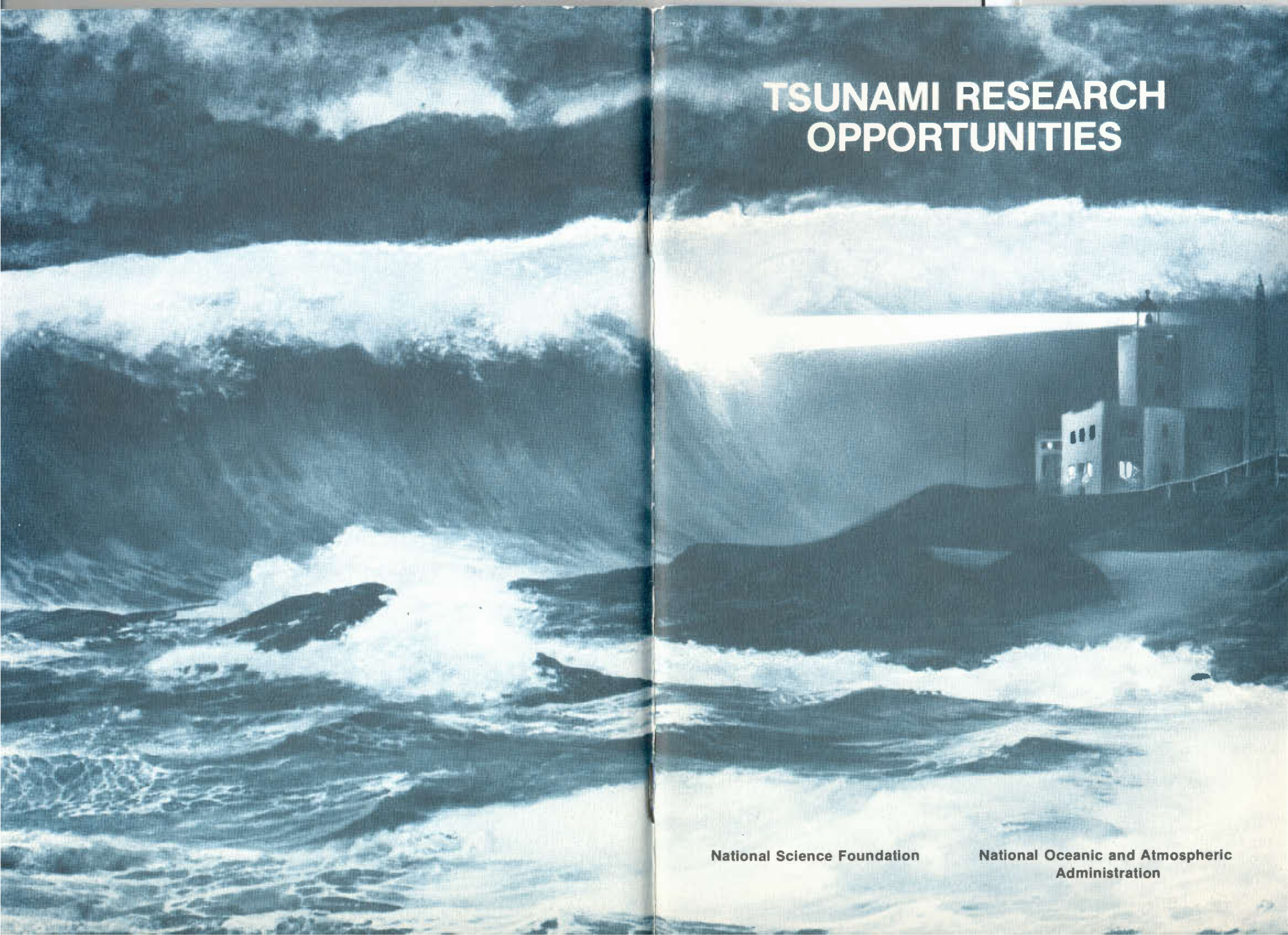
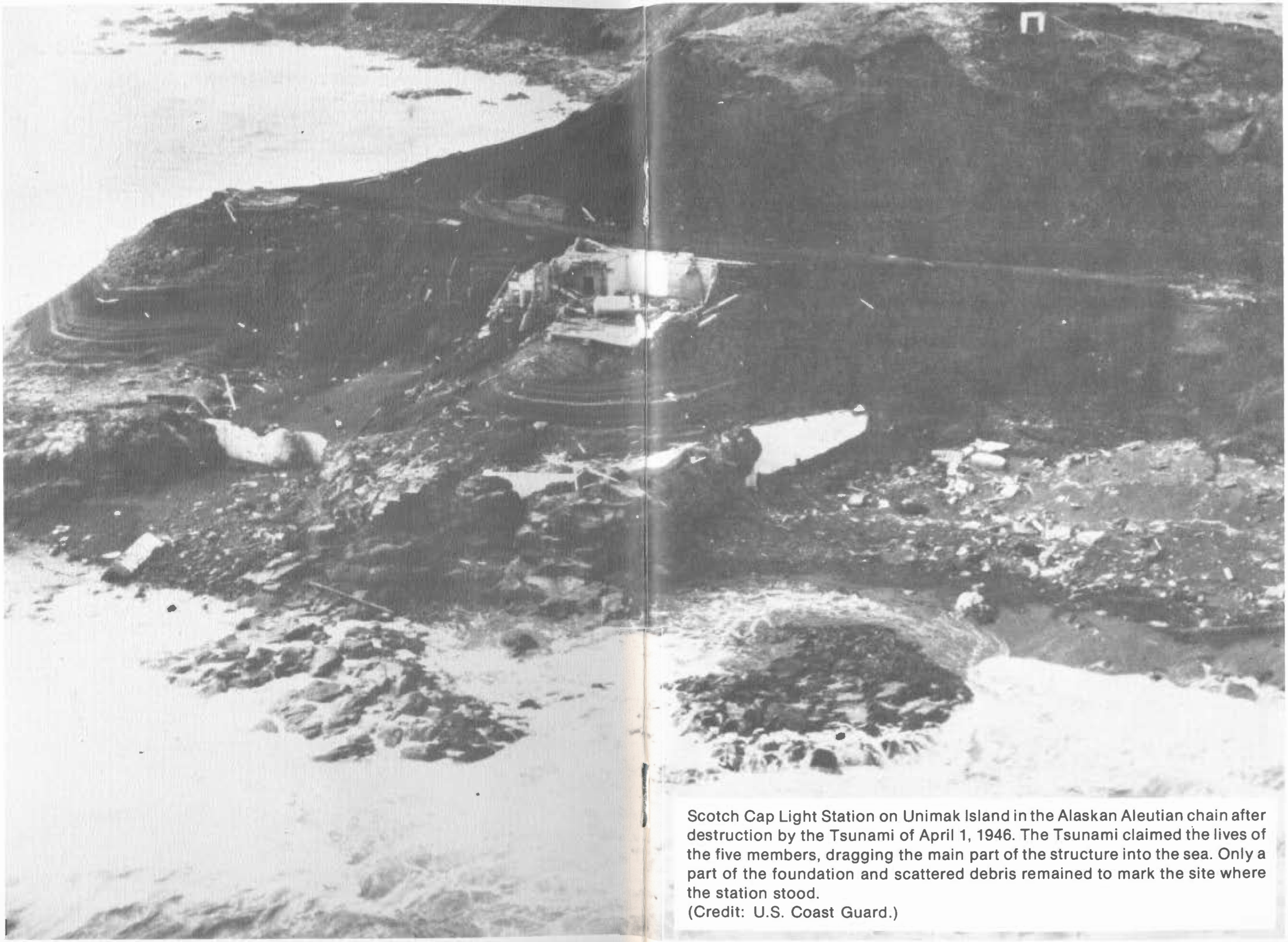


TSUNAMI RESEARCH OPPORTUNITIES

National Science Foundation

National Oceanic and Atmospheric Administration



Scotch Cap Light Station on Unimak Island in the Alaskan Aleutian chain after destruction by the Tsunami of April 1, 1946. The Tsunami claimed the lives of the five members, dragging the main part of the structure into the sea. Only a part of the foundation and scattered debris remained to mark the site where the station stood.
(Credit: U.S. Coast Guard.)

TSUNAMI RESEARCH OPPORTUNITIES

An Assessment and Comprehensive Guide

National Science Foundation

National Oceanic and Atmospheric Administration

Washington
September 1981

TABLE OF CONTENTS

Cover:

Scotch Cap Light Station on Unimak Island in the Aleutian chain. A mountain of frigid water rises above the 92 feet elevation of the concrete lighthouse, with a crew of five Coast Guard men inside.

PREFACE

Tsunami are large ocean waves, often of tremendous destructive potential, generated by impulsive geophysical events. *Tsunami Research Opportunities* is designed to foster a course of action that will focus and optimize research and fund allocation to achieve the dual goals of *forecasting tsunami dangers* and *evaluating coastal tsunami hazards*. The forecasting of tsunami dangers can provide a basis for evacuating people, moving boats and ships, and specifying fire-fighting and police procedures. The evaluation of coastal tsunami hazards can lead to the provisions of land-use guidelines and engineering design criteria for potentially threatened areas. Achieving these goals should reduce the impacts of future tsunami.

Tsunami are a widely unrecognized hazard to life and property along the coastlines of the United States. Damage from tsunami is the direct result of three factors: inundation, wave impact on structures, and erosion. Strong tsunami-induced currents have led to the erosion of foundations, the collapse of bridges, and the destruction of seawalls. Flotation and drag forces have moved houses and overturned railroad cars. Tsunami-associated wave forces have demolished light frame buildings and wooden structures; and, on occasion, these forces have damaged structural steel and reinforced concrete structures. Considerable damage also is caused by the resultant floating debris, including boats and cars which become dangerous projectiles crashing into buildings, piers, or other vehicles. Ships and port facilities have also been damaged by surge action, even in rather weak tsunami. Fires resulting from oil spills or combustion on affected ships in port, or from damaged coastal oil storage and refinery facilities, can cause damage greater than that inflicted directly by the tsunami. Other secondary damage from sewage and chemical pollution following destruction, or damage of intake, discharge, and storage facilities also can present dangerous problems. Of increasing concern is the potential effect of tsunami drawdown when receding waters uncover cooling water intakes associated with nuclear power plants.

The continental United States has not been seriously affected by a tsunami since 1964; and, during this 17-year hiatus, interest in tsunami research conducted in the United States has decreased sharply. This declining interest was confirmed at a 1979 workshop sponsored by the National Science Foundation (NSF) to review the state of tsunami research. The workshop report states that tsunami research has not provided satisfactory estimates of tsunami impacts for effective input to warnings, risk analysis, or engineering design.

Present techniques of tsunami prediction are severely limited. The only way to determine, with certainty, if an earthquake is accompanied by a tsunami, is to note the occurrence and epicenter of the earthquake and then detect the arrival of the tsunami at a network of tide stations. While it *is* possible to predict when tsunami will arrive at coastal locations, it *is not* yet possible to predict the wave height, number of waves, duration of the hazard, or the forces to be expected from such waves at specific locations. A tsunami warning without order-of-magnitude estimates is analagous to an earthquake warning without a magnitude estimate. Lacking quantitative estimates of force, appropriate mitigation measures cannot reasonably be taken to protect persons or property. The present warning system reflects this critical problem; it is a reactive system and will remain so until research is directed toward creating a forecasting system.

The NSF assumed responsibility for assessing the requirements for tsunami research because of its leadership role in earthquake hazard mitigation research. At the tsunami workshop held in Southern California in May 1979, a group of about seventy tsunami scientists and engineers reported on the present status of tsunami research and elected an ad-hoc advisory committee to determine the direction of future research activities. The advisory committee met in Honolulu in October 1979 and recommended that an assessment and planning guide be developed with the assistance of agencies supporting tsunami research. To address this recommendation, the National Oceanic and Atmospheric Administration (NOAA) and the NSF co-sponsored a planning workshop held near Seattle, Washington, in August 1980. This document contains the resulting recommendations for a coherent plan of tsunami research, developed by the scientists and government representatives at the Seattle workshop. To further clarify and enhance the body of the plan, the editors have added and expanded materials that explore the nature of tsunami and their potential destructive impacts, examine Federal agency involvement, and explain priority actions to correct deficiencies in current research efforts. This document is intended to provide the framework for a coordinated interagency effort by offering program options and guidance for agencies concerned with mitigation of tsunami hazards through research.

