

UNCLASSIFIED

AD **4 5 5 7 6 3**

DEFENSE DOCUMENTATION CENTER

FOR

SCIENTIFIC AND TECHNICAL INFORMATION

CAMERON STATION ALEXANDRIA, VIRGINIA



UNCLASSIFIED

NOTICE: When government or other drawings, specifications or other data are used for any purpose other than in connection with a definitely related government procurement operation, the U. S. Government thereby incurs no responsibility, nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.

**Best
Available
Copy**

CATALOGED BY DDC
AS AD No.

455763

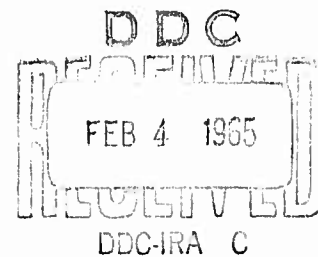
Technical Note N-622

TSUNAMI DAMAGE AT KODIAK, ALASKA, AND CRESCENT CITY,
CALIFORNIA, FROM ALASKAN EARTHQUAKE OF 27 MARCH 1964

BY

W. J. Tudor

November 1964



U. S. NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

TSUNAMI DAMAGE AT KODIAK, ALASKA, AND CRESCENT CITY, CALIFORNIA, FROM
THE ALASKAN EARTHQUAKE OF 27 MARCH 1964

Y-F008-08-02-128

Type C

by

W. J. Tudor

ABSTRACT

A survey of water wave damage to waterfront facilities at Kodiak, Alaska, and Crescent City, California, made about one week after the 27 March 1964 Alaskan earthquake of about 8.3 Richter scale indicates light to moderate damage from four to ten feet inundation and heavy damage from impact by wave-driven ships and debris.

The series of six seismic sea waves at Kodiak had crests ranging from 15 to 24 feet above MLLW and periods varying from 27 to 90 minutes. The largest wave at Crescent reached 21 feet above MLLW and had a period of 55 minutes.

At Kodiak Air Station: Three killed; few injuries; power station flooded; debris in hangar area; Cargo Dock damaged completely; two bridges and road washed out; barracks cracked; some subsidence and radioactive contamination; buoy washed ashore; oil slick on vehicles. At Kodiak City: 40% business district and many houses destroyed; 30% fishing facilities ruined; 75% food supplies lost; 25 killed; 77 fishing boats destroyed or missing; 3 canneries lost; king crab docks damaged; city dock, warehouse and harbor master building missing; numerous piling, anchors, lines, and piers damaged; boats floated aground inland; City settled 5 feet. At Crescent City: Rock and tetrapod breakwater not damaged; heavy damage in harbor; 15 boats capsized; Citizens Dock damaged severely; Dutton Dock nearby not damaged; seawall eroded; earthmover overturned; 25 ton concrete block pushed from pedestal; 12 killed.

It is concluded that at Kodiak and Crescent City: Piers with moored ships had decking damaged; piers with adequate deck-pile connections did not have decking uplifted; lines to large buoys not designed for full submergence; fishing boats moored in harbor were damaged by breakaways, grounding, and sinking; single-story, light-frame structures did not

survive well; multi-story buildings demonstrated good resistance; power-plants, communication lines, equipment and vehicles had functional failure when submerged.

Reconstruction of all low-lying sections of cities and ports should consider defense against tsunami.

Qualified requesters may obtain copies
of this document from DDC

CONTENTS

	Page
OBJECTIVE	1
INTRODUCTION	2
General	2
Wave Damage	2
Wave Action	2
U. S. NAVAL STATION, KODIAK, ALASKA	11
Damage	8
Wave Action	13
KODIAK CITY, ALASKA	41
Damage	41
Wave Action	44
CRESCENT CITY, CALIFORNIA	44
General	61
Damage	61
Wave Action	65
FINDINGS	115
CONCLUSIONS	116
RECOMMENDATIONS	117
ACKNOWLEDGEMENTS	118
REFERENCES	118
APPENDICES	
I. Tsunami Waves	123
II. Earthquake Energy Versus Nuclear Weapon Energy	127

LIST OF FIGURES

No.		Page
1.	Location of Epicenter and Cities Damaged by Tsunami	7
2.	Marigram at Sitka, Alaska on 28 March 1964	9
3.	Map of U. S. Naval Station, Kodiak, Alaska	15
4.	View of First Tsunami Wave at Kodiak NAVSTA	17
5.	Recession of First Crest at Kodiak NAVSTA	17
6.	Cargo Pier, Kodiak NAVSTA	19
7.	Damaged Deck of Cargo Pier	19
8.	Elevated Deck of Cargo Pier	21
9.	Moored Barge at Marginal Pier	23
10.	Road from NAVSTA to Holiday Beach	23
11.	Pilings of Hobby Shop and Engine Generator Building	25
12.	Crack in Black-Top of Taxiway	25
13.	Differential Settlement in Hangar Decks	27
14.	Little White House on End of Taxiway	27
15.	Power Plant Building	29
16.	Radioactive Ground Electronics Building	29
17.	Mooring Buoy Resting on Station Taxiway	31
18.	Oil Slick on Jeep at NAVSTA	33
19.	Reconstructed Tsunami Profile at Kodiak	35
20.	Tsunami Seiche in Old Womans Bay	37
21.	Offshore Profile at Kodiak and Crescent City	39
22.	Aerial Photo of City of Kodiak	45

No.		Page
23.	The Victory Maid and the Lucky Star	47
24.	Fishing Fleet Two Hours Before the Quake	49
25.	View of St. Paul Harbor	49
26.	Reinforcing Rods from Bowling Alley Foundation	51
27.	Fishing Boats Scrambled Together with City Buildings	51
28.	Vehicle and Boat Owners Can Collect Insurance	53
29.	Canopy and Utility Pole Helped Save Building	53
30.	Skeleton-like Timber Piling Marks Former Site of Cannery	55
31.	Cannery Was Displaced One Mile by Tsunami Waves	55
32.	Transit-Shed Type Building Did Not Survive	57
33.	View of the Main Street Shows Erosion	59
34.	Haberdashery Was Washed Right Off Its Foundation	59
35.	Crescent City Harbor	69
36.	Breakwater Protection at Crescent City	69
37.	25 Ton Tetrapod Monument Moved	71
38.	Cross Section of Breakwater	73
39.	Tetrapods on Outer Breakwater	73
40.	Reconstructed Crescent City Marigram	75
41.	Cross Section of Citizen Dock	77
42.	Damaged Decking of Cargo Pier	79
43.	Bollard Was Wrenched From Cargo Pier	79
44.	Timber Members of Cargo Pier	81
45.	Moored Barge Damage to Cargo Pier	83

No.		Page
46.	Tide Shack on Citizens Dock Was Fully Submerged	85
47.	Snake-like Approach to Citizens Dock	85
48.	Concrete Wave Barrier Under Citizens Dock Was Broken	87
49.	Dutton Dock Unharmed When Submerged	87
50.	Steel Straps and Cross Bracing Helped Dutton Dock Survive	89
51.	Abandoned Sause Dock Was Further Damaged	89
52.	Decking of the Sause Dock Sprawls to One Side	91
53.	Erosion Causes Pole Tipping	91
54.	Erosion Bares Elk River Concrete Box Culvert	93
55.	Scour at Parking Lot	95
56.	Waterfront Logs Were Driven Into Walls	97
57.	Plywood Now Boards Broken Windows	99
58.	Barber Shop Blocks Second Street	99
59.	Turbulent Waters Moved Two-Story Odd Fellows Hall	101
60.	Home on Front Street Broke in Half	101
61.	Flow and Pressure Diagrams Around House	103
62.	Five Feet of Flowing Water Moved Housing Unit	105
63.	Side Wall of Turf Club Bulges Outward	105
64.	Transit Shed Wall Collapses	107
65.	Deflected Utility Box	109
66.	Deflected Fish Shacks	111
67.	Marigram at Astoria, Oregon	113

No.		Page
68.	Earthquake Frequency	125
69.	Earthquake Magnitude vs. Equiv. Nuclear Weapon Energy	129
70.	Wave Height in Tsunami Train	131
71.	Wave Period in Tsunami Train	133

LIST OF TABLES

No.		Page
I.	Tsunami Damage at Kodiak City	42
II.	Recent Tsunamis at Crescent City	68
III.	Cities with Extensive Tsunami Damage	121
IV.	Speed of Tsunami Waves	123

OBJECTIVE

The objective of this task is to survey and report on damage to waterfront structures at the Kodiak Naval Station and city of Kodiak, Alaska, and at Crescent City, California, by water waves generated by the 27 March 1964 Alaskan Earthquake.

This report and necessary travel have been funded by the Defense Atomic Support Agency (DASA) through the Bureau of Yards and Docks, under DASA subtask No. 14.083 which has the objective of obtaining data and criteria to improve the design of important waterfront structures against explosion generated air and water disturbances.

INTRODUCTION

General

The author personally surveyed the wave damage in Kodiak and Crescent City; consequently, extensive data are presented on these localities. Tsunami damage information on other localities was gathered from early reports by the U. S. Coast Guard, U. S. Army Engineers, U. S. Geological Survey, newspaper and magazine articles.

The Alaska earthquake occurred at 1736 hours AST,* 27 March 1964, with estimated magnitude of 8.2 to 8.4 Richter scale. It was the strongest earthquake recorded in North America and the second or third strongest recorded anywhere. It ranks after the 16 August 1906 quake of 8.4 magnitude in Valpariso, Chile, and another Chilean quake of 21 May 1960 of magnitude 8.75.

Although the epicenter--the point of focus at which the rock gave way, snapping and shifting in an instant with the force of 12,000 Hiroshima-size 20 KT atomic explosions (See Appendix II)--was apparently on land, the area of vertical deformation and perturbations of the earth's surface in deep ocean areas was extensive. In fact, somewhere off the crescent of Alaska's southern coast, an almost circular area of 11,700 square miles heaved and a nearly rectangular area 20,800 square miles plunged violently, setting almost 20,000 cubic miles of salt water in motion. This generated a tsunami, a seismic sea wave, that transmitted energy throughout the entire Pacific Ocean (Figure 1) arriving in Antarctica nearly one day later with onshore amplitudes of one foot or more. In Japan, mild tidal symptoms were marked by maximum tide rises of up to 20 inches along coasts of Hokkaido and northern Honshu.

Wave Damage

The tsunami caused damages throughout the Gulf of Alaska, along the west coast of North America, and in the Hawaiian Islands.

*The times used in this note are Alaskan Standard Time (AST) which is 9 hours earlier than Greenwich (Z); i.e., $AST = Z - 9$ hours, and Pacific Standard Time (PST) which is eight hours earlier than Greenwich; i.e., $PST = Z - 8$ hours.

Waves with heights of 30 feet or more along the coast of Alaskan Kenai Peninsula to Cordova and along the coast of Kodiak Islands caused heavy damages. The communities hardest hit in Alaska were Kodiak, Seward, Valdez, Chenega, and Whittier. At Seward the wave damage included: The seawall which sank out of sight; the small boat harbor which was ruined; boats ripped loose from the dock; a trailer park which disappeared; the highway which was destroyed; a number of bridges which were swept away without a trace; railroad facilities which were lost totally; tugs lying on their sides in the mud and water; a tanker beached and burned; a 60-ton locomotive overturned; tracks and equipment and railroad cars at the waterfront burned; heat and power supplies cut off; sewage system destroyed; water contaminated; approximately 90% of the industry was destroyed.

At Valdez: The docks, piers, fuel-storage terminal and small boat harbor were gone. More than 40 boats had been smashed by the large waves. The railroad port facilities were demolished at Whittier but an Army dock there still remained in good shape.

In the Aleutian villages of Afognak, Ouzinkie, Kaguyak and Old Harbor on Kodiak Islands the destruction was almost complete. Only a handful of houses remained. Timbers of other houses slapped at the shore and other dwellings, still intact, were driven miles across the water to distant beaches. Most of the people in the villages escaped because of radio warning. Tsunami waves also caused heavy damage along the Canadian shores of North America. For example, at Port Alberni, Vancouver Island, the waves damaged buildings and surged 40 miles through the Alberni Canal.

At Homer, Alaska, the harbor disappeared into a funnel-shaped pool within 1-2 minutes after the tremors started. A lighthouse once on the harbor breakwater is now 40 to 50 feet below MSL. Ten-foot waves at 2-minute intervals were reported at the time of ground shock. Port Aston and San Juan experienced waves splashing bottom of pier decks. Piers were not damaged even though old. There was one boat sunk and a cannery damaged at Port Oceanic where a relatively small wave rose 5 minutes after quake, followed by one 20-30 feet high. Ten thousand gallons of jet fuel was spilled into the harbor at Anchorage, Alaska, when the dock fuel lines were damaged. An oil well drilling vessel, the GLOMAR, owned by Global Marine Exploration Company, was at sea and was undamaged. The city port dock, built with steel piles, suffered very little damage. The Army dock nearby, built with wooden piles, was put out of service (Stephenson, 1964).

Wave damage along the United States Pacific Coastline was minor and isolated, except at Crescent City, California, where the energy of the tsunami may have been focused by the offshore topography and the harbor shape such that serious damage resulted.

At DePoe Bay, Oregon, the wave rolled over and drowned a family of four. At Gray Harbor County, Washington, it washed out a bridge over the Copalis River, and turned over several trailer homes. At Seaside, Oregon, it pushed back the Necanicum River, flooding a trailer park as residents fled.

Power and telephone services were cut off at Cannon Beach where the wave toppled several houses off their foundations. Numbers of small craft moored to a wharf at the beach were swept to sea after the wharf gave way to the surging water pressure. The same type of damage occurred at Gold Coast, Oregon, where water ripped out docks and smashed small boats on the Rogue River. A wall of water reportedly surged into the Siuslaw River at Florence, Oregon, raising it 8 feet in 8 seconds.

At Santa Cruz, California, a 35-foot floating dredge was set adrift. Damage in the harbor was slight, but a 38-foot power cruiser fell apart and sank. The story was much the same as far south as San Diego. Evacuation warnings were issued, small craft tore loose and dock installations suffered minor damage. In San Francisco Bay water surged through the Golden Gate, setting adrift a beached ferry boat and 350-ton houseboat. The Coast Guard reports that at Fort Point, just beneath the Golden Gate Bridge, the water dropped 7 feet in a matter of seconds before the wave hit. Damage to Marin County, California, small boats and berthing facilities is estimated at one million dollars; mostly at Loch Lorman Harbor, San Rafael. All but a few of the 310 boats tied up there sustained some degree of damage. Workmen had to clear debris from San Rafael Canal so boats could get out into San Francisco Bay.

Wave Action

Two types of wave disturbance were evident: Surging (i.e., bore action) and flooding. Near the epicenter a number of highly destructive surges or bores were experienced during and almost immediately after the quake. The early waves that hit Seward and Valdez were of this type and were definitely generated by submarine landslides. A general impression is obtained that the wave damage in Prince William Sound was due to a general northward surge of water throughout the Sound--the same as might be experienced by a quick uplift of a pan of water.

At Seward large waves were generated by submarine landslides and radiated from them at high speed. Before the shaking stopped, or within a few minutes thereafter, these waves hit the north side of Lowell Point, the Seward waterfront, and the north and east sides of Resurrection Bay. Wave height was estimated to be about 30 feet at the north side of Lowell Point where trees behind the beach show bruises between 12 and 14 feet above their bases. About 30 minutes after the first wave, a seismic sea-wave entered Resurrection Bay, increased in height as it entered shoaling water, and inundated the low areas of Lowell Point, Seward, and the flats.

This wave reportedly reached 100 feet above water level, but in most places, its highest trim lines were roughly estimated to be 25 to 35 feet above the water surface, which was at low tide at that time.

The wave that destroyed all but the school and one house in Chenega is described as a wall of water 90 feet high. This wave, which struck within 3 minutes after the earthquake ended, was preceded by a smaller wave and a pronounced withdrawal of water. The actual wave was at least 35 feet above high-tide level, and runup entered the school building which stands on a knoll above the village at an elevation of 90 feet. The exceptional height of this wave may be attributed to focusing (refraction) of the onrushing water by the hydrography around a small group of islands situated in the middle of Knight Island Passage, approximately 4 miles southeast of Chenega (USGS 1964).

The surge of water that shot into Valdez Arm and Port Valdez overtopped and destroyed a navigation light in Valdez Passage, and struck the north shore of Port Valdez near the Cliffmine. It was reflected to the southeast shore, striking at Jackson Point then spent itself along the head of Port Valdez. The wave destroyed wooden buildings at the Cliffmine and deposited debris 170 feet above sea level. Runup reached 220 feet, as indicated by broken and freshly-scarred shrubbery. At Jackson Point the Dayville Cannery was floated away and the wave heaped driftwood to a height of 17 feet above the highest tide level (USGS 1964).

In communities more than several hundred miles from the epicenter, the first bore wave was not evident in the incident tsunamic wave train, the first of which was reported at Cape Chiniak (20 miles southeast of Kodiak) about 30 minutes after the initial quake tremors.

At the Kodiak Naval Station flooding rather than bore action was observed. The flooding resembled that of a river (Figures 4 and 5). Specifically, the tsunami waves resembled flood waves going down a river including the silt load and driftwood. This may make it easier to visualize the extent of and forces induced by flooding due to tsunami waves.

The nearest tide gage to the epicenter which survived was at Sitka (Figure 2) where a 16-foot rise was recorded on the third wave. Review of the irregular pattern of the record indicates that initial bore waves, and following tsunami seiche, and reflected waves, are superimposed on the water level variation that occurred at this range from the tectonically elevated and depressed generating areas. The Coast Guard reported that a dock collapsed on Baranof Island at Sitka, the only community in the southeast Alaska "panhandle" reporting damage.

The entire island of Kodiak underwent a 5-1/2-foot subsidence during the quake. Subsequent high tides will likely cause additional water damage.

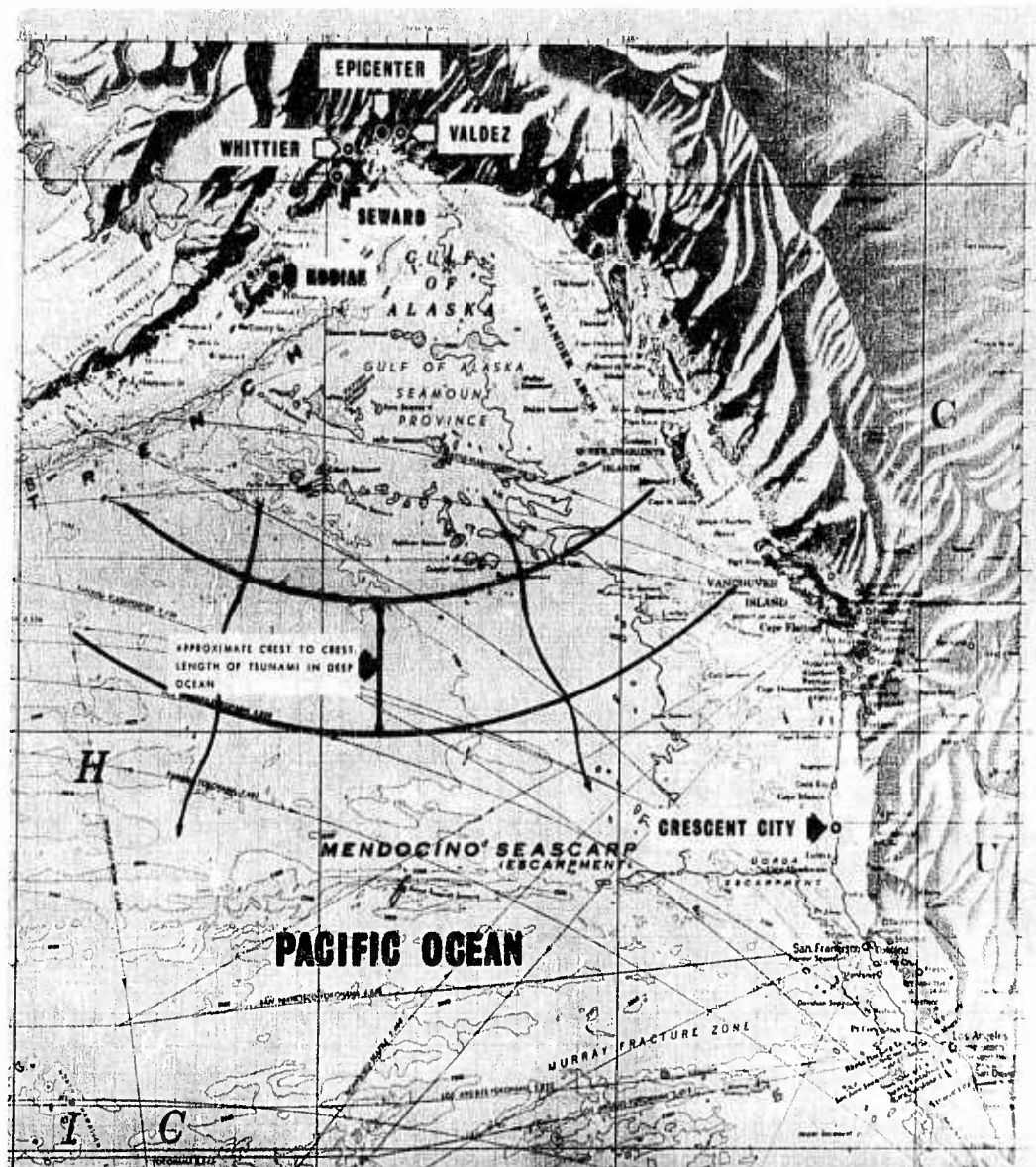


Figure 1. Location of epicenter and cities damaged by tsunami.
(Map by U. S. Navy Hydrographic Office)

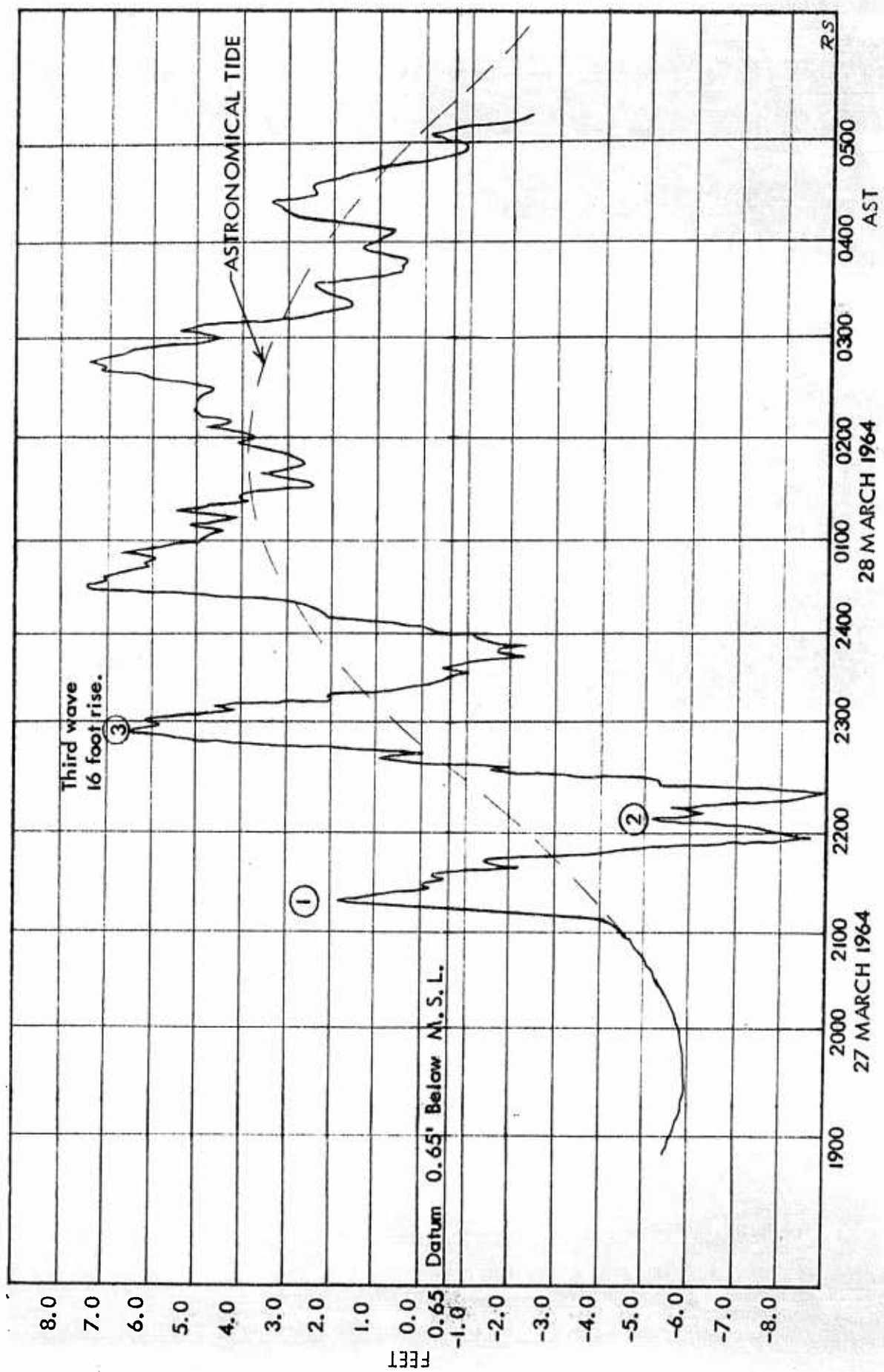


Figure 2. MARIGRAM AT SITKA, ALASKA 120°W ON MARCH 28, 1964 (USCGS)

U. S. NAVAL AIR STATION, KODIAK, ALASKA

Damage

This base sustained light to moderate damage when the earthquake and seismic sea waves struck on Friday, 27 March. A moderate to severe earthquake was active from 1732 to 1740 AST. The initial and strongest tremor lasted five minutes, cracking water mains and causing minor damage in both Kodiak City and Naval Station. Numerous, milder shocks followed.

Disaster struck at 1835 AST. The first of a series of giant tsunami waves, the highest estimated at 30 feet, hit the base one after the other. Fortunately, few injuries occurred and the death toll of 3 was surprisingly low. Credit for this low loss is due to observation of the warning in NAVSTA KODIAK INSTRUCTION 3160.1B, Subject: Seismic Sea Wave Disaster Bill, dated 11 July 1963, which reads in part: "At some places the advancing turbulent wave front is the most destructive part of the wave. Where the rise is quiet, the outflow of water to the sea between crests may be rapid and destructive, carrying great rocks and buildings with it."

