FORECAST OF TSUNAMIS FROM THE JAPAN-KURIL-KAMCHATKA
SOURCE REGION

A THESIS SUBMITTED TO THE GRADUATE DIVISION
OF THE UNIVERSITY OF HAWAII IN PARTIAL FULLFILLMENT
OF THE REQUIREMENT FOR THE DEGREE OF

MASTER OF SCIENCE

IN

OCEAN AND RESOURCES ENGINEERING

August 2004

BY

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ACKNOWLEDGEMENTS

I would like to express my appreciation to all who contributed to this thesis and in particular to Dr. Kwok Fai Cheung, whose thorough engineering knowledge and valuable academic advice have contributed to the realization of this project. Many thanks also go to the committee members, Dr. Hans-Jürgen Krock and Dr. Geno Pawlak, for their advice and comments on this thesis. I would also like to thank Mr. George D. Curtis for sharing his tsunami modeling experience with me, Dr. George Pararas-Carayannis for giving his comments about tsunami arrival times, Dr. Kenji Satake for providing helpful information on the technical literature, Dr. Yoshimitsu Okada for his insights on the Okada formula, Dr. Hal Mofjeld for providing recorded tsunami waveforms at the warning points for the 1994 Kuril event, and Dr. Tatsuo Kuwayama for supplying the 20'' bathymetry data around the Japan coastlines. Thanks are also due to Mr. Yong Wei for his valuable input and support on the project. Many thanks go to Ms. Edith Katada for her time and expertise in departmental procedures.

Financial support in the form of a graduate research assistantship was provided by the National Tsunami Hazard Mitigation Program via Hawaii State Civil Defense Division.

ABSTRACT

This study investigates and defines the subfault distribution along the Japan-Kuril-Kamchatka subduction zone for the implementation of a far-field tsunami forecast algorithm. Analyses of earthquakes with surface wave magnitude greater than 6.5 from years 1900 to 2000 define the subduction zone, which in turn is divided into 222 subfaults based on the distribution of the fault parameters. For unit slip of the subfaults, a linear long-wave model generates a database of mareograms at water-level stations in and around the subduction zone and at selected warning points away from the source. When a tsunami occurs, an inverse algorithm determines the slip distribution from near-source tsunami records and predicts the tsunami waveforms at the warning points using the pre-computed mareograms. The jackknife resampling scheme uses various combinations of input tsunami records to provides a series of predictions for the computation of the confidence interval bounds. The inverse algorithm is applied to hindcast three major tsunamis generated from the Japan-Kuril-Kamchatka source and the computed tsunami heights show good agreement with recorded water-level data.

TABLE OF CONTENTS

ACKNOELEDGEMENTS	iii
ABSTRACT.....	iv
LIST OF FIGURES	vii
LIST OF TABLES	viii
1. INTRODUCTION.....	1
1.1 Tsunami Warning.....	1
1.2 Tsunami Forecast.....	2
1.3 Goal and Objective.....	2
2. SUBFAULT DISTRIBUTION	4
2.1 Fault Parameters.....	4
2.2 Fault Analysis.....	5
3. SYNTHETIC MAREOGRAMS.....	7
3.1 Water-level Stations and Warning Points	7
3.2 Long-Wave Model	8
3.3 Model Setup	9
3.4 Mareograms	10
4. FORECAST METHODOLOGY	12
4.1 Inverse Algorithm	12
4.2 Jackknife technique.....	13
4.3 Implementation	14
5. RESULTS AND DISCUSSION	16
5.1 The 1944 Tonankai Earthquake	16
5.2 The 1946 Nankai Earthquake.....	19
5.3 The 1994 Kuril Earthquake.....	21
6. CONCLUSIONS AND RECOMMENDATIONS.....	23

REFERENCES.....	50
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LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1. Definition of fault parameters	25
2. Historical tsunamigenic earthquakes with surface wave magnitude greater than M_s 6.5 along the Japan-Kuril-Kamchatka source region from 1900 – 2000	26
3. Historical tsunamigenic earthquakes used in the re-construction of the subduction zone	27
4. Determination of fault area for 1978 Kuril earthquake.....	28
5. Fault areas and assumed subduction zone.....	29
6. Subfault distribution.....	30
7. Subfault number.....	31
8. Water-level stations along Japan coastlines.....	32
9. Water-level stations and warning points in the Pacific and the computaional domain.....	33
10. Sample mareograms at the observation points for subfault 112	34
11. Sample mareograms at the warning points for subfault 112.....	35
12. Computed slip distributions of the 1944 Tonankai earthquake	36
13. Waveforms at water-level stations after the 1944 Tonankai earthquake	37
14. Waveforms at warning points after the 1944 Tonankai earthquake.....	38
15. Computed slip distributions of the 1946 Nankai earthquake.....	39
16. Waveforms at water-level stations after the 1946 Nankai earthquake.....	40
17. Waveforms at warning points after the 1946 Nankai earthquake	41
18. Computed slip distributions of the 1994 Kuril earthquake	42
19. Waveforms at water-level stations after the 1994 Kuril earthquake.....	43
20-1. Waveforms at warning points after the 1994 Kuril earthquake	44
20-2. Waveforms at warning points after the 1994 Kuril earthquake.....	45

LIST OF TABLES

<u>Table</u>	<u>Page</u>
1. Published Fault Parameters of Historical Tsunamigenic Earthquakes	46
2. Computed Slip Distribution of the 1944 Tonankai Earthquake	47
3. Computed Slip Distribution of the 1946 Nankai Earthquake	48
4. Computed Slip Distribution of the 1994 Kuril Earthquake	49

1. INTRODUCTION

1.1. Tsunami Warning

The Hawaiian Islands, located at the center of the Pacific Ocean, are subject to tsunamis generated from around the Pacific Rim. Destructive tsunamis reaching Hawaii have primarily been generated in three main source regions: Alaska-Aleutian, Japan-Kuril-Kamchatka, and Peru-Chile. The Alaska-Aleutian source region is the nearest and a tsunami generated there takes about 5 hours to reach Hawaii. Local civil defense agencies need three hours to evacuate the low-lying coastal areas leaving a little time to determine whether the tsunami is destructive or not.