The final draft was reviewed by Tsunami Research Planning Workshop participants listed on page 48. However, the responsibility for the format and presentation of the plan rests with the editors.

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I. INTRODUCTION

Nature of Tsunami

Large oceanic waves generated by impulsive disturbances of geophysical origin are known as tsunami.* The most common tsunami are those due to earthquakes and caused by displacements of large portions of the sea bottom over the continental shelves and slopes, creating corresponding water displacements. These dislocations may consist of several meters of vertical uplift over areas of tens of thousands of square kilometers. Such sea bottom displacements are a manifestation of the global tectonic processes responsible for earthquakes.(1) Tsunami also may be generated by other mechanisms. Instances can be cited from historical records of tsunami generation by volcanic eruptions, landslides, rockfalls, and submarine slumps.

The waves that are generated by these impulsive geophysical events form in groups having great lengths from crest to crest and long periods. A tsunami radiates outward from its source and crosses the ocean at speeds of hundreds of kilometers per hour. In deep oceans, a tsunami has the appearance of a sequence of gentle buldges with a very small change in sea level. Mid-ocean wave heights from even a large tsunami may be only a meter or less.(2) Nevertheless, the wave energy is enormous. As the tsunami waves propagate into shallow water, they grow in height and steepen. By the time the tsunami reach shore, the series of waves have been amplified sometimes leading to widespread flooding and destruction. The area of destructive impact may be confined to the shoreline near the earthquake source (local tsunami effects); or, may include distant shores, as tsunami frequently travel across the entire ocean and create considerable damage when they arrive at distant shores (teleseismic tsunami effects). For example, the tsunami associated with the earthquake near Valparaiso, Chile, in 1960, traveled 17,800 kilometers across the Pacific Ocean to Japan where these waves killed 200 people and damaged over 12,000 boats and structures.(3) Tsunami can disrupt the ecological balance along the shore and in coastal waters, as well as destroy lives and property. To the extent that a local economy depends on port facilities or the plants and animals that are destroyed, further hardship can be created for an area's commercial base or recreational appeal.(4)

*The terms "seismic sea wave" or "tidal wave" also are used, but the latter, in a strict technical sense, is associated with the tide-producing forces of the moon and sun, and identified with the rising and falling of the tide.

Tsunami of April 1, 1946, Hilo, Hawaii.

Impact on the United States

Though firm estimates are not available of the number of potentially endangered persons in each country bordering the Pacific, many thousands of kilometers of coastlines are exposed to tsunami in the United States, Canada, Mexico, Central and South America, Japan, the Kamchatka Peninsula, the Philippines, and scattered Pacific islands. The map of epicenters of tsunami-generating earthquakes occurring from 1876 to 1976 suggests the extent of vulnerability (Figure 1). Notice that coastlines of the Atlantic Ocean, Mediterranean Sea, Black Sea, and Caspian Sea are also subject to tsunami dangers. In the year 1755, for example, the tsunami associated with the great earthquake that destroyed much of Lisbon, Portugal, crossed the Atlantic to impact the Carribean Islands. However, since the probability of tsunami affecting Atlantic coastlines is very low, this assessment is concerned with tsunami in the Pacific Basin.

Tsunami originating in, or reaching the shores of, the United States have occurred periodically throughout recorded history. Hawaii, Alaska, California, and Washington all have had their share of local and teleseismic tsunami. Data on historical tsunami are subject to considerable uncertainty, depending frequently on isolated eye-witness accounts, often of dubious accuracy. Hawaii has a long history of damaging tsunami due to its high exposure and vulnerability to tsunami from South America, the Aleutian Islands, the Kamchatka Peninsula, Japan, the Philippines, the Hebrides, and the Tonga Kermadec arcs. From 1813 to 1980, 87 tsunami were observed in the Hawaiian Islands with 16 of them resulting in significant damage. Most damage to these islands came from tsunami generated a great distance from Hawaii. In the last

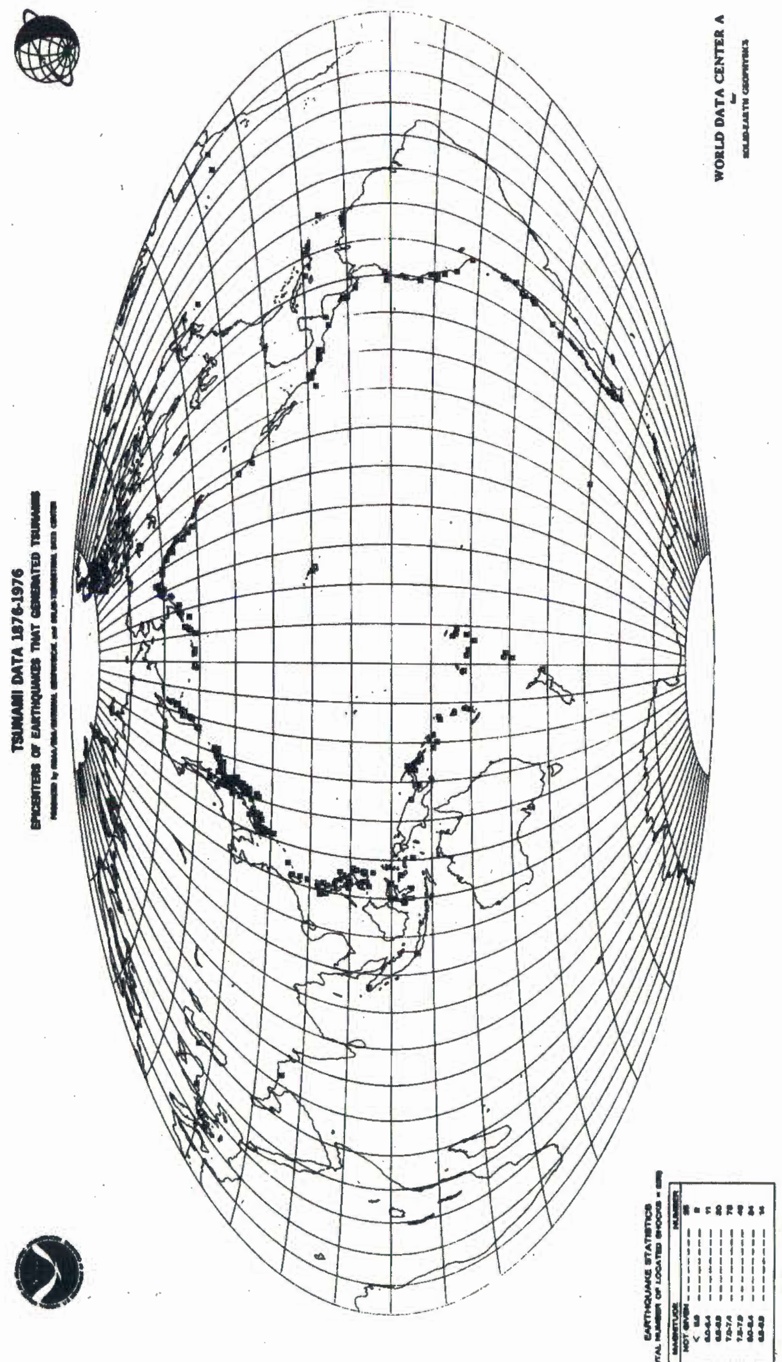


Figure 1 Tsunami Data (1876-1976)

100 years, six local tsunami were generated in the Hawaiian chain; two of these were extremely destructive.(5)

In contrast to Hawaiian tsunami, the majority of the damaging tsunami in Alaska and the Aleutian Islands have been locally generated. The record of Alaskan tsunami is particularly fragmentary due to the undeveloped and uninhabited nature of a large portion of Alaska in the early years. From 1788 to 1980, there were 53 tsunami reported, of which 30 were locally generated. Only one was extremely destructive — the tsunami from the 1964 great Alaskan Earthquake.(6) The records also indicate that a number of local tsunami in the past had extremely large wave run-ups, but their destructiveness was mitigated by lack of inhabitants and settlements at the time of occurrence.

California, Washington, and Oregon also have been subjected to numerous small tsunami originating from Japan, South America, Alaska, the Kamchatka Peninsula, and the Kuril Islands. From 1840 to 1980, there were 45 tsunami observed in California, with concurrent observations, in some cases, in Washington and Oregon.(3) Of these, 32 were of teleseismic origin. The most severe tsunami observed was the 1964 tsunami from the Great Alaskan Earthquake. Except for Crescent City, California, few of the affected areas suffered severe damage.(7) The main effects of small tsunami were largely confined to damage to ships and harbor facilities due to seiche*-induced oscillations in harbors.

In summary, the average number of tsunami observed per century is 52 for the Hawaiian Islands, 28 for Alaska and the Aleutians, and 34 for California. A number of Alaskan and Aleutian tsunami probably have gone unrecorded.

Table I shows the estimates of fatalities and damages due to major tsunami in the United States since 1946. The damages are quoted in 1980 dollars. For the less severe tsunami, damages ranging from a few thousand to a few million dollars have been reported.

Congressional Reaction to Tsunami Disaster

As with other natural disasters, Congress has reacted to mitigate the impact of tsunami on the United States. Through the years, references to tsunami have been included as part of several Congressional reviews of disaster potential.

Prior to 1900, Congressional intent was expressed in laws concerned generally with environmental disturbances. In 1890, the Weather Bureau Act (15 U.S.C. 313) established an effort to meet the warning requirements of those events pertinent to the interests of agriculture and commerce. While the major thrust of the Act was aimed at meteorological conditions, the National Weather Service (essentially created by the 1890 Act) eventually acquired

*Rapid harbor drainage.

Table I

Major Tsunami Impacting U.S. Since 1946

Date	Places of Major Impact	Source Location	Tsunami Fatalities	Tsunami Damage* 1980 $ ($ Millions)
1946	Hawaiian Islands	E. Aleutian Islands	173(3)	119.2(3)
1952	Hawaiian Islands	Kamchatka	0(3)	2.1(3)
1957	Hawaiian Islands	Aleutian Islands	0(3)	10.5(3)
1960	Hawaiian Islands	S. Chile	61(3)	66.9(3)
1964	Alaska N. California Hawaiian Islands	Prince William Sound, Alaska	119(3)	282.3(3)
1975	Hawaiian	Hawaiian	2(5)	4.2(5)
		TOTAL	355	485.2

*Adjustment of damage to 1980 dollars using the CPI, aided by:
Information Please Almanac
Atlas and Year Book, 1979
33rd Edition
Viking Press, N.Y.

responsibility for flooding and tsunami warnings (Tsunami Warning System)*. As technology and understanding improved, the HUD Acts of 1968/1969, and the Flood Disaster Protection Act of 1973 (for example) were passed. These Acts were synthesized into the National Flood Insurance Program, (42 U.S.C. 4001-128) designed to mitigate the effects of flooding (whether caused by tsunami or meterological conditions) by spreading financial risk. Inclusive in this effort and in the Act of 1890 was an implied call to scientists to provide the needed research to define high-risk areas and efforts appropriate to avoid losses. In 1974, with the passage of the Disaster Relief Act (42 U.S.S. 5121-202), the Congress expressed concern that events such as tsunami involve more than financial recovery, and directed that research to improve tsunami prediction and understand the behavior of structures under stress also was required for addressing the disaster potential.