The waves were incredibly high, almost silent tides stealing into low-lying areas of Naval Station Kodiak, inundating buildings and inflicting over six million dollars in damages to structures, materials and equipment (see Figure 3). The main power station was flooded and all electrical power and steam to the centrally-heated station buildings and quarters were lost. Breaks occurred in the water mains which necessitated a shut down of the water system.

The sea plane ramp into Old Woman's Bay is one of the lowest spots on the NAVSTA. It is shown in Figure 4 with Hangar #3, and the northern slope of Old Woman's Mountain in the background. In the foreground, debris swirls along in the wave. Two PV2 Neptune aircraft of Patrol Squadron TWO parked in front of the hangar were undamaged due to quick thinking by personnel who maneuvered them to higher ground. Each succeeding tsunami wave carried debris from Old Woman's Bay into the hangar area. Figure 5 shows Hangar #1 in the foreground and Hangar #3 in the background. Both hangars were flooded by 6 to 8 feet of water.

The Cargo Dock, Structure No. 454, which was in a deteriorated condition, was completely damaged by the tsunami. Prior to the earthquake all ship and cargo supplies were loaded and unloaded at this dock. The tsunami-induced motion of moored ships raised the bollards and damaged some fendering (Figure 6). A more extensive analysis of failure to fenders by moored ships is reported by O'Brien (1963) in an analysis of damage to Apra Harbor, Guam, during Typhoon Karen. There it was found that the fender damage was due to thrashing by vessels moored alongside. All occupied fenders there suffered damage. The 5-1/2-foot tectonic settlements of NAVSTA enables the high tides to nearly inundate the Cargo Dock.

The elevated waters lifted (buoyed) sections of the pier decking off the piling and moved it laterally. This shifting caused failure of many framing and bracing members. Several piles were pulled from their pile-holes along with the elevated decking. The reason is that great difficulty is experienced upon driving piles in the rocky bottom, and in some instances, the pile-holes have to be augered. When the water receded, the buoyed decking and extracted piles did not return to their original positions (Figures 7 and 8). This resulted in differential elevations of several feet in the decking. The Marginal Pier suffered minor damage such as that on the approach (Figure 9) where a moored barge under tsunami action loosened a bollard and some decking.

The two bridges and Chiniak Road between the Naval Station and Holiday Beach were washed out causing loss of vehicular contact with the NAVRADSTA (Figure 10). The power line in the swamp flat 4 miles to the south was damaged. NAVRADSTA (T), Buskin Lake, and NAVRADSTA (R), Holiday Beach, stand on high ground and were not damaged. The Holiday Beach barracks cracked open along a line separating the mess hall and the dormitory area.

Two small waterfront structures, the Hobby Shop and Engine Generator (TACAN) Building, located on the edge of Old Woman's Bay were completely swept away except for the foundation pilings (Figure 11). Lack of adequate ties between floor beams and piling made the structure vulnerable to water uplift and lateral forces.

The asphalt pavement covering the taxiways between the hangars and seaplane ramps were cracked under the seismic action (Figure 12). In the hangar there was differential settlement between the pile-supported columns and fill-supported hangar deck (Figure 13) and settlement between the hangar deck and hangar structural footings around the perimeter of the hangar. The hangars were constructed on approximately 15-20 feet of glacial till fill which was consolidated under the tectonic shock and loading action of the subsequent tsunami waves. This subsidence was further accompanied by ripple and surface erosion near the hangars. The differential settlement of several inches between the slabs and hangar door footing produced an obstacle step for aircraft entering and leaving the hangar. Some of the hangars suffered slight bracing deformation and broken glass from subsidence.

At the edge of the seaplane ramp, a small white house (Figure 14) survived the floodings and was not carried away because of the hold-down cables over the roof. This type of construction is not too unusual along waterfronts subjected to high tides.

The ground floor of the main power plant was repeatedly flooded (Figure 15) by water with a heavy silt load. Heavy fuel oil on the water coated the boilers, blowers, motors and pumps on the boiler flat (deck). The maximum water elevation was below the generator deck where the high voltage switching gear and control instrumentation were located.

Low-level radioactive contamination occurred in the Ground Electronics Building when tsunami waters scattered traces or minute sources of radionuclides. This was a bit unusual (Figure 16).

Near the Crash Boat Harbor, sea shells brought in from the harbor by the tsunami were found deposited on land 10 to 15 feet above MLLW. Adjacent to the supply building a 16-foot-diameter mooring buoy (Figure 17A) was washed ashore after being torn from its offshore anchorage. The magnitude of the force on the buoy when submerged is estimated in Figure 17B. This estimate indicates that where the buoy is fully submerged, as it was by the tsunami, the added load is approximately 36 times the load from an assumed mooring chain while neutrally floating. This would seem enough to tear the mooring from its anchorage.

Vehicles partially or fully submerged by the elevated waters were for the most part a total loss due mainly to the corrosive effect of the salt water on the motor and wiring. In addition, the oil slick from the water was deposited heavily on many vehicles. In Figure 18, the oil slick coats the windshield of a jeep that was nearly floated from its parking spot on Nyman's Peninsula on NAVSTA.

Wave Action

The only reliable record of the tsunami waves along the Gulf of Alaska was recorded by the personnel of the U. S. Fleet Weather Central, Kodiak, Alaska, CDR. Dodson, USCGS, commanding. All tide gages were rendered inoperative by the quake. Fortunately, Barney and Morrow of the Coast and Geodetic Survey made visual observations of tsunami high-water marks as follows: After each crest, a pencil mark or visual estimate was made at the resultant water line on a building near the water. This water line was later referenced to the staff at the tide gage.

The log of Barney and Morrow, from which the Figure 19 marigram was reconstructed, follows. Times are AST.

RESUME OF WAVE ACTIVITIES - 27 March 1964

- 1750 - Tide Station inoperative due to earthquake damage.
- 1810 - Cape Chiniak reports 30-foot tsunami.
- 1820 - Water rising rapidly. No recession has previously occurred.
- 1835 - Water crested 22 feet above Tide Staff zero.

1836 - Water ebbing.
 1907 - Maximum low ebb, estimated 15 to 18 feet below MSL.
 1930 - Water rising.
 1940 - Water crested at 24 feet above staff zero.
 2000 - Water maximum low level. Elevation unknown.
 2030 - Water crested at 21 feet above staff zero.
 2040 - Water crested again at less than 21 feet. Oscillation appears to be superimposed on tsunami period.
 2130 - Water started to rise again, minimum level unknown.
 2200 - Water crested 25 feet above staff zero.
 2210 - Water slowly ebbing. Heights unknown, small amplitude, believe seiche.
 2215 - Water slowly rising; 2219 - water slowly ebbing; 2225 - water slowly rising: Heights unknown, small amplitude, believe seiche.
 2227 - Water crested at 21 feet above staff zero. Intervening minimum height not observed.
 2248 - Water rapidly rising and falling. Small amplitude, believe seiche.
 2316 - Water crested 30 feet above staff zero.
 2317 - Water ebbing rapidly.
 2319 - Water rising rapidly, crest 30 feet again. Intervening ebb level unknown.
 2322 - Water ebbing.
 2324 - Water has risen and crested at unknown level, but below 30 feet above staff zero.

RESUME OF WAVE ACTIVITIES - 28 March 1964

0015 - Minimum low water estimated about 5 feet below staff zero.
 0045 - Water crested at 23 feet above staff zero.

Readings continued until at 1530, 28 March, the tide gage was overhauled and placed back in operation. Initial staff reading was 18.7 feet as shown on Figure 20. This shows the tsunami seiche action in Old Woman's Bay.

The offshore profile at Kodiak in Figure 21 illustrates the present wave problem. At the continental slope an appreciable depth change takes place over a distance which is small compared with a typical wave length. The wave action as shown here would have a reflection. The water running onshore with the crest and offshore with the trough would correspond to the flood and recession. Denoting Q as the quantity flow, H the height, and T the period of the incident wave, then the pertinent dimensionless parameter would be Q/H^2T . Or by consideration of the energy expended, the tsunami can be thought of as a pump with varying onshore discharge (crest) and suction (trough) where once again, Q , H , and T (or wave length L) are the important variables.



Fig. 4 View of first tsunami wave which crested at 16 ft above the old MLLW deluged the seaplane ramp leading from Old Woman's Bay. The two PV2 aircraft in front of Hanger #3 were saved by moving them to higher ground.
(Photo by PIO, Kodiak NAVSTA)



Fig. 5 Debris and ice cakes are deposited on the seaplane taxiways after recession of first crest. Damage to the Stations three hangers is placed at more than \$1 million dollars. (Photo by PIO, Kodiak NAVSTA)

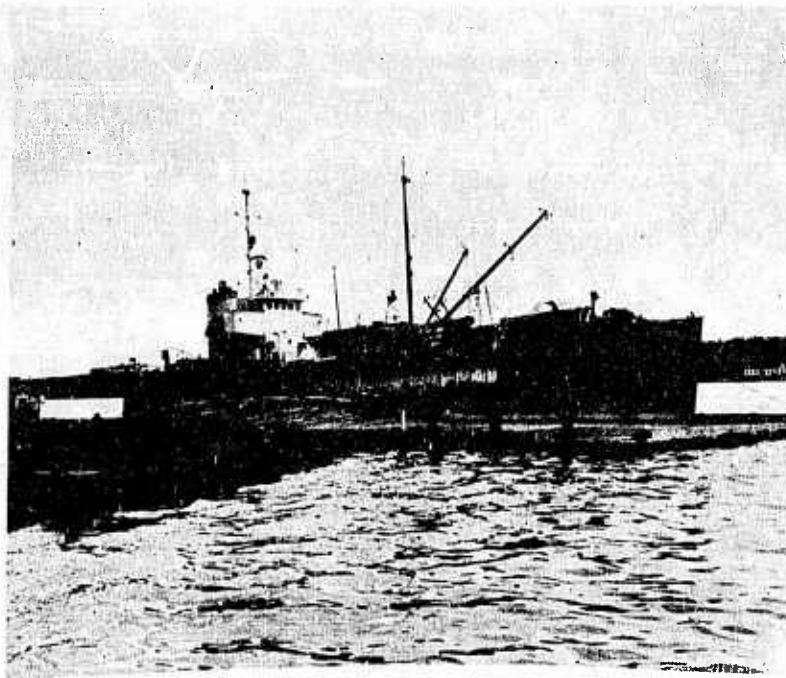


Figure 6. Cargo Pier deck nearly inundated by high tide after tectonic settlement of NAVSTA. Tsunami-induced motion of moored ships raised bollards.



Figure 7. Local elevation of Cargo Pier deck caused when tsunami-extracted piles did not return to augered pile holes in rocky bottom.

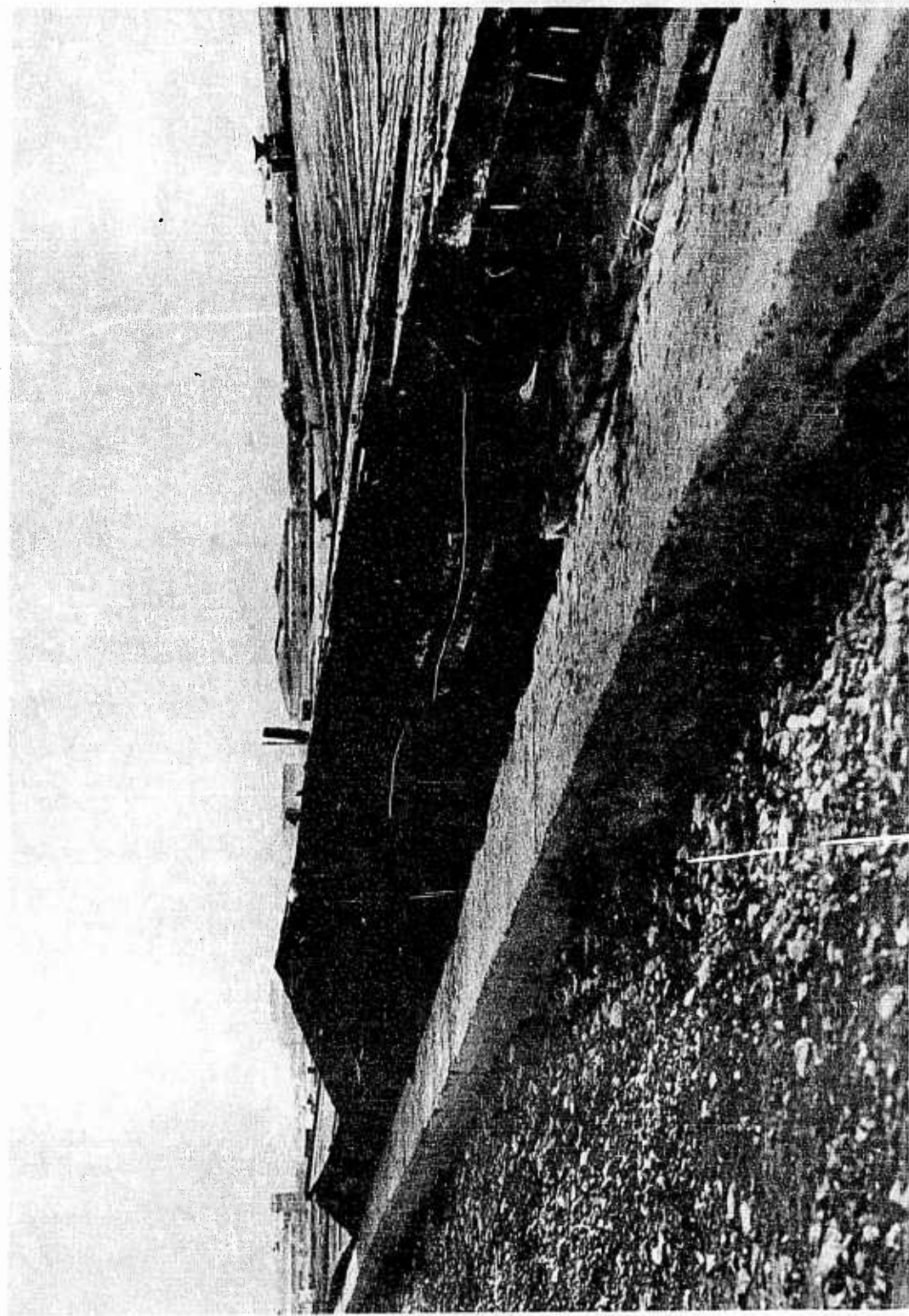


Figure 8. Waviness of Cargo Pier deck resulted when decking buoyed by tsunami failed to return to original location. (Photo by PIO, NAVSTA)



Figure 9. Moored barge under tsunami action pulled decking and bollard loose from marginal pier.



Figure 10. Kodiak Island subsidence of 5-1/2 feet allows high tide to wash over road to NRS(R) Holiday Beach. Cargo Pier in background.

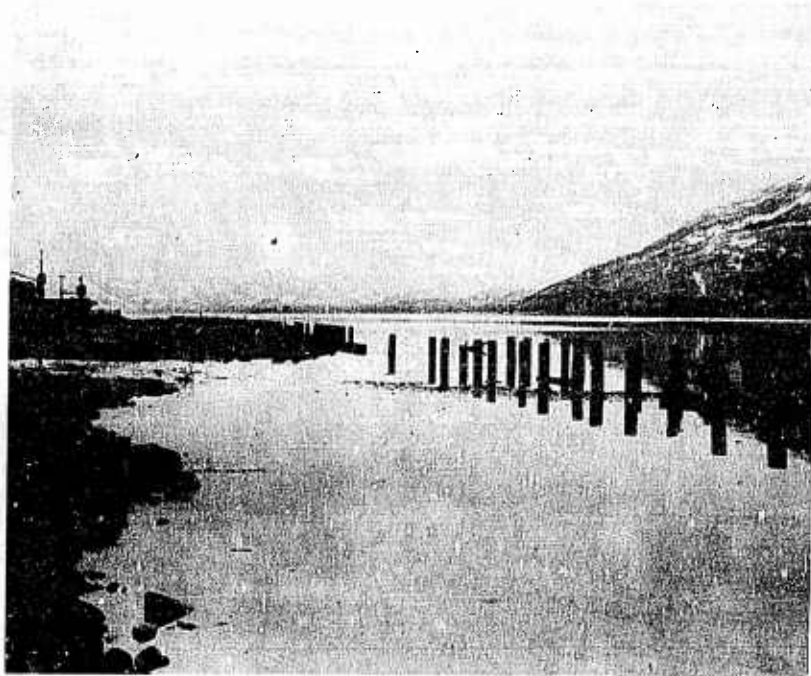


Figure 11. Piling is all that remains of the Hobby Shop and Engine Generator (TACAN) Buildings on edge of Old Women's Bay. Fuel Pier in background.



Figure 12. Seismic action produced 1" cracks in asphalt pavement of taxiway. Fuel Pier in background.



Figure 13. Hangar decks had differential settlement up to 1 foot under four to six feet of flooding. Columns on piles did not settle.

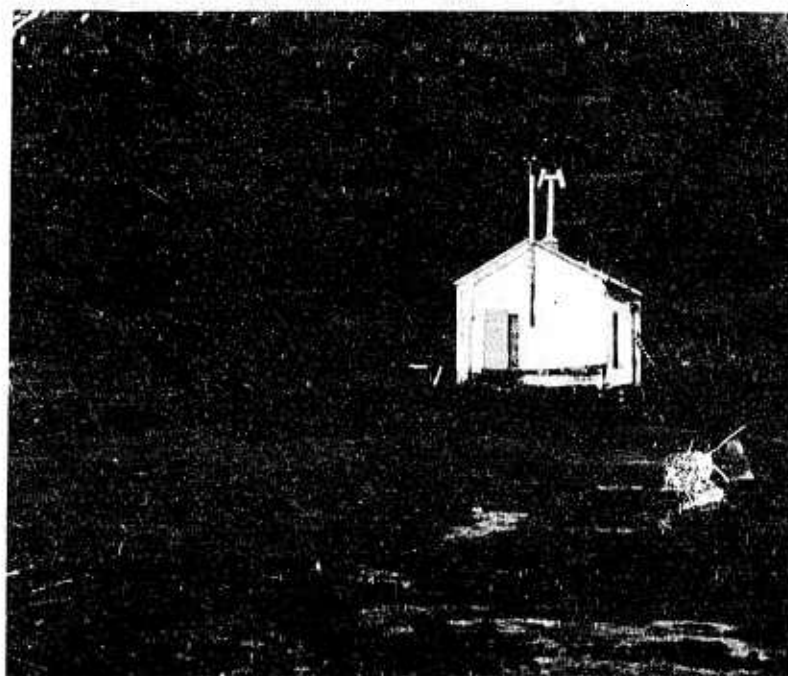


Figure 14. Little white house on end of taxiway was held in place by three hold down cables to roof. Water in foreground left by high tide.

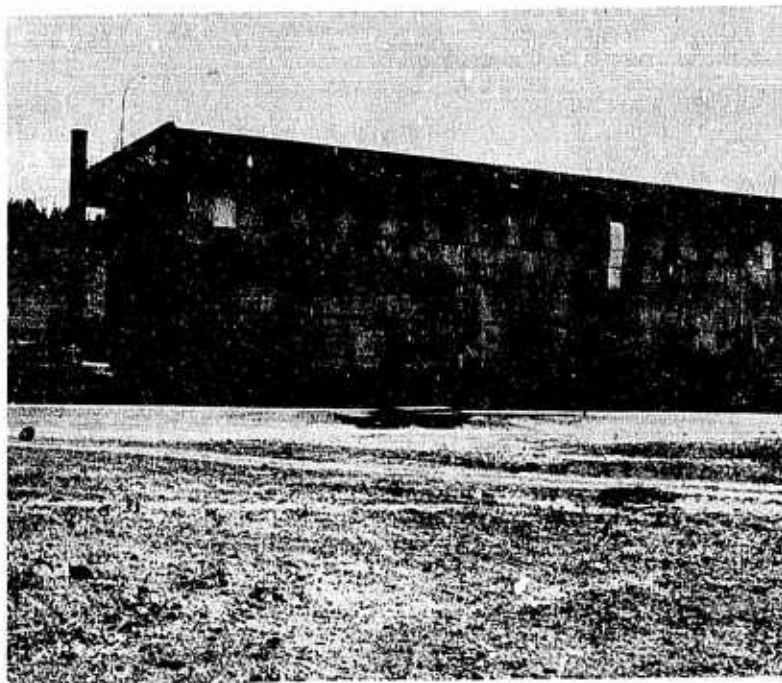


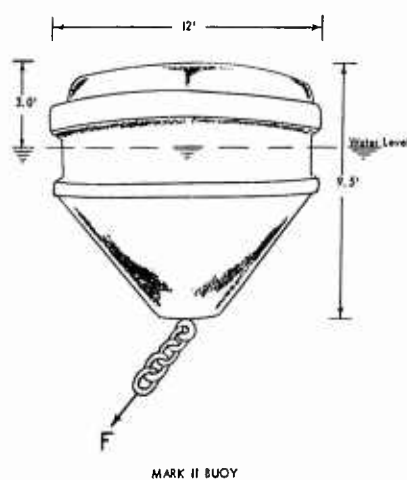
Figure 15. Power plant repeatedly flooded. Note black oil-slick level. Generator flat not flooded. Boilers and auxiliary flats were pumped dry.



Figure 16. Low-level radioactivity from wave-damaged electronic tubes and radioisotopes in Ground Electronics Building was detected and posted.



Figure 17A. Mooring buoy weighing over 10 tons now rests on the Station taxiway. Third tsunami wave cresting at 24 ft. above old MLLW drove this buoy inshore.



Problem: Force to tear out ring from bottom of mooring buoy.

Assume: Total buoy vol. = 789.7 cf
Vol. below water = 450.6 cf
Reserve displacement = 789.7 - 450.6 = 339.1 cf
Wt. of mooring chain = 20 lbs/ft
Neglect current and wind.

Net force on mooring bottom upon full submergence equal
reserve displacement x unit weight of water.

$$F = 339.1 \text{ cf} \times 64 \text{ lbs/cf}$$

$$F = 21,700 \text{ lbs.}$$

$$\text{Force on mooring bottom} = \text{Total wt. of chains}$$

$$\text{when floating.}$$

$$= 30' \times 20 \text{ lbs/ft}$$

$$= 600 \text{ lbs.}$$

$$\text{Therefore, } \frac{\text{Submergence}}{\text{Floating}} = \frac{21,700}{600} = 3.6$$

Figure 17B. Mooring Buoy action under tsunami waves.

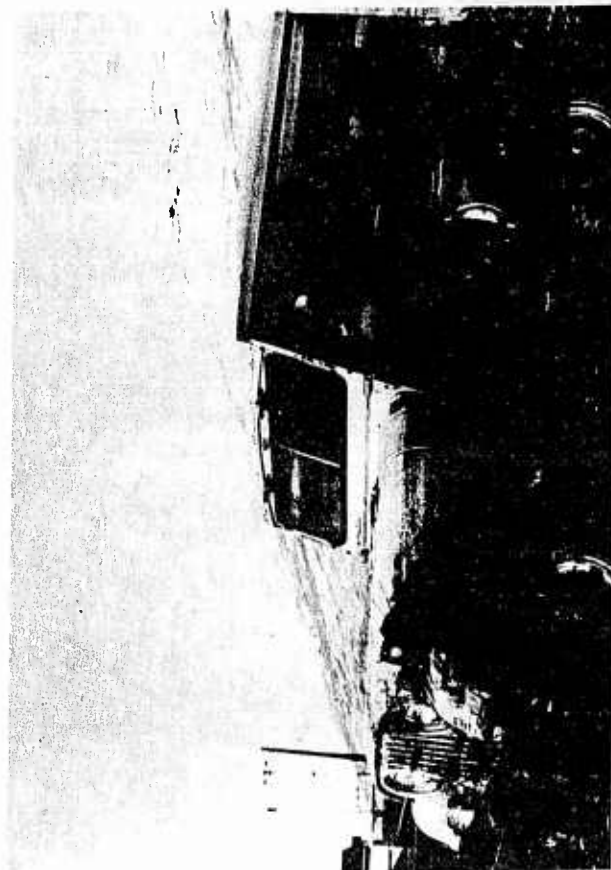


Figure 18. Well-oiled jeep almost floated away from its parking spot on Nyman's Peninsula on NAVSTA when the tsunami waves struck March 27th.

