

## CHAPTER ONE HUNDRED EIGHTY NINE

### COASTAL DESIGN CRITERIA IN SOUTHERN CALIFORNIA

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#### ABSTRACT

Southern California was subjected to a series of severe winter storms in 1983 that caused record damages to the coast. In the aftermath of the storms, emergency repairs were made and new designs were developed that responded to the severe conditions. These designs were often considerably more conservative than those previously undertaken. Agencies, owners, and engineers were compelled to use both higher design criteria and longer recurrence intervals to account for the wave characteristics and water levels that caused damages along the coast. This paper briefly discusses the unusual circumstances of the storm conditions and the associated damages. The primary purpose of the paper is to present new data that incorporates the effects of the 1983 winter storms to estimate the change in perception of what the wave climate and design criteria may be in this highly developed coastline. The results indicate that the design wave height for a given recurrence interval has increased approximately 26 percent, the wave periods are longer than previously used, and the severe storms tend to coincide with the extreme water levels. The engineer should consider the impacts of the 1983 winter storms in future designs. Despite the record damages, many structures survived. Merely using the highest water elevations and most severe waves of record may not be the most prudent design criteria. The concept of project life and economics must be employed to develop a design.

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## INTRODUCTION

A series of intense storms during the winter of 1983 caused extensive damages to the Southern California coast. Several piers, breakwaters, revetments, homes and beaches were damaged due to a combination of unusually high waves with long periods from an unusual direction of approach coincident with high water elevations. In the aftermath of the storms, public outcry was for more stringent design criteria. Newspapers across the state quoted expert opinion that the wave conditions and water elevations experienced in 1983 were only the beginning of a long-term trend of severe weather for the state and the 1983 storms should be used as the new design storms. The addition of new storm waves and water levels plus the increase of design recurrence intervals may result in an unwarranted compounded increase in design criteria.

## RECENT COASTAL DAMAGES

The winter of 1983 was characterized by several extreme extratropical storm events that occurred during high water levels. The storm events were among the strongest of recorded history; the water levels were the highest of recorded history. The severity of the storm events and the high water levels have been associated with the El Nino-Southern Oscillation (ENSO) as described by Seymour, Strange, Cayan and Nathan (11). These storms were estimated by the U.S. Army Corps of Engineers and the State of California (14) to have caused in excess of \$116 million to coastal structures. Figure 1 shows a summary of the piers that were damaged and Figure 2 is a summary of the breakwaters and jetties that were damaged. Over 70 percent of the damages occurred in Southern California. Several beaches lost considerable quantities of sand and there was conjecture that these beaches would never return because the sand was carried too far offshore to return under normal wave conditions. Many coastal streets, utilities, homes and restaurants were flooded by overtopping waves and high water levels. An oil island located off Seal Beach was completely destroyed. Many of the destroyed structures had survived for 80 years with only minor repairs. Other structures were in need of repair prior to the storms. The primary factors in the damaged structures appear to be the extreme high water level and the high waves with unusually long wave periods approaching from a westerly direction.

Two examples of damages were the San Pedro Breakwater and the San Clemente Pier. The San Pedro Breakwater that protects Los Angeles Harbor was built in the early 1900's. Overtopping waves caused a 400-foot (122 meters) long gap after 80 years of service. A post-storm survey by the U.S. Army Corps of Engineers (13) indicated that there were 166 repair areas to the breakwater and that 87 percent of the failures were on the backslope. Walker, et al. (15) explains the failure mechanism due to excessive water levels and wave heights in relation to the crest elevation. Another mode of failure was the possibility that the stone size was not sufficient for the storm event. The breakwater was repaired by the U.S. Army Corps of Engineers in a manner similar to the original construction.

