CHAPTER 4

STRUCTURAL DAMAGE BY TSUNAMIS

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This paper presents a brief discussion of structural damage by tsunamis based primarily on damage produced by recent tsunamis along the northern California coast. Of these recent tsunamis, by far the most damaging was the one of March 1964 which caused approximately $11,000,000 damage at Crescent City, about $300,000 damage at other coastal locations, and about $200,000 damage in San Francisco Bay. At Crescent City, where the maximum runup reached about 21 feet above mean lower low water, damage was largely to wood frame structures of relatively light construction and to floating vessels. At other locations, damage was primarily to commercial fishing and pleasure vessels and associated shoreside structures.

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INTRODUCTION

Extensive sections of the coasts that border the Pacific Ocean are now populated and undergoing continuing development. Many of these developments are taking place in areas possibly subjected to tsunamis. The design of structures in these coastal areas must consider the effects of tsunamis just as the effects of seismic or wind loadings must be considered. Although the application of the methods of fluid mechanics provides solutions for calculation of the forces produced on structures by fluids, tsunamis produce a number of specific problems which may not generally be considered. It is hoped that this paper, based on observations of the effects of tsunamis made along the northern California coast during the past two decades will contribute toward a better understanding of the damage produced by tsunamis, and also will assist persons engaged in design of coastal structures in northern California.

Although tsunamis have been studied scientifically for over a century, it is only recently that practicable design information is becoming available. Recent systematic studies of tsunami generation and propagation have been published by Wilson, 1/ 2/ Cox, 5/ and Wiegel 3/. A Comprehensive Annotated Bibliography of Tsunamis has also been published 4/. Of these publications, probably the best suited to the coastal engineer is Wiegel 3/.

Although tsunamis may be generated by a number of causes, damaging tsunamis are usually produced from major seismic disturbances. The active seismic areas of the Pacific Ocean where tsunamis originate are discussed by Wilson 1/ and by Wiegel 3/. Recent tsunamis that produced damage along the northern California coast are given in Table 1 below.

TABLE 1

Recent Tsunamis Affecting the Northern California Coast 7/ 8/ 9/

Year	Date	Source	Richter Magnitude	Northern California Damage
1946	1 April	Aleutian Is.	6.4	Slight
1960	22 May	Chile	8.5	Slight
1964	27-28 March	Gulf of Alaska	8.5	Major

Van Dorn 6/ describes the source mechanism of the 27-28 March 1964 tsunami as "generating a long solitary wave which radiated out over the Pacific with very little dispersion."

Characteristically the tsunami waves generated have periods (as observed along the coast) ranging from about 5 to 30 minutes. These waves travel outward from their source with a velocity approximately given by $c = \sqrt{gd}$ where g is the acceleration of gravity and d is the water depth. Therefore, the wave velocity is dependent only on the depth of water in which the wave is traveling. For the average depth of water in the Pacific Ocean (about 14,000 feet) the corresponding velocity would be about 480 miles per hour. In deep water the tsunami waves are believed to be very low (say 1 to 2 feet high) and have a "length" measured between two successive points on the wave of between 50 to 150 miles. Thus, a ship in the open ocean would not be able to notice a passing tsunami. As the wave approaches the shore, the wave height increases rapidly depending on the wave characteristics, the bottom topography, and the resonant characteristics of the coast. Although the technique of calculation of tsunami heights along any specific reach of shoreline is not fully developed, an order of magnitude increase from the deep ocean depths to the shoreline may be expected. This problem is under study by a number of theoretical investigators and significant contributions are being made towards obtaining a fundamental understanding of the characteristics of long period waves at any given coastal location. At the present time, however, the only practical method available for determining a design tsunami height is by obtaining the history of tsunamis at the site under study. Such a historical study has been conducted for Hilo Harbor by Doak Cox and published by Wiegel 3/.

Due to the complex nature of tsunamis, the presently accepted method for detailed study of reduction of the damaging effects of a tsunami at a specific location is by use of a hydraulic model. Such a model study has been conducted for Hilo, Hawaii 10/. The structural damage produced at Hilo has also been extensively documented both by the Matlock Reese and Matlock 11/ and also by the U.S. Army Engineer District, Honolulu, Hawaii 13/.

EFFECTS OF RECENT TSUNAMIS IN NORTHERN CALIFORNIA

This section contains observed effects of recent tsunamis along the northern California Coast. The effects of the 1946 tsunami were reported by Bascom 12/ and the Corps of Engineers 14/. Effects of the 1960 and 1964 tsunamis were obtained by personal observation and extensive interviews by Magoon 25/ and other Corps of Engineers personnel.

With the exception of two locations to be described later, recent tsunamis along the northern California coast have all exhibited the same general characteristics. This consists of a series of rapid undulations of the ocean surface reaching a maximum rate of change of from 1 to 2 feet per minute measured vertically for five to ten minutes -

Generally, the major waves of the tsunami are experienced in the beginning of the disturbance, particularly along the outer coast. The effect is often recorded along the coast for up to one week following the initial disturbance, but the waves are greatly reduced in amplitude by the second day. Inside of San Francisco Bay the tsunami has generally been about the same or lower than the tidal range. In this case, the maximum water height is reached when the tsunami is in the phase with the high tide.

Strong reversing ebb and flood currents are usually observed to occur simultaneously with the water level fluctuations. These currents are most severe in locations where water is either passing through a constriction or over a shallow bottom.

At the mouths of the Noyo and Albion Rivers, the rivers enter the ocean at the landward end of relatively deep bays. Observers at these locations in 1964 described an almost vertical wall of water progressing upstream, apparently similar to a bore. At Noyo this disturbance was traveling upstream at approximately 20 miles per hour. The remaining portion of this section contains a summary of the pertinent observed characteristics of and damages produced from the tsunamis of 1 April 1946, 22 May 1960 and 28 March 1964 along the northern California coast.

The characteristics of the three tsunamis mentioned as they affected the northern California coast are given in Table 2. The site numbers referred to in Table 2 are located on Figure 1. The affects of the March 1964 tsunami inside of San Francisco Bay are given in Table 3. The site numbers referred to in Table 3 are shown on Figure 2.

TABLE 2

SUMMARY OF RECENT TSUNAMIS ALONG NORTHERN CALIFORNIA COAST

Site No.	Site	Location (County)	North Latitude	Coastal Description	Maximum Water Elevation Above MLLW (Feet)			Maximum Wave Height (Feet)			Time of Maximum Water Level [c] (PST)			Damage ($)			Remarks
					46	60	64	46	60	64	46	60	64	46	60	64	
101	Point Lobos	Monterey		Exposed coast	-	-	x	-	-	-	-	-	-	-	-	x	
	Point Lobos to Carmel (3)	Monterey		Exposed coast	-	-	x	-	-	x	-	-	-	-	-	x	
102	Pacific Grove (2)	Monterey		Open cove	10.3	+7	+7	-	6	6	-	-	-	-	-	x	
103	Monterey Harbor (2)	Monterey		Protected harbor (breakwaters)	-	+8	+7.5	-	5	9	-	0940	0330	x	x	1,000	1964 damage: one tier of small boats broke loose, only minor damage. 1946 and 1964: whirlpools at seaward end of Monterey breakwater, no damage. Spectral analysis made of 1964 tsunami from pressure gage by Marine Advisors 15/ and analysis and discussion of float and pressure gage records by Wilson 16/.
104	Moss Landing Harbor (2)	Monterey		Protected harbor (jetties)	x	-	+7	x	5	9	-	-	-	x	x	200	1964 damage: one skiff broke apart, strong currents in channels.
	Moss Landing to Capitola	Monterey Santa Cruz		Exposed coast	-	-	-	-	-		-	-	-	-	-	x	At seacliff Beach State Park maximum wave from +5 to -1 MLLW. At New Brighton Beach State Park, maximum wave from +5 to -12 MLLW (1964)
201	Capitola Pier (1)	Santa Cruz		Cove open to south	-	-	-	-	-	14	0	0	0130	-	-	x	
202	Santa Cruz Harbor (1)	Santa Cruz		Protected harbor (jetties)	-	-	12.4	0	0	10	0	0	-	0	0	100,000	(Constructed 1962). 1964 damage consisted of the loss of a dredge and cabin cruiser which broke loose during tsunami. Major effect was strong currents. Wave gage recorded wave not less than 7.5 feet, observers reported 10-foot wave with minimum elevation about -8 MLLW. Most boats and facilities in harbor undamaged.

