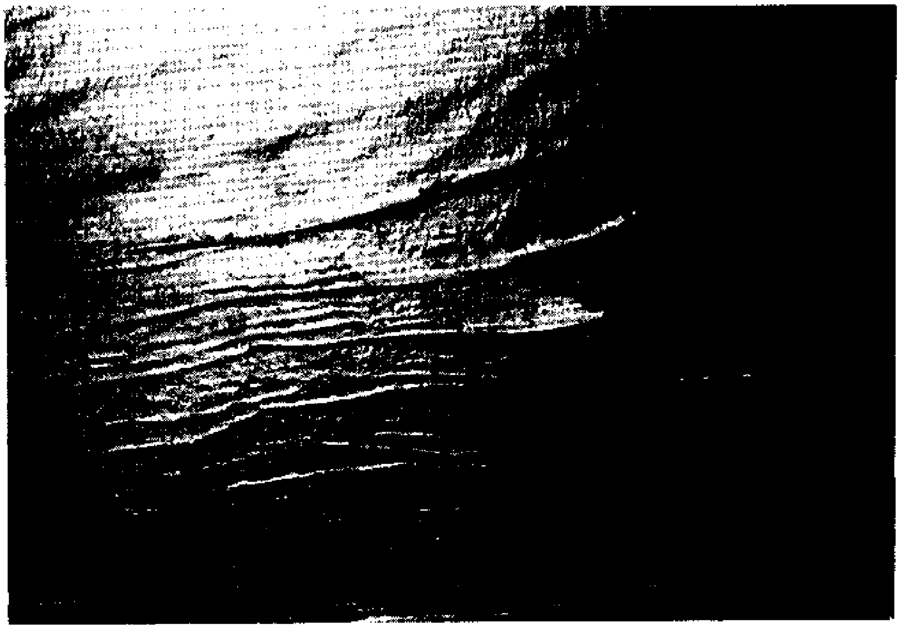


Plate 5.1. Wave reformation over reef at Waikiki

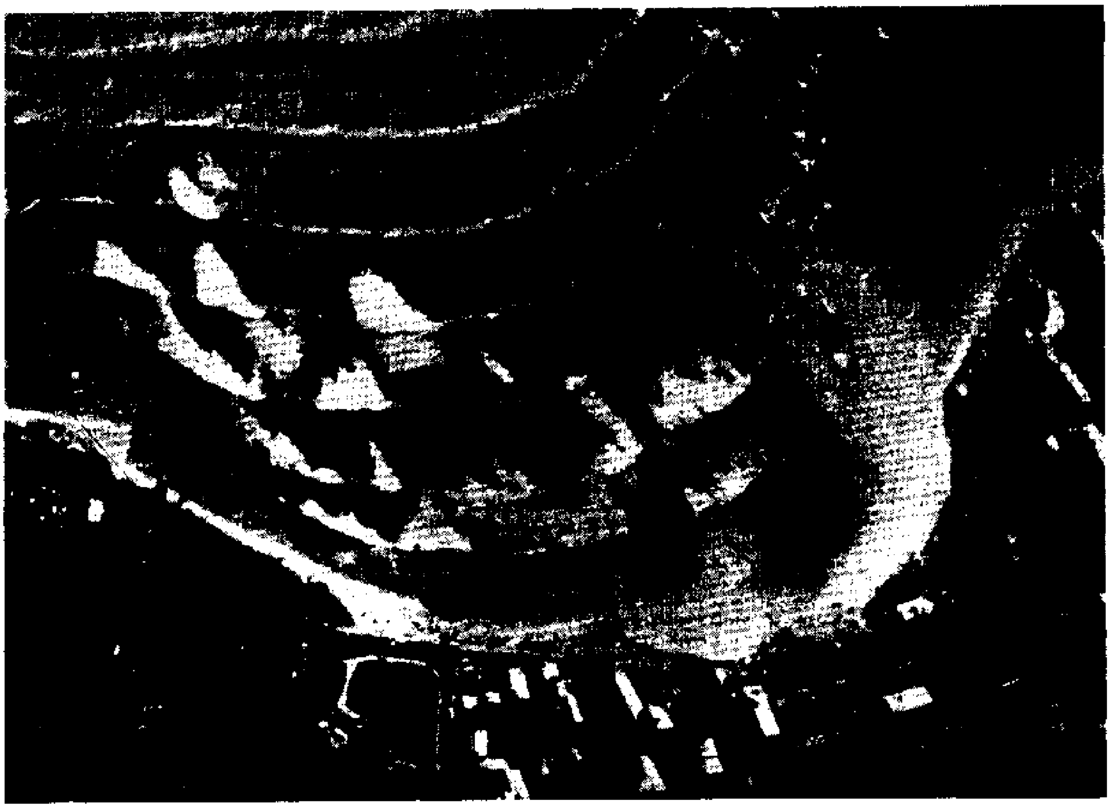
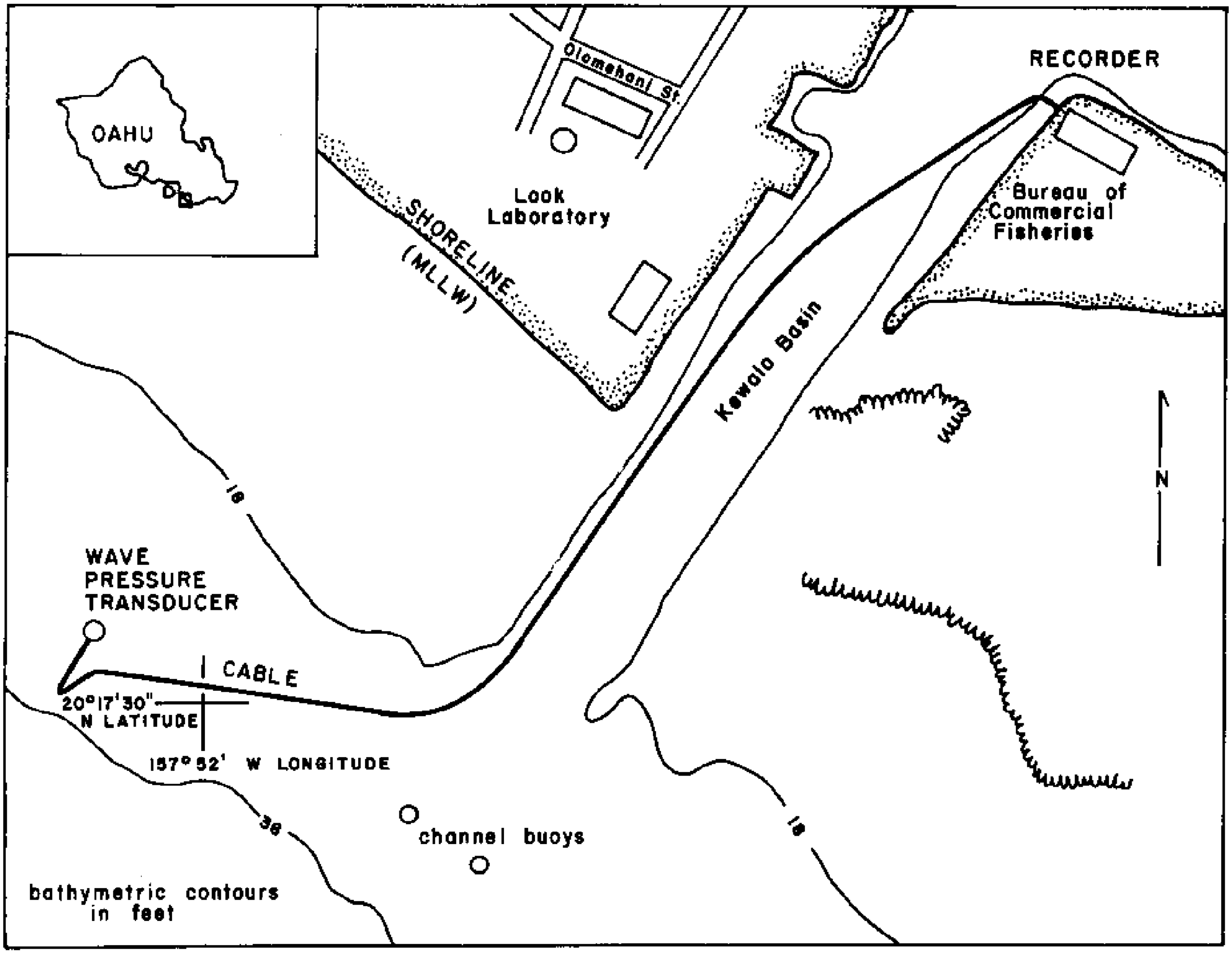


Plate 5.2. Strong rip currents off Waikiki Beach during high surf conditions on April 26, 1972



After Walker, 1974a

Figure 5.6. Location of wave pressure transducer off Kewalo Basin, Oahu

3. Frequency distributions for wave height, both for offshore waves and for the waves over shallow reefs to evaluate the difference in wave climate between these two stations and to determine whether observations made at Kewalo Basin have significance for Waikiki Beach

Wave spectra off Waikiki Beach. Wave spectra were determined from measurements with the self-recording bottom-mounted wave recorder and analyzer, Model DNW-2.

Table 5.2 gives the results of several months of data collection at Waikiki Beach. It shows $\overline{\eta}$, the average surface elevation above MSL; H_s, the significant wave height; T_{max}, the period at which the spectral density, S_{max}, reaches its maximum value; and T_{sub}, the periods where secondary peaks, if any, occur. These periods correspond to predominant wave periods during the recording period. Several types of characteristic wave spectra are shown in Figure 5.7.

TABLE 5.2. WAIKIKI BEACH WAVE SPECTRA DATA

Date	$\overline{\eta}$ (m)	H_s(m)	T_{max}(sec)	T_{sub}(sec)	S_{max}(m^2 sec)
07-08-72	-0.38	1.54	32	15 & 16	4.2
09	-0.40	1.34	12	-	4.0
10	-0.32	1.29	13	-	3.5
11	-0.36	1.08	12	-	2.1
12	-0.37	1.04	13	11	2.1
13	-0.42	1.33	13	-	4.8
14	-0.60	1.31	12	18	3.9
15	-0.46	1.61	16	14	6.4
16	-0.48	1.95	15	13	9.5
17	-0.58	2.11	15	20	12.0
18	-0.54	1.64	14	19	6.6
19	-0.71	1.38	13	18	3.7
20	-0.83	1.26	16	13	3.2
21	-0.75	1.03	15	-	1.8
22	-0.89	0.95	13	18	1.1
23	-0.87	1.42	18	14	6.6
24	-0.86	2.11	17	13	18.8
25	-0.86	1.98	15	12	13.6
26	-0.87	1.66	14	11	7.1
27	-0.96	1.42	13	-	4.5
04-22-73	-1.60	1.53	15	12, 7	3.9
23	-0.20	1.54	14	-	4.8
24	-0.18	1.67	8	13	4.0
25	-0.21	1.90	9	15	8.0
26	-0.28	1.89	8	14	5.7
27	-0.41	1.53	14	9, 16	2.8
28	-0.49	2.51	15	9, 17	20.0
29	-0.62	3.89	14	9	37.0
30	-0.56	3.82	15	9	58.0

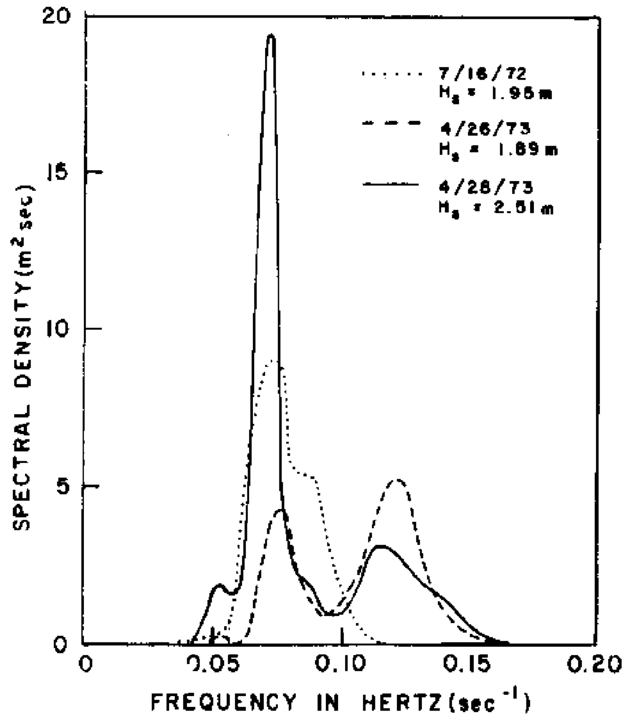


Figure 5.7. Examples of several daily wave spectra off Waikiki Beach, Oahu based on two hours of continuous pressure records

Wave measurements at Kewalo Basin. Kewalo Basin, a small boat harbor located about 2 miles west of Waikiki Beach near Look Laboratory of Oceanographic Engineering, has been a convenient location for wave measurements throughout the project. Since the distance between Kewalo Basin and Waikiki Beach is small, it was expected that offshore wave conditions would only differ slightly between the two locations and therefore offshore wave measurements near Kewalo Basin would provide valuable information for the Waikiki Beach area study.

Figure 5.6 shows the arrangements for the measurements of waves at Kewalo Basin. A cable connected the wave sensor to a recording instrument on shore. Wave data from the Kewalo Basin gage have been used to arrive at wave height frequency distributions (Walker, 1974a; Fallon et al., 1971).

Variability of wave conditions between Waikiki Beach and Kewalo Basin. A comparison of some recorded wave data off Waikiki Beach and Kewalo Basin is shown in Figure 5.8 where the significant wave heights at both locations are plotted in a regression diagram. Although there are significant differences in individual values, a closer correspondence is expected on a statistical basis.

Figure 5.9 shows the comparison between the average periods off Kewalo Basin and Waikiki Beach. The agreement was not very good. The wave period at Waikiki Beach varied to a lesser degree than the period at Kewalo Basin. The reason for this difference was not investigated.

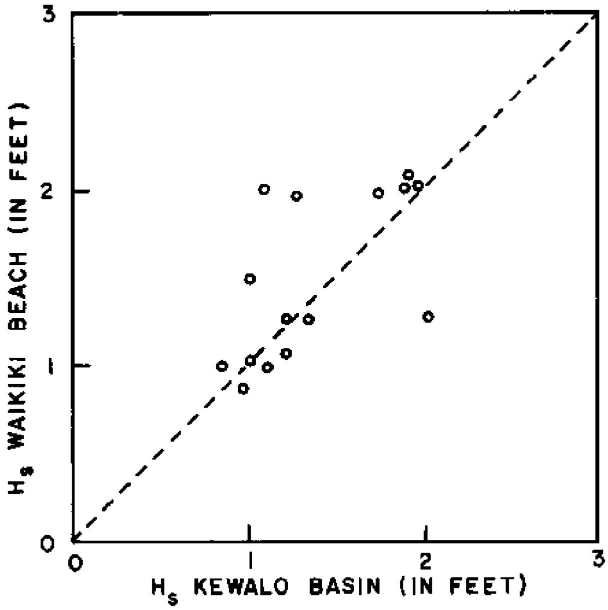


Figure 5.8. Comparison of significant wave heights measured off Waikiki Beach and Kewalo Basin, Oahu

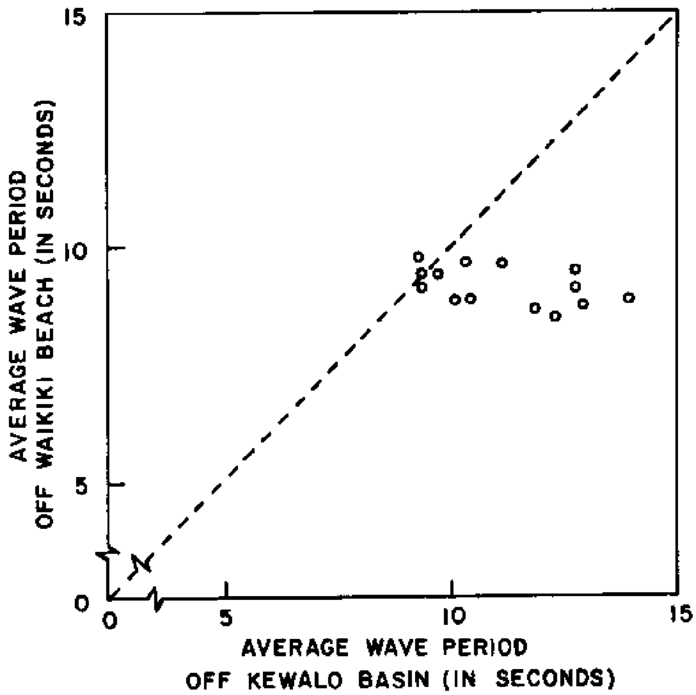


Figure 5.9. Comparison of average wave period measured off Waikiki Beach and Kewalo Basin, Oahu

Frequency distributions of wave heights in the Waikiki Beach area. In order to evaluate the frequency of occurrence of wave heights on the leeward coast of Oahu, wave data of different origin were used. The following data were analyzed:

1. Data from the Marine Advisors wave study (Homer, 1964)

2. Gage readings at Waikiki Beach by the US Army Corps of Engineers, Honolulu District (1963)

3. Computations on significant wave height and period regarding a number of distinct storms by the US Army Corps of Engineers, Honolulu District

Various ways to construct frequency diagrams have been evaluated; the one that seemed most useful is presented in Figure 5.10. Frequencies of waves in relatively deep water offshore and in shallow depths nearshore have been computed for Waikiki Beach. The frequency distributions for shallow water (Figure 5.10a) have been derived from the deep water wave conditions using a Rayleigh distribution for wave height and a simple breaking criterion, $H_b = \alpha h_b$, for the maximum wave height, H_b, in which h_b represents the water depth and α is the breaking ratio factor. The latter was assumed to be equal to 0.78 (Gerritsen, 1972). The significant wave heights for shallow water can be obtained by constructing diagrams of the form of Figure 5.10b which corresponds to an offshore wave height of 17.5 ft.

Tides

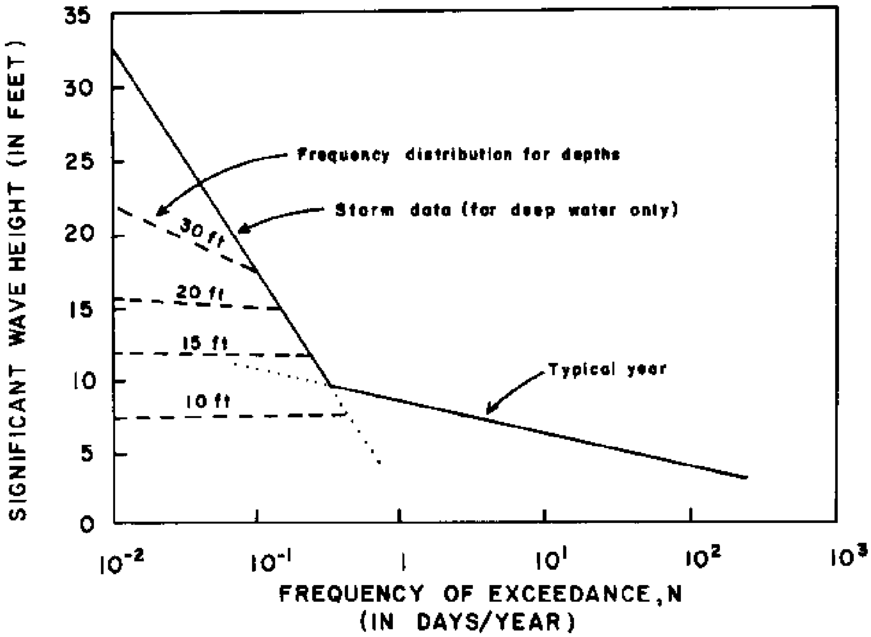
In order to compare the tides at Waikiki Beach with those at Honolulu Harbor, a recording tide gage (Stevens type) was installed at the Natatorium (Figure 5.1). The comparison shows a 0.3 ft smaller tidal range at Waikiki Beach, while the times of high and low water are nearly 15 minutes before the predicted values for Honolulu Harbor (from the Dillingham tide calendar). The comparison between the predicted hydrograph at Honolulu Harbor and the observed one at Waikiki Beach is shown in a sample record in Figure 5.11.

The tide gage at the Natatorium (Figure 5.1) was located near shore and may occasionally have been affected by wave setup in that area, although no measurements were conducted to confirm this.

Currents and sediment movement

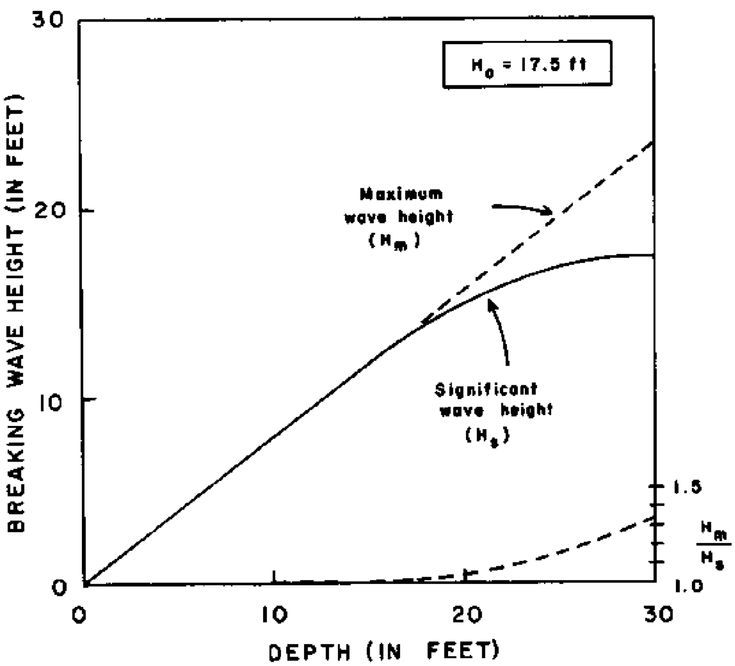
The emphasis of the field studies at Waikiki Beach was on measuring currents. Both dye patches and drogues were used to determine the dominant current patterns in the area. Attempts to use a current meter appeared to be impractical because the effect of the wave-induced orbital movements dominated the action of the other types of currents.

A comparison between drogue and dye paths showed that differences between the two may occur, the drogue at times moving faster than the dye streak. For most measurements, the observations of the movement of the dye patches were used to determine characteristic current patterns. In order to track the dye



(a)

After Gerritsen, 1972



(b)

Figure 5.10. Wave data for Waikiki area: (a) frequency distribution diagrams for offshore and nearshore waves and (b) breaking wave criteria for maximum and significant wave heights

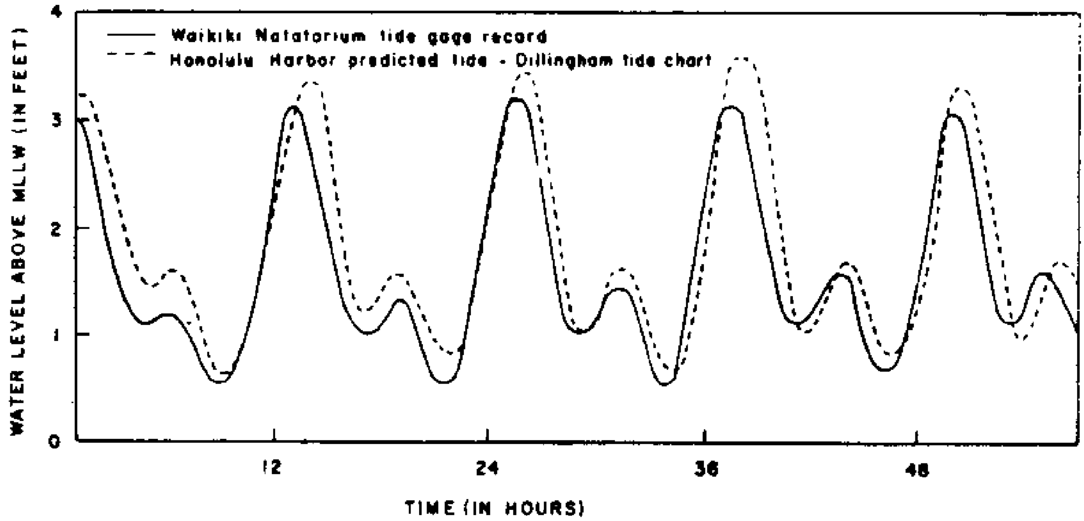


Figure 5.11. Comparison of the predicted tide for Honolulu Harbor with the actual tide gage record from Waikiki Natatorium

patches, a small boat was kept in the approximate center of the patch. The position of the boat was determined by triangulation with two shore-based transits. A total of four stations were used. Radio contact was maintained between both surveyors and the boat to facilitate the simultaneous recording of bearings.

The currents in the Waikiki Beach area are strongly affected by the tide, except in the nearshore area where wave-induced currents prevail. Results of current measurements were grouped into two categories: flood and ebb currents. If the corresponding vertical tide is above MSL, the current is defined as a flood current; if below MSL, then it is called an ebb current.

Predominant current patterns for flood and ebb flows are shown in Figure 5.12. Inside the 40-ft depth contour, ebb and flood currents have the same general direction toward the southeast. At greater depths, ebb currents flow southeasterly but flood currents westerly.

The maximum currents occur in the southern part of the study area, with values of 2.0 fps for ebb and 1.6 fps for flood.

The nearshore flood currents averaged 0.15 to 0.5 fps while the average ebb velocity nearshore ranged from 0.15 to 0.8 fps.

In the large-scale circulation patterns offshore of Waikiki Beach, as shown in Figures 4.8, 4.9, and 4.10, the general set of the flood current is toward the west while the ebb current flows in the opposite direction. However, close to the shoreline the flood current also runs eastward, signifying an eddy pattern off Waikiki Beach.

The measurements conducted in this study confirm this circulation pattern.

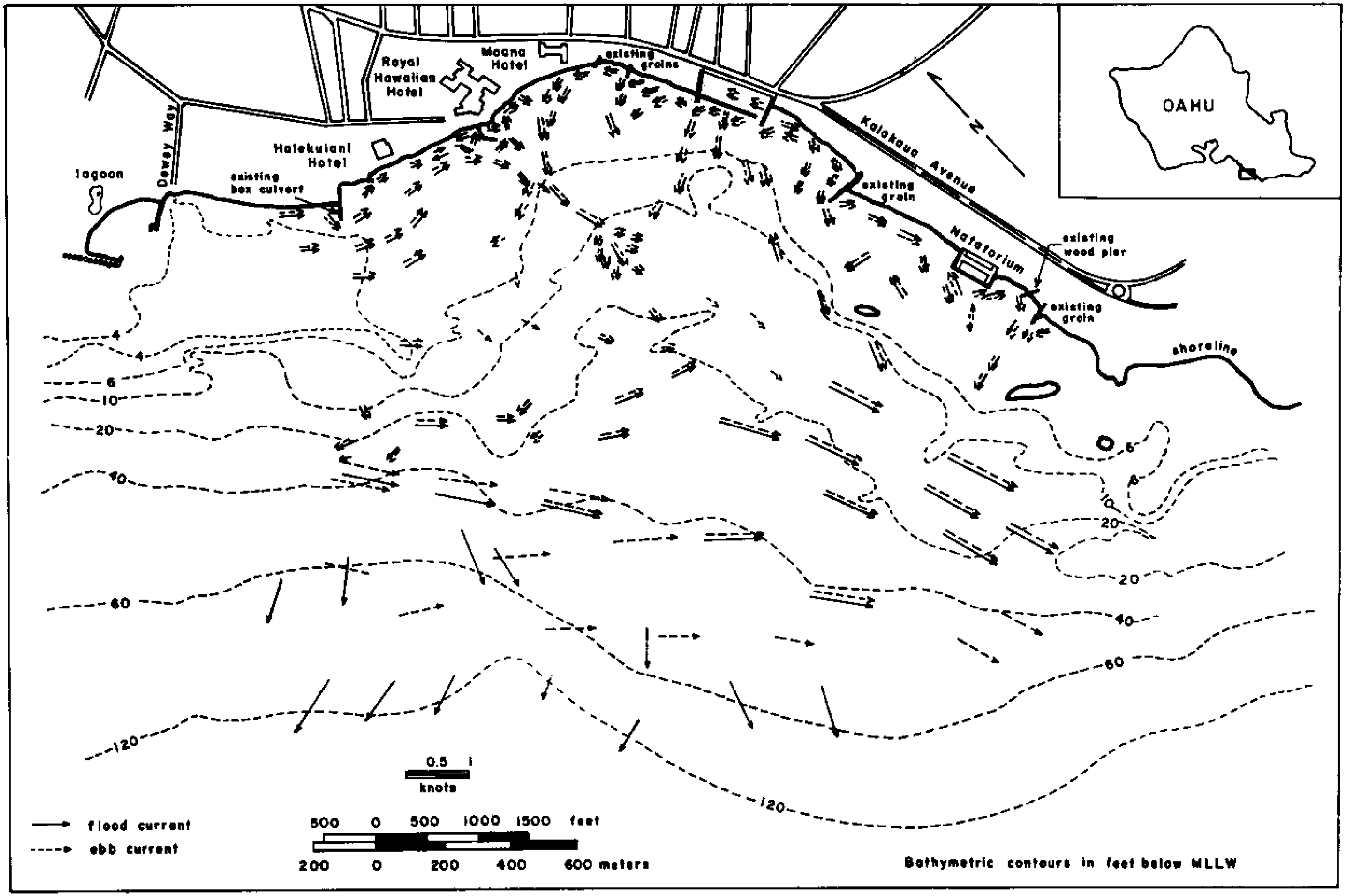


Figure 5.12. Nearshore ebb and flood current patterns at Waikiki Beach, Oahu

Results of current measurements along the southern part of the study area in the vicinity of the Natatorium are shown in more detail in Figure 5.13. The trend is similar to what has been observed for the Kuhio Beach section; that is, during both ebb and flood, offshore currents occur in a southeasterly direction. Their magnitude is small, usually below 0.5 ft/sec. Immediately along the shoreline, currents are wave-induced and variable, but very small. Consequently, littoral transport parallel to the shoreline is usually small.

As far as the effect of offshore currents parallel to the shoreline on sediment motion is concerned, the maximum values of the currents are hardly above threshold values for sediment motion. In the presence of waves, however, the orbital motions along the bottom stir up sand from the bottom into suspension, in which case the resulting currents transport the suspended material. As a result of this, movement of the sediment in a southeasterly direction, more or less in agreement with the dominant flow patterns during ebb and flood, may be expected. During part of the tidal cycle, weak, seawardly directed current components will carry sediment into water of greater depth, if wave action provides the stirring action on the bottom.

Wave-induced currents in the study area are of two types: the longshore currents parallel to shore and the rip currents more or less perpendicular to shore. Longshore currents are affected by the height of the breaking wave. In agreement with the dominant directions of the incoming waves, the longshore currents inside the surf zone flow from southeast to northwest most of the time.

The wave-induced longshore current is a major cause for the direction and magnitude of the littoral drift. Along Waikiki Beach the littoral drift is therefore mostly in the westerly direction. Accumulations of sand east of the Queen's Surf groin and east of the Royal Hawaiian Hotel groin are indications of a predominatly westerly littoral drift. Occasionally waves from opposite directions cause a reversal of the littoral drift pattern.

The wave-induced rip currents in the Waikiki Beach area are only evident if the wave heights exceed a certain not-well-defined value. During this study a major rip current was observed during the high wave conditions of April 26, 1972, as shown on Plate 5.2. In addition to the major rip current off the Royal Hawaiian Hotel, three minor rip currents along the eastern part of the study area were observed (Figure 5.12). In the major rip currents, velocities of over 3 ft/sec were observed. Aerial photographs taken during this particular high surf condition show a significant transport of sediment in the offshore direction. The major rip current at Waikiki Beach, which is present under conditions of heavy swell, is considered to be the most important source of sand loss from the Waikiki beaches. The large deposits of sand in the offshore areas, which are similar in composition and grain size to the characteristics of the beach sand, may be indicative of either onshore or offshore sand movements. The occurrence of the dominant rip current off the Royal Hawaiian Hotel (Plate 5.2) suggests that the offshore transport is greater than possible inshore sand movements in that area.

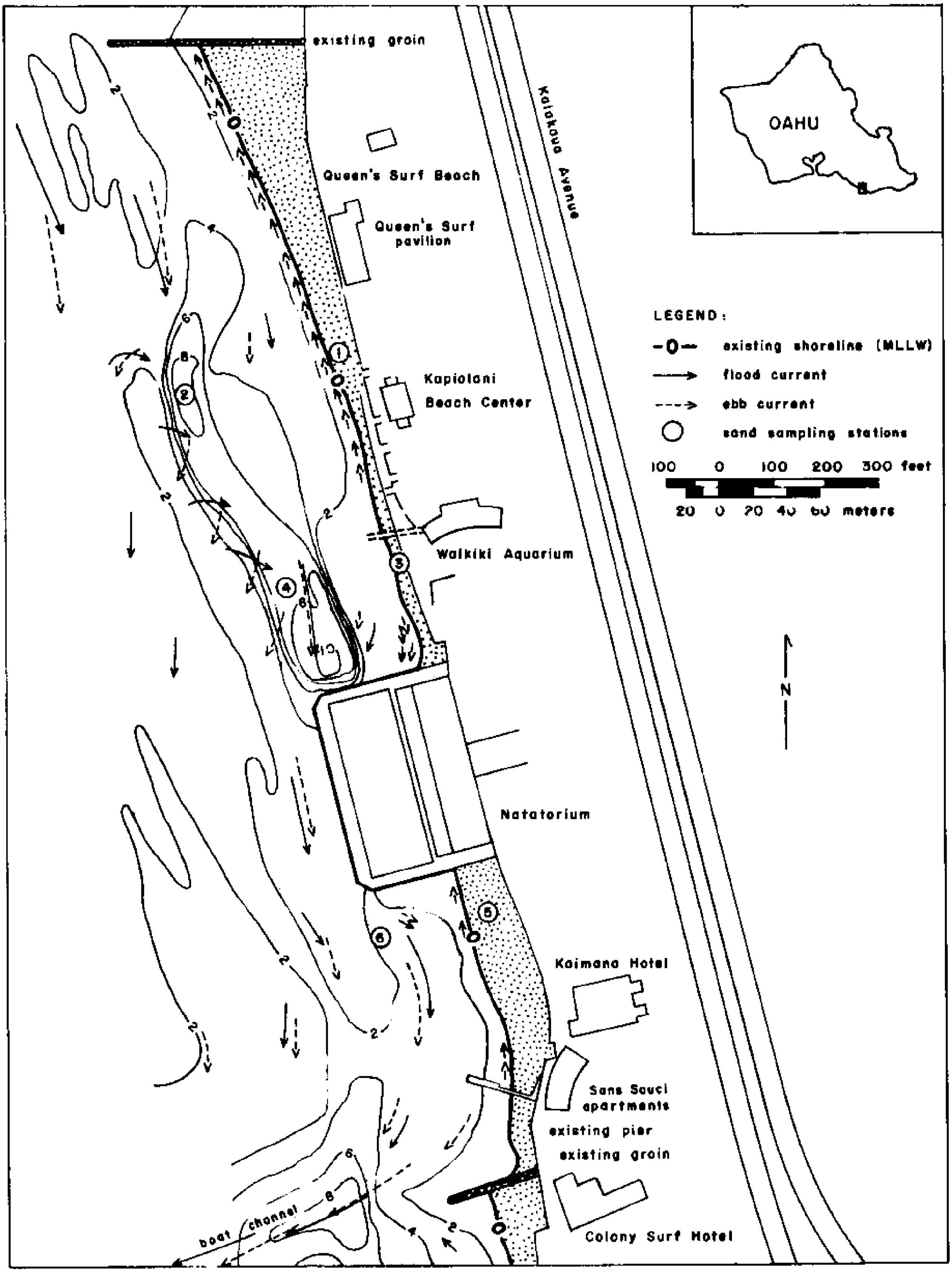


Figure 5.13. Detailed ebb and flood current patterns around the Natatorium

Theoretical studies on rip currents (Bowen and Inman, 1969; Noda, 1972) suggest that the occurrence of edge waves may contribute to the generation of rip currents. Edge waves are long-period, low-amplitude waves with crestlines perpendicular to the shoreline. They may occur as progressive waves or as standing waves. The topography of the offshore area may also contribute to the generation of rip currents. The offshore bottom topography may therefore give rise to the generation of a standing edge wave and an associated rip current pattern.

The section between the Natatorium and the small groin off the Kaimana Hotel has a cuspate formation, with one cusp in the middle part of the beach. A long-period oscillation with a period of approximately 3 minutes may occasionally be observed parallel to the shore at times which may be related to the formation of the cusp. (See Chapter 8 where the relationship between cusp formation and edge waves is discussed.) Other possible reasons are the direction of incoming waves through the boat channel and the reflection of the incoming waves against the eastern wall of the Natatorium.

Beach profiles

In order to study the variability in beach profiles, 11 traverses were established roughly perpendicular to the general orientation of the beach. Eight traverses covering the beach between Fort DeRussy (traverse 1) and the Kaimana Hotel (traverse 8) and three traverses (1K, 2K, and 3K) covering Kuhio Beach are shown in Figure 5.1. Beach elevations were measured at the various traverses over different periods of time between 1971 and 1973. The results of the measurements are shown in Figures 5.14 through 5.22; the upper part of the figures gives the results of the first year of study, the lower part of the second year.

Traverse 1 (Figure 5.14) is situated westward of the Fort DeRussy groin. This beach area was previously nourished with crushed coral and its behavior is somewhat different from the other traverses. From October 1971 to July 1972, few changes were observed, but in the period from September 1972 to March 1973, considerable changes in height occurred. The maximum change in elevation in any spot during that period was about 3 ft.

Traverses 2 through 5 are situated in an area nourished by the littoral drift coming from the Kuhio Beach section. The stability of this section is likely to be adversely affected by sand losses to deep water by means of the major rip current. The beach at traverses 3 and 4 extended the greatest distance seaward from the baseline on March 17, 1972. During the period from March 17 through July 12, 1972, a considerable loss occurred, whereby the beach retreated 20 to 25 ft shoreward. This is most likely due to the high surf conditions of April 14-27, when a strong rip current developed in this area (Plate 5.2).

Traverse 6 is situated south of the Kapahulu storm drain (Figure 5.1). This traverse is very stable. Neither nourishment nor loss of beach material was observed.

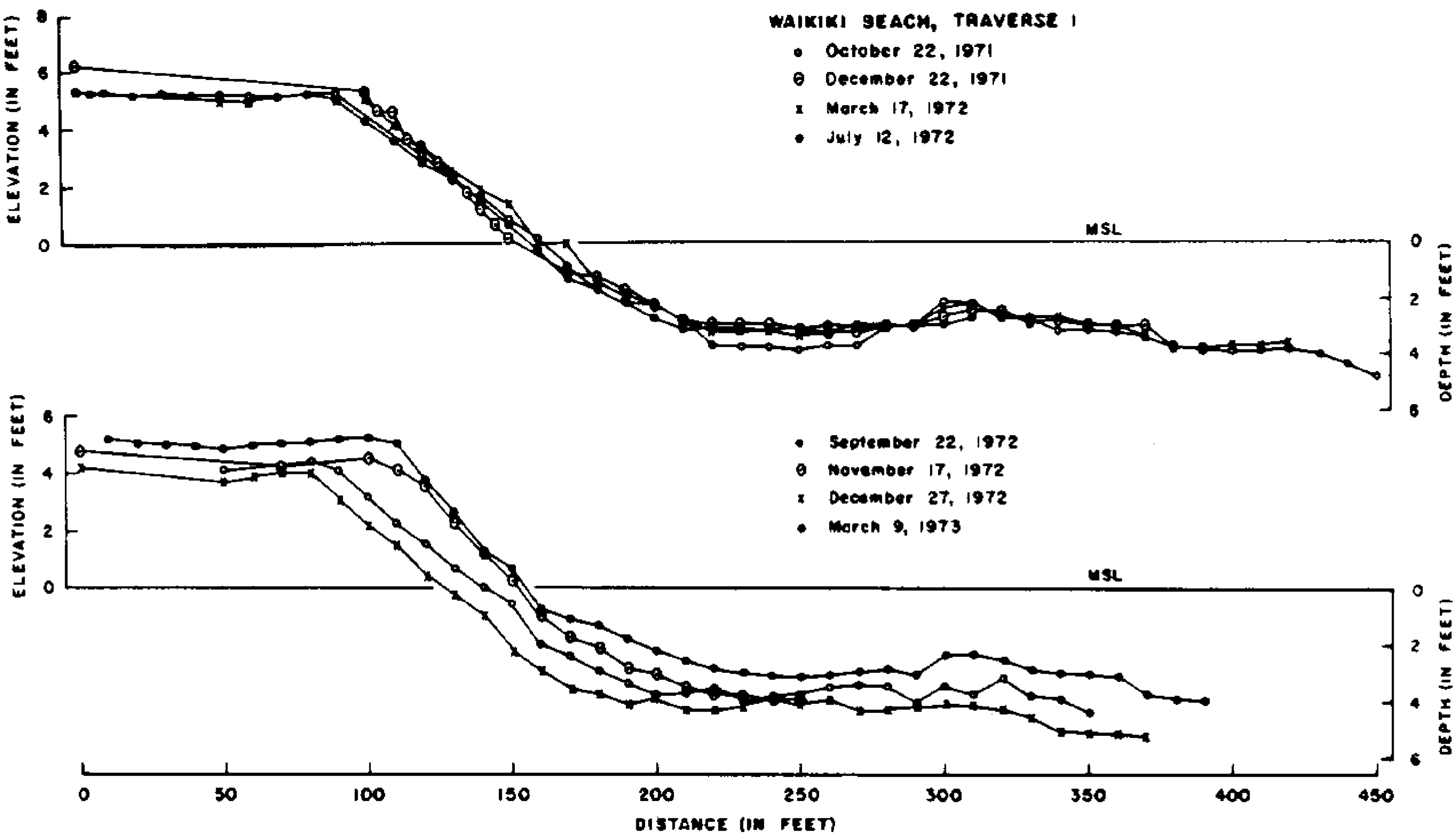


Figure 5.14. Beach profiles for traverse 1, Waikiki Beach, Oahu. (See Figure 5.1 for traverse location.)

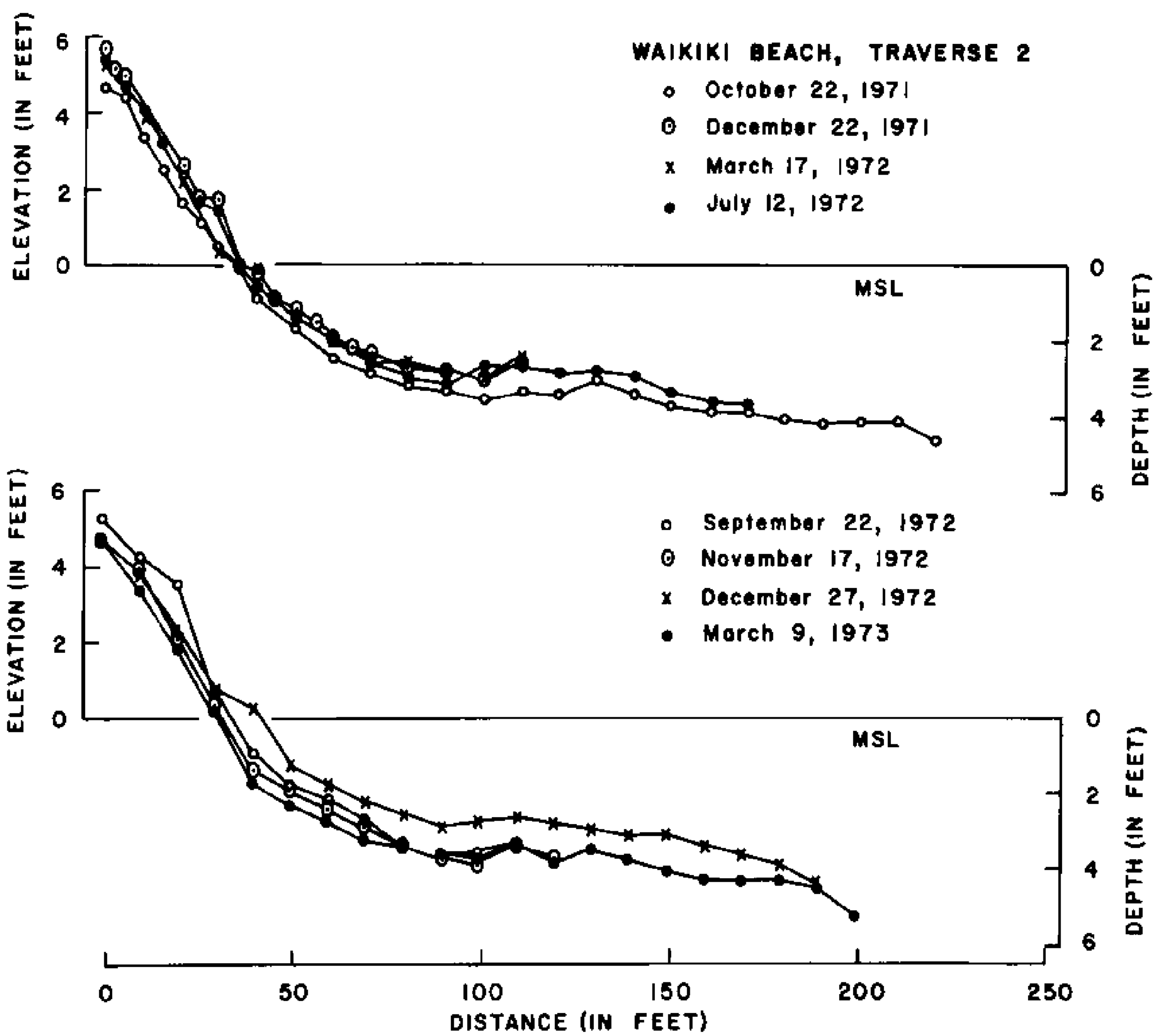


Figure 5.15. Beach profiles for traverse 2, Waikiki Beach, Oahu. (See Figure 5.1 for traverse location.)

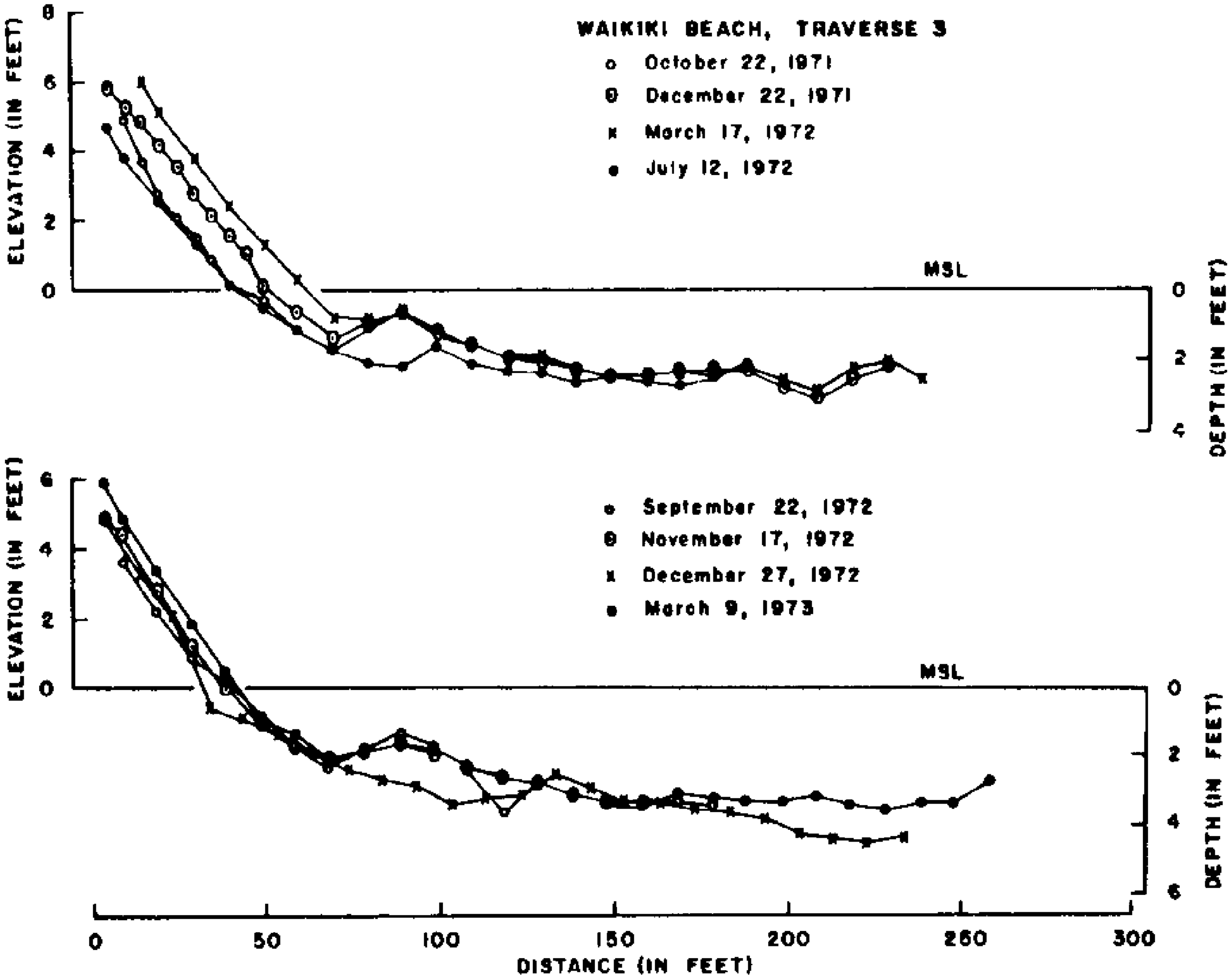


Figure 5.16. Beach profiles for traverse 3, Waikiki Beach, Oahu. (See Figure 5.1 for traverse location.)

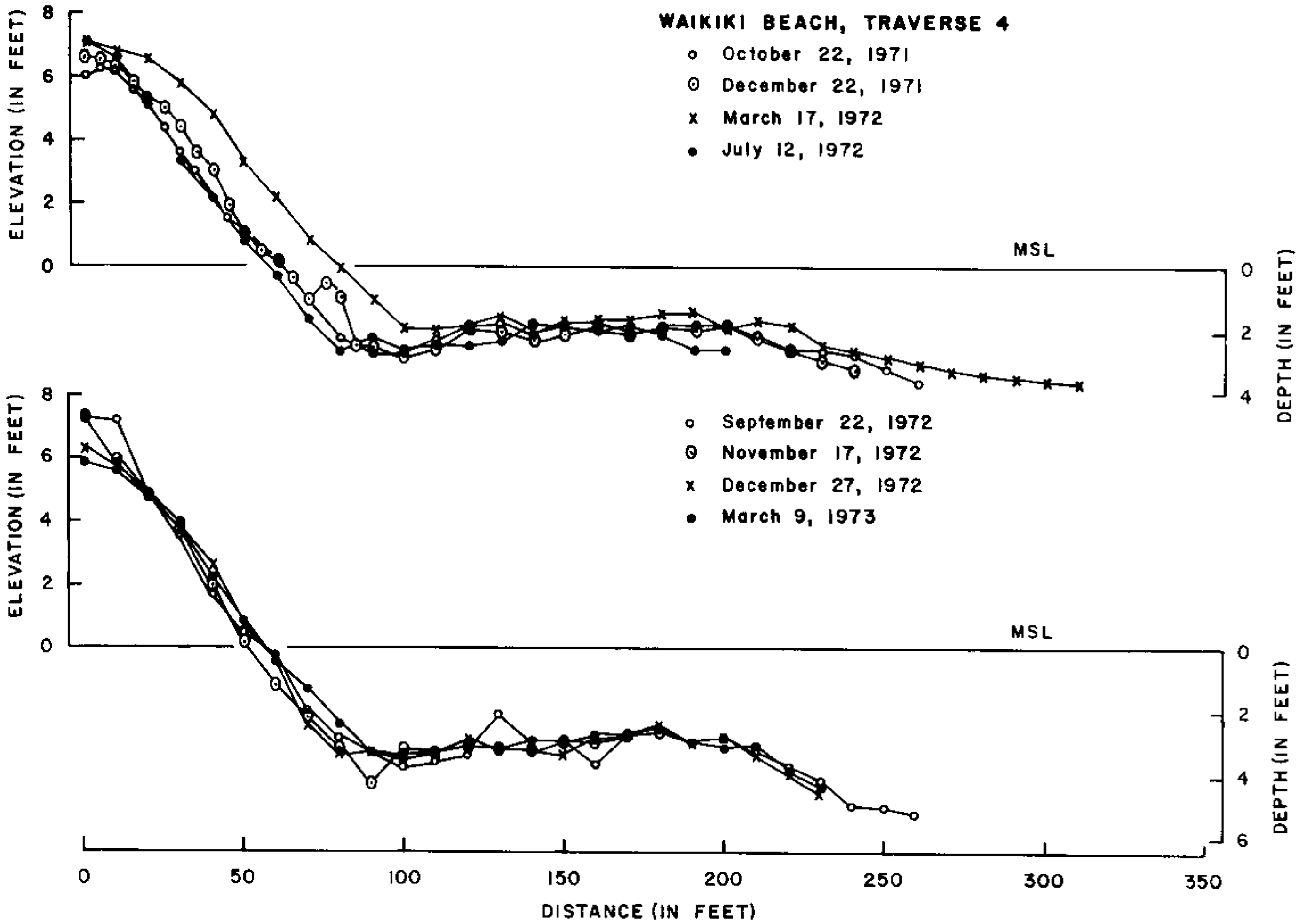


Figure 5.17. Beach profiles for traverse 4, Waikiki Beach, Oahu. (See Figure 5.1 for traverse location.)

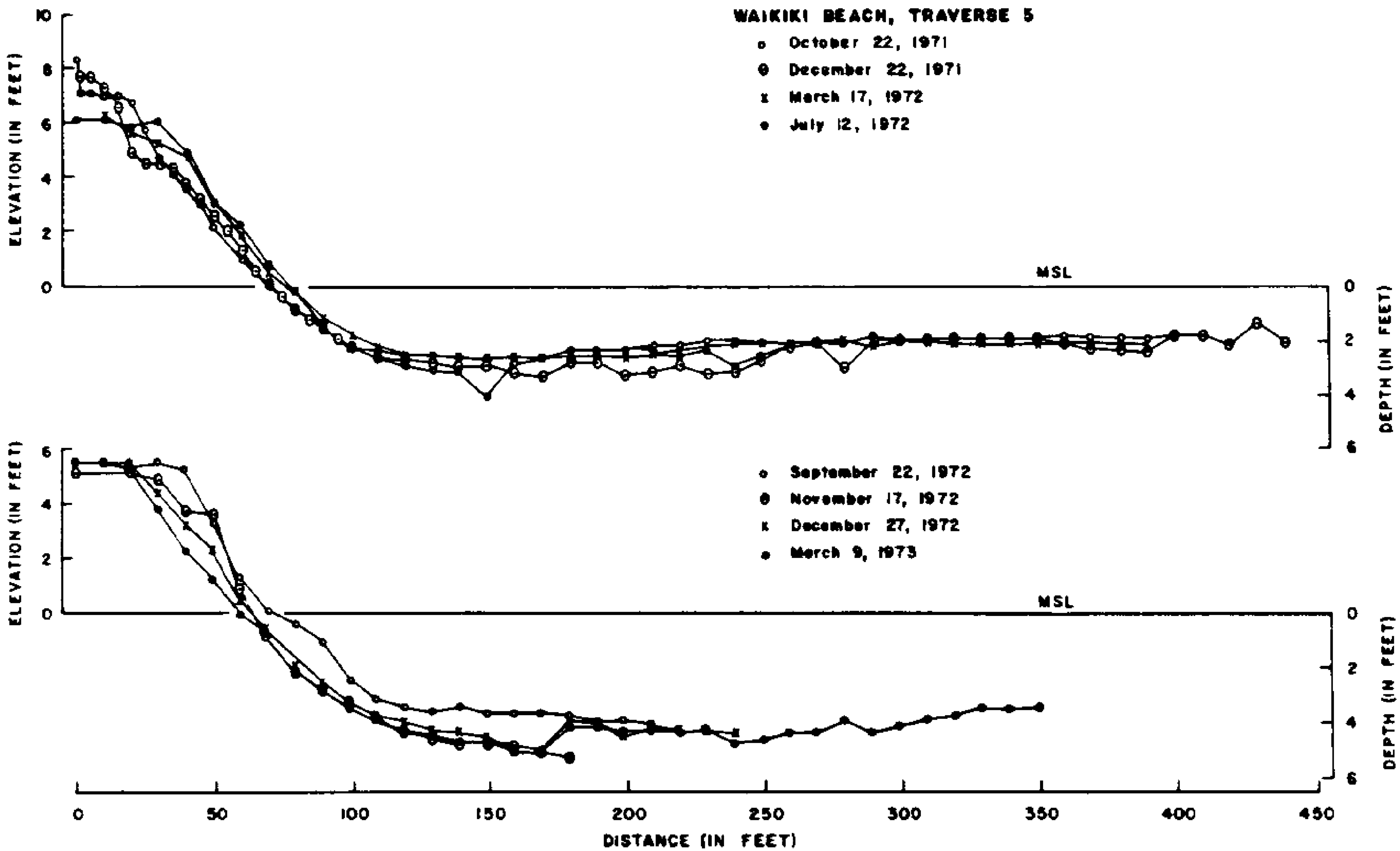


Figure 5.18. Beach profiles for traverse 5, Waikiki Beach, Oahu. (See Figure 5.1 for traverse location.)

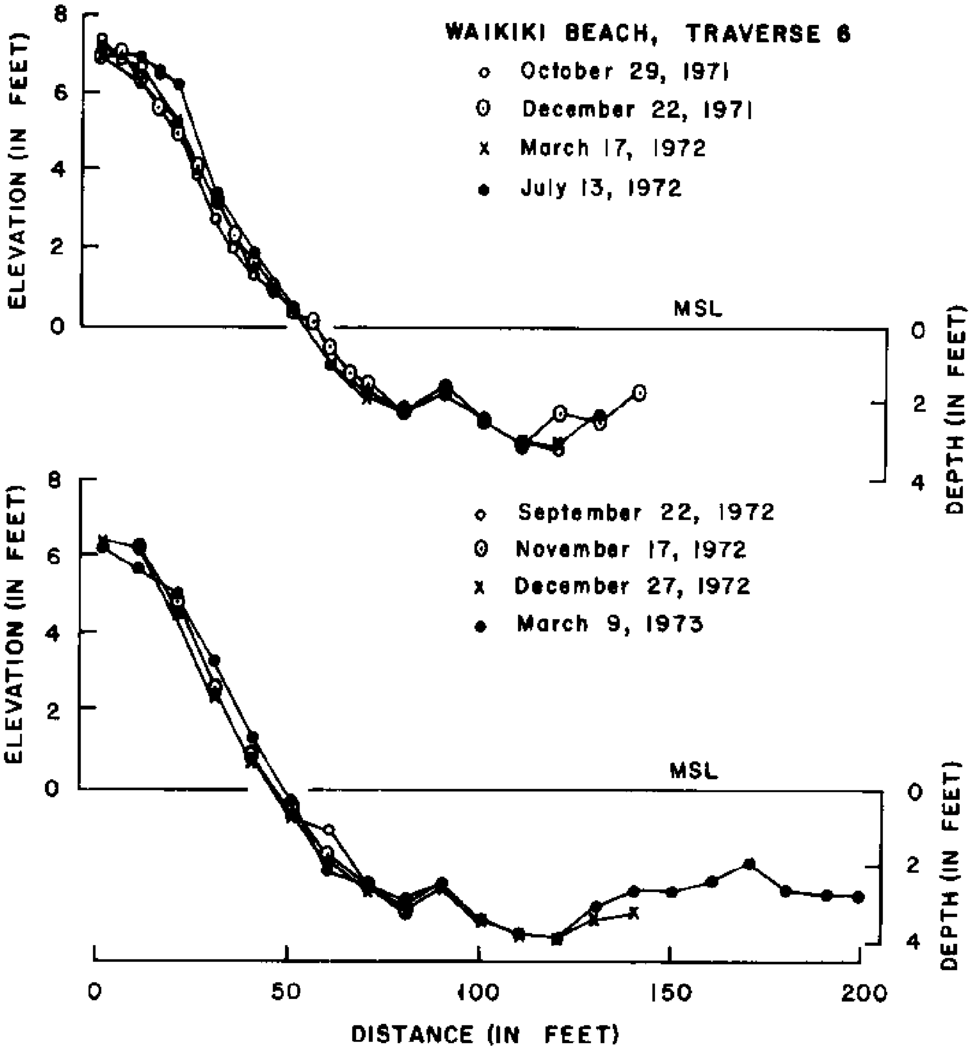


Figure 5.19. Beach profiles for traverse 6, Waikiki Beach, Oahu. (See Figure 5.1 for traverse location.)

