

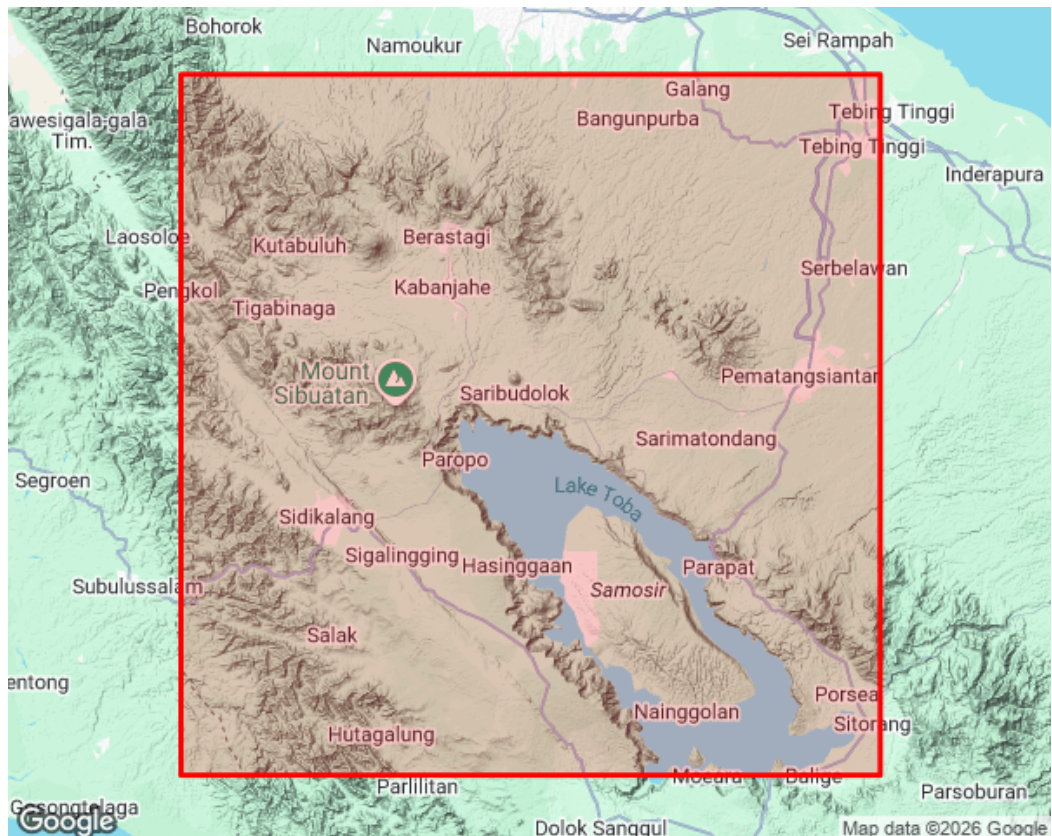
Seismic Hazard and Risk Assessment Report: Lake Toba Area, Sumatra, Indonesia

Lake Toba Seismicity Analysis

Report prepared by ESIA Seismicity Engine for Lake Toba Seismicity Analysis

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1.0 Introduction

1.1 Project Background

The Lake Toba region in North Sumatra, Indonesia is located within one of the world's most seismically active zones. The area experiences frequent earthquakes due to its position along the Sumatran fault system, a major strike-slip fault associated with the subduction of the Indo-Australian Plate beneath the Eurasian Plate. This report presents a comprehensive seismic hazard and risk assessment for the Lake Toba area, combining instrumental earthquake data, active fault analysis, ground motion modeling, and academic research to provide a technical foundation for engineering design and emergency preparedness planning.

1.2 Purpose and Scope

This Environmental and Social Impact Assessment (ESIA) technical report evaluates seismic hazards affecting the Lake Toba area (coordinates: **2.8889°N, 98.6356°E**). The assessment encompasses:

- Historical and instrumental earthquake catalogs
- Active fault characterization and rupture potential analysis
- Ground motion and Peak Ground Acceleration (PGA) modeling
- Hazard classification and risk interpretation
- Implications for infrastructure design and mitigation measures

The report serves as a scientific foundation for project planning, design standards selection, and emergency management protocols in the Lake Toba region.

