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Liquefaction potential studies of the synclinal area of Indo-Burmese Range, Tripura, India

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ABSTRACT

Soil liquefaction is a major concern in tectonically dynamic areas, where unscientific urbanization is increasing rapidly. The present study area falls in the Neogene outer wedge of Indo-Burmese Ranges, where subduction related earthquakes dominate, and the synclinal valleys are dominated with younger, unconsolidated, unmatured, loose sediments with varying fines contents and shallow groundwater conditions which are favourable site for liquefaction. Dharmanagar, part of strongly deformed domain of Indo Burma wedge, subjected to frequent earthquake due to ongoing subduction activity of Indian plate beneath Burmese plate. The deterministic liquefaction potential index (LPI) in the Dharmanagar syncline shows significant part of the town falls in very high liquefaction probability zone (33%) and high liquefaction probable zone (38%), which is underlined by recent alluvium and Dupi Tila Formation. The moderate (20%), low (5%), and non-liquefiable (4%) areas of the Dharmanagar occupies mainly the anticlinal, which is dominated with Tipam and Boka Bil Formation. Liquefaction potential in the area shows the requirement of seismic building norms with respect to the rapid urban expansion and the building styles in the Urban and Suburban areas. Also, these younger alluvial areas are vulnerable to even smaller magnitude earthquake (M ≥5), signifies the importance of LPI in the subduction tectonic areas for disaster management and urban development.

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1. Introduction

Soil liquefaction is a major concern in the contemporary densely inhabited places, proximal to the tectonically active areas where thick Quaternary deposits of loose, unpacked, and poorly sorted sand with shallow ground water conditions persist. Liquefaction is a phenomenon wherein a mass of soil loses a large percentage of its shear resistance, when subjected to monotonic, cyclic, or shock loading, and flows like liquid. It can also be explained as the transformation of granular material from solid to liquefied state as a consequence of increased pore water pressure and reduced effective stress (Marcuson, 1978). When pore water pressure increases, then the granular particle in a compact stage is subjected to cyclic shear deformation (Seed, 1979). Liquefaction mainly occurs in loose to moderately dense granular sandy soils capped with seams of impermeable sediments with shallow groundwater conditions. The world attention on soil liquefaction obtained its momentum after the Niigata earthquake in 1964, Alaska Earthquake in 1964, Chi-Chi Earthquake in 1999, etc. (Seed, 1979; Ishihara, 1993; Robertson and Fear, 1995).

There are two major methods for the evaluation of liquefaction potential, namely, laboratory tests and in situ tests/ index tests. In-situ tests namely Standard Penetration Test (SPT) and Cone Penetration Test (CPT) with appropriate empirical formulas are very good starting points for the estimation of the liquefaction potential in a quite short period. But the geological condition (especially soil heterogeneity) of the site is very complicated to rely only on the SPT and CPT tests since there is no clear presence of soil layers with clean sands and stratification of the sandy soil layers.

Therefore, extensive laboratory tests were conducted at the laboratory to understand the dynamic property of soil. The methodology proposed by Iwasaki et al, (1982), is widely used for understanding the spatially distributed probability of liquefaction-induced surface of a study area. Later, Seed et al, (1985) has improved the procedure by calculating the safety factor per layer (FS), as the ratio of cyclic resistance ratio (CRR) to the cyclic stress ratio (CSR). Soil layers with a normalized SPT blow count $(N1)_{60}$ less than 22 have been known to be liquefiable (Seed et al.,1985). Later, Marcuson et al (1990) suggested that an SPT value of $(N1)_{60}$ less than 30 is the threshold to use for suspecting liquefaction potential. Further, Seed et al, (2003) shows that, soils are liquefiable while checking the following criteria: (i) a degree of Saturation (Sr) close to 100%, (ii) a Fraction of the fine (FC) less than 35%, (iii) The grains size diameter lies between 0.05 mm and 1.5 mm, and uniform granulometry that correspond to a Coefficient of uniformity (Cu) < 15.