TABLE 2

SUMMARY OF RECENT TSUNAMIS ALONG NORTHERN CALIFORNIA COAST

Site No.	Site	Location (County)	North Latitude	Coastal Description	Maximum Water Elevation Above MLLW[a,b] (Feet)			Maximum Wave Height (Feet)			Time of Maximum Water Level[c] (PST)			Damage ($)			Remarks
					46	60	64	46	60	64	46	60	64	46	60	64	
203	Santa Cruz (1)	Santa Cruz		Cove open to south	12.4	-		10	6	10[e]		1,000		x	x	x	1964 and 1946, one life lost due person being trapped in cave during tsunami and subsequently drowned.
	Santa Cruz (3) to Martin's Beach	Santa Cruz San Mateo		Exposed coast	-	-	x	-	-	x	-	-	-	-	-	x	
301	Martin's Beach (1)	San Mateo		Very small exposed cove	-	-	10	-	-	20	-	-	-	-	x	x	Tsunami always higher at north end of cove. Minimum elevation -10 MLLW.
	Martin's Beach to Half Moon Bay (4)	San Mateo		Exposed coast	-	-	-	-	-	-	-	-	-	-	-	x	1964, two observers reported unusual lows reached by tsunami.
302	Half Moon Bay Harbor (1)	San Mateo		Protected Harbor (breakwaters)	15	11.5	10.1	17.3			-	-	-	-	-	1,000	Low wave height in 1964 probably caused by construction of harbor
303	Pacifica (Shelter Cove) (1)	San Mateo		Very small exposed cove	-	6.5	7.2	-	8	9	-	-	-	-	-	x	
400	Golden Gate (Presidio)	San Francisco		Entrance to bay	5.8	6.5	8.4	1.7	2.9	7.4	1,000	1,200	0100	-	-	-	San Francisco Bay Area - See Table 3.
501	Muir Beach (1)	Marin		Coves open to south	13.4	-	9	-	-	-	-	-	-	-	-		1946 Wave cut through lagoon bar.
502	Stinson Beach (1)	Marin		Coves open to south	-	-	-	-	10	-	-	-	-	-	-	x	
503	Bolinas (1)	Marin		Coves open to south	-	-	-	-	-	-	-	-	-	-	-		1964, one life lost by drowning on Duxberry Reef 29 March 1964
505	Tomales Bay (entrance) (1)	Marin		Bay with entrance restricted	-	-	-	-	-	6.5	-	-	-	-	-	6,000	1964, 25 mph current reported. 1960 and 1946, strong currents reported. 1964, damages are to "Lawson's Pier, located inside entrance.
504	Drakes Beach, Bay (1)	Marin		Cove open to south	8	-	8	-	-	-	-	-	-	x	-	x	

TABLE 2 (Continued)

SUMMARY OF RECENT TSUNAMIS ALONG NORTHERN CALIFORNIA COAST

Site No.	Site	Location (County)	North Latitude	Coastal Description	Maximum Water Elevation a,b Above MLLW (Feet)			Maximum Wave Height (Feet)			Time of Maximum Water Level c (PST)			Damage ($)			Remarks
					46	60	64	46	60	64	46	60	64	46	60	64	
506	Marshall (1)	Marin		Protected bay	-	-	-	-	-	2	-	-	-	-	-	x	
507	Jensen Oyster Beds (1)	Marin		Protected bay	-	-	-	-	-	2	-	-	-	-	-	x	
508	Inverness Yacht Club (1)	Marin		Protected bay	-	-	-	-	-	1	-	-	-	-	-	x	
601	Bodega Bay inside entrance (1)	Sonoma		Bay with entrance jetties	-	-	-	-	2	5	-	-	0100	-	-	2,000	1964, damage to navigational aids. 1946, 1960, 1964, strong currents reported in entrance; 1964 reported 8 knots.
602	Bodega Bay, N.E. side (2)	Sonoma		Bay with entrance jetties	-	-	-	x	x	1	-	-	-	x	x	x	
603	Salmon Creek Beach (1)	Sonoma		Exposed beach	-	-	12e	-	-	-	-	-	-	-	-	x	1964, fisherman on beach reported that wave reached elevation higher than usual high tide plus runup resulting in loss of fish catch.
604	Jenner Beach (1)	Sonoma		Exposed shallow cove	-	-	10e	-	-	-	-	-	-	-	x	x	1964, no effect in Russian River.
	Jenner to Gualala (3)	Sonoma		Exposed coast	-	-	-	-	-	-	-	-	-	-	x	x	
605	Gualala River Bar (1)	Sonoma		Exposed shallow cove	-	-	-	-	-	-	-	-	-	-	x	x	1960, two waves washed over bar at mouth into Gulala River.
700	Arena Cove (1)	Mendocino		Exposed cove	14	-	-	16	-	12	-	-	-	x	x	x	
701	Point Arena Light Station (1)	Mendocino		Exposed point	-	-	12e	-	-	-	-	-	-	-	x	x	
702	Van Damme State Park (1)	Mendocino		Protected cove	-	-	8.8	-	-	-	-	-	-	-	x	x	1964, maximum wave progressed about 500 yards into Little River (from mouth at beach).

TABLE 2 (Continued)

SUMMARY OF RECENT TSUNAMIS ALONG NORTHERN CALIFORNIA COAST

Site No.	Site	Location (County)	North Latitude	Coastal Description	Maximum Water Elevation Above MLLW (Feet)			Maximum Wave Height (Feet)			Time of Maximum Water Level [c] (PST)			Damage ($)			Remarks
					46	60	64	46	60	64	46	60	64	46	60	64	
703	Russian Gulch State Park (1)	Mendocino		Protected cove	-	-	11.3	-	-	-	-	-	-	-	x	x	
704	Albion River (2)	Mendocino		Coastal river; 100-foot wide mouth	-	-	9	-	-	-	-	-	0002	-	-	500	1964: Observers reported 4 or 5 low bores traveled up river making a loud noise. Currents scoured out river mouth. Effect of wave was felt at least 1-1/4 mile up river from entrance. Damage was due to delays to fishing vessels.
705	Noyo River (4)	Mendocino		Coastal river; 150-foot wide entrance	11.2	-	12.6	-	-	13	-	-	1140	-	-	124,000	1964: Observers reported that second and third waves progressed up river from mouth like a bore with the forward face consisting of a series of small step-like jumps. Wave travel about 35 mph. Damage to boats floating structures.
801	Shelter Cove	Humboldt		Protected cove	-	-	-	-	4e	-	-	-	-	-	x	x	
802	Humboldt Bay	Humboldt		Bay with entrance jetties	-	-											
803	U.S.G.S. Station North spit (1)	Humboldt			-	-	9e	-	-	12			-			x	1964: 14 (estimated) knot current and 6-foot change in water level in about 20 minutes in channel opposite of station.
804	Municipal Marina (1)	Humboldt			-	-	12.4	-	-	-			-		x	x	Strong currents in entrance 1960 and 1964.
805	King Salmon (Entrance to King Slough) (1)	Humboldt															

TABLE 2 (Continued)

SUMMARY OF RECENT TSUNAMIS ALONG NORTHERN CALIFORNIA COAST

Site No.	Site	Location (County)	North Lati-tude	Coastal Description	Maximum Water Elevation a,b Above MLLW (Feet)			Maximum Wave Height (Feet)			Time of Maximum Water Level c (PST)			Damage ($)			Remarks
					46	60	64	46	60	64	46	60	64	46	60	64	
806	P.G.& E. Power Plant (0.6-Mile upstream of entrance to King Slough) (1)	Humboldt			-	-	9.7	-	-	-	-	-	0005	-	-	x	
807	Trinidad (1)	Humboldt		Protected cove	-	-	18	-	-	-	-	-	-	-	-	-	
	Trinidad to Klamath River (5)	Humboldt Del Norte		Exposed cove	-	-	-	-	-	-	-	-	-	-	-	x	
901	Klamath River	Del Norte		Coastal river with restricted entrance													
	Requa Boat Dock (1) (0.7-mile above mouth)	Del Norte			-	-	-	-	-	-	-	-	-	-	-	4,000	1964: Damage to boat dock and boats strong currents.
	Panther Creek Lodge (1) (1 mile from mouth)	Del Norte			-	-	-	-	-	-	-	-	-	-	-	x	1964: Strong currents; water level "3 feet above normal high tide."
	Chinock Trailer Court (1) (1.6 miles above mouth)	Del Norte			-	-	-	-	-	-	-	-	-	-	-	200	1964: Damage to boat dock and boats
	Deans Camp 0.7 Mile (1) South of entrance	Del Norte			-	-	-	-	-	-	-	-	-	-	-	x 17/	1964: Water level "2 feet above normal high tide)

TABLE 2 (continued)

