# SCIENCE OF TSUNAMI HAZARDS

The International Journal of The Tsunami Society
Volume 2, Number 2 1984

**OBJECTIVE:** The Tsunami Society publishes this journal to increase and disseminate knowledge about tsunamis and their hazards.

Submit manuscripts of articles, notes, or letters to:

SCIENCE OF TSUNAMI HAZARDS
Box 8523
Honolulu, HI 96815, USA

If article is accepted for publication the author(s) must submit a camera ready manuscript. A voluntary $50.00 page charge will include 50 reprints.

SUBSCRIPTION INFORMATION: Price per copy: $20.00 USA Hardcopy

ISSN 0736-5306

Published by The Tsunami Society in Honolulu, Hawaii, U.S.A.

# IMPORTANCE OF LOCAL CONTEMPORARY REPORTS OF EFFECTS OF HISTORICAL TSUNAMIS IN TSUNAMI RISK ANALYSIS*

Doak C. Cox
University of Hawaii, Environmental Center
2550 Campus Road
Honolulu, Hawaii 96822

## ABSTRACT

To a continuing Pacific tsunami cataloguing effort has been added an intensive review of the history of tsunamis in Hawaii, based so far as possible on local, contemporary sources of information on the events. The review has indicated that there are errors and omissions of several sorts in previously available compilations of tsunami occurrences and effects: errors in the identification of phenomena as tsunamis, omissions of some tsunami or possible-tsunami events, errors in place-specific tsunami runup heights, and omissions of records of runup heights or of effects from which runup heights might be estimated. Corrections and additions to the information in the earlier compilations have proved to be highly significant in the evaluation of tsunami risk from place to place, for example in the estimation of tsunami hazard zones in the application of the National Flood Insurance Program to Hawaii. The results of the search for and use of local contemporary records of historic tsunamis in Hawaii and of similar studies in Japan and at two places in California indicate that such studies are warranted on all coasts on which the tsunami hazard is significant and on which there are near-shore marine-dependent settlements with histories approaching or exceeding a century.

---

**Presented at Conference on Physics and Mitigation of Natural Hazards, August 1982, Honolulu, Hawaii. University of Hawaii, Environmental Center, contribution no. CN:0028.*

This paper is based on the results to date of two continuing investigations in which the author is involved, one (with K. Iida, S. L. Solov'ev, and G. Pararas-Carayannis) into the history of Pacific tsunamis (Iida et al. 1967, Solov'ev and Go, 1974, 1975), the other (with J. Morgan) into the history of tsunamis in Hawaii (Cox and Morgan, 1977; Cox, 1978, 1979).

These investigations indicate that in many previously available compilations of tsunami occurrences and effects there are defects that detract seriously from their reliability as bases for tsunami risk evaluation. The defects are easily explainable. The information in most previously available compilations has been drawn from earlier compilations and notices, and at each stage of recording or compiling there has been the potential for omissions and for errors of several sorts including: a) identification of other phenomena as tsunamis; b) date errors that, through merging of lists, have resulted in multiple entries of single events; c) confusion among different measures of tsunami size; d) simple errors in copying place names and numerical data.

The Pacific tsunami record now includes about 1400 reported event dates since early in the present era. It is impossible to check original sources of information for all of the reported events but, on the basis of the records that have been checked, about 600 of the dates are considered definitely those of tsunamis, about 600 definitely not, and the remainder probably, questionably, or very doubtfully those of tsunamis.

The Hawaiian record dating from 1813 and reasonably reliable since 1837, includes about 160 reported event dates. From the search for and review of original documentation for these events, including contemporary newspaper accounts, institutional records, and personal diaries, it appears that about 95 of these dates are those of tsunamis definitely observed in Hawaii and about 45 are erroneous or pertain to phenomena other than tsunamis.

The importance of reference to contemporary local documentation may be illustrated by summarizing the effects of incorporating the results in the evaluation of tsunami risk in Hawaii that has been made under the National Flood Insurance Program (NFIP). In this program, the width of the zone of 100-year inundation and the depth of flooding are estimated, place to place, from 100-year, near-shore tsunami runup heights, taking into account terrain slope and roughness. The 100-year runups have been estimated (by Houston et al., 1977) for about 700 sites from site-specific estimates of the runups of historic tsunamis. Values representing contemporary measurements or estimates predominate in the records for only 2 or 3 sites, and the records for most sites are entirely synthetic. The values of contemporary origin are of critical importance, not only in the evaluation of the hazard at the sites to which they pertain, but for adjustment of the results of the models on which the synthetic values for other sites are based.

Of the results of the continuing investigation, only those pertaining to events reported as representing tsunamis of local or possible local origin and tsunamis from Japan have been published to date. Of 29 such events in the list on which the NFIP evaluation was initially based, 4 initially considered definite tsunamis and 5 initially considered possible tsunamis have been found not to represent tsunamis, and 2 initially considered only possible tsunami occurrences have been identified as definite occurrences. One definite and 9 possible tsunamis have been added to the list. Out of 86 site-specific historic runups in the initial NFIP record, 24 have been significantly changed; and 45 additional site-specific runups have been added from contemporary documentation.

The revisions in the historic runup records have resulted in revisions of 100-year runup estimates equalling or exceeding 5 feet for at least 5 sites on the coasts of the islands of Maui and Hawaii. The revisions are of little economic significance on coasts where the land slopes steeply or where development is prohibited. However, at some places, notably the west coast of the island of Hawaii, the economic consequences of the resulting revisions of the horizontal extent of 100-year flooding are considerable. For example, the downward revision of the estimated near-shore 100-year runup heights along one 8-mile stretch of that coast resulted in a decrease in the estimated width of the 100-year inundation area that probably increased the market value of the lands affected by several 10's of millions of dollars.

Increases in the estimated extent of 100-year inundation are as likely as decreases to be indicated by the results of the investigation, although as yet it has not indicated any increase as significant economically as the decrease on the west coast of Hawaii.

Similar investigations have been made by others for two places in California and several places in Japan. Taken together, the results of such investigations indicate that, although they may not everywhere be as productive as in Hawaii, they are warranted on all coasts on which the tsunami hazard is significant and on which there are near-shore marine- dependent settlements with histories approaching or exceeding a century.

## References

Cox, D. C., and J. Morgan, (1977). Local tsunamis and probable local tsunamis in Hawaii. Hawaii Inst. Geophys., HIG 77-14.

Cox, D. C., 1979. Local tsunamis in Hawaii -- implications for hazard warning. Hawaii Inst. Geophys., HIG 79-5.

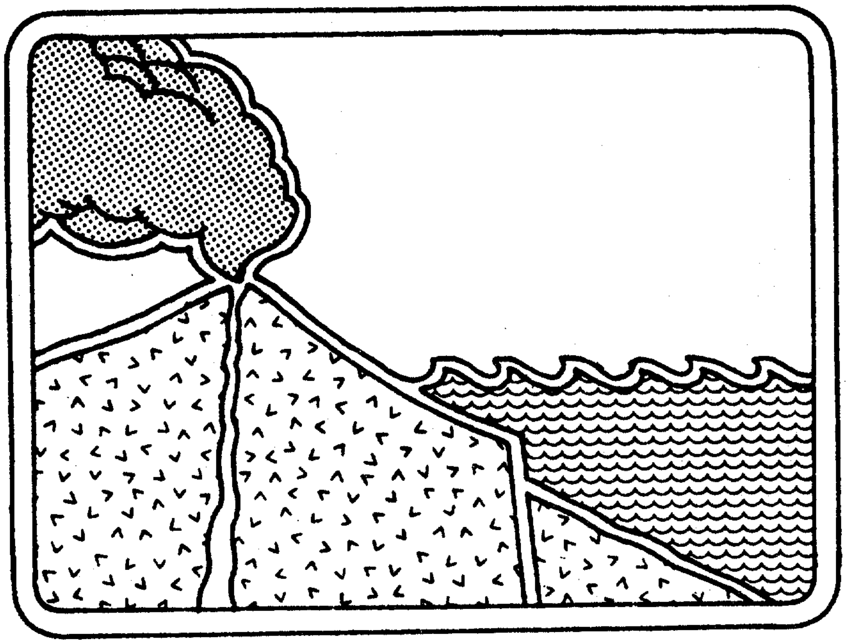
Cox, D. C., 1980. Japanese tsunamis in Hawaii -- a preliminary report. Univ. Hawaii Environ. Ctr., SR:0025.

Houston, J. R., R. D. Carver, and D. G. Markle, 1977. Tsunami-wave elevation frequency of occurrence for the Hawaiian Islands. U. S. Army Engineer Waterways Experiment Station, H-77-16.

Iida, K., D. C. Cox, and G. Pararas- Carayannis, 1967. Preliminary catalog of tsunamis occurring in the Pacific Ocean. Hawaii Inst. Geophys., HIG-67-25.

Solov'ev, S. L. and Ch. N. Go, 1974. Catalog of tsunamis on western coasts of the Pacific Ocean (in Russian), Akad. NAUK, USSR.

Solov'ev, S. L. and Ch. N. Go, 1975. Catalog of tsunamis on eastern coasts of the Pacific Ocean (in Russian), Akad. NAUK, USSR.



# A LANDSLIDE MODEL FOR THE 1975 HAWAII TSUNAMI

Charles L. Mader
Los Alamos National Laboratory
Los Alamos, New Mexico 87545
and
Joint Institute for Marine and Atmospheric Research
University of Hawaii
1000 Pope Road
Honolulu, Hawaii 96822

## ABSTRACT

The Hawaii tsunami of November 29, 1975, was calculated assuming a landslide for the source using a shallow-water-wave code and a three-dimensional code for solving the incompressible Navier-Stokes equation. The observed tsunami wave profile near the source, a second wave larger than the first, is not consistent with a landslide source.

## Introduction

The tsunami of November 29, 1975, has been investigated by Loomis. He described the observed runup heights in reference 3 and a numerical study of the tsunami source in references 4 and 9.

The tsunami was generated by an earthquake near the Hawaii Volcanoes National Park with a magnitude of 7.2 on the Richter scale. Near the source, the first wave was smaller than the second. Coincident with the earthquake was considerable subsidence (up to 3 meters) of the shoreline.

Loomis, in reference 4, examined a model of the southeastern coast of Hawaii. The bottom slopes seaward at a ratio of 1:15 until it reaches a constant depth of 6000 meters. The sources examined by Loomis included both initial uplifts and depressions and he reported that such source motions would not generate the essential features of the tsunami; that is, a second wave larger than the first.

In reference 7 we described the use of the SWAN code described in references 5 and 6 to solve the long-wave, shallow-water equations and examine the tsunami generation problem. We confirmed Loomis' calculated results using our shallow-water-wave code. We also used the SOLA-3D code that solves the three-dimensional, incompressible Navier-Stokes equations to model the tsunami. Close to the source of the wave the second wave was calculated to be larger than the first wave with a source motion of an initial uplift of the ocean surface.

In this paper we extend the study to investigate landslide source models. The landslide model has been evaluated by Cox in reference 1. He concluded that a landslide could not be distinguished from strictly tectonic displacement by the comparison of arrival times and travel times.

## I. The Calculated Shallow-Water-Wave Results

Our model is essentially identical to that used previously in reference 7. A 40-by-69 rectangular region of 207 km along the coast and 120 km seaward is described using a mesh of 3 km by 3 km. The bottom slopes at a ratio of 1:15 until it reaches a depth of 6 km. The source is 30 km wide, of which half is included in the calculation and is separated from the other half by a reflective boundary as shown in Fig. 1.

The source we investigated was an undersea landslide. The landslide ocean bottom profile assumed the bottom dropped 3 meters at the shoreline and slid to form the profile shown in Fig. 2. Landslides are observed to pile up the bottom 1/3 of their run. This gives the surface wave profile shown in Fig. 3. The calculations were performed on the University of Hawaii Harris Computer using the Hawaii version of the SWAN code described in reference 8.

The shoreline wave heights at various times for the shallow-water-wave model with the initial water surface displacement of Fig. 3 are shown in Fig. 4. While the wave-heights are consistent with the observed behavior of the tsunami, we must check the results with the SOLA code since it has been demonstrated in references 6 and 7 that the shallow-water model is inadequate to describe the waves generated from surface deformations of the water surface.

## II. The Calculated Navier-Stokes Results

Three-dimensional, time-dependent, incompressible flow using the full Navier-Stokes equation was calculated for the model shown in Fig. 1 using the SOLA-3D code.

The SOLA-3D code is a three-dimensional version of the two-dimensional SOLA code described in reference 2. The program has evolved from the marker-and-cell (MAC) finite difference technique which uses pressure and velocity as primary dependent variables. A variable mesh capability has been included to improve the numerical resolution. The surface height of the center of each cell is computed each cycle according to the kinematic equation

$$\frac{\partial H}{\partial t} + U\frac{\partial H}{\partial x} + V\frac{\partial H}{\partial y} = W \quad ,$$

similar to that described in reference 2 for the SOLA-SURF version of the SOLA code. The Navier-Stokes equations for incompressible viscous fluid flow are

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0$$

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} + W\frac{\partial U}{\partial z} = -\frac{\partial P}{\partial x} + g_x + \nu\left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} + \frac{\partial^2 U}{\partial z^2}\right)$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + W\frac{\partial V}{\partial z} = -\frac{\partial P}{\partial y} + g_y + \nu\left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2}\right)$$

$$\frac{\partial W}{\partial t} + U\frac{\partial W}{\partial x} + V\frac{\partial W}{\partial y} + W\frac{\partial W}{\partial z} = -\frac{\partial P}{\partial z} + g_z + \nu\left(\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial y^2} + \frac{\partial^2 W}{\partial z^2}\right)$$

where

U, V, W are velocity components in the x, y, z directions,
t is time,
P is pressure,
$g_x$, $g_y$, $g_z$, are x, y, z components of gravity, and
v is the kinematic viscosity coefficient.

The equations are solved using the finite difference technique described in reference 2.

The geometry of the model used to calculate the tsunami is shown in Fig. 1. The mesh used in the calculation had 20 cells in the x-direction, 25 cells in the y-direction, and 18 cells in the z-direction. The 20 cells in the x-direction were 6 km wide. The 18 cells in the z-direction starting at the ocean floor were 100 meters high for the first two cells, and 400 meters thereafter. The water depth was 6000 meters and the surface was located at the center of cell 17. The 25 cells in the y-direction starting at the source were 3.0 km for the first 5 cells which described the source (15 km wide). The remaining cell widths were 5.75, 6.16, 6.56, 6.97, 7.37, 7.78, 8.18, 8.59, 9.0, 9.4, 9.8, 10.2, 10.6, 11.0, 11.4, 11.8, 12.2, 12.6, 13.0, and 13.5 km, for a total of 206.8 km.

The viscosity coefficient was 2.0 g-sec$^{-1}$-m$^{-1}$ (0.02 poise). The gravity constant, $g_z$, was -9.8 m-sec$^{-2}$, and $g_x$ and $g_y$ were 0.0. The time step for the calculation was 5 seconds. The tsunami source was modeled over 90 by 15 km of the water surface, as shown in Fig. 3.

The calculated wave profiles are shown at various locations along the shoreline as a function of time in Fig. 5 for a landslide source. The observed tsunami wave profile of the 1975 Hawaii tsunami near the source of the second wave larger than the first is not reproduced by a landslide source in an incompressible three-dimensional Navier-Stokes calculation in contrast with results obtained using the shallow-water model. We previously reported in reference 7 that a source of a 3-meter uplift of the water surface was consistent with the observed tsunami wave profile. These calculations do not support a landslide source for the 1975 Hawaii tsunami.

The differences between the shallow-water and full Navier-Stokes calculations are that the water waves formed in the full Navier-Stokes calculations are deep-water waves which move slower than the shallow-water waves formed in the shallow-water calculations. The nature of the surface collapse is also different with the collapse occurring throughout the source region in the Navier-Stokes calculations and mostly at the sides in the shallow-water calculations.

## Conclusions

The observed tsunami wave profile of the 1975 Hawaii tsunami near the source of the second wave larger than the first wave is not reproduced by a landslide source, but is reproduced by a simple uplift or drop of the water surface over the source area.

The shallow-water approximation is not appropriate for studying waves generated from surface deformations that are small relative to the water depth.

## Acknowledgements

I wish to recognize the contributions of Dr. H. Loomis and Dr. Doak C. Cox of the University of Hawaii, and Dr. Dennis W. Moore, George Curtis, and Sharon Lucas of the Joint Institute for Marine Atmospheric Research (JIMAR) at the University of Hawaii where the author was a visiting scientist on sabbatical from the Los Alamos National Laboratory while performing this study.

I also recognize helpful discussions with C. W. Hirt of Flow Science, Inc., and James D. Kershner and Allen L. Bowman of the Los Alamos National Laboratory.

## References

1. Cox, Doak C., "Source of the Tsunami Associated with the Kalapana (Hawaii) Earthquake of November 1975," Hawaii Institute of Geophysics Report, HIG-80-8 (1980).

2. Hirt, C. W., Nichols, B. D. and Romero, N. C., "SOLA - A Numerical Solution Alogorithm for Transient Fluid Flows," Los Alamos National Laboratory Report, LA-5852 (1975).

3. Loomis, Harold G., "The Tsunami of November 29, 1975, in Hawaii," Hawaii Institute of Geophysics Report, HIG-75-21 (1975).

4. Loomis, Harold G., "On Defining the Source of the 1975 Tsunami in Hawaii," JIMAR Report to Nuclear Regulatory Commission (1978).

5. Mader, Charles L., "Numerical Simulation of Tsunamis," Hawaii Institute of Geophysics Report, HIG-73-3 and J. Phys. Oceanography, Vol. 4, pp. 74-82 (1974).

6. Mader, Charles L., "Calculation of Waves Formed From Surface Cavities, "Proceedings of the 15th Coastal Engineering Conference, pp. 1079-1092 (1976).

7. Mader, Charles L., Tangora, Robert E., and Nichols, B. D., "A Model of the 1975 Hawaii Tsunami," Natural Science of Hazards, Vol. 1, pp. C1-C8 (1982).

8. Mader, Charles L. and Lucas, Sharon, "SWAN-A Shallow Water Long Wave Code," Hawaii Institute of Geophysics Report, HIG-84-4 (1984).

9. Sklarz, M. A., Spielvogel, L. Q., and Loomis, H. G., "Numerical Simulation of the November 29, 1975, Island of Hawaii Tsunami by the Finite Element Method," J. Phys. Oceanography, Vol. 9, No. 5, pp. 1022-1031 (1979).

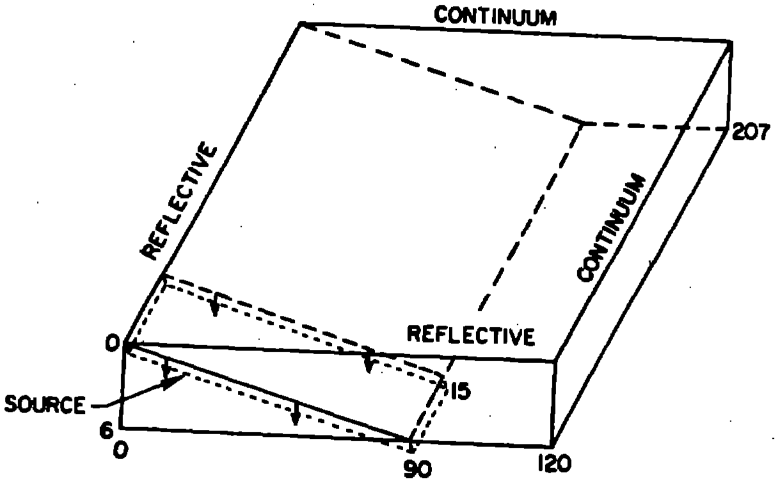


Figure 1. Sketch of model used to numerically simulate the tsunami generation.

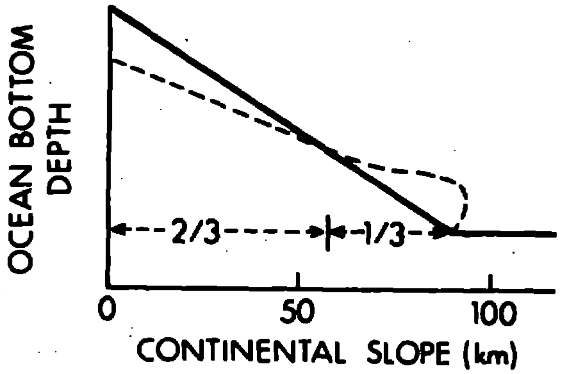


Figure 2. Sketch of the final ocean bottom profile after a landslide for the source region.