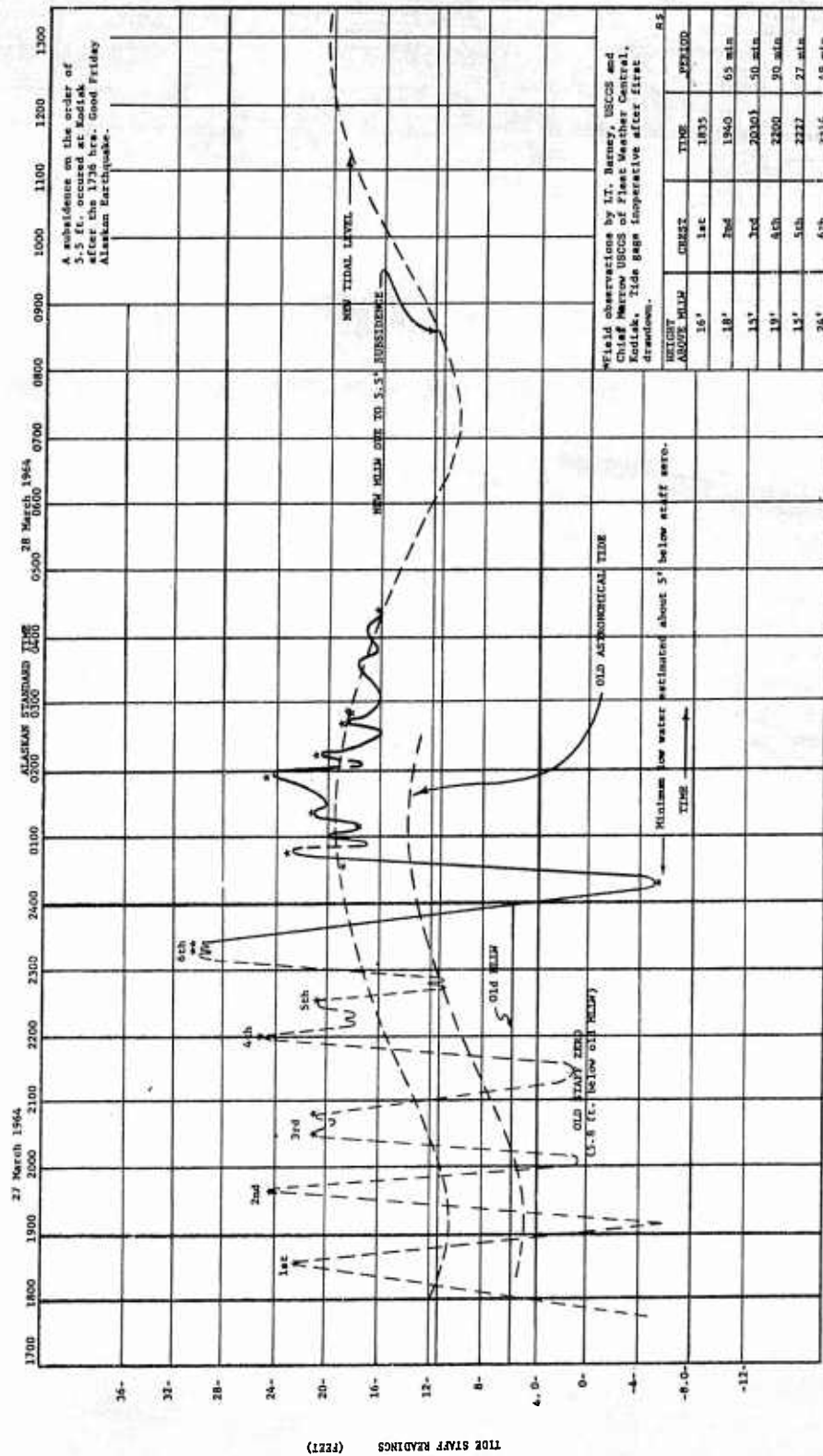


Figure 19. Reconstructed Tsunami Profile at Kodiak Naval Air Station, Alaska.

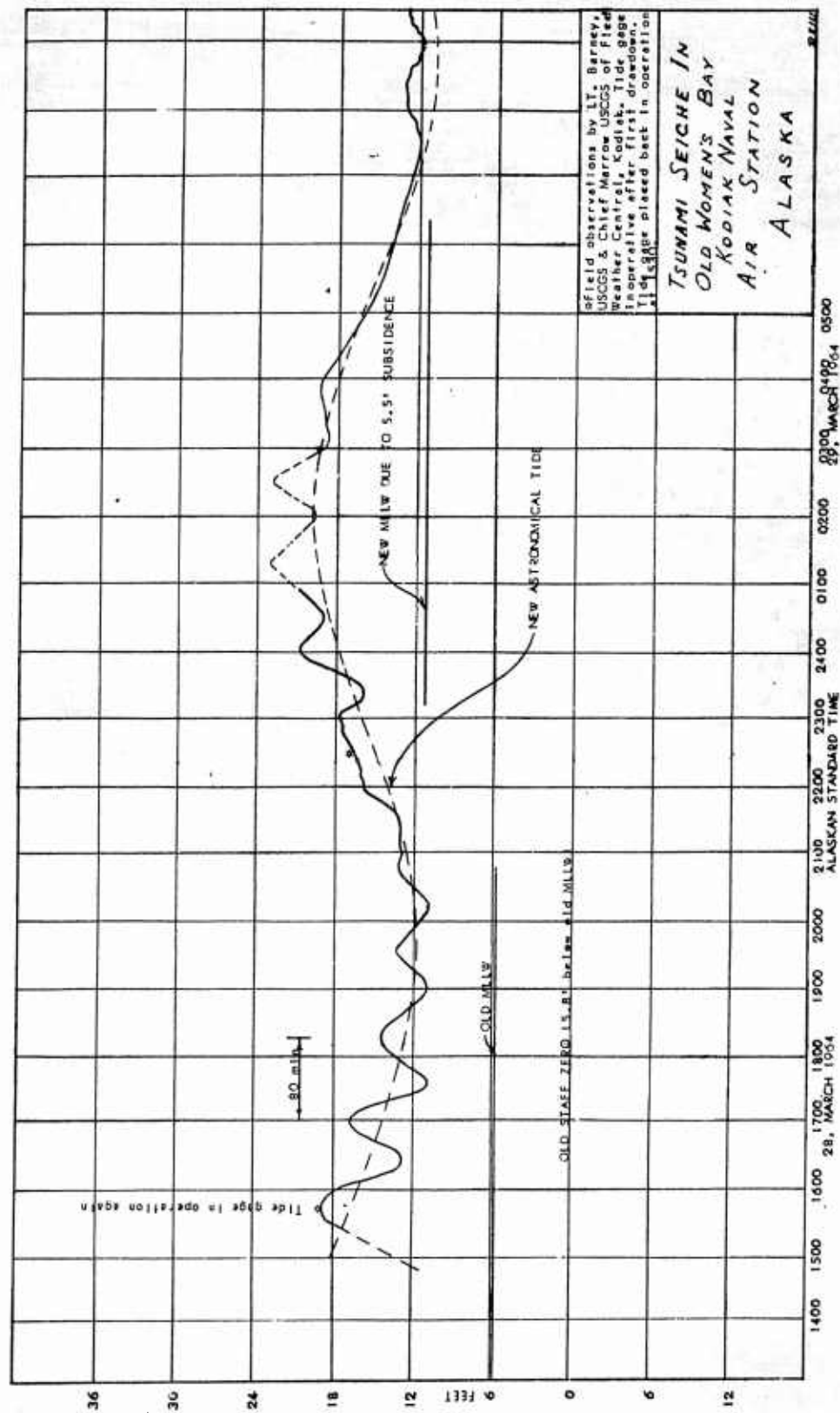


Figure 20

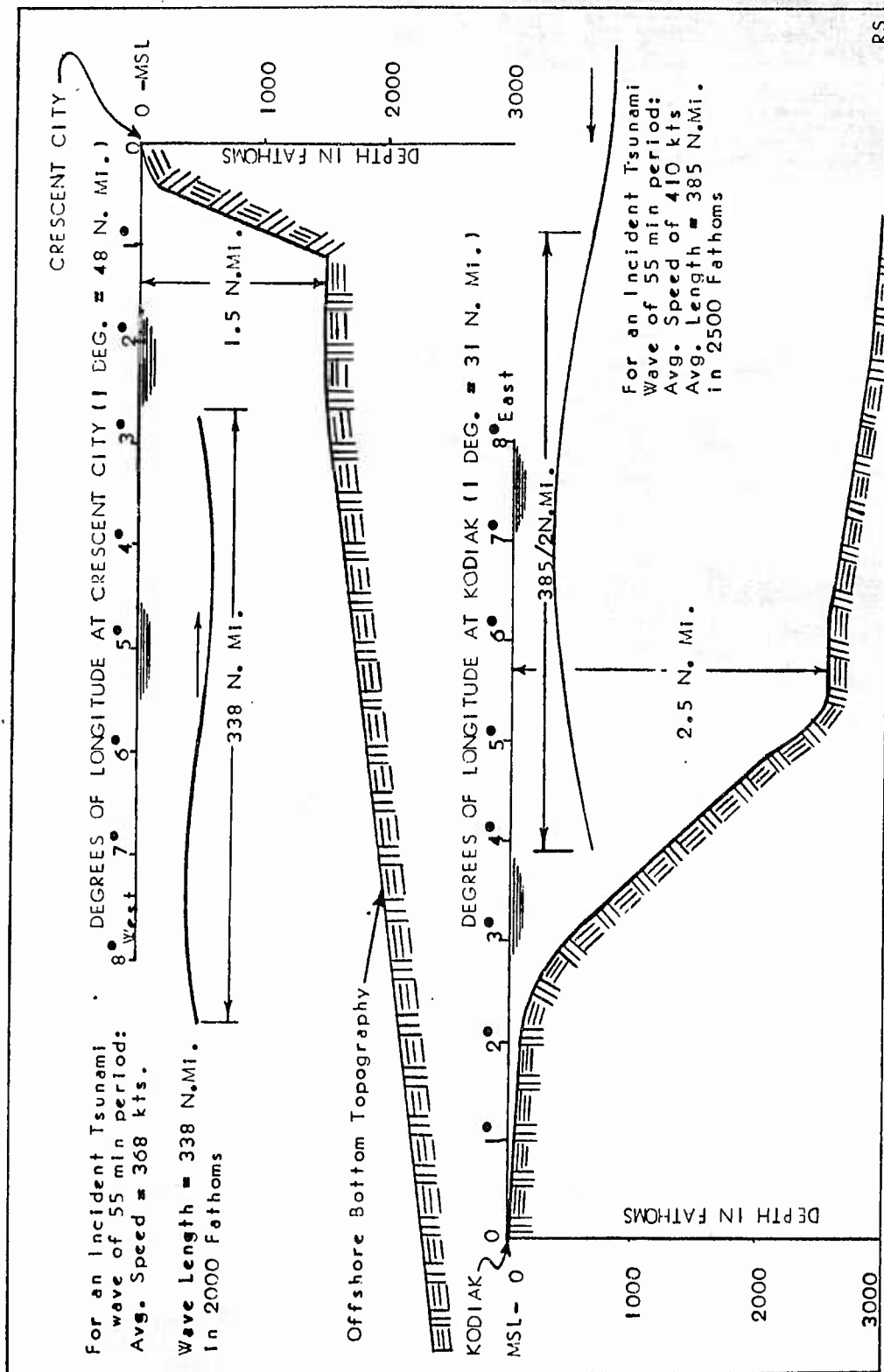


Figure 21. Offshore profile at Kodiak and Crescent City.

KODIAK CITY, ALASKA

Damage

The city of Kodiak, with its population of 2,600 persons, is the headquarters of one of the largest fishing fleets in Alaska. Shrimp, crab, halibut, salmon and scallops abound in the ice-cold waters surrounding the islands. Built for the most part on low ground, the city was critically hurt by the huge waves (Figure 22). Four waves successively emptied and filled the harbor. Forty percent of the business district and many homes were wiped out (see Frontpiece), and 30 percent of the fishing industry facilities were ruined. An estimated 75 percent of the city's food supplies were lost in the destroyed buildings. The dead totaled 25 in spite of a 30-minute siren warning given residents to reach high ground.

The earthquake in Kodiak was less spectacular than the resulting waves. Even so, it shook houses, tumbled dishes and broke water mains. Aftershocks of Richter magnitude 5 to 6 were occurring a week later while the author was at Kodiak. They did no seismic damage and did not create a tsunami (see Appendix II).

Seventy-seven of the total of 160 crab and salmon boats were missing or fearfully mauled (Table I), two of the canneries were swept away, and the others were unable to operate for 1 or 2 months. An example of boat damage is shown in Figure 23 which also shows a ruined portion of the harbor dock shown in Figure 24.

The harbormaster building was completely destroyed when a large fishing boat collided with it at about 15 knots. The 6 to 8 feet of submergence by the higher tsunami waves buoyed the City Dock's decking off the pilecaps because the deck stringers were only drift-pinned to the pilecaps. The vertical motion accompanied by lateral movement destroyed the decking. When the bulkheads and more than two dozen piles under the approach to City Dock were destroyed, the approach decking floated away. The warehouse and equipment were also swept from their foundations. There is presently no protection from Alaska Bay waves (Figure 25). Temporarily, the natural harbor at Gibson Cove, 1 mile away in the St. Paul Harbor area, is being used.

Some of the townspeople, who had climbed the hills with flashlights, related that when the four waves came onto land, the impact of ships being swept into the city produced high level grinding and grinding noises. The second wave, in particular, came with a roar, and numerous pilings, anchors, lines and piers snapped and broke and the harbor became a dizzy whirlpool.

Table I. Tsunami Damage at Kodiak City, Alaska
(Data from Civil Defense)

Boat Harbor (Inner Harbor)	\$ 250,000	Boats Sunk or Aground	35
Dredging Boat Harbor	150,000	Boats Missing	17
Harbormaster Building	10,000	Boats with Major Damage	10
Breakwater	500,000	Boats with Considerable Damage	15
City Dock and Warehouse	1,200,000	Boats with Slight Damage	<u>20</u>
City Dock Equipment	55,000	Total	97

42

Losses of private and commercial property		Estimated 42 boats lost in Kodiak area outside of City of Kodiak Estimated Value . . . \$840,000
Buildings	\$11,346,000	
Stock	6,000,000	
Equipment	<u>2,000,000</u>	
	\$19,346,000	Cost of Repair to Replace Vessels listed above . . . \$1,600,000
Losses of public property . . . \$5,400,000		
		Dwellings Destroyed by Tsunami Waves Total . . . 1,608,000
		Household Effects of Dwellings Damaged Total . . . 320,000

NOTE: The Kodiak fisheries in 1963 processed a total of 41,500,000 pounds of king crab; 330,000 cases of salmon; and 12,000,000 pounds of shrimp.

The lateral thrust by the waves and ship impact was sufficient to level a bowling alley at the harbors edge to its foundation slab. Only a few reinforcing rods protrude from the slab of this former concrete block structure (Figure 26). Several fishing ships that did not collide with obstacles were buoyed-in more than 1/2 mile from the harbor into the lowest-lying part of the city where a culvert drains into the harbor (Figure 27).

Vehicles in the flooded area were ruined. Furnishings and equipment of homes and offices were damaged when water poured in through broken windows and doors (Figure 28 and 29). Most boat owners and vehicle owners with comprehensive insurance can collect on damages. Interviews with townspeople revealed that the home and business owners did not carry seismic sea wave insurance because of its nonavailability or prohibitive cost.

One cannery with its floor system drift-pinned to a timber pile foundation was entirely removed. The drift pins still remaining on the center row of piling point in the direction in which the second wave swept away the cannery (Figure 30). Another similar timber cannery was floated more than 1 mile into the harbor from its foundation and was lodged on the breakwater (Figure 31). The rubble-rock breakwater is now practically submerged by the higher tides. This breakwater settled 3-1/2 feet from seismic disturbances in addition to the entire Kodiak Island 5-1/2-foot seismic subsidence.

A welding shop near the harbor's edge with corrugated steel plate side and roof did not survive well (Figure 32). When the tsunami waters reached the roof level the sides were torn away. The heavy welding equipment and steel stock was not swept away because of the dike action from the elevated ground around the shop.

There was scour under sidewalks and the mainstreet road where the tsunami had penetrated furthest in the city. The scour in Figure 33 occurred under 12 feet of flooding. One light structure near the harbor slid off its foundation when the rear was undermined (Figure 34).

The 5-1/2-foot tectonic settlement of Kodiak City will allow the usual high tides to engulf lands never before touched. High tides at Port Wakefield, about 45 miles south of Kodiak, have already put 4 inches of water in the Wakefield Fisheries Cannery. Even higher tides are expected. Also, high tides, packing ice floes the size of houses, have already pushed into the community of Portage.

Wave Action

The first wave arrived at 1847 AST, 27 March, as a gentle gradual flood with swirls resembling river flow followed by a gradual ebb. After the first wave receded, Kodiak's fleet looked for a brief time as if it were all in one gigantic drydock. The sea returned and in minutes Alaska's largest king crab fishing center was all but wiped out, boats, canneries, and all. There was full agreement among the natives concerning the second wave; that it was a cresting 30-foot-high wall of water that thundered up the channel, floated 50 to 100-ton crab boats and pushed them over the harbor's stone breakwater, and sometimes two or three blocks into town.

The third wave arrived 55 minutes later with less force, but greater than 30 feet in height. Again, ships were whirled around and driven through buildings, and eventually beached.

The fourth wave was less violent than the others; however, it refloated several of the ships. The waves continued at about a 55-minute period and progressively weaker amplitude until 0300 AST next morning, i.e., Saturday, 28 March 1964.

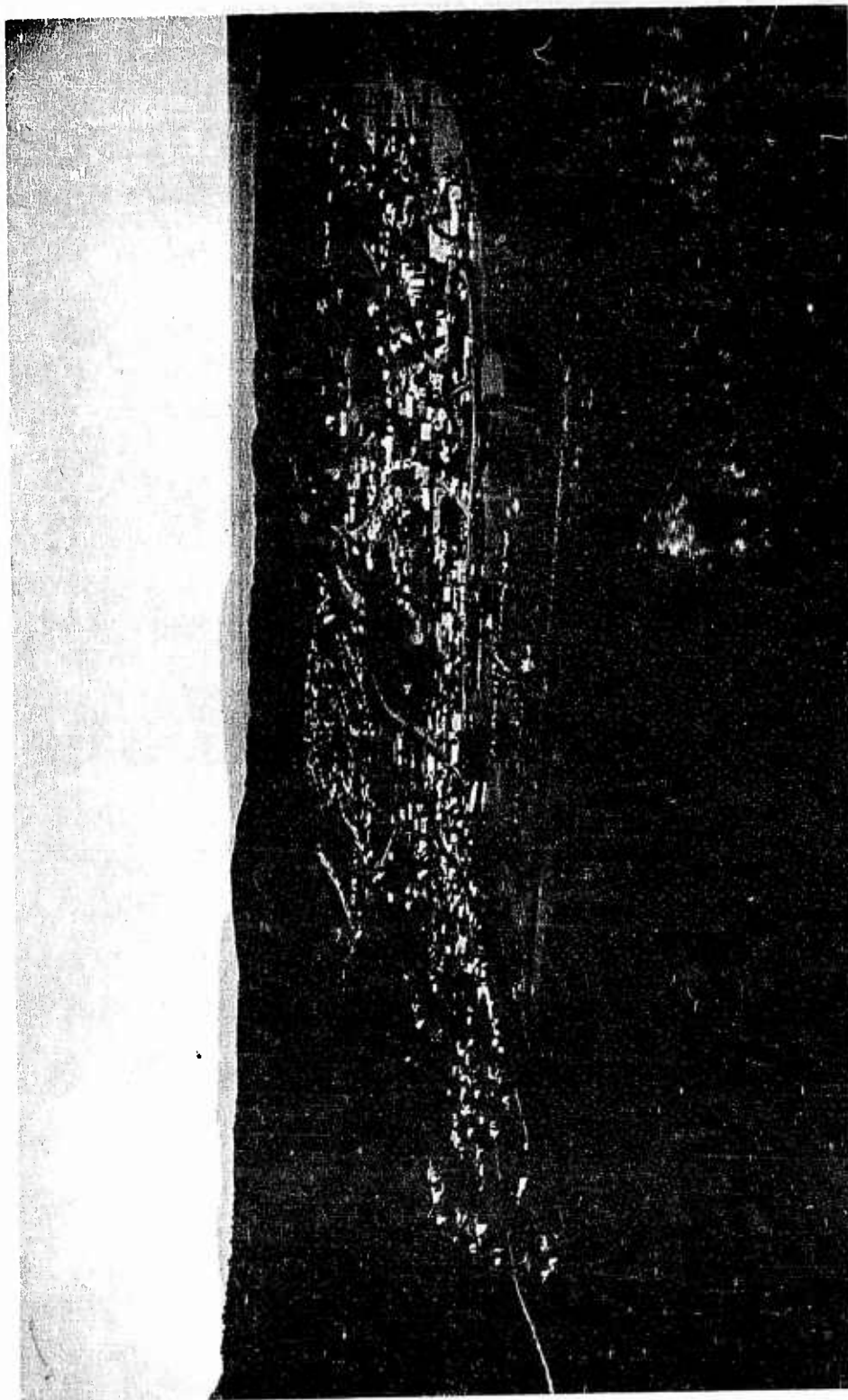


Figure 22. Aerial photo of City of Kodiak, center of one of the largest fishing fleets in Alaska.
Solid line shows highest level reached by waves. (Photo by Alf Madsen)

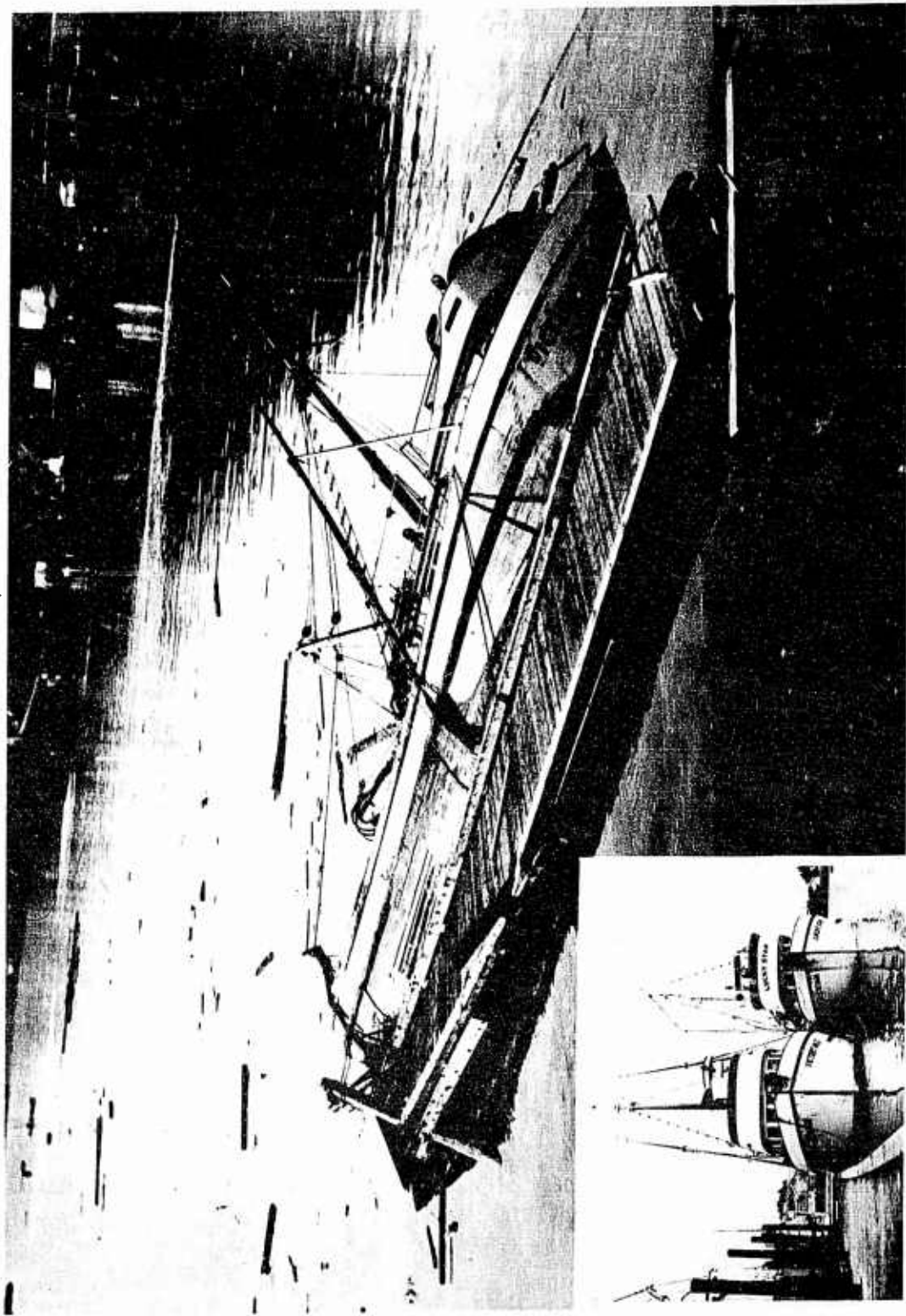


Figure 23. The view in the lower photo insert shows the Victory Maid and the Lucky Star of the Kodiak's fishing fleet resting serenely hours before the earthquake. The Lucky Star, which was declared a complete loss was not as lucky as her companion the Victory Maid, which is lying to port following the Alaskan Good Friday tsunami. (Photos by PIO, Kodiak NAVSTA)

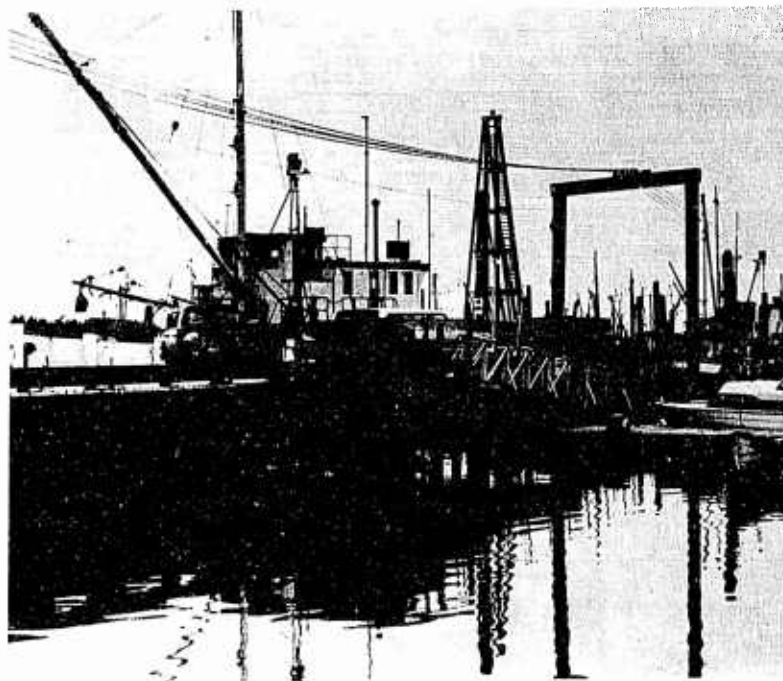


Figure 24. Fishing fleet two hours before the quake. Some boats were maneuvered to safer coves by their owners, while those unmanned rammed into the business section of the city. (PIO, Kodiak NAVSTA)



Figure 25. View of harbor after four successive waves filled and emptied the harbor demolishing the piers and sweeping away the fishing boats.

