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California Coastal Erosion and Storm Damage During the Winter of 1982-83

A Reconnaissance Report

Committee on Natural Disasters
Commission on Engineering and Technical Systems
National Research Council

California Coastal Erosion and Storm Damage During the Winter of 1982-83

A Reconnaissance Report Prepared by:

Robert G. Dean (Team Leader), Professor of Coastal and Oceanographic Engineering, University of Florida, Gainesville

George A. Armstrong, Department of Boating and Waterways, State of California, Sacramento

Nicholas Sitar, Assistant Professor of Civil Engineering, University of California, Berkeley

For:

Committee on Natural Disasters
Commission on Engineering and Technical Systems
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INTRODUCTION

The 1982-83 winter season in California was marked by an unusual number of severe storms. By some authoritative accounts, the waves generated by these storms were the most severe of the century. The resulting erosion and structural damage along the California coast were estimated to constitute a loss of several hundred million dollars.

One particularly damaging storm occurred from February 27 to March 2, 1983. Following this storm, the Committee on Natural Disasters, a standing committee of the National Research Council, decided to deploy a study team on a brief reconnaissance of the California coast. The team's purpose was to observe the effects of the storm and to gather perishable data related to the characteristics of the storm and its effects on structures and the natural system.

The reconnaissance began near the Mexico-California border on March 9, 1983, and ended at Stinson Beach on March 13, 1983, covering a distance of approximately 600 miles (see Figure 1). The time available to the team members was limited to these five days. The team's main effort was focused on visiting, observing, and photographing as many areas along the coast as possible. The weather during most of the trip was cloudy and rainy, eliminating the possibility of extensive aerial surveys. On March 12 the weather became favorable for aerial reconnaissance, and a flight originating at Santa Barbara covered an area from Rincon Point on the south to Morro Bay on the north.

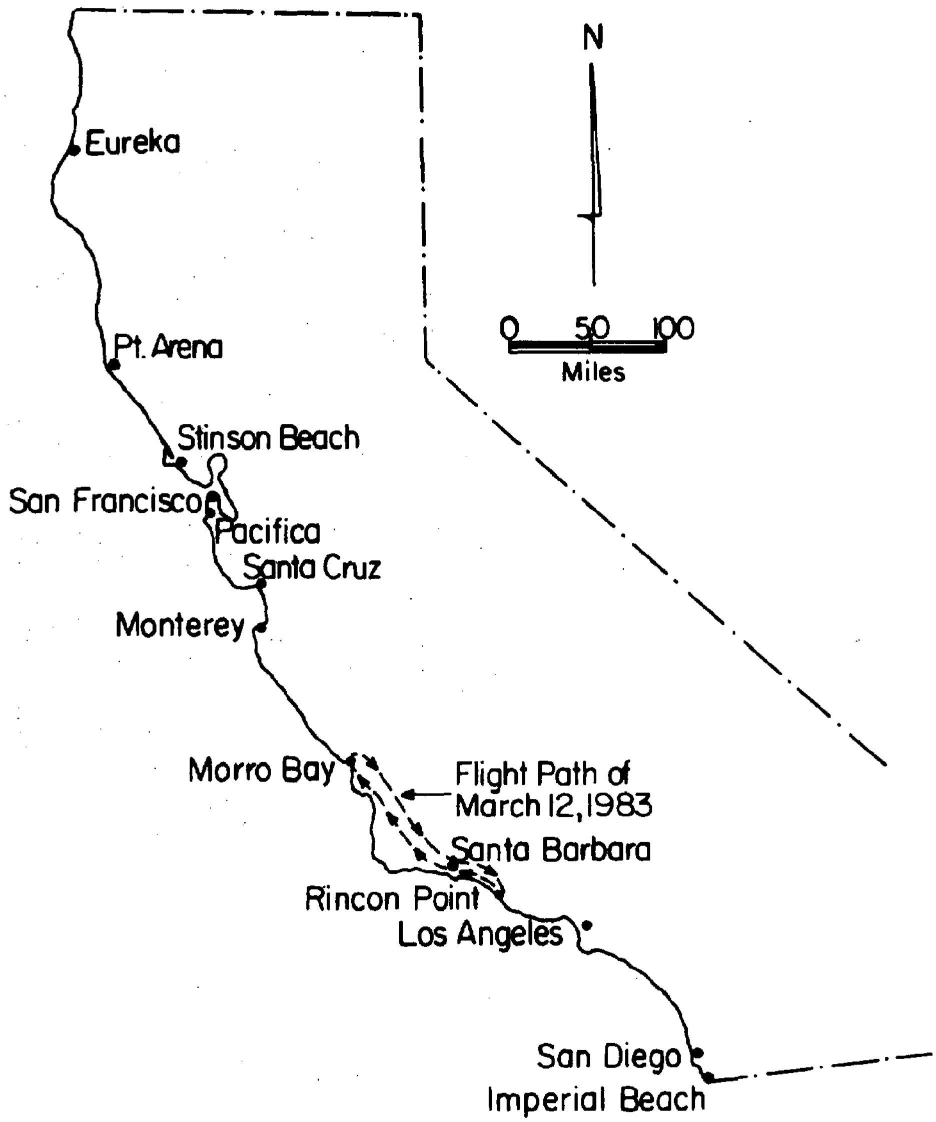

FIGURE 1 The California coast. The reconnaissance visit extended from Imperial Beach to Stinson Beach.

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METEOROLOGICAL AND OCEANOGRAPHIC EVENTS DURING THE WINTER OF 1982-83

STORMS

The winter storms that affect California typically originate over the Pacific Ocean between Hawaii and the Gulf of Alaska. The storms generally move in a northeasterly or easterly direction under the control of a high-altitude jet stream. During most of the year a high-pressure cell exists off the coast of northern California, keeping the jet stream and the storms well north of the California-Oregon border. In winter this high-pressure cell weakens and moves southward, allowing the jet stream to follow a more southerly route that brings the storms into central and southern California. Figure 2 shows the winter storm tracks across the Pacific recorded in January 1983. The most severe storm and wave conditions along the California coast usually are caused by storm fronts arriving from the southwest.

The late fall of 1982 and the winter of 1983 were periods of extreme storminess along the Pacific Coast. A number of storms hit the coast of California, bringing record amounts of precipitation, high winds, and large waves. The first two major storms that caused large waves occurred on November 30-December 1, 1982, and December 14-16, 1982. Winds reached 60 mph along most of the California coast on November 30, and significant amounts of rain fell throughout the state (Table 1). However, the intensity of the storm was greatest in the northern parts of the state. The December storm was possibly even more intense, with 80-mph winds recorded along the coast of Oregon, but it was centered sufficiently far north to affect only the northern part of the state, as can be seen from the precipitation data in Table 1. Although these two storms caused some damage to coastal installations, their main effect was apparently to initiate beach erosion that left the beaches more vulnerable to the storms of January, February, and March.

The stormiest period occurred during January, February, and March 1983, with successive storms bringing high winds, high waves, and record-breaking amounts of precipitation. The worst periods occurred at the end of January and again at the end of February. The Mariners Weather Log for the summer of 1983 (National Oceanic and Atmospheric Administration, 1983b) reported six storms striking the west coast of the United States from January 22 to 29, of which the fifth storm, on January 26-27, inflicted the heaviest damage. A weather satellite

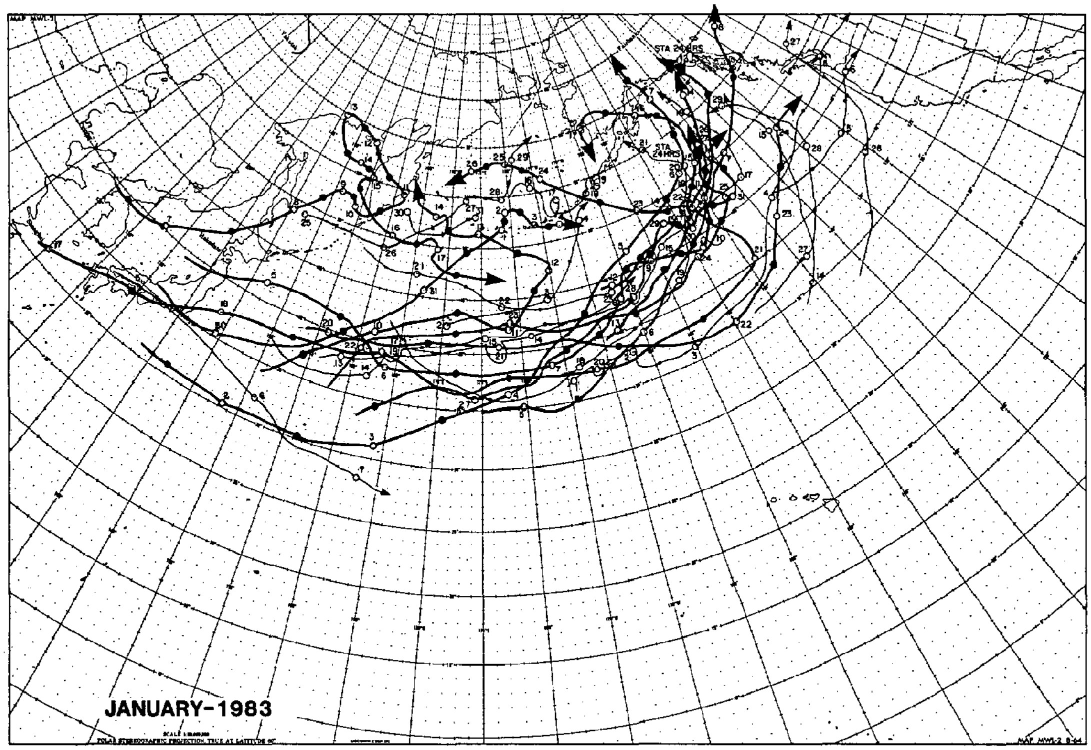


FIGURE 2 Principal tracks of the centers of cyclones at sea level over the North Pacific during January 1983. Closed circles indicate positions at midnight Greenwich mean time and open circles indicate positions at noon Greenwich mean time. Squares indicate stationary centers. Cyclone tracks marked with a heavy line are described in the Mariners Weather Log. Note that although most paths were well north of California, the cyclonic (counterclockwise) winds and large scale of these systems caused substantial waves in northern California. Source: National Oceanic and Atmospheric Administration, 1983b.

photograph taken on January 28, 1983, graphically shows the succession of storms (Figure 3). The winds associated with the storms reached 70 mph along parts of the coast, and a 96-mph gust was recorded at Pillar Point south of San Francisco. In addition, copious amounts of rain fell along the entire coast (Table 1).

The stormy period at the end of February and beginning of March also consisted of a series of fronts moving across the coastline. A weather satellite photograph taken on February 28, 1983, illustrates the magnitude of this weather system (Figure 4). Winds in excess of 50 mph were recorded along the coast, and the situation was again aggravated by large amounts of rainfall (Table 1). The rainfall caused large-scale flooding, especially in the southern parts of the state.

TABLE 1 Precipitation from Major Storms During Fall 1982 and Winter 1983 (in inches)

Station	Fall 1982						Winter 1983						
	Nov. 29	Nov. 30	Dec. 01	Dec. 14	Dec. 15	Dec. 16	Jan. 26	Jan. 27	Jan. 28	Jan. 29	Feb. 28	Mar. 01	Mar. 02
Eureka	.53	1.41	.28	.35	1.16	2.84	2.44	.47	.03	.57	.43	.03	.05
San Francisco	.63	.53	.01	--	--	.16	1.52	.34	.33	.16	.60	.69	.82
Santa Cruz	1.43	1.36	.42	--	--	--	trace	1.29	.10	1.01	.47	2.04	1.39
Los Angeles	.41	.81	--	--	--	--	--	1.95	1.16	.23	.18	3.42	1.26
Long Beach	.21	1.07	--	--	--	--	--	1.08	.60	.05	.06	3.46	1.17
Ocean Tide	.3	.5	--	--	--	--	--	.86	.02	.88	.27	.79	.55
San Diego	.26	.33	--	--	--	--	--	.67	.32	.52	.17	1.03	1.49

Source: National Oceanic and Atmospheric Administration, 1982, 1983a.

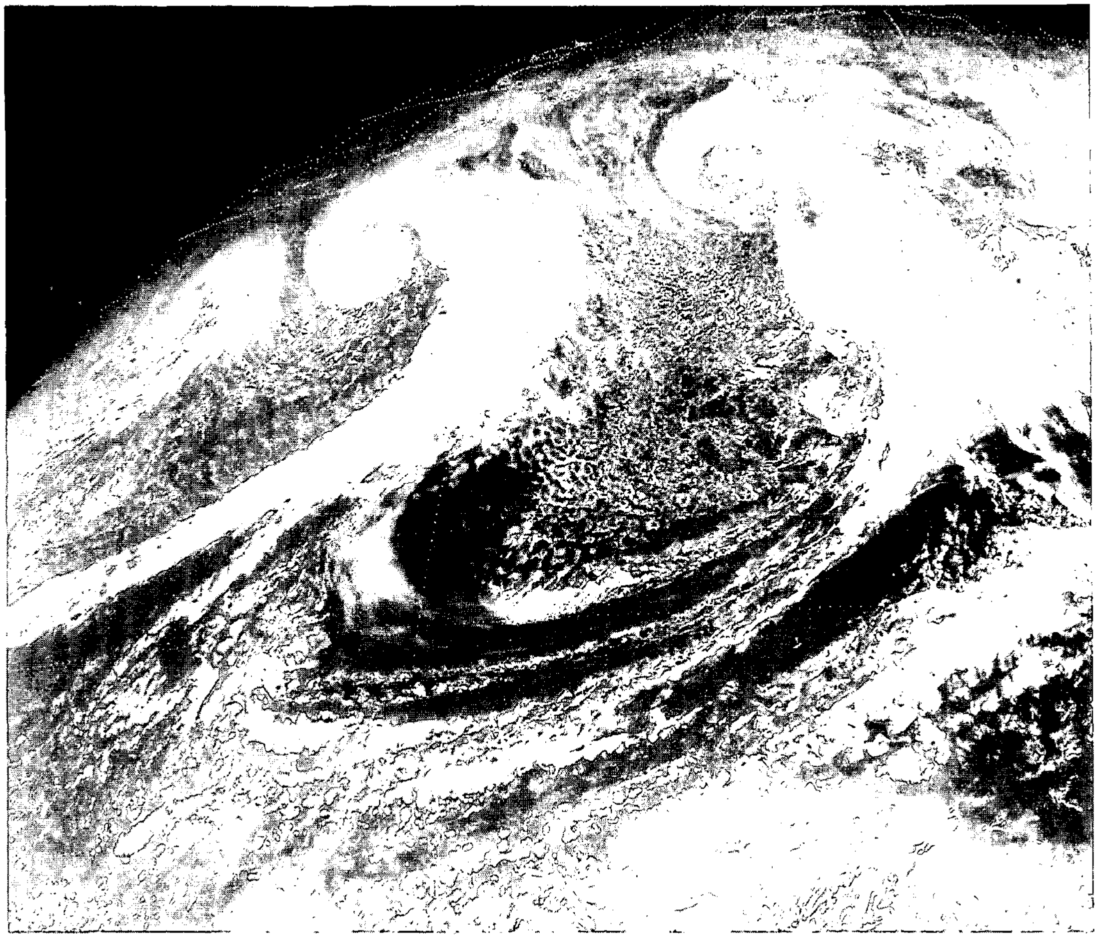


FIGURE 3 Weather satellite photograph of the storm pattern on January 28, 1983.

WAVE ACTIVITY

The wave activity during the winter season was unusually intense. Table 2 summarizes those periods for which the significant wave height at the north Monterey buoy exceeded 4 m. During March 2, 1983, data were obtained from the Farallon Island buoy, as the north Monterey buoy was not operating. Correlations based on periods when both gages were reporting demonstrate good correspondence.

As seen from Table 2, during the period November 1, 1982, to March 31, 1983, a total of eight storms exceeded the criterion for significant wave height of 4 m at the Farallon Island or north Monterey buoys. The two dominant events were the November 30-December 2, 1982, and the February 27-March 2, 1983, storms, which generated maximum reported significant wave heights of 7.2 and 6.9 m, respectively.

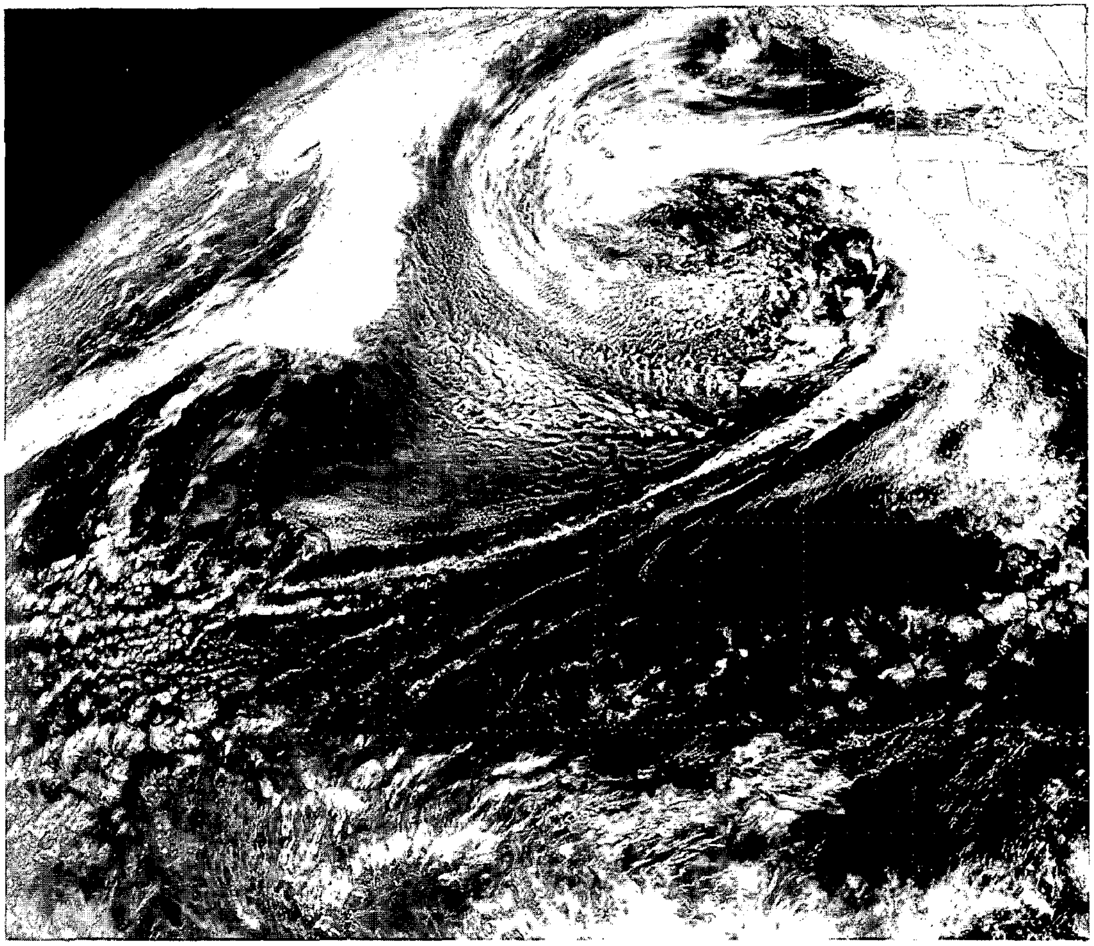


FIGURE 4 Weather satellite photograph of the storm pattern on February 28, 1983.