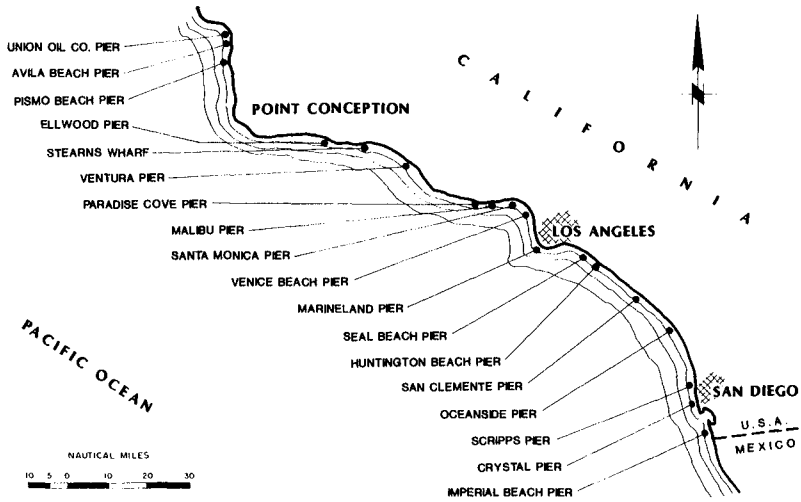


Figure 1. Pier Damage

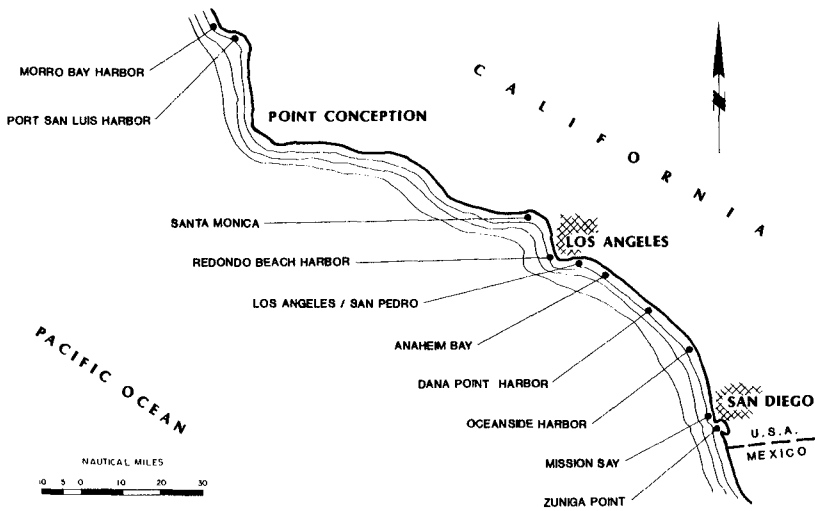


Figure 2. Breakwater and Jetty Damage

The San Clemente Pier was a wooden pile structure that lost approximately 500 feet of the seaward end. Figure 3 shows the existing pier elevation and depth-controlled breakers. Two wave crest elevations are given. The one labeled "prior to 1983" represents the depth-controlled breaker on a 6.0-foot (1.8 meters) mean lower low water elevation that was used as the original design criterion. The wave crest elevation labeled "1983" represents the depth-controlled breaker on a recorded 7.5-foot (2.3 meters) mean lower low water elevation that was measured in San Diego Harbor during one of the events in 1983 that damaged the pier. In this case, damage was attributed to the combination of the wave crest exceeding the pier deck, scour at the sea bed, excessive wave-induced forces on deteriorated piles, and broken pile debris impacting on other piles. Arbitrarily raising design criteria in one aspect may not solve all of the problems. The damage can be readily described using normal water elevations without the need to resort to wave setup and other factors that could raise the water level by 2.0 to 3.0 feet (0.6 to 0.9 meters).

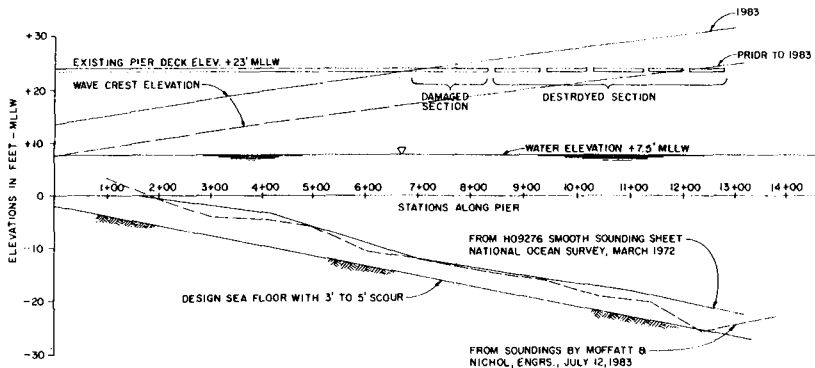


Figure 3. San Clemente Pier

#### EFFECTS OF 1982-1983 WINTER

The ENSO of 1982-1983 was exceptionally strong and had several effects that lead scientists and engineers to suspect that there may be a correlation between high water levels and storm events. When strong ENSOs occur, the water levels are increased, the extratropical cyclones approach from more westerly directions and are closer to the coast, wave heights are higher and periods are greater [see Seymour, et al. (11)]. Shoreline segments that are typically sheltered by the offshore islands and refraction effects from northwesterly waves were more directly exposed to the westerly waves.