The Richard H. Hagemeyer Pacific Tsunami Warning Center (PTWC) in Hawaii monitors coastal tide gauges and deep-water pressure sensors throughout the Pacific for tsunami occurrences. When a tsunamigenic earthquake occurs, the PTWC staff compares the water-level data near the source with historical tsunami records and determines the severity of the event. Also available for comparison are pre-computed tsunami heights at 99 tide gauges for 204 hypothetical tsunamigenic earthquakes in the three source regions (Whitmore and Sokolowski, 1996; and Whitmore, 2003). Comparison of water-level measurements with pre-computed tsunami heights near the source would identify the closest tsunami in the database and provides the tsunami height predictions at the remaining tide gauges.

Most tide gauges are located in harbors or restricted waterways. The recorded data at these tide gauges are prone to local oscillations and show damping and phase shift, which affect comparisons (Van Dorn 1984). The National Oceanic and Atmospheric Administration (NOAA), Pacific Marine Environment Laboratory (PMEL), experimented with bottom-pressure recorders for tsunami detection (Eble and González 1991; González et al. 1991) and then deployed six bottom-pressure recorders off the Alaska-Aleutian and West coast of North America for operation (González et al. 1998). These recorders,

which have real-time data transmission capability, are commonly known as the deep-ocean assessment and reporting of tsunamis (DART) gauges. The DART gauges are located relatively far away from the coastline so that oscillations near the coastline would have minimal effects on the recorded waveforms.

1.2 Tsunami Forecast

The DART gauges provide clear signals of an approaching tsunami, but like the tide gauges, still cannot provide quantitative predictions of the tsunami away from the source. Satake (1987, 1989), however, has successfully used tsunami waveforms recorded by tide gauges to determine the seismic source parameter through an inverse algorithm. His approach requires a database of mareograms at the tide gauge locations for unit slip of pre-determined subfaults in the source region. Titov et al. (1999) discussed the use of the inverse approach to define the initial conditions for real-time simulation of trans-Pacific tsunamis. Wei et al. (2001, 2003) extended Satake's approach by using the predicted source parameters to determine the tsunami waveforms away from the source for warning and emergency management.

Wei et al. (2001, 2003) developed the mareogram database for the Alaska-Aleutian source region based on the seismic data analysis of Johnson (1999). The algorithm is able to hindcast tsunami heights within 20% of the recorded values in Honolulu Harbor for the 1964 Prince William Sound and 1996 Andreanov tsunami events. The analysis also shows the effectiveness of the DART gauge data in producing accurate results. With funding from the National Tsunami Hazard Mitigation Program, NOAA PMEL is in the process of deploying additional DART gauges off the Japan-Kuril-Kamchatka source region and developing a comprehensive tsunami forecast system for the PTWC.

1.3 Goal and Objectives

The study extends the mareogram database of Wei et al. (2001, 2003) to include the

Japan-Kuril- Kamchatka seismic source region. The objectives are

- Compile and review historical tsunamigenic earthquakes in the Japan-Kuril-Kamchatka source region.
- Determine the subfault distribution and fault parameters such as the fault area, focal depth, strike angle, dip angle, and rake angle in the subduction zone.
- Construct a mareogram database at coastal tide gauges and DART gauges using a linear long-wave model.
- Verify the mareogram database using actual events along Japan-Kuril-Kamchatka source region.

This research is conducted in coordination with NOAA PMEL and PTWC under the auspice of the Natural Tsunami Hazard Mitigation Program. The inverse algorithm can predict tsunami heights not only at Hawaii, but also at any warning point in the Pacific Ocean.

2. SUBFAULT DISTRIBUTION

2.1 Fault Parameters

The seafloor deformation caused by an earthquake can be defined by a set of fault parameters that include the fault area, focal depth, strike angle, dip angle, and rake angle (Mansinha et al., 1971). As shown in Figure 1, the fault area is located at the focal depth below the reference point and its orientation is defined by the strike and dip angles. The rake angle indicates the direction of fault movement during the earthquake and the amount of the movement is known as slip. These fault parameters are needed to provide the initial conditions in numerical models for the tsunami.

This study covers potential tsunamigenic earthquakes in the entire subduction zone along the Japan-Kuril-Kamchatka fault line. There is no certain method to predict the seafloor deformation of future tsunamigenic earthquakes. However, earthquakes generated at the same area often have similar deformation characteristics. The standard approach is to assume that future earthquakes have similar seafloor deformation as the historical events in the same area (e.g., Wei et al., 2003). Hence, the first step of this study is to identify and compile the fault parameters of historical events along the Japan-Kuril-Kamchatka fault line. Figure 2 shows the 161 tsunamigenic earthquakes with surface wave magnitude over 6.5 during the last 100 years. Surface magnitude is most commonly used expression of earthquake magnitude. The locations of these events show the outline of the subduction zone.

Geophysicists have determined the fault areas and other seismic parameters for major tsunamigenic earthquakes along the Pacific Rim during the last century. In particular, Kanamori (1971b) and Abe (1973) analyzed the fault characteristics using geodetic data, while Satake (1989), Tanioka and Satake (2001a), and Johnson and Satake (1999) reconstructed the seafloor deformation by inverting tsunami records. These studies cover 16 major tsunamigenic earthquakes long the Japan-Kuril-Kamchatka fault line over the

last 100 years and provide fault parameters for the reconstruction of the subduction zone.

Since the 16 major events do not cover the entire subduction zone, it is necessary to evaluate some minor events to provide a more complete set of fault parameters. The Historical Tsunami Database for the Pacific Region provides the aftershock distributions of all recorded earthquakes from year 47 BC to 2000 (Gusiakov, 2001). In addition, the Regional Catalogue of Earthquake provides fault parameters estimated by several agencies for all events since 1982. These documents provide additional 8 events over the last one hundred years that have more complete records and have surface wave magnitude of over 6.5. Figure 3 shows the 24 events used to estimate the subduction zone in this study.

The fault areas of several of the selected earthquakes have not been published, while other fault parameters are readily available. The present study uses the approach of Kanamori (1971b) to define the fault area as the extent of aftershocks within one day after the main earthquake. As an illustration, figure 4 shows the locations of the epicenter and aftershocks within one day after the 1978 Kuril earthquake, which occurred on March 23 at 00:31. The fault area is defined by a quadrilateral covering the majority of the aftershocks. It should be noted that this approach provides an approximation of the fault area. The previous studies of the major events using geodetic or tsunami records provide more precise representation of the faults and rupture zones.

