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Integrating Real-Time Seismic Monitoring for National Resilience: A Case Study of Timor-Leste

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Introduction

Timor-Leste is situated at one of the world's most complex tectonic junctions, primarily defined by the interaction between the north-northeast moving Australian Plate and the Banda Microplate (see Figure 1). High-resolution GPS measurements indicate a convergence rate of approximately 70–80 mm/year (7–8 cm/year), a velocity that drives the intense deformation and shortening observed across the Timor-Leste orogen [1]. As the dense oceanic crust of the Australian Plate has already subducted, its thick, buoyant continental crust is currently colliding with the Banda Arc. This collision has "jammed" the subduction zone, forcing the seafloor upward to create the island of Timor. This intense tectonic activity defines the nation's high seismic risk profile.

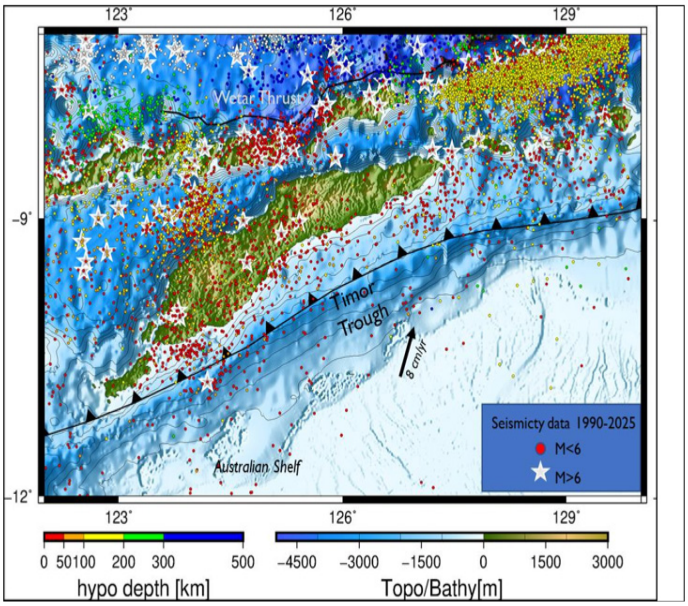

Figure 1: Regional tectonic map of the Timor sector of the Sunda–Banda arc system. Earthquake epicenters from 1990–2025. Seismicity delineates the active subduction interface south of Timor, intraslab events beneath the Banda Sea, and back-arc thrusting along the Flores–Wetar system, illustrating the strain partitioning characteristic of arc–continent collision.

Tectonic velocity data and plate boundaries are adapted from Nugroho et al. and regional seismicity catalogues.

This high-energy tectonic activity defines the nation's high seismic risk profile. Historical data confirms the region's vulnerability to devastating events, most notably the 1938 M8.5 "Great Banda Sea" earthquake, originating from the complex subduction-collision boundary north of Timor [2]. In 1995 M6.9 shallow event in the Ombai Strait, which triggered a 1–4 meter tsunami impacting Dili and Maubara [3,4]. More recently, the 2021 M7.3 Banda Sea earthquake highlighted the continued threat, likely causing land rupture as far inland as Venilale (IPG catalog, 2022).

In response to these persistent geological threats, the Instituto de Geociências de Timor-Leste (IGTL), formerly the IPG, has spearheaded the development of a robust national monitoring backbone. The primary objective of the IGTL framework is to modernize the national seismic network, transitioning from a localized "offline" recording system to a dynamic "real-time" telemetry network. By integrating high-fidelity sensing with automated processing, the IGTL aims to enhance National Resilience and Disaster Risk Reduction (DRR) capabilities.

As the following sections detail, this modernization bridges the gap between raw geoscientific data and actionable safety parameters. While the tectonic setting ensures that seismic activity is a geographic certainty, the integration of real-time monitoring provides the essential tools— including rapid notifications, ShakeMaps, and engineering design spectra—to ensure that disasters remain optional.

Evolution of the National Seismic Network in Timor Leste

The development of Timor-Leste's seismic monitoring capabilities represents a strategic shift from basic data acquisition to an advanced, real-time early warning and hazard assessment infrastructure. This evolution can be categorized into two distinct technological eras:

Foundational Development (2016–2021)

The inception of the national network involved the strategic placement of three permanent seismic stations designed to establish a baseline for regional seismicity. During this period, the Instituto de Geociências de Timor-Leste (IGTL) focused on identifying high-risk seismic zones and testing the durability of instrumentation in the nation's tropical and mountainous terrain.