SUMMARY OF RECENT TSUNAMIS ALONG NORTHERN CALIFORNIA COAST

Site No.	Site	Location (County)	North Latitude	Coastal Description	Maximum Water Elevation a,b above MLLW (Feet) 46	60	64	Maximum Wave Height (Feet) 46	60	64	Time of Maximum Water Level c (PST) 46	60	64	Damage ($) 46	60	64	Remarks
902	Crescent City	Del Norte		Improved harbor	-	18.5	20.7	-	10+	28e	-			see remarks			1960: $30,000 damage confined to Citizens Dock area and debris in streets 1964: Tsunami produced major damage at Crescent City consisting of an estimated $11,000,000 17/ to the waterfront and downtown areas. In addition, 8 lives were lost.
903	Pebble Beach (2)	Del Norte		Exposed beach	-	-	15	-	-	-	-	-	-	-	-	x	
904	Pelican Beach (1)	Del Norte		Exposed beach	-	-	-	-	-	-	-	-	-	-	-	x	Driftwood stranded on beach backshore not moved by tsunami
905	Smith River (1) (0.3 mile above mouth)	Del Norte		Coastal River, 300-foot wide mouth	-	-	13.3	-	-	-	-	-	-	-	-	6,000	Damage to floating structures, strong currents in river, water level higher on right bank than on left

NOTE: see page 7 for legends

TABLE 2 (continued)

SUMMARY OF RECENT TSUNAMIS ALONG NORTHERN CALIFORNIA COAST

Legend:

- \- No data available.
- x Observers noted no effects or damage.
- ( ) Number of interviews, 1964.
- e Estimated from very general description.
- a Maximum high water elevations shown to the tenth of a foot have a probable accuracy of $\pm$ 1 foot.
- b Maximum high water elevations shown to the whole foot have a probable accuracy of $\pm$ feet.
- c Times given are in Pacific Standard Time. 46 is actually 1 April 1946; 60 is actually 23 May 1960; and 64 is actually 28 March 1965.

15/ Marine Advisors, A Broad-Frequency-Band wave Study at Monterey Harbor, California July 1964 (U.S. Army Contract No. DA-04-203-CIVENG-64-7)

16/ Wilson, Basil, Progress Reports, Surge Study for Monterey Bay and Harbor, California. (U.S. Army Contract DA-22-079-CIVENG-65-10)

17/ Clifton, Paul, Personal Communication from information compiled by State of California, 1964.

In general, these field investigations were made in an attempt to determine the monetary value of damage caused by the tsunami, the maximum elevation attained by the tsunami and the characterics of the highest wave. With the exception of the reports of a bore-like disturbance at the entrance to the Noyo and Albion Rivers (sites 704 and 705) observers have reported that the tsunami was similar to a tide, but with greatly accelerated vertical movement and horizontal currents. A check was also made of all U.S. Geological Survey coastal stream gage records in northern California that might have shown the tsunami. No indication of the tsunami was found on any of the records.

With the exception of Crescent City in 1964 and possibly Half Moon Bay in 1946, all damage reported has been to commercial fishing or pleasure craft and their associated shoreside facilities caused by unusually swift horizontal currents. A typical example of a location subject to damage by horizontal currents is Santa Cruz Harbor, shown in Figure 4. During the 1964 tsunami the water level varied from a high of 11 feet to a low of about -8 feet MLLW. During the major portion of the drop in elevation, the water level dropped at a rate of about one foot a minute for about 10 minutes. Obviously, strong horizontal currents were produced by this disturbance. A floating hydraulic dredge was docked near the entrance just before the tsunami arrived. One of the early waves induced such a drag on the dredge that the mooring lines parted and the dredge was swept seaward. As it moved out the entrance, it struck the east jetty and finally sank along the entrance channel and on the centerline extended of the east jetty. Shortly thereafter a 38-foot cabin

TABLE 3

EFFECTS OF MARCH 1964 TSUNAMI in SAN FRANCISCO BAY

Location	Site	Site Number	Maximum Water Elevation Above MLLW (Feet)	Maximum Wave Height (Feet)	Time of Maximum Wave (PST)	Damage ($)	Remarks
San Francisco	Golden Gate	A					Recording gage
Sausalito	Bauman Bros. Sales	16			0130	None	
Sausalito	Marinship Yacht Harbor	18	5.5	4	0200		
Sausalito	Clipper Yacht Harbor	19		4	0200	100,000	Damage to floating structures and boats.
Belvedere	San Francisco Yacht Club	22		5	0200	None	
San Rafael	San Rafael Yacht Harbor	31	8.			7,500	Damage to floating structures and boats.
San Rafael	Lowries Yacht Harbor	36	6.6	5	(0100-0200) 0200 Max.	10,000	Damage to floating structures and boats.
San Rafael	Loch Lomond Harbor	39				60,000	One large pleasure boat broke loose causing damage to other boats and floating facilities.
Vallejo	Mare Island Naval Shipyard	G	.55			None	Recording gage.
Vallejo	Glen Cove Harbor	103	Slight			None	Fish stopped biting.
Benicia	Benicia	6	0.4				
Suisun	Paul's Yacht Harbor	105	None			None	
Antioch	Big Break Resort	52	None			None	
Antioch	Lauritzen Yacht Harbor	53	None			None	
Antioch	Bridge Marina	55	None			None	
Antioch	San Joaquin Yacht Harbor	57	-			None	

TABLE 3
(Continued)

EFFECTS OF MARCH 1964 TSUNAMI in SAN FRANCISCO BAY

Location	Site	Site Number	Maximum Water Elevation Above MLLW (Feet)	Maximum Wave Height (Feet)	Time of Maximum Wave (PST)	Damage ($)	Remarks
Antioch	Tommie's Yacht Harbor	57	None			None	
Antioch	Jay's & Dee's Harbor		None			None	
Pittsburg	Pittsburg Marina	107	None			None	
McAvoy	Harris Yacht Harbor	59	None			None	
McAvoy	McAvoy Harbor	66	None			None	
Crockett	Eckley's Resort	62	None			None	
Crockett	Dowrelio's Harbor	63	None			None	
Rodeo	Rodeo Marina	64	None			None	
Pt. San Pablo	Standard Oil Company	66	7.4	4.4	0150	None	Effects lasted about 10 days.
Pt. San Pablo	Pt. San Pablo Yacht Harbor	65	5.5	6 to 6.5	0200	None	Like fast tide.
Pt. Richmond	Red Rock Marina		7 (est.)		After 1:30	None	Boats touch bottom.
Richmond	Richmond Yacht Service	67	5.5 to 6	1.5		None	
Richmond	Richmond Yacht Harbor	68	+6	7		None	Low water to -1 MLLW.
Richmond	Channel Marina	70	+6	9		Not evaluated - slight	Low water to -1 MLLW.

TABLE 3
(Continued)

EFFECTS OF MARCH 1964 TSUNAMI in SAN FRANCISCO BAY

Location	Site	Site Number	Maximum Water Elevation Above MLLW (Feet)	Maximum Wave Height (Feet)	Maximum Wave (PST)	Damage ($)	Remarks
Berkeley	Berkeley Yacht Harbor	71			0240	100	Damage low because emergency crews on hand to adjust lines. 10K current in entrance.
Oakland	Norwalk Yacht Harbor	72	+6.4	7.4	0145	None	Low water to -1 MLLW.
Oakland	Jack London Marina	112	+6	7		None	Low water to -1 MLLW.
Oakland	Embarcadero Yacht Harbor		+6	8		None	Low water to -1 MLLW.
Oakland	Hans Glaser Boat Service		None	None		None	
Oakland	Oakland Marina	77	+7			None	
Oakland	Lani Kai Harbor	81	+2			None	
Oakland	Oakland Yacht Club	80				None	
Oakland	Nordic Yacht Imports					None	
Oakland	Tompkin Boat Sales	112				None	
Oakland	Evans Radio Dock					None	
Alameda	Bay Yacht Service					None	
Alameda	Pacific Marina	74				None	
Alameda	Alameda Yacht Club	73				None	
Alameda	Aeolian Yacht Club	84				None	

TABLE 3
(Continued)

EFFECTS OF MARCH 1964 TSUNAMI in SAN FRANCISCO BAY

Location	Site	Site Number	Maximum Water Elevation Above MLLW (Feet)	Maximum Wave Height (Feet)	Maximum Wave (PST)	Damage ($)	Remarks
San Leandro	San Leandro Marina	115				None	
Alviso	Alviso Marina	117				None	
Palo Alto	Palo Alto Yacht Harbor	2				None	
Redwood City	Redwood City Muni.	4				None	
Redwood City	Redwood Marina	3				None	
Redwood City	Pete's Harbor	5				None	
Burlingame	Coyote Point Harbor	8				None	
South San Francisco	Oyster Point Marina	118				None	
Alviso	Entrance to Alviso Slough	C		1.1		None	Recording gage. (Santa Clara County)
Alameda	Naval Air Station, Alameda	D		5.4		None	Recording gage. (U.S.C. & G.S.)
Richmond	Standard Oil Company	F		4.0		None	Recording gage. (Standard Oil Company)
Benicia	Benicia Harbor	H		0.4		None	Recording gage. (State Department of Water Resources)
Collinsville and beyond		I		Less than 0.1		None	Recording gage. (State Department of Water Resources)

cruiser struck a submerged object (presumably the sunken dredge) while attempting to leave the harbor, and it also sank. The strong currents induced by the tsunami also caused movement of the material in the entrance channel bottom. Several small floats located near the public pier were damaged due to being caught against the public pier and were wrecked or twisted as the water fell. With the exception to the damage to the small floats mentioned above, all other floating facilities withstood the tsunami.

