Seismic Risk Evaluation of Nuclear Research Reactors in Indonesia: Enhancing Monitoring and Nuclear Test Verification

Rizkita PARITHUSTA ASSEF [1], and Gatut DANIARSYAD[2]

[1]Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) / Seismic Safety Solution
Email: Parithusta@gmail.com / Rizkita.ASSEF.PARITHUSTA@ctbto.org

[2]Coordinator for Earthquake Observation System (BMKG) – Indonesia
Email: lp.daniarsyad@gmail.com

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INTRODUCTION AND MAIN RESULTS

Indonesia located at the convergence of major subduction zones and active faults, making its nuclear research reactors vulnerable to seismic hazards. Probabilistic seismic hazard analysis shows that TRIGA 2000 in Bandung faces the highest risk (PGA ~0.30g) due to the influence of the Lembang and Cimandiri Faults. The Kartini reactor in Yogyakarta has a moderate hazard level (PGA ~0.30g), while Swabesi in Serpong records a lower PGA (~0.20g) but is strongly affected by soil amplification. These findings highlight the importance of integrating reactor sites into Indonesia's seismic monitoring network, not only to enhance local hazard preparedness but also to strengthen regional detection of low-magnitude events for CTBTO nuclear test verification.

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P3.4-558

Abstract

Indonesia, located at the intersection of major subduction zones and active fault systems, such as the Sunda Trench, Lembang and Cimandiri Faults, is vulnerable to seismic hazards that pose risks to critical infrastructure, including nuclear research reactors.
This study evaluates seismic risks at three reactor sites — Kartini (Yogyakarta), Swabesi (Serpong) and TRIGA 2000 (Bandung) — using probabilistic seismic hazard analysis (PSHA) based on the 2009–2024 earthquake catalogue from BMKG, incorporating data from 6 Auxiliary IMS stations in Indonesia as part of the CTBTO's monitoring network.
The analysis integrates fault-based models, ground motion prediction equations and site-specific soil amplification effects to estimate peak ground acceleration (PGA) for a 475-year return period. TRIGA 2000 faces the highest seismic hazard (PGA ~0.3g), influenced by the Lembang and Cimandiri Faults. Kartini Reactor experiences moderate risk (PGA ~0.3g), while Swabesi Reactor, with a lower PGA (~0.20g), faces significant amplification effects due to soft soils. The results align with previous study Parithusta (2018), emphasizing fault-based hazards and soil amplification. This study explores integrating these reactors into Indonesia's seismic network to enhance low-magnitude event detection linked to underground nuclear tests. Strategically located near active faults, these reactors can strengthen regional monitoring and support nuclear test verification under the CTBTO.

Why This Study?

Indonesia's Seismic Setting Located at the convergence of Indo-Australian, Eurasian, and Pacific plates.
Major tectonic structures:

- Sunda Trench (subduction, Mw 7.5–9.0).
- Active crustal faults: Lembang, Cimandiri (West Java), Opak (Yogyakarta).
- High recurrence of Mw 6–9 earthquakes (BMKG, 2009–2024).

Nuclear Research Reactors in Seismic Zones:

- TRIGA 2000 (Bandung): Near Lembang & Cimandiri faults.
- Kartini (Yogyakarta): Near Opak Fault + subduction influence.
- Swabesi/RSG-GAS (Serpong): On soft alluvial soils, vulnerable to amplification.

Strategic Relevance
National: Ensure safe reactor operation under Design Basis Earthquakes (IAEA TECDOC-2067).

Global: Reactors can be integrated into CTBTO seismic monitoring network → enhancing detection of low-magnitude events relevant to nuclear test verification.

Objectives of the Study

Technical Objectives:

- Assess seismic risk at TRIGA 2000 (Bandung),
- Kartini (Yogyakarta), Swabesi (Serpong).

- Apply Probabilistic Seismic Hazard Analysis (PSHA) using BMKG (2009–2024).
- Use Campbell & Young GMPE, compare with BJF02 & Atkinson & Boore.
- Incorporate soil amplification (Vs30-based).
- Estimate PGA (475-year return), hazard curves, and deaggregation.

