Citation: Chodavarapu, P., Y. Ohta, B. Shibazaki (2023), Rapid determination of tsunamigenic source parameters and real time inundation modelling for Tews, Synopsis of IISEE-GRIPS Master's Thesis.

RAPID DETERMINATION OF TSUNAMIGENIC SOURCE PARAMETERS AND REALTIME INUNDATION MODELLING FOR TEWS

Patanjali Kumar CHODAVARAPU[1]
MEE22710

Supervisor: Dr. Yusaku OHTA[2*]
Bunichiro SHIBAZAKI[3*]

ABSTRACT

INCOIS-MoES established the Global Navigation Satellite System (GNSS) - Strong Motion Accelerometer (SMA) network of 35 stations in the Andaman and Nicobar Islands to monitor the coseismic displacements caused by tsunamigenic earthquake occurrences. This study adopts a robust methodology for estimating the uncertainties in coseismic fault models with the GNSS data using the Markov Chain Monte Carlo (MCMC) method and conducts a real-time tsunami inundation modeling using TUNAMI simulation code and ADCIRC for the assumed earthquake scenarios in the vicinity of the Andaman and Nicobar archipelago. The results of the probability density function for a range of source parameters estimated by the MCMC method for a rectangular fault model, including stress drop and the Variance Reduction (VR) Index for the various assumed earthquake scenarios and tsunami inundation results for the Port Blair and Car Nicobar regions.

Our findings emphasize the critical roles that the station density and the spatial configuration play in accurately determining certain fault parameters. While the fault length, strike angle, and slip amounts are reliably recovered through the existing GNSS station network, the dip angle, depth, and fault width estimation warrant further improvement. Our study demonstrates the efficient computation of tsunami inundation, achieving results within a mere 5 min computational time for a 12 h simulation of tsunami propagation and inundation modeling for the Andaman and Nicobar archipelago. Finally, this study recommends that implementing the MCMC single rectangular fault model inversion with the real-time tsunami inundation modeling at the ITEWC will significantly enhance the capability of the operational tsunami services for the Andaman and Nicobar archipelago and the Indian Mainland.

Keywords: GNSS Data, MCMC, TUNAMI, ADCIRC, Realtime Inundation.

1. INTRODUCTION

On December 26, 2004, the Indian Ocean tsunami brought widespread devastation, highlighting the urgent need for improved disaster management and warnings. The Indian subcontinent, notably the Andaman and Nicobar Archipelago, suffered severely, pushing nations to reshape disaster preparedness. This led India to establish the Indian Tsunami Early Warning System (ITEWS) in 2007, using real-time seismic monitoring, tide gauges, with backbone support of Open Ocean Propagation Scenario Database (OOPSDB) of tsunami numerical simulations and following a unique Standard Operating Procedure (SOP) to handle near source and far source regions in order to predict tsunamis and provide timely

[1] Indian Tsunami Early Warning Center (ITEWC), INCOIS, MoES, Govt of India, India.
[2] Associate Professor from the Graduate School of Science, Tohoku University.
[3] International Institute of Seismology and Earthquake Engineering, Building Research Institute.
* Chief examiner

advisories by avoiding false alarms. Despite challenges like earthquake magnitude underestimation and communication issues, ITEWS has significantly enhanced disaster readiness by expanding its upstream component with deployment of advanced observation network. The Global Navigation Satellite System (GNSS) - Strong Motion Accelerometer (SMA) network comprising 35 stations in the Andaman and Nicobar Islands was established by INCOIS-MoES. This GNSS-SMA network monitors tsunamigenic earthquake-induced coseismic displacements. In this context, current study is the first of its kind in the study area that carried out with two important research objectives: (a) adopting the Markov Chain Monte Carlo (MCMC) method to estimate uncertainties in coseismic fault models using GNSS data as described by Ohno et al. (2021); and (b) conducting real-time tsunami inundation modeling through the TUNAMI simulation code and ADCIRC for Andaman and Nicobar archipelago.