TIDES

It is well-known that high tides substantially augment the erosive action of large waves. The effects are twofold. First, the high tides allow the waves to act farther landward and upward on the beach profile. By this mechanism, structures can become subject to the direct action of breaking waves. The second effect, which is probably of greater significance to beach erosion, is due to the concave shape of beaches. Water levels that are higher than normal result in beach profiles that are out of equilibrium in a manner that leads to erosion and transport of sediment seaward.

TABLE 2 Wave and Tide Characteristics for Major California Storms of the Winter of 1982-83

Dates	Maximum Significant Wave Height[a] (m)	Wave Period[b] (s)	Tidal Range[c] (m)	Maximum Set-Up (m)
Nov. 30-Dec. 2	7.18	15	2.0	0.4
Dec. 15-19	5.79	13	2.0	0.1
Dec. 22-24	5.11	11	1.2	0.5
Jan. 19-20	4.82	17	1.4	0.2
Feb. 10	5.16	15	1.8	0
Feb. 12-14	5.50	17	1.8	0.2
Feb. 18-21	4.42	13	1.7	0.2
Feb. 27-March 2[d]	6.88	20	2.1	0.5

[a]Wave heights and periods are from the Coastal Data Information Program for the north Monterey buoy. Data are presented for days on which the maximum significant wave heights exceeded 4 m. The significant wave height for a particular time interval is defined as the average of the highest one third of the wave heights during the interval.

[b]Wave periods are the middles of ranges containing the greater percentage of energy.

[c]Tidal ranges and maximum set-ups are from the Point Reyes tide gage.

[d]March 2 data are missing from the north Monterey buoy; missing data were replaced by those from the Farallon Island buoy.

Components of Tides

Before discussing the actual tides that occurred during the 1982-83 winter storms, it should be noted that there are several components of tides. The four most important in the present case are (1) the astronomical component, (2) the wind set-up component, (3) the barometric tide, and (4) the wave set-up component.

Astronomical Tides

The astronomical tide is due to the relative positions of the earth, moon, and sun and the modification of the tide by the particular ocean basin, including the effects of the continental shelf and coastal indentations such as bays. The general characteristics of the astronomical tides along the California coast are well known and are forecast annually by the National Ocean Survey. Briefly, these tides are semidiurnal (with a period of 12.4 h) and have mean and spring ranges of approximately 1.2 m and 1.7 m, respectively. As discussed earlier, if a storm should extend over the maximum of a spring tide, the erosive effect would be much greater than during a neap tide.

Wind Set-Up Component

The wind set-up component is due to the wind stress acting shoreward over the continental shelf. The slope of the water surface is roughly proportional to the square of the wind speed and inversely proportional to the water depth. For an idealized shelf of uniform depth, the wind set-up at the shore is proportional to the shelf width. Due to the relatively narrow continental shelf along the California coast, this component is usually not significant unless wind speeds are extremely high.

Barometric Tide

For slow-moving storms, the static barometric tide, η_B, is related to the atmospheric pressure deficit, Δp_B, by the simple equation

$$\eta_B = 0.34 \Delta p_B,$$

where Δp_B is the atmospheric pressure deficit at the shore in inches of mercury and η_B is the barometric tide in meters. As an example, the maximum pressure deficit along the California coast for the 1982-83 winter storm occurred on March 2, 1984, at Point Reyes and amounted to 0.72 in. of mercury. The resulting increase in water level would be 0.25 m.

Wave Set-Up

Wave set-up is due to the shoreward momentum transport by waves and is apparent as a generally increasing mean water level in the shoreward direction across the surf zone. The wave set-up, which is negative at the breaker line, is approximately

$$\overline{\eta}_B = -H_B/20,$$

where H_B is the height of the breaking wave. Across the surf zone at the undisturbed water depth h, the set-up is approximately

$$\overline{\eta} \cong 0.19(h_B - h) + \overline{\eta}_B.$$

The maximum set-up occurs at the shoreward limit of set-up and is approximately

$$\bar{\eta} = 0.22H_B.$$

The above equations are theoretical. Field measurements have shown that, due to bottom friction and other effects, the actual set-up values are somewhat less than those given by these equations (Dean, 1979). Nevertheless, the wave set-up can be reasonably large. For example, if the height of the breaking wave is 4 m, the maximum set-up could be on the order of 0.9 m.

Measured Tides

To determine the possible role of the tides in California's coastal damage, the recorded tides from La Jolla, Newport Beach, and Point Reyes were obtained and analyzed for the period January 1, 1982, to March 31, 1983. Table 3 gives characteristics of the locations of the tide gages. The tidal analysis was carried out by D. Lee Harris (Coastal and Oceanographic Engineering Department, University of Florida, Gainesville), Jack Fancher (National Ocean Survey, Silver Spring, Maryland) and Jeff Lillycrop (Coastal Engineering Research Center, Vicksburg, Mississippi). The analysis included plotting the measured tides, generating the predicted tidal elevations based on the tidal constituents available from the National Ocean Survey, and determining the storm-related tide by subtracting the predicted from the measured tides.

The results are presented in Figures 5 through 7 for the storm of late February and early March. Each plot includes the measured tidal fluctuations, the tidal set-up, and the significant wave height at the nearest wave gage. This tidal set-up is presumably the combined result of wave and wind set-up and El Nino effects due to warmer water in the North Pacific during the winter of 1982-83. As can be seen, there is a tidal set-up on the order of 0.3 m at the location of the tide gages. Moreover, large tidal ranges did occur at the same time as high waves. The maximum set-up at the Point Reyes tide gage for each of the eight major storms is listed in the last column of Table 2. It should be emphasized that the reported set-up values are those in the vicinity of the tide gage. The actual set-up in the shallow portions of the surf zone would be substantially greater.

COMPARISON OF 1982-83 WAVES WITH THOSE OF PREVIOUS YEARS

Seymour (1983) has analyzed the wave data collected from deepwater buoys maintained as part of the California Wave Data Network. These data are available from 1980 to the present. Due to this relatively short time span, it is not possible to estimate return periods for the 1983 storm waves. Seymour concludes that the storms of January, February, and March 1983 caused waves that were significantly larger than those in the

TABLE 3 Characteristics of the Three Tide Gages Discussed in this Report

Gage Location	National Ocean Survey Identification No.	Characteristics
La Jolla	941-0230	Mounted near end of Scripps Pier. Water depth approximately 6 m.
Newport Beach	941-0580	Mounted on pier inside Newport Bay. Water depth approximately 4 m.
Point Reyes	941-0520	Located on pier on leeward side of Point Reyes (Chimney Rock). Water depth approximately 4 m.

previous three years. The mean significant wave height for the eight major storms of 1983 identified by Seymour (not the same eight as those in Table 2) was 5.5 m. During the same three-month period in 1980-82, there were 15 major storms with a mean wave height of 4.3 m. The mean wave period for the 1983 storms was also substantially longer than for the 15 storms of January, February, and March of 1980-82--19.5 seconds versus 14 seconds.

Dormurat (1978) has reported on a series of Pacific coastal storms that occurred during the 1977-78 winter season. Four major storms occurred from October 1977 to February 1978, causing considerable erosion and structural damage, primarily along the northern and central California coast. To compare conditions during 1977-78 with those of 1976-77 and 1975-76, Dormurat calculated a wave power index (defined as the square of the wave height multiplied by the wave period), as shown in Figure 8. As can be seen, the 1977-78 winter season was considerably more severe than the previous two seasons. Dormurat noted that the resulting beach erosion was due to a combination of "high astronomical tide, strong onshore winds, high storm waves and excessive rainfall." The highest observed tide was 2.5 m at Golden Gate, compared with a predicted high tide of 2.1 m. Table 4 presents the measured wind and hindcast wave data presented by Dormurat. The wave information was obtained from hindcasts conducted by the Fleet Numerical Weather Center at Monterey, California, for a location 60 miles west of Golden Gate. The significant wave height and period do not differ much from those recorded in the 1982-83 winter season. However, it must be remembered that the wave information in Table 4 is based on hindcasts, and therefore it probably cannot be directly compared with wave measurements.

At least one very severe storm also occurred during the winter season of 1979-80. A Sea Grant-sponsored research program termed the Nearshore Sediment Transport Study documented the waves during this storm and the associated shoreline response.

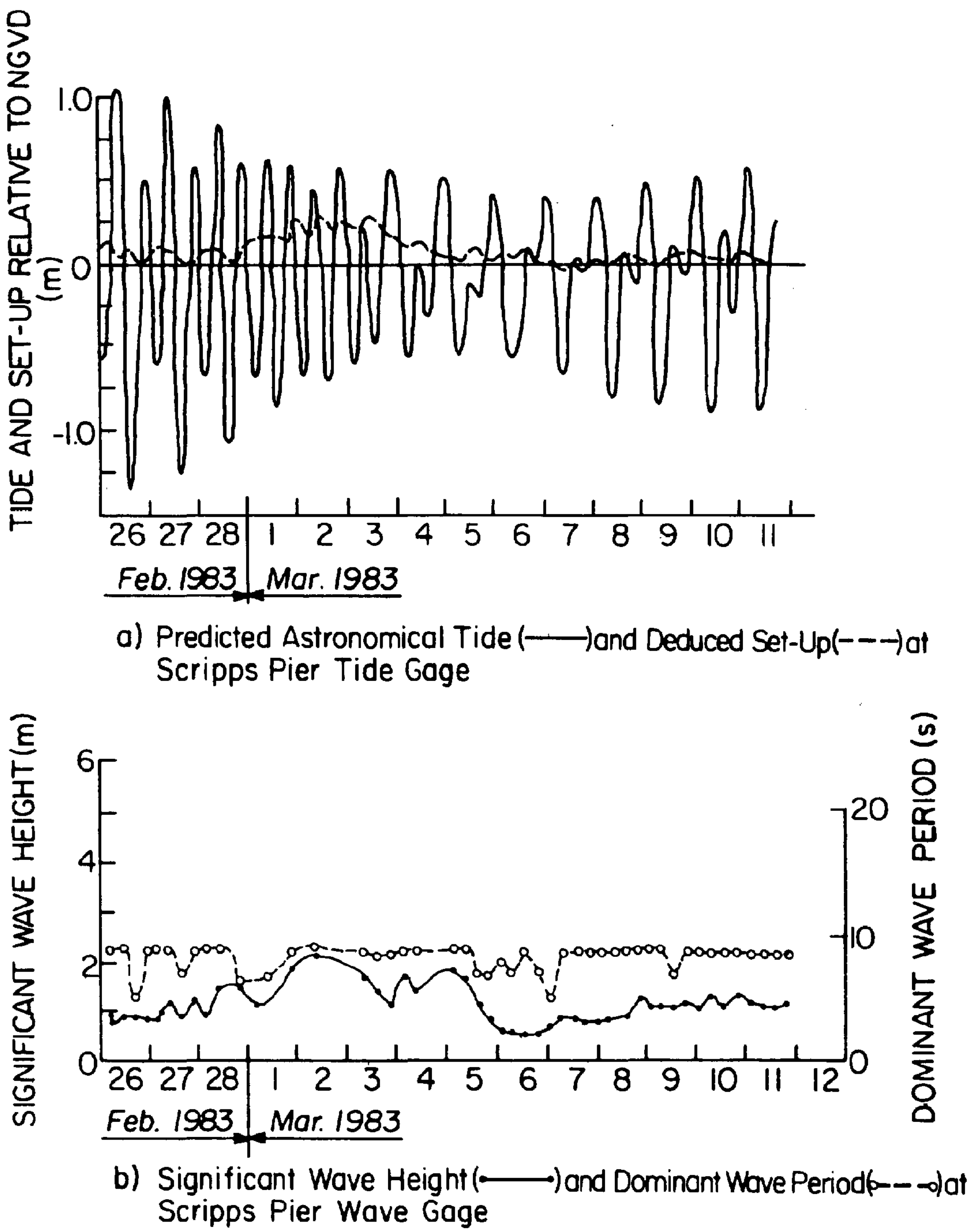
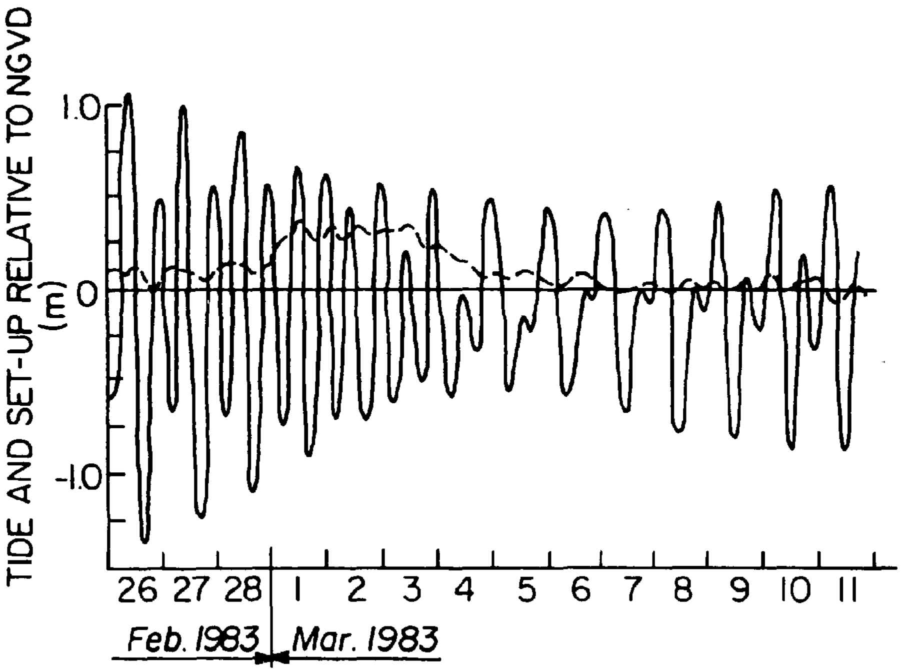
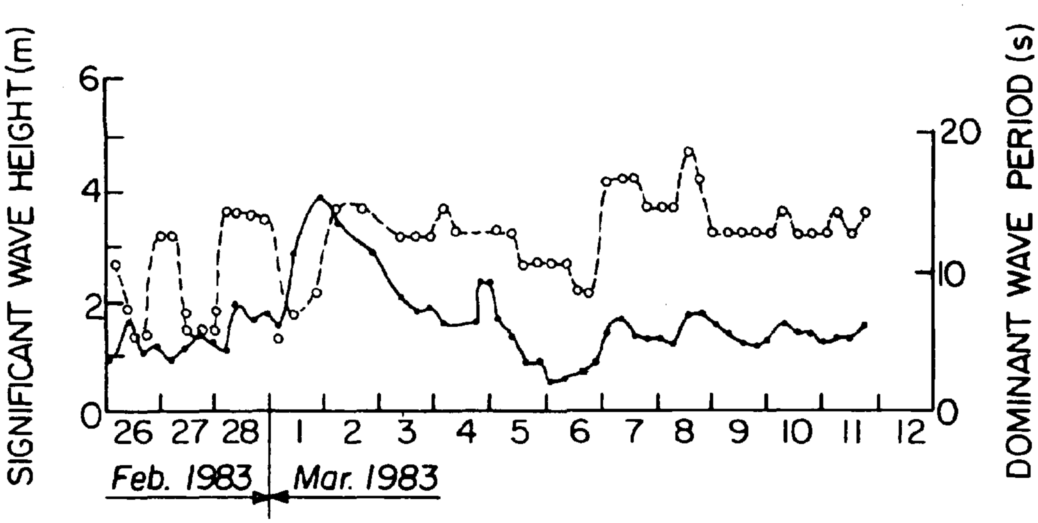


FIGURE 5 Tide and wave characteristics at Scripps Pier from the storm of February-March 1983.

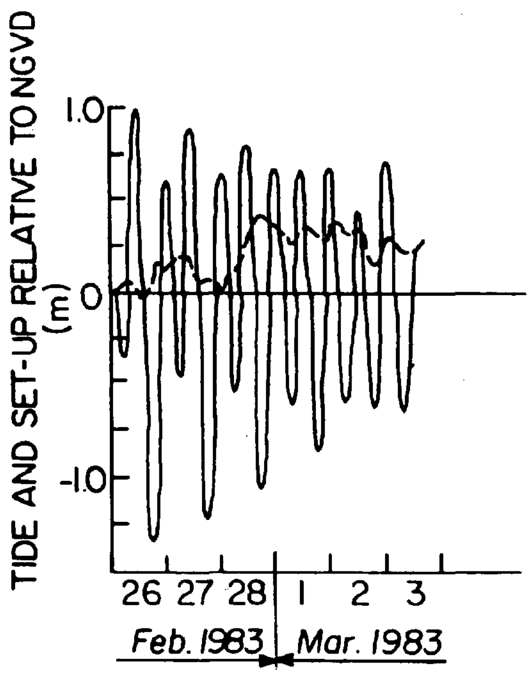


a) Predicted Astronomical Tide (——) and Deduced Set-Up (– – –) at Newport Beach Tide Gage

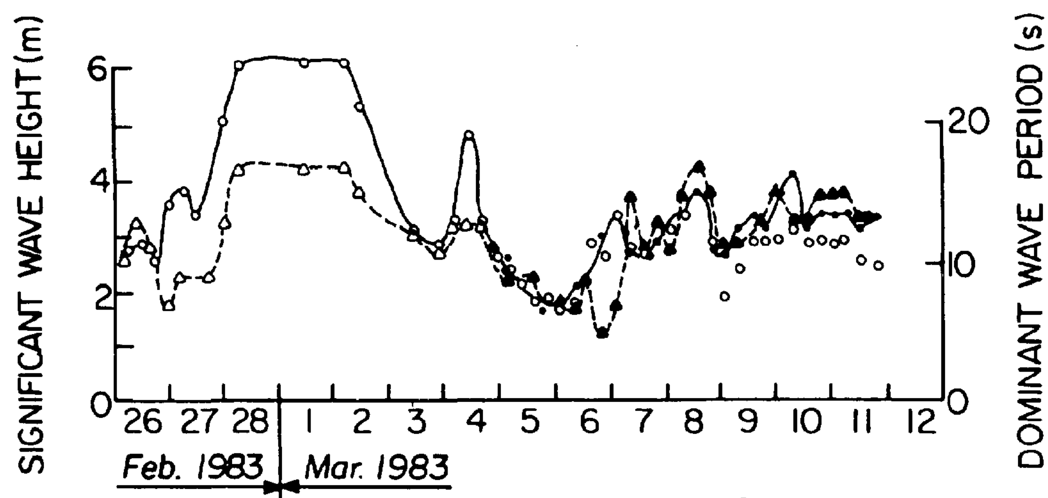


b) Significant Wave Height (•——•) and Dominant Wave Period (o– – –o) at Sunset Beach Wave Gage Array

FIGURE 6 Tide and wave characteristics at Newport Beach and Sunset Beach, respectively, from the storm of February-March 1983.



a) Predicted Astronomical Tide(——)and Deduced Set-Up(- - -)at Point Reyes Tide Gage. Note: Data Analysis Problems Occurred for Times Later than Mar. 3, 1983



b) Significant Wave Height: Point Reyes Buoy; Farallon Buoy

Dominant Wave Period: Point Reyes Buoy; Farallon Buoy

FIGURE 7 Tide and wave characteristics at the Point Reyes tide gage and wave characteristics at the Point Reyes buoy (when reporting) and the Farallon buoy.