The Coastal Zone Management Act of 1976 (16 U.S.C. 1451 et seg.) specifies "a national interest in the effective management, beneficial use, protection, and development of the coastal zone . . ." (16 U.S.C. 1451). As part of this program calling for ecological management of the uses of the coastal zone came a definitive requirement for "research and technical assistance" for coastal zone management. In the following year, the Earthquake Hazards Reduction Act (41 U.S.C. 7701-6) designated as one of the major threats: "earthquakes and their related seismic events." [Tsunami, caused by earthquake energy transferred into the ocean as waves, were recognized as an appropriate subject for research to increase existing knowledge and to create methods to forestall the effects of the disaster (42 U.S.C. 7704).]

*Development of the Tsunami Warning System

The Tsunami Warning System (TWS) was created in 1948 with tacit rather than official Congressional sanction as the Seismic Sea Wave Warning System (SSWWS) under the auspices of the U.S. Coast and Geodetic Survey (later to become part of the National Oceanic and Atmospheric Administration, U.S. Department of Commerce). Until 1965, SSWWS was maintained by the USC&GS as an internal operation based at its magnetics and seismological observatory in Honolulu, Hawaii. Due to Congressional action following the 1964 Alaska earthquake and tsunami, the SSWWS received its first major funding assistance (FY-1965 of $660,000). From 1965 until 1980, the SSWWS has undergone two reorganizations and one name change. In 1965, it became part of the Environmental Science Services Administration; in 1970, it followed ESSA into NOAA. During these changes, its name changed to the Tsunami Warning System and it became part of NOAA's National Weather Service. Over the years, the TWS developed two centers: the Pacific Tsunami Warning Center (in Hawaii), and the Alaska Tsunami Warning Center, covering their respective regions. The Hawaii warning center has the responsibility of issuing international warnings to the 21 participating countries that request warning services.

This research plan focuses on the two research goals of forecasting tsunami dangers and evaluating coastal hazards as a means to reduce tsunami impacts on our society. Implicit in mitigating the effects of tsunami is the increase in science and engineering knowledge of this natural hazard.

II. TSUNAMI THREAT

Destructive Force: The Alaskan Tsunami of 1964

In 1964, an earthquake in Alaska of 8.5 on the Richter scale brought into sharp focus the destructive forces of tsunami. After the earthquake, a devastating sequence of tsunami occurred, and it was determined that 95 percent of the deaths were caused by the tsunami.(4) This series of waves struck the United States in Alaska, Oregon, Hawaii, California, and Washington, carrying death and destruction thousands of miles from the original site of the earthquake.

The tsunami waves experienced from the 1964 event created two separate threats to human life and property, one locally and the other many hundreds of kilometers away. The first tsunami were experienced locally at the northeast shoreline of the Gulf of Alaska. These waves caused approximately $10,000 per capita damage in the hardest hit coastal towns, or three times the average suffered by the effects of the earthquake alone.(8) Further, the waves were felt shortly after the earthquake itself, allowing little time for evacuation. The people living in the relatively flat areas between the sea and Alaska's mountains fell victim not only to the waves themselves, but to the debris carried along.

The second tsunami threat resulted from the propagation of these waves over a long distance. In Crescent City, California, 2800 kilometers from the earthquake epicenter, the warning was given to the citizens only hours before the expected arrival of the tsunami waves. The citizens of this city responded only partially, for few had ever seen a tsunami or could believe the destructive possibilities. The first two waves, each about 2 meters high, caused minor flooding and some people returned to town to clean up.(9) Then waves three and four, the true destroyers in this event, arrived. The results told a tragic story of 11 dead, 35 injured, 30 blocks of the city destroyed, and overall damage amounting to millions of dollars. These latter waves, each approaching seven meters, caused death and destruction primarily by turning floating objects and debris — logs, cars, boats, and building materials — into projectiles with tremendous force. In one instance, a wave lifted a gasoline tank truck and propelled it into a building, causing a fire which spread to a nearby fuel storage tank farm. The resutling fire continued to spread and burn uncontrollably for three days.(9) Hence, a modern city with good transportation and communication networks was severely crippled by a sequence of waves originating hundreds of kilometers from its impact.

Forecasting Ability: Progress Since the 1960's

In 1964, the people of Crescent City were informed that a tsunami would strike at a certain time, but no information was provided on potential wave height, force, or potential extent of danger. Today, in 1981, the Tsunami Warning System can provide no better forecast information to Crescent City than it

could in 1964. While the speed of disseminating the warning message has increased, the warning still does not specify either height or limits of inundation.(10)

The limited warning message was a factor in the Crescent City disaster where 11 persons lost their lives.(11) Another major factor was Crescent City's past experiences with Tsunami warnings where waves arrived that were hardly distinguishable from local harbor waves. This, coupled with the limited information given by the tsunami warning service, caused many to return to town, or not to evacuate, prior to the arrival of the largest waves.(11)

Since the 1960's, the west coast of the United States, Alaska, and Hawaii have experienced a rapid growth in both population and facilities. Overall, the coastal counties of these areas have seen a 50 percent increase in population and a 28 percent increase in housing units built.(12) Although inflation has increased the price of consumer products approximately 200 percent during this period, the real property values have increased over 350 percent.(13) In total, approximately 17 million permanent residents live in the Pacific coastal counties of the United States. (12) Numerous people are attracted to these shorelines for recreational and other purposes. The threat of tsunami disaster extends into these shoreside areas, exposing these people to tsunami dangers. As in Crescent City in 1964, it is reasonable to expect that a significant proportion of the population will not have experienced a tsunami. This implies that the tsunami threat to the United States is much greater now than in 1964.

The ability to forecast wave height and duration of tsunami hazard would permit local authorities to assess the potential tsunami dangers. The determination of coastal hazard zones would ensure an orderly evacuation and provide more effective property protection. These two improvements can be expected to mitigate the loss of life and property.

III. FEDERAL/STATE AGENCY PARTICIPATION

Current Programs

Most tsunami-related research and warning activities in the United States are funded by the Federal Government and the State of Hawaii.* Table II illustrates the Fiscal Year 1980 expenditures by the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), the Army Corps of Engineers (COE), the State of Hawaii (HI), the Nuclear Regulatory Commission (NRC), the United States Geological Survey (USGS), and the Federal Emergency Management Agency (FEMA). The categories of funding include basic and applied research; operations, including maintenance of a Tsunami Warning System and archiving of historical earthquake and tsunami data; and emergency management. As shown in Table II, Federal and state research support exceeded the cost of operating the Tsunami Warning System in Fiscal Year 1980. Table II does *not* include state and county support for civil defense activities associated with tsunami warnings. Emergency management was about 13 percent of other categories. The total United States effort (excluding state and county warning activities) was approximately $2,500,000.

No Federal agency has clear responsibility for conducting or supporting seismological research related to tsunami and, therefore, there is no organized research program. The gap apparently was created when the responsibility for earthquake research was transferred from NOAA to USGS in 1973. This omission was pointed out to the Office of Science and Technology Policy in a letter from the Chairman of the National Academy of Sciences Committee on Seismology, dated March 14, 1980.

National Oceanic and Atmospheric Administration

The National Oceanic and Atmospheric Administration (NOAA), the largest supporter of the United States tsunami effort, operates the national and international Tsunami Warning System, conducts tsunami research, and manages the tsunami data base. Total Fiscal Year 1980 expenditures by NOAA were approximately $1,300,000 for these activities.

*All data on agencies noted were obtained by the editors in recent correspondence with the program managers of the respective agencies.

Table II

Tsunami Related Expenditures by Federal/State Agency*
FY 1980 ($000)

		Research	Operations		Emergency Management
			Warning	Data Archiving	
NOAA	(1285)	345	900	30	10
NSF	(475)	475			
COE	(230)	230			
State of Hawaii	(150)	150			
NRC	(75)	75			
USGS	(135)	35	100		
FEMA	(130)				130
TOTALS	(2480)	1310	1000	30	140

*Includes administrative and operational costs.

NOAA and predecessor organizations have operated the Tsunami Warning System in the Pacific since 1948, and have warned the public of every teleseismic tsunami. Through the dedicated efforts of the International Tsunami Information Center (ITIC), the system has strengthened relations among nations of the Pacific. The combined labors of 21 nations are a fine example of international cooperation to reduce the tsunami hazard in the Pacific. Regional Tsunami Warning Systems are operated by NOAA in Alaska and Hawaii to provide rapid warnings for locally generated tsunami.

NOAA conducts basic research in the fluid dynamics of tsunami to improve the Tsunami Warning System and the identification of coastal hazards for zoning purposes. A federal research group, working closely with scientists from the University of Hawaii since 1968, has contributed to the scientific understanding of tsunami in these areas:

- Examination of nonlinear effects in the run-up regime.
- Development of self-contained ocean bottom pressure gages capable of measuring tsunami. These instruments have been used in two US/USSR experiments. Though major tsunami did not occur during the experiments, processing the data yielded important information on background noise in the tsunami frequency band.

- Development of instruments to relay seismic and tide gage data via satellite in real time.
- Use of numerical techniques to simulate generation and propagation of tsunami and their effects on harbors and islands.
- Development of a tsunami travel-time computer program for use in the Pacific Tsunami Warning Center.

NOAA also supports the investigators through grants from the Environmental Research Laboratories (ERL) and Sea Grant.* In Fiscal Year 1980, the University of Hawaii was awarded $35,000 from Sea Grant and Harvard University was granted $20,000 from ERL.

Through the World Data Center System (WDCS), NOAA manages a tsunami data base to provide researchers with the following services:

- A continually growing file of tide records containing national and international tsunami data.
- Computer programs to extract seismic and tsunami wave data information on events from 1845 to 1975, from over 900 tide records.
- A bathymetric file of some 11,000,000 coastal depth soundings for use in tsunami modeling.

National Science Foundation

The National Science Foundation (NSF) is the largest supporter of long-term, tsunami-related research. During the past ten years, research has been supported through the earthquake hazard mitigation, fluid mechanics, and oceanography programs. As a component of the earthquake hazards mitigation program, NSF has granted funds in the following areas:

- Numerical modeling of tsunami generation and propagation.
- Laboratory and analytical studies on tsunami generation and propagation.
- Harbor response and resonance studies.
- Tide gage data analysis.
- Social and public policy research.

For the past two years, NSF has had an annual expenditure of about $475,000 for tsunami-related research projects conducted primarily at academic institutions. For example, in Fiscal Year 1980, the following institutions were awarded grants: Scripps, $115,000; University of Hawaii, $77,000; North Carolina State University, $71,000; State University of New York, $60,000; and Harvard University, $50,000. Private organizations receiving funds were Urban Regional Research, $93,000; and Tetra Tech Inc., $10,000. Various associated research topics relevant to the tsunami phenomenon, such as studies of oceanic waves, seismology, and ocean engineering also have been supported by NSF.

*ERL Headquarters: Boulder, Colorado
Sea Grant Headquarters: Rockville, Maryland

Corps of Engineers

The tsunami program of the Corps of Engineers involves basic and applied research, flood level predictions performed for the Federal Emergency Management Agency (FEMA), and engineering design and coastal planning for District and Division Offices of the Corps of Engineers. The Waterways Experiment Station (WES) of the Corps has performed 13 tsunami studies since 1974. These include tsunami hazard predictions for FEMA for the entire west coast of the continental United States and the Hawaiian Islands; the development of models of tsunami interactions with Barbers Point Harbor, Hawaii; tsunami predictions for American Samoa; and basic and applied research studies and contract studies. The Coastal Engineering Research Center (CERC) of the Corps has written a tsunami engineering manual and has contracted for tsunami investigations with consulting firms and universities. Fiscal Year 1980 funding totaled $180,000 for WES, and $50,000 for CERC.

State of Hawaii

The State of Hawaii funds tsunami research through its contribution to the Joint Institute for Marine and Atmospheric Research (JIMAR), jointly funded by NOAA and the State of Hawaii. The University of Hawaii employs four scientists who are partially involved in tsunami research. These scientists developed instrumentation for measuring tsunami in the open ocean, examine tsunami run-up problems, and compile historical data for use in tsunami research. In Fiscal Year 1980, $150,000 was spent by the State of Hawaii for salaries and administrative costs on tsunami-related research.