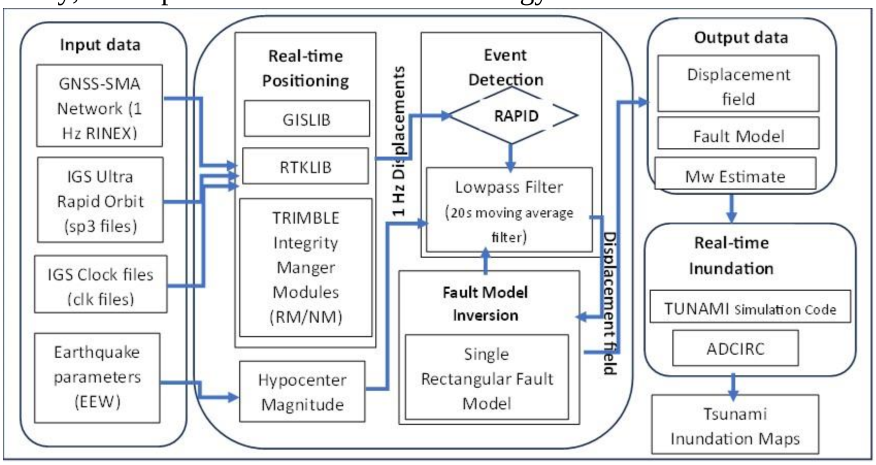
2. DATA

Several crucial datasets are required to perform a comprehensive analysis encompassing co-seismic displacement, event detection, fault parameter estimation, and real-time tsunami inundation modeling in the Andaman and Nicobar Islands. Firstly, a dataset of high-precision GNSS measurements from 35 stations spread across the islands is essential. This dataset captures the subtle ground movements during seismic events, forming the foundation for co-seismic displacement analysis and event detection. The temporal and spatial resolution of these measurements is vital for accurately assessing the dynamic nature of seismic activity. Secondly, the co-seismic displacement data needs to be integrated to estimate the nine source parameters of a fault model (latitude, longitude, magnitude, fault length, width, slip, strike, dip, and rake). This dataset is essential to characterize the earthquake's underlying fault mechanism and magnitude accurately. This information is crucial for creating realistic initial conditions for subsequent tsunami modeling simulations.

Furthermore, the combination of GEBCO 15-arc-second bathymetry data and SRTM 15-arc-second topography data is critical. These datasets provide detailed elevation information for underwater and land areas. They enable the construction of accurate topographical models necessary to establish modeling grids for real-time tsunami inundation simulations. The precise elevation data ensures the fidelity of the simulations and their ability to predict the potential extent of tsunami inundation. By integrating these datasets, comprising GNSS measurements, fault parameter estimates, and detailed elevation information, a comprehensive analysis of seismic events, co-seismic displacements, and tsunami impacts can be conducted in our study area, i.e., the Andaman and Nicobar Islands. This holistic approach will enhance understanding of the region's seismic behavior and improve preparedness and response strategies for future seismic and tsunami events.

3. METHODOLOGY

In the context of our current study, we implemented a robust methodology to estimate uncertainties in various parameters of coseismic fault models. Figure 1 illustrates the methodology's data and process flow outline, which was adopted from the work of Kawamoto et al. (2017) and Ohta et al. (2012). Drawing inspiration from the research conducted by Ohno et al. (2021), our approach involved the utilization of GNSS data and integrated the MCMC



Kawamoto et al. (2017) and Ohta et al. (2012)

method, alongside the Metropolis-Hastings (M-H) algorithm for sampling. The goal was to gain insights into parameters such as longitude, latitude, moment magnitude (Mw), focal depth, strike, dip, rake, fault length, width, amount of slip, stress drop, and VR Index. Through the integration of precise GNSS measurements and the application of the MCMC technique with the M-H algorithm, we generated a diverse set of fault models that aligned with observed data. This ensemble of fault models enabled a comprehensive analysis of parameter uncertainties with probability density functions (PDFs). Additionally, our methodology considered geological constraints and adhered to physical principles, bolstering the accuracy of the estimated fault parameters. In this study, we utilized the shallow water equation in our methodology to perform real-time calculations for tsunami propagation and inundation. Both the TUNAMI simulation code (Yanagisawa, 2022-2023) and ADCIRC (Luettich et al., 1992; Pringle, 2020) were applied to simulate tsunamis in open oceans and coastal regions, as well as to model coastal inundation. The initial deformation conditions were determined by estimating earthquake source parameters using MCMC methodology.