The liquefaction studies in India were started with 1988 Assam Earthquake (Gupta, 1993). Later, liquefaction potential studies were carried out in various Indian cities like New Delhi , Mumbai (Dixit et al, 2012), Chennai (Ganapathy and Rajawal, 2012), Guwahati ,Agartala (Das et al, 2020) etc. Northeastern part of India falls in seismic zone V, and most tectonically active domain subjected to number of earthquake and soil liquefaction is the major threat to the cities in this area. Various studies in northeast of India showing, irrespective of the magnitude and distance the soil liquefaction is predominant in foreland basins of Brahmaputra and in synclinal areas of Tripura Mizoram fold belts (Debbarma et al, 2017; Rajendran and Rajendran, 2021; Bhadran et al, 2024a & 2024b). Its vitrine the significance of detailed liquefaction potential studies in Northeast of India. In view of this, for the present study an effort has been made to comprehend the liquefaction potential of Dharmanagar, part of Deo-Juri-Dharmanagar syncline, falling in strongly deformed domain of Indo Burma Ranges (IBR, Fig 1).

1.1 Study area

The tectonic domain in the eastern end of the Indian Plate and associated margins witnessed two great earthquakes (M $\geq$8.0) and more than fifteen strong earthquakes (7.9 $\leq$ M $\geq$7.0) in the last two hundred years due to the various tectonics such as pop-up tectonics in the margin of the Shillong plateau (Bilham and England, 2001), continental-continental collision along Himalayas (Kayal, 2010), seismicity associated with loading along the peripheral collisional foreland basin ie. Bengal Basin (Hossain et al, 2019) and deep focus earthquakes in the subduction margin. These earthquakes caused severe liquefactions, coseismic landslides, ground settlements and other structural damages in the hills as well as in the valleys, irrespective of their magnitude and distance due to various conditions like type of building, compactness of the soil, ground amplifications, groundwater conditions (Bhadran et al, 2024b). The recent 2017 Manu earthquake (M 5.7) and 1918 Srimangal earthquake (M 7.6) within the fold thrust belt and Bengal Basin respectively caused ground liquefaction, lateral spreading, etc indicates that the magnitude of earthquake is less significant than the ground condition for the liquefaction. The present study area, Dharmanagar covering an area of 100 Km^2, is the second largest Town in Tripura(~150 km NE of Agartala), which is situated in the western margin of Bengal Basin, and belongs to the strongly deformed domain of Indo-Burma Wedge (Das et al, 2022), falls under the seismic zone V with a zone factor of 0.36g, (BIS, 2002).

The study is bounded by various active faults such as Chittagong coastal fault (CCF) in the east, Kaladan Fault (KF) in the west and Dauki Fault (DF) in the north. The CCF divides the Bengal basin to the deformation front of the Tripura-Mizoram Fold Thrust (TMFT) belt whereas the KF act as the mega thrust which separates the Paleogene – Neogene boundary in the TMFT belt and host many deep and shallow focus earthquakes with varying magnitudes. The area under study comprises sediments from Neogene to Recent. Geologically, the entire area consists of Surma Group (Miocene), Tipam Formation (Mio-Pliocene), Dupi Tila Formation (Plio-Pleistocene), and recent Alluvium (Kesari et al, 2011). Surma group consists of arenaceous units of Bhuban and argillaceous unit of Boka Bil Formations. Most of the core and hinges of the anticline consists of Bhuban and Boka Bil Formation respectively. Tipam Formation, which is loose medium sand with false bedding, cross bedding, and herringbone structures are well exposed along the limb of major anticlines around Dharmanagar as Patharia (in north), Lengai (in east), Khubai (in south) and Machhithilum (in west).The Dupitila sediments consisting of yellowish to brown silty clay, mottled clay, clayey sandstone and coarse to gritty ferruginous sandstone and lies unconformably over Tipam Formation, occupies major part of synclinal areas. Active and paleo channels of main rivers in Dharmanagar (Juri River, Kakri River) are filled with recent alluvium (Fig 1c).