Nuclear Regulatory Commission

The Nuclear Regulatory Commission (NRC) has the responsibility for siting nuclear facilities and is required to evaluate the effects of natural phenomena on the safety of these structures. In particular, NRC is concerned with determining the effects of tsunami run-up (flooding and dynamic water loads) and run-down (for coolant water intake structures). NRC has funded research to determine tsunami behavior for Pacific sites using ocean-wide numerical models that predict hypothetical maximum tsunami, and to determine the feasibility of modeling local tsunami effects. In Fiscal Year 1980, NRC spent $75,000 on tsunami research grants, investigating the simulation of the 1975 Hawaiian tsunami and compiling a tsunami bibliography.

United States Geological Survey

The United States Geological Survey (USGS) currently operates global seismic networks consisting of analog and digital recording stations. Certain of these stations, located in the coterminous United States and Alaska, and additional stations in Norway, transmit data in real time to the National

Earthquake Information Service (NEIS) which locates earthquakes rapidly, and notifies the Tsunami Warning System (TWS) as required. Most seismic stations that are operated by, or report to the USGS, are not well-suited for real-time study of entire records from tsunamigenic earthquakes because the sensors are overdriven, the instruments have limited bandwidths, or the data are recorded on-site in analog form. A substantial number of the Worldwide Standard Seismograph Network stations will be converted to low-gain, broad-band stations in 1981 and 1982. For these stations, a magnitude 8 earthquake will be on-scale at distances greater than 2000 kilometers, and periods less than 300 seconds will be recorded. The stations in the United States will transmit short period seismic data in real time to the NEIS, and automatic detection and location of earthquakes is planned. Techniques are being developed to extract information other than arrival times from digitally recorded data, so that some earthquake source properties can be automatically estimated. Such data are fundamental for identifying tsunamigenic earthquakes. The USGS funded a $35,000 research effort in Fiscal Year 1980 to differentiate between tsunamigenic and non-tsunamigenic earthquakes.

Federal Emergency Management Agency

The Federal Emergency Management Agency (FEMA) is responsible for managing the emergency preparedness activities for natural disasters. It assists states in planning procedures for tsunami events. FEMA (through the Federal Insurance Administration) has funded research to predict frequency of occurrence for tsunami since 1972. Maps of tsunami flooding elevations and 100-year, 500-year inundation limits for the islands of Hawaii are being produced. In Fiscal Year 1980, $130,000 was spent on the evaluation of existing state operating procedures for tsunami events.

Distribution of Research Activities

Table III shows a distribution of tsunami research resources by topic for Fiscal Year 1980. It illustrates the relative emphasis by each agency in the various areas of tsunami research and development. Each category is fully defined in Section V beginning on page 24. The greatest emphasis is on *terminal effects*, which account for almost 40 percent of all research dollars. Next, the three areas of *tsunami propagation, generation*, and *social impact/risk analysis* constitute about 15 percent each. *Instrumentation* is represented by about 10 percent of the expenditures, while research on *tsunamigenic earthquake* and *warning systems* account for the other 5 percent of resources.

With respect to the two goals of forecasting tsunami dangers and evaluating coastal tsunami hazards, about 95 percent of the present research dollars are being spent on the latter. NOAA has the responsibility for providing forecasting services through the Tsunami Warning System, and the USGS supports tsunamigenic earthquake research directed toward expanding the knowledge base and identifying tsunami hazards. Though derivatives from

Table III

Fiscal Year 1980 Distrubution of Research Resources ($000)

	NOAA	NSF	COE	HI	NRC	USGS	Total $	%
Tsunamigenic Earthquakes	20	0	0	0	0	35	55	4
Tsunami Generation	75	30	0	0	75	0	180	14
Tsunami Propagation	125	55	0	50	0	0	230	18
Terminal Effects	50	215	230	0	0	0	495	36
Instrumentation/Observations	25	0	0	100	0	0	125	10
Tsunami Warning	50	0	0	0	0	0	50	4
Social Response/Risk Analysis	0	175	0	0	0	0	175	14
Total	$345	475	230	150	75	35	1310	
Percentages (of Total)	26	36	18	11	6	3		100

such research should be applicable to the forecast mode, studies are rarely conducted in a manner that makes the transfer of results feasible. This problem arises, in part, because the products of research grants generally are publications, not technology transfer. Thus, the burden for transfer activities rests with the recipient; e.g., the warning centers need to be staffed with people that have both the interest and ability to effect such transfers.

In summary, the independent involvement of seven agencies in an area of research as limited as tsunami contributes to a lack of focus and a duplication of effort. Though the nature of Federal agency involvement and the dual science disciplines of tsunami research (oceanography and seismology) probably prohibit the consolidation of resources in one agency, improved interagency coordination should be encouraged and supported. A single agency could be given lead responsibility for coordinating and monitoring multi-agency participation for the entire tsunami program.

IV. A COMPREHENSIVE TSUNAMI RESEARCH PLAN

To achieve the goals of *forecasting tsunami dangers* and of *evaluating coastal tsunami hazards* in order to reduce loss of life and destruction of property from future tsunami, these goals must be carefully defined, the present state of knowledge must be evaluated, and appropriate objectives must be formulated and steps taken to achieve them.

Forecasting tsunami dangers for selected coastal locations means the prediction of the following within one hour of tsunami generation:

1. time of tsunami arrival
2. maximum wave heights
3. duration of hazard
4. maximum currents in harbors

For tsunami that impact United States coastlines in less than one hour after generation, special mitigation measures should be taken based on the identification of the hazard zone.

Such predictions provide a basis for evacuating people, moving boats and ships, outlining fire fighting and police procedures, and allowing people to return to evacuated areas when the hazard is over.

Evaluating coastal tsunami hazards means:

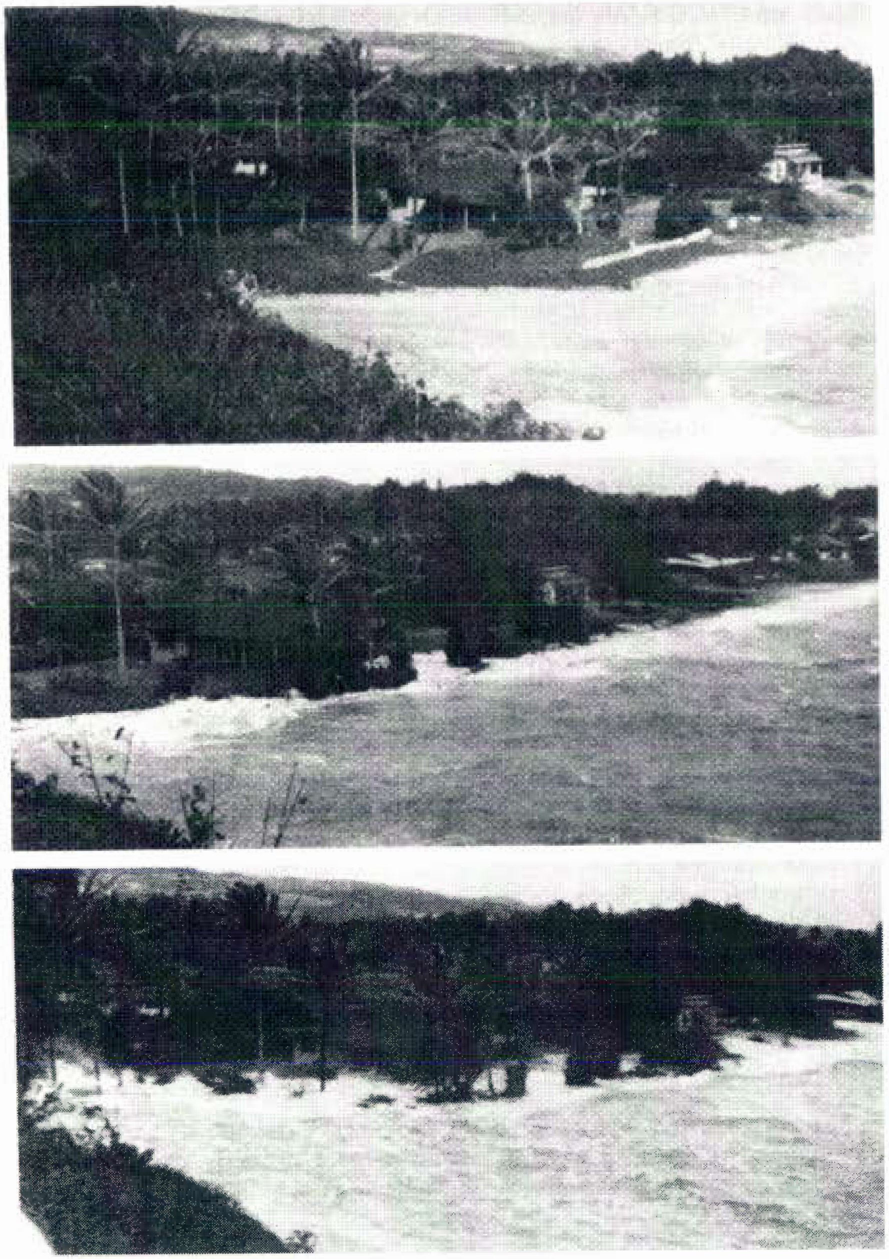
1. determining the probability of occurrence within the limits of available historical data.
2. delineating the maximum limits of inundation for zoning and evacuation purposes.
3. determining maximum forces exerted on stationary and moveable objects within inundation zones for land use regulation and structural standards.

Such information provides land use guidelines and engineering design criteria for potentially threatened areas, and establishes a basis for reducing life and property loss from tsunami.

The use of forecasted data, coupled with hazard zone determination, enables communities to react to save lives and protect property with minimal disruption to essential services. The Tsunami Research Plan is directed toward this effort.

Evaluating Knowledge of Tsunami

In Section V of this document, the status of current tsunami research is described in seven areas that range from geophysical understanding of the



Tsunami of March 9, 1957, Oahu, Hawaii. Sequence of photos shows arrival of major wave at Laie Point.
(Credit: Henry Helbush.)

phenomenon to emergency use of this information. These divisions are necessary to illustrate the interdependency between science and engineering and policymaking. Table IV presents a summary assessment of the current status of research in the order that each area of research occurs in Section V.

An evaluation of the state of the art of each research area is given in the second column of Table IV. This evaluation describes the status as either *low* (know almost nothing of value to mitigate tsunami hazards), or *moderate* (know enough to assess what needs to be done next to yield value in mitigating tsunami hazards).

The State-of-the-Art Column is divided into *modeling* (analytical or physical representation of tsunami) and *observations* (measurements of tsunami). As one examines the state of the art, note that moderate modeling with low observations means that measurements are necessary to verify modeling efforts. Only with verification will modeling advance forecasting abilities or hazard zone determinations. Likewise, moderate observations with low modeling illustrates a need for data analysis and interpretation to ensure mitigation of tsunami hazards.

The next column in Table IV lists recommendations to mitigate tsunami hazards for each area of research. These recommendations emerged from the Seattle Tsunami Workshop and are based on thorough review of the state of art and policy concerns. The candidate agencies to conduct or fund the research are listed in the final column. For a full description of the state of the art and rationale for the recommendations, refer to Section V.

Identifying Needs

From the groups of recommendations listed in Table IV and explained in Section V, the workshop participants translated these recommendations into priorities based on relative needs as shown in Table V. With the goal of mitigating tsunami hazards as a guide, two need levels emerged. *High need* means that the effort is essential to mitigate the hazards of tsunami, and *moderate need* means that the effort is significant to reduce tsunami hazards.

