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RAPID SIZING OF POTENTIALLY TSUNAMIGENIC EARTHQUAKES
AT REGIONAL DISTANCES IN ALASKA

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ABSTRACT

The Alaska Tsunami Warning Center (ATWC) is a regional warning center responsible for providing tsunami warnings for potentially tsunamigenic earthquakes occurring in Alaska and the west coasts of Canada and the USA. Since regional warnings are initiated using seismic information alone, the ATWC developed and implemented a long period MS scale to aid in rapid magnitude determinations for large regional earthquakes. Sixteen shallow earthquakes ($MS \geq 5.7$) occurring along the Aleutian subduction zone are evaluated. Long period ($T_0 = 20s$) vertical seismometer amplitudes from stations less than 20° from the source are compared to the National Earthquake Information Center's published PDE MS values computed from the IASPEI formula (with $D > 20^\circ$ and $18s \leq T \leq 22s$). We found that for the period range $18s \leq T \leq 22s$:

$$\begin{aligned} MS &= \log(A/T) + 1.66\log D + 3.3 & D > 16^\circ \\ MS &= \log(A/T) + 0.94\log D + 4.2 & 5^\circ < D < 16^\circ \end{aligned}$$

where A is the null-to-peak ground motion in microns and D is the distance in degrees. These formulae were successfully used during the recent tsunami warnings that were initiated by the ATWC. Additionally, this approach readily lends itself to automation, utilizes existing seismic instrumentation and computers, and enhances accuracy and standardization of procedures.

INTRODUCTION

The Alaska Tsunami Warning Center (ATWC) is responsible for providing tsunami warnings to the Pacific coasts of Alaska, Canada, Washington, Oregon, and California for potentially tsunamigenic earthquakes which occur in these regions (Sokolowski, 1985). Rapid issuance of warnings translates directly into lives saved of those individuals in the immediate vicinity of a tsunamigenic event. Earthquakes are located and sized by the ATWC using numerous short period and 6 long period seismometers. Since regional warnings are initiated based on seismic data alone, it is necessary to locate the event rapidly (Sokolowski et al., 1983) and to determine whether it has exceeded a warning threshold. One of the main difficulties in issuing warnings quickly is an accurate determination of whether or not the event has exceeded the threshold magnitude.

The tsunami generation potential of an earthquake is often related to its magnitude (Murty, 1977). Rayleigh waves of 20s period are reliable for sizing earthquakes above magnitude 6.0 and below saturation at about $7 \frac{3}{4}$ (Kanamori and Given, 1983). The longer wavelength of the 20s wave more accurately describes the source size and process time of large earthquakes than shorter wavelength body and surface waves. Iida (1970) showed that the boundary between nontsunamigenic and tsunamigenic earthquakes is near magnitude 7 (within the range of MS reliability). Therefore, the use of 20s period Rayleigh waves is acceptable for issuing regional tsunami warnings. It has been proposed that the very long period surface waves (50-200s) and thus the seismic moment are better still to predict tsunami generation (Gusiakov, 1983; Kanamori and Given, 1983; Talandier et al., 1987). However, the proper instrumentation for recording very long period surface waves is not presently available at the ATWC.

This paper discusses a relationship between Rayleigh wave amplitude and distance for epicentral distances less than that for which the standard IASPEI surface wave magnitude formula is valid. The IASPEI formula:

$$MS = \log(A/T) + 1.66 \log D + 3.3 \quad (1)$$

where A is the null-to-peak ground motion in microns, T is the period in seconds, and D is epicentral distance in degrees, is taken to be valid over the period range $18s < T < 22s$ and distance range $20^\circ < D < 160^\circ$ by the National Earthquake Information Center. This relationship was examined, using ATWC long period data, to empirically determine an MS method that can be used to rapidly size potentially tsunamigenic regional earthquakes. Prior to the implementation of a regional MS scale, methods of sizing potentially tsunamigenic earthquakes available at the ATWC were: 1.) traditional ML computations, and 2.) MS determinations with $D > 20^\circ$. Traditional ML computations suffer saturation effects for events with $M > 6.5$ (Heaton, et al., 1983) and are not very good for evaluating the tsunamigenic potential of an earthquake. MS determinations from distances greater than 20° have proven very reliable for earthquakes $6.0 < M < 7 \frac{3}{4}$ which are of interest for regional warnings. However, the travel time for Rayleigh waves for a distance of 20° is about 11 minutes. To this time, about 5 minutes must be added for the maximum amplitude within the acceptable period

range to develop. Therefore, sizing of a potentially tsunamigenic earthquake cannot be initiated in less than about 15 minutes using the traditional MS distances. Also, depending on the location of the earthquake and the distribution of sites, the distance may be considerably greater than 20° to the nearest appropriate long period seismometer. A regional MS scale will have the advantages of being more accurate than local magnitudes and will yield a more rapid result than using surface wave magnitudes at distances greater than 20° .

Several studies have been performed using surface waves at regional distances (Solovyev and Solovyeva, 1968; Wagner, 1970; Basham, 1971; Evernden, 1971; Marshall and Basham, 1973; Nuttli, 1973; Nuttli and Kim, 1975; Thomas et al., 1978) and are summarized by Bath (1981). Most of the work concerned discrimination between explosions and earthquakes using MS:Mb ratios. For explosions, MS is often too small to be seen at teleseismic distances so regional data must be used. Most of the above studies used intraplate earthquakes with $M < 5$. In contrast, this study uses subduction zone earthquakes with $M \geq 5.7$.

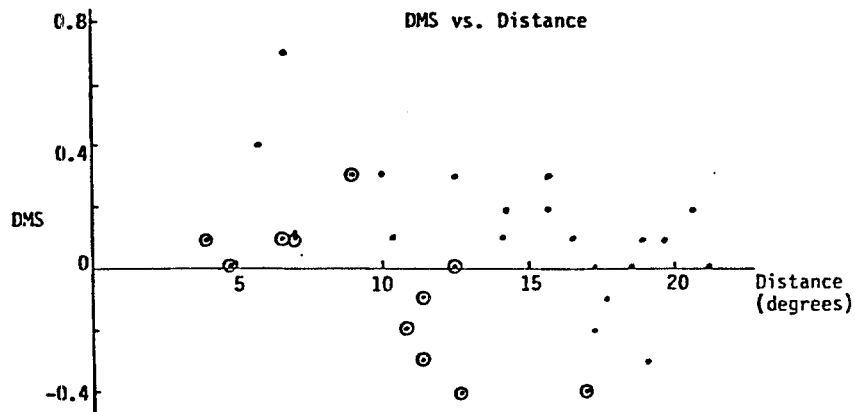


Figure 2. DMS (from eq. (2)) as a function of distance. MS_{ATWC} computed from eq. (1) using the maximum amplitude regardless of period. Circled points indicate magnitudes computed from Rayleigh waves with periods less than 18s.

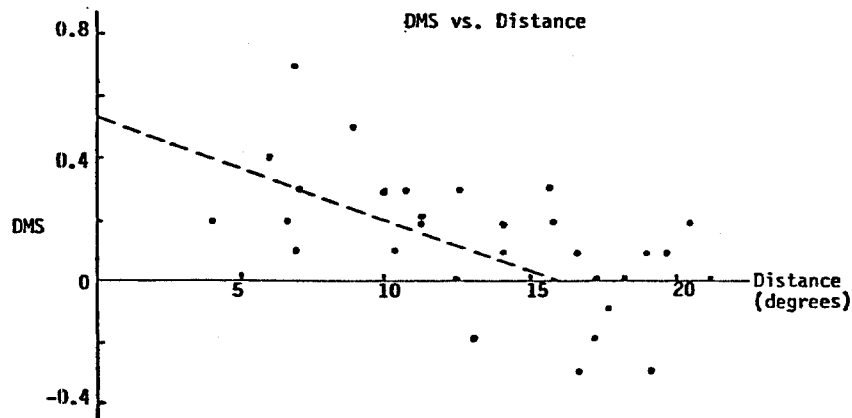


Figure 3. DMS plotted as a function of distance. MS_{ATWC} computed from the maximum amplitude Rayleigh wave between 18s and 22s period. Dashed line is a linear correction added to MS_{ATWC} to equate it with the teleseismic value.

DATA

Long period seismograms from sixteen earthquakes ranging from MS 5.7 to 7.7 were evaluated. The earthquakes were located along the Aleutian subduction zone (Figure 1). Figure 1 also shows the location of the long period seismometers in Alaska which are recorded in real-time at the ATWC. Not shown are long period sites at Newport, Washington and Golden, Colorado that also telemeter data to the ATWC in real-time. The long period seismometers are vertical, Model 7505A GeoTech seismometers with $T=20s$. These are recorded at different gains ranging from 0.005K to 1.0K. All of the earthquakes evaluated were less than 50km deep (see Table 1 for earthquake parameters).

TABLE 1
Earthquake Parameters

Eq. #	Date	Lat.	Long.	Dep.	MS _{PDE}	S.D.
1	1-30-81	51.7N	176.3E	33	7.0	0.27
2	5-9-85	51.5N	177.9E	33	6.0	0.21
3	5-24-85	51.3N	178.3W	34	5.8	0.19
4	10-9-85	54.8N	159.6W	30	6.6	0.21
5	4-11-86	54.2N	167.9W	33	5.9	0.19
6	5-7-86	51.4N	174.8W	22	6.0	0.30
7	5-7-86	51.4N	174.7W	35	7.7	0.31
8	5-8-86	51.3N	175.4W	18	6.2	0.31
9	5-15-86	52.3N	174.7W	33	6.4	0.24
10	5-17-86	52.3N	174.5W	26	6.6	0.24
11	7-19-86	53.6N	167.2W	33	5.7	0.28
12	9-13-86	56.2N	153.3W	33	6.3	0.30
13	1-5-87	52.5N	169.3W	33	6.6	0.21
14	2-27-87	53.5N	167.3W	18	6.7	0.28
15	5-6-87	51.2N	179.9W	33	6.4	0.28
16	6-21-87	54.2N	162.5W	33	6.2	0.27

S.D. - standard deviation of MS_{PDE}

Each long period seismogram was evaluated by measuring several amplitude peaks in the Rayleigh wave train for periods ranging from 10s to 24s. The MS computed at the ATWC (MS_{ATWC}) was determined for each using eq. (1) regardless of period and epicentral distance. The difference (DMS) between the average MS published in the Preliminary Determination of Epicenters Monthly Listing (MS_{PDE}) and MS_{ATWC} was then computed from

$$DMS = MS_{PDE} - MS_{ATWC} \quad (2)$$

DMS is plotted as a linear function of distance in Figures 2 and 3. In Figure 2, MS_{ATWC} is computed from the maximum amplitude regardless of period. Circles in Figure 2 indicate magnitudes computed from Rayleigh waves with periods less than 18s. Figure 3 shows MS_{ATWC} computed taking the maximum amplitude in the

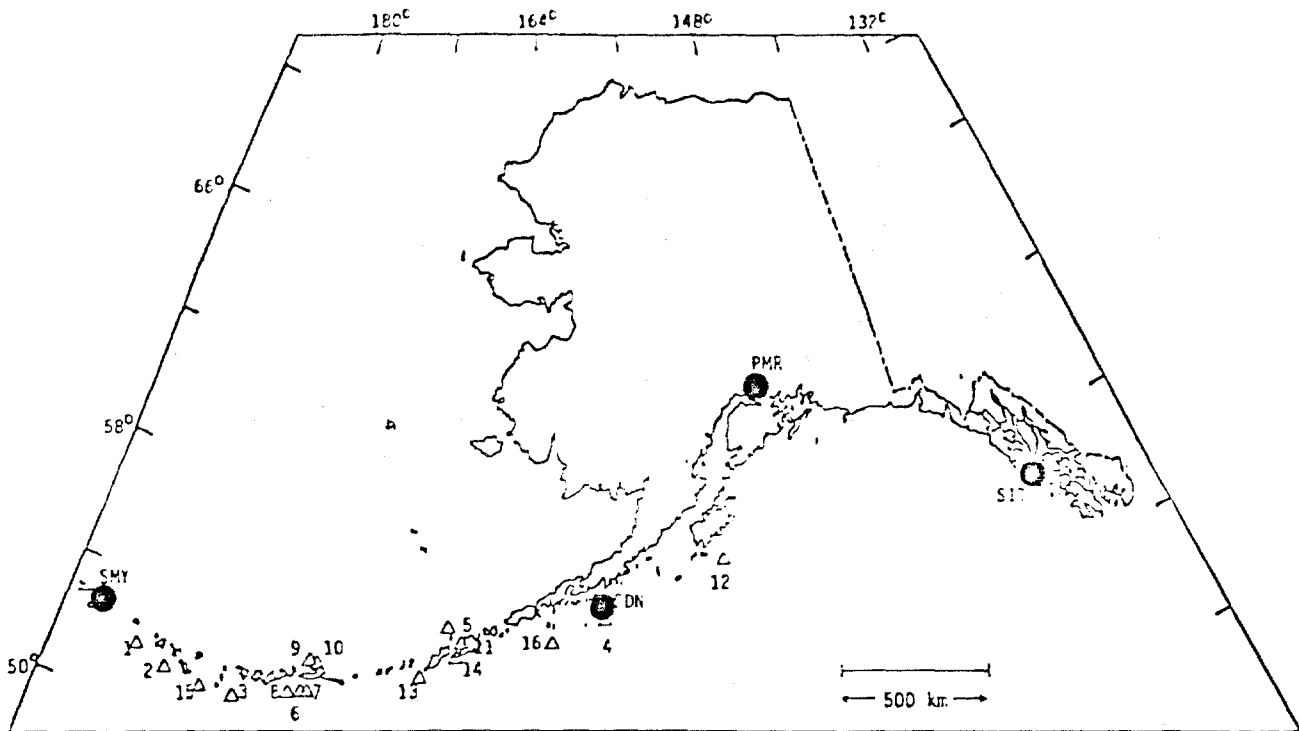


Figure 1. Earthquake and LP seismometer locations.

● - Long Period seismometer; PMR - Palmer, SIT - Sitka, SDN - Sand Point, SMY - Shemya I.
 Δ - Earthquake locations (see Table 1 for parameters).

period range 18s to 22s. The data in Figures 2 and 3 were also considered as a logarithmic function of distance, but the results were no more consistent than the linear plots.

$\log(A_{\max}/T)$ is used throughout the magnitude computations instead of $\log(A/T)_{\max}$ because this quantity is easier to compute. Ease and quickness in computations is important in a warning situation. Over the limited period range 18s to 22s, the quantities are usually equal.

RESULTS

Comparison of Figures 2 and 3 indicates that magnitudes computed using the maximum amplitude regardless of period are not as consistent as those computed over the narrower period band 18s to 22s. This implies the amplitude vs. distance relation varies with period (i.e., the constants in eq. (1) vary as a function of the period measured).

Figure 3 shows that MS_{ATWC} computed from eq. (1) shows an increasing divergence from the teleseismic value with decreasing distance. This is equivalent to saying the amplitude at these close-in distances is lower than expected from eq. (1). Therefore, an eyeball fit correction, C , which is linear with distance can be added to the calculated MS_{ATWC} value to remove the divergence from the teleseismic value;

$$C = 0.53 - 0.033D \quad 5^\circ < D < 16^\circ. \quad (3)$$

The dashed line in Figure 3 is a graphical representation of C .

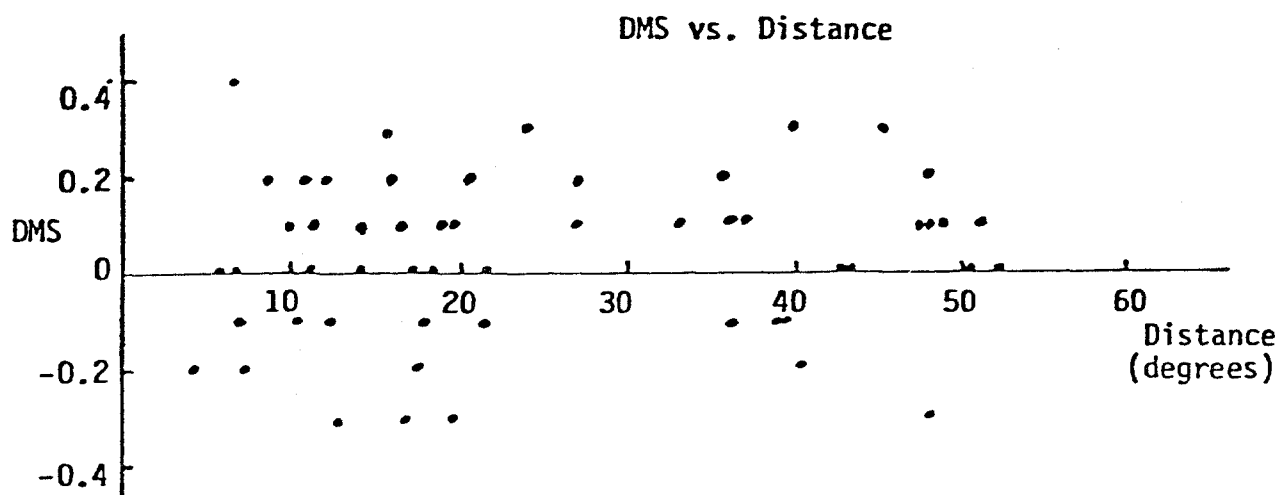


Figure 4. DMS, from eq. (2) with MS_{ATWC} computed from eq. (4) or eq. (1) depending on epicentral distance. (Eq. (4) used from 5° to 16° and eq. (1) for 16° and greater.) Rayleigh waves from 18s to 22s are used for magnitude calculations.