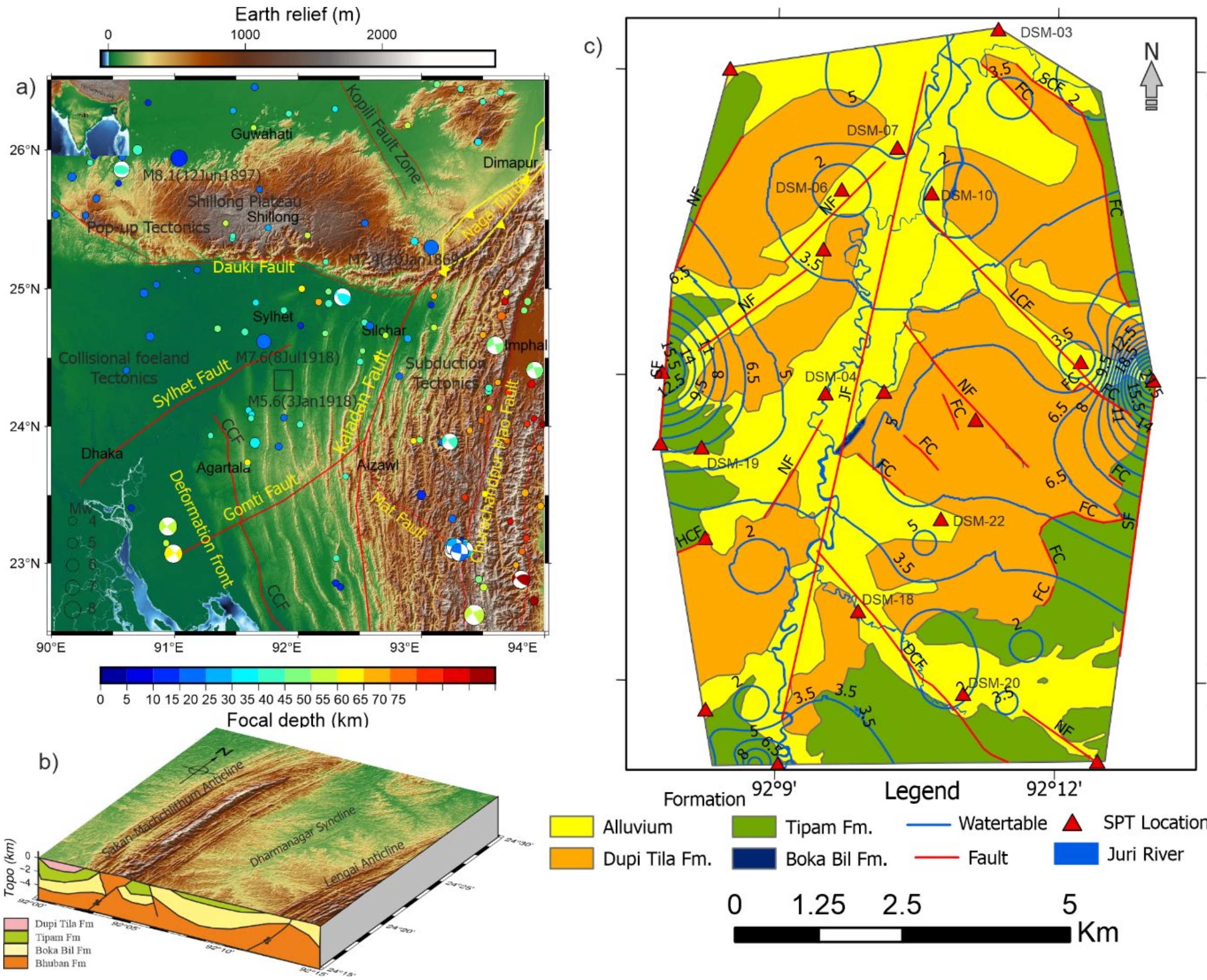

Fig 1. a) Tectonic setup around the study area and the distribution of earthquake with magnitude >5Mw(study area shown in black box, red lines indicate the major faults); **b)** 3D view of the Deo-Juri Dharmanagar syncline and surrounding anticlines; **c)** Geology of the study area, in which major faults in the study area is shown in red lines (FC-faulted contact, NF- Neotectonic Fault, DCF- Deocherra Fault, LCF- Lalcherra fault, SCF- Sanicherra fault, HCF- Halflongcherra fault, JF- Juri Fault) along with groundwater contour (bgl) in meters.

