Geo-INQUIRE installation: PTHA - Probabilistic Tsunami Hazard Assessment (TA2-541- 6/TA2-541-7/TA2-541-8)

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Project: Geo-INQUIRE
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Project report ID: C2_TA2-541-6_1
Transnational access principal investigator: Dr. Siva Srinivas Kolukula
Science Domain: Earth and Climate Science
Date of visit: Not Applicable
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Data Products: Tsunami simulation results to be uploaded to the Simulation Data Lake (SDL)

Project title: Site-specific PTHA for India coasts in PCTWIN

1. Introduction

The catastrophic December 26, 2004, Indian Ocean tsunami exposed India's extreme vulnerability to marine hazards, claiming over 16,000 Indian lives and devastating thousands of kilometres of coastal communities [1]. India, due to its hyper-dense coastlines and critically narrow tsunami arrival windows, is at risk of being struck by waves from nearby subduction zones that can strike land within 15 to 120 minutes. In response, India established a Tsunami Early Warning Centre at the Indian National Centre for Ocean Information Services (INCOIS) in Hyderabad, which successfully utilises a network of seismic sensors, deep-sea pressure recorders and tide gauges to issue timely regional alerts [2]. However, critical operational gaps remain: the current system relies on a deterministic, "worst-case scenario" model that may cause false alarms, struggles to quickly characterise complex non-seismic threats like submarine landslides, and fails to bridge the "last mile" communication gap to ensure marginalised villagers know exactly how to evacuate. To solve these vulnerabilities, India launched the People-Centred Tsunami Early Warning for the Indian Coastlines (PCTWIN) initiative, a collaborative four-year research project with the UK. Co-led by University College London (UCL) and INCOIS, the initiative integrates advanced probabilistic forecasting models with deep community-level readiness along vulnerable Indian coastlines [3]. Instead of relying on deterministic, worst-case-scenario forecasts, the project PCTWIN utilises real-time probabilistic forecasts to calculate precise impacts, generate detailed risk maps for vulnerable populations, and establish inclusive, village-level evacuation plans. To enable local hazard analysis for local sites, researchers in PCTWIN applied for the present Transnational Access project PTHA-WESTIND offered through Geo-INQUIRE.

One of the core pillars of PCTWIN is a site-specific Probabilistic Tsunami Hazard Analysis (PTHA), under which several high-risk coastal pilot sites, such as Edavanakkad, Purrakkad village in Kerala's Ernakulam district, have been strategically selected for intensive inundation studies. Because these specific communities were heavily inundated and suffered severe

casualties during the 2004 disaster, researchers are utilising their historical exposure data to model probabilistic flooding scenarios and design locally tailored evacuation maps [4]. To this end, a few pilot sites, namely Purakkad in Kerala along the west coast of India, Chennai in Tamil Nadu and Noliasahi in Odisha along the east coast of India, were selected for numerical modelling of potential inundation from various tsunamigenic seismic sources. The simulations are being performed using the Hyperbolic Systems and Efficient Algorithms (HySEA) package, a high-performance code developed by the EDANYA group at the University of Málaga, Spain [5]. Specifically, Tsunami-HySEA v4.2.0, Monte Carlo edition, installed on the Leonardo supercomputer located in Italy and operated by CINECA, is being utilised. Prior to simulating site-specific inundation scenarios, HySEA was run to test the nested grids for the 26 December 2004 tsunami.

2. HySEA modelling of the 2004 Indian Ocean Tsunami

The objective of site-specific studies is to implement high-resolution numerical modelling to establish highly localised, site-specific PTHA for the Indian coastline. Before running tens to hundreds of thousands of simulations to predict future risks and generate hazard curves and hazard maps, the HySEA nested-grid setup must be calibrated and verified. To this end, the historic 26th December 2004 Great Sumatra Earthquake was simulated, and the model's accuracy was assessed by comparing simulated water levels with real-world observations. Figure 1 shows the nested multi-resolution grid configuration used for the current study.

