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TSUNAMIS AND EARTHQUAKE MECHANISMS IN THE ISLAND ARC REGIONS

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ABSTRACT

The generation of tsunamis with the help of a simple dislocation model of an earthquake and their propagation in the basin with the bottom relief typical for the island arc region is discussed. A set of eight source models presenting the basic types of faulting in the sources of the island earthquakes is considered. This set of source models includes low-angle thrust, steep dip-slip fault, dip-slip fault with a strike component of dislocation, strike-slip fault, the so-called combined source (combination of thrust-type fault and dip-slip), thrust fault with branching up the dip-slip (Fukao's model), double fault (block-type source), and simple elliptical elevation.

For all the source models considered tsunami wave forms at the coast are computed, and the distributions of the maximum tsunami heights along the coastline are obtained. The dependence of the tsunami efficiency on the source mechanism and some other source parameters is examined.

It was found that two source models most typical for island arc regions (steep dip-slip and low-angle thrust) generate tsunamis with practically equal amplitudes, periods, and phases.

Among the other sources considered the Fukao's model and the block-type source produce the tsunami waves with some greater heights at the nearest part of the coast. However, the increase of wave heights as compared to the other sources is insufficient to explain all the features of tsunami-earthquakes for which these source models were proposed.

The seismic moment of a source was found to be the main parameter determining the tsunami intensity at the coast. Theoretical relationship obtained between the tsunami intensity and moment-magnitude of a source corresponds fairly well to the empirical data.

Introduction

The problem of the evaluation of tsunami danger of submarine earthquakes is one of the important practical tasks of the seismological investigations in the Pacific region. It is well known that more than 80% of the total seismic energy produced on the Earth is concentrated in the Pacific seismic belt, where about 200 earthquakes with magnitudes up to 6.0 annually occur. Island arc regions, such as Aleutian, Kurile, and Japanese arcs, are the most active parts of this seismic belt. According to the plate tectonic conception seismic processes in these regions are the result of the mechanical interaction between the subducting oceanic and overriding continental lithosphere plates (Kanamori, 1971; Nishenko, McCann, 1979). The major earthquakes associated with the main lithospheric interface are believed to be a result of a rebound of the continental lithosphere, which is dragged by the underthrusting oceanic lithosphere, so its predominant source mechanism should be a low-angle thrust.

As it is known that the source mechanism is nonuniquely determined by P wave first motion data as two nodal planes perpendicular to each other, the choice of one of them as a real fault plane in an earthquake source has to be done on the basis of additional data such as the distribution of aftershock hypocenters.

Mass determinations of source mechanisms in the northwestern Pacific made in the 1960's and the beginning of 1970's revealed that for island arc earthquakes one nodal plane is directed, as a rule, along the island arc and it is steeply dipping toward a trench, while the second plane with the same, in general, strike direction is gently sloping under the island arc. Upholders of plate tectonics consider the second plane as a real plane of rupture and in accordance with this believe the source mechanism to be a low-angle thrust (Kanamori, 1971; Abe, 1973; Nishenko, McCann, 1979). Other seismologists following the geosinclinal theory consider the first plane as a real plane and accept the dip-slip faulting as a predominant mechanism of island arc earthquakes (Averianova, 1968; Balakina, 1972; Burymskaya, 1983). They believe the steeply dipping planes to be better consistent with the morphology of the island arc slope, whose relief is characterized by the presence of a number of steps (deep sea terraces).

The most detailed model of seismic processes in the island arc regions is elaborated in the works by Nishenko, McCann (1979), Lobkovsky, Sorokhtin (1980), Lobkovsky, Baranov (1982, 1984). In the base of this model lies the conception of subduction and the notion of seismic cycle. The important elements of the model are the transverse faults breaking the overriding edge of continental lithosphere on the separate blocks (keys), which are relatively independent one from another in the conditions of weak lateral compression, typical for Kurile and Japanese arcs (Averianova, 1968; Balakina, 1972).

Let us describe shortly the cycle of seismic process as it is believed to be in the framework of the model mentioned. It consists of four recognizable stages, which may be explained in terms of Reid's (1910) elastic rebound model. During the fast coseismic stage the separate block of lithospheric edge moves forward to the trench at the distance of several meters (the magnitude of the displacement in the sources of great shallow earthquakes). The next postseismic stage of a few years duration is characterized by the full strain release in the source region and involves the aftershock series. This stage is usually regarded as the last stage of the recurrent seismic cycle and signifies the beginning of a new cycle. During the most prolonged interseismic stage (with duration about one hundred years), the advanced block is passively displaced back to the island arc, dragged by the motion of subducting oceanic plate, so far as it will be stopped by the island arc. From this moment the preseismic stage of the cycle begins. This stage lasts usually for about a few years and is characterized by the fast accumulation of elastic strain. After the strain exceeds the limit of stability of the medium, a new large event occurs and the next seismic cycle begins.

On the basis of numerical and physical modelling of crustal movements in the subduction zones, Lobkovsky and Baranov (1982, 1984) showed that in the framework of this model, except for the thrust-type earthquakes, the events with a dip-slip mechanism can occur. The displacements in the sources of these earthquakes lie along the steeply dipping faults, which are formed in the thickness of leading edge of continental lithosphere under the action of tangent component of stresses at its foot (Fig. 1).

Lobkovsky and Baranov (1982) distinguished four basic types of earthquake mechanisms which are characteristic for the island arc regions:

- low-angle thrust earthquakes;
- dip-slip earthquakes;
- strike-slip earthquakes with displacement along the transverse faults;
- the so-called combined type of earthquakes having in its sources practically simultaneously both possible types of faulting (low-angle thrust and dip-slip).

The main purpose of the present work is to evaluate the tsunami potential of these and some other types of earthquakes on the basis of existing mathematical models of tsunami generation and propagation.

Mathematical models which have been applied to study the tsunami generation problem may be divided into two main kinds. The more appropriate are those in which the liquid layer (a model of the ocean) and the elastic halfspace (a model of the Earth crust) forms a coupled system, in which wave behavior is described by a single system of equations. This kind of model was used by Podyapolsky (1970), Alekseev, Gusiakov (1974), Yamashita, Sato (1974), Ward (1980, 1981, 1982); and Comer (1984a). The other kind of models widely applied to numerical simulation of tsunami can be called after Comer (1984b) the "partially coupled" approach. In this approach the calculated or observed static bottom deformation in the epicentral region is used to generate tsunami waves in incompressible ocean with otherwise rigid bottom (see, for example, Aida, 1978; Ando, 1982; Chubarov et al., 1984).

It was shown earlier (Podyapolisky, 1970; Cromer, 1984b) that in long wave approximation both approaches to the tsunami generation problem are equivalent.

In the present work we use the "partially coupled" model because it allows us to consider the ocean with variable depth and to transfer the initial tsunami heights from the epicenter region to the coast, where we usually have all field observations of tsuanmis. In the framework of the first approach, we have to consider, as a rule, the ocean with flat bottom since in case of variable depth the solution of government equations is possible only by numerical methods, application of which to three-dimensional dynamic problemsis still rather complicated.

We calculate the vertical static displacement $\zeta(x,y)$ on the surface of elastic homogeneous halfspace with the inner distributed source of dislocation type. This source is a simple fault plane of a rectangular shape described by six parameters: the length L, the width W, the depth of the upper rim of the fault h_{top}, the dip angle of the fault plane δ, the strike angle of the fault dislocation measured from the horizontal axes λ, and the average dislocation over the fault D_0 (Fig. 2). The details of the solution of this static elastic problem can be found in Gusiakov (1978).

The computed vertical displacement $\zeta(x,y)$ is introduced in the discontinuity equation of the linear shallow water model, which is used for the description of tsunami propagation in the ocean with a variable depth.

Without Coriolis and friction terms, these equations can be written as

$$u_t + g\eta_x = 0 \tag{1}$$

$$v_t + g\eta_y = 0 \tag{2}$$

$$(\eta-\zeta)_t + ((H-\zeta)u)_x + ((H-\zeta)v)_y = 0 \tag{3}$$

Here $u(x,y,t)$, $v(x,y,t)$ are average velocity components in x and y directions, respectively, $\eta(x,y,t)$ is water surface displacement, $H(x,y)$ is the ocean depth.

System (1)-(3) is solved numerically by the finite difference method. The details of calculations can be found in Marchuk et al. (1983). The bottom displacement $\zeta(x,y)$ is regarded to be established instantaneously, or, more specifically, during one time step of the difference scheme equal to 10 sec, since the time of process in the sources of tsunamigenic earthquakes (10-100 sec) is much less than a typical period of tsunami waves (600-1000 sec).

Calculations of tsunami propagation were carried out on the model of typical bottom relief of Kurile-Kamchatka region. The perspective view of the bottom model is shown in Fig. 3 in some arbitrary scale, which is different in vertical and horizontal directions. It includes inclined shelf, forearc basin, steep continental slope, deep-sea terrace, outer (continental) slope of deep-water trench, and the inner (oceanic) slope of the trench, transferring to deep-water oceanic basin.

The calculation region with dimensions 550 x 320 km was covered with a rectangular 111 x 65 grid, whose mesh size is $\Delta x = \Delta y = 4.76$ km (Fig. 4). The computed wave forms were output on the plotter at 12 inner grid points and 21 boundary grid points located along the coastline.

Model sources were located in the region of deep-sea terrace, where tsunamigenic earthquakes occur most frequently. In addition to the above four basic kinds of earthquake sources, four other source models were regarded:

- dip slip fault with a strike component of dislocation (λ=50°) as intermediate model between pure dip-slip (λ=90°) and strike-slip (λ=0°) faults;
- low-angle thrust with branching from its upper part, the steep dip-slip fault. This kind of source was proposed by Fukao (1979) as a possible source model of the so-called tsunami-earthquakes;
- subvertical displacement of the whole block of the overriding edge of continental lithosphere limited by normal and inverse faults from both sides. Balakina (1983) indicates the possibility of such a type of movement in the sources of tsunamigenic earthquakes on the basis of studying the seismograms of 1975 Shikotan earthquake, each having two clear consecutive set-ons of opposite signs;
- simple elliptical elevation of water surface, which can be produced by a linear isotropic source located at some depth within the elastic halfspace. This hypothetical source is used for investigation of the relationship of amplitudes and periods of computed mareograms with the type of initial water displacement in the tsunami generating area.

Fault parameters of the examined source models are summarized in Table 1. The length of fault plane L was taken equal to 100 km, the width W = 50 km, so the aspect ratio L/W = 2, which is a typical value for a Pacific earthquake (Abe, 1975). With the dislocation D_0 = 2 m and the module of rigidity $\mu = 5\cdot10^{10} N\cdot m^{-2}$, it gives the seismic moment $M_0 = 5 \cdot 10^{20}$ N·m. According to the relationship between seismic moment and the surface wave magnitude M_s suggested by Aki (1972)

$$M_s = (\log M_0 - 9)/1.5 \tag{4}$$

moment of $5 \cdot 10^{20}$ N·m is equivalent to the magnitude $M_s = 7.8$.

The computed static displacements due to eight examined source models are shown in Fig. 5 as cross-sections of vertical displacement and in Fig. 6 as perspective views of bottom deformation near the source region. For sources M1, M2, M3, and M5 bottom deformation pattern has, in general, a similar form with landward subsidence and trenchward uplift. The pattern for source M4 (strike-slip fault) has a form of a symmetric four-loops diagram with essentially smaller vertical amplitudes. The source M8 produces the elliptical elevation of the bottom, which is symmetric in two perpendicular cross-sections.

A distinctive feature of static deformation produced by sources M6 and M7 is the subsidence of a trenchward portion of the tsunami generating area. Comer (1983) was the first to indicate this feature of Fukao's model. He investigated the mareograms recorded at Wake and Midway Islands for a number of tsunamigenic earthquakes of Kurile-Kamchatka region and found that the records of typical tsunami-earthquakes of October 20, 1963, and June 10, 1975, have a clear downward first motion, while the records at these two islands from nearby ordinary tsunamigenic earthquakes such as events of October 13, 1963, and August 11, 1969, have the upward first motion.

Figures 5 and 6 present the computed static deformation of the ocean bottom. As it is mentioned above, the time-history of bottom movement is assigned to be a ramp-function with rise time $\tau_0 = 10$ sec. Due to a short duration of bottom movement ($\tau_0 \ll T$) and its large spatial scale ($L \gg H$), a pattern of the initial displacement of water surface practically repeats a pattern of bottom deformation.

Table 1 also lists a number of parameters characterizing the bottom deformation patterns for all the sources considered, in particular, the change of basin volume

$$V_0 = \int_{s_1} \zeta(x,y)\,dxdy \quad , \tag{5}$$

the total volume of bottom deformation

$$V = \int_{s_1} \left|\zeta(x,y)\right| dxdy \quad , \tag{6}$$

and the initial tsunami energy E_t calculated by the formula

$$E_t = \frac{1}{2}\rho_0 g \int_{s_1} \zeta^2(x,y)\,dxdy \tag{7}$$

In (5)-(7) s_1 is the area of tsunami generating region, $\rho_0 = 1$ is the density of water, g is the acceleration of gravity. According to Kajiura (1970), the quantity E_t reproduces with a sufficient accuracy the total tsunami energy for fast bottom movement.

Except for the source M4, having the essentially smaller value E_t, the initial energy of other sources is found in the limits of $0.6\text{-}1.5\cdot10^{20}$ ergs, varying not more than 2.5 times. Kajiura (1981) gave the formula for evaluation of tsunami energy E_t from the moment-magnitude M_W of an earthquake

$$\log E_t = 2M_W + \log F + 5.5 \tag{8}$$

where F is the function of fault parameters having the maximum value about 0.1. The moment-magnitude M_W is defined by the seismic moment of an earthquake M_0 and for examined source models with $M_0 = 5.10^{20}$N·m, its value is 7.8. If we put the value 7.8 in (8), then the range of computed tsunami energy for the sources with a single fault (M1, M2, M3, and M4) is provided by variation of the function F in the limits of 0.01 - 0.1, which are consistent with the value of F given by Kajiura (1981). For source models with double fault, the function F has some larger value (up to 0.18 for source M6).

Computed wave forms at 11 points along the coastline are shown in Fig. 7 for sources M2 (dip-slip fault) and M8 (elliptical elevation). Due to a short distance from a tsunami source to the coast and the simplicity of bottom relief, the computed mareograms consist of only two-three waves, among them the leading wave has the highest amplitude. The direction of the first motion of tsunami for source M8 is always positive, the sign of the first motion for source M2 changes along the coastline. At the coast points located directly opposite the source, the first motion is negative in accordance with the subsidence of landward portion of tsunami source. At the distance greater than 150 km from the source, the first motion becomes positive. It means that due to refraction on the inclined bottom, these parts of the coast are reached first by the waves radiating from a rising trenchward part of the source region.

The period of waves varies along the coast and for all the sources has the minimum value at the central grid point (3.56), where come the waves radiating from the source lengthwise to its short axes, and it has the maximum value at point (3.16) where appear waves leaving the source lengthwise to its long axes. At all the points, a visible period for source M2 is shorter than for source M8 due to a more complicated profile of the initial disturbance.

The distribution of maximum wave heights (from crest to trough) along the coastline is shown in Fig. 8 for sources M1, M2, M3, M4, and in Fig. 9 for sources M5, M6, M7, and M8. These distributions are the basis for the analysis of comparative tsunami efficiency of considered source models. Since the wave height at the coast strongly depends on the distance to a source (see Fig. 10) and for different source models, the position of the maximum of bottom displacement with respect to a fault plane does not coincide; in each case the source position was chosen in such a way that the maximum of bottom deformation was found at the same distance from the coast.

Under this condition, the two basic source models with a single fault - a low-angle thrust (M1) and steep dip-slip fault (M2) has practically equal tsunami efficiency. The difference in tsunami amplitudes between these sources does not exceed 10 cm. In the presence of a strike component of fault dislocation, the wave heights are decreased in proportion of sin λ. Small asymmetry of the wave height distribution for source M3 is the result of asymmetry of the initial bottom deformation.

As was to be expected, the pure strike-slip fault has essentially smaller tsunami efficiency. The maximum wave heights do not exceed 30 cm, which is only 1/6 part of the height produced by sources M1 or M2 with the same seismic moment.

Sources with a double fault (M5, M6, and M7) have a little stronger directivity and produce the waves with some larger heights at the nearest section of the coast. But in general, as one can see from Fig. 9, sources M6 and M7 have not got any noticeable distinctions in tsunami efficiency comparatively with other considered sources. At the distance more than 200 km, wave heights for all the sources except for M8 are very close to each other. Source M8 has a more uniform directivity caused only by its ellipticity and it produces the waves with larger height at long distances from the source.

Basic parameters of tsunami waves generated by eight considered sources are listed in Table 2. The first two columns contain the values of the maximum and the average wave heights. The largest waves are produced by source M6; source M8 gives the largest average value of heights. The third column contains the magnification coefficient K_m, which is calculated as the ratio of the maximum wave height at the coast to the maximum initial displacement at the source. Its value is determined by the resonance response of the bottom relief on the incident waves with a different wave length. For all the sources except M4, K_m is more than 1 and varies from 1.3 to 2.7.

The computed wave heights at the coast allow us to calculate tsunami intensity I defined by

$$I = \frac{1}{2} + \log_2 h_{av} \tag{9}$$

where h_{av} is the average inundated height over the part of the coast "where tsunami activity was significant" (Soloviev, 1972). We took as h_{av} the maximum positive wave amplutude averaged over the section of the coast of 200 km long and multiplied by the factor of 1.4, since water rises determined from visual observations are usually 1.4 times as large as those determined from tide gauge records (Soloviev, 1978). The fourth column of Table 2 contains the values of I calculated by the formula (9). The lowest value of I equal -2.4 is provided by the strike-slip fault. The other sources have approximately equal values of I with a difference less than 0.5. It shows that except for strike-slip earthquakes, the variations of source mechanism slightly affect the tsunami intensity, which is determined mainly by the strength of a source, that is by its seismic moment in the framework of the source model used.

The computed wave heights at the coast allow us also to evaluate the tsunami-magnitude M_w of considered sources. This new magnitude scale for tsunamigenic earthquakes was originally suggested by Abe (1979, 1981). For the regional events M_t is defined by

$$M_t = \log h + \log \Delta + 5.55 \tag{10}$$

where h (in meters) is the average of the maximum tsunami amplitudes recorded by the tide gauges at least 100 km away from a tsunami source and Δ (in kilometers) is the distance from the observation point to the earthquake epicenter.

The fifth column of Table 2 contains the computed values of Abe's magnitudes. Again sources M4 and M8 give the extreme value of M_t, for all the other sources, its values vary within the limits of 7.4 - 7.6.

Except for source mechanism, the wave heights at the nearest part of the coast is affected also by the source position on the island slope. This pronounced effect is illustrated in Fig. 10 presenting the distribution of wave heights along the coast for four variants of source position. The waves with the maximum heights at the coast are generated by the source located within the forearc basin at the distance 100-150 km from the coast. The decrease of wave amplitudes for more distant sources is conditioned by the geometrical divergence of wave front, for closer sources it is conditioned by the smaller water depths at the source region and by diminishing the effect of wave amplitude magnification during the propagation across the inclined shelf.