Inside of San Francisco Bay both the May 1960 and March 1964 tsunamis were greatly attenuated after passing through the Golden Gate. Based on very limited data, a tsunami is reduced to one-half the height at the Golden Gate at Richmond on the north and Hunter's Point on the south. A tsunami is reduced to less than one-tenth the height at the Golden Gate at the easterly end of San Pablo Bay and Alviso on the south. These values are shown on Figure 4. Damage in San Francisco Bay was largely to pleasure boats. The highest damage was reported from Marinas in Marin County where strong currents caused boats and in some cases portions of floating slips to break loose. These objects attained the velocity of the moving water and caused damage when they struck other craft.

At Noyo Harbor (site 705, also see Figure 4) the entrance is restricted, but the harbor is also restricted and the full affects of the wave were felt over the entire reach of the harbor. In the March 1964 tsunami the first wave rose relatively slowly, and exhibited the characteristics as observed elsewhere along the coast. The second wave occurring about 15 minutes after the first, formed a bore-like face, about 7 feet high, consisting of a series of step-like jumps. One observer saw the bore form at the entrance and rapidly drove his automobile parallel to the travel of the bore, but was unable to pass it. At Noyo, damage was to floats and to commercial fishing vessels that broke loose during the tsunami.

Due to the relatively severe tsunami damage produced at Crescent City in 1964, an investigation was made of the coast on both sides of Crescent City to determine the water levels reached by the tsunami. Based on elevations determined at locations positively identified as those caused by the tsunami, it is concluded that the runup elevation reached by the third wave (fifth wave of Tudor 18/) of this tsunami was essentially constant at the shore for a distance of almost 2 miles southwest of Crescent City and probably only slightly diminished for 1 mile northeast of Crescent City. This high water elevation along the shore reached 20 to 21 feet above MLLW. The line of maximum tsunami inundation, as shown on Figure 6 generally followed the +20 MLLW contour where the ground elevations increased to landward from the shore. This would include most of downtown Crescent City and the pasture land in the vicinity of HWM No. 5.

A definite departure from this characteristic runup pattern was found where the ground elevation decreases to seaward from the coast and either decreases or remains essentially level landward from the coast. Under this condition, water flowed over the narrow coastal dunes or raised areas near State Highway 101 in a similar manner as water flowing over a broad weir. Apparently the quantity of water transported landward in the individual waves was insufficient in some instances to fill the low areas to landward thus reducing the runup. This condition was reported both in the area of HWM 316 and also at HWM's 1 and 2 shown on Figure 6.

A detailed presentation of the depths of submergence (in feet) and buildings known to have been destroyed in the downtown section of Crescent City during the 1964 tsunami are shown on Figure 7. The water depth observations were taken by experienced flood damage crews within the first two weeks after the tsunami. The survey on which these water depth elevations are superimposed was made in 1965, approximately 1 year later and thus show man-made changes in topography. With the exception of the buildings, no significant departures have been made from the 1964 topography. Buildings shown as shaded were a total loss. Buildings shown as lost are taken from Corps of Engineers contract files for removal of debris, aerial photographs taken on 1 April 1964 and ground photographs taken shortly after the tsunami. Arrows indicate the direction of movement of buildings. Additional sheets covering the entire coastal area inundated in the vicinity of Crescent City have also been prepared by the U.S. Army Engineer District, San Francisco.

Damage at Crescent City has already been reported on in numerous papers and publications 18, 19, 20, 21, 22, 23, 24, 26, 27/. In addition, the two Crescent City newspapers, the Crescent City American, the Del Norte Triplicate in Crescent City, and the Humboldt Times in Eureka, California, have published a number of excellent photographs of damage produced by the tsunami.

STRUCTURAL DAMAGE AT CRESCENT CITY
from tsunami of March 1964

Structural damage at Crescent City is discussed and illustrated by the above referenced authors. In searching for the reasons for the severity of damage at Crescent City, it should be remembered that the primary industry of the northwestern portion of the State is the production of commercial lumber. Thus the majority of buildings are of wood frame construction, many of which appeared to have been built a number of years ago. Prior to the tsunami, the coastal area to the southeast of Crescent City and also the harbor shoreline were covered with vast quantities of timber debris, including large logs and tree stumps. A typical view of the debris south of Crescent City is shown on Slide 1.

Figure 8 snows the harbor area about 2 years before the tsunami. Figure 9 shows the harbor one week after the tsunami. Note the increased width of the small creek in the harbor and also the erosion scars along the beach. Severe damage was observed in areas where the tsunami exceeded 4 to 6 feet above the ground surface (see Figure 7). The water depth reached or exceeded 6 feet along the entire length of Front Street, and about nine blocks of the main portion of Crescent City. The majority of the one story wood frame structures in this area were either totally destroyed or damaged to such an extent that they were a menace to public health and had to be torn down.

It is the opinion of the writer that the majority of structural damage at Crescent City was the result of one or a combination of three conditions listed below.

The first, and probably the most damaging, was the impact of logs and other objects such as automobiles or baled lumber directly on structures.

This debris caused damage by either destroying the load carrying capacity of walls or by bending or breaking relatively light unprotected columns and allowing subsequent failure. As pointed out by Matlock et al 11/ the effect of debris is highly indeterminate. For example, the debris may build-up in front of a structure to such an extent that the debris actually forms a shield for further damage, or the increased area resulting from this debris may result in sufficient force from the tsunami to cause the entire structure to be swept away. As mentioned earlier, observers reported that the inundation from the tsunami rose relatively gradually and definitely not resulting in a bore as described at Hilo Hawaii, by Matlock et al 11/.

Structures that were insufficiently anchored (generally on non-continuous footings) floated off their foundations and were seriously wrecked or rendered useless when they finally settled on the ground.

The third major cause of loss was the general lack of resistance to horizontal forces in many structures, normally provided by shear walls in buildings and cross bracing in open-pile structures.

Generally, the more substantially constructed structures, particularly multistory wood, hollow block and reinforced concrete, withstood the tsunami. These structures required considerable internal refurbishing due to water damage, but are in use today.

One particular light building shown on Slide 7* was located seaward of Front Street at D Street. This slide, taken shortly after the tsunami, shows the high water mark on the structure. Note that the windows are still intact. It is believed that the reason that such an obviously light building is still standing when other similar buildings were destroyed is that it is rigidly held down to the foundation and that it was not struck by any major pieces of debris.

CONCLUSION

No specific conclusions were reached in this study regarding particular design criteria to be followed in designing structures to resist tsunamis. It is obvious that if structures must be constructed in portions of the coast subjected to tsunamis, care must be taken to provide for sufficient lateral resistance to allow the structure to withstand the battering of flowing water and heavy debris. Wiegel 18/ suggests that multistory buildings be designed so that even though the first floor is completely swept away, the supporting columns are sufficient to retain the structural integrity of the building. Consideration should also be given so as to prevent the structure (or a portion thereof) from floating and subsequently being swept away or wrecked. This is particularly important in light-wood frame buildings where a well designed foundation and tie-downs are essential.