### Water Elevations

Prior to 1983, water levels were based primarily on the recordings of nearby harbors such as the gages at Los Angeles and San Diego. These gages incorporated the effects of astronomical tides, ENSO anomalies and some components of storm surge such as the barometric effect. Designers would often add a foot to some water level to account for storm surge and wave setup.

Table 1 is a summary of design water elevations taken from design documents<sup>1</sup> over the last 40 years for typical shore protection structures. Design water elevations were typically lower than the highest of record. The rationale for this was that the probability of the design wave occurring at the same time as the highest water elevation is small. Design water elevations for shore protection structures have increased from mean higher high water [5.4 feet (1.6 meters) above mean lower low water] in the 1940's and 1950's to 10.0 feet (3.0 meters) above mean lower low water in 1984. Design reports showed an increase of 2.0 to 4.0 feet (0.6 to 1.2 meters) following the 1983 winter storms.

TABLE 1

#### Design Water Elevations

1940's - 50's: 5.4 to 6.0 feet (1.6 to 1.8 meters) above MLLW  
1960's - 70's: 6.0 to 7.0 feet (1.8 to 2.1 meters) above MLLW  
1980's: 7.0 to 7.5 feet (2.1 to 2.3 meters) above MLLW  
After 1983 storms: 8.0 to 10.0 feet (2.4 to 3.0 meters) above MLLW

In Southern California, the highest tides of the year usually occur in January; the same month which extratropical storms frequently occur. Record-high water elevations of 7.96 feet (2.43 meters) above mean lower low water and 8.35 feet (2.55 meters) above mean lower low water were recorded on January 27, 1983 at Los Angeles and San Diego, respectively. At the same time, deepwater significant wave heights up to 27.0 feet (8.2 meters) were recorded offshore. The previous record-high water elevations occurred on November 30, 1982. The recorded elevations were 8.09 feet (2.47 meters) above mean lower low water at San Diego and 7.76 feet (2.37 meters) above mean lower low water at Los Angeles.

Recorded annual extreme high water elevations obtained from the National Ocean Service for the San Diego Bay and Los Angeles Outer Harbor reference tide stations were statistically analyzed using the Gumbel (also termed Fisher-Tippett I) distribution. The "tide year" was defined as September to the following August such that the winter season is included within the year. Water elevation records from the San Diego station are available from 1926; Los Angeles water elevation records are available from 1923.

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<sup>1</sup>The principal source is U.S. Army Corps of Engineers, Los Angeles District, General Design Memorandums.

Figure 4 is a plot of the annual extreme high water elevations versus recurrence intervals for the San Diego and Los Angeles stations, respectively. For each station, the dashed line is a plot of the annual extremes prior to the 1982-1983 record-high water elevation; the solid line is a plot of the annual extremes which have incorporated the record-high water elevation into the data set.

Comparing annual extreme high water elevations at the Los Angeles tide station before and after the 1982-1983 record-high water elevations show that an 8.0-foot (2.4 meters) mean lower low water elevation prior to 1982-1983 has a recurrence interval of approximately 130 years. When the record-high water elevation is added to the data set, the recurrence interval for an 8.0-foot (2.4 meters) water elevation is now approximately 80 years. A 10.0-foot (3.0 meters) mean lower low water elevation with the 1982-1983 water elevation included in the data set has a recurrence interval greater than 500 years. A similar trend is shown for the San Diego Harbor station.

#### Wave Characteristics

Selection of design wave characteristics for coastal structures in Southern California is either based on published hindcasted wave data for a station in deep water or on a hindcast for a specific site. The published data sources typically used in Southern California are hindcasted wave data from the most severe storms occurring between 1900 and 1957 by Marine Advisers (5), from 3-year hindcasts by Marine Advisers (6) and by National Marine Consultants (9), or from once-daily wave computations from 1951 to 1974 by Meteorology International Incorporated (7). Measured wave data which was available during these periods formed short records or records with notable gaps during high wave episodes. Design waves were therefore obtained strictly through hindcast techniques, which differed considerably as a result of a number of factors. First, and most important, is the lack of good meteorological data from ships at sea prior to the mid-1940's. Compounding the problem is the fact that wave forecast techniques differ appreciably among themselves and all utilize empirical wave data collected in the Atlantic, not the Pacific. The same forecast techniques can produce different results when used independently by meteorologists whose experience in the field may differ.

