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PROBABILISTIC SEISMIC HAZARD ANALYSIS (PSHA) FOR MACAU AND MOSSORÓ (RN)

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Abstract Summary

We present a probabilistic seismic hazard analysis **(PSHA)** for the municipalities of Macau and Mossoró, Rio Grande do Norte (RN), northeastern Brazil, where intraplate seismicity is recurrent along reactivated Precambrian structures and intensified by intensive subsurface exploitation. An updated, homogenized earthquake catalogue was declustered and tested for completeness; Gutenberg–Richter parameters were then estimated for zoned seismic sources, and temporal occurrence modeled with a Poisson process. Monte Carlo simulations were used to sample inter-event times and validate recurrence distributions. Fault displacement and stress were inferred from seismic moment relations to bridge statistical rates and geomechanical implications. A central contribution is the Anthropogenic Impact Factor (AIF), a scalar that downscales natural recurrence times to account for mining- and extraction-induced stress loading. Minor events ($M < 3.0$) recur every 3 – 4 days, while natural recurrence for moderate events ($M_w \approx 4.5–4.7$) lies between ~19 and 24 years; with AIF = 4 – typical of active salt-mining zones – these intervals shrink to ~4.8 – 6.0 years, and Monte Carlo realizations indicate rupture probabilities peaking within 2 – 3 years in worst-case scenarios. Distinct b-values (0.62 for Mossoró; 0.50 for Macau) suggest heterogeneous stress regimes. The workflow highlights how anthropogenic loads can meaningfully elevate short- to mid-term seismic risk in otherwise low-hazard intraplate settings and offers a transferable framework for similar regions.

Introduction

Brazil is commonly classified as a low-to-moderate seismicity country, yet clusters of intraplate earthquakes recur along reactivated Precambrian structures in the Northeast, particularly within the Potiguar Basin (Rio Grande do Norte state). Macau and Mossoró stand out as recurrent epicentral zones where shallow events, although moderate in magnitude, can threaten pipelines, industrial plants, embankments, and urban infrastructure that were designed under the assumption of negligible seismic demand. Traditional hazard maps for Brazil are often regional and deterministic, providing limited guidance for engineering design or risk management at the municipal scale.

To address this gap, we perform a probabilistic seismic hazard analysis (PSHA) tailored to Macau and Mossoró. The workflow integrates (i) a homogenized and declustered earthquake catalogue, (ii) completeness assessment and Gutenberg–Richter parameterization for distinct seismic sources, and (iii) temporal occurrence modeling via a Poisson process complemented by Monte Carlo sampling of inter-event times. Beyond purely natural drivers, we incorporate an Anthropogenic Impact Factor (AIF) to represent how subsurface extraction (e.g., salt mining, hydrocarbon operations) may accelerate stress accumulation and fault rupture, effectively shortening recurrence intervals. By combining statistical recurrence, geomechanical inferences, and anthropogenic modifiers, the study delivers site-relevant hazard metrics—peak ground accelerations and return periods—that inform mitigation strategies and provide a transferable template for other intraplate, resource-intensive regions.

Methodology

Catalogue construction and homogenization

Seismic data from national/regional bulletins (e.g., RSBR/UFRN) and international agencies (ISC, USGS) were merged. Reported magnitudes were converted to moment magnitude M_w using published empirical transformations. Dependent events (foreshocks/aftershocks) were removed using a Gardner–Knopoff/Reasenberg declustering scheme, yielding a mainshock set. Completeness was checked through MAXC/Stepp tests, defining, for example, that magnitudes $M_w \geq M_1$ are complete since $YEAR_1$, etc.

Seismic source zonation

The study area was partitioned into N_S areal sources based on mapped faults, seismicity clustering, and tectonic domains. Within each polygonal source, activity rate and b-value were considered spatially uniform.

Recurrence modeling

For each source i, Gutenberg–Richter parameters (a_i, b_i) were estimated by maximum likelihood:

$$\log_{10} N_i(M \geq m) = a_i - b_i m$$

where N_i is the expected annual number of events $\geq m$. The minimum magnitude M_{min} was set by catalogue completeness; M_{max} followed empirical/geological constraints. Uncertainty in (a, b) was handled via confidence intervals or bootstrap resampling.

Temporal model and Monte Carlo sampling

Assuming a Poissonian temporal process with rate λ, the probability of at least one exceedance in time t is $P(T \leq t) = 1 - e^{-\lambda t}$. Monte Carlo draws of inter-event times followed:

$$T = -\frac{1}{\lambda} \ln U \, , U \sim u(0{,}1)$$

These simulations generated distributions of waiting times for varying magnitude thresholds and AIF scenarios.

Anthropogenic Impact Factor (AIF)

To represent stress acceleration from mining and subsurface exploitation, we applied a scalar AIF:

$$\lambda_{adj} = \lambda_{nat} \times AIF \text{ or equivalently } T_{adj} = \frac{T_{nat}}{AIF}$$

AIF values (>1) were assigned based on extraction intensity – AIF = 4 captured active salt-mining conditions.

Geomechanical linkage

We linked statistical rates to mechanical implications using:

- Seismic Moment: $\log_{10} M_0 = 1.5\, M_w + 9.1 \; (N.m)$
- Average Displacement: $D = \frac{M_0}{\mu A}$, with $\mu \approx 30\ GPa$ and typical fault area $A \approx 25 \times 10^6\ m^2$
- A rupture stress threshold of $\sim 5.2\ MPa$ flagged scenarios approaching failure.

