Research Article

Liquefaction susceptibility of central Kerala

M. Akhila[1] · K. Rangaswamy[1] · N. Sankar[1]

Abstract

This paper aims to analyze the liquefaction susceptibility of central Kerala (Ernakulam), India. This region is selected as it is the most seismically active zone in Kerala. Soil type details and standard penetration test values of the area were collected using field methods for the analysis. Liquefaction analysis was carried out, for a PGA of 0.2 g and earthquake magnitude (to be specific, moment magnitude, M_w) of six, using NovoLiq software. It was found that the majority of the sites selected are prone to liquefaction. The results are expressed in terms of factor of safety against liquefaction, probability of liquefaction, lateral spreading and vertical settlement. Also, the effect of variation in PGA, earthquake magnitude and ground water table on the factor of safety against liquefaction has been elaborated.

Keywords Clay · Ernakulam · Kerala · Liquefaction · Silt

1 Introduction

The primary reason for the large earthquakes in India is the movement of the Indian tectonic plate into Asian tectonic plate (initial movement was at high speed of 18–20 cm year^{-1} before the collision with Eurasian tectonic plate and at a reduced speed of 2–4 cm year^{-1} afterward [1]). The other reason may be the accumulation of seismic energy in the peninsular region of India [2]. Geographical statistics of India show that almost 54% of the land is vulnerable to earthquakes. The earthquake zoning map of India [given in the earthquake resistant design code of India—IS 1893 (Part 1-2002)] divides India into four seismic zones (Zone 2, 3, 4 and 5). Previously it consisted of five zones. Zone 5 exhibits the highest level of seismicity, whereas Zone 2 is associated with the lowest level of seismicity. The present study area, Ernakulam - the central part of Kerala—lies in Zone 3.

Ernakulam is called as the commercial capital of the state of Kerala. The Kerala High Court, the Cochin Stock Exchange, many educational institutions and business firms are situated here. The geotechnical characteristics and probable natural hazards of the Ernakulam region are shown in Fig. 1. Because of the lineaments and faults present in this region, the chance of a seismic event is high.

Liquefaction, which is one of the seismic hazards, is responsible for tremendous amounts of damage all over the world. When the saturated soil mass is subjected to seismic or dynamic loads, there is an abrupt build-up of pore water pressure within a short duration. If the soil cannot dissipate the excess pore water pressure, it leads to a reduction in effective shear strength of soil mass. In this state, the soil mass behaves like a liquid and causes huge deformations, settlements, flow failures, etc. This phenomenon is called soil liquefaction. Liquefaction effects on damages of structures are commonly observed in low-lying areas near the water bodies such as rivers, lakes, and oceans. Ernakulam region is highly prone to earthquakes, and therefore, identification and mitigation of liquefaction are essential for this region. In this paper, the liquefaction susceptibility of Ernakulam region has been elaborated.

✉ M. Akhila, akhila144@gmail.com | [1]Department of Civil Engineering, National Institute of Technology, Calicut, Kerala, India.

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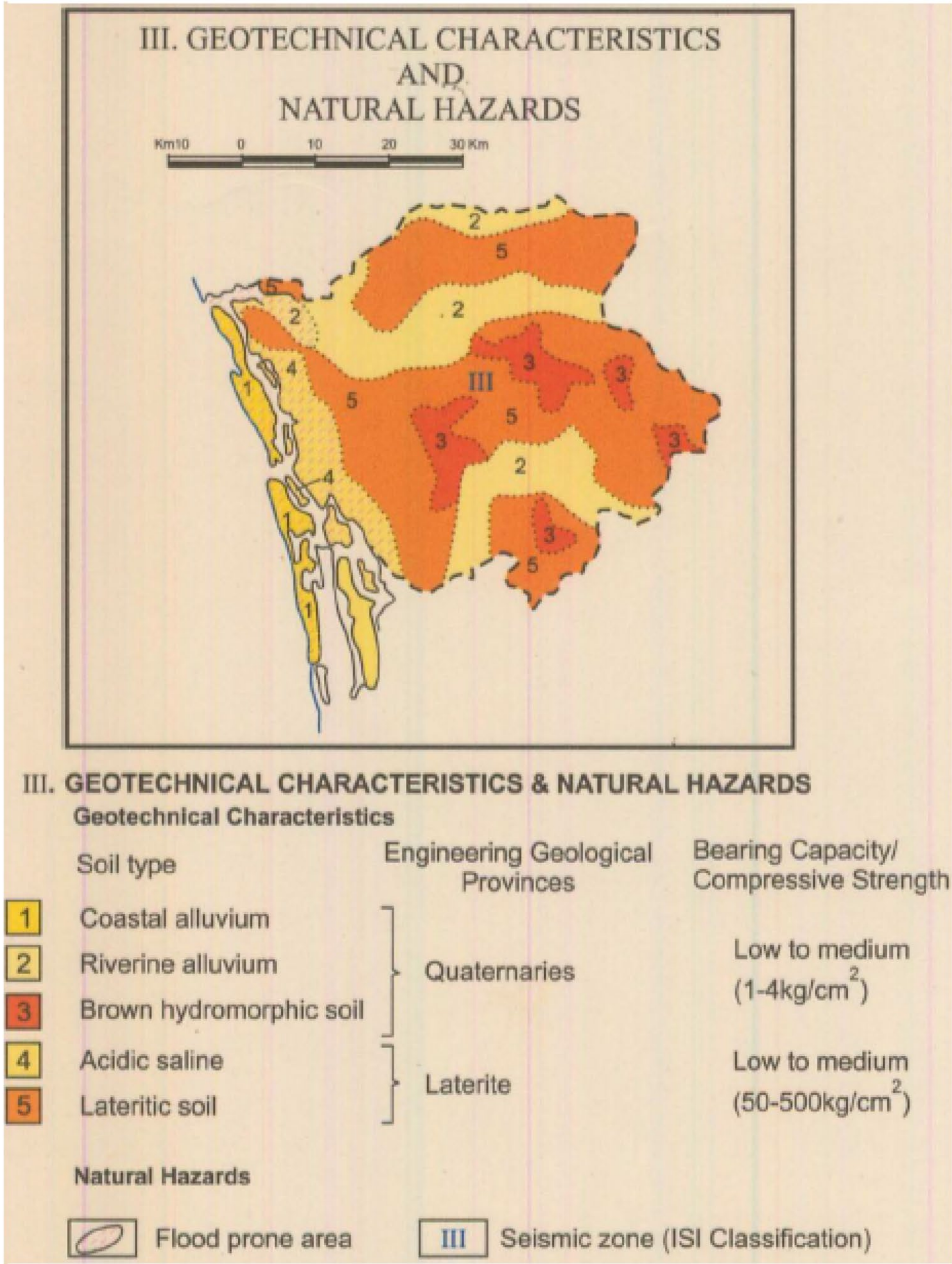


Fig. 1 Geotechnical characteristics of Ernakulam region (*Source*: District survey report of minor minerals – Ernakulam District, prepared by Dept. of mining and Geology, Govt. of Kerala)

2 Literature review

A detailed review has been carried out to analyze the seismicity of Kerala and also to familiarize with the various methods for evaluating liquefaction potential.

2.1 Seismicity of Kerala

Kerala lies in Zone 3 of seismic zones in India, which is classified as Moderate Damage Risk Zone which is liable to MSK VII (Medvedev–Sponheuer–Karnik scale) and Ernakulam is ranked as 7 out of the top 10 earthquake-prone areas in India (source: https://www.linkedin.com/pulse/top-10-earthquake-prone-areas-india-book-andgo/). On 12 December 2000, an earthquake with a local magnitude of 5 was felt strongly in the central part of Kerala (source: http://asc-india.org/lib/20001212-kerala.htm).

Nair [3] carried out extensive studies on the geomorphology and Quaternary geology of the coastal areas of Kerala. Other researchers include Erattupuzha and George [4], Pawar et al. [5], Mathai and Nair [6], Rajendran et al.

[7], Kunte [8]. The study by Ganesha Raj et al. [9] shows that there are 41 medium/major lineaments in Kerala with length more than 20 km. According to Rajendran et al. [10], the central Midland must be considered as the most seismically potential region in Kerala. Also, the authors suggest that an earthquake of magnitude (M_L) 4.5 to 5.5 can be expected to occur in the central Midland of Kerala every 25±22 years.

By comparing many available datasets, a diagram showing the distribution of earthquake events in and around Kerala was prepared by Sreevalsa and Sitharam [11]. Anbazhagan et al. [12] reported that there are many minor lineaments in Kerala and also a probable future earthquake zone in the vicinity of the central region. They reported that an intensity of 6.5 is expected due to probable source zone, with a maximum magnitude (M_w) of 6.0 (the maximum is expected to occur in central Kerala). The studies done by Biju et al. [13] conclude that "the earthquakes in central Kerala region exhibit a spatial association with NW-SE trending Periyar lineament/fault."

The literature gives a clear idea about the seismicity of Kerala and especially the central region. The occurrence of an earthquake may lead to seismic hazards. The important seismic hazards listed by Kramer [14] are ground shaking, structural hazards, liquefaction, landslides, retaining structure failures, lifeline hazards, tsunami and seiche. Out of all these, liquefaction is one of the most important and complex topics in the field of earthquake geotechnical engineering. Liquefaction is defined as the "transformation of granular material from a solid to a liquefied state as a consequence of increased pore water pressure and reduced effective stress" [15]. Until recently, liquefaction-related studies concentrated on clean sands with the assumption that only sands are susceptible to liquefaction. However, a few earthquakes like the 1976 Tangshan earthquake, the 1989 Loma Prieta earthquake, the 1999 Kocaeli earthquake, the 2010 Chile earthquake, and the 2011 Christchurch earthquake, etc. showed that sand with considerable amount of fines could also liquefy. The investigations about the liquefaction can be done mainly in four ways: field investigations, laboratory investigations, modelling (physical and numerical) and analysis using any commercially available software. A brief review of these methods is presented in the following section.