The insert table in Fig. 10 contains the values of tsunami intensity I and magnitude M_t for considered variants of the position of the source. Despite the great difference in the maximum wave heights, the average heights and consequently the value of I vary insignificantly. The tsunami magnitude M_t reveals remarkable stability in respect to the position of the source. This stability is the result of taking into account the distance between the observation and source regions in (10) and the limitation of its minimum value (not less than 100 km).

As mentioned above, the wave heights at the coast mainly depend on the size and the seismic moment of the source. Figure 11 presents the distribution of the tsunami heights for the thrust-type sources with different seismic moment. The length of fault varies from 25 up to 300 km; its width changes so that the aspect ratio L/W remains constant and equal 2. The fault dislocation D_0 increases in proportional to $\sqrt{L \times W}$, what can be regarded as rather realistic dependence (Aki, 1972). Under these conditions, the seismic moment of considered sources varies three orders of its value (from $7.5 \cdot 10^{18}$ N·m up to $7.5 \cdot 10^{21}$ N·m). As it is seen from Fig. 11, the tsunami amplitudes changes more than 200 times (from 3.2 cm up to 7.6 m). So we can conclude that among other considered source parameters, the seismic moment is the leading parameter for tsunami generation problems.

The insert table in Fig. 11 contains the values of I, M_t and M_w for examined sources. It is interesting to note that for all the sources the values of magnitudes M_t and M_w are very close. When Abe's magnitude scale was established, it was experimentally adjusted to the moment-magnitude scale M_w defined by Kanamori (1977). One can see that the conformity of both scales is also provided by our numerical model of generation and propagation of tsunami.

The relationship between I and M_w obtained by means of these numerical experiments is plotted in Fig. 12 with the data on tsunami intensity for those tsunamigenic earthquakes of 1958-1983 from Kurile-Kamchatka region for which the determination of the seismic moment was made and consequently the moment-magnitude M_w is known. As it is seen, the general trend of obtained theoretical relationship which is expressed by

$$I = 3.55\, M_w - 27.1 \tag{11}$$

corresponds fairly well to the empirical data.

In conclusion let us briefly formulate the main results of this study.

The generation of tsunamis and their propagation in the basin with the bottom relief typical for the island arc regions has been discussed on the basis of a simple source model of an earthquake and linear shallow water theory. There were considered eight source models presenting the basic types of faulting in the sources of the island earthquakes. The distributions of the maximum tsunami heights along the coast were calculated and their dependence on source mechanism and some other source parameters were examined.

It was found that two source models most typical for island arc regions (steep dip-slip and low-angle thrust) generate tsunamis with practically equal amplitudes, periods, and phases. Therefore, in tsunami forecasting the events with a thrust-type mechanism should be considered as tsunami dangerous as dip-slip earthquakes. The use of source mechanism as an indication of tsunanmigeneity is possible only for the elimination of strike-slip earthquakes, which are, however, relatively rare in these regions.

Results of numerical modelling of tsunami generation and propagation showed that the seismic moment of a source is the main parameter, determining tsunami intensity at the coast. The obtained theoretical relationship between tsunami intensity and the moment-magnitude of a source was found to be in good correspondence with the empirical data.

Among other considered source models, M6 (Fukao's model) and M7 (block-type source) generate the tsunami waves with some greater heights at the nearest part of coast. These models also have a distinctive feature of their pattern of initial displacements in the source region (subsidence of its trenchward portion), as obviously took place during the typical tsunami earthquakes of October 20, 1963, and June 10, 1974, near the Kurile Islands.

So, sources M6 and M7 can be considered as the most appropriate models of tsunami earthquakes. However, the increase of wave heights as compared to the other examined sources is insufficient to explain unusually large tsunami amplitudes with respect to the surface wave magnitude M_s of tsunami earthquakes. One can assume that the lower rupture velocity characteristics of the sources of tsunami earthquakes and the location of their sources at shallow depths within the leading edge of the continental lithosphere consisting of deformable sediments can result in the decrease of seismic energy radiated within the range of periods of 15-20 sec, which is used for the determination of the surface wave magnitude. Then at the fixed value of seismic moment, we obtain the below-average value of magnitude and at the same time the increased tsunami amplitudes at the nearest part of the coast.

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Table 1. Basic Parameters of Source Models

			L km	W km	D_0 m	ζ_u cm	ζ_d cm	$\Delta\zeta$ cm	V_0 km^3	V_A km^3	$E_t^{10^8}$ J
M1 Low-Angle Thrust	20°	90°	100	50	2.0	72	21	93	1.8	3.4	6.2
M2 Dip-Slip Fault	110°	-90°	100	50	2.0	98	43	141	1.6	4.3	10.0
M3 Dip-Slip with Strike Component	110°	-50°	100	50	2.0	76	33	109	1.3	3.2	6.1
M4 Strike-Slip Fault	90°	0°	100	50	2.0	15	15	30	0.0	0.6	0.2
M5 Combined Source	20° 110°	90° -90°	100 100	30 20	2.0 2.0	88	33	121	1.8	4.3	9.2
M6 Fukao's Model	20° 80°	90° 90°	100 100	35 15	1.8 2.5	142	38	180	1.6	4.0	14.8
M7 Double Fault (block-type source)	110° 110°	-90° 90°	100 100	30 20	2.0 2.0	91	37	128	1.82	4.7	11.2
M8 Elliptical Elevation	-	-	-	-	-	68	0	68	4.0	4.0	10.0

Table 2. Basic Parameters of Tsunami Waves from Considered Sources

	h_{max} cm	$\bar{h}$ cm	K_m	I	M_t
M1 Low-Angle Thrust	170	117	1.8	0.4	7.6
M2 Dip-Slip Fault	180	126	1.3	0.6	7.55
M3 Dip-Slip with Strike Component	140	100	1.3	0.2	7.4
M4 Strike-Slip Fault	26	16	0.9	-2.4	7.1
M5 Combined Source	195	135	1.6	0.7	7.6
M6 Fukao's Model	210	125	1.2	0.4	7.5
M7 Double Fault (block-type source)	205	133	1.6	0.7	7.6
M8 Elliptical Elevation	185	149	2.7	0.6	7.8

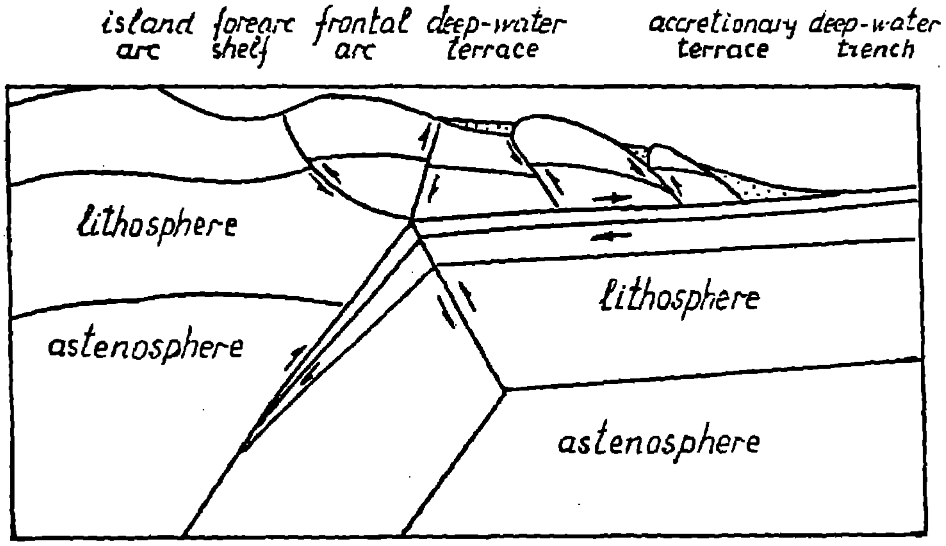


Figure 1. Schematic cross section of the subduction zone in the Kurile-Kamchatka region (after Lobkovsky, Baranov, 1982). Arrows represent the directions of possible crustal movements along the faults.

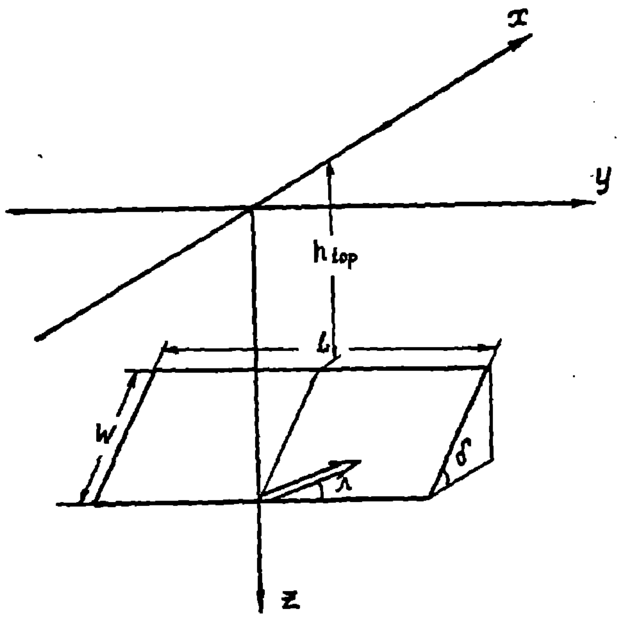


Figure 2. Geometry of a fault model.

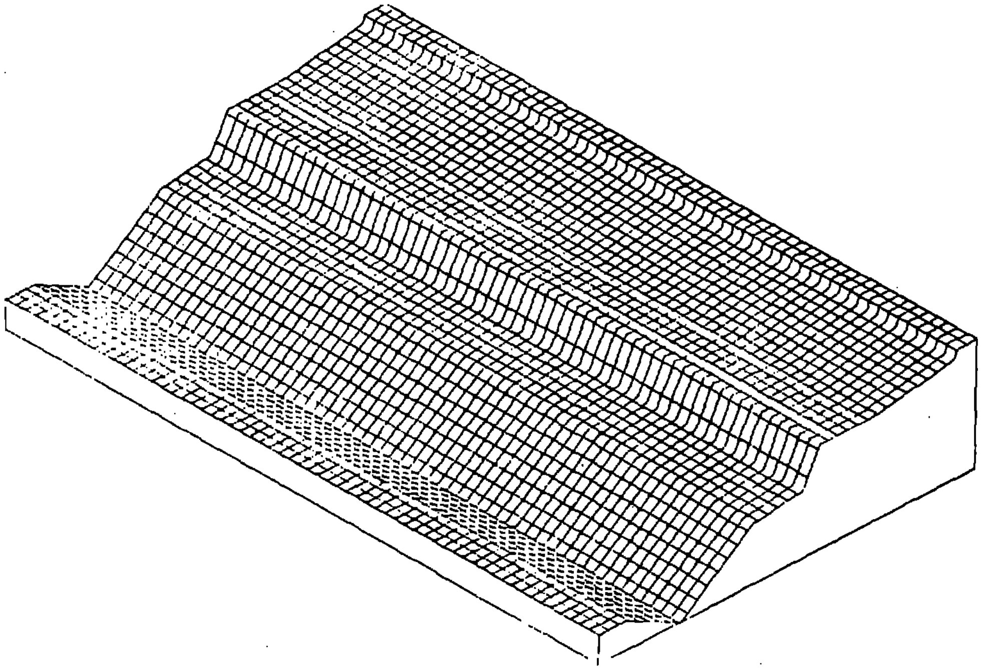


Figure 3. Model of the bottom relief of Kurile region.

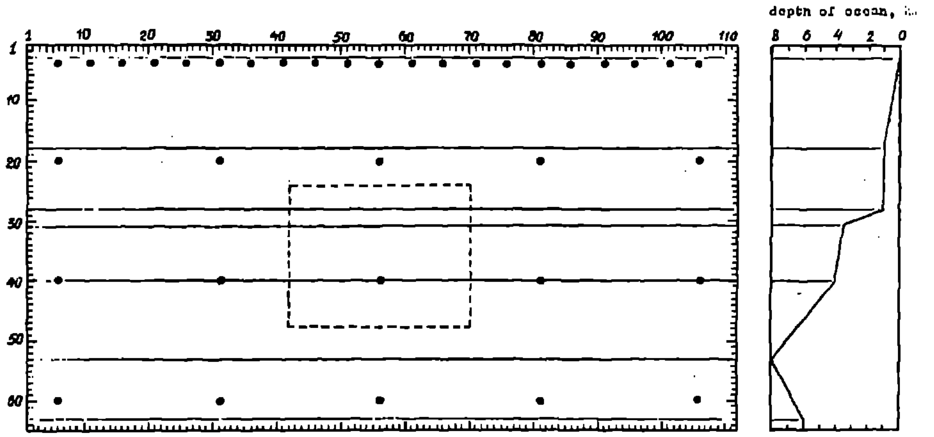


Figure 4. Computational grid used for tsunami calculation. The steps of bottom topography are shown with solid lines (profile of bottom is shown to the right). The dotted line contours the position of tsunami source. The solid circles note the grid points where the theoretical mareograms were calculated.

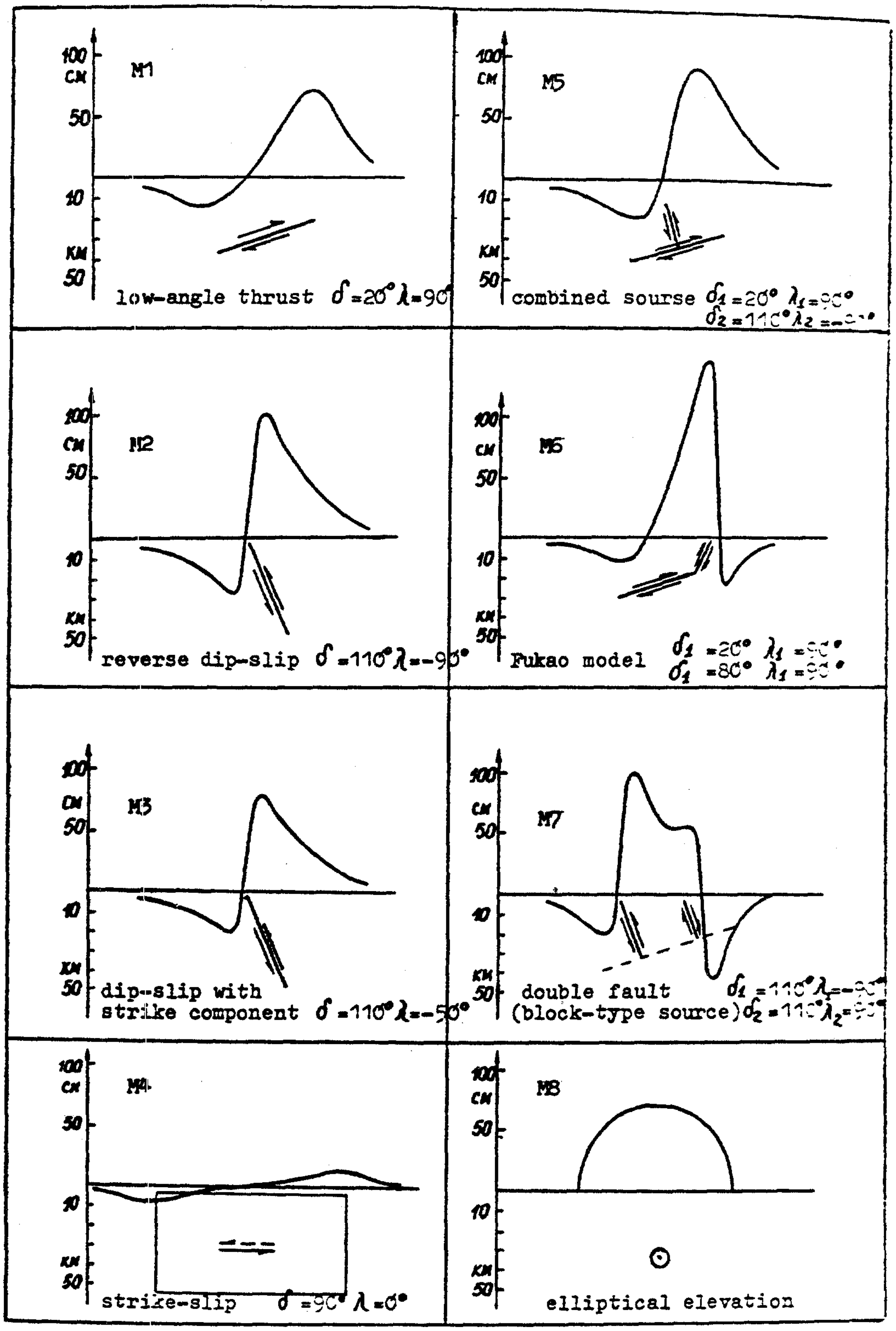


Figure 5. Profiles of vertical static displacement due to eight examined models of sesmic sources.

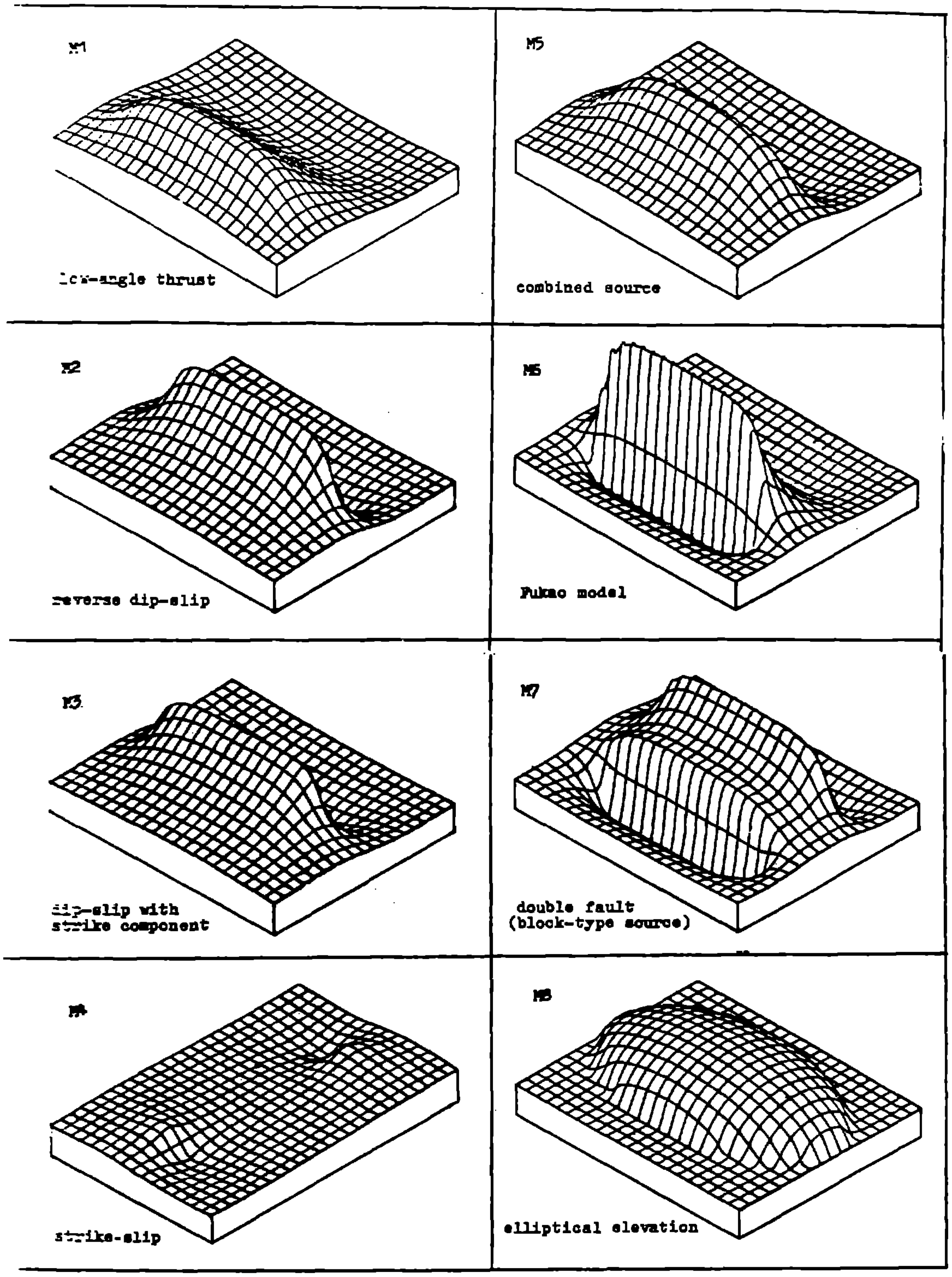


Figure 6. Perspective view of bottom displacement patterns due to eight examined models of seismic sources.