2.2 Subfault Analysis

Figure 5 shows the fault areas determined in this study through aftershock distributions as well as those determined in previous studies based on geodetic or tsunami data. Table 1 lists the fault parameters of the 24 events used in the present study. The approximate area of the subduction zone can be estimated from the fault areas of these historical events and are delineated by the dash lines.

The fault areas provide a good geographic coverage of the significant events over the

last 100 years as shown in Figure 2. The next step is to divide the subduction zone into a number of subfaults for the development of the mareogram database. The division of the subduction zone into subfaults is based on the seafloor deformation characteristics and fault areas of the historical events. Since there are no historical records of tsunamigenic earthquake with surface wave magnitude over 6.5 in the region between Kamchatka and Kuril, the strike angle is taken to be along the trench (e.g., Tanioka et al 1996; Tanioka and Satake, 2001b; and Hirata et al., 2003) and other parameters are interpolated through the existing dataset.

Figure 6 shows the entire subfault distribution along the Japan-Kuril-Kamchatka source region and Figure 7 is a schematic of the same distribution showing the subfault number. The subfaults, which are arranged to fit in the subduction zone, represent the local tectonic structures. There are 222 subfaults with dimensions of $50 \text{ km} \times 50 \text{ km}$. Tanioka et al. (1996) used subfaults as small as $30 \text{ km} \times 45 \text{ km}$, while Johnson and Satake (1999) have maximum subfault dimensions of $100 \text{ km} \times 100 \text{ km}$. In theory, the finer the subfaults the better the predictions will be. However, the accuracy of the prediction is also limited by the quality and number of water-level records as well as the validity of the linear model used in the generation of the mareograms. The subfault dimensions of $50 \text{ km} \times 50 \text{ km}$ are selected to provide sufficient resolution of the complex bathymetry in the subduction zone and the uneven slip distributions reported in the previous studies.

3. SYNTHETIC MAREOGRAMS

3.1 Water-level Stations and Warning Points

The inverse algorithm requires a database of mareograms, which are numerically generated tsunami waveforms at water-level stations or warning points due to unit slip of the subfaults. Figure 8 shows the locations of the 14 selected water-level stations along the Japan coastlines. The water-level stations are all tide gauges maintained by the Japan Meteorological Agency (JMA). These gauges are selected to provide an even coverage of the source region and the recorded water levels will provide input to the inverse algorithm. Tsunami waveforms recorded by tide gauges in restricted waterways and harbors are distorted by the local conditions and these tide gauges are avoided if possible. Other considerations in the selection are the PTWC's access to the data, the sampling rate, and the frequency of data transmission.

Figure 9 shows the distribution of the warning points away from the source where the inverse algorithm predicts tsunami heights. NOAA PTWC and PMEL supplied the warning points in the North Pacific Ocean. The warning points are either DART gauges or tide gauges near Alaska and Hawaii. The inverse algorithm will provide predictions of tsunami waveforms at these warning points. The predictions at the warning points, such as Midway and Wake Island, can be compared with recorded water-level data before the tsunami arrives at populated regions for quality control. An additional warning point, known as Hawaii Observation Point, is included to the north of the Hawaiian Island chain. It's located at a water depth of 4,400 m so that the island bathymetry does not affect the predicted waveforms, but the location is close enough to provide meaningful results indicative of the wave conditions for Hawaii.

3.2 Long-Wave Model

This study uses the long-wave model developed by Liu et al. (1995) to generate the mareograms at the water-level stations and warning points. The nonlinear long-wave equations consist of a continuity equation and two momentum equations in the x and y directions, given respectively by

$$\frac{\partial \zeta}{\partial t} + \frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} = 0 \quad (1)$$

$$\frac{\partial P}{\partial t} + \frac{\partial}{\partial x} \left(\frac{P^2}{D} \right) + \frac{\partial}{\partial y} \left(\frac{PQ}{D} \right) + gD \frac{\partial \zeta}{\partial x} + D\tau_x = 0 \quad (2)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\frac{PQ}{D} \right) + \frac{\partial}{\partial y} \left(\frac{Q^2}{D} \right) + gD \frac{\partial \zeta}{\partial y} + D\tau_y = 0 \quad (3)$$

where t = time; ζ = water surface elevation; $D = \zeta + d$ with d = water depth; g = gravitational constant; (P, Q) = velocity flux in the x and y direction; and (τ_x, τ_y) = bottom shear-stress computed from an input Manning coefficient. The model uses the simplified linear long-wave equations for wave propagation in the open ocean and the nonlinear equations for wave transformation and runup in coastal regions.

The numerical solution is obtained by a staggered finite-difference scheme with up to four levels of nest grids of increasing resolution. An explicit leapfrog time-integration scheme provides the surface elevation and fluxes at each time step. The nested grids are dynamically coupled with a complete cycle of information exchange between an outer and an inner grid over each outer grid time step. The time-step size at each level must satisfy the Courant condition to maintain stability of the finite difference scheme. It can simulate reflecting boundaries or fixed coastlines as well as moving boundaries for runup calculation. If only a region of an ocean is modeled, an open boundary condition can be implemented to prevent wave reflection from the artificial boundaries.

3.3 Model Setup

This study uses two levels of nested grids at 1' and 15'' resolution in the computation. Modeling of tsunamis in the open ocean typically uses a grid with 1' to 5' resolution (e.g., Johnson, 1999; Tanioka, 2001; and Wei et al., 2003). The level-1 grid covers most of the North Pacific from 130°E 15°N to 115°W 60°N with a resolution of 1'. This resolution is needed to model the wave propagation from the Japan-Kuril-Kamchatka region to the Hawaiian Islands, because deep trenches and sea mounds exist over this region and the bathymetry varies significantly at several locations. The level-2 grid covers South Japan from 131°E 30°N to 141°E 36°N, where the bathymetry is very complex and requires a finer 15'' grid to resolve the data. The General Bathymetric Chart of the Oceans (GEBCO) provides the North Pacific bathymetry at 1' resolution and the Japan Meteorological Agency (JMA) supplies the South Japan bathymetry at 20'' resolution.