Table IV
Status of Tsunami Research

Research Area	State of the Art: Modeling	State of the Art: Observations	Recommendations to Mitigate Tsunami Hazard	Agencies
Tsunamigenic Earthquakes	Low	Moderate	Instrumentation, telemetry and data processing to permit real-time inference of sea floor displacement	USGS/NSF/FEMA
Tsunami generation	Moderate	Low	Field surveys of tsunamigenic earthquakes to determine surface deformations for modeling purposes	USGS/COE/NSF/HI
Tsunami Propagation	Moderate	Low	Measurements of tsunami in oceanic and coastal areas	NOAA/NSF/HI
Terminal Effects	Moderate	Low	Measurements of surge velocity, pressure, and other fields to advance modeling of run-ups, drawdown, bore formation, and forces on structures	NSF/COE
Instrumentation	Moderate		a) Real-time seismic and tsunami measurements b) Coastal tsunami measurements	NOAA/COE/HI
Warning: Teleseismic			Ability to predict tsunamigenesis from seismic data and run-up	NOAA/FEMA
Local			Emergency Preparedness Programs to prepare public	
Social Response/ Risk Analysis	Low	Low	Increase and verify existing data sets in World Centers A and B* and the International Tsunami Information Center for application to risk analysis	NOAA/FEMA NRC/NSF

*A: Boulder, CO
B: Moscow, USSR

FORMULATING PLANS: OPPORTUNITIES

Tsunami Observational Program

In every proposed effort in Table V, the need for measurement of tsunami is specified. At present, no instrument in use is capable of recording any single phase of tsunami activity with both precision and accuracy. The highest need, therefore, is to design and install instruments that will accurately measure tsunami and tsunami forces. The observational program includes the following elements:

a. Tsunami Along the Coastline

1. **Measurements in Shallow Water**
   Install standard tsunami gages with fixed, calibrated frequency band at key locations.
2. **Wave Force Measurements During Tsunami Flooding**
   Create a highly specialized group responsible for designing and activating an observational plan. The Army Corps of Engineers has established a hurricane response team which can deploy instruments to measure flooding forces in potentially affected areas. Perhaps a tsunami group could be a subset of this larger effort. Also, the Earthquake Engineering Research Institute surveys the impacts of major earthquakes throughout the world. The tsunami group could complement the earthquake survey for tsunami events.

b. Tsunami in the Open Ocean

An array of instruments to measure open-ocean tsunami should be deployed continuously until data adequate for model verification have been acquired.

MODELING AND DESIGN RELATED TO TERMINAL EFFECTS

a) Establish Theoretical and Laboratory Program for Fluid/Structure Interactions

A theoretical and laboratory program is needed to analyze and understand the fluid/structure interactions responsible for tsunami damages. Such programs should lead to a classification of the modes and extent of structural damages by structural types and damage mechanisms. Observed damages should be documented and quantified as rapidly as possible following a tsunami, and prior to relief operation work. Follow-up studies should be planned to determine the replacement and repair costs.

b) Determine Structural Design Criteria

Better engineering design criteria for structures exposed to possible

Table V

Tsunami Research Plan Priorities

Need	Proposed Efforts	Priority	Research Area
High	**Tsunami Observation Program** Design and install instruments to measure a) Tsunami along the coastline b) Tsunami in the open ocean	I	All Areas
High	**Modeling and Design Related to Terminal Effects** a) Establish theoretical and laboratory program for fluid/structure interactions b) Determine structural design criteria	II	Terminal Effects
High	**Tsunamigenic Earthquake Identification** Establish a coordinating body of Federal agencies to examine seismic characteristics of tsunamigenic earthquakes	II	Instrumentation/ Tsunamigenic Earthquakes
Moderate	**Tsunami Data Set Creation** Increase and verify existing data sets and utilize in risk analysis	III	Social Response/ Risk Analysis
Moderate	**Emergency Preparedness Program Development** Create public awareness program of potential dangers of tsunami	III	Warning

tsunami inundation can be developed through an observation program to collect data on damages that have occurred in previous tsunami. The theoretical and experimental programs should strive to link investigations of wave/structure interactions to relevant tsunami characteristics in order to provide useful engineering design criteria for tsunami protection.

Tsunamigenic Earthquake Identification

Instrumentation, telemetry, and data processing to permit real-time inference of sea floor displacement is recommended to identify tsunamigenic earthquakes from seismic data. This would be a costly activity that should be conducted in coordination with other seismological research and monitoring activities. Coordination of seismological research to examine the seismic characteristics of tsunamigenic earthquakes may be a cost-effective way to explore an insufficiently understood area of research. A coordinating group should be established to define tsunami seismological research requirements to accomplish the goal of seismically differentiating between tsunamigenic and other earthquakes as they occur.

Tsunami Data Set Creation

Increase and scrutinize the tsunami historical data sets at World Data Centers A in Boulder, CO, and B in Moscow, USSR, and the International Tsunami Information Center. These data can be used in determining the risks from tsunami flooding which, in turn, can be utilized for policy planning.

Tsunami risk analysis should be undertaken as an integral part of studies related to social response, using the criterion of balancing the impact of tsunami with the cost of mitigating impacts. Risk analysis, as performed for other hazards such as flooding, severe storms, and earthquakes, should be utilized for tsunami hazard problems.

Emergency Preparedness Program Development

A major educational plan should be undertaken to prepare the public for future tsunami as historical data exist to identify potentially threatened communities. The program should include the local authorities who establish standard operating procedures, enforcing officials who implement these procedures, and the affected public. A model available for study is the State of Hawaii, County of Hawaii, plan.(14) Because of the dedicated efforts of the Hawaiian county authorities, the public is well educated and responded well to a *locally generated* tsunami in 1975. As a result of this continuing public education effort, only two persons died during an event which would have killed more people. This action has a priority below that of observations and earthquake signal analysis in terms of the research plan, but should have top priority within the emergency preparedness agencies.

V. STATUS OF CURRENT RESEARCH

TSUNAMIGENIC EARTHQUAKES

State of the Art

The most destructive tsunami are caused by large magnitude, shallow-focus submarine earthquakes that induce vertical sea-floor deformations. Not all earthquakes of this type, however, generate tsunami. At present, it is not possible to distinguish tsunamigenic from other earthquakes utilizing seismic data alone. The ability to identify a tsunamigenic earthquake with seismic data would facilitate the forecasting of tsunami dangers because seismic waves propagate about 30 times as rapidly as tsunami. For example, geophysical seismic waves travel 3000 kilometers in about 8 minutes, while tsunami travel the same distance in about 4 hours. This travel time difference gives valuable lead time in providing tsunami forecasting and warning services.

There are several faulting mechanisms with tsunamigenic potential. Clearly, a normal fault on the sea floor will generate a tsunami. However, the largest tsunami appear to be caused by thrust faults in the continental plate at a subduction zone. The accumulating strain is released in the rebound of the continental plate which, along with associated imbricate faulting, produces the sizeable uplift necessary for tsunami generation.(15)

The use of seismic gap theory along subduction boundaries appears to hold promise in predicting potential source areas(16) (Figure 2). This theory holds that if an earthquake has not occurred in 40 years in a seismically active area, then the potential for an earthquake increases. The ability to forecast earthquakes in this mode is accurate to within a decade. Also, examination of long period seismic waves (longer than 100 sec) by Kanamori(17) suggests modification of the existing Richter scale criterion upon which tsunami watches and warnings are issued.

Seismologists believe that the most important earthquake source parameters needed to determine tsunamigenesis are: 1) epicenter location, 2) depth of the source, and 3) magnitude and faulting mechanism.

Epicenter Location

With the current networks used by NOAA and USGS, most large ($M_s > 7$) earthquakes in the world can be located within 30 minutes after their occurrence with a location accuracy of 50 km. This accuracy is useful for identifying the starting point of the tsunami. Location is also important in estimating tsunami potential based on the tectonic setting. For very large events ($M_s > 8$), the rupture directivity is important and greater location accuracy is desired to determine the spatial locations of events following the main shock.

Tsunami of May 22, 1960, Hilo, Hawaii. Originated from Earthquake in Chile.

Depth

The determination of the focal depth (depth at which the earthquake rupture begins) with the current detection system is accurate within about 50 km. Since it is thought that the earthquake's rupture must penetrate the crust's surface to generate a tsunami(18), development of improved techniques to determine focal depth is desirable. The possibility of using various depth phases, bodywave forms, and other earthquake signals should be investigated for this purpose.

Magnitude and Mechanism

The question of the relation of the "size" of the potential earthquake to the observed tsunami has long been a challenge to seismologists. Pioneering studies(19) based on surface wave magnitude have not been totally successful and Kanamori(20) has systematically tried to explain the so-called "tsumani-earthquake," whose tsunami were much greater than expected from the surface wave magnitude (M_s). Careful studies by Kanamori(20) and Abe(21) have suggested that the seismic moment (a rough measure of deformation area) of the earthquake is more representative of the source behavior. This result, also developed theoretically by Ben-Menahem and Rosenman(22), was supported in a recent extensive review of tsunamigenic earthquakes(23),

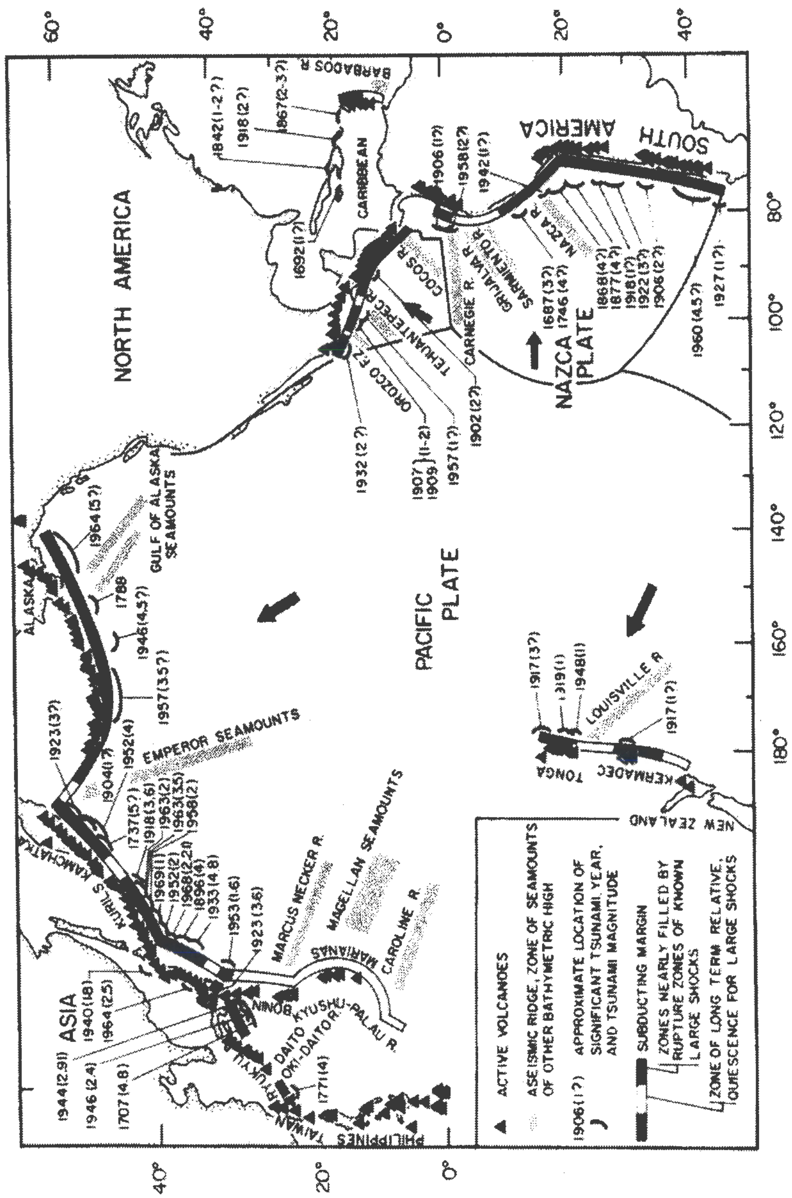


Figure 2 Map of Tsunami Source Area

which showed that a magnitude scale based upon seismic moment could be correlated with tsunami amplitudes. The saturation of Ms around 8.2, and the discrepancy between Ms and seismic moment for gigantic events, have been explained in terms of scaling laws by Geller(24) and Kanamori(25) and are responsible for the unsatisfactory Ms vs. tsunami magnitude results reported by Iida.(19)

Non-Seismic Signals

In addition to seismic information, measurements of atmospheric pressure waves(26), oceanic acoustic waves (T phase)(27) and ionospheric disturbances(28) have been correlated with tsunamigenic earthquakes. These effects are still under investigation.