2.2 Evaluation of liquefaction potential

A detailed list of various methods for the evaluation of liquefaction potential is listed in Table 1. Tolon [16] listed several software available for the analysis of liquefaction which is given in Table 2.

Table 2 Lists of software for liquefaction analysis [16]

1D analysis		2D analysis	3D analysis
Shake2000	Apollo	Versat-2D	DYNAFLOW
LASS-II	LiqIT	Swandyne	FEQDrain
CUMLiq	Peysanj		Diana
CPTInt	SoilGeophysical		Flac 3D
Liquiter	SPTLiq		
CLiq	LiquefyPro		
CPTLiq	Geostress		
LatSpread	CyberQuake		

Table 1 Summary of methods to evaluate the liquefaction potential

Area	Tests	References
Field investigations	SPT	[25, 26, 27, 28, 29, 30, 31, 32]
	CPT	[33, 34, 35]
	Shear wave velocity	[36, 37, 38, 39, 40, 41]
Laboratory investigations	Cyclic triaxial tests	[42, 43, 44]
	Large-scale simple shear tests	[45]
	Cyclic torsional cylindrical shear test	[46]
	Cyclic undrained simple shear tests	[47, 48, 49]
	Cyclic hollow torsional test	[50]
Physical modeling	Large-scale shaking table tests	[51, 52, 53]
	Dynamic centrifuge test	[54, 55]
Numerical modeling	Elasto-plastic models	[56, 57, 58]
	Lade's model with a double plastic potential	[59]
	Generalized plasticity models	[60, 61]
	Incremental octo-linear model	[62]
	Incrementally non-linear model	[63]
	Hypoplasticity models	[64, 65]

2.3 Critical assessment of the literature

The first section of the literature gives an idea about the seismicity of Kerala. Most research has been concentrated on the areas such as Idukki and Palaghat [10, 13, 17]. But studies conducted in the commercial capital area are limited. Hence the authors have selected this area for the study. To study the liquefaction susceptibility, some of the available methods have been listed and discussed in the second part of the literature review. Since the SPT data of the study area were available, the authors have chosen the analysis using NovoLiq. The details about the analysis are given in the methodology section.

3 Methodology

Borehole data were collected from 37 locations in Ernakulam district of Kerala state [data courtesy: Engineers Diagnostic Centre (P) Ltd.] and analyzed for liquefaction susceptibility. The locations of boreholes are shown in Fig. 2. The details of soil types and levels of the ground water table are given in Table 3. SPT-based analysis has been carried out to find the liquefaction susceptibility. The main formulae used for the liquefaction analyses are as follows:

The factor of safety against liquefaction (FS) is given by:

$$\mathrm{FS} = \frac{\mathrm{CRR}_{7.5}\mathrm{MSF}}{\mathrm{CSR}} \tag{1}$$

where $\mathrm{CRR}_{7.5}$ = cyclic resistance ratio for an earthquake with magnitude 7.5, MSF = magnitude scaling factor, CSR = cyclic stress ratio.

The cyclic stress ratio, CSR, as proposed by Seed and Idriss [18], is given by

$$\mathrm{CSR} = \frac{\tau_{av}}{\sigma'_v} = 0.65\left(\frac{a_{\max}}{g}\right)\left(\frac{\sigma_V}{\sigma'_v}\right)r_{\mathrm{d}} \tag{2}$$

where $a_{\max}$ = maximum horizontal ground surface acceleration (g), g = gravitational acceleration, σ_v = total

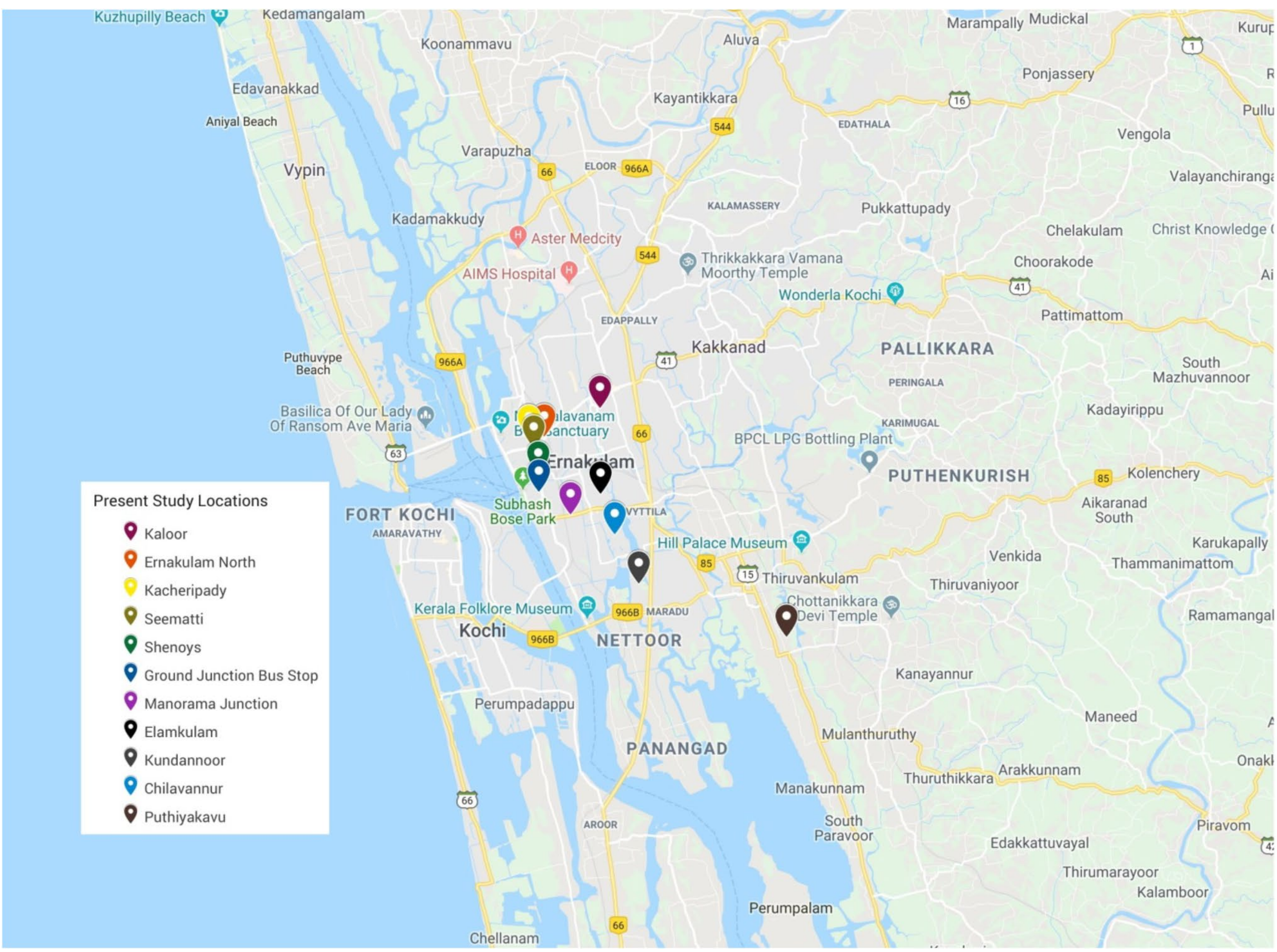


Fig. 2 Location of sites

Table 3 Details of the areas

No.	Area	Location		Number of boreholes	Distance from the previous site	Major soil type	GWT (m)
		Latitude (N)	Longitude (E)				
1	Kaloor	9.997	76.302	3	–	Silty clayey sand	1 to 1.8
2	Ernakulam North	9.989	76.285	2	2.8 km	Silty sand in top layers; clay from 6 m depth	1
3	Kacheripadi	9.989	76.281	2	1.2 km	Silty sand and silty clay; laterite from 16 m depth	0.7
4	Seematti Junction	9.986	76.282	4	750 m	Fine and clay; laterite at greater depths	0.4 to 1.5
5	Shenoy's	9.978	76.283	1	850 m	Laterite clay with sand (but very low N)	0.5
6	Ground Junction	9.973	76.284	4	700 m	Clay and silty clay	< 1
7	Manorama Junction	9.966	76.293	2	2.6 km	Clay with silt	1
8	Elamkulam	9.974	76.301	4	1.6 km	Clay and silt (presence of organic matter)	0.7 to 1
9	Kundanoor	9.947	76.314	8	5.3 km	Silty clay; laterite at greater depths	0
10	Chilavannur	9.963	76.306	2	5 km	Alternate layers of clay and sand	0.5
11	Puthiyakavu	9.932	76.358	5	9.8 km	Sand clay with laterite (dense condition)	< 1

Table 4 Qualitative assessment of abundance and general character of liquefaction effects as a function of LSI for areas with widespread liquefiable deposits [21]