The generation of mareograms is based on tsunami propagation in the open ocean and therefore only the linear component of the long-wave model is applied. Flooding and drying of the coastal area are therefore not considered. Two types of boundary conditions are used in this finite difference computation: the land-ocean boundary and the open ocean boundary. The land-ocean boundary condition is defined as a vertical wall at the coastline and the region where the water depth is less than 10 m along coastline is set to 10 m. The open boundary condition is applied at the artificial boundaries in the open ocean, where surface waves are allowed to leave the computational domain without reflection.

The initial condition corresponds to still water with a specified surface wave generated by the seafloor deformation due to the earthquake. If the rupture occurs within several minutes, a direct energy transfer from the sea floor to the water can be assumed under the linear long-wave approximation (Kajiura 1970). The initial surface wave is

treated as identical to the sea floor deformation, which can be calculated from the algorithm of Okada (1985) based on the fault parameters that include the strike, dip, and slip angles, focal depth, the amount of slip, and the dimensions and location of the fault. The amplitude of the wave is a linear function of the slip, and the horizontal dimensions are linearly proportional to those of the fault.

3.4 Mareograms

The mareograms at the 14 water-level stations and 16 warning points are generated for 1 m slip of the 222 subfaults using the long-wave model. Each subfault generates a different tsunami signal owing to its distinct seafloor deformation characteristics and location. All computed mareograms are run through a low pass filter to remove components with periods shorter than 4 min.

Figure 10 shows the mareograms at selected water-level stations due to 1-m slip of subfault 112 near the Hokkaido Islands. The nearest station, Kushiro, registers the tsunami signal shortly after the slip. The tsunami signals at stations further away exhibit smaller amplitudes. Every mareogram shows distinct effects of the coastal configuration and bathymetry. The local oscillation, however, might not be modeled accurately by the linear long-wave model, because it does not consider dissipation and friction that might become significant in shallow water. The DART gauges, which are currently not available off the Japan coasts, are expected to produce distinct tsunami signals near the source as demonstrated by Wei et al. (2001, and 2003) for the Alaska-Aleutian source.

Figure 11 shows the corresponding mareograms at selected warning points. All mareograms shows some degree of prolonged oscillation, including those computed at the DART gauges, which are located at some distance offshore. Those gauges are located off the Alaska and US west coast and the tsunami getting there would have traveled a long distance from the source and experienced significant scattering due to refraction and diffraction along the way. In addition, those gauges receive not only direct tsunami

signals from the source, but also continuous reflection of the tsunami from the adjacent coastlines. The mareograms at the tide gauges are further affected by local conditions and less clearly correlated with the tsunami characteristics. The mareogram at Hawaii Observation Point, on the other hand, shows a relatively clear signal of the approaching tsunamis.

4. FORECAST METHODOLOGY

4.1 Inverse Algorithm

The inverse algorithm estimates the slip distribution of a tsunamigenic earthquake through regression of recorded tsunami waveforms against a pre-computed database of mareograms. It makes use of the linearity of tsunami generation and propagation. Let m denote the number of subfaults in the database and n the number of recorded tsunami waveforms. Superposition of the pre-computed mareograms provides an approximation of the tsunami waveforms recorded at the water-level stations

$$a_i(t) = \sum_{j=1}^m A_{ij}(t)x_j \quad \text{for } i=1, \dots, n \quad (4)$$

where $t = 0$ is the time of the earthquake; $a_i(t)$ = measured tsunami waveform at water-level station i ; $A_{ij}(t)$ = pre-computed mareogram at water-level station i generated by unit slip of subfault j ; and x_j = slip at subfault j . The tsunami waveforms $a_i(t)$ are obtained from real-time water-level data near the tsunami source after eliminating the astronomical tides. Since $a_i(t)$ are time series of data points of several minutes long, there are significantly more known variables than unknown values of x_j . Therefore, Eq. (4) is solved by a nonnegative least-squares method to give the slip distribution x_j that produces the best fit between the measured and regressed waveforms at the water-level stations. The inverse algorithm requires at least two water-level stations in order to estimate the earthquake source.

Once the slip distribution x_j is determined from the water level records, the seismic source characteristics and the resulting tsunami can be determined. In addition, seismic moment and moment magnitude can be calculated from estimated slip distribution. These can be compared with previous studies to confirm the accuracy of the predicted slip distribution using the inverse algorithm. Kanamori (1977) defined the seismic moment as

$$M_0 = \mu \sum_{j=1}^m \alpha_j x_j \quad (5)$$

where α_j = area of subfault j (m^2) and μ = rigidity, which is between 4×10^{10} to 6×10^{10} N/m². The moment magnitude is expressed in terms of the seismic moment as

$$M_w = \frac{2}{3} \log M_0 - 6.07 \quad (6)$$

Wei et al. (2001, 2003) extended the inverse algorithm of Satake (1987) to provide forecasts of tsunami waveforms away from the source. The predicted waveforms at the warning points are estimated from the pre-computed mareograms as

$$b_k(t) = \sum_{j=1}^m B_{kj}(t) x_j \quad (7)$$

where $b_k(t)$ = predicted tsunami waveforms at warning point k and $B_{kj}(t)$ = pre-computed mareogram at warning point i due to unit slip of subfault j .

4.2 Jackknife Technique

For tsunami warnings, it is useful to know the upper and lower bounds of the predicted waveforms for a given confidence interval. The reliability of the prediction can be determined by a re-sampling procedure known as the jackknife technique (e.g., Efron, 1982; and Wu, 1986). The jackknife technique provides a number of waveform predictions at each warning point by using various sub-samples of the available water-level records as input to the inverse algorithm.