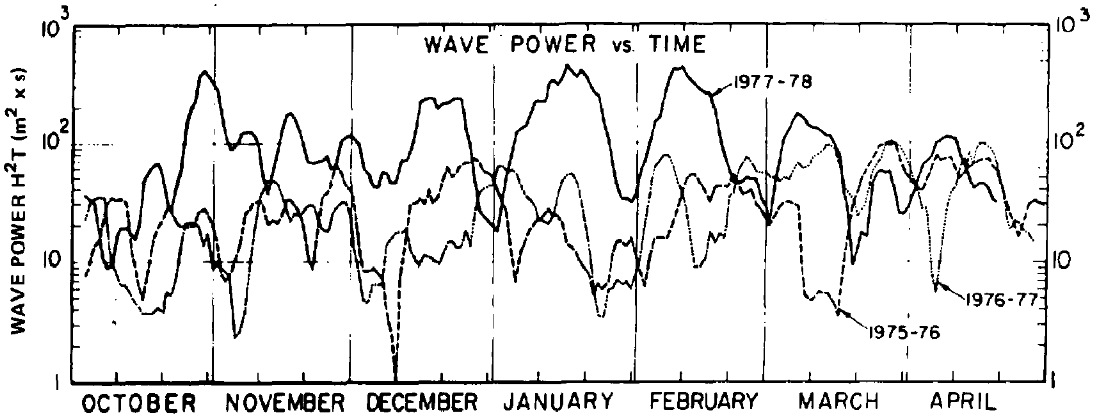


FIGURE 8 Variation of wave power for three successive winter seasons. Source: Dormurat, 1978.

TABLE 4 Measured Winds and Wave Hindcasts for Storms of January and February 1978

Date	Wind* Speed (mph)	Wind* Direction	Significant Wave** Height (m)	Significant Wave** Period (s)	Significant Wave** Direction
Jan. 9	40	SW	4.3	18	SSW
Jan. 13	40	SW	6.5	14	S
Jan. 16	55	SW	5.5	16	WSW
Feb. 9	50	S	6.1	16	SSW
Feb. 10	45	WNW	4.9	12	SSW
Feb. 13	45	NW	5.2	16	SSW

*Wind data measured at Farallon Island.

**Wave data obtained 60 miles west of Golden Gate.

Source: Dormurat, 1978.

Due to the limited time during which quality wave data have been collected (about six years), the only rational way to establish the return period for the 1982-83 wave season is through hindcasting that uses the same procedures for all years. Most hindcasters modify their procedures as additional knowledge is gained and more data become available. Thus, to get comparable wave hindcast information over the more recent past, when meteorological data of good quality are available, it is necessary to carry out a hindcast in which the same methodology is applied to these recent data. Such an analysis is beyond the scope of this reconnaissance report.

3

DAMAGE TO COASTAL AND OFFSHORE STRUCTURES

Damage occurred to a variety of coastal and offshore structures during the winter of 1982-83, including revetments, piers, breakwaters, and at least one offshore island. The information presented below is based on the reconnaissance study and on various reports. It should not be considered all-inclusive.

DAMAGE TO REVETMENTS

Revetments are structures parallel to the shore consisting of stone units usually laid at slopes of 1:3 to 1:1. The purpose of the revetment is to "harden" the shoreline, thereby limiting the landward extent of erosion. The rocks in a revetment are usually placed in layers, with the outer layer having the largest rocks. The one or more underlayers consist of progressively smaller rocks, so that the finer stones will not wash out of the interstices of the more stable overlying stones. A plastic filter layer is commonly recommended under the lower layer to prevent the sand of the embankment (if present) from washing out through the revetment. Units not underlain by the filter material usually settle substantially, requiring the placement of additional stone.

The study team observed a number of damaged revetments. Particular examples of revetment damage are given below.

Santa Barbara

A revetment had been placed adjacent to the Santa Barbara Yacht Clubhouse following the storms of 1979-80. The purpose of this revetment was to protect the clubhouse and the parking lot to the north. This revetment, which consisted of large rocks, did not incorporate a graded-rock construction and did not appear to be underlain by a woven fabric material.

The condition of this revetment during the study team's visit is shown in Figure 9. The storms of 1982-83 removed a considerable amount of sand from behind the breakwater, "stranding" the revetment. It also appears, although it is not certain, that the larger revetment units settled substantially.

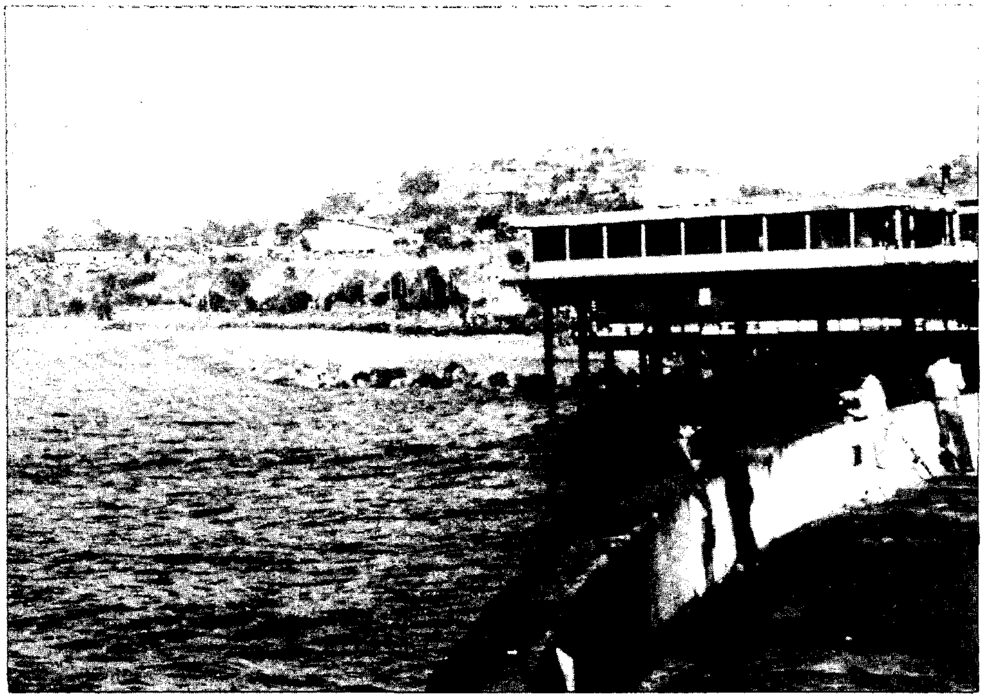


FIGURE 9 Revetment adjacent to the Santa Barbara Yacht Clubhouse at the base of the Santa Barbara breakwater. Note the complete loss of sand from behind the revetment.

Delmar Beach

In Delmar Beach a revetment had been placed to protect a low bluff where houses were located. Fronting the revetment, presumably to protect the toe of the revetment, was a long sand-filled woven plastic tube (Longard).

The revetment rock appeared to the study team to be in relatively good condition. However, the Longard tube had been ruptured and contained little sand (see Figures 10 and 11). Moreover, although the revetment had not failed structurally, it had been severely overtopped. The structures behind the revetment had suffered damage from overtopping water and flying debris.

Stinson Beach

At Stinson Beach a Longard tube had also been placed parallel to the shoreline to provide some protection of the beach and structures. This tube, which had been ruptured and rendered ineffective by earlier storms (Dormurat, 1979), was not evident during our visit.

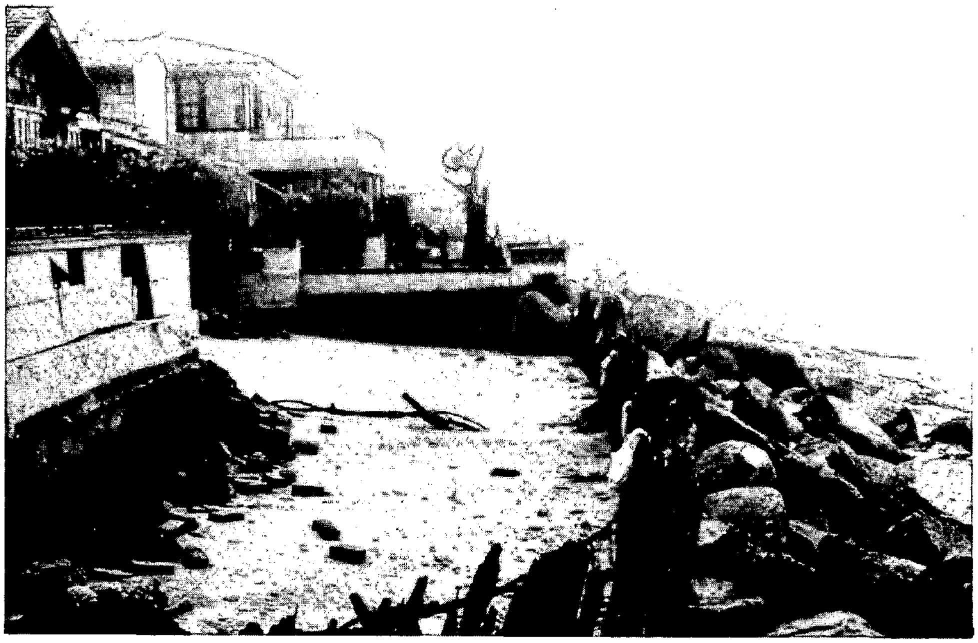


FIGURE 10 A view of Delmar Beach showing the light ineffective seawall, revetment, and damaged Longard tube. Note the small Caterpillar in the background moving sand to the upper portions of the beach.

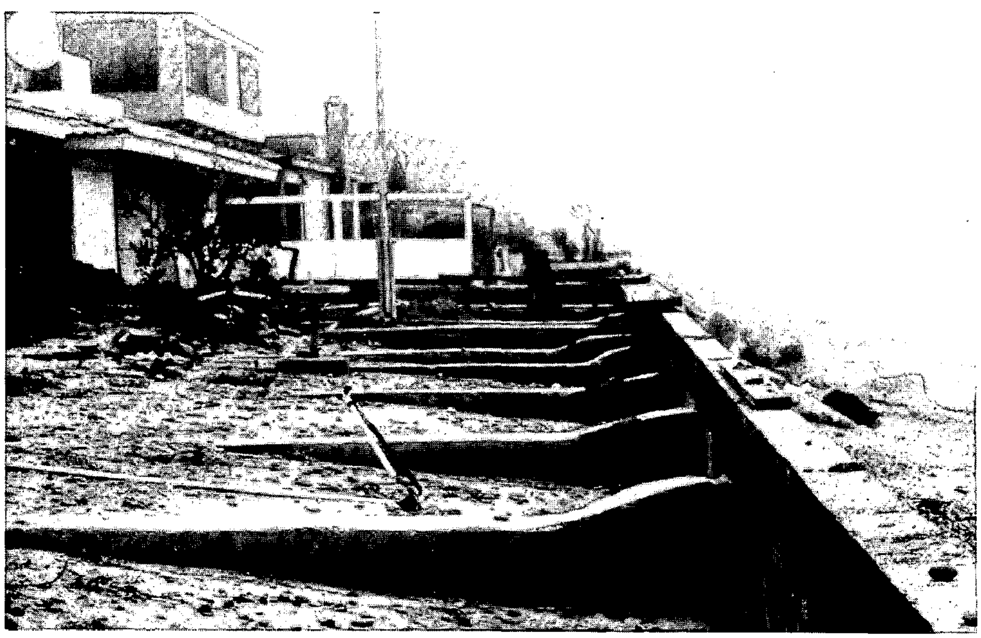


FIGURE 11 Delmar Beach showing the seawall with the damaged Longard tube in the background. Note the effect of the waves overtopping the seawall and causing erosion on the lee side.

DAMAGE TO BREAKWATERS

Corps of Engineers' Breakwaters

The Los Angeles District of the U.S. Army Corps of Engineers (1983) has detailed the damage to the breakwaters under its responsibility. Table 5 summarizes the locations, character of damage, and repair costs for those structures. Figure 12 shows their locations. The total repair cost is $17.8 million. In discussing this damage, the Corps comments that the storm waves were "most certainly the largest since 1941, and perhaps the largest since 1838 or before."

Diablo Canyon Breakwater

The Diablo Canyon breakwater was damaged during the 1982-83 winter season. The primary damage occurred to the west breakwater and consisted of an erosionlike process, with most of the armor and underlayer materials displaced to the east in a spitlike deposit.

Santa Barbara Breakwater

The Santa Barbara breakwater was constructed in 1930 and has required only minor repairs since then. An inspection of this breakwater did not identify any damage from the storms of 1982-83.

DAMAGE TO OFFSHORE ISLANDS

Island Esther

Island Esther off Huntington Beach was constructed in 1964 in a nominal water depth of 12 m and served as a drilling base for up to 120 oil wells (Nobel and Dornheim, 1975). This island was completely demolished by the March storm immediately prior to the study team's visit. The island had apparently experienced damage earlier in the 1982-83 winter season, and all production on it had ceased for repairs at the time of the March storm. The nature of the damage appeared to be loss of fine sand material under the island, which resulted in subsidence. Reportedly, the island had experienced limited damage in earlier years and grouting had been used as a remedial measure.

Rincon Island

Rincon Island is located in water approximately 15 m deep and is armored by tribar units weighing 31 tons each on the seaward side. Construction of the island was completed in August 1958 (Blume and Keith, 1959). Figure 13 shows an aerial view of Rincon Island taken during the reconnaissance trip. No damage is evident.

TABLE 5 Damages to U.S. Army Corps of Engineers' Breakwaters and Harbors During the 1982-83 Winter Season

Structure	Description of Damage	Estimated Repair Costs (dollars)
Morro Bay Harbor	South breakwater: two large voids 10 to 12 m long, general deterioration, and displaced rock.	1,400,000
Port San Luis	Two sections 30 m long and 60 to 90 m long destroyed.	600,000
Port Hueneme and Channel Islands Harbor	Structures experienced no substantial damage.	3,500,000
King Harbor, Redondo Beach	Void 20 m long.	750,000
Los Angeles/Long Beach Harbor, San Pedro	Gap 123 m long, several gaps 7 to 21 m long, numerous stones displaced.	3,900,000
Anaheim Bay	East jetty and mole: one major breach and 13 scalloped areas. West jetty: 120 m lost off end, four breaches.	800,000
Dana Point Harbor	Relatively minor damage. Five large and several minor voids.	600,000
Oceanside Harbor	Shoaling of harbor entrance.	2,200,000
Mission Bay	Minor damage to revetment, piling, jetties, Scour also occurred adjacent to structures.	3,800,000
Zuniga Jetty	One navigational light destroyed, one damaged. Complete damage survey not available.	250,000 (to date)

SOURCE: U.S. Army Corps of Engineers, 1983.

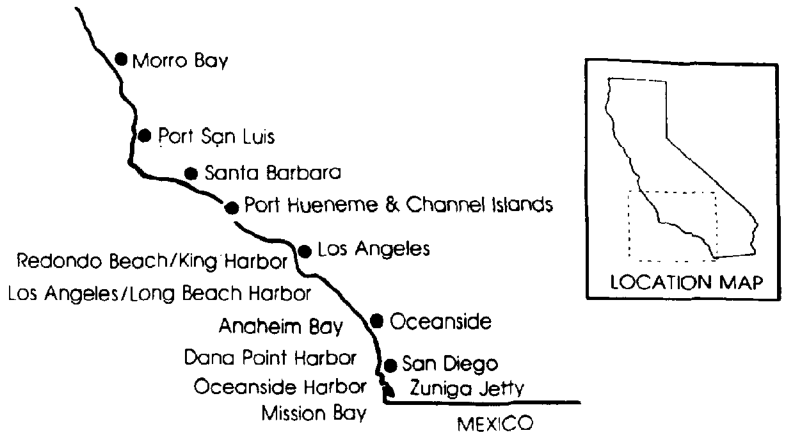


FIGURE 12 Locations of damaged breakwaters under the responsibility of the Los Angeles District of the U.S. Army Corps of Engineers.

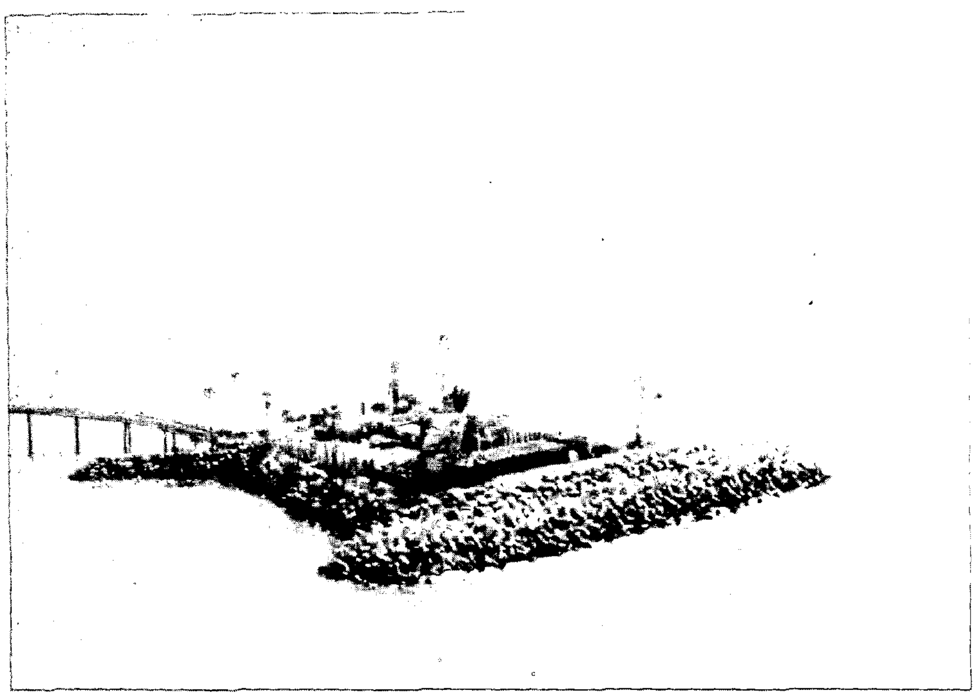


FIGURE 13 Rincon Island showing no apparent damage.

DAMAGE TO PIERS

Storm damage to public and private piers was substantial. The State of California Coastal Conservancy (1983) estimated that of the more than $35 million in damage to public recreational facilities, more than half that amount ($18,767,000) was due to the partial or complete destruction of 17 recreational piers. The conservancy did not give damage estimates for individual piers, but its estimates for recreational facilities including piers are given in Table 6.

The detailed causes of pier damage are not known and may differ for various structures, but the more probable causes are given below.