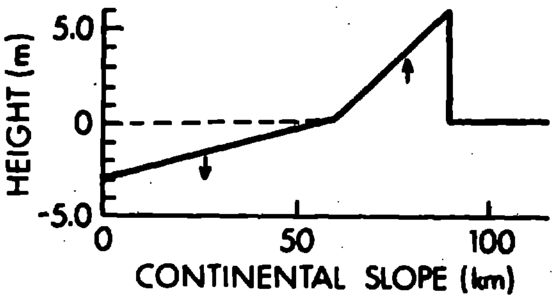


Figure 3. Sketch of height of water surface after a landslide on the ocean bottom.

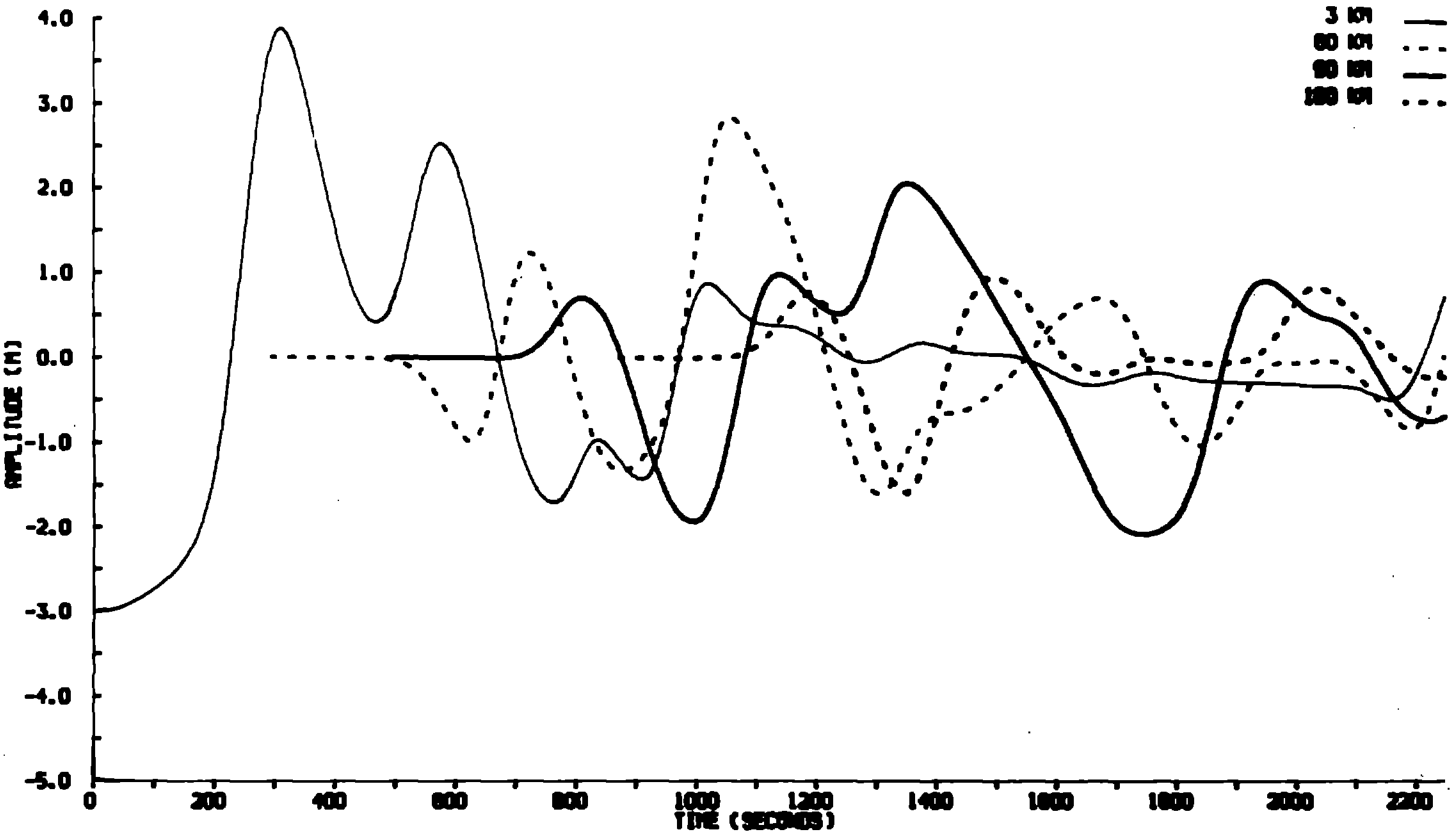


Figure 4. Shoreline waveheights for a shallow-water-wave model resulting from the initial water surface displacement shown in Figure 3.

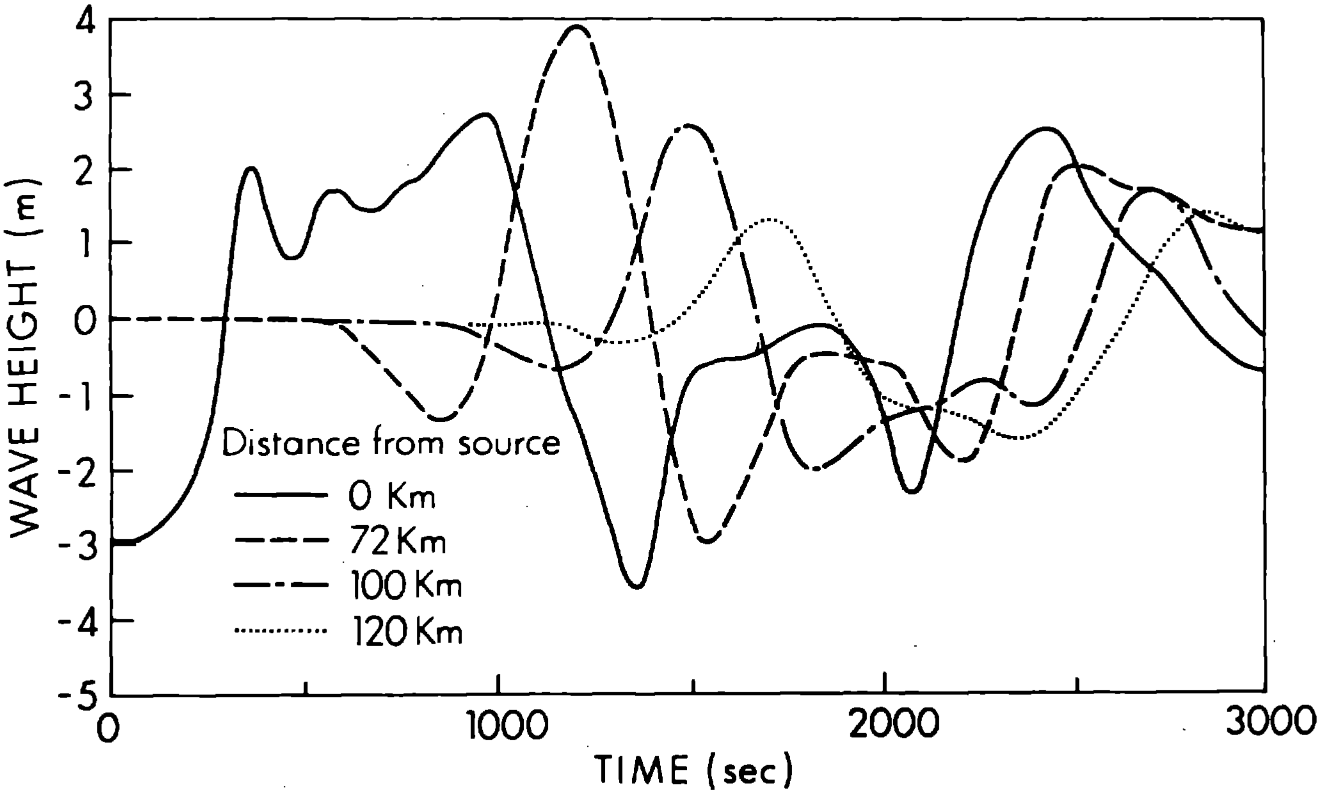
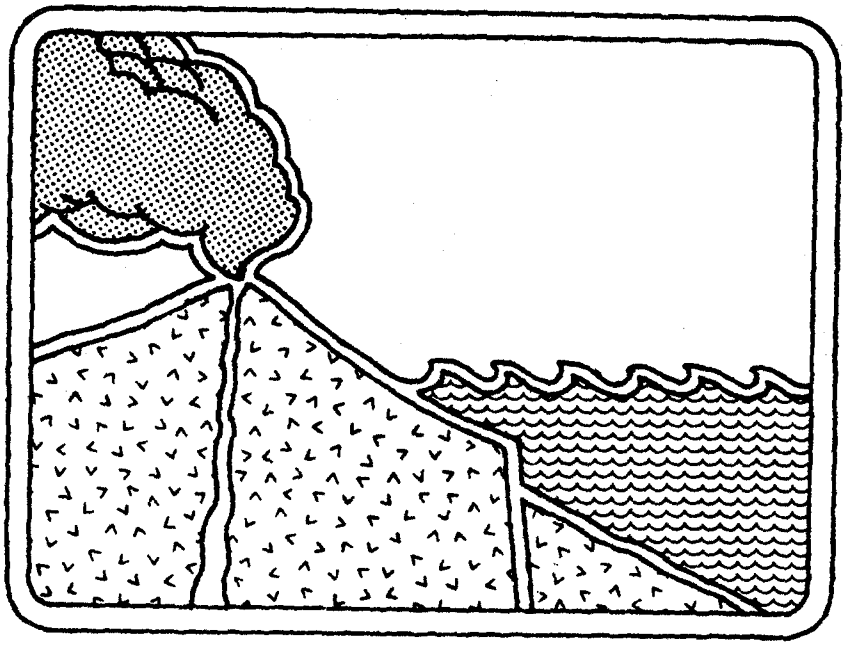


Figure 5. Shoreline waveheights for a full three-dimensional incompressible Navier-Stokes equation calculation with the landslide source shown in Figure 3.



# PROBABLE ALEUTIAN SOURCE OF THE TSUNAMI OBSERVED IN AUGUST 1872 IN HAWAII, OREGON, AND CALIFORNIA*

Doak C. Cox
University of Hawaii, Environmental Center
2550 Campus Road
Honolulu, Hawaii 96822

Guest worker, NOAA Environmental Data and Information Service,
National Geophysical and Solar-Terrestrial Data Center, Boulder, Colorado.

## ABSTRACT

Reports of a tsunami occurring at Nawiliwili, Hanalei, Hilo, and Honolulu, Hawaii on 23 or 27 August 1872, and recorded at Honolulu, at Astoria, Oregon, and at San Francisco and San Diego, California on 24 August, relate to the same event. The Honolulu marigram cannot now be located, but from the reports of the tsunami arrival at the four places in Hawaii and the marigraphic evidences of its arrival at the three places in Oregon and California its source has been determined as off the Aleutian Islands, most probably at about 170°W longitude. The most probable origin time was about 18:02 UT on 23 August.

---

**University of Hawaii, Environmental Center, contribution no. CN:0029*

## Introduction

The observation or recording in August 1872 of waves of tsunami type at several places in Hawaii and on the west coast of the continental United States has been noted in a number of reports. In all of the reports the waves were considered to have been of seismic or volcanic origin. However, the reports differed as to dates of occurrence of the waves at various places and their probable sources, and no report noted the occurrence at all the places of observation or recording.

It is shown in this paper that the occurrences at all of the places may be attributed to a single tsunami that originated off the Aleutian Islands.

### Previous documentation and suggestions as to origin

The previously available information on the tsunami may best be described in terms of four lines of documentation:

1. A report on the observation of the waves at Hilo on the island of Hawaii in a letter from Titus Coan (1872), a missionary stationed there, who reported that the highest wave rose to 4 feet 2 inches (1.3 meters) (probably above high water mark). Coan's letter was the basis for subsequent notes by Dana (1891), Brigham (1909), Hitchcock (1909), Sapper (1917, 1927), Jaggar (1931, 1948), Powers (1946), Macdonald and Shepard (1947), Shepard et al. (1950, Iida et al. (1967), Pararas-Carayannis (1969), and Pararas-Carayannis and Calebaugh (1977).

2. Accounts of the observation of the tsunami at Hanalei and Nawiliwili on the island of Kauai, Hawaii, and its observation and marigraphic recording at Honolulu on the island of Oahu, in two Honolulu newspapers, the Hawaiian Gazette (28 August 1872) and the Pacific Commercial Advertiser (31 August 1872). The maximum range reported for Honolulu was 15 inches. No estimate of size was reported from Hanalei, but a range of 2 or 3 feet (0.6 to 0.9) meters was reported from Nawiliwili.

3. A note on the marigraphic recording of the tsunami at San Francisco, California, in the Pacific Commercial Advertiser (6 October 1872).

4. Remarks by Professor George Davidson before the California Academy of Science (Yale, 1872) concerning the marigraphic recording of the waves at San Francisco and San Diego, California, and Astoria, Oregon, and their reported recording at Honolulu. Davidson's remarks were noted subsequently by Joy (1968).

The occurrences in Hawaii were dated 23 August by Coan, in the Honolulu newspapers, and in most subsequent notes on the tsunami, although Hitchcock, Jagger, and Powers assigned the observation at Hilo to the date of Coan's letter, 27 August. The occurrences on the west coast were dated 24 August, the Greenwich date, by Davidson and Joy.

The connection between the waves recorded in Honolulu and those recorded in San Francisco was recognized by both the Honolulu Advertiser and Davidson. However, Solov'ev and Go (1975) listed, as if separate tsunamis, one occurring in Hawaii on 23 August on the basis of documentation line 1 and one occurring in Oregon and California on 24 August on the basis of documentation line 4. Documentation lines 1, 2, and 3 seem first to have been coupled by Cox and Morgan (1977) who, however, were unaware of the recording of the tsunami at Astoria and San Diego. The identity of the phenomena observed and recorded at all seven places in Hawaii and on the west coast seems not to have been noted in any previous publication.

The phenomenon observed in Hawaii was identified by Coan and in the Honolulu newspapers merely as a "tidal wave." Coan's mention of it was incidental to a discussion of activity of the Hawaiian volcanoes -- in particular an eruption of Mauna Loa occurring not long before. Brigham indicated that the phenomenon had no evident connection with the Mauna Loa eruption, but Sapper associated it with the eruption, and Jaggar speculated that it originated from a local volcanic disturbance on the sea floor. Powers, Macdonald et al., and Shepard et al. considered a local origin in

Hawaii probable; and Iida et al., Pararas-Carayannis, and Pararas-Carayannis and Calebaugh considered a local origin possible. The Pacific Commercial Advertiser initially suggested, on the basis of the difference between the reported arrival times of the waves on Kauai and on Oahu, that the waves came from the west of Hawaii, but later, on the basis of the difference between the arrival times at Honolulu and San Francisco, that they came from the north.

On the basis of the arrival times of the waves at Astoria, San Francisco, and San Diego, and some reported arrival time at Honolulu, Davidson, who identified them as "earthquake waves," considered that their origin was probably about midway between Kamchatka and Japan. Solov'ev and Go suggested that their origin might have been in the Bonin Islands, where a tsunami had occurred following an earthquake sometime during the Fall of 1872 (Solov'ev and Go, 1974). In their original report, Cox and Morgan (1977) considered that the reported arrival times at Honolulu and San Francisco were inconsistent with an origin near either of those places. Mistakenly thinking that the arrival at San Francisco preceded the arrival at Honolulu, they later (Cox and Morgan, 1978) suggested an origin on the Alaska coast near Yakutat or on the Chile coast near Antofagasta.

Other than those cited, no reports are known that suggest the occurrence of a tsunami in any part of the Pacific on a date consistent with the dates of its occurrence in Hawaii, Oregon, and California.

According to T. S. Murty of the Canadian Institute of Ocean Sciences (personal communication), no tide gages were in operation at the time on the west coast of Canada, and according to Patricia Lockridge of the NOAA Environmental Data and Information Service (personal communication), there were none in Alaska, Washington, Oregon, or California, other than those at Astoria, San Francisco, and San Diego, that might have recorded the tsunami.

## Outline of study methodology

In most cases, a historic tsunami may be assumed to have originated off the coast where a large earthquake occurred not long before the tsunami was observed. The tsunami in the Bonin Islands, which Solov'ev and Go (1974, 1975) considered might have accounted for the effects described in Hawaii and recorded on the Oregon and California coasts, accompanied an earthquake felt in the Bonin Islands. The date of the event is not known, but it is reported to have occurred on a Sunday about midnight. Even if the report referred to the middle of the night between Saturday, 24 August, and Sunday, 25 August, in other words between 03:00 and 04:00 Hawaiian time on the 24th, the Bonin tsunamis could not have arrived in Hawaii on August 23. There are no other reports of the occurrence of a significant earthquake with which the tsunami of August 1873 may be associated.

A line of possible locations of the source of tsunami may be determined by the difference between its arrival times at two distant points if adequate bathymetric data is available. The determination is facilitated if charts of tsunami travel time (inverse refraction diagrams) have already been prepared from the bathymetric data. If such a line of position crosses a commonly tsunamigenic region, and only one such region, it may be assumed with some confidence that the tsunami originated in that region. More exact location may be possible if lines of possible position may be determined from the arrival times of the tsunami at two or more pairs of distant places.

Arrival times of the August 1872 tsunami at several places were reported or may be estimated from marigraphic records. Hence, in principle, it should have been possible to determine lines of possible source position for the tsunami from the arrival-time differences for several pairs of places. However, its origin in the tsunamigenic region off the Aleutian arc has been determined from a single line of position, that defined by the arrival-time difference for Honolulu and San Francisco, or rather from the band of possible positions defined by the range of possible values for that arrival-time difference.

The only arrival-time difference estimated in contemporary reports pertained to Honolulu and San Francisco, and, among places where the tsunami was observed or recorded, those are the only ones for which tsunami travel-time charts have been published. Nevertheless, neither the originally reported estimate of the arrival-time difference nor the published travel-time charts have been used in the final source estimation. The reasons for their disregard, and the methods that had to be used in the estimation are outlined below.

1. Davidson (in Yale, 1872) reported that the tsunami arrived at Honolulu 2-3/4 hr. earlier than at San Francisco. The only commonly tsunamigenic region crossed by the line of possible source position indicated by this difference and the published travel-time charts for the two places (Anon, 1971) was found to be that off Hokkaido. However, it seemed probable that a tsunami generated off Hokkaido, if large enough to account for the effects described in Hawaii, would have been included in the Japanese tsunami record, or at least that an accompanying earthquake would have been reported.

2. Reports of the arrival times of the tsunami at Honolulu and San Francisco in the Pacific Commercial Advertiser (31 Aug. and 6 Oct. 1872), when converted to a common time system, suggested an arrival-time difference of only 1¼ hr. To determine whether Davidson's estimate or that implied by the arrival times reported in the Advertiser was the more reliable, copies of the marigrams for the two places were sought. The Honolulu marigram could not be located in either the files of the U. S. Coast and Geodetic Survey, which had cooperated in the tide gaging with the then independent Hawaiian Government or in the Hawaiian Archives.

3. Hence all reports of the arrival of the tsunami in Hawaii were reviewed. The reports were found to be mutually inconsistent even as to whether the first manifestation of the tsunami was a rise or fall of water level.

4. It could not be determined with certainty which of the oscillations recorded on the San Francisco marigram represented the first feature of the tsunami, and similar uncertainties were found in the case of the Astoria and San Diego marigrams which were obtained to assist in the interpretation of the San Francisco marigram.

5. To further the interpretation, possible San Francisco-Astoria and San Diego-San Francisco tsunami travel-time differences were needed. Because no travel-time charts have been published for Astoria or San Diego, recourse was made to a hybrid method of travel-time estimation described below, and the hybrid method was applied to the estimation of travel times to Honolulu and San Francisco as well. Comparisons indicated that the published travel-time charts were unreliable, particularly that for San Francisco.

