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Probabilistic Seismic Hazard Analysis (PSHA) and Mapping of Andaman and Nickobar Islands and offshore regions

Gourab Tarafder

Abstract:
Present study is about the Probabilistic Seismic Hazard Analysis (PHSA) study of Andaman – Nickobar Islands and offshore regions. PHSA is estimated generally considering three probability density functions, such as Probability of uncertainty of magnitude of future events [p_M (m)], Probability distribution function of hypocentral distance of the future events and Probability of exceedance of spectral acceleration or peak ground acceleration. Disaggregation study is also performed to relate the earth quake events with their respective faults in this study. The values of Peak ground Accelerations necessary for the calculation of the Probability of exceedance of spectral acceleration are collected from our previous study described in Tarafder (2026).

Index Terms: Disaggregation, Probability of uncertainty of magnitude of future events (p_M), Probability distribution function of hypocentral distance of the future events, Peak ground Acceleration (PGA), Probability of exceedance of spectral acceleration or peak ground acceleration, Annual frequency of exceedance, Probabilistic seismic hazard analysis map (PHSA) etc.

INTRODUCTION

Andaman and Nickobar Island is well-known for its seismo-tectonic peculiarities. This island region is situated at the far south east part of India within the latitude from 6° N to 14°N and within the longitude 92°E to 95° E. However, in the present study we have considered an area from 6° N to 15°N in latitude and 90°E to 95° E in longitude, just similar to our previous study give in Tarafder (2026). In this study we are trying to make a tentative PHSA map of this region.

As the basic data used in this study like PGA value, sea floor elevation, bathymetry etc. are computer generated, it may differ to some extent from the actual field data. Thus, further field study is necessary. However, we are trying to get an overall idea about the earthquake vulnerability of this region.

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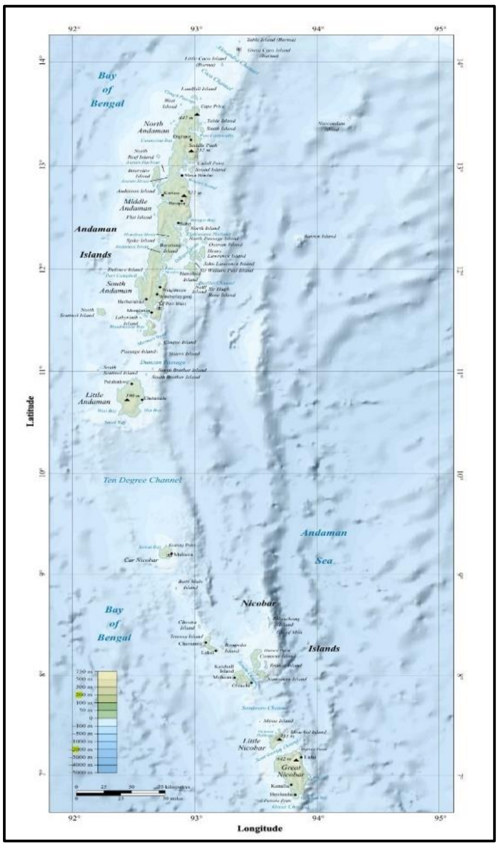

GEOLOGY AND TECTONICS

The western boundary of the Andaman–Nicobar region is bordered by the Bay of Bengal and is marked by the Andaman–Sumatra Trench, one of the most prominent geomorphic features of the northeastern Indian Ocean. This boundary extends from the Coco Islands in the north to the Nicobar Islands in the south. In the east of these islands there is a transition between the Andaman Sea and the Myanmar continental margin, extending toward the Coco Islands and the Irrawaddy Delta. This boundary forms the northern continuation of the Andaman island arc system and connects with the tectonic structures of Myanmar. In the eastern part of the Andaman–Nicobar region there is Andaman Sea, Mergui Terrace, and the Myanmar–Thailand continental margin. It represents the back-arc side of the Andaman island arc system and is characterized by extensional tectonics, sedimentary basins, and continental shelf environments and finally the southern boundary of the Andaman–Nicobar region is marked by the Great Channel and the northern margin of Sumatra (Indonesia). It represents the transition between the Andaman island arc and the Sunda Arc of Indonesia, where the Andaman subduction system merges with the Sumatra subduction zone.