1. General deterioration and damage by wave impact or impact of floating debris. Once several elements of the pier are loose and floating, the potential for damage through impact by these elements increases.
2. Weakening of the piling through sand abrasion in the zones of highest sand transport. This mechanism has been reported to be the cause of degradation of various elements that penetrate the sand-water interface.
3. Localized erosion over the sand profile. In addition to scour that would occur if a pier were not present, localized scour usually occurs around a piling. The maximum localized scour depth is on the order of several piling diameters. Another component of scour, more extensive than the local piling scour, has been identified at the Coastal Engineering Research Center (CERC) pier in Duck, North Carolina. A trough forms with an alignment roughly along the pier. The trough appears to be dynamic, with its maximum depth changing with wave conditions. The maximum documented depth of the component of scour for the CERC pier is in excess of 2 m and is located near the end of the pier (Miller et al., 1983).

Several examples of pier damage observed during the study team's visit are listed below.

Avila Beach

The public pier at Avila Beach suffered an estimated $400,000 damage. The Union Oil Company loading pier was almost totally demolished. This pier was used for importing petroleum products for the southern San Joaquin Valley. It was founded on steel piling and probably had not been maintained regularly. Its replacement cost is approximately $10 million.

San Clemente Pier

Figure 14 shows the San Clemente Pier. A segment near the shore was removed by the storm action.

TABLE 6 Damage to Selected Recreational Facilities Including Piers

Location	Facilities Damaged	Estimated Replacement Cost (dollars)
Imperial Beach	Pier, miscellaneous recreational facilities.	550,000
San Diego City	Pier, access stairs, beach parks.	1,600,000
Oceanside	Pier, seawall, miscellaneous recreational facilities.	2,000,000
San Clemente	Pier, lifeguards stations, etc.	820,000
Newport Beach	Pier, miscellaneous recreational facilities.	25,000
Seal Beach	Pier, bike trail, lifeguard station, revetment, miscellaneous recreational facilities.	3,500,000
Redondo Beach	Pier, boat launch, Seaside Lagoon, revetment, miscellaneous recreational facilities.	650,000
Santa Monica	Pier, miscellaneous recreational facilities.	8,000,000
Los Angeles County (including all county-managed facilities)	Piers, access stairs, beach parks, bike trail, parking, lifeguard stations, miscellaneous recreational facilities.	6,000,000
Santa Barbara County	Access stairs, beach parks, piers, boat launch, miscellaneous recreational facilities.	750,000
Pismo Beach	Pier, RV park, access trail, seawall.	2,300,000
Port San Luis/ Avila Beach	Pier, miscellaneous recreational facilities, revetment.	400,000
Cayucos	Pier, access stairs, seawall, parking, miscellaneous recreational facilities.	500,000
Capitola	Pier, stairs, bike trail.	320,000
Pacifica	Pier, parking, bike trail.	75,000
TOTAL		27,540,000

NOTES: (1) Estimated total damage to public recreational facilities: $35,000,000. (2) Estimated total pier damage: $18,676,000.

SOURCE: State of California Coastal Conservancy, no date.

FIGURE 14 Nearshore section of the San Clemente Pier removed by storm.

Venice Pier

As shown in Figure 15, the nearshore section of Venice Pier was damaged. Some of the park's other facilities also experienced damage.

PERFORMANCE OF FOUNDATIONS

In general, the foundations of coastal structures seem to have performed well, with one notable exception. The approach ramp to the Venice Pier was separated from the pier as a result of differential settlement between the ramp and the pier (see Figure 15). The approach ramp was a U-shaped reinforced concrete box apparently founded on spread footings placed about 2 to 3 m below the preexisting level of the beach. The storms removed the entire thickness of the beach above the foundation grade and undermined the structure, causing more than a foot of differential settlement between the approach ramp and the pier.

This failure underscores the importance of taking into account the potential depth of wave erosion when designing the foundations of coastal installations. To illustrate this point, Figure 16 shows a small building housing restrooms and changing rooms adjacent to the Venice Pier. This structure escaped destruction because it was founded on piles, even though spread footings would have been enough to carry the foundation's loads.

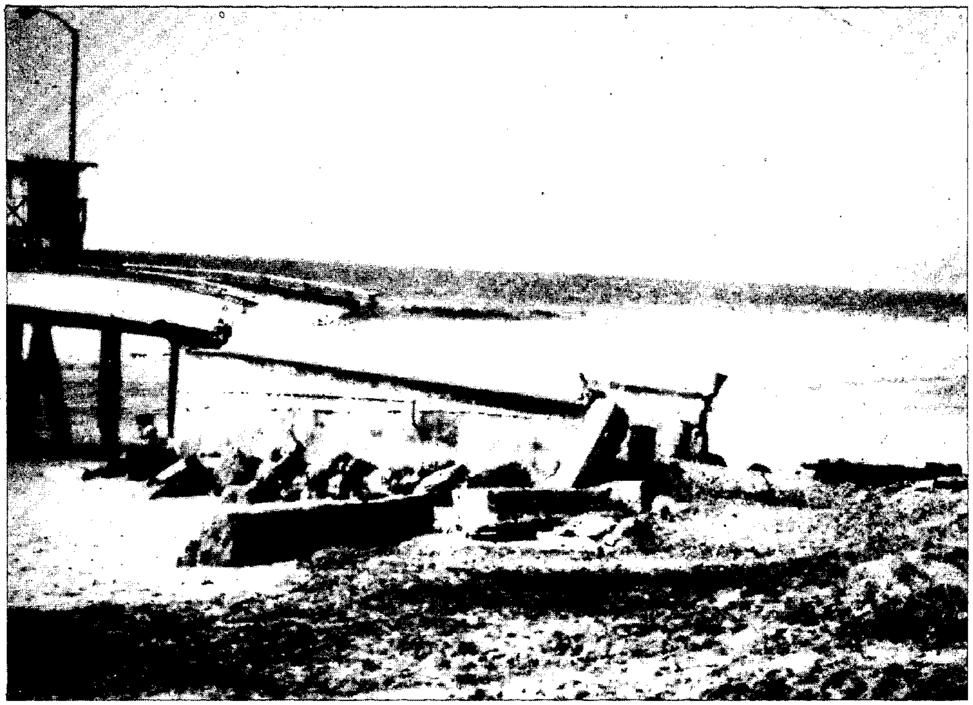


FIGURE 15 The Venice Pier was damaged due to undermining and settlement of the approach ramp.

FIGURE 16 This structure supported by light piles escaped direct wave damage. The Venice Pier is in the background.

It is also worthwhile to note that many of the piers that suffered substantial damage and partially collapsed during the storms were actually overtopped by waves. Thus their supporting piles were likely subjected to substantial uplift and pull-out forces. However, it is impossible to ascertain whether any of the piles were actually pulled out or whether they failed due to other causes. Also, in several cases, such as the Seal Beach Pier and Santa Monica Pier, the piles were so closely spaced that the piles that failed first may have acted as battering rams, damaging their neighbors because they could not float free of the structure. The design alternatives are relatively simple: the piles can be designed for uplift, or the deck can be allowed to lift off with a wide spacing between piles to lessen the chances of a broken pile damaging its neighbors.

WAVE DAMAGE AT ARENA COVE ON JANUARY 26, 1983

Arena Cove, shown in Figure 17, is one of the few relatively sheltered small fishing harbors along the coast of northern California. On the morning of January 26, 1983, a succession of three very large waves in conjunction with a 2.2-m tide essentially destroyed a newly reconstructed pier and a fishhouse and heavily damaged a boathouse and a shoreside cafe. The occupants of the cafe barely escaped serious injury.

The succession of events was recorded in a series of spectacular photographs presented in Figures 18A-18D. Figure 18A shows a large wave

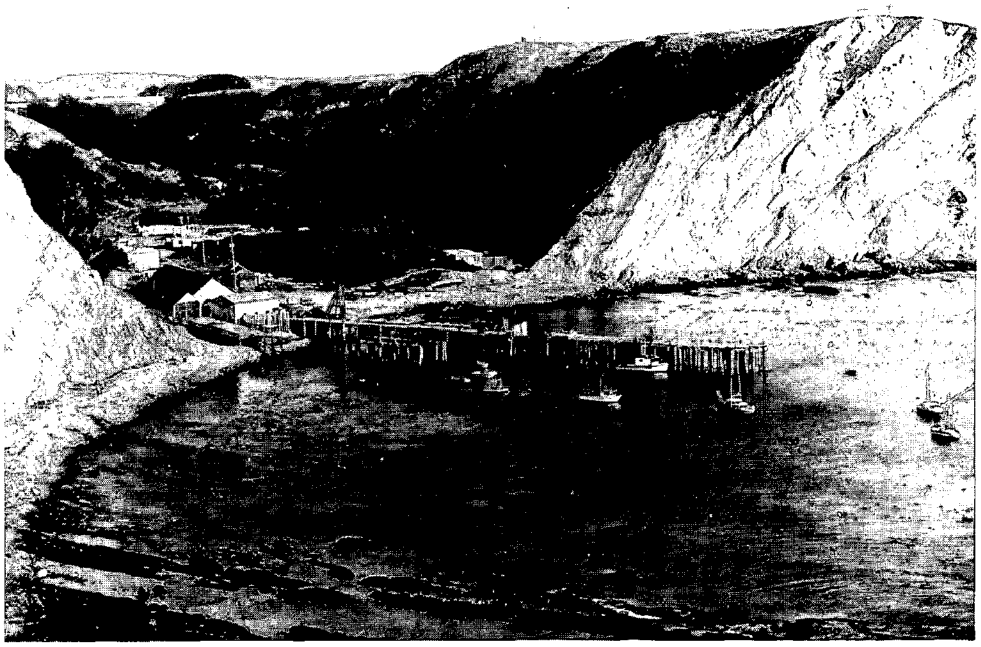


FIGURE 17 Arena Cove on August 29, 1980. Photograph copyright ©Nicholas King.

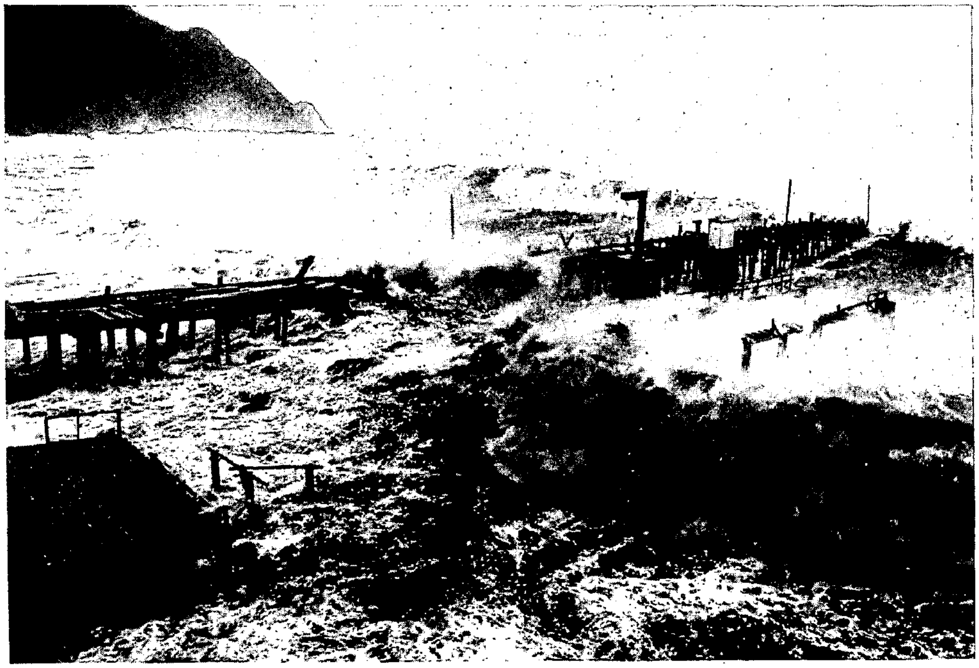


FIGURE 18A Arena Cove on January 26, 1983. The first very large wave is just hitting the top of the pier. Photograph copyright © Nicholas King.

FIGURE 18B Arena Cove on January 26, 1983. The second large wave looms just beyond the end of the pier and stretches across the whole cove. Photograph copyright © Nicholas King.

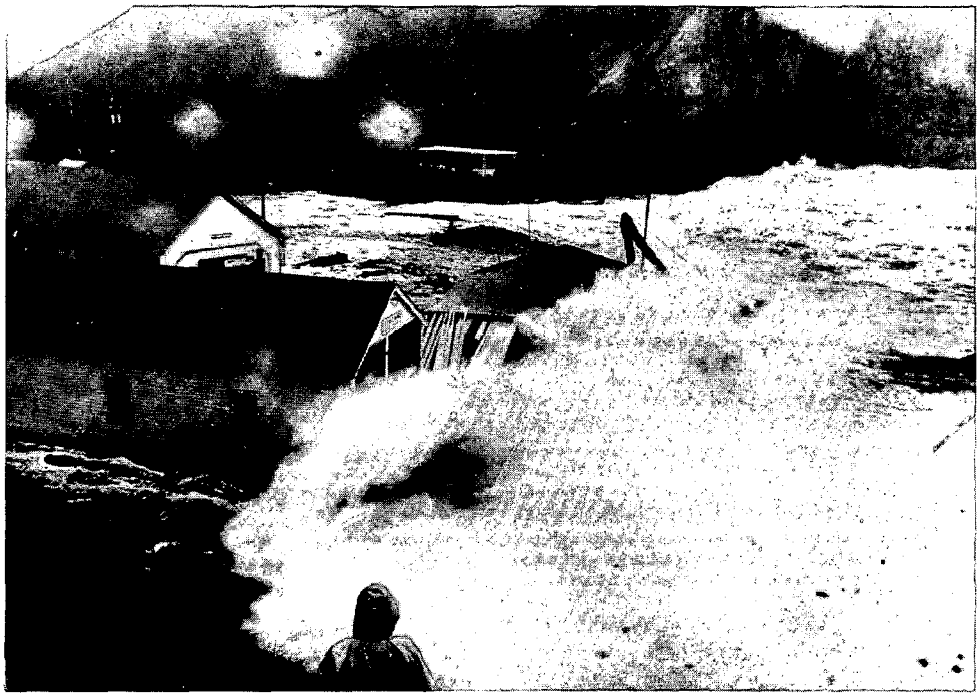


FIGURE 18C The boathouse and fishhouse being attacked by waves. Photograph copyright © Nicholas King.

FIGURE 18D The boathouse and fishhouse being attacked by waves. Photograph copyright © Nicholas King.

overtopping a portion of the pier, with the first of the three very large waves just at the seaward tip of the pier. Figure 18B shows a portion of the pier totally submerged under the very large wave, with the following wave rising across the entire width of the cove. Figures 18C and 18D document the damage inflicted by the waves to the fishhouse (in the center), the boathouse (center left), and the cafe (behind the boathouse).

4

BEACH EROSION

The effects of high tides and waves combine to cause offshore transport of sand. During storms an offshore bar forms with a trough located just landward of the bar. If a bar exists prior to a storm, the bar-trough system is usually displaced offshore until the crest of the bar coincides with the predominant breakpoint of the waves.

In a pure two-dimensional case, transported sand is not lost to the system, having been displaced from the dry beach to the offshore bar. Nevertheless, this appears as beach erosion. These cycles of storm erosion and recovery are generally superimposed on a long-term trend of erosion due to the gradually rising sea level. Thus, although the short-term storm-induced fluctuations do not result in any net erosion, the long-term trend causes a gradual encroachment of sea onto the land. Figure 19 presents an idealized illustration of the superimposed components of shoreline change due to storms and the rising sea level.

Along much of the California shoreline, the encroachment of the sea is evident in the relatively narrow beaches backed by steep and fairly high bluffs and cliffs. During severe storms the beach sand is stripped away and the waves and tides can attack the cliffs directly. The cliffs generally do not contain large percentages of beach-sized sand. Rather they contain significant fractions of very fine muds and silts and some large cobble-sized material. Beach erosion is also caused by the interruption of transport by submarine canyons, which act as sinks to drain sediment out of the system, and by structures that impound the natural transport on the updrift side and result in a deficit of sand on the downdrift side.

Ultimately, beach erosion is responsible for much of the damage from coastal storms. If a wide beach with a high berm were present, the waves would dissipate much of their energy on the beach rather than on upland structures. Moreover, as erosive waves transport substantial quantities of sand seaward and deposit it in a bar, energy is dissipated on the bar rather than on the shoreline and upland structures. However, as described below, the beaches of California and other parts of the nation are in general not widening. Rather, they are gradually narrowing through natural and man-related causes, leading to less sand that can be transported seaward before the waves reach and expend their energy on upland structures, whose positions are fixed relative to the receding shorelines. In some locations, the recognition of this

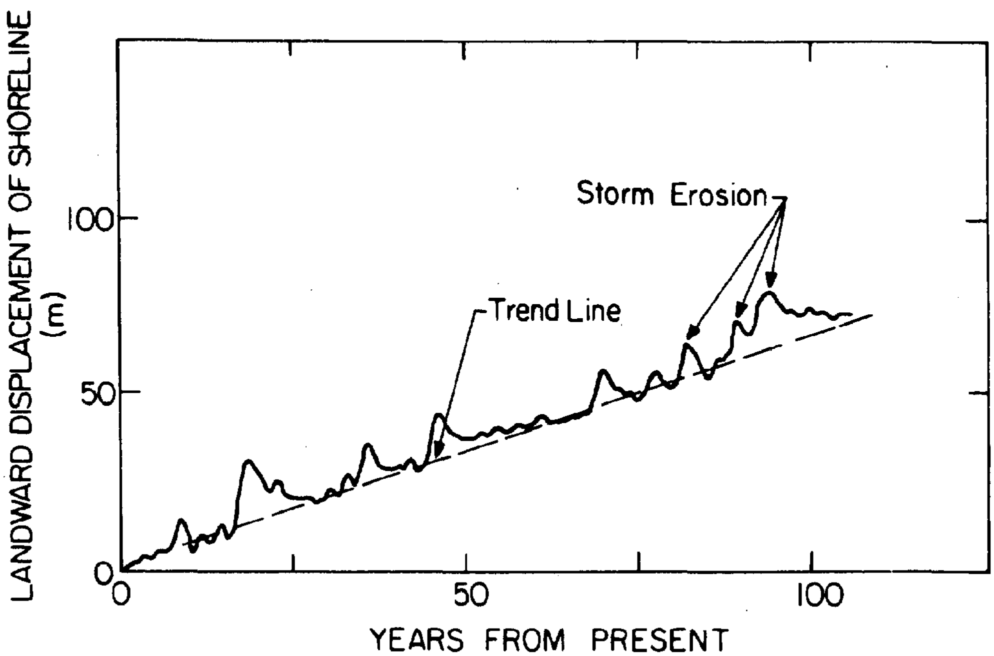


FIGURE 19 Idealized superposition of the erosional trend due to sea level rise and the relatively short-term erosion and recovery caused by storms.

erosional trend has led to the establishment of coastal construction control lines (or setback lines). In other areas, where upland structures are in place and the economics justify it, beach nourishment has been carried out, a process in which large quantities of sand are placed on beaches to widen them artificially.

CAUSES OF BEACH EROSION

The long-term component of beach erosion can be considered a slow, inexorable trend on which the effects of storms and other perturbations are superimposed.