LSI	Abundance and general character of liquefaction effects
5	Very sparsely distributed minor ground effects include sand boils with sand aprons up to 0.5 m (1.5 ft) in diameter, minor ground fissures with openings up to 0.1 m wide, ground settlements of up to 25 mm (1 in.). Effects lie primarily in areas of recent deposition and shallow ground water table such as exposed stream beds, active flood plains, mud flats, shore lines, etc.
30	Generally sparse but locally abundant ground effects include sand boils with aprons up to 2 m (6 ft) diameter, ground fissures up to several tenths of a meter wide, some fences and roadways noticeably offset, sporadic ground settlements of as much 0.3 m (1 ft), slumps with 0.3 m (1 ft) of displacements common along steep stream banks. Larger effects lie primarily in areas of recent deposition with a ground water table less than 3 m (10 ft) deep
90	Very abundant ground effects include numerous sand boils with large aprons, 30% or more of some areas covered with freshly deposited sand, many long Assures with multiple strands parallel streams and shore lines with openings as wide as two or more meters, some intact masses of ground between Assures are horizontally displaced a couple of meters down gentle slopes, large slumps are common in stream and other steep banks, ground settlements of more than 0.3 m (1 ft) are common

Table 5 Relation between vertical settlement and extend of damage [23]

Settlement (cm)	Extend of damage	Phenomena on ground surface
0–10	Light to no damage	Minor cracks
10–30	Medium damage	Small cracks, oozing of sand
30–70	Extensive damage	Large cracks, spouting of sands, large offsets, lateral movement

overburden pressure at depth z, σ_v' = effective overburden pressure at depth z, r_d = stress reduction factor.

Liquefaction analyses were carried out in NovoLiq (Version 2.40.2012.1006) [19]. NovoLiq software is designed for soil liquefaction analysis during the earthquake and supports multi-layer as well as single layer stratigraphy. The software presents the results of the analysis as a factor of safety against soil liquefaction, the probability of soil liquefaction, post-liquefaction site conditions, including ground settlement, lateral movement (spreading), etc.

From the input, i.e., the soil profile details, the NovoLiq calculates the CSR value based on Eq. (2). Then, the CRR values for the present study are calculated using the NCEER Workshop (1997) method. The factor of safety is then calculated using Eq. (1). Other than the factor

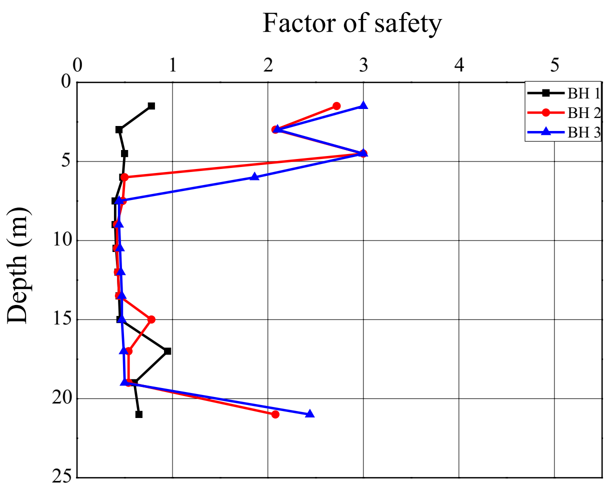


Fig. 3 Depth versus factor of safety against liquefaction—Kaloor

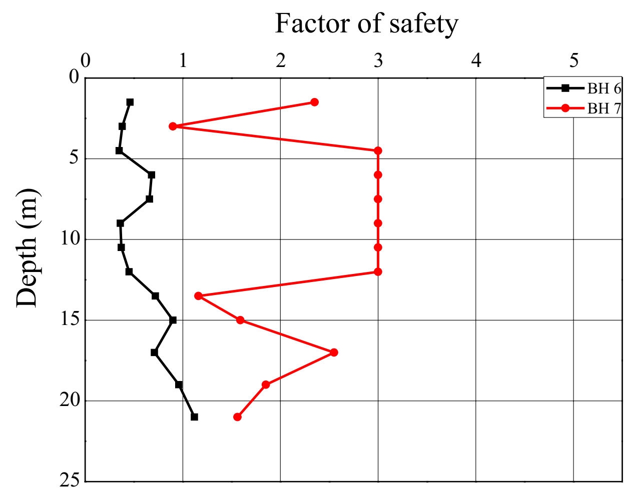


Fig. 5 Depth versus factor of safety against liquefaction—Kacheripadi

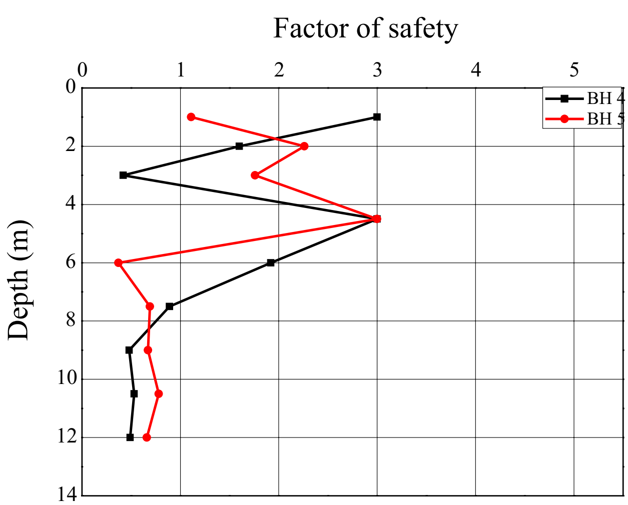


Fig. 4 Depth versus factor of safety against liquefaction—Ernakulam North

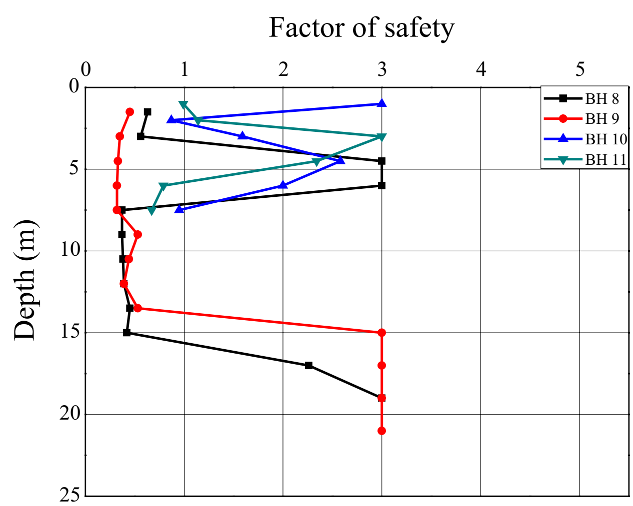


Fig. 6 Depth versus factor of safety against liquefaction—Seematti junction

of safety against liquefaction, the following are also analyzed:

- The probability of liquefaction [20]: It is calculated based on the probabilistic triggering correlation for clean sands for $M = 7.5$.
- Liquefaction severity index [21]: LSI, a measure of ground failure displacement, is based on the displacement of lateral spreads. LSI is useful for determining the relative liquefaction hazard and provide an index of possible maximum ground displacement. The general range of LSI values and its corresponding liquefaction effects are given in Table 4.
- Lateral spreading [22]: the method proposed by Zhang et al. [22] (which was developed using case history) is quite simple and can be applied with only a few additional calculations following SPT- or CPT-based liquefaction-potential analysis.
- Vertical settlement [23]: the extent of damage corresponding to the settlement is proposed by Ishihara and Yoshimine [23] based on the case histories. The range and corresponding description are given in Table 5.

Results are discussed in the following section.