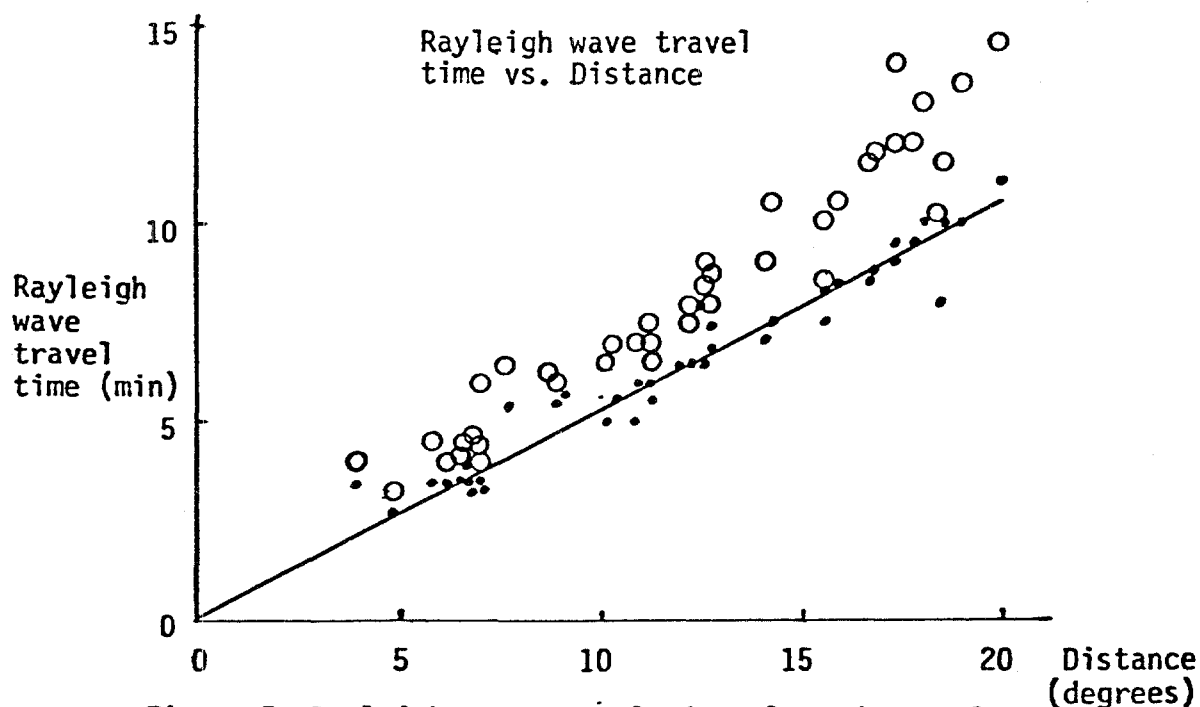


Figure 5. Rayleigh wave travel time plotted as a function of distance. Dots indicate time to the first Rayleigh wave arrival. Circles indicate time to maximum amplitude within the period range 18s to 22s. The time indicated by the circles is essentially the minimum time required to initiate a warning. The line is the calculated arrival time using a Rayleigh wave velocity of 3.5 km/s.

Equation (3) is added to eq. (1) and a least-squares fit is computed to yield the resulting equation in standard form;

$$MS = \log(A/T) + 0.94\log D + 4.2 \quad 5^{\circ} < D < 16^{\circ}. \quad (4)$$

This procedure is essentially equivalent to plotting the results as a logarithmic function of distance and computing a least-squares fit. For distances greater than 16° , there does not seem to be a distance related variation as there is from 5° to 16° . This is also seen in Figure 4 which shows DMS vs. Distance from 0 to 60° . Therefore, we extend eq. (1) to $D \geq 16^{\circ}$.

DISCUSSION

We have chosen to use just the 18s to 22s period Rayleigh waves for regional MS computations for four main reasons. First, the attenuation is generally more consistent over different paths for surface waves with $T > 16s$ than for waves with $T < 16s$ (Mitchell, 1975). That is, the constants in eq. (4) will vary less as a function of the path travelled for 18s to 22s Rayleigh waves than for waves with $T < 16s$ due to the quality factor, Q , being nearly constant for longer wavelengths. Second, measuring a relatively narrow band of frequencies will prevent variations of the attenuation coefficient as a function of frequency over an area of constant Q (Nuttli, 1973). Third, due to the greater velocity of long period surface waves, the 18s to 22s waves will often arrive up to a minute before those with $T < 16s$ at regional distances. Therefore, an earthquake can be sized faster with the 18s to 22s period waves. Fourth, the empirical data presented here show the greatest consistency in the 18s to 22s period Rayleigh waves.

MS values computed in this study ($D < 20^{\circ}$) using eqs. (4) and (1) fall within 0.2 of the teleseismic MS_{PDE} value 82% of the time. Standard deviations of the MS_{PDE} values are listed in Table 1. These normally range from 0.2 to 0.3. This implies there is no more scatter in using eq. (4) for data from 5° to 16° than there is from using eq. (1) at distances greater than 20° . In Figure 4, DMS values from ATWC stations using eqs. (1) and (4) are plotted vs. distance. The regional values no longer show a systematic deviation from MS_{PDE} with distance.

Nuttli & Kim (1975) showed theoretically that MS for 20s period Rayleigh waves with $10^{\circ} < D < 30^{\circ}$, assuming an attenuation coefficient of 0.015/degree, should obey the formula

$$MS = \log(A/T) + 1.07\log D + 4.16. \quad (5)$$

This is similar to the formula presented here and to several others which were empirically derived (see Table 2). The differences between the formulae may be due to: 1.) differences in the period of Rayleigh waves measured, 2.) geologic differences in the areas examined, and 3.) not measuring pure Rayleigh waves on the seismogram. One and two above are differences which will change the value of the actual attenuation which is present. The third factor may be due to higher modes adding with the fundamental mode Rayleigh wave which can produce complex seismograms at regional distances

(Nuttli,1973; Forsyth,1976). Note that in the two other studies listed in Table 2 which use surface waves of periods comparable to what we used (Evernden,1971 and Nuttli and Kim,1975 which studied earthquakes from different tectonic provinces than studied here), the maximum difference in MS from $5^{\circ} < D < 16^{\circ}$ is about 0.1. This implies the most important factor of those listed above is the period measured and that the path travelled is not critical when using surface waves of periods near 20s.

TABLE 2
Regional MS formulae (modified from Bath (1981))

Source	Formula	D($^{\circ}$)	T(s)	Comments
Wagner(1970)	$MS = \log(A/T) + 1.66 \log D + 2.4$	<40	4-12	N. Am. explosions
Basham(1971)	$MS = \log(A/T) + 0.79 \log D + 4.54$	4-45	8-14	N. Am. explosions
Evernden(1971)	$MS = \log(A/T) + 1.0 \log D + 4.22$	<25	10-14 17-19	USA explosions USA earthquakes
Marshall and Basham(1973)	$MS = \log(A/T) + 0.8 \log D + P(D)$	<25	12	P(D)=path corr., use per. of A_{max}
Nuttli(1973)	$MS = \log(A/T) + 1.66 \log D + 2.6$	2-20	3-12	east USA quakes
Nuttli and Kim(1975)	$MS = \log(A/T) + 1.07 \log D + 4.16$	10-30	17-23	theoretical eq. & Eurasian quakes
Thomas et al. (1978)	$MS = \log(A/T) + 1.15 \log D + 4.17$	0-150	26	1.15 = ave. val. of amplitude decay
Whitmore and Sokolowski	$MS = \log(A/T) + 0.94 \log D + 4.2$	5-16	18-22	Alaska quakes

A future possibility for refining this technique is to filter the long period signal with a trapezoidal bandpass filter with 18s and 22s the respective low pass and high pass parameters. This could be done in near real-time at the ATWC. Filtering out the higher and lower frequencies will probably change the constants in eq. (3) since we will be looking at closer to a pure 20s Rayleigh wave. By filtering out the higher modes, bandpass filtering should reduce the scatter at close-in distances and may permit extrapolation of this technique to within 5° .

A certain amount of scatter between the average teleseismic MS and the regional MS will be present no matter how much filtering, etc. is performed on the data. A way to minimize this scatter is by having additional regional long period seismometers to average MS values for each large quake.

Using eq. (4), a potentially tsunamigenic event can be sized rapidly and a tsunami warning issued. Figure 5 shows the time required before sizing an event (and thus the initiation of a warning) for distances less than 20° . Points in Figure 5 show the time to the first arrival of the Rayleigh wave while circles indicate the time to the maximum amplitude within the range $18s < T < 22s$. The first arrivals under 20° correspond to a Rayleigh wave velocity of 3.5 km/s. The maximum amplitude then takes from 1 to 5 minutes to develop.

CONCLUSIONS

We conclude from this study that:

- 1.) MS computed from eq. (4), which corrects for amplitude variations as a function of distance, does not have a consistent deviation from the MS_{PDE} value with distance, and is within 0.2 of that value 82% of the time,
- 2.) Eq. (1) is valid to about 16° ,
- 3.) Surface wave magnitudes computed from seismograms at regional distances are good, rapid estimates of an earthquake's size in the magnitude range 6 to 7 3/4.

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Numerical Computation of Tsunami Run-up by the Upstream Derivative Method

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Abstract

A numerical method based on the upstream formulation for the advective term is applied to calculate run-up. The third order and fourth order approximations have been built on five-point and seven-point stencils to describe nonlinear advective term. The derived numerical solutions are compared with the analytical solutions by Carrier and Greenspan (1958), Ball (1964) and Thacker (1981).

Introduction

The problems in simulating run-up are related to nonlinearity and to the moving boundary (Lewis and Adams, 1983). The boundary line between water and dry land belongs to both environments and has no clear predictive equation which defines geometry of this boundary in time. Generally two numerical techniques have been developed to overcome this obstacle.

In the first approach a system of equations is solved by finite-difference method with the moving boundary defined by special set of conditions (see e.g., Sielecki and Wurtele 1970, Flather and Heaps 1975, Lewis and Adams 1983).

In the second approach a transformation of variables is applied and the independent variables x, t are transformed as

$$X = \frac{x}{l(t)} \quad \text{and} \quad T = t$$

Where $l(t)$ is the distance from the origin of coordinate to a shore line. Through this transformation the variable region $0 \leq x \leq l(t)$ is transformed into a fixed region $0 \leq X \leq 1$, and no special boundary condition is required. The method has been extensively applied by L'atkher et al.(1978), Johns (1982) and Takeda (1984).

In this work we shall apply the former approach but we resolve nonlinear terms with a high order approximation by the multi-point upstream method. This method generates both a stable and an accurate solution without nonlinear instabilities at the moving boundary which often require a special treatment (Lewis and Adams, 1983). It also reduces diffusion generated by a simple upstream method and dispersion caused by the symmetrical numerical forms (Mesinger and Arakawa, 1976).

Equations and their difference forms

The vertically integrated set of equations of motion and continuity is used and only one dimensional problem is considered:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} = -g \frac{\partial \zeta}{\partial x} \quad (1)$$

$$\frac{\partial \zeta}{\partial t} = - \frac{\partial (H_1 u)}{\partial x} \quad (2)$$

All the notation is standard with positive u representing onshore velocity, ζ is the sea level variation and H_1 is the average water depth H plus sea level variation ζ . To construct a numerical scheme, a

space staggered grid is applied which requires either sea level or velocity as a boundary condition. The leap-frog scheme is used for the time differencing. Alternatively, the Euler scheme is applied at regular intervals (every 20 time steps) to suppress the computational mode inherent to the leap-frog scheme (Mesinger and Arakawa, 1976). This mode can be also suppressed by time filtering (Ramming and Kowalik, 1980). Denoting j as index of integration along x direction and m as index for the time stepping, the leap-frog and Euler numerical forms are:

$$\frac{u_j^{m+1} - u_j^{m-1}}{2T} = -\left(u \frac{\partial u}{\partial x}\right)_j^m - g \frac{\zeta_j^m - \zeta_{j-1}^m}{h} \quad (3)$$

$$\frac{\zeta_j^{m+1} - \zeta_j^{m-1}}{2T} = -\frac{u_{j+1}^m 0.5(H_{1,j}^m + H_{1,j+1}^m) - u_j^m 0.5(H_{1,j}^m + H_{1,j-1}^m)}{h} \quad (4)$$

$$\frac{u_j^{m+1} - u_j^m}{T} = -\left(u \frac{\partial u}{\partial x}\right)_j^m - g \frac{\zeta_j^m - \zeta_{j-1}^m}{h} \quad (5)$$

$$\frac{\zeta_j^{m+1} - \zeta_j^m}{T} = -\frac{u_{j+1}^{m+1} 0.5(H_{1,j}^m + H_{1,j+1}^m) - u_j^{m+1} 0.5(H_{1,j}^m + H_{1,j-1}^m)}{h} \quad (6)$$

In the above equations time step is denoted as T and space step is h . Also notice that the j index for sea level and velocity denotes two different spatial points (sea level is located to the right of the velocity point). In constructing the finite difference form of the advective term $u \frac{\partial u}{\partial x}$, the high order upstream difference is used (see Appendix).

Run-up condition and the results of experiments

Because the boundary location is changing in time, we need to determine position of the moving boundary at each time step to apply boundary conditions. This was done by a simple algorithm proposed by Flather and Heaps (1975) for the storm surge computations. To answer whether u_j is a dry or wet point, the sea level is tested at this point;

$$\begin{cases} u_j \text{ is wet point,} & \text{if } 0.5(\zeta_{j-1} + \zeta_j) \geq 0; \\ u_j \text{ is dry point,} & \text{if } 0.5(\zeta_{j-1} + \zeta_j) < 0 \end{cases} \quad (7)$$

The point u_j is defined to be a right boundary if u_{j-1} is wet and u_j is dry. The point u_j is defined as a left boundary if u_{j+1} is wet and u_j is dry.

Next Sielecki and Wurtele's (1970) extrapolation of the sea level to the first dry point was used. The tsunami "predictor" is based on continuity equation (2) and this equation serves to extrapolate sea level from the last wet point $j-1$ toward the first dry point j by the following numerical expression:

$$\zeta_j^m = (\zeta_j^{m-2})_{ext} - \frac{2T}{h} [(u_j^{m-1} H_{1,j}^{m-1})_{ext} - 0.5(u_{j-1}^{m-1} + u_j^{m-1}) H_{1,j-1}^{m-1}] \quad (8)$$

Here

$$\begin{aligned} (\zeta_j^{m-2})_{ext} &= 2\zeta_{j-1}^{m-2} - \zeta_{j-2}^{m-2} \\ (u_j^{m-1} H_{1,j}^{m-1})_{ext} &= 2 \frac{(u_j^{m-1} + u_{j-1}^{m-1})}{2} H_{1,j-1}^{m-1} - \frac{(u_{j-1}^{m-1} + u_{j-2}^{m-1})}{2} H_{1,j-2}^{m-1} \end{aligned}$$

The velocity in the first dry point was extrapolated linearly from the two last points,

$$u_j^m = 2u_{j-1}^m - u_{j-2}^m \quad (9)$$

Linear extrapolation is easy to program but caution should be used in the case of a rough beach.

Ball (1964) and Thacker (1981) described analytically the oscillations of the planar surface in the parabolic basin for the frictionless fluid. This seems to be a strongly nonlinear problem in which depth and sea level variations are of the same order. We have simulated numerically one period of such oscillations. The results depicted in Fig.1 are exactly the same as derived from analytical solution. Even though this simulation seems to be successful, the oscillations of a planar surface in a parabolic basin are a function of the velocity only, the theory predicts no gradients of velocity, which in fact makes the problem linear.

Therefore, we have simulated another case which has been solved analytically by Carrier and Greenspan (1958). The wave running up the beach without friction is considered. The distribution of the sea level along the sloping beach at the various time given both by analytical and numerical means is plotted in Fig.2.

Appendix.

Higher order upstream approximation to the advective term

It is well known that the upstream (or upwind) method is stable, conserves positive definite property and is quite simple to program, but it has an excessive diffusion coefficient (Mesinger and Arakawa, 1976). It is therefore reasonable to explore the same approach and to find out whether this method can be improved by application of the higher order of approximation to the first derivative. If a three-point stencil is given (Fig.3a) the expression for the first space derivative can be chosen depending on the direction of the current. If velocity is negative, the advective process is treated by the following difference equation,

$$\frac{u_j^{m+1} - u_j^m}{T} + \frac{u - |u|}{2} \frac{u_{j+1}^m - u_j^m}{h} = 0 \quad (A1)$$

If on the other hand velocity is positive,

$$\frac{u_j^{m+1} - u_j^m}{T} + \frac{u + |u|}{2} \frac{u_j^m - u_{j-1}^m}{h} = 0 \quad (A2)$$

Although a three-point stencil is used the derivative is constructed from the two points only. It would appear that a five-point stencil may bring better approximation and a smaller numerical diffusion (Fig.3b). This approach has been successfully employed to describe advective processes in a diffusion equation (Chen and Schiesser, 1980). In the application to the run-up problem the construction of the first (upstream) derivative can be carried over through various means, i.e., using three-point or four-point formulas. For three-point formulas, the negative flow can be resolved by the derivative,

$$\frac{\partial u}{\partial x} = \frac{-3u_j^m + 4u_{j+1}^m - u_{j+2}^m}{2h} + O(h^2) \quad (A3)$$

based on the function given at the three points $j, j+1$, and $j+2$. To resolve the positive flow,

$$\frac{\partial u}{\partial x} = \frac{3u_j^m - 4u_{j-1}^m + u_{j-2}^m}{2h} + O(h^2) \quad (A4)$$

three points $j - 2, j - 1$, and j are applied. Let us assume that the computational grid runs from a point $j = JS$ to point $j = JE$. The application of the expressions (A3, A4) is straightforward, except in close proximity to the boundaries. At the left boundary ($j = JS$), expression (A3) is applied, one point away from the boundary for $j = JS + 1$ the formula (A3) is easily applied but to apply (A4) we are lacking one point. One possibility is to use the first order expression (A2), which of course will lose the advantages of the second order approximation. A similar procedure can be implemented at the point $j = JE - 1$ by using (A1). Another possibility is to use a symmetrical expression for the first derivative.

The four-point formulas constructed on the five-point stencil give a more consistent approach both for the interior points and boundary points. The location of the upstream points is depicted in Fig. 3c. The derivative for the positive flow is

$$\frac{\partial u}{\partial x} = (u_{j-2}^m - 6u_{j-1}^m + 3u_j^m + 2u_{j+1}^m)/(6h) + O(h^3) \quad (A5)$$

In addition to two grid points to the left of the point j , one point to the right of the central point is introduced as well. For negative flow the first derivative,

$$\frac{\partial u}{\partial x} = (-2u_{j-1}^m - 3u_j^m + 6u_{j+1}^m - u_{j+2}^m)/(6h) + O(h^3) \quad (A6)$$

is constructed by using two upstream points $j + 1$ and $j + 2$ and one downstream point $j - 1$. In the interior of the integration domain from point $JS + 2$ to point $JE - 2$ the formulas (A5, A6) are used. For point $JS + 1$ expression (A6) are applied and for point $JE - 1$ expression (A5). For the boundary points, a four-point upstream formulas can be introduced which uses only points to the left or to the right from the central point j . At the left boundary

$$\frac{\partial u}{\partial x} = (-11u_j^m + 18u_{j+1}^m - 9u_{j+2}^m + 2u_{j+3}^m)/(6h) + O(h^3) \quad (A7)$$

first derivative is constructed from the upstream points $j + 1, j + 2$ and $j + 3$. At the right boundary antisymmetrical formula is used,

$$\frac{\partial u}{\partial x} = (-2u_{j-3}^m + 9u_{j-2}^m - 18u_{j-1}^m + 11u_j^m)/(6h) + O(h^3) \quad (A8)$$

Thus, in this approach all grid points are treated in a consistent manner by the four-point algorithm which has a third order of approximation.