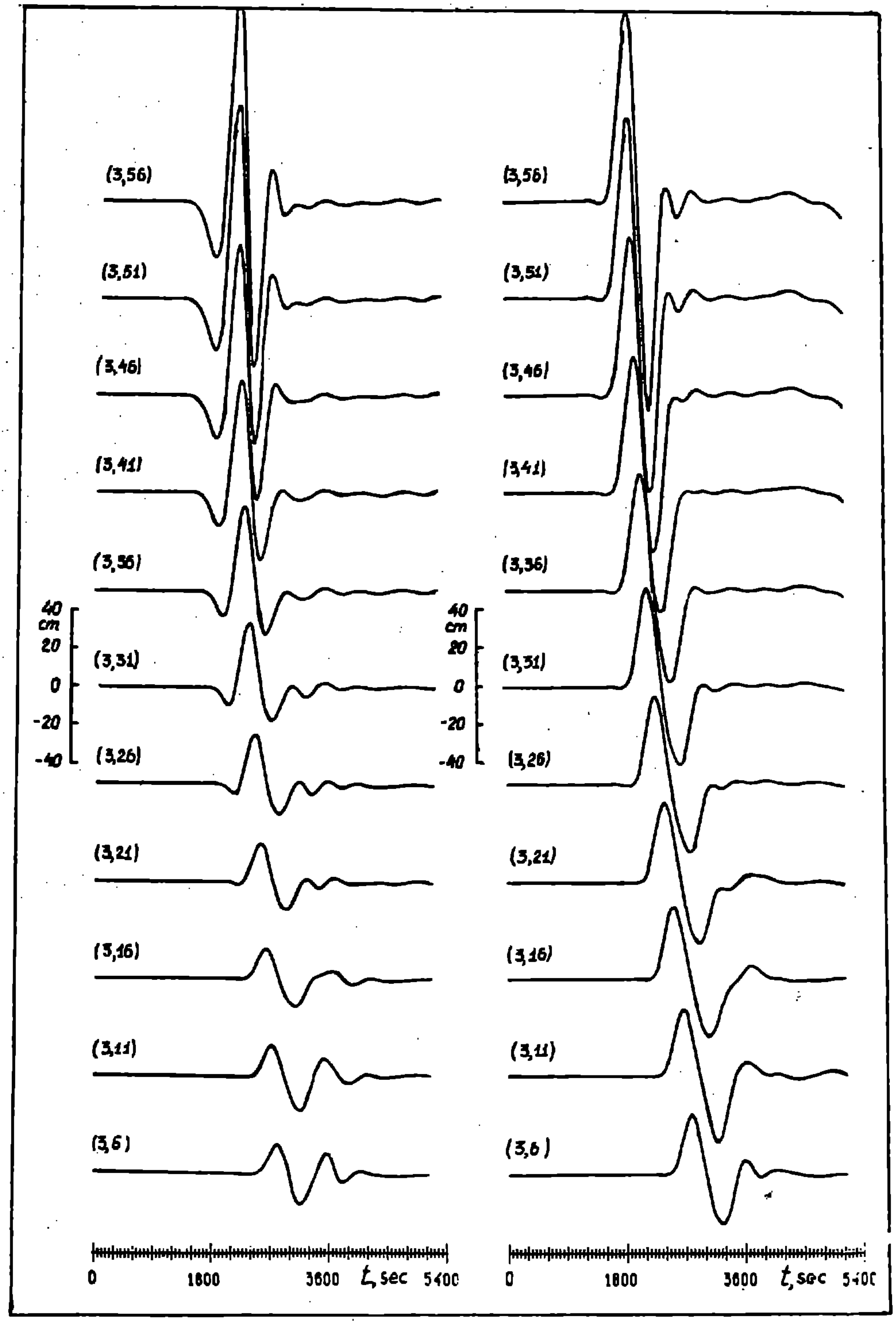


Figure 7. Computed wave forms for source M2 (to the left) and for source M8 (to the right). Figures in the parenthesis mean the position of grid point (in accordance with Fig. 4) where the wave form was calculated.

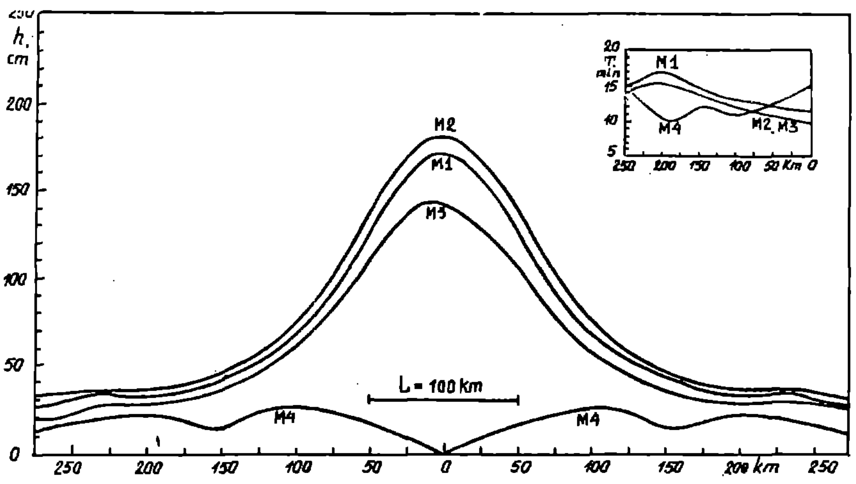


Figure 8. Distribution of maximum wave heights along the coastline for sources M1, M2, M3, and M4. Section of solid line shows the length and the position of seismic fault. Dependence of the period of maximum wave on the distance along the coast is shown in the insert figure.

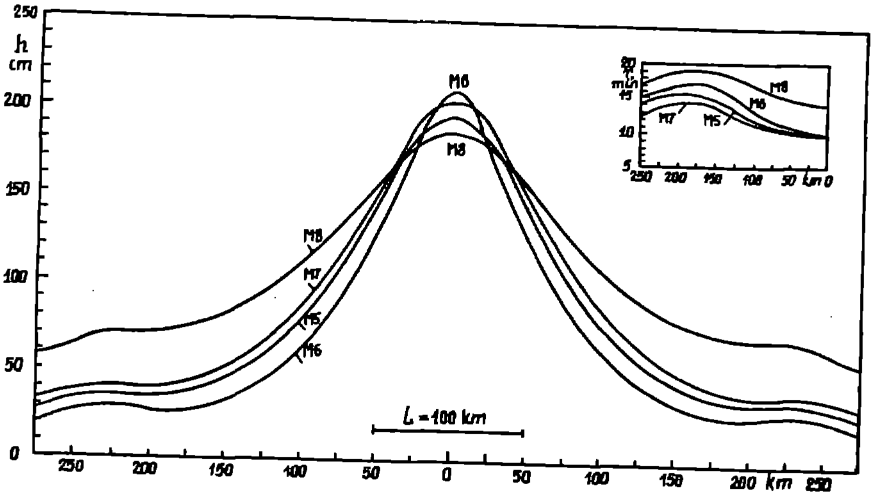
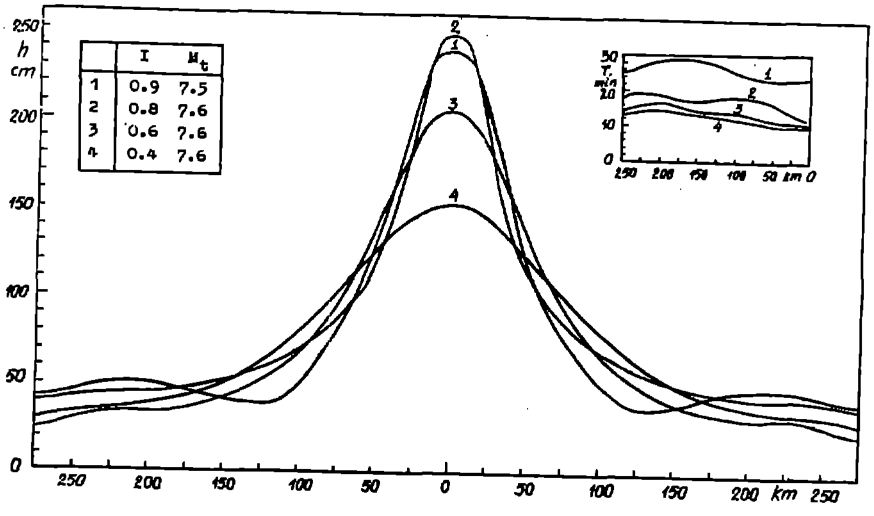
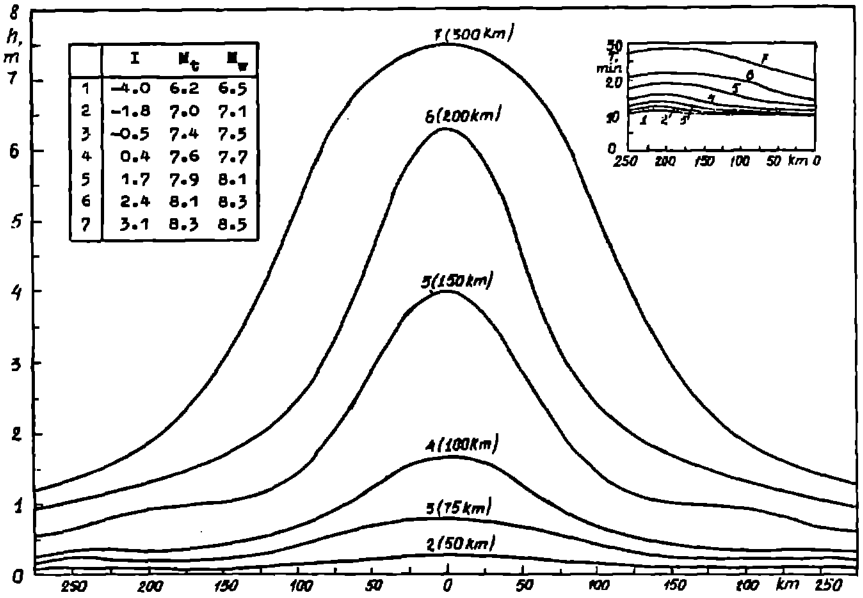


Figure 9. The same as in Fig. 8 for sources M5, M6, M7, and M8.



	I	M_t
1	0.9	7.5
2	0.8	7.6
3	0.6	7.6
4	0.4	7.6

Figure 10. Distribution of maximum wave heights along the coastline for source M2 at the different distances from the coast: 1 - 90 km, 2 - 140 km, 3 - 180 km, 4 - 230 km. Dependence of the period of maximum wave on the distance along the coast for each source position is shown in the insert figure to the right. Insert table to the left presents the computed values of I and M_W for each case.



	I	M_t	M_w
1	-4.0	6.2	6.5
2	-1.8	7.0	7.1
3	-0.5	7.4	7.5
4	0.4	7.6	7.7
5	1.7	7.9	8.1
6	2.4	8.1	8.3
7	3.1	8.3	8.5

Figure 11. Distribution of maximum wave heights along the coastline for six from seven examined variants of source M1 with different seismic moment. The figures in the parenthesis mean the length of fault. Dependence of the period of maximum wave on the distance along the coastline for each source variant is shown in the insert figure to the right. The insert table to the left presents the computed values of I, M_t, and M_w for each variant.

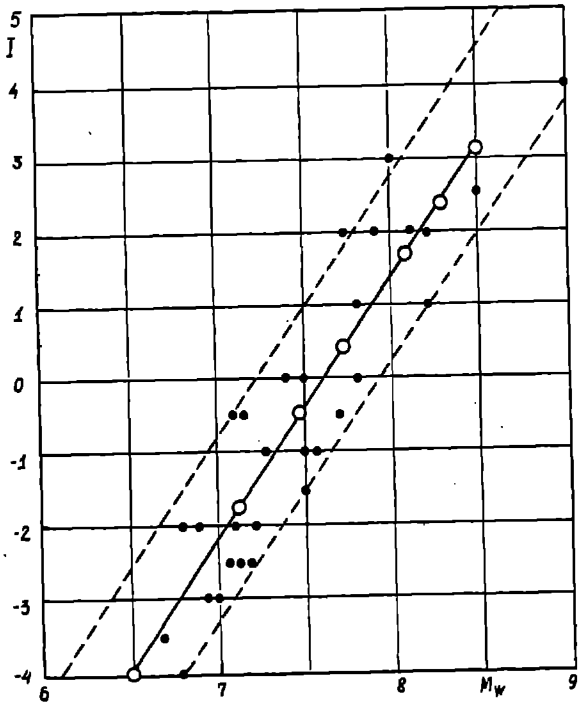


Figure 12. Relationship between tsunami intensity I and moment magnitude M_w for events of 1958-1983 occurred in Kurile-Kamchatka region. Solid line represents the theoretical relationship (11).

Numerical Modeling of Tsunami Waves (CHISLENNOE MODELIROVANIE VOLN TSUNAMI), written by An. G. Marchuk, L. B. Chubarov, and Iie. I. Shokin, Academy of Science of USSR, Siberian Branch, Institute of Theoretical and Applied Mathematics. The source was Nauka Press, Siberian Branch, Novosibirsk 1983. Translated into English for the Los Alamos National Laboratory from the original Russian by Leo Kanner Associates, Redwood City, California 94063, in August 1985. Distribution limited to U.S. Government Agencies and their contractors. Others should contact Leo Kanner Associates directly.

This monograph describes the numerical modelling of the tsunamis by using finite difference methods. A comprehensive set of programs has been developed on the basis of the finite-difference algorithms of the linear and nonlinear shallow water approximation. They are described in detail in this book and used to carry out calculations of tsunamis from the source of origin to the shoreline. The results of the numerical modelling of the Shikotan tsunami of 1973 are described.

The book is aimed at scientists who are interested in the study of wave processes in a liquid by using the methods of computational mathematics.

The book has 103 illustrations, 8 tables, and 151 references.

TSUNAMI, written by Crawford Kilian and published by Bantam Books, New York, New York, August 1984, 218 pages.

Reviewed by William Mansfield Adams

You will love reading this novel--if you have a morbid fascination for disasters and little knowledge of their physics. The book begins with a submersible being trapped in a turbidity current and almost ends in a submersible. Along the way, a submersible is used to sink a Navy cruiser. Even prior to the start, the world has presumably been subjected to extremely strong solar flares, reducing the ozone layer with burning consequences--such as malignant melanoma and photophthalmia (yes, you do need a medical dictionary handy, even if you are a physician).

The tsunamiologists will be most fascinated by an earthquake in Antarctica so large that the resulting tsunami passing under the Golden Gate Bridge is "...well over 50 meters high..." Fortunatley, "It was just beginning to break as it struck the Marin shore..." because the heroine "...watched the shock wave moving towards her at the speed of sound,..." Her scientific training is barely evident as she mutters, "The bugger is going to seiche." As for the wave velocity, try one hundred kilometers per hour along the San Francisco waterfront, with "...stones and mud hydraulically blasted from Treasure Island." And the north tower of the Golden Gate Bridge collapses. The clincher is that the "...seiches in the bay were scouring out the landfill..."

In this book, the warning of the tsunami is issued from Hilo (so now we know where the Pacific Tsunami Warning Center is being moved to!). The remainder of the book makes sense if you will but imagine that all of the conterminous United States EXCEPT for California has slipped into the ocean. This is because all activities are at locations along the Pacific Coast--Vancouver, San Francisco, Monterey Bay, Carmel, and Southern California.

Just to keep the plot credible, a local earthquake occurs. And despite the potpourri of disasters and resulting crises, an embryonic research project on bacterial production of methane is accelerated and successfully brought on line!

The social response is akin to "Lord of the Flies" being role-played by big boys. While, however, illustrating the additional adage that "Power and wisdom are mutually exclusive attributes of a human being." But the allegorical aspects are subservient to the action. Indeed, this book must have been written with the expectations of becoming a movie; certainly it is not suitable for teaching the physics of natural hazards. For the layman, this book may be morbidly entertaining; for the scientist, it is totally hilarious.

THE ALASKA TSUNAMI WARNING CENTER'S RESPONSIBILITIES AND OPERATIONS

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ABSTRACT

The Alaska Tsunami Warning Center was established in 1967 to provide timely tsunami watches and warnings to Alaska for Alaskan tsunamigenic events. Since the initial inception to the present time, many changes have occurred in areas, such as: responsibility, data networks, technique developments, operational procedures, and community preparedness. The watch and warning responsibilities have increased to include the west coasts of Canada and the United States. Seismic and tide data networks have been enlarged to enhance the accuracy of earthquake locations and sizing, and for confirming the existence of a tsunami. New procedures are continually being implemented at the ATWC, using advanced techniques and mini and micro computer systems, for processing data and disseminating information. In addition to advancing the ATWC's operational capabilities, community preparedness efforts continue to aid those individuals who may be caught in the immediate vicinity of a violent earthquake and its subsequent tsunami.

Introduction

The Alaska Regional Tsunami Warning System (ARTWS) was established as the result of the great earthquake occurring in the Prince William Sound area of Alaska on March 27, 1964. This event alerted State and Federal officials to the need for a facility to provide timely and effective earthquake and tsunami information for Alaska and the northern Pacific. The city of Palmer, located 40 miles north of Anchorage, was selected as the site for a primary observatory. Two other observatories, located at Sitka and Adak, were incorporated into the system. An extensive telecommunication and data telemetry network was established in 1967 and the ARTWS became operational. Initially, the tsunami watch and warning responsibility for Alaska was shared by the three observatories. The responsibilities of Adak and Sitka were to issue a tsunami warning if an event were to occur within 300 miles of each location. In later years, the responsibility to provide tsunami warning services for Alaska was transferred from the Adak and Sitka Observatories to the Palmer Observatory. In 1973, the Palmer Observatory was transferred to the National Weather Service's Alaska Region, and subsequently, renamed the Alaska Tsunami Warning Center (ATWC). In 1982, the responsibility for issuing tsunami watches and warnings to the U.S. west coast and Canada, for earthquakes occurring in those areas, was transferred to the ATWC. From the inception of this system to the present time, many operational changes have taken place and are discussed in this paper.