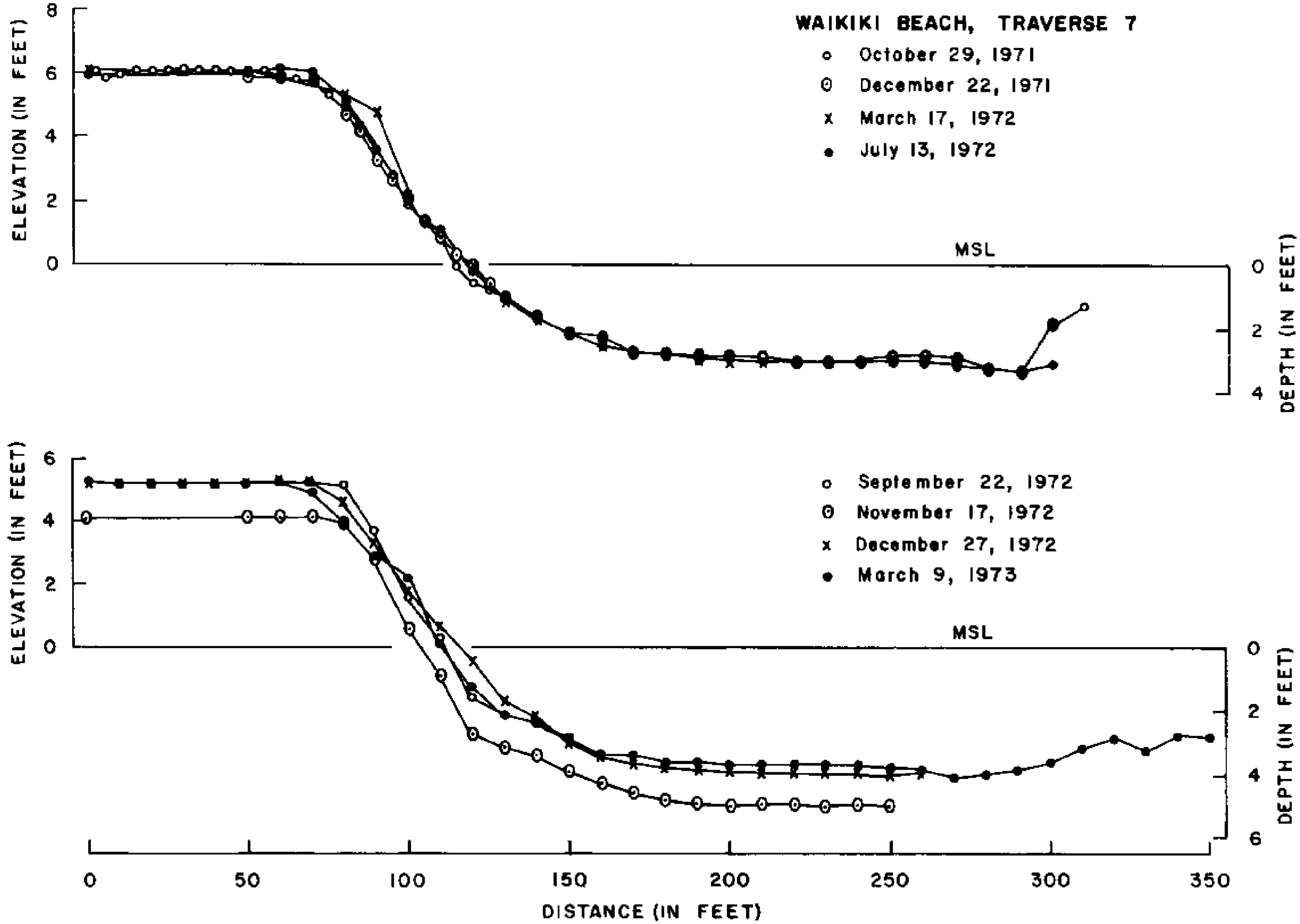


Figure 5.20. Beach profiles for traverse 7, Waikiki Beach, Oahu. (See Figure 5.1 for traverse location.)

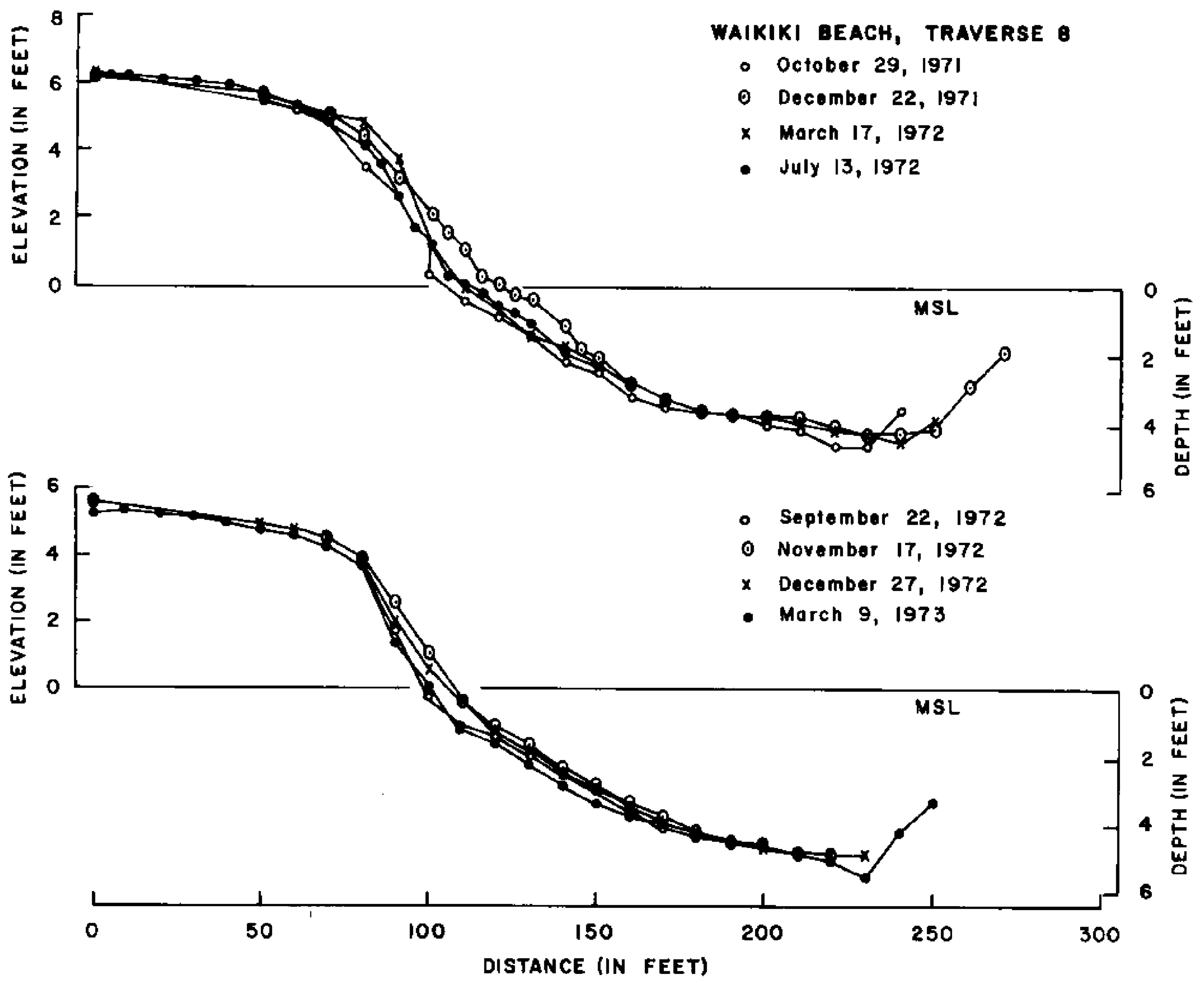


Figure 5.21. Beach profiles for traverse 8, Waikiki Beach, Oahu. (See Figure 5.1 for traverse location.)

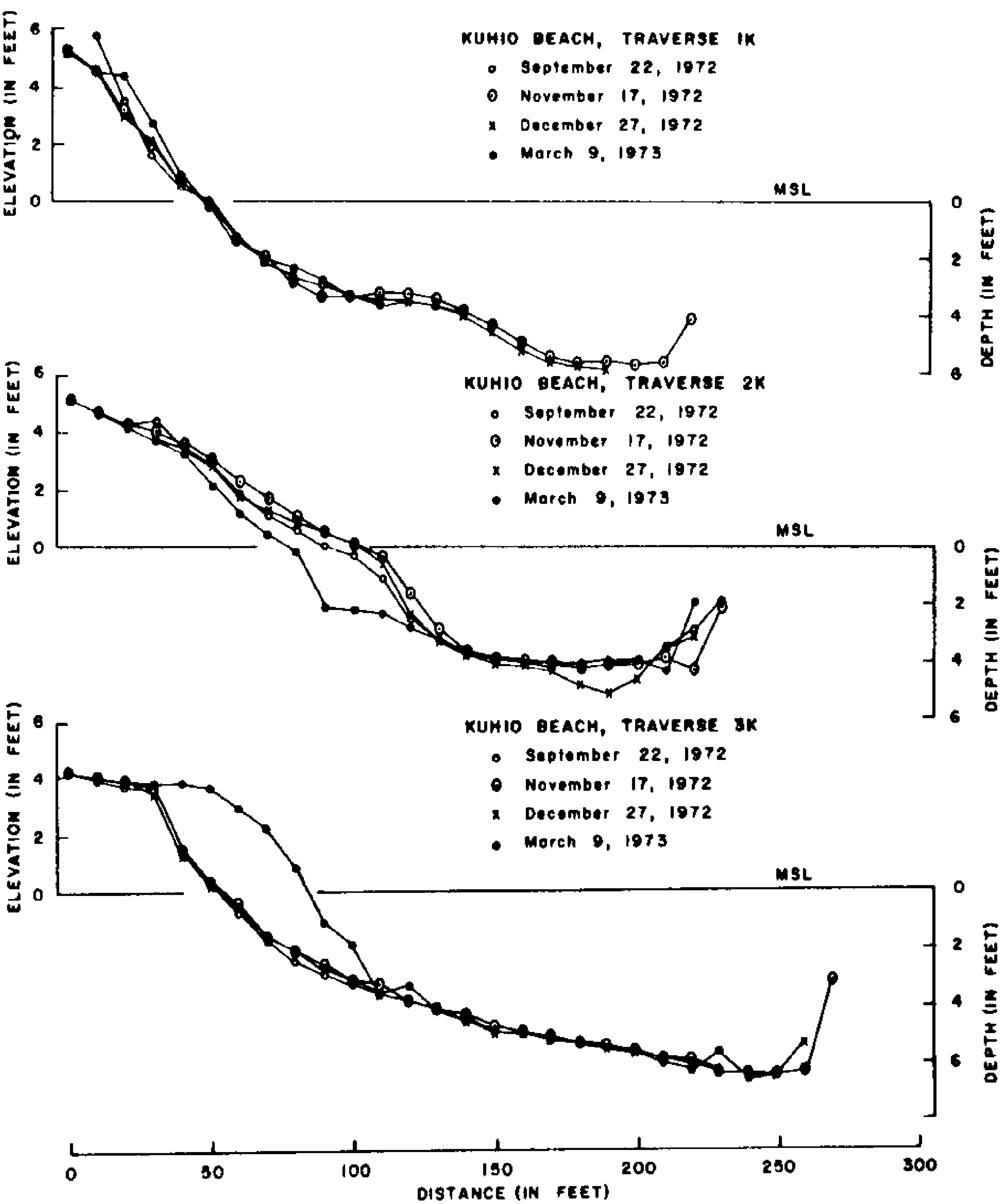


Figure 5.22. Beach profiles for traverses 1K, 2K, and 3K, Waikiki Beach, Oahu. (See Figure 5.1 for traverse location.)

Traverse 7 is situated updrift of the Queen's Surf groin and is also relatively stable. The survey of November 17, 1972, as shown in Figure 5.20, is possibly in error. The orientation of the beach in this section corresponds to the direction of the approaching wave crests. The relative stability of the beach suggests that the direction of the approaching waves was fairly constant during the period of the survey. There seems to be very little transport in the longshore direction; the Queen's Surf groin apparently acts as a complete barrier to the littoral drift.

The beach south of the war memorial (Natatorium) where traverse 8 is situated is also relatively stable with some modest fluctuations. During the period from October 29 to December 22, 1971, there was a modest gain in beach width of about 11 ft at MSL. This gain disappeared over the period from December 22, 1971 to March 17, 1972. Over the period from March 17 to July 13, 1972 when significant losses occurred at traverses 3 and 4, there was only a minor loss at traverse 8 at levels of 1 to 5 ft above MSL.

Two traverses at Kuhio Beach, 2K and 3K, show evidence of much sand movement in opposite directions. Although the surveys of these traverses were conducted after the artificial nourishment program had terminated, changes of beach alignment may still have been under the influence of the past operations, suggesting a period of natural adjustment. The most significant changes occurred in traverse 3K over the period from December 27, 1972 through March 9, 1973.

An overview of the changes in sand volume in the Waikiki Beach area is given in Figure 5.23 where computed cross-sectional areas at the various traverses are plotted against time, covering the period from October 1971 to March 1973. The period was too short to reveal a significant long-term trend; besides, the profiles have been somewhat affected by the artificial nourishment operations. The greatest fluctuations occurred in the period from September 1972 to March 1973. The general pattern is one of relative stability.

Sediment characteristics

In addition to the measurement of beach profiles, sand samples were collected from both the beach and the offshore areas. The samples were dried, sieved, weighed, and subsequently analyzed for grain size distributions. A computer program was utilized to obtain significant parameters of the sediment samples.

Since much of the sand in the Waikiki Beach area is of foreign origin (not locally generated), significant differences in beach material characteristics over the area were expected. Characteristic distributions for the sand in the swash zone at the time of the survey are presented in Figure 5.24. A summary of the median diameters of the waterline samples and of the samples taken at 10 ft offshore from the waterline is presented in Table 5.3. The table shows that the differences in grain size characteristics are not as large as were anticipated. Most sand samples at the waterline were in the medium-sized sand range, with ϕ values between 1 and 2. The material at 10 ft offshore was consistently somewhat coarser than the material at the waterline.

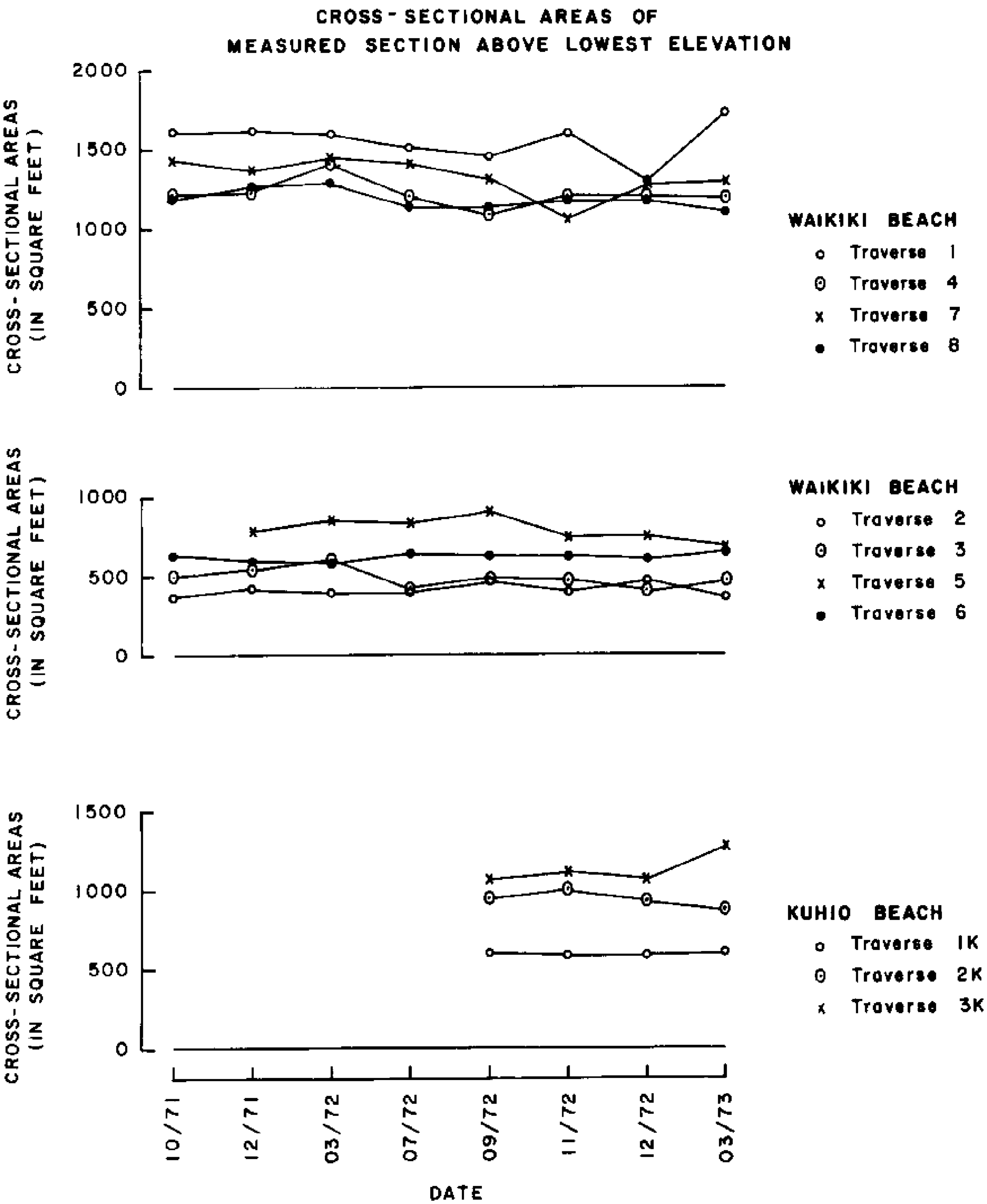


Figure 5.23. Changes in cross-sectional area of beach profiles at Waikiki Beach traverses

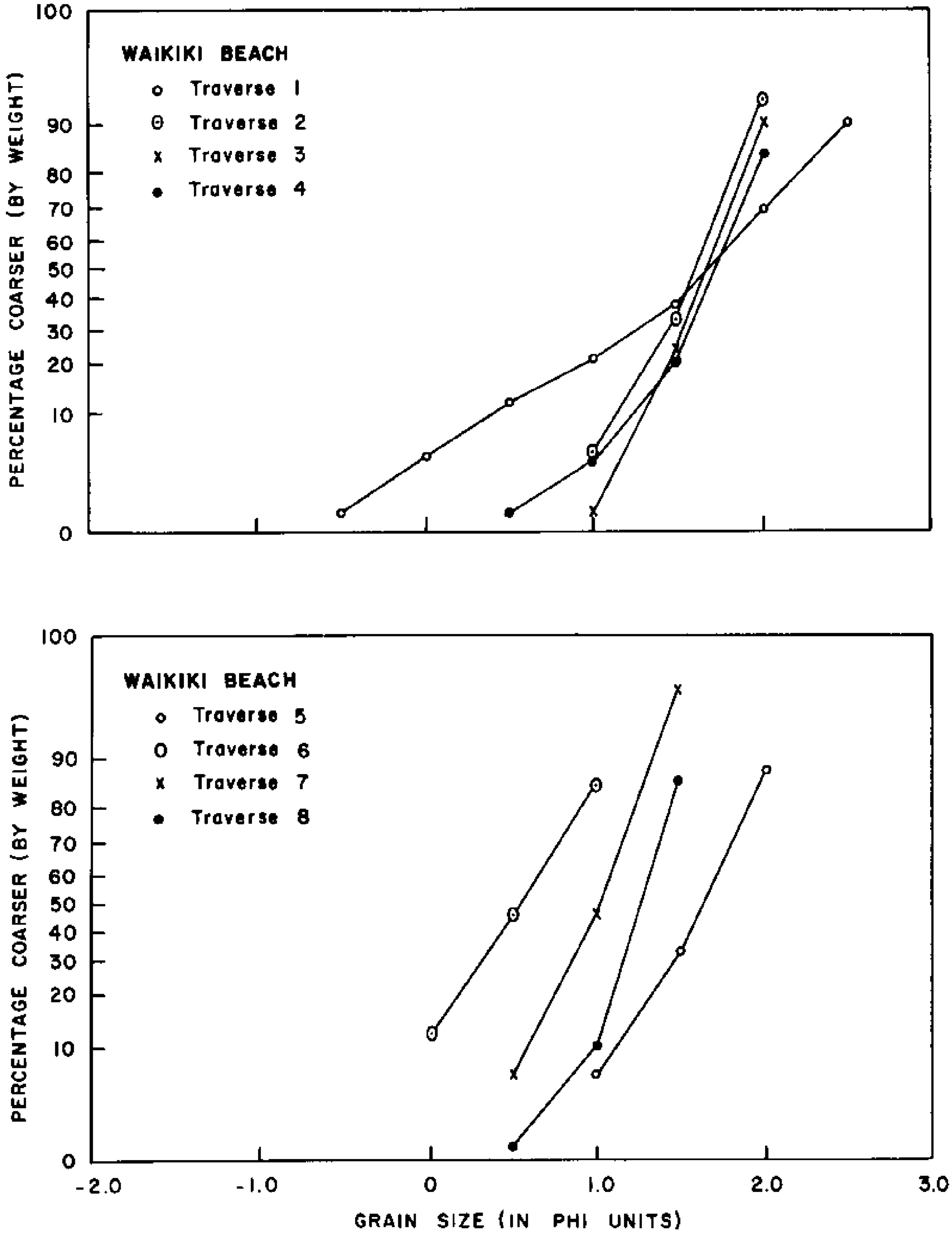


Figure 5.24. Grain size distributions for swash zone sand from Waikiki Beach

TABLE 5.3. MEDIAN DIAMETER OF BEACH SAND AT WAIKIKI BEACH

Traverse	Median Diameter of Sediment at Waterline		Median Diameter of Sediment 10-ft Offshore	
	ϕ	mm	ϕ	mm
1	1.70	0.31	-0.89	1.85
2	1.60	0.32	1.15	0.45
3	1.65	0.32	1.46	0.36
4	1.73	0.30	1.62	0.33
5	1.62	0.32	1.60	0.32
6	0.54	0.70	0.45	0.73
7	1.04	0.50	0.65	0.64
8	1.29	0.40	1.04	0.49

Table 5.4 presents various statistical size characteristics of the samples taken from the swash zone. The differences between the medium and mean diameters appear to be small.

TABLE 5.4. SIZE CHARACTERISTICS OF WAIKIKI BEACH SAND SAMPLES TAKEN FROM SWASH ZONE

Traverse	Phi Medium Diameter (M_d ϕ)	Phi Mean Diameter (M_ϕ)	Deviation Measure (σ_ϕ)	Skewness (α_ϕ)	Kurtosis (β_ϕ)
1	1.70	1.53	0.77	-0.22	0.80
2	1.60	1.54	0.34	-0.18	0.79
3	1.67	1.65	0.27	-0.07	0.70
4	1.73	1.70	0.28	-0.11	1.36
5	1.62	1.59	0.35	-0.09	0.87
6	0.54	0.53	0.43	-0.02	0.61
7	1.04	1.00	0.30	-0.13	0.67
8	1.29	1.29	0.22	0.00	1.23

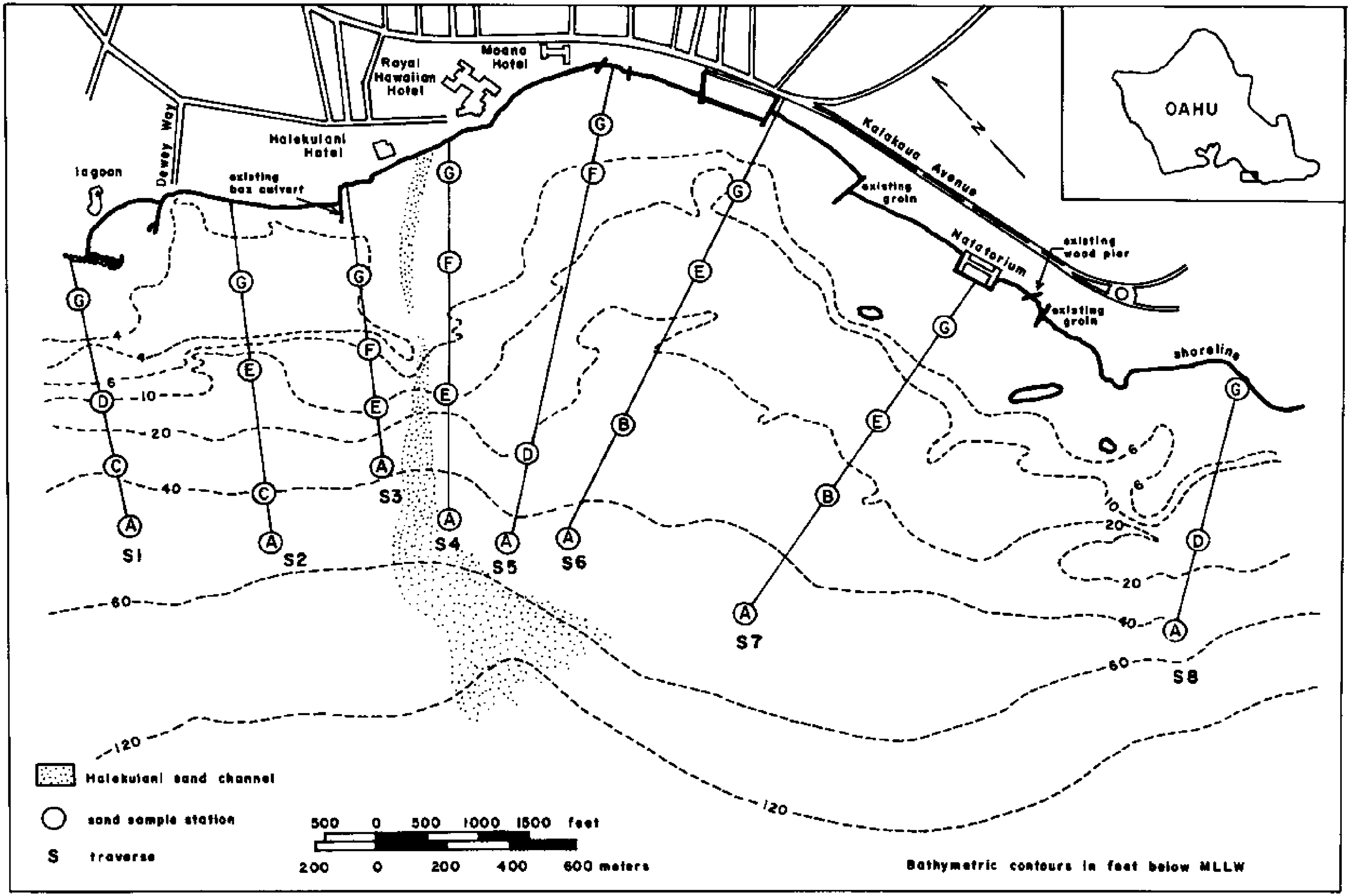
In order to compare beach samples with offshore sediments, a summary of Chave and Tait's (1973) analysis of offshore bottom sediments is listed in Table 5.5. This table gives several statistical characteristics of the offshore sands at depths ranging from 1 to 58 ft. The locations of traverses S1 through S8 are given in Figure 5.25; the stations of the traverses are identified as A through G.

A comparison of Tables 5.3 and 5.5 shows that the median ϕ values of the beach sand between traverses 2 and 5 (see Figure 5.1) correspond quite well with the median ϕ values for the offshore sand deposits between traverses S4 and S5 (Figure 5.25).

TABLE 5.5. STATISTICAL CHARACTERISTICS OF OFFSHORE SANDS OF WAIKIKI BEACH

Traverse and Station		Depth (ft)	Median Diameter (M_d ϕ)	Mean Diameter (M_ϕ)	Deviation (σ_ϕ)	Skewness (α_ϕ)
S1	A	-50.0	-0.30	-0.20	0.50	0.20
	C	-40.0	0.40	0.45	-1.25	-0.04
	D	-10.0	-0.30	-0.20	-1.00	-0.10
	G	- 3.0	0.80	0.65	-1.05	0.14
S2	A	-58.0	0.70	0.65	-0.85	0.06
	C	-42.0	1.80	1.80	-0.60	0.00
	E	-17.0	0.90	1.05	-1.25	-0.12
	G	- 3.0	1.20	1.05	-1.25	0.12
S3	A	-45.0	2.10	2.00	-0.70	0.14
	E	-17.0	-0.10	0.10	-0.90	-0.22
	F	- 7.0	-1.20	-0.65	-0.85	-0.65
	G	- 4.0	-0.30	0.10	-0.90	-0.44
S4	A	-55.0	1.10	0.65	-1.65	-0.27
	E	-25.0	1.00	1.00	-0.60	0.00
	F	- 4.0	1.60	1.70	-0.50	-0.20
	G	- 3.0	1.70	1.70	-0.50	0.00
S5	A	-55.0	0.20	0.20	-1.20	0.00
	D	-33.0	1.90	2.00	-0.60	-0.18
	F	- 7.0	1.40	0.85	-1.05	0.52
	G	- 3.0	1.75	1.65	-0.75	0.13
S6	A	-50.0	1.00	1.05	-1.25	-0.04
	B	-28.0	2.20	2.05	-0.65	0.23
	E	-17.0	1.60	1.60	-0.40	0.00
	G	- 9.0	-0.20	0.10	-1.20	0.25
S7	A	-50.0	0.25	0.50	-0.65	-0.40
	B	-25.0	1.40	0.80	-1.60	3.58
	E	-16.0	1.60	1.55	-0.35	0.14
	G	- 2.0	0.15	0.25	-1.05	-0.10
S8	A	-50.0	1.70	1.40	-1.10	0.27
	B	-35.0	2.25	2.15	-1.10	0.09
	D	-15.0	1.80	1.70	-0.70	0.14
	G	- 1.0	-0.20	0.00	-1.10	0.18

From Chave and Tait, 1973



After Chave and Tait, 1973

Figure 5.25. Locations of traverses and sand sample stations at Waikiki Beach, Oahu

The median ϕ value for samples at the waterline is 1.65; whereas, for stations F and G of traverse S4, values of 1.60 and 1.70 were found. Stations D, F, and G of traverse S5 have median ϕ values of 1.90, 1.40, and 1.75, respectively.

The correspondence of grain size characteristics of the material on the beach and on the adjacent offshore area supports the hypothesis, made earlier, that the major rip current in this area carries beach material in a seaward direction. This can be a prime source of erosion in that area.

Aerial photographs of the study area show that large offshore portions are completely covered with sand, whereas other portions are bare reef, usually with sand pockets. Figure 5.26, made from such an aerial survey, shows this. The general characteristics of the offshore bottom sand (fine, medium, etc.) for the various survey stations are shown in Table 5.5.

For a more detailed description of the bottom characteristics, reference is made to Chave et al. (1973) in which the percentages of cover for live coral and algae are listed.

In the southern part of the study area, sand samples were taken on both sides of the Natatorium for onshore and offshore stations 1 through 6 (Figure 5.13). The results of the analysis are shown in Figure 5.27 and in Table 5.6.

The distribution for station 5 corresponds reasonably well with the distribution for station 1 (Figure 5.27) which was taken on a different date. At station 6 sand is somewhat coarser than at stations 2 and 4. Onshore station 3 has much coarser sand than stations 1 and 5.

A possible explanation for the coarser sand at station 3 is its location downdrift of the Natatorium. This deprives it from adequate nourishment of sand from the south. In addition, the fine parts are washed out by the waves and not replenished by the littoral drift.

<u>Sand transport measurements</u>

Quantitative measurements of littoral sand movement were attempted by conducting tracing experiments in the area off the Royal Hawaiian Hotel. It was of particular interest to find out whether or not the groin off the Royal Hawaiian Hotel has a significant effect on the location and generation of the major rip current in that area.

In the tracing experiments, Rhodamine-B dye was used to color beach sand and fluorescent tracing techniques were used to count the number of fluorescent particles in sand samples. About 50 pounds of dyed sand was placed in the surf zone about 120 ft east of the groin. The experiments confirmed a westerly drift toward the groin, and some bypassing of sand beyond the groin was also noticed. Flow measurements indicated that the major rip current concentrated itself at a distance away from the groin and did not seem to be significantly influenced by the existence of the Royal Hawaiian Hotel groin. As to the effect of the groin on the rip current, the measurements were inconclusive.

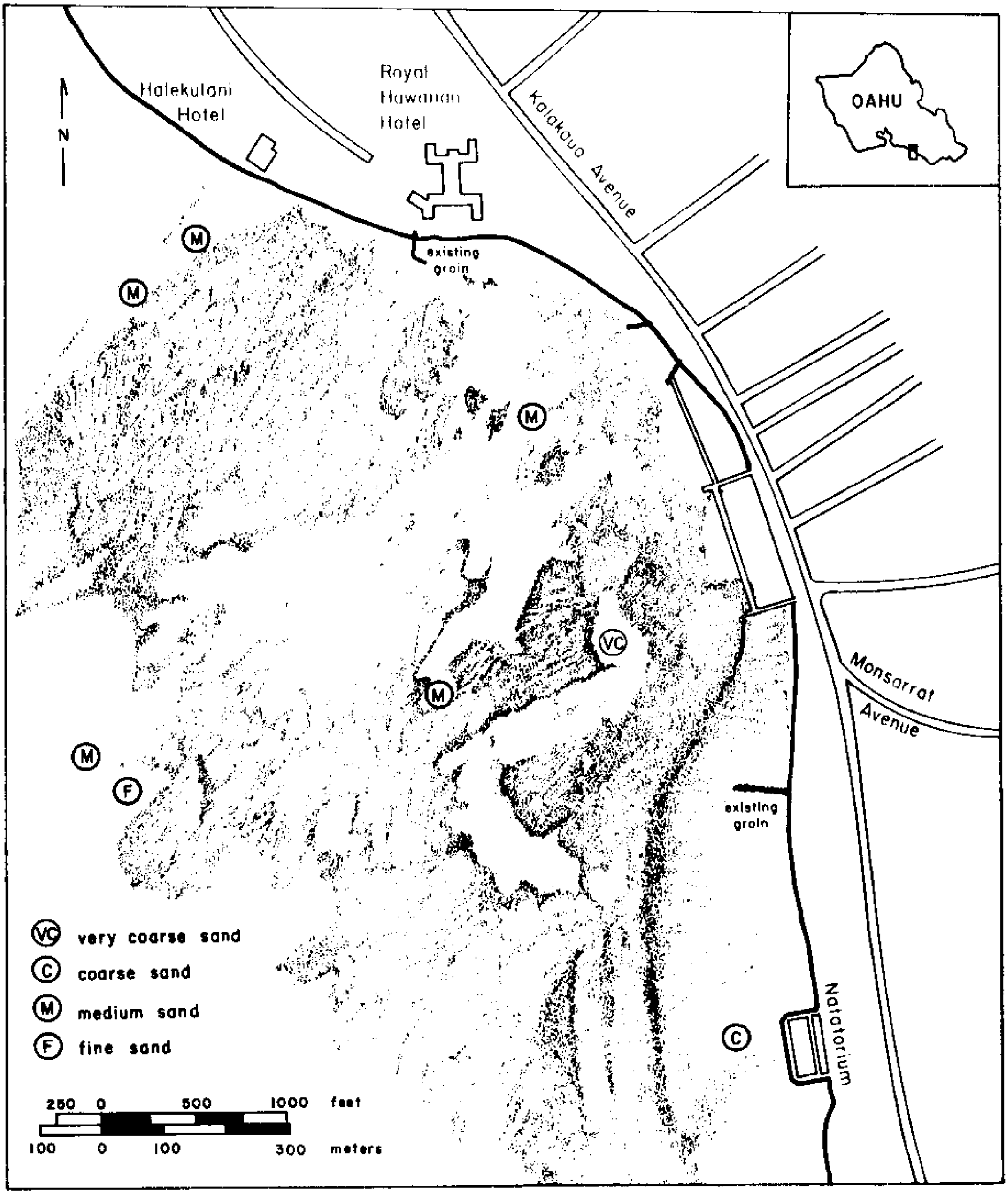


Figure 5.26. Offshore sand distribution at Waikiki Beach based on sand samples and aerial photographs

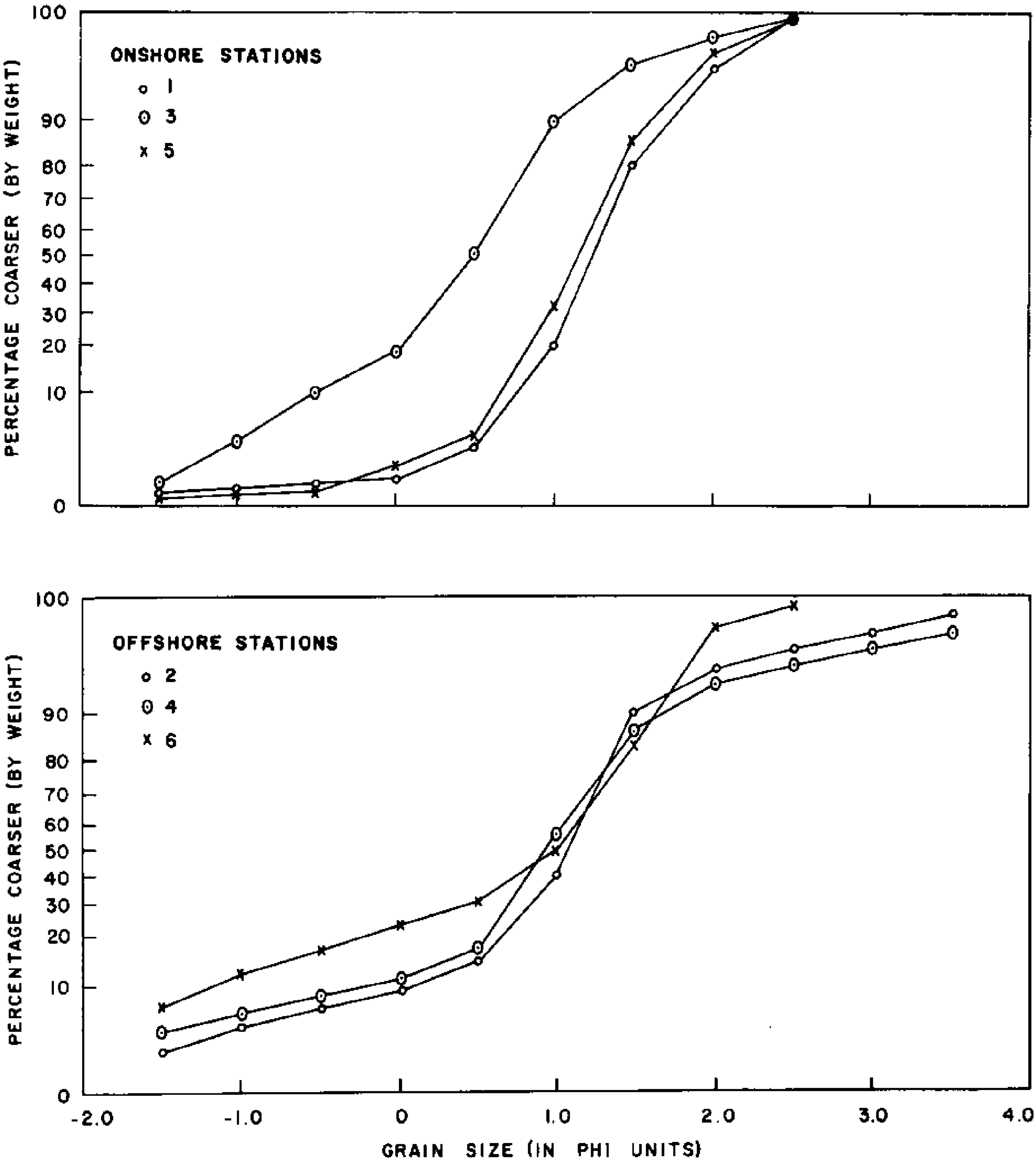


Figure 5.27. Grain size distribution for swash zone and offshore sands north and south of the Waikiki Natatorium

TABLE 5.6. MEDIAN DIAMETER OF ONSHORE AND OFFSHORE SAND NEAR NATATORIUM

Onshore Station	Median Diameter of Beach Sand (ϕ)	Offshore Station	Median Diameter of Offshore Sand (ϕ)
1	1.2	2	1.1
3	0.4	4	0.9
5	1.15	6	1.0

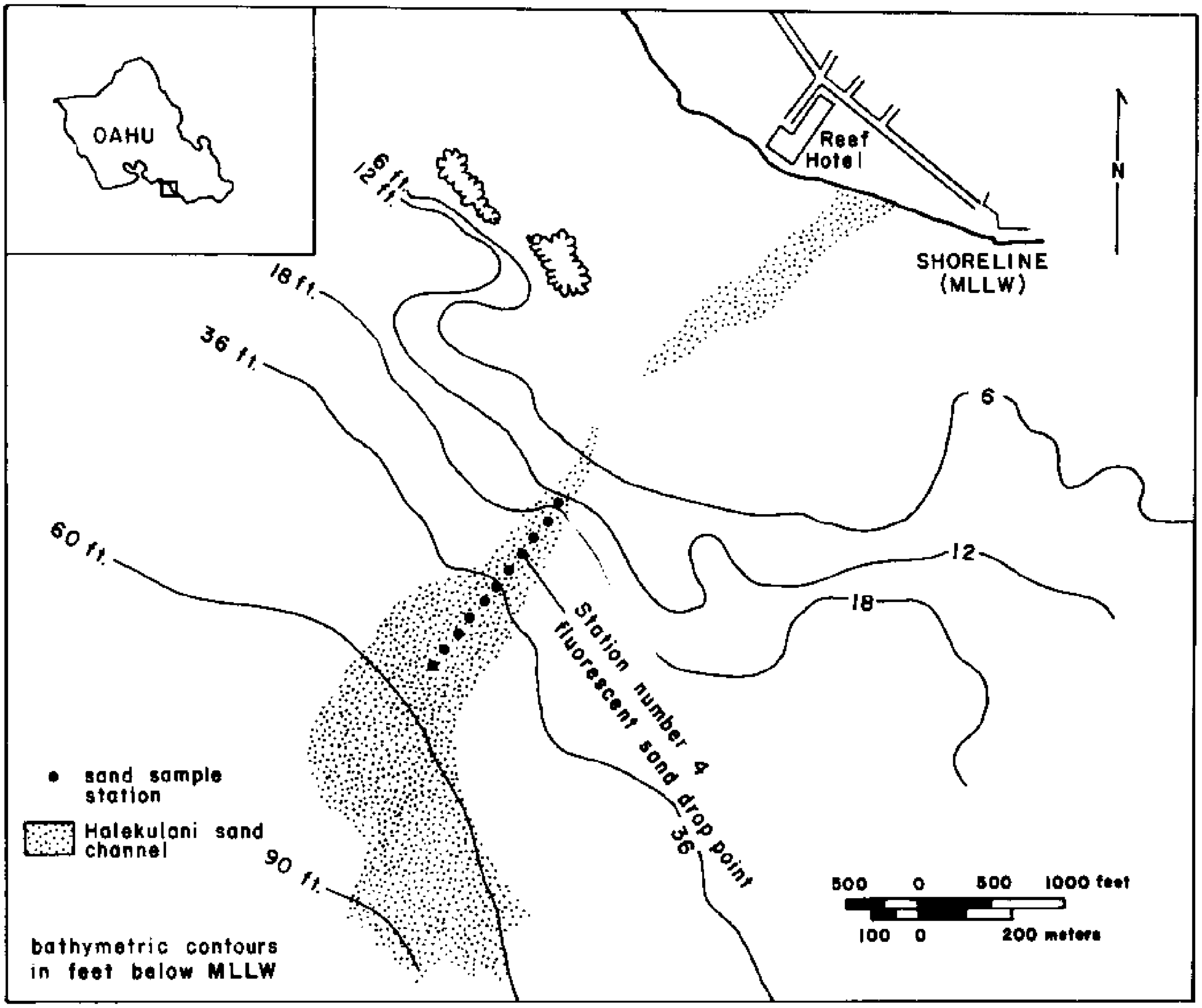
The tracing tests had to be carried out at night in order to avoid interference with recreational beach use during the day. The experiments were laborious and time consuming. In order to be of significant value, the tests would have required a considerable amount of additional time and effort, which was not justified in this situation. For this reason, the tracing tests were discontinued.

Earlier measurements of sand transport were made in the Waikiki Beach area (Kern, 1970). Aerial photographs and bathymetric data indicated the presence of two shallow offshore channels in this area. One of the two is the Kuhio Beach channel, which is located seaward and somewhat westward of the Kapahulu groin. The other is the Halekulani channel, off the Halekulani Hotel. Both channels are partly covered with sand and are supposedly remnants of two river mouths in this area.

It had previously been suggested that the Halekulani sand channel could function as a drain to the littoral drift carrying sand seaward from the beach. To investigate this possibility, a study of sand tracing was made by Casciano and Kern and reported in Kern (1970). A summary of their method and analysis is given below. Stations in the Halekulani channel were marked by iron bars 100 ft apart, as indicated in Figure 5.28. On both sides of station 4, a grid system of bars 10 ft apart was installed for detailed observations. Rhodamine-B dye was used as a tracer. An initial deposit of 362 pounds of colored sand was made at station 4 and observations were made to study its movement.

Surface samples were collected by divers with the use of bottle caps coated with vaseline (petroleum jelly). From January 23, 1970, two days after the fluorescent sand was deposited in the channel, to May 22, 1970, 13 sets of surface cap samples were taken, each on a different day. The time between successive sampling days ranged between two days in the beginning of the study and two weeks near the end. In addition to the collection of surface samples, sand cores were taken at the end of the study period. The number of colored grains in each sample was counted using ultraviolet light.

Assuming that the number of grains counted in a surface sample would be a measure of the total sand movement, the count at the stations on the seaward and landward sides of the deposition point would then indicate whether there was a resultant seaward or landward movement of the bottom sand in the channel.



After Kern, 1970

Figure 5.28. Halekulani sand channel study site and sampling stations

Figure 5.29 shows the total count of all sand grains at all stations in the channels. This count and the results of individual counts during each of the observations indicated a resultant sand transport in the landward direction of the channel during the period of observation. The results of an analysis of sand cores confirmed the findings of the surface sampling.

In addition, at each station the height of the iron bar over the (average) bottom was measured. At the most landward station, the observed bottom elevation increased about 0.1 m; at the other stations, the elevation of the bottom did not change significantly.

One may ask whether the period of observation (4 months) was long enough to justify a general conclusion. This is partly answered by the results of the flow measurement. During the large southern swell observed in March 1972 and also during other periods of observations, there were no indications of a rip current in the Halekulani channel; on the contrary, the currents under most conditions seemed to move parallel to the shoreline, possibly with a very small shoreward component. Consequently, evidence was found for net material transport in an onshore direction in the Halekulani channel.

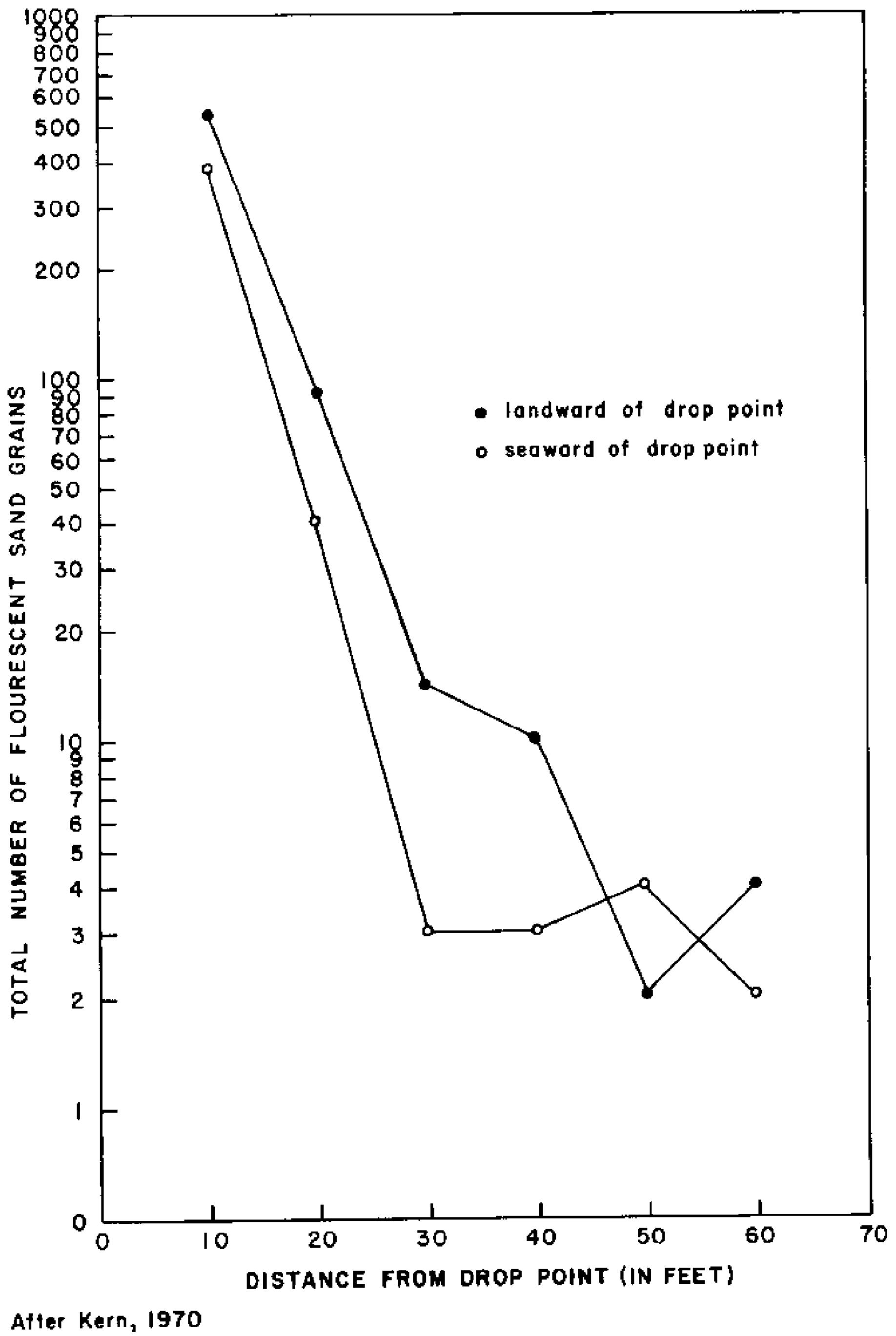


Figure 5.29. Cumulative count of fluorescent sand grains at various stations in the Halekulani sand channel

Measures for improvement

Any possible measure of improvement proposed for Waikiki Beach is likely to become the subject of intense discussion, such as was demonstrated by the history of events in the development of the most recent plans for Kuhio Beach. After preliminary model testing in the Look Laboratory of Oceanographic Engineering and the development of a plan by the state of Hawaii, much opposition was raised to the state plan because of environmental concerns in general and adverse effects on surfing in particular.

In 1970 the Kuhio Beach Advisory Committee was created by the late Governor John A. Burns. The committee was chaired by Dr. C.L. Bretschneider and was instrumental in developing a compromise plan, as discussed under "beach history" (Figure 5.2).

Suggestions for additional improvement are therefore submitted with utmost reservation: first, because the scope of this present study has not been comprehensive enough for more definite conclusions; and second, because it is realized that environmental concerns and surfing interest do play an essential and legitimate role in the shaping of any new plans.

Nevertheless it was felt that this report would not be complete if the author's viewpoints on improvement of the beach, from a purely technical standpoint, were not given.

Field measurements carried out under this study and considerations of previous studies show the following characteristics of the study area:

1. Predominant direction of the littoral drift from southeast to northwest

2. Little natural nourishment of the beach areas

3. Beaches relatively stable during most of the year but occasionally losing sand during high surf conditions

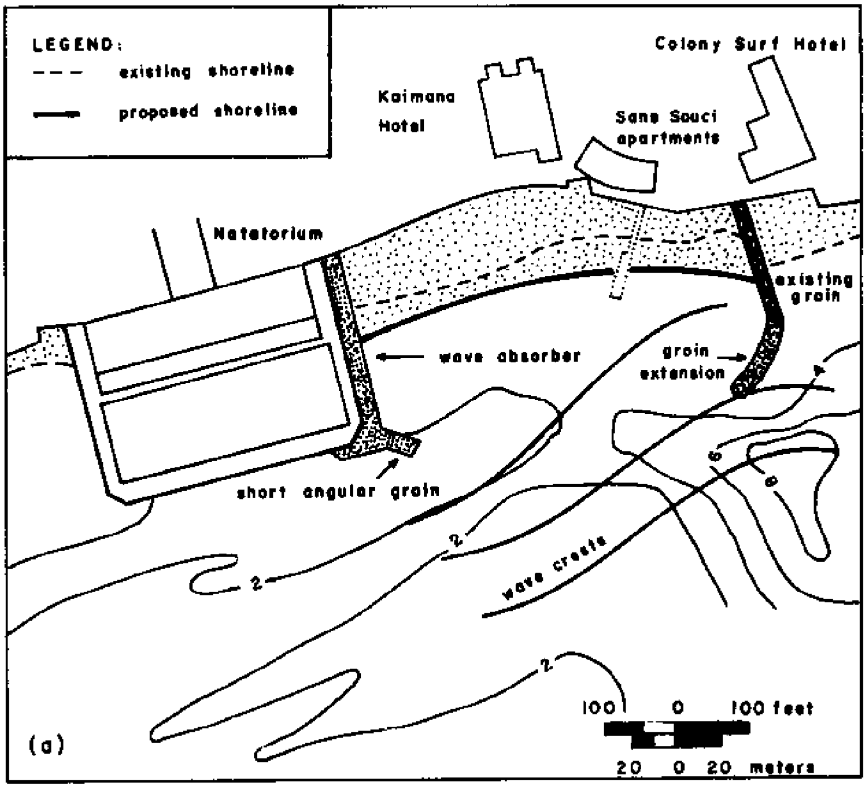
4. Loss of sand from Kuhio Beach predominantly due to a series of well-developed rip currents during high surf conditions. The major rip is situated off the Royal Hawaiian Hotel and carries a significant amount of sand from the beach into deeper water.

5. Considerable portion of the offshore reef flats covered with sand. The sands on the beach and on the reef flats have similar characteristics.

6. Currents of tidal origin on reef flats, flowing from northwest to southeast during both ebb and flood tides. In combination with waves the currents are capable of transporting sediment in that direction.

Based on the above-mentioned environmental conditions, suggestions for improvement of the various beach sections are presented for further evaluation.

Section between Natatorium and Colony Surf Hotel. The beach in this section is very narrow at its southern end and widens toward the Natatorium. It is in a relatively stable condition. Between the Natatorium and the Kaimana Hotel, the beach often shows one beach cusp formation. Wave attack on this beach is affected by the 8-ft deep small boat channel dredged across the reef as shown in Figure 5.13 and Figure 5.30. Furthermore, wave reflection from the south wall of the Natatorium may affect the beach configuration. When considering measures for improvement of this particular section it is to be realized that under the existing conditions the beach is relatively narrow but that the offshore reef provides an attractive and quiet swimming area. Improvement of the beach in terms of widening it will result in a decrease in the dimensions of the offshore swimming area. From a total recreational point of view this may be an important point of consideration. It seems that any beach widening in this area should therefore be of limited scale, whereby various alternatives may be considered.



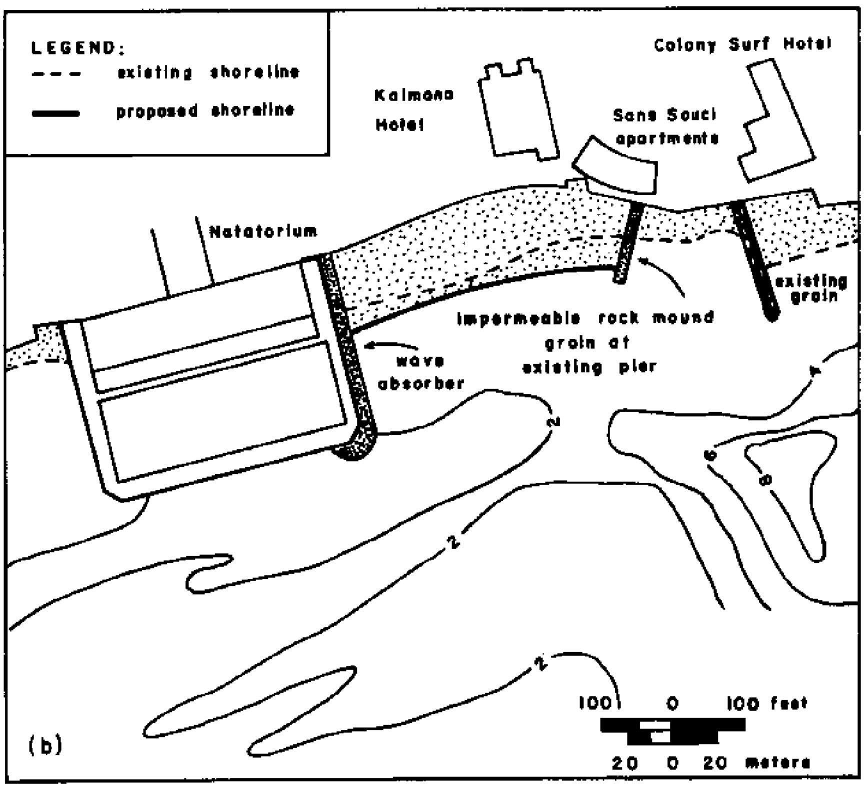


Figure 5.30. Suggestions for improvement of beach south of Natatorium, Waikiki Beach: (a) wave absorber, angular groin, and groin extension and (b) wave absorber and groin at existing pier

1. Construction of an extension of the groin at the south end of this beach will cause a change in wave approach by diffraction and will therefore allow beach widening at this end (Figure 5.30a).

2. Construction of a wave absorber along the south wall of the Natatorium will reduce or eliminate wave reflection and will therefore have a beneficial effect on beach stability. A short angular groin forming the extension of this wave absorber will enhance this effect (Figure 5.30a). The beach section between the Sans Souci apartments and the Colony Surf Hotel, situated between the existing (permeable) pier and the (impermeable) groin, is subject to higher wave attack because it is situated opposite the dredged channel across the reef. This section is therefore subject to erosion under existing conditions, but will be somewhat protected by the curved groin (Figure 5.30a).

3. A cheaper, but possibly acceptable, solution may be obtained by maintaining the beach between the pier and the groin as a wave absorber but sacrificing it as a recreational beach, thereby constructing an impermeable rubble mount groin underneath the existing pier (Figure 5.30b). At the north end, the Natatorium wall is to be provided with a wave absorber (as discussed above) but without the angular groin extending from it.

<u>Section between Natatorium and Queen's Surf groin</u>. This section presently has the following characteristics:

1. A slight, predominant littoral drift in northerly direction

2. Accumulation of sand and a stable beach south of the Queen's Surf groin

3. A very narrow and undernourished beach between the Kapiolani Beach Center and the Natatorium

4. A predominant offshore drift in a southerly direction

5. A relatively deep offshore channel between Queen's Surf pavilion and the Natatorium

6. Extensive, shallow offshore reef areas along this whole section

This beach section is relatively stable but the southern part is in need of improvement. It is not clear in which manner nourishment of the beach takes place, but there is some indication of a sand channel perpendicular to the beach south of the Waikiki Aquarium through which material moves in a shoreward direction over the shallow reef. However, the amount of nourishment, if any, is very small.

Improvement of this section may be comprised of the following measures:

1. Widening the beach by means of artificial nourishment

2. Construction of structures to stabilize the widened beach. Construction of perpendicular groins similar to the existing groin at the

north end of the section is expected to be less effective due to the lack of adequate nourishment in the southern part of this section. Construction of a T-groin in the middle of this section and an angular groin extending from the northwest corners of the Natatorium (Figure 5.31) are expected to provide better protection of the beach due to wave diffraction from the seaward ends of the groin. Instead of the T-groin, the parallel portion of it may suffice to act as an offshore breakwater.

3. Filling of this channel up to 5 to 6 ft below MLW in order to reduce the loss of beach sand to the deep offshore channel

The question of whether the Natatorium should be removed or whether it should be preserved is still in discussion.

If a decision to remove the Natatorium is made, the measures for beach stabilization will have to be adjusted. Figure 5.32 shows such a plan, which consists of the construction of another T-groin or offshore breakwater at the site of the Natatorium.

Section between Queen's Surf groin and Kapahulu groin. Due to refraction of waves over the shallow offshore reefs of the previous section, waves approach this beach more or less perpendicular to the coastline. Even though this beach section is not very wide, it is relatively stable.