The application of the third order formulas greatly improved the numerical calculations reducing both the numerical diffusion, observed in the upstream first derivative, and the dispersion observed in the symmetrical first derivative. The success of the four-point derivative prompted the development of the five-point derivative on the seven-point stencil (Fig. 3d). This method, has again the same boundary problems. At the left boundary a five-point upstream formula is constructed,

$$\frac{\partial u}{\partial x} = (-25u_j^m + 48u_{j+1}^m - 36u_{j+2}^m + 16u_{j+3}^m - 3u_{j+4}^m)/(12h) + O(h^4) \quad (A9)$$

To the point $JS + 1$ the main formula for the negative velocity can be applied,

$$\frac{\partial u}{\partial x} = (-3u_{j-1}^m - 10u_j^m + 18u_{j+1}^m - 6u_{j+2}^m + u_{j+3}^m)/(12h) + O(h^4) \quad (A10)$$

Point $JS + 2$ again has to be treated in a special way,

$$\frac{\partial u}{\partial x} = (u_{j-2}^m - 8u_{j-1}^m + 0u_j^m + 8u_{j+1}^m - u_{j+2}^m)/(12h) + O(h^4) \quad (\text{A11})$$

At the right boundary similar problems will be encountered. For the point $JE - 2$ expression (A11) is used. For the point $JE - 1$ the principal expression for the positive flow can be applied,

$$\frac{\partial u}{\partial x} = (-u_{j-3}^m + 6u_{j-2}^m - 18u_{j-1}^m + 10u_j^m + 3u_{j+1}^m)/(12h) + O(h^4) \quad (\text{A12})$$

Finally, at the right boundary the following formula is used,

$$\frac{\partial u}{\partial x} = (3u_{j-4}^m - 16u_{j-3}^m + 36u_{j-2}^m - 48u_{j-1}^m + 25u_j^m)/(12h) + O(h^4) \quad (\text{A13})$$

The construction of the multipoint derivatives (usually approached through Lagrange polynomials) is illustrated in the numerical analysis text books (see, e.g., Burden et al. 1981).

Acknowledgments

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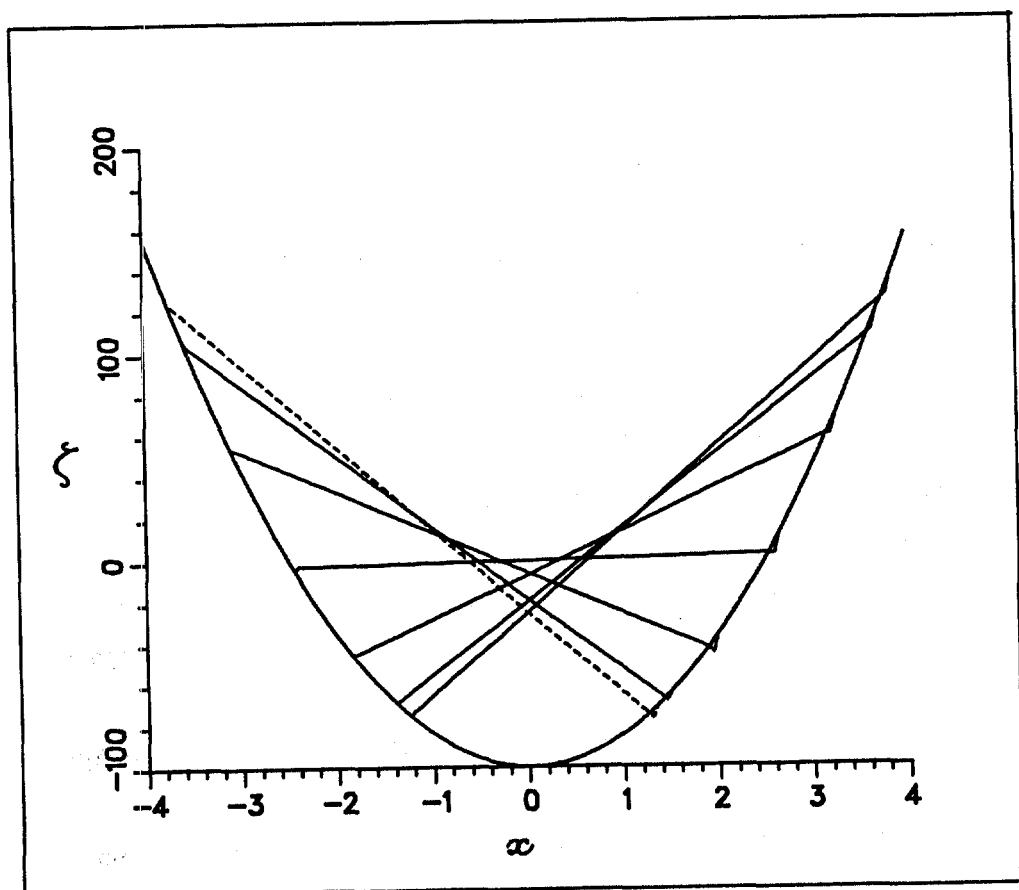


Fig.1 Numerical simulation of the Ball's (1964) problem. Planar surface oscillates without distortion. Dashed line shows initial geometry. The sea level is drawn every 150 time steps. Horizontal distance is given in km and sea level in cm. Computations are done with time step of 2.5 s and space step of 50 m.

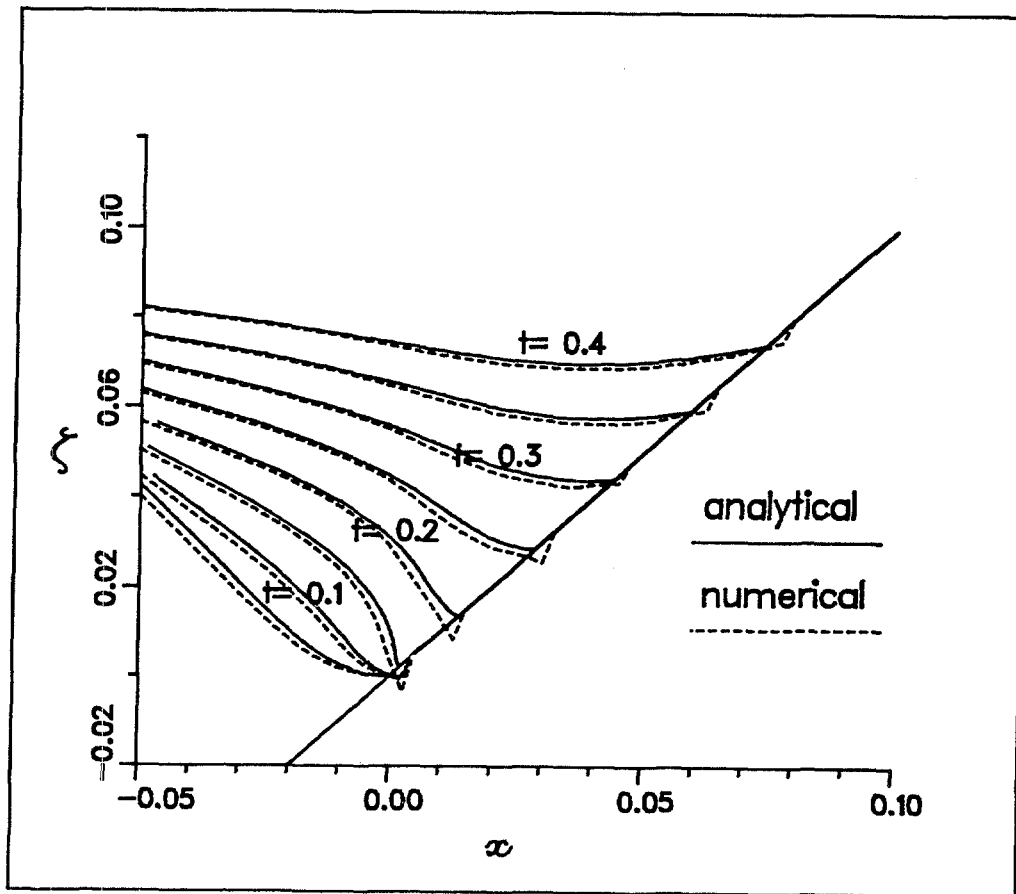


Fig.2 Numerical simulation of Carrier and Greenspan's (1958) problem. All variables, i.e. sea level, time and horizontal distance are dimensionless. The numbers in figure represent time from the onset of the wave run-up. Computations are performed with time step of 0.0005 and space step of 0.0025.

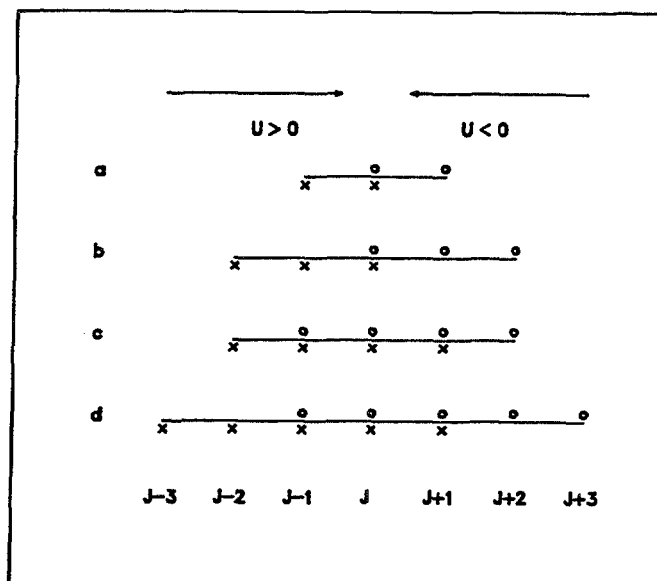


Fig.3 Numerical stencils and grid points used to construct first derivative by upstream method. Open circles denote points for the negative flow and crosses denote points for the positive flow.

**CALCULATIONS OF TSUNAMI TRAVEL TIMES CHARTS
IN THE PACIFIC OCEAN (MODELS, ALGORITHMS,
TECHNIQUES, RESULTS)**

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ABSTRACT

The mathematical techniques and the details of the computations for the production of a new set of tsunami travel-time charts for the Pacific Ocean are described. The production of these charts is requested by the International Coordination Group for the Tsunami Warning System in the Pacific Ocean.

Introduction

Tsunami waves are the most dangerous natural hazards suffered by the population living near the World ocean coasts in connection with the increasing intensity of economic exploitation of the coast there are increased socio-economical consequences of hazardous action of tsunami waves originating as a result of submarine seismic activity and other causes.

National services are patronized by the Intergovernmental Oceanographic Commission (IOC) of UNESCO, which coordinates efforts on the study of tsunamis and forecasting tsunami danger.

The General Conference of UNESCO, at its Fourth Extraordinary Session (Paris, November 23–December 30, 1982), formulated the Second Medium–Term plan (1984–1989), which, under Program X.2, stated that “Natural hazards have particularly serious implications in that they hardly attract any attention except when they manifest themselves as disasters and that the lessons learned from such disasters are soon forgotten.” The general Conference of UNESCO at its Twenty–Second Session (Paris, 1985), in doc. 2.2 C/5, identified among the ways to combat natural hazards of a geophysical origin such as earthquakes, volcanic eruptions and tsunamis, are studying their nature, underlying mechanisms and frequency in space and time. Studies of this kind will improve the monitoring, understanding and prediction of natural hazards and thus help to mitigate their consequences.”

Note, that high velocity of wave propagation, reaching hundreds of kilometers per hour, casts doubt on the possibility on predicting tsunami evolution in a real time scale and increases the importance of an operative prediction. Due to the fact that in a linear approximation travel times of long waves from the source to the point of observation and back are equal, one can compute wave travel times charts for a particular point, taken as a source of the perturbation. Upon receiving information on a tsunamigenic earthquake one can estimate the time of arrival by knowing the location of the source (for example, such as amplitude, frequency, size of the overlapping, etc.).

Isochrone charts were first made in 1947 by the American Coastal Service after a disastrous Aleutian tsunami in the Pacific coast [Zetler, 1947].

In 1971 these charts were evaluated and enlarged and about fifty charts were used by the Tsunami Warning System [ANON, 1971].

The Eighth Session of the International Coordination Group for Tsunami Warning System in the Pacific, by Resolution ITSU–VIII.2, expressed a strong need of Member States for additional tsunami travel time charts and the Ninth Session by Resolution ITSU–IX.2 recommended “The Secretary IOC.... to take necessary measures to commence production of the required charts.”

In 1984 IOC of UNESCO concluded on agreement with the Computing Center of the Siberian Branch of the USSR Academy of Sciences (Krasnoyarsk) to construct tsunami travel times charts for a number of new locations of the Pacific coast. This work has been done in the process of fulfilling the agreement.

I. Review of methods of constructing tsunami travel times charts.

At present a number of methods for computation of tsunami propagation times and based on different approximate wave theories, is known.

In early works [Green, 1961; Gilmoure, 1961] in order to determine the wave velocity use was made of the expression:

$$c^2 = (g \lambda / 2 \pi) \tanh (2 \pi h / \lambda),$$

where λ is the wave length; C is the speed of propagation; g is acceleration due to gravity; h is the depth of the ocean. Since tsunami wave lengths are 300–400 km and the average depth of the Pacific ocean is about 4 km, then, with the account that $h \ll \lambda$, follows:

$$c^2 = g h \tag{1.1}$$

For a particular ray with the trajectory S the propagation time is defined by the formula:

$$\tau = \int \frac{dS}{c}$$

Arcs of great circle, connecting the assigned points, are called ray trajectories.

Application of such approximated trajectories of wave propagation cannot ensure a sufficient accuracy of computation of temporal characteristics. Later, in the work of Mo-moi, 1964, for computation of the wave travel times "use was made of direct integration

of the ray" equation:

$$\frac{d^2\gamma}{dt^2} + p \frac{d\gamma}{ds} + q\gamma = 0, \quad (1.2)$$

where

$$p = -(\cos \alpha)/c \frac{\partial c}{\partial x} - \frac{\sin \alpha}{c} \frac{\partial c}{\partial y}, \quad \gamma = l/l_0,$$

$$q = -\frac{\sin^2 \alpha}{c^2} \frac{\partial^2 c}{\partial x^2} - \frac{2 \sin \alpha \cos \alpha}{c^2} \frac{\partial^2 c}{\partial x \partial y} + \frac{\cos^2 \alpha}{c^2} \frac{\partial^2 c}{\partial y^2}.$$

l, l_0 is the widths of the ray tube at the arbitrary and initial points, respectively; S is the trajectory of the wave ray; α is the angle of wave ray to the axis X ; x, y are grid coordinates; C is the speed of wave propagation, defined by the formula (1.1). Equation (1.2), as the author notes, can be solved either by the Kelvin method with approximating the integral curve by fragments of the arcs of a great circle, or by finite-difference methods, substituting equation by its difference analogue. The author, referring to the work of Griswold, 1963, asserts that the Kelvin method has advantages in accuracy, and makes use of it in making calculations. Assigning at the initial time the location of the source and the initial outward angle of the wave tube by formula (1.2), calculation is made of the wave travel time for any point of the region.

The simplest energetic relationships, determining conservation of energy in the ray tube, are used by the author for calculation of the wave height ξ :

$$\xi_2/\xi_1 = (c_1/c_2)^{1/2} (l_1/l_2)^{1/2} \quad (1.3)$$

Unfortunately in the work no description is given of the comparison calculated results with natural data, this one cannot evaluate the accuracy of the calculation. Note, that in this method the earth's sphericity is not taken into account and the question of passing caustics and foci, formed in the regions, complicated by non-homogenous depth distribution is not studied. In these cases, formula (1.3) turns out to be non-applicable for calculation of wave heights.

In the works of Braddock, 1961, 1971 and Braddock, Doilibi, Voss, 1981, 1983 there has been developed a method of constructing trajectories and fronts of wave propagation in non-homogenous media, called Grid Iteration Technique, in which the final result is obtained by constructing a converging sequence of mutually orthogonal trajectories and fronts.

This technique is based on minimization of functional

$$T^* = \min_S \int_S \frac{dS}{c} \quad (1.4)$$

along all possible trajectories S , connecting assigned initial and end points.

As initial trajectories use is made of arcs of a great circle, connecting the source with assigned points on the shore. Further, by the fixed temporal interval points with equal wave travel time are marked at these trajectories, whose connection forms the wave front.

In this technique a spherical system of coordinates is used, the beginning of coordinates is placed in the source and the arc length is determined by the formula

$$dS = R \left[(\Delta\varphi)^2 + \cos^2 \varphi_1 (\Delta\Psi)^2 \right]^{1/2},$$

where R is the Earth's radius, φ_1 is latitude; Ψ_1 is longitude of the current point; $\Delta\varphi, \Delta\Psi$ is increment of latitude and longitude respectively.

In order to find the trajectory, use is made of a minimization of the functional (1.4). Then the wave front is determined more exactly by the assigned time interval. Such an iterating process is repeated until a constructing of the grid "trajectory-front" changes in the range of the desired accuracy.

Overcoming the peculiarities of perturbation propagation (caustics, foci) is exercised using Danzig's algorithm [Danzig, 1960], according to which every grid node correspond to the wave propagation time from the source to this node and the immediate preceding along the trajectory node is indicated.

Braddock [Braddock, 1969] applied the developed technique for determining ray trajectories from Alaska tsunamis of 1946 and 1964 and obtained satisfactory accuracy, especially in the regions with complicated bathymetry. Main shortcomings of the techniques are associated with iteration structure, which results in a considerable growth of the required memory of the computer to store grid nodes and all its characteristics, especially in constructing transoceanic trajectories. Besides, as described in T. S. Murty's monograph [Murty, 1981] this technique possesses ambiguity in choosing trajectories. Application of this technique for the determination of the wave propagation time in the Tasman sea gives an error of 1-2 min per hour of wave propagation.