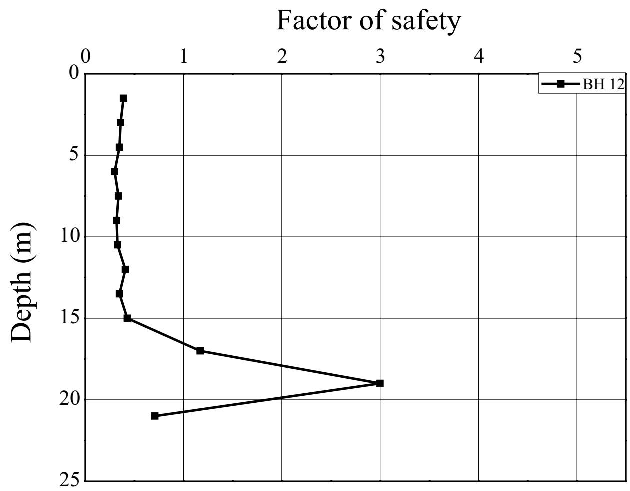


Fig. 7 Depth versus factor of safety against liquefaction—Shenoy's

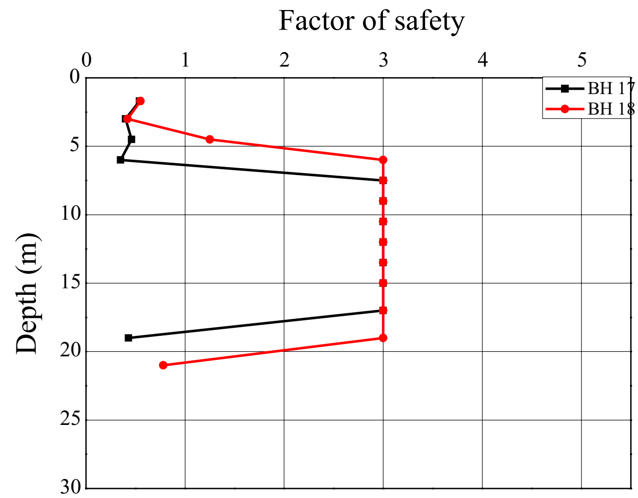


Fig. 9 Depth versus factor of safety against liquefaction—Manorama junction

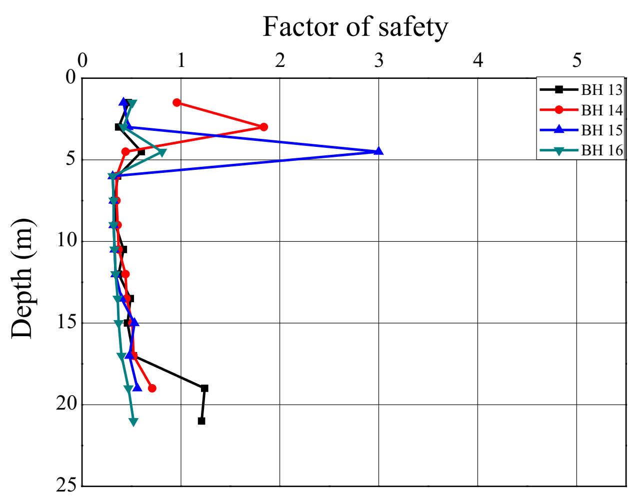


Fig. 8 Depth versus factor of safety against liquefaction—Ground junction

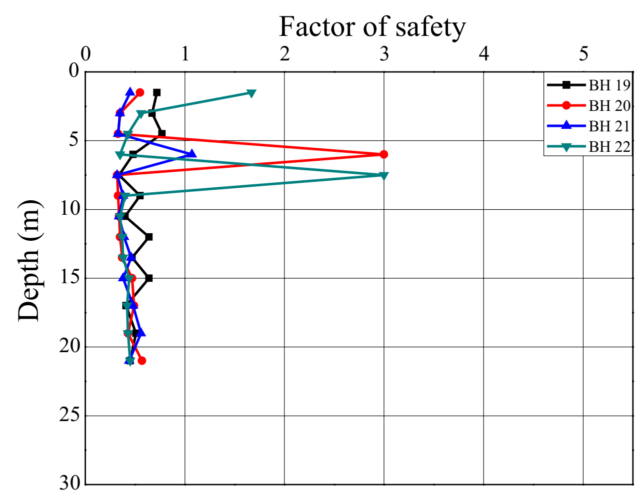


Fig. 10 Depth versus factor of safety against liquefaction—Elamkulam

4 Results and discussion

Liquefaction analyses have been done on 37 borehole data for a PGA of 0.2 g and an earthquake magnitude of 6 (the ground water table is varied for each location as per the real site data). The depth versus factor of safety against liquefaction graphs of all regions is shown in Figs. 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13 and 14. The results are briefed in Tables 6 and 7 by differentiating the depth of each borehole into "prone to liquefaction" and "safe against liquefaction." It can be seen that the majority of the sites are prone to liquefaction. (i.e., factor of safety against liquefaction is less than one). Various maps have been prepared which shows the factor of safety against liquefaction at 1.5 m depth, 7.5 m depth, an average factor of safety (average factor of safety of all considered depths) and the average of the 10 analyses carried out at a particular borehole (Figs. 15, 16, 17, 18).

Also, maps which show the probability of liquefaction, lateral spreading, and vertical settlement are also included (Figs. 19, 20, 21). The numerical values of the same are given in Table 8. The liquefaction severity index for all locations (for an earthquake of magnitude 6 and PGA 0.2 g) was found to be 3 (refer LSI = 5 in Table 4). The probability of liquefaction (PL) is more than 50% for 24 boreholes considered and less than 10% for 3 boreholes. The high values of PL are in Chilavannur and Kundannur regions and least values correspond to the Puthiyakavu region. The lateral spreading and vertical displacement are higher

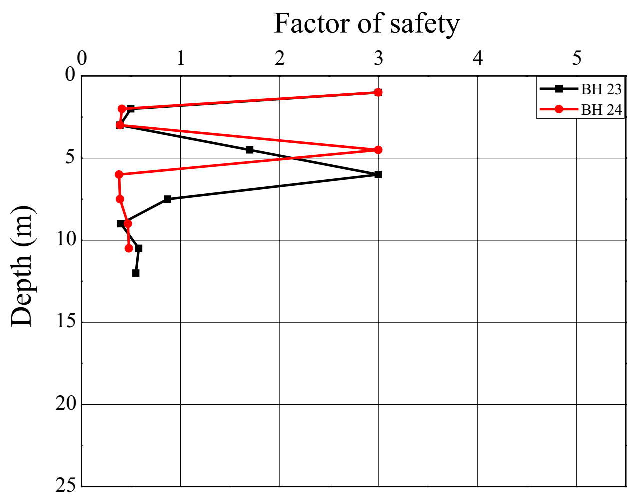


Fig. 11 Depth versus factor of safety against liquefaction—Chilavnnur

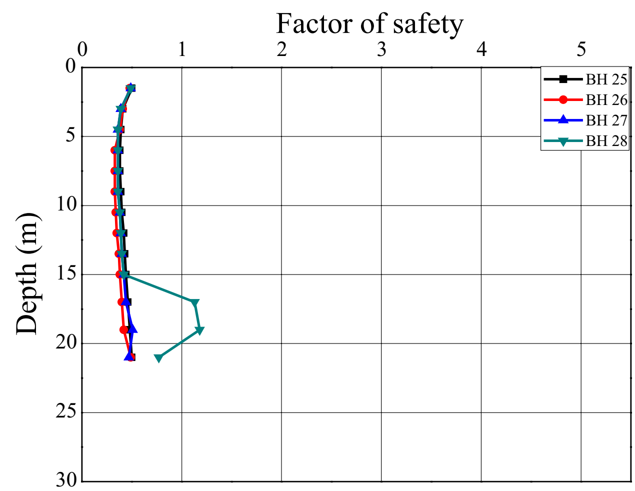


Fig. 13 Depth versus factor of safety against liquefaction—Kundannur 1

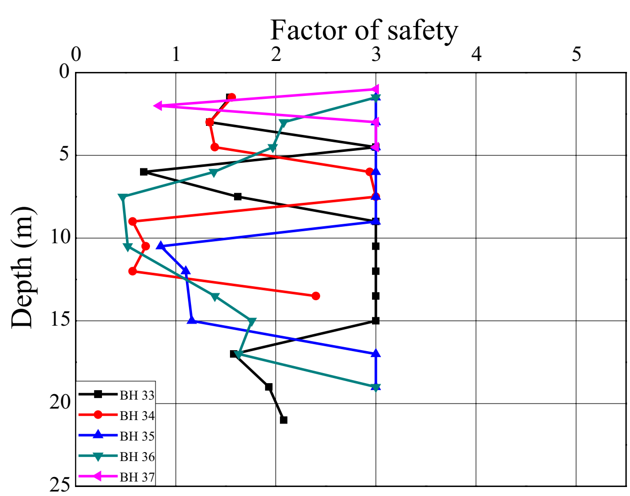


Fig. 12 Depth versus factor of safety against liquefaction—Puthiyakavu

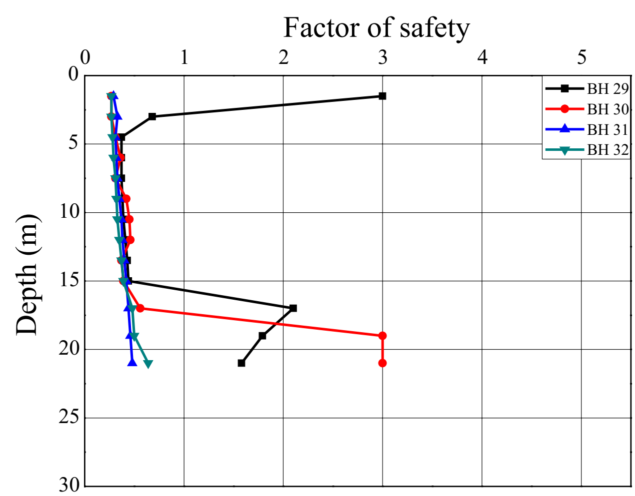


Fig. 14 Depth versus factor of safety against liquefaction—Kundannur 2

for Kundannur area and least for Puthiyakavu. In Kundannur area, the values of lateral spreading are gone up to 168 cm and the vertical settlement up to 39 cm, whereas in Puthiyakavu area, both the lateral spreading and the vertical settlement are in the range of 0–2 cm only.

5 Region wise analyses

In the Kaloor area, only the top layers (BH 2 and 3) are safe against liquefaction (Fig. 3). These layers consist of fine gravels which give an SPT N value greater than 10. All other soil layers of Kaloor region have SPT N less than 5. The average probability of liquefaction is greater than 50% in all the 3 boreholes. Similar results are obtained for the Ernakulam North region (Fig. 4) also. There, the top layers consist of sand with SPT N > 10. But the deeper layers are of silt and clay with SPT N < 5. According to Peck et al. [24], when SPT N values are between 0 and 4, the soil state is *very loose* and when SPT N is 5 and 10, the soil state is *loose*. Both soils show high susceptibility to liquefaction. However, the probability of liquefaction is around 38% only.