Possible losses of the beach area during high surf conditions are offset by offshore-onshore movements of sand generated along the outer reef edge to the south of this section.

Near the Kapahulu groin the offshore area is extensively utilized by surfers. Beach improvement structures in this section would most likely interfere with surfers' interests and therefore are not recommended at the present time.

Section between Kapahulu groin and the groin off the Royal Hawaiian Hotel. The recently completed improvement works at Kuhio Beach include the following:

1. Artificial nourishment of the beach by trucking in about 21,500 cubic yards of sand

2. Improvement of the seawall and boulevard

3. Improvement of the existing groin

4. Improvement of part of the offshore breakwater

The improvements made are considered adequate for the section between the Kapahulu groin and the Kuhio Beach recreational center.

Wave attack, littoral drift, and beach stability in the area between the recreational center and the Royal Hawaiian Hotel are affected by the offshore topography (note in particular the form of the 6-ft contour line in Figure 5.25) which induces wave refraction and the major rip current off the Royal Hawaiian Hotel.

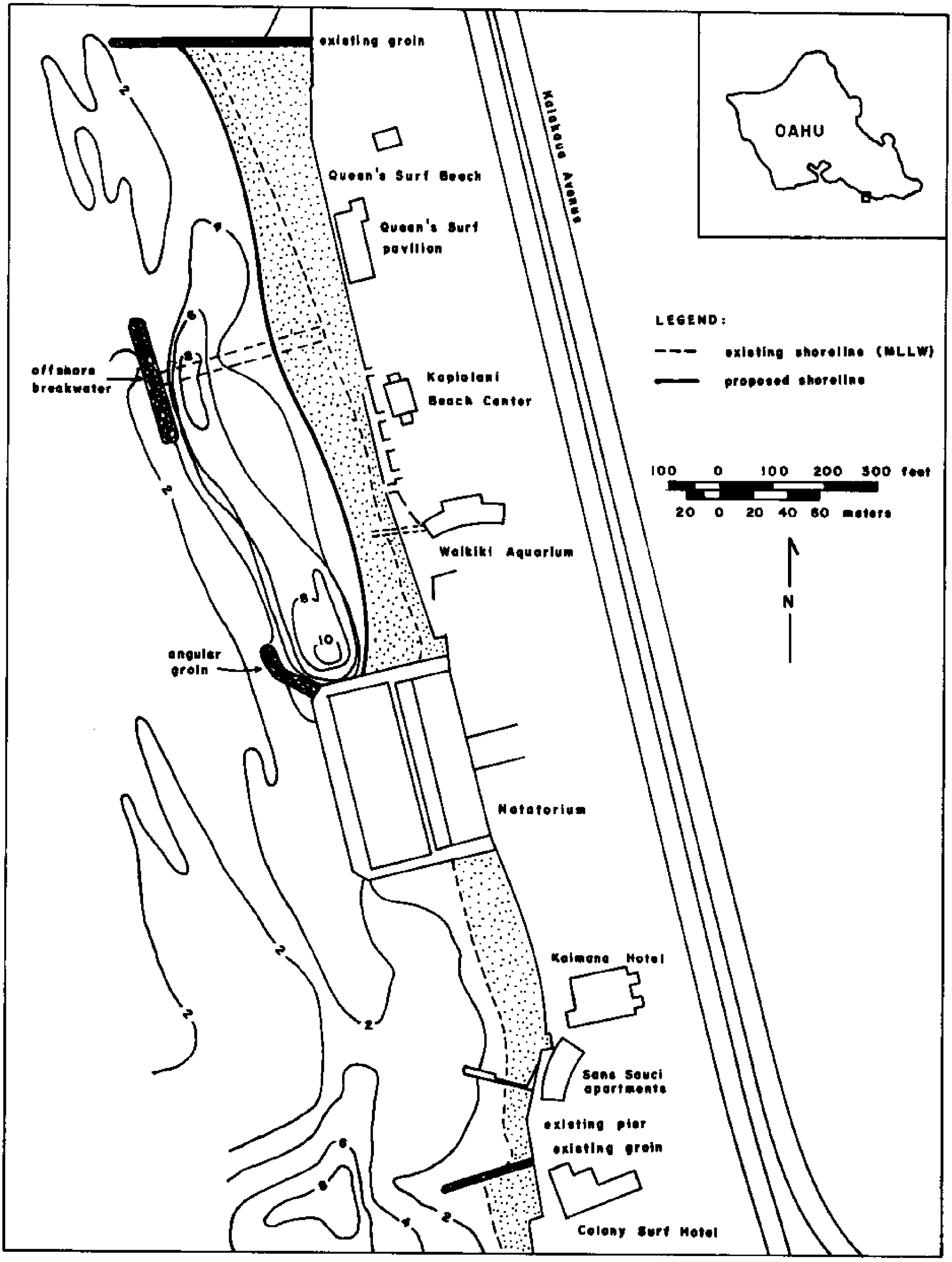


Figure 5.31. Improvement of beach between Natatorium and Queen's Surf groin

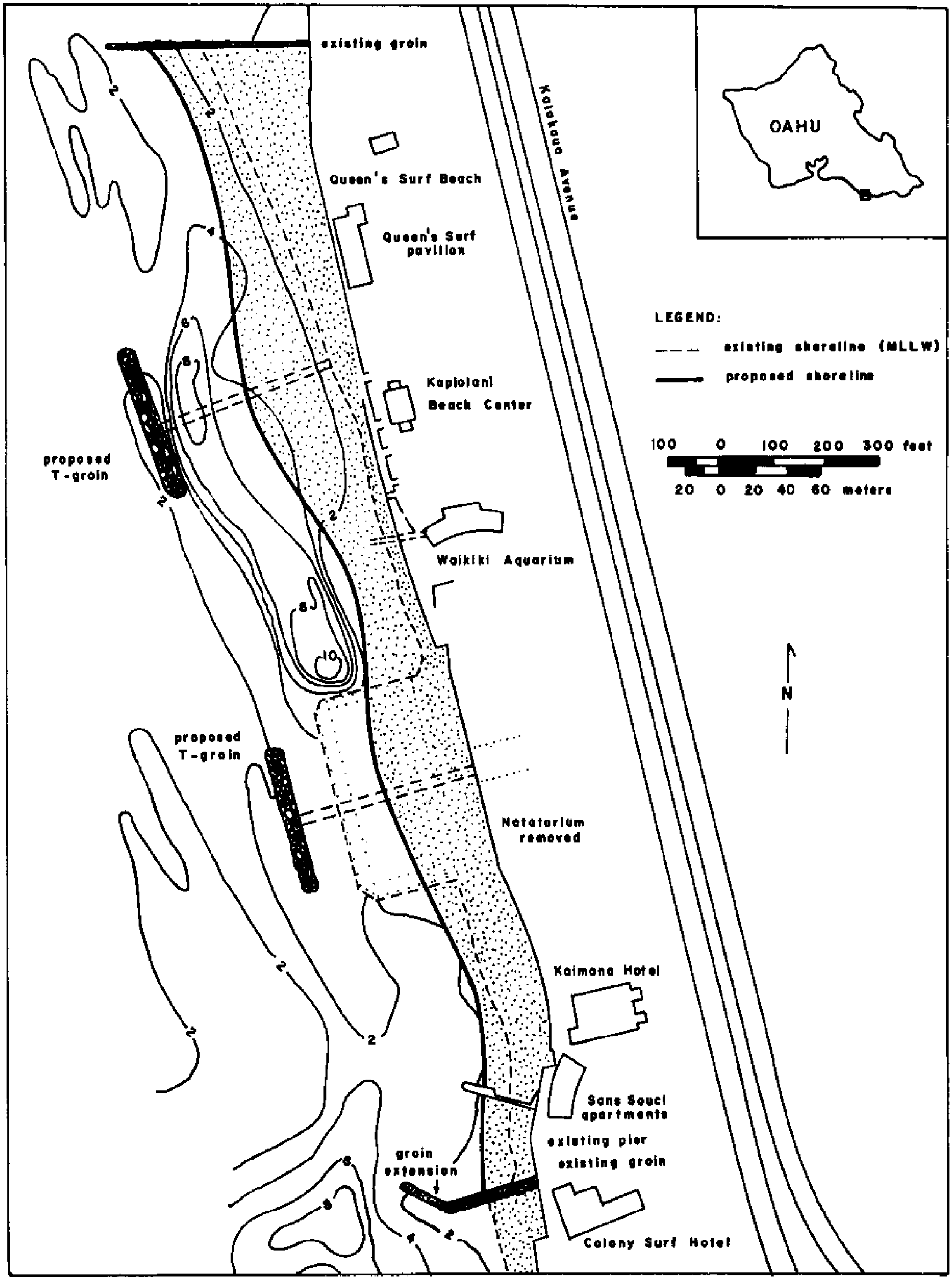


Figure 5.32. Improvement of beach near Natatorium, with removal of Natatorium

Patterns of wave refraction are shown in Figures 5.4 and 5.5. It appears that the curved form of the shoreline in this section of the beach area is induced by the curved crests of the refracted waves in such a manner that the crests of the breaking waves are at a small or zero angle with the shoreline. Consequently, a change in direction of the approaching waves will induce a change in shoreline configuration. A small change in angle, furthermore, will affect a change in the rate of littoral drift.

In accordance with the usual angle of wave approach, the littoral drift in this area is predominantly toward the northwest. The curved groin off the Royal Hawaiian Hotel acts as an incomplete barrier to the littoral drift resulting in a usually stable and well-nourished beach section to the south of this groin.

The major rip current is located in this area. It was noted earlier that this rip current is strong under heavy swell conditions and carries beach material seaward. Only part of this material will be returned to the beach during periods of low swells; the part of it that is lost constitutes a drain in the balance of the littoral drift.

There are two possible causes for the major rip current in this area:

1. The offshore topography of the area may have an effect on wave behavior and wave-induced radiation stresses which in turn contribute to wave-induced currents.

2. The groin near the Royal Hawaiian Hotel may affect the wave-induced littoral current.

Although both generating mechanisms are possible, it is considered most likely that the first mentioned mechanism is dominant.

If this is true, measures to eliminate the strong rip can only be effective if they include a change in the offshore bottom topography. Although man-made changes are feasible, it does not seem likely that such large-scale changes in bottom topography can be realized without changing wave breaking characteristics which may in turn affect surfing. Therefore, without corrective measures, occasional losses of beach sand due to the major rip current will continue to take place.

The strength of the rip current and consequently the amount of sand loss can be reduced by compartmentalizing the beach under study. The following suggestions may be considered (Figure 5.33):

1. Construction of an angular groin "A" at the north end of the offshore breakwater at Kuhio Beach

2. Construction of a parallel offshore breakwater "B" off the Moana Hotel

3. Adapting the existing groin "C" off the Royal Hawaiian Hotel into a T-groin

4. Occasional nourishment of the beach to offset natural losses

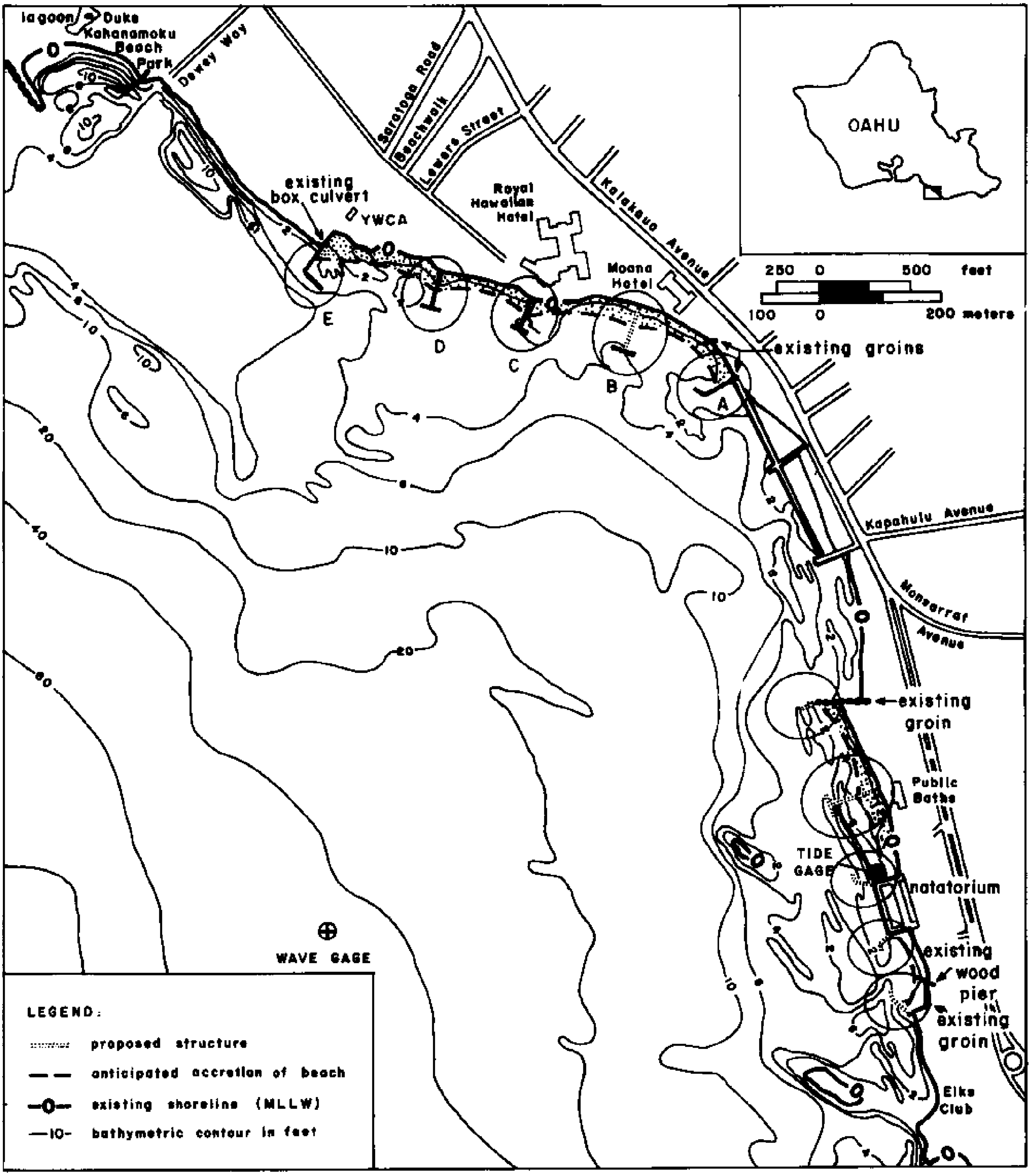


Figure 5.33. Suggested improvements for Waikiki Beach, Oahu

In view of the relative conformity of sand on the beach and in offshore deposits it would be desirable to develop a system in which suitable offshore sand deposits could be pumped back to the beach for nourishment.

Section between Royal Hawaiian Hotel and the YWCA. This section is presently undernourished because of impounding of the littoral drift by the Royal Hawaiian Hotel groin. Consequently, stability conditions are poor. Vertical seawalls too close to the waterline add to the eroding tendencies.

The Halekulani sand channel is a characteristic offshore feature in this area. Tracer studies have shown that significant offshore-onshore movements of sediment do not exist in this channel. Consequently, it is assumed that material movement is basically in the form of littoral drift parallel to the shoreline.

Beach elevation measurements at traverses 2 and 3 (Figure 5.1) and visual observations on the characteristics of shoreline behavior in this area confirm that shoreline variations are induced by a change of wave approach. At times the YWCA groin acts as a barrier to the westerly littoral drift by which accretion occurs. At other times the drift is directed toward the east causing retrogradation of the same shoreline section.

The best solution for shoreline stabilization of this section seems to be artificial nourishment and compartmentalization. The following measures are recommended (Figure 5.33):

1. Construction of T-groin "D" in the middle of the section

2. Increasing the length of the YWCA groin "E" and converting it into an angular groin

These measures, in addition to the improved T-groin replacing the existing Royal Hawaiian Hotel groin, will provide adequate compartmentalization and stabilization.

Fort DeRussy section. The beach west of the YWCA groin, known as Fort DeRussy, has recently been enlarged by the US Army Corps of Engineers. Although the material used for beach construction has not been completely suitable for the project, no further improvements are recommended at the present time.

Closing remarks. In the above paragraphs, suggestions for possible improvements to Waikiki Beach have been presented. For the detailed planning and design of the coastal structures involved, the use of a hydraulic model study is considered essential to obtain a clear insight to the hydraulic aspects involved. The cost of such a study is usually only a small portion of the total project cost involved.

For artificial nourishment, two possibilities may be particularly suitable:

1. Replenishment of the beach by trucking in sand of suitable characteristics from a suitable source for the beach under consideration

2. Replenishment of the beach from material deposited offshore. A special sand pumping device similar to Casciano's (1973) submarine sand recovery system may offer interesting possibilities for this area.

Waimanalo Beach

Location and description

Waimanalo Beach is situated at the southeastern end of the windward coast. The beach forms the shoreward boundary of Waimanalo Bay and is predominantly exposed to tradewind waves. It is the longest continuous beach on the island of Oahu.

The beach is a crescent-shaped stretch approximately 5.5 miles long. It is bounded on the north by Wailea Point and on the south by the Makai Range pier near Makapuu Point. Going from north to south, beach sections are: Bellows Air Force Base, Waimanalo Beach Park and Kaiona Beach (Figure 5.34).

The shallow water and offshore islands near the northern and southern boundaries of Waimanalo Beach act as incomplete headlands. The offshore islands are probable remnants of complete headlands that existed at one time in the past. The incomplete headlands affect the wave behavior on the adjacent beaches and contribute to the crescent shape of the beach.

Geomorphology

The sand on the beach is of calcareous origin. The largest component of the sand is foraminifera (Moberly and Chamberlain, 1964). It is coarse to medium grained and varies from well sorted to poorly sorted. Along part of the beach is a series of low dunes, such as found at Waimanalo Beach Park.

Waimanalo Bay is protected by a barrier reef at an average distance of 1 mile from the shoreline. Over large portions of this reef, the depth is 9 ft or less, causing the larger waves to break before reaching the shoreline. The bay area has large areas of sandy bottom and is irregular in shape. A broad sand-bottomed channel crosses the northern part of the reef. Figure 5.35 shows the reef flat sand reservoir and the large offshore sand channel in the southern part of the bay.

The beach at Waimanalo is characterized by cuspate formations over most of its length. The cusps vary from well-defined shapes in some locations to almost indistinguishable shapes in others. The average length of the shorter cusps is about 90 ft, with a range of 40 to 150 ft. The shorter cusps are superimposed on a system of much larger cusps whose lengths are about 10 times those of the shorter cusps. These large storm-induced cusps are set back farther from the waterline than the smaller cusps; thus, their features sometimes become indistinguishable because of vegetation cover.

More detailed information about cusp behavior at Waimanalo Beach is presented in Chapter 8. One finding of particular interest is that cusps at Waimanalo Beach show little longshore displacement.

Waves

In the Oahu Water Quality study (City and County of Honolulu, 1970) it is indicated that wave conditions at Waimanalo Bay may range in significant wave height from 1 to 13 ft with a mode of 3 ft and a range in period of 5 to 18 sec.

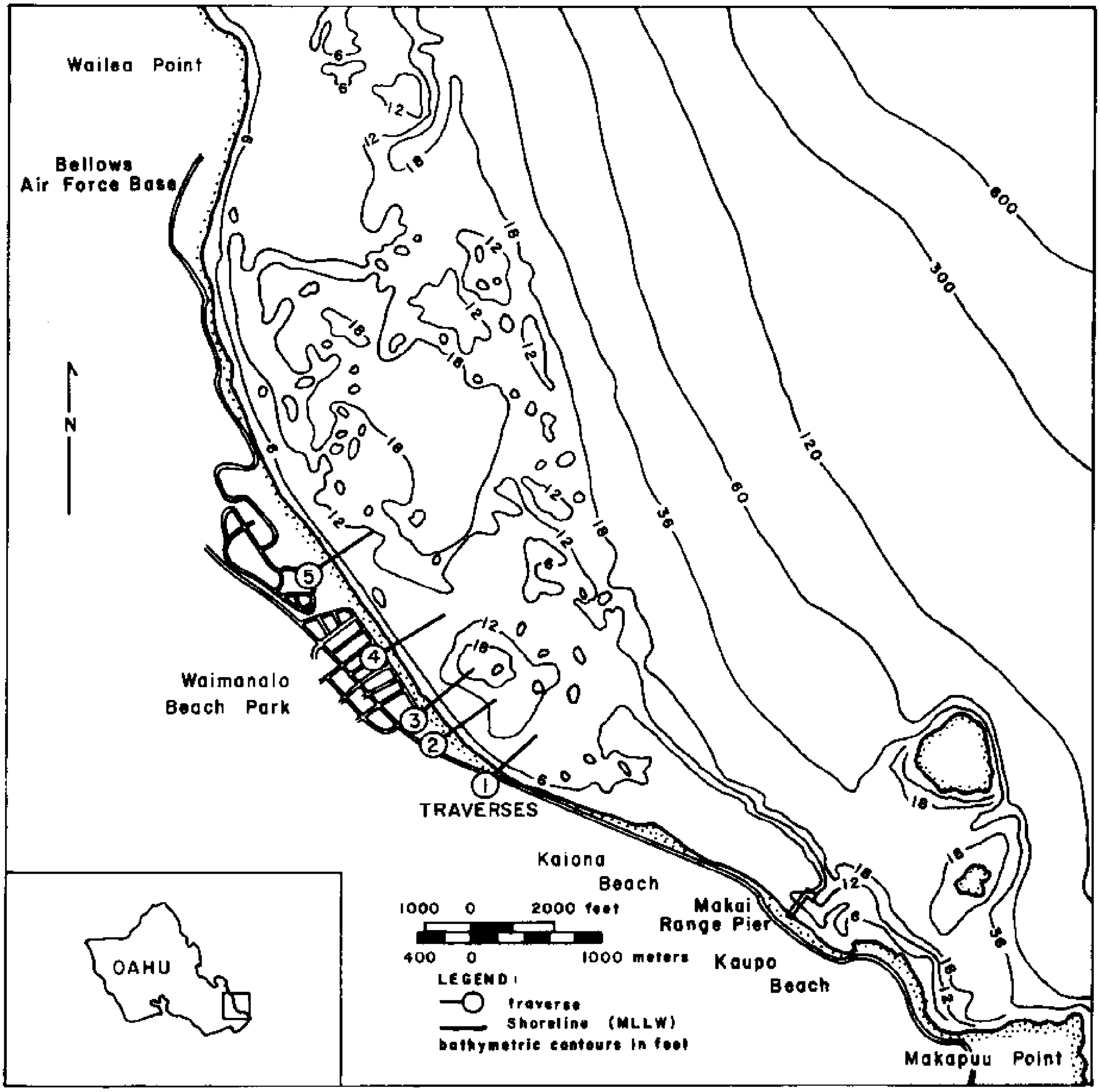
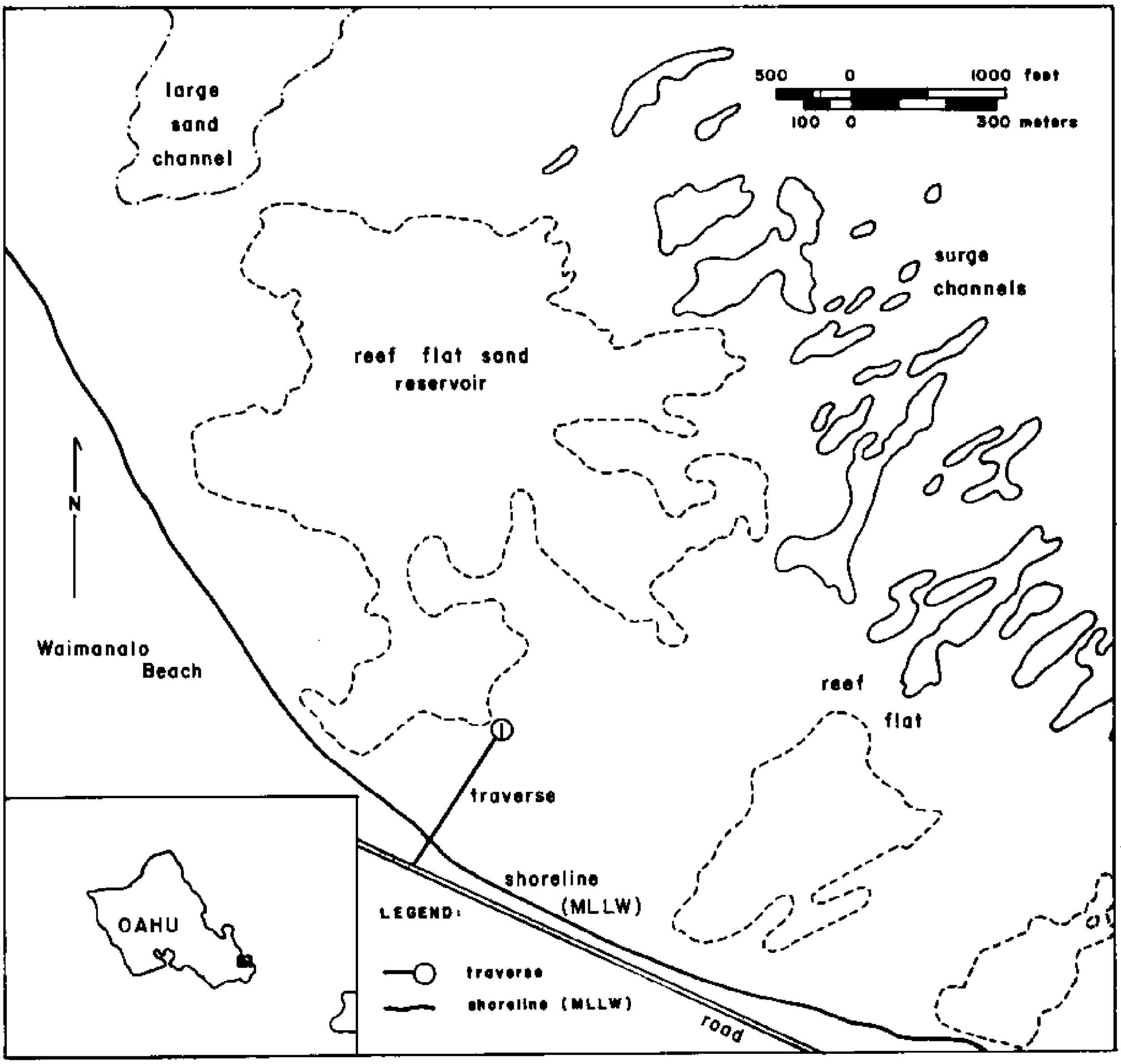


Figure 5.34. Waimanalo Beach, Oahu study site showing profile traverses and depth contours

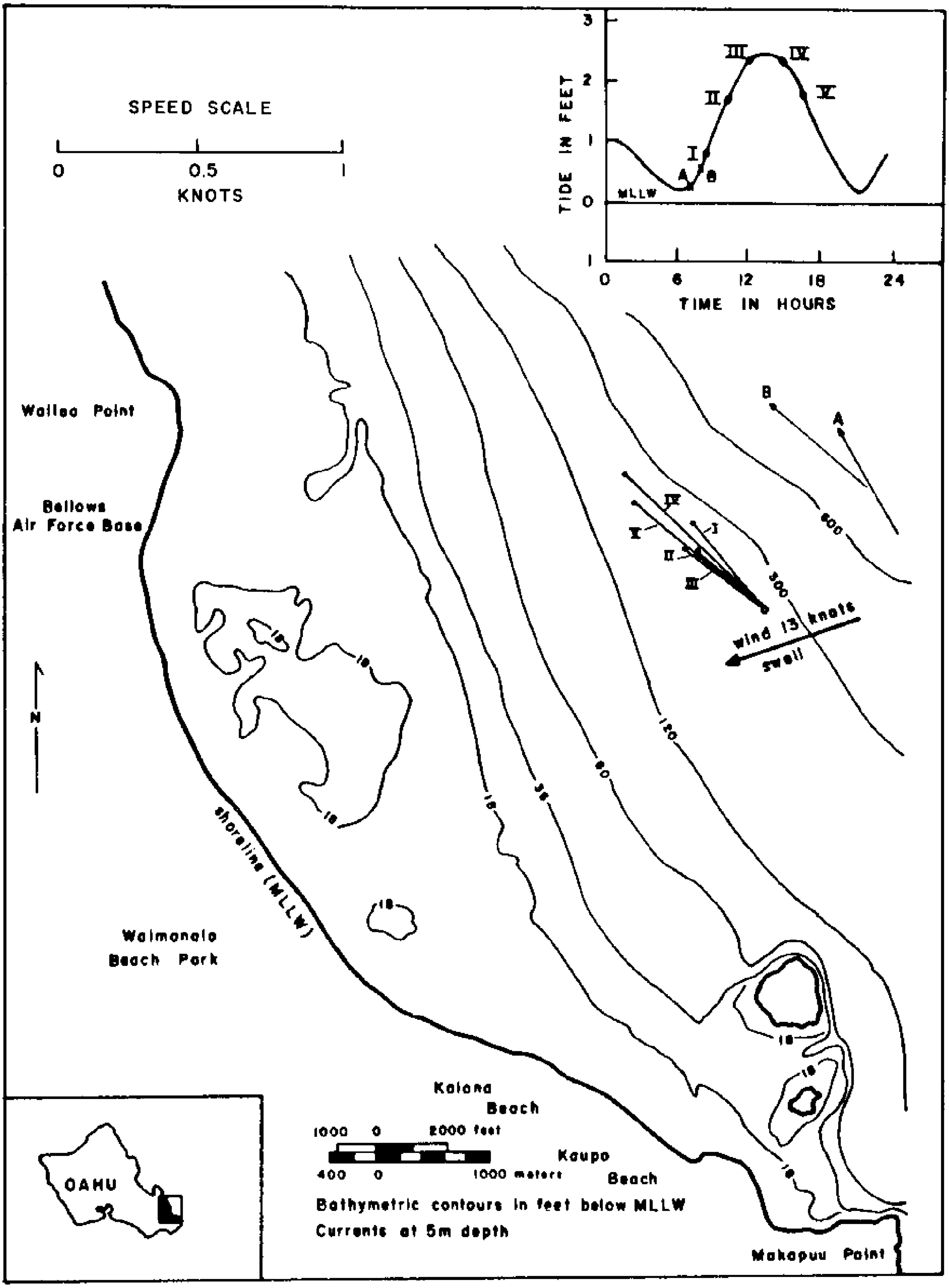


After Moberly and Chamberlain, 1964

Figure 5.35. Offshore bottom features at Waimanalo Beach, Oahu

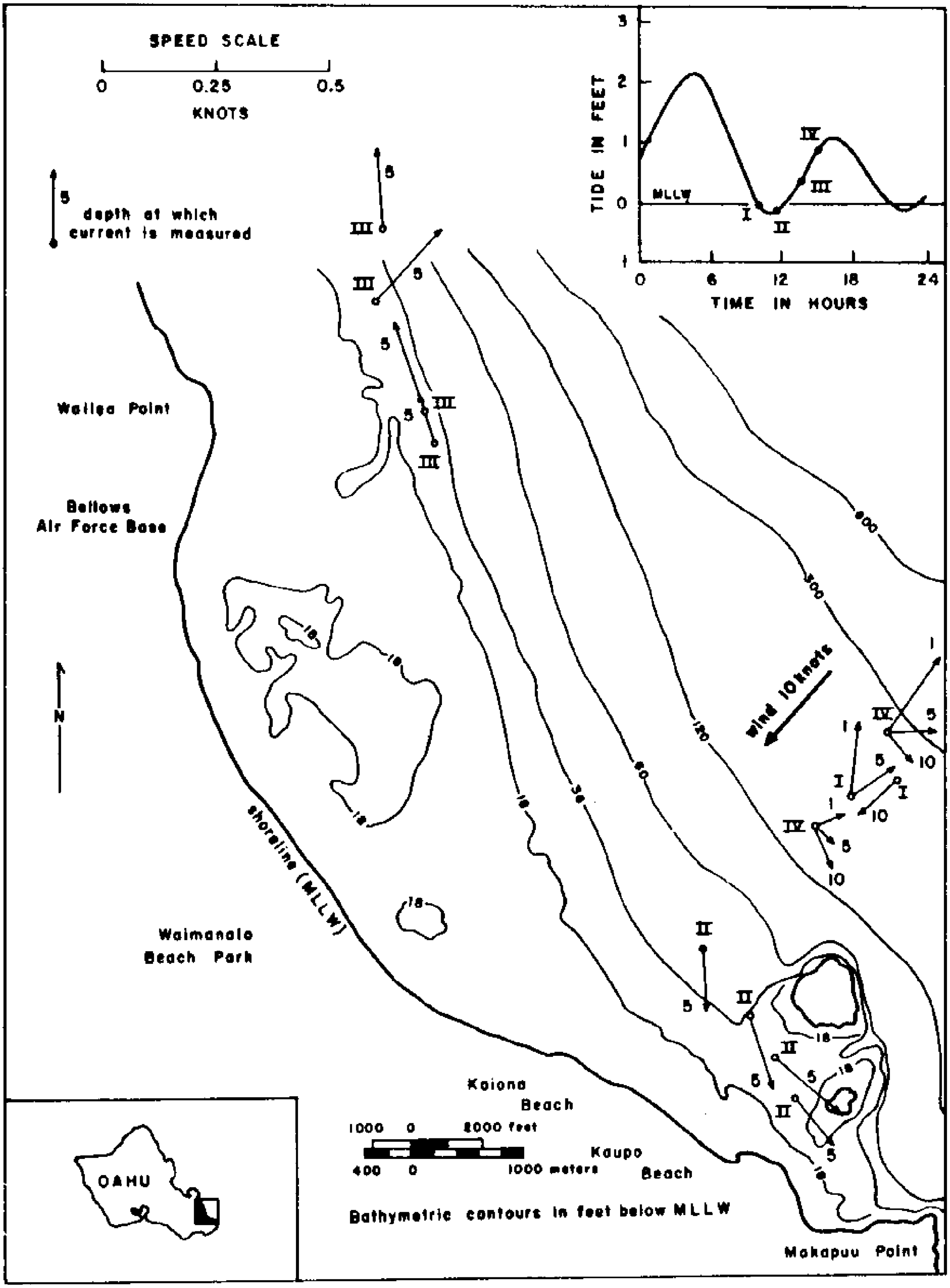
Currents

Water circulation patterns at Waimanalo Beach have been determined by other investigators. The results of these earlier studies show that the currents off Waimanalo Beach are complex and difficult to fit into a specific pattern. Figures 5.36 and 5.37 show the results of current measurements by Laevastu et al. (1964). Although northwesterly currents with maximum speeds of about .75 knot predominate over most of the outward portion of the bay, the currents reverse at times, especially in shallow water. Figures 4.9 and 4.10 show the general nature of the circulation around Oahu for the winter and summer seasons, indicating that the northwestern currents prevail off Waimanalo Bay throughout the year. Inside the bay, circulation is weak and has a negligible effect on sand transport. In the surf zone, however, wave-induced currents have a significant effect on sediment transport.



After Laevastu et al., 1964

Figure 5.36. Results of drogue measurements of currents off Waimanalo, September 11, 1962



After Laevastu et al., 1964

Figure 5.37. Offshore currents at Waimanalo Beach, Oahu measured on February 23, 1963 at 1, 5, and 10 m depths

Beach profiles

To study beach behavior, five traverses were established at which beach elevations were taken at regular time intervals. The traverse locations are shown in Figure 5.34 and their profiles are presented in Figures 5.38 through 5.42. The measurements show that the beach at Waimanalo is relatively stable and that significant changes occur only during high wave conditions. During periods of high waves from the northeast, the northern end of the study section (traverse 5) experienced erosion, while at the southern end (traverse 1) accretion was observed. The average beach slope was 1:10.

In order to obtain an indication of the dynamics of beach behavior in this area, the position of the mean lower low waterline and of the +2-ft beach contour were plotted as a function of time (Figures 5.43 and 5.44) and of distance (Figure 5.45).

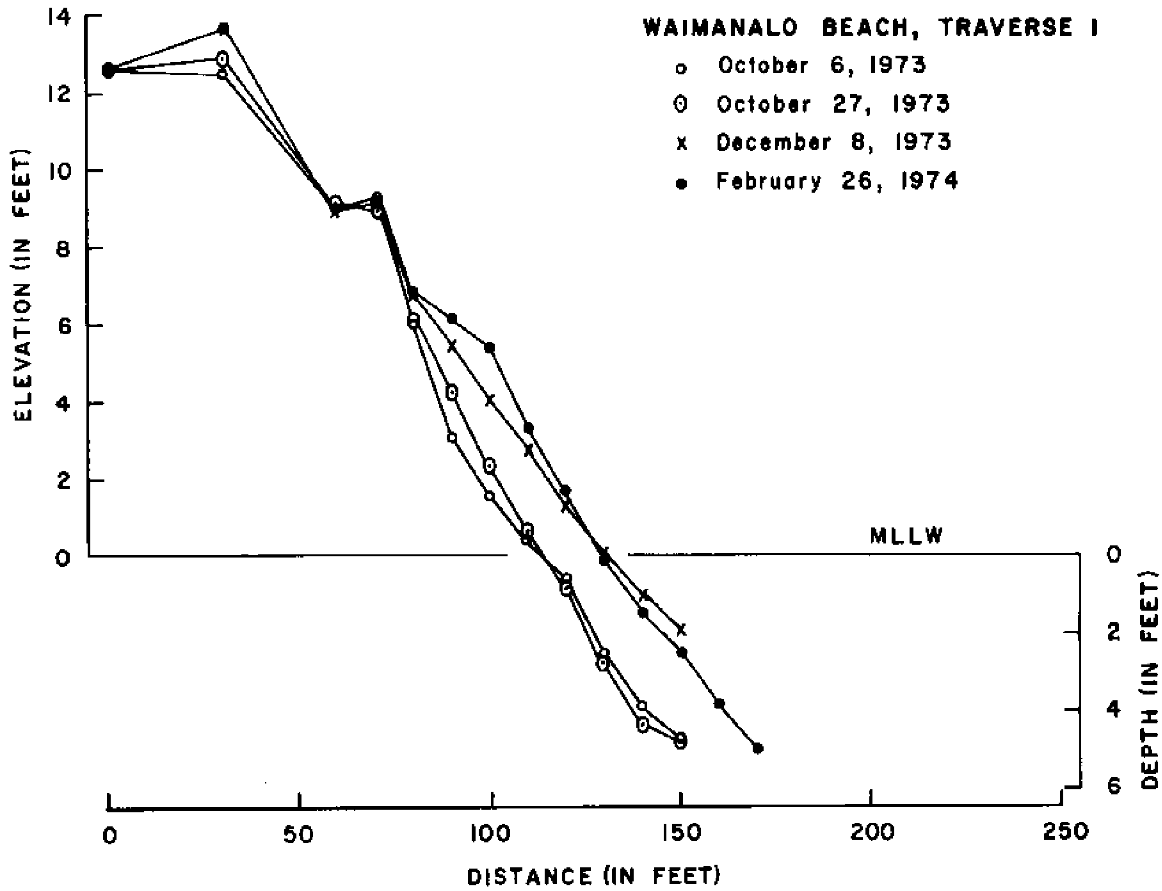


Figure 5.38. Beach profiles for traverse 1, Waimanalo Beach, Oahu. (See Figure 5.34 for traverse location.)

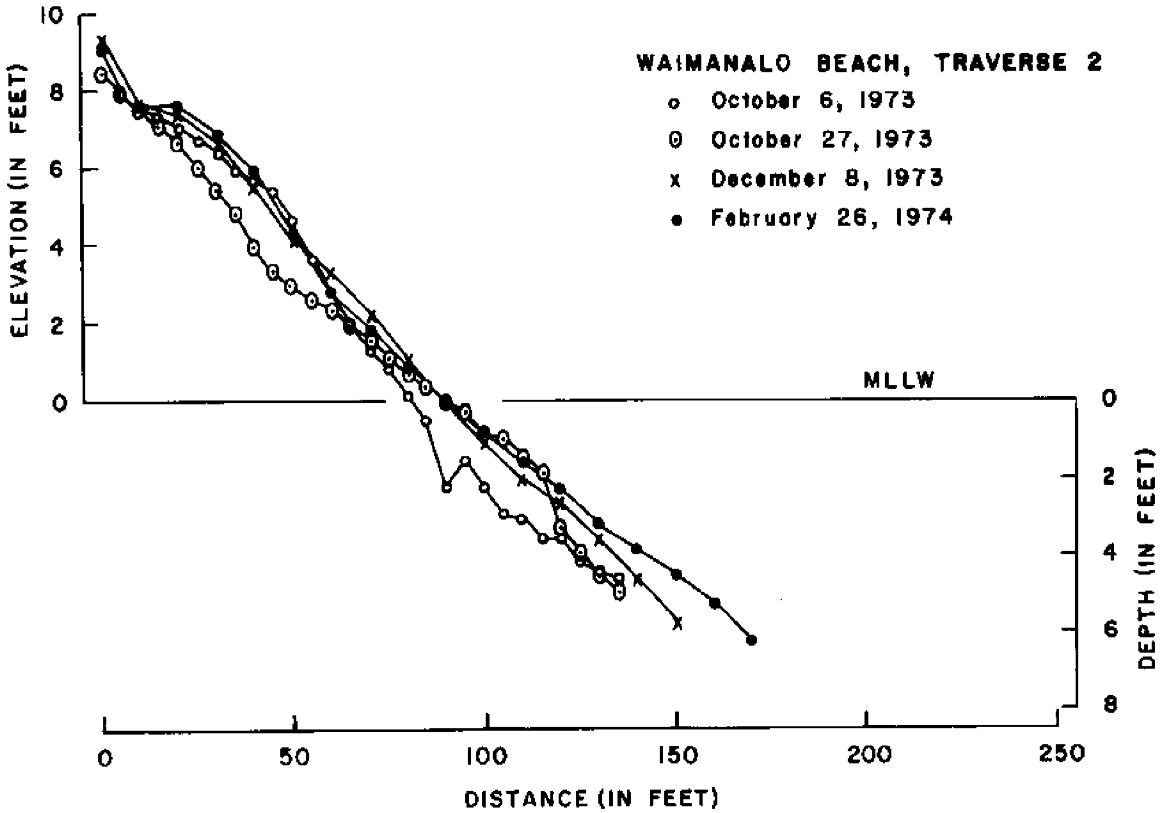


Figure 5.39. Beach profiles for traverse 2, Waimanalo Beach, Oahu. (See Figure 5.34 for traverse location.)

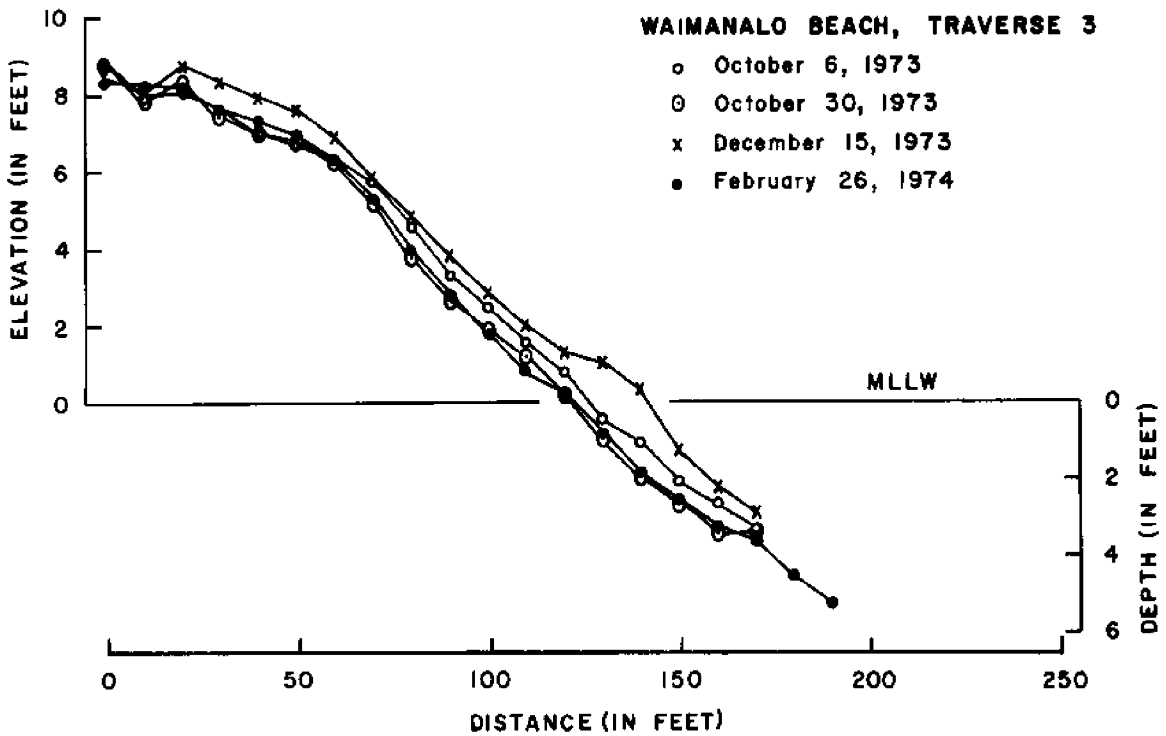


Figure 5.40. Beach profiles for traverse 3, Waimanalo Beach, Oahu. (See Figure 5.34 for traverse location.)

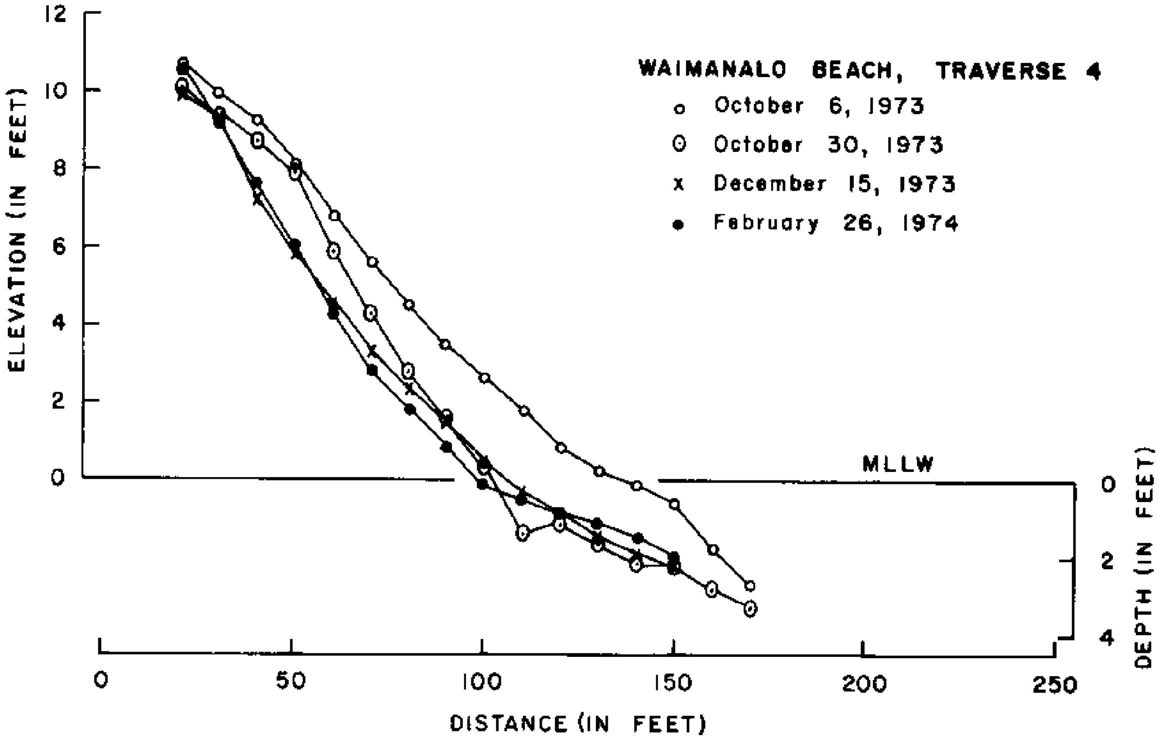


Figure 5.41. Beach profiles for traverse 4, Waimanalo Beach, Oahu. (See Figure 5.34 for traverse location.)

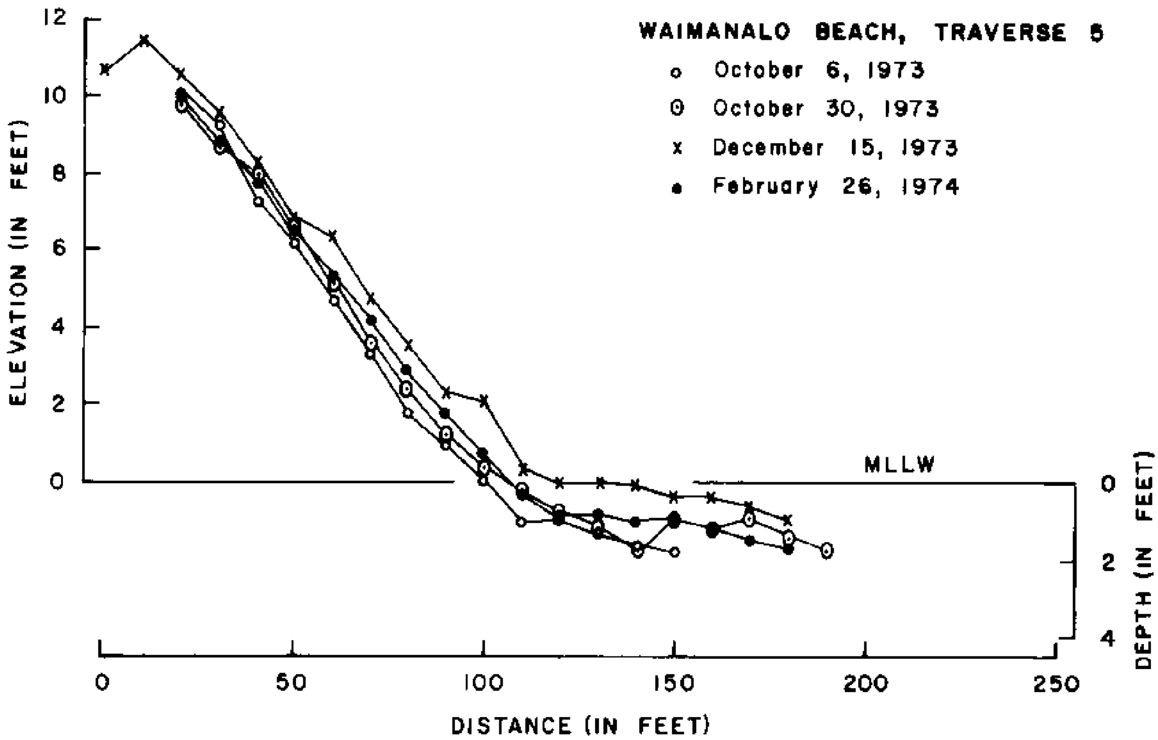


Figure 5.42. Beach profiles for traverse 5, Waimanalo Beach, Oahu. (See Figure 5.34 for traverse location.)

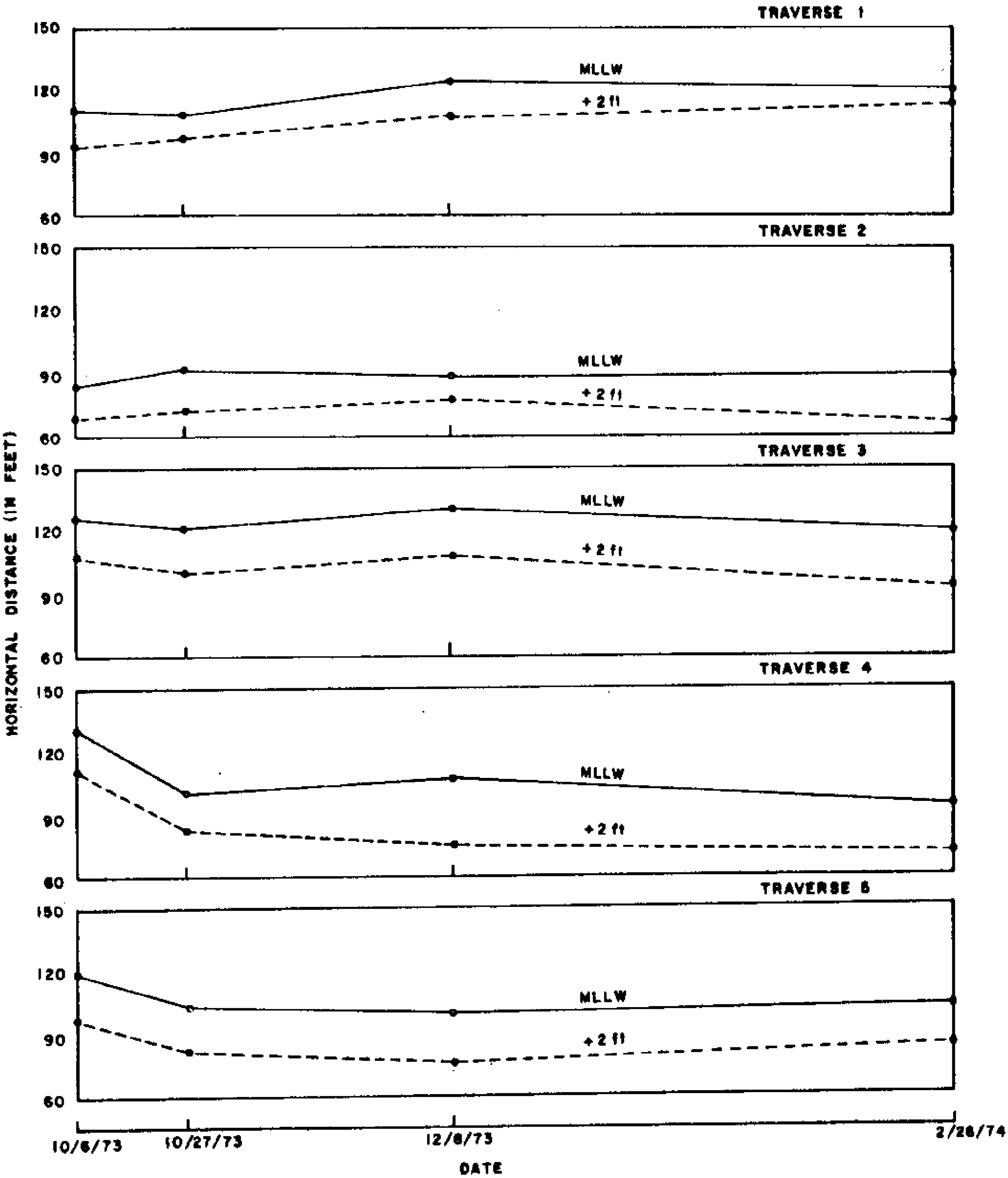


Figure 5.43. Behavior of MLLW and +2-ft elevation in traverses 1 through 5 as a function of time

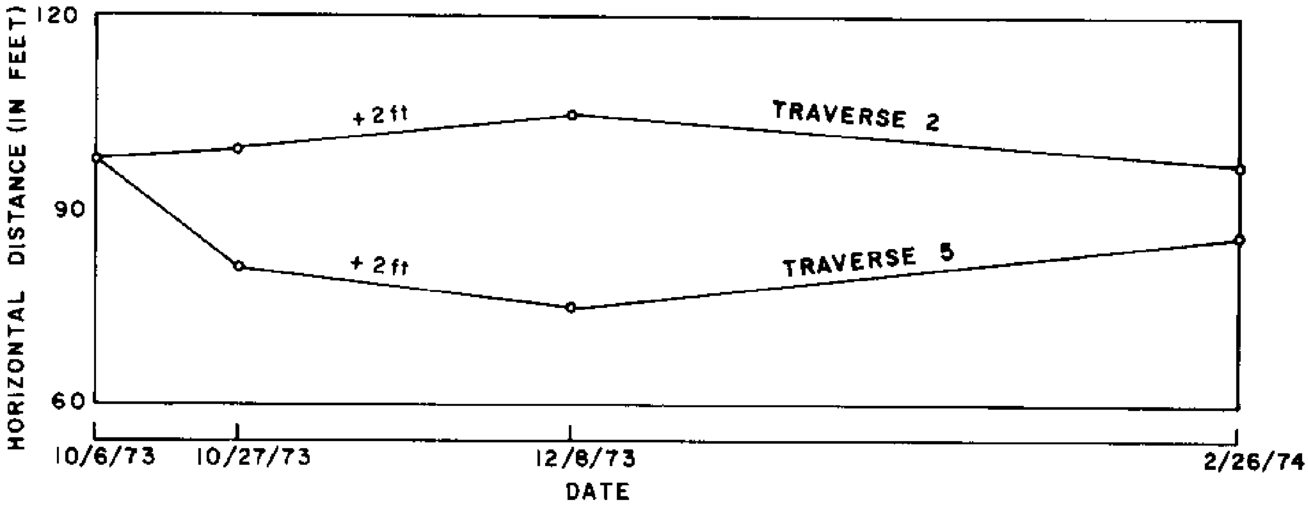


Figure 5.44. Behavior of +2-ft elevation for traverses 2 and 5 as a function of time

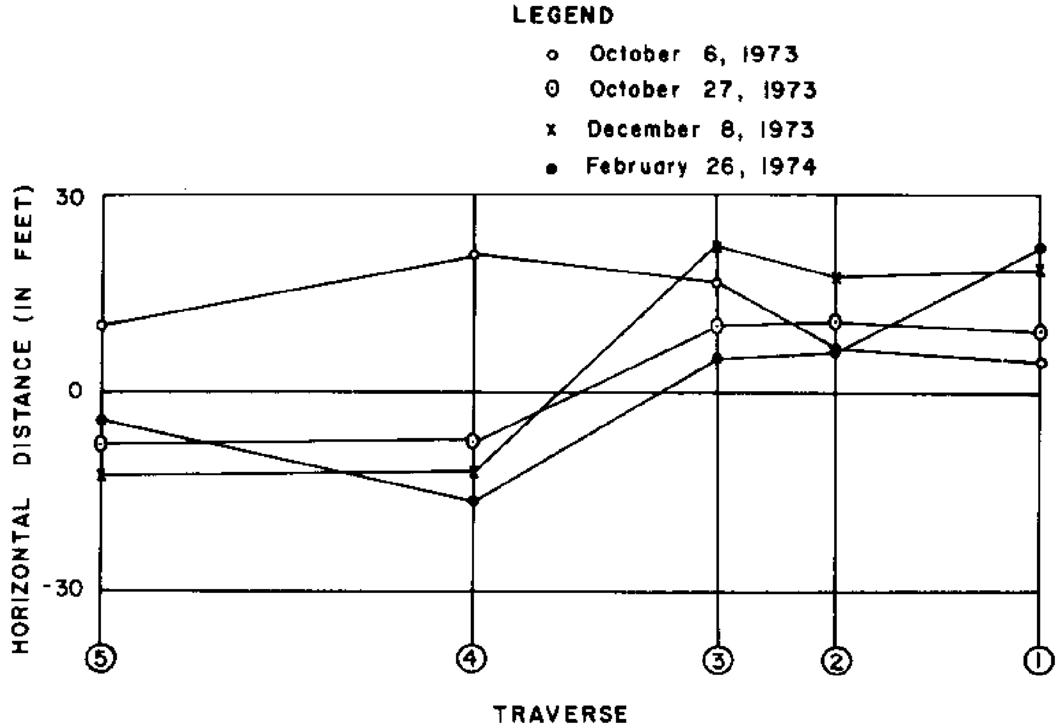


Figure 5.45. Behavior of +2-ft elevation in traverses 1 through 5 as a function of traverse location

Although there is a considerable gap in time from December 8, 1973 to February 26, 1974 the overall characteristics of the beach become visible.

The horizontal distance between the location of the mean sea level line and the +2-ft elevation in Figure 5.43 is a measure for the beach steepness. Although the two lines have the same trends in all traverses, the changes in steepness of the beach is greater in traverses 1 and 2 than in traverses 3, 4, and 5. The beach steepness is also greater in traverses 1 and 2.

Considering the trend in the location of the +2-ft elevation and comparing the various traverses, it appears that at times the northern beach section (traverses 4 and 5) was eroding, the southern part of the study area (traverses 1 and 2) was accreting, and vice versa (Figure 5.43).

As to the periodicity of the beach wave behavior, the location of the +2-ft elevation has been singled out in Figure 5.44.

These trends can also be made visible by plotting the location of the +2-ft elevation versus distance (Figure 5.45). The four lines shown on this diagram represent the four dates of the survey.

Although the data used are not detailed enough to document beach behavior without reservation, the diagrams in Figures 5.43, 5.44, and 5.45 suggest the existence of a "standing beach wave."