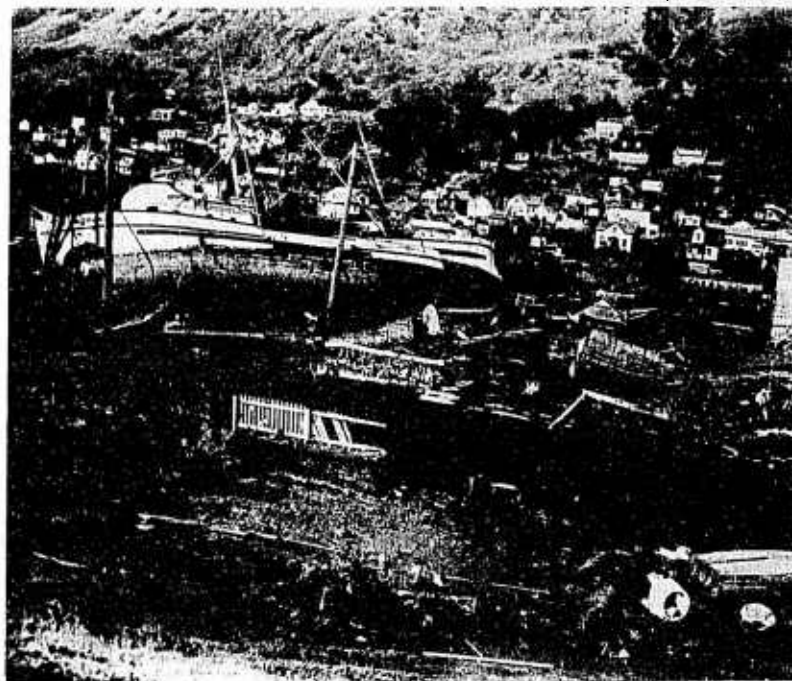


Figure 26. Arrows point to reinforcing rods from foundation of bowling alley at edge of harbor. Buildings were removed by ship impact and buoyancy force



Figure 27. Fishing boats buoyed-in more than one-half mile on tsunami waves are scrambled together with city buildings.

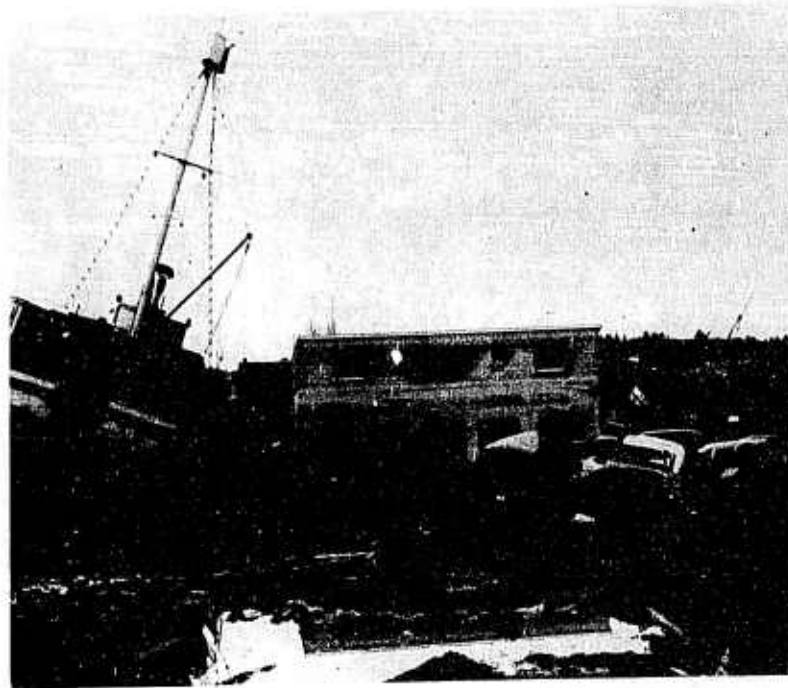


Figure 28. Vehicle and boat owners with insurance can collect on damages. Business and home owners did not carry "tidal-wave insurance".

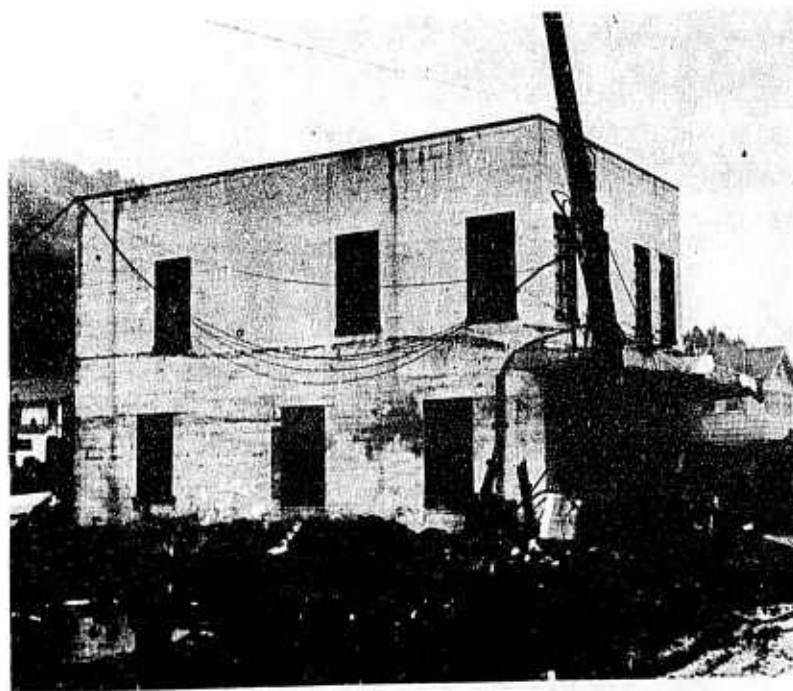


Figure 29. Canopy and utility pole acting as a fender and dolphin helped save concrete block building. Six foot and ten foot high water marks visible.

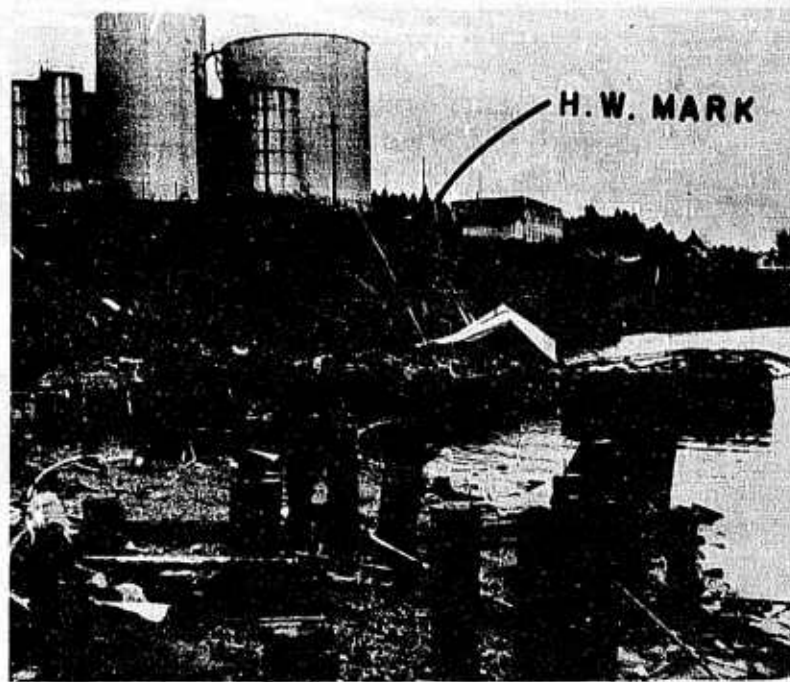


Figure 30. Skeleton-like timber piling marks former site of cannery. Steel drift-pins point direction in which cannery was swept away by second wave.



Figure 31. Cannery was displaced one mile by tsunami waves. Rubble-rock breakwater settled 3 feet in addition to 5-1/2 feet subsidence.

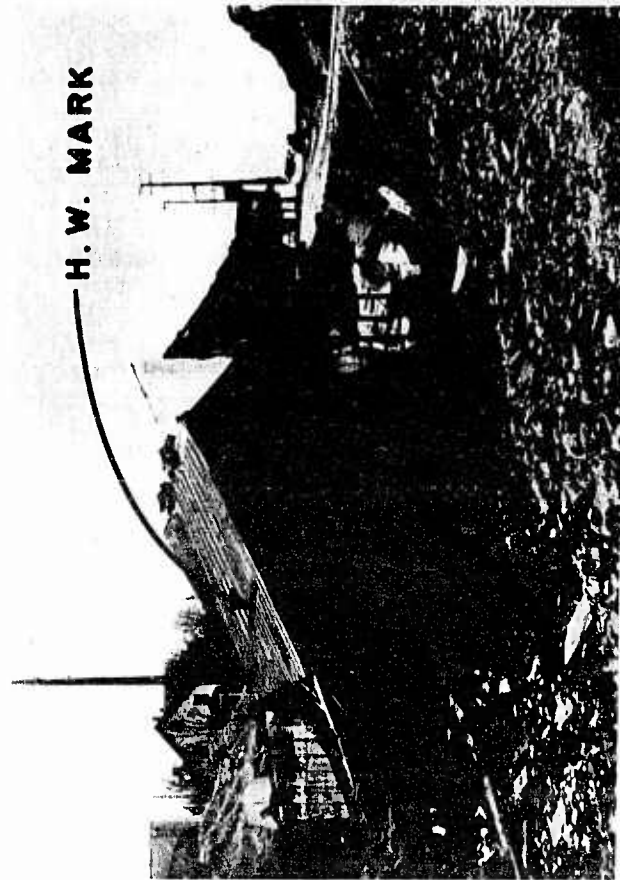


Figure 32. Transit shed type building did not survive well under tsunami deluge. High water mark is on roof of this welding shop.

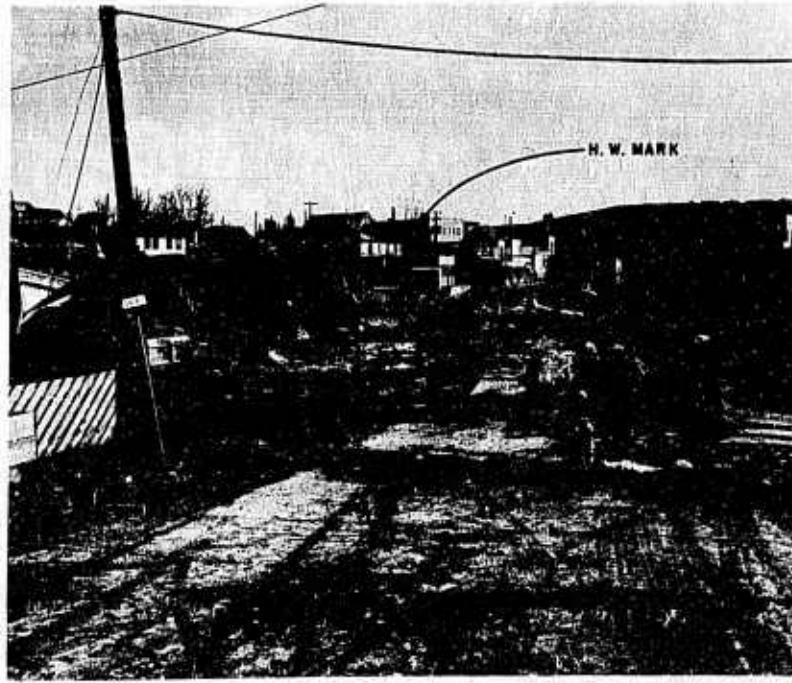


Figure 33. View of the main street shows erosion under roads and sidewalks (middle of photo) caused by tsunami wave inundation. (PIO, Kodiak NAVSTA)



Figure 34. Haberdashery was washed right off its foundation and rested with its rear portion in the harbor.

CRESCENT CITY, CALIFORNIA

General

Crescent City Harbor is one of the oldest on the Pacific Coast; a lighthouse was built there in 1856 (Figures 35 and 36). Over 100 commercial fishing craft are based there, as well as many pleasure craft and sport-fishing charter boats. Lumbering and lumber products are the principal industries. Nearly two hundred million board-feet of lumber are shipped out annually. Crescent City has a population of 3000 persons. The area is served by approximately 75 lumber mills and 7 plywood and veneer plants. Petroleum products, which exceeds 200,000 tons annually, are the greatest import. There was no damage due to the earthquake directly.

Damage

Standing sentinel-like at the city limits and greeting visitors to Crescent City from the South is a giant concrete tetrapod weighing 25 tons. This was erected as a monument in 1958 to mark the first place in the Western Hemisphere where the tetrapod was used in the construction of a breakwater. During the tsunami flooding (Figure 37A) this tetrapod was displaced from its pedestal. It is calculated that a water speed of 14 miles per hour would be necessary to slide this tetrapod from its base (Figure 37B). However, one witness claims he saw a large log bump and shove the tetrapod.

Some 1975 of these tetrapods were used in construction of Crescent City's breakwater where they were placed on the seaward side of the outer breakwater (Figure 38) by the Corps of Engineers in 1956-57 and so interlaced as to keep heavy seas from destroying the breakwater. This breakwater was reportedly overtopped by smooth flowing tsunami water resembling river or weir flow. The surface may have reached 25 feet above MLLW at the outer end of the breakwater. The tetrapods on the breakwater remained intact after submergence by the tsunami waves (Figure 39). No visual damage was observed by the author walking along the caps of the outer breakwater, the inner breakwater and the sand barrier.

The central business section (of 35 blocks) was swept by the largest of the seismic waves; it crested at 0115 PST on 28 March. The lower dashed high water mark in Figure 36 was that reached by the first wave which crested at 2352 PST 27 March; the higher mark is that reached by the largest wave (Figure 40) which crested on the top of a high tide and also at the end of an eighteen minute harbor surge.

A preliminary survey placed the number of dead at 12 and of homeless families at 400. Listed are 54 homes destroyed; 13 suffered major damage, and 24 minor damage. One hundred seventy nine businesses were affected. Of these, 42 small business enterprises were totally destroyed. One hundred eight suffered major damage, and 29 minor damage. Few of these businesses in the central district were covered by seismic wave insurance due to the high cost of coverage. About 150 persons were forced out of their homes temporarily.

After the wave attack, equipment of all types was mobilized to move houses and large logs from streets and highways. Along with debris, automobiles were scattered in the streets. They lay piled atop each other and jammed inside buildings. Automobiles parked by a newly built motel were shoved against the side of the building. Some were propped up on parking meters; others were swept up and rolled over and over. Emergency crews were dispatched to shut off the damaged butane tanks which were leaking explosive gas. Water supplies were available, but gas service was cut off in one downtown area until the lines could be inspected. Telephone and electric lines were damaged but were soon put back in order. Highway 101 north and south of the city was blocked for a time by trees and lumber.

Fire broke out in the southern area and set off the five bulk oil tanks at the Huskey-Texaco Plant. The tanks, each 10 feet in diameter, blew up one by one, with firemen virtually helpless to battle the blaze. Before fires broke out, the tanks had been battered by wave driven redwood logs. The scorched tanks were reminiscent of results of a war-time bombing attack on a supply depot. The fire spread to destroy Nichols Pontiac Garage and Service Station and an adjoining body shop.

Damage in Crescent City Harbor was extremely heavy; 15 fishing boats capsized and 3 are unaccounted for. Eight boats were sunk in the fishing boat moorage area; one was washed over the fuel dock and lodged between it and the inner sea wall; several boats were washed onto the beach at the beachfront development site, and the rest were beached or capsized in scattered areas.

Citizen's Dock; the only cargo and fishing dock in the Harbor, was the pride of the community, which cooperatively had constructed it in 1949. Since then, additional construction and repair had both expanded and kept the dock in tip-top shape. It was twisted and battered as the Harbor was suddenly drained and then surged over five times. The largest wave at 0115 PST caused a giant lumber barge, Pacific No. 2, to smash into the Dock (see Figure 41). Adjacent to the area where the barge was moored, the deck planking of the cargo pier of Citizen's Dock was sorted in piles resembling giant jackstraws (Figure 42). The corbels, decking, and fender system and bollard (Figure 43) were so badly damaged they will need replacement. A typical framing plan for the rehabilitation is shown in Figure 44. Since the bollard was still attached to its base, it appears that less than the allowable load of 60,000 lbs pull at 30 degrees with the horizontal (BUDOCKS DM-25, 1961) wrenched it loose.

The dock area forward of the moored barge location (Figure 45 and 46) had damaged blocking compound, ribbon, fenders and wheel guards all of which will require rebuilding. The area to the stern of the barge was only slightly damaged and will require rebuilding to the several slightly damaged members. Bent Nos. 16 and 23 were badly damaged.

The only damage to the fish pier on Citizen's Dock was along the centerline where the deck raised about six inches. This was due to lack of steel straps between pile caps and stringers. The commercial fish shacks on the pier were displaced (Figure 45).

The approach to Citizen's Dock was damaged and badly twisted when, under the force of the tsunami, the deck was buoyed and the supporting piling snapped. A Corps of Engineers survey boat (foreground of Figure 47) took soundings in the area occupied by the small boat docks before the tsunami. Preliminary soundings available at the writing of this report did not reveal any change in the bottom configuration. According to Magoon (1962) a survey of the harbor after the 1960 Chilean tsunami indicated no significant changes in the harbor basins, but a channel was scoured approximately 80 feet wide and 2 feet deep near the seaward ends of the inner breakwater.

The concrete wave barrier protecting the small boat area by Citizen's Dock was broken and damaged. The piles under the approach that were encased in this barrier were removed with the wall (Figure 48).

The Coast Guard building on Citizen's Dock was swept completely out to sea. It was sighted and taken in tow by the cutter "Cape Carter" but due to other demands on the cutter, it was released. The Dock Cafe was displaced from its location near the dock approach and set aground in a nearby lumber yard. Many channel buoys were torn from their moorings and swept out to sea; they were retrieved by the Coast Guard and replaced in their proper moorings by Sunday, 29 March.

Lumber from Citizen's Dock was scattered up and down the highway and along the beaches; however, lumber piles on Dutton Dock nearby were relatively untouched as was the Dock itself (Figure 49). Dutton Dock survived due to the steel straps and bolted connections between the decking and pile caps and the abundant cross-bracing as shown in Figure 50. The absence of moored ships at the Dock also helped.

The Sause Dock (Figure 51) had already been abandoned for several years and was in a state of decay. The remaining decking which was secured to the pile caps with only drift pins was lifted and displaced by the tsunami waters. The piling and pile caps were not damaged (Figure 52).

The street close to the ocean was badly eroded in spots (Figures 53 and 54). The seawall was eroded. It is normally 2 feet above ground and eight feet buried. Street lights were torn from concrete foundations and corrugated steel drainage culverts bared. A 25-ton earth-mover was overturned completely. The parking lot at Citizen's Dock was scoured (Figure 55). The tractive shear on the parking lot surface which was scoured is estimated to be 1.4 pounds/square foot. Possible soil sloughing from seepage due to tsunami flooding and subsequent rapid drawdown below mean low water is neglected since the soils are granular. Large scale eddies could have contributed to the scour but their effect is not known.

Huge logs (Figure 56) were punched through or partially through buildings. They caused a great part of the damage. The reinforced concrete five-story hotel on Front Street as well as the two-story hardware store and other multi-store (two or more) buildings showed no structural damage or foundation damage (Figure 57). Smaller structures had more damage as might be expected. A barber shop was floated across Second Street (Figure 58). An apparent exception to the above was the two-story IOOF building at the corner of Second and G Streets (Figure 59). This structure was moved thirty feet and rotated approximately 45 degrees. The foundation for this older building consisted of 2-foot square mortared stone pedestals at approximately eight foot intervals. No tie-downs were apparent.

When a portion of a home on Front Street left its foundation (right side of Figure 60) the home was broken in half. The grass lawn at the homesite was not damaged.

The tsunami water elevation at these structures varied from four to eight feet. The streamlines for an ideal flow pattern in these long waves past a typical house is shown in Figure 61A. The fluid pressures at points A, B, and C around the house are given in Figure 61B where the maximum pressures are tabulated. As an example, the horizontal force exerted on a small 10-foot wide housing unit (Figure 62) by water flowing normal to it at 10 fps and 5-foot flooding would be approximately: $100 \text{ psf} \times 5 \text{ ft} \times 10 \text{ ft} = 5000 \text{ lbs force}$. If no foundation ties were provided, then flotation and movement would result.

A different type of structural failure seemed evident at the Surf Club (Figure 63) where one entire wall buckled outward. This stucco covered wall built of boards on a timber frame apparently failed from internal water loading imposed when the nearly equal water levels inside and out were unbalanced by the rapid recession of the flood waters. The effect from the inward acting force of the elevated water is evident in Figure 64 where an entire wall of a warehouse shed constructed of light gage steel sheeting and minimum timber framing collapsed.

Wave Action

Several hours after the Alaskan Earthquake, a bulletin was issued from the Honolulu Observatory, the center of the Seismic Sea Wave Warning System (SSWWS), to the effect that if a tsunami had been generated, its estimated time of arrival at Crescent City would be 2400 PST, 27 March. According to the reconstructed marigram (Figure 35) the first crest actually arrived at 2352 PST, 27 March.

Although a record from the tide gage is available, it is badly torn and water-logged so that it cannot be read accurately. Therefore, in reconstructing the marigram (Figure 40), information from the tide gage record was supplemented by estimates made by hand-leveling of high water marks and by conversation with townfolks. For example, the elevation of the first, second, and largest crests were obtained in this manner. From conversation and survey, the high water marks two miles north of the city at Pebble Beach were estimated to be 15 feet above MLLW. The high water marks just to the south of the city appeared nearly as high as those in the city proper. Fifteen miles to the south near Klamath the high water marks were maybe 10 to 15 feet above MLLW.

One observer related that as the first wave moved into the city bringing log and debris with it, the water rose rapidly with the small waves riding the crest. Front Street was covered in places with considerable water and logs which partially blocked traffic. As the first wave subsided, officers of the City Police and Sheriff's Department moved into the area to survey the damage and to deal with the sight-seers and possible looters. They began moving the public out almost

immediately as the second wave started building up. The second and third waves seemed of lesser magnitude than the first and to hit with less force. But the fourth wave was fast in rising; it hit the city hardest, such that it left in its wake a large area of total destruction. One reporter said the wave came into the city in fingers of water.

Another report indicates that the city was flooded from two sides. In addition to water directly from the ocean, considerable water went up Elk Creek, along the eastern edge of town and then back-washed to create flooding in an inland 4 by 8 block city area.

Another observer reports the first wave in the city at 0009 PST, 28 March. Two more waves came and both threw driftwood onto the street at 0030 and 0045. Then, at 0140, the water began pouring onto the streets, slowly, then more swiftly. When this wave receded cars, refrigerators, gas tanks, and debris of all sorts floated toward the sea. It was this highest wave that was responsible for the 12 dead.

Previous hydraulic model studies of the Crescent City tetrapod breakwater by the U. S. Army Corps of Engineers at Vicksburg, Mississippi (Hudson and Jackson 1955) indicate considerable overtopping of the breakwater will occur for waves larger than about 23 feet in height, and waves larger than about 25 feet in height will probably result in damage. From the tests, the selection of design waves using two layers of tetrapods was:

Less than no damage criterion	H = 23 ft.	T = 14 sec.	L = 610 ft.
Design wave for no damage	H = 25	T = 14	L = 610
Exceeds no damage criterion	H = 26	T = 14	L = 610

(The value of d/L is 0.113 for these cases). The breakwater cap, which varies from elevation 20 feet to elevation 22 feet above MLLW was reportedly overtopped by smooth flowing water such as river flow or weir flow. The water height may have reached 25 feet at the outer end of the breakwater. However, as mentioned before, no visual damage to the cap on the tetrapods, which were topped out at elevation 22 feet, was observed by the author walking along the top one week after the tsunami action.

Further facts from the Hudson and Jackson report are: (1) The most severe storm at Crescent City in the past 20 years resulted in waves estimated to be 26 feet high in deep water; (2) Waves 20 feet high lasted approximately 34 hours during that storm; (3) Refraction diagram analyses indicate that waves with a maximum height of about 33 feet could occur at the breakwater site.

It is thought that the tsunami entered the harbor in much the same direction as the usual surge; that is, the tsunami water rose outside the harbor and flowed into the harbor in the same manner as flow through

a slot. Magoon (1962) reports that the tsunami of 22 May 1960 apparently excited oscillations in one or more modes in the harbor in such a manner that there was a node at Citizen's Dock. He further relates that the wave form at Dutton Dock contained a number of two to three minute period waves not present at Citizen's Dock. The periods of these apparently locally induced waves were not harmonically related. The damage from this 1960 wave action was reported at \$30,000.

Figure 65 shows a utility box on the road to Citizen's Dock bent in the direction of the usual harbor surge. Calculations indicate a velocity of 7.5 MPH could deflect the box. In Figures 66A and 66B, the deflected commercial fish shacks on Citizen's Dock fish pier indicate that the largest force came either from the harbor surge action or water recession. An estimate of the water speed (v) during recession of the highest crest can be found by Mannings formula:

$$v = \frac{1.486}{n} R^{2/3} S^{1/2}$$

where:

S = 0.0018 (Figure 55)

n = roughness coefficient = 0.035

D = depth = 30 feet $\approx$ R

$$v = \frac{1.486}{0.035} 30^{2/3} 0.0018^{1/2} = 17.5 \text{ fps} = 12 \text{ MPH}$$

This 1964 Alaskan Tsunami is not unique as previous tsunamis have excited the ocean water level at Crescent City. Table II lists other recent tsunami wave heights and their associated earthquakes; namely, those of 1946, 1952, 1957, and 1960. The 1964 tsunami wave height is the largest to date.

The Mendocino Seascrap (Figure 1) and the Gorda Escarpment likely effected the Alaska Tsunami. For comparison, the tsunami record at Astoria, Oregon, (Figure 67) is included. The 1964 Alaskan Tsunami action at Crescent City and Astoria seems, on the basis of a necessarily hasty review, to be different from that of the 1960 Chilean Tsunami at Hilo, Hawaii, where the long shoaling beach caused the tsunami to form a bore which was reinforced by a Mach stem effect.