A separate group of computation techniques of travel time are the methods using Guggens' principle [Nakano, 1975, 1978; Groshev et al., 1986; Karev, Sudakov, Chubarov, 1986]. In these techniques the assigned spatial interval local time that is necessary for a wave to cover this interval, is determined. Utilization of discrete bathymetric information and determination of the field of travel times only in a fixed set of initial assignment of depths is unique.

In the process of constructing such a temporal field all grid nodes are divided into three sets:

- 1) nodes, in which travel time is already determined (and they are excluded from further computation):
- 2) nodes, for which a preliminary travel time estimation is obtained.
- 3) nodes, for which travel time is not yet determined.

Then a notion of node influence region is introduced, i.e. a set of nodes close to considered one according to a certain criterion and it is believed that from the assigned node the perturbation can reach only the nodes from its influence region.

Consider two nodes A and B belonging to one influence region. We shall regard the signal to propagate along the arc of a great circle with the speed equal to the arithmetic mean of local speeds of propagation in finite nodes A and B in accordance with the formula $T = 2L / (C_A + C_B)$, in which

$$L = R \arccos(\sin \varphi_A \sin \varphi_B + \cos \varphi_A \cos \varphi_B \cos \Delta\psi),$$

φ_A, φ_B are the latitude of nodes A and B respectively, $\Delta\psi$ is the difference of their longitudes, C_A and C_B are defined by formula (1.1).

To define more exactly travel time from the source to node B use is made of the minimizing relationship

$$T_B^{n+1} = T_B^n + \min_{A_i} T_{A_i B} \quad (1.5)$$

where the nodes A_i belong to the influence region of node B .

Initially, all the nodes of a perturbation source belonging to the set "2" is established. At each step of the algorithm the node is chosen from this set which has a minimal time propagation and it is transferred to the set "1".

propagation and it is transferred to the set "1".

Nodes of set "3", that get into the node influence region of set "2", are assigned the time defined by formula (1.5) and thus they pass on to set "2". After the propagation time has been defined for all nodes one can, using interpolation techniques, construct wave fronts form the assigned temporal interval. This procedure, close to the Danzig's method and the method used for constructing tsunami travel time charts of 1971, has also been used by V. Ju, Karev and in the course of this work.

In choosing a mathematical model for constructing travel time charts the authors proceeded from the main provisions of the shallow water theory leading in linearizing to the eiconal equation describing temporal characteristics of wave propagation. Attempts to use such a technique were made earlier in A. G. Marchuk's works [Marchuk, 1980, Marchuk et al., 1983]. Such an approach allows one, within the framework of one mathematical model, to determine the ray trajectory and wave front without additional hypotheses requiring special substantiation.

2. On estimation of calculation accuracy of travel times.

The main influence on calculation accuracy of travel times in all methods described above, is the accuracy and details of bathymetric information used in calculations.

In the work of Braddock, Doilibi and Voss, 1980 techniques of isochrone calculation are divided into 2 types:

a) techniques using a constant spatial step along the trajectory ΔS (in a specified discrete grid travel times field is calculated);

b) techniques using a constant temporal step Δt (from which the specified temporal interval position of the wave front is determined).

Note, that equation (1.1) links the increments ΔS and Δt along the trajectory and only one of them can be defined independently.

In techniques of the first type the bathymetry error δh determines time calculation error by the formula

$$\delta t = -\delta h / 2hC = \alpha \Delta S$$

i.e. a relative error is inversely proportional to the wave propagation velocity.

In the other group of techniques by the specifying temporal step Δt the spatial wave-front increment ΔS is determined.

$$\Delta S = c \Delta t$$

The relative error δh is related with the spatial increment error by the formula:

$$\delta S = c \Delta t \cdot \delta h / h ,$$

and then the error to determine location is

$$\delta t = \Delta t \cdot \delta h / h = \beta \Delta t .$$

Hence it follows, that α and β are related by the $\beta = \alpha C$ relationship and the value β is sensible to errors of determining depth.

Also note, that in the regions of convergence and divergence of rays a small change of the ocean depth may result in a sharp change of their trajectories and wave front.

Different ways of determination bathymetric information, to smooth local heterogeneities, lead by the estimation of a number of authors [Murty, 1984; Braddock, 1983], to a variation of tsunami wave travel times of 3–5 min per hour of a wave propagation. Therefore, interpolational and approximal procedures employed for calculation of the ocean depths must be representative.

3. Description of the technique and algorithm of calculation of travel times.

Starting to derive the main equations of a mathematical model, consider equations of the shallow water theory, which in a linear approximation for a spherical system of coordi-

nates have the form:

$$\frac{\partial u}{\partial t} = -\frac{g}{R \cos \varphi} \frac{\partial h}{\partial \Psi},$$

$$\frac{\partial v}{\partial t} = -\frac{g}{R} \frac{\partial h}{\partial \varphi},$$

$$\frac{\partial h}{\partial t} = -\frac{1}{R \cos \varphi} \left[\frac{\partial (Hu)}{\partial \Psi} + \frac{\partial}{\partial \varphi} (Hv \cos \varphi) \right], \quad (3.1)$$

where φ is the latitude, Ψ is the longitude, R is the Earth's radius, u, v are velocity components along the directions Ψ and, φ respectively, g is the gravity acceleration, H is the ocean depth. Passing on in (2.1) to the equation for h (elevation of a free surface), we shall obtain:

$$\frac{\partial^2 h}{\partial t^2} = \frac{g}{R^2 \cos^2 \varphi} \frac{\partial}{\partial \Psi} H \frac{\partial h}{\partial \Psi} + \frac{g}{R^2 \cos \varphi} \frac{\partial}{\partial \varphi} H \cos \varphi \frac{\partial h}{\partial \varphi} \quad (3.2)$$

Assuming, that the wave front is described by the equation $S = 0$, and using a geo-

metric expansion of the function $h(\psi, \varphi, t)$ in the form [Witham, 1967]:

$$h(\psi, \varphi, t) = \sum_n \Phi_n(\psi, \varphi) \cdot F_n(S) \quad (3.3)$$

where the functions F_n possess the property

$$dF_n(S)/dS = F_{n-1}(S) \quad (3.4)$$

and substituting expansion (3.3) into equation (3.2), finally, grouping terms at F_n , we shall obtain:

$$\begin{aligned} & F_{n-2}(S) \left[\left(\frac{\partial S}{\partial t} \right)^2 - \frac{gH}{R^2 \cos^2 \varphi} \left(\frac{\partial S}{\partial \psi} \right)^2 + \frac{gH}{R^2} \left(\frac{\partial S}{\partial \varphi} \right)^2 \right] \Phi_0 + \\ & F_{n-1}(S) \left\{ \left[\left(\frac{\partial S}{\partial t} \right)^2 - \frac{gH}{R^2 \cos^2 \varphi} \left(\frac{\partial S}{\partial \psi} \right)^2 + \frac{gH}{R^2} \left(\frac{\partial S}{\partial \varphi} \right)^2 \right] \Phi_n - \frac{2gH}{R^2} \left[\frac{\partial \Phi_0}{\partial \varphi} \frac{\partial S}{\partial \varphi} + \right. \right. \\ & \left. \left. \frac{1}{\cos^2 \varphi} \frac{\partial \Phi_0}{\partial \psi} \frac{\partial S}{\partial \psi} \right] + \left[\frac{g}{R^2} \left(\frac{1}{\cos^2 \varphi} \frac{\partial H}{\partial \psi} \frac{\partial S}{\partial \psi} + \left(\frac{\partial H}{\partial \varphi} - H \operatorname{tg} \varphi \right) \frac{\partial S}{\partial \varphi} \right) - \right. \right. \\ & \left. \left. \left(\frac{\partial^2 S}{\partial t^2} - \frac{gH}{R^2} \left(\frac{1}{\cos^2 \varphi} \frac{\partial^2 S}{\partial \psi^2} + \frac{\partial^2 S}{\partial \varphi^2} \right) \right) \right] \Phi_0 \right\} + \\ & \sum_{n=0}^{\infty} E_n(\psi, \varphi) F_n(S) = 0. \end{aligned}$$

It should be noted, that the functions E_n contain the main term of the form

$$\left[\left(\frac{\partial S}{\partial t} \right)^2 - \frac{gH}{R^2 \cos^2 \varphi} \left(\frac{\partial S}{\partial \psi} \right)^2 - \frac{gH}{R^2} \left(\frac{\partial S}{\partial \varphi} \right)^2 \right] \Phi_{n-2}$$

and other terms with $\Phi_{n+1}, \dots, \Phi_0$ and derivations with respect to S .

Wave equation (3.2) is satisfied, if all coefficients at F_{n-2}, F_{n-1}, \dots are equal to zero, i.e.

$$\left(\frac{\partial S}{\partial t} \right)^2 - \frac{gH}{R^2 \cos^2 \varphi} \left(\frac{\partial S}{\partial \psi} \right)^2 - \frac{gH}{R^2} \left(\frac{\partial S}{\partial \varphi} \right)^2 = 0 \quad (3.5)$$

$$\begin{aligned} & \frac{2g}{R^2} \left\{ H \left(\frac{1}{\cos^2 \varphi} \frac{\partial \Phi_0}{\partial \psi} \frac{\partial S}{\partial \psi} + \frac{\partial \Phi_0}{\partial \varphi} \frac{\partial S}{\partial \varphi} \right) + \right. \\ & \left. \left[\left(\frac{1}{\cos^2 \varphi} \frac{\partial H}{\partial \psi} \frac{\partial S}{\partial \psi} + \left(\frac{\partial H}{\partial \varphi} - H \operatorname{tg} \varphi \right) \frac{\partial S}{\partial \varphi} \right) \frac{\partial S}{\partial \varphi} + \right. \right. \\ & \left. \left. \frac{\partial^2 S}{\partial t^2} - \frac{gH}{R^2} \left(\frac{1}{\cos^2 \varphi} \frac{\partial^2 S}{\partial \psi^2} + \frac{\partial^2 S}{\partial \varphi^2} \right) \right] \Phi_0 = 0, \text{ etc.} \right. \end{aligned} \quad (3.6)$$

For a calculation of temporal characteristics, equation (3.5) is of interest and is called the eiconal equation. It describes the wave front travel (surface $S(\psi, \varphi, t)$ in the space (ψ, φ)).

For further construction it is convenient to discuss the wave front in the form

$$S(\psi, \varphi, t) = t - \sigma(\psi, \varphi),$$

where the family of surface $\sigma(\psi, \varphi)$ const determines a sequential position of the front. Then equation (3.5) has the form:

$$1 - \frac{gH}{R^2 \cos^2 \varphi} \left(\frac{\partial \sigma}{\partial \psi} \right)^2 - \frac{gH}{R^2} \left(\frac{\partial \sigma}{\partial \varphi} \right)^2 = 0 \quad (3.7)$$

A complete system of characteristic equations for (3.7) is written as follows:

$$p = \frac{\partial \sigma}{\partial \psi}, \quad q = \frac{\partial \sigma}{\partial \varphi},$$

$$\frac{d\varphi}{dt} = \frac{gH}{R^2} q,$$

$$\frac{dp}{dt} = -\frac{1}{2H} \frac{\partial H}{\partial \psi},$$

$$\frac{d\psi}{dt} = \frac{gH}{R^2 \cos^2 \varphi} p, \quad (3.8)$$

$$\frac{dq}{dt} = -\frac{1}{2H} \frac{\partial H}{\partial \varphi} - \frac{gH \sin \varphi}{R^2 \cos^3 \varphi} p^2.$$

The initial conditions (φ_0, ψ_0) are added to equations (3.8) – the initial position of perturbation source and slope of characteristics to the coordinate ψ :

$$\Psi|_{t=0} = \psi_0, \quad P|_{t=0} = \frac{R \cos \varphi_0}{\sqrt{gH(\psi_0, \varphi_0)}} \cos \gamma,$$

$$\varphi|_{t=0} = \varphi_0, \quad Q|_{t=0} = \frac{R}{\sqrt{gH(\psi_0, \varphi_0)}} \sin \gamma, \quad (3.9)$$

where γ is the slope trajectory to the coordinate line $\psi = \text{const}$. Introducing new independent variables

$$\tau = \frac{\sqrt{gH}}{R} t, \quad P' = \frac{R}{\sqrt{gH}} P, \quad Q' = \frac{R}{\sqrt{gH}} Q,$$

In the system (3.8–3.9) let us consider the dimensionless form:

$$\frac{d\Psi}{d\tau} = \frac{H}{\bar{H}} \frac{1}{\cos^2 \varphi} P', \quad \Psi|_{\tau=0} = \psi_0,$$

$$\frac{d\varphi}{d\tau} = \frac{H}{\bar{H}} Q', \quad \varphi|_{\tau=0} = \varphi_0,$$

$$\frac{dP'}{d\tau} = -\frac{1}{2H} \frac{\partial H}{\partial \Psi}, \quad P'|_{\tau=0} = \sqrt{\frac{H(\psi_0, \varphi_0)}{\bar{H}}} \cos \varphi_0 \cos \gamma, \quad (3.10)$$

$$\frac{dQ'}{d\tau} = -\frac{1}{2H} \frac{\partial H}{\partial \varphi} - \frac{H}{\bar{H}} \frac{\sin \varphi}{\cos^3 \varphi} P'^2, \quad Q'|_{\tau=0} = \sqrt{\frac{H(\psi_0, \varphi_0)}{\bar{H}}} \sin \gamma,$$

where \bar{H} is the average ocean depth.

Equations (3.10) are used further for a calculation of ray trajectories and wave fronts, and for their solution the Runge–Kutta method of the fourth order of accuracy was used.

In the case of a constant depth $H = \bar{H}$ and location of the source at the beginning of coordinates solution of the system (3.10) has the form:

$$\begin{aligned}\varphi &= \arcsin(\sin\gamma \sin\tau), \\ \psi &= \arctg(\cos\gamma \cdot \operatorname{tg}\tau).\end{aligned}\tag{3.11}$$

These equations describe great circles on the sphere and the time, necessary for perturbation to bend around the sphere, is equal to $\tau^* = 2\pi$ or in dimensional coordinates, $t^* = 2\pi R\sqrt{gH}$, which coincides with the results, obtained by the known Green's formula (1.1).

The algorithm of constructing the wave front in this case looks as follows: a family of trajectories with various initial slopes is emitted from the source and equation (3.10) is sequentially solved per one temporal step. The set of calculated values (ψ_i, φ_i) forms the wave front.

It is known [Pelinovskii, 1982] that the "ray" technique encounters difficulties associated with the appearance of peculiarities of the solution, due to the strong heterogeneity of the wave propagation medium (sharp change of the ocean depth gradient). This causes self-crossing of trajectories (focus) and/or a collapse of the ray tube.

In calculating dynamic characteristics (wave height, velocity field) overcoming of such peculiarities requires use of additional hypotheses on the behavior of solution in these points. Since the problem of determining isochrones requires calculation of temporal characteristics of the process only (minimal time of a signal travel), the pointed out peculiarities can be overcome in a purely algorithmic way.

Thus, for an assigned point of the coast, a calculation of the wave front is made before it reaches the beach with an interpolation of the ocean depth at the calculated points and display of the calculated isochrones on visualizing devices.

Note, that the source of initial perturbation can be like a point as well as represent some connected region with an arbitrary geometry.

The Runge–Kutta method of the fourth order of approximation, chosen for a numerical solution of the equations, is known for its efficiency and satisfies initial requirements of accuracy and economy. Some complications of the calculation, include correction of the ray outlet angle of the external normal of the front, a calculation in the case of col-

lapse of the ray tube at its width less of some magnitude of δ , or adding of some additional trajectories at the width of the ray tube more than 2.1δ in spite of retardation of the algorithm are necessary for obtaining required accuracy and quality of the calculation.

The structure of the algorithm is given in Fig. 3.1.

4. Analysis of results and test calculations.

4.1 To check adequacy of the used mathematical models and algorithms and also to estimate the influence of ways of bathymetry data approximations on the accuracy of the calculated quantities, test calculations have been made with the use of model schematic distributions of depths and calculations allowed us to make a comparison of calculated tsunami wave travel times with observed ones during real events.

In the tests the following algorithms and techniques have been used:

A) In the algorithm of numerical solution of the eiconal equation, described in the previous section; calculations have been made with procedures of bilinear interpolation (method A1) and spline approximation (method A2) of depth.

B) One of the variants of the Guygens' method with the 16-points star is a program realization of V. Ju Karev.

C) The algorithm of a numerical solution of linearized equations of the shallow water theory, described in the monograph [An. G. Marchuk, L. B. Chubarov, Ju. I. Shokin, 1983].

One of the first test experiments allowed a comparison of results, calculated with the algorithm A1 and an accurate analytical solution of (3.11) for the case of the ocean with constant depth ($H=3000\text{m}$), with real configuration of the shoreline. The point source was located near the Hawaiian Islands (coordinates 21.2 n. lat., 157.9 w. long.). Results, depicted in Fig. 4.1, show a complete correspondence of these solutions.

4.2. The next series of test calculations has been conducted to determine the influence of the interpolation method and depth approximation of the accuracy of the calculated temporal characteristics, when procedures of bilinear interpolation and spline approximation being used. A comparison of the obtained tsunami wave travel times for a fixed set of observation points with analogous parameters, calculated by the equations of the shallow water theory, where the front arrival times have been determined from the analysis of calculated mareograms at the same points, also allowed us to estimate a stability of results of a numerical simulations with respect to the choice of a mathematical model.

In these computational experiments calculations of tsunami wave travel times in the

Sea of Japan have been made from a schematical source, having finite dimensions and simulating real events, occurred in May 1983.

All calculations have been made at the initial square grid with the depth numbering step $\Delta X = \Delta Y = 10,000\text{m}$, covering a part of the Sea of Japan from 36 to 44 North latitude and from 130 to 141 East longitude. The Earth's sphericity in these calculations was not included.

The calculation results are given in Table 4.1, and the position of points are in Fig. 4.2.

Analysis of Table 4.1 shows that travel times scattering on the average is 1–2 minutes. Some of the excess travel time calculated with spline approximation for assigning the sea depth, is caused by smoothing strong nonuniformity of bathymetry, especially near the shoreline, and by a corresponding retardation of the wave.

Tsunami wave travel times (min) calculated for the observation point, located on the coast of the Sea of Japan, from a schematic source of a tsunamigenious earthquake of 5-26-83.