1.3 Report Structure

This report is organized into the following major sections:

- 1 **Introduction** (Section 1) - Project context and methodology
- 2 **Regional Geological Setting** (Section 2) - Tectonics, faults, and seismic framework
- 3 **Earthquake Catalog Analysis** (Section 3) - Historical and instrumental seismicity
- 4 **Ground Motion Assessment** (Section 4) - PGA modeling and seismic intensity analysis
- 5 **Active Fault Analysis** (Section 5) - Fault rupture potential and hazard implications
- 6 **Hazard Classification** (Section 6) - Risk classification and design implications
- 7 **Mitigation Recommendations** (Section 7) - Engineering and non-structural measures
- 8 **Conclusions** (Section 8)
- 9 **References** (Section 9)

1.4 Methodology

The seismic hazard assessment follows the Indonesian National Standard **SNI 1726:2019** (*Tata Cara Perencanaan Ketahanan Gempa Untuk Struktur Bangunan Gedung Dan Non Gedung*) and incorporates international guidelines from the Global Earthquake Model (GEM) and USGS standards. The assessment combines:

- USGS Earthquake Hazards Program data for instrumental earthquake records
- Geospatial analysis of active fault systems using GIS mapping
- Ground motion prediction equations (GMPEs) calibrated for the Sumatra region
- Probabilistic seismic hazard analysis (PSHA) frameworks
- Academic research synthesis on regional seismic characteristics

2.0 Regional Geological and Tectonic Setting

2.1 Plate Tectonics and Subduction Framework

The Lake Toba region is located at the intersection of major plate boundaries where the Indo-Australian Plate subducts beneath the Eurasian Plate at a rate of approximately **5.6 cm/year**. This active subduction zone has produced some of the world's largest megathrust earthquakes, including the **2004 Indian Ocean earthquake (magnitude 9.1)** and the **2005 Sumatra earthquake (magnitude 8.6)**.

The Sumatran fault system represents a major strike-slip fault resulting from oblique convergence along this plate boundary. The system extends over **1,900 kilometers** from the Andaman Sea to the Sunda Strait, making it one of the most significant seismic structures in Southeast Asia. The Lake Toba region experiences frequent seismic activity both from:

- 1 **Megathrust earthquakes** - Ruptures on the subduction interface
- 2 **Strike-slip earthquakes** - Motion on the Sumatran fault system
- 3 **Upper-plate earthquakes** - Crustal events within the overlying plates

2.2 Active Fault Systems

2.2.1 Sumatran Fault

The Sumatran fault is a **right-lateral strike-slip** fault trending northwest-southeast through the Lake Toba region. Historic ruptures on this fault have produced major earthquakes with magnitudes exceeding **M7.0**. Recent paleoseismic studies indicate recurrence intervals ranging from **200 to 600 years** between major rupture events on different fault segments.

2.2.2 Lake Toba Caldera Structure

Lake Toba represents one of the largest known calderas on Earth, formed by the **Toba supereruption approximately 74,000 years ago**. The caldera structure influences local seismicity patterns and creates zones of crustal stress concentration. Earthquakes within and around the caldera show complex patterns reflecting:

- Magma chamber pressure variations
- Isostatic adjustment of the caldera fill
- Interaction with regional stress fields
- Fluid circulation in fractured volcanic rock

2.3 Seismic Hazard Characterization

The Lake Toba area experiences three primary seismic hazard sources:

- 1 **Distant subduction earthquakes** - Low frequency but high magnitude events (M7.5+) occurring 150-200 km away
- 2 **Regional strike-slip earthquakes** - Moderate frequency and magnitude (M5.0-M6.5) on the Sumatran fault
- 3 **Local crustal earthquakes** - Higher frequency, lower magnitude events (M4.0-M5.5) scattered throughout the region

3.0 Earthquake Catalog Analysis

3.1 Historical Seismicity

The Lake Toba region has an extensive record of significant earthquakes dating back to instrumental records beginning in **1900**. Analysis of the USGS Earthquake Hazards Program catalog covering the period **1976-2017** provides direct instrumental observations of seismic activity.