Validation:

- Cross-check results with Mangkoesobroto (1998), and Parithusta (2018).) studies.

Strategic Objectives

- Enhance reactor safety reassessment (IAEA TECDOC-2067).
- Integrate reactor seismic data into Indonesia's national network and CTBTO IMS.
- Strengthen global nuclear monitoring and test verification capacity.

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Seismotectonic Framework and Reactor-Specific Seismic Hazard in Indonesia

P3.4-558

Tectonic Setting

- Convergence of Indo-Australian, Eurasian, and Pacific plates.
- Sunda Subduction Zone → frequent Mw 7.5–9.0 megathrust earthquakes.
- Active crustal faults:
    - Lembang Fault (~29 km, M6.5–7.0 potential; Irsyam et al., 2017)
    - Cimandiri Fault (~100 km, multiple historical M6+ events)
    - Opak Fault (Yogyakarta, near Kartini).

•Numerous intraslab earthquakes contribute to hazard at depth.

Seismicity Data

- BMKG Catalogue (2009–2024 and IMS data with Mw 4 – 8+.
- High recurrence of damaging shallow crustal earthquakes in Java.
- Bandung Basin particularly sensitive due to fault proximity and soil conditions

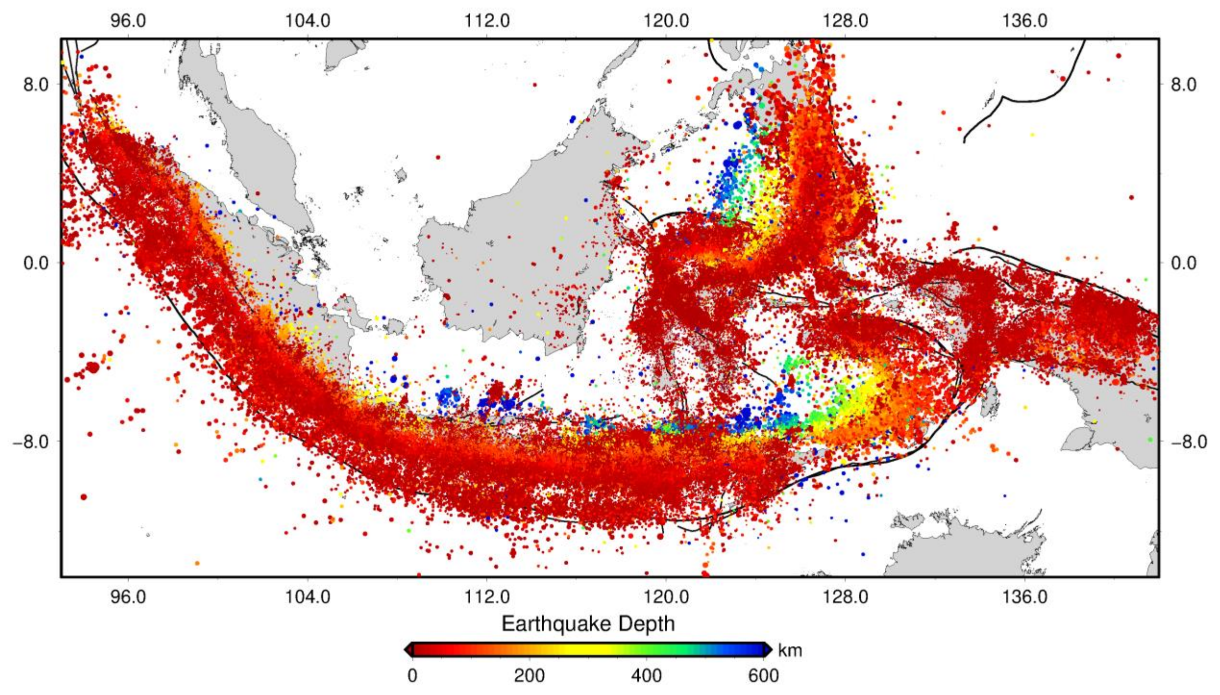

Fig 3. Seismicity Indonesia 2009 – 2024 source BMKG and IMS data (2025)