2. Materials and Methods

To assess the liquefaction potential of the study area, 22 numbers of Standard Penetration Test (SPT) with a spacing of 2.5 km (a depth of 30 m) has been conducted (Fig 1c). Both disturbed and undisturbed samples were collected for geotechnical studies. The details on subsurface geology and SPT-N blow count were recorded at the drilling site itself. SPT drilling is a widely used technique to determine the in-situ properties of the soil and is suited for cohesionless soils as the correlation between the SPT value and phi (φ) is now well established.

Further, data collected from 2000-2022 Central Water Commission(*https://indiawris.gov.in/wris/groundWater*) and the field data collected from 50 dug wells and 22 SPT locations in and around Dharmanagar were used for the preparation of groundwater table condition in the area.

2.1 Estimation of Liquefaction Potential based on Factor of Safety

Liquefaction susceptibility of an area designated based on the factor of safety (FS) as defined by Seed and Idris (1982) (Eqn 1.1), which depends on (1) earthquake loading on soil as cyclic stress ratio (CSR), (2) the soil strength (capacity of soil) to resist liquefaction as -cyclic resistance ratio (CRR) and (3) magnitude scaling factor (MSF).

The obtained factor of safety (FS) can be categorized in terms of the relative degree of liquefaction susceptibility as given in Table 1 (Nath.,2011).

$$FS=(CRR/CSR) \times MSF \ldots\ldots\ldots\ldots.. (1.1)$$

Where, MSF-Magnitude Scaling Factor, CRR-Cyclic Resistance Ratio and CSR- Cyclic Stress Ratio.

2.2 Cyclic Stress Ratio (CSR)

The seismic demand induced by a given earthquake can be characterized by Cyclic Stress Ratio (CSR) and it can be determined from peak ground surface acceleration that depends upon site-specific ground motions. The average shear stress due to earthquake loading (τav) is computed using the following Eq. 1.2 and CSR is calculated using Eqn 1.3 (Seed and Idriss.,1979).

$$\tau av = 0.65 \times \frac{a\,max}{g} \times \sigma\, vo \times rd \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.2)$$

$$CSR = \left[0.65 \times \left(\frac{\sigma}{\sigma'}\right) \times \left(\frac{a\,max}{g}\right) \times rd\right] \ldots\ldots\ldots\ldots\ldots\ldots (1.3)$$

where, σ denotes Vertical overburden Stress, σ' is Effective overburden stress, amax, Peak ground Acceleration [For the present study in Dharmanagar, the highest PGA (0.89g) derived from seismic hazard analysis based on the Maxium Credible Earthquake and using the model by Atkinson and Boore (2003), has been considered to represent the worst case scenario; g is the acceleration due to gravity; rd is stress reduction coefficient and it is estimated based on Liao and Whitman., 1986b.

rd=1-(0.00765× Depth) for water depth <9m

rd=1.174-(0.00267 × Depth) for water depth >9m

2.3 Cyclic Resistance Ratio (CRR)

To determine the cyclic resistance ratio (CRR), the fines content (FC) of the soil is necessary to adjust the updated Standard Penetration Test (SPT), blow count $(N1)_{60}$ to an equivalent clean sand standard penetration resistance value (N1) 60cs. Idriss and Boulanger (2005) proposed a method to calculate the CRR for cohesionless soils with varying fines content, using Equation 1.4. This equation is applicable for CRR calculations for a magnitude 7.5 earthquake, specifically for soils with 5% fines content.

$$CRR=\exp\{(N1)_{60}/14.1+((N1)_{60}/126)^2-((N1)_{60}/23.6)^3+((N1)_{60}/25.4)^4-2.8\} \ldots\ldots\ldots\ldots\ldots (1.4)$$

To evaluate the cyclic resistance ratio (CRR) from Standard Penetration Test (SPT) data, the initial SPT N-value is first measured and then corrected by applying the following adjustments, which lead to the calculation of $(N_1)_{60}$ values. These corrected values are standardized to a 60% hammer efficiency and an overburden pressure of 100 kPa, as described in Equation 1.5.