Modern Real-Time Infrastructure (2021–Present)

The current monitoring era is defined by a significant densification of the network, which now comprises a dual-sensor approach:

- Broadband Seismometers (BBS): Seven high-sensitivity BBS stations provide the capability to detect a wide range of frequencies, allowing for the recording of both distant teleseismic events and local micro-seismicity (typically below M L 2.0).
- Strong Motion Accelerometers (SMA): The deployment of 13 SMA units is critical for urban and infrastructure resilience. Unlike BBS sensors, which may "clip" or saturate during intense shaking, these accelerometers are designed to record high-amplitude ground motions near the epicenter.

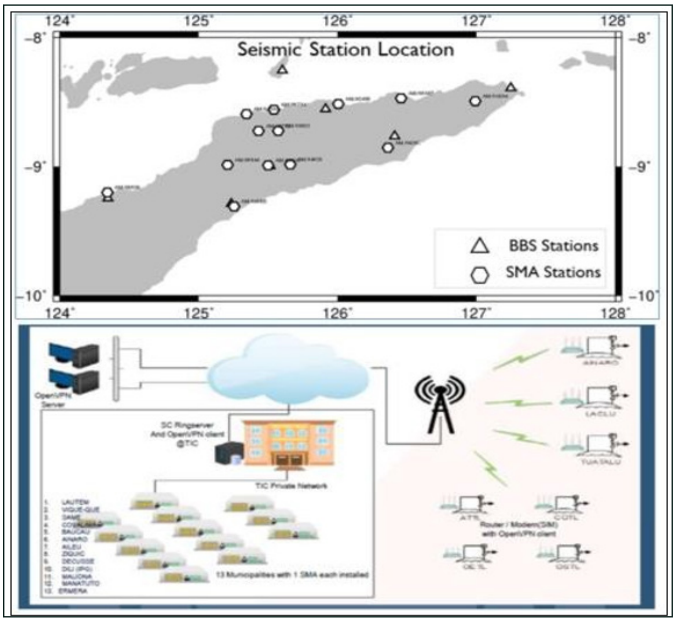

Figure 2: (Top) Geographic localization of the integrated national seismic network. The map illustrates the strategic placement of seven Broadband Seismometers (BBS) and 13 Strong Motion Accelerometers (SMA) across the municipalities. (Bottom) Schematic representation of the network topology and telemetry workflow. This technical diagram details the connectivity between remote field stations and the central processing hub.

Network Topology and Data Integrity

To overcome the geographical challenges of the Timor-Leste landscape, the IGTL has implemented a sophisticated network topology:

- Real-Time Telemetry: By integrating industrial-grade 4G routers, the network has transitioned from "offline" manual data retrieval to continuous SeedLink streaming. This ensures that data reaches the central processing hub in Dili within seconds of a seismic arrival.
- All-in-One Digital Instrumentation: The shift toward all-in-one digital seismometers has streamlined field operations. These units integrate the sensor, digitizer, and GPS timing into a single ruggedized housing, reducing the complexity of site installations and minimizing potential points of failure.
- Station Hardening: Each site utilizes specialized seismic shelters and reinforced enclosures to protect sensitive electronics from environmental degradation, ensuring long-term data continuity in high-humidity conditions.

Methodology and Framework: Real-Time seismic Integration

The primary objective of the IGTL framework is to modernize the national seismic infrastructure, transitioning from a localized, "offline" recording system to a dynamic, "real-time" telemetry network. This modernization is a critical component of Timor-Leste's National Disaster Risk Reduction (DRR) strategy, aimed at reducing lead times for emergency response and enhancing public safety. The integrated monitoring workflow is categorized into three systematic phases. As shown in the framework flowchart (Figure 3), the transition from the Detection to the Decision phase occurs in near-real-time, facilitating rapid characterization of the Banda Sea's complex tectonic events."

The Detection Phase: Signal Acquisition and Telemetry

High-fidelity seismic signals are captured by the broadband and strong-motion sensors and digitized at high sampling rates (typically 100 Hz). These data packets are encapsulated using the SeedLink protocol and transmitted via a dedicated VPN over the 4G cellular backbone. To ensure the highest level of data continuity, the detection phase employs a low-latency telemetry architecture that prioritizes packet delivery from remote stations to the central processing facility in Dili.