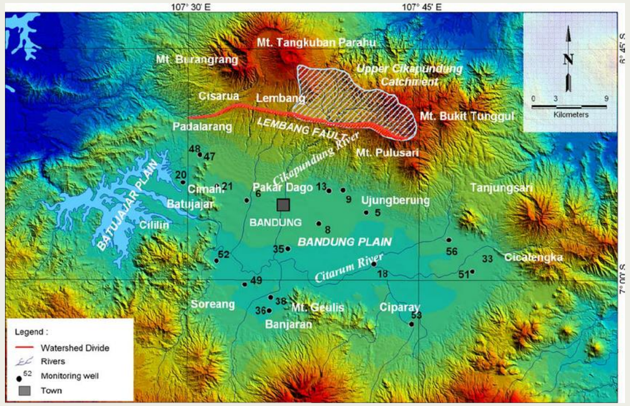

Fig1. The Lembang Fault and Bandung Basin Robert Delinom (2009).

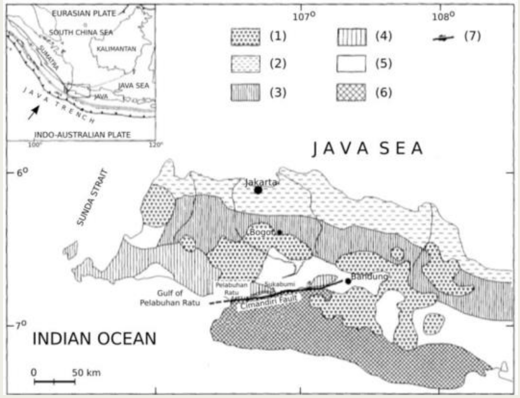

Fig 2. Cimandiri Fault, West Java **Febriani et al. (2013).**

Relevance to Reactors

- **TRIGA 2000 (Bandung):**
    - Within 10–15 km of Lembang & Cimandiri faults
    - Highest hazard → PGA ~0.30g (475-year return)
- **Kartini (Yogyakarta):**
    - Influenced by Opak Fault and Java subduction events
    - Moderate hazard → PGA ~0.30g
- **Swabesi (Serpong):**
    - Further from major faults
    - Lower PGA (~0.20g), but significant soil amplification risk

Methodology: Probabilistic Seismic Hazard Analysis (PSHA)

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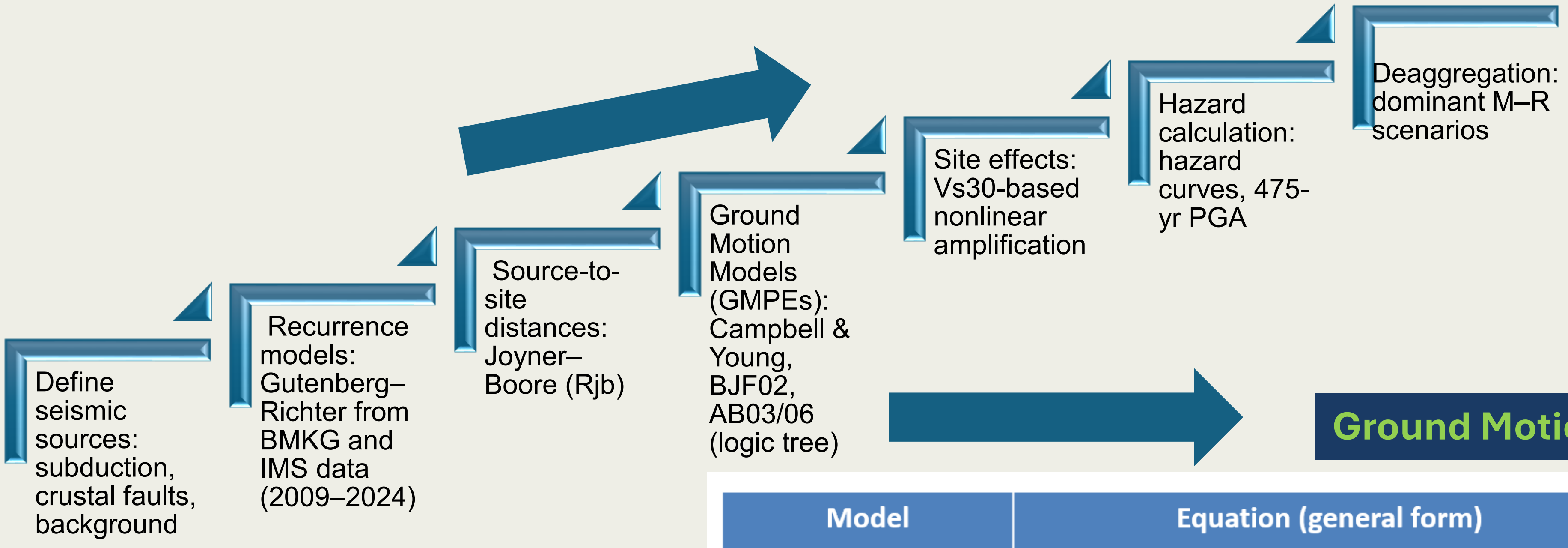