In the study section the amplitude of these waves is largest between traverses 4 and 5 (Figure 5.45) and amounts to about 20 feet. At traverse 1 the amplitude is about 10 ft which is half of the maximum value. A nodal point may exist between traverses 3 and 4.

Assuming longshore sediment transport as the major cause for erosion and accretion, the data suggest that during the period of observation the littoral drift was predominantly in a southerly direction.

The period of the wave appears to be approximately one year, as may have been expected because of the seasonal variations in the wave climate.

Sediment characteristics and sand transport

Sand samples were taken at the waterline and analyzed for grain size distribution. The results for traverses 1 through 5 are given in Figures 5.46 through 5.50 and in Table 5.7. The changes in distribution in traverses 1 and 4 over the period from October 6 to 27, 1973 are of interest to the overall beach dynamics. Consider for example the "percentage coarser" at the ϕ value of 0.5. At traverse 1, the percentage coarser than $\phi = 0.5$ decreased from 52 percent to 3 percent during that time interval, whereas at traverse 4 it increased from 5 percent to 42 percent.

Such change may be considered in correspondence with the beach dynamics discussed earlier.

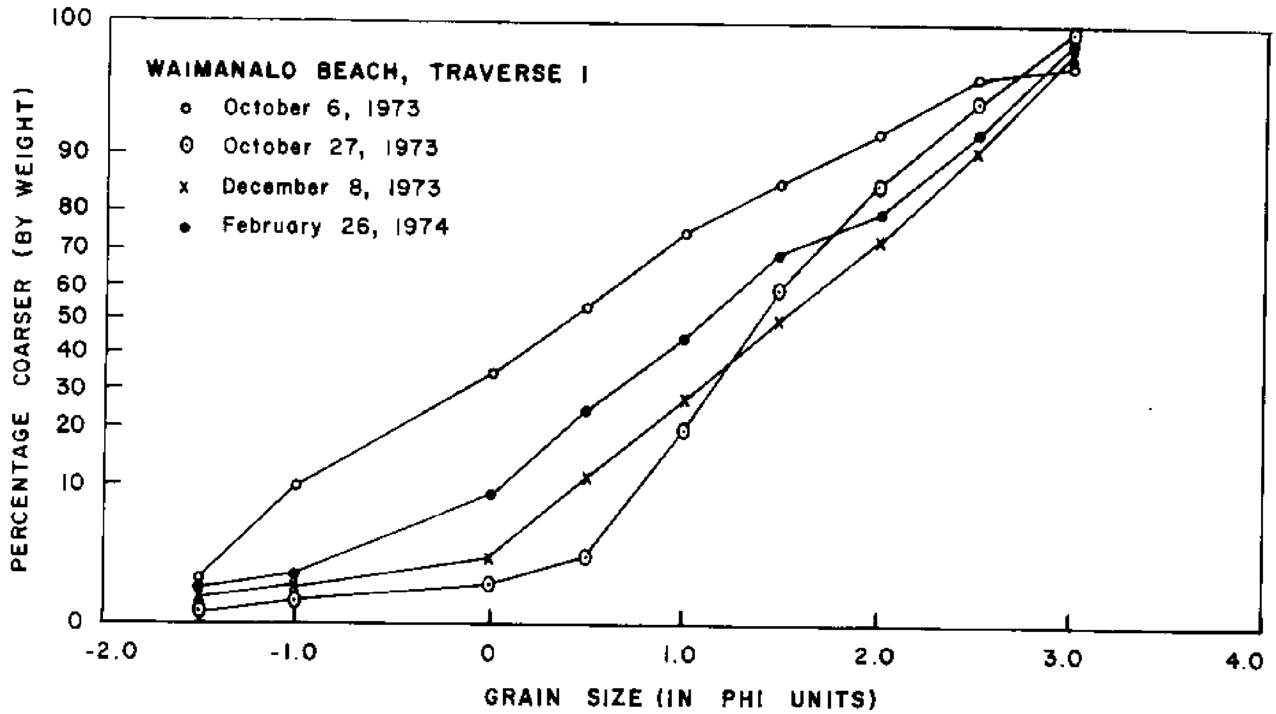


Figure 5.46. Grain size distributions for swash zone sand from traverse 1, Waimanalo Beach, Oahu. (See Figure 5.34 for traverse location.)

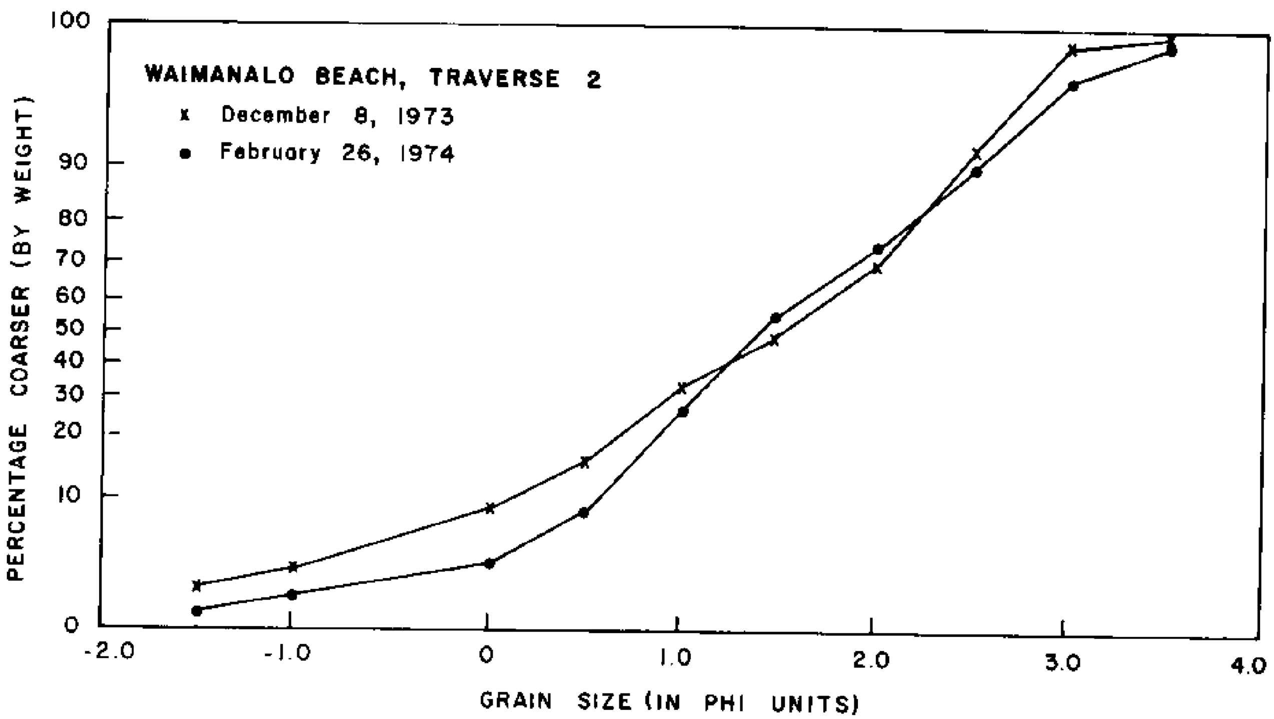


Figure 5.47. Grain size distributions for swash zone sand from traverse 2, Waimanalo Beach, Oahu. (See Figure 5.34 for traverse location.)

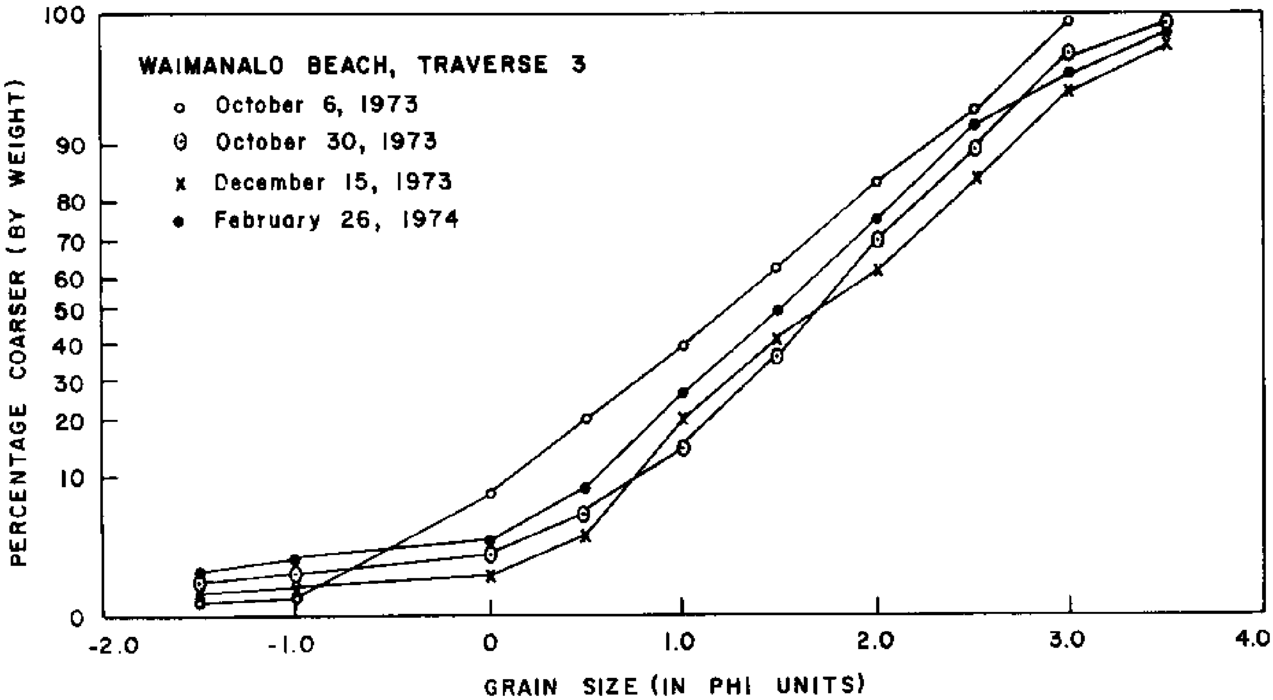


Figure 5.48. Grain size distributions for swash zone sand from traverse 3, Waimanalo Beach, Oahu. (See Figure 5.34 for traverse location.)

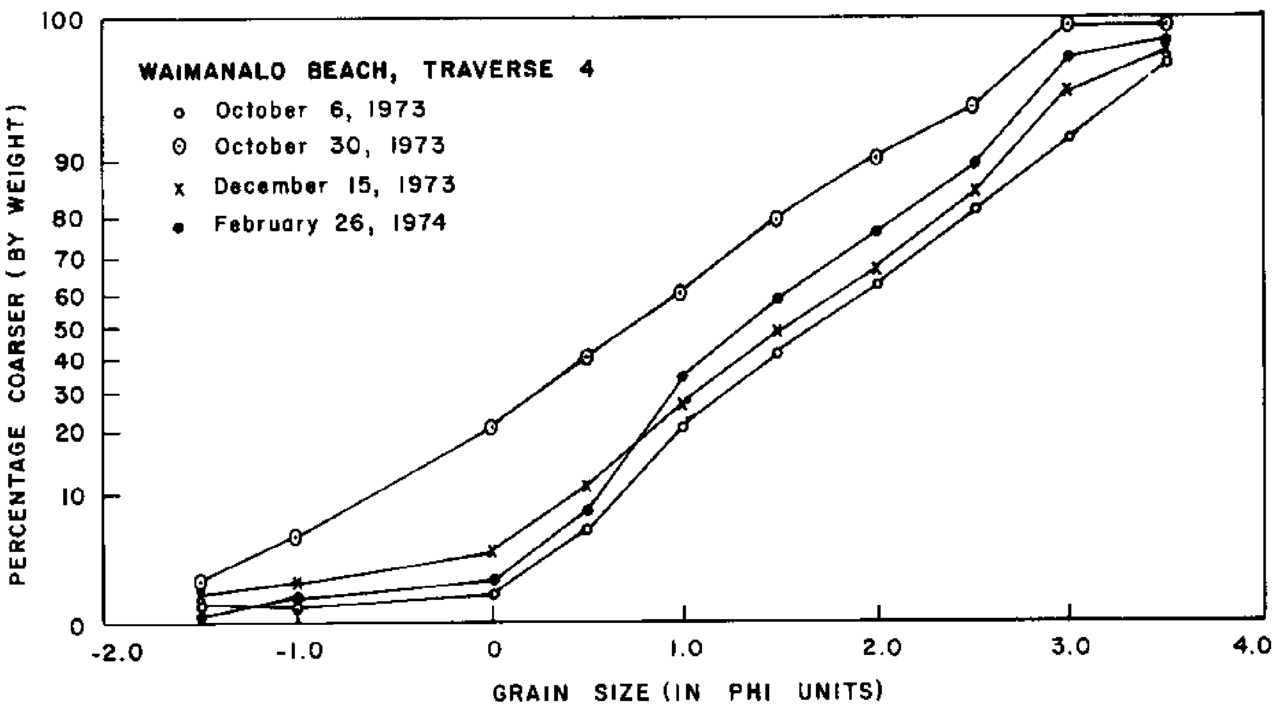


Figure 5.49. Grain size distributions for swash zone sand from traverse 4, Waimanalo Beach, Oahu. (See Figure 5.34 for traverse location.)

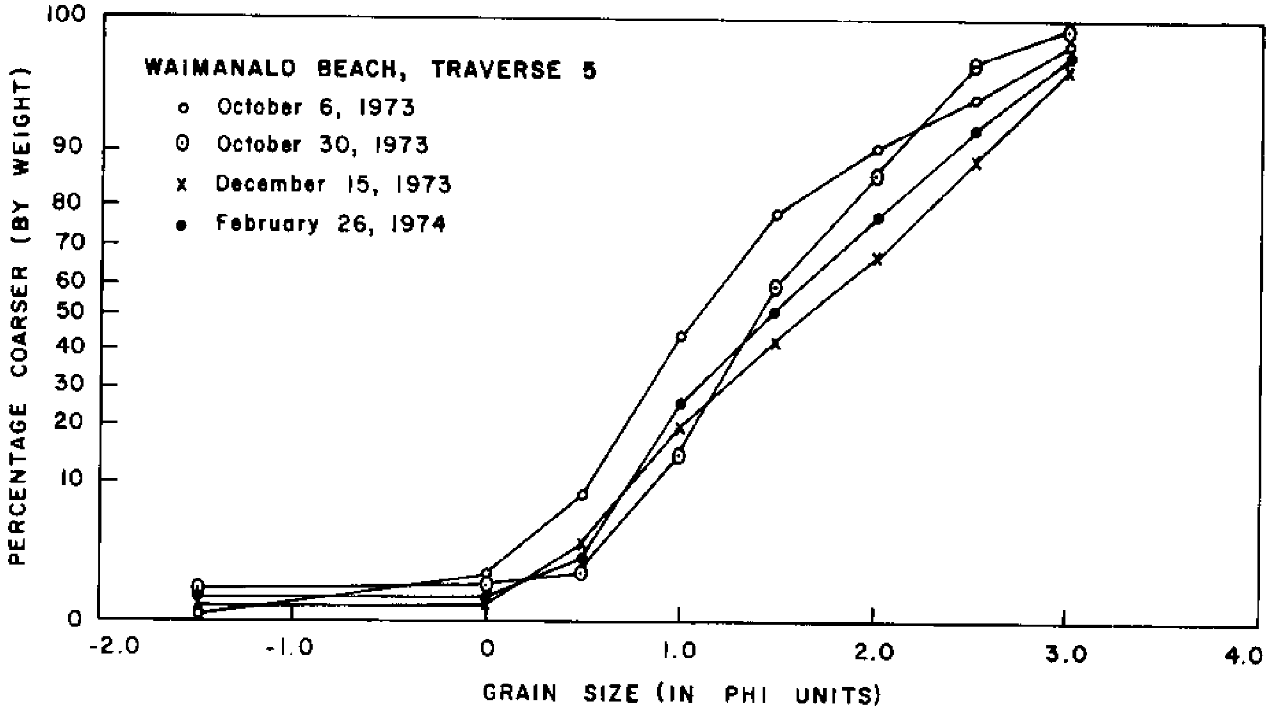


Figure 5.50. Grain size distributions for swash zone sand from traverse 5, Waimanalo Beach, Oahu. (See Figure 5.34 for traverse location.)

TABLE 5.7. SEDIMENT DIAMETER STATISTICS AT WATERLINE OF WAIMANALO BEACH

Location	Date	Mean (ϕ)	Standard Deviation (ϕ)	Skewness (ϕ)	Kurtosis (ϕ)
Traverse 1	10/06/73	0.407	1.002	0.279	2.742
	10/27/73	1.436	0.547	0.073	3.107
	12/08/73	1.456	0.797	-0.415	3.157
	02/26/74	1.133	0.903	0.002	2.871
Traverse 2	12/08/73	1.399	0.920	-0.617	3.196
	02/26/74	1.449	0.787	-0.001	3.034
Traverse 3	10/06/73	1.243	0.852	-0.115	2.880
	10/30/73	1.659	0.729	-0.477	4.203
	12/15/73	1.697	0.776	-0.263	3.176
	02/26/74	1.556	0.802	0.073	3.009
Traverse 4	10/06/73	1.678	0.865	0.021	2.485
	10/30/73	0.775	1.005	0.096	2.563
	12/15/73	1.565	0.886	-0.097	2.781
	02/26/74	1.462	0.785	0.376	2.873
Traverse 5	10/06/73	1.166	0.613	0.691	4.158
	10/30/73	1.445	0.511	0.459	3.761
	12/15/73	1.646	0.719	0.020	3.116
	02/26/74	1.469	0.689	0.442	3.052

Traverse 4 apparently has been subject to heavier wave action due to this period, leading to erosion and transport of the finer particles in a southerly direction.

Consequently, in traverse 1, where accretion occurred, the sediment became finer.

Measures for improvement

The beach at Waimanalo is the longest continuous beach on the island of Oahu and is one of the finest beaches in the state of Hawaii. The beach is stable and subject to relatively small seasonal changes. There is sufficient natural nourishment to maintain conditions of high stability, as evidenced by the occurrence of large and small cusp formations. There is no need for any technical improvement of this beach.

Haleiwa Beach

Location and description

Haleiwa Beach is situated on the north shore of the island of Oahu and is exposed to the northern swell (Figure 2.1). Although the waters of the bay off Haleiwa Beach are very calm during most of the year, large waves during North Pacific swell conditions occasionally affect this beach.

The beach at Haleiwa is 1,500 ft long and is situated between a rocky headland to the north and a long groin to the south. A 160-ft long offshore breakwater parallel to the shoreline protects the beach in front of the bathhouse. The beach forms part of the eastern shore of Waialua Bay; a shoal with water depths of less than 6 ft forms a protective barrier for the beach. South of the beach is the small boat harbor of Haleiwa. Two streams, Anahulu Stream and Lokoea Stream, discharge into the bay south of Haleiwa Beach. There are no indications that sediment discharge from the two streams contributes significantly to the natural nourishment of the beach.

Haleiwa Beach Park is a major recreational facility for this area; the beach is therefore of great recreational value. However, erosion of the beach has long been a problem. The State Legislature allocated funds for a pollution study in this area in connection with the beach erosion project (Belt, Collins and Associates, 1962). The Lokoea Stream was found to be the primary source of pollution for the bay area in front of the Haleiwa Beach Park pavilion.

Waves

Waialua Bay is usually a calm body of water with little wave action. However, during westerly and northerly winds, the water in the bay gets rough and occasionally--possibly a few times per year--during the winter months, the area is subject to high surf conditions. Table 5.8 lists deep water wave characteristics during a number of selected storms.

TABLE 5.8. DEEP WATER STORM WAVE CHARACTERISTICS IN WAIALUA BAY

Date of Storm	Wave Height, H_o (ft)	Wave Period, T_o (sec)	Wave Direction (0°T)
January 3, 1947	11.4	15.0	007
March 5-6, 1954	19.4	15.9	030
November 27-28, 1956	10.8	16.5	326
January 12-13, 1958	27.6	21.5	305
November 22, 1958	20.6	15.7	008
December 23, 1959	17.0	11.3	025
December 9-11, 1960	18.0	19.6	315
December 18-21, 1960	18.2	15.4	330
January 5-8, 1962	16.6	12.8	320
October 16-18, 1962	15.0	13.0	322
October 29 - November 1, 1962	19.8	18.9	318
January 14-17, 1963	22.0	15.3	311
January 29 - February 3, 1965	27.0	17.2	010

From Belt, Collins and Associates, 1962

During tradewind wave conditions, wave action on the beach remains limited due to the protection of Puaena Point (Figure 5.51). In addition, the offshore topography induces refraction of waves which leads to reduction of wave energy over the offshore shoal in front of Haleiwa Beach.

A factor of interest and concern is the possibility of considerable wave setup, coupled with natural oscillations of significant amplitude in the bay, as evidenced during the storm of December 1-4, 1969. This combination of circumstances was probably instrumental to the transport of great quantities of sand from the beach over the berm into the park during that storm.

Currents

Outside of Waialua Bay, coastal currents flow in a predominantly southwesterly direction during flood tides and in a northeasterly direction during ebb tides (Figures 4.8 through 4.10). During the present study, currents were measured near Haleiwa Beach. It was found that the currents off Haleiwa Beach were predominantly wave induced so that they were only significant during heavy surf conditions. Figure 5.52 shows the results of observations during high waves on October 20 and December 15, 1972.

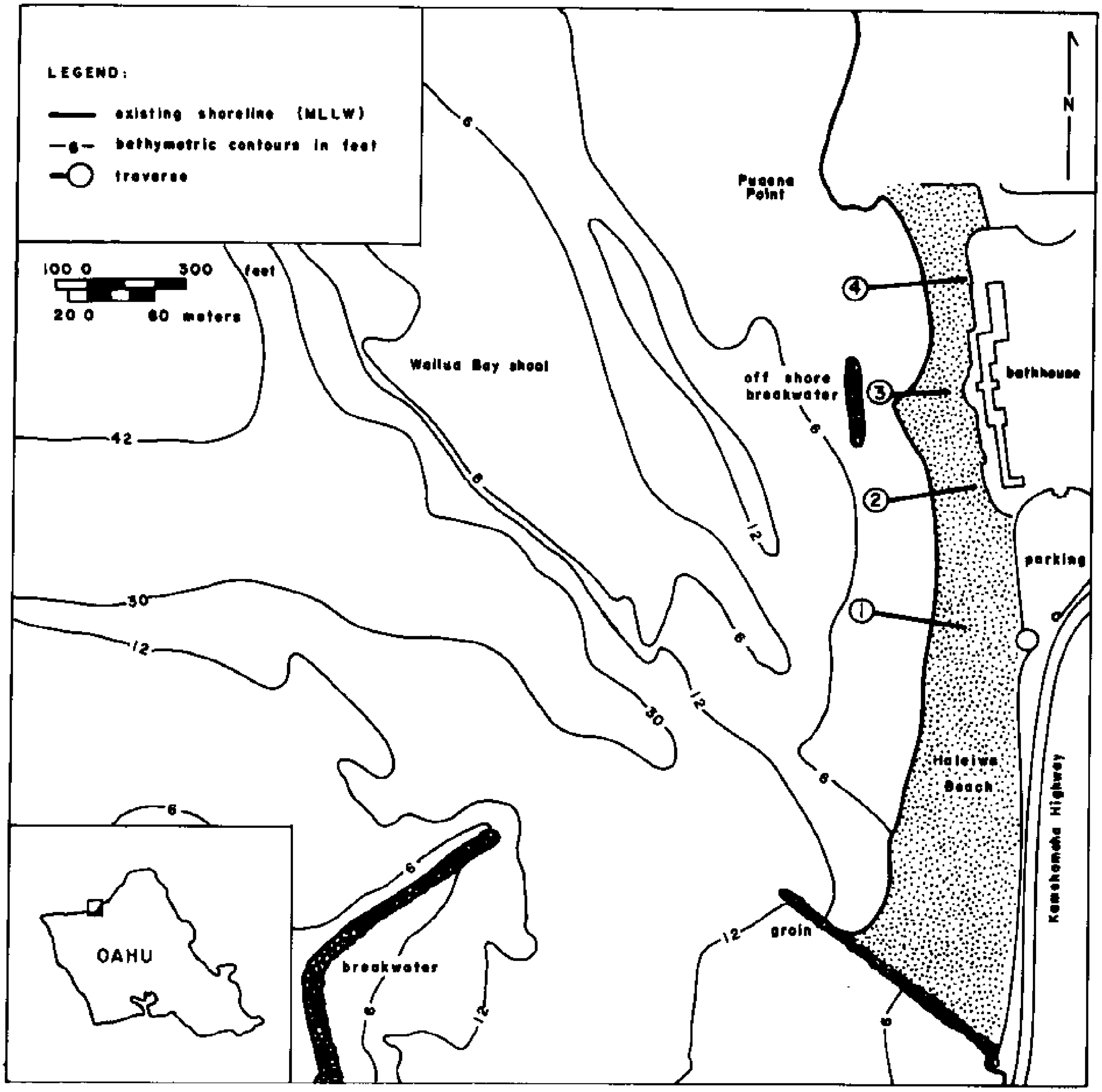


Figure 5.51. Haleiwa Beach, Oahu study site showing traverse locations

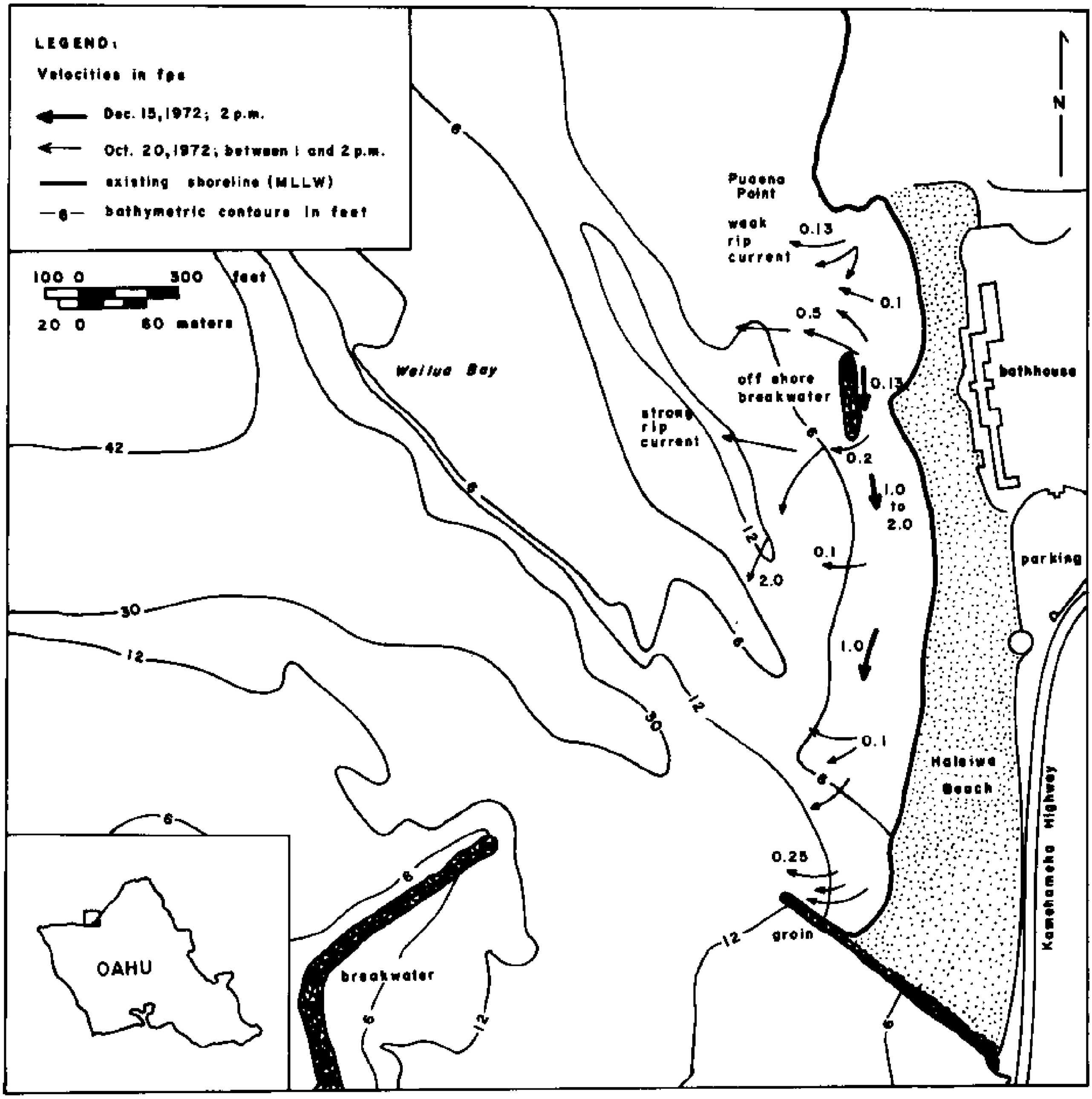


Figure 5.52. Current observations at Haleiwa Beach, Oahu on October 20, 1972 and December 15, 1972

On December 15, a relatively strong longshore current (1.0 to 2.0 fps) was observed in a southerly direction. On October 20, 1972, the pattern was similar except the currents were less strong.

On October 20, a strong rip current was observed south of the offshore breakwater and a weaker rip current was noted north of the breakwater.

Beach profiles

Beach profiles were taken at Haleiwa Beach at traverses 1 through 4 at regular time intervals. The results are shown in Figures 5.53 through 5.56.

The changes in beach elevation appear to have both a seasonal and a long-term trend, which can be seen from the behavior of the MSL-contour as depicted in Figure 5.57.

In traverses 1 and 2, successive periods of erosion and accretion may be observed from December 1971 to December 1972. The accretion during the period from June 21 to July 24, 1972, with subsequent erosion from July 24 to October 1972, are noteworthy.

The changes in the location of the mean sea level contour are largest in traverse 3, as shown in Figure 5.57, despite the fact that traverse 3 is situated behind the offshore breakwater. The MSL-contour receded 38 ft from January 28 to June 21, 1972 in this area.

Minimal changes occurred at traverse 4; the results of the survey show a relatively stable profile in that area.

Long-term trends show gradual erosion at traverses 1 and 2, averaging about 9.5 ft per year over the period of study.

At traverse 3 the rate of erosion was somewhat higher and is of the order of 12.5 ft per year.

At traverse 4 the rate of erosion was smaller, approximately 2 to 3 ft per year.

Sediment characteristics

Sand samples were taken from the beach and analyzed for grain-size distribution. The results are presented in Figure 5.58 and Table 5.8. They show that the material is relatively coarse and ill-sorted.

On October 20, 1972, a deep scarp 1 to 2 ft high was noted at the waterline, with stones and cobbles 1 to 4 inches in size. This material, apparently from the underlying layers, was brought in during an earlier restoration of the beach. At that location, the upper layers of sand were entirely removed by wave action.

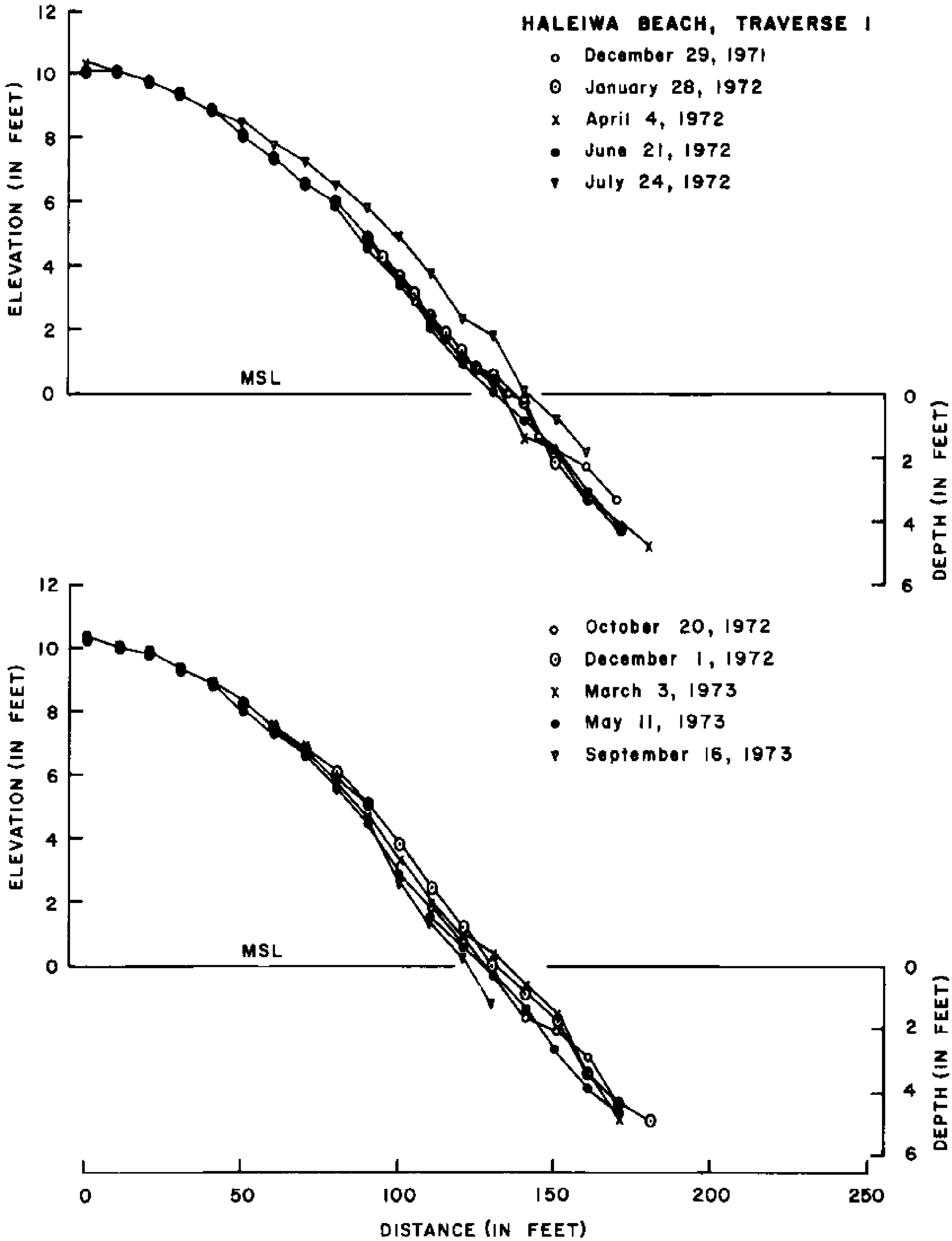


Figure 5.53. Beach profiles for traverse 1, Haleiwa Beach, Oahu. (See Figure 5.51 for traverse location.)

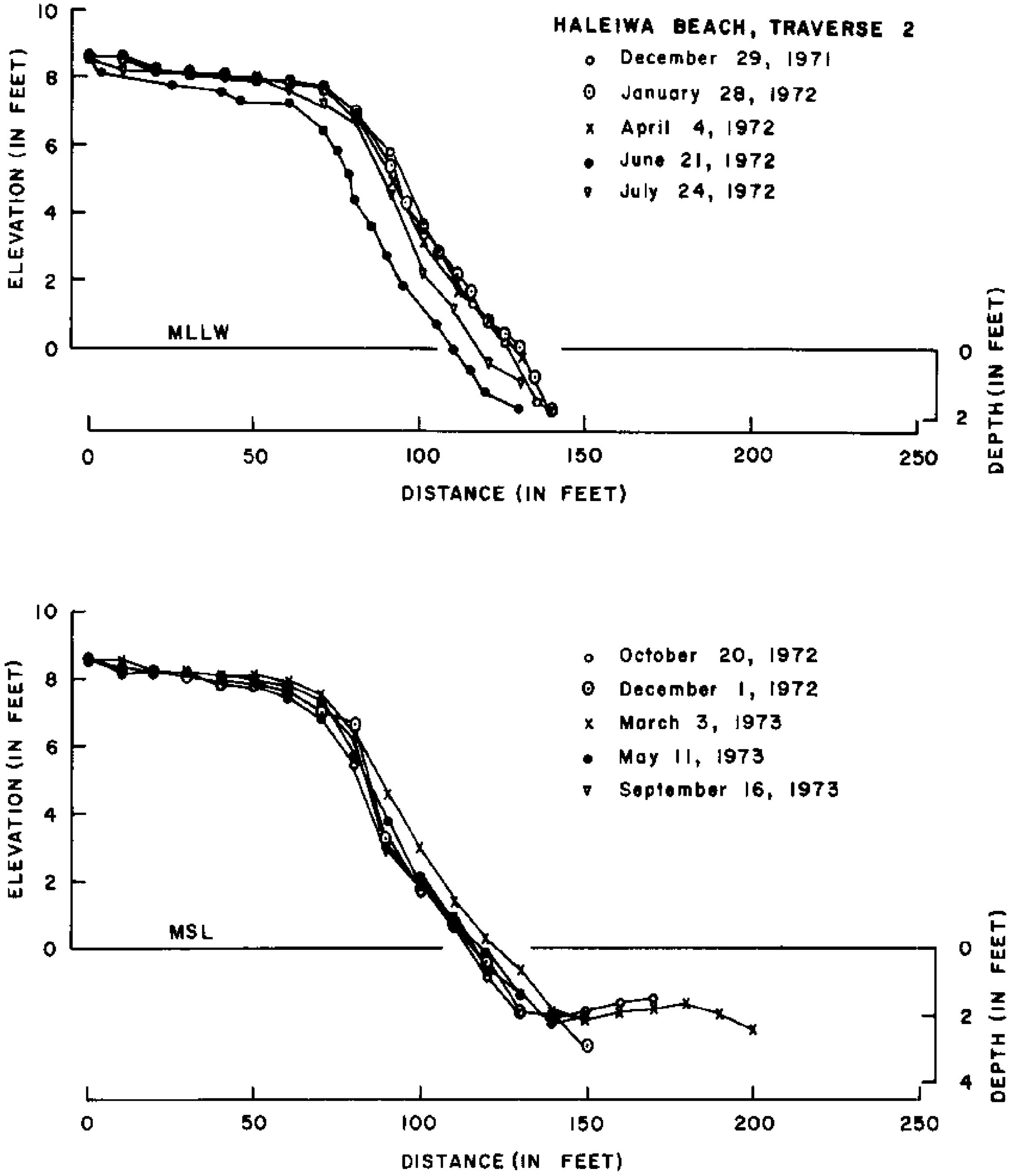


Figure 5.54. Beach profiles for traverse 2. Haleiwa Beach, Oahu. (See Figure 5.51 for traverse location.)

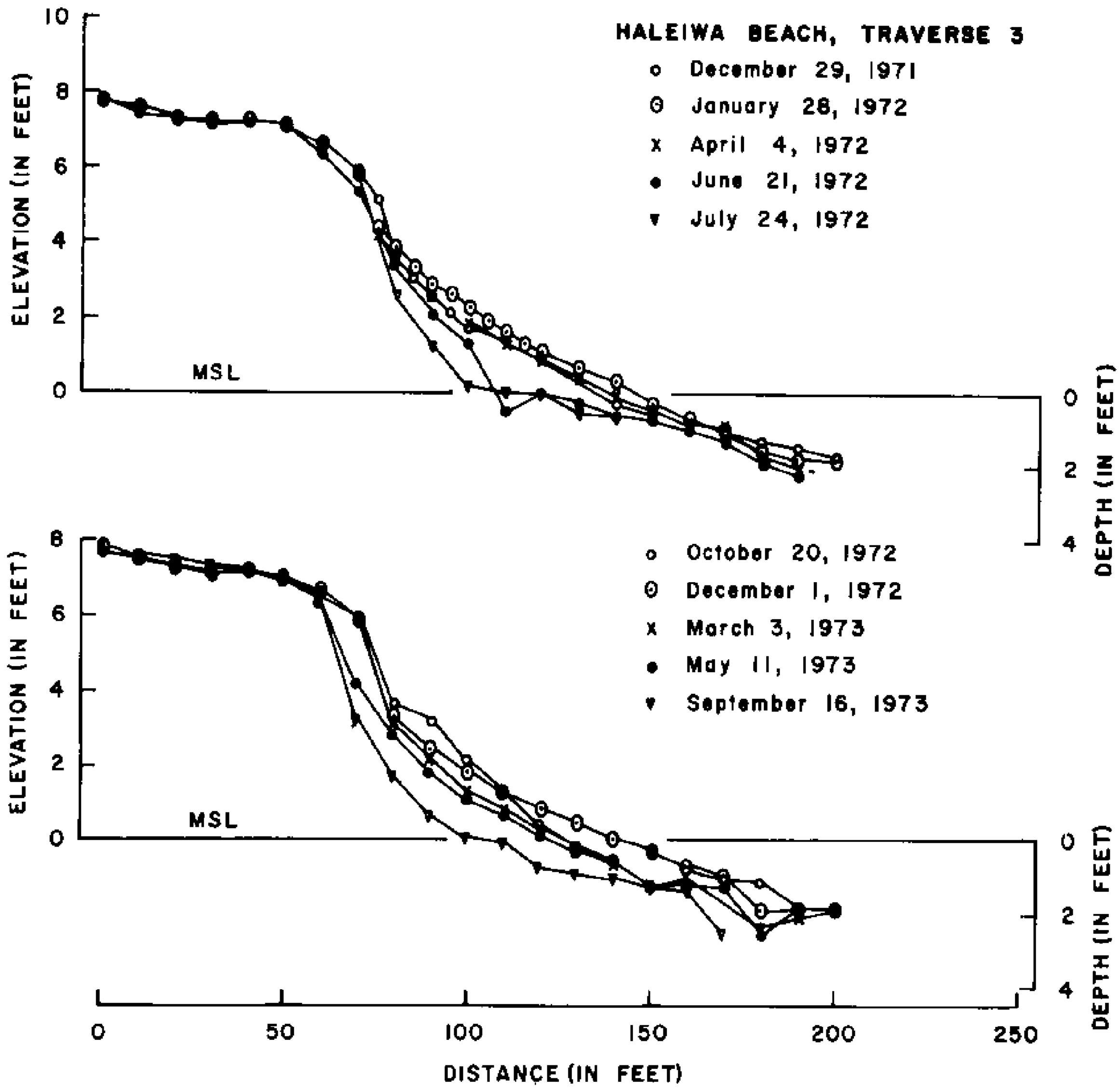


Figure 5.55. Beach profiles for traverse 3. Haleiwa Beach, Oahu. (See Figure 5.51 for traverse location.)

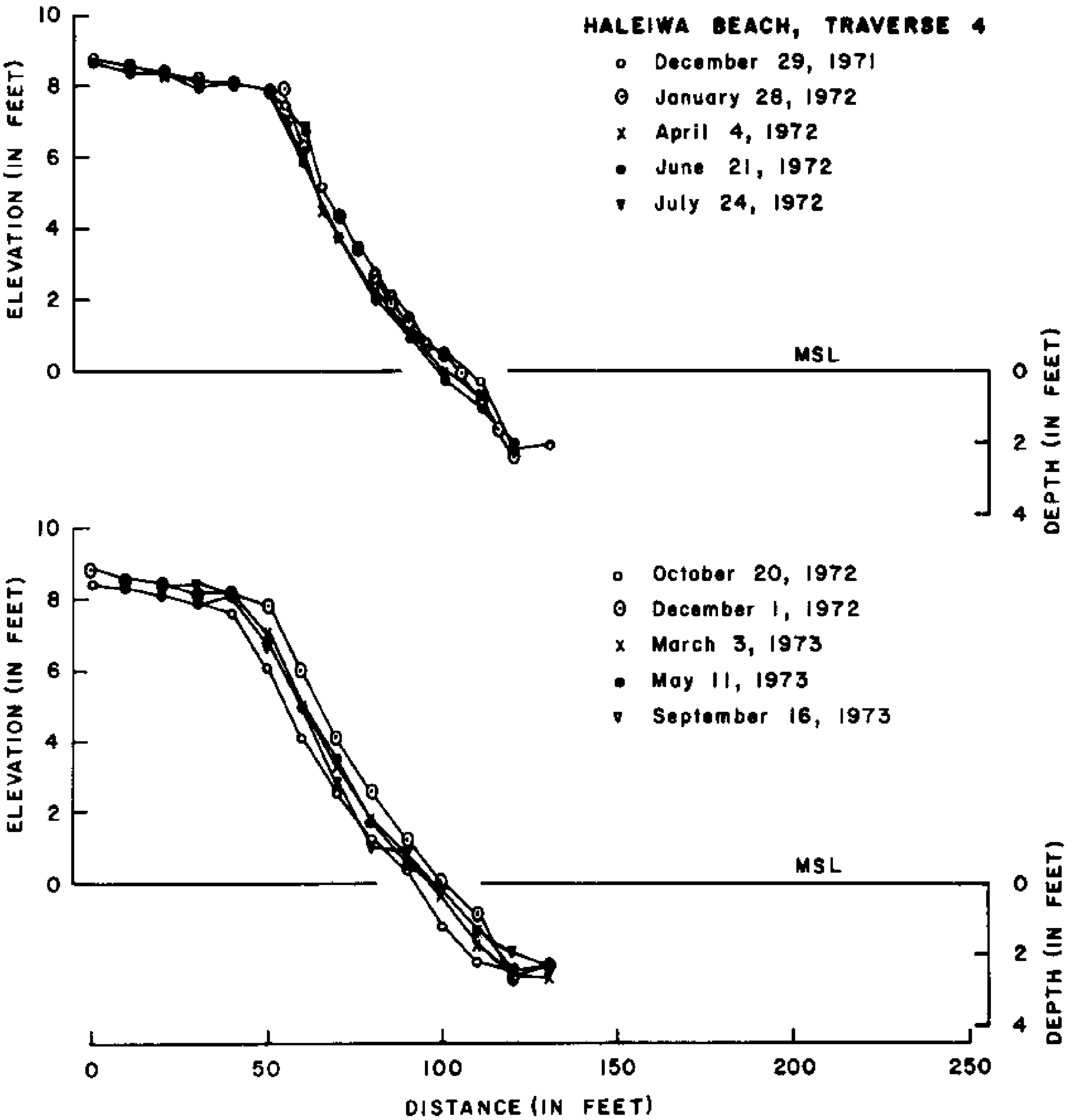


Figure 5.56. Beach profiles for traverse 4. Haleiwa Beach, Oahu. (See Figure 5.51 for traverse location.)

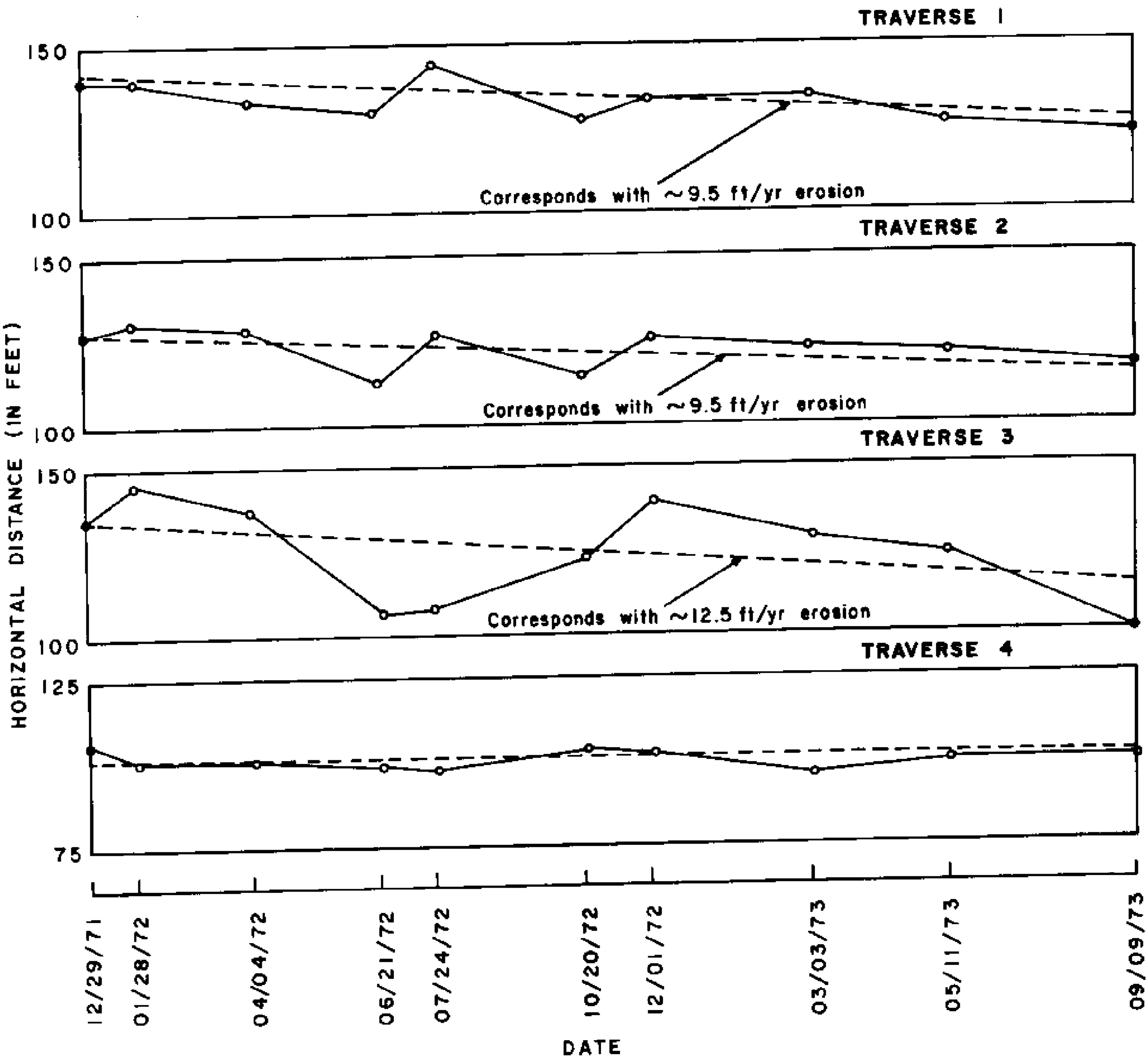


Figure 5.57. Behavior of MSL-contour at Haleiwa Beach for traverses 1 through 4 as a function of time

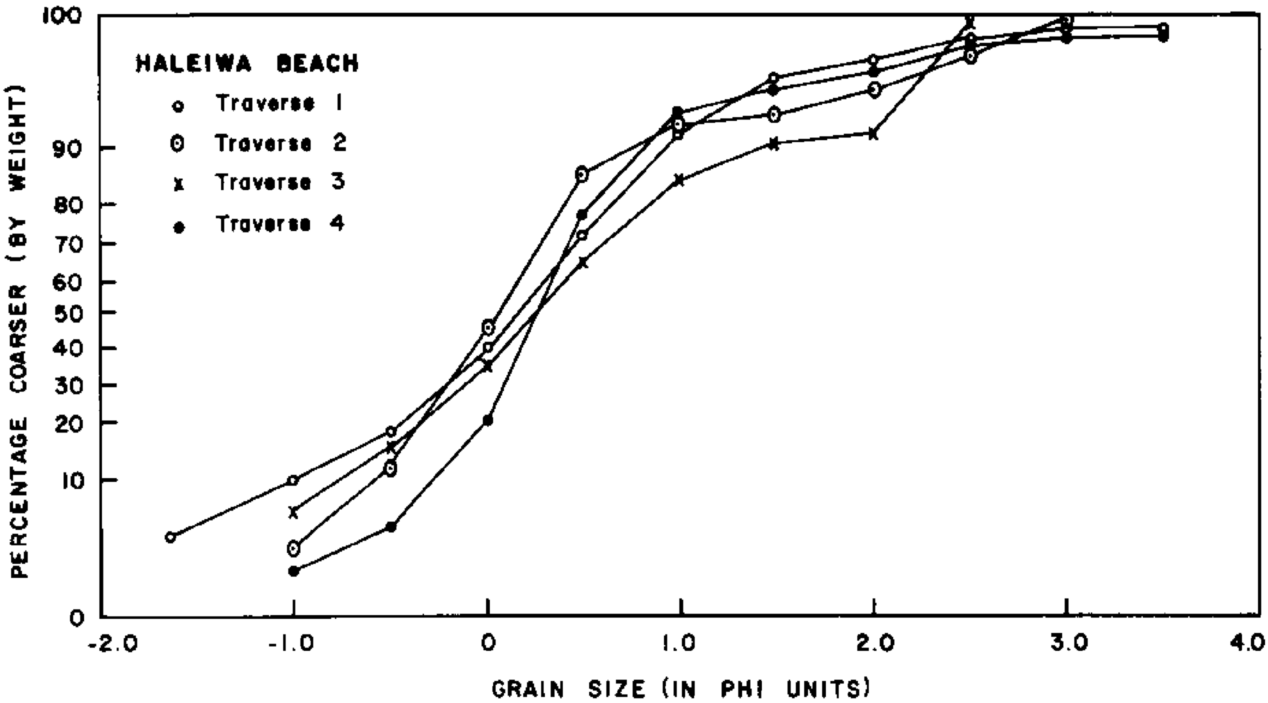


Figure 5.58. Grain size distributions for swash zone sand from Haleiwa Beach, Oahu

TABLE 5.9. SEDIMENT STATISTICS FOR HALEIWA BEACH

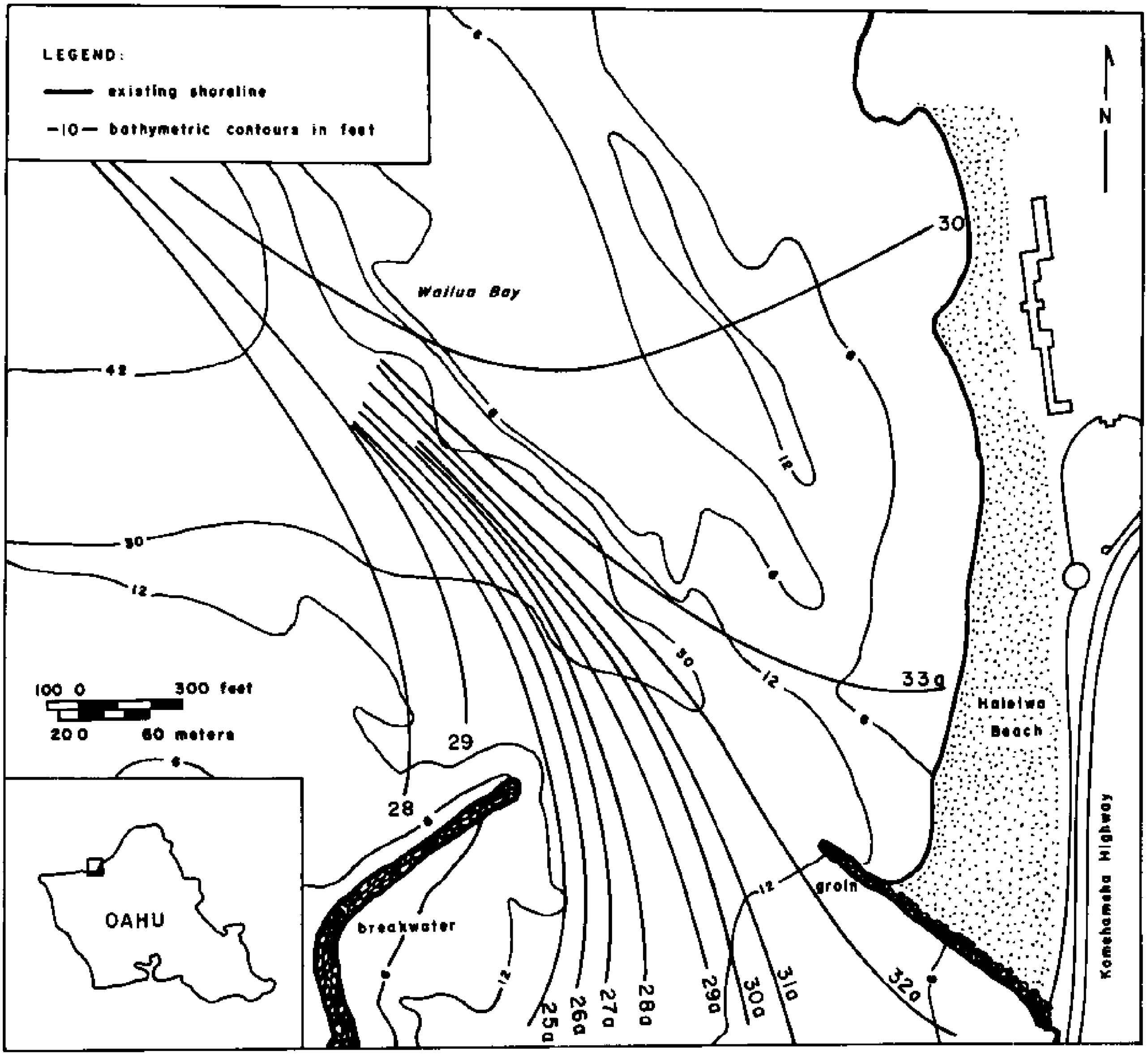
Traverse	Mean (ϕ)	Standard Deviation (ϕ)	Skewness (ϕ)	Kurtosis (ϕ)
1	0.24	0.55	0.16	1.05
2	0.11	0.45	0.02	1.77
3	0.35	0.67	0.19	-2.38
4	0.30	0.61	0.02	0.80

Measures for improvement

The beach profile measurements at Haleiwa show that the beach is slowly eroding and that measures of stabilization are needed.

Current measurements indicate that, along the major portion of the beach, currents flow from north to south. At times a strong rip current was observed south of the offshore breakwater, whereas a weaker rip current occurred north of the breakwater and at the groin at the south end of the beach.

Although no particular measurements on the magnitude and direction of the littoral drift were conducted, the general shoreline form and the current patterns suggest a predominant drift from north to south. Wave approach during northwesterly swell is affected by refraction of the waves in the deep channel from Haleiwa Harbor to the ocean. Figure 5.59 shows a wave refraction diagram for northwesterly swell conditions as determined for the Haleiwa Harbor model study (Lee et al., 1973).



After Lee et al., 1973

Figure 5.59. Wave refraction diagram for northwesterly swell as determined for Haleiwa Harbor model study (T = 15 sec)

The nature of the littoral drift and of the current characteristics suggests that a compartmentalization of Haleiwa Beach, together with replenishment of the beach with adequate sand to cover the exposed cobble layer, would constitute an adequate solution.

The following improvement project is recommended (Figure 5.60):

1. Connect the existing offshore breakwater with the beach, forming T-groin "A", to block longshore currents

2. Construct T-groin "B" halfway between the existing offshore breakwater and the existing groin at the south end of the beach

3. Transform the end-groin into an angular groin "C" by constructing a section parallel to the beach

4. Extend headland to the north of the beach with groin "D"

5. Enlarge the beach with sand of proper grain distribution and quality

Because of the occurrence of rip currents, beach material will occasionally be lost into deep water making replenishment necessary. However, compartmentalization of the beach, as suggested, will reduce the losses and improve overall stability.