In Kacheripadi, the selected soil profiles of 2 boreholes are in two entirely different states. In one, all the layers have soils with SPT N less than 5; but in the other, the soils

Table 6 Results in a nutshell (19 boreholes)

D	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1.5	✗	✓	✓	✓	✓	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
3.0	✗	✓	✓	✓	✓	✗	✗	✗	✗	✓	✓	✗	✗	✓	✗	✗	✗	✗	✗
4.5	✗	✓	✓	✗	✓	✗	✓	✓	✗	✓	✓	✗	✗	✗	✓	✗	✗	✗	✗
6.0	✗	✗	✓	✓	✗	✗	✓	✓	✗	✓	✓	✗	✗	✗	✗	✗	✗	✓	✗
7.5	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✗
9.0	✗	✗	✗	✗	✗	✗	✓	✗	✗	NA	NA	✗	✗	✗	✗	✗	✓	✓	✗
10.5	✗	✗	✗	✗	✗	✗	✓	✗	✗	NA	NA	✗	✗	✗	✗	✗	✓	✓	✗
12	✗	✗	✗	✗	✗	✗	✓	✗	✗	NA	NA	✗	✗	✗	✗	✗	✓	✓	✗
13.5	✗	✗	✗	NA	NA	✗	✓	✗	✗	NA	NA	✗	✗	✗	✗	✗	✓	✓	✗
15	✗	✗	✗	NA	NA	✗	✓	✗	✓	NA	NA	✗	✗	✗	✗	✗	✓	✓	✗
17	✗	✗	✗	NA	NA	✗	✓	✓	✓	NA	NA	✓	✗	✗	✗	✗	✓	✓	✗
19	✗	✗	✗	NA	NA	✗	✓	✓	✓	NA	NA	✓	✓	✗	✗	✗	✗	✓	✗
21	✗	✓	✓	NA	NA	✓	✓	NA	✓	NA	NA	✗	✓	NA	NA	✗	NA	✗	✗

Table 7 Results in a nutshell (remaining 18 boreholes)

D	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
1.5	✗	✗	✓	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✓	✓	✓	✓	✗
3.0	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓
4.5	✗	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓
6.0	✓	✓	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	NA
7.5	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✗	NA
9.0	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	NA
10.5	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	NA
12	✗	✗	✗	✗	NA	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✓	NA
13.5	✗	✗	✗	NA	NA	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	NA
15	✗	✗	✗	NA	NA	✗	✗	✗	✗	✗	✗	✗	✗	✓	NA	✓	✓	NA
17	✗	✗	✗	NA	NA	✗	✗	✗	✓	✓	✗	✗	✗	✓	NA	✓	✓	NA
19	✗	✗	✗	NA	NA	✗	✗	✗	✓	✓	✓	✗	✗	✓	NA	✓	✓	NA
21	✗	✗	✗	NA	NA	✗	✗	✗	✗	✓	✓	✗	✗	✓	NA	NA	NA	NA

Note:

<u>Number and areas</u>

1-3	Kaloor
4-5	Ernakulam North
6-7	Kacheripadi
8-11	Seematti Junction
12	Shenoy's
13-16	Ground Junction
17-18	Manorama Junction
19-22	Elamkulam
23-24	Chilavannur
25-32	Kundanoor
33-37	Puthiyakavu

<u>Colour and Meaning</u>

NA Data not available
✗ Susceptible to liquefaction
✓ Safe against liquefaction

(mainly sand and silt) are in very dense condition which gives high SPT N value. The results of the liquefaction analysis are given in Fig. 5. From Fig. 5, it is clear that one area is completely prone to liquefaction while the other is safe against liquefaction. Probability of liquefaction and settlements are higher for BH 6 and least for BH 7. This is the best example which shows how significant variations

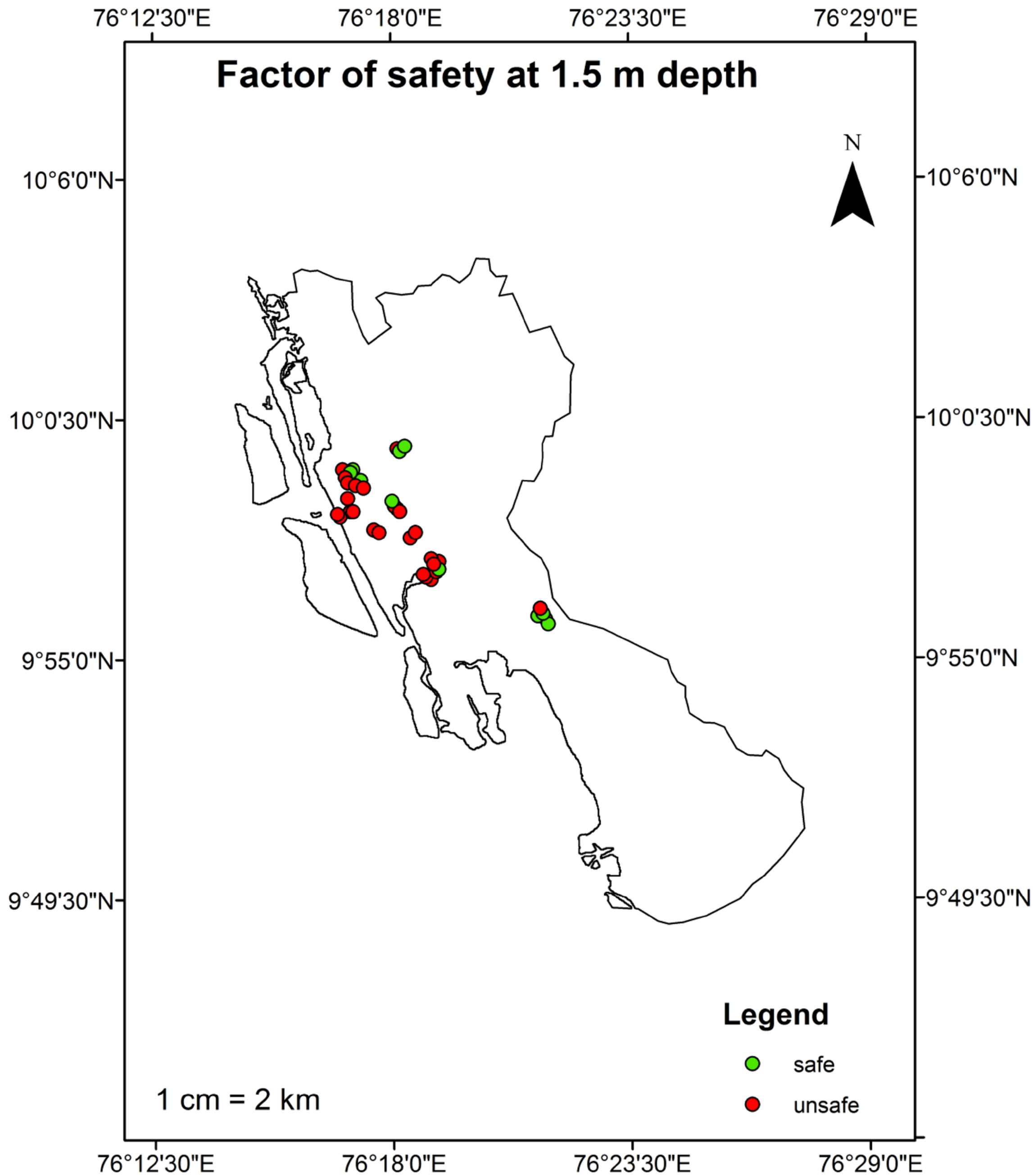


Fig. 15 Liquefaction susceptibility map showing the factor of safety at 1.5 m depth

in liquefaction susceptibility are possible within a short span of distance due to variations in the soil profile.

The soils near Seematti Junction consist of lateritic soils in some layers. Hence these layers offer a high factor of safety against liquefaction in this region (Fig. 6). The probability of liquefaction is less than 20% and the settlements are less than 3 cm. The soil profile of Shenoy's Junction consists of clayey soils (clay content more than 50%) up to a depth of 19 m below which the presence of laterite is seen. Hence the top layers are prone to liquefaction (Fig. 7). The probability of liquefaction is around 67% and lateral spreading is more than 100 cm.