This island region is an important region for the study of earthquake seismology as it is a highly seismically active zone which has provided many mega earthquakes such as Nias–Simeulue Earthquake 2005, Sumatra–Andaman Earthquake 2004, Andaman Islands Earthquake 1941 and Car Nicobar Earthquake 1881. The effect of the oblique convergence of Indian plate under the Southeast Asian/ Burma Plate in the western part of this region has led to the formation of an Accretionary Prism between the subduction zone and a complex right-lateral fault system (Curray, J.R., 2005, et al). Southern part of this region has evidences of volcanic activities with Barren Island as the only active volcano in this region.

Figure 1: Geographical map of Andamaan and Nickobar island region.

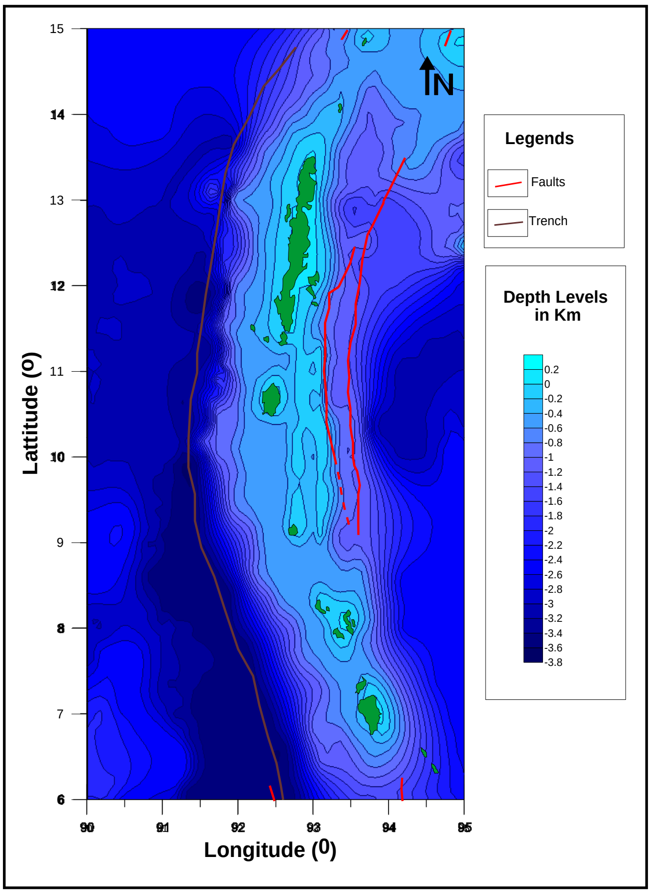

Figure 2: Topographic and bathymetry map of the study region (Tarafder, 2026).

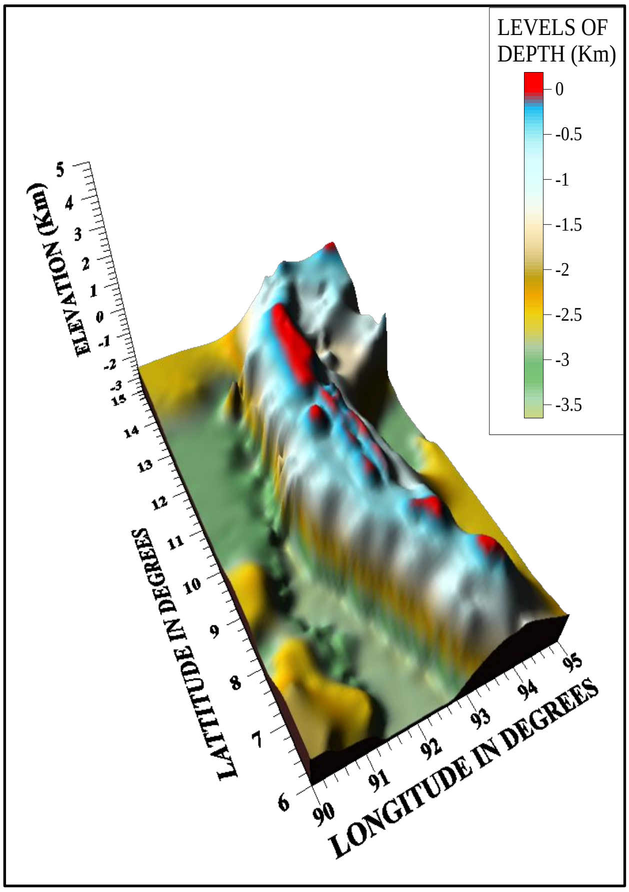

Figure 3: Digital Elevation Model (DEM) of crustal structures of the study regions (Tarafder, 2026).