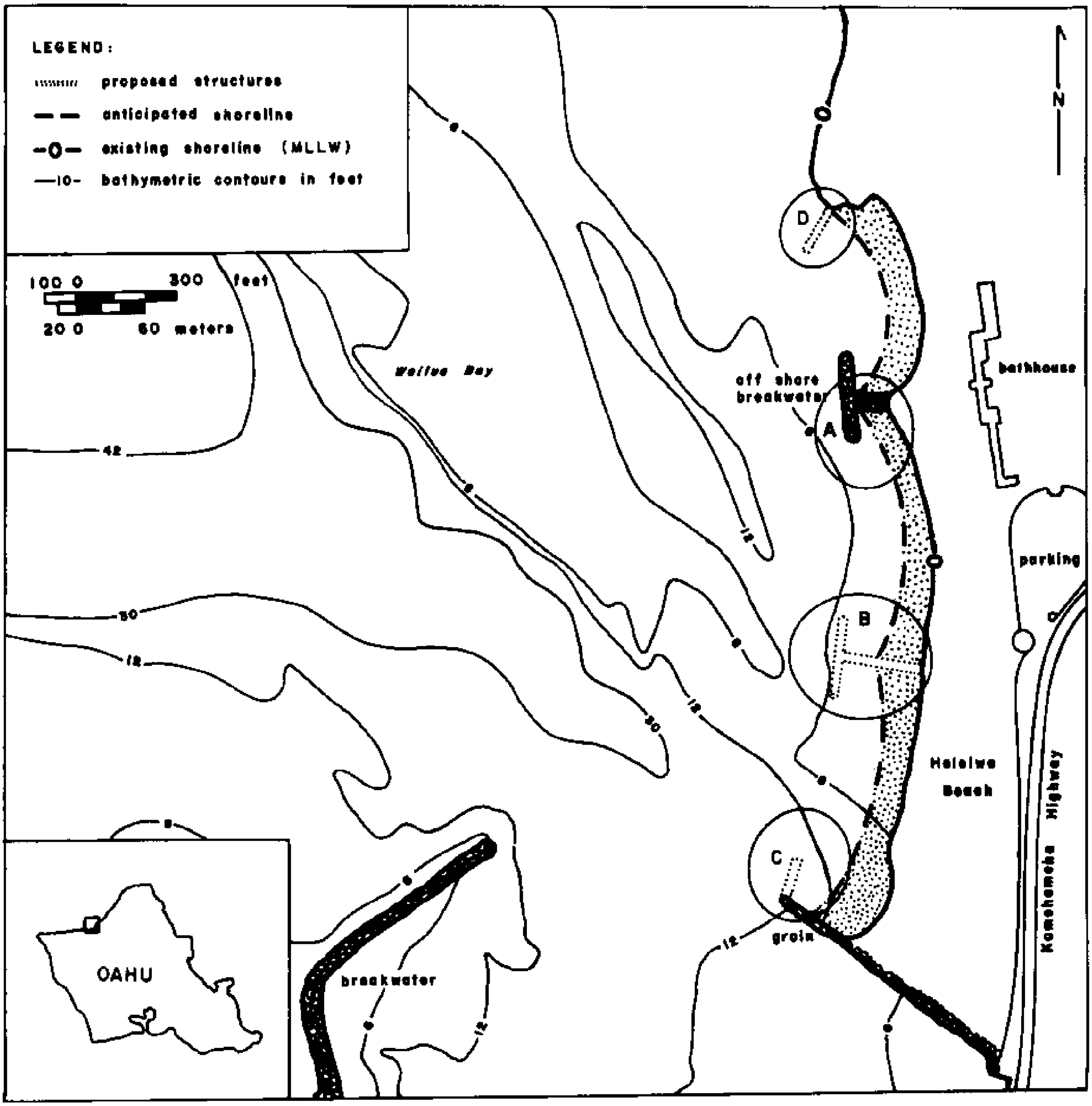


Figure 5.60. Suggested improvements for Haleiwa Beach, Oahu

CHAPTER 6. OTHER BEACHES ON OAHU

The behavior of some beaches on Oahu which have little or no nourishment from the longshore littoral drift because of protruding headlands and which are subject to moderate to heavy wave exposure is discussed in this chapter. The beaches which fall into this category are Waimea Bay Beach, Kuilima Beach, Sandy Beach, and Makaha Beach. Two of these, Waimea Bay Beach and Makaha Beach, have large seasonal exposure to northern swell.

Waimea Bay Beach

Murray Engle, in the *Sunday Star-Bulletin and Advertiser* of Honolulu, August 7, 1977, began an article about Waimea Bay with the following introduction:

> "Waimea Bay is both beauty and the beast. Ancient Hawaiians held it in such awe that its waters were kapu. When they sailed their outriggers across the bay's mouth, they hauled down the sails and kept silent."

Indeed Waimea Bay and its fringing beach is one of the most spectacular sites in the island--beautiful and quiet in the summertime, but wild and rough in the wintertime. The bay has one of the most treacherous rip currents in the world which makes it dangerous for the most experienced swimmer.

Waimea Bay is located on the north shore of the island of Oahu, approximately 4.5 miles northeast of Haleiwa (Figure 2.1) and, during winter months, the beach is often subject to high surf conditions from the North Pacific swell. On both sides the bay is protected by rocky cliffs extending approximately 600 ft seaward from the beach (Figure 6.1). In the center of the bay the offshore area is predominantly sandy with small rocky areas extending from the cliffs. The beach confronting the bay is approximately 1,500 ft long and 100 ft wide; it is occasionally characterized by cuspate formations at its west end. The Waimea River flows into the bay and is usually blocked off by the beach, forming a landlocked pool.

Surf conditions range from nearly flat to extremely high and cause large variations in the beach width. Shortly after large storm waves (estimated at 25 ft in height before breaking) had hit the north shore on January 9-10, 1974, the beach width at MLLW was measured at 170 ft. One month later, on February 26, 1974, the beach was replenished and the width of the beach increased to approximately 240 ft. During the same period, the slope of the upper beach (from 0 to 12 ft elevation) increased from 1:10 to 1:5 (Figure 6.2).

Sand samples collected from the beach indicated that the calcareous beach material at the waterline is coarse. The median ϕ value at the MLW line was 0.687 and 0.723, respectively on the two days of observation (Table 6.1).

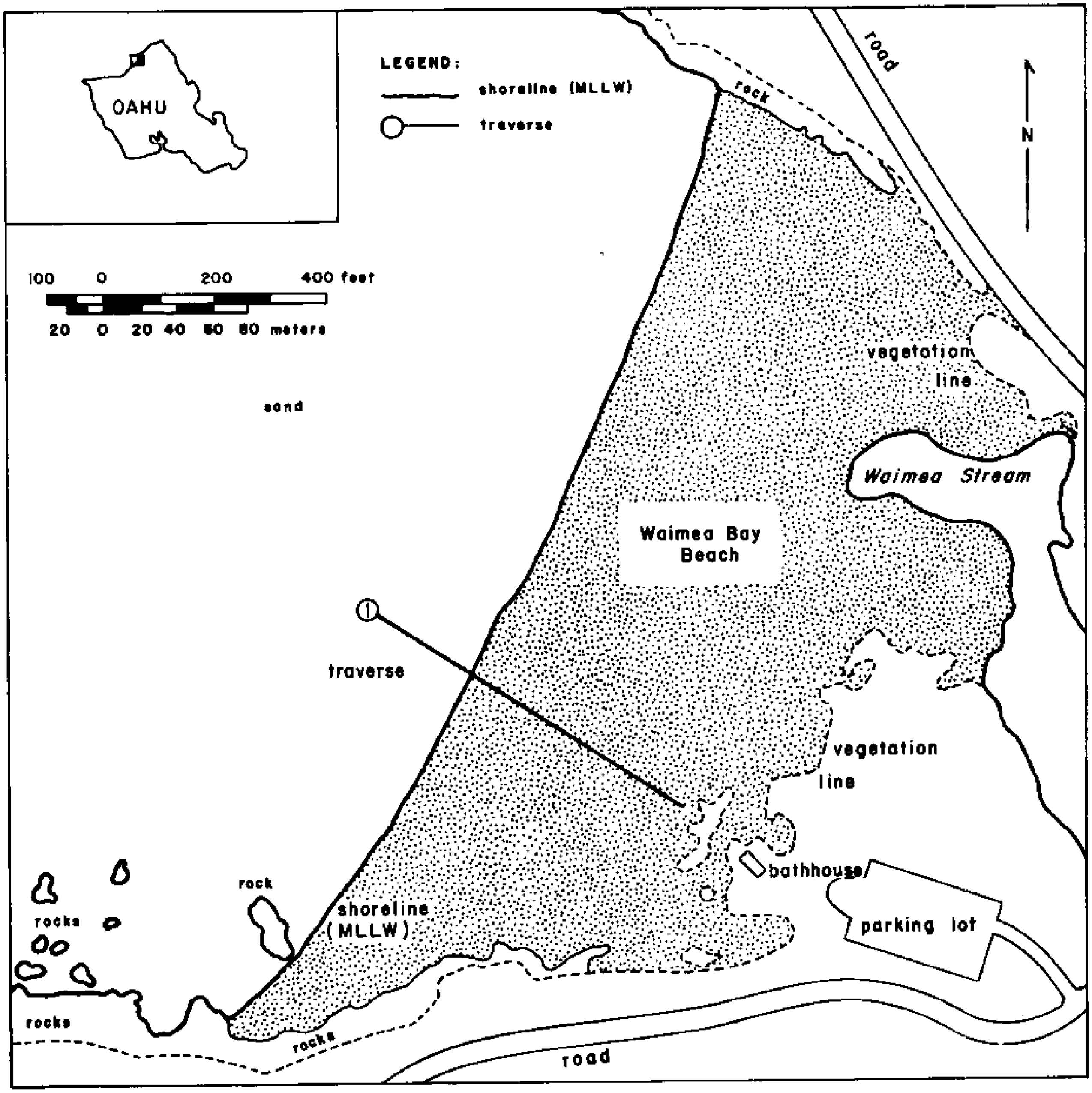


Figure 6.1. Waimea Bay Beach, Oahu study site showing traverse location

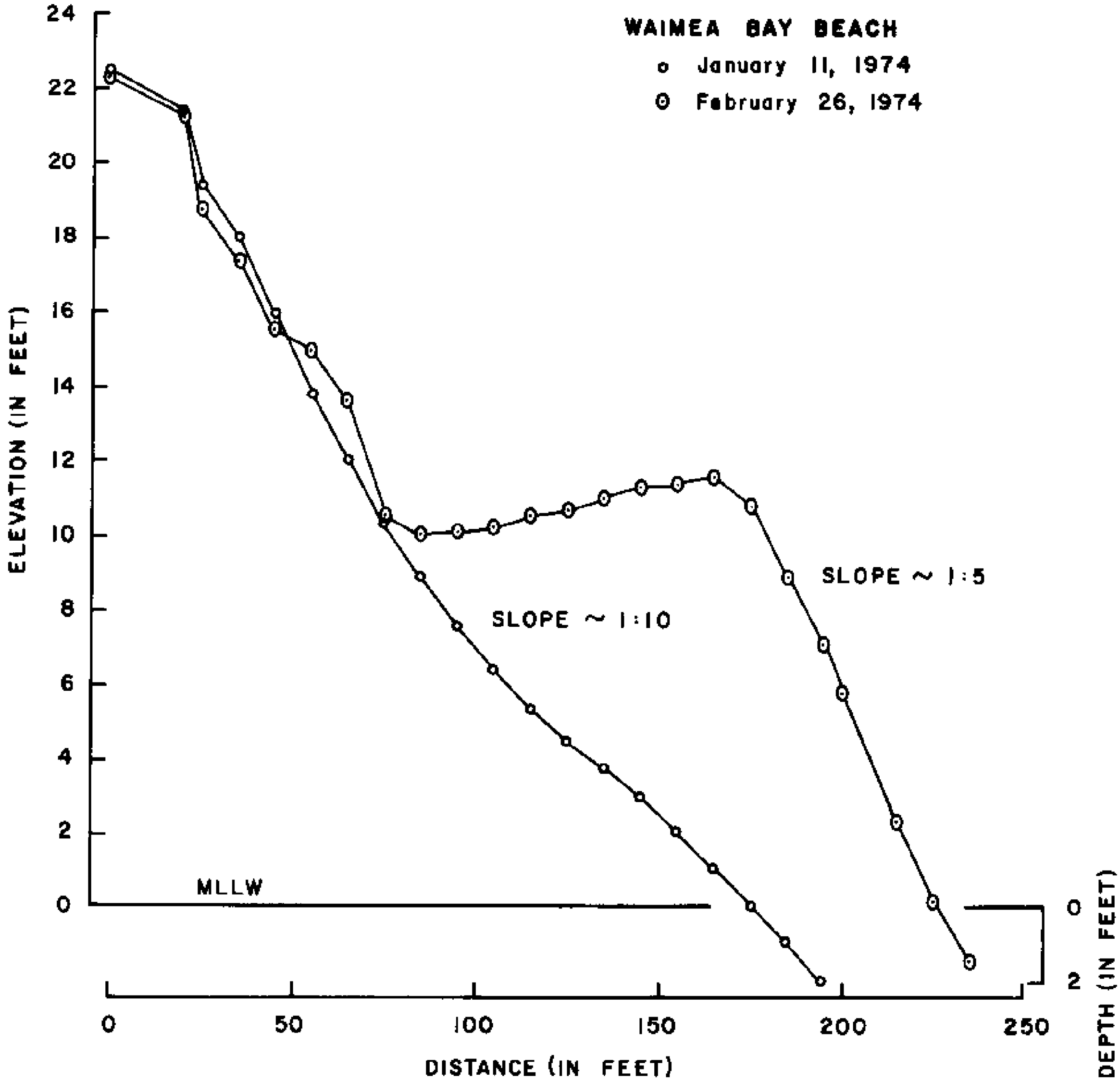


Figure 6.2. Beach profiles for traverse at Waimea Bay Beach, Oahu. (See Figure 6.1 for traverse location.)

TABLE 6.1. SEDIMENT DIAMETER STATISTICS

Location*	Date	Sediment Diameter (ϕ) Median	Standard Deviation	Skewness	Kurtosis
Makaha Beach, Oahu	03/26/74	0.768	0.387	-0.299	5.084
Offshore at 4 m depth		0.780	0.530	-1448	8.296
Waimea Bay Beach, Oahu	01/11/74	0.687	0.341	-0.506	4.501
	02/16/74	0.723	0.472	-0.540	4.052
Sandy Beach, Oahu	11/10/73	1.158	0.452	-0.956	5.911
	12/15/73	1.155	0.420	-0.685	5.198
	01/26/74	1.074	0.468	-0.517	4.559
Wailea Beach, Maui	12/21/73	2.235	0.488	0.066	3.618
Mauna Kea Beach, Hawaii	12/20/73	2.127	0.523	-0.515	4.558
	12/20/73	2.160	0.480	-0.269	4.023
Hapuna Beach, Hawaii	12/20/73	1.942	0.552	-0.439	3.641
Holupoe Beach, Lanai	12/22/73	1.760	0.375	-0.413	6.021
Kuilima Beach, Oahu Traverse 1	09/16/73	0.460	0.567	-0.547	6.161
	10/30/73	0.736	0.401	0.436	4.169
	12/07/73	0.795	0.393	0.760	5.212
	01/11/74	-0.033	0.689	0.226	5.666
	02/26/74	0.709	0.384	0.290	7.011
Kuilima Beach, Oahu Traverse 3	09/16/73	0.496	0.516	-0.323	7.381
	10/30/73	0.429	0.735	-0.486	4.483
	12/07/73	0.658	0.389	0.200	4.100
	01/11/74	0.603	0.580	-0.546	4.615
	02/26/74	0.365	0.540	-0.529	6.283
Port Allen Beach, Kauai	01/17/74	0.600	0.298	0.067	9.882
Poipu Beach, Kauai West	01/16/74	1.111	0.391	0.557	5.165
Poipu Beach, Kauai East	01/16/74	1.892	0.537	-0.763	4.587
Baldwin Park Beach, Maui	12/22/73	1.199	1.105	-0.136	1.817
Spreckelsville Beach, Maui	12/22/73	1.581	0.646	-0.608	5.762

*Measurement made at waterline for Makaha Beach

Kuilima Beach

Kuilima Beach is located on the eastern tip of Oahu's north shore. It is protected against wave and current action by a rocky peninsula to the west, a rocky headland to the east, and an offshore shallow reef covering most of the entrance to the cove (Figure 6.3). The beach is about 500 ft long and 150 ft wide and the foreshore slope of the beach averages 1:8.

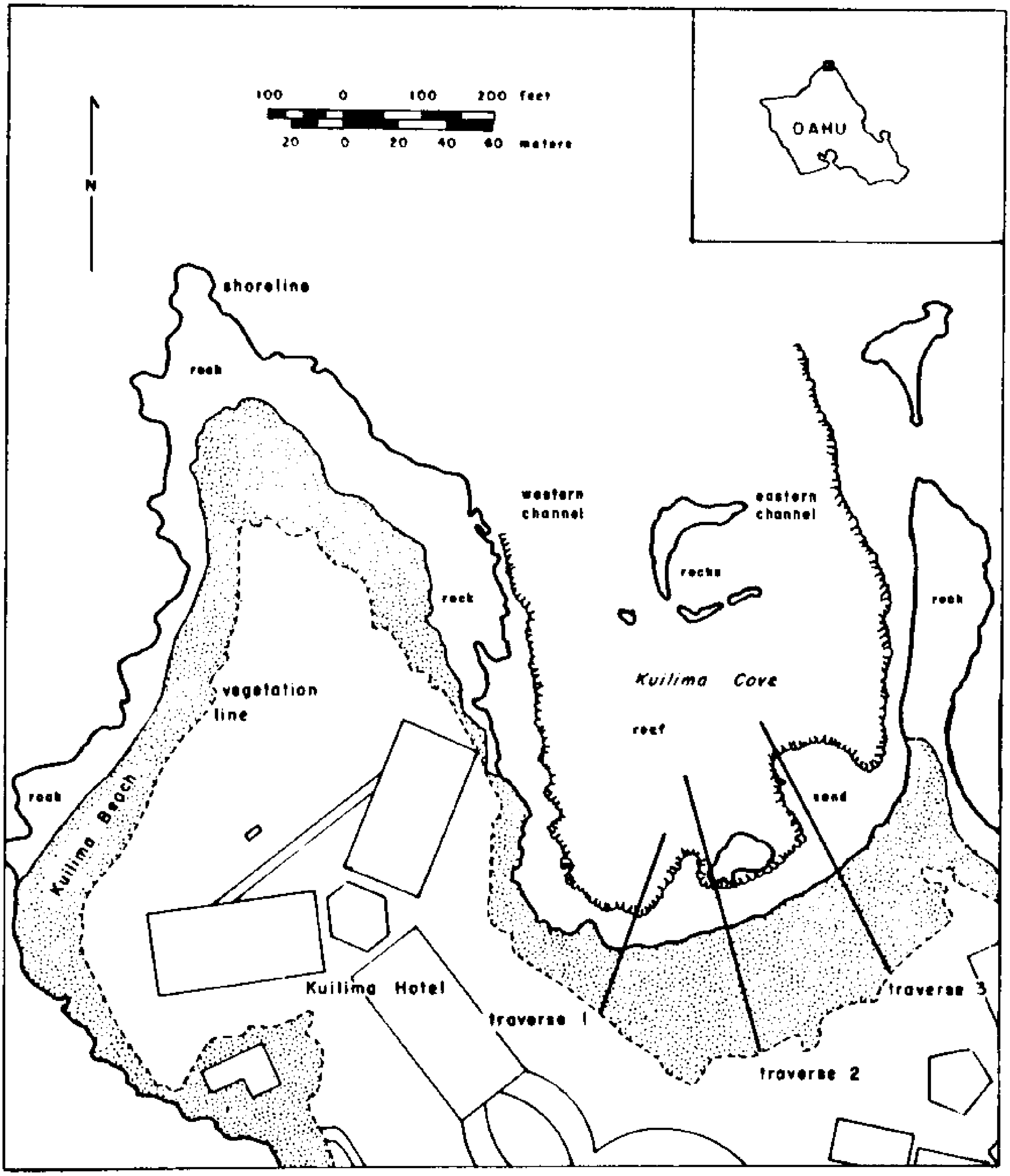


Figure 6.3. Kuilima Beach, Oahu study site showing traverse locations

Kuilima cove is characterized by shallow depths of an average of about 2 to 4 ft. At the entrance to the cove, the submerged lava reef parallel to the beach covers nearly 80 percent of the width of the mouth of the cove. At the entrance to the cove two channels can be identified. The east channel is very shallow, with depths of approximately 1 to 3 ft and a width of 50 to 100 ft depending on the tide. The west channel has depths of 5 to 8 ft and is 60 to 80 ft wide.

The observations at Kuilima Beach were carried out as follows. First, an aerial photographic study was performed to enable the drawing of a map of the study site and to determine the offshore characteristics. The photos also provided the pattern of the incident waves on the day of survey. Second, a bathymetric survey was conducted by divers. Following this, currents and beach elevations were measured and sand samples collected at three traverses. The resulting profiles are shown in Figures 6.4 through 6.6.

The difference between the profiles of December 7, 1973 and January 11, 1974 is probably due to the effect of the January 1, 1974 storm. Traverses 1 and 2 showed overall increases in beach elevation whereas traverse 3 showed an increase in elevation below the 3-ft elevation and a decrease in elevation between the 3 and 9-ft levels. The decrease in beach slope at traverse 3 after the storm is shown in Figure 6.6.

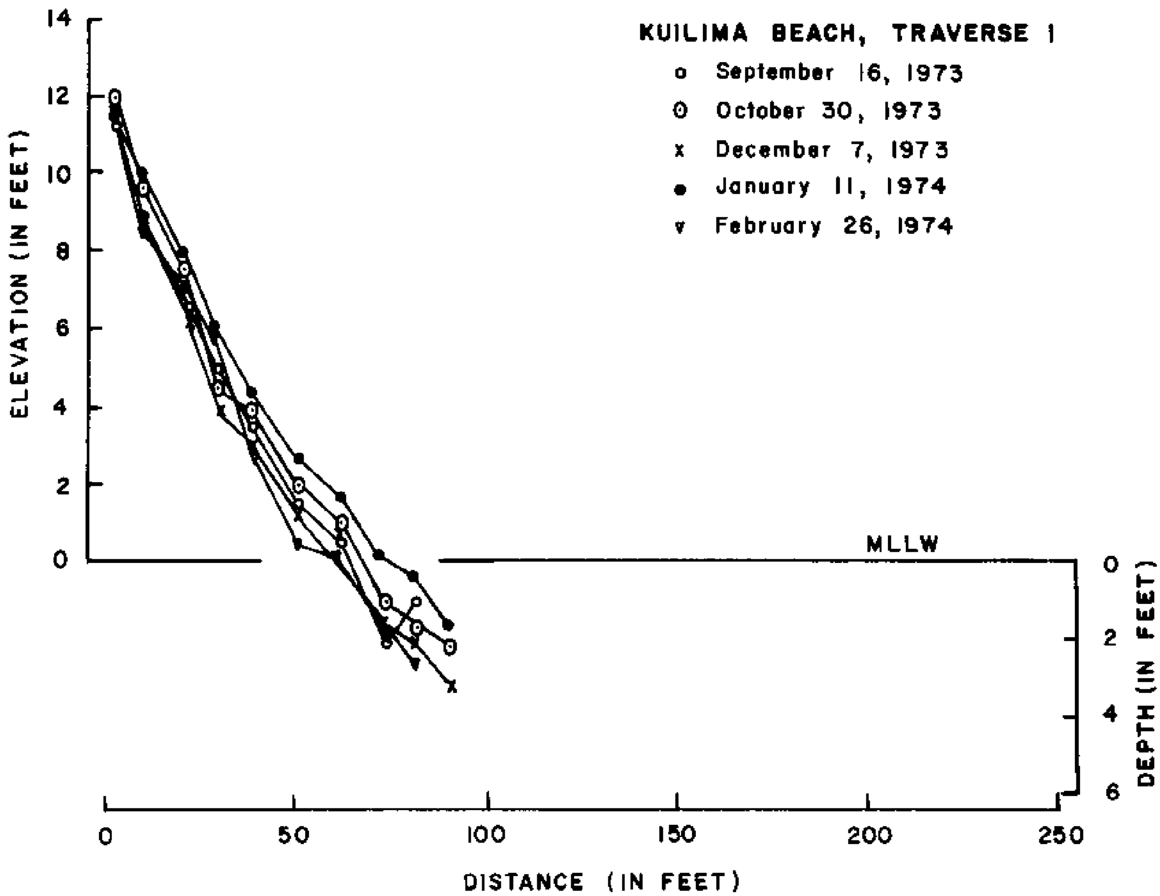


Figure 6.4. Beach profiles for traverse 1, Kuilima Beach, Oahu. (See Figure 6.3 for traverse location.)

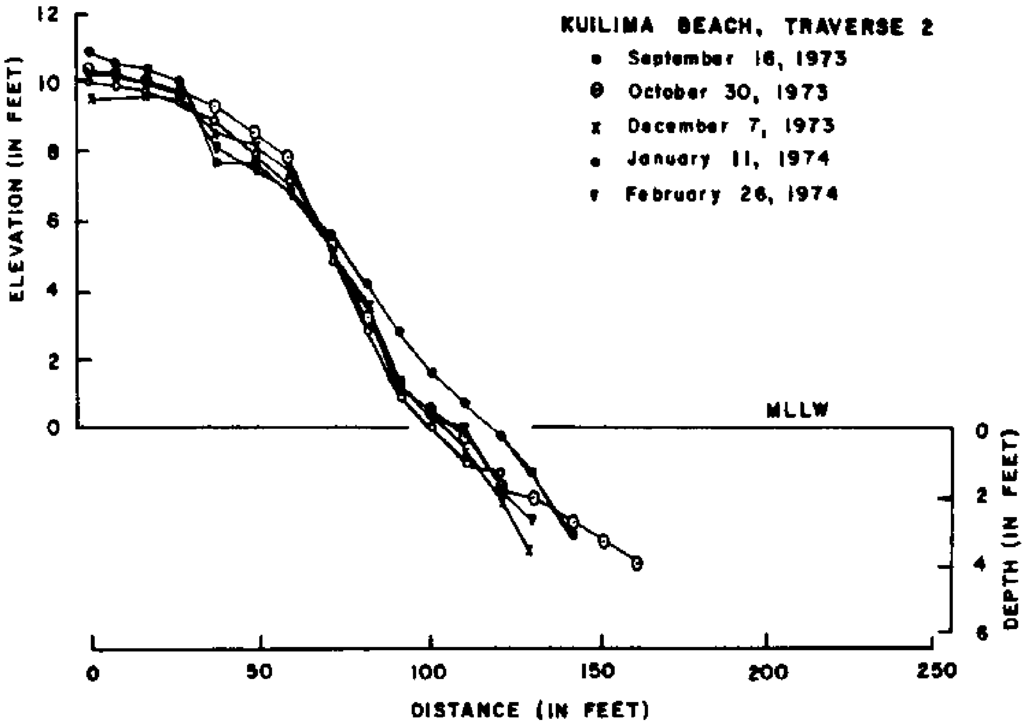


Figure 6.5. Beach profiles for traverse 2, Kuilima Beach, Oahu. (See Figure 6.3 for traverse location.)

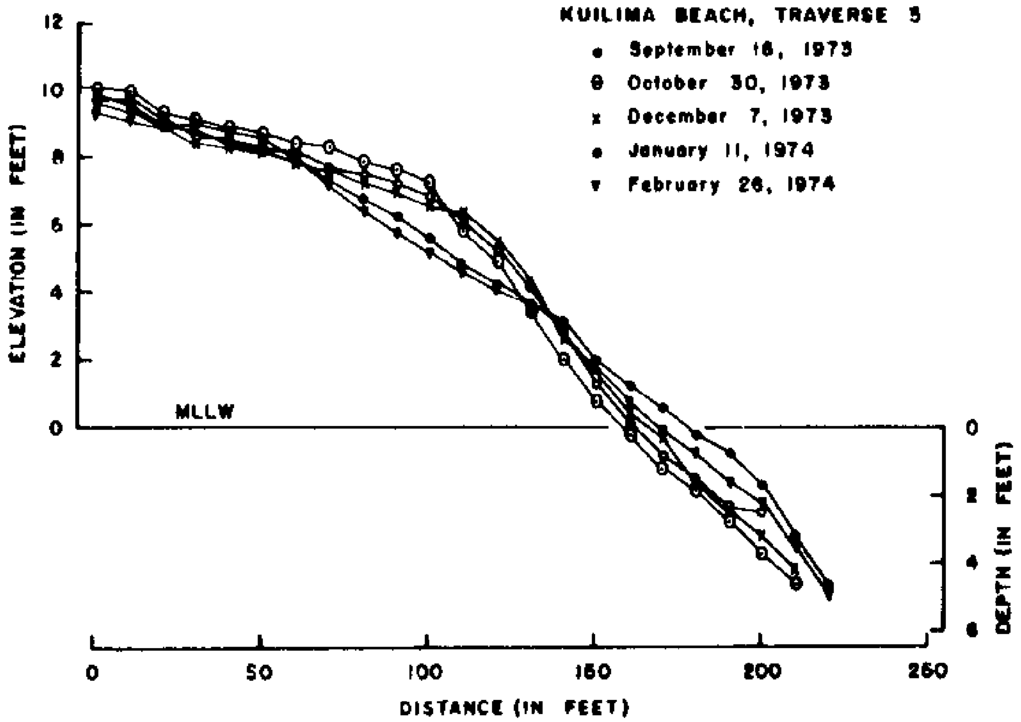


Figure 6.6. Beach profiles for traverse 3, Kuilima Beach, Oahu. (See Figure 6.3 for traverse location.)

The gain in beach elevation may have been due to longshore sand transport from the east across the shoreward part of the rocky headland east of the cove during the storm conditions, or it may have been the result of offshore-onshore transport.

Currents along the beach are predominantly wave induced. During field observations, a counterclockwise circulation was observed with outflow over the eastern channel. Average velocities were 0.3 fps (feet per second) with maximum values of 0.8 fps.

The greater depth of the western channel allows waves to enter the bay along this part of the cove, from which the waves radiate to the beach. Incoming waves are already low because of breaking outside the cove. There appears to be sand nourishment of the beach through the western channel, with a tendency toward offshore transport over the shallow eastern part of the bay. In Plate 6.1 indications of seaward sand movement at the east end of the beach may be seen. Occasionally the beach is nourished artificially to compensate for loss of sand.

Sediment characteristics are shown in Figures 6.7 and 6.8 and Table 6.1. The sample taken at traverse 1 on January 11, 1974 showed very coarse sand at the waterline. This may have been due to transport of coarse sand to the

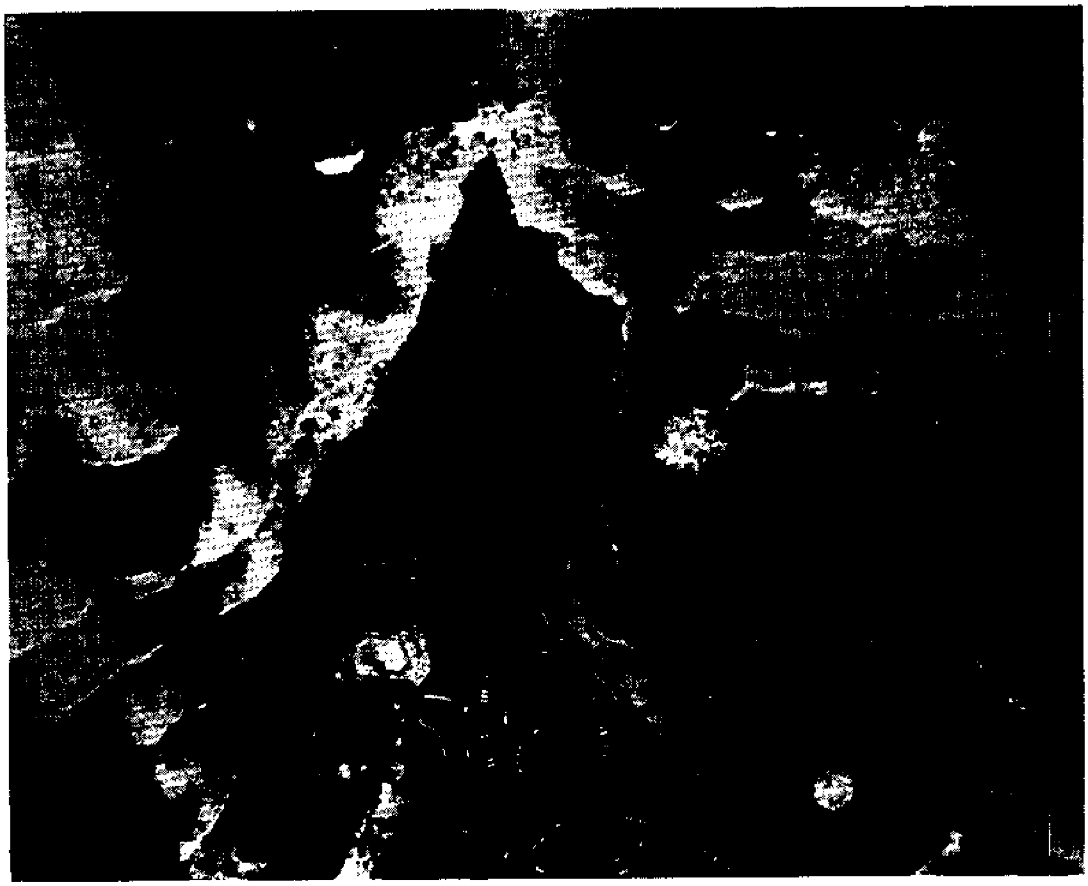


Plate 6.1. Kuilima cove under high surf conditions

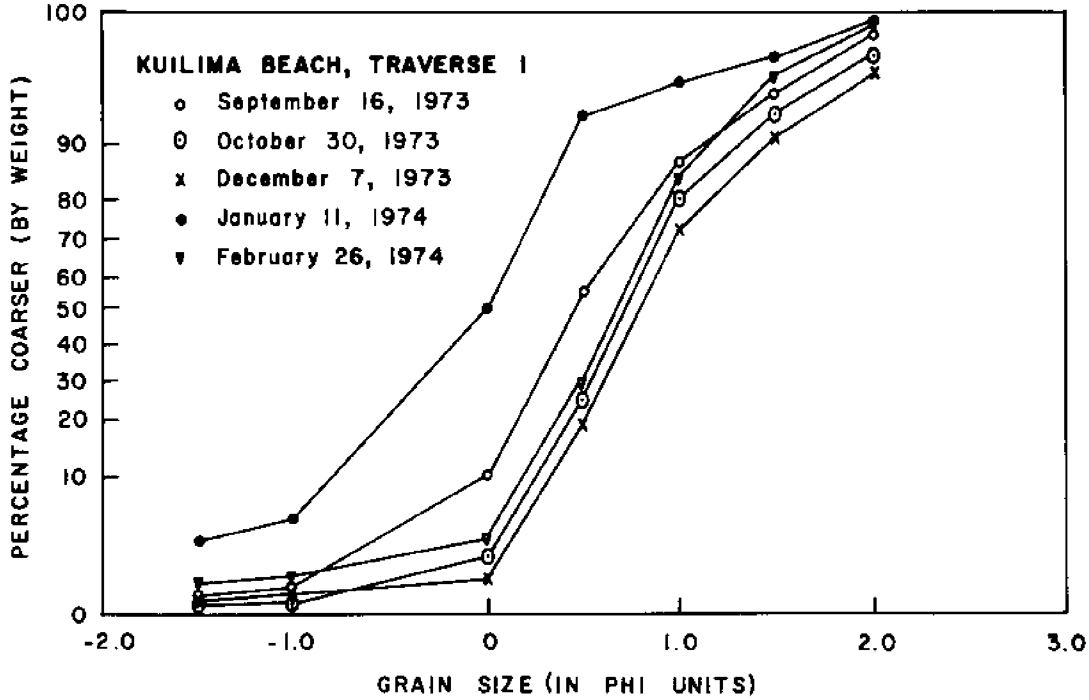


Figure 6.7. Grain size distributions for swash zone sand from traverse 1, Kuilima Beach, Oahu. (See Figure 6.3 for traverse location.)

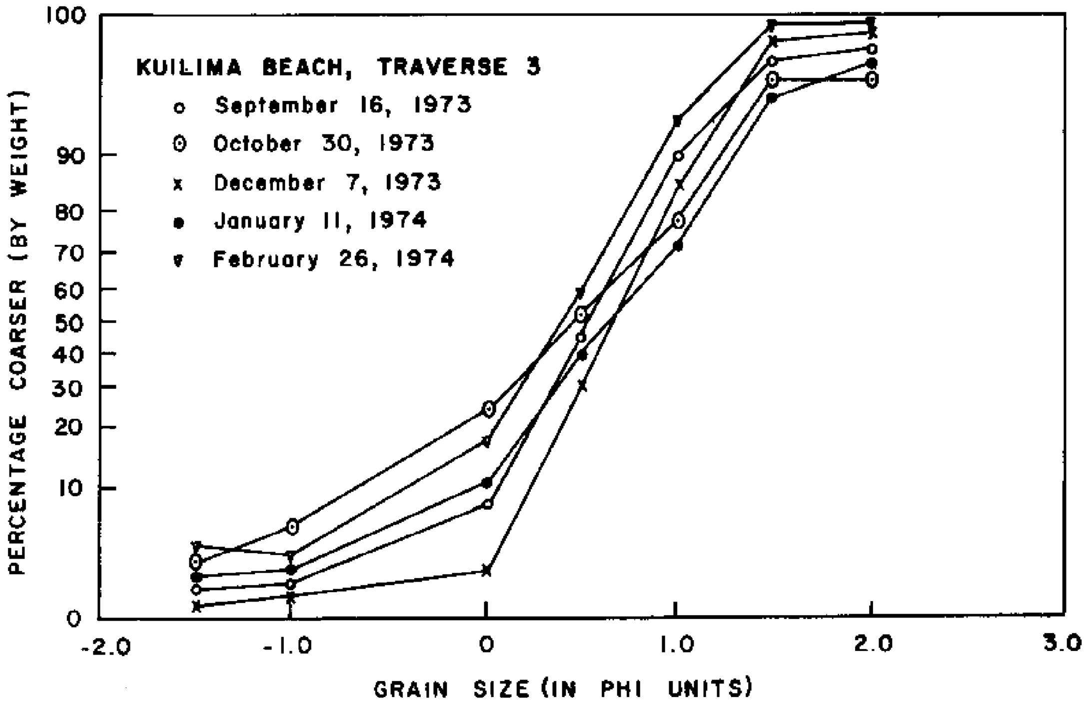


Figure 6.8. Grain size distributions for swash zone sand from traverse 3, Kuilima Beach, Oahu. (See Figure 6.3 for traverse location.)

beach through the west channel and/or due to loss of the fine fractions during the storm of January 1, 1974.

Makaha Beach

Makaha Beach is located on the west coast of the island of Oahu (see Figure 2.1). It is a very popular beach and a world-famous surfing site.

The beach is slightly arcuate in plan form. At each end are shallow, rocky points that are raised reefs (Figures 6.9 and 6.10). The Makaha Stream flows seaward east of the bathhouse. Most of the time the stream is blocked by the beach, but during floods the stream crosses the beach into the ocean.

Opposite the mouth of the stream is an offshore sand channel with shallow reefs on both sides. The beach is marked by a singular cuspate feature opposite the mouth of the stream near the sand channel.

In the nearshore zone currents are wave induced, whereas, beyond the reef, tidal currents prevail. The latter runs from north to south during flood and from south to north during ebb (Laevastu et al., 1964).

During a site investigation on March 26, 1974, strong nearshore currents were running in a southerly direction along the northern section of the beach.

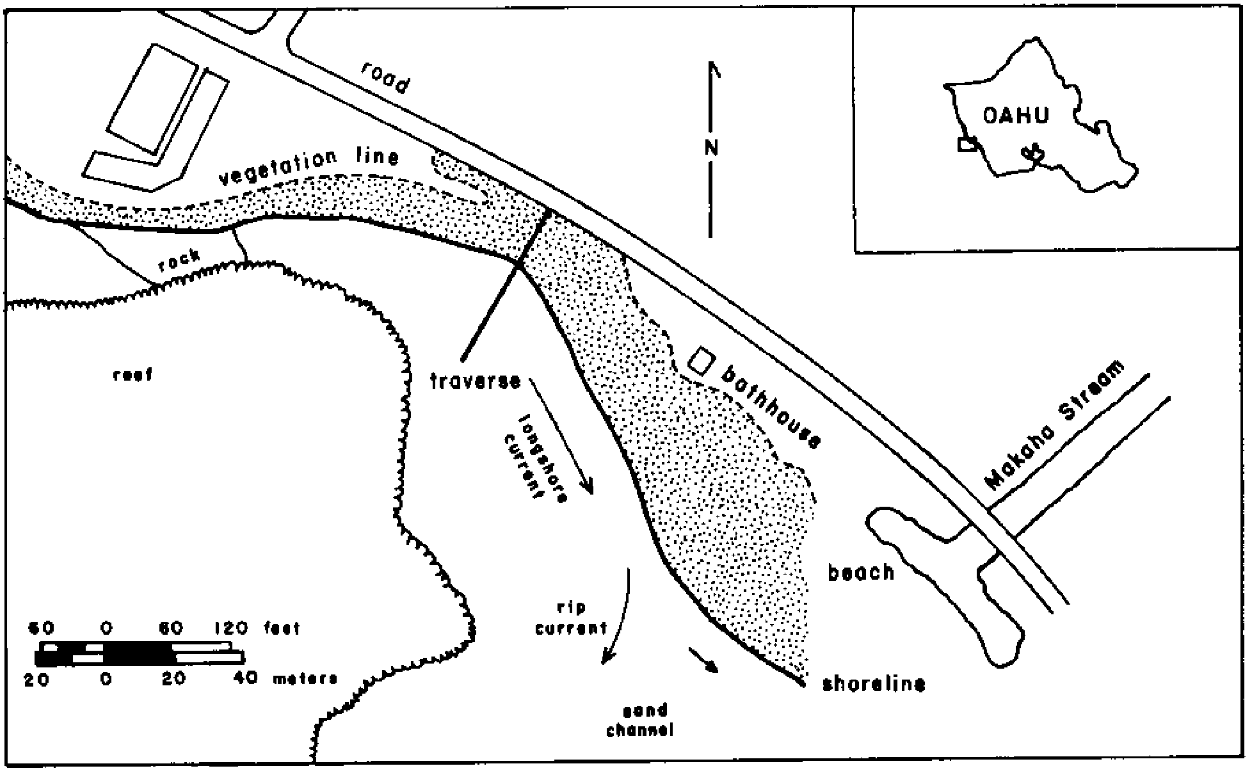
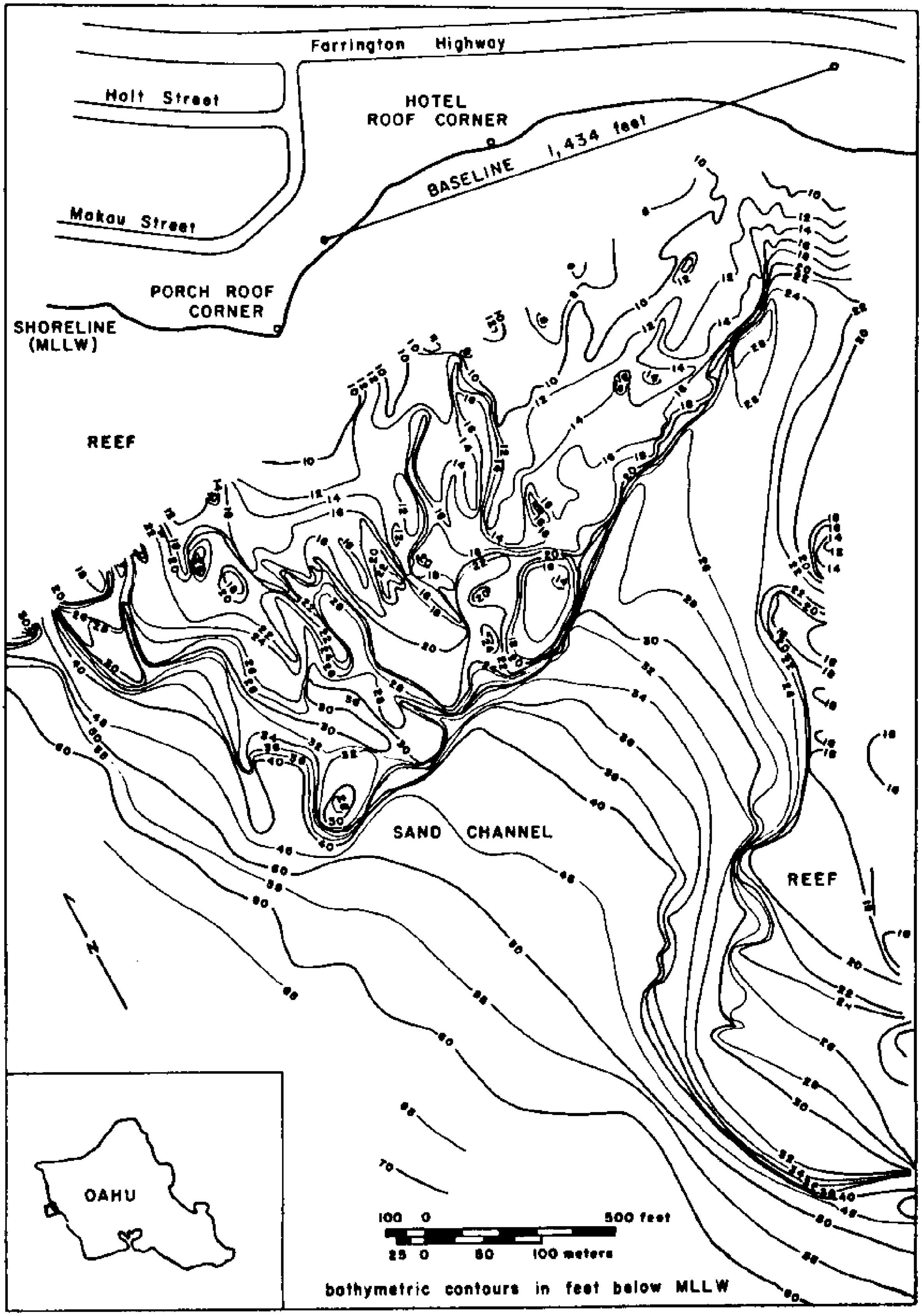


Figure 6.9. Makaha Beach, Oahu study site showing traverse location and current directions



After Walker, 1974 a

Figure 6.10. Detailed offshore bathymetry for Makaha Beach, Oahu

Their maximum strength was close to 3 fps, developing into a rip current of lesser strength opposite the central beach cusp (Figure 6.9).

The beach at Makaha is affected by various types of waves, such as the kona storms, the southern swell, and the North Pacific swell. The latter produces high surf at Makaha Beach during the the winter months.

Due to the complex offshore hydrography, in which a relatively deep sand channel is situated between two extended shallow reefs (Figure 6.10), a complex situation of wave breaking, refraction, shoaling, and reflection occurs. The special merits of the area as a surfing site are discussed by Walker (1974a). He derived a cumulative deep water wave height frequency distribution for this area, as shown in Figure 6.11. In deep water a significant wave height of 17 ft is equalled or exceeded 1 percent of the time during an average year.

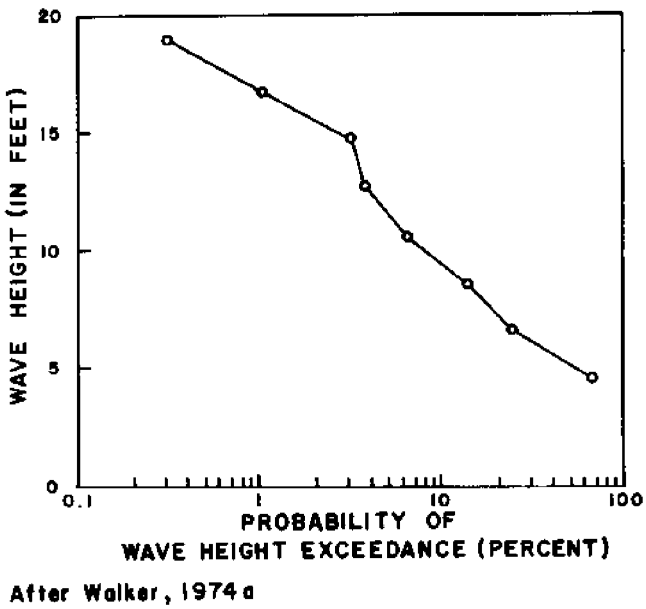


Figure 6.11. Frequency distribution for wave heights at Makaha Beach, Oahu

Beach profiles were measured by Moberly and Chamberlain (1964) at various times. They found that during the period of their study (1962-63), the width of the beach varied between 225 ft (June 1962) and 80 ft (January 1963).

Profile measurements over the traverse of Figure 6.9 taken during this study also showed large variations in width (Figure 6.12). From December 1, 1973 to March 26, 1974 the width of the beach was reduced from 200 ft to 90 ft. Most of this change may have occurred during the storm of March 23-24, 1974, which generated large waves along the north and northwest coasts of Oahu.

The slope of the beach also varies from a relatively flat one in December 1973 to a steeper one in March 1974. Beach slopes immediately above the water level were found to be 1:12 on December 1, 1973, before the storm season, and 1:8 on March 26, 1974, immediately after the storm of March 23-24, 1974.

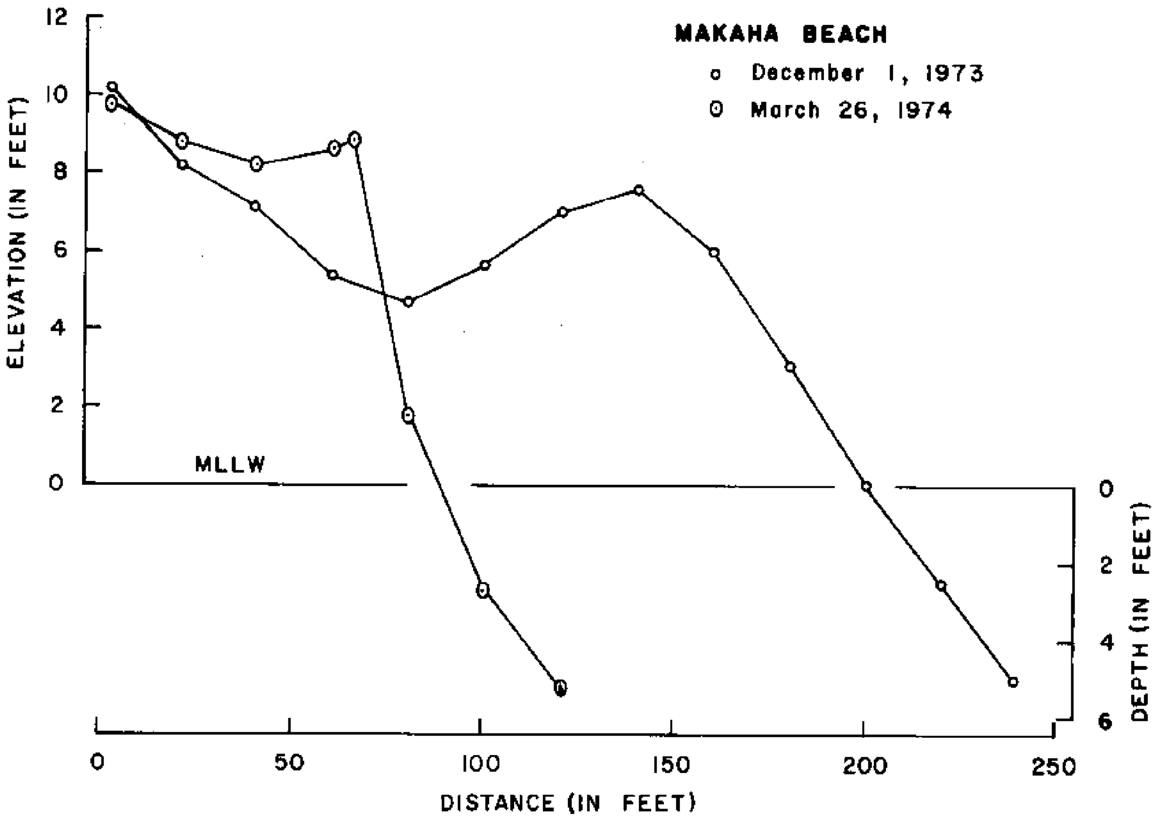


Figure 6.12. Beach profiles for Makaha Beach, Oahu. (See Figure 6.9 for traverse location.)

The sand of the beach was well sorted and medium to coarse in grain size; the beach deposits were very porous. About 80 percent of the beach material is of calcareous origin with foraminifera and mollusk-shell fragments in abundance (Moberly, 1964).

The large beach cusp in the middle of the beach gave rise to some discussion. There are two possible causes for the formation of this cusp:

1. Sand deposits supplied by Makaha Stream

2. Sand supplied by longshore sand transport. There are several reasons to suggest that the beach cusp is indeed a result of littoral drift behavior:

   a. Similarity of beach samples taken at the waterline at the cusp and in the middle of the northern beach section (Figure 6.13)

   b. Characteristics of beach sands similar to those from offshore deposits in the sand channel

c. Southward littoral drift caused by strong southward flowing littoral current. As the strength of the current diminishes and develops into a rip current (see Figure 6.9), the flow of littoral drift is reduced and a cusp is formed. The sand channel is nourished by the flow of littoral drift and is shoaling over time. (The latter was confirmed by depth measurements conducted by the Hawaiian Telephone Company in 1963 and 1971).

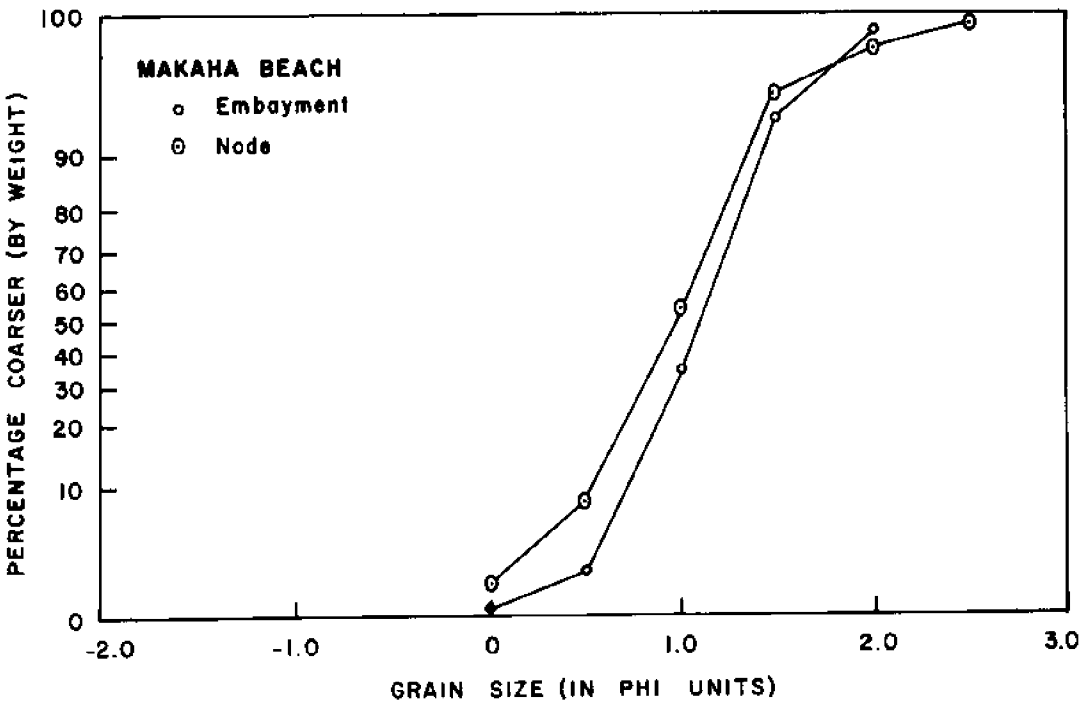


Figure 6.13. Grain size distributions for swash zone sand from cusp at Makaha Beach, Oahu

The conclusion seems warranted that the cusp formation is induced and maintained by the special nature of the littoral drift in this area as derived from the characteristic offshore hydrography.

The beach is nourished from the northerly reef flat and the material moves southward along the beach into the sand channel where the rip current carries part of it seaward.

Sandy Beach

Sandy Beach is located on the southeast tip of the island of Oahu, approximately 1.5 miles northeast of the extinct Koko Head crater. The beach, shown in Figure 6.14 is about 1,200 ft in length and approximately 140 ft in width near the center.

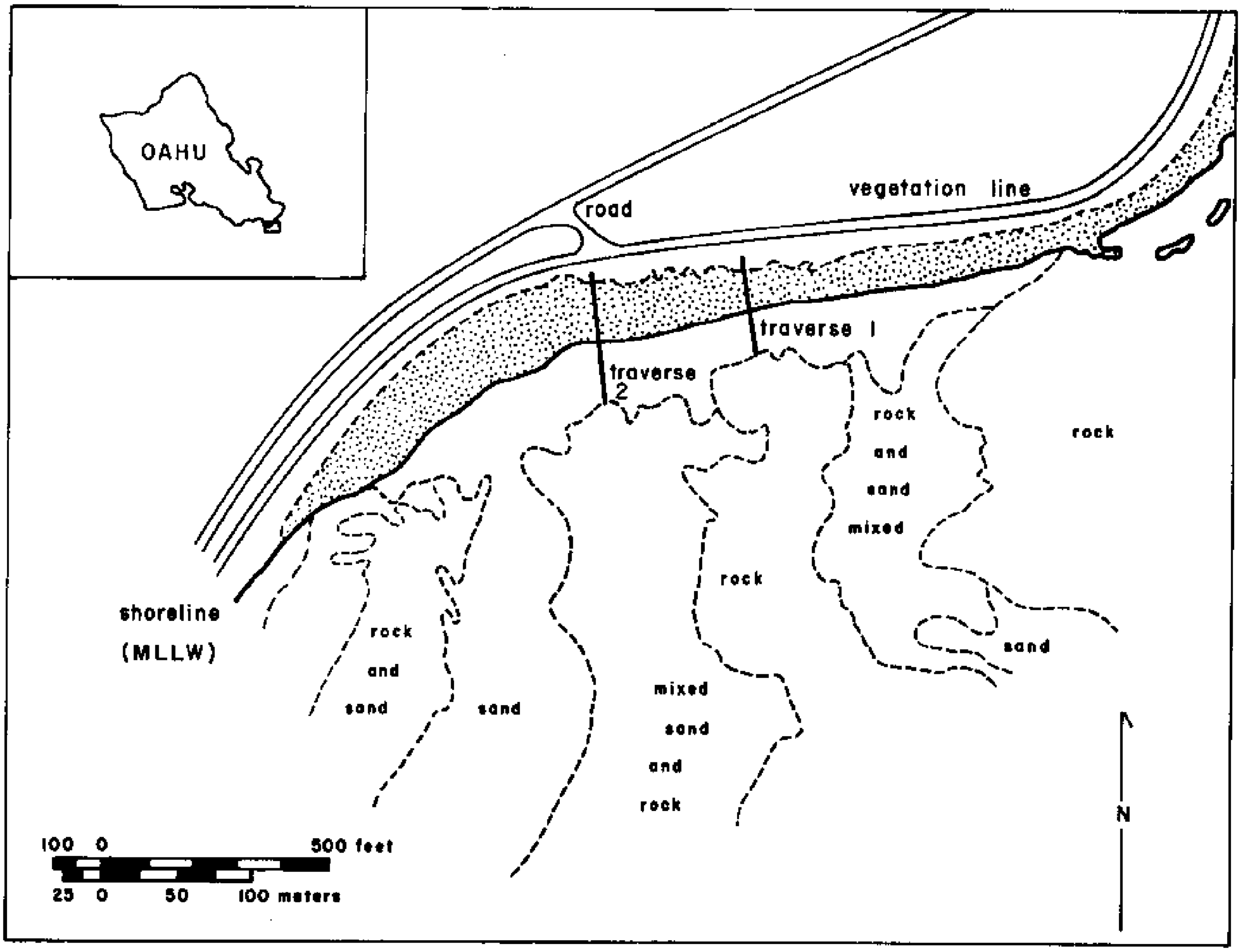


Figure 6.14. Sandy Beach, Oahu study site showing traverse locations

Beach elevations were measured at two different traverses (Figure 6.14) on different dates. The results of the measurements are shown in Figures 6.15 and 6.16. The beach is situated such that it is affected by waves and swells from different directions, particularly the tradewind waves from the east which reach the site after refraction, and the southern swell which affects the area directly. Longshore currents can reach high velocities in this area; values up to 2 knots were measured during periods of high surf.

This slightly arcuate beach is often characterized by cusps. During the period of observations, the beach was marked by five or six cusps with mean cusp lengths ranging from 125 to 150 ft. The cusps were always well defined and, in some instances, two sets of cusps were observed. The older set of cusps was located higher up on the beach and had apparently been formed during times of larger surf and greater run-up.

The beach slopes remained fairly constant, at about 1:9, during the period of this study.

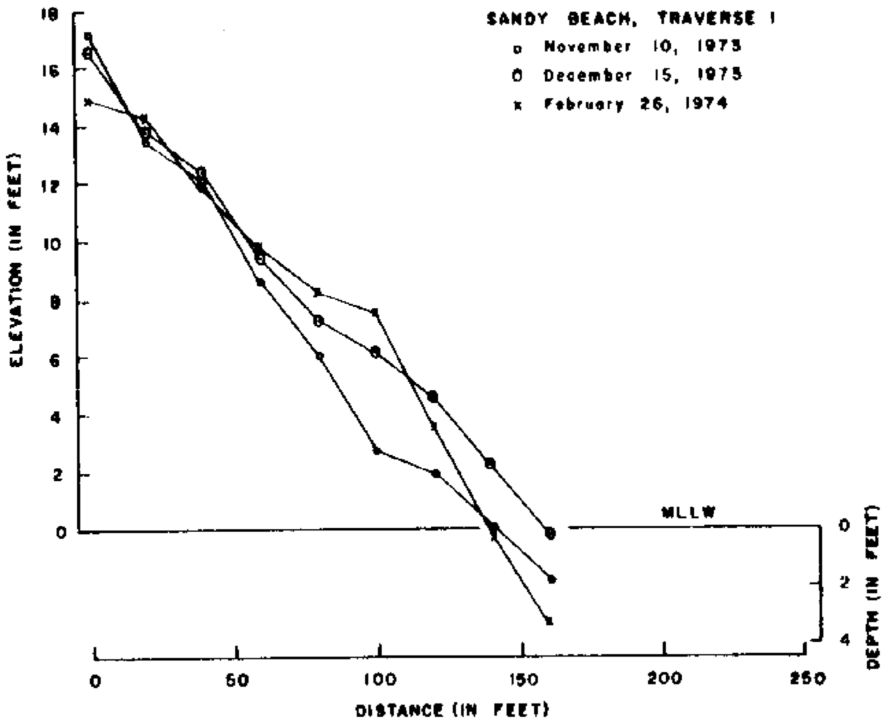


Figure 6.15. Beach profiles for traverse 1, Sandy Beach, Oahu. (See Figure 6.14 for traverse location.)