3.1. Bayesian estimation and MCMC Method

In this case, the fault model parameters, such as longitude, latitude, moment magnitude (Mw), focal depth, strike, dip, rake, fault length, width, amount of slip, stress drop were considered as the unknowns to be estimated based on Bayesian estimation (Ohno et al., 2021). Bayesian estimation of the unknown model parameters conditional to the observations is based on Bayes' theorem that described as equation (1):

$$\boldsymbol{p}(\boldsymbol{\theta}|\boldsymbol{d}) = \frac{\boldsymbol{p}(\boldsymbol{d}|\boldsymbol{\theta})\,\boldsymbol{p}(\boldsymbol{\theta})}{\boldsymbol{p}(\boldsymbol{d})} \tag{1}$$

where $\boldsymbol{\theta}$ is model parameter, $\boldsymbol{d}$ is permanent displacement data, given that N is number of stations, the dimension of $\boldsymbol{d}$ is 3N, $\boldsymbol{p}(\boldsymbol{d})$ is PDF of observation, $\boldsymbol{p}(\boldsymbol{\theta})$ is prior PDF of model parameters (Conditional PDF) represents priori information, assuming a uniform distribution in each assumed range, $\boldsymbol{p}(\boldsymbol{d}|\boldsymbol{\theta})$ is likelihood function measures the degree of fit between observed $\boldsymbol{d}$ and calculated $\widehat{\boldsymbol{d}}(\boldsymbol{\theta})$.

The MCMC methodology (Ohno et al., 2021) was then employed to estimate the uncertainties in the fault model parameters. MCMC method is a statistical technique that generates a large number of samples from the parameter space, based on a given prior distribution and likelihood function. The MCMC algorithm iteratively sampled the parameter space with MCMC sampler- the basic M-H method (Ohno et al., 2021) adopted for sampling. M-H sampler is generating a chain of samples that approximated the posterior distribution of the parameters in three steps as described by Ohno et al. (2021).

3.2. Tsunami simulation

For the present study, we used TUNAMI simulation code (Yanagisawa, 2022-2023) to simulate tsunamis propagating in open oceans and coastal inundation, as well as ADCIRC (Luettich et al., 1992; Pringle, 2020) to model coastal inundation using the initial conditions of deformation computed with estimated earthquake source parameters by MCMC methodology. For real time computations, the TUNAMI simulation code is used in a standard system configuration. Here various parameters like computational domain size, time step size, boundary conditions, nesting grids 1,2,3, and 4, and other modeling parameters required by TUNAMI simulation code appropriately selected based on Courant-Friedrichs-Lewy (CFL) criteria as described by Yanagisawa (2022-2023). The foundational work on ADCIRC and its detailed description was provided by Luettich and colleagues in 1992. For the present study, simulations were conducted using the ADCIRC-2DDI version, allowing for effective analysis and assessment.

4. NUMERICAL SETUP AND RESULTS

4.1 Experimental Setup

Accurately modeling earthquake-induced displacements is of utmost importance when testing the automatic uncertainty estimation of a single rectangular fault model using the MCMC methodology by Ohno et al. (2021) for our study area as described in the methodology section. However, due to the unavailability of actual earthquake event data for the study area, analyzing ground displacements for different historical earthquakes presents a significant challenge. To overcome this limitation, we propose an experimental approach to generate synthetic displacements for GNSS stations in the Andaman and Nicobar Islands, simulating various hypothetical earthquake scenarios with different locations along the trench axis as shown in Figure 2 and combinations of other earthquake source parameters.