CRESCENT CITY

TABLE II
RECENT TSUNAMIS AT CRESCENT CITY

Date	Earthquake	Tsunami Height at Crescent City-Feet	Magnitude
1 April 1946	Aleutian Trench	6	7.4
4 November 1952	Kamchatka Penin.	7	8.4
9 March 1957	Aleutian Trench	5	7.9
22 May 1960	Chile	11	8.5
27 March 1964	Alaska	16	8.2 - 8.4

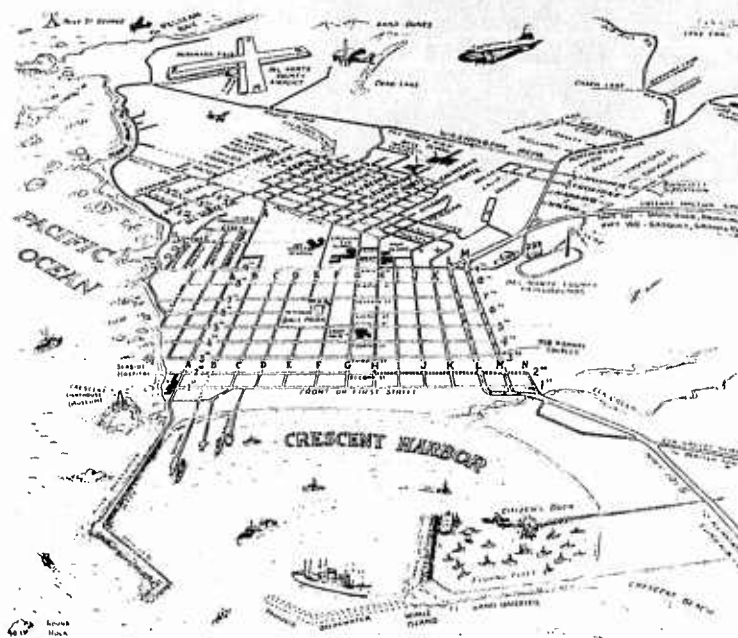


Figure 35. Crescent City's harbor, one of the oldest on the Pacific Coast, gave the city its name. The city itself sits on a low rim of ground facing the ocean. (Sketch from Chamber of Commerce)

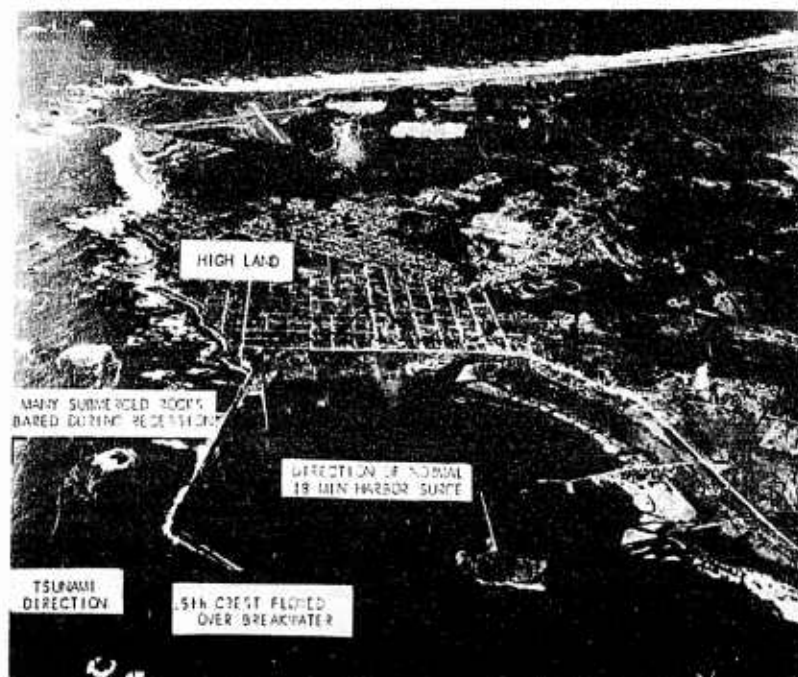


Figure 36. Crescent City's harbor has breakwater protection from storm waves but not from tsunami waves. Dashed lines show high water marks.

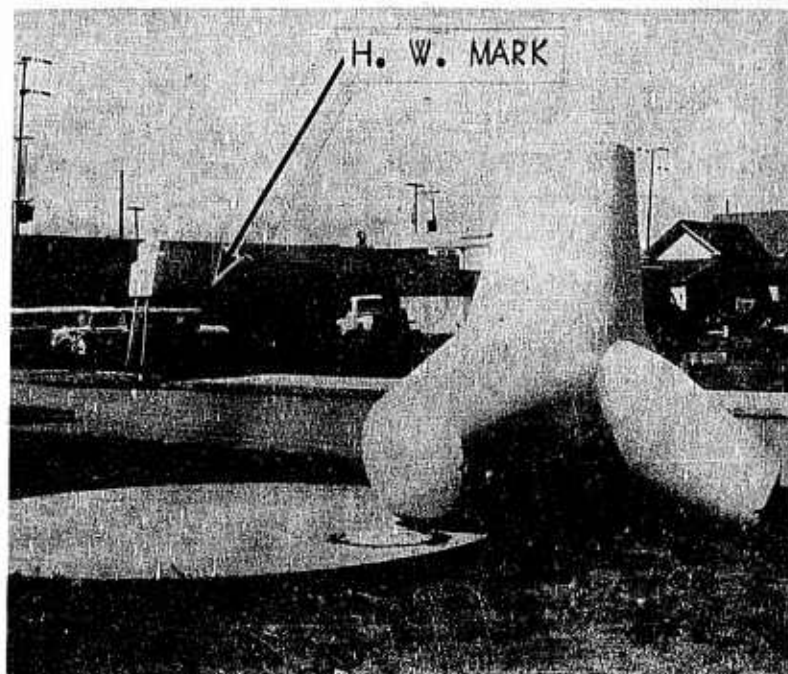
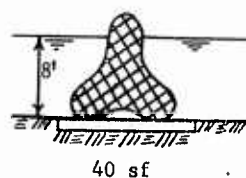
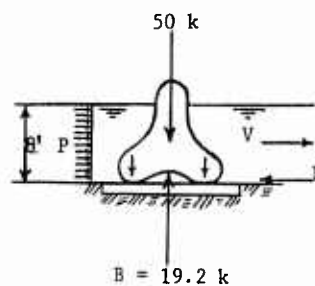


Figure 37A. 25 ton tetrapod monument at Front Street and US 101 was moved from base by water forces and log impact.



Calculation to find water velocity to slide large tetrapod off base:

Wt. = 25 T; Coef. of Frict. = 0.65 Total vol. = 325
 Vol. = 325 cf; Drag coef. = 1.2 Vol. in air = 25
 B = 300 cf x 64 pcf = 19.2 K Subm. vol. = 300

N = 50 - 19.2 = 30.8 K

F = 0.65 x 30.8 = 20 K

P = 20/40 sf = 500 psf.

V = $\frac{500 \times 32.2 \times 2}{1.2 \times 64}$ = 20 fps = 14 MPH

Figure 37B. Unit pressure and approximate velocity required to slide 25 ton tetrapod.

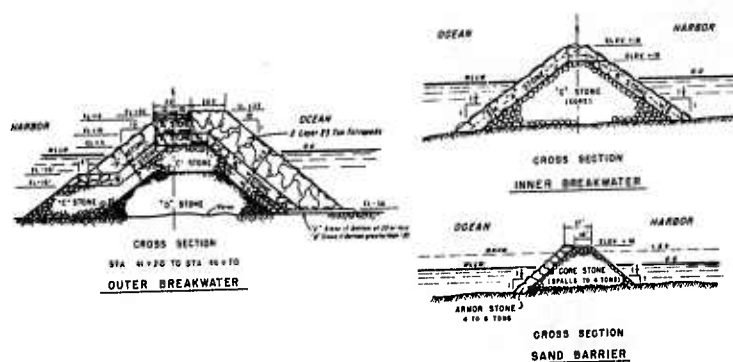


Figure 38. Cross Sections of breakwaters in Crescent City harbor. (Corps of Engineers)

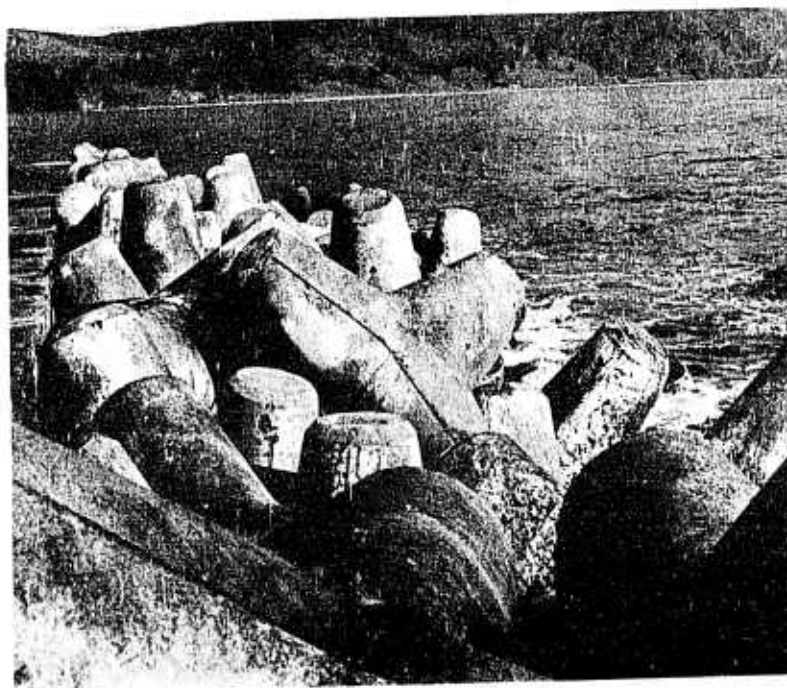


Figure 39. Tetrapods on outer harbor breakwater stayed in place when submerged by the tsunami wave.

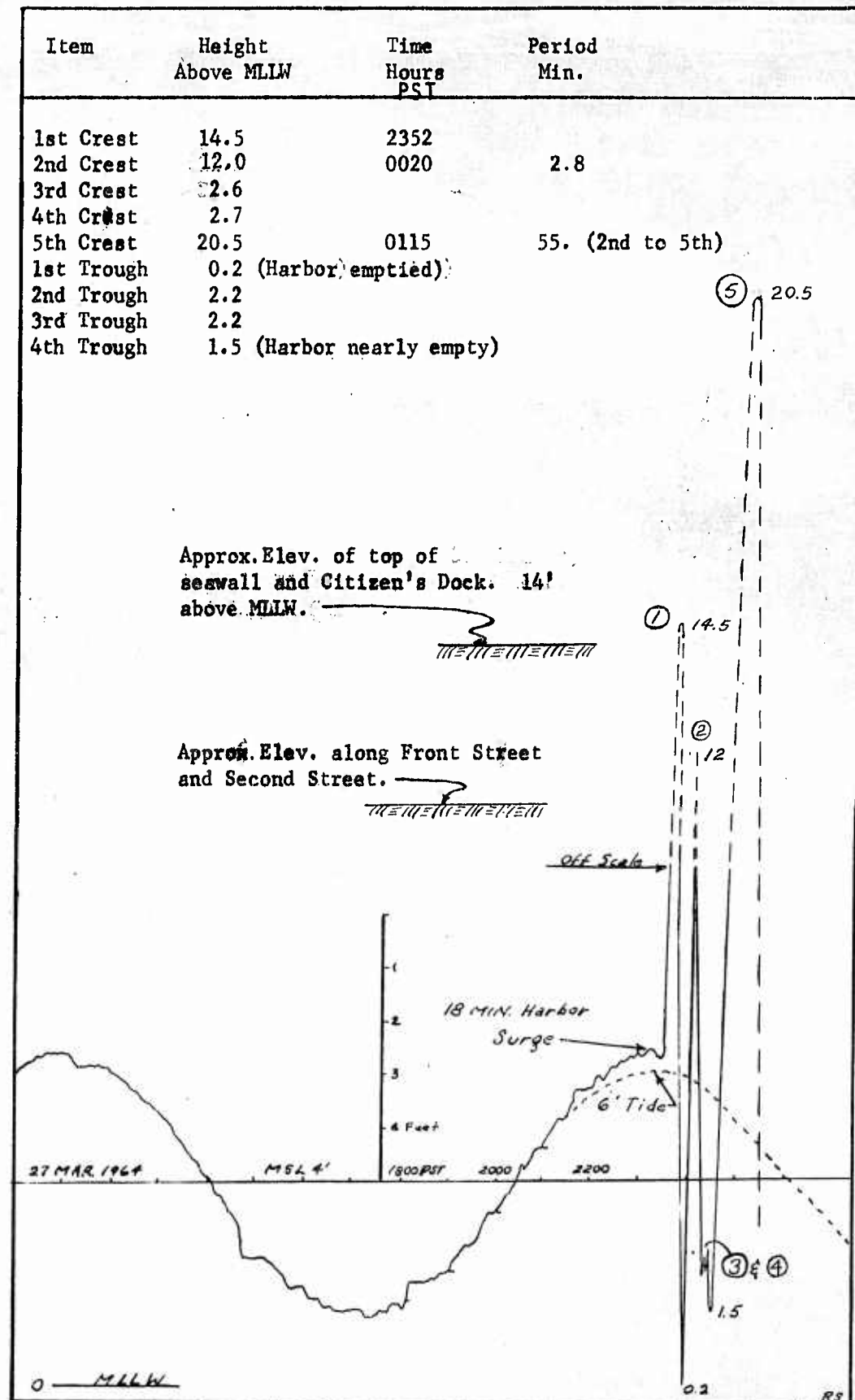


Figure 40 Reconstructed Crescent City Marigram

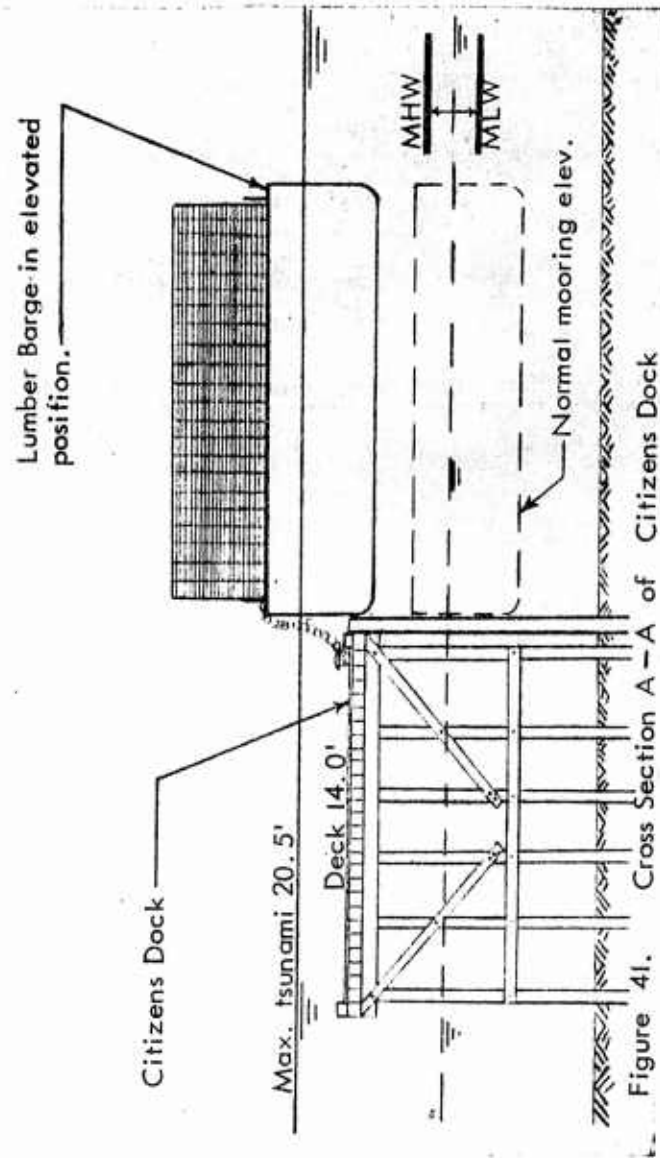


Figure 41. Cross Section A-A of Citizens Dock

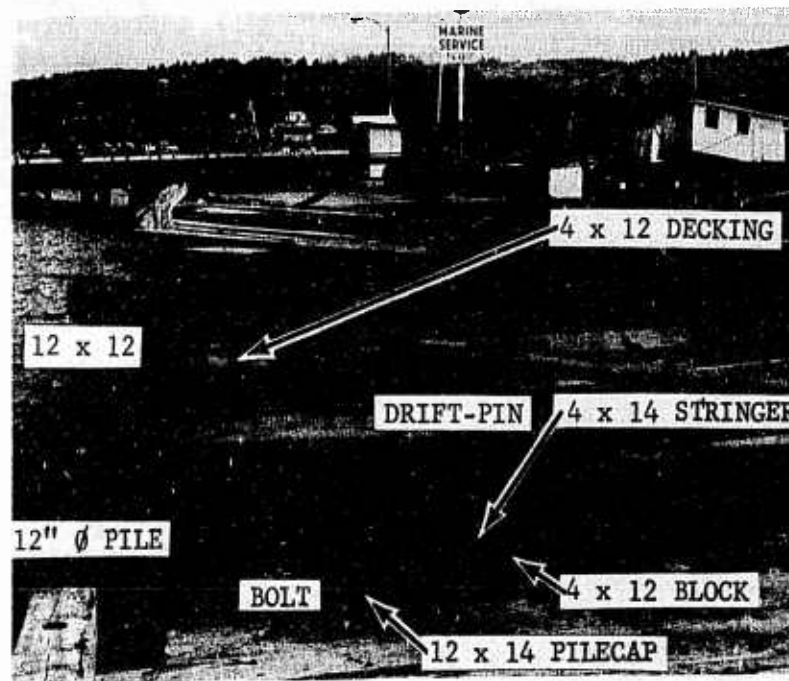


Figure 42. Decking on the cargo pier of Citizens Dock lies jumbled atop damaged stringers. A large lumber barge was moored to the pier during the tsunami action.

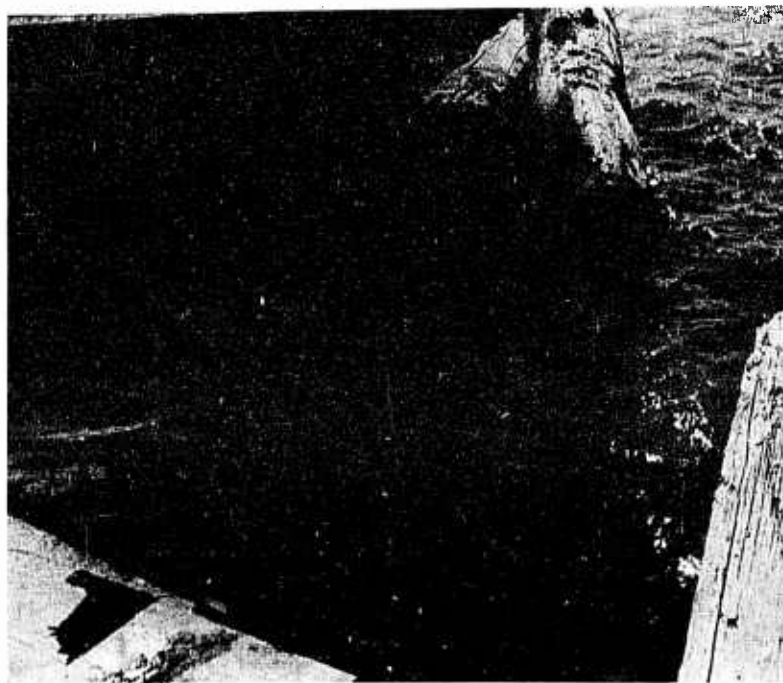


Figure 43. Bollard near amidships of moored lumber barge was wrenched from cargo pier, rotated 180°, now points down at water.

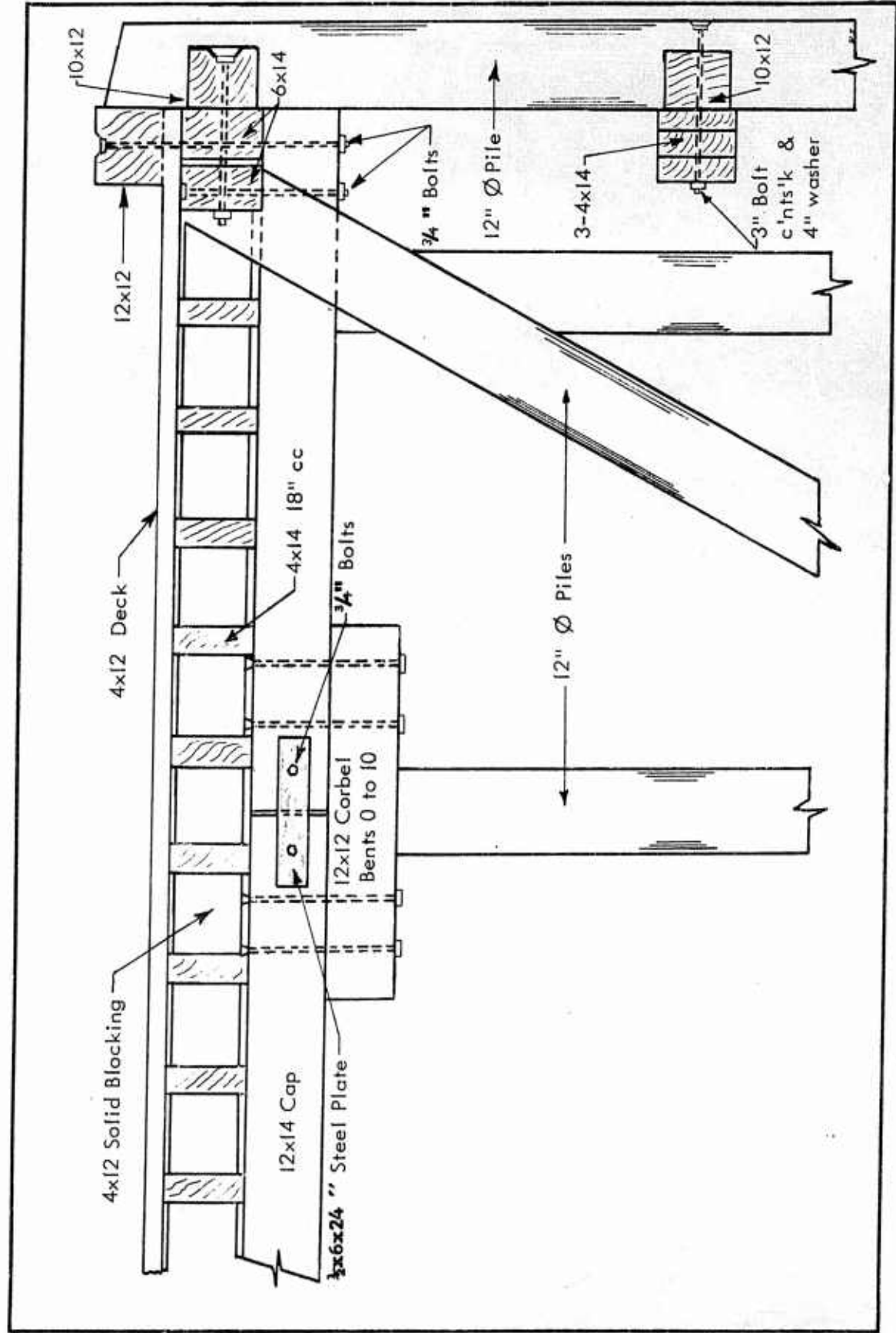


FIGURE 44. TYPICAL SECTION OF CITIZENS DOCK AT CRESCENT CITY, CALIFORNIA
 (From City Engineer, Crescent City) SCALE: $\frac{1}{2}"=1'$

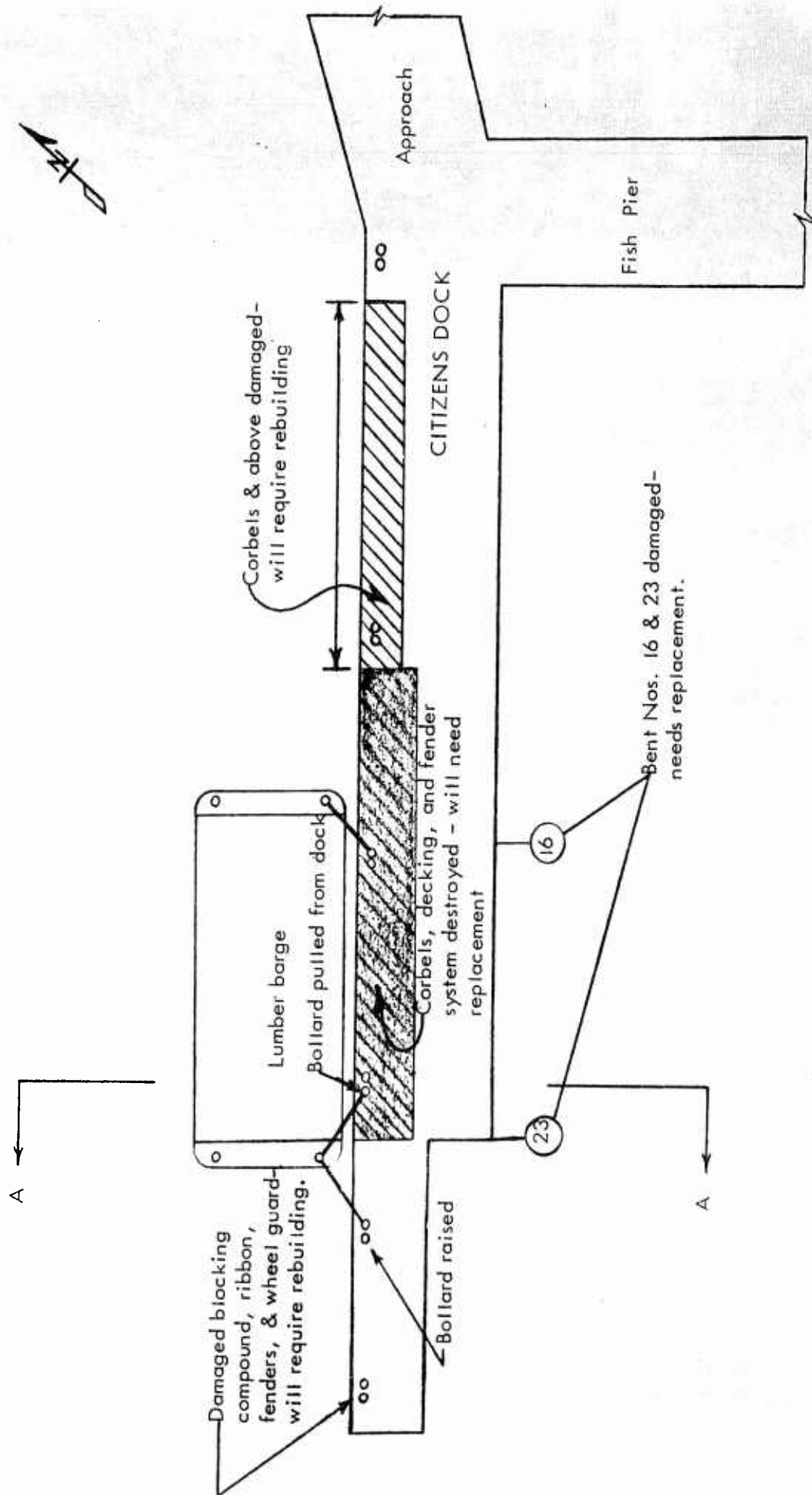


Figure 45. Plan of Citizens Dock showing moored lumber barge and pier.