6. Using the hybrid method for travel-time estimation, no consistency could be found among the possible arrival times of the tsunami at the several places of observation or recording if it were assumed that the tsunami originated in the South Pacific. However, the possible arrival times at most of the places were found to be reasonably consistent if it were assumed that the tsunami originated off the Aleutian Islands. The only inconsistency was in the Astoria marigraphic evidence. As will be shown, this inconsistency could readily be accounted for.

7. San Franscisco-San Diego travel-time differences were found to vary only slightly with possible source location within the Aleutian region. Hence the marigraphic evidences of arrival times at the two places were combined using the hybrid travel-time differences, to produce best estimates of the arrival times at San Francisco assuming, alternatively that the first feature of the tsunami was a crest or a trough and assuming a range of possible source locations in the region.

8. For the same reason, and because none of the reported Hawaii arrival times seemed completely reliable, the reports of these arrival times also were combined to produce ranges of possible arrival times at Honolulu under the same assumptions.

9. The ranges of possible source locations within the Aleutian region, and most probable locations assuming a point source, were determined from differences between the Honolulu and San Francisco arrival times thus estimated, using the hybrid estimates of travel times to the two places, and both alternative first-feature assumptions.

10. The location based on the assumptions that the first feature on the coasts of both Hawaii and California was a crest, as seemed most probable, was adjusted assuming that the source had reasonable finite dimensions.

It should be noted that, in 1872, there was no Standard Time system, and the arrival times reported and marigraphically recorded were local times. For the computation of arrival time differences the local times were converted to Greenwich or Universal Time (UT).

## Hybrid estimates of tsunami travel times

The hybrid method of tsunami travel-time estimation referred to above involved correction of computer-derived values by reference to manually constructed inverse refraction diagrams.

The computer-derived values, made available by W. J. Mass of the Pacific Tsunami Warning Center, Ewa Beach, Hawaii, represented tsunami travel times from a considerable number of hypothetical origin points in a band along the northwestern and northern margins of the Pacific to four foci, one each near Honolulu, Astoria, San Francisco and San Diego (Table 1). The computer program consists of a minimal spanning-tree algorithm developed by Dijkstra (1959) and implemented by Mass and S. Poole to calculate long-wave travel times using a computer file of average ocean depths for one-degree "squares" bounded by m meridians and $(n + \frac{1}{2})^{\circ}$ parallels (m and n being integers). The hypothetical origin points and the four "foci" were located at the intersections of such meridians and parallels.

Table 1. Locations of Mass "foci" near tide stations.

| | Honolulu | Astoria | San Francisco | San Diego |
|---|---|---|---|---|
| Latitude, °N | 21.5 | 46.5 | 37.5 | 32.5 |
| Longitude, °W | 158.0 | 124.0 | 123.0 | 117.0 |

Reference to manually constructed inverse refraction diagrams for correction was neccessitated by the fact that the 1°-"square" bathymetric data do not permit close estimation of the travel times in the shallow water in the vicinity of the tide gages. The method of evaluating the shallow-water effect may be illustrated by reference to the San Francisco case.

A refraction diagram was constructed on a large-scale chart for the vicinity of the San Francisco tide gage and extended on a small-scale chart to a deep water area off the coast. Superimposed on the isochrones of travel times to the tide gage were: a) isochrones of travel time to the Mass "focus" in the vicinity (interpolated from values computed by Mass in the same manner as for the hypothetical origin points); b) rays of tsunami approach from points along the northern margin of the Pacific (transferred from the published San Francisco travel-time chart), and c) normals to the rays, extended to points of tangency with the isochrones. As indicated in the part of the diagram shown in figure 1, a normal to the ray from a hypothetical source at 180° longitude is tangent to the isochrone of 82 minutes travel time to the tide gage and to the isochrone of 30 minutes travel time to the "focus". Hence for a tsunami originating as hypothesized the correction to apply to the Mass estimate of travel time to the "focus" to obtain the hybrid estimate of the travel time to the tide gage was taken to be +52 minutes. The same correction applied in the case of a tsunami originating at 160° E longitude, and a correction of +50 minutes for a tsunami orginating at 160° W longitude.

Similar diagrams were prepared for San Diego and Astoria vicinities--the rays in the San Diego case being based on the published La Jolla travel-time chart and in the Astoria case on the combination of the San Francisco chart and one for Neah Bay, Washington. The corrections in the San Diego case ranged from +24 minutes for a tsunami from 160° E longitude to +26 minutes for one from 160° W longitude, and in the Astoria case were +54 minutes for all north-Pacific-border tsunamis.

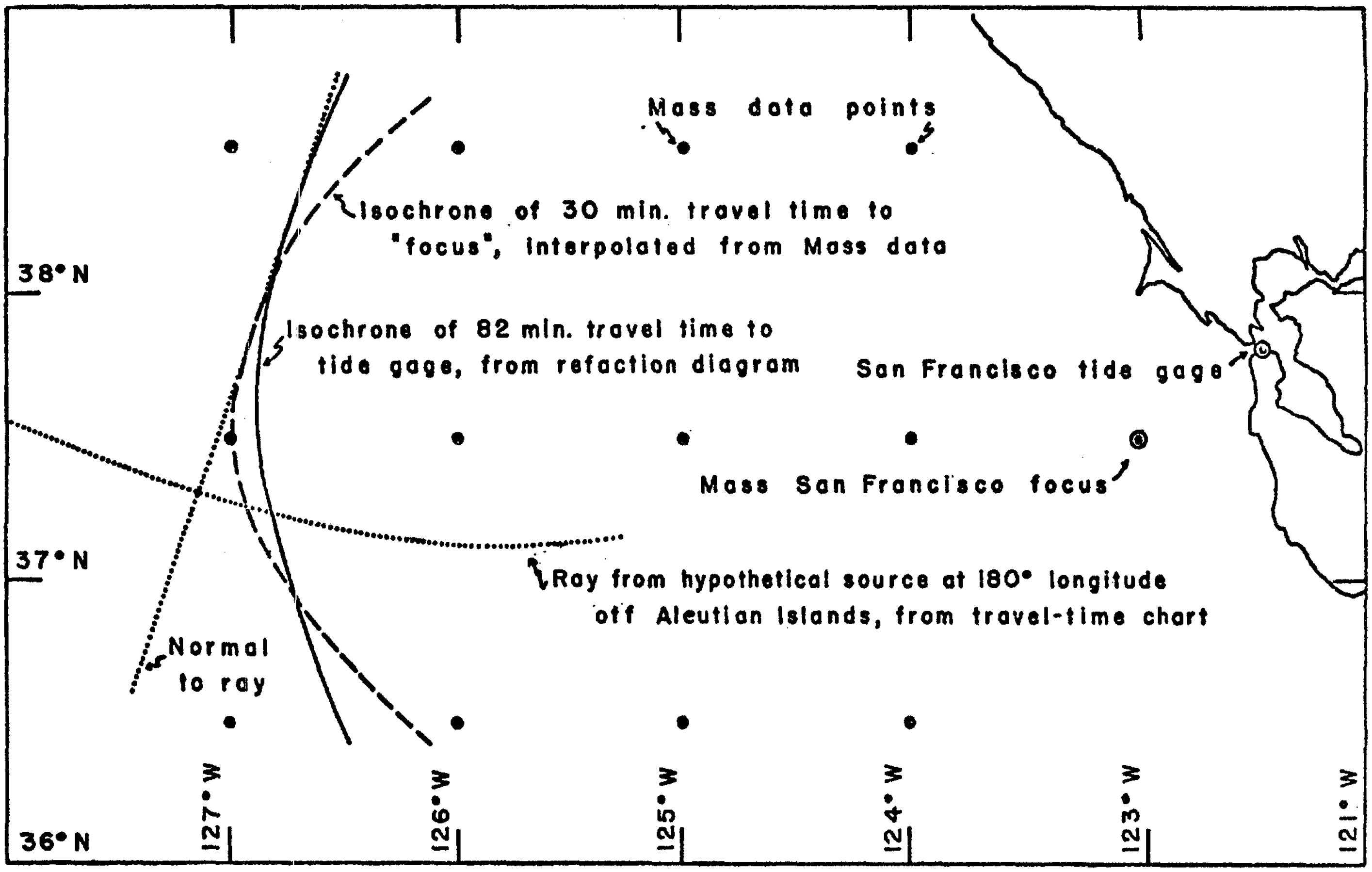


Figure 1. Example of method for determining Mass-to-hybrid travel-time corrections

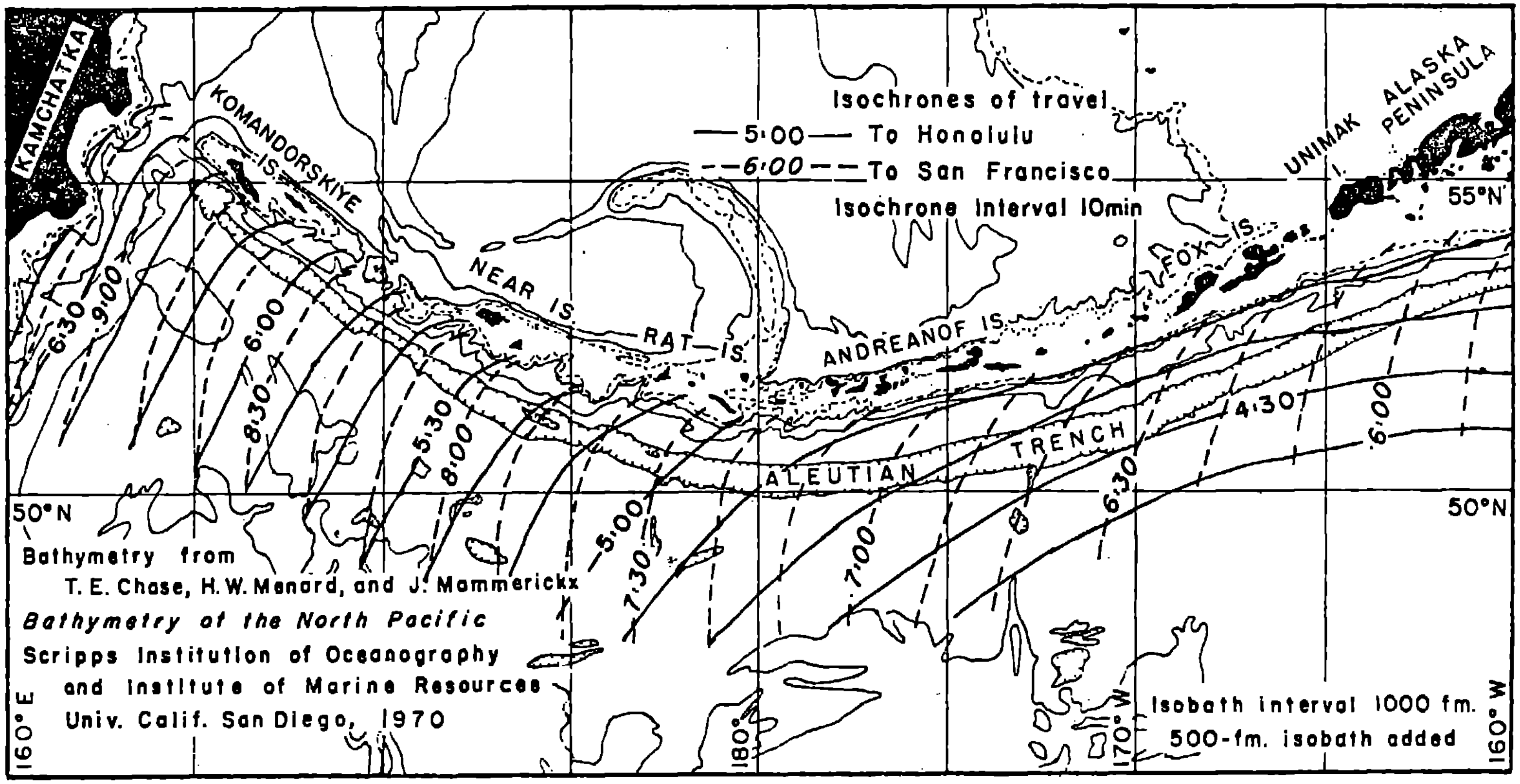
Inverse tsunami refraction diagrams had already been constructed for tsunamis approaching Nawiliwili, Honolulu, and Hilo from the southeast (Cox, 1980). These diagrams were supplemented by a diagram for Hanalei, and extended to a deepwater area sufficiently far to the north of the Hawaiian Islands for the rays to the four points of observation of the tsunami to be considered essentially parallel. The corrections to the Mass estimates travel times to the Honolulu "focus" to obtain hybrid estimates of travel times to the four Hawaiian points of observation of the 1872 tsunami ranged from -7 minutes in the case of a tsunami arriving at Hanalei to +36 minutes in the case of one arriving at Hilo, in both cases for a tsunami originating at 160$^{o}$ E longitude.

Isochrones by tsunami travel times to Honolulu and San Francisco, estimated by the hybrid method, are plotted for the tsunamigenic region along the Aleutian arc in Figure 2.

## Arrival times of the 1872 tsunami in Hawaii

The reported arrival times of the August 1872 tsunami in Hawaii are listed in Table 2. The methods and assumptions used in the two-stage process of interpreting and reconciling the times as well as possible, and combining them to produce best estimates of the Honolulu arrival time will be presented in detail in a later report and merely summarized here.

In the first stage, ranges of possible arrival times and most probable values were estimated for each place of observation on the basis of the report or reports for that place, taking into account the nature of the reports, the time systems probably used, possible watch and clock errors, possible lags between the beginnings of a rise or fall of water level and its first observation, and, alternatively, a failure to notice a small initial trough at Hilo or a small initial crest elsewhere. The estimates, converted from local to Universal Time on 23 August, ranged from 22:04 at Hanalei to 23:30 at Hilo, assuming in both cases that the first feature of the tsunami was a crest.



Bathymetry from T. E. Chase, H. W. Menard, and J. Mammerickx *Bathymetry of the North Pacific* Scripps Institution of Oceanography and Institute of Marine Resources Univ. Calif. San Diego, 1970

Figure 2. Tsunami travel times to Honolulu and San Francisco

Table 2. Reported arrival times of the tsunami in Hawaii.

| Place (and reported first manifestation) | Reference | Source and nature of reports | Reported time, 23 August |
|---|---|---|---|
| Hanalei<br>(Fall) | Gazette<br>(28 Aug)<br>Advertiser<br>(31 Aug) | Personal observation by ship captain in relation to sounding of ship's bell (Ship time was probably local Honolulu time) | 12:00 |
| Nawiliwili<br>(Fall) | Gazette<br>(28 Aug) | Probably second-hand report from ship captain | 12:00 |
| Honolulu<br>(Fall) | Gazette<br>(28 Aug) | Report by unidentified observer in relation to sounding of noon whistle | 12:00 |
| | Advertiser<br>(31 Aug) | Probably the Honolulu marigram | 12:25 |
| Hilo<br>(Rise) | Coan<br>(1872) | Personal observation or report of unidentified observer | 13:00 |

In the second stage, extreme limits to the ranges of arrival times at Honolulu indicated by the reports for all four places of observation, more probable range limits, and most probable values, were calculated assuming both first-feature alternatives and a range of possible source locations along the northern margin of the Pacific. The calculations took into account the travel-time differences estimated by the hybrid method for each pair of places of observation in Hawaii pertinent to each assumed source longitude. In the calculation of the probable values, the values implied by each report were weighted in accordance with the reliability of the report suggested by internal evidence.

For several reasons it seemed most probable that the first feature of the tsunami was actually a crest, and the sample of the results presented in Table 3 represents only the more probable ranges of estimates based on the crest-first alternative.

Table 3. Possible arrival times of the 1872 tsunami at Honolulu assuming its first feature was a crest.

| | UT, 23 August | | |
|---|---|---|---|
| Assumed source longitude | $160^{\circ}$E | $180^{\circ}$E | $160^{\circ}$W |
| Probable earliest | 22:19 | 22:19 | 22:19 |
| Most probable | 22:46 | 22:40 | 22:40 |
| Probable latest | 22:59 | 23:04 | 23:07 |

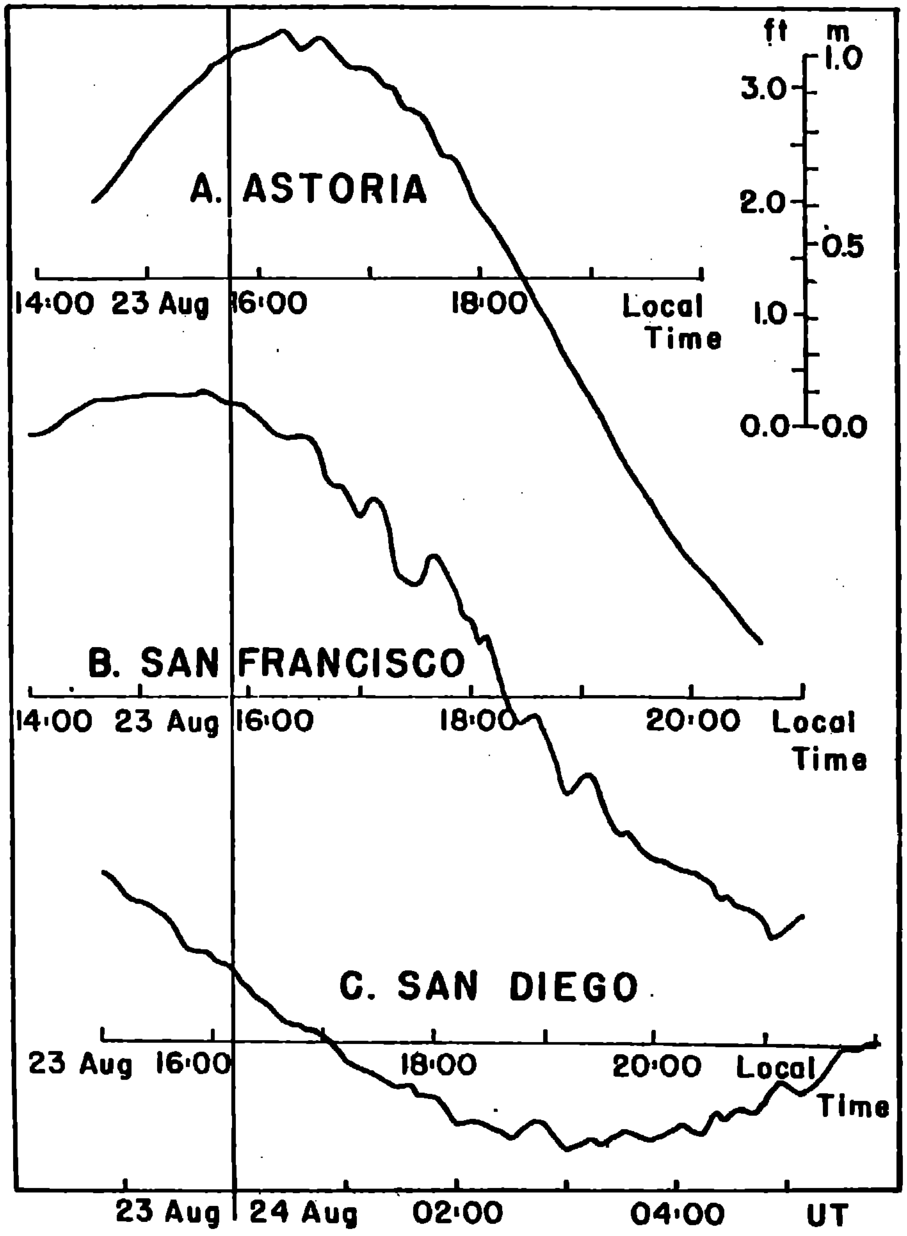


Figure 3. Marigraphic records of the tsunami

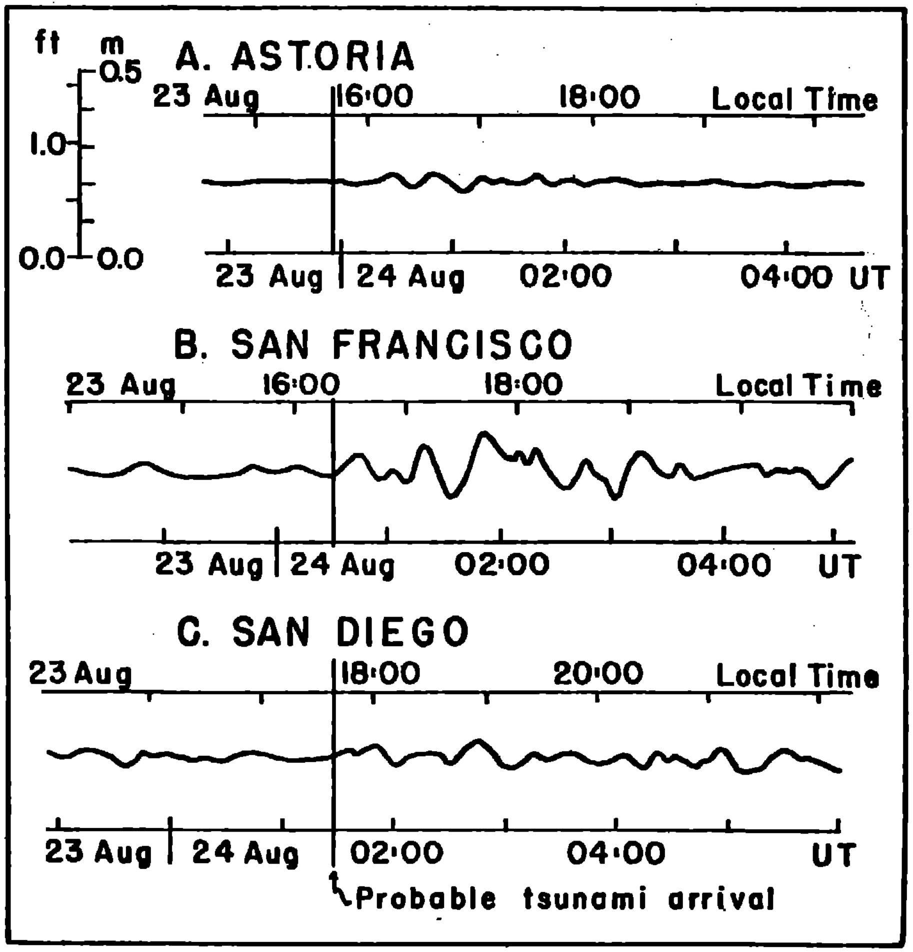


Figure 4. Water-level departures from tide levels derived from marigraphic records

## Arrival times of the 1872 tsunami in Oregon and California

Parts of the Astoria, San Francisco, and San Diego marigrams that show the first detectable oscillations attributable to the tsunami have been plotted to uniform time scales in Figure 3, assuming constant paper speed between the last time check indicated on each record before the tsunami arrival and the first time check after the tsunami arrival. Water-level departures from smooth tide curves drawn by eye through the background and tsunami oscillations on each marigram are shown in Figure 4. The records are aligned in the first figure by Universal Time and in the second on the probable arrival times as finally estimated in this study (in the case of Astoria not one of the arrival times suggested by the marigraphic evidence alone).