The Andaman–Nicobar region exhibits a complex bathymetry shaped by active subduction, volcanism, and back-arc spreading. The seafloor is characterized by a series of distinct geomorphic provinces arranged from west to east such as the Bay of Bengal abyssal plain, the Andaman–Sumatra Trench, the outer arc ridge (Andaman–Nicobar Islands), the forearc basin, the volcanic arc, and the Andaman back-arc basin. Water depths range from less than 200 m on the continental shelves to more than 3,800 m within this region. This region is marked by steep submarine slopes, deep basins, submarine ridges, and volcanic edifices, reflecting its tectonically active nature.

From west to east Andaman and Nicobar Islands are tectonically categorized into following parts - (a) Andaman Trench/Inner Slope (b) Outer High/Trench slope break (c) Fore Arc Basin (d) Volcanic Arc (e) Back Arc Basin and (f) Mergui Terrace. Let us discuss them in brief -

(a) Andaman Trench/Inner Slope – The Andaman Trench (part of the Sunda Trench system) and its associated inner slope form a highly active, oblique subduction zone where

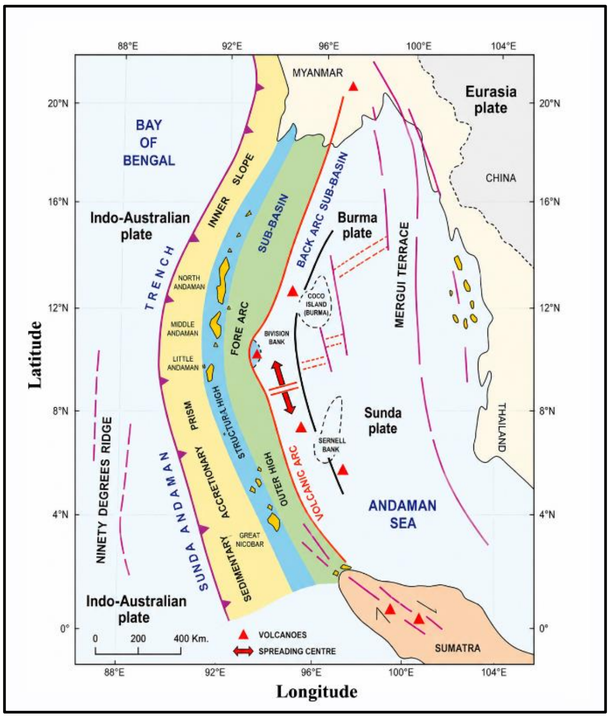

Figure 4: Different types of tectonic set ups of
Andaman and Nickobar Islands

the northeast-moving Indian plate subducts beneath the Southeast Asian/Burma plate. This trench runs for roughly 1,100 km along the western margin of the Andaman-Nicobar ridge. The convergence between the tectonic plates is highly oblique (angled), leading to "strain partitioning."

Immediately east of the trench axis there lies the inner slope, which geologists define as a massive **Accretionary Prism** — a wedge of deep-sea sediments and scraped-off rock that builds up along the inner wall of the trench. It is an imbricate stack of fault slices and folds consisting of ophiolites (sections of oceanic crust and upper mantle) and marine sediments. The western/outer portion of this prism is highly deformed and steep, while the inner portion is smoother, features lower slopes, and acts as a strong "backstop" against the forearc basin.

(b) Outer High/Trench slope break – A structural ridge marking the transition from the deep oceanic trench to the forearc region. It forms due to bending and compression of the subducting plate and represents the boundary between the trench slope and the uplifted forearc high.

(c) Fore Arc Basin – A sediment-filled depression located between the volcanic arc and the accretionary prism (forearc high) in a subduction zone. It develops due to tectonic subsidence and serves as a major repository for sediments derived from nearby landmasses and volcanic activity.

(d) Volcanic Arc – A curved chain of volcanoes formed above a subduction zone where the descending oceanic plate releases fluids into the overlying mantle, causing partial melting and magma generation. The magma rises to the surface, creating a belt of active and dormant volcanoes.

(e) Back Arc Basin – A tectonic basin that forms behind a volcanic arc in a subduction zone due to extension and thinning of the overriding plate. Back-arc basins are often characterized by seafloor spreading, high heat flow, and active tectonic deformation.