The Decision Phase: Automated Processing and Validation

Once the data reaches the central server, it enters the decision phase, which utilizes the SeisComP software suite for automated signal analysis.

- The system performs real-time phase picking (P-wave and S-wave detection) and hypocenter triangulation. This phase involves a rigorous validation process where the software distinguishes between tectonic events, anthropogenic noise, and atmospheric interference. During the decision phase, automated algorithms calculate the magnitude (ML or Mw) and depth of the event, triggering an internal alert if the seismic parameters exceed predefined safety thresholds.
- Refined Analysis: If an event is confirmed, the system automatically generates ShakeMaps and calculates Peak Ground Acceleration (PGA) to estimate the potential impact on built environments.

The Dissemination Phase: Rapid Alerting and Public Information

Upon validation of a significant earthquake, the IGTL framework initiates a multi-channel dissemination protocol. This includes the push of notifications to the official IGTL mobile application, updates to the web-based earthquake portal, and direct data feeds to the National Directorate for Civil Protection.

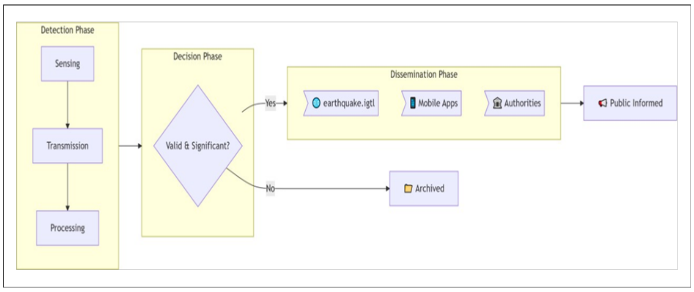

Figure 3: Schematic representation of the IGTL end-to-end seismic monitoring framework. The diagram highlights the transition from physical ground motion sensing (Detection) to algorithmic validation (Decision) and finally to institutional and public notification (Dissemination).

Results: Critical Output for Resilience

The integration of the national seismic network with the SeisComP (Seismic Communication and Processing) software suite allows the IGTL to transform raw waveform data into four high-value analytical products. These outputs serve as the technical foundation for both emergency response and long-term urban planning.

Automated Real-Time Notifications

The system's primary operational output is the rapid characterization of seismic events. By utilizing automated phase-picking algorithms, the system can determine the hypocenter (latitude, longitude, and depth) and magnitude (ML or Mw) of an earthquake within a two-minute window of the initial P-wave arrival. This low-latency notification system minimizes the 'blind zone' for emergency responders, providing immediate situational awareness that is critical for the mobilization of civil protection units during the first 'golden hour' following a significant rupture.

Instrumental Intensity Mapping (ShakeMaps)

Beyond simple point-source parameters, the IGTL framework generates ShakeMaps—near-real- time visualizations of ground motion intensity. These maps combine point-source data with local site conditions to estimate the geographic distribution of shaking. Unlike magnitude, which describes the energy at the source, ShakeMaps describe the instrumental intensity (MMI) experienced at the surface. This allows authorities to identify specific "hotspots" where damage is likely to be most severe, even in areas without direct sensor coverage. By interpolating Peak Ground Acceleration (PGA) across the varying lithology of Timor-Leste, ShakeMaps provide a localized assessment of potential structural impact, facilitating a more targeted disaster response.

High-Resolution Seismic Catalog

The transition to real-time monitoring has significantly lowered the network's completeness magnitude (Mc). The IGTL now maintains a comprehensive database that captures micro- seismicity (events below M L 3.0) that was previously undetected. This high-resolution catalogue is essential for mapping active fault traces and understanding the diffuse deformation patterns within the Banda Microplate collision zone. The accumulation of a high-density seismic catalogue enables the statistical analysis of b-values and return periods, providing a superior empirical dataset for future revisions of the National Seismic Hazard Map.

Engineering Parameters and Design Spectra

A critical bridge between geoscience and public safety is the provision of Peak Ground Acceleration (PGA) and Response Spectra to the engineering community. Data from the 13 Strong Motion Accelerometers (SMA) provide the actual "shaking signatures" required by structural engineers. This data is used to develop Seismic Design Spectra, which ensure that new infrastructure—such as bridges, hospitals, and government buildings—are constructed to withstand the specific spectral accelerations expected in Timor-Leste. The delivery of site-specific engineering parameters facilitates the transition from generic building codes to evidence-based, earthquake-resistant design, effectively reducing the long-term vulnerability of the nation's built environment.