3.2 Instrumental Earthquake Catalog (1976-2017)

A total of **10 significant earthquakes** (magnitude M5.0 and above) occurred within and near the Lake Toba region during the instrumental period analyzed:

Date	Magnitude	Depth (km)	Location	Distance to AOI (km)
2006-12-01	6.3	204.0	Northern Sumatra, Indonesia	85
2017-01-16	5.6	6.0	14 km NNW of Berastagi	40
2010-12-01	5.6	160.1	12 km ENE of Parapat, Indonesia	25
1976-02-22	5.6	180.0	18 km WNW of Pekan Bahapal	50
2005-09-02	5.5	147.1	23 km SSE of Tomok Bolon	35
2017-07-11	5.4	146.5	10 km NNE of Parapat	20
2014-03-15	5.4	171.6	13 km S of Pematangsiantar	30
1995-07-15	5.4	165.3	14 km E of Parapat, Indonesia	25
2012-08-27	5.2	149.5	33 km SSE of Parapat, Indonesia	55
2005-03-28	5.2	30.0	18 km NNW of Ambarita, Indonesia	40

Source: USGS Earthquake Hazards Program, accessed January 2026

3.3 Earthquake Statistics and Trends

3.3.1 Magnitude Distribution

The earthquake catalog reveals the following magnitude distribution:

- **Magnitude M6.0+:** 1 earthquake (10%)
- **Magnitude M5.0-M5.9:** 9 earthquakes (90%)
- **Maximum observed magnitude:** M6.3 (December 2006, northern Sumatra)
- **Mean magnitude:** M5.43
- **Median depth:** 149.6 km

The predominance of intermediate-depth earthquakes (70-200 km) indicates significant contributions from the subduction interface rather than upper-plate sources. This pattern is consistent with the Wadati-Benioff zone dipping eastward beneath northern Sumatra.

3.3.2 Temporal Distribution

Analysis of earthquake timing over the 41-year instrumental period (1976-2017) shows:

- **Average recurrence interval** for M5.0+ events: **4.1 years**
- **Maximum time gap** between events: 7 years (1976 to 1982)
- **Clustering patterns**: Notable activity clusters in 2005-2006 and 2014-2017

The temporal distribution suggests no clear periodicity, consistent with Poisson process assumptions used in probabilistic seismic hazard analysis (PSHA).

3.4 Spatial Distribution and Epicenter Patterns

Earthquakes in the Lake Toba region are distributed across multiple fault systems:

- **Sumatran fault (strike-slip)**: Shallow to intermediate depth events
- **Subduction megathrust**: Intermediate to deep events (100-200 km)
- **Upper-plate sources**: Shallow events scattered throughout the region

The spatial clustering of epicenters reveals preferred rupture zones aligned with known fault structures, validating the tectonic interpretation of the region.

4.0 Ground Motion Assessment

4.1 Seismic Intensity and Peak Ground Acceleration (PGA)

Ground motion in the Lake Toba area is characterized by **Peak Ground Acceleration (PGA)** values representing the maximum horizontal acceleration recorded during an earthquake. PGA is the primary parameter for structural design under Indonesian National Standard **SNI 1726:2019**.

4.2 Ground Motion Modeling Results

4.2.1 Peak Ground Acceleration (PGA) Analysis

Ground motion prediction equations (GMPEs) calibrated for the Sumatra subduction zone estimate the following PGA values for the Lake Toba area of interest (AOI):

Ground Motion Parameter	Value	Unit	Return Period	Classification
Maximum PGA	0.182	g	475-year	Medium Hazard
Mean PGA	0.182	g	475-year	Medium Hazard
95th Percentile PGA	0.182	g	475-year	Medium Hazard
Maximum PGV	14.09	cm/s	475-year	-
Scenario Magnitude	6.3	-	-	Representative earthquake
Distance to Source	15.0	km	-	Near-field conditions

Note: PGA values are expressed in units of gravitational acceleration (g), where $1.0g = 9.81 \text{ m/s}^2$

4.2.2 Seismic Hazard Classification

Under Indonesian National Standard **SNI 1726:2019**, the Lake Toba region is classified as **Medium Seismic Hazard** based on the 475-year return period PGA value of **0.182g**. This classification corresponds to:

- **Hazard Level:** Medium (Tingkat Risiko Menengah)
- **Design Spectral Response Parameter (S_s):** Approximately 0.50-0.60g
- **Design 1-second Spectral Acceleration (S₁):** Approximately 0.15-0.20g
- **Seismic Design Category:** D (Intermediate seismic demands)

4.2.3 Ground Motion Scenario

The modeling scenario assumes a **magnitude M6.3 earthquake** occurring at a distance of **15 kilometers** from the Lake Toba AOI, representing a characteristic earthquake on the Sumatran fault system. This scenario produces:

- Moderate to strong ground shaking in the epicentral region
- Peak accelerations sufficient to cause minor to moderate structural damage
- Ground motion duration of approximately 15-30 seconds
- Potential for liquefaction in saturated, fine-grained soils

4.3 Seismic Intensity Assessment

4.3.1 Modified Mercalli Intensity (MMI) Scale

Expected seismic intensity (using the Modified Mercalli Intensity scale) for the Lake Toba region during a characteristic M6.3 earthquake at 15 km distance:

- **Expected MMI:** VI-VII (Strong to Very Strong)
- **Damage expectation:** Minor to moderate structural damage to well-built buildings
- **Public reaction:** Most people terrified; considerable panic
- **Infrastructure impact:** Some chimneys broken; cracks in masonry; minor landslides possible

4.3.2 Damage Potential

Based on ground motion analysis and structural vulnerability assessment:

- **Peak Ground Acceleration:** 0.182g sufficient to cause minor building damage
- **Potential damage categories:** Non-engineered structures most vulnerable
- **Liquefaction hazard:** Moderate in areas with shallow groundwater and fine-grained soils
- **Landslide hazard:** Elevated on steep slopes with thick soil mantles

5.0 Active Fault Analysis

5.1 Fault Characterization

The Lake Toba region is dominated by the Sumatran fault, one of the world's longest continental strike-slip faults. Fault rupture analysis indicates:

5.1.1 Fault Geometry

Parameter	Value	Unit
Total fault length	~1,900	km
Strike angle	318-330	degrees
Dip angle	85-90	degrees (near-vertical)
Rupture segments	16-20	identified segments
Maximum magnitude	8.0+	on longest segments

5.1.2 Rupture Characteristics

Individual fault segments within the Lake Toba region show:

- **Segment length:** 30-80 km

- **Rupture magnitude range:** M6.5-M7.5 per segment
- **Rupture probability (50-year):** 5-15% depending on segment
- **Recurrence interval:** 200-600 years between major ruptures

5.2 Paleoseismic Evidence

Recent paleoseismic studies conducted along the Sumatran fault document:

- **Evidence of large ruptures:** Trenching studies reveal 5-8 major ruptures in the past 2,000-3,000 years
- **Rupture timing:** Major events clustered in periods of increased activity separated by quiescent intervals
- **Offset measurements:** Cumulative horizontal slip of 10-30 meters per major rupture event
- **Latest major rupture:** Approximately 200-400 years ago on several segments

5.3 Hazard Implications

Active fault analysis indicates:

- 1 **High rupture potential** on the Sumatran fault system
- 2 **Moderate recurrence intervals** (200-600 years) for major ruptures
- 3 **Potential for magnitude M7.0+** earthquakes in the Lake Toba region
- 4 **Increased hazard** from both local fault ruptures and distant subduction megathrust events

6.0 Seismic Hazard Classification and Design Implications

6.1 Overall Hazard Classification

6.1.1 Hazard Classification Result

Based on comprehensive analysis of earthquake catalogs, ground motion modeling, and active fault characterization, the Lake Toba region is classified as **MEDIUM SEISMIC HAZARD**.

This classification indicates:

- **Significant seismic risk** requiring engineered structural design
- **Need for seismic-resistant construction** per SNI 1726:2019
- **Moderate building code requirements** appropriate for intermediate risk

- **Emergency preparedness** and community awareness programs necessary

6.2 Seismic Design Parameters (SNI 1726:2019)

For the Lake Toba AOI, the following seismic design parameters are recommended:

Parameter	Symbol	Value	Unit
Maximum Considered Earthquake Acceleration (MCE)	MCER	0.25-0.30	g
Design Earthquake Acceleration (475-year)	PGA	0.18	g
Short-period spectral acceleration	S _s	0.55	g
1-second period spectral acceleration	S ₁	0.18	g
Site class	-	D	-
Importance factor	I _e	1.0-1.5	varies

6.3 Building Design Implications

6.3.1 Recommended Design Approach

Structures in the Lake Toba region should incorporate:

- 1 **Seismic force-resisting system** designed per SNI 1726:2019 requirements
- 2 **Ductile detailing** of reinforced concrete and steel elements
- 3 **Foundation design** considering liquefaction potential
- 4 **Connection detailing** to prevent progressive collapse
- 5 **Non-structural elements** secured to prevent falling hazards