(f) Mergui Terrace - A broad submarine terrace in the Andaman Sea, located east of the Andaman–Nicobar volcanic arc and west of the Mergui (Myeik) continental shelf of Myanmar. It represents a relatively stable forearc-to-back arc transitional region shaped by tectonic uplift, sediment accumulation, and fault-controlled subsidence.

If we study the stratigraphy of the Andaman and Nicobar Islands and their adjacent offshore basins then we find that it records a complex tectonic evolution from a Mesozoic oceanic basement to a Cenozoic marine and carbonate sequence. On land, the sequence begins with the Late Cretaceous Ophiolite Suite (obducted oceanic crust) and the highly deformed Paleocene-Eocene Mithakhari/ Baratang mudstones and conglomerates, which are unconformably overlain by thick, deep-marine turbidites of the Oligocene Andaman Flysch Group and fossil-rich limestones of the Neogene Archipelago Group. In offshore, this stratigraphy varies based on structural positioning: the western flank is blanketed by thick distal Bengal Fan turbidites; the Forearc Basin contains thick Neogene marine carbonates and reservoir-grade sandstones that serve as primary targets for petroleum exploration; and the active eastern Back-Arc Basin (Andaman Sea) features irregular, rift-disturbed layers of terrigenous muds interspersed with volcanic ash and tuffs.

SOIL CLASSIFICATION

The soil properties of the Andaman and Nicobar Islands vary significantly depending on local topography, coastal influence, and the underlying parent rock. The soils of the Andaman–Nicobar Islands are predominantly red loamy and lateritic, with significant occurrences of forest, alluvial, coastal sandy, mangrove, and volcanic soils. Red loamy upland soils are largely derived from sandstone, shales, and basic volcanic rocks, leading to deep, well-draining soils that support the region's dense tropical rainforests. Coastal and flat valley areas feature fertile alluvial and clay-loam soils. Mangrove soils occupy tidal creeks and estuaries, whereas sandy soils are common along the beaches and coral-fringed coasts. Soil samples in this region have been found to contain relatively high total organic carbon (TOC) levels, often ranging between 2.4% and 5.2%. Although generally rich in organic matter and suitable for tropical crops, the soils are acidic and are typically deficient in available phosphorus and potassium and prone to nutrient leaching and erosion due to the humid tropical climate.

In our present study to mark different types of soils found within boundary of our study area we have considered the Site classification criteria of National Earthquake Hazards Reduction Program (NEHRP). Unfortunately, there is no published, region-wide NEHRP map available in India specifically for the entire Andaman–Nicobar islands and offshore regions. The NEHRP site classification is based on the average shear-wave velocity in the upper 30 m (V_{s30}) of the land. Classification of soils depending on the values of V_{s30} is given in the following table.

Table 1: Site Classification according to the NEHRP site classification criteria.

Site class	Range of Vs_{30} (km/s)
A	$Vs_{30} > 1.5$
B	$0.76 < Vs_{30} < 1.5$
C	$0.36 < Vs_{30} < 0.76$
D	$0.18 < Vs_{30} < 0.36$
E, F	$Vs_{30} \leq 0.18$

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The Andaman–Nicobar region exhibits a wide range of soil and sediment conditions that can be broadly related to NEHRP site classes based on their geotechnical properties. The hilly interiors of the Andaman and Nicobar Islands are predominantly underlain by consolidated sedimentary, ophiolitic, and volcanic rocks, corresponding to NEHRP Classes B and C, which represent hard rock and dense soil or soft rock conditions. In contrast, the coastal plains and river valleys contain unconsolidated alluvial deposits of sand, silt, and clay, generally falling within Class D, characterized by moderately stiff soils. Mangrove swamps, tidal flats, and estuarine regions are dominated by water-saturated clay, peat, and organic-rich sediments with low shear strength, corresponding to Class E, which is associated with soft soils and higher potential for seismic amplification. In offshore, the continental shelf is covered by marine sand, silt, and clay deposits and is generally classified as Class D, while the continental slope consists of a mixture of consolidated marine sediments and exposed bedrock, corresponding to Classes C–D. The forearc basin and back-arc basin contain thick accumulations of unconsolidated marine sediments and are generally assigned Classes D–E, reflecting their relatively soft sedimentary nature. The Accretionary Prism or outer arc ridge is composed of compacted and tectonically deformed sedimentary rocks, corresponding to Class C. Volcanic terrains such as Barren Island and Narcondam are dominated by basaltic and andesitic rocks and therefore fall within Class B. The abyssal plains of the Andaman Sea are covered by thick layers of pelagic clay and fine-grained deep-sea sediments, which are comparable to Classes D–E due to their soft and unconsolidated character. Together, these diverse soil and sediment types reflect the complex tectonic and depositional environment of the Andaman–Nicobar region and play an important role in controlling local seismic response and ground-motion amplification.