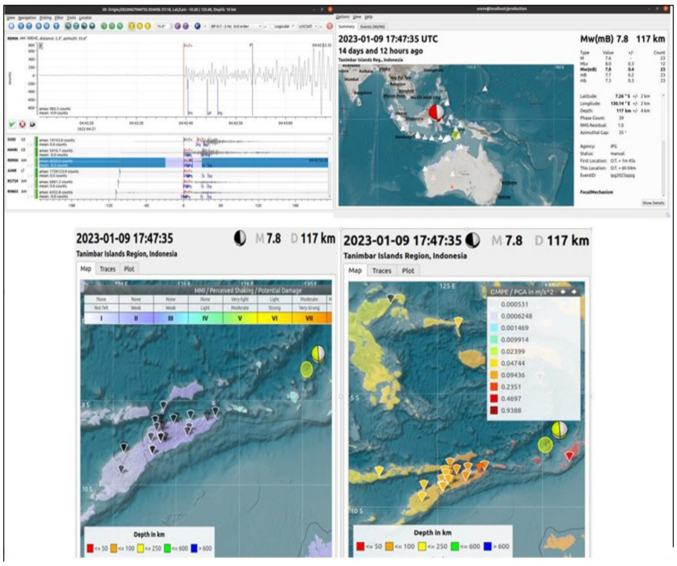

Figure 4: Representative ShakeMap generated by the SeisComP engine, illustrating the spatial distribution of instrumental intensity and its correlation with local tectonic features.

Seismic Hazard Analysis

A critical component of this study involved characterizing the recurrence relationship of regional seismicity through the calculation of b-values from the Gutenberg-Richter law as shown in Figure.

The b-value, which represents the ratio between small and large magnitude events, serves as a fundamental indicator of the tectonic stress regime in the Timor-

Leste region.

- Shallow Crustal Sources (b=0.86): The analysis of shallow crustal events yielded a b-value of 0.86. In seismological terms, a b-value significantly lower than the global average of 1.0 indicates a region under high differential stress with a higher proportion of large-magnitude events relative to smaller ones. This suggests that the crustal faults within the Timor-Leste mainland and the immediate offshore areas are capable of accumulating significant elastic strain, posing a direct threat to surface infrastructure.
- Intra-plate/Subduction Sources (b=1.12): In contrast, the deeper intra-plate events associated with the sinking slab beneath the Banda Sea exhibited a higher b-value of 1.12. This higher ratio suggests a more fractured medium or lower stress levels at depth, where smaller-magnitude earthquakes are more frequent, and the probability of a singular, massive rupture is statistically lower compared to the shallow crustal zones.

The Probabilistic Seismic Hazard Analysis (PSHA) translates these statistical observations into geographic maps that quantify the expected ground shaking over specific time horizons. The spatial quantification of seismic risk is visualized in Figure 6, which provides the probabilistic ground motion levels across the territory for two distinct return periods."Two primary scenarios were modeled to align with international building code standards:

- 10% Probability of Exceedance in 50 Years (475-year Return Period): This map represents the "Design Basis Earthquake." It identifies that a significant portion of the territory is subject to moderate-to-high ground shaking. These maps are essential for standard residential and commercial construction, providing the minimum Peak Ground Acceleration (PGA) that structures must withstand.
- 2% Probability of Exceedance in 50 Years (2,475-year Return Period): Representing the "Maximum Considered Earthquake," this map reveals extreme hazard zones, particularly across the northern coast and central highlands. In these areas, modeled PGA values exceed 400 cm/s² (approximately 0.4g). Such data is mandatory for the design of "Critical Infrastructure," including hospitals, bridges, and power plants, which must remain functional even after a rare, high-intensity event.