In the application here, the re-sampling scheme treats each water-level record as a data point. A “delete-1” jackknife sample is constructed by removing the l -th water-level record from the n records in the original database. Using the resulting jackknife sample, a slip distribution x_j^{-l} can be obtained from a least-squares approximation of

$$a_i(t) = \sum_{j=1}^m A_{ij}(t) x_j^{-l} \quad \text{for } i=1, \dots, n \text{ and } i \neq l; \text{ and } l=1, \dots, n \quad (8)$$

The corresponding waveform at warning point k is given by

$$b_k^{-l}(t) = \sum_{j=1}^m B_{kj}(t) x_j^{-l} \quad (9)$$

Since the inverse algorithm requires at least two records to produce meaningful results, a minimum of three records is needed to generate the “delete-1” jackknife sample

The n possible jackknife samples provide a total of n waveforms, $b_k^{-1}(t)$, $b_k^{-2}(t)$, ..., and $b_k^{-n}(t)$, at each warning point. The average or expected waveforms is presented as

$$\tilde{b}_k(t) = \frac{1}{n} \sum_{l=1}^n b_k^{-l}(t) \quad (10)$$

The standard deviation of the predicted waveform at warning point k is then computed from the various waveforms obtained from the jackknife technique as

$$\sigma_k(t) = \left\{ \frac{n-1}{n} \sum_{l=1}^n [b_k^{-l}(t) - \tilde{b}_k(t)]^2 \right\}^{\frac{1}{2}} \quad (11)$$

The upper and lower bounds of the predicted waveform are thus given by

$$\zeta_k(t) = \tilde{b}_k(t) \pm \xi \sigma_k(t) \quad (12)$$

where ξ correspond to the specified confidence interval of an assumed normal distribution. Tichelaar and Ruff (1989) showed theoretically that the jackknife technique provides the same standard deviation regardless the number of waveforms dropped in the resampling scheme.

4.3 Implementation

This forecast tool requires input of the approximate location of the earthquake and the resulting tsunami signals near the source. Existing software at PTWC can determine the earthquake origin time, location, and magnitude through an international network of seismometers in about 15 minutes after an earthquake. The tsunami waveforms used in the inverse algorithm should include the first wave and the operator may vary the duration of the time series to produce optimal results.

The inverse algorithm uses a least-square technique to match the recorded tsunami

signals regardless of the location of the earthquake. It is therefore necessary to know the approximate location of the epicenter and specify a limited number of subfaults to cover the expected rupture zone in the inverse analysis. The operator needs to evaluate the computed slip distribution and waveforms and further reduce the number of subfaults in to obtain a converging prediction.

5. RESULTS AND DISCUSSION

The inverse algorithm involves a number of assumptions and approximations and needs validation with historical data before its implementation at PTWC. As already shown in Figure 2, there have been numerous tsunamigenic earthquakes in the Japan-Kuril-Kamchatka source region over the last 100 years. Three of the major tsunamigenic earthquakes have well-documented seismic source parameters and water-level data near and away from the source. These are the 1944 Tonankai earthquake (Tanioka and Satake 2001b, and Tanioka 2001), the 1946 Nankaido earthquake (Tanioka and Satake 2001a, and Tanioka 2001), and the 1994 Kuril earthquake (Tanioka et al., 1995, Piatanesi et al. 1999). Although these events did not cause significant damage in Hawaii, the tide gauges in the Hawaiian Islands recorded clear tsunami signals, which can test the capability of the inverse algorithm in predicting tsunamis far away from the source.

5.1 The 1944 Tonankai Earthquake

The Tonankai earthquake occurred along the eastern Nankai Trough on 7 December 1944 at 04:35 GMT. The epicenter was located at 33.70° N, 136.05° E as indicated in Figure 12 and the surface wave moment was estimated to be 8.2 (Kanamori 1972). Great interplate earthquakes have occurred with an interval of approximate 120 years along the eastern Nankai Trough (Ando 1975). These earthquakes are caused by the subduction of the Philippine Plate beneath the overlying Eurasian Plate. The 1944 Tonankai earthquake was the one of the latest events of these earthquakes. Tanioka and Satake (2001b) analyzed the recorded tsunami waveforms using an inverse approach and estimated the main slip region to be near the Shima peninsula. Sagiya and Thatcher (1999) analyzed geodetic data and Kikuchi et al. (1999) used the motion seismograms to arrive at the same conclusion. The analyses of Tanioka and Satake (2001b) and Sagiya and Thatcher (1999) also indicate a slow rupture near the Atsumi peninsula with smaller slip.

Tanioka and Satake (2001b) described 10 observed tsunami waveforms along South Japan coastlines and Tanioka (2001) described the observed waveform at the Honolulu tide gauge. The present study uses six of the 10 waveforms recorded by tide gauges facing the open ocean. The other tide gauges are surrounded by islands or peninsulas and the recorded waveforms might be influenced by local effects. The inverse analysis initially considered subfaults 177 to 222 along South Japan coastlines and the subfaults at the two ends of the segment that slips less than 1.5 m were removed. The second iteration used the remaining subfaults from 193 to 202 with the first 65 minutes of the recorded data. Figure 12 shows the computed slip distribution together with the outline of the subfaults predicted by Tanioka and Satake (2001b). The results in Table 2 show that the main slip occurs at subfaults 193 to 196 and agree with the conclusion of Tanioka and Satake (2001b) and Ishibashi (1981). Based on a rigidity of 5×10^{10} N/m² recommended by Tanioka and Satake (2001b), the computed slip distribution gives a seismic moment of 3.2×10^{21} Nm. This is consistent with those of Ishibashi (1981) and Tanioka and Satake (2001b), who obtained seismic moments of 2.8×10^{21} Nm and 2.0×10^{21} Nm using geodetic and water level data respectively.

Figure 13 compares the calculated and recorded waveforms at the selected tide gauges at Mera, Ito, Uchiura, Fukue, Shimotsu, and Aburatsu. Also included are the 90% confidence interval bounds of the computed results. Figure 12 shows the locations of these tide gauges. The Uchiura tide gauge is nearest to the source and shows the most distinct tsunami signal and the largest oscillation amplitude. The amplitude of the tsunami waveform decreases along the coastlines rapidly away from the source. The computed and recorded waveforms at Mera and Uchiura show good agreement in both the amplitude and arrival time. The computed waveform at Ito, Fukue, and Aburatsu also show reasonable agreement with the recorded data. The Shimotsu tide gauge is sheltered by the Kii Peninsula and the computed and recorded waveforms have the same period, but different phases and amplitudes.

Figure 14 shows the computed and recorded tsunami waveforms at the Honolulu tide gauge. The comparison in Figure 14a shows good agreement in amplitude, but the computed waveform shows an 8-minute delay in the arrival time. Figure 14b shows better agreement of the phase after adjustment for the delay. On the contrary, the inverse algorithm of Wei et al. (2003) produces good agreement in both amplitudes and arrival times for several Alaska-Aleutian tsunamis. The main difference between the two studies is the complexity of the bathymetry between the source regions and the Hawaiian Islands. The seabed between the Alaska-Aleutian source region and Hawaii is relatively flat and gentle, but the bathymetry between Japan and Hawaii is very complex with trenches and sea mounts. The delay in arrival time is likely caused by bathymetry errors, which affect the computed celerity of the tsunami.