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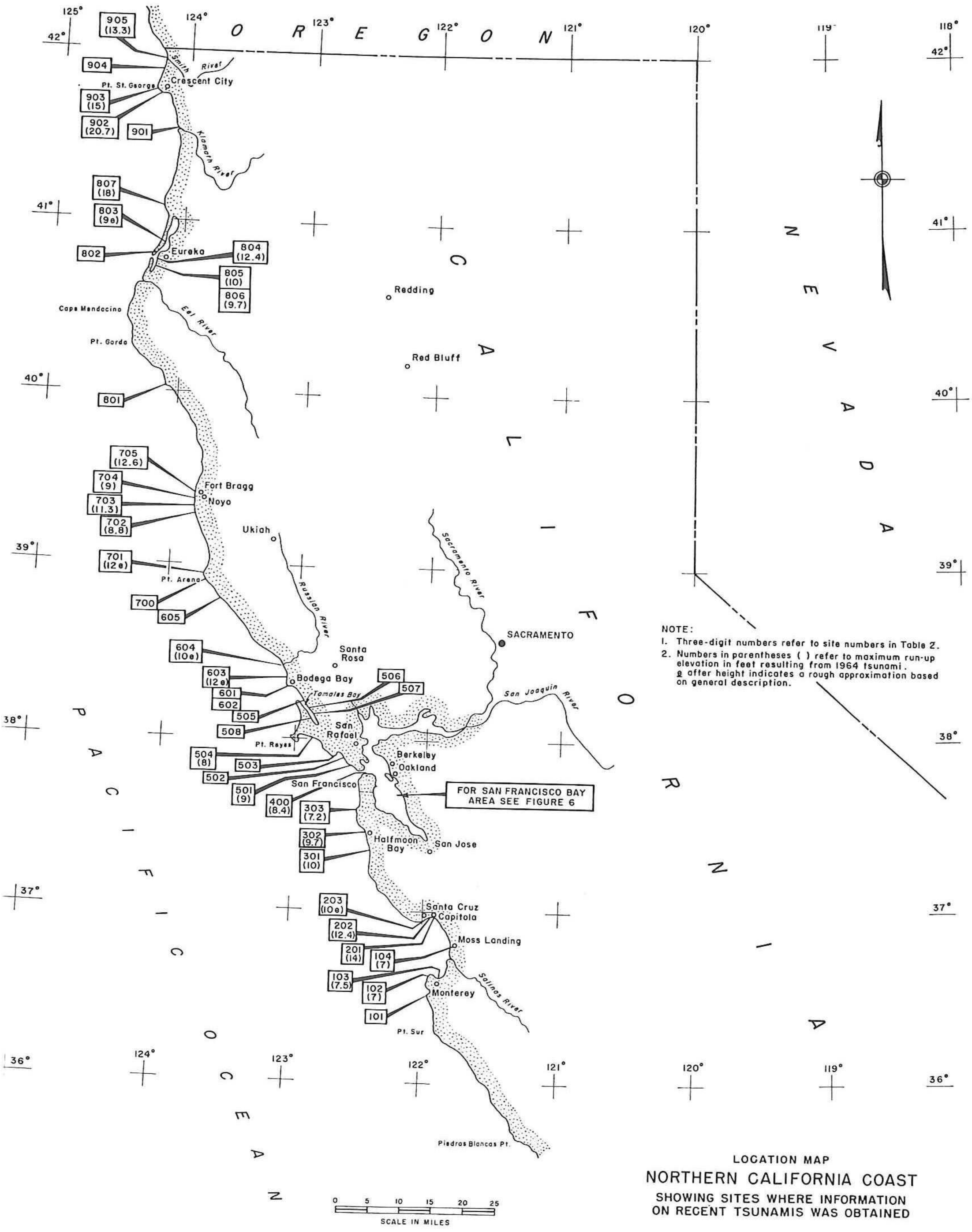
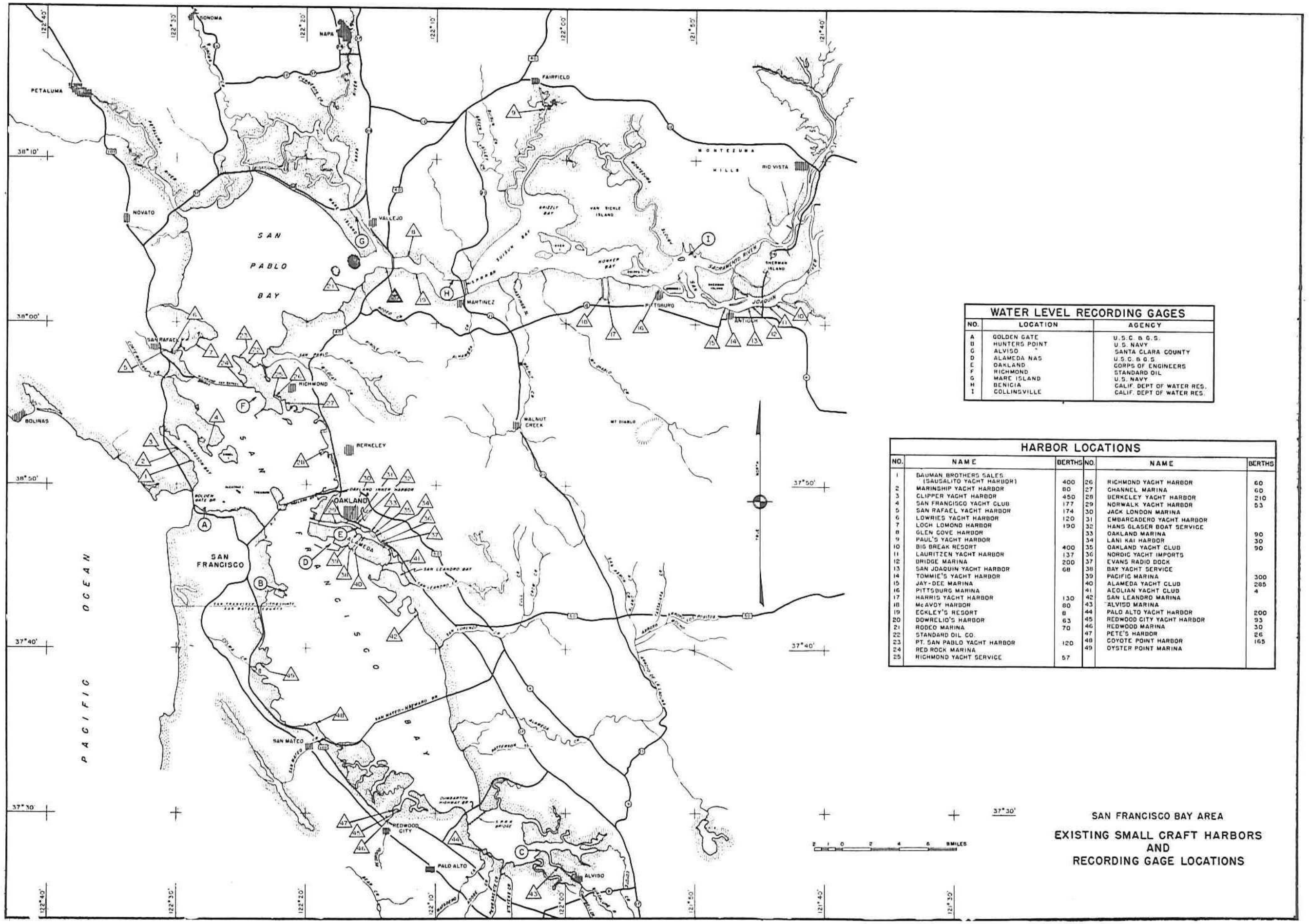

OREGON
CALIFORNIA
NEVADA
PACIFIC OCEAN
905 (13.3)
904
903 (15)
902 (20.7)
901
Pt. St. George
Crescent City
Smith River
Klamath River
807 (18)
803 (9e)
802
804 (12.4)
805 (10)
806 (9.7)
Eureka
Cape Mendocino
Pt. Gorda
Eel River
Redding
Red Bluff
801
705 (12.6)
704 (9)
703 (11.3)
702 (8.8)
Fort Bragg
Noyo
Ukiah
701 (12e)
Pt. Arena
700
605
Russian River
Sacramento River
SACRAMENTO
604 (10e)
Santa Rosa
603 (12e)
601
602
Bodega Bay
Tomales Bay
506
507
505
508
Pt. Reyes
San Rafael
San Joaquin River
504 (8)
503
502
Berkeley
Oakland
501 (9)
San Francisco
400 (8.4)
FOR SAN FRANCISCO BAY AREA SEE FIGURE 6
303 (7.2)
302 (9.7)
301 (10)
Halfmoon Bay
San Jose
203 (10e)
202 (12.4)
201 (14)
104 (7)
103 (7.5)
102 (7)
101
Santa Cruz
Capitola
Moss Landing
Monterey
Salinas River
Pt. Sur
Piedras Blancas Pt.
NOTE:
1. Three-digit numbers refer to site numbers in Table 2.
2. Numbers in parentheses ( ) refer to maximum run-up elevation in feet resulting from 1964 tsunami. e after height indicates a rough approximation based on general description.
125° 124° 123° 122° 121° 120° 119° 118°
42° 41° 40° 39° 38° 37° 36°
0 5 10 15 20 25
SCALE IN MILES
LOCATION MAP
NORTHERN CALIFORNIA COAST
SHOWING SITES WHERE INFORMATION ON RECENT TSUNAMIS WAS OBTAINED