The Marine Advisers (6) and National Marine Consultants (9) wave hindcasts were presented as monthly and annual averages and do not include specific storm wave characteristics. The Marine Advisers (5) and Meteorology International Incorporated (7) do include extreme storm wave characteristics over periods of 58 and 24 years, respectively. The Marine Advisers hindcasts have been used extensively but the Meteorology International Incorporated hindcasts have been judged to be deficient [see Cross (12) and Strange (12)]. For example, only four storms producing combined wave heights of 16 feet (5 meters) or more in twenty-four years were noted. Two of these were not during the storm season, and none of the well-documented high wave episodes are reflected in the statistics. Results of this hindcast have been studied in detail with the conclusion that there are major problems with the methods employed. Therefore, no further

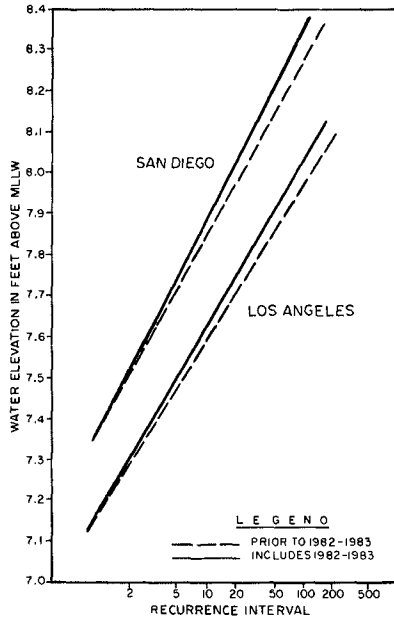


Figure 4. Water Elevation vs. Recurrence Interval

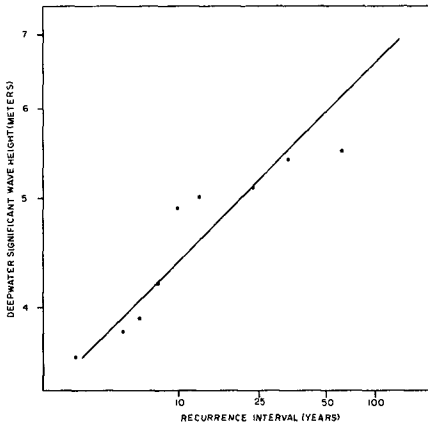


Figure 5. Wave Height Distribution, 1900-1957

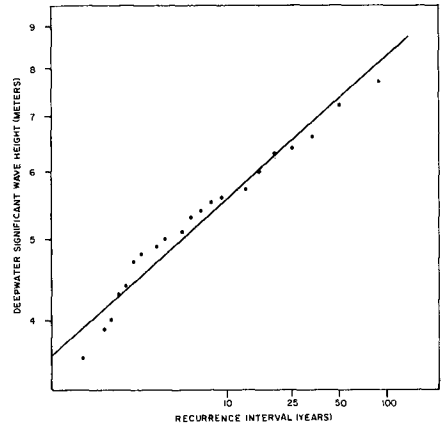


Figure 6. Wave Height Distribution, 1900-1983

consideration is given to the Meteorology International Incorporated wave hindcasted data for purposes of this paper.

The Marine Advisers (5) hindcast study was prepared for the U.S. Army Corps of Engineers to evaluate characteristics of severest probable waves as a basis for design of small-craft harbor protective structures at Oceanside and Dana Point. This study has subsequently been used to determine design waves for other marinas, seawalls, and offshore oil platforms from San Diego County to Los Angeles County. Weather maps, newspapers, and ship observations from 1900 to 1957 were examined. Fifteen storms were selected based on reports for their general severity or coastal damage. Two of the fifteen selected storms gave lower wave heights than anticipated and were thus excluded. Table 2 is a list of the hindcasted results in an exposed deepwater location for the remaining 13 storms.