Need

Until a warning system can distinguish in real time an earthquake which gives rise to a substantial vertical rupture from one which does not, false issuance of tsunami warnings cannot be avoided. Currently, the data produced by the seismic network permit inferences of measures of the magnitude and orientation of the zone of large motions, but not measures of large scale normal displacement of the sea floor. Therefore, improved instrumentation, telemetry, and data processing to permit real-time inference of sea floor displacement should be developed and implemented.

TSUNAMI GENERATION

State of the Art

The study of tsunami in the vicinity of the source during and following a tsunamigenic earthquake is termed the tsunami generation problem. A variety of hydrodynamic theories(29)(30) have been advanced and numerical models(31)(32)(33) developed for simulating this near-field process. These are restricted by the complexity of the three-dimensional character of the ground movement. Progress is considerably hampered by a lack of adequate records of the near-field tsunami signature because high waves often exceed the recording range of local tide gages and may, in fact, damage or destroy them. Contamination of available wave records by local processes not associated with the main tsunami also exists. Furthermore, the signal is dependent on details of the spatial and temporal variations in ground motion as well as effects of the local bathymetry, none of which are presently well known.

Knowledge of the sea floor motion associated with tsunami generation is limited to events such as those that occurred in Alaska (1964) and Chile (1960),

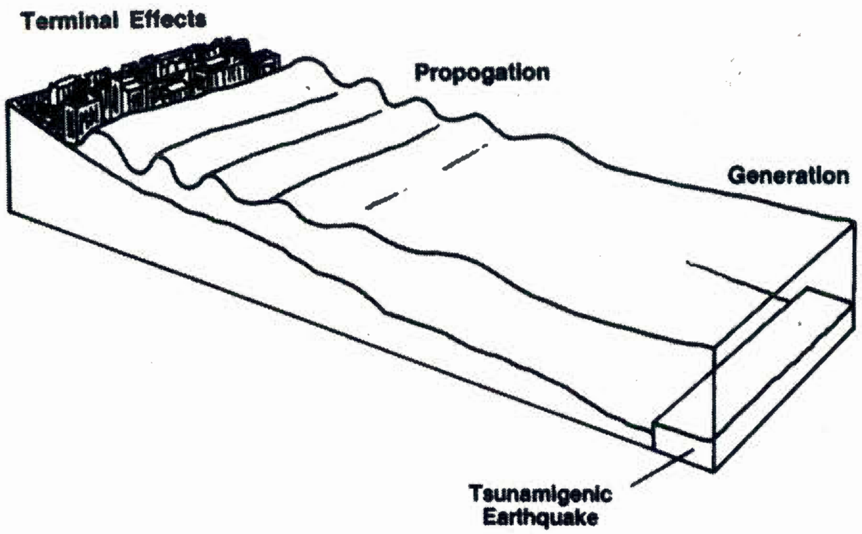


Figure 3 Stages of Tsunami Development

where the source displacements overlapped the shoreline so that the submerged portions could reasonably be reconstructed for modeling purposes. The approximate deep-water signature can be inferred from a large number of wave records from stations distributed uniformly about the source.

At some distance seaward of the source location, a description of the main features of the leading waves has been obtained by using long-wave theory and the assumption that the tsunamigenic ground motions can be represented by an instantaneous initial displacement of the sea bottom with amplitudes prescribed by the permanent sea bottom deformation associated with the earthquake.(34) This method of describing the far-field tsunami generated by an earthquake has been verified indirectly by comparison with a few historical tsunami. A major limitation, however, is the inability to describe the later-occurring tsunami in the far-field, due to the lack of a deep water representation of the generated tsunami that is free from shoreline reflections and topographic influences. Such a measurement would be needed to support any of the variety of theories proposed for predicting the generated tsunami signal.

Laboratory experiments have been conducted in attempts to verify various aspects of the generation theories.(35) In view of the paucity of field data, the continued use of laboratory experiments to investigate individual aspects of the problem in the near field is a valuable investigative tool.

The principal areas of uncertainty may be stated as:

1. The role of nonlinearities and frequency dispersion in the generation areas,
2. Boundary reflectivity at ocean margins,
3. Appropriate source models, and
4. Temporal and spatial predictability of possible sources.

While tectonic displacements are responsible for large transoceanic tsunami, other mechanisms are responsible for a large number of destructive local tsunami. In particular, phenomenon such as waves generated by rockfalls and slides into bays, fjords, lakes, reservoirs and rivers; waves generated by horizontal components of ground-shaking; as well as local uplifts and subsidence due to soil failures (such as submarine and subaerial slumping) have all been observed. Little has been done to quantitatively document these local waves and tsunami and to accurately model their generation mechanisms.

Need

Some modeling efforts have been made to simulate tsunami generation, but little effort has been made toward measuring the tsunami at the generation stage. Understanding generation processes is important to hazard zoning and forecasting tsunami wave heights for locally generated tsunami.

Direct observations of tsunami generation is the most obvious approach for improving understanding of tsunami generation. At this time, however, such a program could not be justified on the basis of the state of the art of earthquake predictions. However, post-tsunami surveys of surface deformations associated with tsunamigenic earthquakes could provide valuable data in hydrodynamic and earthquake modeling. This, in turn, would improve the ability to forecast local tsunami by providing better estimates of the coastal tsunami hazard in earthquake prone areas.

TSUNAMI PROPAGATION

State of the Art

From the moment of oceanic surface displacement, the restoration of equilibrium begins, radiating long-period gravity waves that propagate throughout the ocean basin. As these waves cross the ocean, they are modified by the topography encountered and begin to diffract, refract, and displayed frequency dispersion. The main waves of the highly destructive Chilean (1960) and Alaskan (1964) tsunami can be characterized as being non-dispersive, while the Aleutian tsunami (1946, 1957) displayed frequency dispersion effects over some propagation paths.(36) Because tsunami have small amplitudes in the open ocean, the propagation phase has been modeled

Tsunami of April 1, 1946, Hilo, Hawaii. Major wave entering Ponahawai Street. (Credit: Joint Tsunami Research Effort.)

using both dispersive and nondispersive waves. Tsunami travel times needed for tsunami warning have been determined through the application of these theories.

The propagation phase of tsunami has been the most studied and modeled aspect of the phenomenon, largely because the problem has been made mathematically tractable by the use of shallow water theory.(37)(38) Despite the absence of observational verification, there are claims that the modeling techniques used to describe tsunami propagation can be extended from generation to run-up along the shoreline. Studies involving the use of limited geographical area give rough agreement with tide gage observations.(39) However, there are certain physical constraints present in the modeling assumptions that restrict the limits of application.(40) Questions remain about the validity of results since different modeling techniques (and grid sizes) yield substantially different wave elevations and phases.

Need

The improvement and validation of numerical modeling schemes are essential for evaluating coastal tsunami hazards and for forecasting tsunami dangers. The propagation data are used as input for shoreline models, so errors in the forcing function will accumulate in the shoreline model results. Validation is best assisted by a complete observational program. Observations in the generating area, during propagation (water depths exceeding 1000 m), and during the terminal phase (1000 m to shoreline) will help resolve the present uncertainties. Until accurate measurements are made to compare with modeling efforts, no particular modeling technique can be wholly supported.

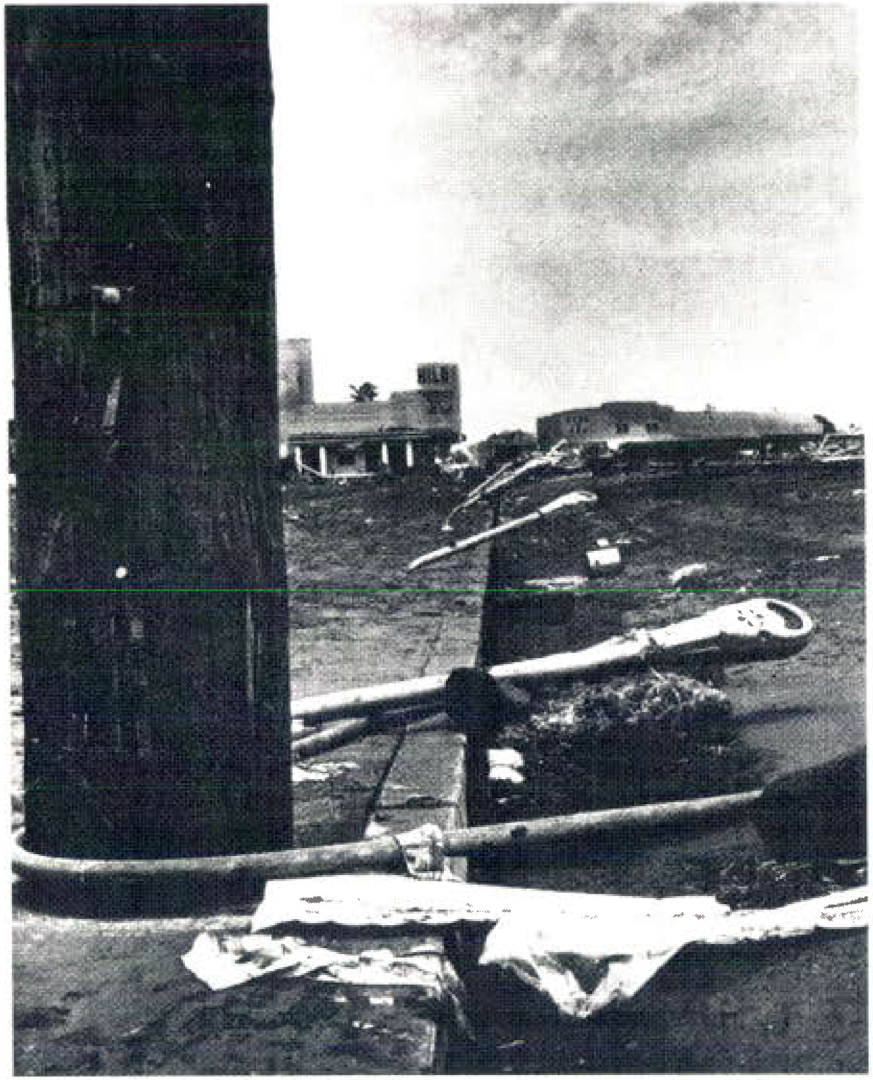
TERMINAL EFFECTS OF TSUNAMI

State of the Art

The arrival of a tsunami at a shoreline may increase the water level as much as 30 meters or greater in extreme cases. Increases of 10 meters (32.8 feet) are not uncommon. The large increase in water level, combined with the surge of the tsunami, can impose powerful forces on shore protection structures, as well as on dwellings and other structures near the shore. Damage or destruction may be caused by: 1) strong currents produced by waves overtopping the structures; 2) the direct force of the surge produced by a wave; 3) the hydrostatic pressure created by flooding behind a structure, combined with the loss of equalizing forces at the front of a structure due to extreme drawdown of the water level when the waves recede; and, 4) erosion at the base of the structure. Major damage also may be caused by debris carried forward by the tsunami in the near-shore area.(41) Tsunami engineers consider investigation in the following areas to be of great significance in advancing knowledge of terminal effects: run-up and drawdown, harbor and bay response, surge on drybed, and forces on structures. Knowledge of wave behavior in the shoreline region is most important in forecasting tsunami dangers and determining coastal hazards.