Tanioka (2001) computed the tsunami waveforms for the same event and the waveform at the Honolulu tide gauge showed a much longer delay of 30 minutes. He also cited errors in the bathymetry data as the main reason of the delay. Since Tanioka (2001) used the earth-topography-two-minute (ETOPO2) data as described by Smith and Sandwell (1997) and the present study uses the 1' GEBCO bathymetry data, both studies show different delays in the tsunami arrival time. Comparison of the two datasets shows that the bathymetry over some areas is slightly shifted. If the bathymetry is shifted near the gentle seabed, the depth and the resulting celerity will not change significantly. However, if the bathymetry is shifted near trenches or sea mounds, the depth will change significantly. As a result, the errors in the bathymetry data will affect the arrival time of tsunamis. Pararas-Carayannis, G. (personal communication, July 19, 2004) also discussed that there were discrepancies of up to plus or minus 10 minutes in the arrivals of first waves, as compared to arrivals of major historical tsunamis shown on tide gauge records.

In addition, the harmonic contents of the recorded and computed results do not agree well because the mareograms are based on a linear model and the gauge is located in shallow water, where nonlinear effects might be important. The primary purpose of the

inverse algorithm is to predict the tsunami height at the warning points. Even though the phase of the computed tsunami might be slightly off, the result is still useful to assess the severity of the event for warning purposes.

5.2 The 1946 Nankai Earthquake

The Nankai earthquake, which occurred on 20 December 1946 at 19:19 GMT, is the other latest great earthquake along the Nankai Trough. The epicenter was located at 33.13°N 135.84°E and the surface wave moment was estimated to be 8.2 (Kanamori 1972). The 1946 Nankai earthquake has also been studied as extensively as the 1944 Tonankai earthquake. Tanioka and Satake (2001a) estimated the slip distribution of the earthquake through inversion of tsunami waveforms and showed that the main slip regions were located south of the Shikoku Island and the Kii peninsula. The 1946 Nankai earthquake had almost three times the seismic moment of the 1944 Tonankai earthquake. However, the tsunami height of the 1946 Nankai earthquake recorded at the Honolulu tide gauge was smaller than that of the 1944 Tonankai event. This is because the rupture zone of the 1946 Nankai earthquake was very close to the land. If rupture occurs at the water depth less than 1000 m, the energy is trapped in the shallow-water region and the resulting tsunami does not propagate toward the open ocean (Tanioka 2001).

The 1946 Nankai earthquake is a difficult event for the inverse analysis. The tide gauges that recorded the tsunami are mostly surrounded or sheltered by islands and peninsulas and the recorded data is affected by the complex coastline and bathymetry of the area. In addition, the mareograms were generated using a linear long-wave model, in which the land-ocean boundary is set as a vertical wall, and do not account for the flooding and drying of coastal areas. The results of the inverse algorithm may contain significant errors if the recorded wave amplitude is large as in this case. Tanioka and Satake (2001a) provided the eight recorded tsunami waveforms along South Japan coastlines. Most of the tide gauges are located in sheltered areas. Six of the eight tide

gauges are selected as the input for the inverse analysis. Tanioka (2001) provided the recorded waveform at Honolulu tide gauge, which is used to verify the computed waveform away from the source.

The inverse analysis initially used subfaults 177 to 222 along South Japan coastlines and up to the first 150 minutes of the recorded waveforms to identify the active subfaults for the 1946 Nankai earthquake. The results showed a maximum slip of 9.06 m and subfaults with slips of less than 1.5 m were eliminated. The inverse analysis with the remaining subfaults, 198 to 214, provides the slip distribution as shown in Figure 15 and Table 3. The computed faults are similar to those determined by Tanioka and Satake (2001a) with the maximum slip occurring to the South of the Shikoku Island even though the epicenter is located to the south of the Kii Peninsula. The resulting slip distribution gives a seismic moment of 5.0×10^{21} Nm (M_w 8.4), which is similar to the values 5.3×10^{21} Nm and 4.7×10^{21} Nm reported by Tanioka and Satake (2001a) and Ando (1982) respectively.

Figure 16 compares the calculated and recorded waveforms at the six selected tide gauges: Sakai, Shimotsu, Fukue, Morozaki, Uchiura, and Ito. The Shimotsu and Sakai tide gauges, which are nearest to the rupture zone, show the strong tsunami signals. The computed and recorded waveforms show reasonable agreement in both amplitude and phase. The recorded waveforms at other tide gauges show larger discrepancies with the computed results. Figure 17 shows the computed and recorded waveforms at the Honolulu tide gauge. The comparison indicates good agreement in amplitude. The first wave is difficult to identify from the recorded data and hence, it is difficult to identify the time lag between recorded and computed waveforms. The computed and recorded waveforms show poor agreement in the phase, because the input waveforms near the source have significant influences of the complex coastline that are not fully represented by the mareograms. The inverse analysis would still try to fit the recorded waveform with the available mareograms, causing errors in the computed waveforms at the warning

points. Nevertheless, the computed tsunami amplitude at the warning point agrees with the measurement.

5.2. The 1994 Kuril Earthquake

The Kuril earthquake occurred off Shikotan Island along the Kuril trench on 4 October 1994 at 13:22:59.54 GMT. The National Earthquake Information Service provides the epicenter at 43.956° N, 147.412° E and a surface wave magnitude M_s of 8.1. The seismic moment estimated from the Harvard Centroid Moment Tensor (CMT) solution is 3.5×10^{21} Nm (M_w 8.3). Typically, earthquakes occur in subduction zones are underthrusting events. The 1994 Kuril earthquake, however, was an intra-slab event tearing the subducting oceanic lithosphere along the direction perpendicular to the trench (Tanioka et al., 1995).

