NUMERICAL SIMULATION OF TSUNAMIS IN THE VANUATU-FIJI-TONGA REGION FOR A TSUNAMI WARNING SYSTEM IN FIJI

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MEE06022

ABSTRACT

Two historical earthquakes were selected from the subduction zones of Vanuatu and Tonga for this tsunami simulation studies. The earthquake magnitude for the Vanuatu trench simulated tsunami was Mw7.7 and that of the Tonga trench tsunami was Mw7.5. Historically tsunamis by these earthquakes were not detected around the Fiji islands so we set the parameters of their fault models which are almost similar to the original fault model, in order to produce ocean floor deformations capable of generating the hypothetical tsunamis through numerical simulation. The tsunami simulation code used in this study, TSNAMI4s was written and developed by Tanioka.
Travel time charts from the tsunami sources in the Tonga and Vanuatu subduction zones to the shores of the Fiji islands were drawn from the numerical simulation results. Tsunami wave heights at 26 coastal areas of the Fiji islands were computed and compared in order to determine the effect of directivity or the influence of the near-shore seafloor topography. The computed maximum tsunami wave height at Momi Bay and Nabukelevu-i-ra from the simulated Vanuatu trench tsunami is 45 cm and 42 cm respectively.

Keywords: Numerical Simulation of Tsunamis, Ocean Floor Deformation, Tsunami Directivity, Travel Time, Fault Model

INTRODUCTION

The performance and effectiveness of a tsunami warning system is extremely important in terms of saving lives of the coastal communities that are in the path of an approaching tsunami. The absence of any tsunami warning system during a devastating tsunami attack is disastrous and can be overwhelming, for the world has witnessed this Mega-Tsunami disaster during the December 26th 2004, Sumatra Earthquake (Mw9.0). A Tsunami warning system is one the many facets of Tsunami Disaster Management and Mitigation; it should have the capability to rapidly detect and assess the possibility of generation of tsunami from its "source earthquake, compute its expected arrival times and wave heights at various coastlines that are in the direct path of the tsunami and disseminate the tsunami warning message in a timely manner.

A Tsunami Warning System can have two operational components, on one hand is the real tsunami detection and warning system, on the other hand is the virtual tsunami warning system. In an event of tsunami detection, information obtained from the real tsunami detection system can be cross referenced with that of the virtual tsunami warning system.

The virtual tsunami warning system consists mainly of a comprehensive database of information on simulated tsunamis from every possible source regions that have been identified as tsunami hazard areas. The pre-calculated tsunami simulation results such as expected arrival times,

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expected wave heights at coastal areas are instantly retrieved whenever a real tsunami is detected and its source region identified.

The virtual tsunami warning system can act as a backup for the real tsunami warning system and furthermore it facilitates the timely issue of tsunami warning. The aim of this study is to investigate the tsunami travel time to the shorelines of Fiji from various source regions in the Vanuatu-Fiji-Tonga waters and determine the underlying parameters that dominantly influence the tsunami height computed by the simulation program for the Tsunami Warning System.

The goals of tsunami simulation include the production of travel-time charts from source to the coasts, the computation of tsunami wave heights at the coastal areas, forecasting tsunami arrival times, expected wave heights and the production of tsunami inundation maps.

DATA

Bathymetric Data

The bathymetric data for the deeper part of the southwest Pacific region was obtained from the Global Earth Bathymetric Chart of the Oceans (GEBCO) website, 1 arc minute grid resolution of the deep ocean, and 12 arc second resolution for the Fiji waters. The finer grid near-shore bathymetric data of the Fiji islands has a grid resolution of 75 meters which was obtained from the South Pacific Geoscience Commission (SOPAC) website.

Selected Earthquakes

Two historical earthquakes were selected from the Global Centroid Moment Tensor data for the shallow depth earthquakes of magnitudes Mw > 7.0 that have occurred in the Vanuatu –Fiji –Tonga plate subduction zones. The earthquake from the Tonga Trench occurred on the 19th December 1982 which had a magnitude of Mw7.5, focal depth of 29 km at the epicenter location 175.1W, 24.31S. The Vanuatu Trench earthquake occurred on the 16th May 1995 having its epicenter location at 170E, 23.051S with a magnitude of Mw7.5 at focal depth of 25 km. These earthquakes were selected for the primary aim of investigating the directivity of the tsunami waves they generate towards the Fiji islands with minimal dispersion effect from the back-arc subduction trench islands of Tonga and Vanuatu.