$$N1(60) = N \times C_N \times C_E \times C_B \times C_R \ldots\ldots\ldots\ldots\ldots\ldots (1.5)$$

where, N is the Observed N value; $\mathbf{C_N}$ denotes Overburden pressure correction; $\mathbf{C_E}$ -energy correction factor for the SPT hammer. For donut hammers CE = 0.5–1.0; for trip type donut hammers; CE = 0.8–1.3; $\mathbf{C_B}$ - borehole diameter correction. For borehole diameters 65–115 mm use CB = 1.0; for borehole diameter of 150 mm, use CB = 1.05; for borehole diameter of 200 mm, use CB = 1.15; $\mathbf{C_R}$ -rod length correction. For rod length < 3 m, use CR = 0.75; for rod length 3–4 m, use CR = 0.8; for rod length 4–6 m, use CR = 0.85; for rod length 6–10 m, use CR = 0.95; for rod length 10–30 m, use CR = 1.0.

However, correction factor suggested for CRR $N1(60)_{FC}$ is calculated based on Eqn 1.6

$$N1(60)_{FC} = a+bN1(60) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.6)$$

Where,

N1(60) - Corrected N value based on Eqn 6

$$a=0 \text{ for } FC<5\%$$

$$a=\exp\left[\frac{1.76-190}{(FC)^2}\right] \text{ for } 5\% < FC < 35\%$$

$$a=5 \text{ for } FC > 35\%$$

$$b=1 \text{ for } FC< 5\%$$

$$b=\left[0.99+\frac{(FC)^{1.5}}{1000}\right] \text{ for } 5\% < FC < 35\%$$

$$b=1.2 \text{ for } FC >35\%$$

2.4 Magnitude Scaling factor (MSF)

In Dharmanagar, the equation for MSF (Eqn 1.7) suggested by Seed and Idris (1982) has been calculated**.** MSF vary for different magnitude and the details are given in Table 1.

$$\mathbf{MSF} = \frac{(10)^{2.24}}{(M)^{2.26}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.7)$$

Were, M – Magnitude of Earthquake [For Dharmanagar, Maximum Credible Earthquake

(MCE)(Mw=7.9) has been considered]

Table 1 Magnitude Scaling Factor (MSF) suggested by Idris 1995

Earthquake Magnitude	MSF
5.5	2.2
6	1.76
6.5	1.44
7	1.19
7.5	1
8	0.84
8.5	0.72

In addition to above, liquefaction potential index (LPI), a measure of liquefaction severity during an earthquake, which was introduced initially by Iwasaki et al. (1982) (Eqn 1.8) for the soil having FS<1. Later it has been modified by Luna and Frost (1998). However, recent studies shows that FS>1 also subjected to liquefaction and the threshold of FS value increased to 1.2. Accordingly, liquefaction potential has been categorized as per the FS value upto 1.2 (Sonmez., 2003). Table 2 represent the level of liquefaction potential suggested by various studies. For the present study LPI classification based on Sonmez ,2003 has been considered.

$$LPI= \int_0^{20} F(z).w(z)dz \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1.8)$$

Where, z is depth of the midpoint of the soil layer (0 to 20 m) and dz is differential increment of depth.

Table 2 Liquefaction potential categories by various studies

LPI	Iwasaki (1982)	Luna and Frost (1998)	LPI	Sonmez (2003)
0	Very Low	Little to none	0	Non-Liquefiable
0<LPI≤5	Low	Minor	0<LPI≤2	Low
5<LPI≤15	High	Moderate	2<LPI≤5	Moderate
LPI>15	Very High	Major	5<LPI≤15	High
			LPI>15	Very High

The weighting factor, w(z), and the severity factor, F (z), are calculated as per the following expressions:

$F(z) = 1 - FS$ for $FS < 0.95$

$W(z)=2 \times 10^6 e^{-18.427Fs}$ for 1.2>FS>0.95

W(z)= 0 for z>20m and FS≥1.2

F (z) = 0 for FS ≥ 1.2

w(z) = 10 − 0.5z for z < 20 m w(z) = 0 for z > 20 m

3.Results

3.1 Groundwater condition in Dharmanagar, North Tripura

The data from Dharmanagar shows the groundwater fluctuation is 0.5-25m below ground level(bgl). Shallow water table conditions were observed in the central portion of the studied area. Anticlinal area's water table were deeper due to the topographic effect (Fig 1c).