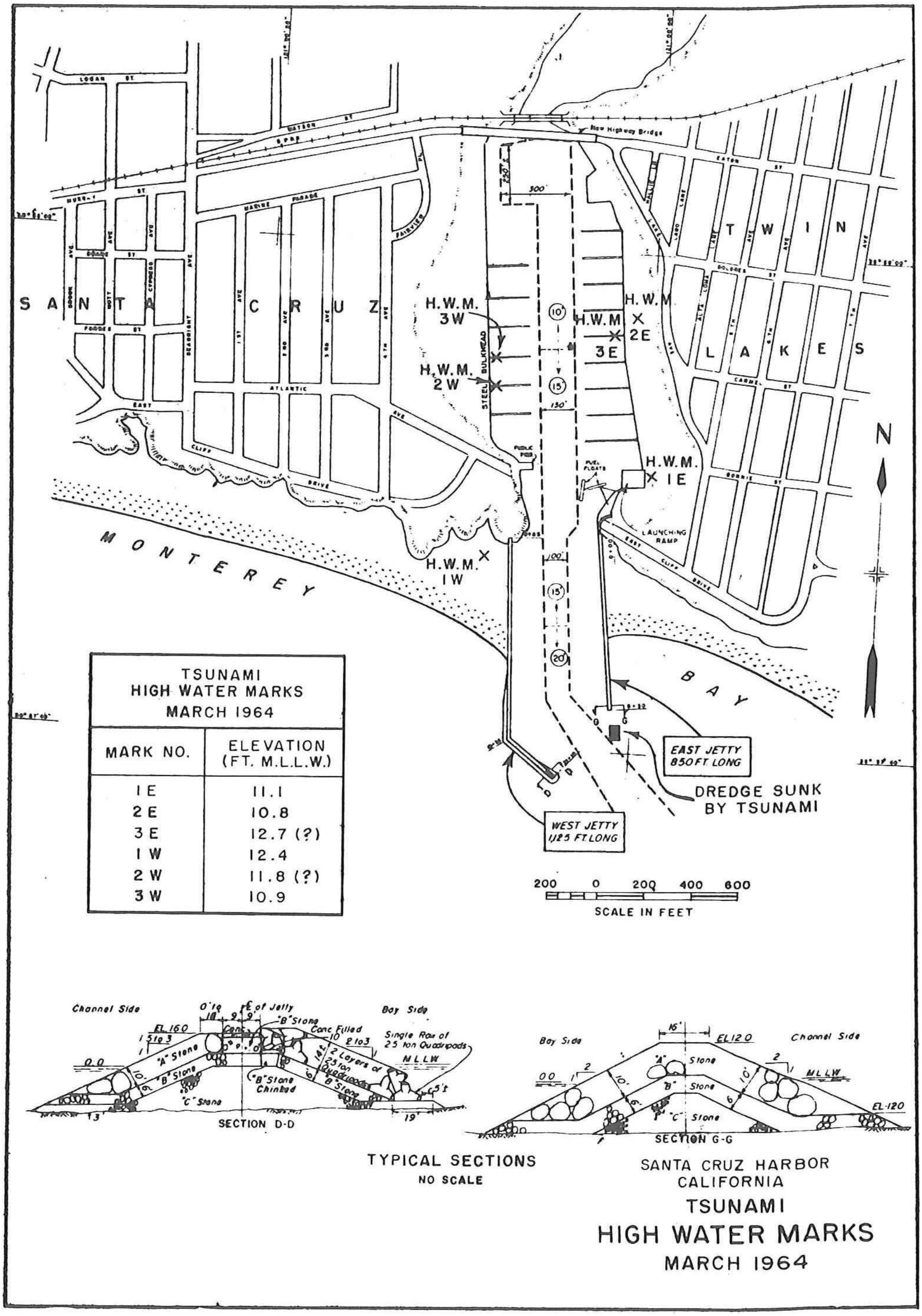
Figure 1



WATER LEVEL RECORDING GAGES		
NO.	LOCATION	AGENCY
A	GOLDEN GATE	U.S.C. & G.S.
B	HUNTERS POINT	U.S. NAVY
C	ALVISO	SANTA CLARA COUNTY
D	ALAMEDA NAS	U.S.C. & G.S.
E	OAKLAND	CORPS OF ENGINEERS
F	RICHMOND	STANDARD OIL
G	MARE ISLAND	U.S. NAVY
H	BENICIA	CALIF. DEPT OF WATER RES.
I	COLLINSVILLE	CALIF. DEPT OF WATER RES.

HARBOR LOCATIONS					
NO.	NAME	BERTHS	NO.	NAME	BERTHS
1	BAUMAN BROTHERS SALES (SAUSALITO YACHT HARBOR)	400	26	RICHMOND YACHT HARBOR	60
2	MARINSHIP YACHT HARBOR	80	27	CHANNEL MARINA	60
3	CLIPPER YACHT HARBOR	450	28	BERKELEY YACHT HARBOR	210
4	SAN FRANCISCO YACHT CLUB	177	29	NORWALK YACHT HARBOR	53
5	SAN RAFAEL YACHT HARBOR	174	30	JACK LONDON MARINA	
6	LOWRIES YACHT HARBOR	120	31	EMBARCADERO YACHT HARBOR	
7	LOCH LOMOND HARBOR	190	32	HANS GLASER BOAT SERVICE	
8	GLEN COVE HARBOR		33	OAKLAND MARINA	90
9	PAUL'S YACHT HARBOR		34	LANI KAI HARBOR	30
10	BIG BREAK RESORT	400	35	OAKLAND YACHT CLUB	90
11	LAURITZEN YACHT HARBOR	137	36	NORDIC YACHT IMPORTS	
12	BRIDGE MARINA	200	37	EVANS RADIO DOCK	
13	SAN JOAQUIN YACHT HARBOR	68	38	BAY YACHT SERVICE	
14	TOMMIE'S YACHT HARBOR		39	PACIFIC MARINA	300
15	JAY-DEE MARINA		40	ALAMEDA YACHT CLUB	285
16	PITTSBURG MARINA		41	AEOLIAN YACHT CLUB	4
17	HARRIS YACHT HARBOR	130	42	SAN LEANDRO MARINA	
18	McAVOY HARBOR	80	43	ALVISO MARINA	
19	ECKLEY'S RESORT	8	44	PALO ALTO YACHT HARBOR	200
20	DOWRELIO'S HARBOR	63	45	REDWOOD CITY YACHT HARBOR	93
21	RODEO MARINA	70	46	REDWOOD MARINA	30
22	STANDARD OIL CO.		47	PETE'S HARBOR	26
23	PT. SAN PABLO YACHT HARBOR	120	48	COYOTE POINT HARBOR	165
24	RED ROCK MARINA		49	OYSTER POINT MARINA	
25	RICHMOND YACHT SERVICE	57			