Missions

The primary mission of the ATWC is detecting and locating major earthquakes (events), and if they are potentially tsunamigenic, providing tsunami watches and warnings for Alaska, California, Oregon, Washington, and British Columbia in Canada, for events that occur in those regions. For non-tsunamigenic events, or ones outside of those regions, the event's parameters and other associated information are immediately disseminated to the Pacific Tsunami Warning Center (PTWC), National Earthquake Information Center (NEIC), and other appropriate agencies. This service is provided on a 24 hour basis, for each day of the year, by two duty personnel. During those times that the Center is not manned, the duty personnel are in a paid standby status. To ensure a rapid response to events occurring at night and on weekends, all personnel are required to live and remain within 5 minutes travel time to the Center. They are notified of the occurrence of an event, or irregularities in the Center's operations, by a radio-alarm system that can be activated by eight separate devices.

In addition to performing the primary mission, the ATWC personnel process, archive, and disseminate collected data; participate in fulfilling cooperative agreements; and, conduct advanced technique and equipment developments to improve the present system. The improvements involve both the reactive and predictive areas of the ATWC operational system. The reactive part concerns the reduction of response time between the occurrence of a tsunamigenic event and the issuance of a tsunami warning to people in the affected areas. In particular, this part seeks improvements in procedure modifications, present scientific methods used and development of advanced methods; advanced equipment and instruments; present and new software development and/or modifications; and, personnel performance. The predictive part involves both in-house and cooperative work efforts with other experts and/or agencies concerning areas, such as, tsunamigenic earthquakes and zones, and tsunami formation, propagation, run-up, and interaction with coastal shores.

The ATWC has both formal and informal cooperative agreements with many agencies and institutions. The agreements concern telemetry of seismic and tide data; seismic and tide site installations; cooperative technique and equipment developments; communications; equipment maintenance; and the exchange, reduction, and analysis of data. Some of these agreements involve daily collecting, processing, archiving, and disseminating data and records, to appropriate agencies. Additionally, develocorder data from the ATWC network are archived at the ATWC, and made available to visiting scientists to assist them in their work projects.

Seismic and Tide Networks

The ATWC is a large geophysical data acquisition Center which consists of 5 subnetworks owned and maintained by the ATWC, U.S. Geological Survey at Menlo Park (USGS-MENLO), NEIC, University of Alaska, and PTWC in Hawaii. These networks utilize more than 10,000 terrestrial miles of dedicated circuits to record and monitor approximately 120 analog seismic data traces in one common location at Palmer.

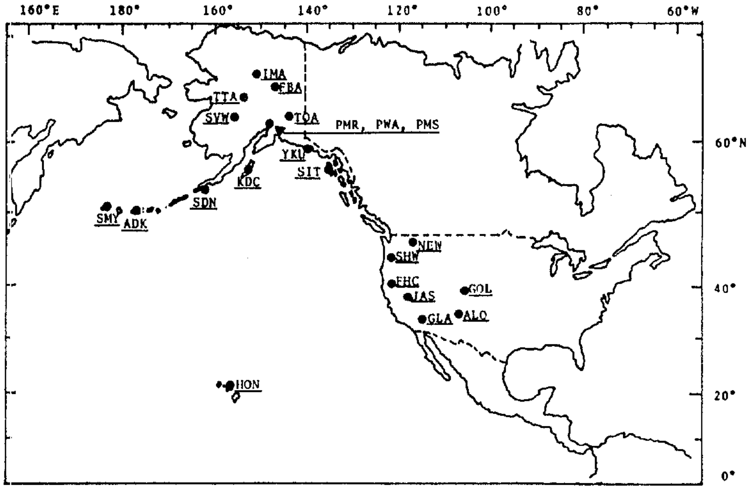

Fig. 1. A map showing seismic site locations in the U.S. that are telemetered to the ATWC in real-time.

The ATWC's seismic network, which extends throughout Alaska, is telemetered by satellite and microwave with very little interruption of data flow from the remote sites. Figure 1 shows the geographical location of the present ATWC network, and some site locations from the NEIC's network in the conterminous U.S. and PTWC's network in Hawaii. Not shown are approximately 80 seismic sites that telemeter data to the Center and belong to the University of Alaska and the USGS-MENLO. The ATWC's sites are visited each year for preventive maintenance, and as soon as possible, after equipment failure.

Tide data are available to the ATWC from subnetworks that are owned and maintained by NOAA's National Ocean Survey (NOS) and Canada. Figure 2 shows tide site locations near the coastal areas of Alaska and the west coasts of Canada and the U.S. Through a cooperative agreement with the NOS, the ATWC has equipment at each of the NOS sites in Alaska for telemetering data to the Center in real-time. Visitations to these sites, by personnel from the NOS and ATWC, are coordinated to minimize cost and maximize aid to each other. Data, from the tide sites near the west coasts of the U.S. and Canada, are not telemetered to the ATWC in real-time, and are obtained via teletypewriter, telephone, and the National Warning System.

All of the seismic and tide data, telemetered to and recorded at the ATWC, are monitored daily to ensure a continuous flow of data for conducting an earthquake/tsunami investigation.

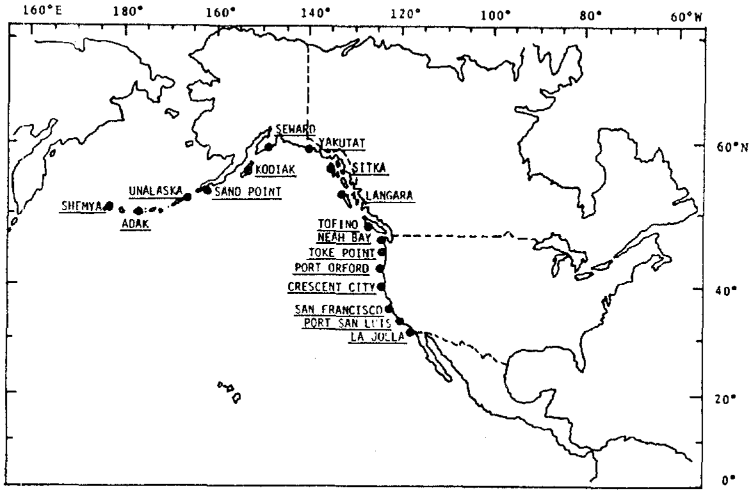

Fig. 2. A map showing the telemetered tide site locations near the coastal areas of Alaska and the west coasts of Canada and the United States.

Radio-Alarm System

The Center's personnel are alerted to large events, or equipment failure, by a radio-alarm system (RAS) which is connected to detectors that monitor incoming seismic data, a telephone system, and an uninterruptible power system (UPS). For events, six detectors continuously monitor both short and long period data from Palmer, Adak, Sand Point, and Sitka in Alaska, and Jamestown in California. The long period detector has its minimum threshold set for an event of magnitude 6.5 at a distance of 80 degrees (8889 km). The short period threshold, for local events, are set for a magnitude 6.0 at a distance of 8 degrees (889 km). Smaller magnitude earthquakes can activate the RAS if an event occurs near a site whose data are being monitored by a detector. Furthermore, the distribution of sites, that are monitored by detectors, permit multiple activations of the RAS for large events, thus ensuring notification that an event has occurred.

The Center's RAS can also be activated by dialing a special telephone number and by the failure of the UPS. Normally, for a commercial power failure, the UPS system and generator are automatically activated which results in no power loss or surges to the equipment. The RAS would be activated if the UPS or generator failed, or the equipment became overheated.

During those times that the station is unmanned, the RAS will activate alarms in the duty personnel's residences, as well as each person's VHF pocket-voice receiver. To ensure this station coverage, the following equipment is used to activate the Center's radio-alarm system: leased telephone lines from the office to each employee's residence; commercial automatic phone answering and recording devices; VHF transmitter with high gain omni-directional antennae; and, VHF pocket-voice receivers. For an event or equipment failure, the RAS will cause the telephone to ring continuously via the office switchboard/leased telephone lines , and simultaneously a continuous high pitched signal is emitted by the VHF pocket-voice receivers. When the unlisted number is dialed, the RAS will ring the telephone bell and a device answers and records the message(s). The caller's message is transmitted by the RAS to the VHF pocket-voice receivers, thus permitting the duty personnel to listen to the caller. This provides them with immediate knowledge of the caller and the urgency of the situation.

This system, which has been evolutionary over the years, provides total coverage even when the duty personnel are between the Center and their residences. The VHF system functions as both a primary alarm system and as an excellent backup to the leased line telephone system.

Earthquake/Tsunami Investigations

Events that activate the ATWC's RAS necessarily initiate an earthquake/tsunami investigation (ET) which includes locating and sizing the event, and culminates in processing the event routinely or in the issuance of a watch/warning (WW). During the past 17 years, the ATWC's personnel have conducted an average of 12.3 ET's per month. Figure 3 shows a block diagram of an ET when the office is not manned, e.g. at night.

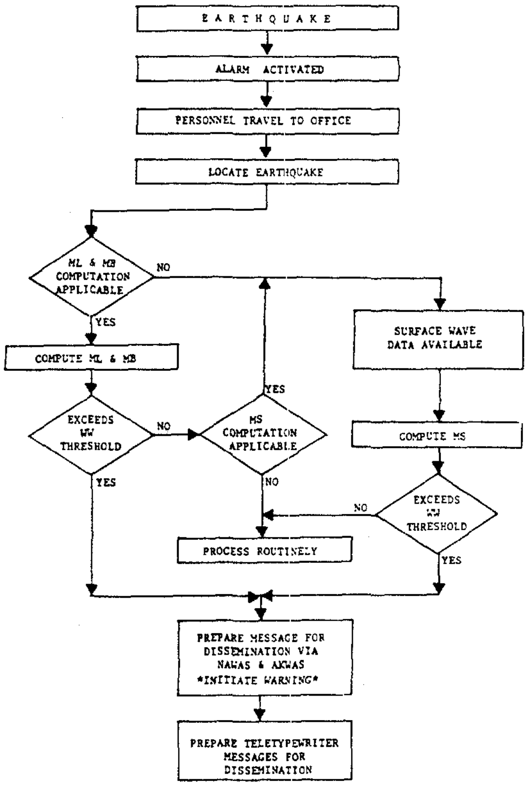

Fig. 3. A block diagram showing the procedural steps in conducting an earthquake/tsunami investigation.

An event's location and size are always the first actions to be taken for any ET which dictates whether the event will be processed in a routine manner or as a WW. Unfortunately, there is no single device, site, or method that would accurately, consistently, and rapidly size any local, regional, or teleseismic event. Therefore, as shown in the ET diagram, several accepted and appropriate magnitude determining methods are used to complete an ET. Event size determinations have been, and are being developed to enhance procedural responses in this area (Sindorf, 1972, 1974).

Appropriate tsunami and/or earthquake information which results from an ET are immediately provided to: Alaska Division of Emergency Services; Alaska Air Command; NEIC; PTWC; USGS-MENLO; Japan Meteorological Agency, Tokyo; USGS Observatory, Guam; Royal Observatory, Hong Kong; news media; and to many other recipients including both State and Federal disaster preparedness agencies and military bases, and appropriate agencies in Canada.

A WW is issued by the ATWC when the magnitude of an event has exceeded a predetermined magnitude threshold, and the event's location is near a coastal area, from Kamchatka through southern California. The threshold magnitude for issuing a WW to Alaska, for events in Alaska, is 6.75. The threshold for events near Kamchatka or near the west coasts of the U.S. and British Columbia is 7.5. When an event's magnitude has exceeded an area's threshold, a limited geographical area is placed in a warning status. Other geographical areas, outside the warned area, are placed in a watch status. A warned area includes those places that are within about 3 hours of water wave travel time from the epicenter.

After the initiation of a WW, tide site's data that are nearest the epicenter are monitored for the existence of a tsunami. Upon confirmation that a tsunami has been generated, the previously designated watch areas are upgraded to a warning, and the information is communicated to the recipients. Event's that are smaller than threshold, and important to Alaska, are processed on a routine basis and the information disseminated to appropriate officials.

The main methods for disseminating emergency and routine information (U.S. Department of Commerce, 1984) are by the National Warning System (NAWAS), Alaska Warning System (AKWAS), commercial telephones, Alaska Division of Emergency Services, VHF radio system, Federal and Military teletypewriter systems, VHF Weather Radio, HF Marine Weather Radio, Emergency Broadcast System (EBS) through the National Weather Service, and EBS and HF via the Coast Guard. The NAWAS, a voice disseminating system, is the primary one used to alert disaster officials in the U.S. and Canada of large events. The AKWAS, which is the State side of NAWAS, permits immediate voice communication with Alaska disaster officials. A teletypewriter system is a secondary means of disseminating the information which immediately follows the voice communicated messages.

Community Preparedness

The ability of any warning system to successfully save lives and reduce property damage depends upon getting the information to the public and getting them to respond to the emergency. The ATWC cooperates with the Alaska Department of Emergency Services and many other hazard officials on the west coasts of the U.S. and Canada and the far western Aleutian Is. to maximize the effectiveness of the community preparedness efforts. The main purpose of this program is to educate the public to help themselves if they are caught in the middle of a violent earthquake and/or tsunami. Additionally, the program involves the gathering of information concerning each community's preparedness procedures and their potential tsunami hazard (Carte, 1984). To each community, the program presents a detailed briefing of the TWS, seismicity of their area, past historical earthquake/tsunami damage, and estimates of what might happen if an earthquake/tsunami were to occur. The presentations use slides, movies, brochures, and other materials concerning the effects of earthquakes and tsunamis.

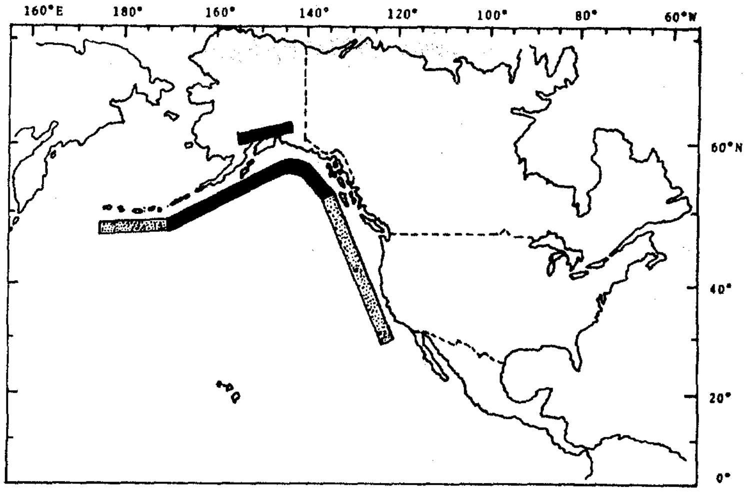

Fig. 4. A map showing areas involved in the ATWC's community preparedness efforts. Darkened areas are visited by the ATWC personnel. Stippled areas are ones where the ATWC personnel cooperate with hazard officials in those coastal areas.

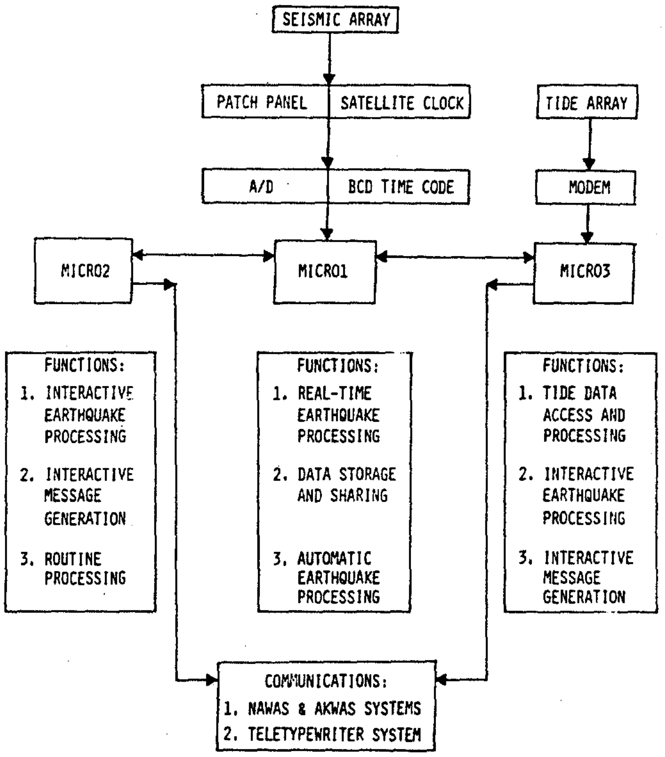

Fig. 5. A block diagram showing a distributed system of micro computer systems and their functions.

All professional staff members are involved in the preparedness program which includes visits to distant out-lying coastal communities from Ketchikan to Dutch Harbor and to coastal and other local group facilities and schools that are within commuting distance of the ATWC. Also, presentations are given to hazard officials who are responsible for the far western Aleutian Is. and the west coasts of the U.S. and Canada. These areas are shown in Figure 4. In addition to the outside presentations, the ATWC facilities are opened to the public each Friday from 1 to 3 in the afternoon for local and other visitors.

The darkened areas in Figure 4 are ones that are visited by the ATWC personnel, either yearly or biennially, depending upon available resources. Frequent visitations are made to those areas that are within reasonable driving distance from the Center. Visitations to out-lying communities are made in alternating years. Groups, such as schools, are encouraged to video tape the ATWC presentations for later use. The stippled areas are ones where the ATWC cooperates with and/or assists hazard officials who are responsible for community preparedness in those areas.

ATWC Micro Computer Developments

The ATWC is continually improving its operations as a result of advancements in equipment and technique developments. In the last two years, the ATWC has integrated an automatic earthquake processing system (Sokolowski et al., 1983) into the operational procedures. An advancement of this system initiative has been introduced by the ATWC, and involves the use of several micro computer systems.

During the past year, the ATWC has conducted a feasibility study to determine the potential for integrating micro computers into the operations of the ATWC. This study has shown that the interactive processes of locating earthquakes, generating messages, and processing routine day-to-day tasks can be done by a micro computer. The test micro can interactively accept data from 32 seismic sites to rapidly compute an event's parameters. It can also produce computer generated messages for dissemination via the NAWAS and teletypewriter systems.

As a result of this feasibility study, the ATWC has introduced a micro computer system concept to integrate a distributed network of micro computers into the ATWC operations. Figure 5 shows a block diagram of the micro system and gives an outline of their functions. This concept envisions three micro systems (Sokolowski, 1985) that are physically distributed in the Center to maximize aid for the personnel, thus minimizing the response time between the occurrence of an event and the dissemination of critical information to the TWS recipients. The concept is evolutionary in that future tasks and additional micro systems can be integrated into the ATWC operations to enhance both the reactive and predictive parts of the operation. The micro systems are intended to communicate with each other, or function independently, to perform the operational tasks. This concept includes concurrent real-time and interactive processing in addition to obtaining and processing tide data in near real-time.