Run-up and Drawdown

The basic hydrodynamics of run-up and drawdown of long waves over a plane bathymetry has been developed.(42) However, accurate and generally applicable numerical models for the prediction of run-up of long waves have yet to be demonstrated. The work of Hibbard and Peregrin(43) demonstrates recent progress. Less is known about drawdown than run-up. Only limited careful experiments have been conducted to confirm or refute some of the two-dimensional theories which have been developed; a need exists for such data with well-defined incident waves that are not necessarily periodic in form. Longshore irregularities create spatial variations in run-up which are neither well-determined nor well-modeled. With complicated bathymetry, the wave run-up and drawdown are much more difficult to evaluate, and theoretical treatments of this subject are practically nonexistent. Three-dimensional effects are amplified in shallow water to the point where, even in a two-dimensional wave flume, transverse instability develops and gives a run-up which varies along a plane beach. The theoretical difficulties lie in nonlinearity, vertical acceleration, and dissipation processes. Some success has been obtained with models of Crescent City based on nonlinear long-wave



Tsunami of May 22, 1960, Hilo, Hawaii. flattened parking meters show direction and force of Tsunami.

equations; but in the case of Hilo Bay, the best method has been physical modeling.

Harbor or Bay Resonance

For more than 20 years, specific research has been conducted dealing with the

excitation of harbors by incident waves. These studies generally have concentrated on the linear problem, with consideration given to the steady-state response of harbors. These studies, identified as steady-state, linear, and two-dimensional efforts, have lead to an understanding of the basic problem of harbor resonance. A significant accomplishment has been the inclusion of energy radiation from the harbor entrance back into the open sea, in determining the amplification or attenuation of open-ocean waves in harbors or bays.(44) A logical extension of this has been work related to the steady-state, linear, three-dimensional problem. This effort has lead to the development and application of finite element numerical models to investigate the steady-state response of harbors, bays, and islands to continuous trains of waves.(45) During the past five years, attempts have been made to define important energy-dissipating mechanisms in harbors.(45) More recently, nonlinear effects have been investigated to establish their importance in the harbor response problem.(46)

The problem of transient excitation of harbors has been evaluated with linear equations. Current efforts are focusing on nonlinear contributions and the definition of energy-loss mechanisms for harbors.(47)

Bore and Surge on Drybed(48)

The accurate prediction of a bore is important for the calculation of forces on structures. Bore inception is fairly well-predicted by nonlinear long wave theory over a steep slope in the case of plane bathymetry. With a very gentle slope, the theory predicts bore inception too soon due to the neglect of the dispersion effect. Much must be learned about the fine structure of the flow in a bore and about three-dimensional bores. The problem of surge on a drybed requires further investigation to calculate impact forces of tsunami waves on fixed structures. Investigations of wind/wave and surges in conjunction with tsunami are also required.

Forces on Structures(41)

Five types of forces may result from tsunami:

1. *Buoyancy forces*, caused by partial or total submergence in the surging water.
2. *Surge forces*, caused by the leading edge of the surge impinging upon a structure.
3. *Drag forces*, caused by the high velocity of the surging water.
4. *Impact forces*, caused by buildings, boats, or other material carried forward by the surging water.
5. *Hydrostatic forces*, caused by partial or total submergence of structures by the tsunami.

These forces, singly or in combination, cause structures to collapse, float away, or to be damaged by floating debris. Objects as large as locomotives can be moved about by the surging water. Coastal structures are collapsed by changes in hydrostatic pressure which are beyond normal design considerations. Foundations are scoured and eroded, undermining overlying structures. These forces can be calculated as long as surge velocities and pressures are known.

Need

Observations of surge velocity, pressure, and other fields are required to advance modeling of run-up, drawdown, bore formation, and forces on structures. In conjunction with the observational program, a theoretical and laboratory program is needed to understand the complex interactions between waves and shoreline structures. This area of research is critical in establishing coastal zone building codes and engineering structural designs.

INSTRUMENTATION

State of the Art

Since observations are essential to all areas of tsunami investigation, improved instrumentation is crucial for minimizing death and destruction from future tsunami. Oceanographic measurements of tsunami are critical for verifying models of tsunami generation, propagation, run-up, and interaction with structures on the shore. Real-time seismic and oceanographic measurements and efficient telecommunications are keys to forecasting tsunami dangers. The following summary of the state of tsunami instrumentation for seismology, oceanography, telecommunications, and other sicences is presented. Without accurate measurements of tsunami during their lifespans, modeling and assessment efforts remain unvalidated.

Seismology

The field of seismological instrumentation is quite sophisticated, and applications to tsunami are technically feasible and viable. Seismometers have been developed which have very broad frequency responses, digital outputs, and low-power requirements. Thus, a wide range of seismic features can be measured in remote locations, and either stored or transmitted digitally. Such qualities lend themselves perfectly to tsunami purposes where rapid evaluation of seismic parameters is necessary. The USGS has developed instruments that can process raw data and transmit or store important parameters, as needed. Use of this technology has been limited in the area of tsunami warning.(49)

The data produced by the existing seismic network permits inferences of measures of the magnitude and orientation of the zone of large motions, but not measures of large scale normal displacement of the sea floor. Therefore, instrumentation, telemetry, and data processing which would permit real-time inference of sea floor displacement should be developed and implemented to improve our ability to forecast tsunami dangers.

Oceanography

Historically, observational data on tsunami have come from three sources: 1) analogue tide gages operated by NOAA; 2) special long-period wave recorders installed temporarily on small Pacific islands for research purposes by the Department of Defense (DOD)(50); and 3) *ad hoc* post-event damage surveys conducted after major tsunami by specially organized research teams. Warning functions were also performed by key tide stations via radio communication of visual signals.

However, as a result of the relatively long interval (17 years) since the last major tsunami and intervening federal restructuring, *there remains today not a single instrument in operation that is capable of recording any phase of tsunami activity with precision and accuracy.* Tidal measurements are now accomplished by digital sampling for automatic analysis. The sample rate of six minutes renders the records almost useless for post-event analysis of tsunami. The Tsunami Warning System, operated by NOAA, now uses analogue bubbler gages that are equipped with a swell-suppressing throttle valve, thus introducing an unknown filter factor. This filtering, together with the reduction in chart width over previous tide records, renders bubbler gage records similarly ambiguous for most post-event analysis.

Two prototype instruments have been developed recently which may prove useful in obtaining tsunami measurements. An inexpensive prototype portable digital tsunami gage was developed to supplement existing tide gage records.(51) These instruments would be attached to pier pilings when a tsunami is expected and recovered immediately afterwards, giving measurements of the tsunami at more points along the shoreline. The instrument system includes a pressure transducer, an internally digital recording system, and a watertight case. It can measure waves up to 10 meters with 2 percent resolution and can record for eight hours at a 30-second sample rate. A second instrument is a self-contained, internally recording deep-water pressure gage capable of measuring sea level changes of one cm while resting on the ocean floor at 4000 m depth.(52) Five instruments exist which can be left on the ocean bottom to record pressure every minute for two months, after which they are recovered. Newer instruments that record data for a full year are now available. No tsunami has yet been recorded in the open ocean but background noise in the tsunami band has been measured and investigated.(53)

Telecommunications

The rapid transmission of tsunami-related data for evaluation and dissemination is critical for forecasting tsunami dangers. The tsunami warning activity can be characterized as a communication center that collects data, analyzes them, and disseminates appropriate messages. The keys to effective operation are the quality of data and the reliability and speed of the communication system. Major improvements are possible through use of satellite telecommunications. Efforts are underway to install satellite transmitters on tide gages throughout the Pacific for reliable transmission of tide data.(54) Satellite communications can be used for collecting seismic or other data and for disseminating warnings rapidly and reliably.

Other Sciences

Earthquake engineers have used various types of instruments to measure forces and accelerations of buildings responding to earthquakes.(1) These instruments also could be used to measure forces exerted by tsunami waves on structures.

Great earthquakes that generate tsunami are sometimes accompanied by seismic waves which disturb the ionosphere. These disturbances propagate through the lower atmosphere about 20 times faster than the tsunami.(55) Instrumentation to detect ionospheric changes has been developed by the University of Hawaii(28) and is used in a research mode at the Pacific Tsunami Warning Center. The detection and analysis of acoustic waves (T phases) in the ocean generated by earthquakes also are potential indicators of tsunami.(27) Standard seismometers installed close to shorelines can detect T phases.

Need

Open-ocean tsunami measurements and earthquake wave measurements in real time are vital to forecasting tsunami dangers. Open-ocean and coastal tsunami measurements, not necessarily in real time, are needed for model verification and engineering design.

WARNING

State of the Art

The Tsunami Warning System, operated by NOAA, detects major earthquakes in the Pacific region, evaluates the earthquake tsunami potential in terms of epicenter and Richter scale magnitude, determines if a tsunami has been generated, and issues appropriate warnings and information to minimize the hazards of tsunami. The international monitoring system is composed of twenty-two seismic stations and sixty-two tide stations throughout the Pacific Ocean (Figure 4). The international warning system employs teletypewriter and voice communication links to acquire data and disseminate tsunami information to twenty-one nations. Transmission times can take from 10 minutes to 1 hour, depending on the efficiency of communication relay points. Regional warning systems for locally generated tsunami exist for Hawaii (Figure 5) and Alaska (Figure 6). These monitoring systems are real-time radio

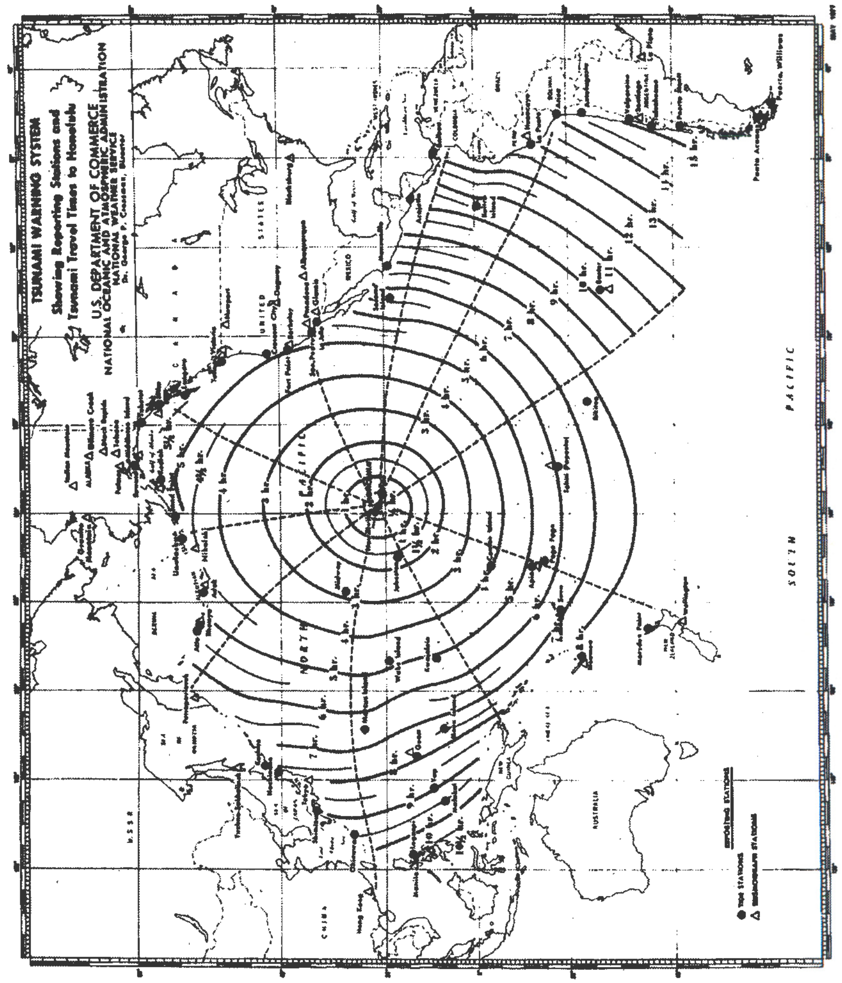


Figure 4 Tsunami Warning System

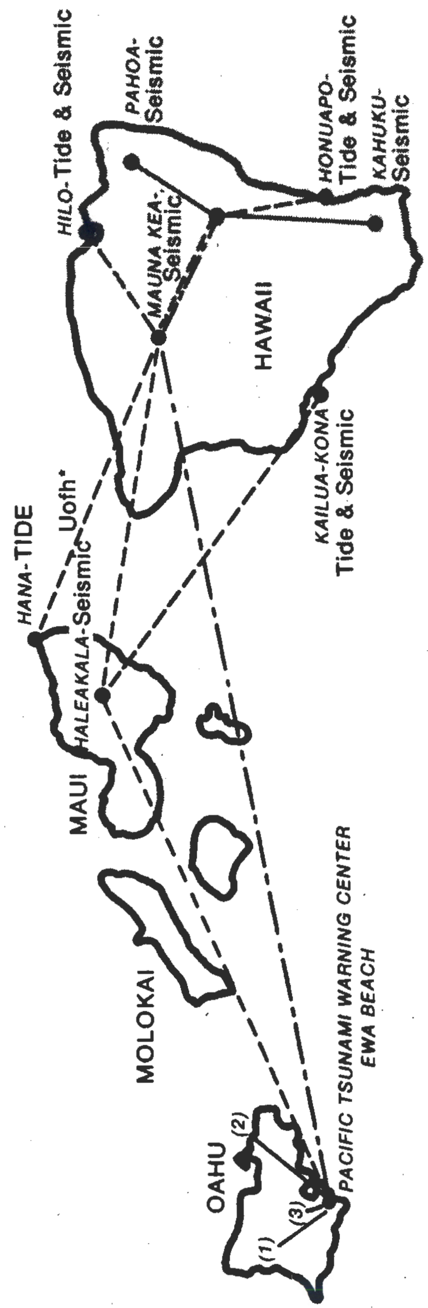


Figure 5 Hawaii Regional Tsunami Warning Network
Showing Telemetry Links and Sensor Sites