The naturally induced erosional trend is due predominantly to the slow rise of sea level. Equilibrium beach profiles tend to be concave upward. An increase in sea level causes this profile to be out of equilibrium. The profile responds by foreshore erosion, with the material transported offshore elevating the profile (thereby reestablishing the equilibrium). Bruun (1962) showed that the shoreline recession, R, due to an increase, S, in sea level is given by

$$R = SW/h,$$

in which h is the vertical dimension over which the adjustment occurs and W is the associated width (see Figure 20). For most beaches, the

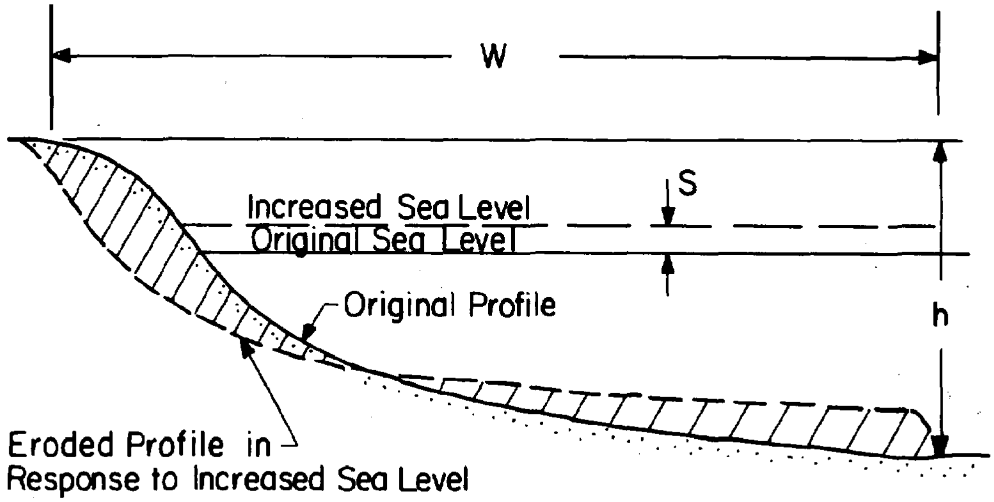


FIGURE 20 Schematic diagram of the long-term response of beach profile to sea level rise. Source: After Bruun, 1962.

geometry is such that for one unit of rise in sea level, the corresponding horizontal recession is some 100 to 300 units. The lower figure is more appropriate for California beaches. The sloping dashed line in Figure 19 represents this erosional trend.

Superimposed on the gradual erosional trend are the abrupt erosional events caused by storms. These are followed by much longer recoveries as sand returns to the portions of the beaches above water. The erosion from a severe storm may occur in 12 or 24 hours, whereas the recovery can require on the order of three to seven years (see Figure 19). Complete recovery for a severe storm takes much longer than for a storm of moderate intensity.

This discussion of natural erosional processes has been greatly simplified. Much of the California coastline would be classified as "young," in which case equilibrium beach profiles have not been formed and cliffs would be attacked and eroded to form the equilibrium profile even if the sea level were stable. The sand supplied to the shoreline by rivers and the loss of sand in submarine canyons add to the natural complexity of the California shoreline.

The major human influence on shorelines is probably the reduction in the supply of sand to the coastline by rivers because of impoundments designed for flood control, recreation, and water supply. Other human-related perturbations can cause local effects; however, these usually result in an accretion in one location and an associated erosion elsewhere. An example is the Santa Barbara breakwater constructed in 1928-30, which caused the net deposition of approximately 1.5 million m^3 of sand, which now forms Leadbetter Beach, and an associated erosion to the east (see Figure 21). The depositional area formed by the breakwater is now filled to capacity, so the sediment is transported around the breakwater and deposited as a spit in the lee of its eastern end. When the spit encroaches on the entrance channel into Santa

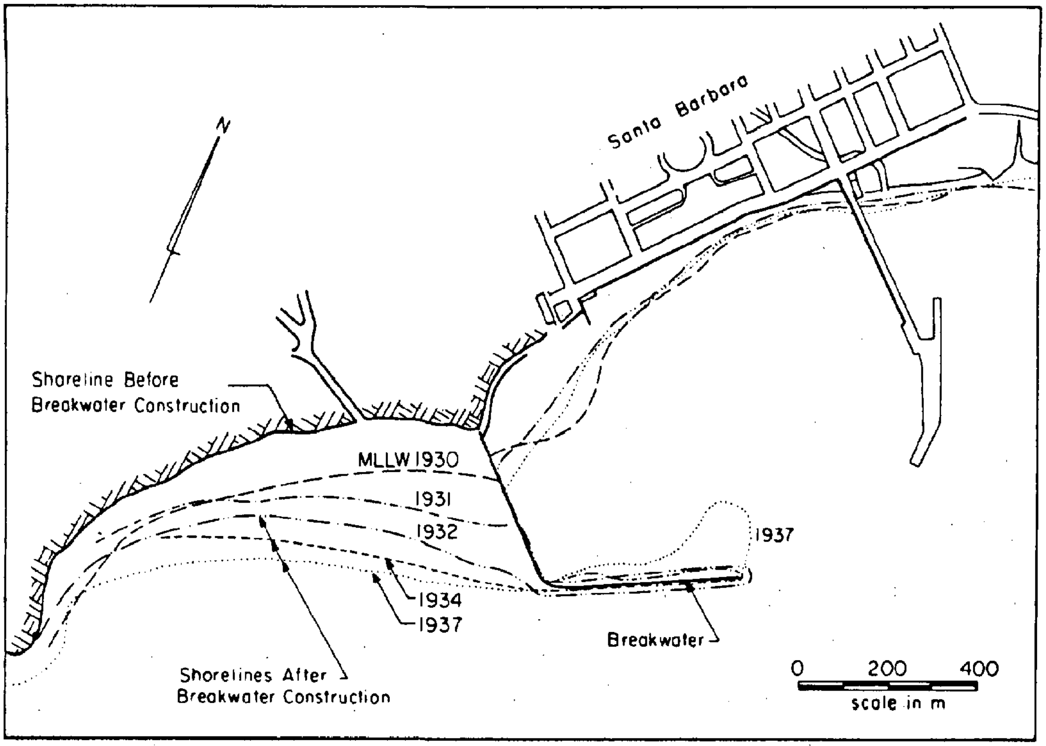


FIGURE 21 Response of the updrift (west) shoreline to construction of the Santa Barbara breakwater. Source: After Johnson, 1957.

Barbara Harbor, the sand is dredged and deposited on the beaches to the east.

Finally, the processes and degree of stability at each beach should be considered unique. The conditions at beaches range from prograding to receding. Nevertheless, the high bluffs and narrow to nonexistent beaches along most of the California shoreline are a constant reminder of the long-term erosion that is generally occurring along these beaches.

BEACH EROSION AND RELATED DAMAGE FROM THE WINTER 1982-83 STORMS

In considering the following examples of erosion and damage, it is helpful to keep in mind that, in addition to the overall erosional trend, beaches wax and wane in response to long-term variations in storm season cycles. Thus many of the structures on California beaches may have been constructed during periods of relative stability, although in some cases erosion may have progressed to the locations of these structures at some time in the past. Also, structures on coastal cliffs were probably built without the knowledge that, through rainfall runoff and base erosion, these cliffs erode and supply sand to the beaches.

Figures 22, 23, and 24 present the locations discussed in the following paragraphs.

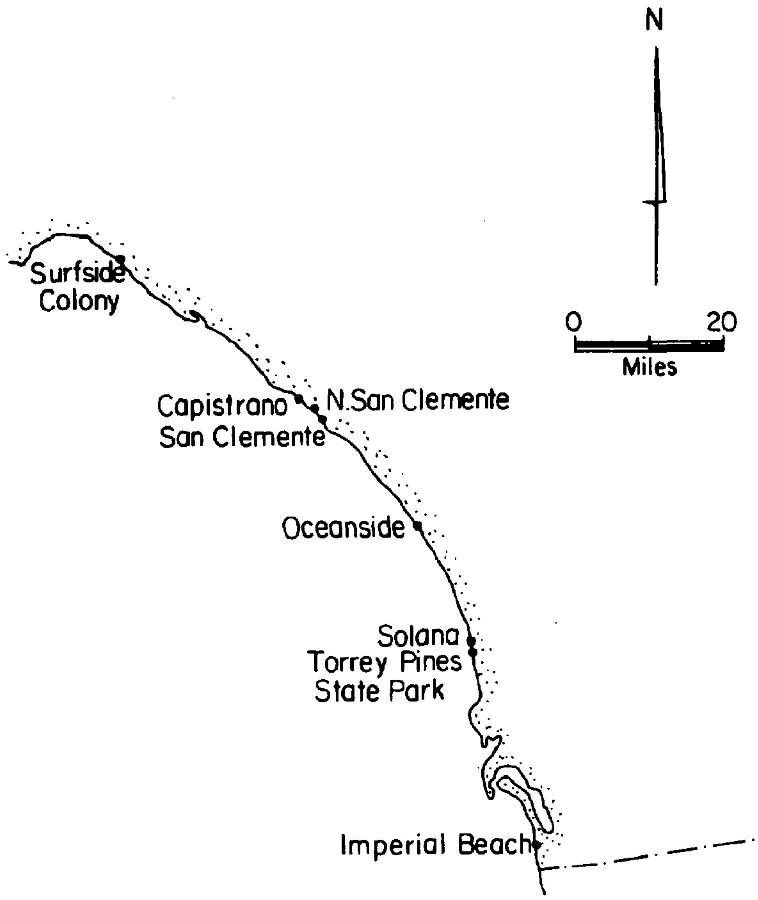


FIGURE 22 Locations visited during the reconnaissance trip between Imperial Beach and Surfside Colony.

Imperial Beach

Beach structures in Imperial Beach are located on a fairly low-lying coastal barrier of sand. It is generally believed that in recent years the stability of this barrier has diminished and erosion has increased because of a lowered elevation of sand in the Tijuana shoals due to an impoundment on the Tijuana River that has reduced the sand supply.

The structures (Figures 25 and 26) consist primarily of single-family dwellings. They have remained largely undamaged because of the presence of very large and high revetments. As shown in the photographs, the beaches are very narrow. At the time of the study team's visit, no well-defined offshore bar was evident, although sand had clearly been transported seaward from the beach. Attempts to control beach erosion at this location by constructing three groins were unsuccessful. Based on model testing conducted at the Waterways Experiment Station, the U.S. Army Corps of Engineers plans to construct a series of offshore breakwaters to control erosion.

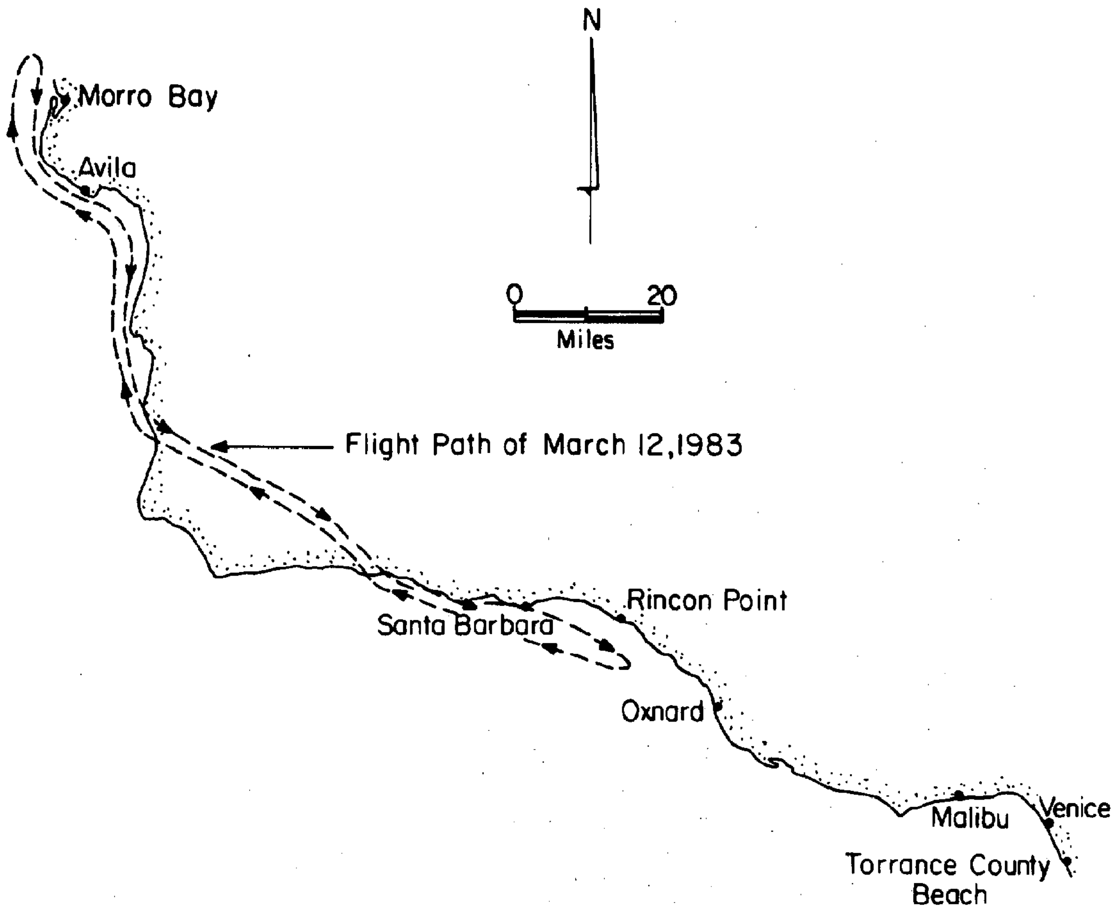


FIGURE 23 Locations visited during the reconnaissance trip between Torrance County Beach and Avila.

Torrey Pines State Beach

Figure 27, which shows Torrey Pines State Beach toward the south from the access road, contains several features of interest. First, the sand on the beach, at least in places, has been transported and deposited offshore, leaving a more resistant lag deposit of cobbles. Also of interest are the steep cusps that have been formed of the cobbles. The average slope of the horns and swales of these cusps is 25° and 10°, respectively. Figure 28 presents a sketch of the cusp geometry.

Solana Beach

Bluff and cliff erosion at Solana Beach are prevented only by the presence of a narrow sand beach. At the time of the visit, this beach had been reduced in width to the extent that the high tides and waves of the 1982-83 winter season acted directly on the cliffs.

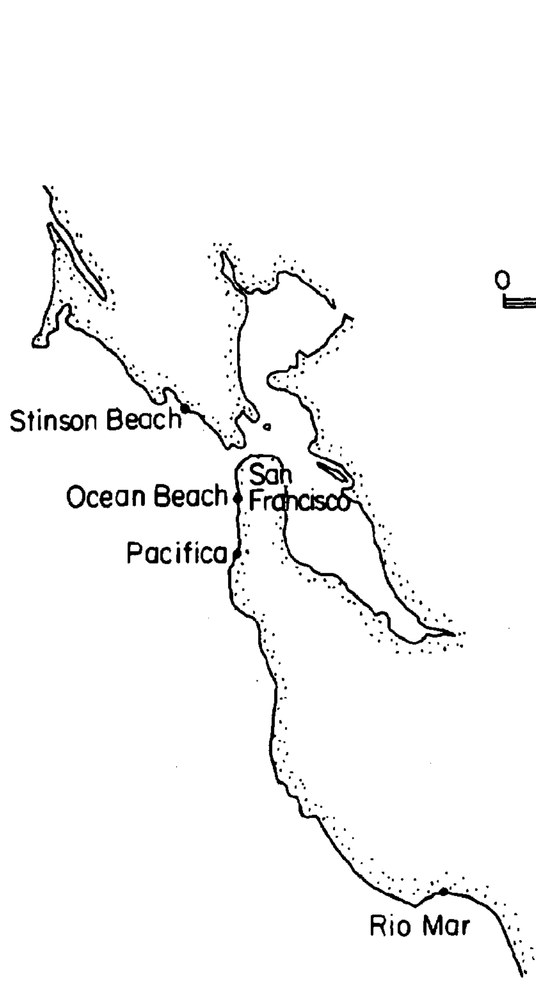


FIGURE 24 Locations visited during the reconnaissance trip between Capitola and Stinson Beach.

Oceanside Beach

Oceanside Beach has a history of erosion that is believed to be due largely to the stress imposed by the Oceanside Harbor breakwater immediately to the north. Sediment has been deposited north of the harbor complex and also offshore of the breakwater. Figure 29 shows the beaches south of the Oceanside Pier (which is in the background). At other locations, waves have removed some of the sand from the beach, exposing the cobble base. Observers reported that, during the storms, cobbles with diameters of up to 15 cm were propelled by wave action across the street (Pacific Street) paralleling the ocean. It is of interest to note that within the last two years approximately 750,000 m^3 of high-quality sand have been placed on the Oceanside beaches.

Figure 30 shows sandbag protection along Pacific Street and the sand carried onto the street by storm waves. In Figure 31, attempts are

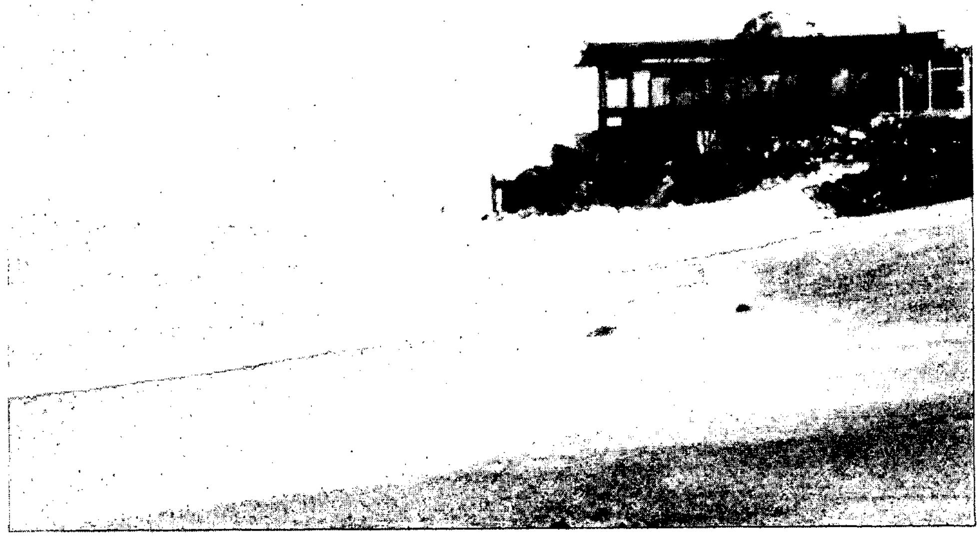


FIGURE 25 View of Imperial Beach showing eroded beach and home protected by revetment (photograph was taken at low tide).

FIGURE 26 Closeup of revetment shown in Figure 25.

FIGURE 27 Torrey Pines Beach. Note the cobble berm and steep cusp formations.