The first micro (Micro1) will be dedicated to detecting events and storing their associated data, and automatically computing the event's parameters. The seismic data will be selected from the network of sites that are available to the ATWC. The incoming data will be digitized, analyzed and processed in a similar manner to the existing mini computer system (Sokolowski et al., 1983). Appropriate data, stored by the Micro1 processes, would be made available to Micro2 and Micro3 for concurrent interactive processing.

Micro2 would be used to interactively compute an event's parameters using data that are passed to it from Micro1, or manually read from the ATWC's helicorders and/or develocorders. The amount of interactive data, collected for processing, are dependent upon the event's size and location which normally dictate procedural expediency. This micro will also be used to interactively generate the messages for disseminating earthquake/tsunami information.

Micro3 will be used for processing tide data from sites that do not telemeter data to the ATWC in real-time. The first efforts will be to obtain data, in near real-time, from the west coast tide sites for analysis and processing at the ATWC. This will considerably enhance the ATWC's present procedures for obtaining tsunami confirmation from tide sites along the west coast. This micro will also be used for concurrent earthquake processing and message dissemination. Depending upon the ability of Micro1 to perform real-time processes, Micro3 could also serve as an aid to the Micro1 system in this area.

Conclusion

The ATWC continues to improve both the reactive and predictive areas of its operations to enhance the timeliness, quality, and quantity of data and information that are disseminated to the TWS recipients. The reactive area continues to examine and enhance the response time between the occurrence of an earthquake and the initial dissemination of critical warning information with regard to: procedure modifications; present scientific methods used, plus development of new methods and procedures; additional equipment requirements; present and new software development and/or modifications; and, personnel performance. In-house and cooperative work efforts with other agencies and individuals, continue to address the predictive areas. This concerns problems related to tsunamigenic earthquakes and zones, and tsunami formation, propagation, run-up, and interaction with coastal shores. The integration of micro computer systems into the operations provides considerable future potential for enhancing both the reactive and predictive areas, and thus the services to the TWS recipients. Getting the public to respond to disseminated earthquake/tsunami information is a vital part of the ATWC efforts and necessitates an educational community preparedness program. This program covers selected areas in large geographical areas, and in cooperation with other agencies and hazard officials.

Acknowledgments

The author expresses his appreciation to Mr. Stuart G. Bigler, Alaska Regional Director, and his staff for their valued comments and constructive criticism of this paper.

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NEEDS AND DEVELOPMENTS IN TSUNAMI MONITORING*

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ABSTRACT

More and better data on tsunami characteristics and effects in various locations--deep-water, coastal, and inundated areas--are needed to: (1) better define zoning and structural codes in order to mitigate the hazards of tsunamis. (2) refine the definition of the evacuation areas, and (3) improve warning systems. In Hawaii, this problem is being approached in several ways--development of a deployable pressure gauge suitable for real-time field use in shallow depths offshore from terminal areas; development of a sophisticated seismic trigger system for local earthquakes; extensive photographic methods for real-time recording of a tsunami; and in situ procedures for personnel to perform post-event run-up measurements and related field observations. In this presentation, each of these approaches is described and the possibility of application to small, non-damaging tsunamis is examined. The source mechanism for such tsunamis is assumed to be similar to that of large tsunamis; however, this assumption requires investigation.

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OBJECTIVES AS ENDS OF THE MEANS

The gathering of data is a means to ends. Here we discuss some important features of these end objectives--the efficient monitoring of tsunamis. We first consider the zoning of coastal areas for insurance and building code purposes, then we apply and extend the concepts for zoning to evacuation during a tsunami alert or warning. Finally, we consider the improvements possible in a tsunami warning system and in civil defense actions, with additional and/or improved data.

Insurance Zoning: About ten years ago, a federal program for flood insurance was initiated. The inundation of a tsunami is categorized as flooding and hence is included in that program. The delineation of the statistically expected 100-year inundation requires an awareness of the acceptance of a risk. In the analogous river situation, many years of good statistics usually are available to provide valid 10-and 100-year probabilities; in the case of tsunamis, data are sparse and imperfect, but a line had to be drawn. Such quantification of risk and recognition of the various trade-offs made versus risk greatly aid in objectifying the making of decisions. A typical Federal Flood Insurance Rate Map (FIRM) is shown in figure 1. (It should be noted that these maps also include river and stream flooding).

Evacuation Zoning: One type of zone of intense interest is the zone (or zones) of evacuation, in which officials or the police endeavor to assure that a maximum number of the populace are removed before the first tsunami wave arrives. Again, as in the insurance program, there are many trade-offs. For example, to take an historical approach, in Hawaii the first proposed evacuation zones were the envelope of the historical inundations (Cox, 1961; Adams, 1968). From observations and study of the behavior of coastal residents (Havighurst, 1967), it later seemed appropriate to use standard statistics and consider the "expected" tsunami inundation (Adams, 1970). Further following statistical procedures, the introduction of "conditional expected tsunami inundation" (CETI) seemed desirable for real-time operations, as the prediction could be improved by recognizing that certain information such as the source region would be known in real time (Adams, 1973). In figure 2 we see the evacuation zones for Kahuku, Oahu, Hawaii: first the zone using Cox's criteria (1961) and second, that zone as expanded inland by Civil Defense to well-known cultural boundaries, and finally the conditional expected tsunami runup heights, conditional upon the tsunami magnitude and source direction (Adams, 1973). Note that the objective is not to reduce the area (or volume) being evacuated, but rather to minimize the loss of life. This goal can be achieved indirectly by establishment of an evacuation zone that will elicit maximum cooperation from coastal residents. The variation in expected inundation clearly will have a significant effect on the evacuation zone.

A significant factor in the problem of evacuation is the general increase in population density in coastal areas in recent years. In the State of Hawaii, for example, the population has increased 58% since the last evacuation in 1966. Much of this increase has been along the shorelines. For the area shown in the figures, the percentage is much higher. Thus there is a large populace living in the present evacuation zones who have never experienced a tsunami warning, and who will be shepherded to safety along limited routes by authorities most of whom also have not experienced an evacuation. To prevent confusion - "people stumbling over each other" and thus reduction of everyone's chances of survival

- it is essential to delimit the evacuation areas by careful, quantitative planning.

From such studies of estimating suitable evacuation zones, scientists are developing the ability to provide to policy makers and public officials a multi-level zoning (Adams, 1976). Thus one boundary may be used if the source is known to be in the Aleutians, another if the source is in Chile. And such a boundary may be further refined to represent knowledge of the source tsunami magnitude. See, for example, figure 2 which gives the conditional expected inundation (runup heights) dependent upon (a) the source region and (b) the magnitude of the tsunami (using the logarithmic scale of Adams (1973)). The evacuation zone may be a volume instead of an area. This is appropriate when high-rise buildings in the inundation zone (Hawaiian Telephone Co., Oahu Directory, 1985) have been determined by engineers as certain to survive the expected tsunami inundation.

Clearly, more and better data on tsunami effects will add to the capability of scientists to predict tsunami inundation more accurately and will also add to the confidence level placed on more limited evacuation zones. Some of the means to achieve this end are discussed later.

The utility of additional data, especially in hazard areas, is well illustrated by the procedures used by Houston, Carver, and Markle (1977) and the subsequent manual for tsunami hazard mapping. In many areas of the Hawaiian Islands extensive interpolation had to be done to "synthesize" run-up factors for 100-year flood contours. The run-up factors for those areas have a significant variance associated with them. The run-up factors have not been validated but the computer model generates numbers and the numbers are used as facts, often erroneously (Adams, 1984).

Warning Systems: Any warning system usually benefits from additional information. It has been recommended Pararas-Caryannis and Bernard (1979), but not yet formally implemented, that satellite-transmitted tide data be provided from critical locations upon request by the Tsunami Warning Centers. Addition of sea-level data from stations established for other purposes shows promise. However, a prompt processing capability is necessary to assure that such information is contributing positively to the decision-making and not saturating the analysis procedures. Such decision-making (Adams, 1966; Cox, 1979) can be considered to be the reduction of many numbers to a few--the avowed objective of statistics. It is important in any such decision-making process that the backward trail of information be known. That is, the dependence of the final conclusion upon each step along the way should be demonstrable. In analogy to such tracking in accounting procedures, the decision making must be "auditable." The testing of the decision-making process may be done by using "scenarios", e.g., assuming a tsunami-genic source in some seismic gap region and proceeding through a role-playing "game." By using multiple runs with various decision makers, the sensitivity of the processing can be estimated.

DATA GATHERING AS A MEANS

We will consider the present state-of-the-art of gathering tsunami data by going from the land to the coast and then from the coastal zone to the water. Because of the rarity of tsunamis, the development of computer-aided decision-making by local officials seemed appropriate (Adams, 1979) and was implemented with then-current technology. A view of the tsunami seismic switch that was evolved is shown in figure 3. Now it is possible to improve such instrumentation by using various features of the electronics evolved during the past decade (Adams and Curtis, 1984). In particular, the objective of recording should be added to the original objective of alarming, as discussed in the above cited paper and related unpublished proposal.

Concurrent with the tsunami arrival at selected coastal areas, image-monitoring by trained observers and over-flights by airplanes carrying photographers have been arranged (Curtis, 1982a). These efforts are supplemented by post-event measurements of run-up made by trained personnel previously trained in such procedures. A teaching procedure for such persons was developed by Curtis (1982b) and was conducted in 1983 and 1984. See figure 4.

As tsunamis do not always cooperate by arriving in the coastal areas during the daylight hours, it is necessary to supplement such field efforts with instrumentation that can capture data during the night. A real-time deployable, in-situ pressure recorder has been designed and prototypes constructed (Curtis, 1983). This gauge has dual range capability, obtained by simple manual pre-set. A view of the prototype is shown in figure 5 and a block diagram in figure 6. The amplitude response of this instrument is calibrated by using observations of the tide. If such an instrument is produced in large numbers, the cost can be low; the high reliability is achieved by having no moving parts in the recorder (Curtis and Loomis, 1979/1982; Curtis, 1982b).

The productivity of the data gathering can be enhanced by developing the ability to observe smaller, non-destructive tsunamis, as emphasized by Van Dorn (1960, 1963) and others (Snodgrass, et al., 1958). The additional data thus obtained should significantly reduce the variance of the estimates that must be made in real-time warning systems. However, as indicated by Adams (1978), it is possible that the mechanisms of such tsunamigenic earthquakes may differ and this possibility should be incorporated into the procedures for inclusion of such additional data into the decision-making process. Adams (1978) has shown that the mechanism of a "super-tsunami" such as the 1896 and 1933 northeastern Honshu events is probably different, as indicated by their greater generation efficiency. However, large, medium, and small tsunamis are usually assumed to have tectonically similar source mechanisms.

Congruent with this recognition of the potential benefits of observing non-damaging tsunamis is the need for categorizing such events. This would improve communication as does any working vocabulary (Adams and Nakashizuka, 1985). Thus we suggest the following terminology:
Tsunami (generic): having a wave of more than two meters peak to trough, observed, or normalized to, one thousand kilometers from the source area.

Mini Tsunami: having a normalized wave of less than two meters but more than two decimeters peak to trough observed.

Micro Tsunami: having a normalized wave of less than two decimeters but more than two centimeters peak to trough.
Comments on these suggestions would be appreciated.

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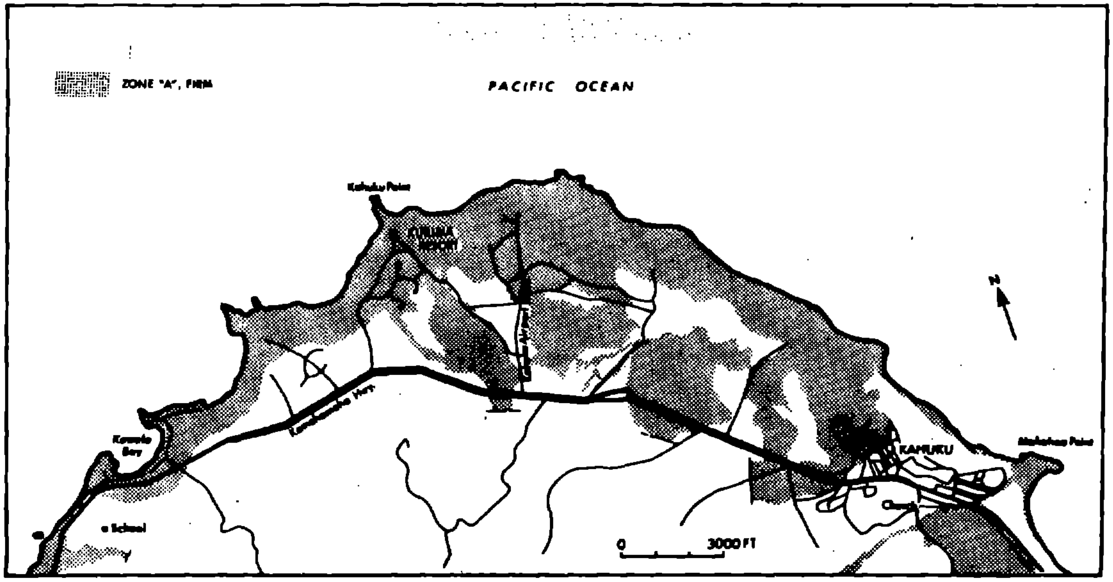

Figure 1. Flood Insurance Rate Map (FIRM).

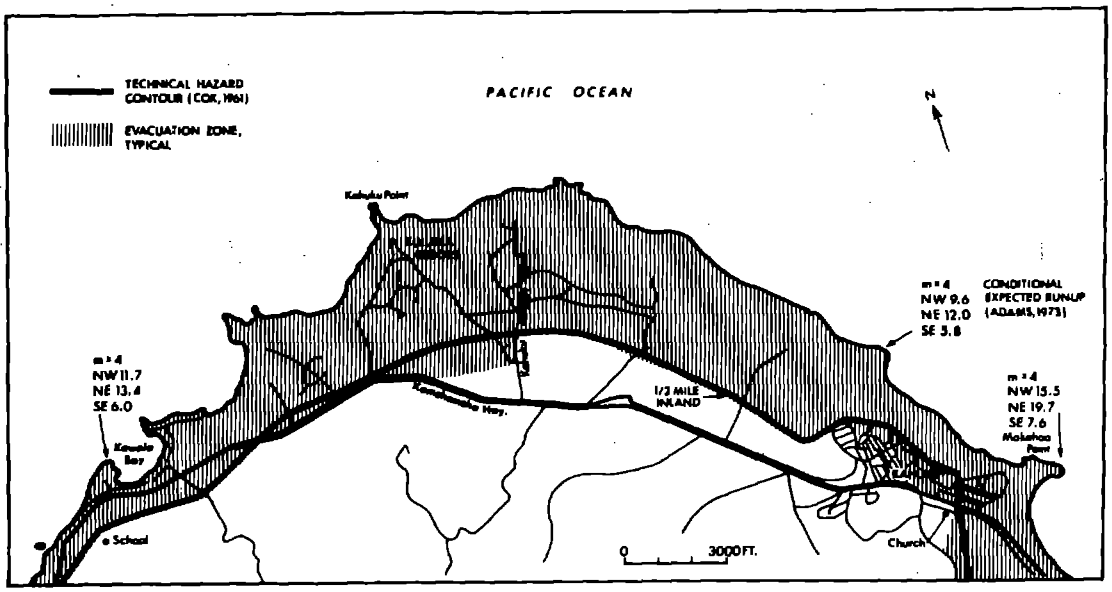

Figure 2 - Various tsunami zonations for Kahuku; the Technical Hazard Contour (Cox, 1961); as modified by Hawaii Civil Defense Office (Telephone Book, Hawaiian Telephone: 1984); Expected Run-up Heights at selected locations, conditional upon a source of tsunami magnitude 4 and known quadrantal direction (Adams, 1973).

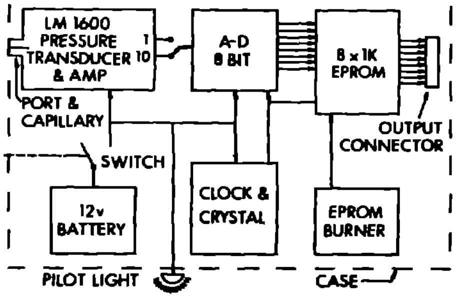

Figure 6 — Block Diagram, Deployable Gauge.

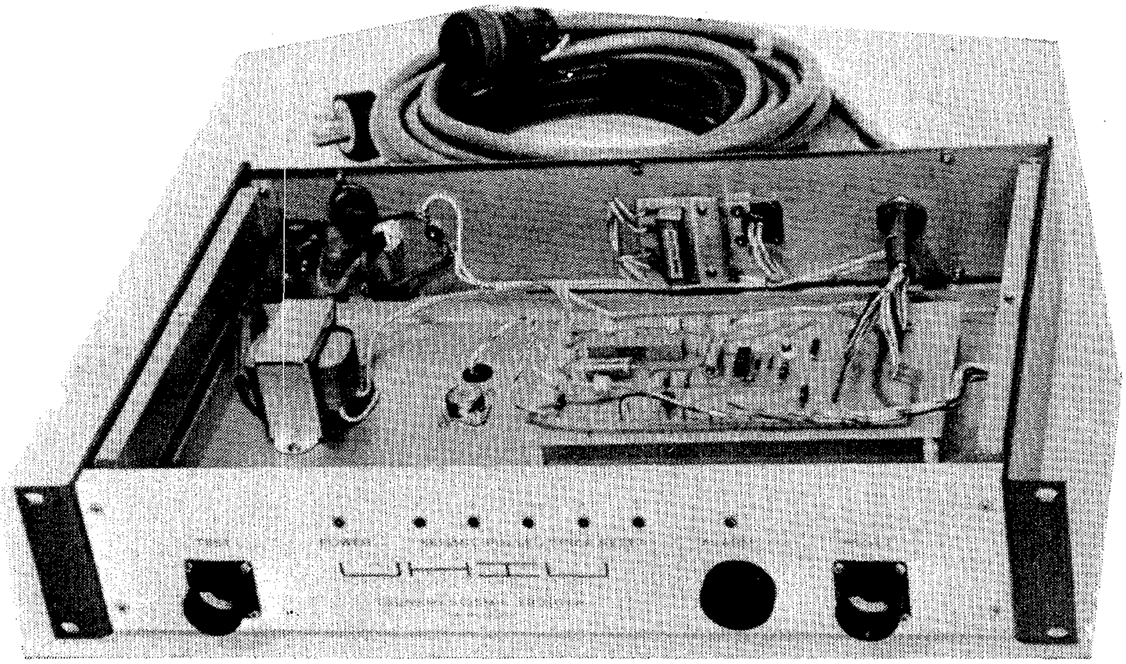

Figure 3 - Photo, Tsunami Seismic Switch.

Figure 4

Photo, Post-Event Run-up Class at an Oahu Beach. Third person right is using hand level to measure increment of run-up.