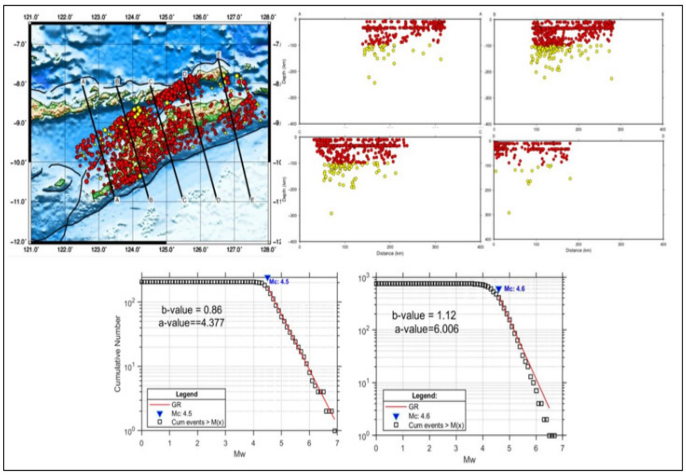

Figure 5: Analysis of the Gutenberg-Richter relationship for the Timor-Leste study area. The primary plot displays the cumulative and non-cumulative number of seismic events relative to magnitude. Vertical cross- sections (Profiles A-A' and B-B') showing the hypocentral distribution of seismic events from the surface to the deep mantle.

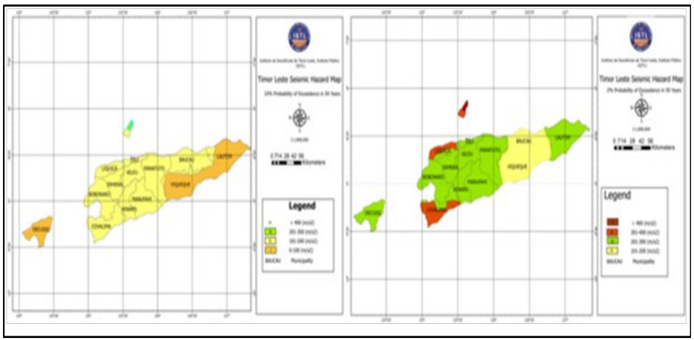

Figure 6: National-scale seismic hazard maps expressed in terms of Peak Ground Acceleration (PGA) in cm/s². (Left) The 10% probability of exceedance (475-year return period) represents the Design Basis Earthquake (DBE) for standard structural engineering. (Right) The 2% probability of exceedance (2,475-year return period) represents the Maximum Considered Earthquake (MCE), highlighting extreme hazard zones (PGA >400 cm/s²) across the northern coast and central highlands. These maps integrate the updated national seismic catalogue and local tectonic source models to provide a basis for municipal building code enforcement.

Discussion

The discrepancy between the calculated b-values for crustal and intra-plate sources highlights the fundamental necessity of adopting a layered hazard approach for Timor-Leste's seismic mitigation strategy. By distinguishing between high-stress shallow faults (b=0.86) and deeper, more fractured intra-plate systems (b=1.12), this study emphasizes that local seismic building codes must prioritize the mitigation of shallow, high-amplitude ruptures that pose the greatest risk to surface structures. Furthermore, by identifying specific geographic zones where Peak Ground Acceleration (PGA) values exceed 400 cm/s², the IGTL provides the Ministry of Public Works with the necessary empirical justification to implement stricter reinforcement requirements and specialized engineering standards in high-risk municipalities, most notably in Dili, Baucau, and Lautem. Ultimately, these PSHA results represent a significant milestone in national geoscientific research, as they mark the first time that national-scale hazard maps have been derived from a synergistic combination of high-density local station data and a rigorous integration of the historical seismic catalogue. This evidence-based framework not only refines our understanding of the Banda Microplate collision but also establishes a reproducible methodology for continuous seismic risk assessment in the region. As evidenced by the 2% probability map in Figure 6, the anticipated ground shaking in the northern corridor necessitates a revision of existing reinforcement standards for high-occupancy public buildings.

References

1. Nugroho H, Harris R, Pratt A, McCaffrey R (2009) GPS constraints on variations in accommodation of plate convergence across the arc–continent collision in the Banda Arc. Tectonophysics 479: 110-1132.
2. Okal E A, Reymond D (1996) The 1938 Banda Sea Earthquake: A reconsidered magnitude. Pure and Applied Geophysics.
3. McCaffrey R (1996) Slip vectors and seismic hazard of the Banda Sea region. Journal of Geophysical Research: Solid Earth 101: 15665-15676.
4. Yeh H, Liu P L F, Synolakis C E (1996) The 1995 Dili, East Timor Tsunami. Tsunami: Progress in Prediction, Disaster Prevention and Warning 95-108.