Tanioka et al. (1995) provided 13 recorded tsunami waveforms along North Japan coastlines and Mofjeld et al. (1997) provided 24 recorded waveforms at warning points in the Pacific Ocean including the Honolulu tide gauge and the bottom pressure sensors. Six of the 13 tide gauges that face the open ocean are selected and up to 75 minutes of each record is used in the inverse algorithm. Subfaults 90 to 128 in the Kuril region covering the approximate area of the rupture zone are used in the inverse analysis. Figure 18 shows the slip distribution obtained from inverse algorithm and Table 4 shows the amount of slips at the subfaults. The result shows a distinct fault area over the epicenter and good agreement with the fault area determined by Tanioka et al. (1995). The seismic moment estimated from the resulting slip distribution is 3.7×10^{21} Nm (M_w 8.3), which is close to the Harvard CMT estimation of 3.5×10^{21} Nm and is consistent to 3.0×10^{21} Nm estimated by tsunami waveform inversion (Tanioka et al., 1995).

Figure 19 shows comparisons of recorded and calculated waveforms at the six input tide gauges: Hanasaki, Kushiro, Hachinohe, Miyako, Onahama, and Choshi. The Hanasaki tide gauge was nearest to the epicenter and recorded the largest wave

amplitude. Even though only the first 75 minutes of the records is used in the inverse analysis. The computed waveforms show good agreement in both amplitude and phase with the measured data well beyond this period. Figure 20 shows comparisons of the computed and measured waveforms at the warning points. The results indicate that the computed tsunami reaches the warning points earlier than the actual event. Similar to the other events, the inverse algorithm correctly calculates the amplitude of the tsunamis at the tide gauges, but cannot fully account for the timing and phase. The computed recorded waveforms at the DART gauge, WC62, show very good agreement in both the amplitude and phase except arrival time.

Compared with the other two events considered here, the 1994 Kuril tsunami show the best overall agreement. The major difference is that the 1994 events have better quality data recorded by tide gauges facing the open ocean near the source. For future events, the proposed network of DART gauges will produce event better quality data for the input of the inverse algorithm. Therefore, it is expected that predictions of the same level of accuracy as the 1994 Kuril event can be obtained for future events.

6. CONCLUSIONS AND RECOMMENDATIONS

The inverse algorithm is an effective method to forecast far-field tsunamis at warning points using real-time water-level data near the earthquake source. The present study has developed the two essential elements of an inverse algorithm, the predetermined subfaults and precomputed mareograms, for the Japan-Kuril-Kamchatka source region for tsunami forecast in the Pacific with emphasis on the Hawaiian Islands.

This forecast method involves a number of assumptions and approximations. First, future events will follow the seafloor deformation pattern of historical events with the same fault parameters. Analysis of historical events with M_s over 6.5 from 1900 to 2000 produces 222 subfaults in the source region. Second, the initial condition for tsunami modeling corresponds to still water with a specified surface wave identical to the seafloor deformation caused by earthquakes. Third, tsunami propagation follows a linear process and the land boundaries correspond to vertical walls at a constant depth. In the implementation, at least two recorded waveforms near the source are required for the input and three is necessary to obtain the confidence interval bounds.

Despite the assumptions, the inverse algorithm provides reliable estimations of tsunami heights at tide gauges around the Hawaiian Islands for three major historical events occurred along the Japan-Kuril-Kamchatka subduction zone. Most of the input waveforms contain the first wave of the tsunami and that typically involves 1 to 2.5 hours of records. The results, however, show a minor lag between the recorded and computed waveforms due to errors in the bathymetry data. In addition, the harmonic contents of the recorded and computed waveforms at the coastal tide gauges do not agree well due to increasing importance of nonlinear effects in shallow water. The good agreement obtained at a deep-water station shows the capability of the DART gauges when used along with an inverse algorithm.

It would be a worthwhile effort to extend the database of the inverse algorithm to

include the Peru-Chile source region along the west coast of South America. This will provide a comprehensive forecast tool for the entire Pacific Ocean and provide reliable quantitative estimations of far-field tsunamis generated along the Pacific Rim. This tsunami forecast tool will become a component of the comprehensive tsunami warning system to be developed at NOAA PMEL for PTWC and WCATWC.

Figure 1. Definition of fault parameters

Figure 2. Historical tsunamigenic earthquakes with surface wave magnitude greater than M_s 6.5 along the Japan-Kuril-Kamchatka source region from 1900 – 2000

Figure 3. Historical tsunamigenic earthquakes used in the re-contruction of the subduction zone

Figure 4. Determination of fault area for 1978 Kuril earthquake

Figure 5. Fault areas and assumed subduction zone: — = fault areas determined in the previous studies; — = fault areas determined in this study; — — — = assumed subduction zone

Figure 6. Subfault distribution

Figure 7. Subfault number

Figure 8. Water-level stations along Japan coastlines

Figure 9. Water-level stations and warning points in the Pacific and the computational domain: Δ = tide gauge stations; $\circ$ = bottom-pressure recorders

Figure 10. Sample mareograms at the warning points for subfault 112

Figure 11. Sample mareograms at the warning points for subfault 112

Figure 12. Computed slip distributions of the 1944 Tonankai earthquake: ● = tide gauges used in the inverse; ● = epicenter; — = the outline of the subfaults predicted by Tanioka and Satake (2001b)

Figure 13. Comparisons of recorded and calculated waveforms at water-level stations for the 1944 Tonankai earthquake: — = measurement; — = inverse method; ■■■ = 90 % confidence interval

(a) Honolulu

(b) Honolulu with time shift

Figure 14. Comparisons of recorded and calculated waveforms at the warning points for the 1944 Tonankai earthquake: (a) inverse result; (b) inverse result with time shift: — = measurement ; — = inverse method ; — = inverse method with shift; [red shaded area] = 90 % confidence interval

Figure 15. Computed slip distributions of the 1946 Nankai earthquake: ● = tide gauges used in the inverse; ● = epicenter; — = the outline of the subfaults predicted by Tanioka and Satake (2001a)

Figure 16. Comparisons of recorded and calculated waveforms at water-level stations for the 1946 Nankai earthquake: — = measurement; — = inverse method; ■■■ = 90 % confidence interval

Honolulu

Figure 17. Comparisons of recorded and calculated waveforms at Honolulu tide gauge for the 1946 Nankai earthquake: — = measurement ; — = inverse method; [red dotted area] = 90 % confidence