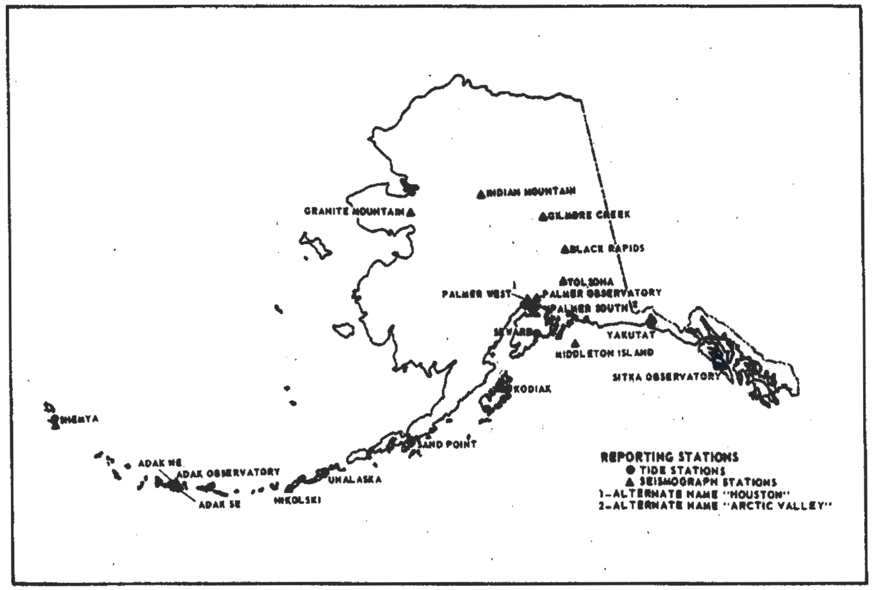


Figure 6 Alaska Regional Tsunami Warning Network

links from seismometers and tide gages to the respective centers.(10) Regional warnings are issued on the basis of earthquake magnitude alone. *There is no regional warning system for the west coast of the United States* (California, Washington, and Oregon).

Dissemination of tsunami information for regional warnings takes place over the National Warning System telephone network so transmission is as rapid as the reaction of warning center personnel to events. Both regional centers are operated by a small staff of geophysicists working on a rotating, standby basis to provide warning services 24 hours a day. This means that geophysicists are not actually in the warning centers 24 hours each day. During off hours they are automatically alerted when earthquake waves trigger alarm systems.

The warnings delivered by these centers include earthquake locations (± 50 km), earthquake Richter scale magnitude (± .3), tsunami arrival time (± 20 min), and reports of tsunami wave heights as recorded by tide gages.(14) The earthquake parameters and tsunami arrival times are usually disseminated to the 54 international warning points within one hour after the occurrence of an earthquake. The time of receipt of tsunami wave reports varies with the travel time of the tsunami from its origin to the tide gages, the dependability of observers, and the communication links. Recent developments in communication and computer technologies hold promise for improving the communication and data analysis portions of the operations. Mini-computers installed in each warning center help in rapid analysis of seismic data and transmission of messages.(10) A prototype tide gage, operational since 1978 and capable of relaying water level data via satellite, reduces wave reporting times.(49)

Although the acquisition of tsunami data can be accelerated, the analytical techniques for forecasting tsunami dangers remain poor. For example, if a tide station reports the wave amplitude at one location, the information cannot be used to accurately forecast the tsunami run-up at other coastal points. The highest priority to enhance the warning effectiveness would be to predict the maximum extent of tsunami run-up and to determine from seismic data, alone, if a tsunami has been generated. Other needs include more accurate travel time determinations and better estimates of the duration of tsunami hazard. This information, in the hands of competent local authorities, would reduce loss of life from teleseismic tsunami.

In the United States, tsunami watch and warning messages are transmitted by the Pacific and Alaska Tsunami Warning Center (now operated by the National Weather Service) to state Civil Defense agencies which forward them to local officials who disseminate the warnings to the population affected. In Hawaii and Alaska, warnings are given to the public directly by radio and television and indirectly through county Civil Defense agencies which utilize siren systems, wardens, and county police for dissemination in coastal communities.(14) For California, Oregon, and Washington, dissemination takes place through state emergency agencies.

A tsunami warning alone cannot save lives and property. At a minimum, local officials must designate the tsunami hazard zone. Citizens must know the evacuation procedures in advance. A very large part of the responsibility rests at the local level. Even a superbly designed and functioning regional detection and warning system cannot ensure against all casualties.

The reduction of public confidence in the system due to "overwarning" has been noted in several investigations.(56) This is more serious where destructive tsunami are rare than where disasters are common. Further, with long intervals between tsunami, the public forgets the significance of warnings and responds incorrectly. Along the coasts of Japan where earthquakes are common and tsunami frequent, response to tsunami warnings is good. Hawaii's experience with tsunami of distant origin indicates effective response to the warning system. Where the occurrence of significant tsunami is much less common, less effective response can be expected.(57)

A further limitation to the utility of warning systems lies in an inability to issue warnings rapidly enough to be of value in the immediate areas of tsunami generation (local tsunami). Every community must supplement a regional detection and warning system with an emergency preparedness program to ensure maximum protection from tsunami hazards. For example, persons in earthquake-prone shore areas should be alerted to seek high ground immediately in the event of earthquake tremors.

Need

To increase the effectiveness of the Tsunami Warning System, the need exists for predicting the maximum extent of tsunami run-up for evacuation purposes and for determining from seismic data alone if a tsunami has been generated. Public education programs should be designed to prepare the inhabitants and visitors of threatened shorelines for appropriate reaction to warning information. The benefits derived from such activities would ultimately reduce the loss of life in future tsunami.

SOCIAL RESPONSE/RISK

State of the Art

Social Response

The public's knowledge or perception of tsunami hazards is an essential factor in the organization and planning of hazard reduction and mitigation measures. Society's perception of the tsunami risk will determine its demand for, or resistence to, tsunami protection, construction, tsunami insurance, land-use and building code regulations; as well as, Federal, state, and local funding of emergency relief planning, and other public policy options.

Tsunami can cause extensive loss of life, property damage, and social disruption. Tsunami affect the public in three distinct ways: (1) *Initial Costs* or those incurred by erecting or strengthening structures and avoiding use of particular sites; (2) *Continuing Costs* such as insurance and the operation of warning systems; (3) *Life Loss and Property Damage Costs* when the event occurs. The challenge is to balance the impacts of tsunami with the costs to reduce these impacts. Strategies that can be used to mitigate these impacts include:

(1) *Abatement* to prevent the hazard or reduce its likelihood; e.g., by limiting development in high hazard areas;
(2) *Regional protection* such as the placement of levees and breakwaters;
(3) *Site Development* such as raising the natural contour of the lands;
(4) *Structural Engineering* design to increase the strength of structures and provide better foundations;
(5) *Warning and associated preparedness planning;*
(6) *Emergency Response* to provide life- and property-saving assistance;
(7) *Relief, Reconstruction, and Relocation* to restore the individual, institutions, and community to their prior states.

Each of these mitigation strategies must be taken as part of a total effort, with the understanding that reliance upon any one may not lead to a net reduction in risk.

A tsunami warning alone cannot save lives and property. At a minimum, local officials must designate the tsunami hazard zone. Citizens must know the evacuation procedures in advance. A very large part of the responsibility rests at the local level. Even a superbly designed and functioning regional detection and warning system cannot ensure against all casualties.

Critical facilities are an especially important consideration in studying tsunami hazards. Such facilities encompass not only nuclear power plants and liquified natural gas storage facilities, but also those facilities for which the potential impacts of failure far exceed the damage to the facility itself, or those which provide vital services for which no substitute exists. The latter category includes petroleum transfer and storage points, naval or other military facilities, some loading docks, dry docks, hospitals, bridges, fresh water supply, and transportation facilities.

It must be emphasized that rather common facilities can be "critical" if a substitute does not exist within the region affected. While the nationally regulated critical facilities will likely receive social and economic scrutiny, other facilities, i.e., warehouses, are unlikely to be discussed, and thus should be a focus for investigation. The NSF has funded a study of land management guidelines for tsunami hazard areas that should lay the framework for applying existing knowledge to these socio-economic problems.(58)

Risk Analysis

For other hazards such as flooding, severe storms and earthquakes, there is a serious attempt at quantitative risk analysis. For the tsunami hazard, risk analysis is not highly developed. In the design and operation of the Tsunami Warning System, there is almost no evaluation of the relationship between risk, effectiveness of operation, and costs. Yet, the tsunami hazard could be quite amenable to risk analysis.

The present data set for tsunami risk analysis consists of measurements of inundation limits, estimates of wave heights from historical accounts, and tide gage records. This data set is very incomplete and not readily accessible by researchers. The data available in World Data Centers A and B and the International Tsunami Information Center have not been compiled in easily accessible publications or data files. Further, the data in all of these centers collectively are by no means identical to all existing historical data. Compilations contain errors and omissions that are significant to risk assessment and that may be rectified only through studies of reasonable scope and intensity. Such studies would include the acquisition of more data sets and careful examination of questionable events in existing data sets.

Coastal flooding risk is a statistical problem. The form, or forms, of the distribution of wave heights need further analysis. The problem of error bars on parameter estimates along with the uncertainties that these will cause in predicted wave heights, is as yet unexamined. There are two kinds of uncertainties, one where data exist from previous tsunami, the other where no data exist. A further step of relating probable wave-height distributions to property risk has hardly been studied.

Potential tsunami situations should be studied in advance. Certain sources are likely to generate tsunami in the near future while others are not so likely (seismic gap theory). Prior analyses can be used to design a warning system for maximum effectiveness for a given effort. Lee outlined a program of merging risk analysis techniques with tsunami model results that may offer future rewards.(59)

Need

The historical data set on tsunami should be augmented and carefully reviewed to make these data available to the research community. The data at World Data Centers A and B and the International Information Center should be compiled in a form easily accessible by researchers for modeling verification, risk analysis, and other studies. By making such data available, risk analysis studies can be initiated that quantify the risks to society. Such information defines the coastal hazard more accurately and provides a foundation for appropriate mitigation measures.

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TSUNAMI RESEARCH PLANNING WORKSHOP SEATTLE, AUGUST 1981

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Scotch Cap Light Station, destroyed by Tsunami of 1946, killing all five occupants. Built in 1940 of concrete to replace a wooden structure built in 1903, it stood 60 feet high and 92 feet above water level.
(Credit: U.S. Coast Guard.)