3.2 Liquefaction Potential of Dharmanagar, North Tripura

Based on the above empirical equation, liquefaction potential index of Dharmanagar, North Tripura has been prepared. The factor of safety (FS) value indicates, except the boreholes near to the anticlinal areas, most of the boreholes are in critical to very critical liquefaction condition. The SPT boreholes, which lies near to the anticlinal areas shows the FS>3. The boreholes, in which FS <1.2 (DSM-03,04,06,07,10,18,19,20 & 22, Fig 1c), liquefaction potential index has been calculated, in these boreholes mainly silty clay, clay, silty sand and sand dominates (Fig 2a). The LPI calculated for the various lithologs in Dharmanagar is shown in Fig 2b, Table 3. Most of the boreholes collected from northern part of the study area, part of syncline possessing a layer of driftwood (paleo flood deposit) with thickness ~ 2 metres at various depth (3 metres in DSM -10, 4.5 meter in DSM-4 & 7.5 meters in DSM -3). The SPT-N value and shear wave velocity (Vs30) drops drastically at these layers (driftwood) and their disposition in the borehole shows the active nature of the basin. A representation on various lithology is shown with two lithologs (DSM-3 & DSM-10), Fig 3.

The distribution of LPI in Dharmanagar was prepared with the aid of ArcGIS Pro 3.2.2 and is shown in Fig 4. It shows that, significant part of Dharmanagar town and its northeastern part- which makes up 33% of the research area- fall within the very high liquefaction probability zone. High liquefaction probable zone covers the 38% of the study area, which occupies the southern and western part of Dharmanagar. The moderate (20%), low (5%), and non-liquefiable (4%) areas are mainly covered in the anticlinal portion of Dharmanagar, which is in the southwest and northeast side of the study area.

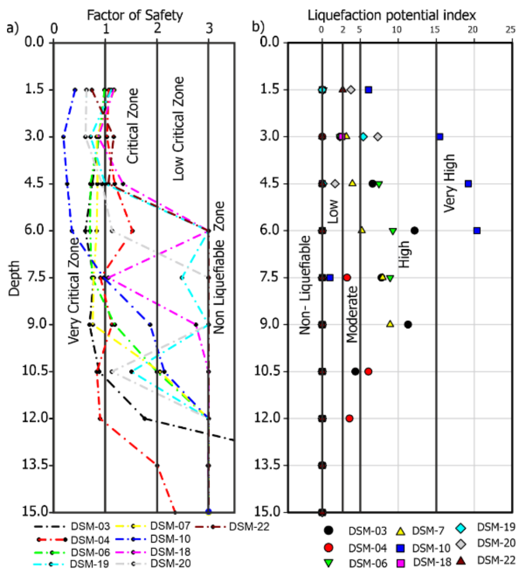

Fig. 2. (**a**) Shows variation of FS value and (**b**) shows the corresponding LPI value variation with depth.

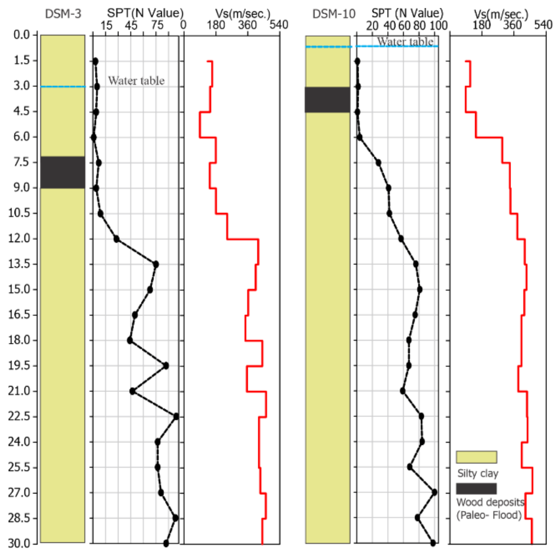

Fig. 3. Distribution SPT-N value, shear wave velocity (Vs30) and lithological variation in DSM 3 & 10.