Fault Model Modification

Historically these earthquakes did not generate tsunamis so we set the parameters of their fault models which are similar to the original fault model in order to generate our hypothetical tsunami through numerical simulation. The shallower dip angle of the fault model are always taken into consideration from the standpoint of tsunami generation, Abe (1973), and the earthquake magnitudes were increased in order to increase the fault length and widths. Fault parameters scaling law proposed by Abe (1989), were used to obtain the fault lengths and width from the earthquake magnitudes. In the case of the Tonga trench earthquake the fault length and width was increased to 100 and 50 km respectively. As for the Vanuatu trench earthquake, the fault length and width was set to 112 and 56 km respectively. The fault model of the Tonga trench earthquake is that of reverse fault type, tsunami generating earthquakes in subduction zones have reverse fault mechanisms, Satake and Tanioka (1999); on the other hand the Vanuatu trench earthquake is a normal fault type which is rather uncommon in plate subduction zones. The epicenter location of the Vanuatu trench earthquake was moved closer to the trench in order to examine the effect of its tsunami directivity on the southern islands and coastal areas of Fiji.

NUMERICAL METHOD

The ocean floor deformations were computed from the fault models of the earthquakes. The maximum uplift and subsidence computed from the Tonga trench earthquake was 42.3 cm and 11.01 cm respectively. The Vanuatu trench earthquake produced a maximum uplift of 85.8 cm and a maximum subsidence of 7.8 cm.

The numerical code used in this study is TSNAMI4s which was written and developed by Tanioka of the Institute of Seismology and Volcanology at Hokkaido University. The code is written in Fortran Language and is capable of running on high-end laptops that have dual processors. The only disadvantage about this code is that it does not have the subroutine to plot tsunami travel time chart in map form. In this study, the travel time chart was produced by tracing the wave front of the first elevated wave of the tsunami at 10 minute interval snapshots produced by the simulation program. TSNAMI4s is a linear numerical simulation code for tsunami propagation; it also has a nonlinear version, TSNAMI-non, but was not used in this study.

Stability condition

The tsunami simulation process is done in two separate sections; the first section contains the coarse grid (1 minute resolution) for the deep ocean region from the tsunami source to the specified boundaries of the Fiji waters. The second section contains the fine grid (75 meter resolution) within the Fiji waters and the linear long wave hydrodynamic equations are used in both sections. The tsunami simulation propagation is connected from the region of coarse grid bathymetric resolution onto the finer grid resolution region through interpolation, in reference to Peregrine, (1972), theory on equations for water waves and the approximations behind them.

The integration time step (Δt) for the entire simulation program was set at 1.0 second in order to maintain the Courant Frederick Lewis (CFL) condition of stability, $\Delta t \leq \Delta x / \sqrt{2gd}$ where Δx is the maximum grid size, g is the acceleration due to gravity and d is the maximum depth. The coarse grid section is 1 minute resolution which is 1850 meters and the maximum water depth is taken to be 9,000 meters when considering the water depth at the subduction trenches. The fine grid section has a maximum grid resolution of 12 arc second (370 meters) and the maximum water depth is considered to be 4,652 meters near the Kadavu islands. Substituting these parameter values in the CFL condition of stability equation, 4.2 seconds is obtained for the coarse grid section and 1.2 seconds is obtained for the fine grid section. The CFL condition of stability is satisfied in both sections.

Computed Tsunami Wave Heights

Tsunami wave heights were computed through the numerical interpolation subroutine for 26 coastal areas in Fiji. Wave heights were compared to examine the effect of tsunami directivities and the influence of near-shore seafloor topography. Figures 1 and 2 show a sample of comparison of wave heights computed from the Vanuatu and Tonga trench simulated tsunamis at Laucala Bay.

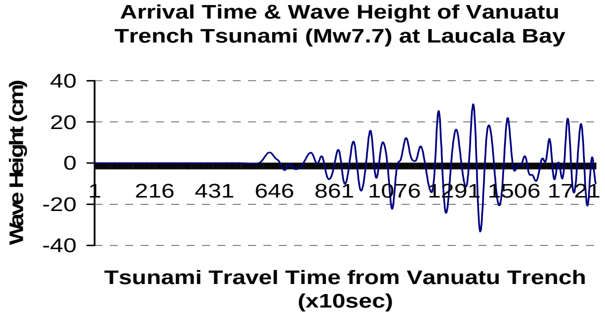

Figure 1. Computed wave heights of Vanuatu trench simulated tsunami at Laucala bay.