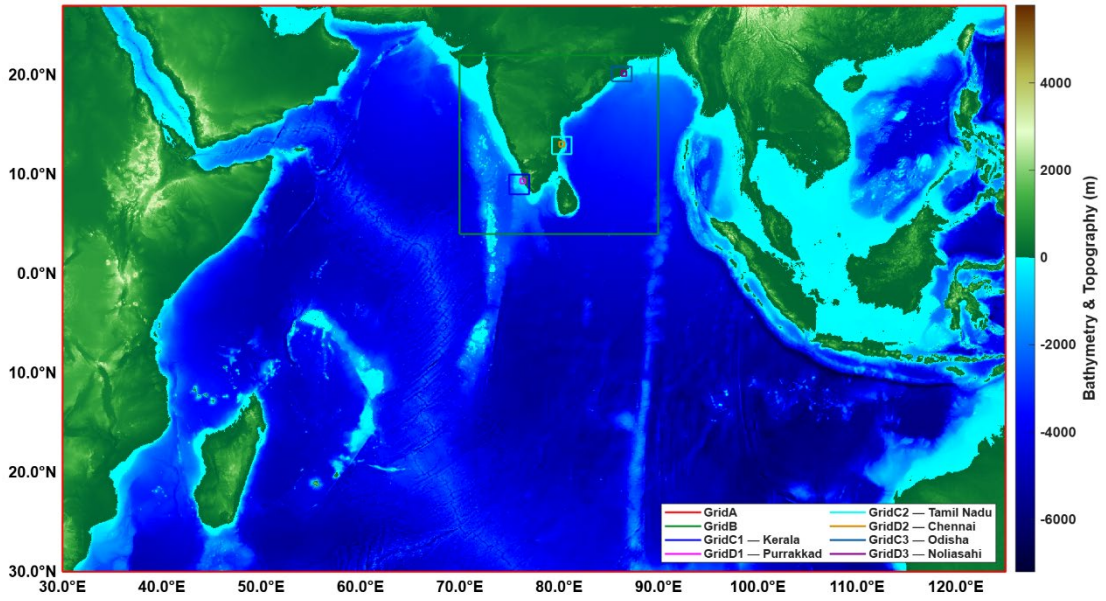

Figure 1: HySEA nested grid configuration for the historic 26th December 2004 great Sumatra Earthquake

The nested grid system spans a broad range of resolutions, from 960 m in Grid A to 30 m in Grid D, with finer resolution implemented near the site-specific coastal region to capture detailed flooding behaviour due to tsunamis. Grids A and B, which cover the large, deep-water open-ocean domains, are structured at resolutions of 960 m and 480 m, respectively, using bathymetry from the General Bathymetric Chart of the Oceans (GEBCO) [6]. Grids C and D, representing the shallow-water and inundation zones, have finer resolutions of 120 m and 30 m, respectively. To simulate local coastal effects, the models use a merged elevation dataset at

these resolutions: 120 m for Grid C and 30 m for Grid D. Grids C and D incorporate combined and smoothed topography and bathymetry from GEBCO, 100 m high-resolution coastal bathymetry from the Copernicus Marine Environment Monitoring Service (CMEMS) [7], and precise land topography from Fathom DEM [8], a global elevation model. The various topographic and bathymetric data sources were reprojected to a common 30 m coordinate grid and smoothed along the coastline using Gaussian filtering to avoid artefacts.

The initial disturbance for the tsunami generation is simulated using a five-segment fault rupture mechanism configured with fault lengths, widths, depths, and slip displacements based on Grilli et al. (2007) using Okada surface deformation model [9]. The initial surface heights are also corrected for across horizontal and vertical directions employing HySEA's inbuilt Satake-Tanioka and Kajiura filters. The initial vertical displacement of the seafloor directly forces the ocean surface up, generating the initial tsunami wave train. The simulated wave energy propagated outward from the Sumatra–Andaman subduction zone across the Indian Ocean basin, exhibiting highly amplified wave heights in the Bay of Bengal and directed energy corridors toward southeast India and Sri Lanka. Figure 2 shows the maximum wave height captured across the domain from a 24-hr HySEA simulation; the figure also displays the locations of the tide gauges at which the simulated tsunami water levels are compared with observations.