Fig 4. Schematic of PSHA Methodology

Ground Motion Models (GMPEs)

Model	Equation (general form)	Key Features
Campbell & Young (1997, 2007)	$\ln Y = c_1 + c_2 M + c_3 (M - M_h)^2 - \ln\left(R + c_4 e^{c_5 M}\right) + c_6 R + F_{site} + F_{fault}$	Subduction + crustal; near-fault terms; interface vs intraslab
Boore–Joyner–Fumal (2002)	$\ln Y = b_1 + b_2(M-6) + b_3(M-6)^2 - \ln(R + b_4 e^{b_5 M}) + b_6 R + f_{site}(V_{s30}, Y_{ref})$ Site term: $f_{site} = c_1 \ln\left(\frac{V_{s30}}{V_{ref}}\right) + c_2 \left[\ln\left(\frac{Y_{ref} + c_3}{c_3}\right)\right]$	Nonlinear soil amplification via Vs30; reference rock scaling
Atkinson & Boore (2003/06)	$\ln Y = a + bM + cR + d \ln R + S$	Subduction-specific; separate interface & intraslab; soil vs rock factors
Abrahamson & Silva (2014, NGA)	$\ln Y = f_{mag}(M) + f_{dist}(R, M) + f_{site}(V_{s30}, \kappa) + f_{directivity} + f_{hangingwall} + \epsilon\sigma$	Advanced NGA; directivity, Vs30 scaling, hanging wall, variability
Logic Tree Purpose	$\text{Hazard} = \sum_{i=1}^{N} w_i \, H(GMPE_i)$	Combines multiple GMPEs; reduces epistemic uncertainty

Seismic Hazard Results for Indonesian Research Reactors

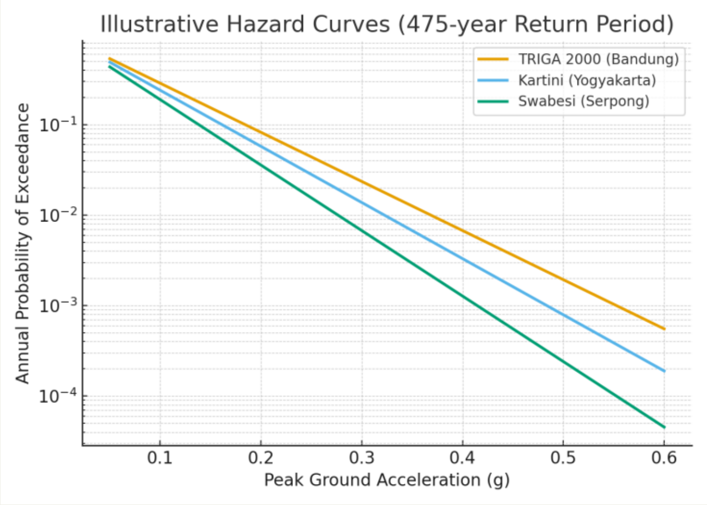

Fig 5. Hazard Curves (475- year return period)