The earthquake source parameters for these simulations are selected based on historical earthquakes and available geophysical datasets. Accordingly, the realistic synthetic displacements are generated by defining coseismic fault model parameters, specifying the assumed epicenter's location along the trench axis, near the trench axis, and far from it for the proposed numerical experiments. Moreover, considering the depth and dip angle of the coseismic fault is crucial as it influences the pattern of ground displacements; variations in strike angle of fault are also considered for this study by considering depth, dip and strike angles based on subduction zone geometries from USGS SLABs 2.0 by Hayes. (2018). The other parameters like fault length, width and amount slip are calculated based on Wells and Coppersmith (1994) scaling laws that relate these parameters to the earthquake magnitude, which are commonly used in seismology and fault studies.

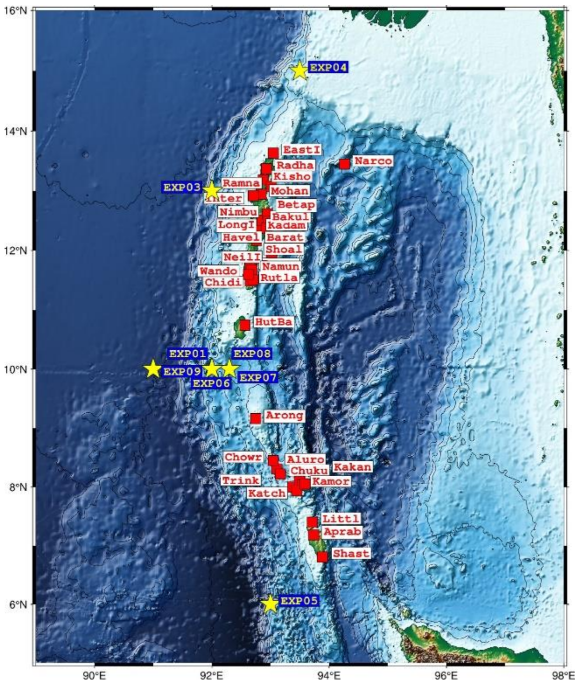


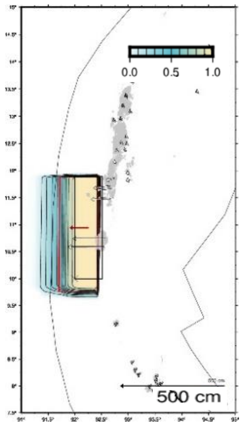
Figure 2. Locations of assumed earthquakes (yellow stars) along with GNSS-SMA network of 35 stations (red rectangles) in Andaman and Nicobar archipelago (study area).

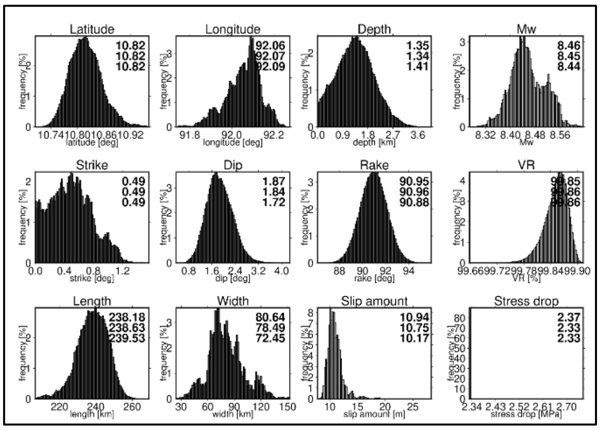
4.2 Uncertainty estimation for coseismic fault model parameters

For the sake of simplicity, we will focus on the Mw 8.2 scenario adjacent to the Andaman and Nicobar Islands with parameters shown Table 1. Upon successfully producing synthetic displacements for all 35 GNSS stations using the MUDPY software (Melgar & Bock, 2015) in conjunction with the Okada formulation (Okada, 1985), a stochastic technique was implemented to inject random noise as well. Through the application of the MCMC algorithm, it became possible to sample from the posterior distribution of model parameters. Upon the execution of the MCMC algorithm, PDFs for each parameter of the fault model were derived. These PDFs, as depicted in Figure 3, furnish a comprehensive illustration of the uncertainty linked to each individual parameter. In Figure 3, sections (a) estimated coseismic fault models and (b) portray the Posterior PDFs, which illustrate the estimation process of fault parameters. To evaluate the overall performance of the model the Variance Reduction (VR) Index comes into play. A higher VR Index signifies a strong alignment between the synthetic displacements and the GNSS observations.