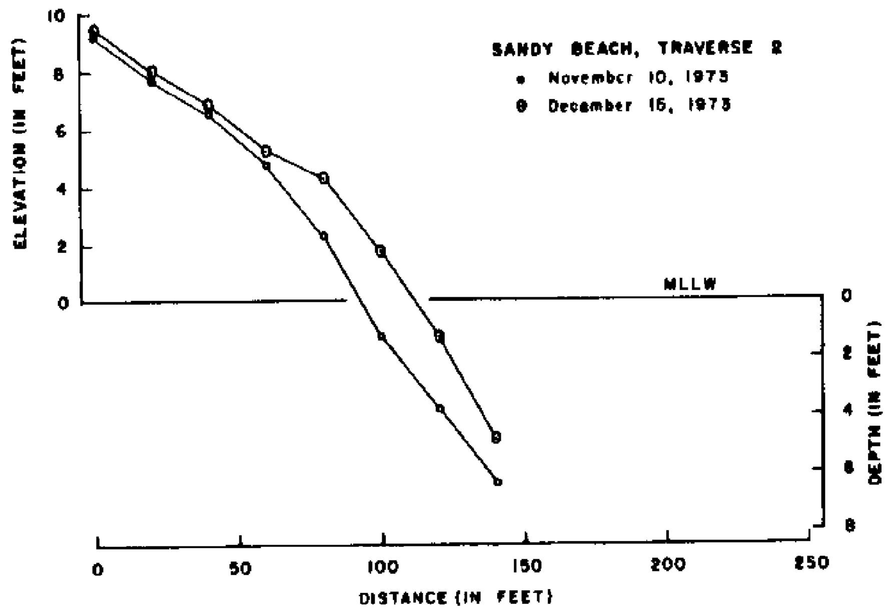


Figure 6.16. Beach profiles for traverse 2, Sandy Beach, Oahu. (See Figure 6.14 for traverse location.)

From Table 6.1 it may be seen that the sand at Sandy Beach is predominantly medium in grain size with median ϕ values ranging from 1.074 to 1.158. The grain size distributions are shown in Figure 6.17.

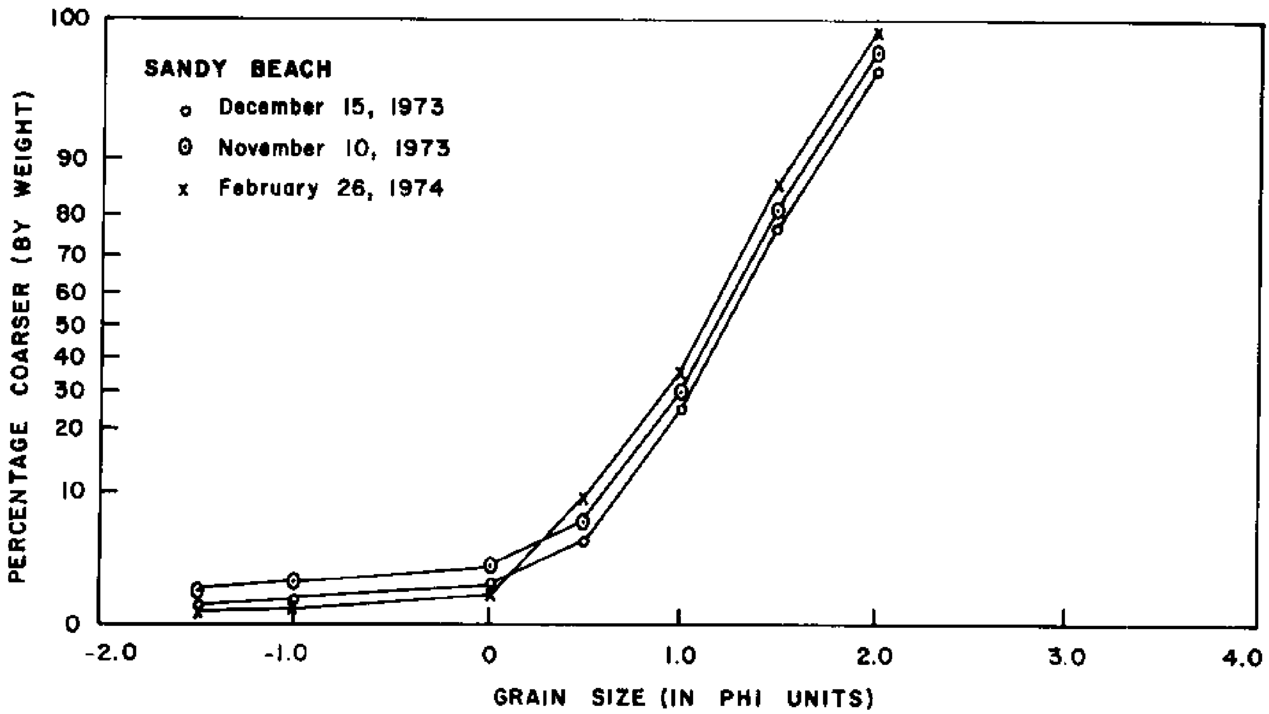


Figure 6.17. Grain size distributions for swash zone sand from traverse 1, Sandy Beach, Oahu. (See Figure 6.14 for traverse location.)

CHAPTER 7. BEACHES ON NEIGHBOR ISLANDS

A few beaches on the neighbor islands were included in this study because of particular features. Two characteristics were of particular interest: (1) occurrence of cusp formations and (2) rock formations functioning as offshore barriers, T-groins, or headlands. Within the framework of the amount of time and money available, it was not possible to make detailed morphological studies of the selected sites; instead, the objective was to identify beach situations that could become subjects of future study and which would enable formulations of detailed study programs in future investigations. The following is the result of a first orientation. The observations are predominantly of a descriptive nature.

Most study sites in this group were observed from the air. Aerial photographs were taken and maps were drawn from them. Then a site visit was made to measure beach elevations and sediment characteristics. The philosophy behind the study of these phenomena was to see how natural formations affect beach behavior and to determine how man can learn from nature in his search for effective and aesthetic coastal protection systems.

Cusps

Hanalei Bay Beach, Kauai

Hanalei Bay Beach is located on the north coast of the island of Kauai. The beach faces a large, circular bay (Figure 7.1). The field survey at this beach was carried out at two traverses, one on the east and another on the south side of the bay.

The slope of the southern section of the beach is approximately 1:10. The area is marked by cusps whose wavelengths average approximately 70 ft. The cusps are fairly well defined.

The slope of the beach on the east side of the bay is approximately 1:30. The width of the beach here is greater than on the south side and the sediment is also much finer. Cusps on the east side of the bay have an average length of approximately 85 ft, but are ill defined.

At the time of this study, mean diameters of the sediment of the southern and eastern parts of the beach were $M_\phi = 1.251$ and $M_\phi = 2.379$, respectively. The coarser sediments and the steeper slope on the south side of the bay are in agreement with heavier wave exposure of this side due to the predominant waves from the east refracting into the bay.

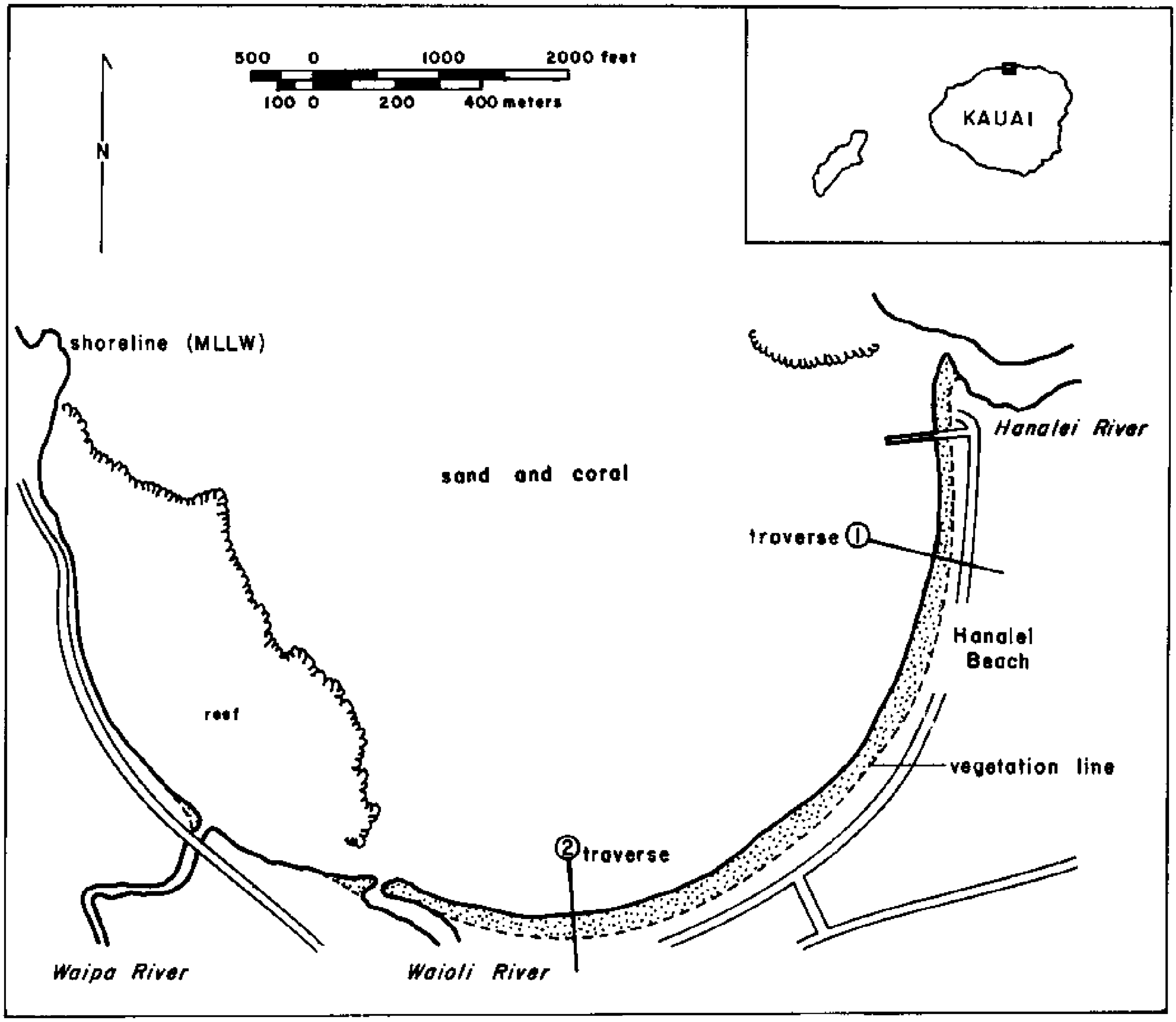


Figure 7.1. Hanalei Bay Beach, Kauai study site showing traverse locations

Holupoe Beach, Lanai

Holupoe Beach is located on the south coast of the island of Lanai. This is a slightly arcuate pocket beach approximately 1,100 ft in length (Figure 7.2). The beach is protected by a rocky point to the east and by low terraces to the west. It is approximately 100 ft wide and has a slope at the waterline of approximately 1:6. The upper beach area is very flat and there is a very well-defined berm.

At the time of this study, a singular cusp was observed at the western end of the beach. It is suggested that this feature is related to the effect of the offshore formations similar to Makaha Beach. There was some evidence of remnants of storm-related cusps along the upper portion of the beach. The offshore area is sandy toward the center of the bay with rocky areas and reefs along both sides. The sand is medium to coarse with an average grain size of M_ϕ = 1.76.

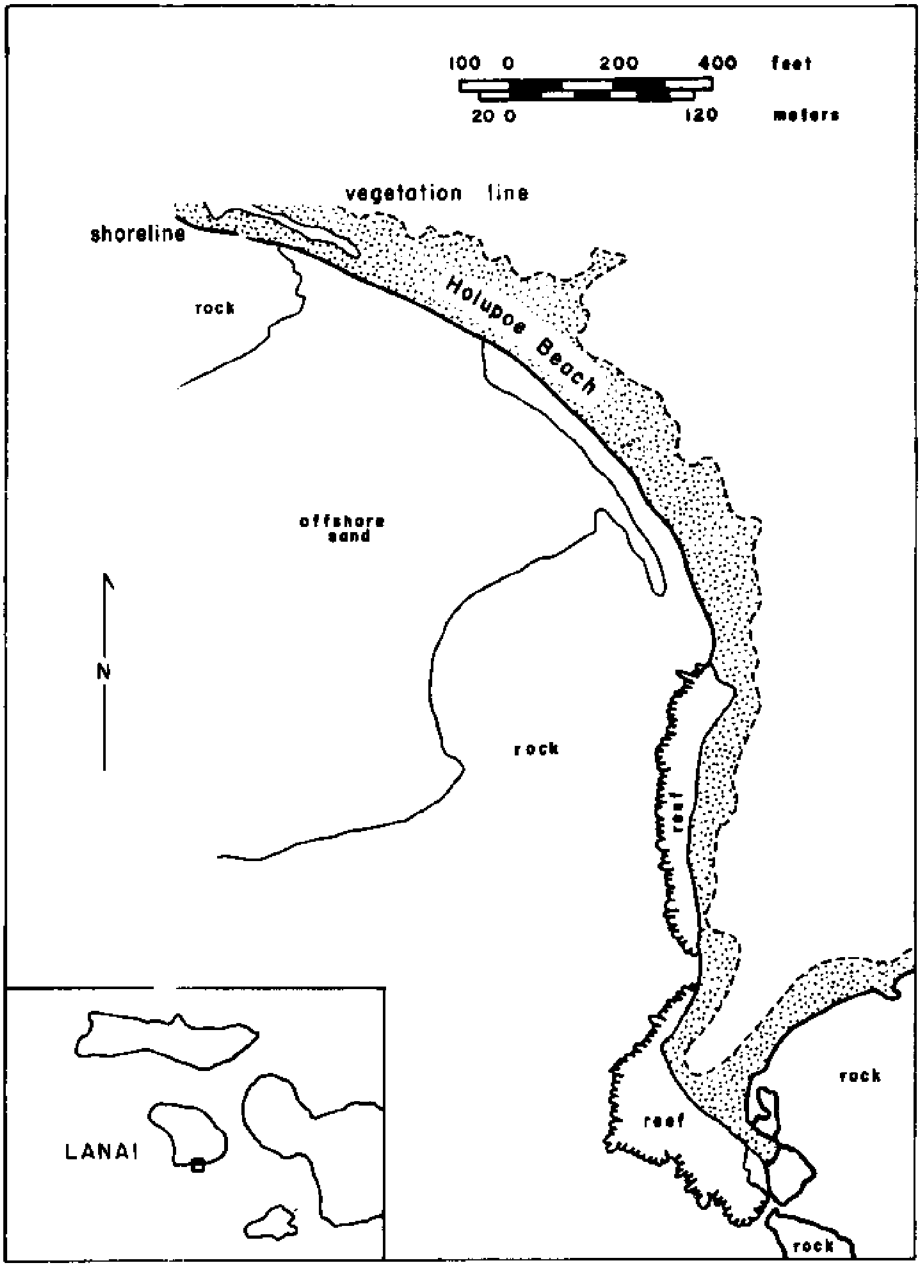


Figure 7.2. Holupoe Beach, Lanai study site

Mauna Kea Beach, Hawaii

Mauna Kea Beach is an arcuate pocket beach isolated inside Kawaihae Bay on the west coast of the island of Hawaii (Figure 7.3). The beach is about 1,300 ft long and 290 ft wide. Its slope is gentle, about 1:20 over the full length of the beach. A characteristic beach profile is shown in Figure 7.4. The offshore area is generally rocky with sand patches and sand channels. The reef, which is located about 500 ft from the center of the beach, becomes partly emerged at low tide and acts as sections of an offshore breakwater between which wave energy penetrates into the bay and gives it the arcuate form.

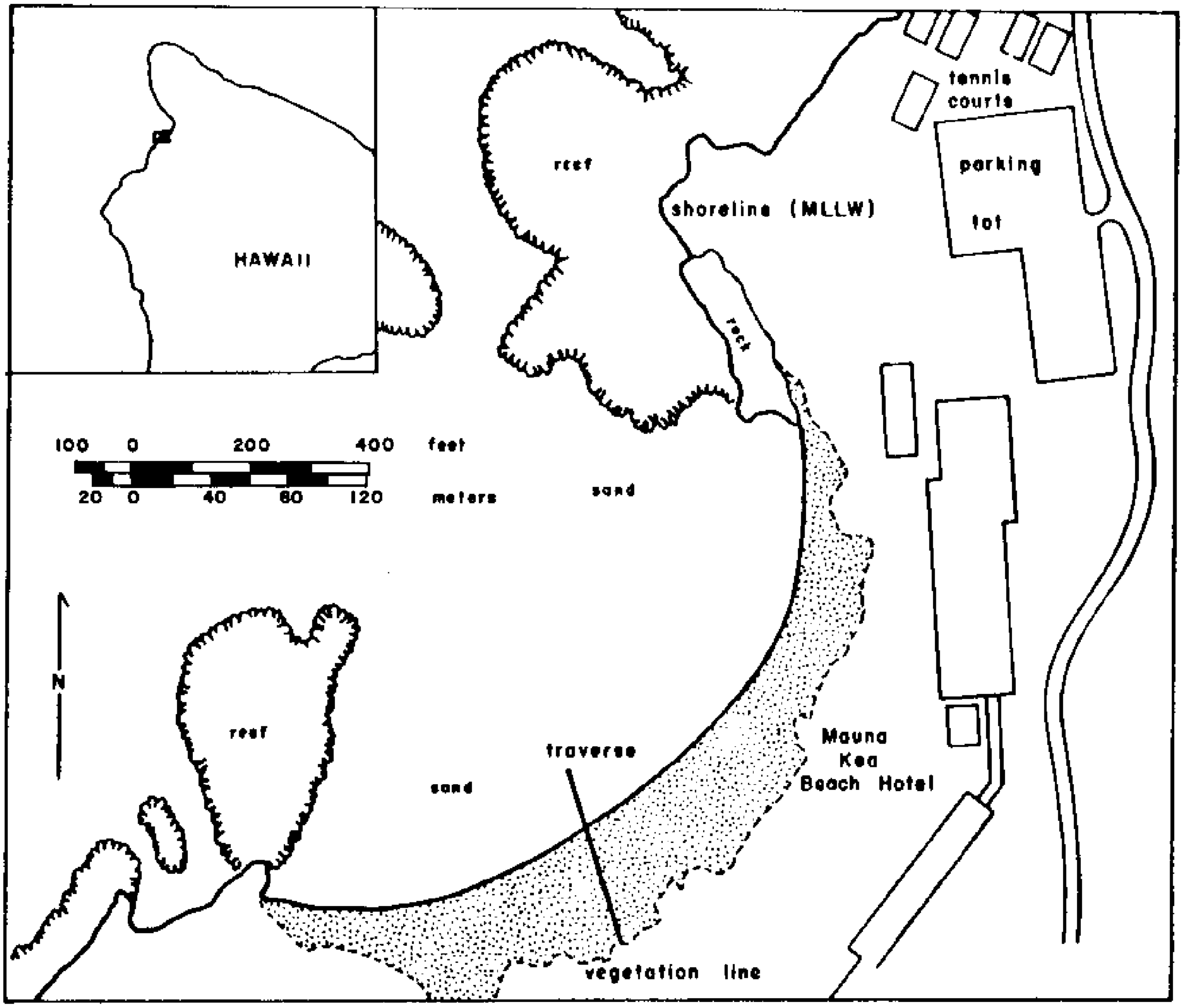


Figure 7.3. Mauna Kea Beach, Hawaii study site showing traverse location

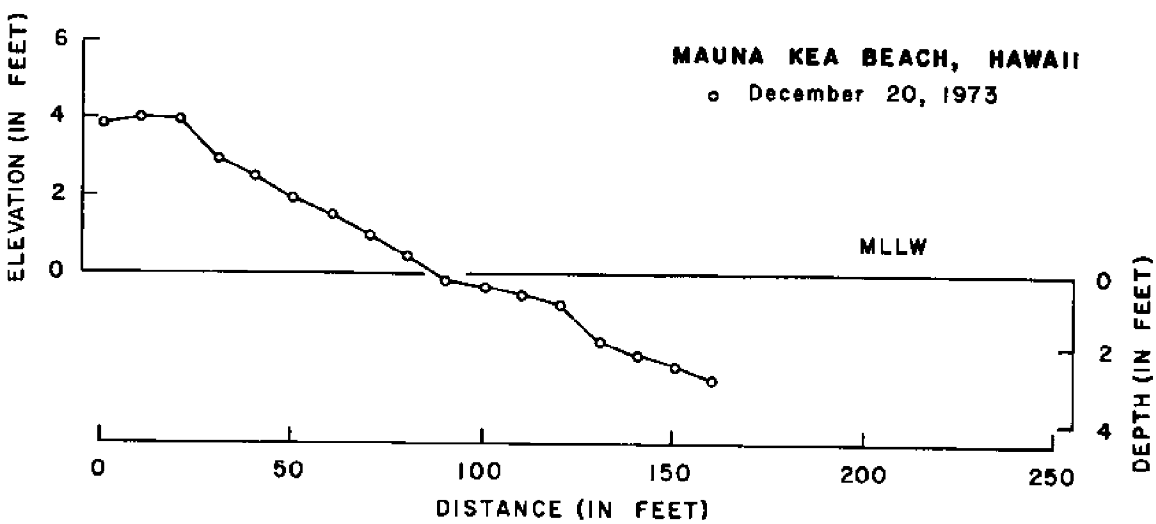


Figure 7.4. Beach profile for Mauna Kea Beach, Hawaii. (See Figure 7.3 for traverse location.)

Sediment characteristics along the beach are uniform and may be classified as fine; M_ϕ = 2.13. The fine sand and the uniform beach slope indicate an even distribution of wave energy over the beach and a high degree of protection against storm waves. The entire beach is characterized by a series of uniform well-defined cusps which are evenly spaced and have an average cusp length of 90 ft. During site visits to this area, waves were always breaking parallel to the waterline (Plate 7.1). Currents in the bay and along the beach were very small during periods of observation.

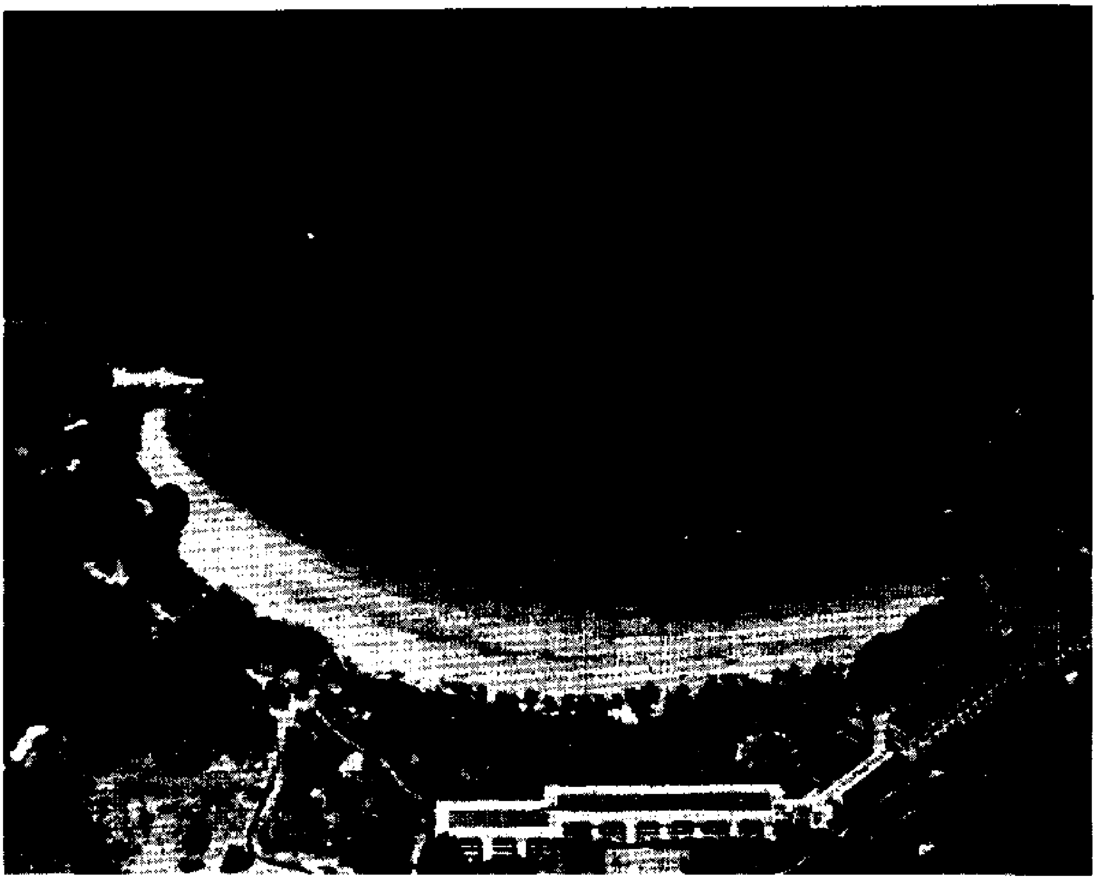


Plate 7.1. Mauna Kea Beach, Hawaii. (Note cusps on beach and offshore reef formation.)

Hapuna Beach, Hawaii

Hapuna Beach is located inside Kawaihae Bay on Hawaii's west coast, a few miles south of Mauna Kea Beach. The beach is straight, approximately 1,800 ft long, and protected by rocky headlands on both ends (Figure 7.5). It is about 150 ft wide, but varies significantly (up to 100 ft) with the seasons (Moberly and Chamberlain, 1964). The slope is 1:20 over the entire beach. A profile is shown in Figure 7.6. The sand is fine to medium; M_ϕ = 1.942. The offshore area consists of rock and coral with numerous sand pockets and some sand channels.

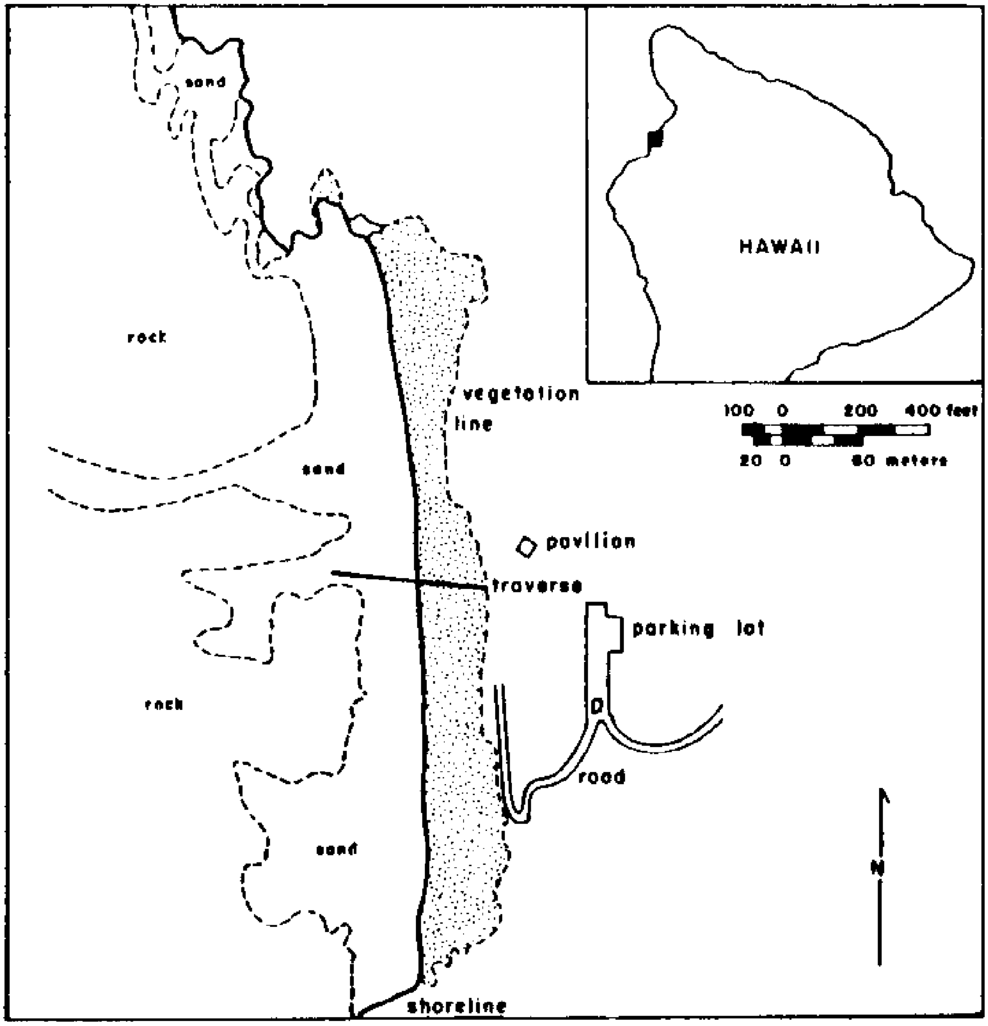


Figure 7.5. Hapuna Beach, Hawaii study site showing traverse location

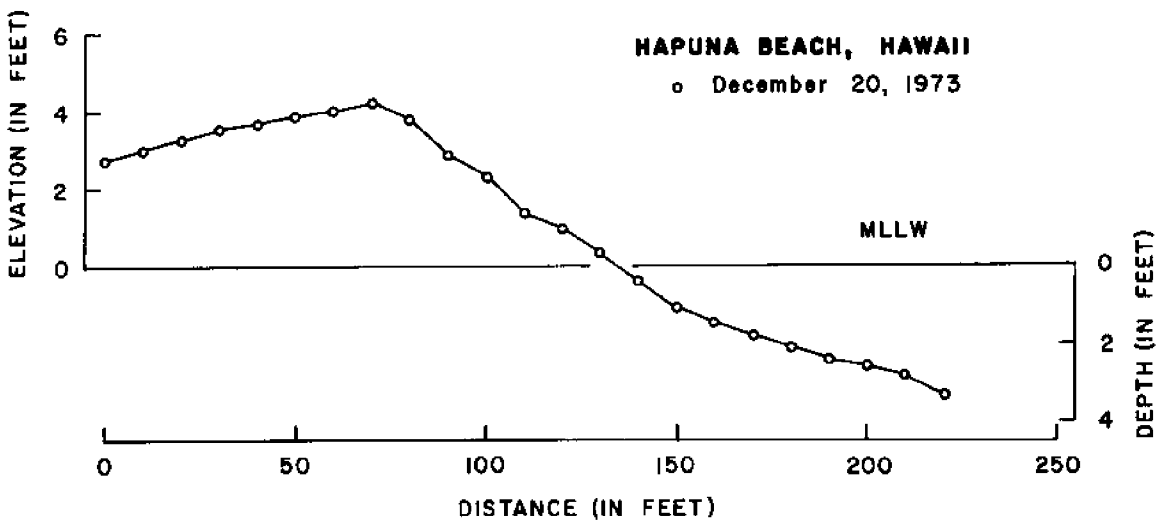


Figure 7.6. Beach profile for Hapuna Beach, Hawaii. (See Figure 7.5 for traverse location.)

During the time of the survey, Hapuna Beach was marked by 21 well-defined cusps, with an average cusp length of 90 ft. The cusps were similar in form and evenly spaced.

A comparison between the characteristics of Hapuna Beach and the previously described features of the nearby Mauna Kea Beach shows similarities in beach slope, sand size, and cusp length, which indicate equal wave exposure. The major difference is that the shoreline of Hapuna Beach is fairly straight, whereas the shoreline of Mauna Kea Beach is curved. The difference lies in the offshore features. The offshore rock formations at Hapuna Beach apparently provide a distribution of wave energy to the beach whereby the direction of the approaching waves is the same over the entire length of the beach. At Mauna Kea Beach, the offshore formations induce diffraction of waves causing a curved shoreline.

Headlands

The following beaches are characterized by moderate-sized headlands.

Puu Olai Beach, Maui

Puu Olai Beach is located on the southwest point of the leeward coast of the island of Maui near the cinder cone Puu Olai (Figure 7.7). The beach is approximately 2,500 ft long; it is protected to the southwest by a lava rock

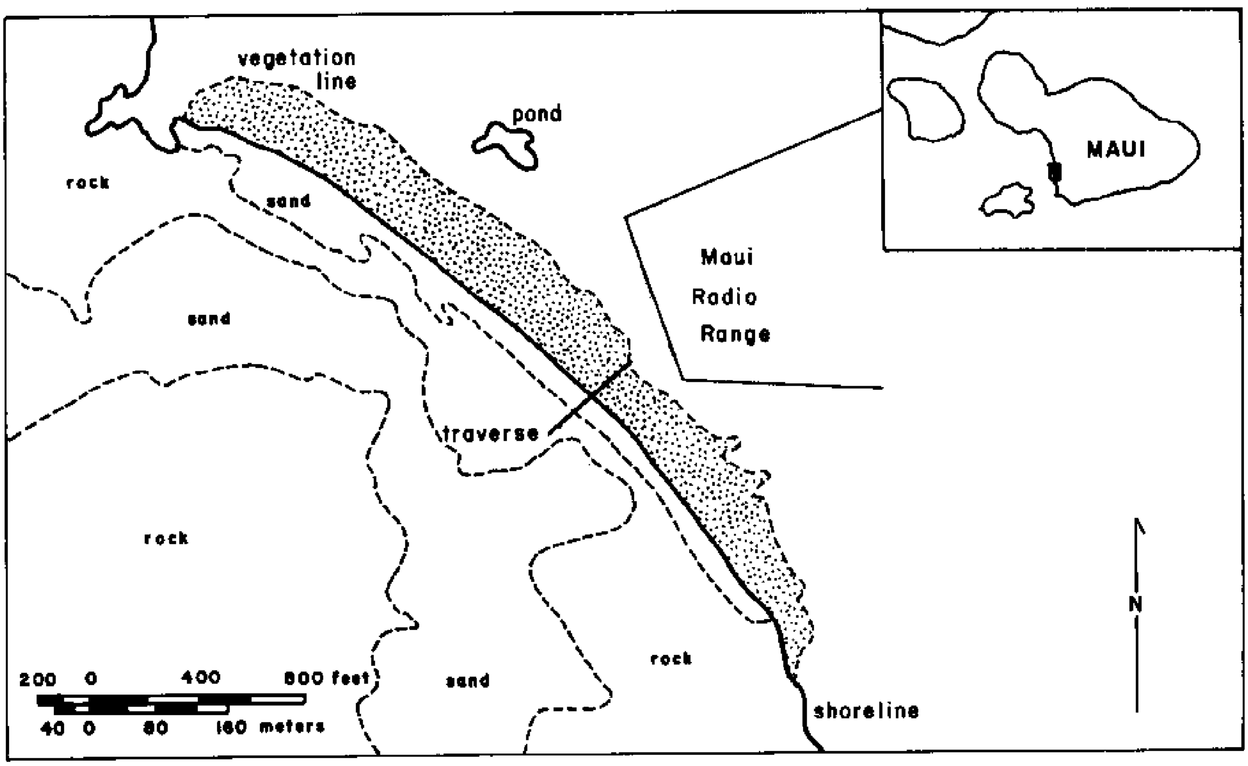


Figure 7.7. Puu Olai Beach, Maui study site showing traverse location

outcropping and to the northeast by cusps along its entire length. At the time of this study, the main set of cusps had an average wavelength of 120 ft. The beach slope varied from about 1:6 on a cusp node to approximately 1:14 at the cusp embayment. There was evidence of several sets of cusps apparently formed at an earlier time. The beach was also marked by small wave-cut cliffs at several of the cusps along the beach (Plate 7.2)

Plate 7.2. Puu Olai Beach, Maui. (Note distinct cusp formations.)

During the time of the investigation, the longshore current was relatively strong; the beach appeared to be subject to continuous changes, as evidenced by the various cusp systems observed. The mean grain size at the cusp node was found to be $M_\phi = 1.494$; at the embayment of the cusp it was somewhat finer ($M_\phi = 1.653$). Profiles at the cusp are presented in Figure 7.8.

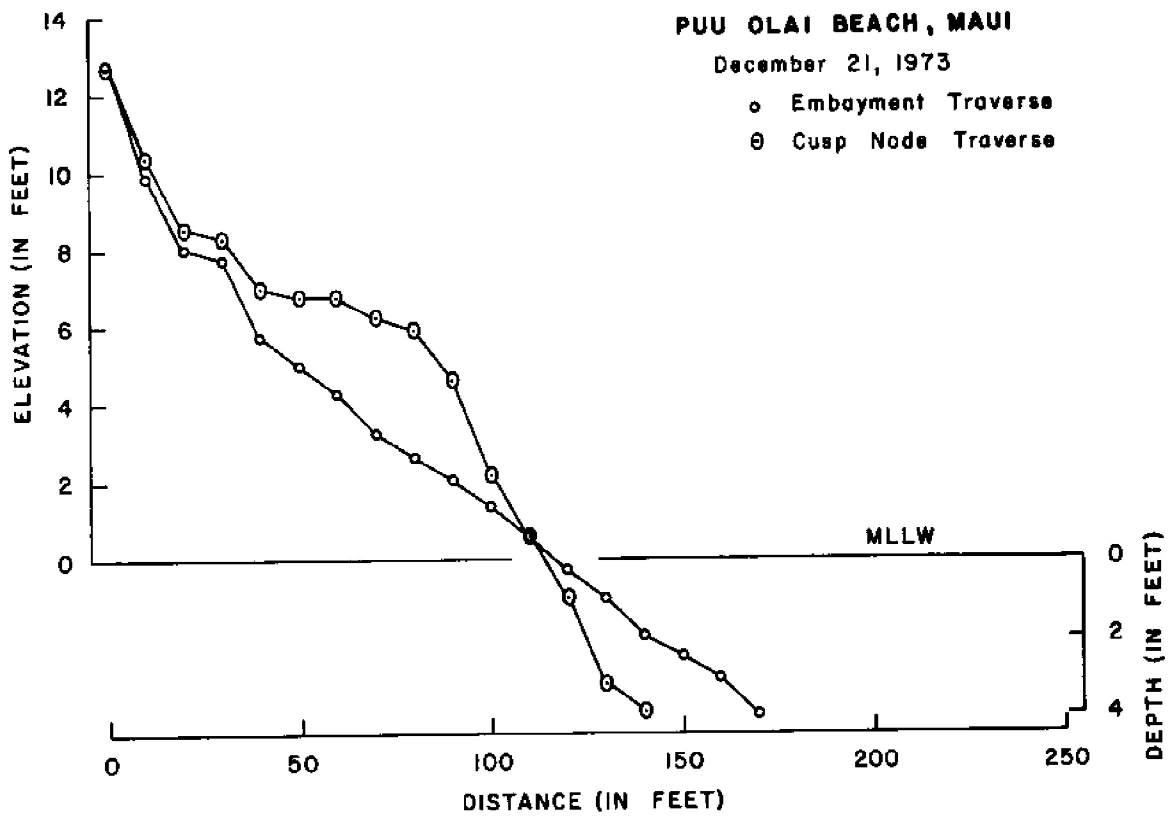


Figure 7.8. Beach profiles for Puu Olai Beach, Maui. (See Figure 7.7 for traverse location.)

Wailea Beach, Maui

Wailea Beach is situated north of Puu Olai Beach on Maui's west coast. It is a fairly straight beach, approximately 1,300 ft long and 250 ft wide (Figure 7.9). At both ends it is protected by lava cliffs. The beach slope is approximately 1:20 (Figure 7.10). The entire length of the beach is marked by a single set of uniform, evenly spaced and well-defined cusps, with, at the time of observation, an average cusp length of 70 ft. The sand is fine to very fine, mixed with some medium-sized sand, with the mean diameter of M_ϕ = 2.235. Low headland-type rock formations act as natural groins and form stabilizing elements for the beach.

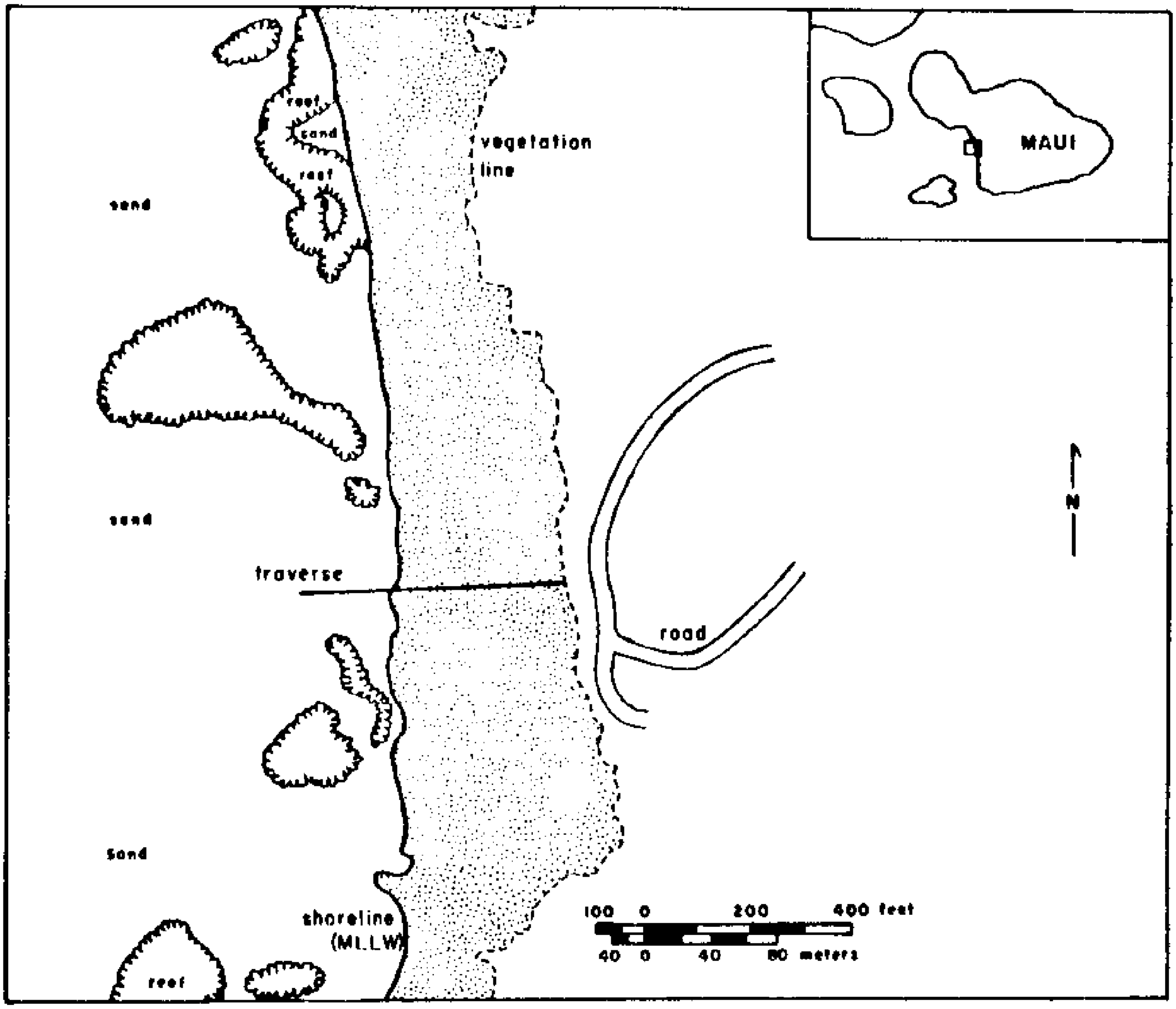


Figure 7.9. Wailea Beach, Maui study site showing traverse location

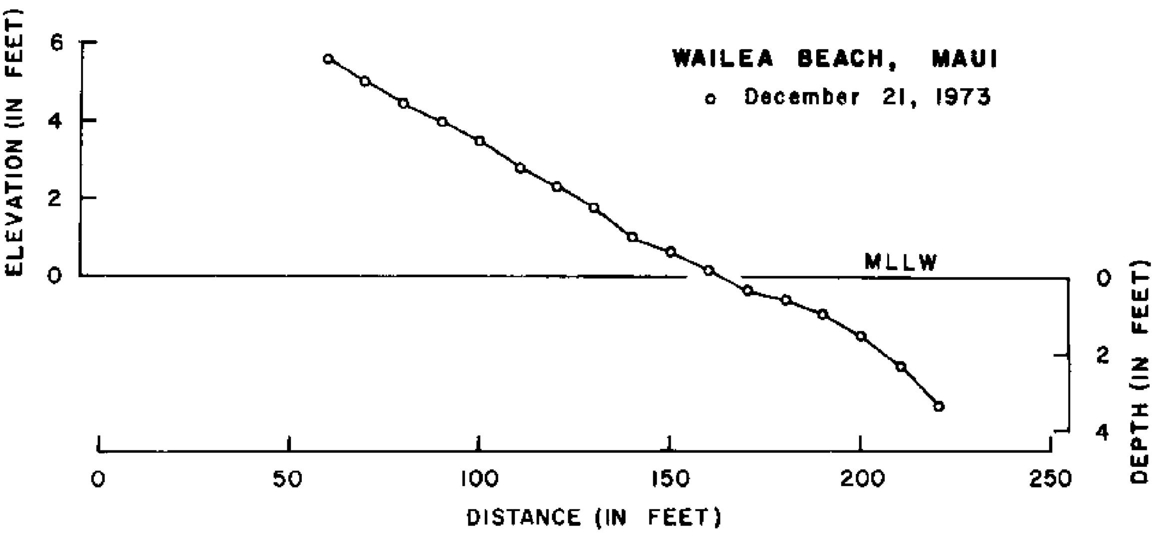


Figure 7.10. Beach profile for Wailea Beach, Maui. (See Figure 7.9 for traverse location.)

Offshore Reefs

The following beaches are affected by offshore parallel reefs and protective rocks, giving rise to tombolo-type shorelines.

Port Allen Beach, Kauai

This beach is located directly west of the Port Allen landing field. It is an arcuate beach, the shape of which is affected by outcroppings of lava on both sides and by offshore, usually submerged, outcroppings of lava and lava boulders over the bay (Figure 7.11). The lava outcropping is most predominant at the western end of the beach. The protective lava formations on both sides act as protecting headlands and the form of the beach conforms to a typical headland beach (see Chapter 9). The slope of the beach is about 1:8 (Figure 7.12) and its width approximately 50 ft. The average grain size at the waterline is $M_\phi = 0.600$, classifying it as a coarse sand beach. The coarse sand suggests high wave exposure.

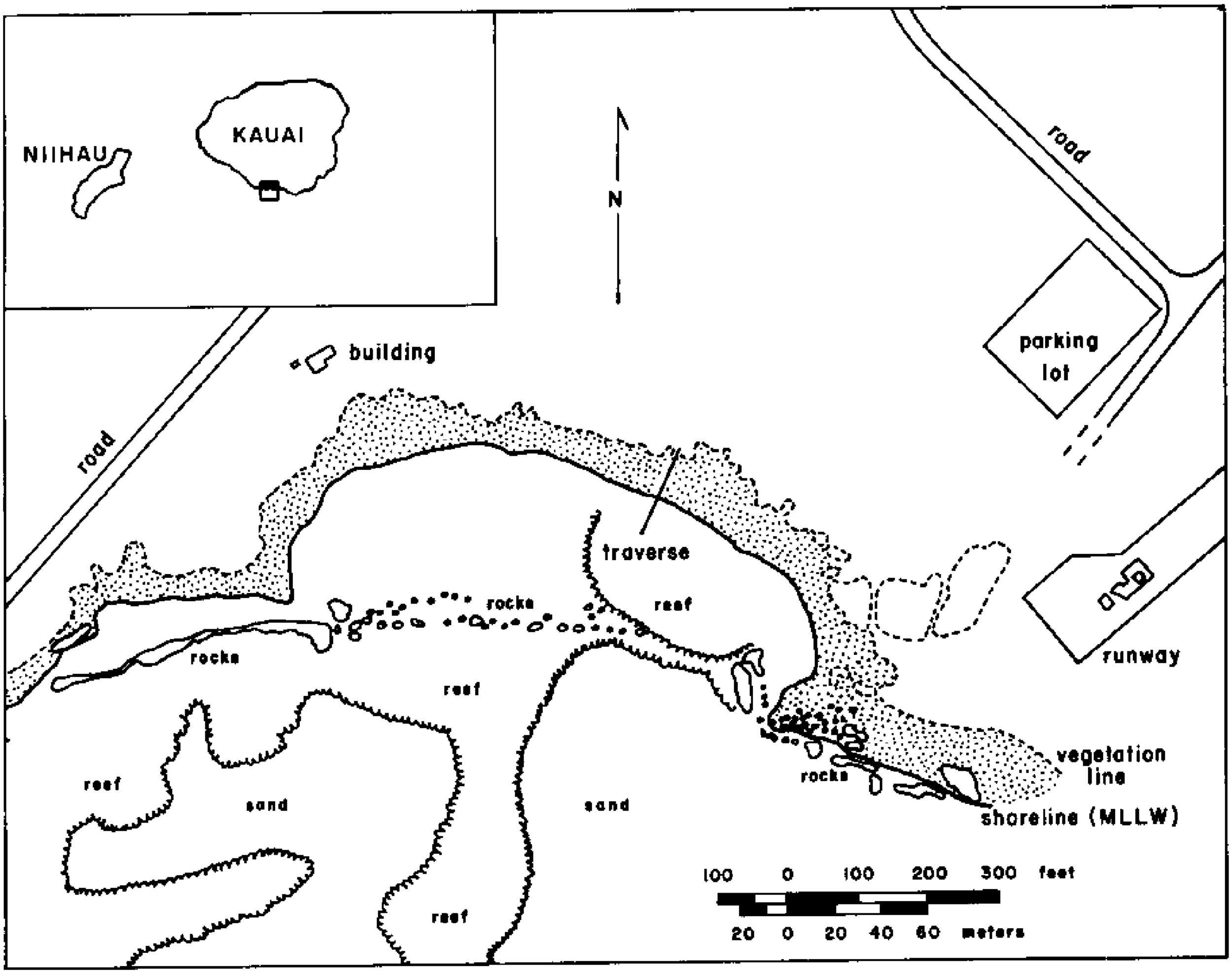


Figure 7.11. Port Allen Beach, Kauai study site showing traverse location

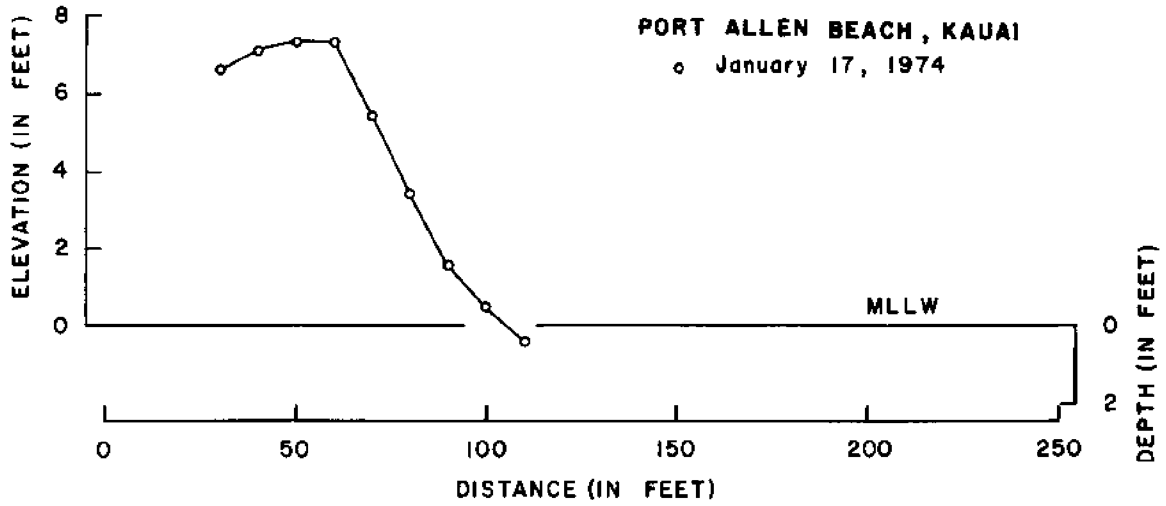


Figure 7.12. Beach profile for Port Allen Beach, Kauai. (See Figure 7.11 for traverse location.)

Spreckelsville Beach, Maui

This beach is located approximately 3.5 miles east of Kahului harbor on Maui's north shore (Figure 7.13). Characteristic of this beach is a natural offshore rock formation in the form of a T. This formation consists of four major sections: one part is perpendicular to the beach extending 75 ft seaward; the other three sections run parallel to the beach and form the top of a "T." These three sections are approximately 25 to 35 ft wide and extend over a total length of 450 ft. The width of the beach is approximately 125 ft at the rock groin, narrowing to about 100 ft to the west and to about 60 ft to the east. The slope of the beach is approximately 1:30, steepening to about 1:5 towards both the east and the west. At times the beach at the "T-groin" protruded to where it was connected with the parallel rock formation (Figure 7.13). The leg of the "T" was then covered by the beach and the tombolo closed (Moberly and Chamberlain, 1964). The sand was medium to coarse with a mean particle size of M_{ϕ} = 1.581.

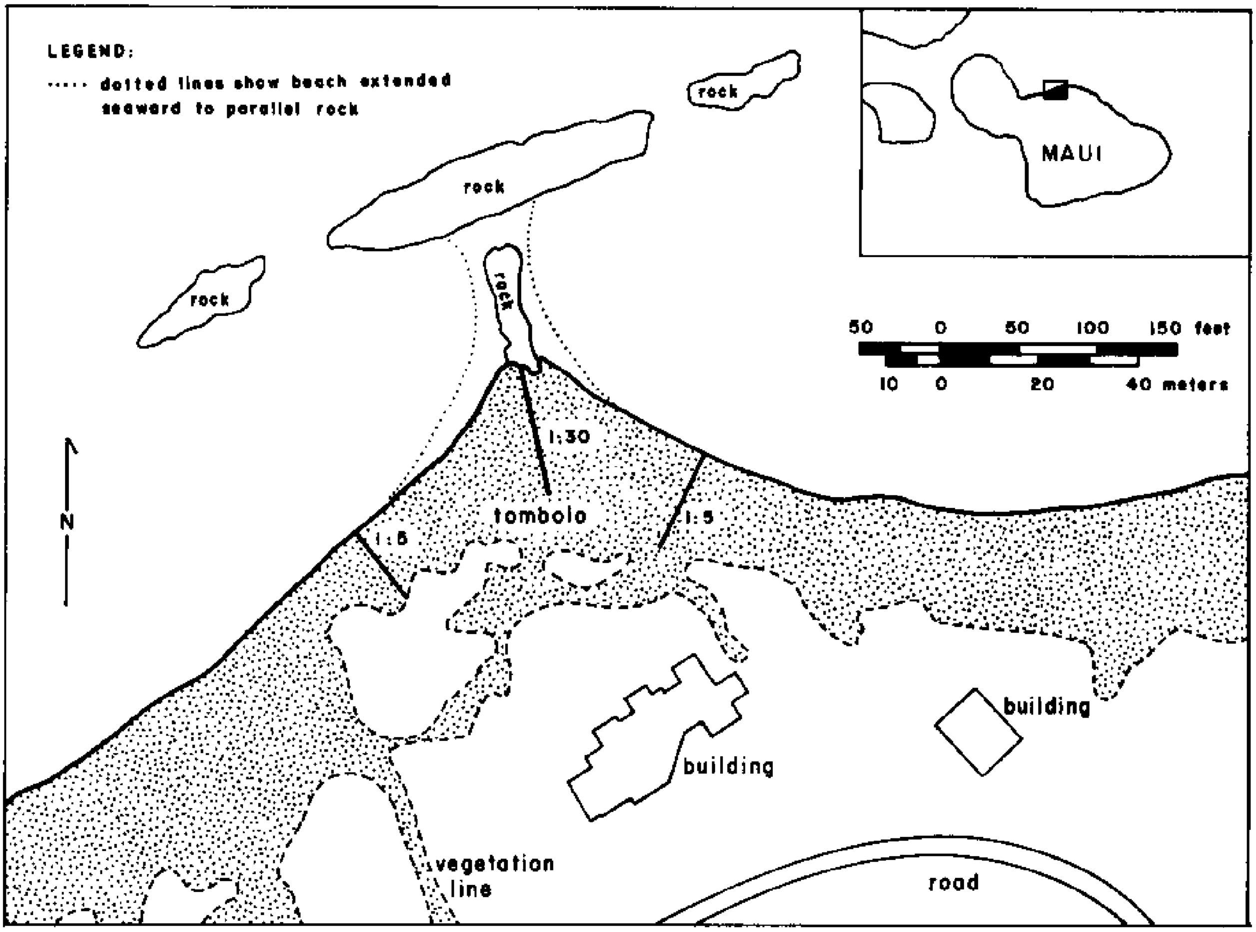


Figure 7.13. Spreckelsville Beach, Maui

Baldwin Park Beach, Maui

This beach is located about 4.5 miles east of Kahului harbor (Figure 7.14). It is characterized by two types of protective structures: a series of parallel strips of lava behind which a protruding sand spit is formed and a protective rock formation at the eastern boundary. The sand spit behind the parallel strips of rock is an incomplete tombolo formation; the beach between the tombolo and the rock formation to the east has the form of a headland beach. The width of the beach is approximately 125 ft at the spit, narrowing to 60 ft to the west and 90 ft to the east. The beach is exposed to tradewind waves from the northeast; the shape of the eastern beach section between the beach rock formation and the sand spit is in agreement with this type of wave exposure. The lava strips are about 10 ft wide, average about 100 ft in length, and are spaced about 30 ft apart. The slope of the beach is approximately 1:15 at the spit, steepening to about 1:6 going west from the spit. The sediment is of mixed sizes, ranging from coarse to fine, with a mean particle size of M_ϕ = 1.199.