DATA AND METHODOLOGY

The earthquake data required for the calculation is collected from the USGS site. The data is freely available in the website. The data set includes the earthquake events occurring from the year of 1978 to 2009 within the study region. The depth of the events ranges from 8.0 Km to 181.8 Km. and M_w varies from 5.2 to 7.3 in moment M_w scale.

After generating the PGA contours (Tarafder, 2026) the frequency - magnitude study of the region is done to find the b-value (Fig- 5). The b-value obtained is near about 1.78.

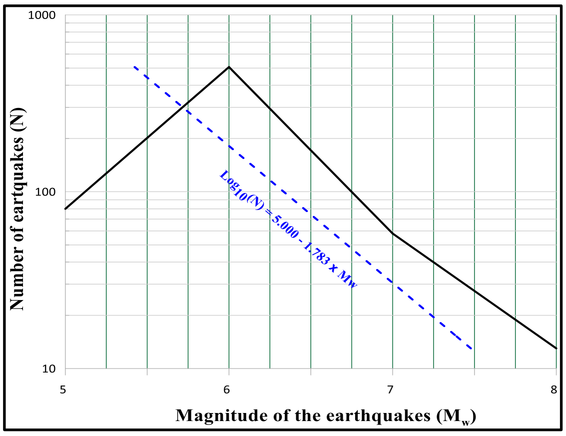

Figure 5: Frequency – Magnitude curve.

Disaggregation - Disaggregation study is performed after following the disaggregation process given in Iyengar and Ghosh (2004) and Raghukanth and Iyengar (2006). In this study we have tried to relate the earthquake events with respective faults. This is done after considering the detail tectonic map of the region showing all the active faults and trenches. After this we become able to find out two weightage factors as follows-

$$\propto_s = \frac{L_s}{\sum L_s} \text{ And } \delta_s = \frac{n_s}{\sum N_z}$$

where,
L_s=length of the s-th fault
ΣL_s =total length of the faults
n_s= total number of the past events associated with the s-th faults
N_z= total number of the earthquake events considered

So, considering the above two parameter we can calculate the average seismic activity of the s-th fault, as follows-

$$N_s(m_0) = 0.5(\propto_s + \delta_s)N(m_0)$$

where,
$N_s(m_o)$= number earthquake events of magnitude m_o associated with s-th fault,
$N(m_o)$= total number of earthquakes events of magnitude m_o.