Table1: Assumed Earthquake

Lat (°)	Long (°)	Mag (M_w)
10	92	8.2
Str (°)	Dip (°)	Rake (°)
360	6	90
Length (km)	Width (km)	Slip (m)
211	56	7.7



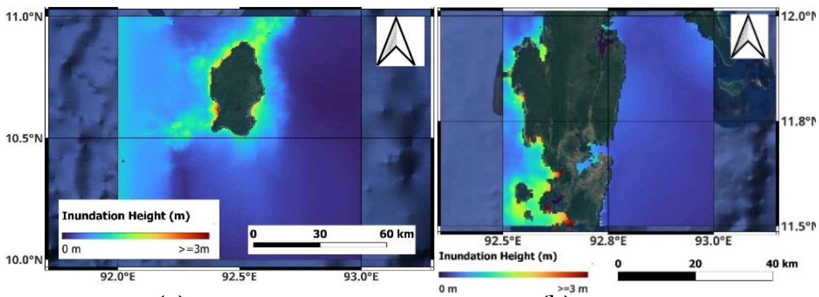


(a) (b)

Figure 3. Results from MCMC method for the scenario of Mw 8.2 near the Andaman and Nicobar Islands with the parameters listed in Table 1: (a). estimated coseismic fault models with varying color gradient from light blue to yellow (0.1 to 1.0) indicate the range of solutions, with yellow representing the most probable fault model. The estimated coseismic fault model (mode value) is represented by the red rectangle with a red vector of the slip direction for the estimated fault. The black and white vectors denote the observations (synthetics) and calculations based on coseismic fault model respectively. and (b). posterior PDFs of nine source parameters of the estimated coseismic fault model including Latitude, Longitude, Depth, Strike, Dip, Rake, Length, Width and Slip amount along with Mw, VR and Stress drop. The ranges on horizontal axis reflect the maximum search ranges for each parameter. Inserted values in the upper right-hand corner denote the mean, median and mode in the top, middle and bottom positions respectively.

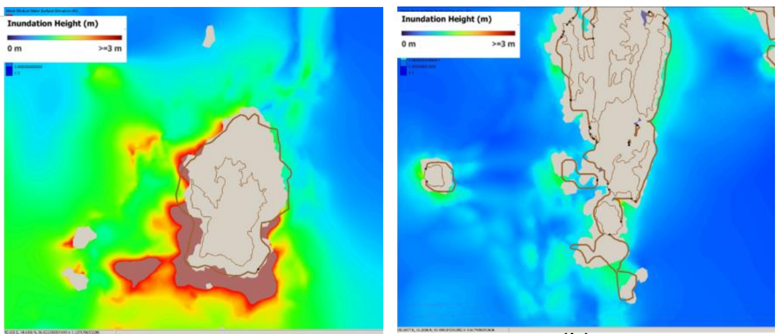
4.3 Real time tsunami inundation modelling

The TUNAMI simulation code, developed by Dr. Hideaki Yanagisawa, Tohoku Gakuin University (Yanagisawa, 2022-2023), was harnessed to calculate the inundation caused by the hypothetical Mw 8.2 earthquake near the western shoreline of the Andaman and Nicobar Islands. The initial sea floor deformation required for numerical simulation of tsunami propagation and inundation is calculated using the Okada formulation with those nine fault parameters estimated through the MCMC method. This deformation is then given to TUNAMI simulation code and ADCIRC, both employing numerical techniques to address nonlinear shallow water equations, for computation of tsunami propagation and inundation in our study area.