TABLE 2

Hindcasted Maximum Significant Wave Characteristics  
in Deep Water for 1900 to 1957

<u>Date</u>	<u>H<sub>s</sub></u> <u>(Feet)</u>	<u>T</u> <u>(Seconds)</u>	<u>Azimuth</u> <u>(Degrees)</u>
9-10 Mar 1904	17.9	12.0	225
8-10 Mar 1912	17.5	11.5	270
16-17 Dec 1914	13.0	9.9	180
28-30 Jan 1915	16.3	11.8	205
1-3 Feb 1915	16.5	12.4	280
26-28 Jan 1916	14.0	9.6	250
1-2 Feb 1926	12.6	16.0	260
6-8 Apr 1926	11.8	13.8	270
6-12 Dec 1937	11.6	16.4	270
15-25 Sep 1939 <sup>a</sup>	26.9	14.0	205
20-23 Jan 1943	16.2	10.8	180
13-14 Mar 1952	11.7	11.7 <sub>p</sub>	250
6-8 Jan 1953	16.0	19.2 <sup>b</sup>	260

<sup>a</sup>tropical storm

<sup>b</sup>15.0 to 15.8 seconds was recorded at Camp Pendleton

Source: Marine Advisers (5).

Following the 1983 storms, the Marine Advisers severe storm hindcasted wave data set was updated with wave hindcasts prepared by Pacific Weather Analysis (10) for severe storms occurring between 1958 and 1983 in Southern California in deep water outside the offshore islands. Table 3 is a summary of the maximum wave characteristics hindcasted for each of the storms by Pacific Weather Analysis.

Direct comparison of Tables 2 and 3 is not statistically valid. The wave hindcasts were prepared using different procedures, different quantities of synoptic data, different time periods, and varying degrees of experience which have calibrated wave hindcasts with



TABLE 3

Hindcasted Maximum Significant Wave Characteristics  
in Deep Water for 1958 to 1983

<u>Date</u>	<u>Classification</u>	<u>H<sub>s</sub></u> <u>(Feet)</u>	<u>T</u> <u>(Seconds)</u>	<u>Azimuth</u> <u>(Degrees)</u>
Jan 1958	sea	9.0	9-10	280
	swell	15.2	13-14	270
	summation	18.1	13-14	-
Apr 1958	sea	7.4	8-9	280
	swell	20.0	17-18	293
	summation	25.1	17-18	-
Feb 1960	sea	14.2	11-12	290
	swell	15.3	18-19	294
	summation	18.3	18-19	-
Feb 1963	sea	11.8	10-11	150
	swell	15.9	14-15	269
	summation	19.5	13-14	-
Sept 1963 <sup>a</sup>	swell	10.3	14-15	167
Feb 1969	sea	7.5	8-9	280
	swell	14.3	14-15	284
	summation	15.6	14-15	-
Dec 1969	swell	14.4	20-21	276
Aug 1972 <sup>a</sup>	swell	11.6	17-18	156
Jan 1978	sea	5.1	7-8	290
	swell	16.6	16-17	284
	summation	18.6	16-17	-
Feb 1980	sea	10.3	9-10	220
	swell	15.3	13-14	255
	summation	15.6	14-15	-
Jan 1981	swell	15.4	17-18	265
Jan 1981	sea	4.8	6-7	210
	swell	21.1	15-16	269
	summation	21.5	15-16	-
Sept 1982 <sup>a</sup>	swell	10.1	17-18	158
Nov 1982	sea	17.1	12-13	290
	swell	17.6	14-15	293
	summation	20.4	10-11	-
Jan 1983	sea	7.3	8-9	160
	swell	19.7	20-21	283
	summation	21.0	20-21	-
Feb 1983	sea	3.5	5-6	320-340
	swell	16.7	16-17	275
	summation	17.1	16-17	-
Mar 1983	sea	12.6	11-12	160
	swell	22.3	18-19	263
	summation	23.6	18-19	-

<sup>a</sup>tropical storm

Source: Pacific Weather Analysis (10)

recent wave measurements. The proper procedure would be to update all storms of record using similar hindcast procedures. Such an effort was not possible for the purposes of this paper. It was assumed that the methodologies of the two hindcasts are similar enough to permit a reasonable estimate of wave height distribution over the entire period of record.