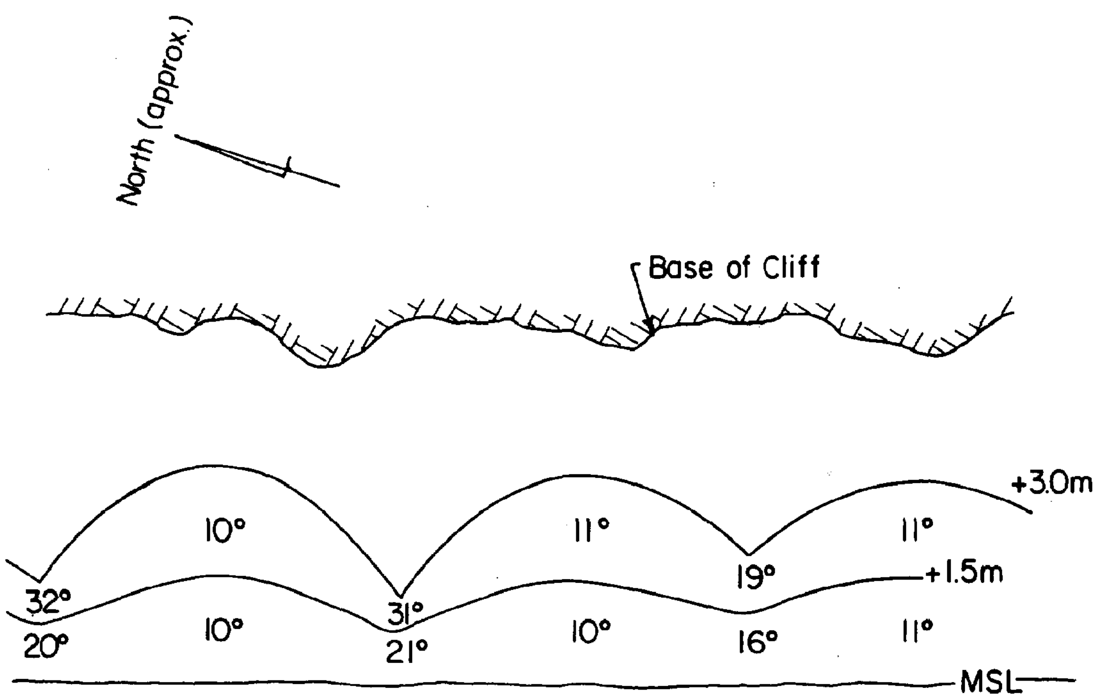


FIGURE 28 Approximate planform geometry of the cusps at Torrey Pines Beach on March 9, 1983. Most of the cobbles on the upper portion of the beach were about 6 cm in diameter. The local beach slope was about 21°.

FIGURE 29 Oceanside Beach with Oceanside Pier in the background. Note the narrow beach, revetment, and evidence of overtopping.

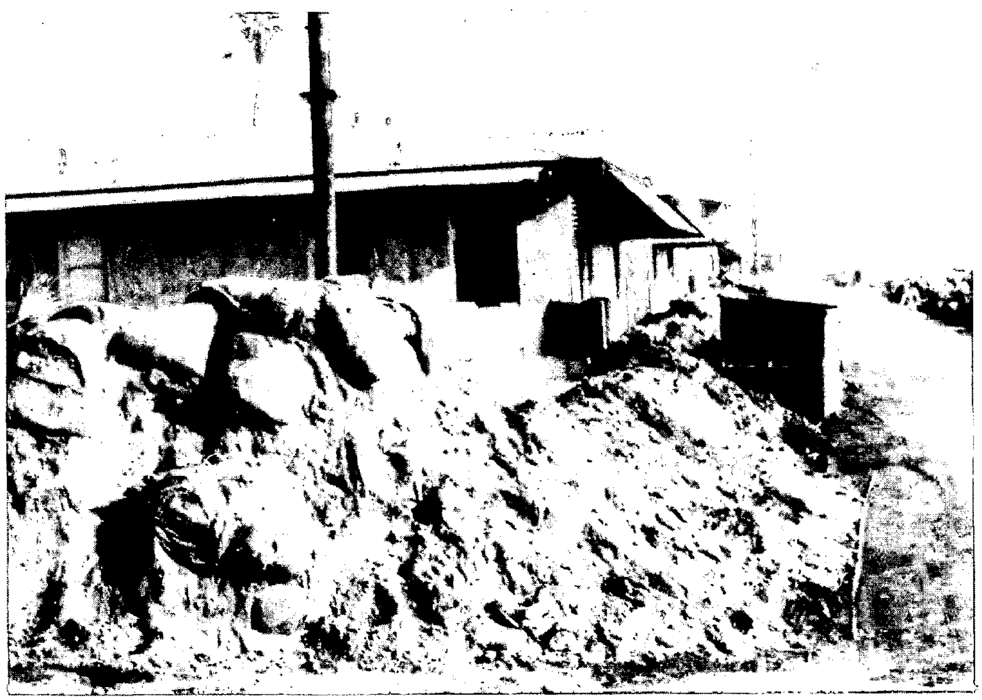


FIGURE 30 Oceanside Beach showing efforts to protect oceanfront cottages against water and debris damage.

evident to protect a structure against the waves' splash. Figure 32 shows the limited damage to the south breakwater at the entrance to Oceanside Harbor.

Capistrano Shores, San Clemente

At a trailer park in Capistrano Shores, a vertical wooden seawall had been constructed to limit erosion. As shown in Figures 33 and 34, high tides and breaking waves transported water over the seawall. This caused loss of backfill material and damage to the trailers near the shore.

North San Clemente Beach

North San Clemente Beach had experienced substantial losses of sand, which undermined several restrooms and other structures (see Figure 35). The location of the house shown in Figure 36 just north of this beach places it in jeopardy from high tides and waves. The transient nature of this beach in the long term is indicated by the wave-cut cliff behind it. That the coastal railroad passes along this fairly narrow beach attests to the fact that, at least in recent years, waves have not acted on the cliff frequently.

Surfside Colony

Surfside Colony, a shorefront development, is located just downdrift (southeast) of the entrance to Anaheim Bay. This probably accounts, at least in part, for the relatively large erosional stresses on this beach and the associated need for periodic nourishment. Figure 37 shows a large dike of sand placed to reduce flooding by overtopping. This dike is located over a protective revetment. Figure 38 shows the south jetty at the entrance to Anaheim Bay. Dwellings in Surfside Colony received only limited water damage.

Torrance County Beach

The Torrance County Beach experienced substantial erosion and limited damage to structures, as shown in Figures 39 and 40.

Malibu Beach

Malibu Beach, which extends over a distance of about 1 km, is the location of quite expensive homes that face and are near the shorefront. Many of these homes "cascade" over a cliff from an elevation of 10 to 15 m down to somewhat above the normal reach of high tides and waves. When the study team visited this area, almost all of the sand had been stripped from the shoreline, leaving the underlying rock bare. Previous

FIGURE 31 Oceanside Beach just south of the mouth of the San Luis Rey River. Heavy revetment and wooden splash guards can be seen. Oceanside Pier is in the background.

FIGURE 32 Small breach in the south breakwater at Oceanside Harbor.

FIGURE 33 Capistrano Shores. A light timber seawall is fronting the trailer park. Note the evidence of overtopping.

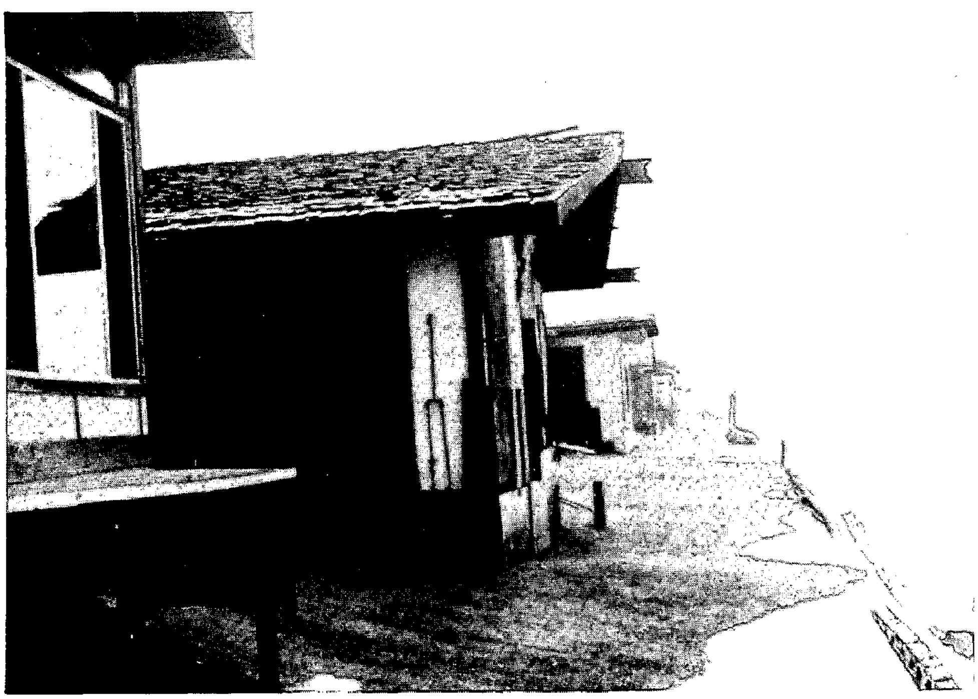


FIGURE 34 Capistrano Shores in the same vicinity as Figure 33.

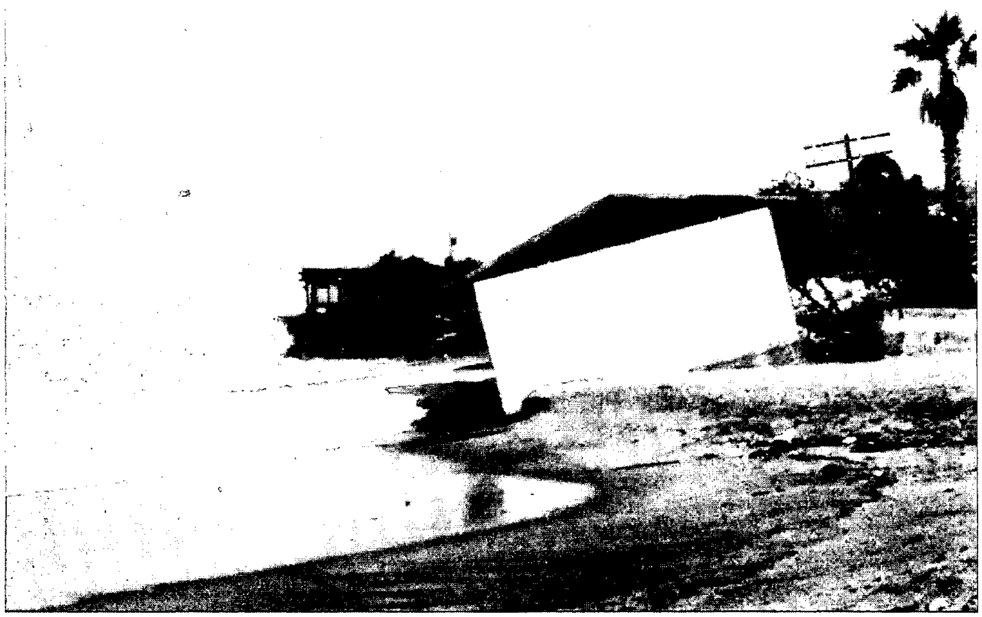


FIGURE 35 This foundation on North San Clemente Beach failed due to undermining of the slab.

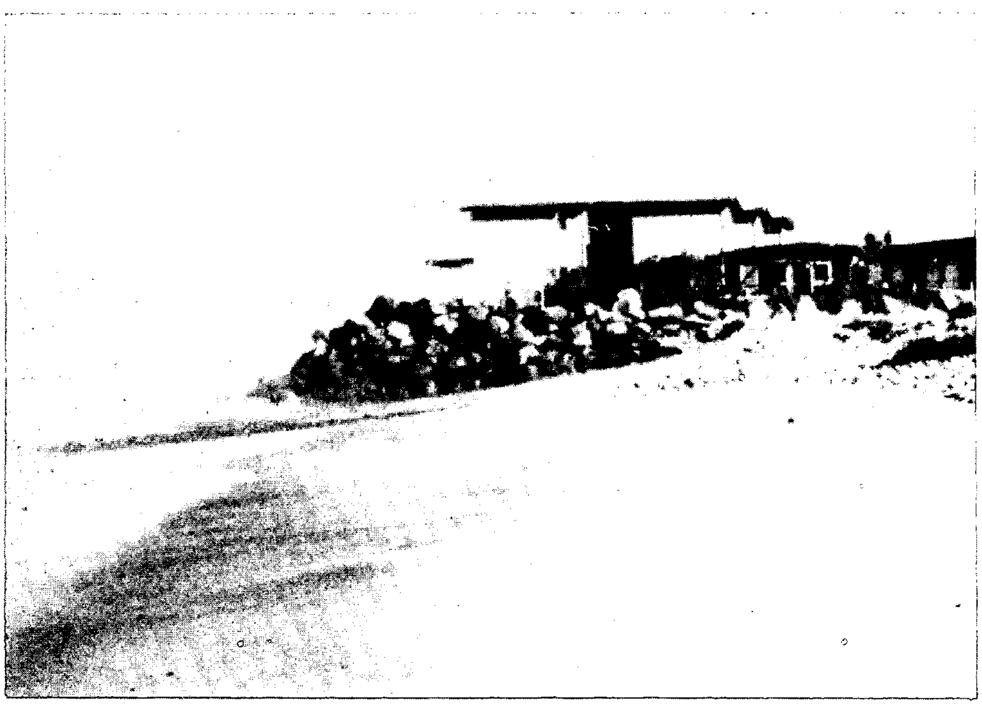


FIGURE 36 Revetment protects this North San Clemente Beach dwelling.

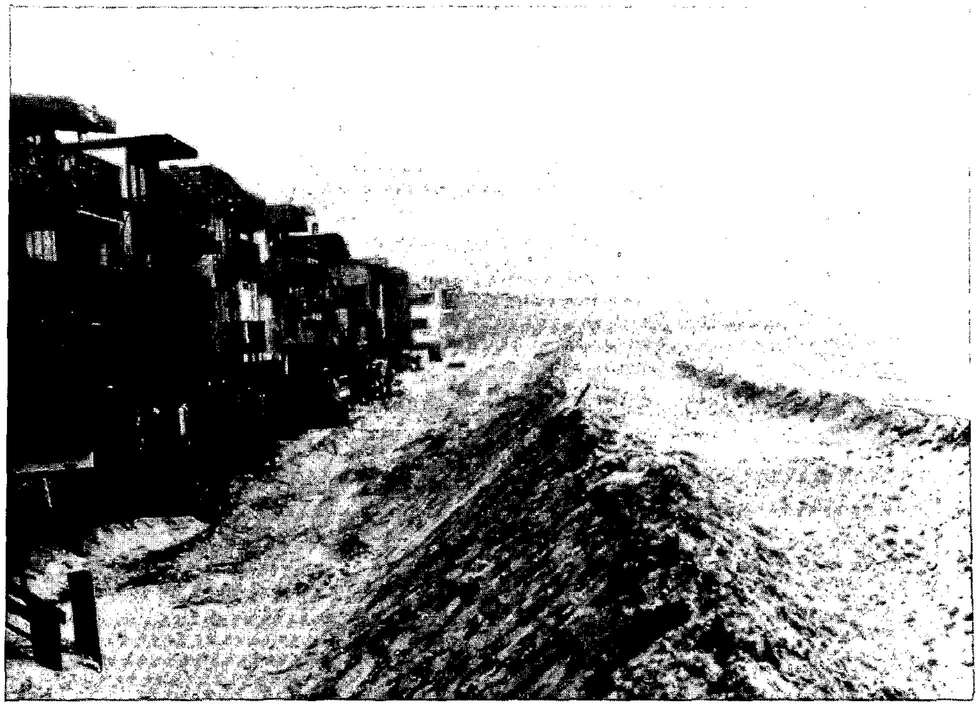


FIGURE 37 A sand berm overlies revetment as protection against flooding at Surfside Colony.

FIGURE 38 The south jetty at the entrance to Anaheim Bay.

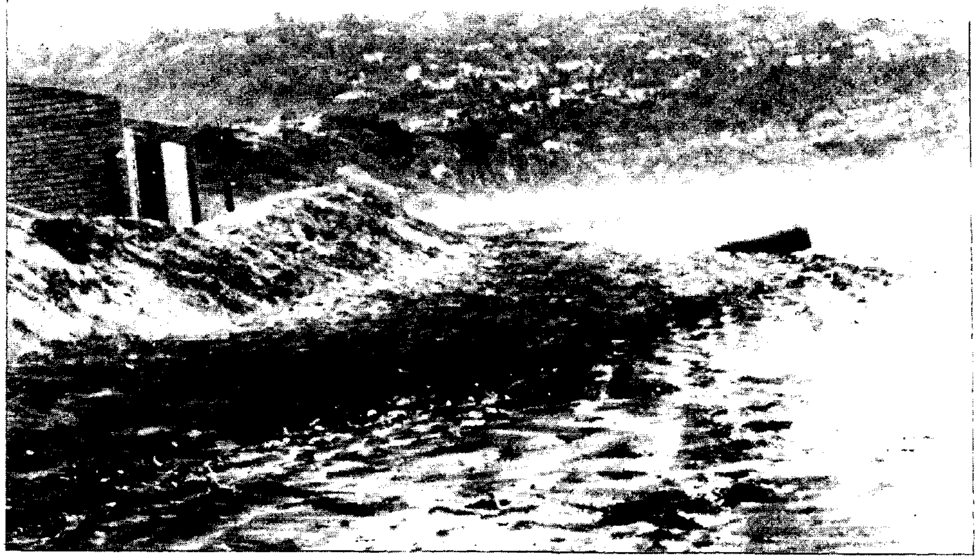


FIGURE 39 Torrance County Beach. Severe erosion is threatening the restroom facilities. Heavy minerals (black sand) were left as "lag" deposits on the beach. The Palos Verdes Hills are in the background.

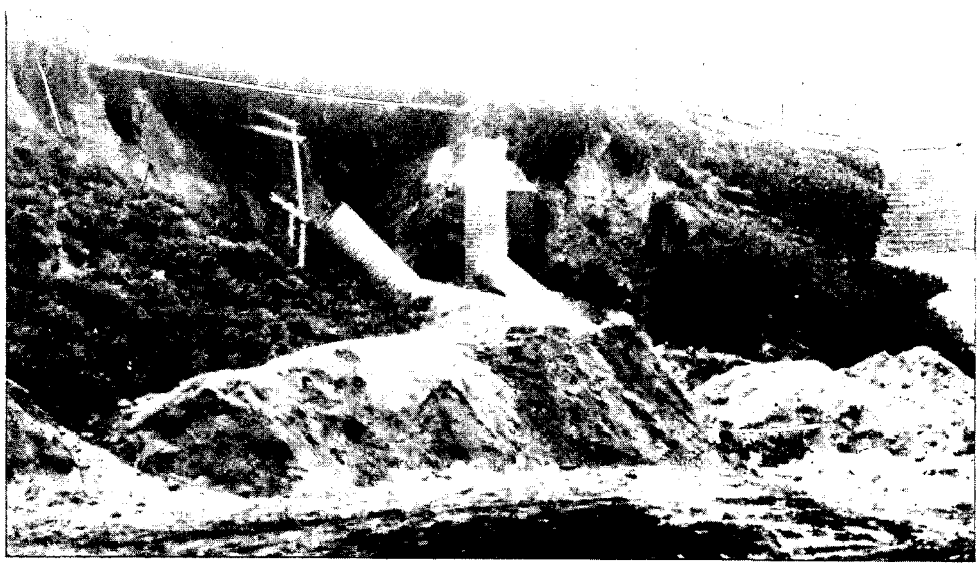


FIGURE 40 Torrance County Park. This view toward land shows damage to drainage conduits and water lines. The erosion was probably due to a combination of waves and runoff.

winter storms, including the most recent, had destroyed a number of homes, although most of the debris from these homes had been removed prior to the visit. Figures 41 through 45 show some of the remaining evidence of damage.