The most distinctive of the tsunami traces is that for San Francisco. The first conspicuous evidence of the tsunami on the marigram is a drop in water level beginning at about 16:30 (local time) but not exceeding the rate of tide-level drop until about 16:36. This was, however, preceded by a small crest, more distinctive on the plot of departures from tide level, the rise beginning about 16:21. From the less distinctive traces on the other two marigrams, it would appear that the probable first feature of the tsunami at each place was a crest, the rise at Astoria beginning at about 16:00, and that at San Diego at about 17:37.

It was recognized that what seem from the marigrams to be the earliest recorded features of the tsunami might not be the actual first features. Hence, not only the possible arrival times noted above but the beginnings of other possible tsunami features suggested by the marigraphic evidence are listed in Table 4.

Table 4. Possible arrival times
of the tsunami in Oregon and California.

| Feature identified on marigram as first feature of the tsunami | Arrival time<br>Local 23 Aug | <br>UT 24 Aug |
|---|---|---|
| **Astoria, Oregon** | | |
| (a) Crest (possibly tsunami) | 16:00 | 00:15 |
| (b) Trough (possibly tsunami) | 16.12 | 00:27 |
| (c) Crest (certainly tsunami) | 16:24 | 00:39 |
| **San Francisco, California** | | |
| (a) Crest (probably not tsunami) | 15:53 | 00:03 |
| (b) Trough (probably not tsunami) | 16:00 | 00:10 |
| (c) Crest (probably tsunami) | 16:21 | 00:31 |
| (d) Trough (certainly tsunami) | 16:36 | 00:46 |
| **San Diego, California** | | |
| (a) Crest (probably not tsunami) | 16:47 | 00:36 |
| (b) Trough (probably not tsunami) | 17:00 | 00:49 |
| (c) Crest (possibly tsunami) | 17:37 | 01:26 |
| (d) Trough (possibly tsunami) | 17:48 | 01:37 |
| (e) Crest (certainly tsunami) | 17:50 | 01:39 |

Travel times estimated by the hybrid method between hypothetical sources at a range of longitudes along the northern margin off the Pacific and the Oregon and California ports at which the tsunami was recorded are listed in Table 5, together with San Francisco-Astoria and San Diego-San Francisco travel-time differences. As will be seen, the differences vary only slightly with source longitude. Hence, even if it were certain which of the oscillations recorded at the three ports represented the first feature of the tsunami, a reliable line of position could not be determined from the differences for any pair of the ports. However, the differences permit port-to-port correlations among the oscillations recorded.

Table 5. Tsunami travel times from hypothetical sources to Astoria, San Francisco, and San Diego.

| | | | |
|---|---|---|---|
| Hypothetical source: | | | |
| Longitude | 160°E | 180° | 160°W |
| Latitude | 52½°N | 51½°N | 54½°N |
| Travel times (hr:min) to: | | | |
| Astoria | 8:38 | 6:50 | 5:21 |
| San Francisco | 9:13 | 7:26 | 5:54 |
| San Diego | 10:07 | 8:21 | 6:52 |
| Travel time differences (min): | | | |
| San Francisco minus Astoria | 35 | 36 | 33 |
| San Diego minus San Francisco | 54 | 55 | 58 |

The difference between the arrival times corresponding to the crests identified as (c) in Table 4 for both San Francisco and San Diego is exactly the difference between travel times to these ports from a source at 180° longitude and differs by no more than 3 minutes from the travel-time differences for other possible source longitudes in the Aleutian region. The agreement is almost as good for the arrival times corresponding to the troughs identified as (d), but poor for other comparable features. None of the features identifiable with the tsunami from the Astoria marigraphic evidence were recorded early enough to correlate with features definitely identifiable with the tsunami at the other two ports. Hence it could be concluded that the first feature of the tsunami arriving at San Francisco and San Diego was either the trough identified as (d) or, more probably, the crest identified as (c), and that the first feature arriving at Astoria was too small to distinguish from background oscillations.

## San Francisco-Honolulu arrival-time differences

Possible differences between the arrival times of the 1872 tsunami at San Francisco and Honolulu were calculated, for the range of longitudes of possible sources in the tsunamigenic region along the northern margin of the Pacific, from the full range of possible arrival times at Honolulu suggested by the Hawaiian reports and from the arrival times at San Francisco suggested by both the San Francisco and San Diego marigrams. The probable minimum and maximum differences and most probable values, assuming the first feature of the tsunami in both Hawaii and California was a crest, are listed in Table 6.

## Probable source of the tsunami

San Francisco-Honolulu tsunami travel-time differences for tsunamis originating in the Aleutian region, estimated from the travel times plotted in Figure 2, are shown in Figure 5. Each isochrone in this figure represents, of course, a line of possible source positions for a tsunami whose San Francisco-Honolulu arrival-time difference is equal to the travel-time difference indicated by

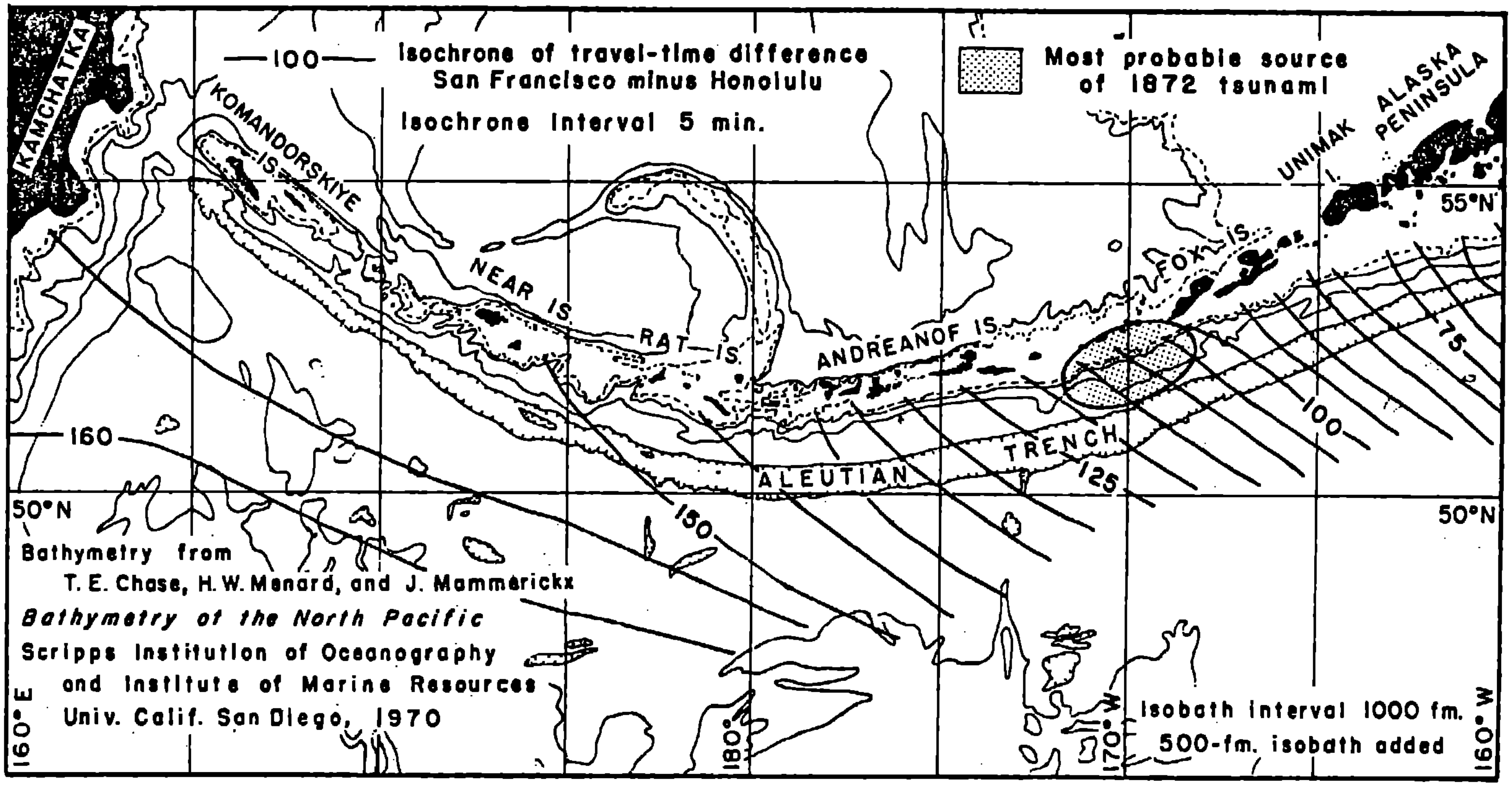


Figure 5. Tsunami travel-time differences, San Francisco-Honolulu, and most probable source of the tsunami

the isochrone. However, because the estimates of possible arrival time differences for the 1872 tsunami were source-longitude dependent, the corresponding respective lines of possible source position could not be considered to correspond exactly to isochrones in the figure even if the tsunami were assumed to have had a point source. Furthermore, the tsunami must actually have originated over a sea-floor displacement that had substantial horizontal dimensions, and differences between its origin time and times of its arrival at Honolulu and San Francisco must have represented travel times to those places from the edge of the source area rather than from its center.

Table 6. San Francisco-Honolulu arrival-time differences for the tsunami.

San Francisco arrival time minus Honolulu arrival time (min), assuming the first feature was a crest.

| | Assumed source longitude | | |
|---|---|---|---|
| Difference | 160°E | 180° | 160°W |
| Probable minimum | 92 | 87 | 81 |
| Most probable | 106 | 111 | 110 |
| Probable maximum | 133 | 132 | 132 |

Assumptions.

| Difference | Arrival times | |
|---|---|---|
| | Honolulu (from Table 5) | San Francisco (See text) |
| Probable minimum | Probable latest | Earlier |
| Most probable | Most probable | Mean |
| Probable maximum | Probable earliest | Later |

Table 7 indicates positions of the center of the source area implied by the probable minimum, the probable maximum, and the most probable of the arrival-time differences listed in Table 6. In the determination of each possible position it was assumed that the boundary of the source area was an ellipse 250 km. long and 125 km wide that was: a) centered near the edge of the continental shelf (actually at the 500-fathom bathymetric contour, ie. at approximately 1000 meters depth); b) elongated parallel to the trend of the Aleutian arc; and c) so located that the difference between Honolulu and San Francisco travel times along isochrones of travel time to those ports, tangent to the southern and southeastern part of the ellipse, was equal to the difference between the arrival times at the two ports corresponding to the longitudes at the respective points of tangency.

The source area suggested by the most probable San Francisco-Honolulu arrival-time difference lies, as indicated in Figure 5, over the continental shelf and slope between the Andreanof Islands and Fox Islands. The origin time of the tsunami corresponding to this source location is 18:02 UT on 23 August. Origin times corresponding to other possible source locations are shown in Table 7.

Whether the first feature of the tsunami in Hawaii or California was assumed to be a crest or a trough turned out to make little difference in the estimation of possible source positions except in the case of the western limit of the range. An arrival-time difference of 162 minutes, corresponding to a source off the northernmost Kuril Islands, would be suggested by the combination of the earliest possible crest arrival time at Honolulu suggested by the Hawaiian reports and the trough arrival time at San Francisco suggested by the San Francisco marigram. However, it is quite unlikely that all of the assumptions represented in this combination are valid, and no other combination would suggest a source west of the central Aleutian Islands. If the tsunami originated at the place and time considered most probable, it should have arrived at Astoria at about 23:56. As indicated in Figure 3, a slight rise in water level was shown on the Astoria marigram beginning at this time, although this rise could not be identified with the tsunami from the evidence of the marigram alone.

Table 7. Possible source locations and origin times of the tsunami assuming first feature was a crest.

| Nature of estimate | Source center | | Origin time UT 23 Aug |
|---|---|---|---|
| | Lat. | Long. | |
| Probable easternmost | 53°N | 165°W | 18:24 |
| Most probable | 52°N | 170°W | 18:02 |
| Probable westernmost | 52°N | 176°W | 17:36 |

## Seismological implications

It is conceivable that the August 1872 tsunami was generated by a submarine slump on the Aleutian continental slope. A slump large enough and rapid enough to cause the tsunami would probably have had to be triggered by an earthquake. More probably, the tsunami was generated by a tectonic displacement of the continental shelf or slope accompanied by an earthquake of considerable magnitude. Hence the possible seismologic implications of the probable source of the 1872 tsunami merit examination.

That there is no report of an Aleutian earthquake occurring at the time the 1872 tsunami was generated is not surprising considering the very small population of the Aleutian Islands at the time and the very poor communications between them and scientific centers.

The Honolulu, Hilo, and San Francisco runup heights and marigraphic amplitudes of tsunamis originating along the Aleutian arc are very poorly correlated with the magnitude of the earthquakes which the tsunamis accompanied. Hence the magnitude of the earthquake with which the 1872 tsunami was probably associated cannot usefully be estimated from the runup heights or marigraphic amplitudes of the tsunami. However, the implications of the probable occurrence of the earthquake with respect to Aleutian seismicity merit discussion.

Two segments of the Alaska-Aleutian arc, one between about 165° E and 170° E longitude off the Komandorskiye (Commander) Islands, the other between about 158° W and 166° W longitude off the Shumagin Islands, have been identified as seismic gaps--segments in which there have been no major tectonic ruptures for over 75 years. Another segment, between about 163° W and 166° W longitude off Unalaska, has been identified as a possible seismic gap (Sykes et al., 1980; Davies et al., 1981; House et al., 1981). The most probable source of the 1872 tsunami was not within a gap, and the Commander gap lies to the west of the probable western limit of possible sources. However, if the source had finite dimensions similar to those considered most probable but lay at the probable eastern limit of possible locations, it might have spanned the postulated Unalaska gap.

The two significant earthquakes occurring most recently in the vicinity of the postulated Unalaska Gap were the tsunamigenic earthquakes of April 1946 and March 1957. The epicenters of those earthquakes were respectively, at about 163° W and 176° W longitude. There is a gap between the rupture zones of those earthquakes if the rupture zones corresponded to the respective aftershock areas. However, using a method similar to that employed in this study, Hatori (1981) has estimated, from the Sitka (Alaska) and Dutch Harbor (Unalaska) arrival times of the tsunami generated by the 1957 rupture, that the source area of that tsunami extended eastward to about 164° W longitude, and from the Ayukawa and Miyako (Japan) arrival times of the tsunami generated by the 1946 rupture, that the source area of that tsunami extended westward to about 168° W longitude. If Hatori's estimates are valid, and if the limits of earthquake rupture zones are indicated better by the source areas of accompanying tsunamis than by the areas of associated aftershocks, there is no seismic gap off Unalaska.

## Acknowledgements

The study reported here, although begun and ended at the University of Hawaii, was carried out for the most part at Boulder, Colorado where I was a guest worker at the National Geophysical and Solar Terrestrial Data Center of the NOAA Environmental Data and Information Service and visiting researcher of the University of Colorado Cooperative Institute for Research in Environmental Sciences. I am indebted to James Lander, Director of the NGSDC, for making the arrangements for my work at the Center and to its staff for various kinds of assistance, particularly John Nelson and Patricia Lockridge who made available the Astoria, San Francisco, and San Diego marigrams.

I am especially indebted to William J. Mass of the Pacific Tsunami Warning Center, Ewa Beach, Hawaii for the computer-derived travel times used in this study, and his critical review of a draft of this report. The availability of Mass's data was initially called to my attention by H. J. Loomis of the Hawaii Institute of Geophysics. T. S. Murty of the Canadian Institute of Ocean Sciences kindly checked on the possible availability of Canadian marigrams on which the tsunamis might have been recorded. Noreen Tashima drafted one of the figures in the report.

Lander, Mass, and Max Wyss of the University of Colorado CIRES reviewed a draft of this report and made suggestions that led to its improvement. Further changes were made on the result of suggestions by a Tsunami Society reviewer. The final version was edited by Jacquelin Miller of the University of Hawaii Environmental Center.

## References

Anon., 1971. Tsunami Travel Time Charts for Use in the Tsunami Warning System (revised edition), NOAA, National Ocean Survey (50 charts).

Brigham, W.T. 1909. The Volcanoes of Kilauea and Mauna Loa, Mem. B.P. Bishop Museum, v. 2, n. 4, 222 pp.

Coan, Titus, 1872. Recent eruption of Mauna Loa. Am. J. Sci., ser. 3 v. 4, n. 23, pp. 406-407.

Cox, D.C. and J. Morgan, 1977, 1978, Local Tsunamis and Possible Local Tsunamis in Hawaii. Univ. of Hawaii, Hawaii Inst. Geophys. HIG-77-14, 118 pp. (Nov 1977); Supplement, 6 pp. (1978).

Cox, D.C., 1980. Source of the Tsunami Associated with the Kalapana (Hawaii) Earthquake of November 1975. Univ. Hawaii, Hawaii Inst. Geophys, 46 pp.

Dana, J.D., 1891, Characteristics of Volcanoes. Dodd, Mead & Co., New York, 399 pp.

Davies, J., L. Sykes, L. House, and K. Jacob, 1981. Shumagin seismic gap, Alaska Peninsula: History of great earthquakes, tectonic setting, and evidence for high seismic potential, Jour. Geophys. Res., v. 86, no. B5, pp. 3821-3855.

Dijkstra, E.W. 1959, A note on two problems in connexion with graphs. Numerische Mathematik, v. 1, pp. 269-271.