(a) (b)

Figure 4. Inundation heights for Grid - 4 of the (a) Car Nicobar and (b) Port Blair regions generated by TUNAMI.



(a) (b)

Figure 5. Inundation heights for the (a) Car Nicobar and (b) Port Blair regions generated by ADCIRC.

Figure 4 offers a depiction of inundation heights for Grid – 4, highlighting the regions of Car Nicobar and Port Blair within the scenario of the Mw 8.2 earthquake near the Andaman and Nicobar Islands calculated using TUNAMI simulation code whereas Figure 5 depicts those calculated using ADCIRC.

5. DISCUSSION AND CONCLUSIONS

In the context of our numerical experiment, we meticulously designed scenarios encompassing both interplate and intraplate (outer rise) earthquakes. These experiments aimed to shed light on the complex interplay between earthquake characteristics and observational constraints within the context of a given station network.

One significant finding was the successful constraint of the most probable source area or location, a triumph largely attributed to the density of stations incorporated within the network. In general, these estimates fell within the predefined range of input parameters. Yet, notable exceptions were observed in the case of dip angle, fault width, and depth. These parameters suffered from discrepancies owing to the distinctive configuration of the station distribution, which was structured as a linear array extending from south to north of Andaman and Nicobar Islands. For earthquakes situated near the network, both strike angle and fault lengths were notably well-recovered, a testament to the network's effectiveness in these cases. However, the estimation process encountered challenges when addressing dip angle, fault width, and depth. In particular, the estimated fault width often leaned towards overestimation, potentially due to the constraints imposed by the linear station arrangement. A pivotal observation pertained to instances where the station network effectively captured the fault rupture area.

To sum up, in this research, we used a strong approach to figure out uncertainties in earthquake fault models using GNSS data. We also performed simulations of how tsunamis would spread using TUNAMI simulation code and another one ADCIRC, based on hypothetical earthquake scenarios. Moreover, we could quickly calculate tsunami effects in just 5 minutes for a 12-hour simulation, highlighting the efficiency. Ultimately, we suggest that using the MCMC method along with real-time tsunami simulations at the ITEWC can greatly improve how well we can predict tsunamis and offer better tsunami warning services.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisors Dr. Yusaku Ohta, Dr. Bunichiro Shibazaki for their valuable support and experience which helped me to complete my research successfully, and to Dr. Yushiro Fujii for his guidance and advice during my individual study. I would also like to acknowledge Dr. M. Ravichandran, Chairman, INCOIS, Secretary, MoES, and Dr. Tummala Srinivasa Kumar, Director, INCOIS for nominating me as ***Frist Participant*** from India and permission to use GNSS data from GNNS-SMA Network in Andaman and Nicobar Islands.

REFERENCES

Kawamoto, S., Ohta, Y., Hiyama, Y., Todoriki, M., Nishimura, T., Furuya, T., . . . Miyagawa, K. (2017). Journal of Geophysical Research: Solid Earth, 122(2), 1324-1349.

Luettich, R. A., Westerink, J. J., & Scheffner, N. W. (1992). ADCIRC-2DD1 and ADCIRC-3DL

Ohno, K., Ohta, Y., Kawamoto, S., Abe, S., Hino, R., Koshimura, S., . . . Kobayashi, H. (2021). Earth, Planets and Space, 73(1), 127. https://doi.org/10.1186/s40623-021-01425-0

Ohta, Y., Kobayashi, T., Tsushima, H., Miura, S., Hino, R., Takasu, T., . . . Demachi, T. (2012). Journal of Geophysical Research: Solid Earth, 117(B2)

Okada, Y. (1985). Bulletin of the seismological society of America, 75(4), 1135-1154

Pringle, W. J. (2020)., Zenodo, https://doi.org/10.5281/zenodo.3911282,. In

Yanagisawa, H. (2022-2023). Lecture Notes on "Numerical Simulation of Tsunami Inundation and Its Application", IISEE/BRI.

Wells, D. L., & Coppersmith, K. J. (1994). Bulletin of the seismological Society of America, 84(4), 974-1002.