Oxnard Shores

The Oxnard Shores housing development appears to be located on a somewhat transient depositional feature originating by outwash from floods in the Santa Clara River and possibly modification of dunes in conjunction with the development. Storms have caused substantial erosion, requiring that structures be protected from further erosion and direct wave impact (see Figure 46).

Santa Barbara

The Santa Barbara area includes Leadbetter Beach (extending from Santa Barbara Point to the west and to the shore-connecting leg of the breakwater to the east), the outer leg of the breakwater, the spit in the lee of the breakwater, and East Beach (extending from the harbor entrance to the east). Figure 47, a photograph taken in 1979, shows part of this area. Figure 48 shows this same area after the winter of 1982-83.

The most impressive effect of the storms of 1982-83 on the Santa Barbara area was the extent of erosion on Leadbetter Beach. The pocket beach had eroded back well beyond limits that have occurred over at least the past several decades. This undermined the parking lot and removed sand from behind a revetment constructed after the winter storms of 1979-80 (see Figure 9). A profile taken off Leadbetter Beach is presented in Figure 49. Of interest are the presence of the offshore bar and the cobble layer limiting the depth of the trough immediately landward of the bar.

The spit in the lee of the tip of the Santa Barbara breakwater was reduced in elevation by storm wave energy to below mean sea level. Figures 47 and 48 present "before" and "after" oblique aerial views in 1979 and on March 12, 1983, respectively. The flight on March 12, 1983, was conducted at low tide and the spit was barely emergent. At high tide the spit was completely submerged.

Figures 50 and 51 present views looking west along Leadbetter Beach. In addition to undermining the parking lot, erosion caused a number of palm trees to be lost. Figure 52 shows the timber sheet-pile structure extending north from near the tip of the Santa Barbara breakwater. Usually there is a sand spit on both sides of the timber structure up to 1 m above the mean high water level.

East Beach also experienced substantial erosion and undermining of vegetation. In addition, a number of small boats were beached by the storm, an example of which is shown in Figure 53.

FIGURE 41 Construction during low tide of protective revetment fronting a newly installed seawall.

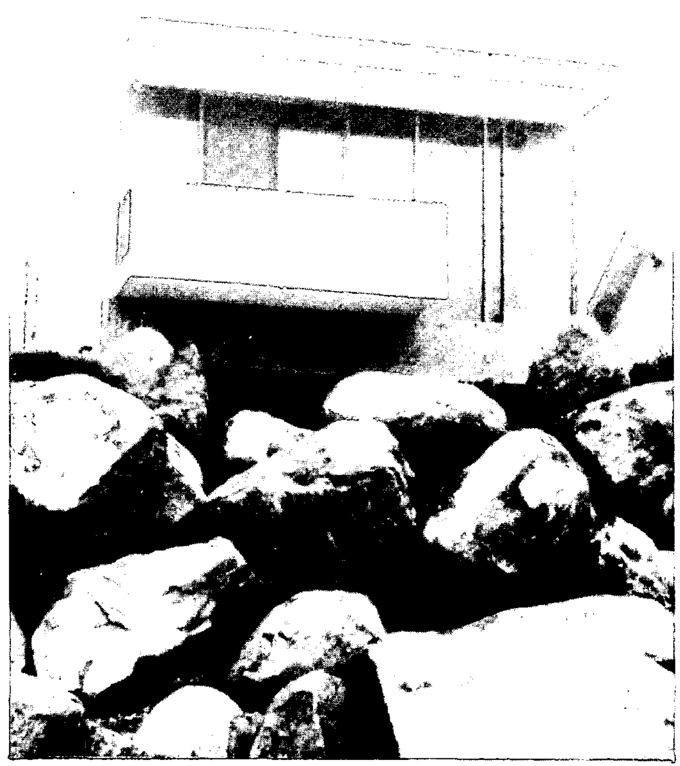


FIGURE 42 Heavy revetment fronting a dwelling in Malibu Beach.

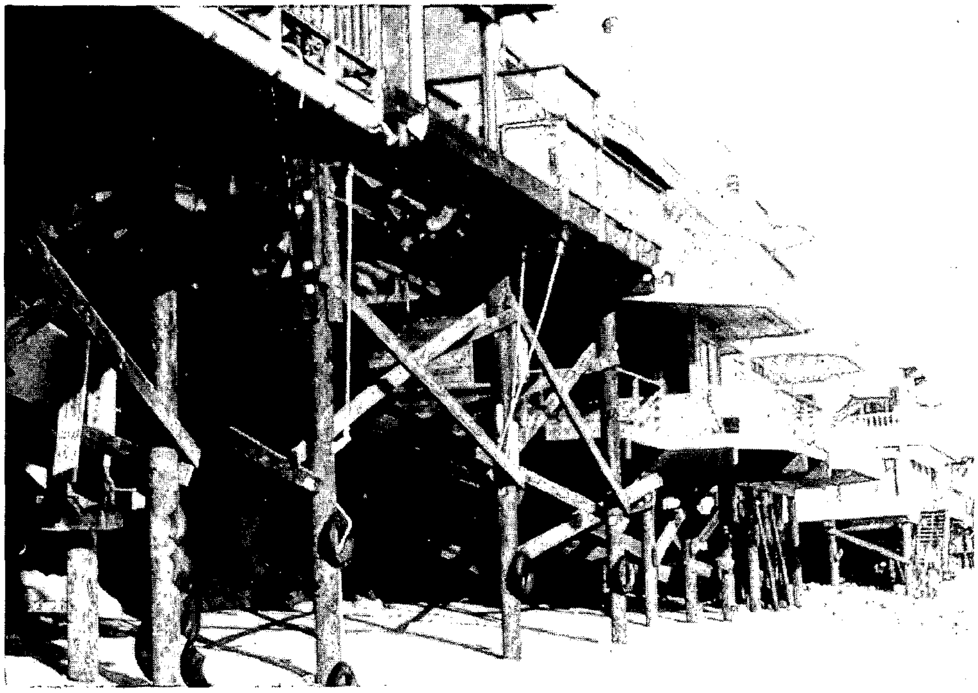


FIGURE 43 Pile-supported structures in Malibu Beach are located near a zone of high wave energy.

FIGURE 44 Location where a dwelling in Malibu Beach was destroyed by waves. Most of the debris had been removed at the time of this photograph.

FIGURE 45 Road damage in Malibu Beach due to wave or runoff erosion.

FIGURE 46 Dwellings in Oxnard Shores located on unstable shoreline.

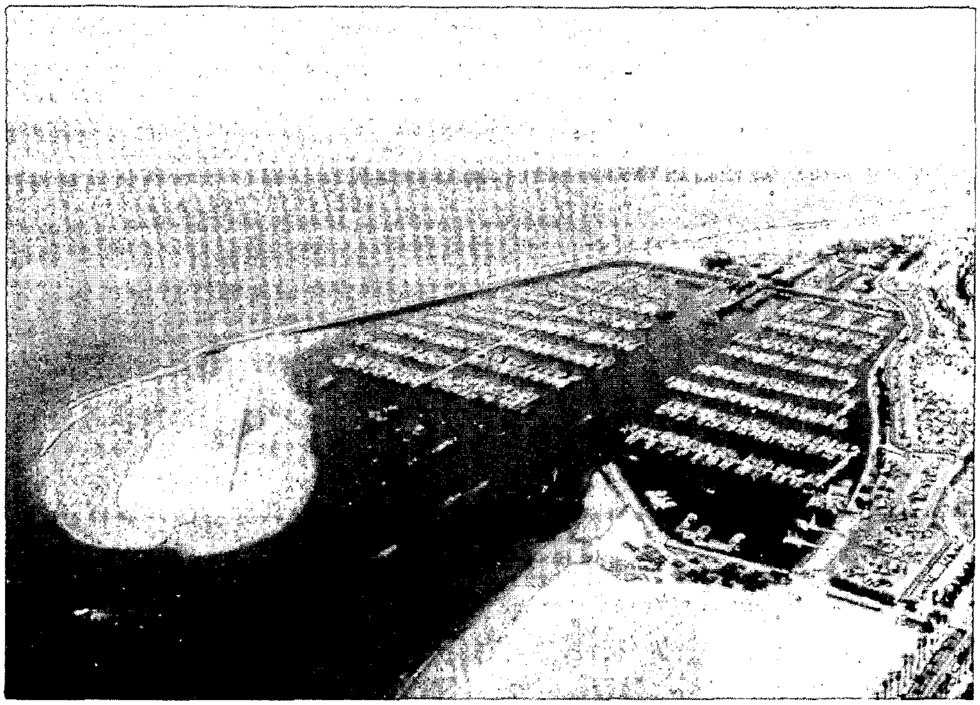


FIGURE 47 The Santa Barbara area looking southwest. The Santa Barbara breakwater with lee spit and East Beach can be seen in this 1979 photograph.

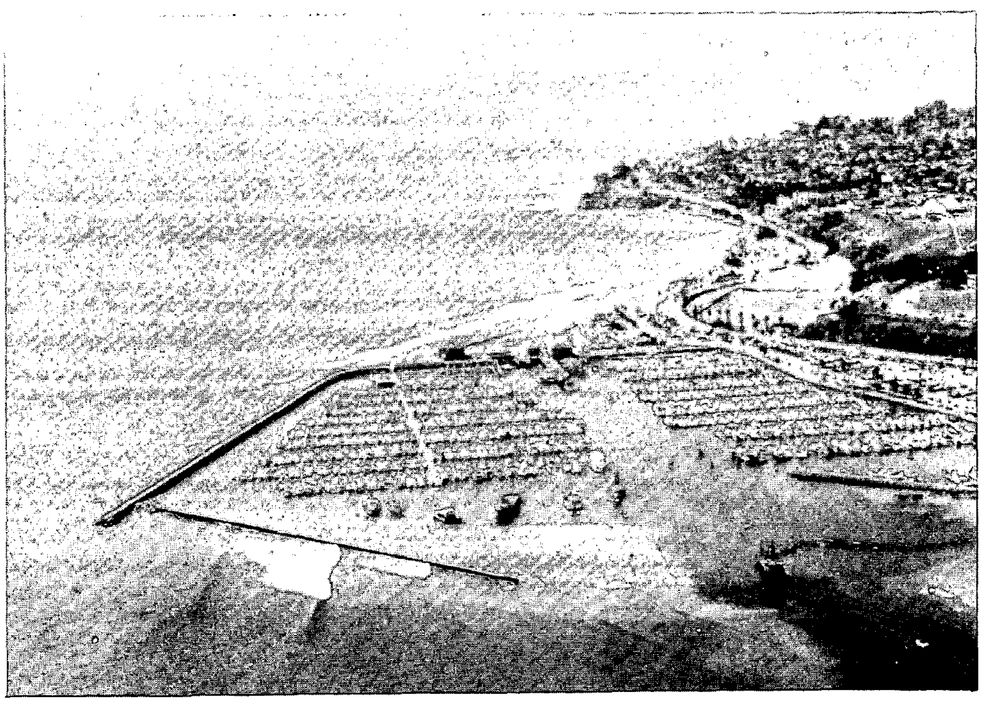


FIGURE 48 The Santa Barbara area. Note the degraded spit and beach areas compared with Figure 47.

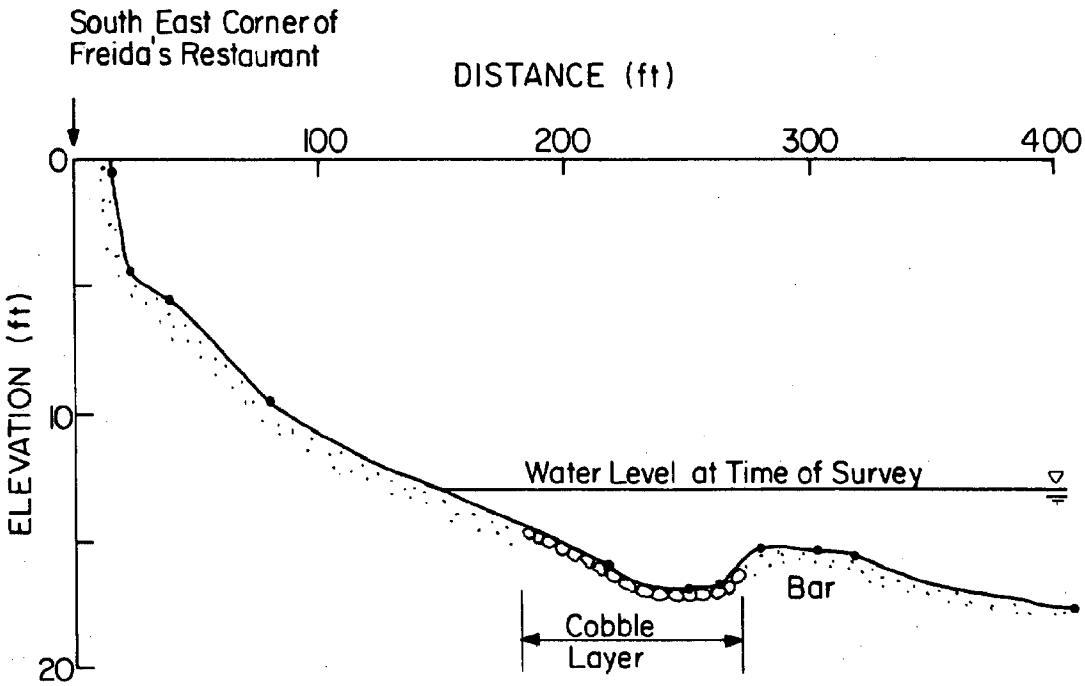


FIGURE 49 Profile taken off Leadbetter Beach in Santa Barbara on March 12, 1983, at 2:30 p.m. The profile heading was 170°.

FIGURE 50 View west along eroded Leadbetter Beach.

FIGURE 51 View west from west end of Leadbetter Beach. The beach and upland were substantially eroded, with the loss of a number of palm trees.

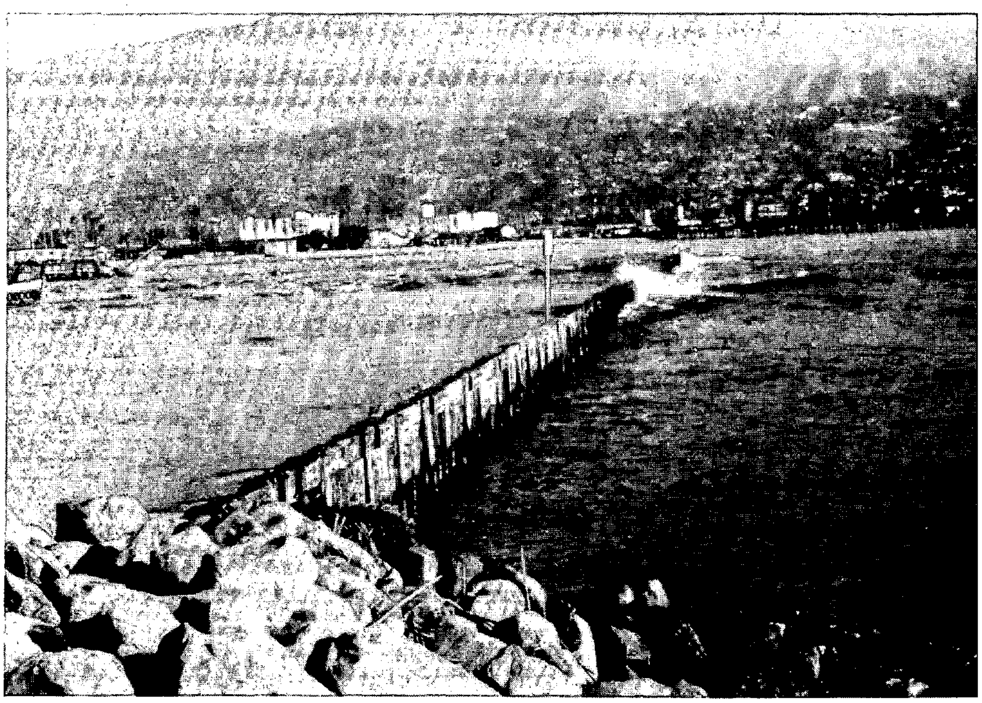


FIGURE 52 View looking north from the base of the timber sheet-pile structure that extends north from the Santa Barbara breakwater.

Rio Del Mar Beach

A number of houses have been constructed along relatively narrow Rio Del Mar Beach in the Via Gaviota and Seascape subdivisions. A fairly substantial revetment, shown in Figure 54, was constructed to protect some of these homes. Where the revetment is not present, some homes were destroyed (see Figures 55, 56, and 57). In other areas the sand elevation decreased by approximately 2 m (see Figure 58).

Pacifica

Portions of Pacifica are marked by fairly high cliffs fronted by nonexistent to narrow beaches. These cliffs appear to have receded substantially during the 1982-83 winter storms. Figures 59 and 60 show the cliff adjacent to a trailer park, which has lost part of its pavement. Immediately north of this site a Masonic Hall was threatened by cliff recession and was being relocated (see Figure 61).

Ocean Beach

Ocean Beach, which is just south of the entrance to San Francisco Bay, is the site of a new sewer outfall that is under construction. In response to substantial erosion (see Figure 62), stone debris, including headstones from a cemetery, was randomly dumped to form a makeshift revetment (see Figure 63). Storms also grounded the offshore construction derrick barge Betty L, which was being used for the outfall project. Attempts were under way during the study team's trip to free this vessel (see Figure 64).

Stinson Beach

Stinson Beach is a spit some 2 km long that partially encloses Bolinas Lagoon. Low-density single-family dwellings are located along the southern kilometer of this beach. The primary effects of the storms evident during the visit were beach erosion, damaged structures, sand washover deposits, and flooding, as shown in Figures 65-70. As noted previously, a sand-filled Longard tube had been constructed earlier, but it had failed and was not apparent during our visit.