In Fig. 4.2 there are depicted depth isolines of a part of the Sea of Japan, some mareographic points are marked showing the location of the mareograms, calculated by the linearized equations of the shallow water theory. At all points I observed the excess of the wave front arrival times, obtained by the algorithm *A*, with bilinear interpolation and spline approximation, and algorithm *B* in comparison with the arrival time of the leading wave in the mareogram, which is related to the calculating smearing of the front in a numerical shallow water model. When using a bilinear interpolation, travel times, lying between the quantities calculated by the algorithm *B* and mareogram wave arrival times, are obtained.

5. Comparison with experimental data.

A group of experiments is considered which permit estimation of the degree of correspondence of calculated tsunami wave travel times to natural data, taken from the works [S. L. Solovyov, 1978; T. S. Murty, 1986]. In some cases it turned out to be possible to compare calculation results, carried out by the authors of the present work by the algorithms *A1*, *B*, with the calculation results served as the basis for making the isochrone Atlas of 1971.

Both results of solving direct problems will be described. The source of initial perturbation was located in the source zone of a tsunamigenious earthquake and wave arrival times to the observation point on the shore were determined. Results of solving a number of inverse problems, i.e. such problems in which the use of the principle reversibility of

the shore (assuming, that the source of initial perturbation is located in the vicinity of this place), and, to determine the wave travel time from it to any epicentral zone. From the force of the mentioned assumption this time is considered equal to the travel time from the source of perturbation to the observation point.

In Fig. 5.1–5.4 tsunami wave isochrone charts are presented, calculated for point sources, simulated sources of real tsunamigenious earthquakes.

Table 5.1
A list of events for which tsunami
wave travel times have been calculated.

Date	Place	Hypocentre coordinates	
09.03.1957	Aleutian Islands	51.3. n. lat.	175.8 e. long.
28.07.1957	Mexico	16.6. n. lat.	99.0 w. long.
22.05.1960	Chile	39.5. s. lat.	74.5 w. long.
01.09.1981	Samoa	15.0. s. lat.	175.9 w. long.

These events have been chosen for the following reasons. First, they generated tsunami waves of an appreciable intensity; second, earthquake sources are located in remote from one another main seismoactive zones, covering the water area of the Pacific Ocean. Two of these events (Aleutian, 1957, Chile, 1960) were used by T. S. Murty [Murty, 1986] to estimate accuracy of the isochrone Atlas of 1971. A comparison of natural observations with calculated data for the event used at adjusting the technique (Aleutian, 1957), displays a considerably less deviation, than a comparison with the control event (Chile, 1960).

In Table 5.2 the results of data control comparisons are presented, calculated by the algorithm A1 with the Atlas data of 1971 and natural observations, given by Murty [Murty, 1986].

Average deviations of travel times, calculated by the algorithm A1 are approximately three times less, then average deviations of times given by Murty.

The following series of test calculations has been made for a set of control stations, well covered by ischrone charts, calculated earlier for the Atlas of 1971.

The tsunami catalog [S. L. Solovyov, 1978] has become the source of natural data. The set of control stations was organized so that all of them were provided at most possible natural material. For seven stations (Honolulu, San Francisco, Attu, Truk Island, Wake Island, Johnston Island, Tofino) the isochrone charts were calculated earlier in making the Atlas of 1971. Three stations (Talara, La Libertad, Caldera) were included (Table 6.1). Isochrone charts were calculated for 23 points along the coast of Central and South America and South-East Asia.

In Table 5.3, the number of the event by the Catalog, date of event, region, source hypocentre coordinates and some of its geometric characteristics are indicated under: "extent of source". Twenty seven tsunamigenious earthquakes for the period from 1918 to 1975 occurred in the most active coastal seismic zones of South America, the Aleutian islands and Alaska, Kuril-Kamchatka zone and Japan, are taken into account.

The results of the comparison are given in Table 5.4. All the calculations have been made with the use of bathymetric data in one degree grid. The magnitudes of constants are $g=9.81\text{m/sec}$, Earth $R=6371.2 \times 10^3 \text{ m}$, $\bar{H}=4000\text{m}$, step in time Δt in the algorithm A1 was 6 minutes.

Thorough analysis of the results has shown that all the considered calculated data show some excess of the wave propagation velocity in comparison with the natural data. This peculiarity of algorithms, based on linear models, has also been pointed out by T. S. Murty [T. S. Murty, 1981]. Travel times, calculated by the algorithm A are 2 minutes less than the observed ones per hour of the wave propagation, calculated for the Atlas of 1971 - 0.9 minutes, and, results of the algorithm B - 7 minutes.

The average quadratic deviations of the relative travel times, calculated by the algorithm A, are about 40% less than those according to the data of the 1971 Atlas; this is due to a smaller spread of the numerical results.

A correlation coefficient for calculated data with natural data for the algorithm A is 0.992; for the algorithm B is 0.991 and for the data of 1971 is 0.964.

The impossibility taking into account the influence of the seismic nature of the tsunami source on the character of the wave propagation may lead to different arrival times in the natural data. For example, the Chilean tsunamis of 1960, having practically the same source coordinates, but differing by intensity, manifested the difference of arrival times (by the Catalog) at the same point in the coast of Kamchatka of 2.9 hours. In such cases one should, evidently, assume the presence of some inaccuracy in natural data.

The character of the results spread in presented in Fig. 5.5 - 5.7, where along the horizontal axis "real" travel times, and along the vertical calculated data from Table 5.4 are plotted. On the whole one can note a good agreement of the results, especially for the close tsunamis and tsunamis of middle remoteness.

A quantitative estimate of reliability of results is given by statistical parameters – average and average quadratic deviations.

A set of the isochrones charts, calculated in the course of this work, allow an estimation of reciprocal travel times for a number of points. Using that, the source was placed at the point X_i and travel times were marked at the points X_j .

Analysis of a complete set of isochrone charts with sources, placed in each i -th point, resulted in forming Table 5.5. In Table 5.5 there are marked: T_{ij} – travel times from the source X_i to the observation point X_j at $i < j$ and $\Delta T_{ij} = T_{ij} - T_{ji}$ – travel time deviation from the point to the source and back at $i > j$.

Essentially, it appears possible to estimate the influence of error of a finite-difference approximation of the ocean bottom relief, since, trajectories of ray propagation from the source to the observation point and back do not coincide. It happens because at the initial moment a finite set of wave rays is released from the source, whose transformation is traced only during the temporal interval Δt , after which the wave front becomes the source of the following finite set, calculated for the time moment $t^2 = t^{n-1} + \Delta t$ etc.

As shown in Table 5.5, deviations prove to be sufficiently small for points of different remoteness and do not exceed 3% or 2 min per hour.

In summary, note that both algorithms used (A and B) proved their efficiency and the adequacy of the results obtained with them.

Algorithm A is preferable due to its greater flexibility, possibility of governing the accuracy of calculations with the choice of a temporal step and constructing a corresponding interpolation procedure, which is supported also by better error estimations. The test calculations have also shown fitness of the procedure of a bilinear depth interpolation.

6. Calculation of Travel Time Charts for the Pacific Tsunami Warning System.

As noted previously, the objective was to calculate the tsunami wave travel time charts to 23 places of the Pacific coast, mainly of the American continent. Later the list was supplemented with a chart for Honolulu, as the main control place. Coordinates are given in Table 6.1.

The charts, supplemented by the scheme of location of places, are given in Supplement 1.

Thus, the calculation of tsunami travel time charts in the Pacific has been completed. In the course of which there has been developed algorithms and soft-ware, reliability established of the obtained results, errors estimated of calculated techniques, and produced

tsunami travel time charts for all the required places. Unfortunately, due to a number of circumstances not dependent on the authors, we failed to make calculations at the five-minute bathymetric grid, available in World Data Center – A.

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Number of the Observation Point	Calculation by the A method with linear interpolation of depth (A 1)	Calculation by the A method with the spline-approximation of depth (A 2)	Calculation by the B method
31	66.0	70.0	69.0
32	72.0	74.0	70.0
33	72.0	84.0	77.5
34	67.0	70.0	67.0
35	60.0	62.0	57.0
36	62.0	63.0	67.0
37	49.0	51.0	50.0
38	48.0	51.0	50.0
39	54.0	56.0	53.0
40	51.0	54.0	52.0
41	56.0	60.0	58.0
42	54.0	56.0	54.0
43	52.0	54.0	52.0
44	54.0	56.0	56.0
45	52.0	54.0	52.0
46	53.0	56.0	55.0
47	56.0	58.0	57.0
48	53.0	54.0	54.0
49	55.0	54.0	54.0
50	48.0	50.0	47.5
51	48.0	50.0	46.5
52	48.0	50.0	46.5
53	50.0	54.0	49.0
54	48.0	54.0	43.0
55	48.0	48.0	42.5
56	50.0	52.0	46.5
57	46.0	46.5	45.2
58	46.0	46.0	46.0
59	50.0	50.0	52.0
60	51.0	52.0	53.0
61	73.0	76.0	72.5
62	80.0	82.0	76.5
63	76.0	80.0	74.5
64	76.0	82.0	72.0
65	66.0		65.0
66	48.0	50.0	45.0
67	46.0	45.0	46.0
68	42.0	44.0	42.0
69	46.0	48.0	47.0
70	50.0	54.0	51.0
71	52.0	54.0	53.0
72	54.0	56.0	55.0
73	54.0	56.0	53.5
74	48.0	50.0	47.5
75	46.0	50.0	47.5
76	46.0	50.0	47.0
77	46.0	54.0	47.0
78	48.0	54.0	50.0
79	50.0	52.0	50.0

Table 4.1

Tsunami wave travel times (min) calculated for the observation points, located on the coast of the Sea of Japan, from a schematic source of a tsunamigenic earthquake of 5-26-83.

Table 5.2

Observation point	Natural data t_x	Calculation by A 1		Atlas of 1971	
		t_p	$t_p - t_x$	t_p	$t_p - t_x$
Midway	3.2	3.2	0.0	3.5	0.3
Jukutat	4.8	4.6	-0.2	4.0	-0.8
Crescent City	5.2	6.0	0.8	5.5	0.3
Encenada	6.8	7.5	0.7	7.5	0.7
Talara	15.0	16.0	1.0	16.0	1.0
La Libertad	16.1	16.2	0.1	15.3	-0.8
Kailao	16.2	16.7	0.5	17.0	0.8
Talkakhuana	19.0	19.1	0.1	18.3	-0.7
Average $\bar{\epsilon} = \frac{1}{N} \sum_{i=1}^N \frac{t_p - t_{x_i}}{t_{x_i}} = -0.263$					
Average quadratic deviation $\sigma = \sqrt{\frac{\sum_{i=1}^N (\epsilon_i - \bar{\epsilon})^2}{N-1}} = 0.346$					
Midi	19.6	19.5	-0.1	21.0	1.4
Keirns	19.8	19.5	-0.3	21.3	1.5
Guam	21.5	20.5	1.0	22.3	0.8
Akapulko	9.9	9.8	0.0	10.5	0.7
Average $\bar{\epsilon} = \frac{1}{N} \sum_{i=1}^N \frac{t_p - t_{x_i}}{t_{x_i}} = -0.017$					
Average quadratic deviation $\sigma = \sqrt{\frac{\sum_{i=1}^N (\epsilon_i - \bar{\epsilon})^2}{N-1}} = 0.021$					

Table 5.3

List of events by the Catalog of S.I. Solov'ov.

N	Year	Region	Source coordinates	Extent of source...	Date
16	1918	Kuril	46.6 n.lat. 151.5 e.long.		8.09
17	1923	Kamohatka	53.0 n.lat. 161.0 e.long.		4.02
18	1923	Kamohatka	56.4 n.lat. 162.8 e.long.		14.04
20	1927	Kamohatka	53.8 n.lat. 161.4 e.long.		29.12
26	1962	Kamohatka	52.3 n.lat. 161.0 e.long.	30 km	6.11
27	1956	Kamohatka	56.1 n.lat. 160.7 e.long.		30.03
28	1958	Kuril	48.6 n.lat. 156.1 e.long.	40 km	17.09
29	1958	Kuril	44.6 n.lat. 148.9 e.long.	80 km	7.11
30	1958	Kuril	44.3 n.lat. 148.9 e.long.	40-60 km	13.11
31	1959	Kuril	44.3 n.lat. 149.0 e.long.	40 km	9.04
33	1960	Peru	15.76s.lat. 72.76w.long.	30-200 km	13.01
34	1960	Chile	37.6 e.lat. 73.6 w.long.		21.06
36	1960	Chile	38.0 e.lat. 73.6 w.long.		22.06
32	1959	Kuril	53.1 n.lat. 160.3 e.long.	20 km	4.06
38	1962	Kuril	43.8 n.lat. 142.4 e.long.	60 km	21.06
40	1963	Kuril	44.8 n.lat. 149.5 e.long.	60 km	13.10
41	1963	Kuril	44.5 n.lat. 150.2 e.long.	20 km	20.10
42	1964	Alaska	61.1 n.lat. 147.7 e.long.	33 km	27.03
44	1965	Aleut	51.2 n.lat. 178.6 e.long.	40 km	4.02
46	1966	Peru	10.7 s.lat. 173.8 w.long.	40 km	18.10
49	1968	Japan	40.9 n.lat. 143.5 e.long.		16.06
50	1969	Kuril-Hokkaido	43.4 n.lat. 147.7 e.long.	30 km	12.08
59	1973	Kuril-Hokkaido	43.1 n.lat. 146.9 e.long.	50 km	17.06
60	1973	Kuril-Hokkaido	43.1 n.lat. 146.5 e.long.	50 km	24.06
62	1975	Kuril-Hokkaido	43.5 n.lat. 148.5 e.long.	40 km	10.06
100	1945	Aleut	52.8 n.lat. 163.5 e.long.		1.04
101	1957	Aleut	51.3 n.lat. 163.5 e.long.		9.03

Table 6.1

Comparison of results, calculated by different algorithms and observed tsunami travel times for 12 places of the Pacific coast.

PLACE	EVENT	NATURE DATA	METHOD A		METHOD B		ATLAS 1971	
			t_p	$t_p - t_k$	t_p	$t_p - t_k$	t_p	$t_p - t_k$
Honolulu (21.2 n.lat., 157.9 w.long.)	17	6.3	6.3	0.0	6.0	-0.3	6.3	0.0
	18	6.6	6.5	-0.1	6.2	-0.4	6.5	-0.1
	20	7.7	6.4	-1.3	6.2	-1.5	6.4	-1.3
	25	6.3	6.3	0.0	5.9	-0.4	6.3	0.0
	27	6.1	6.6	0.5	6.1	0.0	6.5	0.4
	29	6.7	7.0	0.3	6.7	0.0	6.7	0.0
	32	6.2	6.3	0.1	6.2	0.0	6.5	0.3
	40	6.9	6.8	-0.1	6.8	-0.1	6.7	-0.2
	41	7.1	6.8	-0.3	6.8	-0.3	6.7	0.4
	42	5.3	6.3	1.0	6.7	-1.4	6.5	1.2
San Francisco (37.55 n.lat., 122.5 w.long.)	16	9.4	9.0	-0.4	9.3	-0.1	9.3	-0.1
	17	10.0	8.1	-1.9	8.3	-1.7	8.1	-1.9
	18	11.5	8.2	-3.3	8.2	-3.3	8.2	-3.3
	25	8.7	8.0	-0.7	8.2	-0.5	8.2	-0.5
Attu (52.8 n.lat., 173.0 e.long.)	27	1.8	1.6	-0.2	1.3	-0.5	1.2	-0.6
	29	3.0	2.7	-0.3	2.5	-0.5	2.7	-0.3
	30	2.6	2.7	0.1	2.5	-0.1	2.7	0.1
	32	1.7	1.6	-0.2	1.2	-0.5	1.4	-0.3
	42	3.8	4.7	0.9	4.0	-0.2	5.0	-1.2
Truk (7.33 n.lat., 151.66 e.long.)	25	5.8	0.2	0.4	6.2	0.4	6.2	0.4
	40	5.2	5.1	-0.1	5.1	-0.1	5.1	-0.1
	41	5.2	5.1	-0.1	5.1	-0.1	5.1	-0.1
	42	9.4	10.0	0.6	10.8	1.4	10.5	1.1
Wake (19.33 n.lat., 160.66 e.long.)	25	4.2	4.5	0.3	4.5	0.3	4.7	0.5
	27	4.3	4.6	0.3	4.6	0.3	5.2	0.9
	29	6.0	3.8	-2.2	4.0	-2.0	4.0	-2.0
	40	3.8	3.8	0.0	4.0	0.2	4.0	0.2
Tofino (49.0 n.lat., 125.9 w.long.)	16	8.5	8.5	0.0	8.5	0.0	8.8	0.3
	17	7.9	7.4	-0.5	7.4	-0.5	7.7	-0.2
	25	7.7	7.5	-0.2	7.4	-0.3	7.7	0.0
	29	9.1	8.5	-0.6	8.6	-0.5	8.9	-0.4
	50	9.0	8.7	-0.3	8.7	-0.3	8.7	0.3
Talara (4.75 s.lat., 81.27 w.long.)	42	14.3	14.7	0.0	-	-	14.7	0.4
	101	15.0	15.2	0.2	15.3	0.3	16.0	1.0
Caldera (27.05 s.lat., 70.85 w.long.)	25	20.4	19.8	-0.6	20.2	0.2	-	-
La Libertad (2.20 s.lat., 80.93 w.long.)	25	17.8	17.8	0.0	17.4	-0.4	-	-
	101	16.1	16.2	0.1	-	-	15.5	-0.6
Petropavlovsk (53.0 n.lat., 158.6 e.long.)	35	20.5	21.0	0.5	21.2	0.7	-	-
	40	1.8	1.8	0.0	2.0	0.2	-	-
	42	5.7	5.8	0.1	5.7	0.0	-	-

Juzhno-Kurilsk (44.01 n.lat., 145.9 e.long.)	28	2.2	2.1	-0.1	1.6	-0.4	-	-
	29	1.3	1.2	-0.1	0.7	-0.6	-	-
	30	1.5	1.2	-0.3	0.7	-0.8	-	-
	31	1.6	1.2	-0.4	0.7	-0.8	-	-
	33	21.3	21.1	-0.2	20.7	-0.6	-	-
	34	24.9	22.0	-2.3	22.3	-2.6	-	-
	35	22.0	22.0	0.0	22.2	0.2	-	-
	38	1.0	1.0	0.0	1.1	0.1	-	-
	40	1.6	1.2	-0.4	1.1	-0.5	-	-
	42	6.4	7.0	0.6	7.0	0.6	-	-
	44	4.2	3.8	-0.4	3.7	-0.5	-	-
	46	22.3	20.0	2.3	19.7	-2.6	-	-
	49	1.6	1.4	-0.2	0.9	-0.7	-	-
	59	1.1	1.0	-0.1	0.4	-0.7	-	-
60	1.1	1.0	-0.1	0.4	-0.7	-	-	
62	1.2	1.0	-0.2	0.7	-0.5	-	-	
C. Krilion (45.9 n.lat., 142.0 e. long.)	40	2.3	2.6	0.3	1.4	-0.3	-	-
	50	2.3	2.2	-0.1	1.5	-0.8	-	-
Average $\bar{\epsilon} = \frac{1}{N} \sum \frac{t_i^p - t_i^c}{t_i^c}$		-0.036	-0.118	-0.015				
Average quadratic deviation $\sigma = \sqrt{\frac{\sum (t_i^p - t_i^c)^2}{N-1}}$		0.109	0.209	0.139				

Table 5.5

Comparison of results of solving direct and backward problems.