Figure 3 shows the time series of observed tsunami water levels compared with HySEA calculations at coastal stations, along with comparison statistics, regression coefficient (R) and Root Mean Square Error (RMSE). The figure demonstrates that the model successfully reproduced wave arrival times, wave heights, and repeating wave cycles at multiple key geographic locations, such as Male (Maldives), Chennai (India), and Tuticorin (India), yielding high correlation coefficients and low RMSE values. The respective tide gauge locations are shown in the titles of the corresponding plot panels. Simulating 24 hours of tsunami propagation required approximately 5 hours of computational time on the Leonardo supercomputer. Figure 4 shows the inundation results for the three nested Grid D domains—Purakkad in Kerala, Chennai in Tamil Nadu, and Noliasahi in Odisha—that were employed in the simulation. The results reveal very fine-scale inundation features, with significant portions of each region flooded due to the tsunami.

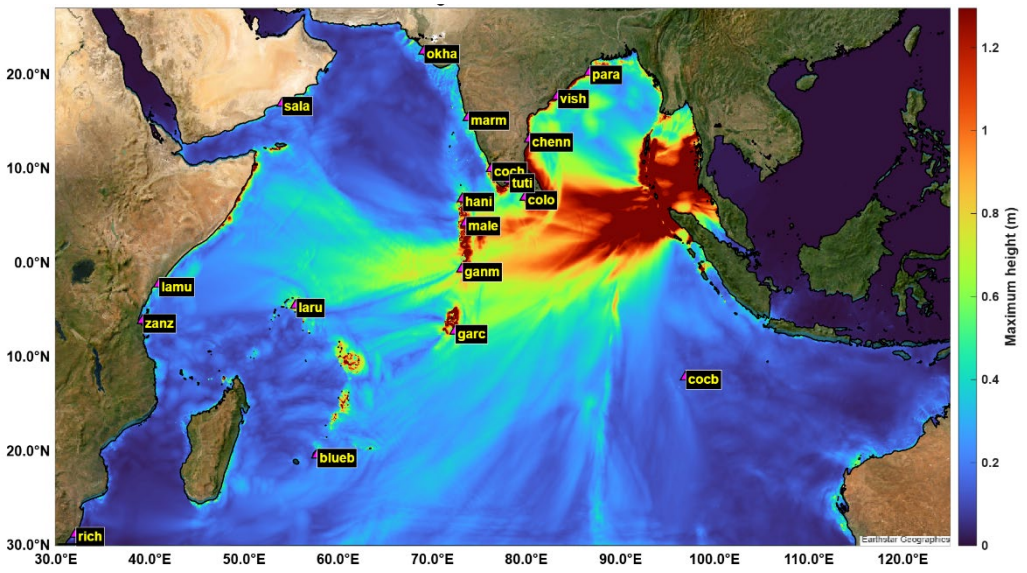

Figure 2: HySEA simulated maximum wave height along with the tide gauge locations used for comparing water level time series