Uncertainty treatment

Epistemic uncertainty was bracketed through alternative $(a, b), M_{max}, GMPE\ choices$ (if/when ground motions are mapped), and AIF values in a simple logic-tree framework. Aleatory variability was inherent in Poisson/Monte Carlo sampling and magnitude–distance distributions. Sensitivity runs quantified how changes in AIF or b-values shift recurrence intervals and hazard metrics.

Results

The combined statistical–geomechanical framework highlights distinct seismic behaviors in Macau and Mossoró:

- Minor events ($M < 3.0$ recur every 3 – 4 days, consistent across both municipalities.

- Natural recurrence for moderate events ($M_w \approx 4.5 - 4.7$) is $\sim 19\text{–}24$ years.
- With AIF = 4, representing intense extraction, recurrence times drop to is $\sim 4.8\text{–}6.0$ years.
- Monte Carlo realizations reveal non-negligible probabilities of rupture within $\sim 2.3\text{–}3.0$ years under high-impact scenarios.
- Gutenberg–Richter b-values differ: 0.62 (Mossoró) vs is 0.50 (Macau), implying spatially heterogeneous stress regimes and/or detection capabilities. A lower b in Macau suggests a relatively higher proportion of larger events (greater stress accumulation or release potential).
- A representative Poisson rate of is $\lambda = 0.2517\ \mathrm{events/day}$ for a given magnitude bin yielded a mean inter-event time of $\sim 3.69\ days$ (Mossoró) and $\sim 3.05\ days$ (Macau), matching histogrammed waiting times.

Figure 1 synthesizes the principal findings by juxtaposing G–R frequency–magnitude relations (with b-value estimates), Poisson exceedance curves, and Monte Carlo histograms of waiting times, together with a comparative view of recurrence metrics under natural and anthropogenic scenarios. The composite format maximizes page economy while effectively conveying the observed trends.

Overall, the PSHA indicates low-to-moderate absolute hazard in terms of ground motion, but elevated short- to mid-term risk for moderate ruptures when anthropogenic loads are considered. The methodological flexibility (AIF scaling, logic-tree uncertainty) is easily transferable to other intraplate regions with intensive resource extraction.

Conclusions

Macau and Mossoró exhibit non-zero, spatially variable seismic hazard that demands tailored design checks for critical infrastructure; the Anthropogenic Impact Factor (AIF) efficiently captures human-driven acceleration of seismic recurrence and can be calibrated with operational data; distinct b-values and recurrence intervals underscore the need for localized parameterization rather than regional averages; and the integrated statistical–geomechanical workflow delivers actionable hazard metrics—such as recurrence times and exceedance probabilities—while offering a transferable template for other intraplate, resource-exploiting areas. Looking ahead, work should focus on refining GMPE choices for Brazilian intraplate conditions, updating catalogue completeness with improved monitoring, and quantifying the AIF through direct measurements of subsurface pressure and stress changes.

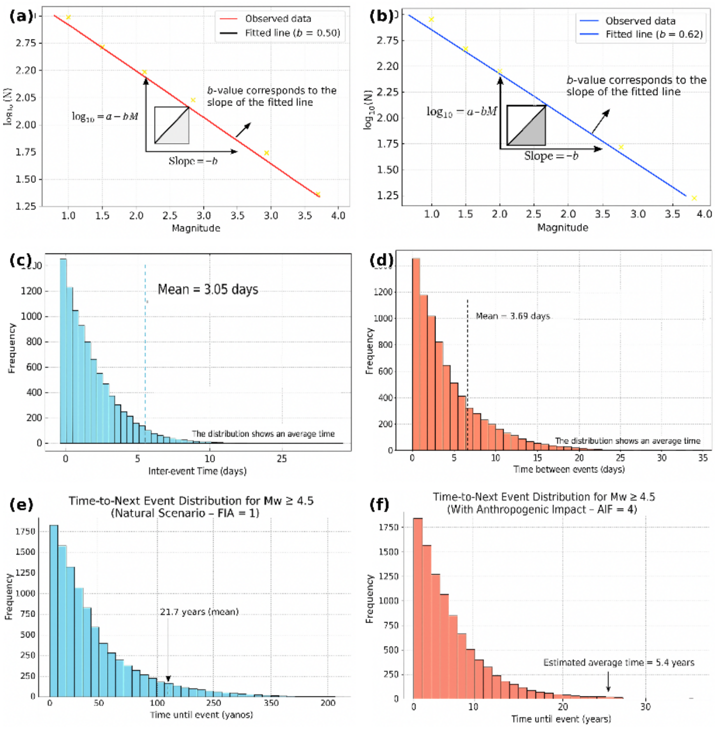

Figure 1: Macau vs. Mossoró seismicity. (a–b) Gutenberg–Richter fits (b = 0.50 and 0.62). (c–d) Inter-event time histograms (means: 3.05 and 3.69 days). (e) Natural Mw ≥ 4.5 waiting-time distribution (AIF = 1; mean ≈ 21.7 yr). (f) Anthropogenic scenario (AIF = 4; mean ≈ 5.4 yr).

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