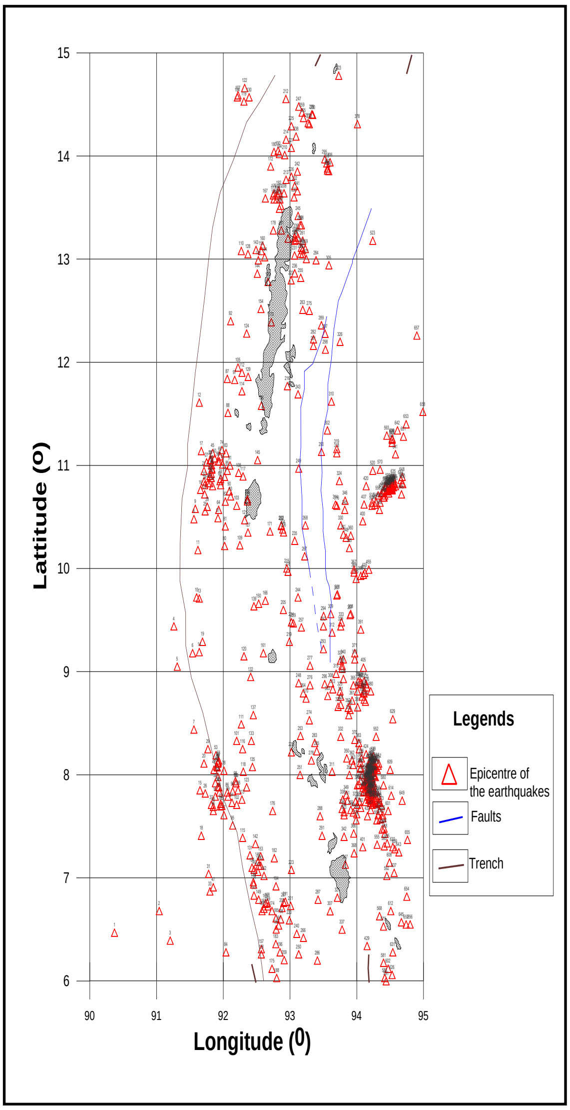

Figure 6: Occurrence and fault associativity of the earthquake events in the study region (Tarafder, 2026).

Generation of Probabilistic Seismic Hazard Analysis map (PHSA)-

To generate PHSA map we have to calculate three probability distribution functions, namely-

i. Probability of uncertainty of magnitude of future events [p_M (m)],

ii. Probability distribution function of hypocentral distance of the future events,

iii. Probability of exceedance of spectral acceleration or peak ground acceleration, Calculations and studies of these three functions are given below –

i. Probability of uncertainty of magnitude of future events [p_M (m)] - After this we become able to calculate the factor of uncertainty in the magnitude of a future event, which can be represented by the following equation (after Development of Probabilistic Seismic Hazard Map of India, Technical Report of The Working Committee of Experts (WCE) constituted by the National Disaster Management Authority Govt. of India, New Delhi).

$$p_M\,(\mathrm{m}) = \frac{\beta e^{-\beta(m-m_o)}}{1-\beta e^{-\beta(m_u-m_o)}}, \quad where\ (\mathrm{m_u} \leq \mathrm{m} \leq \mathrm{m_o})$$

Considering,
β = 2.303 b,
m =magnitude of an earthquake event,
m_o= lower limit of magnitude of earthquake events caused by a rupture = 4.5M_o (taken),
m_u = upper limit of magnitude of earthquake events caused by a rupture = 8.0 M_o (taken);

ii. Probability distribution function of hypocentral distance of the future events-
Every earthquake event causes change in the regional tectonic set up. More over the amount of stress released due to each event is also very uncertain. These two factors make energy radiation pattern of any future event indefinite. Thus, we need to calculate a probability function to account for the uncertainty in hypocentral distance from any station point from any reference point on the rupture plane or hypocentre. To calculate this, we consider the method of Der Kiureghian and Ang (1977), which is as follows-

$$P\langle R < r | M = m\rangle = 0 \qquad for\ \ R < (D^2 + L_0^2)^{\frac{1}{2}}$$

$$P\langle R < r | M = m\rangle = \frac{(r^2-d^2)^{\frac{1}{2}}-L_0}{L-X(m)} \qquad for\ (D^2 + L_0^2) \leq R < \{D^2 + [L + L_0 - X(m)]^2\}^{1/2}$$

$$P\langle R < r | M = m\rangle = 1 \qquad for\ \ R > \{D^2 + [L + L_0 - X(m)]^2\}^{1/2}$$

where ,

X(m) = rupture length (km)which is determined from Wells and Coppersmith (1994) as -
X(m) = min [$10^{(-2.44+0.59(mi))}$, fault length],

L = Total fault length (km),

L_o = Change in the fault length after the earthquake event (km),

M = Magnitude of an earthquake event (M_o),

D = Hypocentral distance (km);

iii. Probability of exceedance of spectral acceleration or peak ground acceleration -

In Probabilistic seismic hazard analysis, we estimate the probability of exceedance of spectral acceleration (SA) or Peak Ground acceleration (PGA) at a site due to all possible future earthquakes. This can be done by assuming that the number of earthquakes occurring on a fault follows a stationary Poisson distribution process. Now if we consider a new standard normal variable (z), then we become able to study the variation of Probability Distribution Function of the Poisson's Distribution. The value of z is as given below-

$$z = \frac{\ln(PGA) - \ln(PGA)}{\sigma_{lnPGA}}$$

where,

σ_{lnPGA} = standard deviation of logarithm of PGA values,

ln (PGA) = logarithm of various targeted peak values (percentage amount of probability exceedance),

ln (PGA) = logarithm of PGA values;