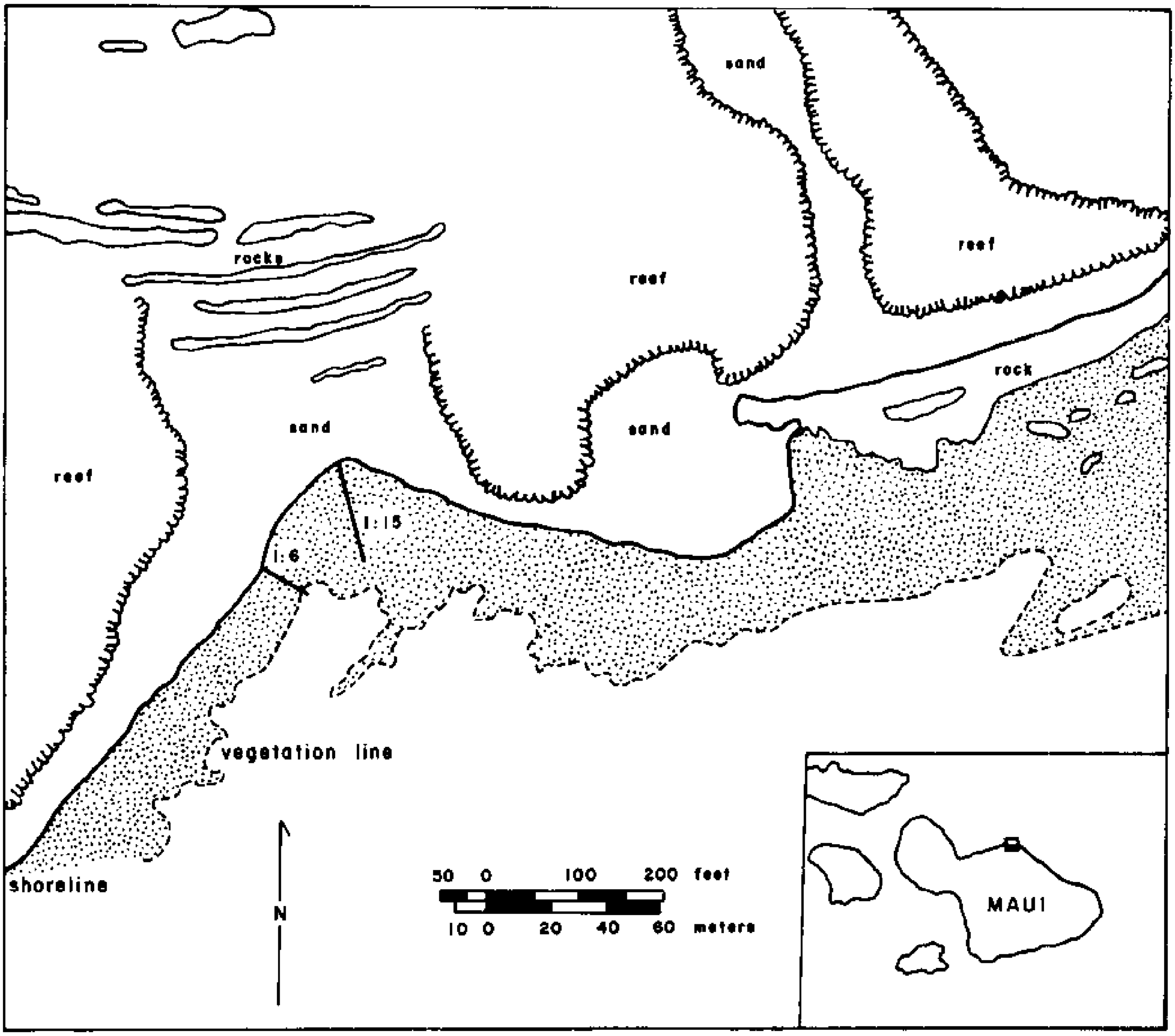


Figure 7.14. Baldwin Park Beach, Maui

Poipu Beach, Kauai

Poipu Beach is located on the southeast point of the island of Kauai (Figure 7.15). The study area consists of two beach sections separated by a tombolo. The tombolo is formed behind an offshore lava rock formation with an average elevation of 2 ft above mean low water (Figure 7.15). The tombolo separating the two beaches is approximately 75 ft in width and 250 ft in length and has a slope of 1:10 on the east side and 1:14 on the west side (Figure 7.16). The beach east of the tombolo is sharply arcuate, 300 ft long and 80 ft wide; to the east it is protected by an L-shaped man-made rock groin, which enhances the stability of this section. The slope of this beach ranges from 1:5 near the tombolo to ∿1:10 in the middle. The sand of this beach section is medium to fine with an average grain size corresponding to M_ϕ = 1.892. The beach to the west is fairly straight, approximately 650 ft in length and 60 ft in width. This section is protected at its west end by a small rocky point of lava boulders and vegetation (Plate 7.3). Its average slope is 1:7.7. There is a small outcropping of rock about 150 ft from the tombolo. The sediment here is medium to coarse, M_ϕ = 1.111.

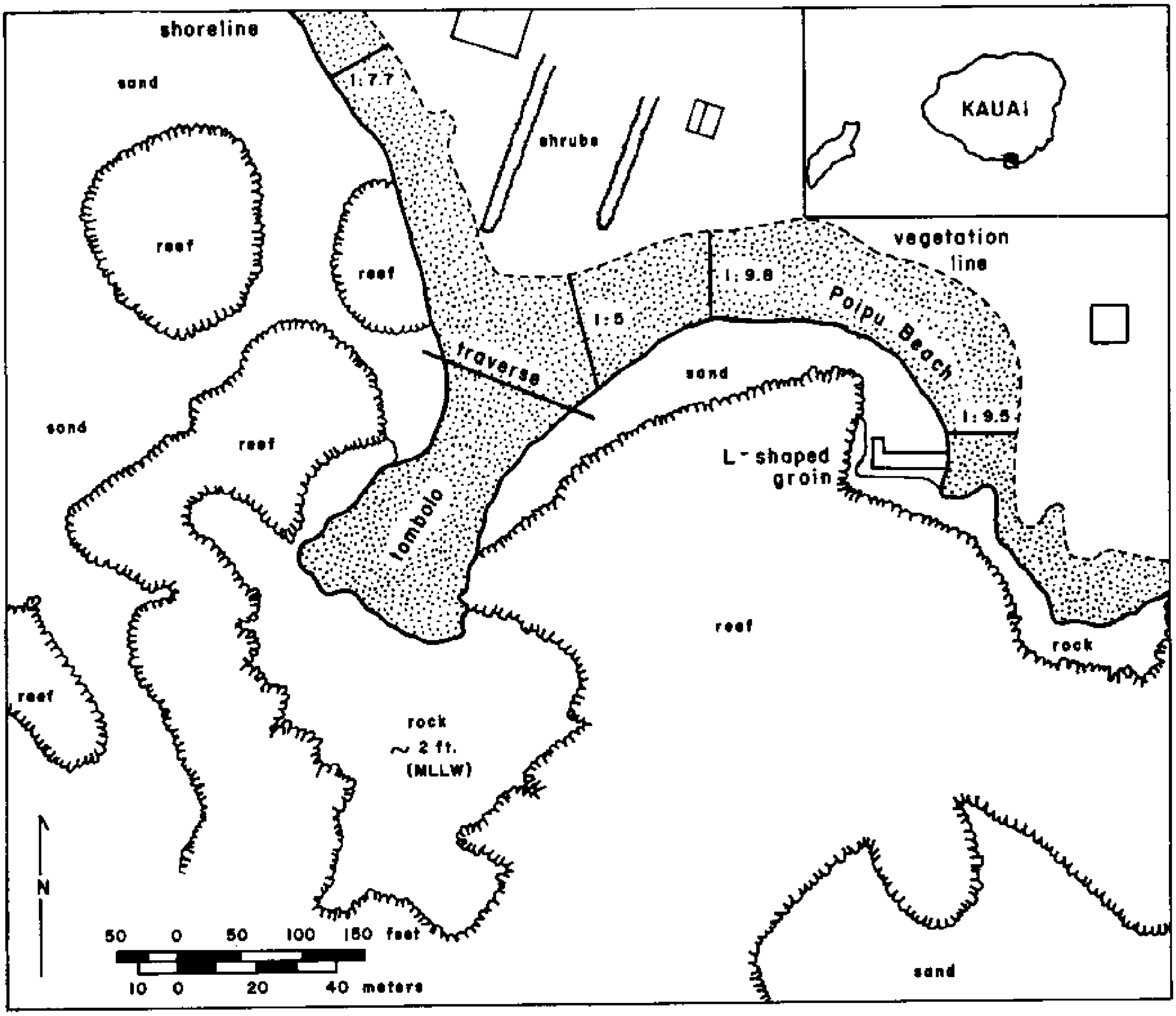


Figure 7.15. Poipu Beach, Kauai study site showing traverse location

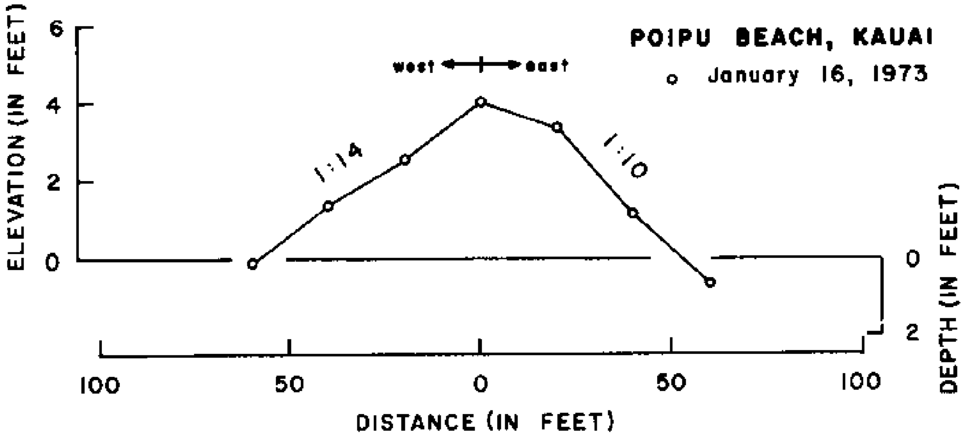


Figure 7.16. Beach profile for Poipu Beach, Kauai. (See Figure 7.15 for traverse location.)

Plate 7.3. Poipu Beach, Kauai

Summary

Offshore reefs are important elements influencing beach behavior. Hapuna Beach and Mauna Kea Beach have similar characteristics, yet the difference in offshore reef conditions accounts for the respective straight and curved shorelines. Parallel offshore formations contribute to beach stability, as in the case of Baldwin Park Beach on Maui. More distinct offshore formations, such as Spreckelsville Beach on Maui and Poipu Beach on Kauai, give rise to a distinct relationship between wave exposure, beach slope, and sediment size. Beaches with high wave exposure tend to have steeper profiles and larger average grain sizes. The variation in conditions at Hanalei Beach is illustrative in this regard.

Natural rock formations are important features for beach stabilization. The low headland-type rock formations at Wailea Beach on Maui are good examples of possible groin concepts. Parallel offshore rock formations and T formations are other examples of nature's way of stabilizing a beach. In almost all examples, the formations have a low elevation and allow sand bypassing; they do not interfere with the nourishment of downdrift beach sections. In certain cases, high and extended headlands create pocket beaches. Man-made high and impermeable groins are modeled after the latter type of formation.

CHAPTER 8. DYNAMIC BEACH BEHAVIOR

General Considerations

The stability of beaches is often evaluated in terms of changes in beach profiles which are induced by a change in wave characteristics. High and steep waves tend to form a well-defined bar profile, whereas low steepness waves usually form a ridge profile. In the literature a great deal of attention has been given to equilibrium beach profiles, even though, in nature, the profile is changing continuously and wave conditions are usually not constant long enough to create a truly stable condition.

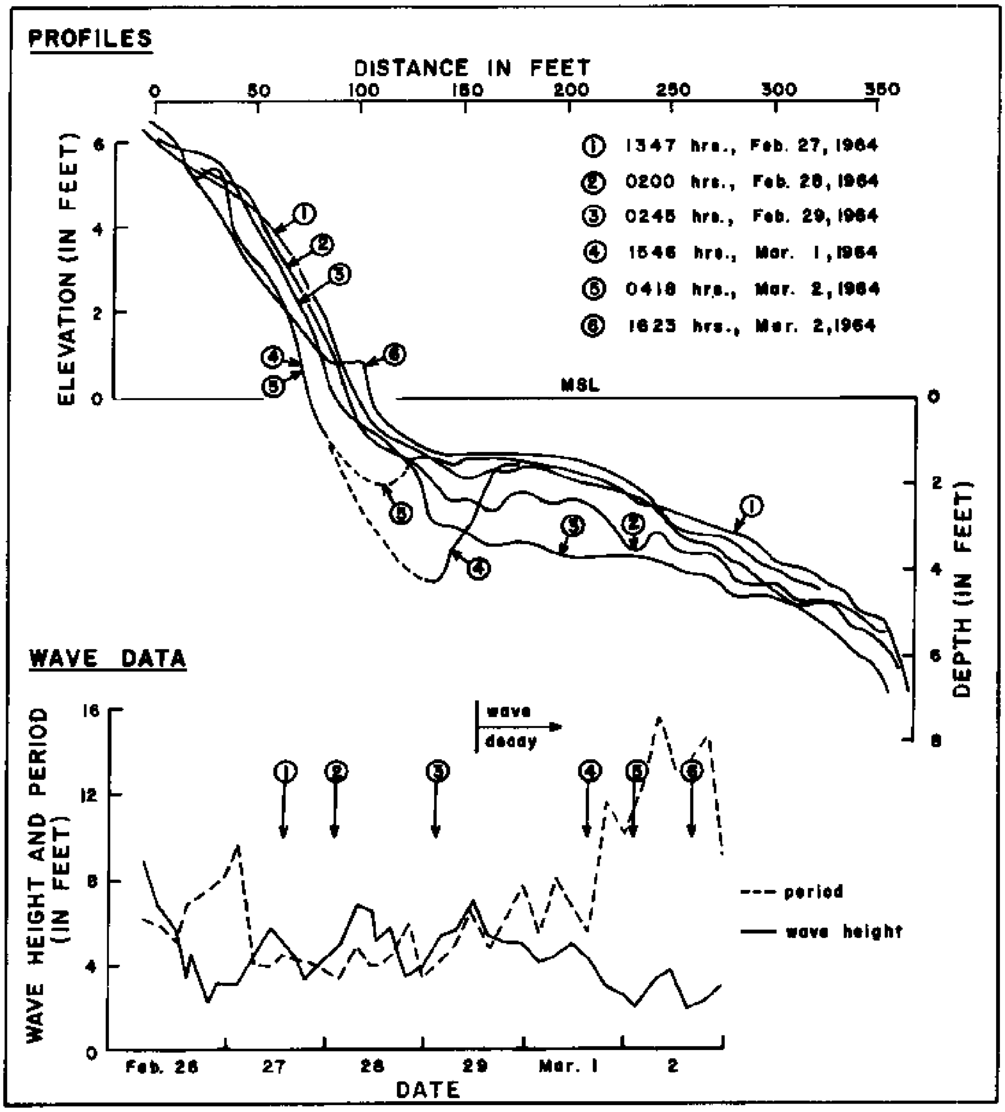
While studying dynamic characteristics of beaches in North Carolina, Sonu (1969) called attention to the role of sand wave activity in the inshore region. He suggested that the dynamics of beach topography could be better explained in terms of the collective behavior of sediments associated with sand waves than by studying the discrete movements of individual sediment particles. The observations made by Sonu (1969) at Nags Head, North Carolina showed interesting short-term changes in beach profile during a storm and a successive decay period (Figure 8.1). During a period of less than one week the beach went through a cycle of changes.

In Figure 8.1 bar-type sand waves may be observed. They have crests parallel to the beach and their origin is tied in with orbital particle motion induced by waves and with wave-induced radiation stresses. In contrast to the bar-type sand waves which move perpendicular to the shore, there are also sand waves which migrate parallel to the beach and are often oriented obliquely to the shoreline, extending across the entire width of the surf zone. At the waterline they often manifest themselves as sinusoidal or trochoidal shorelines.

The literature on sand wave characteristics at the waterline, hereinafter called beach waves, is not always consistent and is sometimes contradictory because the dynamic processes of beach behavior are still not completely understood.

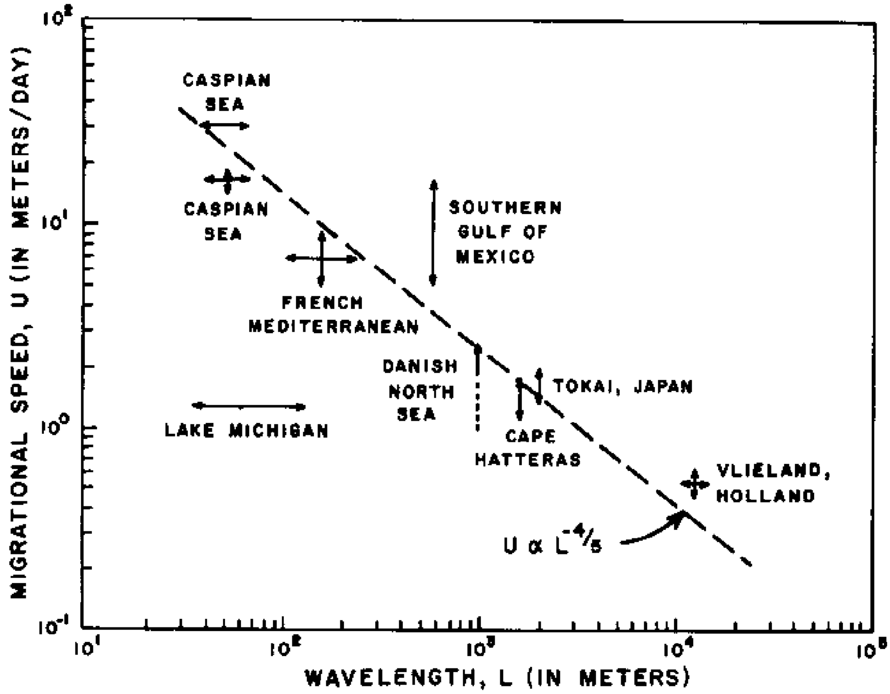
The author feels that it would clarify matters if a distinction is made between beach waves and beach cusps. The former are related to the transport of littoral material parallel to the shoreline and require a littoral current to sustain them. Although the theory allows for standing beach waves to exist, the beach waves are usually of a progressive (migratory) nature.

The literature on beach cusps suggests that these are related to edge wave phenomena along the shoreline. The present studies seem to confirm this concept, as will be discussed later in this chapter. Beach cusps were found to be stable in location; they did not migrate. Sonu (1969) found that, in migratory beach waves, a relationship seems to exist between the velocity of propagation of the sand waves (U) and the distance between two successive crests (L). He suggested the relationship $U \alpha L^{-4/5}$. The migrational speed is plotted against the wavelength in Figure 8.2.



After Sonu, 1969

Figure 8.1. Formation of bar-type sand waves during decay of storm waves at Nags Head, North Carolina



After Sonu, 1969

Figure 8.2. Migration of beach waves with reference to wavelength

In explaining the phenomenon of migratory beach waves, Sonu (1969) drew upon the analogue between the formation of beach waves and of ripples and dunes in a fluvial bed. In the latter the shape of the bed (ripples, dunes, flatbed, antidunes) is related to the Froude number:

$$F = \frac{V}{\sqrt{gh}}$$

where V is the mean velocity of the flow, h the depth, and g the acceleration of gravity. Ripples are associated with low Froude numbers, whereas dunes start to form at higher values of F. If an analogue could be drawn, the velocity V would be represented by the average speed of the longshore current, but it would be difficult to define the Froude number because of variations in h.

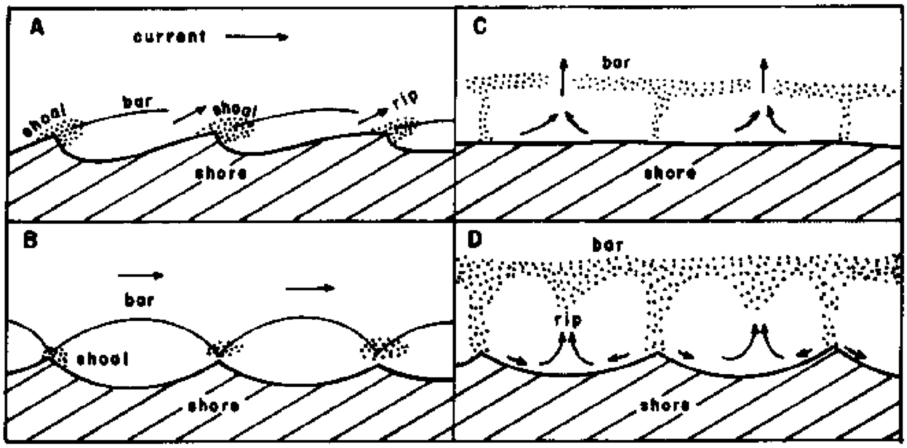
The analogue would further suggest that beach waves of short length are formed with low values of the longshore current, whereas the longer waves would be related to the higher values of the longshore current.

In the author's opinion the validity of the analogue is not without doubt and further study is necessary to clarify this.

Sonu (1969) further concluded that a gentle foreshore and a sustained activity of the longshore current seem to be essential for the generation of migratory beach waves.

The finding of this study that beach cusps have stable locations could be considered contradictory to Sonu's (1969) findings. However, if the distinction is made between beach waves and cusps, as suggested earlier, the contradiction does not really exist.

It has been observed by Shepard and Inman (1950) that, on the West Coast, waves perpendicular to a beach induce a circulation system that is cellular and that gives rise to the formation of rip currents perpendicular to the coast at a certain distance apart. The cause of these circulation patterns may be related to longshore depth variations offshore, but recent studies suggest a relationship with edge waves and variations in wave setup (Bowen and Inman, 1971). Different types of shorelines in relationship to cusp-type formations are presented in Figure 8.3.



After Bowen and Inman, 1950

Figure 8.3. Cusp formation mechanisms for different types of shorelines

Mathematical Analysis of Shoreline Behavior

When introducing a number of schematizations and simplifications in the description of the littoral drift behavior, equations can be derived for the behavior of a shoreline as a function of time. The mathematical equations for a stable shoreline can also be derived.

Consider the stability of a straight beach as shown in Figure 8.4. To describe the problem mathematically, the x-axis of a Cartesian coordinate system is taken along the high waterline and the positive y-axis is taken in the seaward direction, whereby y is the dependent variable. Furthermore, assume that erosion or accretion develops as shown in the cross-section of Figure 8.4, that is to say, the beach moves forward or backward by keeping its slope constant.

If Q represents the rate of total transport of sand parallel to the shoreline in the positive x-direction at time t over the total width of the littoral zone, an equation can be established based on the conservation of mass. The transport Q is hereby expressed in terms of the volume occupied by the sand. Assuming no transport in the y-direction, the requirement of mass conservation gives:

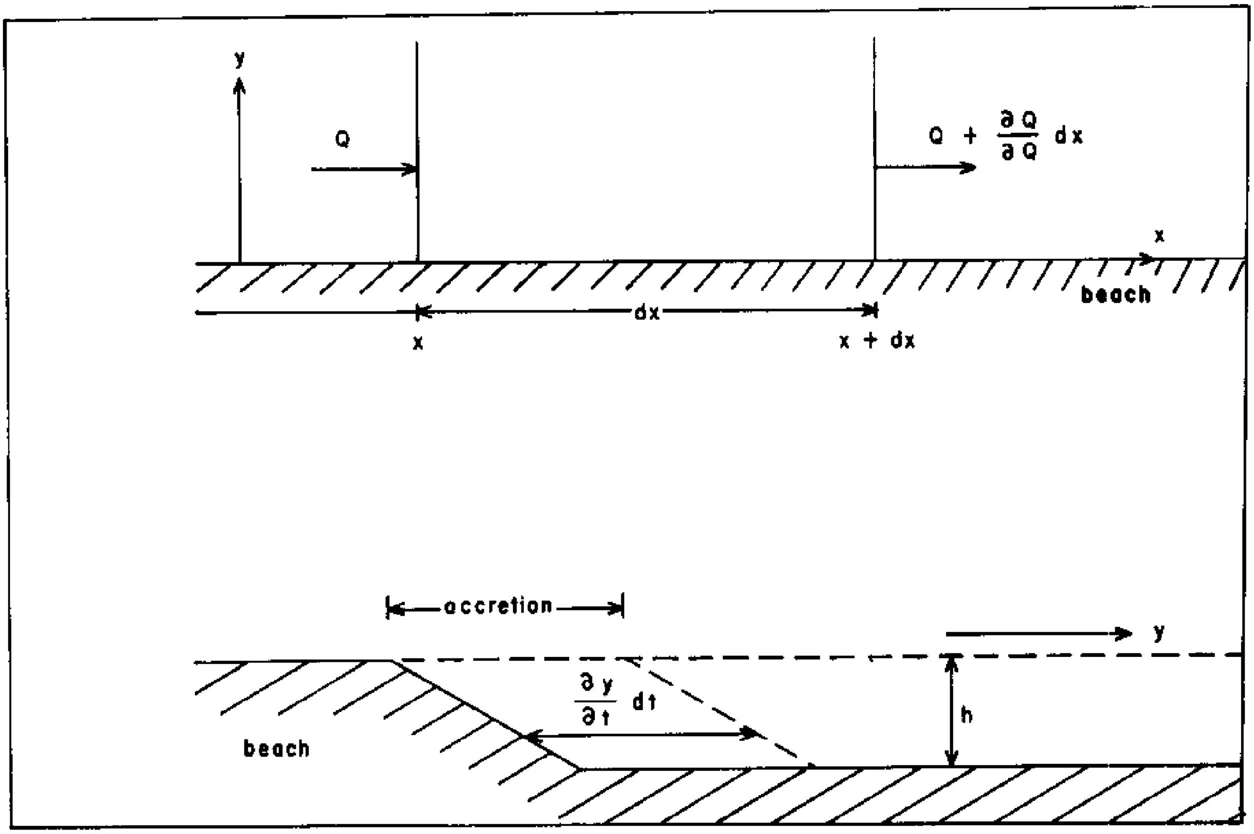


Figure 8.4. Shoreline behavior: coordinate system and boundary conditions

$$Qdt - (Q + \frac{\partial Q}{\partial x} dx)\ dt - h \frac{\partial y}{\partial t} dtdx = 0 \tag{8.1}$$

or

$$\frac{\partial y}{\partial t} = - \frac{1}{h} \frac{\partial Q}{\partial x} \tag{8.2}$$

where

$\frac{\partial Q}{\partial t}$ = the rate of accretion or erosion

$\frac{\partial Q}{\partial x}$ = the gradient of the littoral drift in the x-direction

h = the depth of the offshore region, which in this model is introduced as a constant value (independent of y)

Equation (8.2) provides the condition under which a coastline is stable:

$\frac{\partial Q}{\partial x} = 0$ and $\frac{\partial y}{\partial t} = 0$.

Furthermore, if erosion or accretion is constant along the shoreline,

$$\frac{\partial y}{\partial t} = \text{constant or } \frac{\partial y^2}{\partial x \partial t} = 0,$$

the beach will change its location but will retain its shape, maintaining an equilibrium form.

The equation of motion or dynamic equation in beach processes is the function that relates wave energy and incident wave angle to the rate of sediment transport (US Army Coastal Engineering Research Center, 1973).

This relationship may be written in the form:

$$Q = \frac{1}{2} A\ H_o^2\ c_o\ K_r^2 \sin 2\alpha_b \qquad (8.3)$$

where

Q = rate of littoral drift (volume per unit of time)

A = dimensionless constant

H_o = deep water wave height

c_o = velocity of wave propagation in deep water

K_r = refraction coefficient at point of breaking

α_b = breaking wave angle

If α represents the angle of wave approach in deep water, then:

$$K_r^2 = \frac{\cos\alpha}{\cos\alpha_b} \qquad (8.4)$$

Bruun (1954) found that, for the higher waves that give the largest contribution in shaping the beach, the relationship

$$\sin \alpha_b = \frac{1}{2} \sin \alpha \qquad (8.5)$$

is valid, so that

$$Q = \frac{1}{4} A\ H_o^2\ c_o \sin 2\alpha \qquad (8.6)$$

which represents the equation of motion in the beach processes. Utilizing the symbols of Figure 8.5 and defining

$$d\alpha = -d\psi$$

$$\tan\psi = \frac{dy}{dx}$$

$$\alpha = \alpha_o \text{ at } x = 0,$$

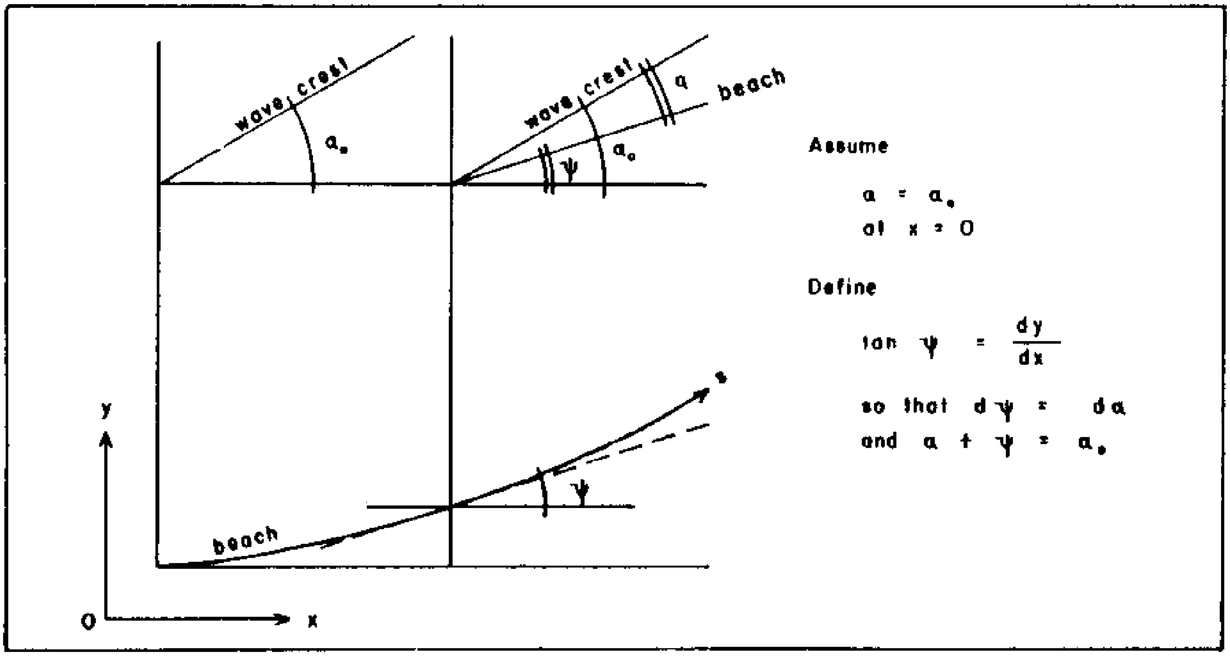


Figure 8.5. Orientation of wave crests relative to shoreline

it is possible to derive a mathematical expression for an equilibrium form. Thus,

$$\frac{\partial Q}{\partial s} = \frac{\partial Q}{\partial \alpha}\frac{\partial \alpha}{\partial s} = \text{constant} = c_m,$$

letting the s-direction correspond with the direction of the beach.

The equation of motion can be simplified by

$$Q = \frac{1}{2} P \sin 2\alpha \tag{8.7}$$

where

$$P = \frac{1}{2} A H_o^2 c_o.$$

Then:

$$\frac{\partial Q}{\partial \alpha} = P \cos 2\alpha$$

and

$$P \cos 2\alpha \cdot \frac{\partial \alpha}{\partial s} = c_m.$$

With only two variables, α and s, the equation may be written:

$$P \cos 2\alpha \, d\alpha = c_m \, ds$$

which can be solved.

Since $dx = ds \cos \psi = ds \cos (\alpha_o - \alpha)$

$dy = ds \sin \psi = ds \sin (\alpha_o - \alpha)$

this leads to:

$$P \cos 2\alpha \, d\alpha = c_m \frac{dx}{\cos(\alpha_o - \alpha)}$$

and

$$\frac{P}{c_m} \cos 2\alpha \cos(\alpha_o - \alpha) \, d\alpha = dx.$$

Also,

$$\frac{P}{c_m} \cos 2\alpha \sin(\alpha_o - \alpha) \, d\alpha = dy.$$

Solving these equations in parametric form gives:

$$x = \frac{P}{c_m} \left[-\cos\alpha \sin(\alpha_o - \alpha) + \frac{4}{3} \sin\alpha_o \cos^3\alpha + \frac{4}{3} \cos\alpha_o \sin^3\alpha - \frac{2}{3} \sin 2\alpha_o \right] \quad (8.8a)$$

and

$$y = \frac{P}{c_m} \left[\cos 2\alpha \cos(\alpha_o - \alpha) - \frac{4}{3} \cos\alpha_o \cos^3\alpha + \frac{4}{3} \sin\alpha_o \sin^3\alpha + \frac{1}{3} \cos 2\alpha_o \right] \quad (8.8b)$$

When $\alpha_o = 0$, the equations develop into:

$$x = \frac{P}{c_m} \left[\sin\alpha - \frac{2}{3} \sin^3\alpha \right] \quad (8.9a)$$

and

$$y = -\frac{P}{c} \left[\cos\alpha - \frac{2}{3} \cos^3\alpha - \frac{1}{3} \right]. \quad (8.9b)$$

Given the values for wave energy flux in deeper water (P) and for the gradient in the littoral drift (c_m), the parametric equations for x and y define equilibrium shoreline conditions.

By utilizing this approach, it is possible to explain characteristic shoreline forms such as those of headland beaches, tombolos, and recurved spits.

The equations also lead to the derivation of the dynamic behavior of a beach in case the littoral drift is interrupted by the construction of a barrier in the form of a groin or a jetty (Bruun, 1976).

For small angles, the equation of motion may be simplified to:

$$Q = \frac{1}{2} P \sin 2\alpha = P \sin\alpha \cos\alpha \simeq P \sin\alpha \quad (8.10)$$

since $\cos\alpha \simeq 1$.

The differential equation for shoreline behavior is then:

$$\frac{\partial y}{\partial t} = \frac{P}{h} \frac{\partial^2 y}{\partial x^2}. \quad (8.11)$$

In case of a littoral barrier, the solution of this equation is of the form

$$y = f_1\left(\frac{x}{\sqrt{t}}\right) = f_2\ (u),$$

where

$$u = \frac{x}{\sqrt{t}}\sqrt{\frac{\alpha_0 h}{4Q_0}}\ .$$

Q_0 and α_0 represent the rate of littoral drift and the angle of wave approach at large distances from the barrier. α_0 is expressed in radians.

Another solution to equation (8.11) is:

$$y = e^{-\frac{P}{h}k^2t}\cos kx \qquad (8.12)$$

which represents a "standing sand wave," with time decreasing amplitude and with wave number $k = 2\pi/L$, in which L is the length of the sand wave (Grym, 1960). Besides the standing and attenuating wave solution, propagating and attenuating wave solutions are possible. An interesting example is the behavior of the shoreline of the island of Vlieland off the Dutch coastline, as depicted in Figure 8.6. This figure shows the shoreline position (distance seaward from baseline) in various locations with increasing distances from the inlet as a function of time (van Bendegom, 1949). At station 36, near the inlet (Figure 8.6), the location of the shoreline shows a large fluctuation, whereas at station 42, 6 km away, the horizontal motion of the shoreline is greatly reduced. The pattern represents the behavior of a large sand wave moving from the inlet in a downdrift direction. The nourishment of the beach near station 42 is in the form of offshore shoals moving shoreward.

The migration rate of the beach waves at Vlieland was plotted by Sonu (1969) (Figure 8.2). The plotting seems to fit in with other experimental data on beach wave migration.

Beach Cusps

In this section beach cusps will be considered and data obtained from this study will be compared with previous findings.

In 1919 Johnson discussed early studies on beach cusps to which he added his own findings. He concluded that:

1. Beach cusps form at all stages of the tide.

2. The periodicity of incoming waves has no effect on cusp formation.

3. Cusps are a product of an onshore and offshore rather than a longshore movement of water.

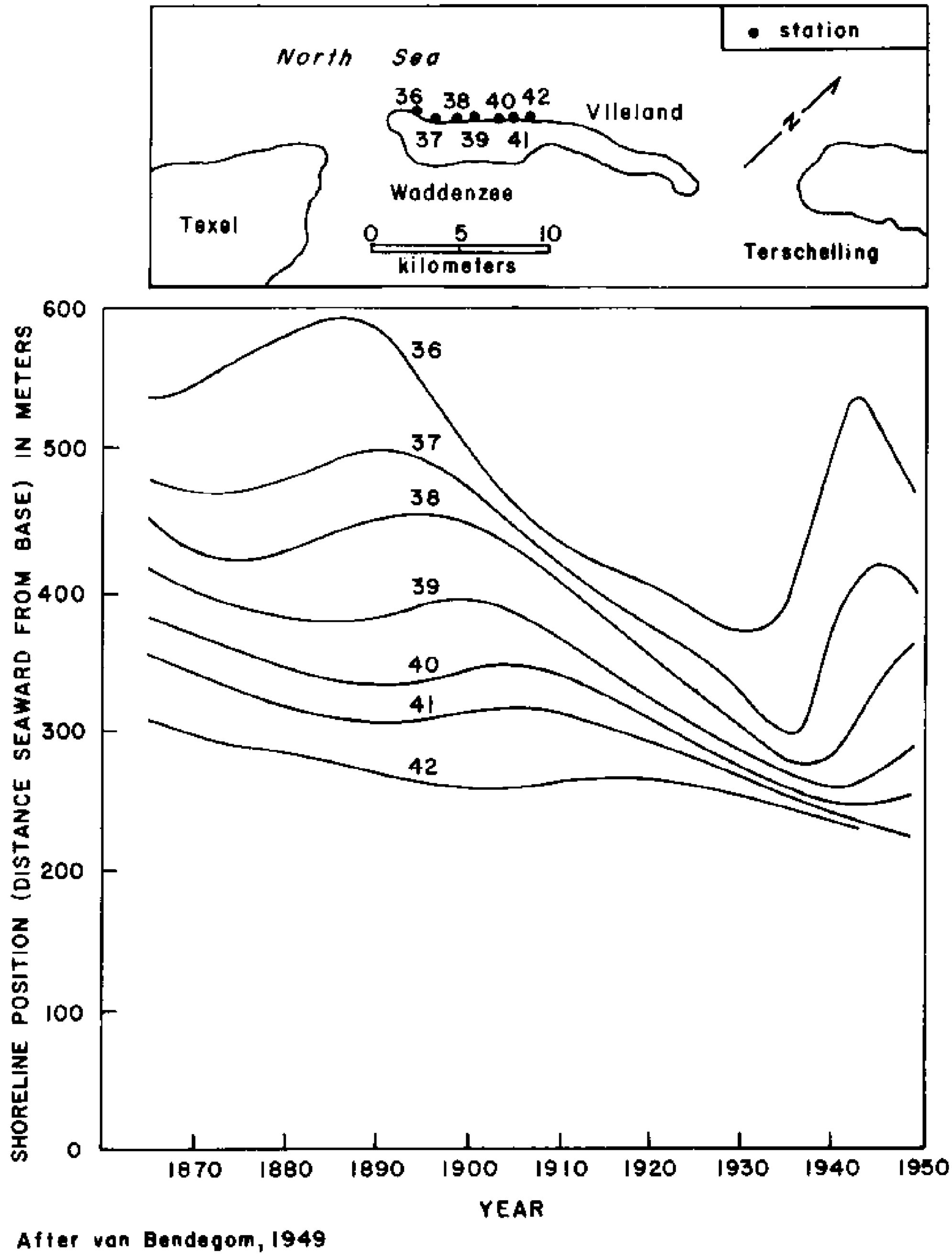


Figure 8.6. Migration of sand waves along Vlieland Coast, the Netherlands

Longuet-Higgins and Parkin in 1962 discussed the results of field observations along the south coast of England and of model experiments on beach cusps. They concluded that the cusp length is not simply related to wave period but rather to wave height and swash length. They also compared cusp wavelengths with edge wave wavelengths and reported negative results. In their comparison, they did not include higher frequency modes.

The work by Bowen and Inman (1971) was referred to earlier; it discusses the relationship between edge waves and rhythmic topographics on the shore and in the nearshore zone. The edge wave discussed is of the standing type. Equations for the orbital and drift velocities of an edge wave were also presented in their paper. The authors demonstrated, in the laboratory, that a standing edge wave has sufficient velocities to create crescentic bars and, in the absence of large waves, cuspate beach features. The crescentic bars and cusps have lengths equal to one-half the wavelength of the edge waves, with the node of the bars (concave shoreward) opposite the node of the cusps (concave seaward).

Komar (1972) examined the role of cell circulation, rip currents, and longshore currents in producing an equilibrium cuspate shoreline. The cusps examined by Komar are larger (500 to 3,000 ft) than the types discussed by the previous authors and, using the terminology introduced earlier in this chapter, constitute beach waves rather than beach cusps.

The work by Sonu (1969) on dynamic sand wave behavior at Nags Head, North Carolina was also referred to earlier in this chapter. The shoreline forms in his work are related to circulation patterns and sand wave characteristics and may be considered relevant to the concept of beach waves.

Hammerwold (1974), in a plan B paper for his M.S. degree in Ocean Engineering at the University of Hawaii, surveyed essential literature on beach cusps and related cusp length for edge wave wavelength. His findings have contributed to the results of the study on beach cusps, as described in the following sections.

Field Observations

In order to get an overall idea of the significance of cusp formation for Hawaiian shorelines, observations were carried out on beach cusp characteristics at various island beaches. In addition to this program of reconnaissance-type measurement, a more detailed program of observations was carried out at Waimanalo Beach, where the development of a particular beach cusp with time was considered and where data were collected on cusp topography and sediment characteristics.

Table 8.1 presents a list of the various sites where observations were made, along with the dates of survey and the location at the cusp where the beach slope was measured. Additional data collected at the various sites are presented in Table 8.2. They include beach slope, average cusp wavelength, and wave period, as well as sediment characteristics.

Figure 8.7 shows cusp characteristics: length, L_c, and vertical amplitude, a_c. The latter is taken in the middle of the line connecting two nodal points. At cusp nodes A and A^1, the beach slope is steep; the area between two cusps where the beach slope is gentler is called embayment.

Beach cusps at Waimanalo Beach were studied for migration characteristics, if any, and grain size distribution over the cusp area. The beach at Waimanalo is free from coastal structures and has well-defined cusp formations most of the time. The study site at Waimanalo Beach was located between traverses 1 and 2 as shown in Figure 5.31.

TABLE 8.1. FIELD SURVEYS OF BEACH CUSPS

Identification Number	Site	Date of Survey	Location at Cusp Where Beach Slope Was Taken
1a	Waimanalo Beach	10-06-73	Node
1b	Waimanalo Beach	10-06-73	Embayment
2a	Waimanalo Beach	10-27-73	Node
2b	Waimanalo Beach	10-27-73	Embayment
3a	Waimanalo Beach	11-10-73	Node
3b	Waimanalo Beach	11-10-73	Embayment
4	Waimanalo Beach	12-08-73	Node
5	Waimanalo Beach	02-26-74	Embayment
6a	Sandy Beach	11-10-73	Node
6b	Sandy Beach	11-10-73	Embayment
7a	Sandy Beach	12-15-73	Node
7b	Sandy Beach	12-15-73	Embayment
8	Sandy Beach	02-26-74	Average slope
9	Mauna Kea Beach	12-20-73	Average slope
10	Hapuna Beach	12-20-73	Average slope
11a	Puu Olai Beach	12-21-73	Node
11b	Puu Olai Beach	12-21-73	Embayment
12	Wailea Beach	12-21-73	Average slope
13	Barking Sands Beach	01-16-74	Average slope
14a	Hanalei Beach	01-17-74	Average slope, west side of bay
14b	Hanalei Beach	01-17-74	Average slope, east side of bay

TABLE 8.2. TABULATED DATA FROM FIELD SURVEYS

Identification Number*	Number of Cusps Measured	Average Cusp Wavelength (ft)	Sediment: Mean (φ)	Mean (mm)	Standard Deviation (φ)	Skewness (φ)	Kurtosis (φ)	Beach Slope	Average Beach Slope	Wave Height (ft)	Wave Period (sec)	Maximum Cusp Amplitude (ft)
1a	20	72.0	0.903	0.540	0.876	0.344	3.315	1:7.4	1:9.9	2	8	2.2
1b			1.215	0.430	0.770	-0.148	3.475	1:12.5				
2a	20	75.0						1:10.9	1:12.1			
2b			1.666	0.320	0.640	-0.264	3.045	1:13.3				
3a	20	79.8	1.085	0.470	0.875	-0.680	3.964	1:10.8	1:11.8	1	11	
3b								1:12.9				
4	20	85.3	1.399	0.375	0.920	-0.617	3.196	1:9.5		1	8	
5	20	81.5						1:11.8			8	
6a	5	149.0						1:7.7	1:8.6	2	10	4.0
6b			1.158	0.450	0.452	-0.956	5.911	1:9.6				
7a	5	153.0						1:8.8	1:9.6	2	11	4.3
7b			1.155	0.450	0.420	-0.685	5.198	1:10.4				
8	6	124.5						1:6.7		4	8	
9	14	91.2	2.217	0.230	0.523	-0.515	4.558	1:21.3		2	10	
10	21	91.3	1.942	0.260	0.522	-0.434	3.641	1:20.8		3	10	
11a	21	117.3	1.494	0.350	0.537	-0.762	4.638	1:6.1	1:10.0	3	6	3.6
11b			1.653	0.320	0.403	-0.486	4.928	1:13.9				
12	18	72.0	2.235	0.210	0.488	0.066	3.618	1:24.4			15	
13	6	117.0	1.660	0.320	0.625	-0.411	3.003	1:8.8		5	6	
14a	4	70.0	1.251	0.420	0.472	0.390	3.592	1:10.0	1:20.0	6	8	
14b	4	85.5	2.379	0.195	0.465	0.187	3.781	1:30.0		6		

*Identification numbers refer to Table 8.1.

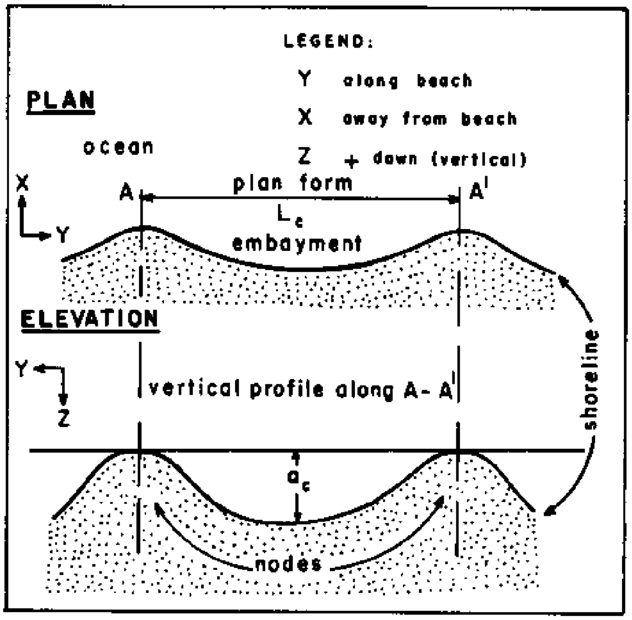


Figure 8.7. Cusp characteristics: length and vertical amplitude

The results of the measurement of a selected beach cusp at Waimanalo Beach are as follows: the topography of the cusp was obtained from measurements along seven traverses, AA' through GG', 25 ft apart (Figure 8.8). Lines of equal elevation are shown in Figure 8.9.

In addition to topography measurements, sand samples were collected in 12 locations as shown in Figure 8.8. The results of the sediment analysis for these 12 samples are given in Table 8.3 and contour lines for equal mean diameter are sketched in Figure 8.9.

In the embayment section an increase in grain diameter with increasing depth may be observed. However, at the node on either side of the middle, large differences in grain size were found: at the location of sample 3 (Figure 8.8) the material was very coarse (d_{50} = 1.820 mm), whereas at the location of sample 12 the material was fine (d_{50} = 0.208 mm). Apparently the distribution of coarse and fine particles over the beach cusp was asymmetrical for reasons not well understood at this time.

Circulation patterns at a beach cusp are complex and not always the same. Observations of uprush behavior suggest that the patterns of uprush and downrush are different for larger and smaller cusps, as schematically indicated in Figure 8.10. The offshore topography affects the direction of approaching waves due to refraction, with usual uprush and downrush patterns for small cusps as suggested in Figure 8.10a. The node of the cusp tends to be built up and stabilized in this way whereby a weak rip current is generated at the node.

On the other hand, it was observed by Sonu (1969) that rip currents are often generated off the embayment of a cusp, as shown in Figure 8.10b. Such a pattern can be explained by considering the wave-induced littoral current instead of the uprush and downrush patterns. For such patterns the cusp should be long enough to allow the build-up of a longshore current and a larger beach cusp may be expected.

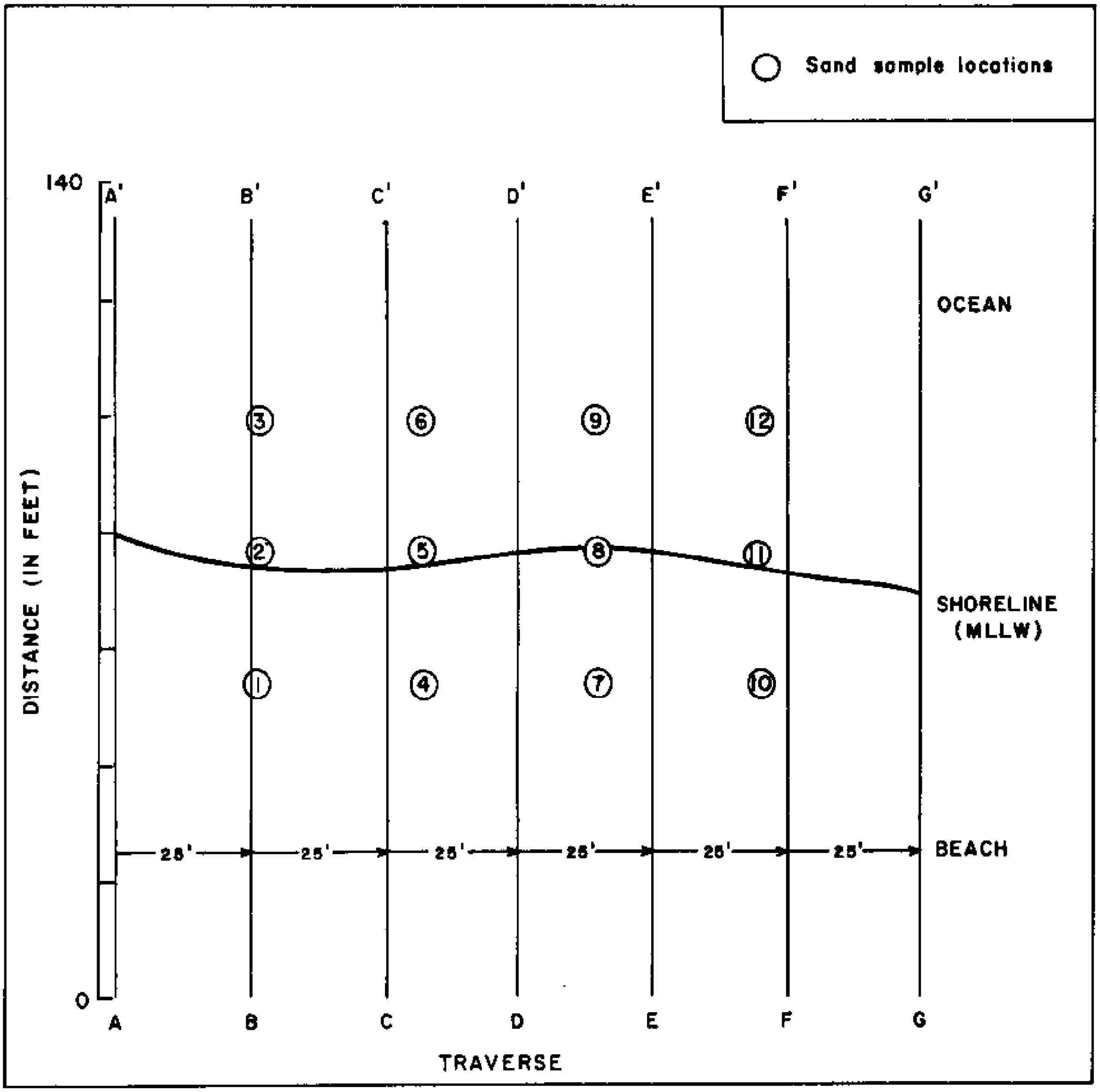


Figure 8.8. Cusp study site showing profile traverses and sand sample locations at Waimanalo Beach, Oahu. (Note: traverse B-B' is traverse 2 on Figure 5.34.)

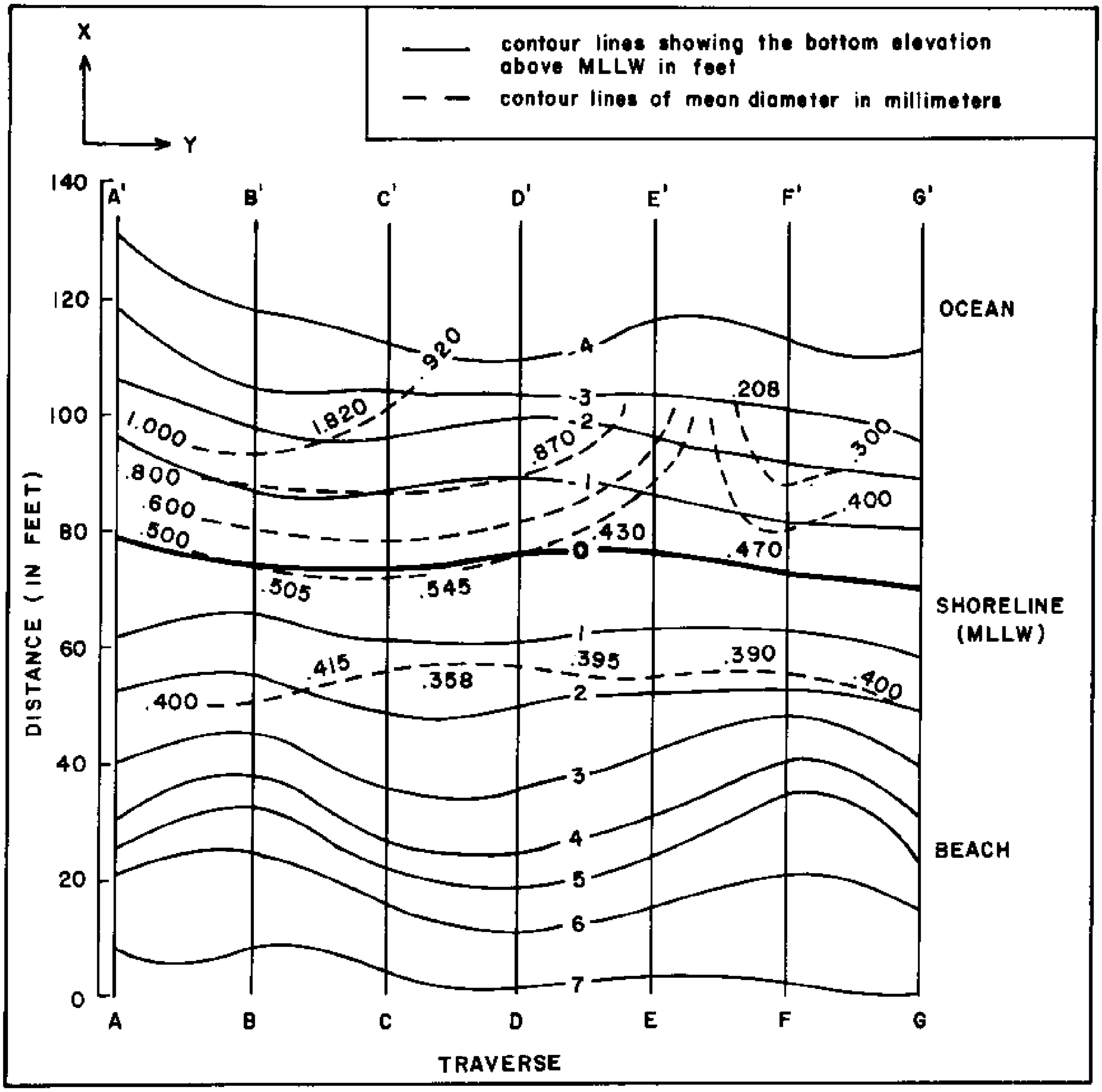


Figure 8.9. Detailed cusp topography and sand distribution from beach survey at Waimanalo Beach, Oahu. (Note: traverse B-B' is traverse 2 on Figure 5.34.)

TABLE 8.3. CUSP SEDIMENT DIAMETER VARIATION AT WAIMANALO BEACH

Sample Number	Mean Diameter (ϕ)	Mean Diameter (ϕ)	Standard Deviation (ϕ)	Skewness (ϕ)	Kurtosis (ϕ)
1	1.274	0.415	0.668	0.071	3.832
2	0.993	0.505	0.876	-0.349	3.315
3	-0.087	1.820	1.077	0.596	0.379
4	1.479	0.358	0.743	-0.222	3.528
5	1.871	0.545	0.935	-0.231	2.889
6	0.112	0.920	1.210	0.825	3.228
7	1.339	0.395	0.766	-0.280	4.105
8	1.215	0.430	0.770	-0.148	3.475
9	0.205	0.870	1.501	0.181	1.856
10	1.349	0.390	0.765	-0.359	4.061
11	1.083	0.470	0.989	-0.690	3.541
12	2.273	0.208	0.602	-1.110	8.473

Note: Samples 1, 4, 7, and 10 taken at crest; samples 2, 5, 8, and 11 at waterline; and samples 3, 6, 9, and 12 at 20 ft seaward from waterline. (See Figure 8.8 for locations of samples.)

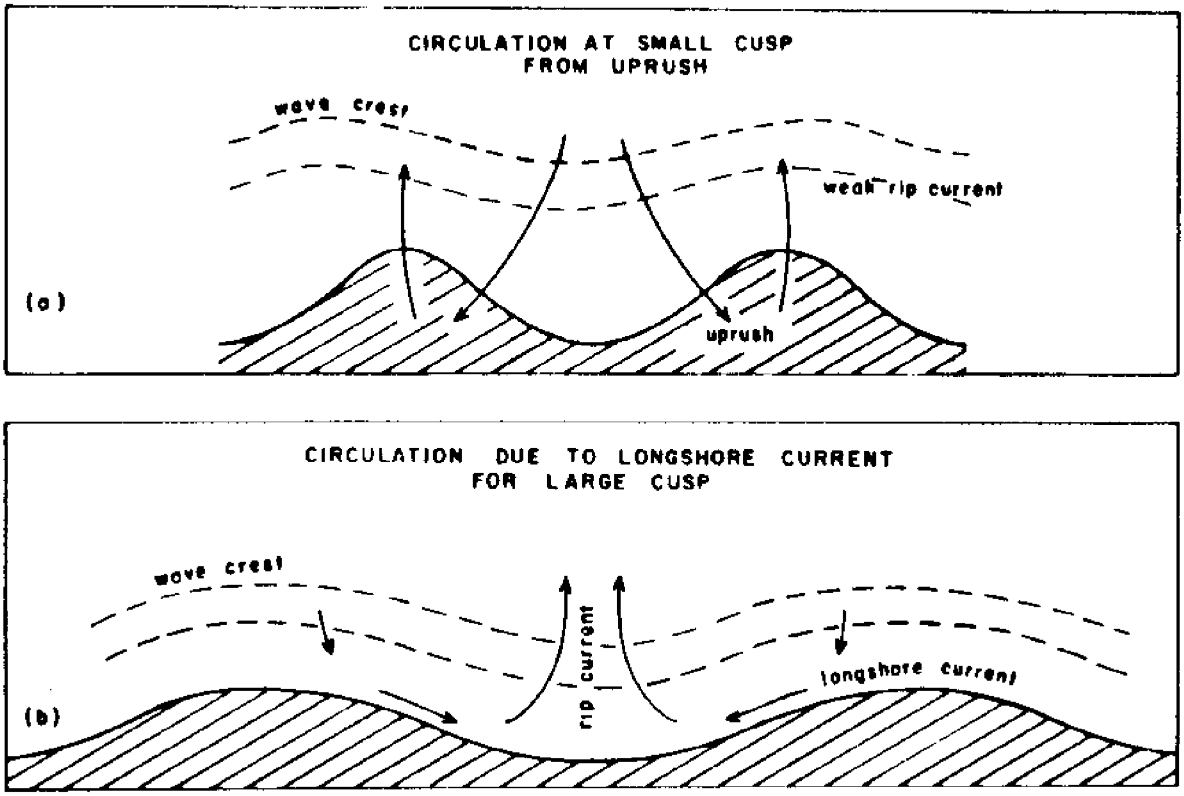


Figure 8.10. Circulation patterns for cusps: (a) small cusp with uprush and (b) large cusp with longshore current

Another element in the dynamics of water motion at beach cusps is the effect of downrush on wave breaking. This effect is different at the node than at the embayment. Wave period is important in this respect because it affects resonance characteristics of uprush as related to beach slope.

Comparison Between Observed and Theoretical Values

Earlier it had been stated that cusps may be formed with lengths equal either to the length or to one-half the length of the corresponding edge wave.

Bowen and Inman (1971) gave an expression for the velocity potential of a standing edge wave:

$$\phi = \frac{ga}{\sigma} L_n \, (2Ky) e^{-ky} \cos kx \cos \sigma t \tag{8.13}$$

where

a = amplitude

σ = angular frequency

k = wave number

x = coordinate along the beach

y = coordinate perpendicular to the beach, positive seaward

L_n $(2ky)$ = the Laguerre Polynomial of order n.