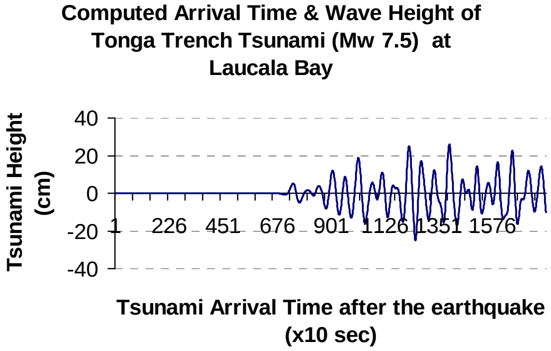

Figure 2. Computed wave heights of Tonga Trench simulated tsunami at Laucala bay.

The aim of comparing the wave heights of these simulated tsunamis which originate from different source regions, Vanuatu and Tonga trench; at certain coastal areas such as Laucala bay, Navua and Pacific harbor is to further investigate the effects of near shore bathymetry on tsunami wave heights in reference to Satake (1988), research on effects of bathymetry on tsunami propagation and wave heights.

NUMERICAL RESULTS

Tsunami Travel Time charts

The simulation result indicates that the travel time of tsunami from the Tonga trench to the nearest inhabited island in Fiji, Ono-i-Lau is about 1hour. Ono-i-Lau is about 582 kilometers away from the tsunami source. This indicates that the average speed of the tsunami wave is 582 km/hr. The travel time of tsunami from the Vanuatu trench near the Hunter Fracture Zone to the nearest inhabited island of Kadavu in Fiji is about 1hr 10 minutes. The southernmost tip of Kadavu, Nabukelevu-i-Ra, is about 784 kilometers from the source area. This indicates that the average speed of the tsunami wave is about 672 km/hr. The computed travel time of the Tonga trench and Vanuatu trench tsunamis are shown in Figures 3 and 4.

The computed wave heights at Laucala Bay and Navua are unusually high considering their relative locations with respect to the directivity of the tsunami; the tsunami energy is expected to be severely dispersed by the eastern and southern islands before reaching these locations. On the other hand, the unusual high wave heights at these coastal areas suggest that their general bathymetric profiles have gentle slopes of 1:0.1. The first wave that arrived at Laucala bay was about 5cm, the highest wave which measured 25cm arrived 87 minutes later, which could mean that picnickers and residents can still possibly evacuate safely after the arrival of the first wave.

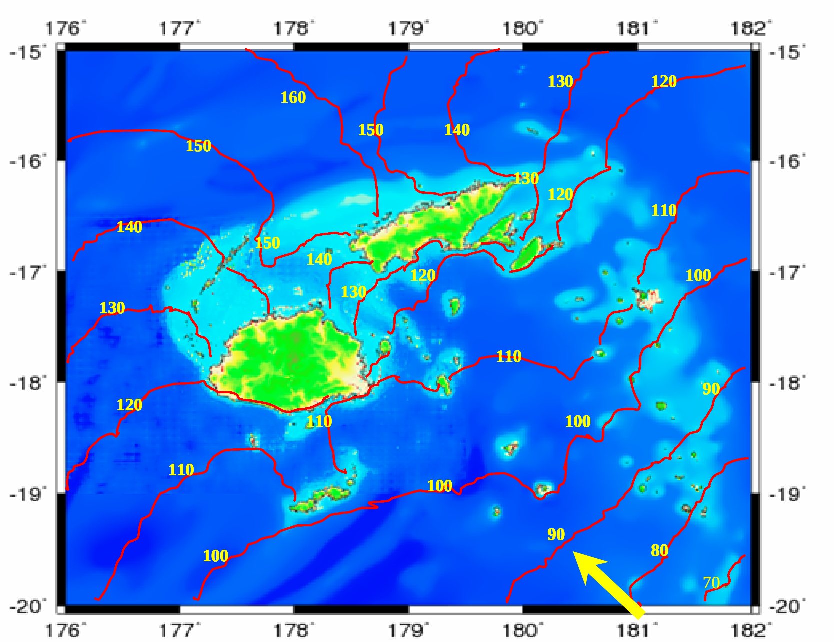

Figure 3. Computed travel time of the Tonga trench tsunami. Each curve indicates wave front at 10 minute increments.