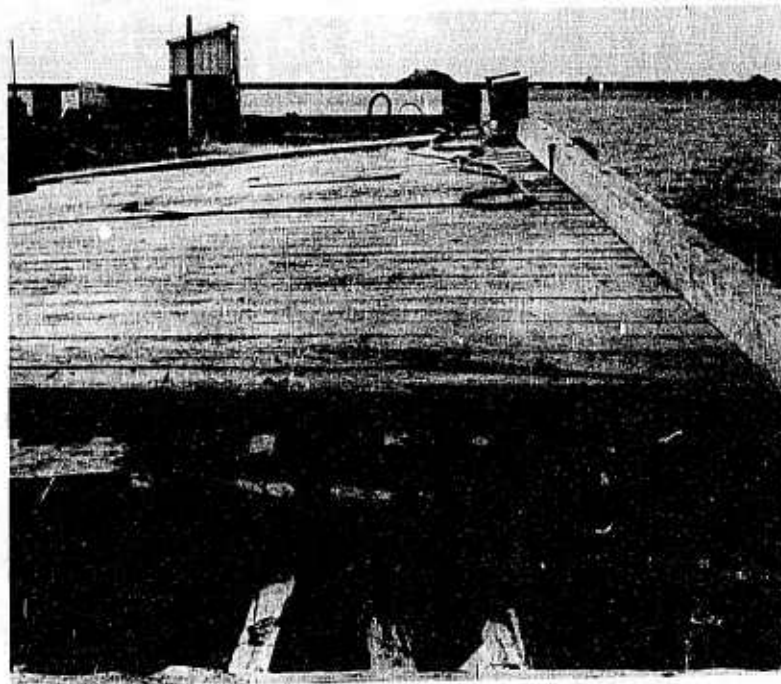


Figure 46. Tide shack on Citizens Dock was fully submerged. Decking is elevated towards one of bollards mooring a lumber barge.



Figure 47. Snake-like approach to Citizens Dock deflected when piling snapped off. The small boat docks occupying this area have disappeared.

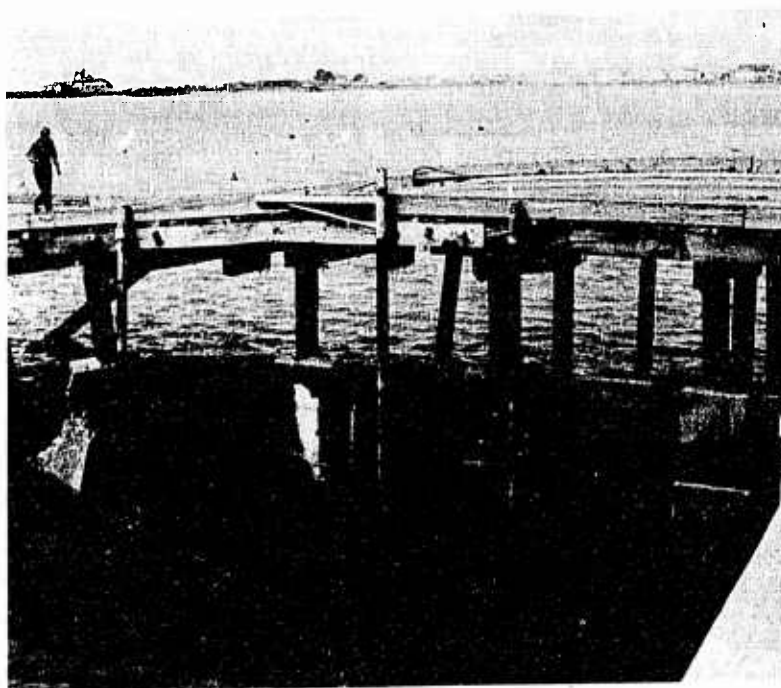


Figure 48. Concrete wave barrier under Citizens Dock approach was broken by log impact and water forces as the harbor filled and emptied. Encased piling was removed with the wall.



Figure 49. Dutton Dock unharmed when submerged 5 to 6 feet under largest tsunami wave. Lumber debris in foreground is from dock.



Figure 50. Steel straps, bolted connections, and abundant cross bracing helped Dutton Dock survive virtually without a scratch.

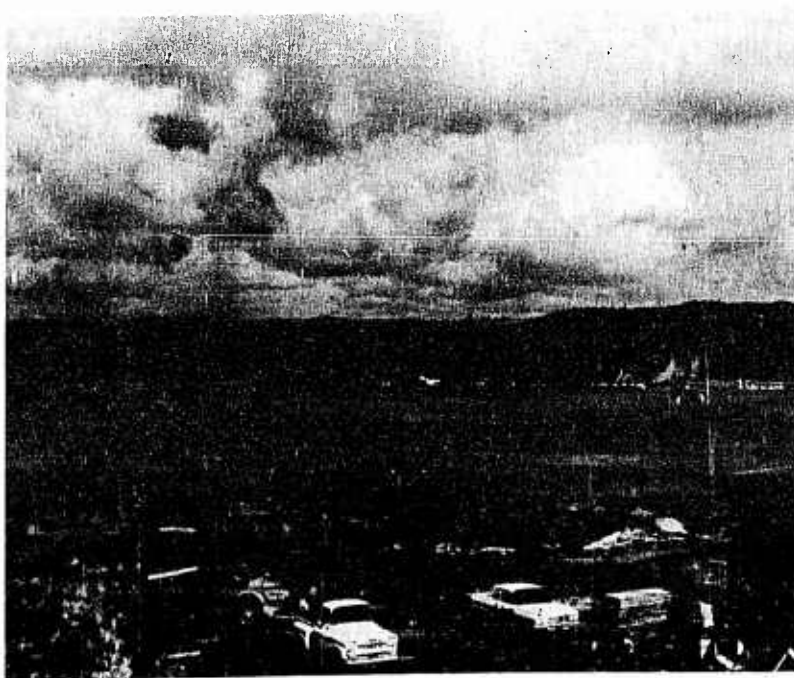


Figure 51. The abandoned and dilapidated Sause Dock was further damaged by the seismic sea waves.

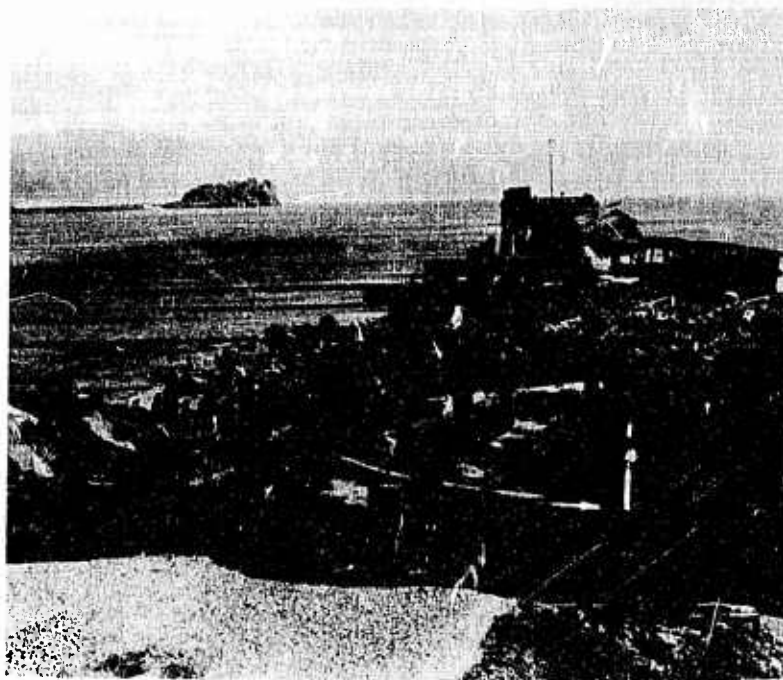


Figure 52. Decking of the Sause Dock sprawls to one side. Drift pins are still embedded in pile tops. Piles and pile caps have survived fairly well.



Figure 53. Erosion causes pole tippage, misalignment of curbing, fragmentation of black top road, and exposure of sea wall.

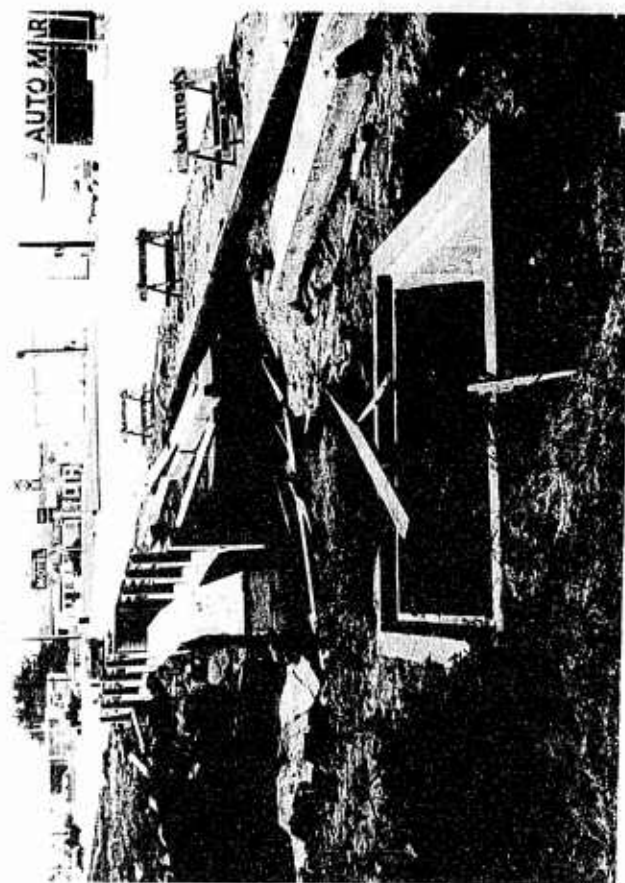
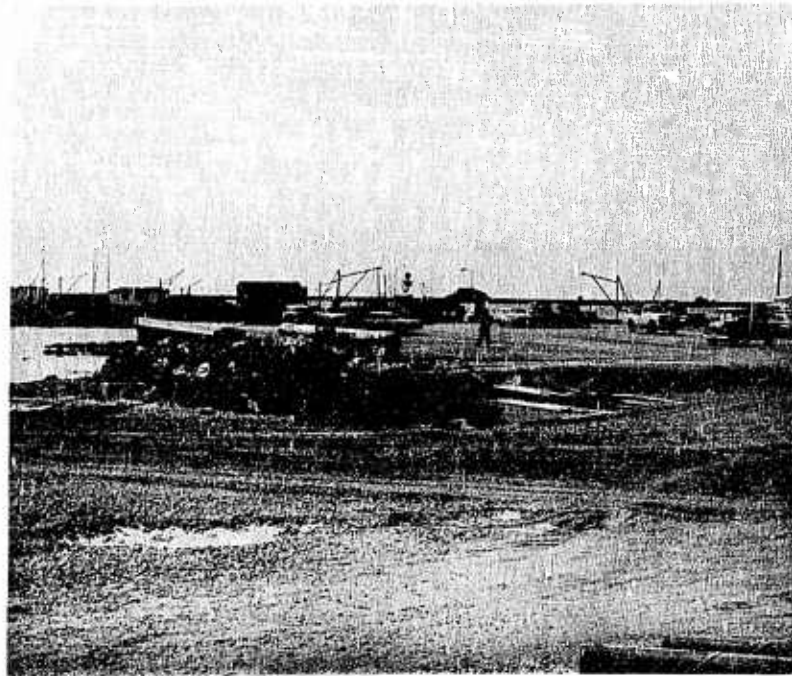


Figure 54. Erosion bares Elk River concrete box culvert and undercuts Highway 101. Steel beam tidal barrier on left normally protects bridge from logs.



Problem: Find intensity of boundary shear pressure, τ , from recession of tsunami wave at Crescent City Citizens Dock parking lot.

γ = unit weight of salt water = 64 pcf

D = water depth = 12 feet

S = energy grade line slope = $\frac{20.5 \text{ (max. tsunami level)} - 6 \text{ (sea level) ft.}}{1.5 \text{ miles} \times 5280}$

$$\tau = \gamma D S$$

$$\tau = 64 \times 12 \times 14.5 / 1.5 \times 5280 = 1.4 \text{ psf}$$

Figure 55 Scour at Citizens Dock Parking Lot

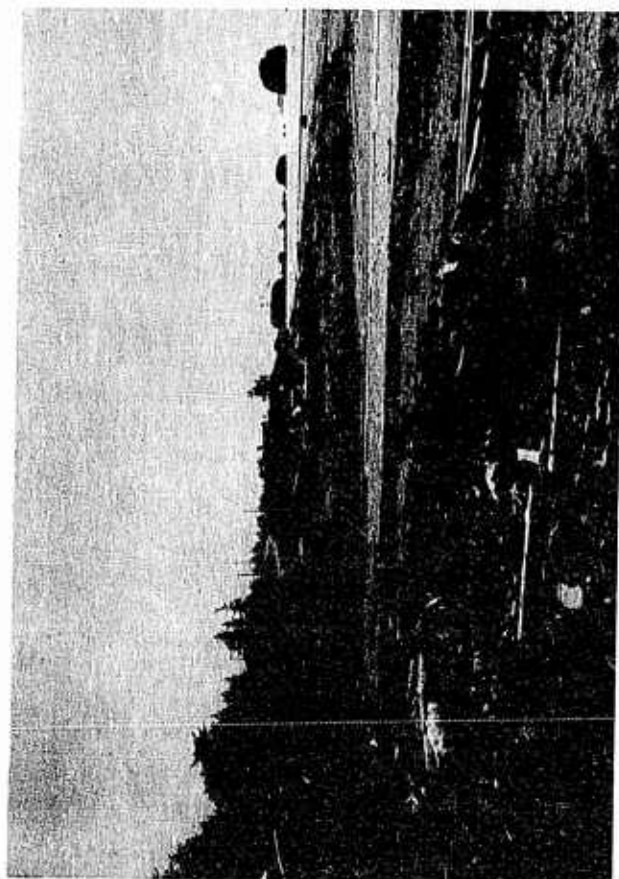


Figure 56. Waterfront logs were being driven into walls and glass windows with the force of a battering ram.

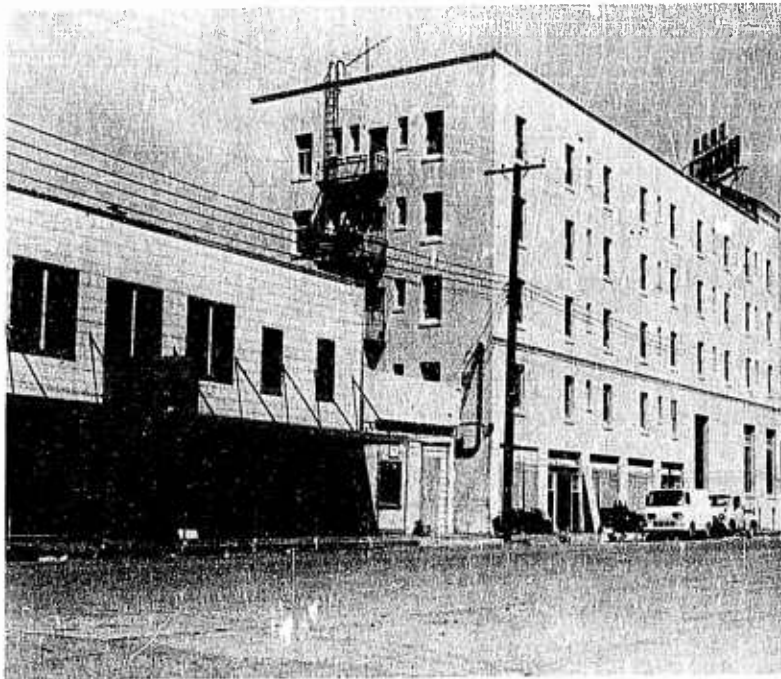


Figure 57. Plywood now boards windows along Front Street broken by floating debris carried on 4- to 6-foot inundation.

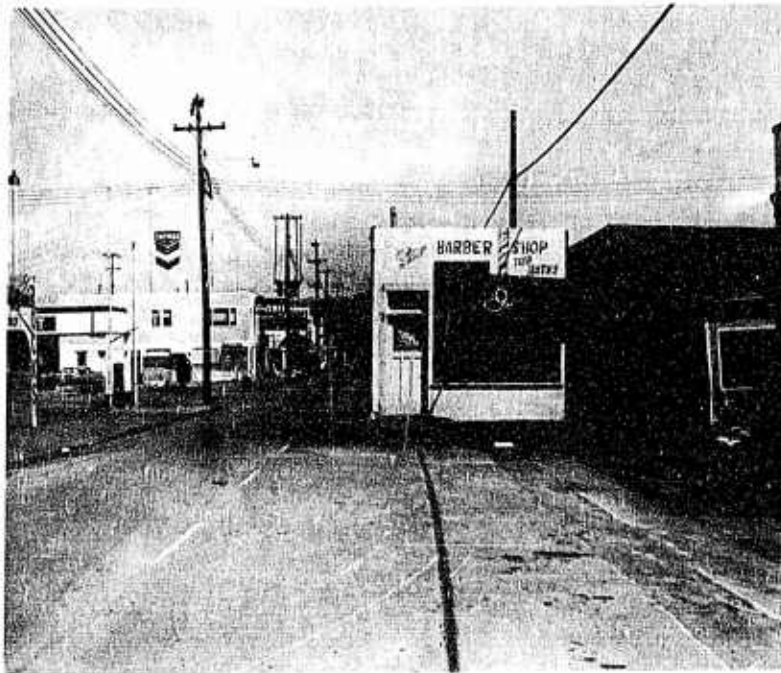


Figure 58. Barber shop was one of many buildings that blocked Second Street by floating across it.

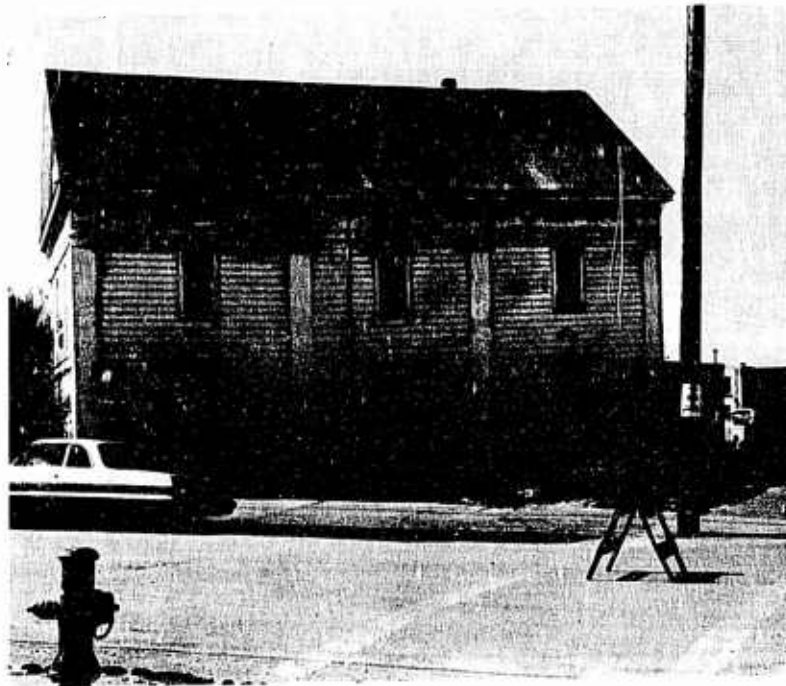


Figure 59. Turbulent waters (5 feet deep) moved two story Odd Fellows Hall 30 feet and rotated it 45°.

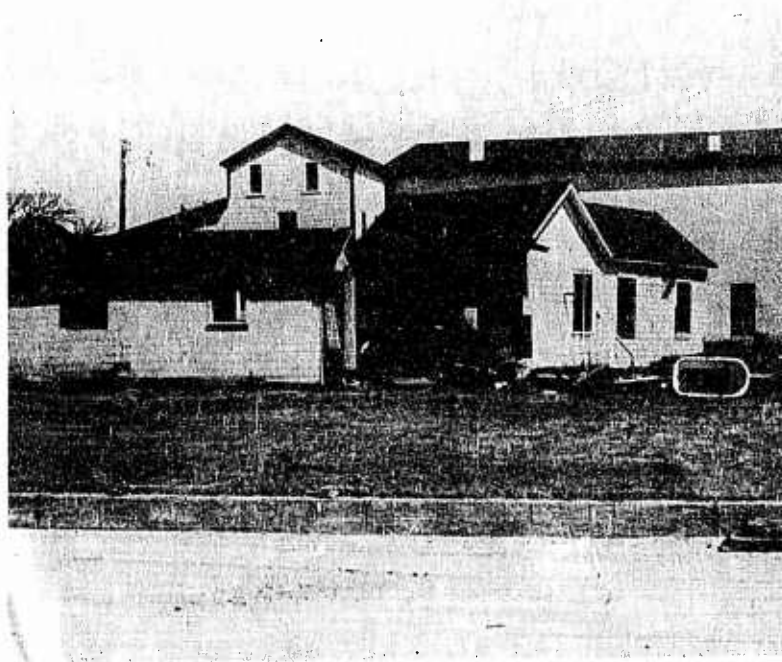


Figure 60. Home on Front Street left its foundation and broke in half. Bathtub still attached to plumbing.

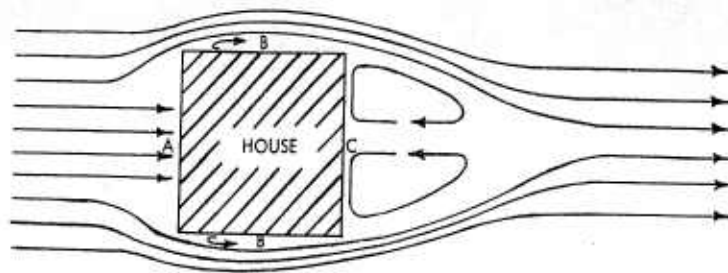
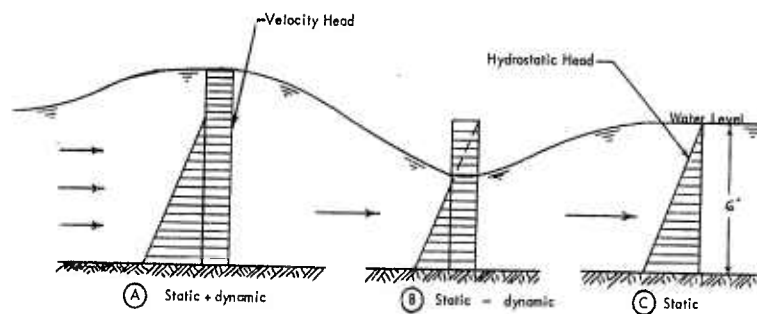


Figure 61A. Flow around typical house.



$V = 5 \text{ fps} \rightarrow$	$384 + 24 = 408 \text{ lbs/sf}$	$384 - 24 = 360 \text{ lbs/sf}$	384 lbs/sf
$V = 10 \text{ fps} \rightarrow$	$384 + 100 = 484 \text{ lbs/sf}$	$384 - 100 = 284 \text{ lbs/sf}$	384 lbs/sf
$V = 15 \text{ fps} \rightarrow$	$384 + 225 = 609 \text{ lbs/sf}$	$384 - 225 = 159 \text{ lbs/sf}$	384 lbs/sf

R 5

Figure 61B. Fluid pressure diagram around typical house.

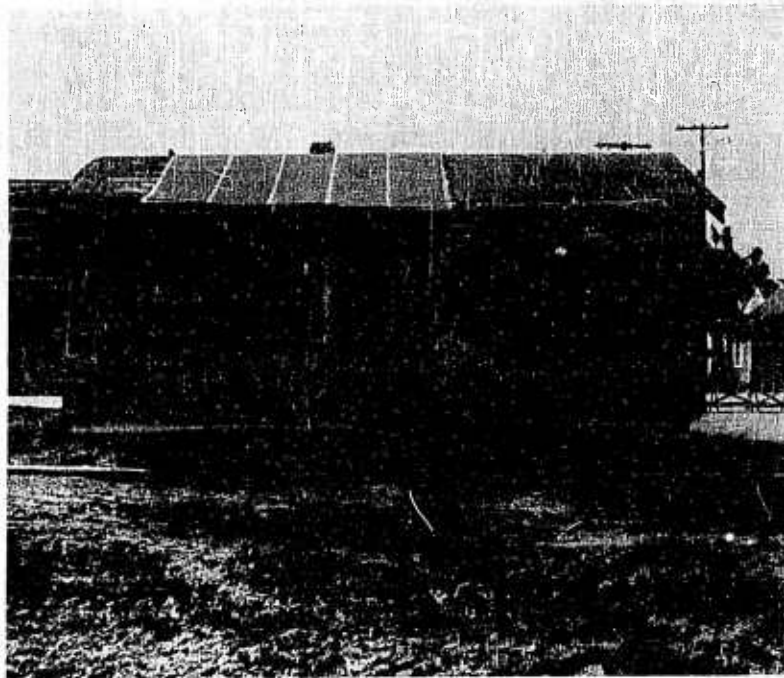


Figure 62. Forces from five feet of flowing water moved housing units up to one block from their foundation.



Figure 63. Side wall of Turf Club bulges outward - caused by rapid recession of tsunami waters.