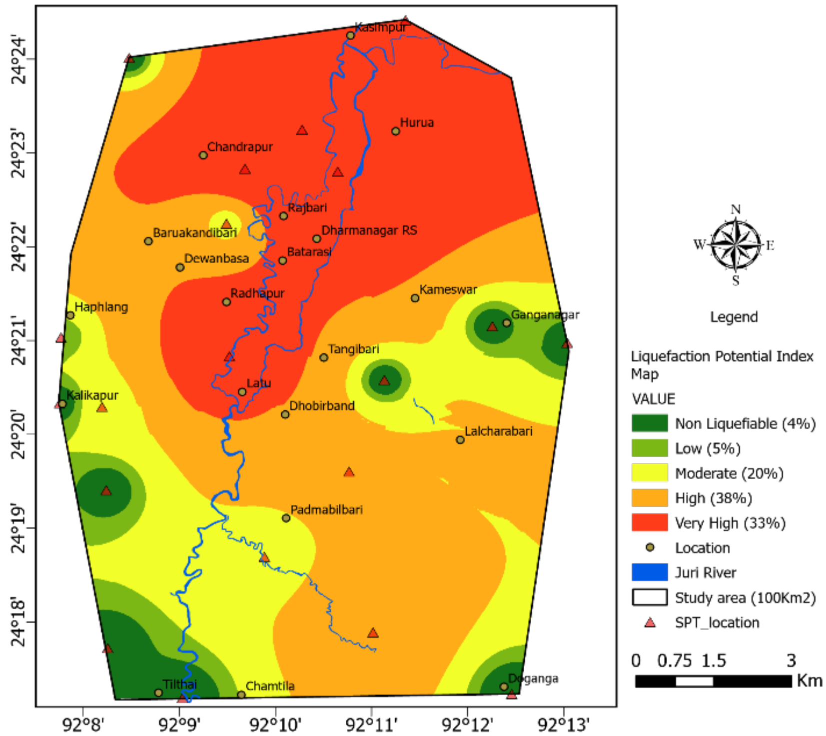

Fig 4. Liquefaction potential index map of Dharmanagar, North Tripura

The LPI calculated for the various lithologs in Dharmanagar is shown in Fig 2b, Table 3. Most of the boreholes collected from northern part of the study area, part of syncline possessing a layer of driftwood (paleo flood deposit) with thickness ~ 2 metres at various depth (3 metres in DSM -10, 4.5 meter in DSM-4 & 7.5 meters in DSM -3).

Table 3. Boreholes collected from northern part of the study area

Depth (m)	1.5	3	4.5	6	7.5	9	10.5	12	13.5	15	
Soil Type	Sand	Sand	Sand	Sand	Sand	Sand	Clay	Clay	Clay	Clay	
N value	1	2	1	4	28	41	42	57	76	81	
FC	8	8	8	8	8	8	8	8	8	8	
Cfine	1.7	1.4	1.7	1.2	1.1	1	1	1	1	1	
N1(60)	0.6	1.3	0.6	2.5	17.5	25.6	26.3	35.6	47.5	50.6	
N1(60)*	1	1.7	1	3	18.5	26.8	27.5	37.2	49.4	52.6	
CRR	0.1	0.1	0.1	0.1	0.2	0.3	0.4	1.8	406.3	4731.9	
σ(kN/m^3)	27.8	55.5	83.3	111	138.8	166.5	194.3	222	249.8	277.5	
σ'(kN/m^3) -u	14.7	29.4	44.1	58.8	73.5	88.2	102.9	117.6	132.3	147	
σ(kN/m^3)	13.1	11.4	24.5	37.5	50.6	63.6	76.7	89.7	102.8	115.8	
rd	1	1	1	1	0.9	0.9	0.9	0.9	0.8	0.8	
CSR	0.1	0.3	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	
MSF	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	
FS	0.42	0.19	0.27	0.35	0.97	1.87	2.14	>3	>3	>3	
z	0.8	1.5	2.3	3	3.8	0	0	0	0	0	
dz	1.5	1.5	1.5	1.5	1.5	0	0	0	0	0	
w(z)	0.6	0.8	0.7	0.6	0	0	0	0	0	0	
LPI	6.1	15.4	19.2	20.3	1	0	0	0	0	0	62.06