Place	1	2	3	4	5	6	7	8	9	10	11
1.Honolulu	x	4.9	5.3	15.2	8.7	5.3	6.5	6.2	6.8	10.7	5.0
2.Aleut 1967	0.0	x	9.5	19.4	1.6	0.4	9.0	9.6	0.2	14.5	6.6
3.Samoa 1981	0.0	0.1	x	12.5	11.0	9.7	1.9	2.4	2.8	11.8	9.6
4.Chile 1960	0.0	0.0	0.1	x	9.6	19.7	13.6	14.2	13.6	6.6	14.6
5.Mexico 1967	0.1	0.0	-0.1	-0.1	x	11.8	12.5	13.2	13.3	3.5	5.7
6.Attu	0.1	0.0	0.0	0.0	-0.2	x	9.0	9.8	10.2	14.5	6.7
7.Rotuma	0.0	0.1	-0.1	-0.2	0.0	-0.1	x	0.8	1.2	13.5	10.2
8.Udu Point	0.0	0.0	-0.1	0.0	0.0	-0.1	0.0	x	0.8	13.2	11.0
9.Lakemba	0.0	0.0	0.2	0.1	0.0	-0.1	0.0	0.0	x	14.0	11.5
10.Baitra	-0.3	-0.2	0.0	0.1	0.1	-0.5	0.0	0.0	0.0	x	8.6
11.San Francisco	0.0	0.0	0.0	0.1	0.1	-0.1	0.0	0.0	0.0	0.0	x

TABLE 6.1
THE LIST OF CALCULATED POINTS

Country	Point	Coordinates
Colombia	Tumaco	1.83 n.lat. 78.73 w.long.
	Bahia de Soland	6.23 n.lat. 77.40 w.long.
	Buenaventura	3.90 n.lat. 77.08 w.long.
Chile	Caldera	27.12 s.lat. 70.83 w.long.
	Coquimbo	29.93 s.lat. 71.35 w.long.
	Iquique	20.15 s.lat. 70.08 w.long.
Ecuador	Puerto Bolivar	3.26 s.lat. 80.00 w.long.
	Isia Baltra	0.45 s.lat. 90.29 w.long.
	Bahia de Caragues	0.59 s.lat. 80.43 w.long.
	Manta	0.95 s.lat. 80.70 w.long.
	Posorja	2.69 s.lat. 80.34 w.long.
	Puna	2.73 s.lat. 79.91 w.long.
	Esmeraldas	0.99 s.lat. 79.94 w.long.
	Puerto Lopes	1.56 s.lat. 80.82 w.long.
Fiji	La Libertad	2.21 s.lat. 90.70 w.long.
	Lakomba	18.20 s.lat. 178.80 w.long.
	Udu Point	16.10 s.lat. 180.00 e.long.
	Rotuma	12.50 s.lat. 177.10 e.long.
Guatemala	Puerto Quetzal	13.92 n.lat. 90.79 w.long.
Hong Kong	North Point	22.30 n.lat. 114.20 e.long.
Peru	Matarani	17.00 s.lat. 72.12 w.long.
	Talara	4.42 s.lat. 81.28 w.long.
Singapore	Singapore	1.33 n.lat. 103.83 e.long.
Honolulu	Honolulu	21.20 n.lat. 157.90 w.long.

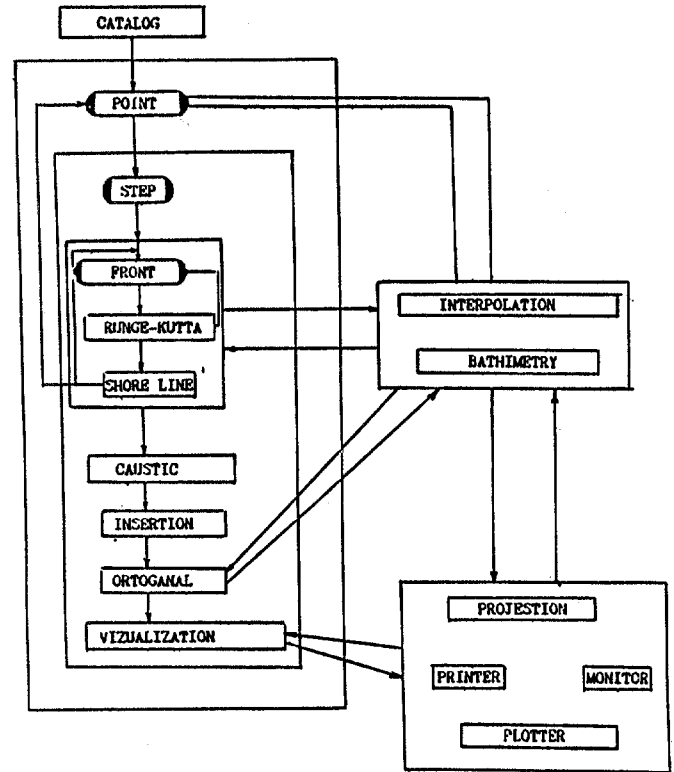


Fig. 3.1 Structure of the algorithm A of calculation of tsunami travel times in solving the seismic equation in spherical system of coordinates.

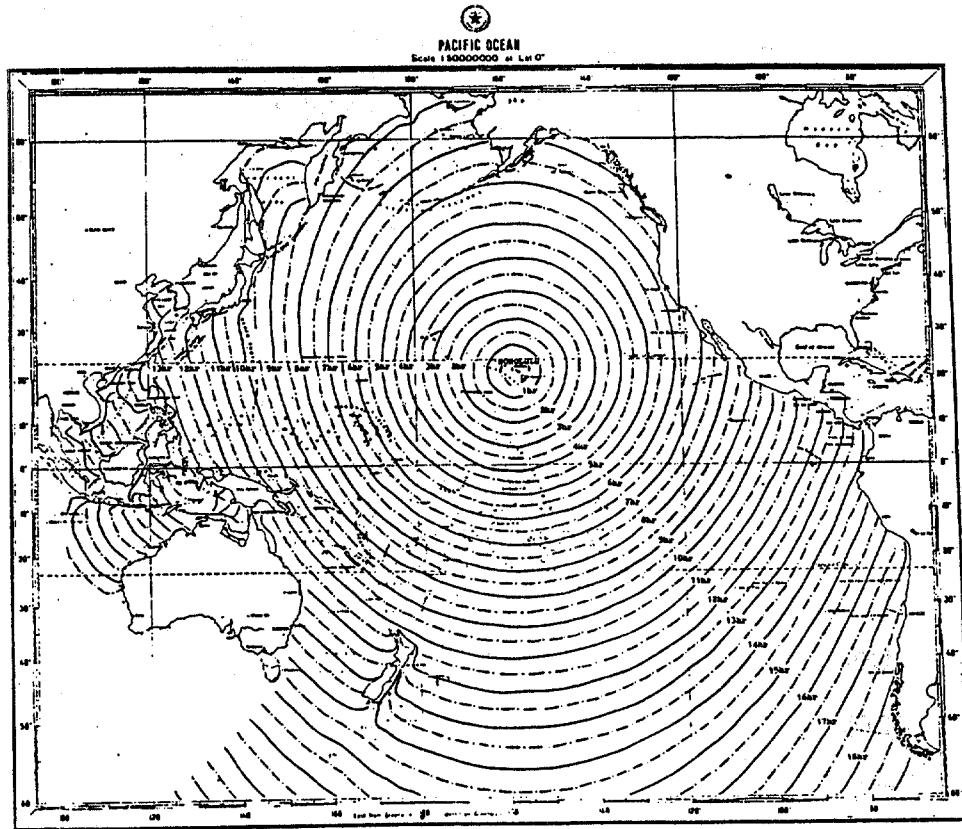


Fig. 4.1. Tsunami propagation time chart in the ocean with constant depth from a point source located in the vicinity of the Hawaii Islands.

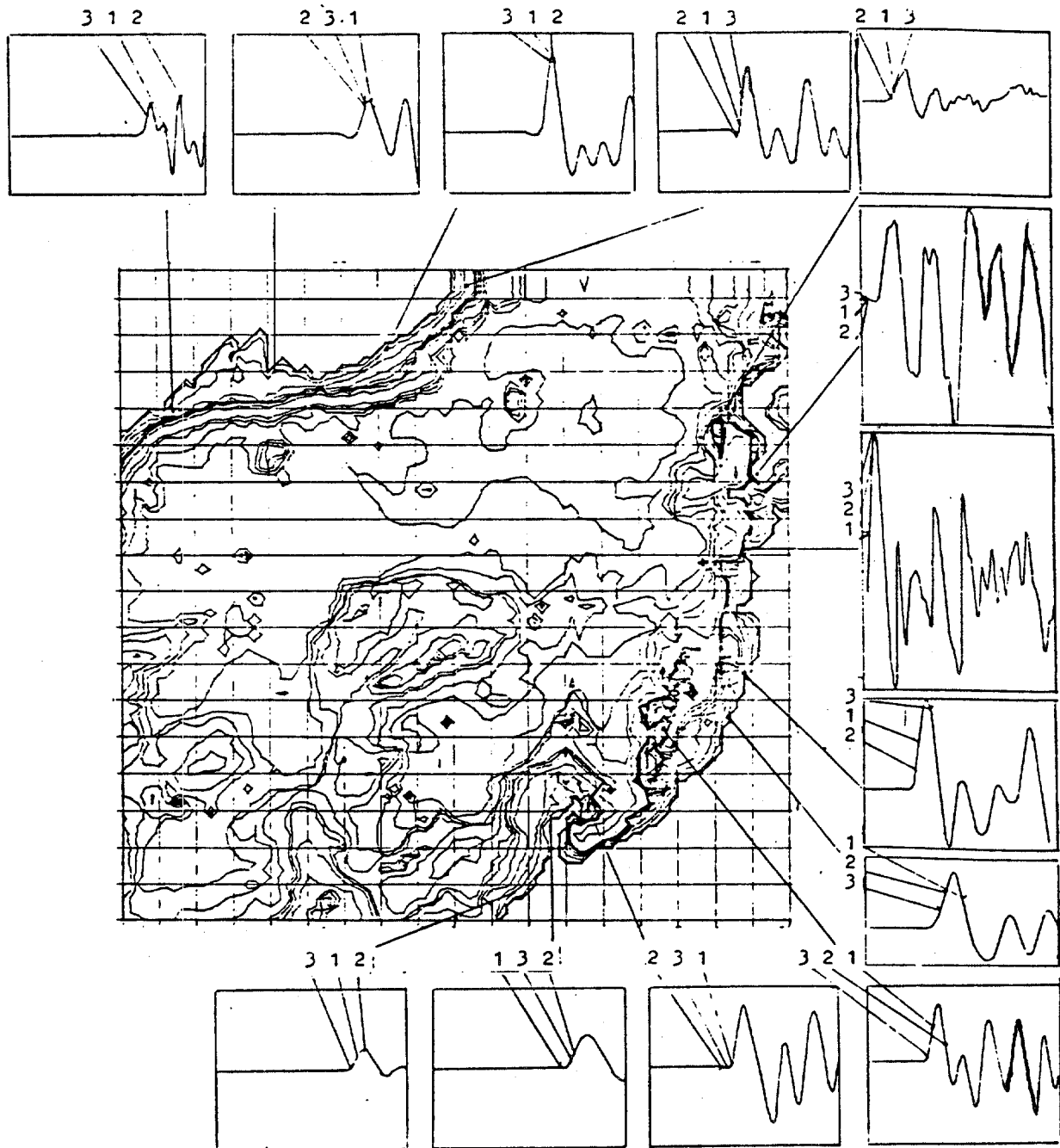


Fig. 4.2. Comparison of temporal characteristics of tsunami propagation in Japan sea., obtained by different techniques. 1 is algorithm A1, 2 is algorithm A2, 3 is algorithm B. Mareograms are calculated by shallow water equations.

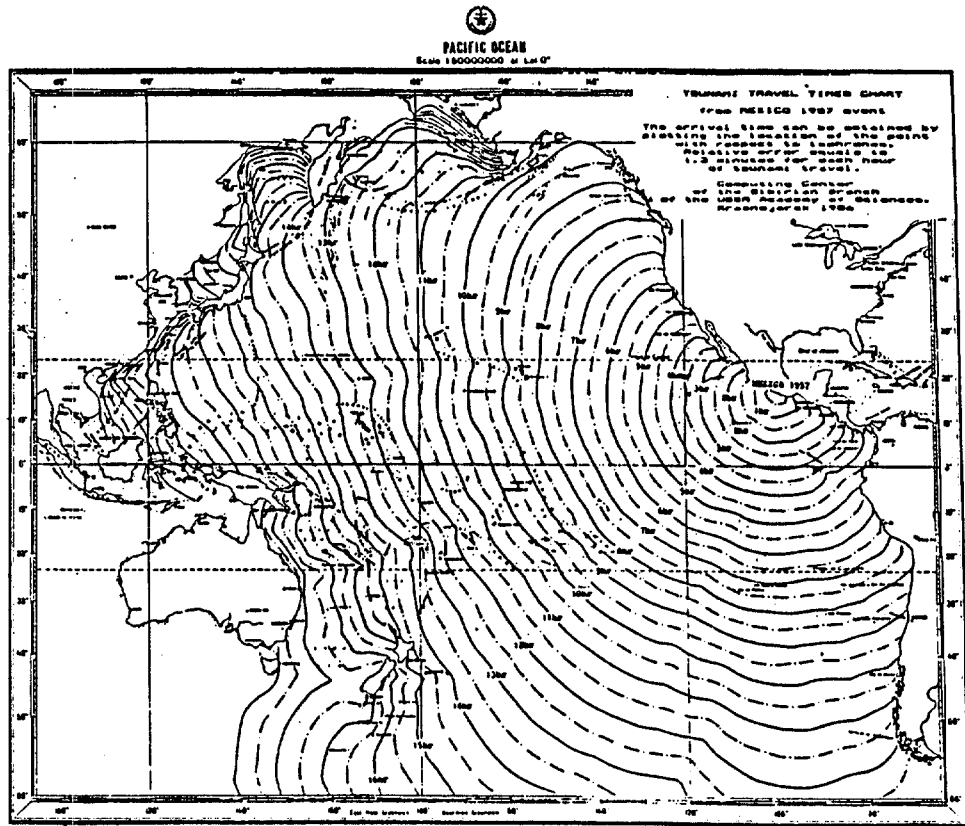


Fig. 5.2. Tsunami travel time chart from a point source located in the hypo- centre of a tsunamigenous earthquake of 28.07.1957 (Mexico).

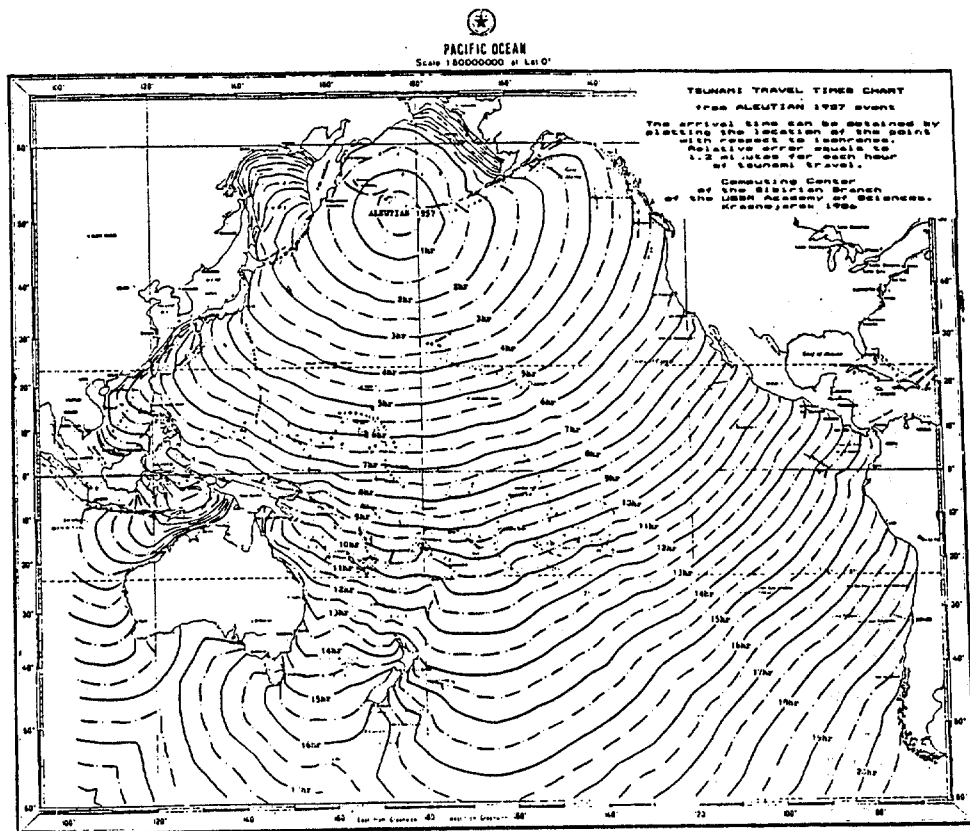


Fig. 5.1. Tsunami travel time chart from a point source located in the hypo- centre of a tsunamigenous earthquake of 09.03.1957 (Aleutian Islands).