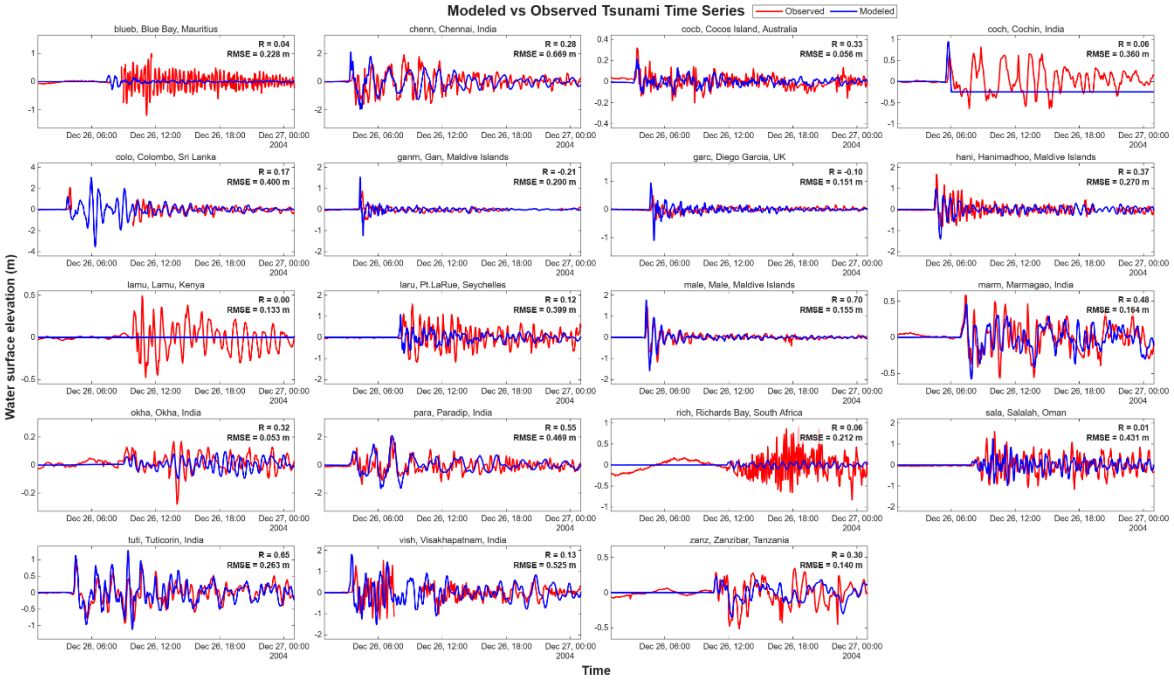

Figure 3: Comparison of the HySEA computed tsunami wave heights against the tide gauge observations at various locations for the Indian Ocean 2004 event. The red colour corresponds to tide gauge observations, and the blue colour represents a numerical simulation. The locations of the tide gauge stations shown as titles on each subplot and shown in Figure 2.

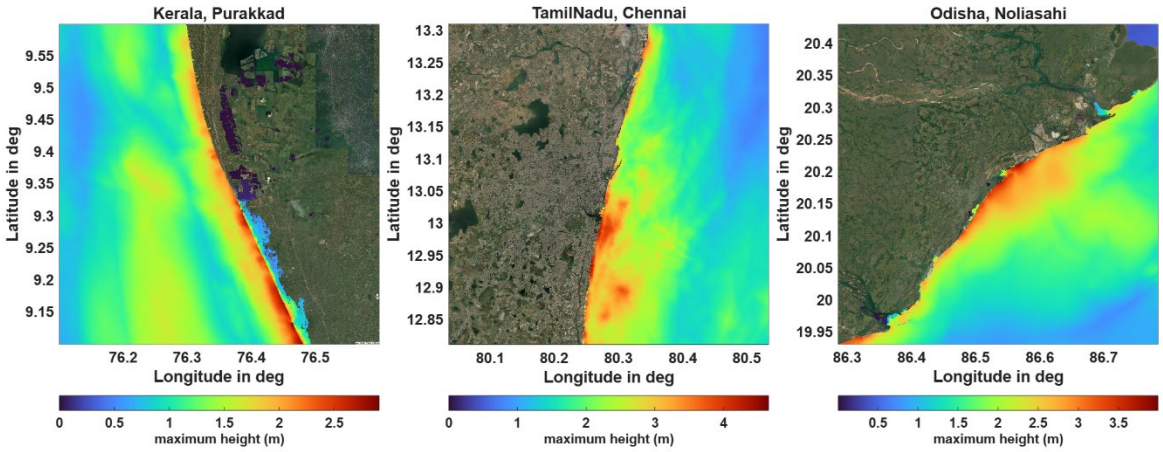

Figure 4: Spatial depiction of inundation extent along the three nested D grids depicting inundation