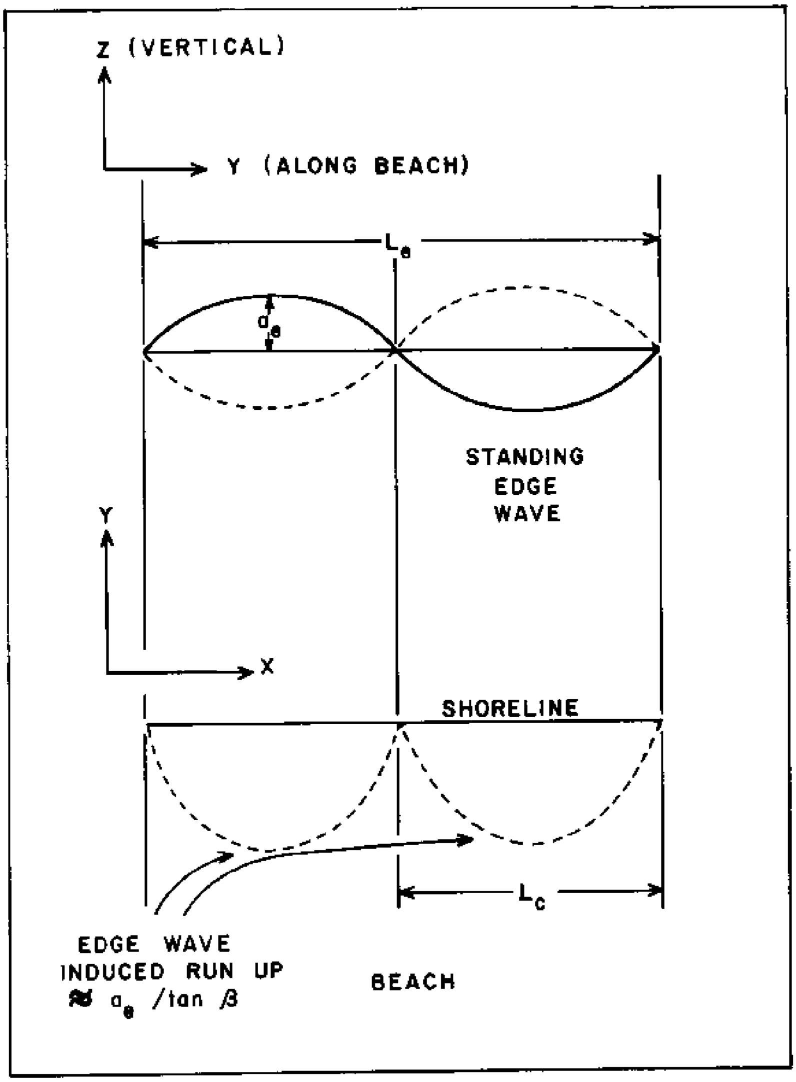
The current velocities parallel to the beach may be found from $V_x = \frac{\partial \phi}{\partial x}$.

Bowen and Inman (1971) suggested that in situations where incoming waves are small, cusp length will be equal to one-half of the length of the edge wave. Figure 8.11 refers to that mode of cusp generation; areas of higher waves and increased impact on the shoreline occur in the anti-nodes of the edge wave so that the latter correspond to the embayment areas of the cusp. The cusp nodes consequently are opposite the nodal points of the edge wave.

Regarding the period of the edge waves, they are most likely to be equal to the period of the incident waves, although a recent study by Guza and Davis (1974) suggests that edge waves can be generated with one-half the frequency of the incidental waves. In this case the zero node is likely the most excitable.

In order to compare measured cusp lengths with theoretical values, Bowen and Inman's (1971) dispersion relationship for standing edge waves is used (Hammerwold, 1974):

$$\sigma^2 = gk(2n + 1) \tan \beta, \; n = 0, 1, 2, \ldots, n \tag{8.14}$$



After Bowen and Inman, 1971

Figure 8.11. Formation of beach cusps by edge waves

where

σ = frequency of edge wave

k = wave number of edge wave

$\tan \beta$ = slope of beach

n = number defining mode of oscillation.

The wavelength of the edge wave may be computed from equation (8.14):

$$L_e = \frac{g}{2\pi} T^2 (2n + 1) \tan \beta. \quad (8.15)$$

The value of L_e will be used for the comparison between theoretical and observed values, using different values for n.

In this procedure theoretical values are computed for edge waves of two different periods: one is equal to the period of the incident wave and another equal to two times the period of the incident wave. Using equation 8.15 the length of the edge wave is computed for various values of n, again following two different concepts, the length of the cusp being equal to the length of the edge wave or equal to one-half of the length of the edge wave.

The value selected as the most probable theoretical value is the calculated length (L_c) that is closest to the measured value (L_o). Measured and calculated data are presented in Table 8.4.

The percentage of difference (p) between measured and calculated cusp length was computed for the set of values that had closest agreement, irrespective of the value of n that was used:

$$p = \frac{L_c - L_o}{L_o} \times 100\% \qquad (8.16)$$

The average value of p was computed for the three columns (p_1, p_2, and p_3) in Table 8.4. The results of the comparison give rise to the following discussion.

The best agreement is found in column p_2 for which the edge wave period equals the period of the incident waves and the cusp length (L_c) is related to one-half of the length of the edge wave ($L_e/2$). In order to get the closest agreement between measured and observed data, however, the higher modes for the frequency had to be used for most situations.

The question arises as to whether or not solutions based on the higher modes of the frequency may be considered physically significant. Other aspects not included so far may also be relevant. These aspects may be related to accuracy of measured data and to the stochastic nature of the incident waves.

Since for the calculation of cusp length (equation 8.15) the period T appears in the second power, an inaccuracy in T is approximately doubled in the determination of the wavelength. Other inaccuracies occur in the measurement of the slope of the beach which is never a straight line.

The wave period observed was found as an average period for 10 consecutive waves breaking on the beach. Without the measurement of the complete wave spectrum offshore it is difficult to determine the physical significance of the measured data on wave period. Measurements conducted at Ala Moana reef indicate that the wave period of the broken wave can be significantly smaller than the period of the incident wave.

It may very well be possible that higher wave frequencies in the wave spectrum play a role in the generation of edge waves in different modes. Further study is necessary to clarify these aspects.

TABLE 8.4. COMPARISON OF MEASURED CUSP LENGTHS AND CALCULATED THEORETICAL VALUES

Identification Number*	Average Measured Cusp Length (L_o) (ft)	Average Measured Wave Period (T) (sec)	Average Measured Beach Slope	$T_{edge\ wave} = T_{incident\ wave}$						$T_{edge\ wave} = 2\ T_{incident\ wave}$		
				n	$L_c = L_e$	Difference p_1 (%)	n	$L_c = \frac{L_e}{2}$	Difference p_2 (%)	n	$L_c = \frac{L_e^1}{2}$	Difference p_3 (%)
1	72.0	8	1:9.9	1	99.0	37.5	2	82.5	14.6	0	66.0	8.2
3	79.8	11	1:11.8	0	52.5	34.2	1	78.8	1.3	0	105.0	31.4
6	149.0	10	1:8.6	1	182.4	22.4	2	152.0	2.0	0	121.6	18.3
7	153.0	11	1:9.6	1	193.8	26.6	2	161.5	5.6	0	129.2	15.5
8	124.5	8	1:6.7	1	146.7	17.8	2	122.3	1.8	0	97.8	21.4
9	91.2	10	1:21.3	1	72.0	21.0	3	84.0	7.9	0	48.0	47.5
10	91.3	10	1:20.8	1	73.8	19.2	3	86.6	5.2	0	49.2	46.1
11	117.3	6	:10.0	3	128.8	9.8	6	120.0	2.3	1	110.4	5.9
12	72.0	15	1:24.4	0	47.2	33.4	1	70.8	1.7	0	94.4	31.0
13	117.0	6	1:8.8	2	105.0	10.3	5	115.0	1.7	1	123.6	5.6
	Average value of p_1, p_2, and p_3					23.2			4.4			23.1

*Identification numbers refer to Table 8.1.

If the higher modes of the angular frequency have a physical significance, the cusp length being equal to one-half the length of the edge wave mode seems to offer the best agreement between observed and calculated data.

In addition to the relationship between cusp length and edge wave characteristics, other relationships were investigated. It was confirmed that no visible relationship existed either between the average cusp length and the mean particle diameter or between the cusp length and wave period. The correlation between cusp length and beach slope was rather low, but there was a tendency for greater cusp length for steeper beaches, as shown in Figure 8.12.

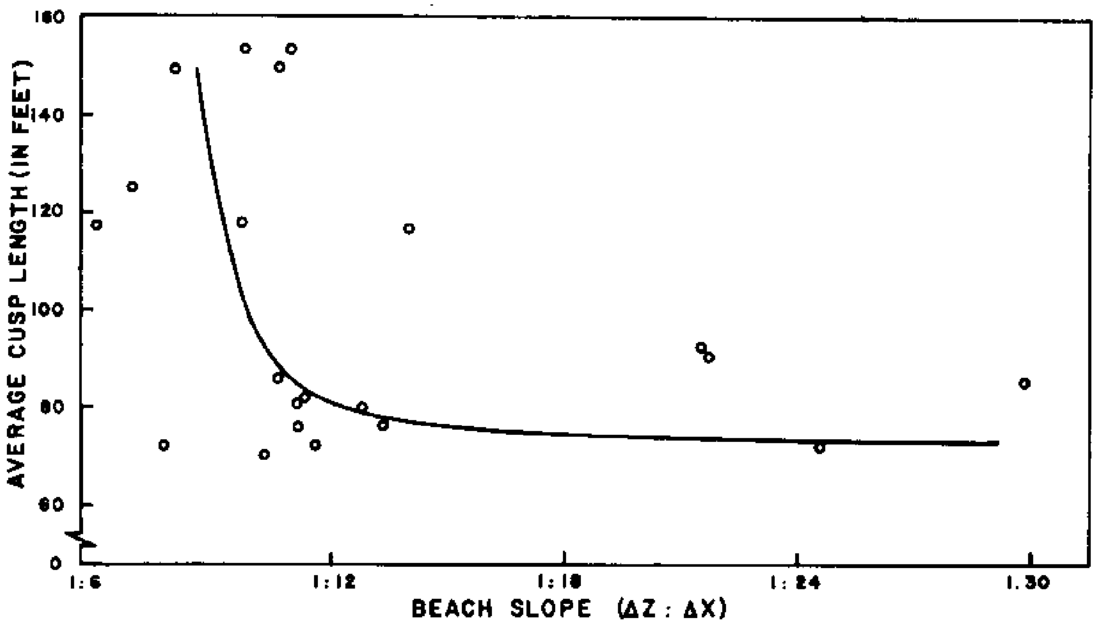


Figure 8.12. Comparison of average cusp length with beach slope

At Waimanalo Beach, it was observed that the cusp was very stable in time with respect to location and that there was no indication of migration. All observations covering a period from a few hours to several months showed no significant migration of the cusp under study.

Comparing these results with data presented by Sonu (1969) seems to indicate disagreement; however, if Sonu's sand wave analysis refers to littoral drift-induced beach waves (as discussed earlier there is no contradiction.

Summary of Beach Waves and Beach Cusps

Dynamic beach behavior may be explained in terms of sand waves in the coastal region. There is a distinction between (1) sandbars situated parallel to the coastline which migrate landward or seaward due to a change in wave conditions and (2) sand waves at the waterline which give the shoreline a wavy appearance and which may or may not migrate along the beach, usually in the direction of the littoral drift.

The investigations described in this report deal with shoreline-connected sand waves which may be caused by two different physical processes:

1. Sand waves induced by the littoral current and littoral drift. They may be of the standing or migratory type; in the latter the speed of migration is related to the length of the sand wave (Sonu, 1969). For the purpose of discussion, this type is called beach wave.

2. Cusp-type sand waves of stable form and location. They do not migrate and their generation and maintenance are most likely related to edge wave phenomena.

Shoreline behavior was analyzed analytically by introducing a number of simplified assumptions and equations. One analytical solution has the characteristics of a standing beach wave, the amplitude of which decreases with time.

At a number of island beaches, beach cusps and relevant wave characteristics were measured. The observed data have been compared with theoretical values.

Using this information an attempt was made to relate cusp length to edge wave wavelength. A reasonable agreement could only be found if higher frequency modes were introduced. The best agreement between observed and computed data was found if the edge wave period was assumed to be equal to the period of the incident wave and the cusp length equal to one-half of the length of the edge waves. A higher frequency mode for the edge wave was usually needed to obtain agreement between theoretical and measured cusp lengths.

It was also found that there is a slight correlation between cusp length and beach slope, the greater length corresponding to the steeper slopes.

Regarding the observations at Waimanalo Beach, it was found that both relatively short cusps (90 ft in average length) and large sand waves with lengths many times the length of the shorter cusps are present most of the time. The shorter 90-ft long beach cusps are stable and do not migrate. At one particular beach cusp at Waimanalo Beach, the mean grain size value showed an asymmetrical distribution over the cusp length.

Dynamic beach behavior apparently involves a spectrum of sand waves of different wavelengths with different behavior. Edge waves seem to play a role in the generation and maintenance of beach cusps. For a more detailed analysis, the wave spectrum and its relationship to edge waves should be investigated.

CHAPTER 9. STABILITY OF HEADLAND BEACHES

In this chapter the behavior of headland beaches as related to changes in the wave environment and aspects of beach nourishment will be analyzed. Headland beaches, in this context, are defined as beaches of finite length and marked by headlands on both sides. Headlands which are relatively high, rocky, and impermeable, and which may or may not allow bypassing of sand of the littoral drift moving along the shoreline will be particularly considered. Either way, the balance of sand for the beach under consideration and, thus, the nourishment conditions and beach equilibrium will be affected. No attempt will be made to quantify the relationships involved although an approach similar to the one developed in the previous chapter may be developed for this purpose. The discussion may improve the understanding of the natural behavior of headland beaches in a littoral drift regime. It is hereby assumed that the transport of sand is concentrated in the surf zone under the influence of the wave-induced littoral current parallel to the beach. For this analysis three-dimensional aspects, such as rip currents which transport sediment perpendicular to the shoreline, are not taken into account. It is suggested that the discussions in this chapter not only give additional insight into the stability problems at some of the headland beaches discussed in this report, but also be of value to predict the behavior of man-made beaches in terms of beach profile, distribution of sediments, and the need for artificial nourishment. The characteristics of a headland beach in plan form are affected by both wave characteristics and nourshment conditions. In this chapter an evaluation of how a change in either of these two conditions will induce a change in plan form will be discussed.

Effects of a Change in Wave Direction

Figure 9.1 depicts a beach between two protruding headlands, A and B, under the effect of two different wave directions, $\alpha 1$ and $\alpha 2$. Assuming that no losses of sand occur from this beach to adjacent beaches or from onshore-offshore movements of sand and assuming that no nourishment of the beach occurs from adjacent beaches, the beach will adjust itself in plan form to a change in wave direction as shown in Figure 9.1. Under the conditions mentioned, erosion and accretion will compensate each other.

Figure 9.2 depicts a situation similar to Figure 9.1; however, in Figure 9.2, one of the two headlands, B, is short and allows bypassing of sand. When this occurs, material moves either to the adjacent beach and serves as a source of nourishment for that beach or it is transported into deep water, in which case it is lost as nourishment for the beach section between A and B. In either case, the volume of erosion is greater than the volume of accretion, as is evidenced by the loss of material from the beach section.

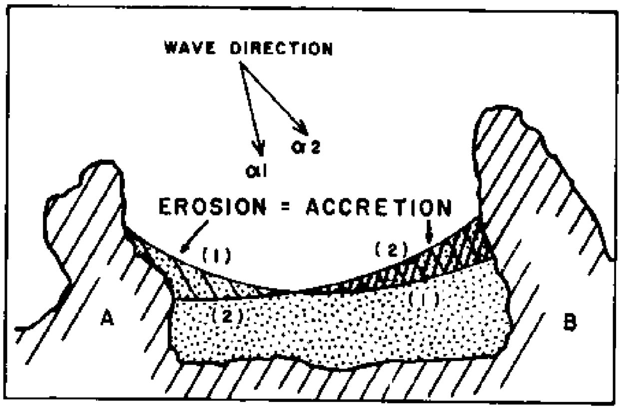


Figure 9.1. Realignment of pocket beach to change in wave direction 1 to 2 where erosion = accretion

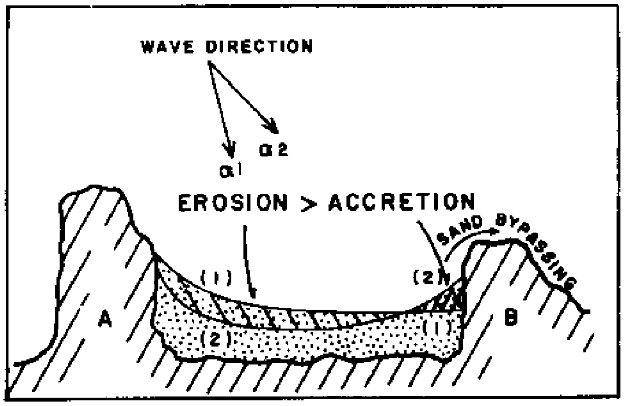


Figure 9.2. Realignment of pocket beach to change in wave direction 1 to 2 where erosion > accretion

The behavior of waves in the vicinity of a headland is schematically shown in Figure 9.3. It is assumed that the change in wave direction is governed by refraction. The wave height just before breaking at any point along the shoreline of the section can be obtained from the relationship:

$$H_b = H_o \cdot K_s \cdot K_r \qquad (9.1)$$

where

H_b = the wave height at breaking

H_o = the deep water wave height

K_s = the shoaling coefficient $\left(K_s = \sqrt{\frac{c_o}{2\sqrt{gh_b}}}\right)$ at the point of breaking in which c_o = phase speed in deep water

h_b = water depth at breaking

K_r = the refraction coefficient $\left(K_r = \sqrt{\frac{b_o}{b_b}}\right)$ at the point of breaking

in which b_o and b_b are the distances between two successive orthogonals in deep water and near the breaking point. The shoreline orients itself parallel to the line of breakers (see Plate 7.1).

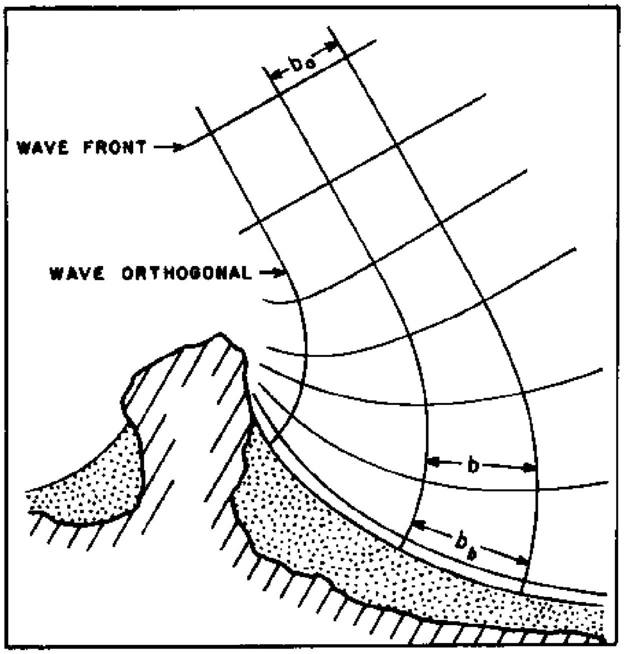


Figure 9.3. Waves approaching a stable shoreline without resultant sand transport

A change in wave direction, as shown in Figure 9.4, will cause erosion in the area near the headland and accretion in the section away from the headland. Figure 9.4 is based on the assumption that no nourishment of the beach takes place so that, at any time, the beach will adjust itself to the direction of the breaking waves.

Effect of Beach Nourishment

Waves approaching the beach at an angle cause transport of material along the shoreline; this is known as littoral drift. In equation (8.3), a formula for the rate of transport is given, relating the magnitude of the transport to the flux of wave energy and the angle (α_b) between the wave crests and the shoreline at breaking. For a stable shoreline, the condition is:

$$\frac{\partial Q}{\partial s} = 0, \qquad Q = \text{constant.} \tag{9.2}$$

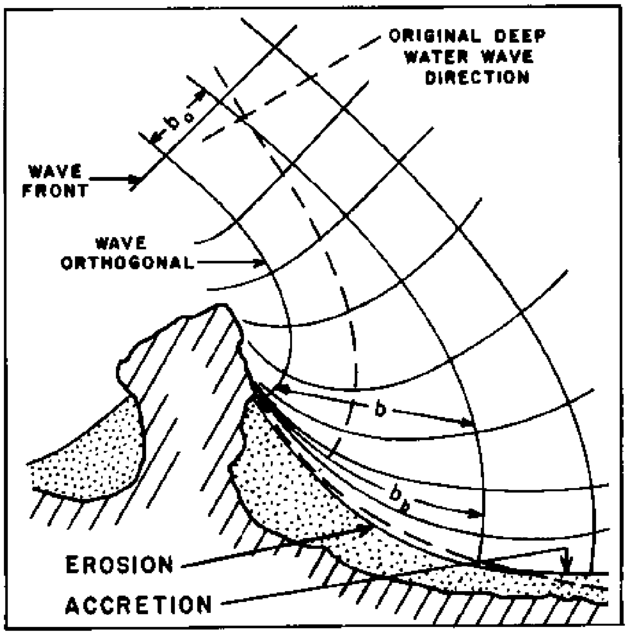


Figure 9.4. Shoreline change due to change in wave direction

For given deep water characteristics (H_o, c_o), the condition of stability is represented by $K_r^2 \sin 2\alpha_b = C$ whereby the value of C is related to the magnitude of the littoral drift. If no supply of sand is available, the littoral drift becomes zero and C = 0. In this case the beach adjusts itself parallel to the direction of the waves at breaking--a situation which is shown in Figure 9.3. If a supply of beach sand is available and has to be transported along the beach, the condition for stability is:

$$K_r^2 \sin 2\alpha_b = C, \qquad C \neq 0. \tag{9.3}$$

The two different types of conditions are represented in Figures 9.5 and 9.6. In Figure 9.5, the beach is nourished with a sand supply, Q, passing by the adjacent headland. The angle, α_b, between the crests of the breaking waves and the shoreline has a non-zero value and is related to the value of the

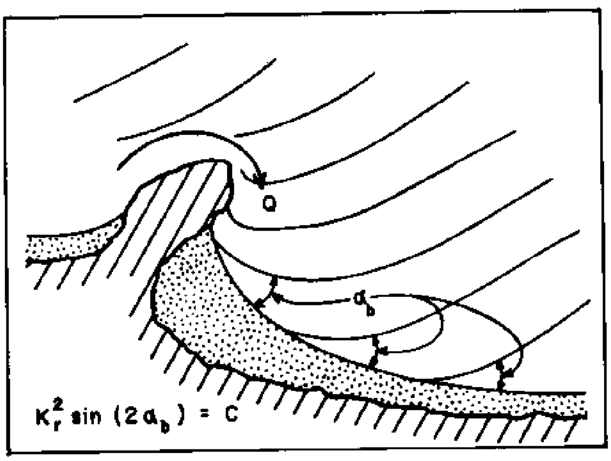


Figure 9.5. Stable beach form with transport of sand

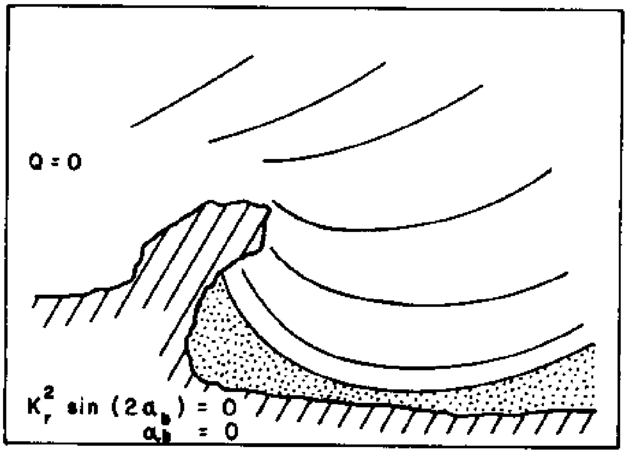


Figure 9.6. Stable beach form without transport of sand

refraction coefficient, K_r. In Figure 9.6, the supply of sand is zero and the beach adjusts itself parallel to the direction of the waves near breaking so that, in each point along the shoreline, the longshore transport rate becomes zero. A change in nourishment conditions will consequently cause a change in the shoreline configuration to meet the conditions of the stability equation. Figures 9.5 and 9.6 represent both equilibrium conditions; the difference is the rate of sediment supply to the beach.

Effect of Changes in Wave Period

In the preceding paragraphs the shape of the beach in plan form as related to the refraction of the waves around the headland was discussed. Since the waves under consideration are relatively long compared with depth, refraction characteristics are likely to dominate over diffraction characteristics. Although no detailed calculations have been made, it is anticipated that a change in wave period will cause a change in the alignment of the beach. Such a change is suggested in Figure 9.7, whereby an increase in wavelength induces accretion to the beach section adjacent to the headland and erosion to the section further away from the headland.

A decrease in wavelength will have the opposite effect.

Effect of Wave Height on Beach Alignment

The angle between a wave crest near breaking and the shoreline is related to the wave height at breaking. Since the latter is related to the depth at breaking, the angle will be larger with increasing wave height. Figure 9.8 schematically shows the trends in shoreline change, with changing wave height. The change in wave height affects the refraction pattern only to a small degree. With an increase in wave height from height 1 to height 2, a change of shoreline configuration (Figure 9.8) may be expected, leading to erosion near the headland and accretion away from it, assuming that the transport (supply), $Q > 0$, around the headland does not alter. As far as the change in shoreline configuration due to changing wave height is concerned, it may be expected that it will be considerably smaller than the change in shoreline, induced by a change in wave direction.

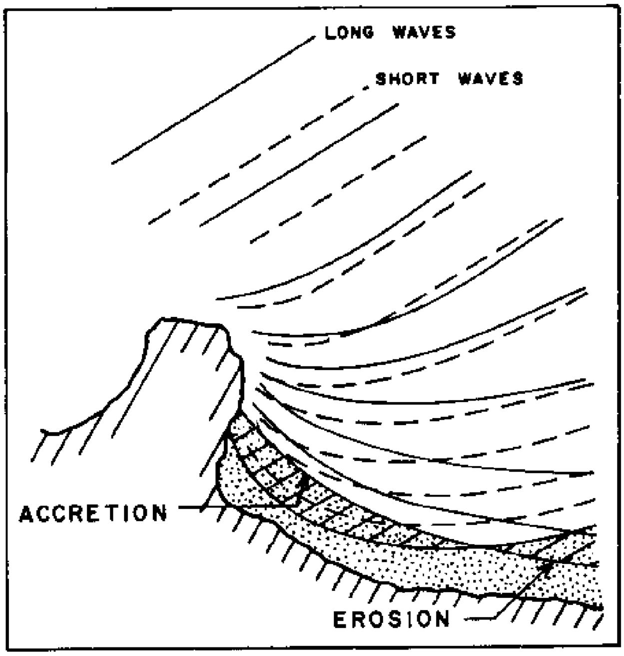


Figure 9.7. Realignment of shoreline due to increase in wavelength of incoming waves

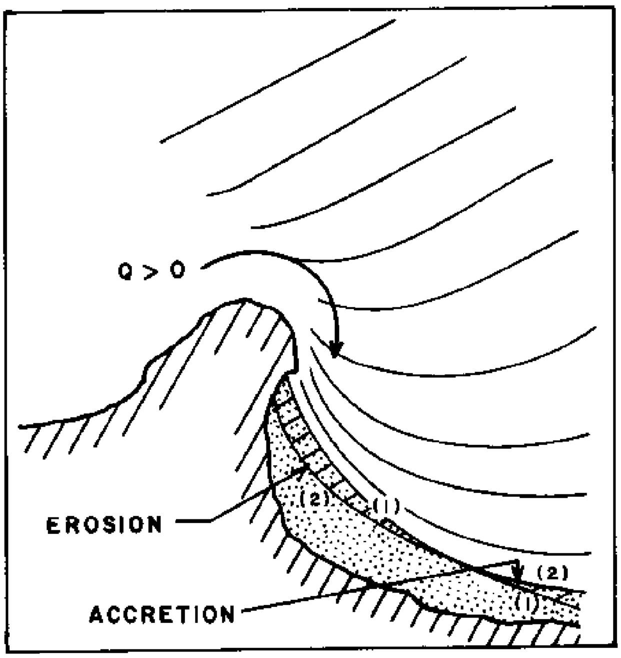


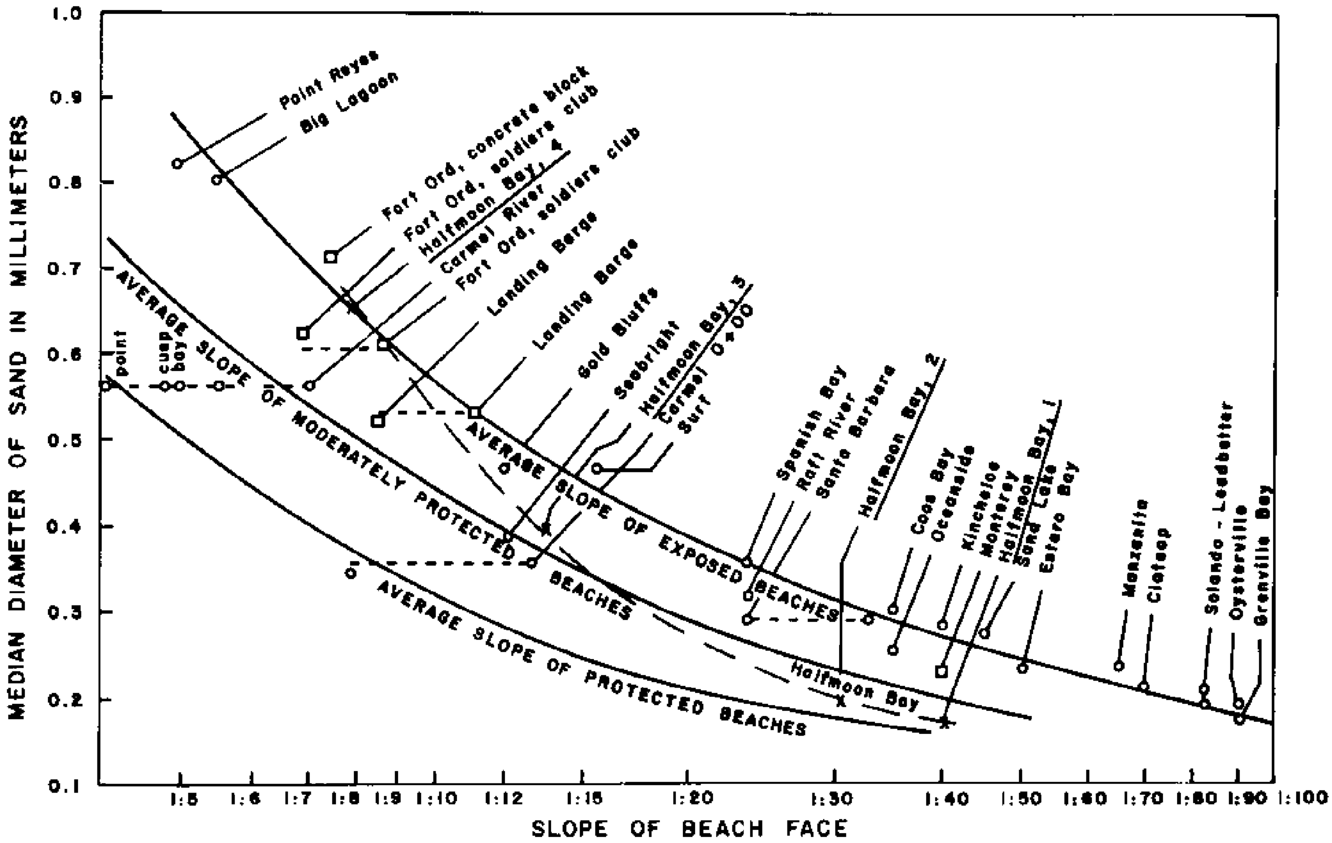
Figure 9.8. Realignment of shoreline due to increase in wave height, 1 < 2

Beach Slopes in Relation to Sand Diameter and Wave Characteristics

It has been known for many years that the slope of a beach varies, depending on the characteristics of the sediments of which the beach is built and on the degree of wave exposure.

As far as the characteristics of the sediment are concerned, various factors play a part, but the most significant one is the grain size of the beach material.

Figure 9.9, after Bruun (1976), shows the relationship between beach slope and median diameter of sand for Pacific coast beaches. The average slope data are grouped into three categories: protected beaches, moderately protected beaches, and exposed beaches.



After Bruun, 1976 (Original source: Bascom, 1951a)

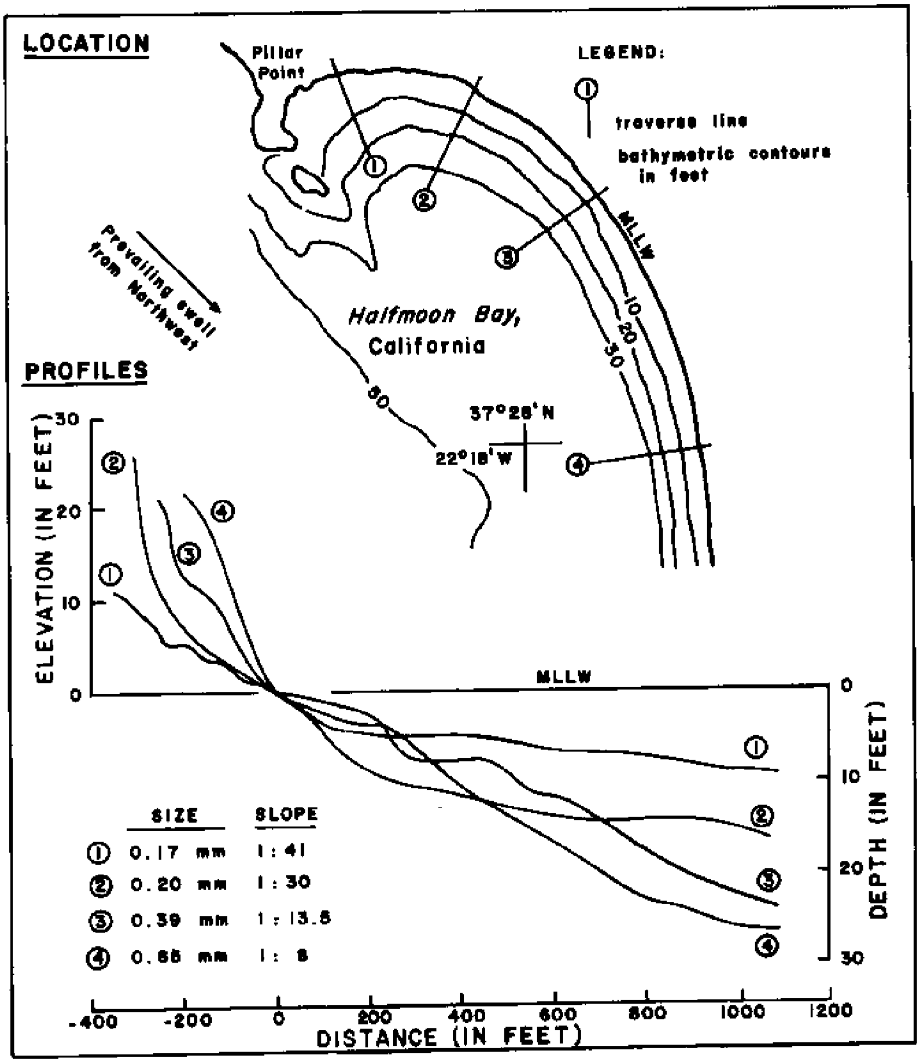
Figure 9.9. Relationship between beach slope and sand size at mid-tide level for Pacific coast beaches

If the conditions at a beach change from unexposed to exposed, an adjustment of its profile takes place. In Chapter 8 reference was made to measurements by Sonu (1969) at Nags Head, North Carolina (Figure 8.1) which indicated that the underwater profile adjusts itself quite rapidly to changing wave conditions.

In addition to beach slope, the beach profile is often characterized by a ridge or a bar. The ridge profile is usually associated with low steepness waves (swells), whereas an offshore bar is usually indicative of waves of higher steepness (storm waves).

The varying degree of wave exposure to a headland beach is schematically shown in Figure 9.3. Close to the headland the distance between orthogonals in the refraction diagram is greater than at a location away from the headland, indicating that waves increase in height in a direction away from the headland.

This tendency is confirmed by measurements of beach profiles at Halfmoon Bay, California (Figure 9.10).



After US Army Coastal Engineering Research Center (Original source: Bascom, 1951b)

Figure 9.10. Profiles and sand diameters for Halfmoon Bay, California measured on April 28, 1947

The four profiles show increasing beach steepness from 1 to 4 and, at the same time, an increase in sand grain diameter in the same direction. The data for these four profiles are plotted in Figure 9.9, which shows that the conditions at the four elevations vary from protected to exposed beaches. The steeper slope corresponds with the larger grain size and the more exposed wave condition.

Slopes of beaches in Hawaii

In order to compare the slopes of beaches in Hawaii with those of Pacific coast beaches, measured beach slopes were plotted against the mean diameter of sand, as shown in Figure 9.11. The majority of the plottings for Hawaiian beaches fall within the two lines that give the average beach slope for protected and exposed beaches for Pacific coast beaches; these lines are also shown in Figure 9.11.

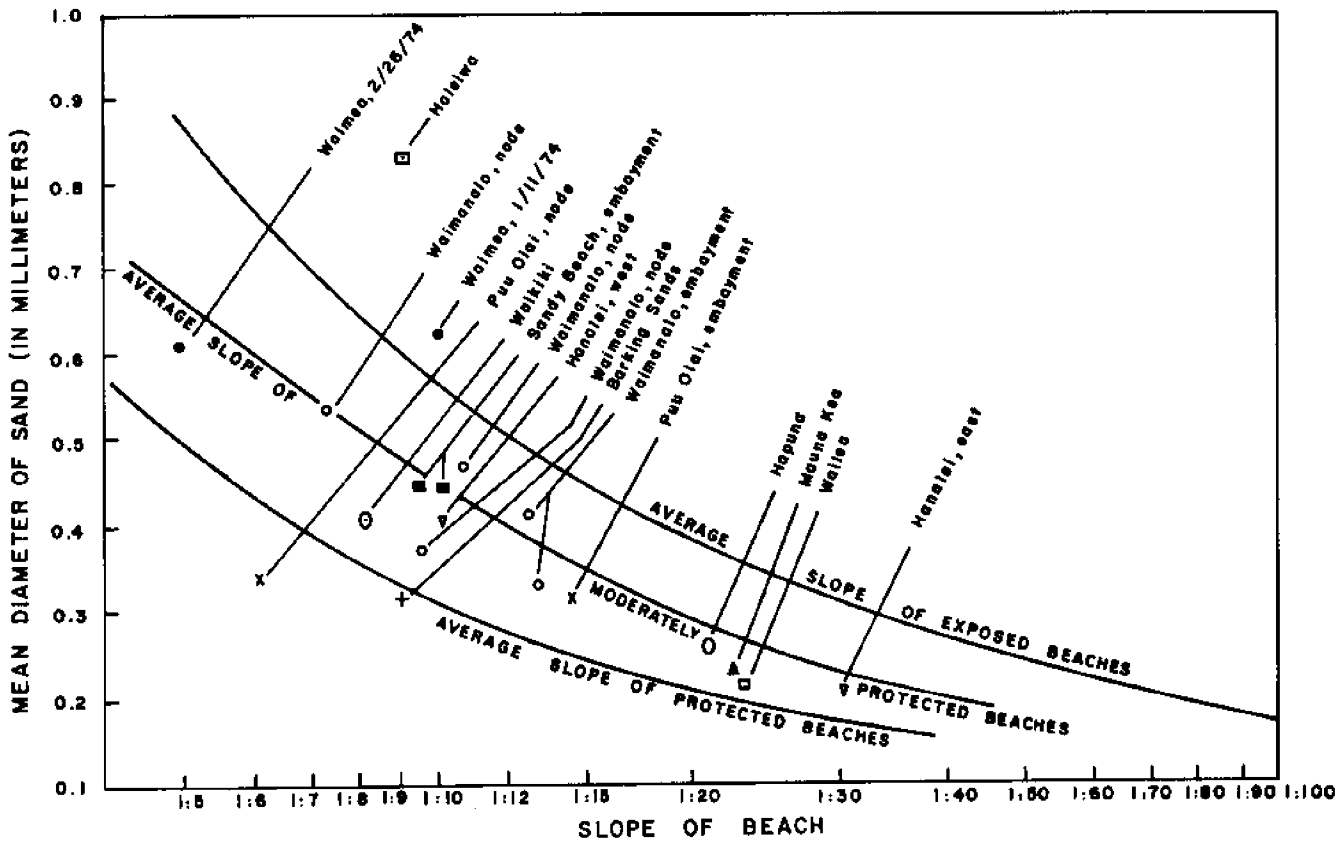


Figure 9.11. Relationship between beach slope and sand size at mid-tide for Hawaiian beaches

The following observations may be made:

- The data shown for Waikiki Beach were computed as an average value for traverses 2 through 8. Their value is close to corresponding values for protected beaches.

- The mean diameter of sand at Haleiwa Beach was considerably larger than would be expected from the general trend in the diagram. Possibly the coarse material underlying the beach, which is occasionally exposed, has been mixed up with the beach sediment.

- The two values for Waimea Bay Beach were taken immediately after a storm (January 11, 1974) and one month later (February 26, 1974). The first observations correspond to values for exposed location; the ones taken one month later to average conditions.

It may be concluded that the slope characteristics of a number of selected beaches in Hawaii correspond with the general characteristics of Pacific coast beaches.

Most beaches considered in this study are exposed to low steepness waves, most of the time. Often a low ridge is present at the water line but is not dominant and therefore escapes observation in the beach profiles considered.

In certain locations (Makaha, Waimea) it was found that the sudden attack of the beach by high swell conditions had a great impact on the beach, whereby recessions of 100 ft and more were experienced in one or two days.

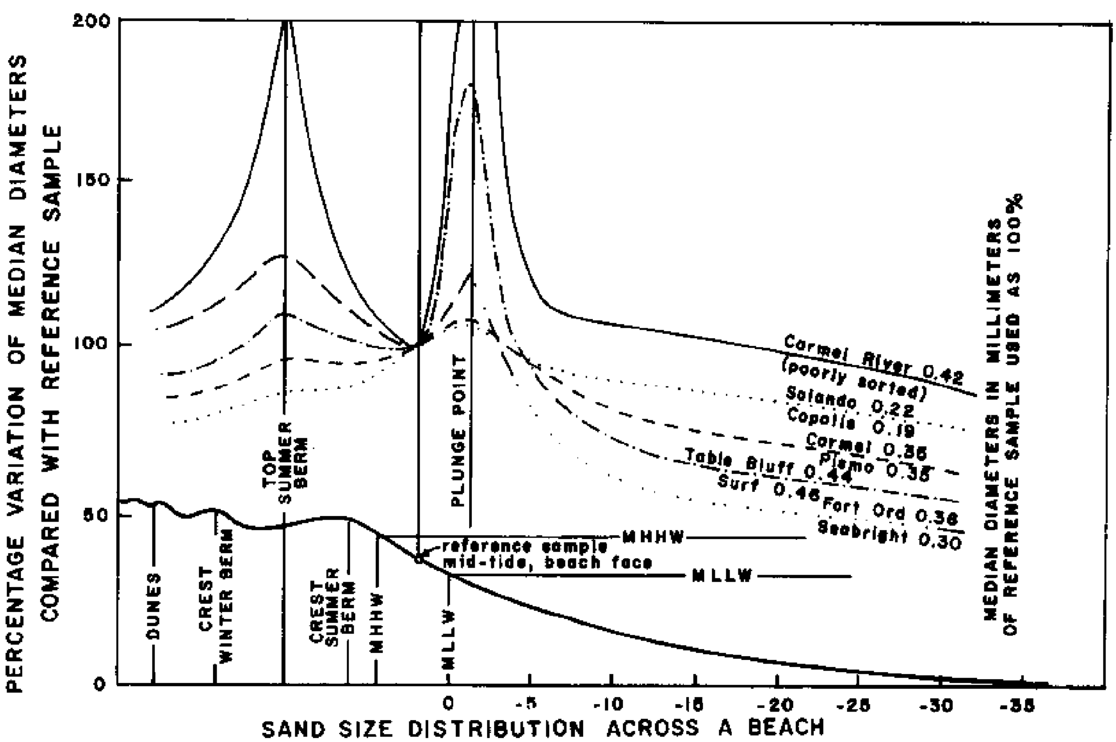
In the case of headland beaches the degree of wave exposure varies along the beach and, consequently, the slope of the beach and the size of the grain vary accordingly. Reference is made to the conditions described for Hanalei Bay on the island of Kauai in Chapter 7.

Variation of sediment characteristics perpendicular to shoreline

In addition to the variation in beach slope and grain size in the longshore direction, sediment characteristics also vary in a direction perpendicular to the beach. Figure 9.12 shows measurements by Bascom for a gradually sloping beach.

In the beaches of the Hawaiian Islands, sorting of beach sand in an onshore-offshore direction was also observed. However, no systematic studies were made of this particular behavior.

At Waikiki Beach, it was found that variations between the size of sediment on the beach and in offshore locations were not very significant.



After Bascom, 1951 a (Original source: Ippen, 1966)

Figure 9.12. Grain size distribution across a beach

Beaches in Hawaii often have reefs in front of them which give protection from heavy wave action and, if the conditions are right, provide the nourishment for the beach system. The situation is therefore different from conditions at mainland beaches and care should be exercised not to indescriminantly apply mainland criteria to the Hawaiian environment.

CHAPTER 10. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A number of beaches in Hawaii were selected for study with a varying degree of effort. Most attention has been given to three primary beaches on the island of Oahu: Waikiki Beach, Waimanalo Beach, and Haleiwa Beach.

In addition, general features of a limited number of beaches on the other islands in Hawaii have been investigated. Particular attention was given to beaches protected by headlands or offshore rock formations and those showing distinct beach cusp formations.

The study was done primarily by conducting a program of field observations. To put the observed phenomena into a general frame of reference, chapters dealing with the mathematical analysis of shoreline behavior, the expected behavior of headland beaches, and the slope characteristics of Pacific coast beaches were included.

It is believed that the program of field measurements carried out for this study has contributed to a better understanding of the physical processes and dynamic behavior of beaches in Hawaii. Specifically the following conclusions and recommendations are made:

Waikiki Beach

Field measurements showed the following characteristics of Waikiki Beach:

1. The predominant direction of the littoral drift is from southeast to northwest.
2. There is little natural supply of material to the beach; hence, sand must be brought in by artificial nourishment. The beach is slowly eroding.
3. Loss of sand from the beach takes place predominantly by means of a series of well-developed rip currents during high surf conditions. The major rip is situated off the Royal Hawaiian Hotel and carries a significant amount of sand from the beach seaward.

There are several means of beach stabilization:

1. Replenishment of the beach may be achieved by trucking in sand of suitable characteristics, as done in the past.
2. Replenishment of the beach may also be done from offshore sand deposits. A special sand pumping device similar to Casciano's (1973) sand pump could be developed for this purpose. The study showed that, in various locations, the characteristics of the offshore sand deposits are similar to the beach material, so that the offshore deposits may be used as nourishment material.

3. Reduction of sand losses from the beach may be accomplished by compartmentalization of the beach by means of structures. A possible plan for such compartmentalization using groins, T-groins, and angular groins is presented in Figure 5.33. This plan needs further study, however.

4. Improvement of the southern part of the beach, off Kapiolani Park, is feasible with or without maintaining the existing war memorial, the "Natatorium." In case the decision would be made to conserve this structure, special measures to reduce wave reflection from both the north and south sides of this structure should be considered.

5. Further studies on the compartmentalization of the beach, as suggested above, should include a hydraulic model study with an appropriate scale.

Haleiwa Beach

The beach at Haleiwa is eroding at an approximate rate of 9.5 to 12.5 ft per year. The beach is exposed to high waves from winter storms in the North Pacific.

The nature of the waves and wave-induced currents at Haleiwa Beach suggests that a compartmentalization of the beach, together with artificial nourishment of adequate sand to cover the cobble underlayer, would improve beach stability. A possible plan for further study is presented in Figure 5.59.

This plan consists of:

1. Connecting the existing breakwater with the shoreline to transform it into T-groin "A"

2. Constructing T-groin "B"

3. Transforming the groin at the south end of the beach into an angular groin by constructing a section parallel to the shoreline "C"

4. Extending the headland to the north of the section with groin "D"

5. Enlarging the beach with sand of proper grain distribution and quality

Because of the occurrence of rip currents, material will continue to be transported from the beach, although at a reduced rate. Artificial nourishment will occasionally be required.

Waimanalo Beach

The beach at Waimanalo is stable and needs no measures for improvement. Through measurements of beach profiles and beach cusps, together with sediment analysis, insight was gained into the dynamic aspects of beach behavior. It was learned that short-length beach cusps are stable and do not tend to migrate. On the other hand, a standing wave behavior may be characteristic for beach waves of greater length.

Waimea Beach on Oahu's north shore and Makaha Beach on its west shore show large profile fluctuations as a result of changing wave conditions. Strong movements of sediment take place in offshore-onshore directions during changes in wave conditions. The changes develop rapidly with time.

As to the beaches on the other islands which were evaluated in terms of their special characteristics, such as cusp formation, headland effects, and the protective nature of offshore formations, it is suggested that some of the natural formations may serve as models for designing coastal protection structures to stabilize beaches.

Chapters 8 and 9, which present considerations about theoretical aspects of dynamic beach behavior and about the nature of headland beaches, serve to improve understanding of the reported behavior of the beaches studied in this program.

New insight has been gained, but many problems remain to be solved. A continuation of this study is therefore recommended.

CHAPTER 11. ACKNOWLEDGMENTS

During the three-year effort, various individuals were involved in the project. In the first and second years, Mr. Upendra Nayak, who was a doctoral candidate in the Department of Ocean Engineering at the time, was responsible for the field work and for organizing the data. Graduate assistants working with him were Messrs. Jerry Crane, Raymond McGrail, Terry Hammerwold, and Marc Stearns.

In the second year, a joint approach was established with the Department of Oceanography, which was working under a contract with the US Army Corps of Engineers to make an evaluation of the physical environment off Waikiki Beach. Particular cooperation was established with Dr. Robert Tait and Mr. Francis Gremse on collecting current data.

Much of the physical data, particularly on currents off Waikiki Beach, collected during that period of cooperation is included in a Hawaii Institute of Geophysics report by Chave and Tait (1973).

During the last year of the study, Mr. Nayak resigned from the project and his position was taken over by Mr. James Walker. Besides doing the experimental work in the laboratory, Mr. Walker supervised the field work. Mr. Hammerwold and Mr. Stearns continued to work on the project through May 1974.

During the summers of 1973 and 1974, graduate assistants on the project were Messrs. Mark Hertel, Joseph Castiel, and Herbert Thatcher. Messers. Hertel and Castiel assisted in the preparation of the final report and Mr. Thatcher worked on the instrumentation. In addition, Mr. Hertel developed a computer program for the spectral analysis of wave data collected at Waikiki under the guidance of Dr. Harold Loomis of NOAA.

Appreciation is given to the University of Hawaii Sea Grant College Program for funding this study. The Hawaii State Legislature and the University of Hawaii supported this project through matching funds.

The author wishes to express his sincere appreciation to Dr. J.A. Battjes, visiting professor at the University of Hawaii, for critically reviewing the manuscript and making suggestions for improvement.

Finally the author's appreciation goes to Mrs. Mildred Frank for secretarial assistance during the course of the project and to the staff of the University of Hawaii Sea Grant College Program publications office for editorial, graphics, and production work.

In particular, thanks go to Mark Hertel for replotting original data, to Wendy Nakano and Donna Shinmura for replotting data and the preparation of final illustrations and graphics, and to Karen Tanoue for conscientious editing of original and improved manuscripts.

Mahalo to all who have made a contribution to this study.

REFERENCES CITED

Bascom, W.N. 1951a. "The relationship between sand size and beach face slope." *Trans. American Geophysical Union* 32(6):866-876.

Bascom, W.N. 1951b. "Shoreline and beach characteristics." *Manual of Amphibrous Oceanography*. Office of Naval Research, Washington, D.C.

Battjes, J.A. 1974. "Computation of set-up longshore currents, run-up and overtopping due to wind generated waves." Report 74-2. Department of Civil Engineering, Delft University of Technology. (Dissertation)

Belt, Collins and Associates. 1962. *Waialua Bay pollution study*. Report prepared for Harbors Division, Department of Transportation, State of Hawaii.

Bottoms, J.D. 1970. *Giant waves hit Hawaii*. Technical Memorandum WBTM PR-8. Department of Commerce, Environmental Science Services Administration (ESSA).

Bowen, A.J., and D.L. Inman. 1969. "Rip currents: laboratory and field observations." *Journal of Geophysical Research* 74(23).

Bowen, A.J., and D.L. Inman. 1971. "Edge waves and crescentic bars." *Journal of Geophysical Research* 76(20).

Bruun, P. 1954. *Coast Stability*. (Dissertation) Copenhagen: Danish Technical Press.

Bruun, P. 1976. *Port Engineering*. 2nd Edition. Houston: Gulf Publishing Company.

Campbell, J.H. 1972. *Erosion and accretion of selected Hawaiian beaches: 1962-1972*. UNIHI-SEAGRANT-TR-72-02, Sea Grant College Program, University of Hawaii, Honolulu. Also HIG-72-20, Hawaii Institute of Geophysics, University of Hawaii, Honolulu.

Casciano, F.M. 1973. *Development of a submarine sand recovery system for Hawaii*. UNIHI-SEAGRANT-AR-73-04. Sea Grant College Program, University of Hawaii, Honolulu.

Chave, K.E., and R.J. Tait. 1973. *Waikiki Beach erosion project: marine environment study*. HIG-73-12. Hawaii Institute of Geophysics, University of Hawaii, Honolulu.

Coulbourn, W.T. 1971. *Sedimentology of Kahana Bay, Oahu, Hawaii*. UNIHI-SEAGRANT-TR-71-03, Sea Grant College Program, University of Hawaii, Honolulu. Also HIG-71-14, Hawaii Institute of Geophysics, University of Hawaii, Honolulu.

Cox, D.C., F. Gerritsen, and T.T. Lee. 1976. "Proposed improvement of Kaimu Beach, Hawaii." In *Proceedings 15th Conference on Coastal Engineering, Honolulu, Hawaii*. Chapter 91, pp. 1552-1571.

Crane, J.K. 1972. "History of the marine structures on Waikiki Beach and their effects upon the beach." Plan B-paper. Department of Ocean Engineering, University of Hawaii, Honolulu.

Dorrestein, R. 1961. "Wave set-up on a beach." In *Proceedings Second Techn. Conference on Hurricanes, June 1961, Miami Beach.* pp. 230-241. Washington, D.C.

Fallon, A.R., F. Gerritsen, R.Q. Palmer, and S.P. Sullivan. 1971. *Model investigation of improvements to Kewalo Basin, Honolulu, Hawaii.* Technical Report No. 17. Look Laboratory of Oceanographic Engineering, Department of Ocean Engineering, University of Hawaii, Honolulu.

Gerritsen, F. 1972. "Hawaiian beaches." In *Proceedings of the 13th Coastal Engineering Conference, July 10-14, 1972, Vancouver, Canada.* pp. 1257-1276.

Grym, W. 1960. "Theoretical forms of shorelines." In *Proceedings of the 7th Conference on Coastal Engineering, Holland.* pp. 197-202.

Guza, R.T., and R.E. Davis. 1974. "Excitation of edge waves by waves incident on a beach." *Journal of Geophysical Research* 79(9):1285-1291.

Hammerwold, T. 1974. "Beach cusps." Plan-B paper. Department of Ocean Engineering, University of Hawaii, Honolulu.

Ho, F.P., and L.A. Sherretz. 1969. *A preliminary study of ocean waves in the Hawaiian area.* SEAGRANT 69-2, Sea Grant Program, University of Hawaii, Honolulu. Also HIG-69-16, Hawaii Institute of Geophysics, University of Hawaii, Honolulu.

Homer, P.S. 1964. *Characteristics of deep water waves in Oahu area for a typical year.* Prepared for the Board of Harbor Commissioners, State of Hawaii. Contract No. 5772. Marine Advisors, La Jolla, California.

Inman, D.L. 1952. "Measures for describing the size distribution of sediments." *Journal of Sedimentary Petrology* 22(3).

Inman, D.L., W.R. Gayman, and D.C. Cox. 1963. "Littoral sedimentary processes on Kauai, a subtropical high island." *Pacific Science* 17(1).

Ippen, A., ed. 1966. *Estuary and Coastline Hydrodynamics.* New York: McGraw Hill Book Company.

Johannes, R.E. 1971. "Coral reefs and pollution." Paper presented at the Regional Symposium on Conservation of Nature -- Reefs and Lagoons. South Pacific Commission.

Johnson, D.W. 1919. *Shore Processes and Shoreline Development.* New York: Hafner Publishing Company.

Kelly, J. 1973. *Surf parameters, Final report, part II, "Social and historical dimensions."* Technical Report No. 33. Look Laboratory of Oceanographic Engineering, Department of Ocean Engineering, University of Hawaii, Honolulu.

Kern, D.E. 1970. "A study of sand movement in the Halekulani Sand Channel off Waikiki, Hawaii." Plan B-paper. Department of Ocean Engineering, University of Hawaii, Honolulu.

Komar, P.D. 1972. *Nearshore currents and the equilibrium cuspate shoreline.* Technical Report No. 239. Department of Oceanography, Oregon State University, Corvallis.

Laevastu, T., D.E. Avery, and D.C. Cox. 1964. *Coastal currents and sewage disposal in the Hawaiian Islands.* HIG-64-1. Hawaii Institute of Geophysics, University of Hawaii, Honolulu.

Lee, T.T., M.A. Sklärz, J.C. Crittendon, R.Y. Rocheleau, and D.Y.Y. Wong. 1973. *Wave action in Haleiwa Harbor, Hawaii.* Technical Report No. 32. Look Laboratory of Oceanographic Engineering, Department of Ocean Engineering, University of Hawaii, Honolulu.

Longuet-Higgins, M.S., and P.W. Parkin. 1962. "Sea waves and beach cusps." *Geographical Journal* 128.

Longuet-Higgins, M.S., and R.W. Stewart. 1964. "Radiationstress in water waves, a physical discussion, with applications." *Deep-Sea Res., II*, pp. 529-562.

Lundgren, H. 1963. "Wave thrust and wave energy level." In *Proc. I.A.H.R. Congress, London,* pp. 147-157.

Moberly, R., Jr., and T. Chamberlain. 1964. *Hawaiian beach systems.* Prepared for the Harbors Division, Department of Transportation, State of Hawaii. HIG-64-2. Hawaii Institute of Geophysics, University of Hawaii, Honolulu.

National Ocean Survey. 1976. *Tide Tables West Coast of North and South Americas, Including the Hawaiian Islands.* Washington, D.C.

Nayak, U. 1975. "On the functional design and effectiveness of groins in coastal protection." Ph.D. Dissertation, Department of Ocean Engineering, University of Hawaii, Honolulu.

Noda, E.K. 1972. "Rip currents." In *Proceedings of the 13th International Conference on Coastal Engineering, Vancouver.* pp. 653-668.

Pararas-Carayannis, G. 1969. *Catalog of tsunamis in the Hawaiian Islands.* WDCA-T 69-2. World Data Center A. US Department of Commerce, ESSA.

St Denis, M. 1974. *Hawaii's floating city development program: the winds, currents and waves at the site of the floating city off Waikiki.* UNIHI-SEAGRANT-CR-75-01, Sea Grant College Program, University of Hawaii, Honolulu. Also Technical Report No. 1, Oceanic Institute, Waimanalo.

Shepard, F.P. 1963. *Submarine Geology*. 2nd Edition. New York: Harper & Row. pp. 106-107.

Shepard, F.P., and D.L. Inman. 1950. "Nearshore circulation." In *Proceedings of the 1st Conference on Coastal Engineering*.

Sonu, C.J. 1969. "Collective movement of sediment in the littoral environment." In *Proceedings of the 11th Conference on Coastal Engineering* 1:373-700.

US Army Coastal Engineering Research Center. 1973. *Shore Protection Manual*. Washington, D.C.

US Army Corps of Engineers, Honolulu District. 1963. *Waikiki Beach, Island of Oahu, Hawaii - Cooperative Beach Erosion Control Study*.

US Army Corps of Engineers, Honolulu District. 1965. *Hawaii Beach Erosion Control Study, Waikiki Beach, Oahu*. House Document No. 104. 89th Congress, 1st Session. US Government Printing Office, Washington, D.C.

US Army Corps of Engineers, Honolulu District. 1970. *Storms of December 1-2 and 4, 1969, Hawaiian Islands*. Circular C57. Post flood report.

van Bendegom, L. 1949. "Fundamentals of coastal protection." (Dutch text) Rÿkswaterstaat, Hoorn, The Netherlands.

Walker, J.R. 1974a. *Recreational surf parameters*. Part I. Technical Report No. 30. Look Laboratory of Oceanographic Engineering, Department of Oceanography, University of Hawaii, Honolulu.

Walker, J.R. 1974b. "Wave transformations over a sloping bottom and over a three-dimensional shoal." Ph.D. Dissertation, Department of Ocean Engineering, University of Hawaii, Honolulu.

Wyrtki, K., V. Graefe, and W. Patzert. 1969. *Current observations in the Hawaiian Archipelago*. HIG-69-15. Hawaii Institute of Geophysics, University of Hawaii, Honolulu.