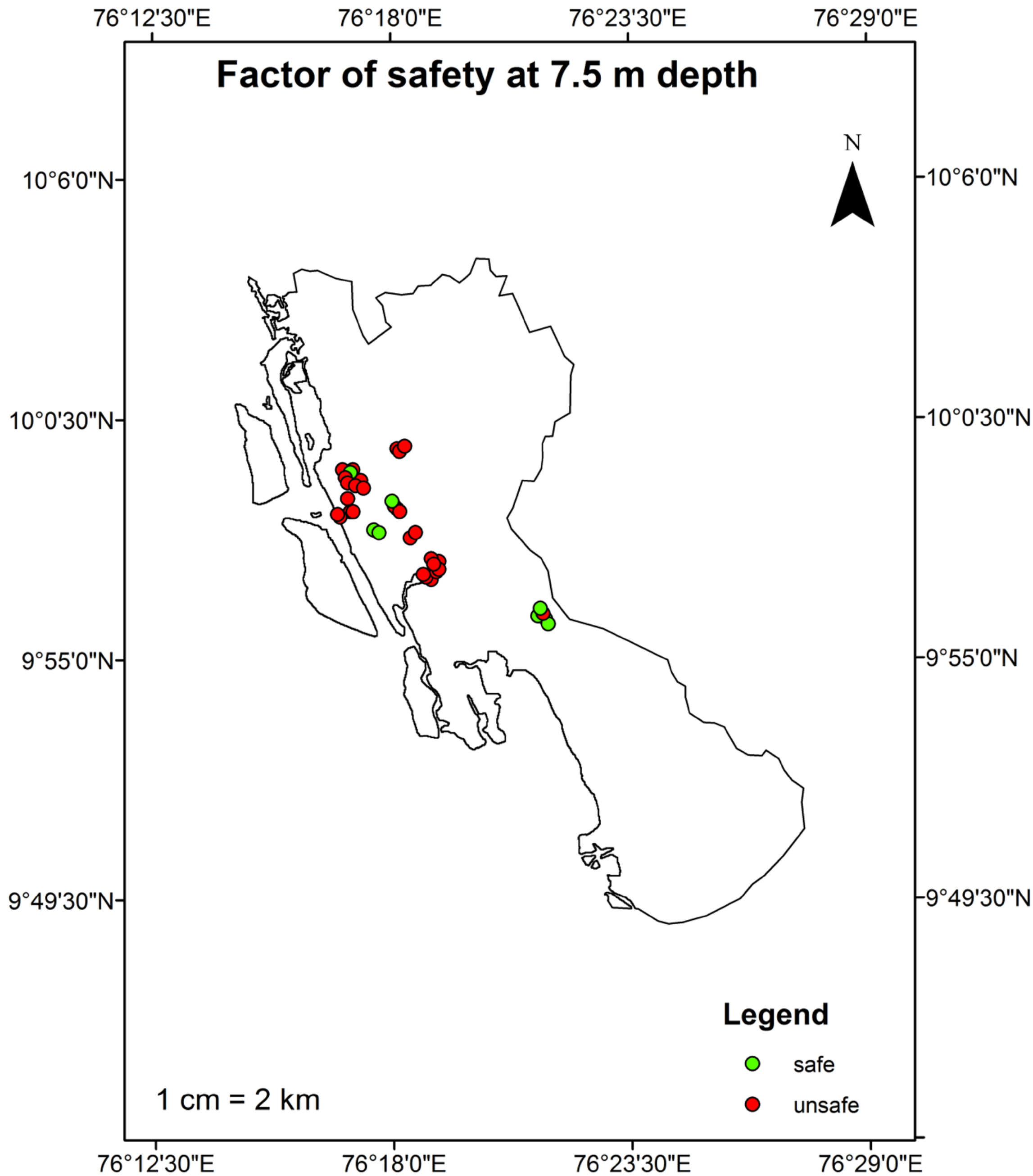


Fig. 16 Liquefaction susceptibility map showing the factor of safety at 7.5 m depth

In Ground Junction area, the major soil type is clay with SPT N less than 5 in most of the layers (with the presence of silt in top layers). The probability of liquefaction is greater than 60% and the settlements are in the order of 50–75 cm. Therefore, this area also is highly prone to liquefaction (Fig. 8). But near Manorama Junction, even from a depth of 4.5 m, the SPT N values are greater than 10. So only the top layers are susceptible to liquefaction (Fig. 9). This region is very safe compared to all other

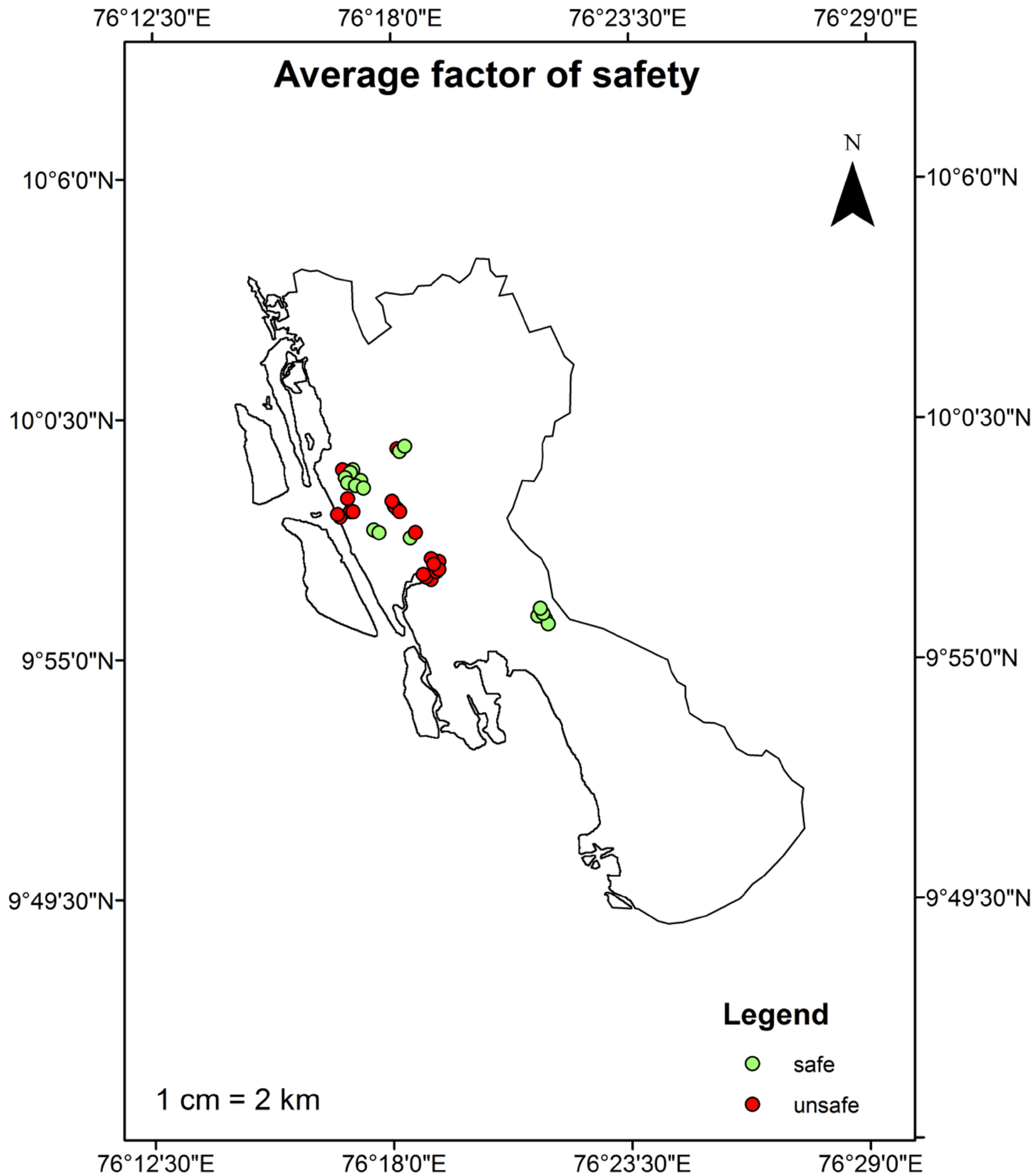


Fig. 17 Liquefaction susceptibility map showing the average factor of safety

regions discussed so far. The probability of liquefaction is less than 30% and settlements are less than 10 cm only.

Elamkulam region shows the presence of organic matter in some soil layers. It may be due to the sewage treatment plant located in this area. The results shown in Fig. 10 depict that Elamkulam region is highly prone to liquefaction under the current analyses parameters. In all locations, the probability of liquefaction is more than 65%. In Chilavannur, some of the soil layers consist of dense sand which offers resistance against the liquefaction (Fig. 11). The SPT tests terminate around 10–12 m depth because of the hard strata consisting of stiff clay. Even then