The extreme wave statistics presented in Tables 2 and 3 have waves from two meteorological sources: extratropical storms and tropical storms. The most frequent and severe waves are due to the extratropical storms. However, the largest hindcasted wave event of record was the 1939 tropical storm that made landfall in Southern California. The three maximum tropical storm swells in Table 3 are included for comparison with the 1939 event. The 1939 tropical storm is usually treated as a rare event and is not included as a design condition for most structures. However, the consequences of damages in the event that another tropical storm similar to the 1939 storm occurs should be considered in design of structures.

The distribution of wave heights without the tropical storms which were used prior to 1983 and after 1983 are compared. Rather than select one probability distribution a priori, five different distributions as described by Isaacson and MacKenzie (4) are fitted to the wave data using a least squares fit; the best-fit curve is then selected among the log-normal, Gumbel, Fretchet, Weibull lower-bound, and Weibull upper-bound distributions. The selected distribution for both data sets is the Weibull lower-bound.

The deepwater wave height distribution for Southern California using the Marine Advisers data set without the 1939 tropical storm is shown in Figure 5. The 100-year recurrence interval wave height is 6.6 meters (21.7 feet). Figure 6 shows the effect of including the severe waves of 1983 and the addition of hindcasts from 1958 to 1983 without the tropical storms. The 100-year recurrence interval wave height is now 8.3 meters (27.2 feet). The additional data increased the 100-year recurrence interval wave height in deep water outside the offshore islands by 25.8 percent.

Measured and hindcasted wave data indicated that peak energy periods were much longer than previously considered. The measured data were from NOAA buoys recently installed in deep water off the coast of California. Prior to the recent storms, typical design waves had periods of 10 to 14 seconds. Some previously used hindcasted data sets indicated that waves of 14 seconds or more existed only as low forerunners. The buoy data on the other hand as shown in Table 4, indicate that rarely is there a high wave episode with peak energy periods below 14 seconds. The peak wave energy periods for the 1983 winter storms ranged from 14 to 25 seconds and these were associated with the peak wave heights.

TABLE 4

Storm Summary of Wave Period

Wave Period (seconds)	Number of Events			
	Marine Advisers	Meteorology International Inc.	Pacific Weather Analysis	NOAA Data Buoy
	1900-1957	1951-1974	1958-1983	1980-1984
9				
10	1	3		
11	2	1	1	
12	2			
13				
14	1		2	
15			2	
16			1	
17			2	4
18			2	1
19	1		2	
20				2
21			2	
22				1
23				
24				
25				1

Another characteristic of the 1983 storms was the direction of wave approach. The storm waves approached from a more westerly direction than normal; 280 degrees in the 1982-1983 winter as opposed to a long term average of 290 degrees. Areas typically sheltered by offshore islands or by refraction effects, such as the Los Angeles Harbor were directly exposed to storm waves as shown in Figure 7. The pre-frontal winds also generated local seas from the south that were higher than normal, and in some cases arrived simultaneously with the westerly swell.

## DISCUSSION

The recent storm events of 1983 have dramatically changed the concept of design criteria. Not only have the individual parameters of wave height, wave period, and water level changed, but also the simultaneous occurrence has been revealed as more likely. The extreme storm events of 1983 would have been classified as having wave heights with over 100-year recurrence intervals prior to their occurrence. The storm waves are now considered to have recurrence intervals on the order of 40 years. These individual storm waves must be brought to shore past the offshore islands and refracted across locally complex bathymetry to nearshore sites. Recurrence intervals are therefore likely to show wide variation from site to site. For instance, design calculations for the San Clemente Pier indicate that the recurrence interval for wave heights hindcasted during the March 1983 storm which would be directly exposed to the site is 100 to 150 years.. [see Moffatt & Nichol, Engineers (8)]. A blanket acceptance

of this storm and the exceptional water levels for all coastal sites and problems may lead to unrealistic design requirements. The engineer needs to analyze the data at the particular site including the particular design circumstances such as safety aspects, economic consequences of the design parameters being exceeded, and the particular experience with similar structures. These data should be discussed with the client to evaluate the risk levels involved; it should be recognized that rare and unusual events can and do occur.