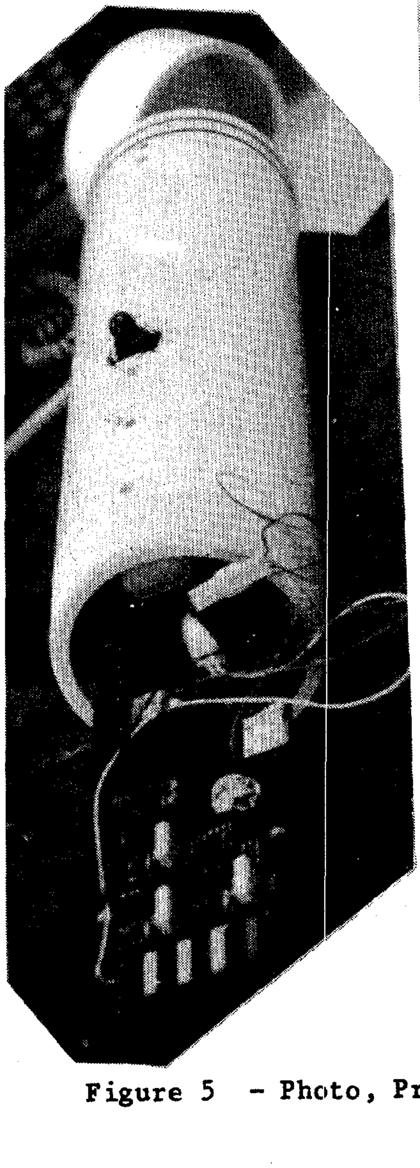

Figure 5 - Photo, Prototype Deployable Tsunami Gauge.

FRACTAL DIMENSION AND LENGTH OF AN IRREGULAR COASTLINE: APPLICATION TO THE ST. LAWRENCE ESTUARY

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ABSTRACT

The concept of fractal dimension is used here to express quantitatively the irregularity of the coastal stretches along the north and south shores of the upper and lower parts of the St. Lawrence estuary. It has been shown that the north shore of the lower estuary is the most irregular, whereas the south shore of the lower estuary is the least irregular. A detailed examination of the topographic maps confirms this result. A classification such as this is useful for planning construction of engineering structures designed for coastal protection from such natural hazards as tsunamis, storm surges and erosion.

INTRODUCTION

Unpublished work by L.F. Richardson (mentioned in Orford and Whalley, 1983) on the measurement of the length of the coastline of the United Kingdom revealed a paradox, later referred to as the Steinhaus paradox (Steinhaus, 1954). This paradox states that, the smaller the unit of measurement, the longer is the apparent perimeter length of the coastline. Mandelbrot (1977) developed the concept of fractal dimension to accurately characterize lines and non-euclidian surfaces. The fractal dimension D is given by

$$D = 1 - B \tag{1}$$

where B is the slope of the best fitting linear regression of the graph between the measurement unit of length and the total length of the coastline, both expressed in the logarithmic form. Note that increasing values of D correlate with increasing irregularity of a given coastline.

This concept of fractal dimension is applied here to examine the coastline length of the St. Lawrence estuary. Such specifications of coastline lengths and irregularities are useful in many practical engineering applications, as well as problems dealing with tsunamis, storm surges, wind waves, coastal erosion and ice ride-up phenomenon.

COMPUTATION OF FRACTAL DIMENSION

Figure 1 shows the geography of the St. Lawrence estuary. Note that here we examined separately the lengths of the south shore and north shore of both upper and lower parts of the estuary separately. The unit of measurement (L_u) varied from 37.1 to 0.9 km; in table 1 we used 0.5 and 0.2 km for the upper estuary. Table 1 lists the lengths of these four sections of the coastline for different values of L_u. The coastline lengths differ slightly when they are measured in an upstream or downstream direction, even using the same unit of measurement length. For this reason average values of the upstream - and downstream - direction measurements are used to compute the fractal dimension

Figure 2 shows the plots of the unit of measurement length L_u on the abcissa versus length of the coastline L_t for the four stretches identified earlier. In each case, the regression equation between L_u and L_t is also shown above each graph.

RESULTS

The fractal dimension D is a quantitative expression of the irregularity of a coastline. Higher values of D ($1.0 \leq D \leq 2,0$) correspond to greater irregularity of a coastline. Thus the concept of the fractal dimension helps us to compare the irregularity of coastlines in a quantitative manner.

Table 2 summarizes the results obtained in the present study. An examination of the values of the fractal dimension D shows that, out of the four coastline stretches studied here, the north shore of the lower estuary is the most irregular and the south shore of the lower estuary is the least irregular. If we examine the south and north shore separately, we recognize that for the south shore, the upper estuary's coastline is more irregular than the lower estuary's coastline. On the other hand, for the north shore, the coastline of the lower estuary is more irregular than the coastline of the upper estuary. Comparison of columns 3 and 6 in Table 2 shows that the relative ranking of the D values agrees with the relative ranking of the L_{tg}/L_{ts}. An examination of the detailed topographic maps of the St. Lawrence estuary confirms that, indeed out of the four coastline stretches considered here, the north shore of the lower estuary is the most irregular and the south shore of the lower estuary is the least irregular.

CONCLUSIONS

The use of fractal dimension D gives us a technique of specifying the irregularity of a coastline in a quantitative manner. The fractal dimension is given by (1-B), where B is the slope of the best fitting linear regression of the graph between the measurement unit of length and the total length of the coastline, both expressed in the logarithmic form.

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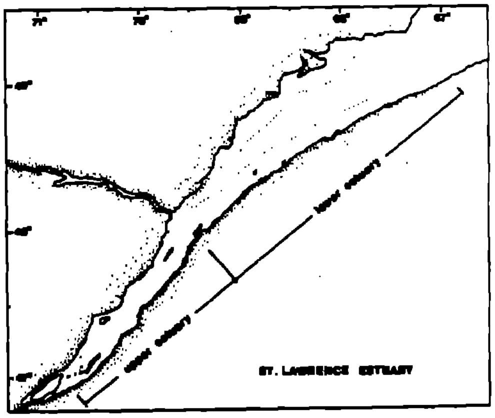

FIGURE 1. Geography of the St.Lawrence estuary.

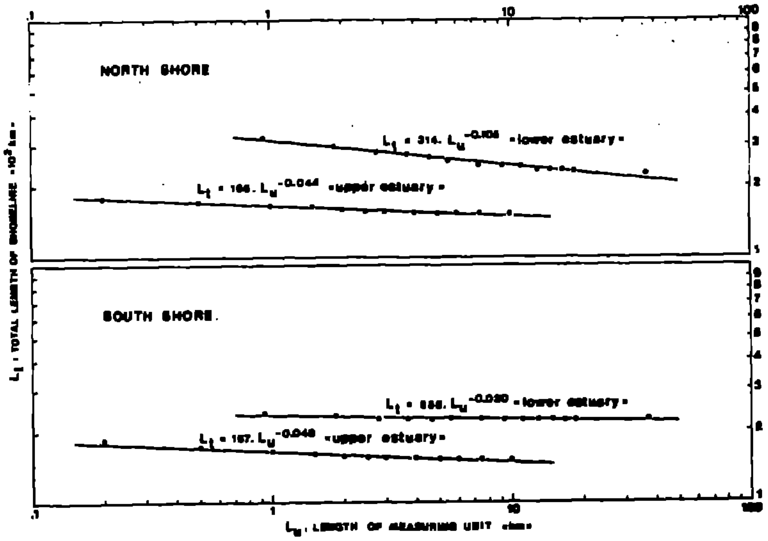

FIGURE 2. The relationship between length of measuring unit (L_u) and the apparent total length of coastline (L_t) when measured by the unit length.

Table 1. Apparent total length (L_t) of the south and north shores for both upper and lower parts of the St.Lawrence estuary when measured by the unit length (L_u). All measurements are in km.

	Upper estuary						Lower estuary						
Unit length (L_u)	north shore			south shore			U. length (L_u)	north shore			south shore		
	A*	B**	Average (L_t)	A*	B**	Average		A*	B**	Average (L_t)	A*	B**	Average (L_t)
10.0	154	151	153	152	151	152	37.1	226	226	226	222	222	222
7.5	151	152	152	152	152	152	18.5	230	234	232	222	222	222
6.0	153	153	153	153	153	153	16.7	234	237	235	222	222	222
5.0	155	156	156	154	154	154	14.8	235	232	234	222	222	222
4.0	153	155	154	155	155	155	13.0	234	232	233	222	224	223
3.0	157	159	158	155	157	156	11.1	245	245	245	222	222	222
2.5	160	158	159	158	158	158	9.3	247	244	245	222	224	223
2.0	160	158	159	159	159	159	7.4	248	247	248	225	225	225
1.5	164	164	164	160	162	161	5.6	258	258	258	225	225	225
1.0	167	165	166	165	167	166	4.6	274	264	269	223	226	225
0.5	172	170	171	172	173	173	3.7	273	276	275	226	228	227
0.2	178	179	179	183	183	183	2.8	280	280	280	226	229	228
							1.9	296	301	298	235	234	235
							0.9	324	324	324	240	240	240

* A : upstream direction

** B : downstream direction

Table 2. Summary of the results.

Shoreline	Slope of the curve B	Fractal dimension D = 1-B	Length (L_{tg}) of the coastline in km when using the smallest value of unit length (L_u)	Length (L_{ts}) of the coastline in km when using the largest value of unit length (L_u)	Ratio of L_{tg}/L_{ts} showing the variation in the coastline length with the unit of measurement
South shore of upper estuary	-0.049	1.049	183	151	1.21
South shore of lower estuary	-0.020	1.020	240	222	1.08
North shore of upper estuary	-0.044	1.044	179	153	1.17
North shore of lower estuary	-0.105	1.105	324	226	1.40

A WORKING VOCABULARY FOR TSUNAMI STUDY*

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ABSTRACT

The study of tsunamis has now progressed to such an extent that tsunamiologists need a working vocabulary. This article is an effort to aid the inductive evolution of such a vocabulary by a deductive extension. Not only are such conventional words as "run-up" given definitive definitions, but incipient jargon, such as "tsunamicity," are provided provisional definitions. Of course, some important terms, e.g., "tsunami magnitude", must be defined in each publication, either by reference to previous articles or by assignment of another unique definition. To a minor extent, incomplete translations prompt this explicit vocabularization.

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*Hawaii Institute of Geophysics Contribution No. 1578.

INTRODUCTION

Let us consider those words in the English language presently used to discuss the phenomenon of a tsunami. As you know, a "tsunami" used to be called a "seismic sea wave" whereas a "seismic sea wave," used to be called a "tidal wave." It is clear that we need a definition of this thing which we wish to discuss:

Fortunately a definition of "tsunami" is given in the Communication Plan for Tsunami Warning System. This reads:

> TSUNAMI - Term used as the first word of a message text to identify a message which pertains to the TWS and which requests or conveys factual information, conditions, or data.

Such a definition may fulfill the purpose of that document but only emphasizes the need for a glossary of terms in international documents. Let us define "tsunami" as the gravity wave generated by the vertical component of a relative motion within the earth or ocean. This definition seems broad enough to include a tsunami on the moon or to cover waves resulting from explosions within the ocean, such as caused by bombs or meteorites. Having a definition, what of its plural? The plural of "tsunami" in its source language, Japanese,[1] is also "tsunami." Should we anglicize this to "tsunamis"? I vote for doing so.[2]

What shall we call someone who studies tsunamis? Some want to call such a person a "tsunamist." but is a person who studies seisms called a "seismist?" No, rather, "seismologist"; so I suggest "tsunamiologist." Sounds awful, does it not? But I think that it is only a matter of time and use until it will be music to your ears. Then what is a "tsunamist"? A "tsunamist" is someone who causes a tsunami--and that is not impossible nowadays with the existence of multi-megaton bombs.

You have undoubtedly heard of the specialization called "earthquake engineering." Surprisingly, one who practices in this speciality is not someone who designs earthquakes but

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[1] Professor K. Kajiura informs me that 'tsunami' in Japanese originally meant "harbor wave" and later meant unusual motion of the water surface caused by either a seismic sea wave or surge from other possible sources. Since the word has been appropriated, internationally, to mean seismic sea wave, "tsunami" in Japanese usage has taken on a restricted meaning comparable to its international definition, with another word now being used to denote oscillations caused by surge.

[2] The Japanese author, Professor K. Iida, who is expert in both English and Japanese, accepted the plural form having the added "s" in the preliminary catalog of tsunamis. And the proceedings of the 1969 meetings in Honolulu were edited for the book entitled "Tsunamis in the Pacific Ocean".

rather someone who designed earthquake-resistant structures. Prof. R. L. Wiegel, in his text entitled, "Oceanographical Engineering", does not mention "tsunami engineering." By analogy, we must let this phase denote the design of tsunami-resistant structures.

The following glossary, comprised of some words already in circulation together with some words for which a need is perceived, is offered for your constructive criticism. The denotation of the part of speech is (n) for noun, (adj) for adjective, (v.t.) for transitive verb, etc.

GLOSSARY

ATSUNAMIC: (adj.) Characterized by a lack of the features typical of a tsunami.

ETA: (n) Estimated time of arrival.

EVACUATION: (n) The process of notifying, guiding, assisting, or forcing persons to depart from areas deemed to be hazardous.

EVACUATION MAP: (n) A map that indicates areas for which planned actions are to be undertaken in case a tsunami becomes recognized as a hazard.

FORECAST: (n) The subjective estimates of quantitative parameters of an event for which the results are unknown, usually in the future. A forecast procedure is not fully teachable.

HAZARDICITY: (n) The relative level of risk from a tsunami, not usually perceived exactly.

HONOLULU OBSERVATORY: (n) Organization at Ewa Beach, Oahu, which serves as communication and analysis center for tsunamic data from the Pacific Basins. Now called Pacific Tsunami Warning Center (PTWC).

INUNDATION: (n) The depth (relative to a stated reference level) to which a stated location is covered by water. See Figure 1.

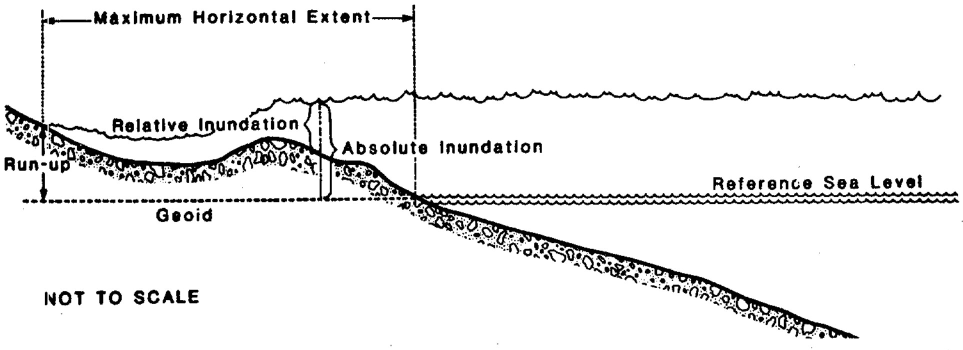

Fig. 1: Schematic diagram illustrating the definitions of "inundation" and "run-up". There are many locations having inundation: run-up is the value of absolute inundation at the maximum horizontal extent of flooding, measured perpendicular to the shoreline.

LOCAL TSUNAMI: (n) A tsunami originating within one wave length of the point of observation.

MICRO-TSUNAMI: (n) A tsunami of such small amplitude that it must be observed instrumentally; not detectible visually.

MICROZONATION: (n) The detailed designation of zones, either by tsunami risk or tsunamicity.

PREDICTION: (n) The action or results of estimating objectively some quantitative parameters of events, for which the results are unknown, usually in the future. A prediction procedure is teachable.

PTWC: Acronym for Pacific Tsunami Warning Center.

RUN-UP: (n) The height above hhwl, measured vertically, to the level of the highest wetted land or structure. See Figure 1.

TELE-TSUNAMI: (n) A tsunamic originating at a distance of more than one wave length from the point of observation.

TSUNAMI: (n) The gravity wave generated by the vertical component of a relative motion within the earth or ocean.

TSUNAMI: Term used as the first word of a message text to identify a message that pertains to the TWS and that requests or conveys factual information, conditions, or data. (CP TWS)*

TSUNAMIABLE: (a) Having the potential of giving rise to a tsunami.

TSUNAMIAGE: (n) Extent of land surface covered at least once by waves of a tsunamic, as measured above mean high-high sea level.

TSUNAMIANCE: (n) The state of a system during which a tsunami occurs. Or from the origin time until the energy density is 1/e th of the initial arrival.

TSUNAMIATE: (v.t. & i.) To generate tsunami energy.

TSUNAMIATIVE: (a) Having a propensity to generate tsunamis.

TSUNAMIATION: (n) The act of generating a tsunami.

TSUNAMIATOR: (n) The generator of a tsunami.

TSUNAMIC: (adj.) Having features analogous to those of a tsunami or description of a tsunami.

TSUNAMICITY: (n) The propensity of a specified region to generate tsunamis.

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*CP TWS = Communication Plan for Tsunami Warning System (see References).

TSUNAMIGENESIS: (n) The generation of a tsunami.

TSUNAMIGENIC: (adj.) Having the demonstrated or potential capability to generate a tsunami.

TSUNAMIING: (v) To wait for a tsunami to be sensed (analogous to fishing). Best done with a jug of wine, a loaf of bread, and your friend.

TSUNAMILY: (adv.) In the manner of a tsunami.

TSUNAMIMETER: (n) Instrument used for measuring some parameter of a tsunami.

TSUNAMIMETRY: (n) The study of the instrumentation for detecting and measuring some parameter of tsunamis.

TSUNAMIGRAPHY: (n) The scientific description of the phenomenon of tsunamis.

TSUNAMIOLOGICAL: (adj.) Pertaining to the study of tsunamis.

TSUNAMIOLOGY: (n) The study of tsunamis.

TSUNAMION: (n) The quantum of tsunami energy.

TSUNAMIOUS: (adj.) Evidencing a tendency to be a source of tsunami energy.

TSUNAMITITE: (n) Any geological material deposited by a tsunami.

TSUNAMI ENGINEER: (n) One who practices tsunami engineering.

TSUNAMI ENGINEERING: (n) The practice of designing structures to be tsunami resistant.

TSUNAMI MAGNITUDE: (n) The size of a tsunami. Best defined, at least by reference, by each author. See Adams (1972) for a brief review of the term.

TSUNAMI-PRONE: (a) Anomalously receptive to tsunamis.

WATCH BULLETIN: Issued when an earthquake has been detected which is of sufficient magnitude and in such a location that the generation of a tsunami is possible. (CP TWS IV-4)*

WARNING BULLETIN: (n) Issued by PTWC upon receipt of positive evidence that a tsunami exists. Contains estimated times of arrival at tide stations in the Warning System. (CP TWS VI-5)*

WATCH CANCELLATION: Bulletin issued when PTWC determines that a wave has not been generated. (CP TWS VI-7)*

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*CP TWS = Communication Plan for Tsunami Warning System (see References).

WARNING CANCELLATION: (n) Bulletin issued by PTWC to indicate that:

1. Warning was issued on basis of erroneous data.
2. Only an insignificant wave has been generated. or
3. A significant wave has been generated but poses no threat to one or more of the areas PTWC warns. (CP TWS VI-7)*

ZONING: (n) Zonation. The partitioning of land areas into different zones deemed to be different with respect to risk from tsunamis, or to tsunamicity.