Figure 2



MARK NO.	ELEVATION (FT. M.L.L.W.)
1 E	11.1
2 E	10.8
3 E	12.7 (?)
1 W	12.4
2 W	11.8 (?)
3 W	10.9

Figure 3

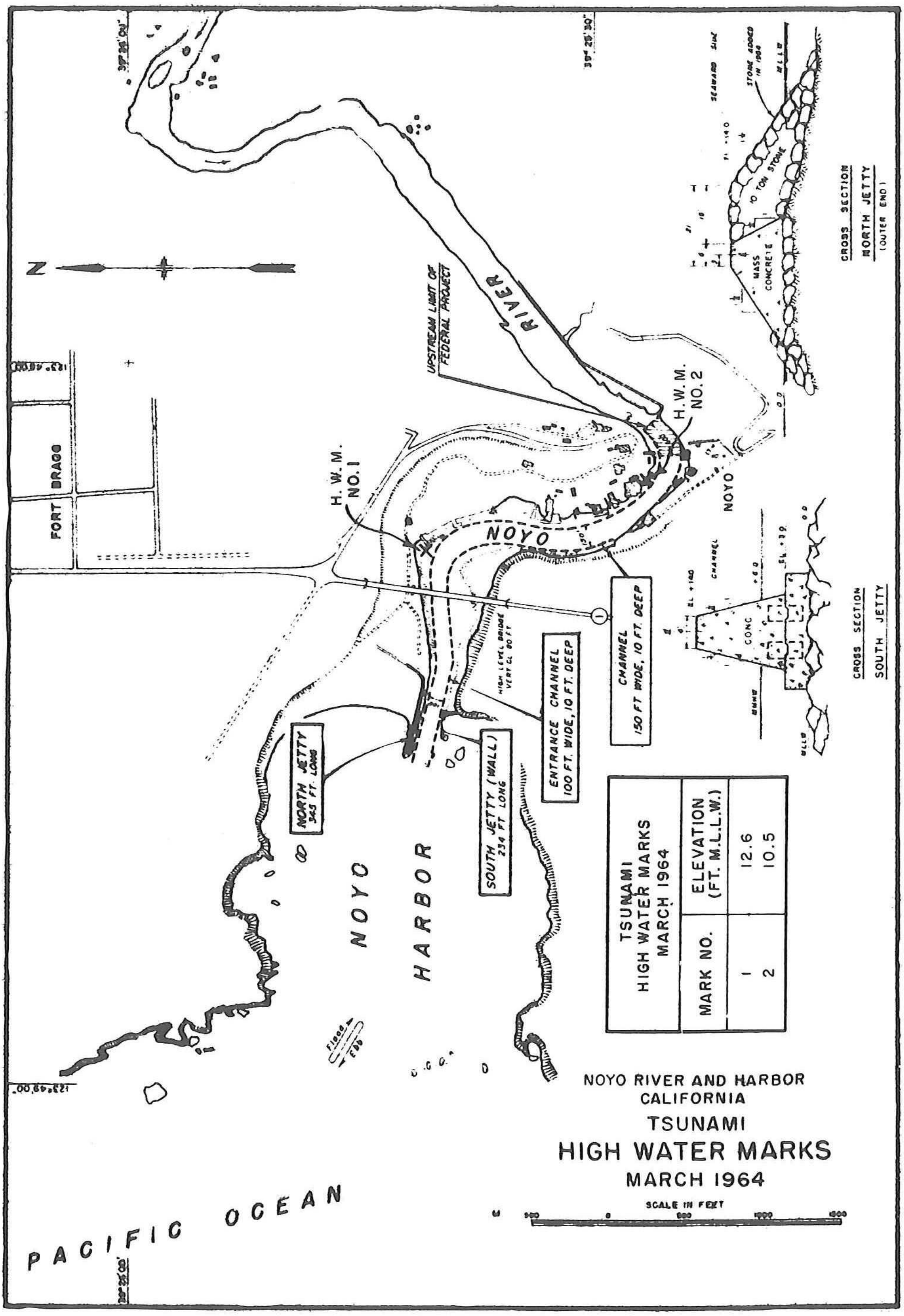
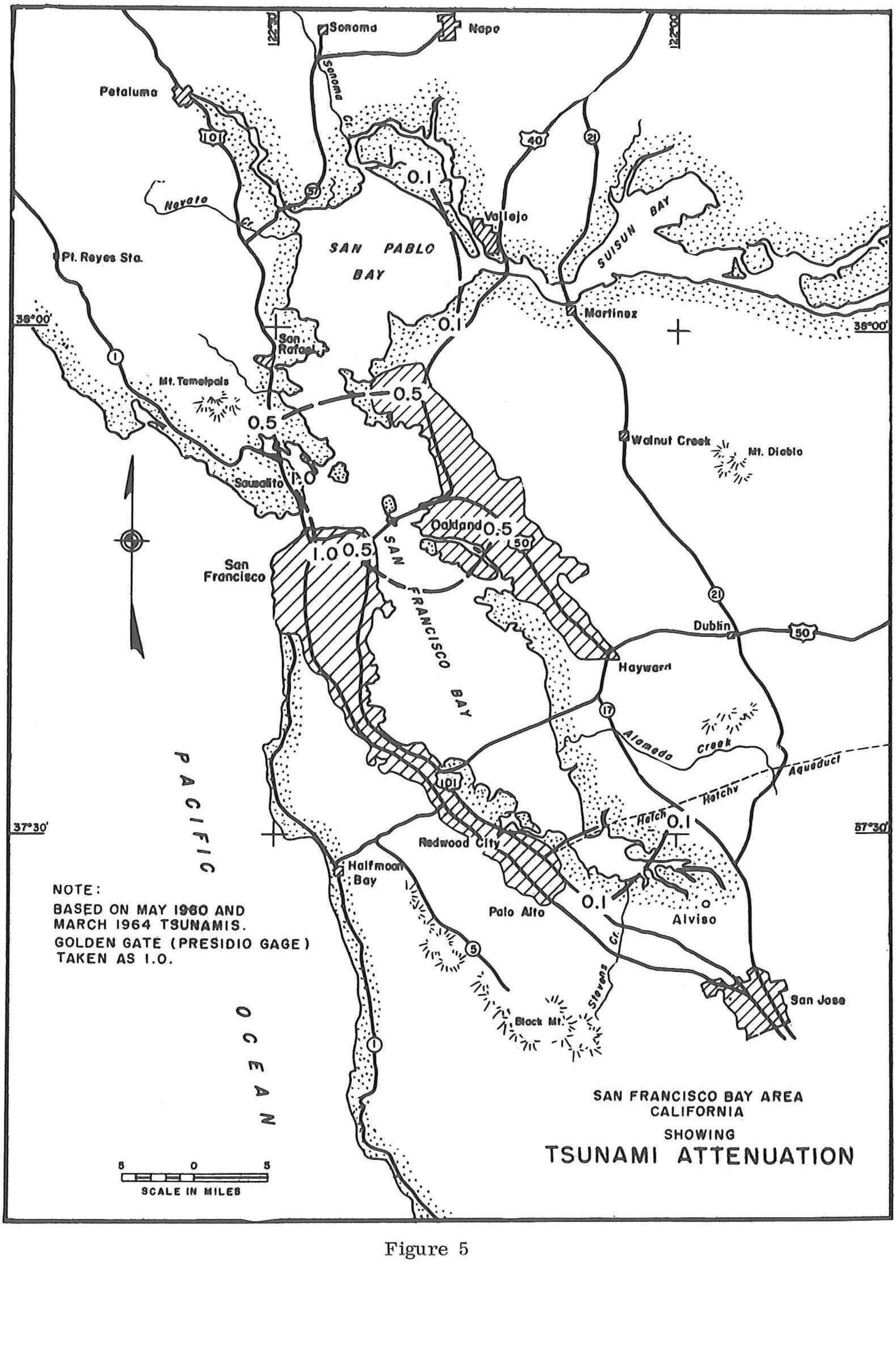

NOYO RIVER AND HARBOR
CALIFORNIA
TSUNAMI
HIGH WATER MARKS
MARCH 1964
SCALE IN FEET
TSUNAMI
HIGH WATER MARKS
MARCH 1964
MARK NO.
ELEVATION (FT. M.L.L.W.)
1 12.6
2 10.5
PACIFIC OCEAN
NOYO HARBOR
NOYO RIVER
NOYO
FORT BRAGG
H. W. M. NO.1
H. W. M. NO.2
UPSTREAM LIMIT OF FEDERAL PROJECT
CHANNEL 150 FT WIDE, 10 FT. DEEP
ENTRANCE CHANNEL 100 FT. WIDE, 10 FT. DEEP
NORTH JETTY 345 FT. LONG
SOUTH JETTY (WALL) 234 FT LONG
CROSS SECTION NORTH JETTY (OUTER END)
CROSS SECTION SOUTH JETTY
MASS CONCRETE
CONC
CHANNEL
FLOOD
EBB
N

Figure 4



Sonoma
Napa
Petaluma
San Pablo Bay
Suisun Bay
Vallejo
Martinez
Pt. Reyes Sta.
San Rafael
Mt. Tamalpais
Sausalito
San Francisco
Oakland
San Francisco Bay
Walnut Creek
Mt. Diablo
Dublin
Hayward
Alameda Creek
Hetch Hetchy Aqueduct
Redwood City
Halfmoon Bay
Palo Alto
Alviso
San Jose
Black Mt.
Stevens Cr.
Pacific Ocean
0.1
0.5
1.0
NOTE:
BASED ON MAY 1960 AND MARCH 1964 TSUNAMIS.
GOLDEN GATE (PRESIDIO GAGE) TAKEN AS 1.0.
SCALE IN MILES
SAN FRANCISCO BAY AREA
CALIFORNIA
SHOWING
TSUNAMI ATTENUATION