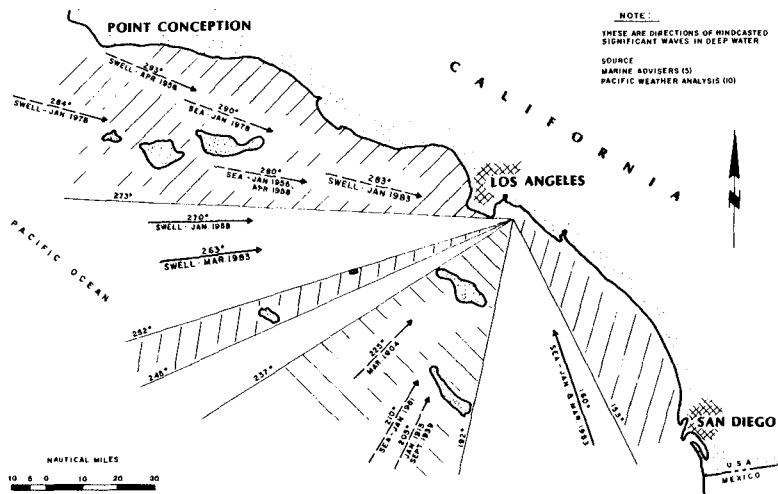


Figure 7. Wave Exposure

The extreme high water levels measured in 1983 coincident with the severe storm waves have caused coastal flooding that has not occurred in the past. This has prompted designers to look for justification for higher design water levels. Review of some of the recent design reports by the authors indicate a compounding of water levels has occurred. For instance, the record-high water level measurements include astronomical tide, barometric tide, sea level rises, and ENSO effects. Addition of 1.0 or 2.0 feet (0.3 to 0.6 meters) to account for these effects appears to be a duplication of the effects. Review of Figure 4 indicates that the 100-year recurrence interval water elevation should be on the order of 8.0 feet (2.4 meters) above mean lower low water at Los Angeles Harbor and about 8.3 feet (2.5 meters) above mean lower low water at San Diego Harbor.

Care should also be exercised in application of the wave setup term. Wave setup varies as a function of the breaking wave characteristics and relative position in the surf zone. For instance, the breaker point has a set down and setup is a maximum at the beach. Large waves persistently breaking offshore may induce a setup on the beach which raises the water level near the shoreline, but not at the seaward end of a pier.

## CONCLUSIONS

The following specific conclusions regarding the relation of the 1983 winter storms to previously used criteria which has been used in design of many coastal projects in Southern California are presented. These conclusions are presented to document the relative importance of the recent storms and to discuss their potential impact on future design policies. No attempt is made herein to establish a specific design criteria.

1. The deepwater wave height for a 20-year recurrence interval and a 50-year recurrence interval has increased from 16.5 and 19.5 feet (5.0 and 6.0 meters) to 21.5 and 25.0 feet (6.5 and 7.6 meters), respectively.
2. The wave period associated with an extratropical storm has increased from a range of 10 to 14 seconds to 14 to 25 seconds.
3. Severe storms usually approach from a more westerly direction during ENSO events.
4. The simultaneous occurrence of an extreme water level and extreme wave event must be considered as dependent events to a greater degree than has been customary.
5. The 1982-1983 winter had three of the top five extreme wave events in deep water over the past 80 years.
6. The coastal damages which occurred were due to a combination of factors including extreme water level, extreme wave height, extreme wave period, direction of approach which exposed segments of shoreline that are traditionally protected by the offshore islands, and to the aged condition of some of the pile structures.
7. Employing all of the considerations cited above may lead to a significant increase in design criteria which could lead to some very conservative and expensive designs.

## RECOMMENDATIONS

It is recommended that designers of coastal structures consider the effects of the 1983 winter storms in their new designs, but that the increase in water level and wave characteristics be evaluated in terms of how neighboring structures performed during the storms and the economical and safety consequences of the design being exceeded by larger waves. It may be very difficult for the engineer to use a 100-year design storm and water level criteria based on the new data set and current design procedures with non-linear waves compared to a 20-year design storm and water level using statistics developed in 1960 and linear wave theories. For instance, most of the breakwaters on the Southern California coast were built using previous criteria. The local rock quarries can supply up to about 12 to 16 ton armor stone and these structures have functioned reasonably well over their project life. If strict application of the data set with the 1983

storms included, quarry stone would be considered impractical and more expensive precast concrete armor units would be required. Then the engineering design must more seriously consider the economics of repairs to the stone structures and the risk of damages. While these optimization design procedures are documented by Bruun (1) and the Delft University of Technology (3), they are rarely explicitly applied in Southern California because local traditional methods have been satisfactory until 1983.

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