4. Discussion

Liquefaction potential studies is paramount in synclinal areas of IBR, where ongoing subduction related tectonics is dominated with a numerous active fault and frequent earthquakes. Furthermore, the 1897 Shillong, 1918 Srimangal, and 2017 Manu earthquake has caused severe shaking and liquefaction in various part of Tripura. Further, Mog and Anbazhagan (2018), studies implies the e possibility of re-liquefaction of soil with magnitude >6Mw in Manu River (30km southwest of Dharmanagar). Hence, the liquefaction potential studies in the synclinal areas of IBR is essential. Detailed geological mapping through field work and subsurface geology through 22 SPT boreholes from Dharmanagar indicate, major part of the city is dominated with recent alluvium and Dupi Tila Formation, consists of clay, silty clay, silty sand and loose sand. In addition, the exposure of driftwood (paleoflood deposits) is also observed at various depth in Dharmanagar. Groundwater condition is shallow in most of the area and the depth increase upto 25 m in anticlinal areas around the study area. The litholog from the SPT drillhole shows that area nearer to anticline is composed of false bedded sandstone and compact bluish shale, which is part of the Tipam and Boka Bil Formations. On the other hand, major part of Dharmanagar city is dominated with recent alluvium sediments and Dupi Tila Formation. The LPI calculated for most of the borehole in and around Dharmanagar city indicates low N value, shallow water condition (~2m) and High LPI values (>30) which implies that the possibilities of high liquefaction and associated ground failure. It shows that, significant part of Dharmanagar town falls in very high liquefaction probability zone (33%) and high liquefaction probable zone (38%).

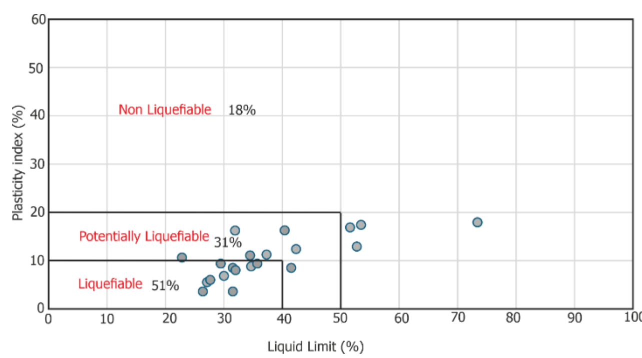

Fig 5. Liquefaction probability based on plasticity index on liquid limit for various drillholes at Dharmanagar (Seed et al, 2003)

This is in support with the liquefaction potential obtained through Liquid limit, LL (%), Plasticity Index, PI (%), and water content based on Seed et al, (2003) method (Fig 5). It implies the fine-grained soil with PI ≤12, LL≤ 37, and water content >80% are highly liquefiable. The presence of numerous faults in synclinal basin of Dharmanagar enhance the possibilities of liquefaction and subsidence. However, the occurrence of driftwood deposits at 3-7m depth with a thickness ~2 m might have acted as a cushion during seismic wave propagation in this - area. Detailed study on this aspect may give more light on earthquake resilient structures and mitigation plan for tectonically active domain.

However, recent unscientific urbanization along with over-exploitation of driftwood may make this area more susceptible to seismic associated damages. In addition, 2023 Bangladesh earthquake (15th August 2023, M=5.4) has caused hydrological changes in western part of Dharmanagar GSI Report (2023) implies the various effect of seismic activity in this area. Moreover, construction of new bypass along Tripura Mizoram fold belt without proper slope management may cause liquefaction related subsidence.

5. Conclusions

The present LPI study in the synclinal area of the strongly deformed outer wedge of Indo-Burmese wedge shows ~80% area of Dharmanagar study area falls under very high to high zones. This data also validates with the geotechnical studies of liquid limit and plasticity index analysis. The large areal extend of the drift wood deposits in the area actually damped many of the previous earthquakes, whereas the unscientific construction of largescale buildings, roads, and over exploitation of driftwood in these areas may cause severe damages in this area. Hence, detailed paleo seismological studies, DGPS studies and InSAR studies along with construction of liquefaction resistant construction is recommended for any future development in this type of area.

CRediT authorship contribution statement.

Drishya Girishbai: Writing–original draft, review & editing, Software. **Arun Bhadran:** Writing – review, Methodology, Software, Data curation. **Joe Joseph:** Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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