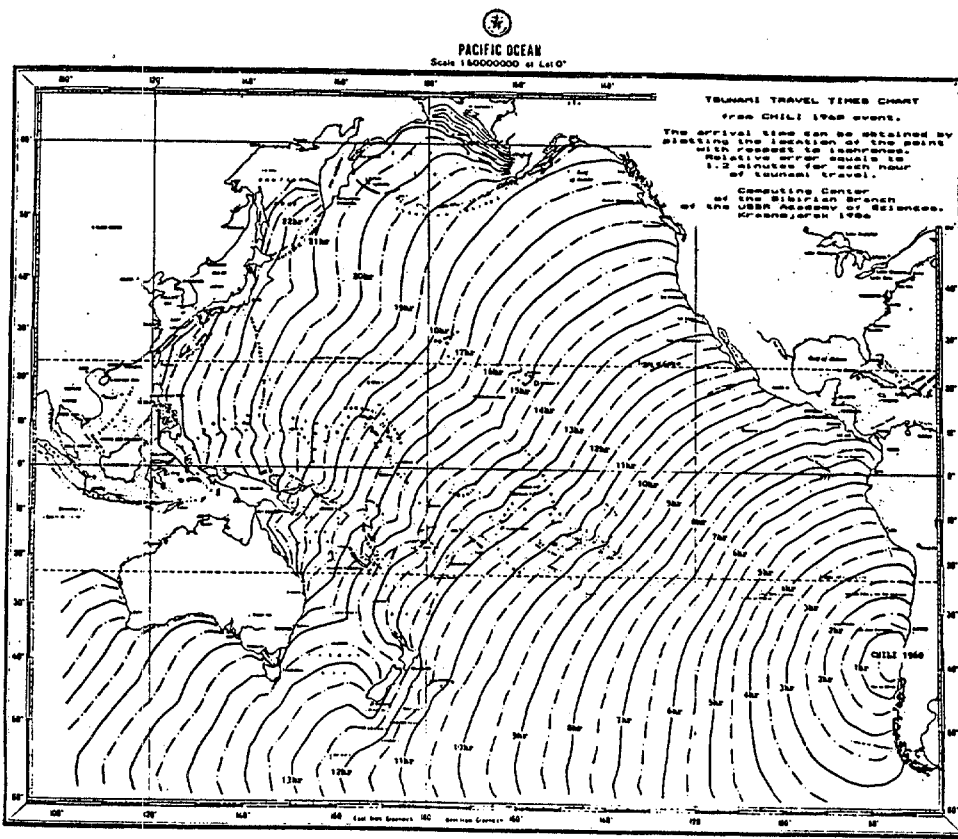


Fig. 5.3. Tsunami travel time chart from a point source located in the hypocentre of a tsunamigenous earthquake of 22.05.1960 (Chile)

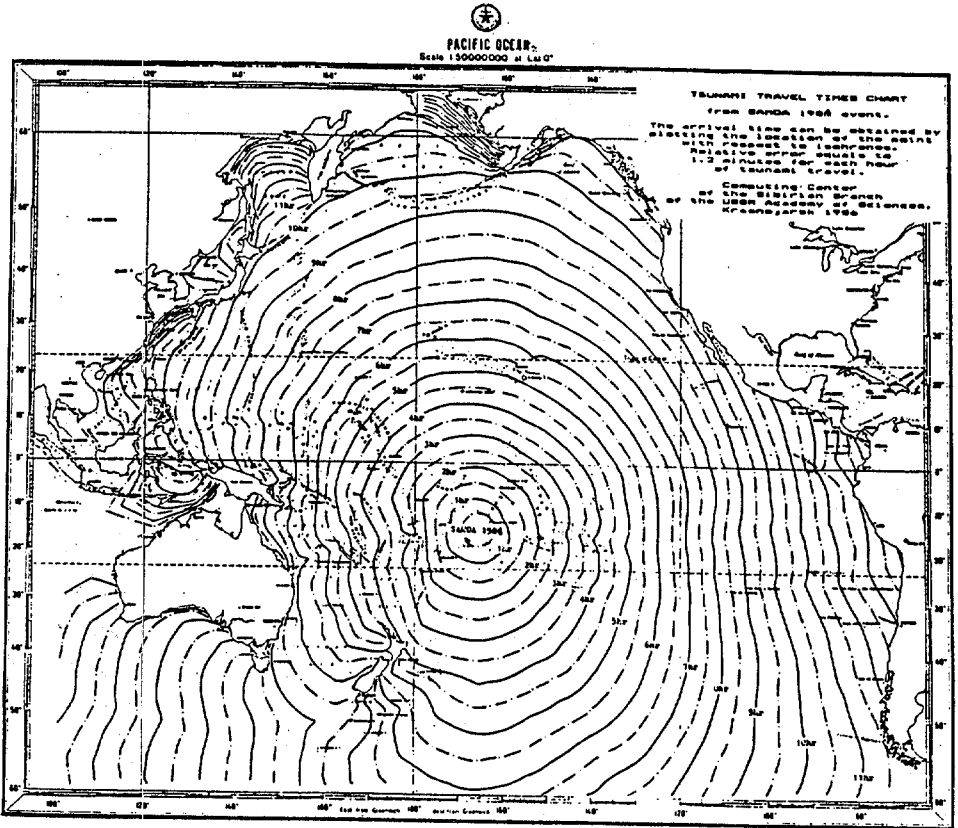


Fig. 5.4. Tsunami travel time chart from a point source located in the hypocentre of a tsunamigenous earthquake of 01.09.1981 (Samoa)

PACIFIC OCEAN
Scale 1:6000000 at Lat 0°

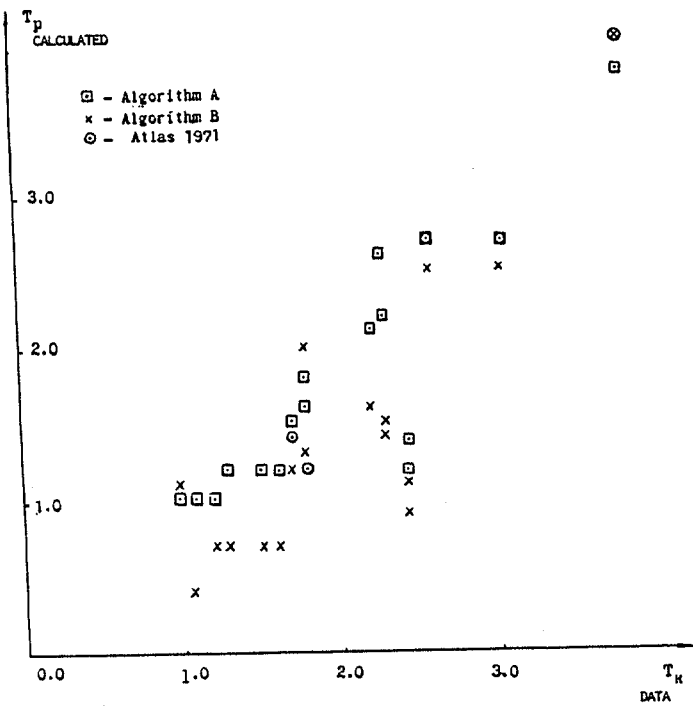
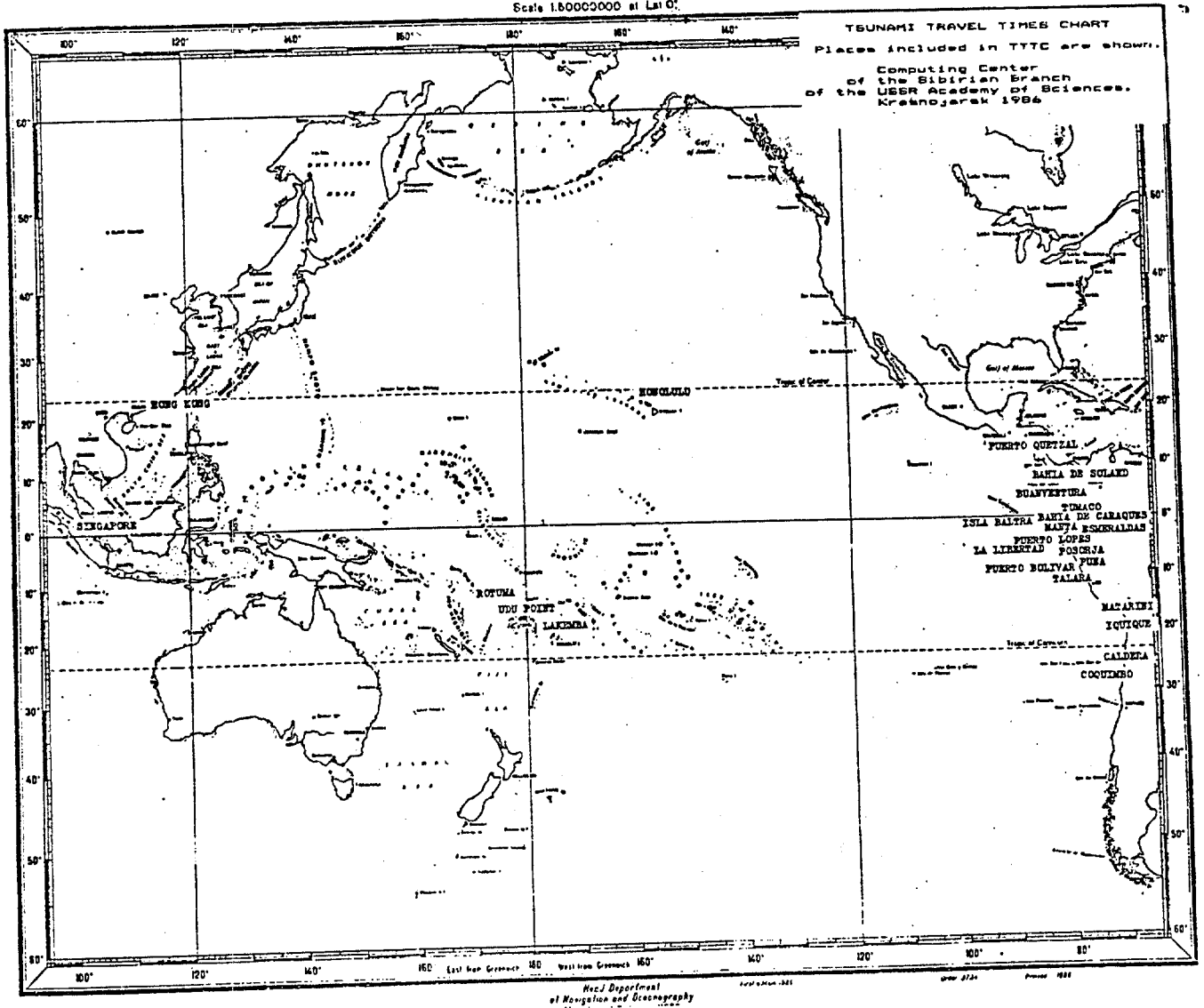


Fig. 5.5. Comparison of calculated by different algorithms and natural travel times for close tsunamis.

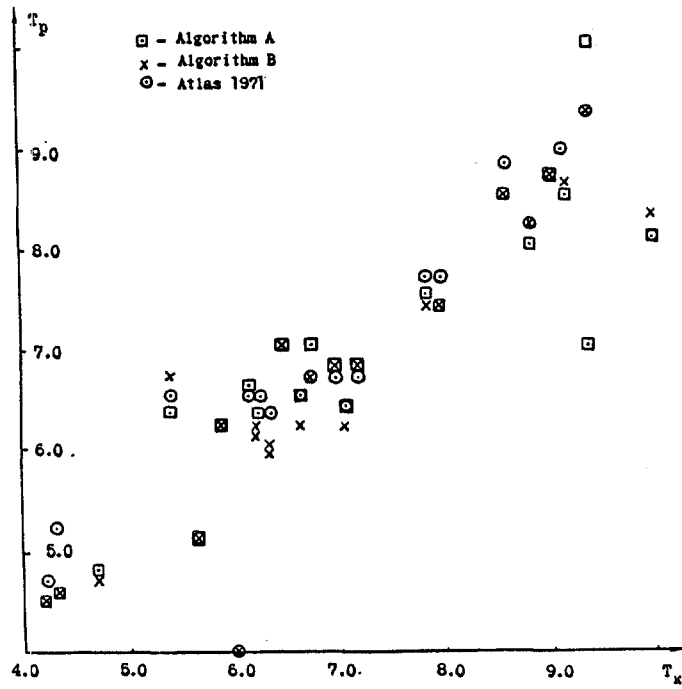


Fig. 5.6. Comparison of calculated by different algorithms and natural travel times for tsunamis of a middle remoteness.

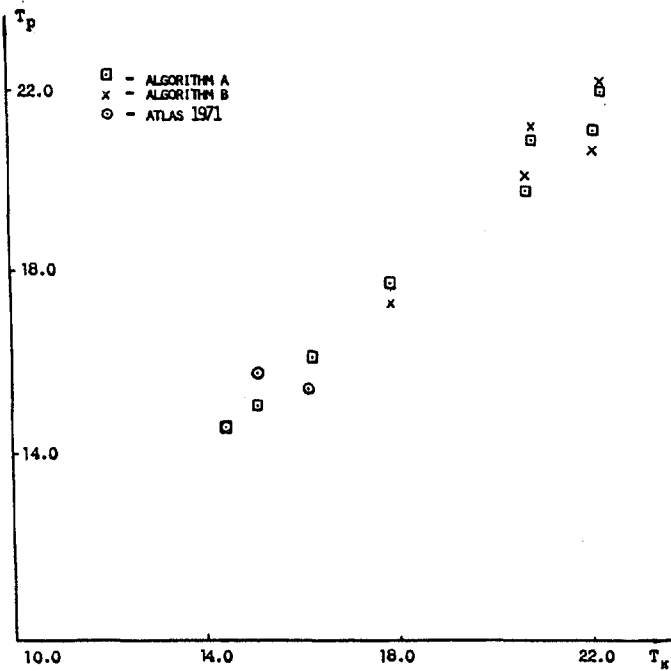


Fig. 5.7. Comparison of calculated by different algorithms and natural travel times for remote tsunamis.

Supplement 1

Contents

Bahia de Careques

Bahia de Soland

Buanventura

Caldera

Coquimbo

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La Libertad

Matarini

Posoria

Puerto Bolivar

Puerto Lopes

Puerto Quetzal

Puna

Rotuma

Singapore

Talara

Tumaco

Udu Point

Supplement 1 will be published separately.



INTERNATIONAL CONFERENCE
NATURAL AND MAN-MADE HAZARDS IN COASTAL ZONES
SAN DIEGO, CALIFORNIA, U.S.A. ENSENADA, BAJA CALIFORNIA, MEXICO
AUGUST 14-21, 1988
SECOND ANNOUNCEMENT / CALL FOR PAPERS

I N T E R N A T I O N A L C O N F E R E N C E

NATURAL AND MAN-MADE HAZARDS IN COASTAL ZONES

San Diego, California, U.S.A.

Ensenada, Baja California, Mexico

August 14 - 21 , 1988

SECOND ANNOUNCEMENT / CALL FOR PAPERS

OBJECTIVES.-

This conference will focus on those hazards which affect coastlines, like storm surges, near-shore earthquakes, tsunamis, and water pollution, among others. The energy source may be local, as in slumping, or distant, as in tele-tsunamis. The conference is directed to the chemical, physical and biological aspects of the hazards.

SPONSORSHIP.-

Organizations that have officially agreed to sponsor:

- +The Tsunami Society, Hawaii, U.S.A.**
- +Ensenada Scientific Research and Higher Education Center (CICESE), Ensenada, Mexico.**
- +Naval Hydrographic Office, Secretary of the Navy, Ensenada, Mexico.**
- +Scripps Institution of Oceanography (SIO), University of California, San Diego, U.S.A.**
- +International Tsunami Information Center (ITIC), Hawaii, U.S.A.**
- +Autonomous University of Baja California (UABC), Baja California, Mexico.**
- +State of Baja California Government (Civil Protection System), Mexico.**
- +Mexican Geophysical Union (UGM).**

CALL FOR PAPERS.-

All members of the world-wide scientific community (oceanographers, meteorologists, earth scientists, engineers, environmentalists, and students) involved in coastal hazards, as well as leaders of organizations (administrators, managers, operation and policy makers) related to hazard prevention and mitigation, are cordially invited to present papers on scientific and legal aspects of natural and man-made coastal hazards. This International Conference will provide a unique and important opportunity to gather and discuss those aspects that may be similar among some of the various hazards, to review the latest developments, and outline new directions for future research. Don't miss it.

Natural science participants are advised to present research advances that would increase the store of knowledge, leading to the answers desired by the society with regard to coastal hazard prediction, prevention and mitigation. Social scientists and community leaders are expected to define those specific questions for the scientific community to answer, and explain their organizational preparedness to reduce the impact of the hazards. Presentations on emergency-response plans, and implementation of educational programs on hazard mitigation for developing countries, are welcomed.

ABSTRACTS.-

Original and two copies of camera ready abstracts (not to extend beyond two pages) should be sent before April 30, 1988 to:

International Organizing Committee
Tsunami Society / Hazards Conference
Suite 6
2919 Kapiolani Blvd.
Honolulu, Hawaii 96826 ,U.S.A.

Camera ready abstracts should be typed on 21.6 x 27.9 cm. paper with 2.5 cm. margins. Spacing between the lines should be single. Elite 12 type is preferred. The heading block should include the following items on successive lines:

- (I) the title in capital letters
- (II) the name(s) of the author(s) in 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 written left justified. A volume of the abstracts will be pre-published and will be made available to the participants prior to the meeting.

LANGUAGE.-

The language of the Conference will be English. Correspondence may be in English or Spanish.

All participants, accompanying persons and students must register, and badges must be worn at all times while attending scientific sessions or social activities. Discount preregistration is available until May 31, 1988. Reduced rates are also available for members of financial co-sponsoring organizations.

Fees in U.S. currency	Financial co-sponsoring members		Everybody else	
	Preregistration	Registration	Preregistration	Registration
Participant	120.00	155.00	150.00	195.00
Accompanying person	55.00	75.00	70.00	95.00
Student	45.00	60.00	55.00	75.00

No single day rates. No fractional special rates for late arrivals.

Fees for regular participants include: Program, Abstracts, Proceedings, Ice-breaker reception, banquet with folkloric ballet, attendance to all scientific meetings, intersession coffee and donut snacks.

Fees for accompanying persons include: special social activities, program, Ice-breaker reception and banquet with folkloric ballet.

Fees for students include: Program, abstracts, Ice-breaker reception, attendance to all scientific meetings, intersession coffee and donuts snacks.