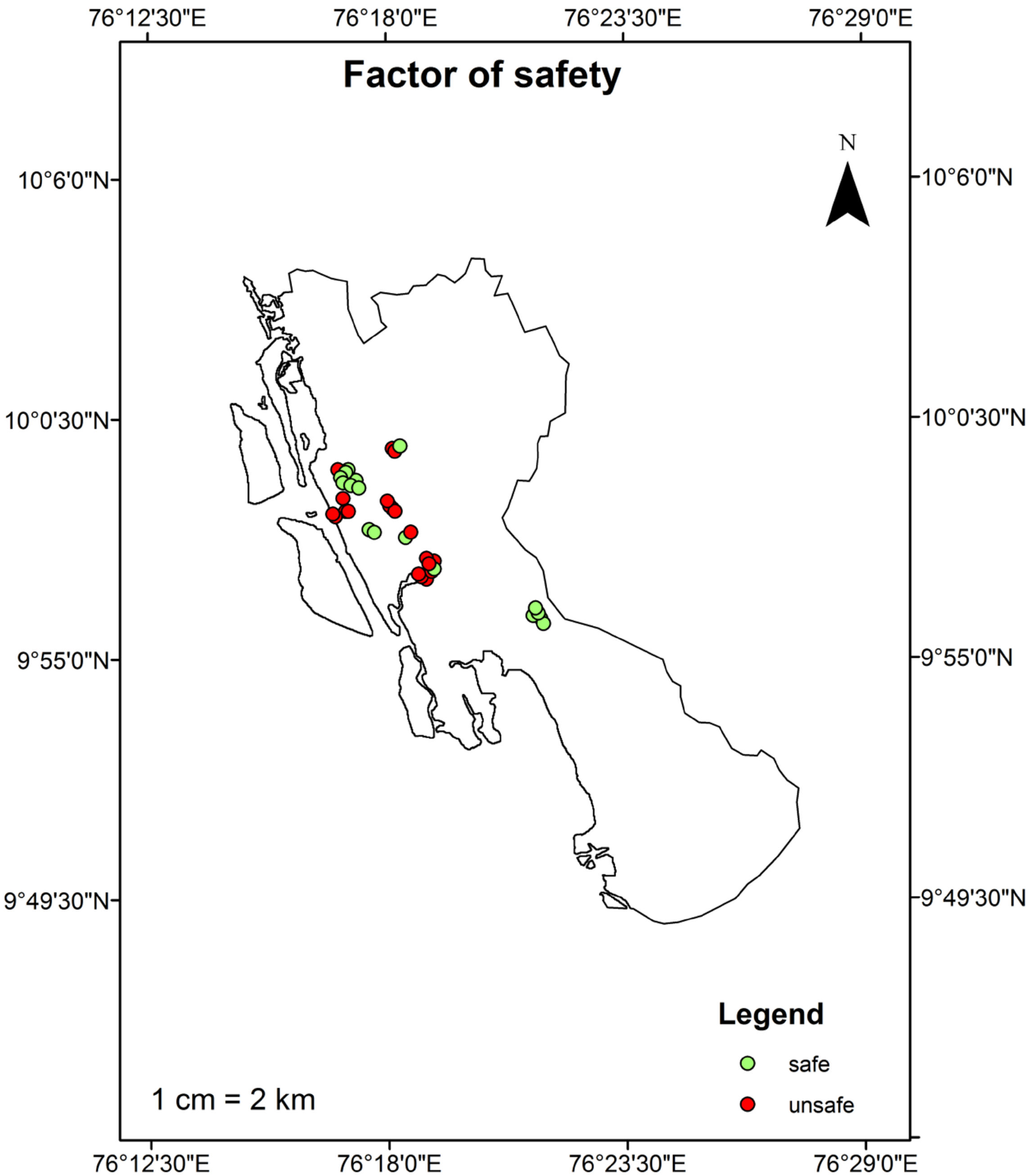


Fig. 18 Liquefaction susceptibility map showing the factor of safety

the average probability of liquefaction is very high (more than 80%). Puthiyakavu, which is situated about three km from Tripunitara, is comparatively safer against liquefaction (Fig. 12). In all the 5 locations, probability of liquefaction is less than 25% and most of the settlements are in the range of 1–2 cm only. This is due to the high SPT N values offered by the stiff soil layers.

Kundannur is a highly developing area of Ernakulam city. It is at the junction of three National Highways, namely NH 47, NH 49 and NH 47A. The Le Meridien and Crown Plaza hotels are situated near Kundannur

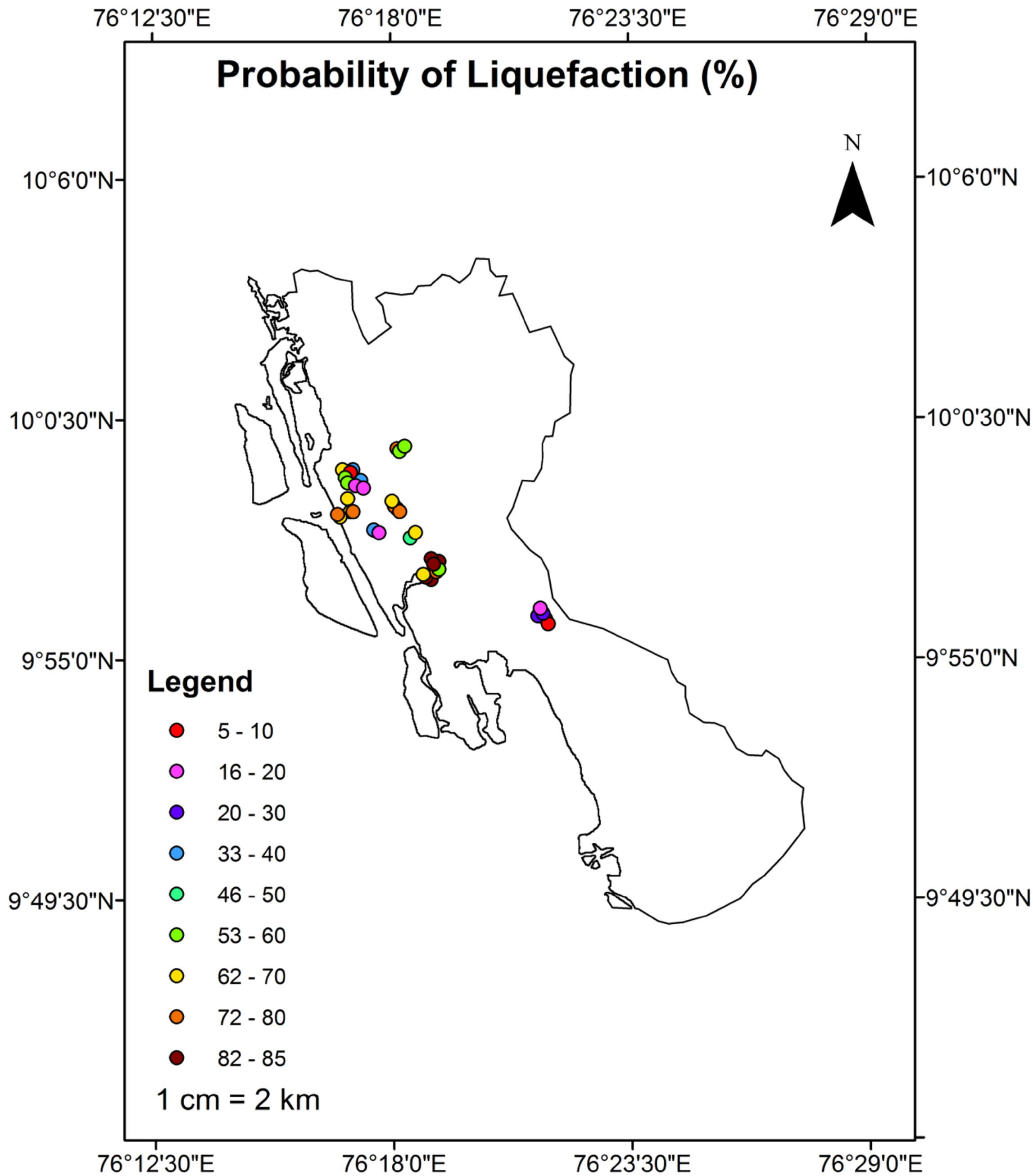


Fig. 19 Map showing the probability of liquefaction of the selected region

junction. Many shopping malls are proposed and under construction in Kundannur. Many automobile companies including Audi, Volkswagen, BMW, etc. have their showrooms in this area which shows the socio-economic importance of Kundannur. Major soil type is silty clay. Laterite is found in greater depth. From the analysis of the data collected from eight boreholes, it is clear that this region is highly susceptible to liquefaction (Figs. 13, 14). In most of the locations, the probability of liquefaction is around 80%. The lateral spreading is gone up to 168 cm and maximum value of vertical settlement is around 40 cm. The main reason may be the ground water table which is at ground level itself.

In short, Manorama Junction, Puthiyakavu and some areas near Kacheripadi are safe against liquefaction as per the analysis. All others are prone to liquefaction if

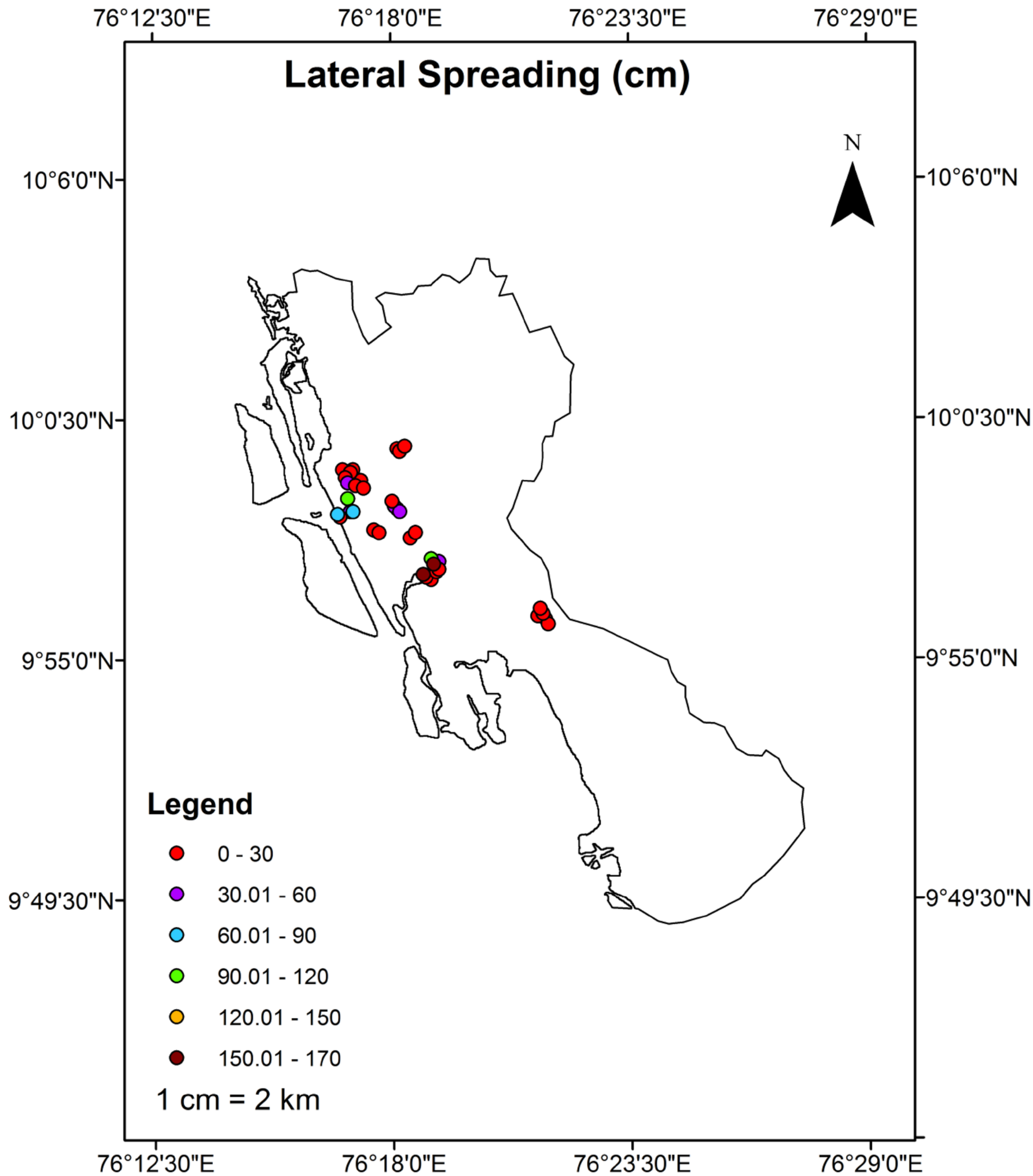


Fig. 20 Map showing the lateral spreading of the selected region

an earthquake with a PGA of 0.2 g and a magnitude of 6 hits the areas.