Hatori, Tokutaro, 1981. Tsunami magnitude and source area of the Aleutian-Alaska tsunamis. Bull. Earthquake Res. Inst., vol. 56, pp. 97-110.

House, Leigh, L.R. Sykes, J.N. Davies, and K.H. Jacob, 1981. Evidence for a possible seismic gap near Unalaska Island in the eastern Aleutians. Third Maurice Ewing Symposium--Earthquake Prediction, edited by P.W. Simpson and P.G. Richards, Washington, D.C.

Iida, Kumizi, D.C. Cox, and G. Pararas-Carayannis, 1967. Preliminary Catalog of Tsunamis Occurring in the Pacific Ocean. Univ. Hawaii, Hawaii Inst. Geophys. HIG 67-10, (251 pp.).

Jaggar, T.A., 1931, Hawaiian damage from tidal waves. Hawaiian Volc. Obs., Volcano Letter, n. 321, pp. 1-3.

Jaggar, T.A., 1946. The great tidal wave of 1946. Nat. Hist. v. 55, n. 6, pp. 263-268.

Joy, J. W., 1968. Tsunamis and their occurrence along the San Diego County Court. Westinghouse Ocean Nes. Lab. rept. for Unified San Diego Co. Civil Defense & Disaster Erg.

Macdonald, G.A., F.P. Shepard, and D.C. Cox, The tsunami of April 1, 1946 in the Hawaiian Islands, Pacific Science, v. 1, n. 1, pp. 21-37.

Pararas-Carayannis, George, 1969, Catalog of Tsunamis in the Hawaiian Islands. U.S. Coast Geod. Surv., World Data Ctr. A: Solid Earth Geophys. Rep. SE-4, 78 pp.

Pararas-Carayannis and Calebaugh, 1977. Catalog of Tsunamis in Hawaii (revised), U.S. Coast Geod. Surv., World Data Ctr. A: Solid Earth Geophys. Rep. SE-4, 78 pp.

Powers, H.A., The tidal wave of April 1, 1946. Hawaiian Volc. Obs., Volcano Letter, n. 491, pp. 1-4.

Shepard, F.P., G.A. Macdonald, and D.C. Cox, 1950. The tsunami of April 1, 1946. Bull. Scripps Inst. Oceanog., v. 5, n. 6., pp. 391-528.

Solov'ev, S.L., and Ch. N. Go, 1974. Katalog Tsunami na Zapadnom Poberezje Tixgo Oceana (Tsunamis Occurring on Western Coasts of the Pacific Ocean), Akad. NAUK, USSR, 310 pp.

Solov'ev, S.L., and Ch. N. Go, 1975. Katalog Tsunami na Vostocnom Poberezje Tixogo Oceana (Catalog of Tsunamis on Eastern Coasts of the Pacific Ocean), Akad. NAUK, USSR, 203 pp.

Sykes, L.R., J.B. Kisslinger, L. House, J.N. Davies, and K.H. Jacobs, 1980. Rupture zones of great earthquakes in the Alaska-Aleutian arc, 1784 to 1980, Science, v. 210, pp. 1343-1345.

Yale, C.G. (Secretary), 1872. Proceedings, Regular Meeting of October the 7th, 1872, Proc. California Acad. Sci, ser. 1, v. 4, pp. 267-269

# DESIGN AND DEVELOPMENT OF AN INTELLIGENT DIGITAL SYSTEM FOR COMPUTER-AIDED DECISION-MAKING DURING NATURAL HAZARDS

W. M. Adams and G. D. Curtis
University of Hawaii
Honolulu, Hawaii, U.S.A.

## ABSTRACT

In 1975, a Tsunami Seismic Trigger was invented by four people working at the Indiana University at Bloomington. Twelve copies were built and installed at various locations in Hawaii. The design utilized hard-wired logic and a mechanical pendulum. The advent of the microprocessor now prompts the design of a new tsunami seismic trigger, using microprocessors and appropriate support chips. In addition to the improved seismic element, the adaptive algorithmic capability of the microprocessor will provide better threshold-setting and better discrimination in favor of tsunamigenic events. Good design should result in both improved reliability and lower cost-per-unit. Such a tsunami seismic-trigger can assist a local public official in making decisions concerning the need for evacuating people from shorelines that may be inundated by a tsunami generated by a nearby underwater earthquake. The need for such decentralized decision-making is evidenced by the difficulty of maintaining real-time communication capability during a large earthquake. The principles involved may have application in other natural hazard warning systems.

## II. Background

The need for a system to provide immediate alerting of residents of coastal areas in the event of a local (as opposed to a trans-ocean) tsunami has long been felt; a device to form the basis of such a system was developed in 1975 by a group from Indiana University and the University of Hawaii (Adams et al., 1977). There were two previous efforts, resulting in Mark I and Mark II: this work at Indiana evolved through Mark III to the final Mark IV version. Twelve copies of Mark IV were built and installed at various locations in the Hawaiian Islands--generally in police stations near tsunami-hazard areas.

This instrument was based on an inverted-pendulum system which sensed only motion in the horizontal plane, of about 2 Hz and higher. If this motion exceeded a threshold level (mechanically set), an electrical signal was generated. Straightforward logic circuitry determined the number of pulses in a given time window and set off an alarm if a (settable) rate and number were exceeded.

Note that many significant parameters--frequency response, damping, amplitude threshold, timing, etc.--were predetermined in the design process. The number of pulses required for an alarm (a value set upon installation) is the only variable available, and there is no response to vertical motion. Thus, while the device reliably detected strong earthquakes, it had a high ratio of alarms from any such events to actual tsunamigenic events, i.e., false alarms.

Inevitably, this lack of discriminatory ability eroded its utility as part of a warning <u>system</u>. Equally vital parts of a warning system are a monitor (in this case human) to observe and act on the alarm, and rapid and effective steps to evacuate people in priority hazard areas. Many officers on duty--especially as memory of the 1975 tsunami on the Big Island of Hawaii grew dim--did not feel justified in diverting all available forces to an evacuation effort which turned out to be unnecessary (see Cox and Morgan, 1977).

Clearly, a more intelligent sensing, evaluating, and alarming device was needed to assist the decision-making for a reliable and dependable warning <u>system</u>.

The NWS/Pacific Tsunami Warning System had the University of Hawaii install a network which included both seismic and water-level sensors on three of the islands. The original system design was developed by one of the present authors (WMA) and Martin Vitousek of the Hawaii Institute of Geophysics (Adams et al., 1971). All information is telemetered to the warning center by telephone and radio links, where it is manually examined to determine an earthquake greater than a given magnitude. While this reduces "false" alarms, it proved to be susceptible to interruptions in the telemetry (sometimes as a result of a seismic event), and too slow in <u>system</u> response; i.e., evaluating the threat and feeding back the decision to officials in the affected locations in a timely manner.

It seems axiomatic that a rapid and accurate evaluation of tsunamicity, presented to the officer who is in the correct locale, and capable of effective public action, is required for a local tsunami warning system to be useful. Thus, the need for a more sophisticated and highly reliable warning device is obvious. This is now also possible.

## III. Performance Objectives and Specifications

The objectives of this instrumentation may be considered and defined as functions. The Tsunami Trigger (TTT) should:

a. Sense one or more parameters of the ground motion and transduce logarithmically this energy to an electrical signal.

b. Process the inputted electrical signal algorithmically to ascertain, probabilistically, whether or not a large earthquake (greater than threshold magnitude, T), has occurred.

c. Estimate the probable tsunamicity of the source, considering, insofar as feasible:
   1. epicentral distance
   2. focal depth
   3. type of earthquake
   4. dip-slip component

d. Display (list) the estimate for the various parameters found feasible.

e. Activate any alarms deemed appropriate to the set of estimated parameter values.

Which parameters, algorithms, and hardware are to actually be implemented require, of course, value judgments. These are best made by experienced, competent, qualified decision-makers, using standard operational research analyses. Naturally, any game theoretic approach must recognize that nature is not malevolent: the personification of "Mother Nature" must be studiously avoided (Adams, 1966).

The foregoing functional specifications constitute an essential set. Other functions may optionally be selected. For example, in addition to distance to the epicenter, the azimuth to the epicenter merits consideration as a parameter. Also, estimation of source magnitude is a possible parameter. The tsunamicity could be indexed—an alternate to GO-NO-GO thresholding.

These and other options may be treated best by the "cost-to-benefit" (or benefit-to-cost) studies.

## IV. Physical Objectives and Specifications

There is no demand for portability of the tsunami trigger (TTT), hence size, weight, and appearance are assigned low weights.

The sensor should be electrical (instead of mechanical as in the present Mark IV). This provides the continuous signal required to attain the recording option desired for research purposes and permits better analysis for alarm purposes.

The geophone should sense the vertical component of motion (instead of the horizontal as in the Mark IV). Thus the sensed parameter correlates better with the dip-slip component of the fault motion.

Particle motion in 3-D should also be obtained. A variety of geophone arrays should be evaluated, following standard antennae theory for infinitesimal elements.

Isolation, amplification, and digitization should all be performed at each sensor. This will minimize error growth due to transmission distortion. Error-correcting codes had best be used.

A choice between relative and absolute timing is essential. Optionally, timing can be derived from toroidal crystals, and if temperature independence is considered to be of great importance, then the differencing of two or more toroidal crystals may be used. The output can, of course, be slaved to atomic standards.

Power is supplied from the AC lines, backed up by lithium batteries. These have the advantages of high energy density and long shelf lives. Thus, an uninterruptible power supply (UPS) is provided. Figure 1 depicts the architecture and applicability of the system.

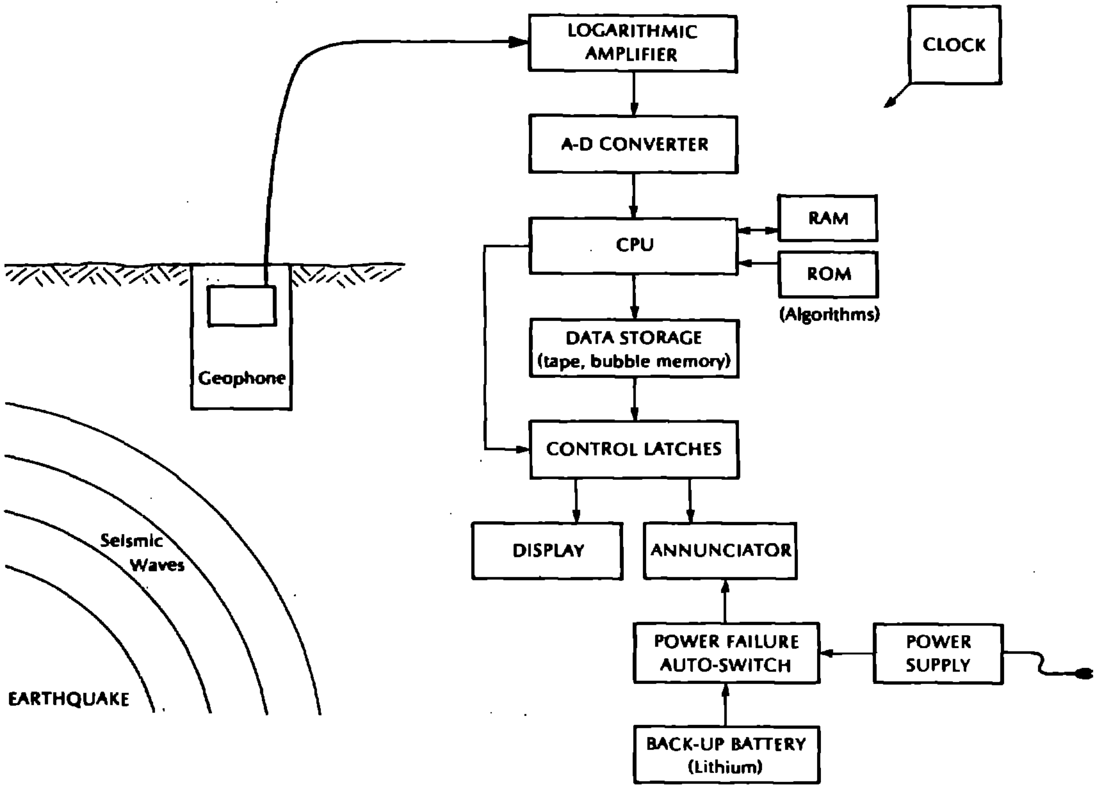


Fig. 1. Block diagram of system components.

The algorithms installed should be subjected to thorough testing by appropriate quality assurance and knowledgable verification processes (see Adams, 1981a). These requirements, although both time-consuming and consequently expensive, provide insurance for credibility and anti-false alarms—features often overlooked in such instrumentation systems.

Displays and alarms must be self-adaptive in space and time. The need for daisy-chaining, as to several physical levels in a hardened command-control post, is apparent.

Effectiveness of the alarming, like the displays, is more dependent on the synoptic condition of the monitors than on the physical and financial constraints. An adaptive optimization analysis incorporating the time variations is most appropriate (see Adams, 1966).

## V. Design Trade-offs and Reliability Analysis

The most significant choice is the cut between the hard-software and the human monitor. Heretofore the processing by the machine has been termed "analysis" and that by the monitoring person "interpretation." Now that the machines can either learn, or be taught, the "interpretation," i.e., are potentially intelligent, this decision is even more difficult--one may choose to avoid making the monitor seem superfluous (see Adams, 1981b).

Other choices are associated with the reliablity of the system. One way of considering this, assuming perfect hardware, is to designate the variance deemed necessary for the respective parameters. Cost then is weighted inversely with the variance sought.

An example of instrumentation which achieves a MTBF of about 200 years is the Swiss Cesium time base, which also has a precision of $10^{-11}$, manufactured by Oscilloquartz. The design consists of three of the Cesium frequency standards phase-lock-looped to one another (Electronics, 1 December 1983, p. 86). Because so much is now technically possible, adherence to achieving specifications derived from users′ needs is far more satisfying (and, incidentally, more likely to be competitive in the scramble for funding) than simply listing the state-of-the-art for every specification. (How many A-D converters really <u>need</u> to be 16 bit?)

Best is the practice of breadboarding and developing with a plan of sequential upgrade; this approach minimizes the likelihood of entrepreneuers searching in some blind alley of the maze of routes for possible changes.

## VI. Cost-to-Benefit Analysis

Costs can be estimated from those incurred with the Mark IV Tsunami Seismic-Trigger. The entire program, including the preliminary, non-operational prototype Mark III, fifteen copies of Mark IV, and travel for installation cost only $40,000 (1976 dollars). Even then, that seemed fortuitously low. So a comparable estimate in 1985 dollars seems to be about $90,000 for twelve copies of the base model, i.e., options and peripherals extra.

Benefits, on the other hand, necessitate considerably more conjecture. If the value of a life saved be assigned a dollar value of $200,000--a not uncommon value in cost-to-benefit studies--and one life is saved per instrument each time TTT is queried (when the ground shakes noticeably), then a query once per ten years at an annualization of $1,000 <u>per instrument</u> should prompt this capital investment, using discounted present-value theory.

Two things must be recalled: (1) such an instrument can also save a life by preventing chaos unnecessarily, i.e., by indicating to a regional civil-defense officer that a coastal evacuation is <u>not</u> warranted (see Adams et al., 1977), and (2) this cost/benefit analysis is for the first dozen units; for subsequent production in larger lots, the costs would be significantly lower per unit, thus improving the already favorable ratio.

## VII. Summary and Conclusions

The advent of economical, ubiquitous microelectronics permits quantum improvements in existing seismic alarms, based on concepts of threshold switching. These advances will involve both the quality of the association and the reliability (that is, less false alarming) achievable by redundancy.

The trend has been from centralized decision-making to regional decision-making for a variety of reasons reviewed elsewhere. Being now caught up in the tide of "personal computing," we would have but little astonishment to see an advertisement for an upgrade kit that would modify a personal computer so that it could function as a zeroth-order TTT. Can that day be far away?

## VIII. References

Adams, W. M., Analysis of a tsunami warning system as a decision-making process, IX Pacific Science Congress, Tokyo, Japan, August 1966, Proceedings of Symposium of Tsunamis and Storm Surges. (HIG contributon 154)

Adams, W. M., A standard vocabulary for tsunami study, presented at the Meeting held by the Tsunami Commission, Wellington, New Zealand, 1977.

Adams, W. M., Relationship of instruments and policy in the Hawaii Warning System, Proceedings of the Ensenada, Mexico, Meeting of the Tsunami Committee, International Union of Geodesy and Geophysics, March 1977, condensation of about ten pages. Appears in full in Marine Geology.

Adams, W. M., Verification, calibration and quality control for tsunami models, presented at the Tsunami Symposium, May 1981a, Sendai and Ofunato, Japan.

Adams, W. M., "Tsunamis, computers and mankind," a popular lecture deliverd in Ofunato, Japan, May 1981b. Interpretation into Japanese was by Naoko Nakashizuka Adams, wife of the author and speaker.

Adams, W. M., R. Blakely, C. Ellis and J. Mead, A signal selective trigger for local tsunami warning, 1977, HIG Report 77-16.

Cox, D. C. and J. Morgan, Local tsunamis and possible local tsunamis in Hawaii, HIG 77-14, 1977.

Adams, W. M., J. Malina, Jr. and R. Nishioka, A seismic trigger for the tsunami warning siren, Cooperative Institute for Research in Environmental Sciences (CIRES), Univ. of Colorado, 1971.

Hawaii Institute of Geophysics Contribution No. 1466.

# VERIFICATION, CALIBRATION AND QUALITY ASSURANCE FOR TSUNAMI MODELS

Wm. Mansfield Adams
University of Hawaii
Honolulu, Hawaii, USA

## ABSTRACT

Numerical modeling has passed from an art to a science. Now each model being presented should have substantiating verification and quality assurance. Verification means the check against the results of an analytical model wherever that is possible; quality assurance is stating statistically the state of evolution of the particular computer program. Calibration is the estimation of coefficients or local parameters from field data; e.g., the Chezy coefficient or its equivalent. Theoretically, the verification, calibration, and quality assurance of a 2- or 3-dimensional model is almost identical to that of a 1-dimensional model. The significance of this is that procedures may be developed for the simple 1-dimensional model and then elaborated for the higher dimensions without requiring extensive theoretical justification. Alternatively expressed, in mechanistic terms, a perception is not necessary--a Turing machine is adequate. Memories that are content addressable may reduce the complexity of the computability.

## INTRODUCTION

Mankind has been trying to "tell" machines what to do for more than a century--about the lifetime of a variety of machines now existing in quantity. For the past quarter-century, this effort to talk to machines has concentrated on storing the message in the machine evanesently: this has the advantage that the instructions may change themselves--a concept attributed to Von Neumann--and the disadvantage that the message, the set of instructions, are lost when the power line is turned off or interrupted. The earlier form of instructions carried on cards, tapes, etc. may be assigned to what is now termed "firmware."

Because of this relatively recent rise to eminence, software, as the set of instructions for a machine is usually called, has been in a state of evolution. Progress has consisted more of multiplication and proliferation than mutations of higher level "families".

This multiplicity, in itself, tends to be overpowering to the novice or dilettante. The attempt to reason by analogy of the machine language to oral languages soon becomes bogged down because of the extreme differences, but a most important point becomes immediately obvious: the machine languages are going to evolve in the direction of the oral languages, that is, greater complexity.

A computer programmer produces software. The well-known procedure is: (1) analyze the problem, (2) select the appropriate algorithms, (3) code, and (4) debug.

A new-hire programmer usually starts coding and, with sufficient "marination," becomes an analyzer. Comparison of this procedure for producing software with production of computer hardware is very instructive. For example, in the production of computer hardware, very important steps are the "burning in" and the quality control--both steps that are effectively missing in the production of software.

The other feature of software production that stands out is its high cost. And this does not mean to include consequential costs! Just the debugged high-level language results average more than $10 per line, and higher is more likely than lower. A skewed distribution, if you will. Addition of the equivalents of "burning in" and quality control, if such seems desirable and possible, can but raise the cost.