Registration may be done by mail or on site. Please fill the Registration Form, make your check or money order in U.S. dollars payable to Tsunami Society / Hazards Conference and mail it with the Registration Form to:

International Organizing Committee
Tsunami Society / Hazards Conference
2919 Kapiolani Blvd. Suite 6.
Honolulu, Hawaii 96826 U.S.A.

Please notice that credit cards can not be used to pay registration fees.

Cancellation Policy:

Before June 1, 1988: \$10.00 handling charge

After June 1, 1988 and before August 10, 1988: \$50.00 handling charge.

After August 10, 1988: \$90.00 (or the whole amount if less than \$90.00) handling charge. Regardless of the above, there will be no refunds after the Conference starts.

PROGRAM OUTLINE.-

Monday 15	10:00	Inaugural Plenary, Reception, Registration, Welcome gathering at Sumner Auditorium, Scripps Institution of Oceanography, University of California-San Diego, La Jolla.
	10:30	Keynote overview presentations by special speakers: Dr. W.G. Van Dorn, Dr. B. Zetler, Dr. W. Munk.
	12:00	Snack-lunch and refreshments at Scripps gardens.
	12:30	Visit to Scripps Aquarium and Research facilities.
	14:00	Participants board buses to Ensenada (buses will stop at Hotels and USCD dormitories to pick up luggage; one bus will stop at the Airport to pick up late arrivals gathered at Travelers Aid Desk).
	16:00	Drop off at Ensenada Hotels.
	17:00 and on	Registration in Ensenada.
	19:00	Ice-Breaker Reception at the Riviera Convention Center and Ceremonial Opening of Exhibits.
Tuesday 16	08:00 and on 09:00	Registration. Official Opening Ceremony at Riviera Convention Center. Welcome by State Government authorities, members of the organizing committees and scientific community.
	10:30 to 12:30 and afternoon	Formal Scientific Sessions, Informal meetings with coffee breaks.
Wednesday 17 to Friday 19	morning and afternoon	Continuation of formal scientific sessions, and Informal meetings with coffee breaks.
Wednesday 17	noon	Two hour guided tour to CICESE and University of Baja California Research Facilities.
Thursday 18	19:00	Banquet with presentation of Mexican Folkloric Ballet in the Cathedral Room at the Riviera Convention Center.
Friday 19	18:00	Closing Ceremony, Official Speakers, Awards.
Saturday 20		Local Hazard Sites Tour. Sport Fishing Tour.
Saturday 20 to Sunday 21		Sierra Mountain Tour.

(Tuesday through Thursday there will be short tours to local tourist attractions, during session hours, for accompanying persons).

ORGANIZATION.-

This conference is being arranged by an International Organizing Committee, an Ensenada Local Organizing Committee and a Scripps Host Committee. The International Organizing Committee is in charge of the technical program, including the lectures and poster sessions, the coordination of sponsorship, and the preregistration and handling of abstracts. The Local Organizing Committee is in charge of local arrangements (transportation, accommodations, exhibits, dining, field trips, on-site registration, and all hosts and activities of the hosts in Ensenada). The Scripps Host Committee is in charge of the inaugural plenary session, and the UCSD campus tour, meal and housing at UCSD dormitories.

TECHNICAL DETAILS.-

Standard equipment in the meeting rooms will be 35 mm. projector and overhead projector. Please request well in advance if additional audio-visual equipment will be required. Special equipment may not be available in Ensenada if ordered during the Conference.

Paper presentations will be in English, and limited to 15 minutes plus five minutes for discussion. Translation to other languages will not be provided.

SCIENTIFIC PROGRAM TOPICS.-

Presentations will be grouped into the following research themes:

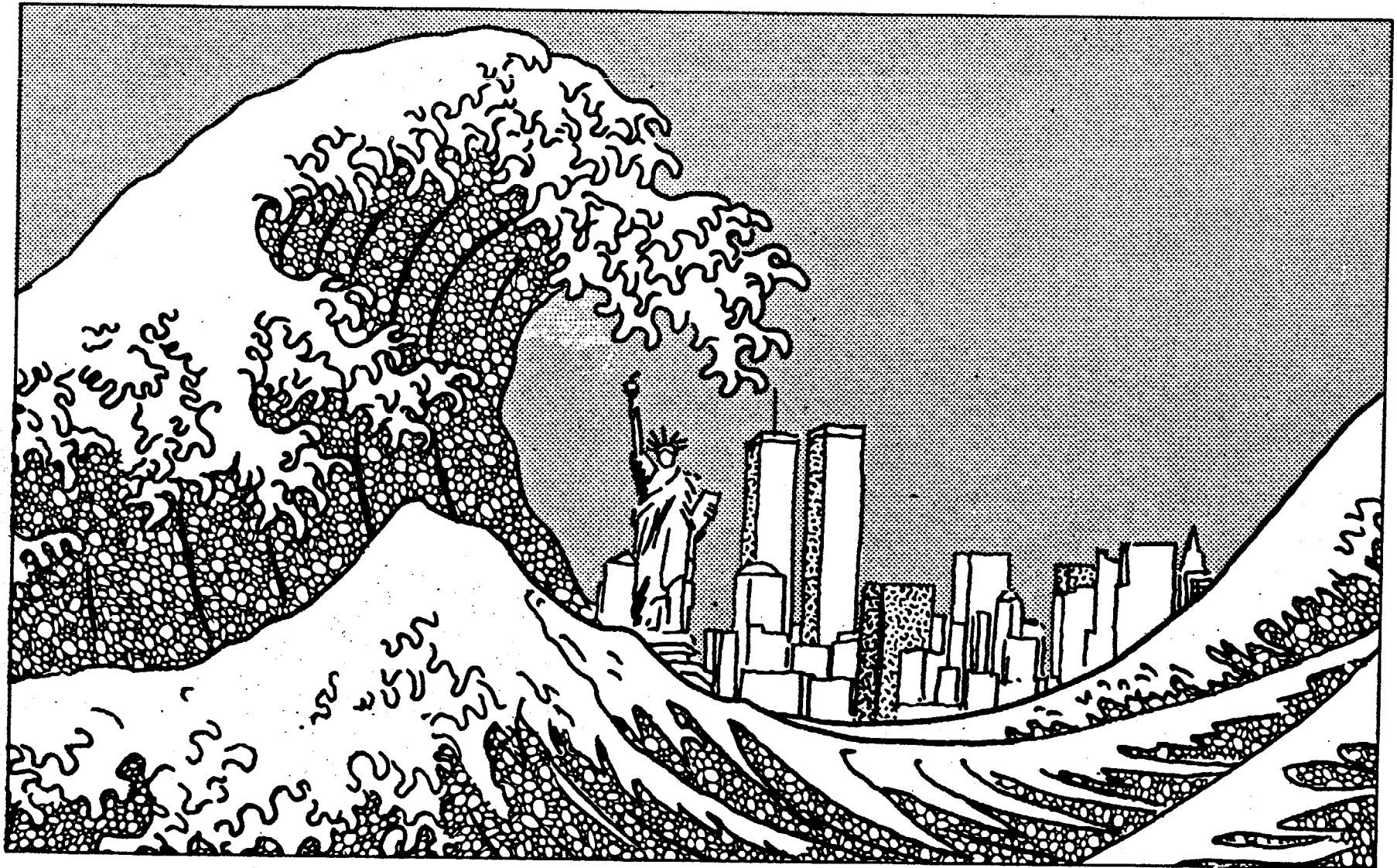
- Near-shore earthquakes and landslides.
- Volcanic eruptions.
- Coastal erosion and engineering aspects.
- Wind storm motion and coastal effects.
- Air and water pollution risk and management.
- Tsunami generation, propagation and coastal impact.
- Ecological hazards to coastal marine environments.
- Legal aspects of coastal hazards prediction and mitigation.
(plans for the International Decade of Natural Hazards Reduction).

AWARDS.-

The following awards will be presented by the Awards Committee during the closing ceremony:

- | | |
|--|-------------------|
| -Best presentation on earthquake research: | G M. Goding Award |
| -Best presentation on Tsunami research: | Nakashizuka Award |
| -Outstanding long-term contribution to research on earthquakes, tsunamis, or tsunami warning system: | Adams Award |

BUSINESS



A N N O U N C E M E N T
CALL FOR PAPERS!

22 and 23 March 1988

Bologna, Italy

Annual Meeting of the European Geophysical Society

SI.7 Tsunamis Generated by Earthquakes and Volcanic Eruptions: Theory and Observations

Conveners: **Prof. W. M. Adams**, University of Hawaii, Hawaii Institute of Geophysics, 2525 Correa Road, Honolulu, Hawaii 96822, USA; tel: (1)-808-9487797, (1)-808-9488760.

Prof. S. L. Soloviev, Institute of Oceanology, USSR Academy of Sciences, 23, Krasikova, 117218 Moscow, USSR; Tel: 124-87-01, Tx: 411968 okean sv.

Prof. S. Tinti, Università di Bologna, Dipartimento di Fisica, Settore di Geofisica, V.le Berti Pichat, 8, I-40127 Bologna, Italy; Tel: (39)-51-243586, (39)-51-243001; Fax: (39)-51-247244; Tx: 520634 infnbo i.

The symposium is intended to encompass the theoretical aspects of the generation and the propagation of the tsunamis including coastal effects; acquisition and treatment of the experimental data and studies on historical and recent tsunamis will also be of fundamental concern.

This meeting is part of the festivities to celebrate the *900th* year of the University of Bologna—the first University in the world! To participate in this celebration is truly a great and memorable honor. Please submit a title for oral or poster sessions.

BOOK REVIEW

TSUNAMI! HAWAII'S OWN DRAMATIC STORIES AND THE FACTS ABOUT THE GIANT WAVES, written by Walt Dudley and Min Lee and published by the University of Hawaii Press, Honolulu, HI, 198 pages. Reviewed by George D. Curtis.

The book jacket-type subtitle does summarize this great book, but seems to mask how well written it is. It skillfully combines first-hand accounts of survivors with scientific information on tsunamis. Dr. Dudley is a Professor of Oceanography at the Hilo campus of the University of Hawaii with a special interest in tsunamis and Min Lee is a Hilo writer and photographer. They have done an outstanding job of covering just about all aspects of tsunamis in a popular, non-scientific, but technically detailed and valid book.

Chapters include: The 1946 Tsunami; What is a Tsunami?; The Warning System: The 1960 Tsunami Disaster; What Went Wrong?; Local Tsunamis; and, The Next Tsunami. The authors alternate graphic, factual stories of tsunami hits with explanations of the social and technical factors involved. Both are thoroughly researched. Some of the accounts have never been published before. The technical side benefits from Dudley's close association with the tsunami research program. The authors are educators, and know how to convey knowledge while holding the readers interest. An excellent selection of photos are included.

Some may feel the accounts are too focussed on Hilo; they are, but that is the prime location to obtain history in the U.S.A. The survivors of the 1946 tragedy are passing on rapidly and will not be available to other writers. The paradox of a working warning system but many deaths in the 1960 event can only be studied in Hilo, but its implications apply elsewhere and to other hazards.

BOOK REVIEW

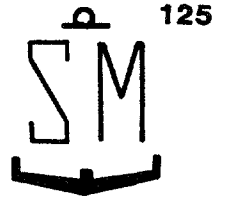
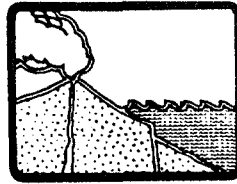
NUMERICAL MODELING OF WATER WAVES, written by Charles L. Mader and published by the University of California Press, Berkeley, CA, 206 pages. Reviewed by T. S. Murty.

This monograph contains four chapters in addition to an introduction, three appendices, and author index, and a subject index. Chapter one is titled Water Wave Theory and gives a good mathematical treatment of the following topics; Equations of Fluid Dynamics, Description of Water Waves, Laitone solitary waves, Airy waves and Stokes Waves.

The shallow water model is discussed in chapter two under three parts. In the first part, the shallow water equations are developed, the finite difference forms are given in part two, and in part three application to the problem of the interaction of tsunami waves with continental shelves and slopes is considered. The title of chapter three is The Two-Dimensional Navier-Stokes Model. This chapter has the following sections: The Two-Dimensional Navier-Stokes equations, the Finite-Difference Equations, Application to Tsunami Wave Propagation, Application to Underwater Barriers, and Application to Waves from Cavities.

The final chapter is about the three-dimensional Navier-Stokes model and is comprised of the following sections: The Finite-difference Equations, Applications to Tsunami Wave Formation, and Future Applications. The references are given at the end of each chapter. Appendix A lists the computer program for the Wave code; Appendix B gives the Swan code and Appendix C lists the Zuni code. Along with the program listings, examples are given.

All in all the monograph packs a lot of valuable information of theoretical and practical interest, with convenient-to-use computer programs. The author should be congratulated for sharing this excellent work with others.



INTERNATIONAL CONFERENCE
NATURAL AND MAN-MADE HAZARDS IN COASTAL ZONES
SAN DIEGO, CALIFORNIA, U.S.A. ENSENADA, BAJA CALIFORNIA, MEXICO
AUGUST 14 - 21, 1988

OBJECTIVES

This conference will focus on those hazards which affect coastlines, like storm surges, near-shore earthquake, tsunamis, and water pollution, among others. The energy source may be local, as in slumping, or distant, as in tele-tsunamis. The conference is directed to the chemical, physical, and biological aspects of the hazards.

SPONSORSHIP

The Tsunami Society is the principal scientific organization sponsoring the Conference, and CICESE Scientific Research and Higher Education Center of Ensenada, B.C. as well as the Secretary of the Navy, both from Mexico, are the hosts and co-organizers of the Conference. Other organizations wishing to be considered for sponsorship should contact the International Organizing Committee.

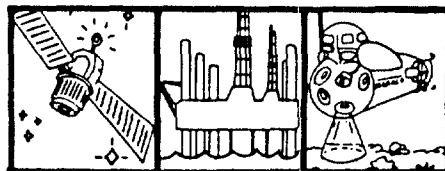
LOCATION

The city of Ensenada, Baja California, Mexico is a small and pleasant fishing town located in the Pacific Ocean shores, 60 miles south of the Mexico-USA border, and accessible by ground transportation from San Diego International Airport (USA) and Tijuana International Airport (Mexico).

CALL FOR PAPERS

The Organizing Committee invites all scientists and engineers who have interest in natural and man-made hazards research to participate in the International Conference on Natural and Man-made Hazards in Coastal Zones which will take place in Ensenada, Baja California, Mexico, 14-21 August, 1988, with an initial plenary session in San Diego, California, USA. The proceedings of this Conference are scheduled for publication as a volume of The Journal of Natural Hazards.

INTERNATIONAL ORGANIZING COMMITTEE
TSUNAMI SOCIETY/HAZARDS CONFERENCE
Suite 6
2919 Kapiolani Blvd.
Honolulu, Hawaii, 96826
USA



PACIFIC CONGRESS ON MARINE SCIENCE & TECHNOLOGY

PACON 88

HONOLULU, HAWAII - MAY 16-20, 1988

OBJECTIVE

The role of marine technology in the economic development of the Pacific Basin resources is of vital concern to planners, policymakers, administrators as well as educators and scholars. The Pacific Congress brings together scholars and resource persons who will address key issues concerning the marine technology related to the ocean economic potential of the region from a multi-disciplinary perspective. The Congress is conducted biannually and facilitates an exchange of views and ideas between representatives of the Pacific Island nations and of the larger rim countries and thereby strengthens future information exchange and collaborative research linkages.

BACKGROUND

The first Pacific Congress on Marine Technology (PACON 84) held at the Princess Kaiulani Hotel, Honolulu, HI, April 24-27, 1984 was attended by 211 participants, including representatives from nine Pacific Rim nations; PACON 86 also was held at the Princess Kaiulani Hotel, March 24-28, 1986 and was attended by 227 participants from eleven nations. Twenty exhibitors displayed their products, programs and services at each of the conventions. Ninety-two papers were presented under nineteen technical sessions at PACON 84 and one hundred forty five papers were presented at PACON 86 in thirty one sessions.

Plans for PACON 88 are already underway for May 16-20, 1988. We hope you will put PACON 88 on your calendar and plan to attend. Additional information will be provided as planning progresses. Please return the attached Pre-Registration Form for any specific information you may require.

PROGRAM FORMAT

The papers and discussions by a multi-disciplinary team of academicians, resource planners, policy analysts, entrepreneurs and administrators, among others, will address economic, legal, defense and socio-cultural dimensions of Pacific Basin ocean resource development and management. Special attention will be paid to the impact of marine technology on the quality of life of the Pacific Islanders. The presentations will combine theoretical insights and empirical research on problems of current and continuing interest to a broad audience.

Sessions on the following topics are planned:

Technology of Fish Finding
and Tracking
Ocean Energy
Marine Mining
Maritime Economics and Policy
Marine Transportation and Ports
Marine Recreation,
Marine Park Technology
Mariculture Technology:
Management Interface
Marine Biotechnology

Undersea Vehicles and
Ocean Robotics
Remote Sensing and
Oceanographic Satellites
Marine Applications of
Global Positioning
Ocean Acoustic Systems
Ocean Engineering Applications
in the Pacific
Tsunami
Pacific Ocean Sea Level
Variability
EEZ Mapping
Software Technology

Workshops

Hawaiian Ocean Experiment
Marine Technology Education
Marine Recreation: Boats and Other
Moving Platforms
Ocean Data Program for Operational Forecasts

REGISTRATION

Registration fee for the Congress is \$215 (US) prior to March 30, 1988, and \$240 thereafter; for members of sponsoring societies, registration is \$180 prior to March 30, 1988 and \$205 thereafter. Price includes luncheons, reception, banquet and a copy of the Proceedings. Spouses's registration is \$95, which includes luncheons, reception and banquet. Student registration is \$15 per day or \$45 for full Congress, including luncheons. Registrations fees cannot be returned. Additional copies of the Proceedings will be available at \$40 (US) each.

ACCOMMODATIONS

A block of rooms have been reserved for the Congress participants at the Ala Moana Hotel. Reservations should be sent directly to the hotel. Special rates are available to PACON guests.

SCIENCE OF TSUNAMI HAZARDS

Publication Format for Camera Ready Copy

1. Typing area shown by border.
2. One column text.
3. All text must be typed single spaced. Indent 5 spaces to start a new paragraph.
4. Page numbers in lower right hand corner in pencil or blue marker.
5. Top half of first page to contain the Title in capitals followed by the authors and author addresses, centered on page.
6. Bottom half of first page to contain the abstract with the heading ABSTRACT centered on page.

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.