This discussion is developing a vocabulary for "tsunamiology"--the study of tsunamis. Note what we are doing: we are trying to find the meaning of words, either by inferring what meaning has been assigned by previous users or by deducing what the meaning should be. This set of actions constitutes a science other than tsunamiology. Such a science is called "semasiology". "Semasiology" is the science of the development of the meaning of words. If we tsunamiologists are to become novice semasiologists, then we should learn what procedures and philosophy to use. Fortunately, the third edition of Webster's Dictionary (1966) states the currently practiced philosophy of developing the meaning by observation. "In conformity with the principle that a definition, to be adequate, must be written only after an analysis of usage, the definitions in this edition are based chiefly on examples of usage collected since publication of the preceding edition." (Gove, 1961). The important point here is that words had to have been used in order to be included. I will call this the "a posteriori" approach.

The semasiologizing tsunamiologist should realize that this "a posteriori" approach has not always been dominant. In the late 1800's, Webster's copyright for his dictionary lapsed, so today, Webster's dictionary is plagarized by many publishers. If we retrieve the original preface by Noah Webster, we learn his approach. "It has been my aim in this work, now offered to my fellow citizens, to ascertain the true principles of the language, in its orthography and structure; to purify it from some palpable errors, and reduce the number of its anomalies, thus giving it more regularity and consistency in its forms, both of words and sentences; and in this manner to furnish a standard of our vernacular tongue, which we shall not be ashamed to bequeath to <u>five hundred millions of people</u>, who are destined to occupy, and I hope to adorn, the vast territory within our jurisdiction.

"If the language can be improved in regularity, so as to be more easily acquired by our own citizens and by foreigners, and thus be rendered a more useful instrument for the propagation of science, arts, and civilization, and Christianity;--if it can be rescued from the mischievous influence of sciolists, and that dabbling spirit of innovation,

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*CP TWS = Communication Plan for Tsunami Warning System (see References).

which is perpetually disturbing its settled usages and filling it with anomalies,--if, in short, our vernacular language can be redeemed from corruptions, and our philology and literature from degradation; it would be a source of great satisfaction to me to be one of the instruments of promoting these valuable objects." (1828)

Noah Webster was the earliest opponent of word pollution; of main interest here is his a priori attitude--that he is providing a "standard". Furthermore, he considers his predecessors to be "a posteriori" standard-bearers as evidenced by his scathing criticism in his Introduction: "The real fact seems to be this: these men have taken for the standard what they were pleased to call the best usage, which, in many cases, is a local usage, or some favorite peculiarity of particular speakers, at least if they have had any authority at all; or they have given the pronunciation which happened to please their fancy, though not authorized by usage. In this manner they have attempted to bend the common usage to their particular fancies."

If we term this creative attitude the "a priori" approach, then we will have a philosophy that we may embrace and thus justify the promulgation of this glossary.

There does seem to be a need to expand this glossary into a full-fledged dictionary. Those having additional entries are invited to submit them to the Tsunami Society.

Of notable interest to any physical scientist is the motivation for Noah Webster to compile his monumental Dictionary. In his Preface to his Dictionary, he states, "About thirty-five years ago, I began to think of attempting the compilation of a Dictionary. I was induced to his undertaking, not more by the suggestion of friends, than by my own experience of the want of such a work, while reading modern books of science. In this pursuit, I found almost insuperable difficulties, from the want of a dictionary, for explaining many new words, which recent discoveries in the physical sciences had introduced into use."

I hope that it does not take me thirty-five years to compile a dictionary for English-speaking tsunamiologists.

In 1812, John Adams said to Benjamin Rush, "We ought to have an American Dictionary." And in 1984, William Adams said to Doak Cox, "We ought to have a tsunamiological dictionary."

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ANNOUNCEMENT

The National Technical Information Service (NTIS) at Springfield, Virginia, is advertising a published search called, "Tsunamis". This is alleged to cover from 1964 to May 1983 and is restricted to those citations in the NTIS Data Base. This carries the identifier of PB83-806984. The cost is about forty dollars ($40.00). The Tsunami Society has purchased a copy.

Some reviewers of this bibliography are preparing a book review. Members of The Tsunami Society are advised to read the book review, which is planned for the next issue, before considering the purchase of this published search.

Tsunami Flood Level Predictions for American Samoa

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ABSTRACT

The paper describes a methodology to determine tsunami flood excedance frequency distributions for islands. A catalog of historical tsunamis in the Samoan Islands was compiled for the study by the International Tsunami Information Center. These data were used to determine a frequency-of-occurrence distribution for Pago Pago Harbor, American Samoa. A hybrid finite-element numerical model with a grid covering American and Western Samoa was then used to extend the historical data at Pago Pago to allow exceedance frequency distributions to be determined throughout all of the islands of American Samoa. Tests of the model included comparisons with known solutions of wave interactions with idealized island bathymetries. In addition, a simulation was performed for the 1960 Chilean tsunami at American Samoa and successful comparisons were made between measured data and numerical model calculations. A methodology is presented for determining tsunami exceedance frequency distributions for American Samoa including the effect of tides on the distributions. Tsunami exceedance frequency distributions (including the effect of tides) were determined at 144 locations throughout the five islands of American Samoa. The methods described can be used for coastal zone management purposes on islands where historical data are available at only a limited number of locations.

INTRODUCTION

American Samoa consists of the five islands of Tutuila, Aunuu, Tau, Ofu, and Olosega (Figure 1). The major population concentration is at Pago Pago on the island of Tutuila (Figure 1). Like other islands in the Pacific Ocean, American Samoa is threatened by tsunamis that occur periodically. Historical data of tsunami activity in American Samoa are concentrated in Pago Pago Harbor. Only isolated reports describe tsunami activity on other parts of the Island of Tutuila, and there are no known reports of tsunami activity on the other islands of American Samoa. In order to obtain as complete and reliable a data base as possible for this study, the International Tsunami Information Center (ITIC) performed a detailed search and analysis of all data sources reporting tsunami activity in American Samoa. These data were combined with the use of a numerical model to predict tsunami elevations along the entire coastline of American Samoa.

NUMERICAL MODEL

The interaction of tsunamis with the islands of American Samoa were determined by using a hybrid finite-element numerical model developed by Houston (1981). The model solves the following equation that governs the propagation of periodic, small amplitude surface gravity waves over a variable depth seabed of mild slope:

$$\nabla \cdot (c c_g \nabla \phi) + \frac{c_g}{c} \omega^2 \phi = 0 \qquad (1)$$

∇ is the horizontal gradient operator, c_g is the group velocity $= \frac{1}{2} c(1 + G)$ where $G = 2kh/\sinh 2kh$, c is the phase velocity $= (\frac{g}{k} \tanh kh)^{1/2}$, k is the wave number, ω is the angular frequency, ϕ is a velocity potential defined by $\vec{u} = \nabla\phi$, $\vec{u}$ is a two-dimensional velocity vector.

Equation (1) was derived by Berkhoff (1976) and Schonfeld (1972) and is discussed in detail by Jonsson and Brink-Kjaer (1973). This equation governs both refraction and diffraction. It reduces to the well-known 'eiconal' equation governing refraction by neglect of the variation of the amplitude function in the horizontal plane. The equation reduces to the diffraction Helmholz equation in deep or constant depth water and to the linear long-wave equation in shallow water.

Equation (1) is solved using a hybrid finite element method originally developed by Chen and Mei (1974) to solve the diffraction Helmholz equation in a constant depth region. Space is divided into two regions as shown in Fig. 2 (finite inner region A and infinite outer region B). Conventional finite elements are used in the variable depth region A. A single super-element is used to cover the constant depth infinite region B. Variational principles are used that incorporate the matching conditions between the regular elements and the super-element as natural conditions. Thus, a symmetric global stiffness matrix is obtained that is very advantageous for highly complex problems.

The variational principle for the boundary value problem requires that the following functional be stationary with respect to arbitrary first variation of the velocity potential ϕ :

$$F(\phi) = \iint_A \frac{1}{2}\left[\frac{cc_g}{g}(\nabla\,\phi^2) - \frac{\omega^2 c_g}{g\;c}\,\phi^2\right] dA + \int_{\partial B_\infty} \frac{ikcc_g}{g}(\phi - \phi_I)^2 dL - \int_{\partial B_\infty} \frac{cc_g}{g}\frac{\partial\phi_I}{\partial n}\,\phi dL \quad (2)$$

where ϕ_1 is the incident wave velocity potential, n a unit normal, and the last two integrals are line integrals at infinity. Analogous to the derivation of Chen and Mei (1974), this functional can be rewritten as follows:

$$F(\phi) = \iint_A \frac{1}{2}\left[\frac{cc_g}{g}(\nabla\,\phi_A)^2 - \frac{\omega^2 c_g}{g\;c}\,\phi_A{}^2\right] dA +$$

$$\int_{\partial A} \frac{1cc_g}{2\;g}(\phi_B - \phi_I)\,\frac{\partial(\phi_B - \phi_I}{n_A} - \int_{\partial A} \frac{cc_g}{g}\,\phi_A\,\frac{\partial(\phi_R - \phi_I)}{\partial n_A} - \int_{\partial A} \frac{cc_g}{g}\,\phi_A\,\frac{\partial\phi_I}{\partial n_A} + \quad (3)$$

$$\int_{\partial A} \frac{cc_g}{g}\,\phi_I\,\frac{\partial(\phi_B - \phi_I)}{\partial n_A} + \int_{\partial A} \frac{cc_g}{g}\,\phi_I\,\frac{\partial\phi_I}{\partial n_A}$$

where ϕ_B and ϕ_A are the velocity potentials in regions B and A, respectively and n_A is a unit normal to the boundary separating regions B and A.

The inner A is assumed to have a variable depth and to be of finite extent. This region is subdivided into finite elements. Here the elements are triangular with simple linear shape functions. The infinite region B is assumed to have a constant depth and is covered with a single super-element. Since region B has a constant depth, the governing equation is the diffraction Helmholz equation. An analytical solution for the velocity potential in region B is well known and can be expressed as follows:

$$\phi_B = \sum_{n=o}^{\infty} H_n(kr)(\alpha_n \cos n\theta + \beta_n \sin n\theta) \quad (4)$$

where α_n's and β_n's are constant and unknown coefficients. $H_n(kr)$ are Hankel functions of the first kind, and r and θ are radial and angular variables in polar coordinates. The velocity potential given in equation (4) satisfies the Sommerfeld radiation condition that the scattered waves must behave as outgoing waves at infinity. Thus, region B can be considered to be a single super-element with a shape function given by equation (4).

If the shape functions are used to evaluate the integrals of equation (3) and the functional is extremized with respect to the unknowns, a set of linear algebraic equations is obtained. Of course, the infinite series given by equation (4) must be truncated at some finite extent. The number of terms that must be retained depends upon the incident wave length and may be found by increasing the number of terms until the solution is insensitive to the addition of further terms. Solution of the boundary value problem thus reduces to the solution of N linear algebraic equations for N unknowns (where N is the number of node points in the finite element discretization plus the number of unknowns in the truncated series).

The symmetric complex coefficient matric K is in general large, sparse and banded. It can be stored and manipulated in the computer in a packed form. The packed form is chosen to be a rectangular array (N variables in length and the semi-bandwidth in width).

MODEL VERIFICATION

To verify this numerical model, comparisons were made between the finite element calculations and both an analytical and a numerical solution for the interaction of waves with a circular island on a paraboloidal shoal. Figure 3 is a sketch of the problem. Hom-ma (1950) presented the analytical solution to the long-wave equation for plane waves incident upon this island.

Figure 4 shows a finite-element grid with 2640 elements used by the model described in this paper to solve the problem of the interaction of long waves with a circular island on a paraboloidal shoal (by symmetry only half the shoal needs to be considered). Figure 5 shows comparisons between Hom-ma's analytical solution and the finite element model solution for incident waves with five different periods. The agreement is excellent with only slight differences for the 240 sec wave (resulting from lower resolution of the incident wave for shorter period waves).

Jonsson et al. (1976) show that for a wave with a 240 sec period interacting with the circular island on a paraboloidal shoal the effect of frequency dispersion is not particularly significant. The ratio of wave length to water depth for this case is approximately 11. However, for a 120 sec incident wave (wavelength to water depth ratio of less than 5), frequency dispersion is quite significant. In order to maintain a resolution of a 120 sec wave that is approximately equal to that obtained for the 240 sec wave using the 2640 element grid, it is necessary to reduce element side lengths by a factor of approximately 2. This reduction results in a quadrupling of the number of elements. Figure 6 shows a finite element grid with 10,560 elements used to calculate the interaction of a 120 sec wave with the island. Figure 7 shows a comparison between a numerical solution of equation (1) using an orthogonal collocation solution equation and the finite element model solution (grid of Figure 5) of this paper.

A long wave version of the finite-element model also was verified in an earlier study (Houston et al. 1977) by numerical simulations of two historical tsunamis in Hawaii (1960 and 1964 tsunamis). The 1960 Chilean and 1964 Alaskan tsunamis are the only major tsunamis for which some reliable information regarding source-generating characteristics exist

The major point of the verification efforts illustrated is to demonstrate that the numerical model and the methodology used are indeed valid and can reproduce known historical tsunami occurrences. Thus for the case of islands that arise abruptly from deep water a linear theory, properly applied, can reproduce major historical tsunami occurrences. Nonlinear effects are not of major importance apparently because the islands have such short shallow-water shelves there is not sufficient time for nonlinear effects to develop.

MODEL USE

The numerical model was used to determine elevations of historical tsunamis along the entire coastline of the islands of American Samoa based upon historical data in Pago Pago Harbor. Figure 8 shows the finite-element grid for the Samoan Islands. Figures 9 and 10 show sections of the finite-element grid for Tutuila and for Olosega, Ofu, and Tau Islands. The model calculated the interaction of tsunamis with American Samoa and determined relative heights along the coastline. The tsunami elevation at an arbitrary location where historical data were not available was determined by multiplying the known historical elevation recorded at a location in Pago Pago Harbor by the ratio of the elevation calculated by the numerical model at the arbitrary location and the elevation calculatd at the location in Pago Pago Harbor. The numerical model takes into account the major processes that would cause different tsunami elevations at the arbitrary location and the location in Pago Pago Harbor where there is a historical record. That is, the model calculates shoaling, refraction, diffraction, reflection, resonance, shielding of the back side of an island by the front side, and reflections between islands.

Deepwater wave forms of historical tsunamis are not known. However, the directions of approach of historical tsunamis and the basic range of wave periods are known. By inputting sinusoidal waves of unit amplitude from the same direction as a historical tsunami into the numerical model over a band of wave periods, the interaction of the historical tsunami with American Samoa was determined. Waves with periods from 10 to 60 min in steps of 150 sec were used as input to the numerical model for each historical tsunami. At every shoreline location, the response to each of the incident wave periods was squared, the squared responses all summed, and a square root of the total sum was taken. Thus, at each shoreline location, a variance of the response wave form was calculated. By multiplying this variance by the ratio of a historical recording in Pago Pago Harbor and the variance of the response wave form calculated at the location in Pago Pago Harbor, elevations for the historical tsunami along all of the coastline of American Samoa were determined.

The method used to calculate tsunami elevations for historical events is approximate since the incident wave energy is spread uniformly over a range of wave periods. For an actual tsunami, there undoubtedly is a distribution of wave energy that is not perfectly uniform. Thus, the method used in this report provided the response for an average ensemble of tsunamis generated in a region. However, the average response may be very similar to the response for a particular tsunami, since it is well known that the tsunami response at a location is more dependent upon characteristics of the location than upon characteristics of the incident tsunami. Thus, two different tsunamis recorded at a single location are often very similar, whereas the same tsunami recorded at two different locations often appears remarkably different.

The 1960 tsunami from Chile is the only tsunami for which there are recordings at several locations on the Island of Tutuila. Using the techniques described above, elevations were predicted and compared with actual historical measurements. The known elevation was taken to be the 9.5 crest elevation at the end of Pago Pago Harbor. The numerical model predicted a crest elevation of only 2.3 ft at Fagaalu (Figure 1) near the mouth of Pago Pago Harbor. Keys (1963) reported that "the sea rose no more than 2.5 ft" at Fagaalu. An elevation of 6.4 ft was predicted at the Administration boatshed in Pago Pago Harbor, and this compared favorably with the 6 to 7 ft reported at this location by Keys (1963). An elevation of 5.1 ft was predicted at the tide gage location. The maximum crest amplitude on the tide gage marigram (Symons and Zetler, 1960) was approximately 4 ft. However, the tsunami had a sufficiently short wave period and great height at the tide gage location that maximum elevations may have been reduced somewhat by tide gage distortion. At Tafuna (Figure 1) near the airport, the numerical model predicted an elevation of only 0.6 ft. Keys (1963) reported that no disturbance was noticed at Tafuna. There was a reported (Keys 1963) maximum trough to crest range of 8 to 10 ft at a location 1/2 mile from the Administration boatshed in Pago Pago Harbor. At this location, the numerical model predicts a range of 7.5 ft. Keys (1963) also indicates there were no reports of tsunami activity outside Pago Pago Harbor. The average crest elevation predicted by the numerical model for all locations outside Pago Pago Harbor was only 1.5 ft. Since the maximum waves arrived at low tide, this crest elevation would have resulted in a combined tsunami and tide elevation just a fraction of a foot greater than mean sea level and about 1 ft less than high tide. Thus, the tsunami would not have produced any flooding at typical locations outside Pago Pago Harbor. The greatest elevation outside Pago Pago Harbor predicted by the numerical model was a 6-ft elevation in Leone Bay. This is an elevation of approximately 3.5 ft above mean high water. It'sinteresting to note that the only report of tsunami damage outside Pago Pago Harbor for any historical tsunami was at Leone where the 1917 tsunami partly demolished the Catholic Church.

TSUNAMI ELEVATION PREDICTIONS

Historical data of tsunami activity in American Samoa were determined by a study conducted by the ITIC. The data for American Samoa were concentrated almost exclusively within Pago Pago Harbor.

Reliable reporting of events in American Samoa probably started around the turn of the century. Therefore, the period of time from 1900 was used in the frequency analysis. Using the ITIC data, the elevations at the end of Pago Pago Harbor for the 1917 1919, 1922, 1946, 1952, 1957, and 1960 tsunamis were 7 ft, 8.3 ft, 4.8 ft, 3.9 ft, 6.8 ft, 2.7 ft, and 9.5 ft, respectively.

The historical data in Pago Pago Harbor allowed elevations to be determined at the end of Pago Pago Harbor for seven historical tsunamis. The finite-element model was then used to simulate the interaction of these historical tsunamis with American Samoa. Using the same techniques as used to calculate the interaction of the 1960 Chilean tsunami with American Samoa, the numerical model calculations were used to determine elevations for these seven historical tsunamis at node prints of the numerical grid all along the coasts of American Samoa.