Here we wish to consider what might be done to improve both the quality and the quantity of software produced. Our motivation for making this effort is that computer programs are being routinely used to model physical phenomena, in particular physical phenomena which cannot be observed easily in nature due to remoteness--as the core of the earth functioning as a dynamo--or due to rarity--as in the case of tsunamis. Often the computer model assumes an aura of life in itself that soon allows the prototype problem to be set aside. That is, the computer model becomes "right" and nature is defective if it does not follow the model! (Perhaps the precedence for this acceptance is from the law, where the decisions of the courts are taken as "right" even when inconsistency between the courts, changes in a given court over time, and political control over the court decisions become blatant.)

We take three approaches, the first being the theoretical classification of computer languages--existing and contemplated--and the second being the forcing of computer programming into the mold of quality control. Lastly we will leave the quantitative and venture into the qualitative, to consider what improvement can be achieved by less objective techniques.

## FORMALIZATION OF COMPUTER LANGUAGES

From the interactions of mathematicians and their logic, linguists and their grammars, engineers and their switching circuits, and zoologists with their neuron models has evolved the multi-disciplinary study of formal languages, now often taught in courses called computer science. The concepts of sets, relations, graphs, and canonical machines become beautifully and productively organized on the hinge-pin of concatenation. As a summary, languages may be objectively defined quantitatively and qualitatively by defining corresponding grammars--where a grammar is a set of relations for transforming symbols of a set. The progressive generality of the relations allows the classification of the grammars, and hence the languages, into progressively more general classes, each inclusive of the former. These are, from simplest upwards, the regular, the context-free, the context sensitive, and the recursively enumerable. And there is nothing more general than the recursively enumerable (within the assumptions of the theory).

Many are the astonishing, un-intuitive results that are spun off in developing such a classification system. Perhaps the most useful immediately is the equivalence of a conceptual machine to each grammar (or language). To the regular sets corresponds the finite deterministic automaton; to the context-free sets corresponds the push-down automaton; to the context-sensitive sets corresponds the linear-bounded automaton; and to the recursively enumerable, the Turing Machine--so talked about and so little understood in its full generality. All other machines prove to be reducible to these canonical ones.

Other results, such as that every non-deterministic finite automation can be equated to some deterministic finite automaton, are encouraging; some results, such as the existence of inherently ambiguous context-free languages, are momentarily discouraging, until we realize that there is a benefit to knowing, in a fog, where you stand--even if it is on a pinnacle. Especially if it is on a pinnacle! The generality and practical consequences of these "throw-away" theorems is positively intoxicating. The practicality is most cogently demonstrated by the efficiency of the parsers in current compilers compared to those in early compilers.

Those choosing to follow this theoretical approach will find enlightment in Hopcroft and Ullman (1979).

## QUALITY CONTROL OF SOFTWARE

Although many have argued fervently that programming is an art and, as a corollary, not subject to quality control, their antagonists have adamantly forced programming into the conventional production model. And with advantages that are to be disdained only at the risk of becoming un-competitive. The modus operandus of this approach will be set forth here in the hope of persuading the reader that his own programming will benefit by the incorporation of this approach. It can be adapted, in fact, to any approach to programming, necessitating only additional monitoring of the process--somewhat akin to documenting your lifestyle in preparation for auditing by the tax collector.

Quality assurance can function in many of the stages of programming production, but here we will concentrate on the quantitative aspects of software testing. We wish to make a statement about the level of confidence which can be placed on the statement, "there are no more bugs in the program." To do this, we test the program by running it in a novel way. And we do this repeatedly. From this process we discern, occasionally, bugs--malfunctions--in the program. We log the process. To interpret these observations, we assume that the probability of finding a new bug is proportional to the number of bugs remaining. Based on this assumption, a model can be developed (Tausworthe, 1979). This model predicts that, on the average, an ensemble of such testing processes will discover bugs at a mean rate and the deviations of the observations from this mean rate will have a characteristic standard deviation. The model finds that the average time to detect a bug, for n bugs, is

$$\bar{T}_n = \text{avg}(T_n) = \frac{1}{\beta} \sum_{k=0}^{n-1} \frac{1}{A - k}$$

where A is the total number of bugs in the program (actually an unknown) beta is
an efficiency of detection parameter
and Tsubn is the total applied time required to find the n bugs.

This function is graphed in Figure 1. The coordinates are the number of anomalies, in total, and the average normalized time. The number on each of the curves is A, the total number of bugs in the program. Since the time axis is logarithmic, the advantages of having a small number of bugs when initiating debugging are apparent! It takes ten times as long to debug a program having a hundred bugs as a program having ten bugs--that is, to the same level of confidence.

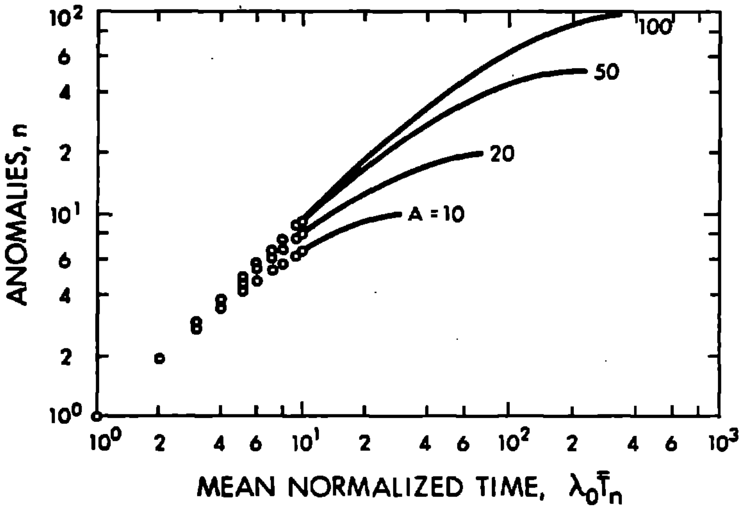


Figure 1 Mean time to find the nth bug, with time normalized by the intial discovery rate, assumed to be a constant. (After Tausworthe, 1979).

The mean-square variance for the deviation of the observations about this mean time is

$$\mathrm{var}(T_n) = \frac{1}{\beta^2} \sum_{k=0}^{n-1} \frac{1}{(A - k)^2}$$

where the symbols mean the same as in the previous equation. This function is graphed in Figure 2.

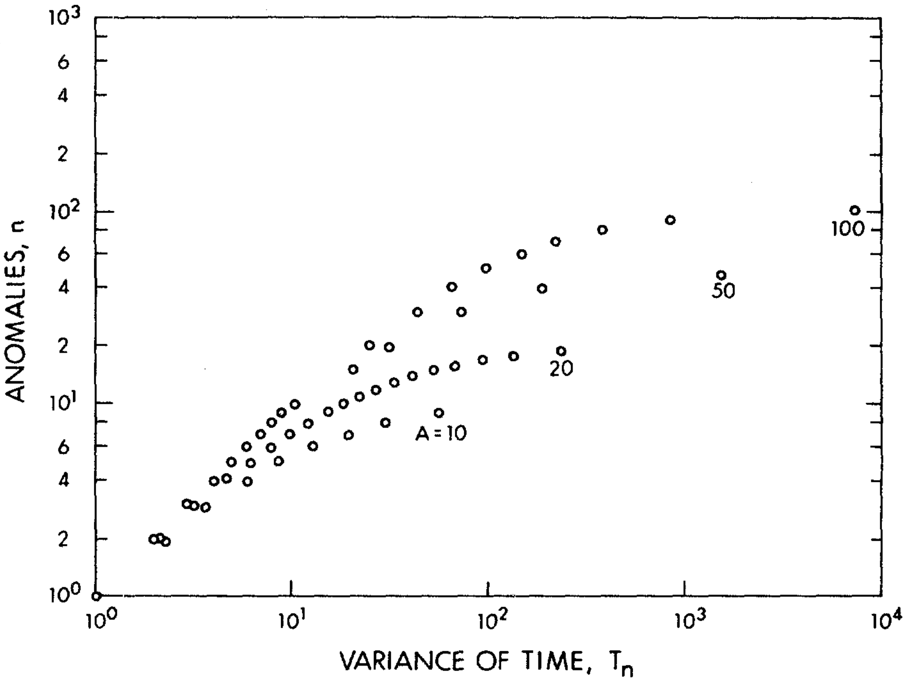


Figure 2 Mean square variance of the time to find the nth bug, variance normalized by the square of the initial discovery rate, assumed to be constant.

Most informative is to inspect the ratio of the variance to the square of the mean (thus making it dimensionless). Then the square root of this ratio is the average relative-completion during the debugging process. This ratio is plotted in Figure 3. From this graph we can estimate the percentage of total effort that will be required to find the last ten percent of the bugs. For 100 bugs, the last ten will take 44% of the total debugging effort, on the average; for 1000 bugs, the last ten percent, 100 bugs, will take 70% of the total debugging effort, on the average. Again an indication of the importance of initiating debugging with as high a quality program as possible.

This testing process is analogous to testing electrical components to ascertain the "mean time between failures" or some other index. From the process, we wish to estimate the values of A and beta. These may be estimated by the maximum-likelihood technique. The resulting equations are

$$AT_n - \frac{n}{\beta} = \sum_{k=1}^{n} (k - 1)t_k$$

$$\beta T_n = \sum_{k=0}^{n-1} \frac{1}{A - k}$$

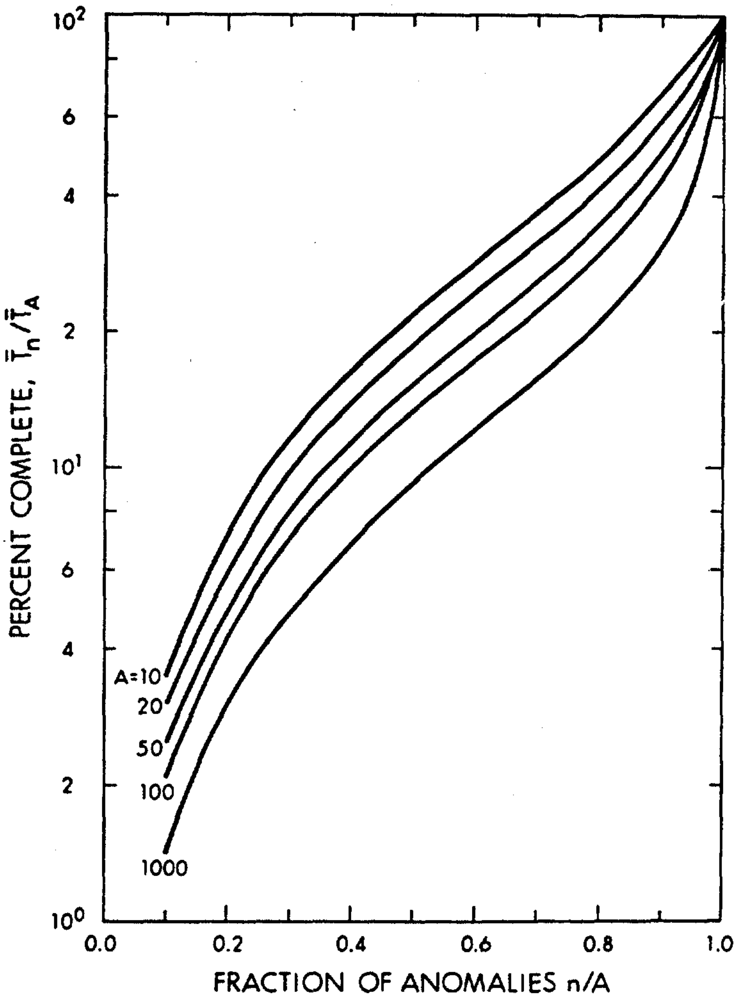


Figure 3 Mean time to find the nth bug, normalized to the mean time to find the last bug. (After Tausworthe, 1979.)

These do not need to be fit simultaneously. Substitute the second into the first, eliminating beta. The resulting function is plotted in Figure 4. The values on the curves are the number of bugs already discovered. Thus to use the figure, enter on the vertical axis with the value observed from experimentation, go to the curve corresponding to the number of discovered bugs, and drop down to the horizontal axis to obtain an estimate of the total number of bugs that were in the program when the debugging process began. This value is then substituted into the second of the last pair of equations to obtain an estimate for beta. Trying a few typical values on this graph will soon reveal one discouraging result--the number of bugs discovered must be a significant percentage of the total number of bugs before a reliable estimate of the total number of bugs can be obtained.

The foregoing analysis is based on the assumption that constant level of debugging effort is being expended to find bugs using methods that randomly find the remaining bugs. An obvious course of action is to either design the testing so that bugs are discovered more efficiently, non-randomly, or to work harder! Or both.

Of course, usage of the program in a production environment is really just a continuation of the testing conducted under the quality assurance, so meticulous records should continue to be maintained on the times of discovering

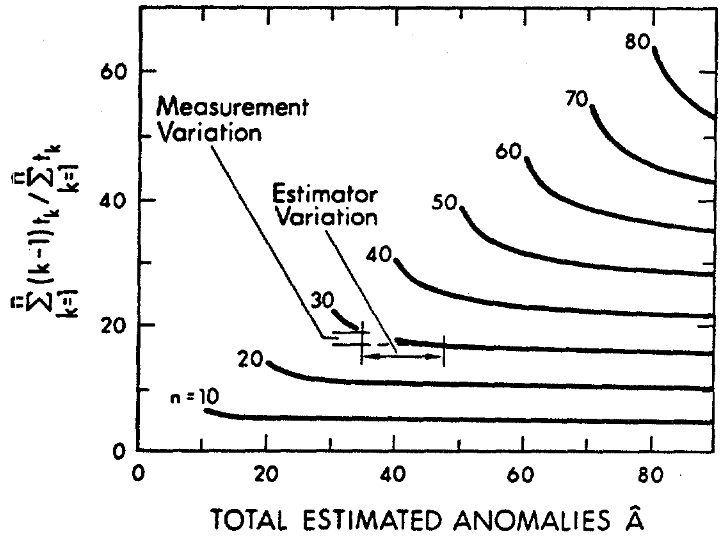


Figure 4 Based on maximum-likelihood estimation, estimates the total number of bugs, given the time history of the n bugs founds.

bugs (in terms of run time, not chronological time, of course) so that the estimates of the values of A and beta can be revised.

For further details on interpreting the mean time between discoveries of bugs, see Wolverton and Schick (1972) and/or Musa (1975).

We have considered the theoretical and quantitative approaches to improving the quality of software and found that both can be productive. Now let us consider the qualitative approach.

## QUALITATIVE APPROACH TO IMPROVING SOFTWARE QUALITY

The overall objective of science is to quantify with the intent of being able to predict. This should not be interpreted, however, to mean that scientists disdain that which is not quantified. Indeed, that is the raw material that is to be quantified! As demonstrated in the previous section on quality assurance, the quality control should be started with as high quality program as possible in order to reduce the resources required to upgrade the quality of the program. This also justifies consideration of qualitative aspects of improving software quality.

The concept of structured programming has been so belabored, from top-down to bottom-up, that additional discussion here is not necessary. So we think in terms of modular programming. There are two major features of the modules in the program that must be emphasized. These are the module strength and the coupling between or among the modules.

Module Strength: We consider each module to be composed of elements, where an element is a statement or some identifiable set of statements smaller than the module itself. We now wish to identify the types of module strength; these need not be mutually independent. For example, if there is no significant relationship among the elements in a module, we consider it to have coincidental strength. If there are some logical relationships among the elements, then we term that logical strength. If there is temporal relation between the elements as well as logical relation, then we call this classical strength. If the procedures must also be performed at the same time, in a multi-procedural module, then the module has procedural strength. If, in addition, all of the elements communicate with one another, then the module is said to have communicational strength. If the module has communicational strength and also deals with a single data structure then the module has informational strength. If all of the elements in the module contribute to the performance of a single function, then the module has functional strength. We now consider the ordering of these various forms of module strength. As indicated by the definitions, the type of strength is determined by the features of the module. These possibilities are arranged in summary matrix style in Figure 5.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Difficult to describe the module's function(s) | Y | N | N | N | N | N | N | N |
| Module performs more than one function | | | Y | Y | Y | Y | Y | N |
| Only one function performed per invocation | | | Y | N | N | N | Y | |
| Each function has an entry point | | | N | | | | Y | |
| Module performs related class of functions | | N | Y | Y | | | | |
| Functions are related to problem's procedure | | | | N | Y | Y | | |
| All of the functions use the same data | | | | | N | Y | Y | |
| Coincidental | X | X | | | | | | |
| Logical | | | X | | | | | |
| Classical | | | | X | | | | |
| Procedural | | | | | X | | | |
| Communicational | | | | | | X | | |
| Informational | | | | | | | X | |
| Functional | | | | | | | | X |

Figure 5a **Matrix to determine type of module strength.**

| *Strength* | *Value* |
|---|---|
| Coincidental | .95 |
| Logical | .4 |
| Classical | .6 |
| Procedural | .4 |
| Communicational | .25 |
| Informational | .2 |
| Functional | .2 |

Figure 5b **Weight for type of strength. (After Myers, 1975)**

To use, estimate if the module has the particular property. If yes, then so indicate. Any module should be able to be placed in one (or more) strength category. Use the highest classification.

The scale of strength runs from coincidental to functional with increasing strength. Strength is increasing the relationships within a module. This is considered desirable insofar as it decreases the relationships among modules.

Module Coupling: The effect of coupling can be easily understood from a concrete example. Think of one hundred light bulbs which follow these rules;

(1) if on, go off during next second with 50% probability.

(2) If off, go on during next second with 50% probability IF one or more connected bulbs is on.

Now consider the performance of this set of 100 bulbs under three types of interconnections. First, no connection between bulbs. It can be shown that the time before all the lamps go off is less than eight seconds. Next consider each bulb connected to every other bulb--the other extreme. Then the time for all bulbs to go off, averaged across an ensemble of such bulb sets is more than 10 to the 29 seconds! For an intermediate condition, consider the bulbs arranged in ten non-connected sets of 10 fully connected bulbs. Then the expected time for all bulbs to go off is 1200 seconds.

This demonstrates heuristically that we should strive to make the coupling between modules minimum. Of course, some coupling is necessary since the set of modules comprise a computer program, presumably performing some task.

If one module refers directly to the contents of another module, use a shared global data structure, then each has common coupling. If two modules each refer to the same externally declared symbol, they are said to have external coupling. If a module passes elements of control as arguments to another module, then the coupling is control coupling. If two modules refer to the same non-global data structure, then they are said to be stamp coupled. If one module passes all input and output to and from another module as data-element arguments, then the coupling is data coupling. A matrix of attributes for the coupling between modules is given as Figure 6 and should permit assigning any coupling to one of these types.

Modeling Program Stability Using Strength and Coupling Types

An algorithm has been developed for modeling the stability of a computer program with the use of types of coupling and types of strength (Myers, 1975). The results of the algorithm is a matrix giving the probability of having to change one particular module if another particular module must be altered. The algorithm is as follows:

Form a matrix with the elements having the coupling values between the respective row and column modules. The matrix will be symmetric.

Form a vector with each element having the strength values of the corresponding module. Elements are ordered in the vector in the same order as the rows and columns of the coupling matrix. Now combine these data using the formula

$$D_{ij} = 0.15(S_i + S_j) + 0.7\ C_{ij} \text{ where } C_{ij} \neq 0$$
$$D_{ij} = 0 \text{ where } C_{ij} = 0$$
$$D_{ij} = 1 \text{ for all } i$$

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Direct reference between the modules | Y | | N | N | N | N | N |
| Modules are packaged together | | Y | N | N | N | N | N |
| Some interface data is external or global | | | Y | Y | N | N | N |
| Some interface data is control information | | | | | Y | N | N |
| Some interface data is in a data structure | | | Y | N | | Y | N |
| Content coupling | X | X | | | | | |
| Common coupling | | | X | | | | |
| External coupling | | | | X | | | |
| Control coupling | | | | | X | | |
| Stamp coupling | | | | | | X | |
| Data coupling | | | | | | | X |

Figure 6a **Matrix to determine type of module coupling.**

| *Coupling* | *Value* |
|---|---|
| Content | .95 |
| Common | .7 |
| External | .6 |
| Control | .5 |
| Stamp | .35 |
| Data | .2 |

Figure 6b Weight for type of coupling. (After Myers, 1975)

to produce another matrix, called the first-order dependence matrix. If there is only one path from each module to every other module, then this is satisfactory. However, in general, there is more than one path from some module to some other module: to include this feature in the analysis is likely to be quite complicated for many multi-paths—deserving of a computer program of its own! This program is provided by Myers (1975) together with details. The resulting matrix is termed the complete dependence matrix. It can be used to compare alternate modular structures for the same program before any coding is begun.