Reactor	PGA (475 yr)	Soil Condition	Controlling Faults
TRIGA 2000 (Bandung)	~0.30g	Stiff volcanic (Vs30 ~500 m/s)	Lembang, Cimandiri
Kartini (Yogyakarta)	~0.30g	Sedimentary (Vs30 ~500 m/s)	Opak, Subduction
Swabesi (Serpong)	~0.20g → ~0.30–0.35g	Soft alluvium (Vs30 180–250 m/s)	Background + Amplification

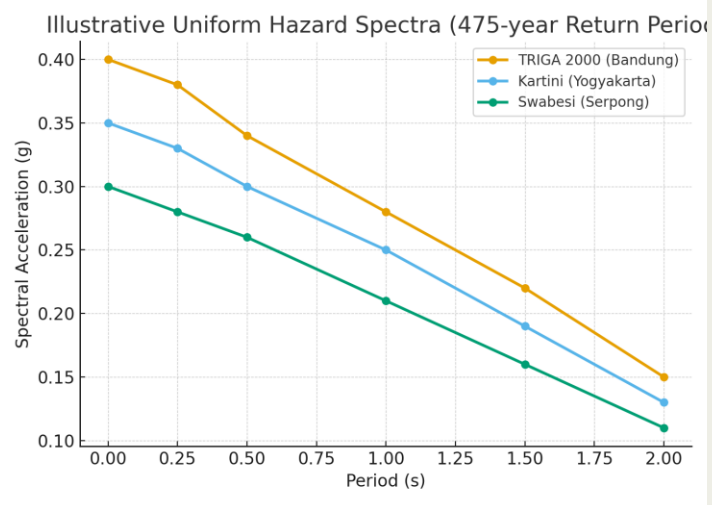

Fig 6. Uniform Hazard Spectra (475- year return period)

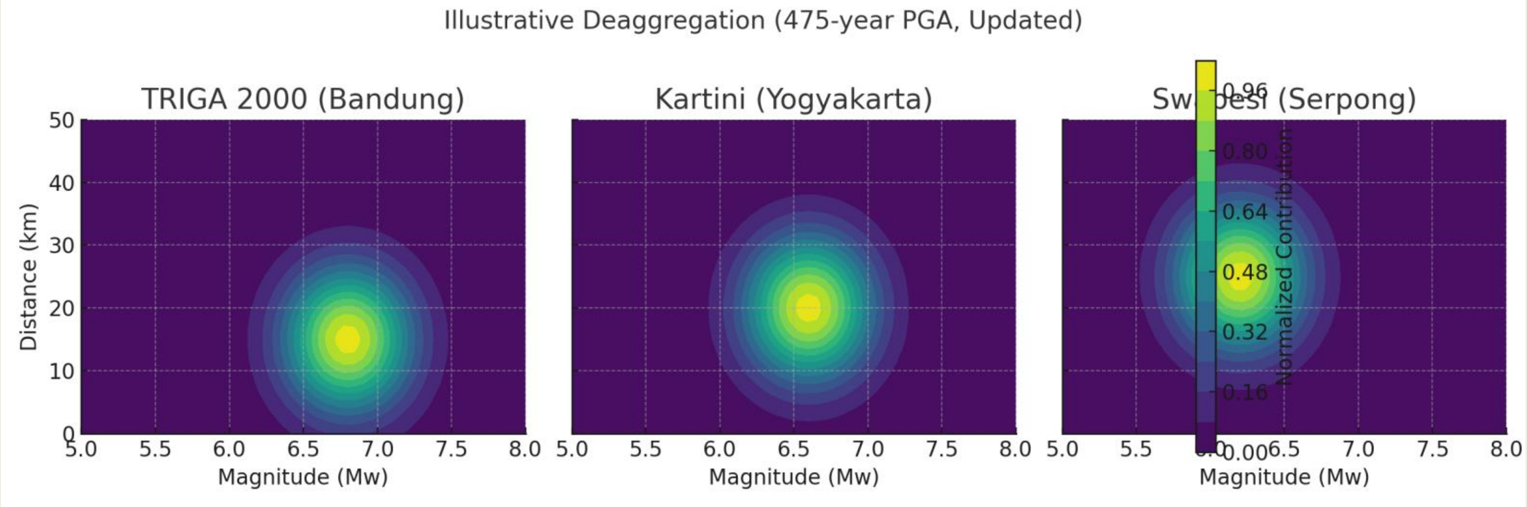

Fig 7. Deaggregation (475- year return period)