Tsunami excedance frequency distributions were determined by ordering the tsunami elevations (including effect of tides as described by Houston, 1980) at each location and relating elevation versus frequency of occurrence (using least-squares techniques) by curves that can be represented by the equation

$$H = -B - A \log_{10} f \tag{6}$$

where

H = elevation of maximum combined tsunami and astronomical tide above mean sea level

f = frequency per year of tsunami occurrence

This relationship between tsunami height and frequency of occurrence has been used previously by several investigators.

100-year tsunami elevations were determined for the entire coastline of American Samoa. The largest elevations occur at the end of Pago Pago Harbor as seen in Figure 11. Smaller peaks in the 100-year elevations were found at Fagasa and Leone Bays on the north and west coasts, respectively, of Tutuila. Historical data confirms these locations have experienced larger than normal elevations during historical tsunamis.

CONCLUSION

A finite element numerical model was shown to adequately simulate tsunami interaction with small islands. A method was developed to use this model in conjunction with limited historical measurements to extend tsunami elevation predictions on islands to locations with little or no historical data.

ACKNOWLEDGMENT

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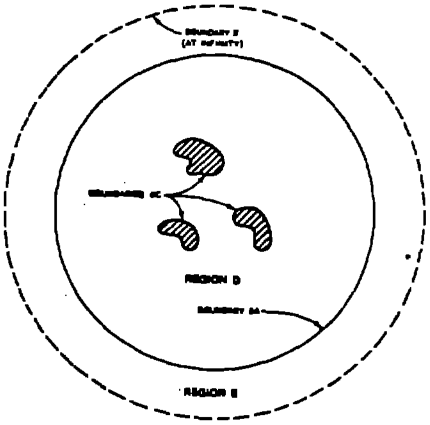


Figure 2. Computational regions

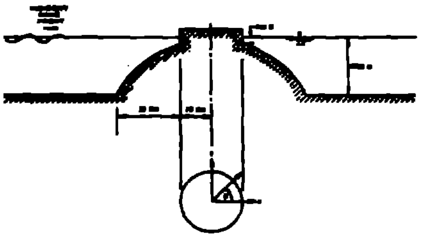


Figure 3. Circular island and paraboloidal shoal

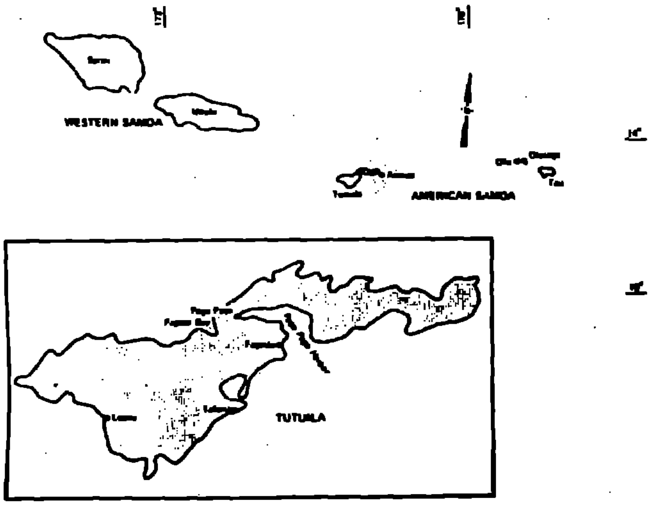


Figure 1. Location of American Samoa and enlargement of Island of Tutuila

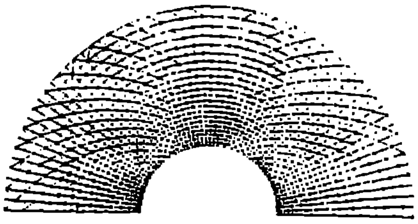


Figure 4. Finite-element grid for one-half of paraboloidal shoal

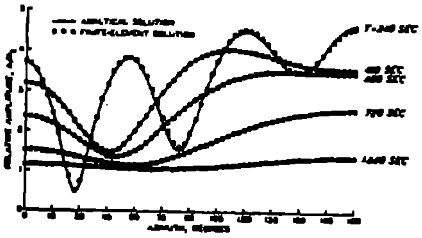


Figure 5. Comparison of finite-element solution with analytical solution

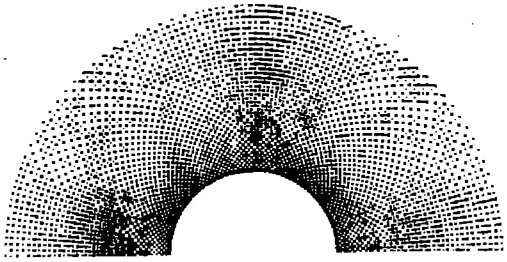


Figure 6. Finite element grid for paraboloidal island (10,560 elements)

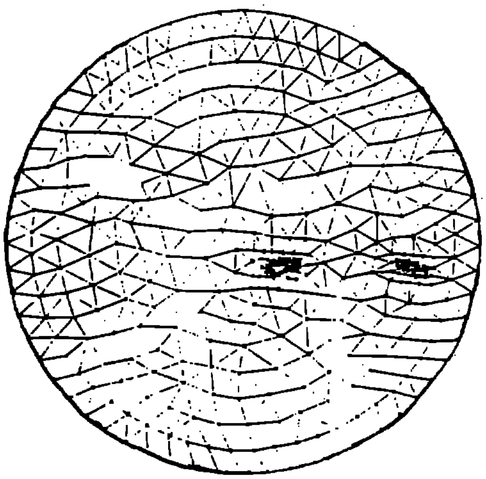


Figure 8. Finite-element grid for the Samoa Islands

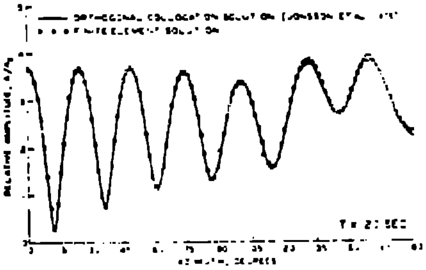


Figure 7. Solutions with dispersion (10,560 element grid)

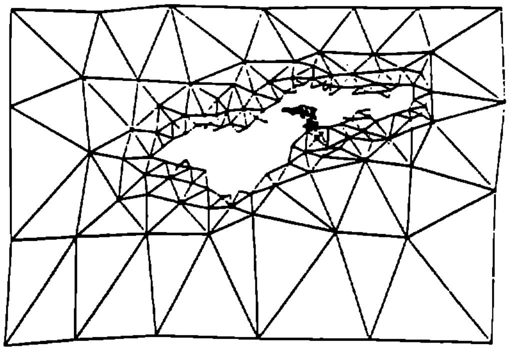


Figure 9. Section of finite-element grid for Tutuila Island

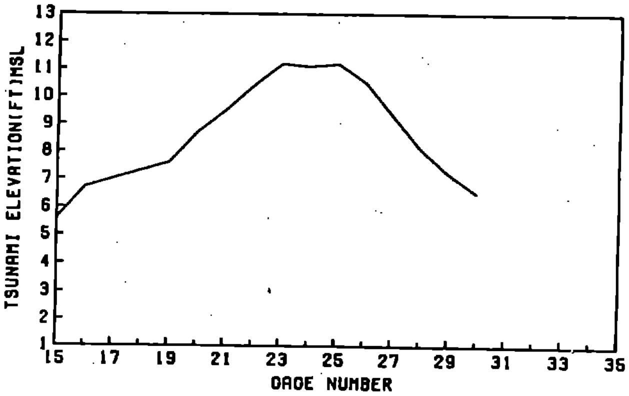


Figure 11. 100-yr tsunami elevation at end of Pago Pago Harbor

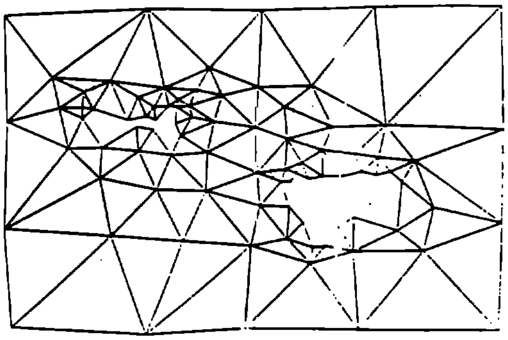


Figure 10. Section of finite-element grid for Ofu, Olosega, and Tau Islands

DATA ANNOUNCEMENT

TSUNAMI DATA

85-EHB-01
April 1985

As part of a continuing program to create a file of tsunami data to support the interests of engineers, oceanographers and seismologists, the National Geophysical Data Center (NGDC) and the collocated World Data Center A (WDC-A) for Solid-Earth Geophysics have compiled a unique set of data bases. Digital historic tsunami data, tide gage records, photographs, bathymetric data, and technical publications are available. The specific data holdings are as follows:

Historic Tsunami Data

This data collection began with the Historical Tsunami Data Base, which consisted of about 1,450 events compiled by Doak Cox of the University of Hawaii. Additional information was added from National Geophysical Data Center files for earthquake epicenters, magnitudes, and depths. Tsunami effects including wave heights, damage, and numbers of deaths were added from several sources including the Catalogues of Tsunamis of the Western and Eastern Coasts of the Pacific Ocean by Soloviev and Go. Currently the data base consists of: about 1,450 events since 49 BC; all Pacific locations reporting tsunami effects in the 20th century; and all earlier Pacific tsunamis reporting waves of 1.5 meters or larger. More information is available for areas such as Hawaii and Chile. Other in-depth regional studies will be completed in the future. The tsunami data are useful in the preparation of tsunami maps, as well as lists of tsunamis having certain characteristics such as location, wave height, damage, and effects.

May 26, 1983, Japan Tsunami

In addition to the Pacific Basin tsunami data described above, NGDC also has limited information about tsunamis that have occurred in other areas, including the Mediterranean and Caribbean Seas and Atlantic and Indian Oceans.

THIS FLIER REFLECTS CHANGES IN DATA, PRICES, AND ORDERING PROCEDURE FOR DATA PREVIOUSLY ANNOUNCED IN MAY 1981.

World Data Center A for Solid Earth Geophysics
National Geophysical Data Center

Tsunami Photographs

Photographs are a permanent way of capturing on film the transient nature of tsunamis as they approach, and inundate, the coastlines. Photographs also preserve a vivid description of the devastating property damage some tsunamis cause to structures near the coasts. NGDC has compiled a collection of more than 700 such photographs. Examples and descriptions of all the photographs including event date, location, and other pertinent information are contained in a publication entitled "Natural Hazards Photographs" available from NGDC.

A unique set of 35-mm slides has been compiled from the photograph collection. Slides in this set depict advancing waves, harbor damage, and before-and-after scenes of structural damage; they also show views of the extent of inundation along the shores. Because photographs show clear-cut evidence of the destructive force of tsunami waves, they provide a unique and affordable educational tool for presentation to both technical and nontechnical audiences.

Publications

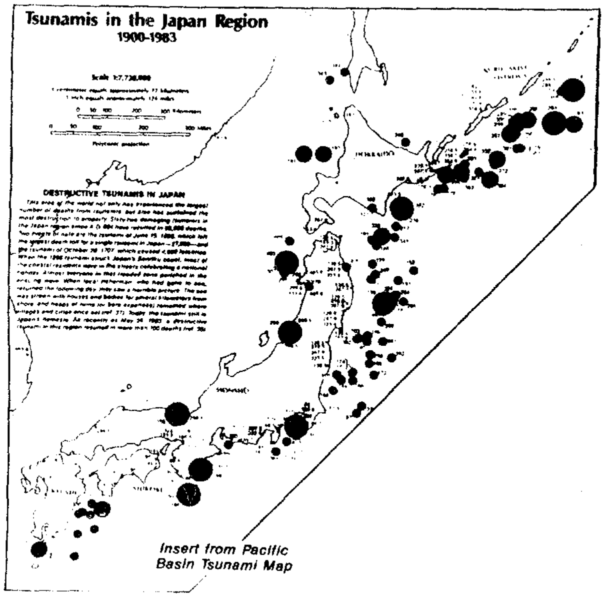
Two tsunami catalogs are available from NGDC. "Catalog of Tsunamis in Alaska" (World Data Center A for Solar-Terrestrial Physics, 1976, by Doak C. Cox, University of Hawaii, and George Pararas-Carayannis, ESSA, Coast and Geodetic Survey) lists tsunamis from 1788 through June 1973 and gives a brief description of each. The list includes date, location, and magnitude of each earthquake and a brief description of tsunami effects. "Catalog of Tsunamis in Hawaii" (World Data Center A for Solid Earth Geophysics, 1977, by George Pararas-Carayannis, ESSA, Coast and Geodetic Survey) is a compilation of data pertaining to tsunamis observed and instrumentally recorded in Hawaii from the early 1800s to 1976. It contains information similar to that in the Alaska catalog.

Tide Gage Records

About 3,100 tide gage records dating back to 1850, from U.S. and foreign tide stations, are available on microfiche. The National Ocean Survey (NOS) has lent these important records to NGDC for filming and distribution. Each tide station has supplied records.

Bathymetric Data

NGDC has three digital data bases that provide both worldwide and regional bathymetric coverage. The Digital Bathymetric Data Base 5 (DBDB5) provides a complete 5-minute grid of bathymetry for the world's oceans. The Geophysical Data System (GEODAS) provides bathymetry from geophysical cruise tracklines worldwide. The NOS Hydrographic Data Base provides highly detailed bathymetry for the coastal waters of the United States. All these data are available on magnetic tape and can be formatted to provide plots, even-space grids, or profiles. For prices and information on how to order call (303) 497-6376, or write NGDC at address given on next page.



Pacific Basin Tsunami Map

A wall-size, multi-color map depicting Pacific Basin Tsunamis (1900-1983) has been prepared using a portion of the NGDC digital data base. The map shows the locations of 405 events (including earthquakes, volcanic eruptions, and landslides) that caused tsunamis during that period. Tables list dates of the events, event parameters, number of deaths, and destruction. Representative locations reporting runup heights of 1.5 meters or larger are also shown on the map.

Pricing Information

Tsunami photograph (8" × 10" print)	$20.00
Tsunami slide (35-mm)	2.20
Tsunami slide set (20 slides)	31.00
Tide gage record (microfiche)	3.50
Tsunami map (folded)	12.00
(flat in mailing tube)	20.00
Tsunami digital data search	50.00
Catalog of Tsunamis in Alaska (SE-1)	1.00
Catalog of Tsunamis in Hawaii (SE-4)	1.00

MINIMUM ORDER $10

(303) 497-6337, FTS 320-6337.

HOW TO ORDER

U.S. DEPARTMENT OF COMMERCE REGULATIONS NOW REQUIRE PREPAYMENT ON ALL NON-FEDERAL ORDERS. Telephone pre-orders are accepted, but data will not be shipped until payment is received. Checks and money orders should be made payable to COMMERCE/NOAA/NGDC. Please add handling fee for ***non-U.S.A.*** orders as follows: $5 for orders up to $50; 10% of cost of total order for orders $50 and over. Please pay in U.S. dollars drawn on a U.S.A. bank. Orders may be charged to an American Express, MasterCard, or Visa card, by telephone or letter; please include card account number, expiration date, telephone number, and your signature with order. Inquiries, orders, and payment should be addressed to:

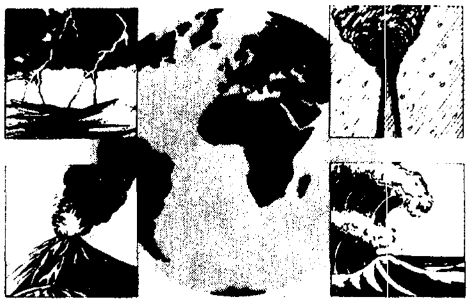
National Geophysical Data Center
NOAA, Code E/GCX2
325 Broadway
Boulder, CO 80303

Direct telephone inquiries to:

Commercial: (303) 497-6541
FTS: 320-6541
Telex: 592811 NOAA MASC BDR

For technical information, please contact:

Note: The prices quoted here are valid through September 30, 1985. Prices applicable after that date may be obtained by calling (303) 497-6541, FTS 320-6541.



International Symposium
on

NATURAL AND MAN-MADE HAZARDS

August 3 - 9, 1986
Rimouski and Quebec City,
Canada

Sponsored by : **The Tsunami Society**

Hosted by : **Université du Québec à Rimouski**
Rimouski, Québec, Canada

Announcement and call for papers

The objectives of the International Symposium on Natural and Man-made hazards are to promote the advancement of the hazards sciences, to perceive and exploit those aspects that are similar for some of the various hazards, to review the newest developements in a few selected fields, and also to outline new directions for future research. The hazardous aspects of the following topics will be included in the Symposium.

Air
- Tropical and extra-tropical cyclones
- thunderstorms, squall lines, lightning, hail, rainfall, snow, acid rain, nuclear winter, carbon dioxide effects, climatic changes, clear air turbulence, air pollution, visibility, fog.

Water
- Tsunamis, storm, surges, wind waves, edge waves, swell, abnormal water levels, tides and tidal bores, hydraulic jumps, flash floods, water spouts, ice flows, icebergs, icing on marine structures, ice jams in rivers, ice ride-up on shore, man-made storage of water resources and their environmental effects, water pollution.

Land
- Earthquakes, land slides, snow avalanches, floods and droughts, soil erosion, deforestation and desertification.

Authors are invited to submit extended abstracts of 2-3 pages (up to 40 lines per page). To maintain a high scientific standard, it is thought that extended abstracts will help in a better screening of the submitted papers. Original and fives copies of the extended abstracts should be sent to the Coordinator of the Symposium before October 31, 1985. Camera-ready abstracts should be typed on 216 x 279 mm paper with 25 mm margins. Spacing between lines should be 1.5mm. Elite 12 type is prefered. The heading block should include the following items on successive lines : (i) the title in capital letters, and (ii) the name (s) of the author (s) in upper and lower case letters, and affiliation. There should be two-line space between the heading block and the text. All lines including the title, names and text are to be typed left justified. A volume of the extended abstracts will be prepublished and will be made available to the participants prior to the meeting. Full papers should reach the coordinator by March 30, 1986. All manuscripts will go through careful and full editorial standards and only good quality papers will be included in the final proceedings of the Symposium. D. Reidel Publishing Company (Dordrecht, Boston, Lancaster, Tokyo) agreed to publish the Proceedings of the Symposium.

Five post-symposium excursions and visits (2-5 days each) are being planned. Interested participants will be offered the choice of either : a Gaspé Peninsula tour, a Saguenay Fjord cruise, a St. Lawrence Estuary cruise (watch the whales), a visit of the Manic-5 hydroelectric project (one of the largest hydroelectric plants in the world) or a visit of the Bay of Fundy (where the largest tides in the world occur).

The meeting comes at a time of the year when the lower St. Lawrence and Gaspé area are most enjoyable. Social and recreational programs are being arranged for spouses, families as well as for the participants. Combining the scientific meetings with holidays is recommended.

A second Circular containing Registration and Housing Information and detailed description of the post-meeting activities will be published in late June 1985.

Those interested in being on the mailing list are invited to complete and return the form below, or write to :

Dr. Mohammed El-Sabh
Département d'océanographie
Université du Québec à Rimouski
310, avenue des Ursulines
Rimouski (Québec)
G5L 3A1

Tél. : (418) 724-1755
Sec. : (418) 724-1770
Télex : 051-31623

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.