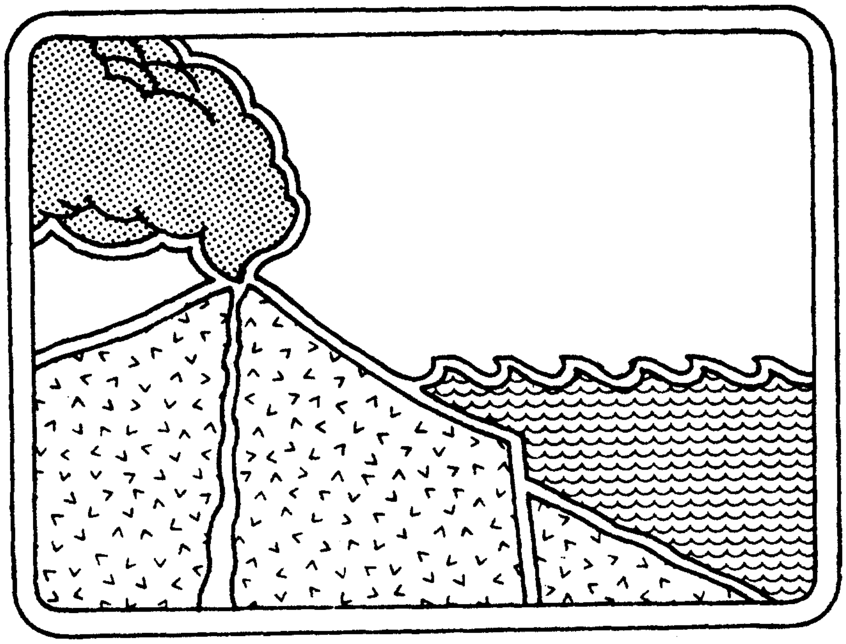
Hopcroft, John E., and J. D. Ullman, Introduction to Automata Theory, Languages, and Computation, published by Addison-Wesley, 1979, 418 pages.

Musa, J. D. "A Theory of Software Reliability and its Application," IEEE Transactions on Software Engineering, Volume SE-1, No. 3, pp. 312-327, Sept. 1975.

Myers, G. J., "Reliable Software Through Composite Design," published by Petrocelli/Charter, New York, 1975, 159 pages.

Tausworthe, R. C., "Standardized Development of Computer Software," Part II, Standards; Prentice-Hall, Inc. 1979, 548 pages.

Wolverton, G., and R. Shock, "Assessment of Software Reliability," Proceedings of the 11th Meeting of the German Operations Research Society, Hamburg, Germany, September, 1972.



# MODELING OF TSUNAMI DIRECTIVITY

A. Zielinski
Memorial University of Newfoundland
St. John's, Newfoundland, A1B 3X5
Canada

N. K. Saxena
Naval Postgraduate School
Monterey, CA 93943, U.S.A.
(on sabbatical leave from the University of Hawaii)

## ABSTRACT

Using a simple, one-dimensional model for tsunami propagation the far-field tsunami directivity is discussed. An expression for tsunami beamwidth $\Omega$ has been found to be

$$\Omega = 2 \sin^{-1}\{\frac{0.443T_0 \sqrt{gh}}{L}\}$$

where $T_0$ - tsunami period
h - open-ocean depth
L - length of fault
g - gravitational acceleration

Beamwidths as small as 16° are predicted by the model developed through using realistic tsunamic parameters.

## INTRODUCTION

The existence of directivity of wave radiation from a tsunami source has been recognized for some time (Miyoshi, 1955). Far-field tsunami patterns may exhibit remarkable directivity (Kajiura, 1970, 1972) with amplitude variations up to 14:1 depending upon the angular position of an observer with respect to the source (Ben-Menahem and Rosenman, 1972). This phenomenon plays an important role in tsunami prediction and warning (Zielinski and Saxena, 1983). Radiation patterns and associated parameters will affect the location and spatial distribution of deep-ocean pressure sensors for a Tsunami Warning System such as has been suggested by Saxena and Zielinski (1981). Directional effects also are important in the consideration of an objective tsunami magnitude scale (Murty and Loomis, 1980).

We propose here a simple, one-dimensional model for tsunami directivity which links beamwidth with dominant frequency and fault length. In spite of its simplicity, the model could provide useful engineering information for the design of an open-ocean tsunami measurement system.

## I. SOURCE DIRECTIVITY

We will use a "line transducer" of length L corresponding approximately to the fault length and driven by a signal x(t) to represent a tsunami source. For a harmonic driving signal $x(t) = e^{j\omega t}$, the far-field radiation pattern of such a transducer (neglecting geometrical spreading) is described by the well known directivity function D(K) (Tucker and Gazey, 1966).

$$D(K) = \int_{-\infty}^{\infty} T(r)e^{-Kr}dr = F\{T(r)\}, \quad (1)$$

where T(r) is the transducer taper function and F{•} represents the Fourier transform. Variable K in Eq. (1) depends upon angle $\alpha$ between a line normal to the transducer and a direction of interest, that is

$$K = (\omega/c)\sin\alpha \quad (2)$$

where c is the phase velocity of wave propagation.
For a uniform taper,

$$T(r) = \begin{cases} 1/L & \text{for } |r| < \frac{L}{2} \\ 0 & \text{for } |r| > \frac{L}{2} \end{cases} \quad (3)$$

Equation (1) yields

$$D(K) = \frac{\sin(KL/2)}{KL/2} \quad (4)$$

Most of tsunamis originate in relatively shallow shelf waters and propagate towards the open ocean through steep continental rises with a depth dependent velocity $c = \sqrt{gh}$. At the depth discontinuity, the wave is refracted according to Snell's law (King and LeBlond, 1982). This constitutes a "defocusing" effect for a directive tsunami generated in shallow water, and the shallow water directivity function $D(\alpha_s)$ has to be modified accordingly to obtain the deep water directivity $D(\alpha_d)$. It is clear that the necessary modification is

$$D(\alpha_d) = D(\alpha_s) \quad \text{with } \alpha_s = \sin^{-1}\left(\sqrt{\frac{h_1}{h_2}}\sin\alpha_d\right), \quad (5)$$

where $h_1$, $h_2$ represents water depth at the shelf and in the open ocean, respectively. It should be noted that, because of the closeness to the source, a shallow far-field directivity function cannot be used to describe propagation on the shelf. It can, however, be used to describe the far-field condition in the open ocean as given by Eq. (5). The angle at which $D(\alpha_d)$ crosses zero can be used to estimate "broadness" of the main lobe of the radiation pattern. For the line transducer this angle is given by

$$\alpha_0 = \sin^{-1} \frac{\lambda}{L}\sqrt{\frac{h_2}{h_1}}, \tag{6}$$

where wavelength $\lambda = c/f$ and $f = \omega/2\pi$.

## II. IMPULSE SOURCE

The analysis presented so far applies only to harmonic disturbances with specified wavelengths or frequencies. Actual generation of a tsunami, however, has an impulsive character, and a tsunami wave contains a range of frequencies. The directivity function changes with frequency, but if a proper, dominant frequency is selected, it still can be useful approximation of tsunami radiation patterns.

For more detailed time-domain analysis, it is convenient to model a tsunami disturbance as a transducer driven by an impulsive signal $x(t)$, and to observe its transformations along a selected propagation angle $\alpha$. We note that for a fixed $\alpha$, the directivity function is frequency dependent through parameter K,

$$D(K(\alpha,\omega)) = D_\alpha(\omega)$$

According to the superposition principle, the Fourier transform of a tsunami signature in $\alpha$ direction $Y_\alpha(\omega)$ can be written as

$$Y_\alpha(\omega) = D_\alpha(\omega)\ X(\omega) \tag{7}$$

where

$$Y_\alpha(\omega) = F\{y_\alpha(t)\}$$

$$X(\omega) = F\{x(t)\}$$

Equation (7) represents a filtering operation performed on the driving signal $x(t)$. The time-domain tsunami signature can be found by applying the inverse Fourier transform on Eq. (7), that is

$$y_\alpha(t) = F^{-1}\{Y_\alpha(\omega)\} = F^{-1}\{D_\alpha(\omega)\ X(\omega)\} \tag{8}$$

or by invoking the convolution theorem

$$y_\alpha(t) = d_\alpha(t) * x(t) \tag{9}$$

where

$$d_\alpha(t) = F^{-1}\{D_\alpha(\omega)\} \tag{10}$$

and the asterisk indicated the convolution operation. With given $d_\alpha(t)$, Eq. (9) provides a useful graphic interpretation of the relationship existing between $x(t)$ and $Y_\alpha(t)$.

For the line transducer, the frequency dependence of the directivity function is found to be

$$D_\alpha(\omega) = \frac{\sin r\omega}{r\omega} \tag{11}$$

where

$$r = \frac{L \sin \alpha}{2\sqrt{gh_2}} \tag{12}$$

The function given by Eq. (11) indicates that a low-pass filtering is performed on x(t) in all directions except $\alpha = 0$ (normal to the transducer). We will interpret x(t) as an open-ocean, far-field tsunami signature, as observed in the direction normal to the fault (transducer), and we will investigate the dependence of a tsunami relative amplitude upon direction $\alpha$.

Let us approximate the leading wave of a tsunami in $\alpha$=0 direction as

$$y_0(t) = x(t) = A_0 \sin(2\pi t/T_0); \quad 0 \leq t \leq T_0/2 \tag{13}$$

where $A_0$ is the tsunami amplitude, and $T_0$ is the tsunami period. We will find the tsunami amplitude $A(\alpha)$ in a $\alpha$ direction using convolution equation (9).

Function $d_\alpha(t)$ given by Eq. (9) (impulse response of the filter) is readily found to be

$$d_\alpha(t) = \begin{cases} \frac{1}{2r} & \text{for } |t| < r \\ 0 & \text{for } |t| > r \\ \delta(t) & \text{for } \alpha = 0° \end{cases} \tag{14}$$

Using Eqs. (14), (13) and (9), one can show that the directivity function for the leading wave of a tsunami becomes

$$G(r(\alpha)) = \frac{A(\alpha)}{A_0} = \begin{cases} \sin(2\pi r/T_0)/(2\pi r/T_0) & \text{for } r < T_0/4 \\ T_0/2\pi r & \text{for } r > T_0/4 \end{cases} \tag{15}$$

It is convenient to characterize the directivity of a tsunami in terms of its half-energy beamwidth $\Omega$. Using Eq. (15) one can readily find

$$\Omega = 2\alpha_0 = 2 \sin^{-1} \left\{\frac{0.443\ T_0 \sqrt{gh_2}}{L}\right\} \tag{16}$$

where $G(r(\alpha_0)) = 1/\sqrt{2}$,

## III. CONCLUSIONS

Tsunamis with short periods generated by elongated earthquakes may exhibit a high directivity of energy radiation. For a typical open-ocean depth of 4.5 km, a fault length of 200 km, and a tsunami period of 5 min., the half-energy tsunami beamwidth as given by Eq. (16) is found to be 16°.

## ACKNOWLEDGEMENTS

The authors are appreciative of criticism and comments received from several reviewers.

## REFERENCES

1. Ben-Menahem, A. and Rosenman, M., 1972, "Amplitude Patterns of Tsunami Waves from Submarine Earthquakes", Jour. of Geophys. Res., Vol. 77, No. 17, pp. 3097-3128.

2. Kajiura, K., 1972, "The Directivity of Energy Radiation of the Tsunami Generated in the Vicinity of a Continental Shelf", Jour. of the Oceanogr. Soc. of Japan, Vol. 28, No. 6, pp. 32-48.

3. Kajiura, K., 1970, "Tsunami Source, Energy and the Directivity of Wave Radiation", Bull. Earth. Res. Inst., Univ. of Tokyo, 48, pp. 835-869.

4. King, D. R. and Leblond, P. H., 1982, "The Lateral Wave at a Depth Discontinuity in the Ocean and its Relevance to Tsunami Propagation", J. Fluid Mech., Vol. 177, pp. 269-282.

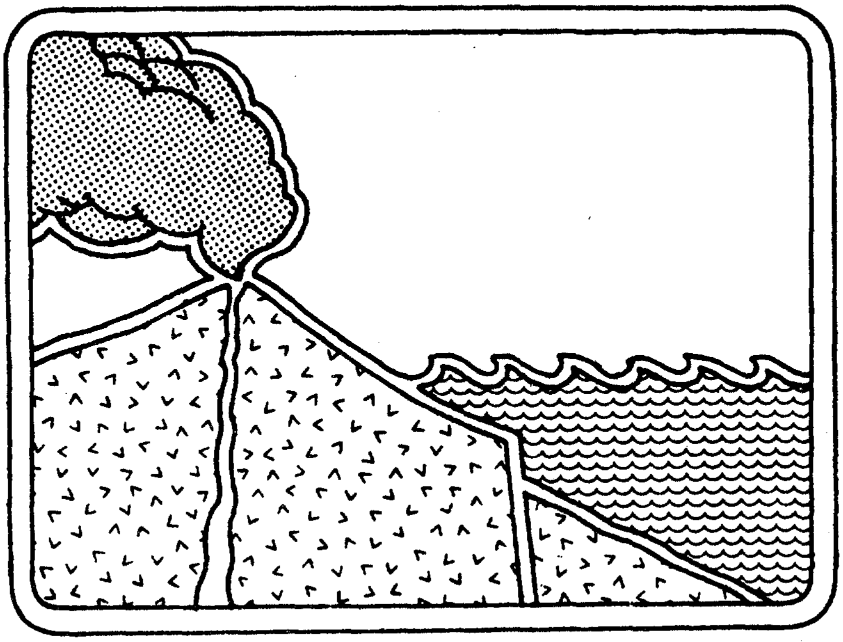
5. Miysohi, H., 1955, "Directivity of the Resent Tsunamis", Jour. of the Oceanogr. Soc. of Japan, Vol. 11, No. 4, pp. 151-156.

6. Murty, T.S. and Loomis, H. G., 1980, "A New Objective Tsunami Magnitude Scale", Marine Geodesy, Vol. 4, No. 3, pp. 267-282.

7. Tucker, D. G. and Gazey, B. K., 1966, Applied Underwater Acoustics, Pergamon Press.

8. Saxena, N. K. and Zielinski, A., 1981, "Deep Ocean System to Measure Tsunami Wave-Height", Marine Geodesy Jour., Vol. 5, No. 1, pp. 55-62.

9. Zielinski, A. and Saxena, N. K., 1983, "Rationale for Measurement of Mid-Ocean Tsunami Signature", Marine Geodesy Jour., Vol. 6, No. 3-4.



# A TSUNAMI PREPAREDNESS ASSESSMENT FOR ALASKA

George W. Carté, Geophysicist
NWS/Alaska Tsunami Warning Center
Palmer, Alaska

## ABSTRACT

I devised a six factor rating system to assess a community's ability to lessen loss of life and injury during and following a tsunami. The six factors used in this assessment are: communications, written action plan, public warning devices, police/fire departments, evacuation sites, and vulnerability of emergency equipment and supplies. Fourty-six Alaskan communities are rated. The degree of preparedness was found to be population sensitive. As might be expected, the larger community's infrastructure gives them the best rating. Eighty-five percent of the communities below 600 in population have a low or marginal preparedness rating. All towns over 1000 population appear adequately prepared. Eight of nine towns with the largest area subject to tsunami flooding are rated low or marginal. These same eight towns are all below 500 in population. This would indicate that most smaller communities will probably need outside help to achieve some minimal level of preparedness.

## INTRODUCTION

The Alaska Tsunami Warning Center has had a community preparedness program for eight years. Many Alaskan coastal communities have been visited and their preparedness assessed. A nine factor rating was devised (Carté, 1981) to objectively rate a community's ability to respond to a tsunami warning and subsequent inundation. The rating is now revised and compacted to six factors. A "perfect" score of 24 will not insure complete safety, but, I believe, a higher score will mean less deaths and injuries in a tsunami. Equally important in assessing potential for loss is the percentage of a community that lies in the tsunami hazard zone. The more area and structures subjected to flooding the more danger for loss of life and loss of essential supplies, equipment and services. The communities are grouped by the percentage of the community that might be inundated by a tsunami.

## RATING FACTORS

The six rating factors shown in Table 1 are not all equal in importance. Communications are the most critical. If the earthquake is not felt and the warning not received because of poor communications, the tsunami could strike before any evacuation would occur. Therefore a communications score of two or less should be considered marginal and dangerous.

A tsunami plan should give concise instructions for evacuation and notification. A trained local emergency management person should review the plan periodically for accuracy and train others in implementing the plan. Since a tsunami could strike very quickly, a rapid means of alerting the endangered population is necessary. A siren system providing good coverage of the coastal areas is the fastest means to alert the public. Since many small villages have citizen band radios (CB's) in most homes, which are usually set on a common channel, they could be used to spread the warning. Several communities are relying on public address system equipped vehicles to alert the public.

Police and fire personnel can aid evacuation and treat injuries, provide rescue and firefighting, etc. If they are dispatched, they will be able to respond more quickly for evacuation duties. Most communities have safe evacuatuion areas which should be easily accessable and provide some protection from the elements. With the help of the Alaska Division of Emergency Services, several communities are now distributing maps or placards describing the safe areas and evacuation signal. The maps and placards can speed evacuation and reduce panic.

Emergency services, equipment, and supplies are more important for recovery than for evacuation. Deaths can occur after the initial disaster due to loss of medical facilities, power, rescue equipment and other essentials. There is no zero in this factor because personal resourcefullness is still very important.

I have estimated that communities with a total rating of nine or less are poorly prepared, with ten to thirteen are marginal, and generally those with a total score over thirteen are adequate. Although the total rating score is significant, any individual factor with a minimum score should be improved if possible.

## PREPAREDNESS ASSESSMENT

The assessments shown in Table 2 were conducted between 1977 and 1983. Updating has occurred when additional information became available. Note that eight of nine towns with the largest area subject to tsunami flooding have marginal or low total ratings. Of the ten towns with the least area in the hazard zone, only four are marginal or below. Excluding Anchorage, the communities with the smallest hazard area average over 800 population, and those with the largest hazard areas average less than 300. Land use planning and building codes of the larger towns probably account for some of this difference.

In Figure 1 the total ratings are plotted linearly against population. It can readily be seen that the smaller towns are poorly prepared compared to the larger communities. Eighty-five percent of the towns below 600 population are rated poor or marginal, while all of the towns over 1000 population appear adequately prepared. Figure 2 shows a good correlation between total rating and population plotted logarithmically. The solid line is a least squares approximation of the relationship. The dashed lines to either side are plus or minus four and inclose all but three of the fourty-five communities plotted.

This means, that given a population, one can predict the total score within four points ninety-three percent of the time. The two communities that appear to be better prepared than their population would indicate can be explained. Both Cold Bay and the Kodiak Coast Guard base are "controlled" communities. The Coast Guard has strict control of their base, of course, and have made excellent progress in preparedness. Cold Bay has a local federal agency directing most of the preparations with the full support of other federal, state, local and private offices.

## COMMUNICATION PROBLEMS

Thirty of the fourty-six communities have to rely on a telephone call from a regional warning point. Smaller villages have only one or two telephones that may be located in the community center, school or health aid's home and may not be accessable twenty-four hours a day. Since the regional warning points have several places to call, delays will occur. The places that are rated two or below have no direct backup such as a Federal Aviation Agency, National Weather Service, or military teletype. The direct backup could reach a community before the call from the warning point.

Indirect backups are becoming better, especially the Emergency Broadcast System (EBS), NOAA Weather Radio and the Marine Radio. The Alaska State-wide Satellite Television System is not being utilized. All of the coastal villages with a population over 25 have satellite television. Nearly every home has a television and they are left on most of the time. At least twenty-one of thirty communities rated two or less in communications would benefit. Any community without full-time electricity would not benefit.

## CONCLUSION

This analysis tends to support the conclusion that smaller towns need help. The best way to help the smallest communities would be to have the warning broadcast over the state-wide television. Where telephones cannot be answered twenty-four hours a day, some other means to quickly warn the community should be devised. The Kenai Peninsula Borough is installing and testing a remotely activated siren system that looks most promising. Possibly another phone could be installed for emergency use only.