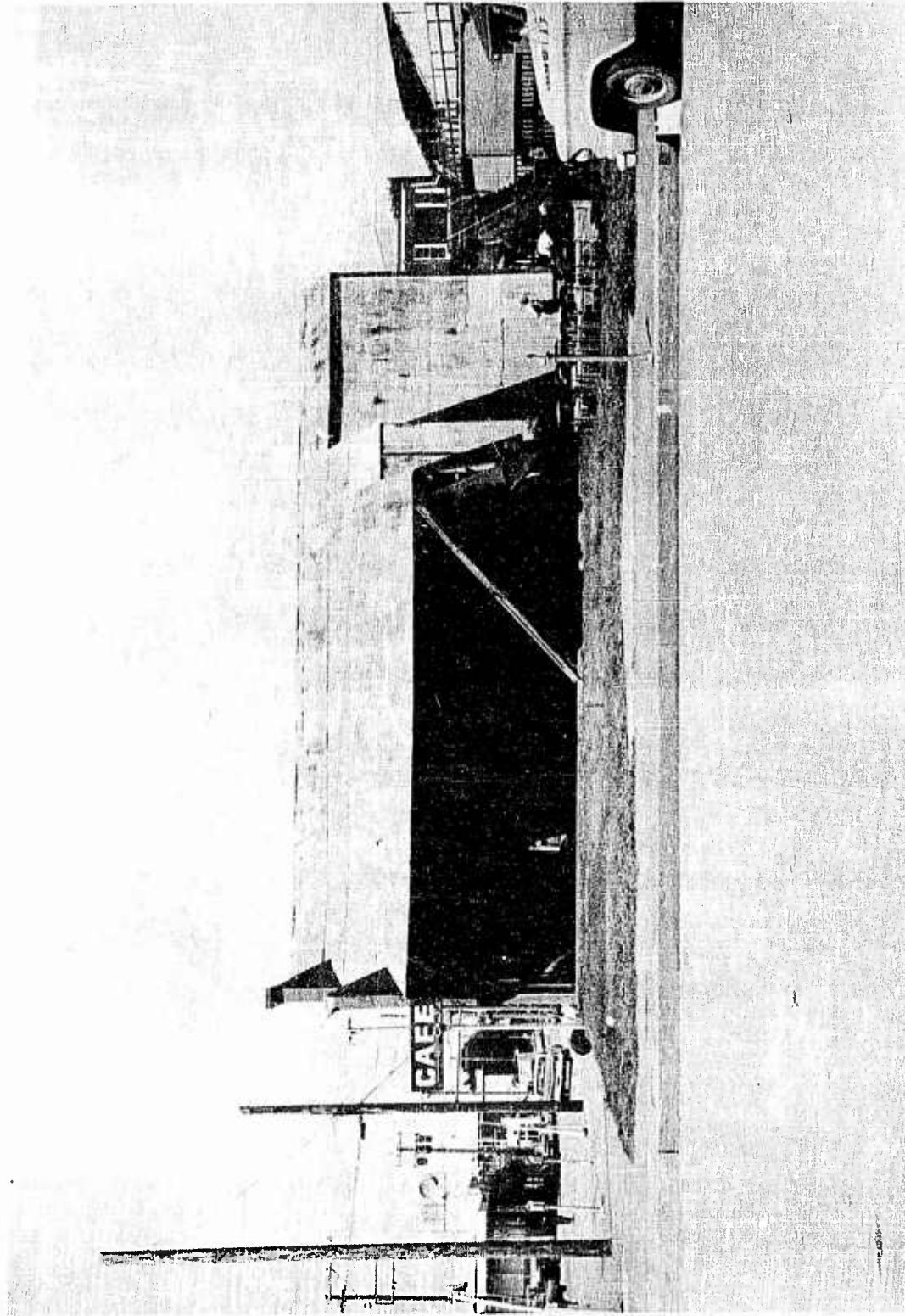
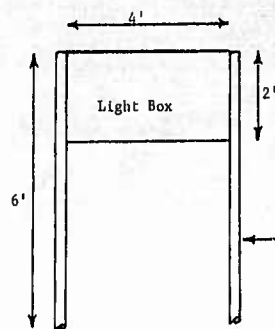


Figure 64. Entire side of corrugated steel transit shed type building along Front Street collapsed.



Prob: Find load per in^2 which will produce yielding of post at base.

Assume: $S = 30 \text{ KSI}$
 $I_{\text{post}} = 1.18 \text{ in}^4$
 $ID = 2.468$
 $OD = 2.375$
 $C = 1.437$
 $C_D = 0.35$
 $\bar{y} = \frac{\sum \Delta y}{\sum A} = \frac{82,080}{1,512} = 54.2"$

$\bar{y} = 54.2"$

$M = \frac{SI}{C} = \frac{(30,000)(1.18)}{1.437}$

$M = 24,600 \text{ in-lb}$

$P = \frac{M}{\bar{y} \sum A} = \frac{24,600}{(54.2)(1512)} = .3 \text{ lb/in}^2$

$P = 43.2 \text{ lb/ft}^2$

$V = \frac{(2)(43.2)(32.4)}{(.35)(64)} = 11.2 \text{ ft/sec}$

$V = 11.2 \text{ ft/sec}$

Dim	Area	$\bar{y}$	Δy
Light Box 2' x 4'	1,152	60	6,9120
2 1/2" ϕ steel pipe	180	36	6,480
2 1/2" ϕ steel pipe	180	36	6,480

$\sum A = 1,512$ $\sum \Delta y = 82,080$

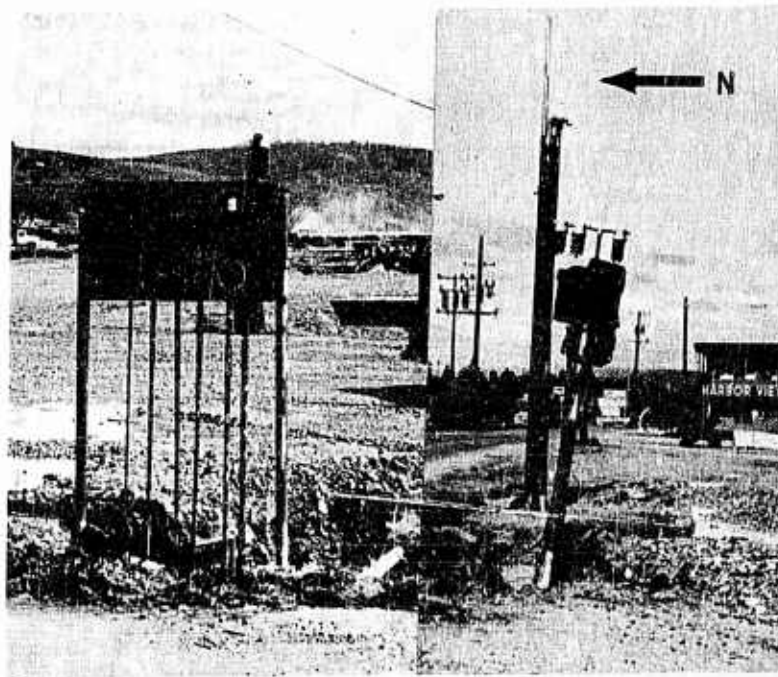


Figure 65 . Wave force and approximate velocity needed to produce yielding of light box at Crescent City Harbor. Bottom photo shows the front and side views of the light box.

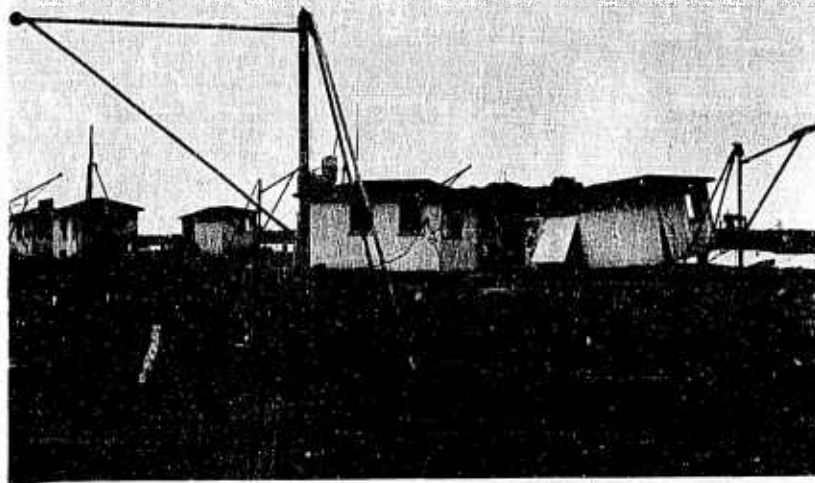


Figure 66A. Commercial fish shacks on Fish Pier arm of Citizens Dock were deflected as tsunami passed.

CRESCENT CITY HARBOR

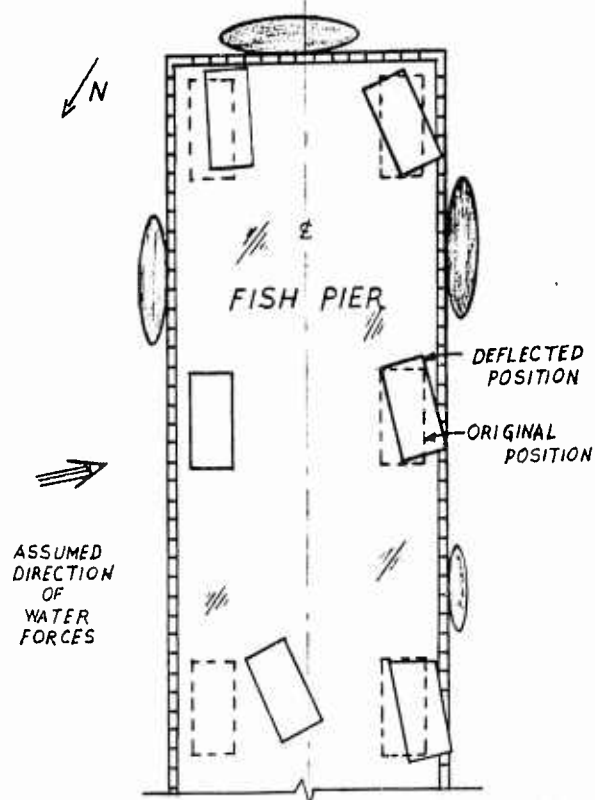


Figure 66B. Fish shacks nailed to decking by 2 X 4's deflected almost inversely proportional to pier corner. Shack that did not move was reinforced and had strong columns at corners.

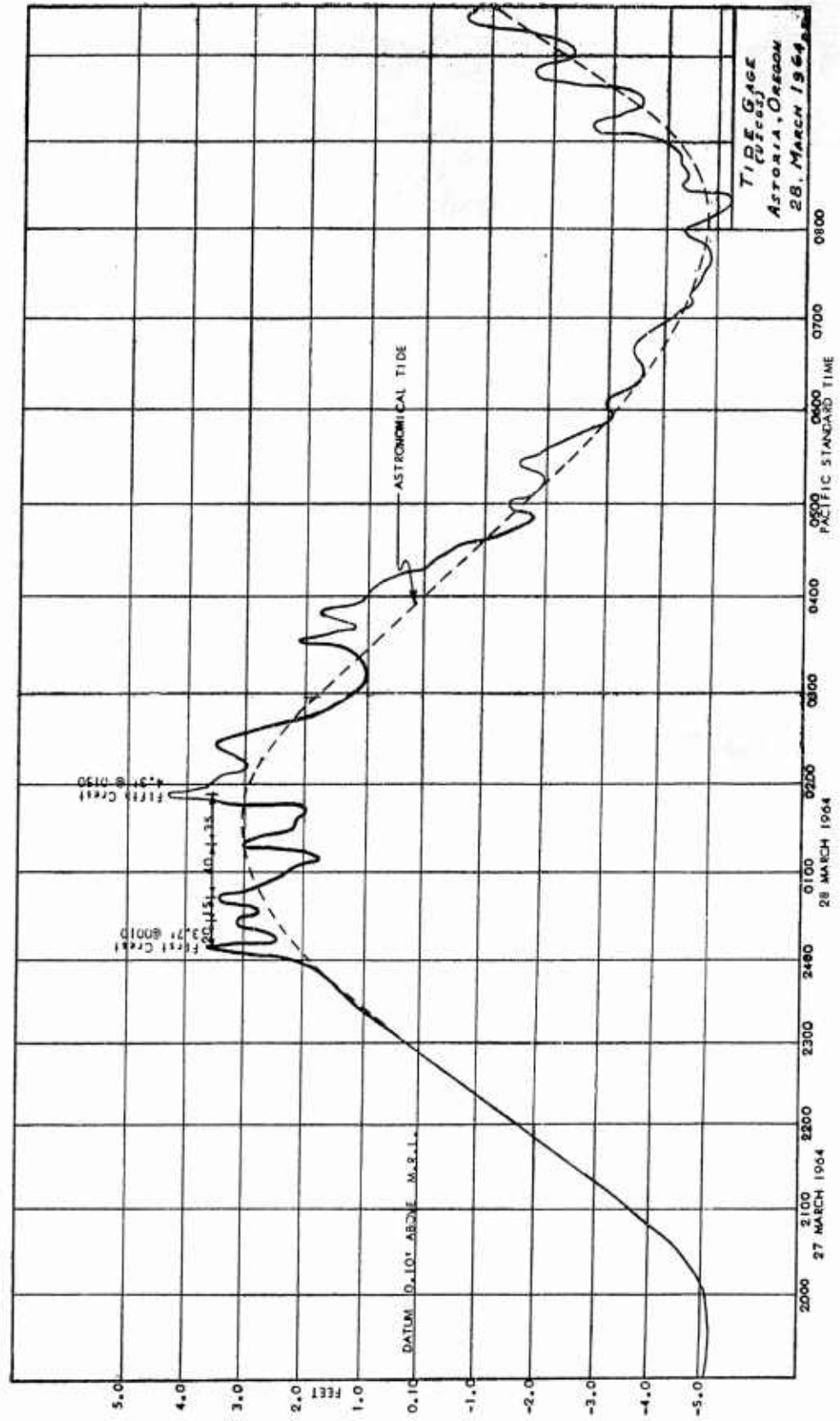


Figure 67. Tide Gage Record at Astoria, Oregon

FINDINGS

U. S. Naval Station, Kodiak

1. Earthquake. (i) Moderate to severe; (ii) one inch cracks in asphalt pavement taxiway; (iii) water main cracked and other minor damage; (iv) NAVSTA subsided uniformly $5\frac{1}{2}$ feet; (v) thirty minute tsunami warning given.

2. Wave Damage. (i) Three dead; few injuries; (ii) six million dollars property damage; (iii) main power station flooded; (iv) debris carried into hangar area; (v) six to eight feet of water in hangars; (vi) cargo dock completely damaged; (vii) two bridges and Chiniak Road washed out; (viii) power line damage; (ix) minor damage at Marginal Pier; (x) some subsidence due in part to erosion; (xi) some contamination by radio-active particles; (xii) twelve foot diameter buoy washed ashore; (xiii) salt water immersion of equipment and vehicles.

3. Characteristics of Wave Action. (i) First of a series of six seismic sea waves arrived one hour after quake; (ii) crests ranged from 15 to 24 feet above MLLW; (iii) wave periods varied from 27 to 90 minutes; (iv) tide gage rendered inoperative by quake; (v) marigram reconstructed from USCGS field notes; (vi) action resembled river flood.

Kodiak City

1. Earthquake. (i) Houses shaken; (ii) water mains broken; (iii) dishes tumbled; (iv) city uniformly settled $5\frac{1}{2}$ feet; (v) local after shocks and tremors did no damage.

2. Wave Damage. (i) Forty percent business district and many homes wiped out; (ii) thirty percent fishing facilities ruined; seventy-seven fishing boats destroyed or missing; (iii) seventy-five percent food supplies lost; (iv) twenty-five killed; (v) twenty minute warning given; (vi) two of three canneries swept away; (vii) rubble rock break-water settled $3\frac{1}{2}$ feet; (viii) City dock and warehouse and harbor-master building swept from foundations; (ix) numerous piling, anchors, lines and piers were broken; (x) boats were floated; they came aground inland.

3. Characteristics of Wave Action. (i) First wave arrived 1847 AST, 27 March as gentle swell; (ii) first wave recession emptied harbor; "drydocked" fishing fleet; (iii) second wave with crest 30 feet high did much of the damage; 50-100 ton boats shoved inland; (iv) third and fourth waves had periods of 55 minutes; crests less than 30 feet; (v) water level oscillations continued throughout night.

Crescent City, California

1. Earthquake Damage. None

2. Wave Damage, General. (i) twenty-five ton concrete, tetrapod monument pushed from foundation; (ii) thirty-six block section downtown damaged; (iii) twelve killed; (iv) one hour tsunami warning given; (v) fifty four homes destroyed; (vi) thirty seven homes damaged; (vii) forty two business establishments totally destroyed; one hundred eight with major damage; twenty nine with minor damage; (viii) houses and logs grounded on streets; (ix) logs driven through windows of buildings; (x) no structural damage to multi-story buildings; heavy damage to many one-store buildings; (xi) hydrostatic pressures of 400 psf and dynamic pressures of 100 psf indicated.

3. Wave Damage in Harbor. (i) Tetrapod-armored outer breakwater and rock inner breakwater not damaged although overtopped; (ii) heavy damage to boats; fifteen capsized; three unaccounted for; (iii) Citizen's Dock damaged severely; moored barge pulled off decking; fish shacks twisted and moved; wave barrier and piles under approach removed; (iv) Dutton's Dock undamaged; constructed with steel straps, bolted connections and heavy cross bracing; (v) scour at Citizen's Dock parking lot; (vi) seawall eroded; (vii) channel buoys torn from moorings; (viii) abandoned Sause Dock further damaged; (ix) Elk Creek culvert undermined.

4. Characteristics of Wave Action. (i) Visual observations only for high water levels; marigram reconstructed from these and the torn and water-logged record from submerged tide recorder; (ii) first crest 14.5 feet above MLLW at 2352 PST, 27 March; second wave slacked off to 12 feet; then two smaller waves; townspeople thought tsunami attack was over based on previous action; then heavy damage by highest wave cresting 20.5 above MLLW at 0115 PST, 28 March; (iii) major flooding produced downtown by dual action; Tsunami backwash from Elk Creek area and direct tsunami rise from harbor; (iv) deep ocean water level variations may have been amplified by focusing on city by action of off-shore hydrography; (v) model tests predict less than no damage from wave with height of 23 feet and 14 second period; (vi) water velocities of 12 MPH predicted during recession of largest wave.

Wave Damage in Other Cities - Damage and wave action for certain cities with major damage other than Kodiak and Crescent City is tabulated in Table III for comparison.

CONCLUSIONS

The following conclusions are based on findings from a survey at Kodiak and Crescent City approximately one week after the Alaskan earthquake and apply only to tsunami action. Seismic action is not discussed:

1. An adequate warning of possible ensuing tsunamis was given after the quake.
2. Lines to mooring buoys and channel buoys were not designed for submergence by tsunamis as evidenced by the many break-aways.
3. Piers with moored ships or barges had fenders, decking and mooring appurtenances damaged.
4. Piers with adequate ties between decking and pile structure did not have decks uplifted.
5. Fishing boats and other small craft moored in harbors exposed to large, tsunami-induced, water level variations were damaged by break-aways, grounding and sinking in place.
6. Operational failure or functional breakdown of powerplants, communication lines, equipment, and vehicles occurred when contacted by tsunami flooding. Salt water corrosion effects due to immersion is a factor.
7. Partial destruction of unsurfaced roads, parking lots and loosely compacted earth fills will occur if such areas cannot withstand scour pressures of several pounds/square foot.
8. Single-story, light-frame structures did not survive well. They were badly damaged or floated away by the hydrostatic and dynamic pressures exerted by the 4 to 10 feet of moving water during flooding and recession. Few of these lighter, and usually older, buildings had adequate ties to the foundation. Multi-story buildings demonstrated good resistance.
9. Continuous water level measurements of the tsunami were not possible because of damage to tide gage recorders by earthquake or by water submergence.

RECOMMENDATIONS

1. The tsunami warning system currently functioning is encouraging; it should be continued toward reducing probability of loss of life.
2. Mooring lines to moors and channel buoys in shallow waters (20 - 30 feet and less) susceptible to tsunamis need to be designed to resist the full buoyant force of submergence.
3. All boats and ships in harbors should put to sea when a tsunami warning is given. This evacuation duty should be assigned to cognizant personnel.

4. Theoretical and experimental studies should be continued. They provide the best means for obtaining a better understanding of the tsunami including its runup on shore installations. Those underway at the Naval Civil Engineering Laboratory Wave Basin with dispersive type water waves are pertinent.

5. In general, the reconstruction of all low-lying sections of cities and ports damaged by the tsunami should incorporate some type of protection against exceptionally high water waves because of the reasonable probability of future tsunami. Oil tanks in particular, should be better protected. Cities and installations in the earthquake belt should be designed on the premise that a tsunami could approach at any time. Revised building codes should require better ties between structures and foundations and also between pier decks and piles. Water supplies should be protected better and citizens should be instructed concerning behavior during a tsunami. The tsunami should receive as much attention in design as the earthquake. This statement is based on comparison of seismic sea wave damage and loss of life as compared with seismic land wave losses.

ACKNOWLEDGEMENTS

The assistance of the following is acknowledged gratefully: Darold G. Richcreek, Harbor Master, Crescent City, California; Albert Wheelon, County Engineer, Crescent City, California; James R. Barr, City Engineer, Kodiak, Alaska; First Lieutenant Delmer L. Brown, U. S. Army, Corps of Engineers, Seattle, Washington; Pierre-Saint-Amand, PhD, Naval Ordnance Test Station, China Lake, California; Commander H. Krackow, CEC, U. S. Navy, Dist. Civil Engineer, Kodiak Naval Station; Lieutenant W. Barney, USCGS, Fleet Weather Central, Kodiak Naval Station; Mr. Frey, Director, Engineering Division, Public Works Department, Kodiak Naval Station; Robert Siu, Engineering Technician, U. S. Naval Civil Engineering Laboratory, Port Hueneme, California.

REFERENCES

1. BUDOCKS, DM-25 (1961), "Waterfront Operational Facilities, Design Manual 25", Department of the Navy Bureau of Yards and Docks, Washington, D. C.
2. Glasstone, S. (1962) "The Effects of Nuclear Weapons", prepared by the U. S. Department of Defense. Published by the U. S. Atomic Energy Commission, Washington 25, D. C. April 1962.
3. Hudson, R. Y. and Jackson, R. A. (1955) "Design of Tetrapod Cover Layer For a Rubble-Mound Breakwater, Crescent City Harbor, Crescent City, California". Technical Memo 2-413, U. S. Army Corps of Engineers, June 1955.

4. Kaplan, K. (1955) "Generalized Laboratory Study of Tsunami Runup". Technical Memo 60. Beach Erosion Board, U. S. Army Corps of Engineers.
5. Magoon, O. T. (1962) "The Tsunami of May 1960 As It Affected Northern California", paper presented at ASCE Hydraulics Division Conference at Davis, 17 August 1962.
6. O'Brien, J. T. (1963) "Study and Analysis of Damage By Typhoon Karen on Guam", Co-authors: R. M. Webb, E. J. Beck, Jr., U. S. Naval Civil Engineering Laboratory Technical Note N-497, p. 70, 29 March 1963.
7. Stephenson, J. M. (1964) "Earthquake Damage to Anchorage Area Utilities", Technical Note N-607, U. S. Naval Civil Engineering Laboratory, Port Hueneme, California, June 1964.
8. USGS (1964) "Alaska's Good Friday Earthquake, March 27, 1964. A Preliminary Geologic Evaluation". Geological Survey Circular 491. By Arthur Grantz, George Plafker, and Reuben Kochadoorian. U. S. Department of the Interior, Geological Survey, Washington, D. C.
9. USCGS (1964) "Preliminary Report. Prince William Sound, Alaskan Earthquakes". March - April 1964, Seismology Division, U. S. Department of Commerce, Coast and Geodetic Survey, Washington, D. C.
10. Wilson, B. W. et al (1962) "The Nature of Tsunamis; their Generation and Dispersion in Water of Finite Depth". USCGS Contract 801 (2442). National Engineering Science Company, B. W. Wilson, Lois M. Webb and J. A. Hendrickson, August 1962.