Seismic Hazard Results for Indonesian Research Reactors

P3.4-558

Validation with Past Studies:

- TRIGA 2000 (Bandung): Highest hazard, already reinforced after earlier studies → improved resilience.
- Kartini (Yogyakarta): Moderate hazard, strengthening still required.
- Swabesi (Serpong): Lower base hazard but significant soil amplification → SSI evaluation needed.
- Mangkoesobroto (1998) and Parithusta (2018): Confirmed that fault-based hazards dominate for Bandung & Yogyakarta sites. Demonstrated that soil amplification effects are critical, consistent with Swabesi's profile.
- Past Validation: Retrofitting improved safety, but hazards evolve over time.
- Regular reassessment every 10 years is required under IAEA TECDOC-2067.

Category	TRIGA 2000 (Bandung)	Kartini (Yogyakarta)	Swabesi (Serpong)
PGA (475-yr Return)	~0.30g (highest hazard) Close to Lembang & Cimandiri faults	~0.30g (moderate hazard) Opak Fault + subduction	~0.20g base rock → ~0.30–0.35g with soil amplification
Hazard Curves & Deaggregation	Mw 6.5–7.0 at 10–20 km Hazard curves show steep rise	Mw 6.5–7.0 at 15–30 km Mixed subduction and crustal sources	Mw 6.0–6.5 at 20–40 km Subduction-dominated and soil effects
Validation with Past Studies	Confirmed. Priority for retrofitting; past reinforcement already improved resilience, but continuous monitoring is essential.	Confirmed. Requires on continues **structural strengthening** to meet updated standards.	Confirmed. Demands **soil–structure interaction (SSI) analysis** and mitigation.

Conclusions & Future Directions

Conclusions

- Seismic hazard evaluation shows TRIGA 2000 (Bandung) faces the highest risk, while Kartini (Yogyakarta) is moderate and Swabesi (Serpong) experiences soil amplification.
- Validation with Mangkoesobroto (1998) and Parithusta (2018) confirms fault-based hazard and soil amplification dominance.
- Integration of multiple GMPEs (Campbell & Young, BJF02, Atkinson & Boore) reduces epistemic uncertainty.
- Hazard curves and deaggregation highlight Mw 6–7 events at 10–30 km as dominant risk drivers.
- Results are consistent with international safety guidance (IAEA TECDOC-2067).
- Past reinforcements improved safety, but residual risk remains, requiring systematic reassessment.

Recommendations

- Periodic seismic safety reassessments should follow IAEA guidance, with reviews recommended at least every 10 years.
- Nuclear safety monitoring should be enhanced by integrating with CTBTO verification systems.
- Future research should focus on improving site-specific hazard maps and applying advanced GMPEs with soil amplification models to improve accuracy.

Reference(s):

Journal(s):

- Campbell & Youngs (1997, 2007) – Subduction & crustal GMPEs
- Boore, Joyner & Fumal (2002) – Nonlinear soil amplification
- Atkinson & Boore (2003, 2006) – Subduction-specific GMPEs
- Abrahamson & Silva (2014) – NGA, directivity & Vs30 scaling
- Baker (2013) – *Intro to PSHA*
- Delinom, R. (2009) – *The Lembang Fault and Bandung Basin*
- Febriani, F. et al. (2013) – *Cimandiri Fault, West Java*
- Mangkoesobroto (1998) – Fault-based hazard dominance.
- Parithusta (2018) – Seismic Risk and Soil Amplification.
- IAEA (2021) – *TECDOC-2067: Seismic Safety of Nuclear Installations*
- CTBTO (2022) – *IMS Monitoring & Nuclear Test Verification*

Data Sources

- BMKG (2009–2024) – Indonesia Earthquake Catalogue
- CTBTO IMS (Indonesia) – Seismic Monitoring Data

Thank You for Your Attention and Feedback