Figure 5

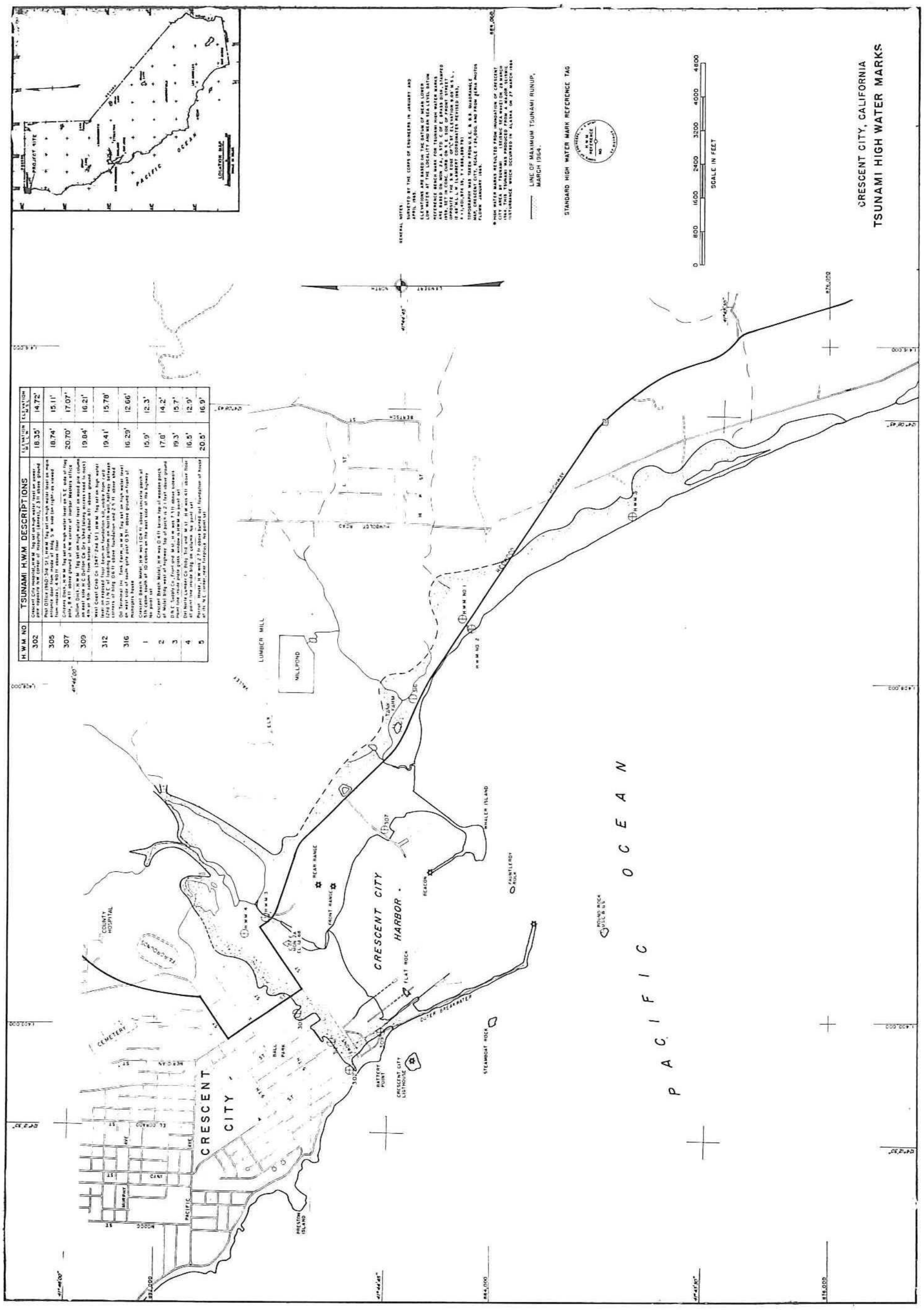

CRESCENT CITY, CALIFORNIA
TSUNAMI HIGH WATER MARKS
TSUNAMI H.W.M. DESCRIPTIONS
LINE OF MAXIMUM TSUNAMI RUNUP, MARCH 1964.
STANDARD HIGH WATER MARK REFERENCE TAG
SCALE IN FEET
0 800 1600 2400 3200 4000 4800
GENERAL NOTES
LOCATION MAP
PROJECT SITE
PACIFIC OCEAN
PACIFIC OCEAN
CRESCENT CITY HARBOR
CRESCENT CITY
LUMBER MILL
MILLPOND
COUNTY HOSPITAL
CEMETERY
BATTERY POINT
CRESCENT CITY LIGHTHOUSE
PRESTON ISLAND
STEAMBOAT ROCK
FLAT ROCK
WHALER ISLAND
FAUNTLEROY ROCK
ROUND ROCK
REAR RANGE
FRONT RANGE
BEACON
OUTER BREAKWATER
TANK FARM
HIGHWAY
NORTH

Figure 6


CRESCENT CITY, CALIFORNIA
INUNDATION FROM
MARCH 1964 TSUNAMI
LEGEND
BUILDINGS DESTROYED
TSUNAMI WATER DEPTH LINES
SCALE IN FEET
CONTOUR INTERVAL
2 FEET
CRESCENT CITY HARBOR
CRESCENT CITY
PACIFIC OCEAN

Figure 7

Figure 8 Crescent City 18 October 1962

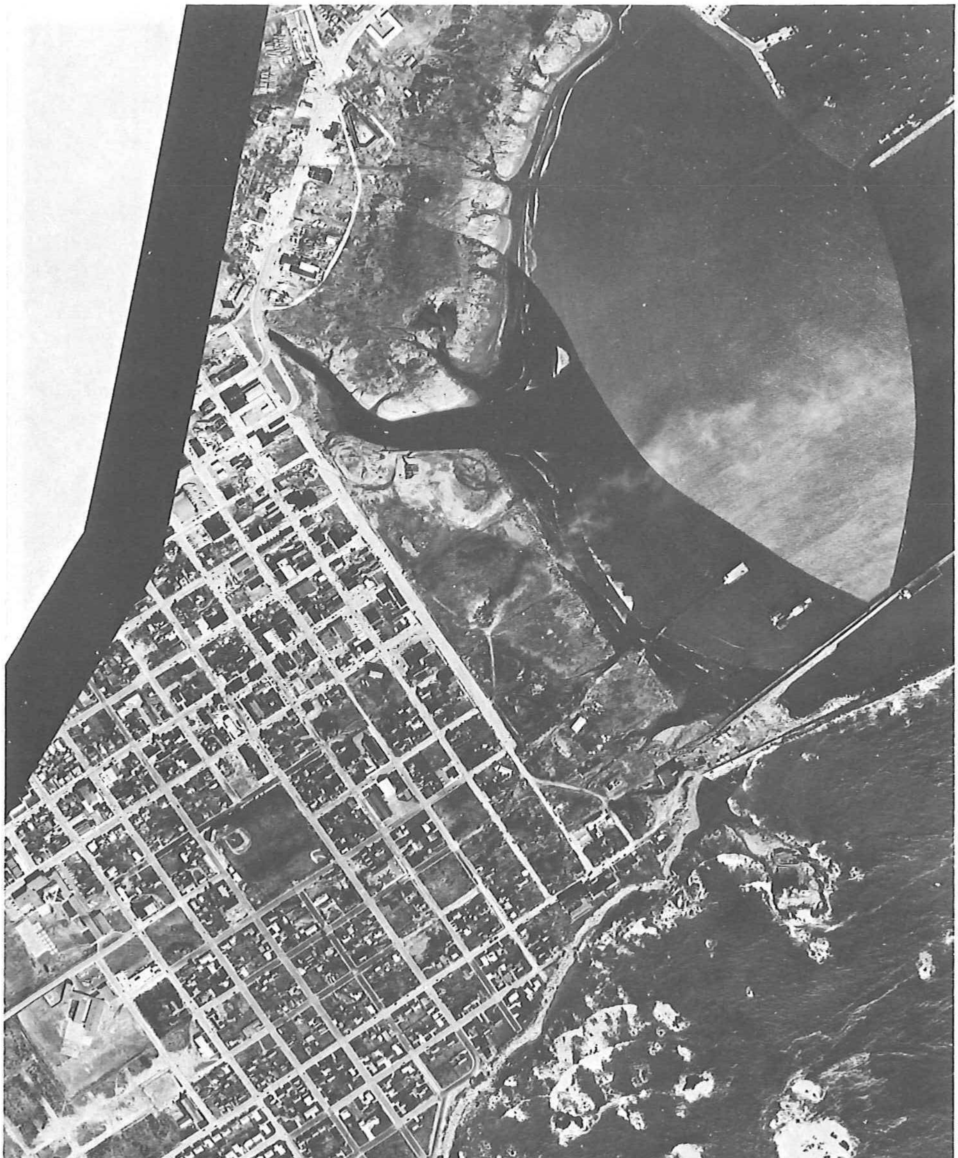


Figure 9 Crescent City 1 April 1964