Figure 18. Computed slip distributions of the 1994 Kuril earthquake: ● = tide gauges used in the inverse; ● = epicenter; — = the outline of the subfaults predicted by Tanioka et al. (1995)

Figure 19. Comparisons of recorded and calculated waveforms at water-level stations for the 1994 Kuril earthquake: — = measurement; — = inverse method; [] = 90 % confidence interval

Figure 20-1. Comparisons of recorded and calculated waveforms at the warning points for the 1994 Kuril earthquake: (a) inverse result; (b) inverse result with time shift: — = measurement ; — = inverse method ; — = inverse method with shift; ■■■ = 90 % confidence interval

Figure 20-2. Comparisons of recorded and calculated waveforms at the warning points for the 1994 Kuril earthquake: (a) inverse result; (b) inverse result with timeshift: — = measurement; — = inverse method; — = inverse method with shift; ■■■ = 90 % confidence interval

Table 1. Published Fault Parameters of Historical Tsunamigenic Earthquakes

Earthquake	Year	Date	Surface Wave	Epicenter		Fault Area		Focal	Strike	Dip	Rake	Reference
			M _s	Latitude (°N)	Longitude (°E)	Length L (km)	Width W (km)	depth d (km)	angle φ (°)	angle δ (°)	angle λ (°)	
Kamchatka	1984	12 / 28	7.0	56.24	163.80	50 ^a	60 ^a	21.5	260	61	162	Parsons (2002)
Kamchatka	1997	12 / 05	7.7	54.31	161.91	95 ^a	180 ^a	33.6	202	23	74	Parsons (2002)
Kamchatka	1952	11 / 04	8.3	52.75	159.50	600 ^b	200 ^b	22.6 ^c	214	13	104	Johnson and Satake (1999)
Kamchatka	1993	11 / 13	7.1	51.93	158.65	-	-	18.0	206	13	83	Johnson et al. (1995)
Kamchatka	1993	06 / 08	7.2	51.22	157.83	-	-	18.0	207	13	79	Johnson et al. (1995)
Kuril	1991	12 / 22	7.4	45.58	151.55	125 ^a	140 ^a	31.2	226	16	99	Parsons (2002)
Kuril	1978	03 / 23	7.5	44.12	149.27	130 ^a	145 ^a	28.3	224	11	91	Parsons (2002)
Kuril	1984	03 / 24	7.1	44.17	148.62	95 ^a	85 ^a	30.6	229	17	109	Parsons (2002)
Kuril	1969	08 / 11	7.8	43.18	147.48	175 ^a	240 ^a	33.0	310	16	270	Abe (1973)
Kuril	1994	10 / 04	8.1	43.96	147.41	90 ^b	70 ^b	29.4 ^c	160	40	30	Tanioka et al. (1995)
Nemuro-oki	1973	06 / 17	7.7 ^c	43.05	145.76	110 ^a	115 ^a	49.0	230	27	117	Shimazaki (1974)
Tokachi-oki	1952	03 / 04	8.1	42.33	145.22	210 ^b	155 ^b	18.2 ^c	238	18 ^c	116 ^c	Hirata et al. (2003)
Tokachi-oki	1968	05 / 16	7.9	40.84	143.22	250 ^b	100 ^b	9.0	336	20	38	Satake (1989), Kanamori (1971a)
Sanriku	1994	12 / 28	7.5	40.53	143.42	120 ^b	210 ^b	24.6 ^c	200	10	90	Tanioka et al. (1996)
Iwaizumi	1989	11 / 01	7.3	39.95	143.08	105 ^a	170 ^a	24.0	183	14	69	Parsons (2002)
Sanriku	1896	06 / 15	7.2	39.50	144.00	210	50	0.0	190	20	90	Tanioka and Satake (1996)
Sanriku	1933	03 / 02	8.3	39.20	144.50	100	185	10.0	180	45	90	Kanamori (1971b)
Miyagi-oki	1978	06 / 12	7.4	38.15	142.22	95 ^a	75 ^a	27.8	340	20	76	Seno et al. (1980)
Shioya-oki	1938	11 / 05	7.7	36.97	141.71	165 ^a	90 ^a	30.0	200	10	85	Abe (1977)
Shioya-oki	1938	05 / 23	7.4	36.58	141.34	75 ^a	75 ^a	40.0	200	10	80	Abe (1977)
Toankai	1944	12 / 07	8.2	33.70	136.05	315 ^b	180 ^b	14.0 ^c	240	12 ^c	110	Tanioka and Satake (2001b), Kanamori (1972)
Nankai	1946	12 / 20	8.2	33.13	135.84	360 ^b	180 ^b	15.0 ^c	250	12 ^c	120	Tanioka and Satake (2001a), Kanamori (1972)
Kyuushuu	1984	08 / 06	7.1	32.38	132.16	30 ^a	20 ^a	29.0	203	85	275	Regional Catalogue of Earthquake ^d
Kyuushuu	1996	10 / 19	6.6	31.79	131.99	25 ^a	30 ^a	22.0	210	17	79	Regional Catalogue of Earthquake ^d

^a fault area determined in this study from the one day aftershock distribution area^b dimensions of the area covered all subfaults determined in the previous studies^c average of parameters for all subfaults^d M_s from the Japan Meteorological Agency (JMA) and the other parameters from the Harvard Centroid Moment Tensor (CMT) solution

Table 2. Computed Slip Distributions of the 1944 Tonankai Earthquake.

Subfault number	Slip distribution
193	6.21 m
194	5.85 m
195	5.06 m
196	5.96 m
197	0.00 m
198	0.00 m
199	1.40 m
200	0.00 m
201	0.00 m
202	1.11 m

Table 3. Computed Slip Distributions of the 1946 Nankai Earthquake.

Subfault number	Slip distribution
198	3.36 m
199	0.12 m
200	1.13 m
201	2.21 m
202	0.66 m
203	1.90 m
204	1.05 m
205	3.42 m
206	2.08 m
207	0.14 m
208	2.12 m
209	2.46 m
210	0.00 m
211	5.53 m
212	9.06 m
213	0.00 m
214	4.42 m

Table 4. Computed Slip Distributions of the 1994 Kuril Earthquake.

Subfault number	Slip distribution
101	9.56 m
102	9.53 m
103	6.20 m
104	4.46 m

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