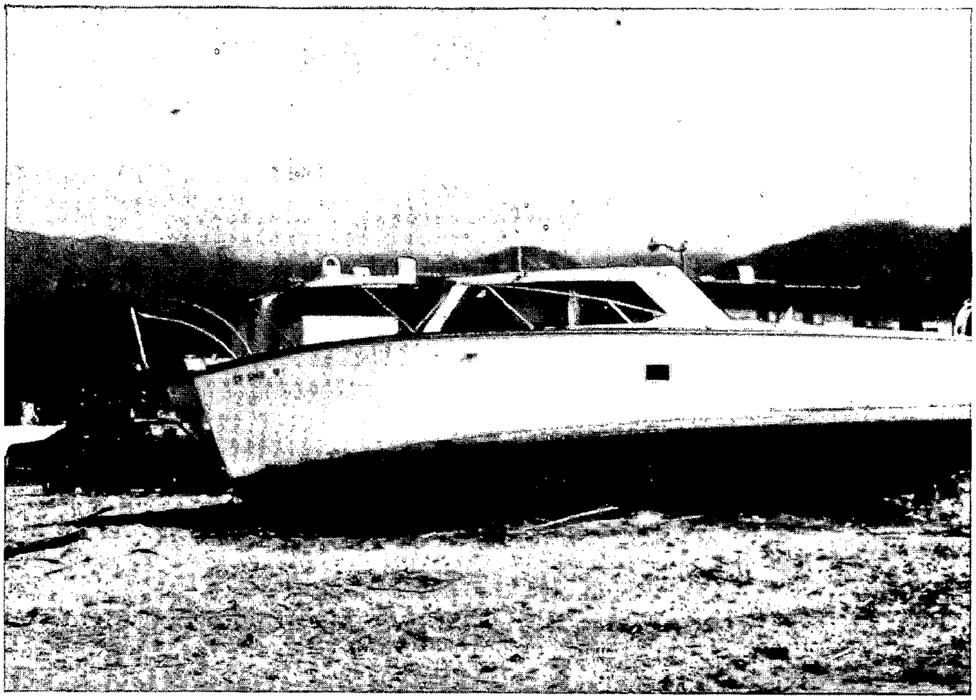


FIGURE 53 Beached boat on East Beach.

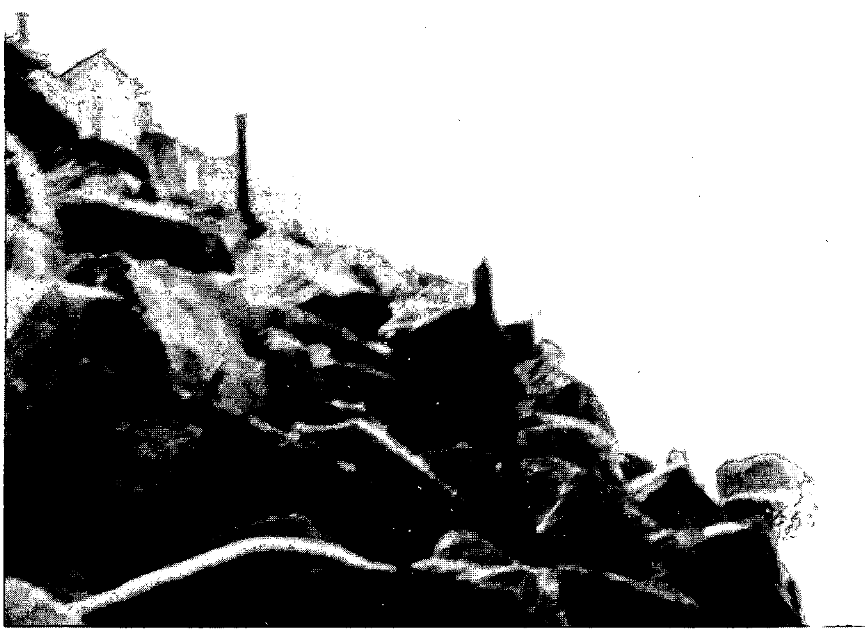


FIGURE 54 Heavy revetment protecting upland structures in Rio Del Mar Beach.

FIGURE 55 Destroyed home in Rio Del Mar Beach. Note the ineffective revetment fronting the structure.

FIGURE 56 Destroyed home in Rio Del Mar Beach fronted by damaged wooden seawall.

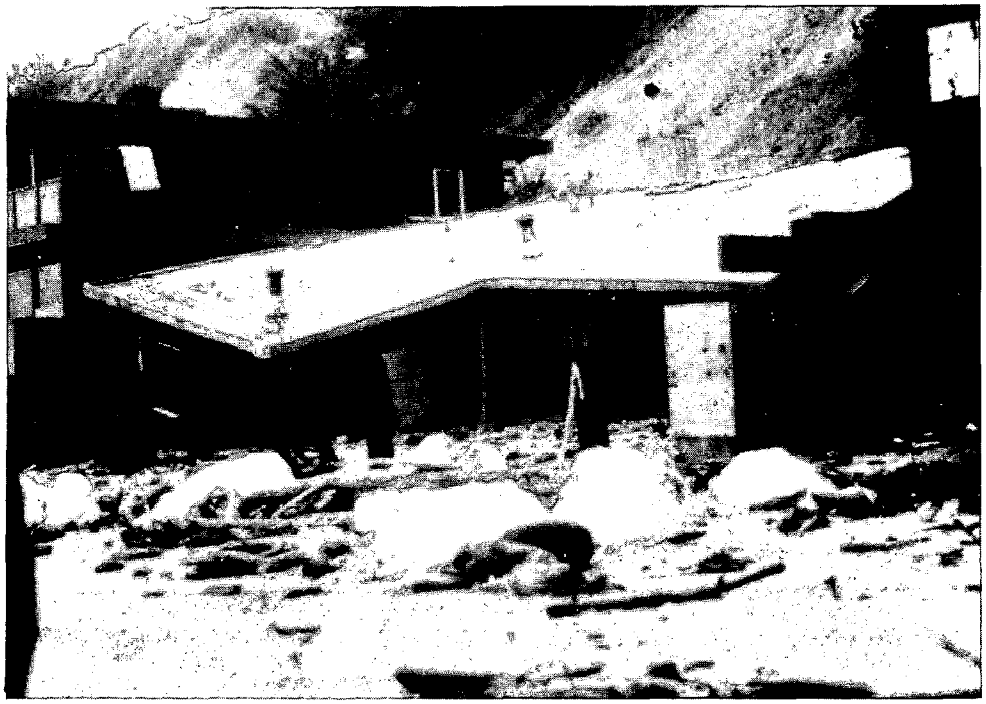


FIGURE 57 Destroyed home in Rio Del Mar Beach with remnants of a poorly designed revetment.

FIGURE 58 Fairly ineffective revetment in Rio Del Mar Beach lowered as a result of scour. The vertical erosion was approximately 2 m.

FIGURE 59 Severe erosion in Pacifica adjacent to trailer park.

FIGURE 60 Vertical scarp of approximately 5 m in Pacifica.

FIGURE 61 Masonic Lodge in Pacifica undercut by wave erosion. The scarp is approximately 10 m high.

FIGURE 62 Beach erosion and road damage at Ocean Beach south of the entrance to San Francisco Bay.

FIGURE 63 Makeshift revetment for road protection at Ocean Beach including headstones from cemetery.

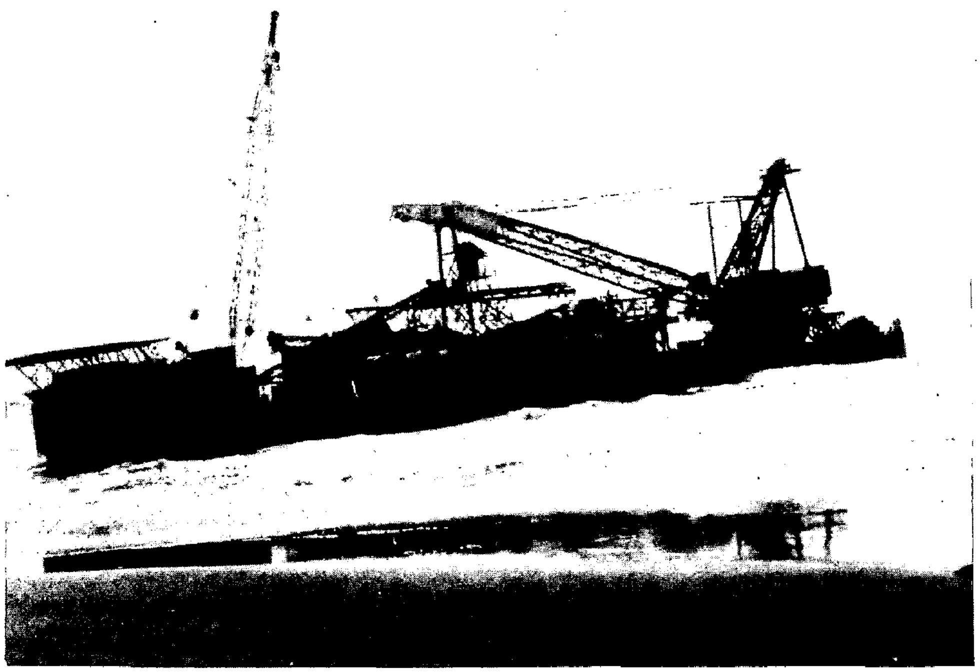


FIGURE 64 The stranded construction barge Betty L at Ocean Beach with efforts under way to free this casualty of the storm.

FIGURE 65 Substantial revetment in Stinson Beach to protect dwellings from erosion and waves.

FIGURE 66 Reinforced concrete seawall in Stinson Beach being constructed.

FIGURE 67 Structures in Stinson Beach damaged and destroyed from erosion undermining and direct action of waves.

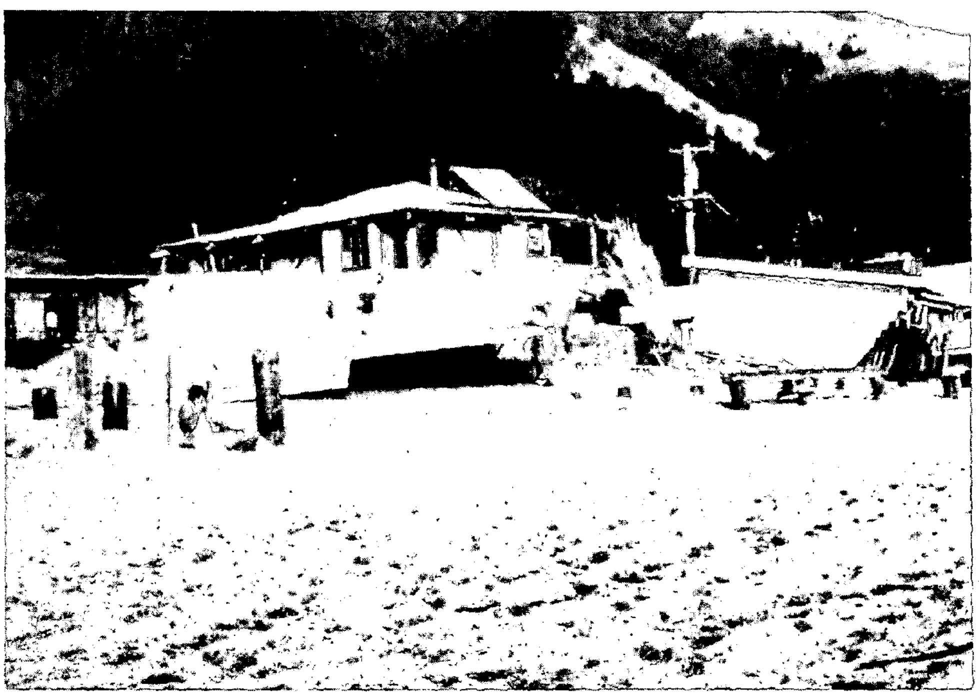


FIGURE 68 Dwellings damaged in Stinson Beach due to erosion undermining and direct action of waves.

FIGURE 69 Overwash deposits of sand deposited approximately one block inland at Stinson Beach.

FIGURE 70 Sandbag barrier at Stinson Beach to prevent flooding from waves and sand deposition from overwash.

5

COASTAL CLIFF EROSION

Coastal cliffs are a common landform along large sections of the geologically young California coast (see Figure 71). The cliffs are the result of active erosion, being subject to periodic retreat during stormy periods. Many of the cliffs consist of relatively soft sandstones, siltstones, and shales, which are highly susceptible to erosion from wave action and surface runoff. Thus in this context the cliff erosion from the winter storms of 1982-83 could and should have been anticipated in many cases. The problem of coastal cliff erosion and retreat is well understood qualitatively and described in the literature (Griggs and Johnson, 1979). However, because the episodes of retreat are relatively infrequent and the overall rate is deceptively slow, property owners tend to have a false sense of permanency and security.

The actual process of cliff erosion and slope retreat and its rate depend to a large extent on the type of material involved. The weathering and erosion of the predominantly sandy rocks in California lead to the accumulation of talus and the formation of sandy beaches. The talus and the beach protect the toe of the slope from wave erosion between major storms, as shown in Figure 71. In areas underlain by stronger, more cohesive rocks, there is often not enough sandy material to form the beaches and the waves tend to lap directly at the toes of the cliffs (see Figure 72). In both cases, however, the rates of cliff retreat tend to be relatively slow in the periods between large storms.

Failures, when they occur, tend to be the result of large eposidic events such as storms or earthquakes. For slopes protected by sandy beaches, the storm waves and tides must be sufficiently large to remove the protective sand before the waves can attack the slopes themselves. Once this occurs, the rate of cliff erosion can be very rapid. For example, in Pacifica more than 15 m of erosion occurred in the span of one month (see Figure 61). Cliffs that are not protected by beaches will obviously be exposed to significant wave action more often, but even then major failures, such as the one shown in Figure 71, will be relatively infrequent and more likely to occur during large storms. Overall, these infrequent failures result in a slow but steady average retreat of coastal cliffs, often at a rate of less than 30 cm per year. More important, a lack of erosion over a period of a few years is not evidence that the retreat of coastal cliffs has been halted.

FIGURE 71. Steep cliff in weak sandstone at Pacifica. Note the wide beach and talus at the base of the slope.

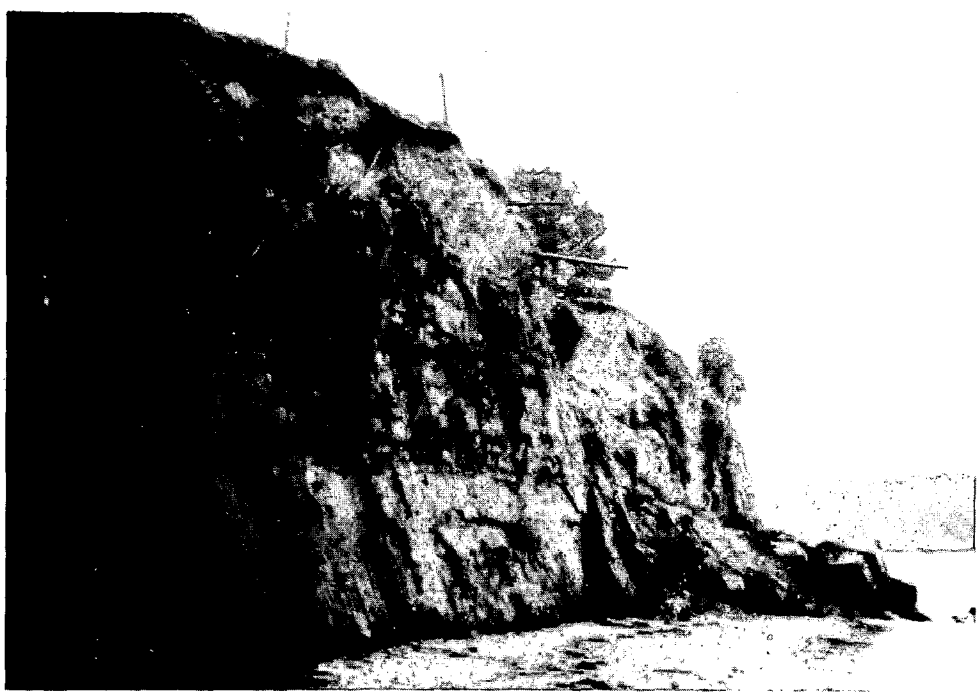


FIGURE 72 Failure of coastal cliff at Capitola.

The winter storms of 1982-83 caused localized cliff erosion. However, it was not possible to quantify this erosion.

COASTAL CLIFF STABILIZATION

Two modes of failure should be considered when protective measures are being contemplated. The first, and most obvious, is toe erosion by water action; the second, and more subtle, is landsliding caused by a decrease in the strength of rocks due to weathering.

In areas with wide beaches, a protective sand berm that would be eroded by the storm waves could provide sufficient protection. The berm could require annual reestablishment before each storm season. In areas without the necessary beach, or where a more permanent solution is desired, the only alternative is to protect the slopes with heavy armoring of either riprap or concrete. In such cases, however, it is necessary to protect the rest of the slope from run-up by deflected waves. This typically means protecting the entire slope by a concrete or a shotcrete wall. Schemes such as this are expensive and are difficult to apply to small sections of the cliffs because erosion will continue on adjacent slopes, threatening to surround and undermine the stabilized sections.

In general, protective structures for coastal cliffs tend to be very expensive and must be carefully designed to serve their intended function. In the absence of protective measures, continual erosion should be assumed in establishing setbacks for structures.

6

SUMMARY AND RECOMMENDATIONS

Substantial damage occurred to coastal structures and beaches in California as a result of the winter storms of 1982-83. The basic reasons for this damage and possible approaches to mitigating future damage are discussed below.

Sea level is undergoing a long-term relative rise, which generally results in a net transport of sand offshore. This process tends to restore equilibrium to the beach and offshore profile. This slow but persistent removal of sand exposes cliffs and dunes to wave attack, which generates material for beach formation, offshore transport, etc. Thus, beach erosion is a natural process as the sea level rises, as evidenced by the geomorphology along much of the California coast. Humans have also contributed to the net and local erosion by damming rivers and building certain types of coastal structures, respectively.

Given this gradual erosional trend, fixed structures located along the shoreline will eventually be exposed to damaging forces such as those accompanying the 1982-83 winter storms. Unfortunately, few approaches are effective in preventing damage to upland structures, and these few are generally expensive. The two general options are armoring and beach nourishment. Expensive armoring can be designed to withstand the forces of quite severe storms. The beach will still be lost, however, due to the slow general retreat of the shoreline. Similarly, where economics justify, nourishment can be effective over very long periods.

It appears that the best way to plan coastal development is by understanding the natural and human-related processes that change the shoreline. Especially important is a knowledge of the rates of erosion. Some areas are relatively stable, and in most locations erosion is reasonably slow. In these latter locations, rather moderate expenditures may reduce the erosion rate substantially. The coastal study program currently being conducted in California by the U.S. Army Corps of Engineers should contribute to a better understanding of many of these problems.

Listed below are specific problem areas in which additional research is needed to understand better the problem of shoreline erosion in California. Results from research such as this would improve the basis for anticipating coastal storm damage and for choosing the best ways to mitigate such damage.

1. The role of waves, onshore winds, and high tides--especially when occurring together--in accelerating erosion. An erosion index (for potential erosion) should be developed as a function of causative factors.

2. The role of offshore bars in limiting the potential for beach erosion. These studies should include field measurements of beach recovery through the shoreward migration of bars. The intent would be to evaluate the effect of a succession of storms at time intervals shorter than that required for beach recovery. Why do bars seem to form on some beaches and not others?

3. Methodologies and studies of sand budgets. These studies should examine reduced sand supplies from rivers and streams, submarine canyons as sinks, and reduced sand supplies due to cliff armoring.

4. The roles of land subsidence and sea level rises in the processes of shore erosion and in requirements for beach nourishment.

5. The effectiveness of various means of mitigating shoreline erosion, including structures and nourishment. These studies should include field measurements of sediment transport around structures.

6. The gathering of quality video documentation of storm effects and damage. Such a long-term program would be a valuable educational tool both for the general public and for students in engineering and scientific programs. An example of the impact possible through such documentation is that made by the films of the failure of the Tacoma Narrows Bridge.

7. The short-term and long-term benefits of toe protection along cliffs.

8. The effect of a cobble underlayer in limiting erosion.

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