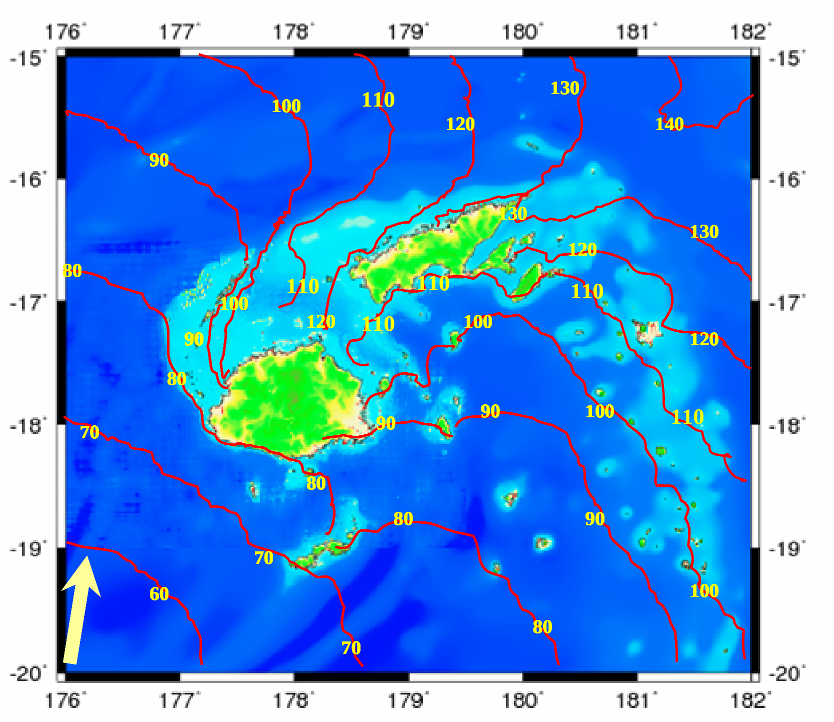

Figure 4. Computed travel time of the Vanuatu trench tsunami. Each curve indicates wave front at 10 minute increments.

The wave heights at Momi Bay, Yasawa-i-rara and Nabukelevu are about 45cm, 40cm and 42 cm respectively, which are relatively very high. The high wave heights are obvious from the fact that these coastal areas are within the range of maximum directivity of tsunamis originating from the Vanuatu Trench. The high wave height at Nabukelevu, the southernmost tip of Kadavu island suggests that the waves propagated directly from the Vanuatu Trench to the shores of Nabukelevu with minimal dispersion. Considering that the numerical simulation carried out in this study is linear, an earthquake of magnitude Mw 8.3 at this same location in the Vanuatu trench may produce 2 meter high tsunami waves at the Momi bay, Yasawa- i-rara and Nabukelevu-i-ra coastal areas.

The Pacific Harbor–Navua coastal area consistently show relative high wave heights indicative that the bathymetric profiles (contours) of these coastal areas are generally shallow gradual slopes.

CONCLUSIONS

The tsunami simulation results generally suggest that the tsunami travel times from the Tonga and Vanuatu trenches to the nearest inhabited Fijian islands are about an hour. In view of these tsunami simulation results, tsunami warnings to the coastal areas of Fiji should be issued within twenty minutes of the earthquake detection. Timely detection of tsunamigenic earthquakes in the Vanuatu-Fiji-Tonga region will pose to be a challenge for Fiji's Mineral Resources Department since it does not have the necessary infrastructure to auto-locate earthquake hypocenters and rapidly determine moment magnitudes (Mw) from earthquake waveform data.

Tsunami wave heights at the coasts can be influenced by the seafloor topography, as seen in the results obtained for Laucala bay, Pacific harbor and the Navua coastal areas, low gradual slopes of the near-shore seafloor can cause the tsunami wave heights to increase.

Although the bathymetric data for Vanuatu-Fiji-Tonga oceanic region is of low resolution, it still serves our purpose well for Numerical simulation using the long wave equation.

Tide gauges equipped with real-time data transmission should be installed at Vatoa, Matuku and Momi bay to effectively forecast the presumed ample lead-time of 20minutes for evacuation of the low-lying coastal areas of Suva.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to the adviser Dr. Hiroshi Inoue, Dr. Bunichiro Shibazaki, Dr. Yushiro Fujii for his continuous support, valuable suggestion and guidance during my study.

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