The probability of exceeding ground motion amplitude in a given period of time is related to annual frequency of exceedance given by the equation (Cornell, 1968):

$$P\,(Z > z|T) = 1 - e^{-v(z)\,T} \qquad z \le v\,(z)\,T$$

where,

P (*Z*>*z*|*T*) = probability of exceedance during a time period (*T*),

v (z) = annual frequency of exceedance,

In our case we have taken data ranging from 1978 up to 2014. So, the value of T= (2014-1978) =37 years. So, putting this value in the above equation we get-

$P\,(Z > z|T) = 1 - e^{-v(z)\,.37}$

The often-used term "return period" is the reciprocal of annual rate of exceedance (μ). The annual rate of exceedance is computed by the equation:

$$\mu = \sum_{n=1}^{N} \sum_{m=m_o}^{m_u} N_i\,(m_i) \sum_{r_j=0}^{r_{max}} P\langle R = r_j | m_i \rangle\, P\,(Z > z|m_i, r_j)$$

where,

ΣN = summation over all (*N*) seismic sources,

$\lambda_n(mi)$ = the annual frequency of occurrence of earthquakes of magnitude *mi* on seismic source *n*,
$P_n(R=rj|mi)$ = the probability of an earthquake of magnitude *mi* on source *n* occurring at a closest distance r_j from the site,
$P_n(Z>z|mi,rj)$ = the probability of ground motion *Z* exceeds a specified value *z* at an earthquake magnitude *mi* and the shortest
distance r_j from the site; m_i is between lower-bound magnitude m_0 and upper-bound magnitude m_u;