3. HySEA nested grid setup for site-specific PTHA

After validating HySEA against the 2004 Indian Ocean tsunami, the high-resolution Grid D model is deployed to map local inundation, transitioning from the simulation of individual historical events to the evaluation of long-term probabilistic risks. The setup focuses on three coastal regions highly vulnerable to tsunami hazards: Purakkad on the west coast in Kerala, Chennai in Tamil Nadu, and Noliasahi in Odisha, both the sites on the east coast of India. Using pre-computed Green's functions, thousands of diverse earthquake fault combinations capable of generating tsunami wave amplitudes greater than 20 cm at the sites are selected to run the simulations, as shown in Figure 5. Approximately 50,000 unique scenarios from the Makran and Sumatra subduction zones are simulated. From each run, the maximum wave height on Grid D and 10-s time series at the points of interest (POIs), shown in Figure 5, are saved for subsequent statistical probability analysis. Each simulation covers 12 hours of physical time and requires approximately 2 hours of wall-clock time. The stochastic slip distributions for the runs are modelled from pyANTI-FASc [10]. Additional thousands of simulations will be performed to account for uncertainties in earthquake scaling laws and variations in the rigidity modulus. Once all simulations are completed, the next phase of the project will focus entirely on analyzing this large dataset. The analysis will extract data from the completed simulations to construct site-specific hazard curves for different thresholds of maximum wave height, inundation depth, and runup height. By compiling these curves, probabilistic hazard maps will be produced to define the statistical likelihood of a specific coastline experiencing a given level of flooding over a specified timeframe. Ultimately, this comprehensive workflow will provide the rigorous, site-specific science necessary to design next-generation, community-cantered early warning systems.

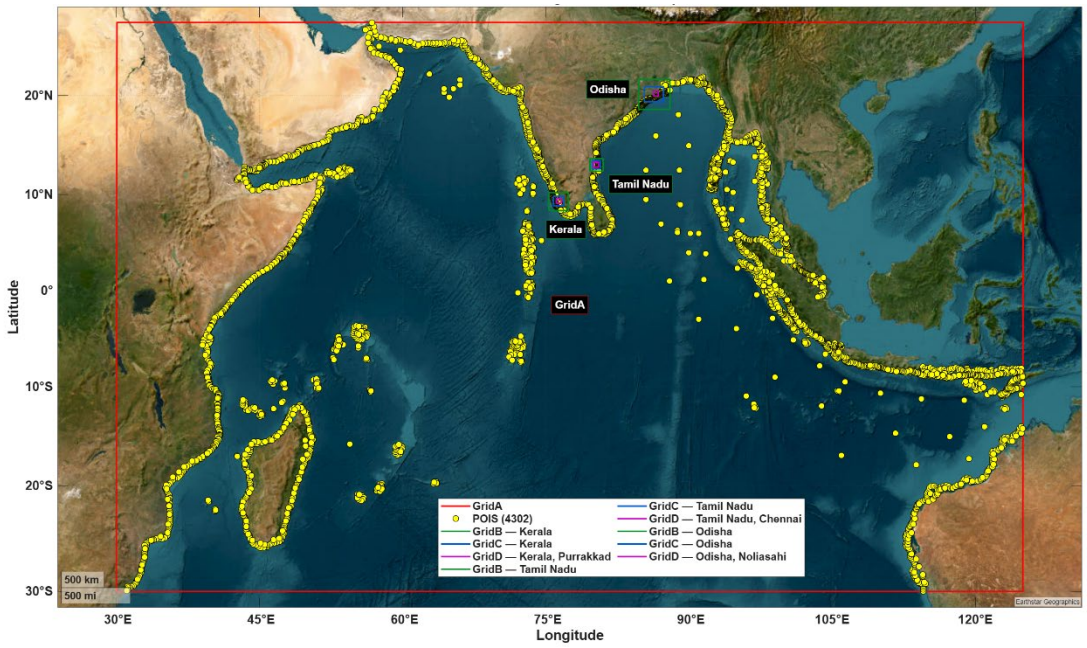

Figure 5: HySEA nested grid configuration for site-specific PTHA studies

Acknowledgement

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