Since most of the funds to build schools, firehalls, water systems, health clinics, etc. comes from the State of Alaska or other non-local sources, a greater effort should be made to construct public facilities outside the tsunami hazard zone, if possible. In many towns this has already been done. There is also a current effort to train more Village Public Safety Officers (VPSO) and volunteer firefighters and emergency medical technicians (EMT). They could include in this training a section on earthquake and tsunami awareness.

The Alaska Division of Emergency Services (ADES) is aware of these problems and has been working within its resources to enhance services. The tsunami hazard zone maps and placards that ADES distributed to a few communities with the help of Federal Emergency Management Agency funding should be continued. A minimum emergency action plan should be drafted for every community and periodically reviewed by local officials with state or borough emergency service personnel.

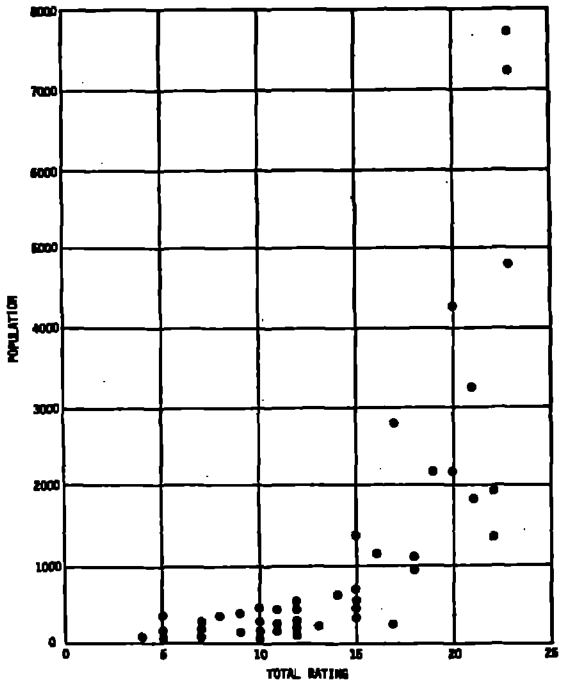
If all of the above recommendations could be accomplished, then most small communities would be raised to at least a marginal level of preparedness.

## ACKNOWLEDGEMENT

I wish to thank Mr. Thomas Sokolowski for reviewing this paper and for his helpful comments.

## REFERENCE

Carté, G.W., 1981, "Tsunami Hazard and Community Preparedness in Alaska," NOAA Technical Memorandum NWS AR-29, Anchorage, Alaska.



Population vs. total rating

Figure 1

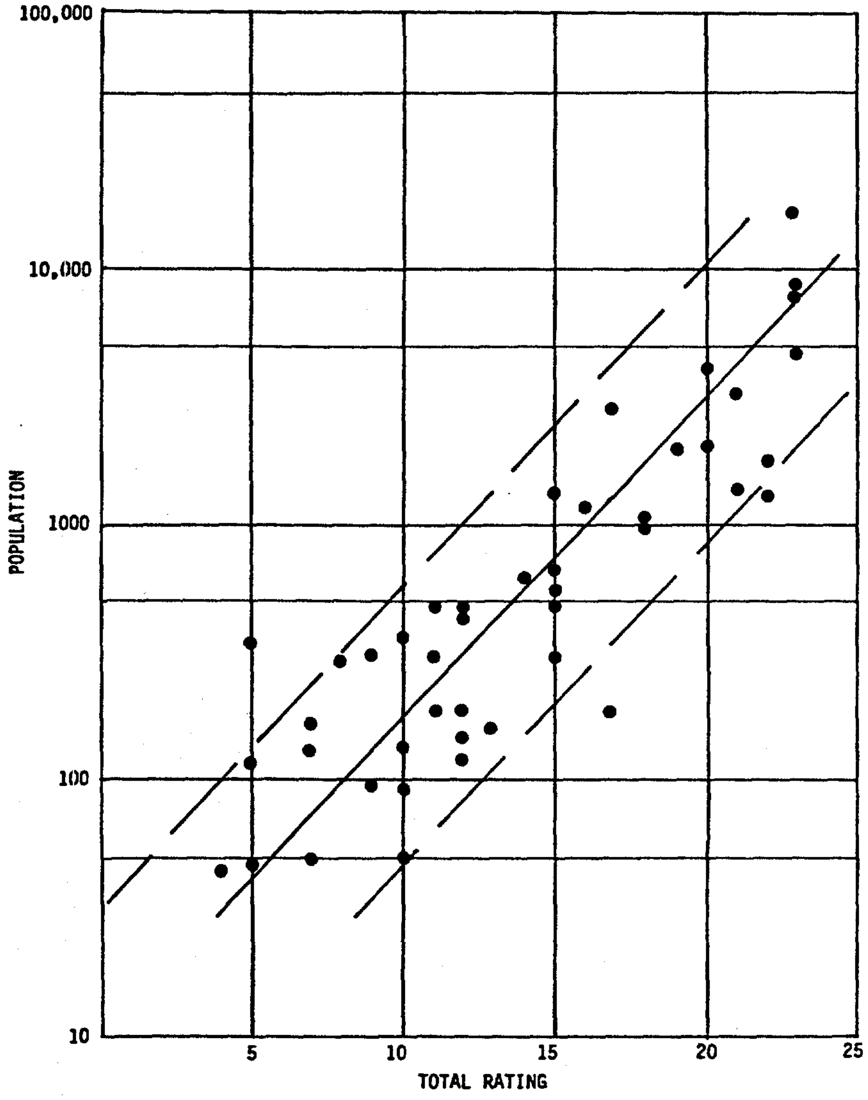
Table 1. Tsunami Preparedness Rating Factors

| FACTORS | RATING |
|---|---|
| COMMUNICATIONS<br>WP means a warning point on "AKWAS" phone system | 5: AKWAS or direct phone, and direct backup<br>4: AKWAS or direct phone, only indirect backup<br>3: Phone from WP with direct backup<br>2: Phone from WP, only indirect backup<br>1: Phone from WP, but not available 24 hours or Only indirect (marine radio, EBS, etc.) |
| WRITTEN TSUNAMI PLAN | 2: Detailed plan and trained CD director<br>1: Minimum outline plan, or plan not kept current<br>0: None |
| SIREN, WHISTLE, CB | 3: Good coverage in vulnerable areas<br>2: Partial siren coverage, or many home CB's, or emergency vehicles with PA systems<br>1: No siren but some homes with CB's<br>0: None |
| POLICE/FIRE DEPARTMENTS | 5: Both full-time, trained and dispatched<br>4: Police available most hours/ trained, dispatched fire volunteers<br>3: Only 1 police/dispatched volunteer fire dept.<br>2: 1 police/undispatched volunteer fire dept. or No police but dispatched volunteer fire dept.<br>1: Only 1 police officer or VPSO or Undispatched but trained volunteer fire dept.<br>0: Neither trained police or fire department |
| SAFE AREAS ADEQUATE | 3: Yes, and easily accessable<br>2: Yes, but somewhat difficult access<br>1: Poor access and/or poor accomendations<br>Note: Add 1 to this category if Placards or maps have been distributed describing safe areas |
| EMERGENCY SERVICES & SUPPLIES VULNERABLE<br>Vis.: water, hospital, fuel, heavy equip, food, fire equipment, generators, etc. | 5: Most available and in a safe location<br>4: Most available, not all safely located or Some available and safely located<br>3: Some available, not all safely located<br>2: Little available but safely located<br>1: Little available and unsafely located |

Table 2. Tsunami Preparedness Assessment

| Town (1980 census) | Comms. | Action Plan | Siren Sys. | Fire/ Police | Safe Areas | Emerg. Equip. | Total |
|---|---|---|---|---|---|---|---|
| 75% - 100% OF COMMUNITY IN TSUNAMI HAZARD ZONE | | | | | | | |
| Akhiok (95) | 2 | 0 | 2 | 2 | 1 | 2 | 9 |
| Chignik (179) | 2 | 0 | 1 | 1 | 1 | 2 | 7 |
| Halibut Cove (45) | 1 | 0 | 0 | 0 | 1 | 2 | 4 |
| King Cove (462) | 2 | 0 | 3 | 3 | 1 | 2 | 11 |
| Kupreanof (47) | 1 | 0 | 2 | 0 | 1 | 1 | 5 |
| Nikolski (50) | 2 | 0 | 0 | 1 | 2 | 2 | 7 |
| Old Harbor (339) | 1 | 0 | 0 | 1 | 2 | 1 | 5 |
| Perryville (108) | 1 | 0 | 0 | 1 | 1 | 2 | 5 |
| Unalaska (1301) | 2 | 1 | 1 | 5 | 3 | 3 | 15 |
| 25% - 50% OF COMMUNITY IN TSUNAMI HAZARD ZONE | | | | | | | |
| Adak (3313) | 5 | 2 | 2 | 5 | 3 | 4 | 21 |
| Cordova (1959) | 5 | 2 | 3 | 5 | 3 | 4 | 22 |
| Craig (522) | 2 | 0 | 3 | 2 | 4 | 4 | 15 |
| Douglas (1200*) | 2 | 2 | 2 | 3 | 3 | 4 | 16 |
| Homer (2211) | 3 | 2 | 3 | 5 | 3 | 4 | 20 |
| Hoonah (677) | 2 | 0 | 3 | 3 | 3 | 4 | 15 |
| Hydaburg (303) | 2 | 0 | 0 | 2 | 3 | 4 | 11 |
| Juneau (19,480) | 5 | 2 | 2 | 5 | 4 | 5 | 23 |
| Karluk (94) | 1 | 0 | 2 | 1 | 3 | 3 | 10 |
| Ketchikan (7248) | 5 | 2 | 2 | 5 | 4 | 5 | 23 |
| Klawock (321) | 1 | 0 | 0 | 2 | 3 | 2 | 8 |
| Kodiak (4746) | 5 | 2 | 3 | 5 | 3 | 5 | 23 |
| Kodiak USCG (1368) | 5 | 2 | 3 | 5 | 3 | 4 | 22 |
| Larson Bay (144) | 2 | 0 | 2 | 2 | 2 | 4 | 12 |
| Metlakatla (989) | 3 | 1 | 2 | 4 | 3 | 5 | 18 |
| Ninilchik (336) | 2 | 0 | 0 | 0 | 3 | 4 | 9 |
| Ouzinkie (173) | 2 | 0 | 2 | 3 | 3 | 2 | 12 |
| Petersburg (2800) | 2 | 1 | 3 | 5 | 3 | 3 | 17 |
| Port Graham (162) | 1 | 0 | 3 | 0 | 3 | 3 | 10 |
| Port Lions (215) | 2 | 0 | 0 | 3 | 3 | 4 | 12 |
| Sand Point (619) | 2 | 1 | 1 | 2 | 4 | 4 | 14 |
| Seldovia (473) | 2 | 0 | 0 | 3 | 3 | 4 | 12 |
| Seward (1842) | 4 | 2 | 3 | 5 | 4 | 3 | 21 |
| Sitka (7764) | 5 | 2 | 2 | 5 | 4 | 5 | 23 |
| Whittier (206) | 2 | 1 | 1 | 2 | 3 | 4 | 13 |
| Wrangell (2174) | 3 | 2 | 2 | 5 | 3 | 4 | 19 |
| Yakutat (449) | 3 | 0 | 0 | 2 | 3 | 4 | 12 |
| 10% OR LESS OF COMMUNITY IN TSUNAMI HAZARD ZONE | | | | | | | |
| Anchorage (173,992) | 5 | 2 | 2 | 5 | 3 | 5 | 22 |
| Anchor Point (229) | 2 | 0 | 0 | 2 | 3 | 4 | 11 |
| Auke Bay (490*) | 2 | 2 | 2 | 3 | 2 | 4 | 15 |
| Cohoe (50*) | 2 | 0 | 0 | 0 | 3 | 5 | 10 |
| Cold Bay (226) | 3 | 2 | 0 | 3 | 4 | 5 | 17 |
| English Bay (125) | 1 | 0 | 0 | 0 | 3 | 3 | 7 |
| Kachemak (402) | 2 | 0 | 0 | 0 | 3 | 5 | 10 |
| Kenai (4326) | 3 | 2 | 2 | 5 | 3 | 5 | 20 |
| Lena Cove (300*) | 2 | 2 | 2 | 3 | 2 | 4 | 15 |
| Nikiski (1114) | 5 | 2 | 0 | 3 | 3 | 5 | 18 |

Note: * Population by 1970 census.



Population vs. total rating with population on logarithmic scale

Figure 2

# COMMENT ON "DEVELOPMENT OF A TSUNAMI - FLOODING MODEL HAVING VERSATILE FORMULATION OF MOVING BOUNDARY CONDITIONS"

by Carter H. Lewis and W. H. Adams, Tsunami Society Monograph, January 1983.

James R. Houston
Chief, Research Division
Coastal Engineering Research Center
U.S. Army Engineer Waterways Experiment Station
P.O. Box 631
Vicksburg, Mississippi 39180-0631

The authors present an interesting paper, but the writer noted certain inaccuracies in reference to past publications of the writer. For example, on page 14 of the monograph is the statement ". . . numerous degrees of freedom have been adjusted in the name of 'calibration' to the point where the model is applicable only to the region used for calibration (Houston and Butler, 1979)." On page 59 there is the statement ". . . which has prompted many investigators to calibrate their models until a fit to historical data has been obtained, rather than truly verify the correctness of model performance (Reid and Bodine, 1968; Houston, et al., 1977; Houston and Butler, 1979)." Again on page 59 there is the statement "The model dynamics may even be altered in a physically unrealistic way to achieve the historical match (Houston, et al., 1977, Houston and Butler, 1979)." All of these statements are erroneous. The writer will discuss the references cited.

The finite element model described in Houston, et al., 1977, was not adjusted in any way to achieve calibration or match historical data. The only parameter that can be adjusted in the model is the permanent vertical displacement of the ocean bottom at the source of the tsunami. However, the permanent vertical displacement data was not adjusted. On page 32 of Houston, et al., 1977, is the statement "The permanent deformation of the ocean's bottom at the source as a function of spatial location was taken from Reference 29 for the Alaskan source and References 30 and 31 for the Chilean source." That is, the permanent vertical displacement was taken from previous publication of other investigators. The model was then run a single time for each tsunami and there were no attempts to improve the match with historical data by adjusting the initial conditions.

On page 28 of Houston and Butler, 1979, it is stated values of Manning's n suggested by Bretschneider and Wybro (1976) were used. Three Manning's n values were selected for distinct areas (ocean, developed areas, riverine floodplain). "No attempt was made to force agreement of numerical calculations and historical recordings of elevations by varying local values of Manning's n (Houston and Butler, 1979). On page 33 is the statement "Neither frictional coefficients nor land elevations were varied in this verification to force agreement with measured elevations, since in an application of the numerical model to an arbitrary location these parameters would not be accurately known." Thus, no attempt was made by Houston and Butler, 1979, to alter the model in a "physically unrealistic way." The friction factors were based upon the published work of others (Bretschneider and Wybro, 1976) and there were no attempts to adjust these friction factors.

The monograph states on page 59 ". . . it is essential to verify the model by comparison of its performance with a known analytical solution." Such a comparison does not "verify" the model. It can show the basic computations are free of errors, but it cannot show that the model can simulate actual prototype events. I noted in both "verifications" presented in the monograph, friction was neglected. Bretschneider and Wybro (1976) present friction as a key parameter influencing tsunami flooding. The "verifications" presented in the monograph are no more than simple tests all numerical modelers use as initial tests of their models. Similar tests have been made at various times for the models presented in Houston, et al., 1977, and Houston and Butler, 1979 (e.g. see Houston, 1981). Comparisons with simple analytic solutions are never considered as verifications of a numerical model. The heuristic depth-assignment scheme described in the monograph was not shown to work for an actual tsunami, tide, or storm surge. In fact, the scheme had difficulties reproducing an analytic solution despite use of smoothing operators, moving averages, and special logic to eliminate asymmetries.

The monograph criticizes the Reid and Bodine (1968) flooding approach because it uses "empirical engineering equations with discharge coefficients of unspecified value." Reid and Bodine (1968) do specify the values of the discharge coefficients used. Typically, the bottom friction and not the discharge coefficients are changed during calibration. Empirical coefficients such as bottom friction are modified during calibration of a prototype event. Then a separate event is modeled with all empirical coefficients fixed at the values established during the calibration. Verification is achieved if good comparisons are obtained with prototype data without the empirical coefficients being changed.

In summary, Houston, et al., 1977, and Houston and Butler, 1979, did not adjust parameters in their models to force agreement with historical data. Any parameters that could be adjusted (e.g., source uplift or bottom friction) were set at values published as the best values by others and they were not varied in any computations to force agreement with data. The model described in the monograph also must select values for bottom friction in any prototype application. The "verifications" presented in the monograph were only simple tests to establish that the model was free of obvious errors. The capacity of the model to model simple analytic solutions does not mean that the model can simulate the real world and thus is verified.

## References

1. Bretschneider, C. L., and Wybro, P. G., Tsunami inundation prediction. Chapter 50 in "Proceedings, Fifteenth Coastal Engineering Conference," Honolulu, American Society of Civil Engineering, 1976, 1, 1006-1024.

2. Houston, J. R., "Combined Refraction and Diffraction of Short Waves Using the Finite Element Method," Journal of Applied Ocean Research, Vol. 3, No. 4, 1981.

3. Houston, J. R., Carver, R. D., and Markle, D. G., "Tsunami-Wave Elevation Frequency of Occurrence for the Hawaiian Islands," (Report H-77-16), Vicksburg: U.S. Army Engineer Waterways Experiment Station, Hydraulics Laboratory, Mississippi, 1977.

4. Houston, J. R., and Butler, H. L., "A Numerical Model for Tsunami Inundation," (Technical Report HL-79-2), Vicksburg: U.S. Army Engineers, Waterways Experiment Station, Hydraulics Laboratory, Mississippi, 1979.

5. Reid, R. O., and Bodine, B. R., Numerical model for storm surges in Galveston Bay, Bay, "Proc. American Society of Civil Engineering Journal Waterways Harbor Div.," 1968, 94 (33).

ITSU-ITS 85

# INTERNATIONAL TSUNAMI MEETINGS

Two international tsunami meetings, ITSU-X and ITS '85 will be held consecutively in Victoria, Canada, in 1985.

ITSU-X The tenth meeting of the International Co-ordination Group for the Tsunami Warning System in the Pacific, July 29 - August 3.

ITS '85 The International Tsunami Symposium of the Tsunami Commission of the International Union of Geodesy and Geophysics, August 5-9. Sessions for ITSU and ITS will be held at the Empress Hotel in downtown Victoria, and at the Institute of Ocean Sciences and the Pacific Geoscience Centre in Sidney, British Columbia, 15 km north of Victoria.

The meetings come at a time of the year when Victoria, Sidney and the connecting Saanich Peninsula are most enjoyable.

Social and recreational programs are being arranged for spouses, families and friends as well as for the participants in the scientific and technical sessions. Sightseeing will include visits to Butcharts Gardens, the renowned British Columbia Museum, and a post-convention excursion to inlets and beaches on the outer coast of Vancouver Island.

Information:

Those interested in being on the mailing list are invited to write:

TSUNAMI '85,
P.O. Box 2267,
Sidney, B.C.,
Canada V8L 3S8

## APPLICATION FOR MEMBERSHIP

**THE TSUNAMI SOCIETY**
P.O. Box 8523
Honolulu, Hawaii 96815, USA

I desire admission into the Tsunami Society as: (Check appropriate box.)

☐ Student ☐ Member ☐ Institutional Member

Name ______________________ Signature ______________________
Address ______________________ Phone No. ______________________
____________________________________________
Zip Code ______________________ Country ______________________
Employed by ____________________________________________
Address ____________________________________________
Title of your position ____________________________________________

| | | | | | | |
|---|---|---|---|---|---|---|
| FEE: | Student | $5.00 | Member | $25.00 | Institution | $100.00 |

Fee includes a subscription to the society journal: SCIENCE OF TSUNAMI HAZARDS.

Send dues for one year with application. Membership shall date from 1 January of the year in which the applicant joins. Membership of an applicant applying on or after October 1 will begin with 1 January of the succeeding calendar year and his first dues payment will be applied to that year.