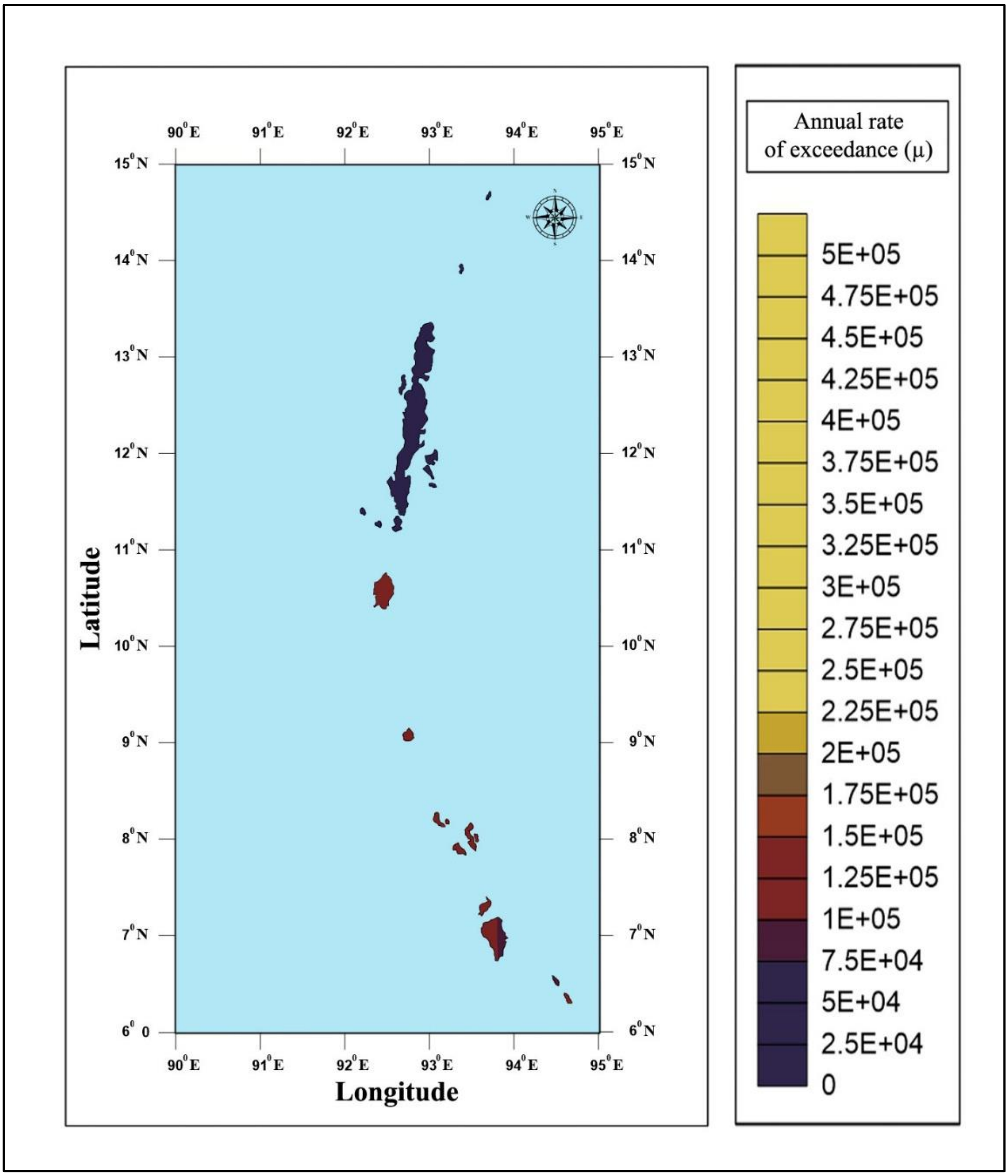

Figure 7: Probabilistic Seismic Hazard Analysis (PHSA) map of Andaman Nickobar Island region.

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DISCUSSIONS AND CONCLUSION

The present PHSA study gives us a detail idea of the earthquake vulnerability of Andaman-Nickobar island regions. It has been observed that the islands of Andaman region are less vulnerable as compared to the islands of Nickobar region.

In PHSA map we generally study the nature of the annual rate of exceedance (μ). The changes of rates of exceedances are parallel to the directions of the ridges and faults of the respective regions, which can be clearly visible in the case of the Great Nickobar Island. The difference in vulnerability levels is due to the difference of seismicity patterns of Andaman and Nickobar regions. The South (or Great) Nicobar Island regions is much more tectonically active than the Andaman region; main causes behind this are - much steeper subduction angles, higher convergence velocities, and heavier sediment loading. The islands of the Nicobar region are situated closer to the highly volatile Sumatra-Java megathrust boundary. These islands are situated directly on the overriding Burma plate. The convergence rates of the under riding Indian plate is much more in the Nickobar region. Convergence rate near Nicobar region reaches about 23 mm/yr, compared to 19 - 21 mm/yr in the northern Andaman region. Faulting and separation of tectonic blocks are very frequent in Nickobar region which result into earthquake swarms. Unlike the Andaman Islands, which feature active folding, thrusting, and mixed uplift, the southern portion of Great Nicobar is undergoing continuous tectonic subsidence. Due to all these reasons Nickobar region becomes highly seismically active providing numbers of large earthquakes and more earthquake hazard prone.

When comparing soil hardness, the islands of Andaman group generally feature harder, higher stress bearing superficial soils than the islands of the Nicobar group. This disparity is driven directly by their parent rock composition, weathering depth, and the dominance of the Mithakhari Mélange versus fine-grained marine flysch matrices.

The soil of Andaman region is very stiff to hard clayey loams & gravelly saprolites. In this region outcropping of Ophiolite and the Mithakhari Mélange are dominant. The inclusion of hard rock fragments (extra clasts, cherts, and gabbroic gravels) gives the shallow soil matrix a high unconfined compressive strength, translating to high mechanical hardness and resistance to penetration. The soil of this region is highly plastic with high-plasticity value A-7. When this soil dries, they exhibit significant apparent cohesion and becoming notably hard. It is highly prone to temporary strength loss (liquefaction) during earthquakes. However, the harder rock horizons are shallow, meaning foundation piles easily strike a hard stratum ($N > 50$) at moderate depths.

On the other hand, in the Nickobar region the soil is comprising with the soft to medium silty-clays & loose coastal sands. Soils of this region are dominated by Nicobar Flysch which is fine-grained turbidite successions of shales and siltstones. The absence of hard ophiolitic fragments results in a structurally softer soil matrix. This region bears poorly drained soils with a pervasively high-water table. As these fine-grained soils remain saturated year-round, they function close to their liquid limit (LL), maintaining a soft to medium-stiff consistency with minimal shear resistance. Due to the severe co-seismic subsidence during tectonic events, many coastal and valley soils became permanently waterlogged in this region which cause an increased pore water pressure which has systematically degraded the effective stress (σ') of the soil, rendering the shallow profiles exceptionally soft.

Due to all of these reasons the soils of Andaman region are hard but the soils of Nickobar region are soft which led to the possibilities of more earthquake hazards.

Thus, from the above discussions we can draw a conclusion that the Nickobar island region is much more earthquake hazard prone than the Andaman island region.

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