TABLE III
CITIES WITH EXTENSIVE WATER WAVE DAMAGE

Location	Loss of Life	Population	Total Damage	Boat Damage	Highest Wave	Wave and Water Damage	Wave Action
Crescent City	12	3,000	\$10,000,000	22	14' (Tsunami)	27 blocks virtually ruined by flooding. 34 homes and 40 businesses destroyed. 400 persons killed. Gas mains ruptured and power lines burst. 5 fuel tanks blew up. Citizens dock heavily damaged.	First wave hit streets of business section. Second and third waves washed off the Fourth wave. Water poured into the city and up Elk Creek. Water brought huge logs that acted as battering rams and were deposited by receding flood.
City of Kodiak	25	2,600	\$50,000,000	97 (+ 42 more in Kodiak area)	30' (Tsunami)	15 blocks (40% of business section destroyed. Fishing industry along waterfront heavily damaged. 30% of fishing facilities wiped out. 75% of city's food supply lost. 30 min. warning given.	Water rose like a fast-rising tide to 22 ft. above MLLW. Fishing fleet was dry-docked after first wave receded. Third crest was somewhat broken in the channel between islands. First crest had swirls - resembled flow in river.
NAVSTA, Kodiak	3	—	\$10,300,000	—	30' (Tsunami)	Main power station flooded. Electrical power and steam heat lost. Bridges to Holiday Beach, NAVSTA were washed out. Major damage to cargo pier - minor damage to fuel pier. Sea plane hangers, ramps and taxiways flooded - some subsidence.	First wave flooded low area of the Naval Station. (partially due to 5 1/2 ft. subsidence of Kodiak Island during 1st quake). Two more waves followed with periods of 55 min. Fourth and highest wave created at 30 ft. above MLLW.
Seward	22	2,200	\$25,000,000	Fishing boats and Marine gone	25' (Surge)	Docks swept away and tanker beached and burned. Flaming oil from water waterfront storage tanks washed into Seward. Water front railroad facilities and rolling stock hurled inland by waves. 90% of industry erased. Most of business section destroyed.	Within 3-5 min. after quake there was a 30 ft. regression of water. Then 30 min. later there was an onrush about 17 ft. Then within 10 min. a 25 ft. wave came and did serious damage. Then 10 large oscillations in Neurrection Bay during night.
Valdez	32	1,220	\$15,000,000	Small boat harbor and fishing fleet gone	30' (Surge)	Wave brought icebergs and debris into Valdez and destroyed waterfront. First wave created (30 ft.) which destroyed oil tank. Pro-wa surge from submarine slump. 15 min. later wave plant and business section a smaller wave flooded waterfront area. A third (under 4 ft. of water). Harbor wave followed several hours later. The last depths changed 30 to 120 ft. Tentative plans to relocate city. 225 homes damaged.	First motion reported as recession (Freighter receded). First wave created (30 ft.) which destroyed oil tank. Pro-wa surge from submarine slump. 15 min. later wave plant and business section a smaller wave flooded waterfront area. A third (under 4 ft. of water). Harbor wave followed several hours later. The last depths changed 30 to 120 ft. Tentative plans to relocate city. 225 homes damaged.
Whittier	13	630	\$10,000,000	—	35' (Surge)	Dock and adjacent buildings destroyed. (Also fire damage when ruptured oil tanks ignited). Steel pier blocked by sunken barge alongside.	Water rose rapidly to 25 ft. after initial recession that was more violent than inrush. Water receded and 1 min. later 35 ft. debris-laden wave came in. Then a min. later a similar wave came but 4 - 5 ft. lower. The 35 ft. wave did most of damage.
Hilo	None	—	\$15,000	None	7' (Tsunami)	Three restaurants and a house inundated. At Kahului, Maui, a shopping center was flooded.	A series of six waves washed onto shores of all major islands in Hawaii, minor flood and then all-clear signal.
Chenega	25	76	—	—	60-70' (Wall of water)	All houses were swept away. School house was undamaged.	First wave struck 3 min. after quake. Wave was a swash rather than seiche, caused by submarine slump.
Cordova	1	3,200	—	—	20' (Tsunami)	Docks extensively damaged. Roads damaged.	First waves 20 ft. high, did not reach to elevate high-tide level, which after the quake was 22 ft. above MLLW. Flooding was 5 ft. above highest high-tide line.

APPENDIX I
TSUNAMI WAVES

TSUNAMI WAVES

In this report the term "tsunami", Japanese for "tsu" (small bay or harbor) and "nami" (long wave), is used to define the seismic sea wave. Tsunamis are waves of long periods from 10 minutes to 12 hours duration. They are very long (200 or 300 miles) waves likely of low height (2 or 3 inches) in deep water and are usually not detectable by the eye until they increase in height when approaching coastlines. Their effects in deep water appear to be negligible. However, upon approaching coastlines, they may rise to heights of 20 to 30 feet. Their form speed (v) in deep water follows the Lagrangian equation:

$$v = \sqrt{gd}$$

where g is the acceleration due to gravity, and d is the water depth.

Typical speed to depth values are given in Table IV.

TABLE IV

SPEED OF TSUNAMI WAVES

<u>Depth</u> <u>(fathoms)</u>	<u>Speed</u> <u>(knots)</u>	<u>Depth</u> <u>(fathoms)</u>	<u>Speed</u> <u>(knots)</u>
10	26	2,000	368
100	82	3,000	451
150	184	4,000	521
1,000	260	5,000	582

Earthquakes and tsunamis are as yet impossible to predict. However, data are available to indicate a trend of the frequency of earthquake occurrence in the world. (Figure 68). As an example, an earthquake of magnitude 8.4 might be expected every 20 or 30 years according to plotted points from previous quakes or as indicated by the trend curve.

Presently, the one characteristic of tsunami waves which can be successfully predicted is the time of arrival of the first wave front (the initial signal) on a coastline. This is done by a refraction diagram which has proven so satisfactory for predicting arrival-times, it has become the basis for all travel-time charts.

With regard to wave heights and energy distribution, however, scientists cannot make accurate predictions and interpretations. Attempts to base energy distribution on refraction diagrams have not been fruitful because of the difficulty of diffractive effects, although there are mathematical analyses of diffractive effects around small sample islands. There is also the additional factor that in many cases, the initial wave itself is not very high, and is often followed by higher waves - the highest and most destructive arriving on high tide hours after the initial wave as happened at Crescent City.

These significantly higher waves are of greater practical importance than the initial wave, yet no reliable method is now available for predicting their heights and arrival time because such predictions require an understanding of the complicated processes which generate tsunamis. Of primary importance in behavior after generation are topographic irregularities, such as variations of bottom slope and curvature, and variable coastlines and shorelines, which influence directly the diffraction, reflection, scattering, and dissipation of the waves.

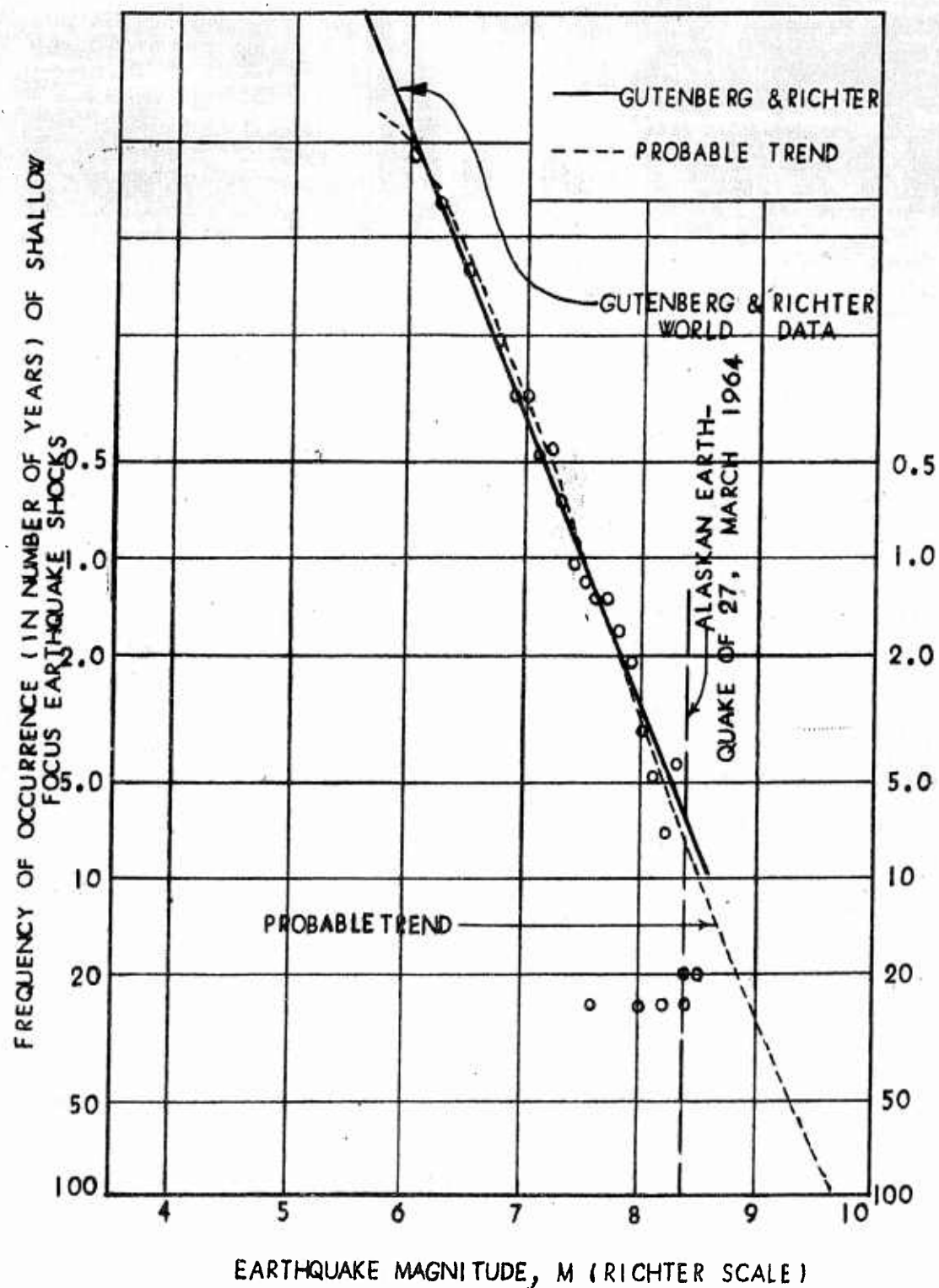


FIG. 68. FREQUENCY OF OCCURRENCE OF SHALLOW FOCUS EARTHQUAKE SHOCKS OF PARTICULAR MAGNITUDES. (BASED ON DATA FROM WILSON 1964)

APPENDIX II
EARTHQUAKE ENERGY VERSUS NUCLEAR WEAPON ENERGY

EARTHQUAKE ENERGY VS. NUCLEAR WEAPON ENERGY

In order to relate (as a guide only) earthquake magnitude M (Richter Scale) and nuclear weapon yield in tons of TNT, the author has assumed that approximately the same ratio of energy of an earthquake goes into water wave generation as in the case of impulsive water wave generation from nuclear weapons. Even though the two generation processes are definitely different, this assumption is probably not too far in error. In both cases, only about 1% or less of the total energy is effective in producing waves (see Wilson 1962). This is further borne out by the fact that seismographs cannot separate with certainty ground motion waves due to underground nuclear blasts from those caused by earth tremors. No statement is made concerning height of burst or depth of water. What really is involved is the effective coupling between earthquake and waves and correspondingly, between an explosion and waves (see Glasstone 1962).

The now commonly referred to Richter Scale magnitude M is the criteria for severity of an earthquake. It has been shown that E , the energy of the quake in ergs, can be expressed as:

$$\log_{10} E = 1.5 M + 13.0$$

This formula (Richter, 1958) is based on the value of 10^{25} ergs as the probable amount of energy released from an earthquake of magnitude $M = 8$. Thus, a large earthquake of magnitude $M = 8$ can be expected to release about 10^{25} ergs in the form of elastic vibration, crushing, uplifting and attrition of rock. This would be about equivalent to the nominal energy of release of a 250 megaton thermonuclear bomb. In comparison, the Hiroshima bomb had a yield of 20 kilotons with an estimated energy release of 8×10^{20} ergs which, on this basis, is equivalent to $M = 5.3$. It is mentioned that the Richter scale number is not a direct indication of the damage resulting from a quake. The damage is dependent greatly upon location, depth below the earth's surface, the structure, and composition of the rock and soil.

Using the above conversion, the data in Figures 69, 70 and 71 were obtained. Figure 68 indicates that tsunamis are not always caused by underground seismic disturbances. Rather, an earthquake intensity of greater than 6.5 or 7 is required for shallow focal quakes and $M \leq 8$ for deep ($D = 80$ km) quakes. Figures 70 and 71 indicate the heights and periods of the larger waves in the tsunami train.

It is emphasized that wave height near the source bears a relation to the amplitude and intensity of the seismic shock, while wavelength is related to the dimensions of the disturbance, which may be one hundred miles or more. Thus, the initial surface disturbance

contains all the frequency components down to that associated with the wavelength of the disturbance. In explosions, the same arguments hold where the disturbance is now the water crater.

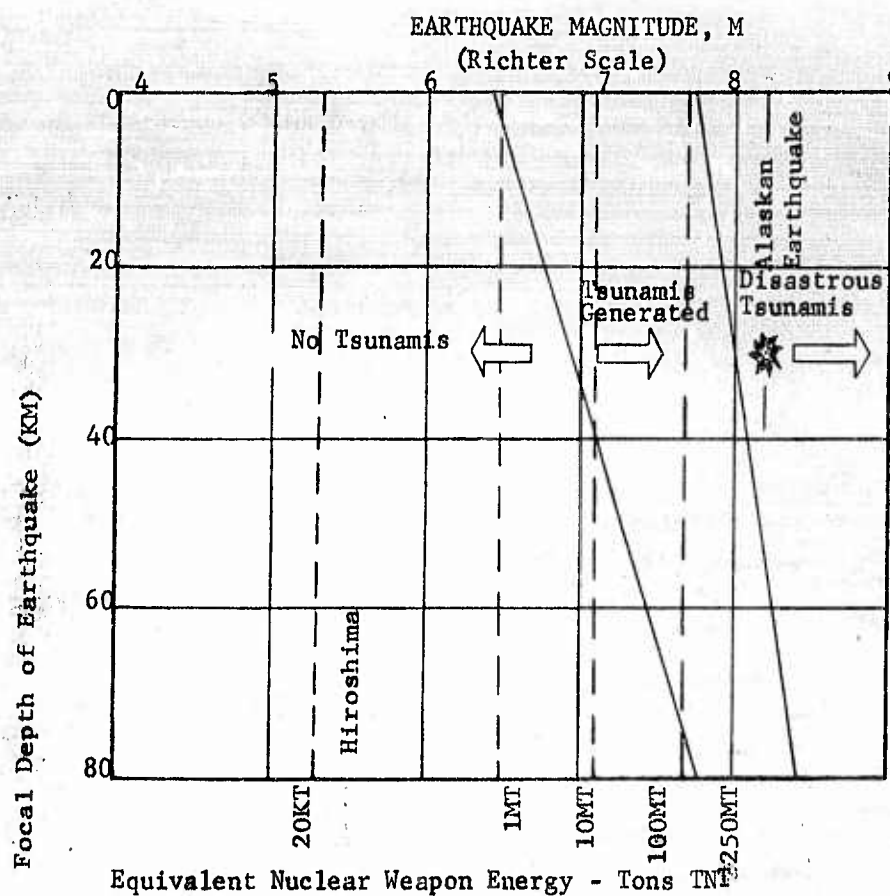


Figure 69.- Approximation of Earthquake Magnitude and Equivalent Nuclear Weapon Energy with Respect to the Generation of Tsunamis. (Earthquake data from Wilson, 1962).

EQUIVALENT NUCLEAR WEAPON ENERGY - TONS TNT

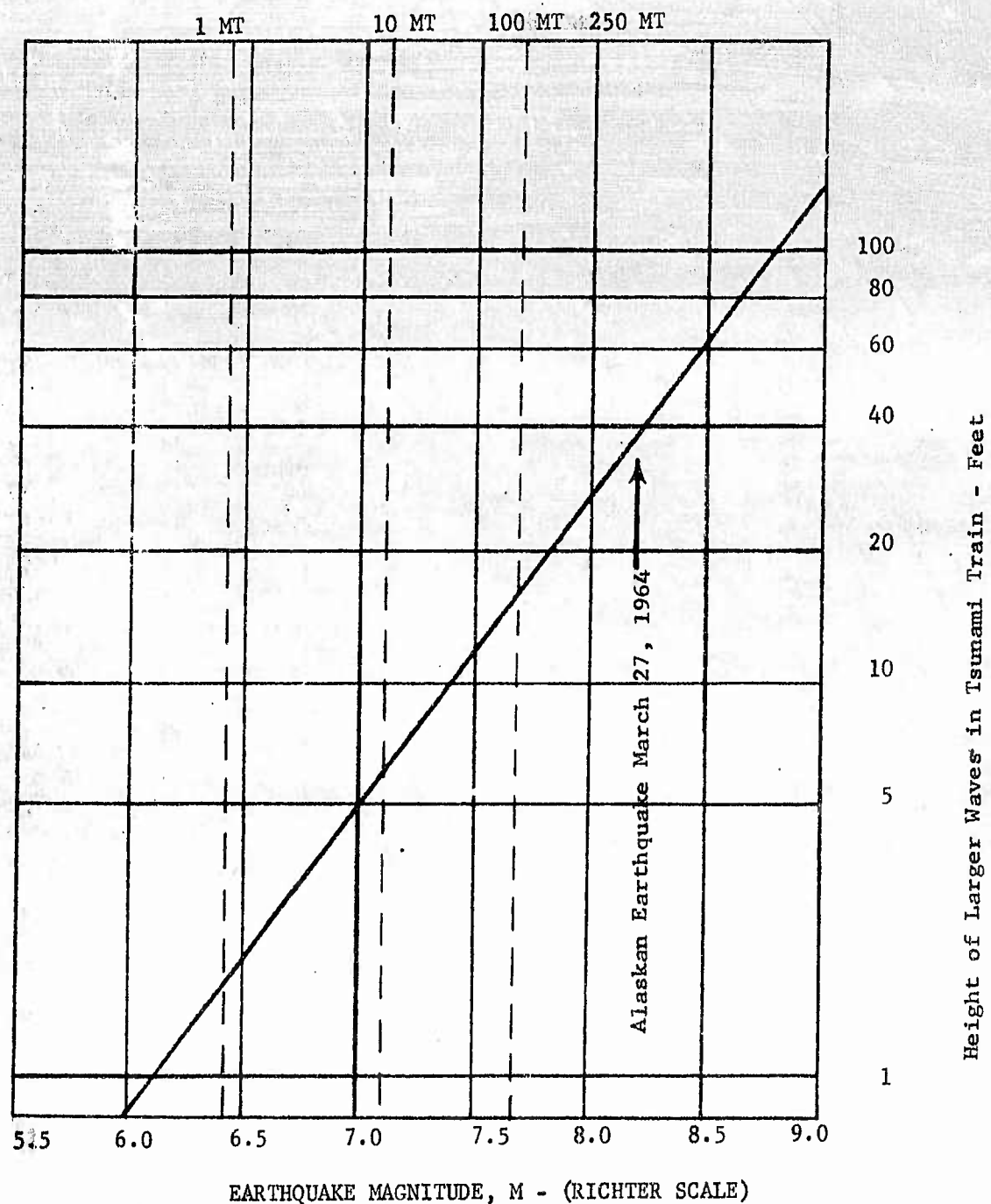


Figure 70. Approximation of the average height of the larger waves in a tsunami train with respect to earthquake magnitude and equivalent nuclear weapon energy. (Heights mainly based on Japanese data within a range of 500 miles; earthquake data from Wilson, 1962).

EQUIVALENT NUCLEAR WEAPON ENERGY - TONS TNT

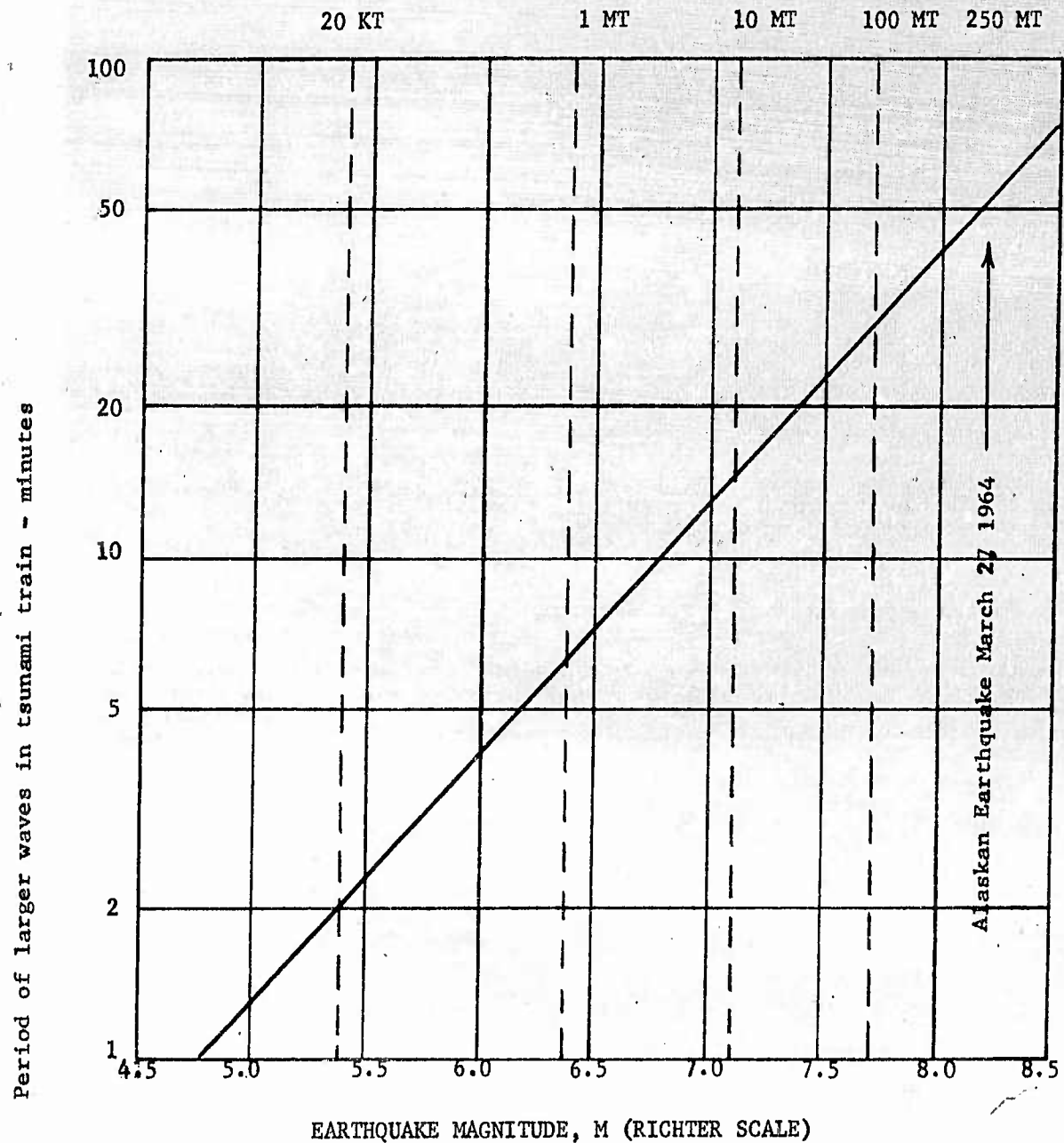


Figure 71. Approximation of period of larger waves in a tsunami train with respect to earthquake magnitude one equivalent nuclear power energy. (Earthquake data from Wilson, 1962).

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R&D		
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)		
1. ORIGINATING ACTIVITY (Corporate author)		2a. REPORT SECURITY CLASSIFICATION
Bureau of Yards and Docks (Naval Civil Engineering Laboratory)		Unclassified
		2b. GROUP
3. REPORT TITLE		
Tsunami Damage at Kodiak, Alaska, and Crescent City, California, from Alaskan Earthquake of 27 March 1964		
4. DESCRIPTIVE NOTES (Type of report and inclusive dates)		
Type C		
5. AUTHOR(S) (Last name, first name, initial)		
Tudor, Walter J.		
6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
August 1964		
8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)	
	TN-622	
b. PROJECT NO		
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
d.		
10. AVAILABILITY/LIMITATION NOTICES		
Qualified requesters may obtain copies of this report from DDC.		
11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY
None		Defense Atomic Support Agency DASA Subtask 14.083
13. ABSTRACT		
A survey of water wave damage to waterfront facilities at Kodiak, Alaska, and Crescent City, California, made about one week after the 27 March 1964 Alaskan earthquake of about 8.3 Richter scale indicates light to moderate damage from four to ten feet inundation and heavy damage from impact by wave-driven ships and debris. The series of six seismic sea waves at Kodiak had crests ranging from 15 to 24 feet above MLLW and periods varying from 27 to 90 minutes. The largest wave at Crescent reached 21 feet above MLLW and had a period of 55 minutes. At Kodiak Air Station: Three killed; few injuries; power station flooded; debris in hangar area; Cargo Dock damaged completely; two bridges and road washed out; barracks cracked; some subsidence and radio-active contamination; buoy washed ashore; oil slick on vehicles. At Kodiak City: 40% business district and many houses destroyed; 30% fishing facilities ruined; 75% food supplies lost; 25 killed; 77 fishing boats destroyed or missing; 3 canneries lost; king crab docks damaged; city dock, warehouse and harbor master building missing; numerous piling, anchors, lines, and piers damaged; boats floated aground inland; City settled 5 feet. At Crescent City: Rock and tetrapod breakwater not damaged; heavy damage in harbor; 15 boats capsized; Citizens Dock damaged severely; Dutton Dock nearby not damaged; seawall eroded; earthmover overturned; 25 ton concrete block pushed from pedestal; 12 killed.		

DD FORM 1473

1 JAN 64

0101-807-6800

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
tsunamis	6					
damage	7					
harbor structures	9					

INSTRUCTIONS

1. **ORIGINATING ACTIVITY:** Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization (*corporate author*) issuing the report.

2a. **REPORT SECURITY CLASSIFICATION:** Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. **GROUP:** Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. **REPORT TITLE:** Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. **DESCRIPTIVE NOTES:** If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. **AUTHOR(S):** Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. **REPORT DATE:** Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. **TOTAL NUMBER OF PAGES:** The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. **NUMBER OF REFERENCES:** Enter the total number of references cited in the report.

8a. **CONTRACT OR GRANT NUMBER:** If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. **PROJECT NUMBER:** Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. **ORIGINATOR'S REPORT NUMBER(S):** Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. **OTHER REPORT NUMBER(S):** If the report has been assigned any other report numbers (*either by the originator or by the sponsor*), also enter this number(s).

10. **AVAILABILITY/LIMITATION NOTICES:** Enter any limitations on further dissemination of the report, other than those

imposed by security classification, using standard statements such as:

- (1) "Qualified requesters may obtain copies of this report from DDC."
- (2) "Foreign announcement and dissemination of this report by DDC is not authorized."
- (3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through _____."
- (4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through _____."
- (5) "All distribution of this report is controlled. Qualified DDC users shall request through _____."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. **SUPPLEMENTARY NOTES:** Use for additional explanatory notes.

12. **SPONSORING MILITARY ACTIVITY:** Enter the name of the departmental project office or laboratory sponsoring (*paying for*) the research and development. Include address.

13. **ABSTRACT:** Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as (TS), (S), (C), or (U).

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. **KEY WORDS:** Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, roles, and weights is optional.

ABSTRACT (cont'd)

It is concluded that at Kodiak and Crescent City: Piers with moored ships had decking damaged; piers with adequate deck-pile connections did not have decking uplifted; lines to large buoys not designed for full submergence; fishing boats moored in harbor were damaged by breakaways, grounding, and sinking; single-story, light-frame structures did not survive well; multi-story buildings demonstrated good resistance; powerplants, communication lines, equipment and vehicles had functional failure when submerged.

Reconstruction of all low-lying sections of cities and ports should consider defense against tsunami.