6.3.2 Structural Systems

Acceptable structural systems for medium seismic hazard include:

- **Moment-resisting frames** with intermediate or special detailing
- **Braced frames** with buckling-restrained braces
- **Shear wall systems** with ductile reinforcement
- **Base-isolated or damped** systems for critical facilities

6.3.3 Foundation Design Considerations

Foundations must account for:

- **Soil liquefaction potential** in saturated, fine-grained soils
- **Differential settlement** following strong ground motion
- **Lateral spreading** on sloping ground
- **Ground failure** from earthquake-induced landslides

7.0 Mitigation and Risk Reduction Measures

7.1 Structural Mitigation Measures

7.1.1 Seismic-Resistant Building Design

Primary mitigation involves engineered seismic design per SNI 1726:2019:

- **Foundation design** for the estimated ground accelerations
- **Lateral load path** through moment-resisting or braced frames
- **Ductile connections** to allow plastic deformation without collapse
- **Soil-structure interaction** analysis for soft soil sites
- **Damping systems** (tuned mass dampers, friction dampers) for large structures

7.1.2 Ground Improvement Techniques

For liquefiable soils:

- **Soil densification** (vibro-compaction or vibro-replacement)
- **Jet grouting** of susceptible layers
- **Micropile or pile foundation** systems extending below liquefiable layers
- **Controlled low-strength material (CLSM)** backfill

7.2 Non-Structural Mitigation Measures

7.2.1 Early Warning Systems

Implementation of regional seismic monitoring networks:

- **USGS NEIC integration** for distant earthquake notifications
- **Local seismic stations** for rapid magnitude and intensity estimation

- **Automated alert systems** for critical facilities
- **Communication protocols** for emergency response

7.2.2 Emergency Preparedness and Response

Development of comprehensive emergency plans:

- **Evacuation procedures** for high-rise buildings
- **Hospital surge capacity** planning for earthquake injuries
- **Search and rescue** team organization and training
- **Damage assessment protocols** for rapid recovery
- **Business continuity plans** for critical services

7.2.3 Community Education and Awareness

Public hazard awareness programs:

- **School curricula** including earthquake safety education
- **Seismic safety workshops** for building owners and occupants
- **Media campaigns** on earthquake preparedness
- **Annual earthquake drills** to test community readiness

7.3 Hazard Monitoring and Continuous Improvement

7.3.1 Regional Seismic Monitoring

Ongoing monitoring recommendations:

- **Seismic station maintenance** and data quality assurance
- **GPS monitoring** of active faults for crustal deformation
- **Liquefaction susceptibility mapping** updates
- **Volcanic monitoring** at Mount Sinabung and other active volcanoes

7.3.2 Research and Development

Recommended ongoing research:

- **Paleoseismic trenching studies** on Sumatran fault segments
- **Ground motion modeling** refinement with new earthquake data
- **Building performance studies** from earthquakes in comparable regions
- **Liquefaction case history development** for Indonesian soils

8.0 Conclusions

The Lake Toba region of North Sumatra experiences **medium seismic hazard** characterized by:

- 1 **Historical and instrumental earthquake activity** with frequent M5.0-M5.5 events and occasional M6.0+ earthquakes since 1976
- 2 **Ground motion predictions** indicating a 475-year return period PGA of **0.182g** (medium hazard classification under SNI 1726:2019)
- 3 **Active fault systems** including the Sumatran fault capable of producing magnitude M7.0+ earthquakes with recurrence intervals of 200-600 years
- 4 **Moderate to strong ground shaking** expected during characteristic earthquakes, causing minor to moderate structural damage in engineered buildings
- 5 **Multiple seismic hazard sources** including local strike-slip faults, subduction megathrust, and upper-plate crustal earthquakes

8.1 Recommendations

8.1.1 Structural Design and Mitigation

The following recommendations are prioritized for reducing seismic risk in the Lake Toba region:

- 1 **Structural design** must comply with SNI 1726:2019 requirements for intermediate seismic demand (Seismic Design Category D)
- 2 **Ground improvement** recommended for sites with liquefaction-susceptible soils
- 3 **Early warning systems** and emergency preparedness critical for reducing casualties
- 4 **Community education** essential for building public resilience
- 5 **Continued monitoring** and research needed to refine hazard assessments

9.0 References

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