The obtained values of the factor of safeties can be used to find the factor of safety against liquefaction for an earthquake with other a_{max} and earthquake magnitude. To find the factor of safety for any other earthquake with different a_{max}, multiply by the ratio of 0.2/a_{max} (the earthquake magnitude remaining the same). Similarly to find the factor of safety for any other earthquake magnitude, multiply by the ratio of MSF of that earthquake magnitude/1.76 (1.76 is the MSF given by Idriss for a magnitude of 6).

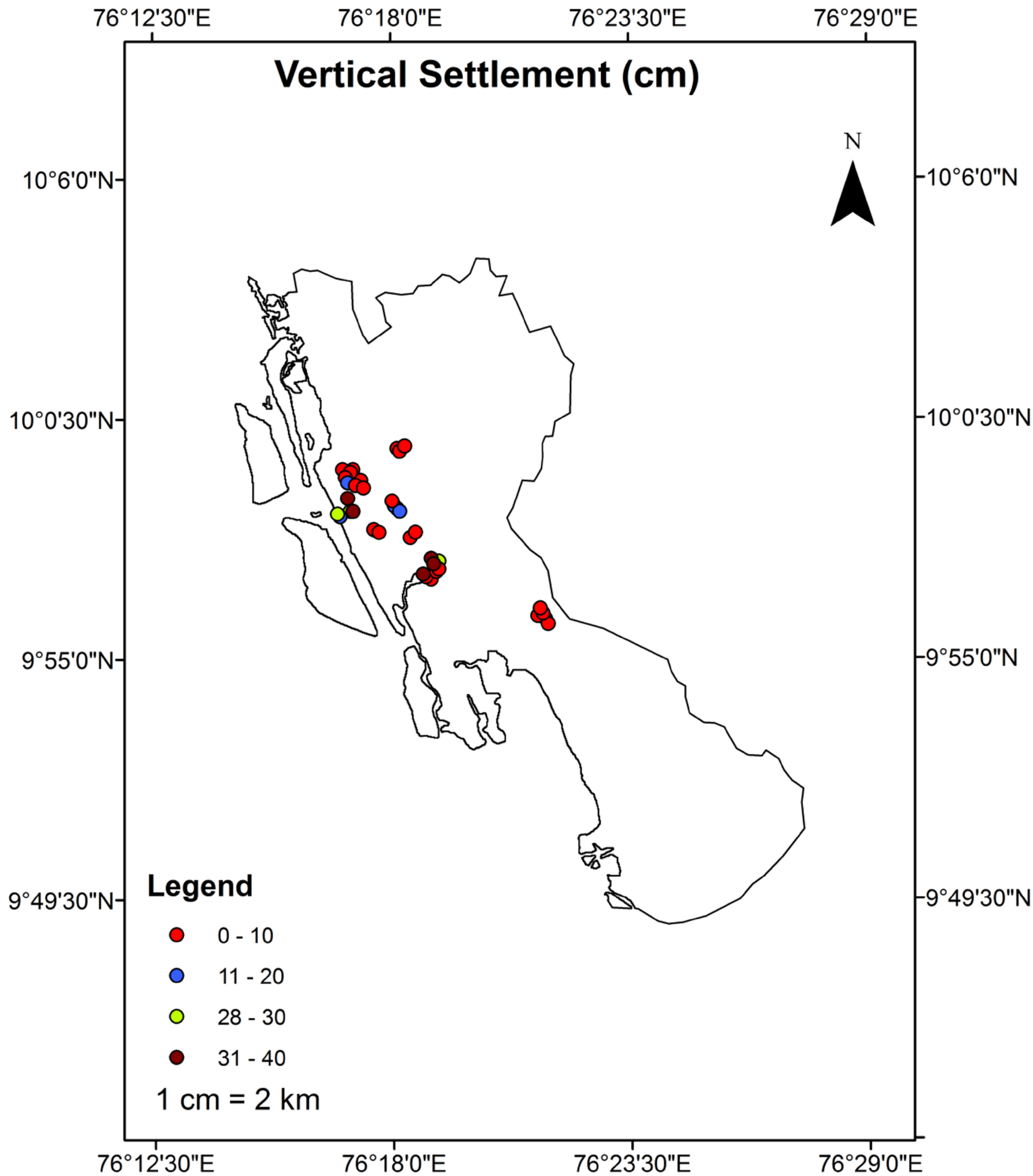


Fig. 21 Map showing the vertical settlement of the selected region

6 Effect of various parameters on liquefaction susceptibility

To find the effect of PGA, earthquake magnitude and ground water table on the liquefaction susceptibility, the PGA is varied from 0.2 to 0.5 g; the earthquake magnitude is varied between 5 and 8, and the ground water table is varied as 0, x, $2x$ and $3x$ (x = original ground water table at the particular location). A total of 10 liquefaction analyses has been performed for each borehole data.

Table 8 Results of liquefaction analysis

BH No	PL (%)	LS (cm)	VS (cm)	BH no.	PL (%)	LS (cm)	VS (cm)
1	72.76	11	6	20	73.14	38	19
2	55.02	10	6	21	74.65	37	19
3	57.51	5	3	22	68.66	17	10
4	38.67	10	6	23	83.92	11	7
5	37.40	5	2	24	82.11	48	28
6	62.37	14	8	25	83.09	16	9
7	4.76	1	0	26	74.61	12	7
8	53.07	8	5	27	57.75	9	5
9	53.62	40	19	28	65.90	156	33
10	15.8	1	0	29	83.21	102	31
11	19.98	3	2	30	81.72	168	39
12	67.12	104	34	31	46.07	8	4
13	66.83	59	30	32	62.1	5	3
14	64.83	20	11	33	7.88	1	0
15	71.92	66	28	34	26.35	2	3
16	75.44	75	31	35	7.68	1	1
17	33.28	10	6	36	20.46	5	3
18	18.05	1	1	37	16.63	0	0
19	66.42	18	10				

PL probability of liquefaction, *LS* lateral spreading, *VS* vertical settlement

When the PGA increased from 0.2 to 0.3 g, 0.4 g and 0.5 g, the factor of safety decreased approximately by 33%, 50% and 60%, respectively (all other factors, i.e., the earthquake magnitude, ground water table, soil properties, etc., being the same). When the earthquake magnitude decreased to 5 from 6, the factor of safety was increased by nearly 20–25%. When the earthquake magnitude is raised from 6 to 7 and 8, the factor of safeties decreased by 31% and 52%, respectively. Figures 22, 23 and 24 illustrate the results of BH 1 of Kaloor, BH 19 of Elamkulam and BH 33 of Puthiyakavu, respectively.

The effect of the ground water table is site-specific. When the ground water table is raised to ground level from x, the factor of safety decreased considerably. For, e.g., in the case of BH 1 of Kaloor (x=1 m in this particular BH), the factor of safety decreased by 5–6% in top soil layers, but around 20% decrease was observed in intermediate soil layers. When the ground water table was lowered to 2x and 3x, factor of safety doubles near the ground surface. In the other layers, an increase between 5 to 10% was observed. In the case of BH 19 of Elamkulam, even if the ground water table is lowered to 2x and 3x (x = 1 m in this case), the factor of safety is less than except in the top 1 or 2 layers. A similar trend was also observed in the BH 33 of Puthiyakavu (x = 1 in this case). These results indicate that the lowering of ground water table does not improve the factor of safety against liquefaction in some of the places.

Table 9 summarizes the effect of change in earthquake parameters and ground water table on other liquefaction parameters such as probability of liquefaction, lateral spreading, vertical settlement and LSI (only results of BH1 of Kaloor is discussed here). It is clear from the table that the probability of liquefaction and LSI vary much only when the earthquake magnitude changes. When there is a change in PGA and ground water table, the change in probability of liquefaction is insignificant and LSI remains same. But the other two parameters, i.e., lateral spreading and vertical settlement, is dependent on all the three parameters (earthquake magnitude, PGA and ground water table).

7 Conclusions

The liquefaction analyses were carried out in 37 boreholes in Ernakulam region and the results obtained (i.e., factor of safety against liquefaction, probability of liquefaction, lateral spreading, vertical settlement and LSI) is discussed

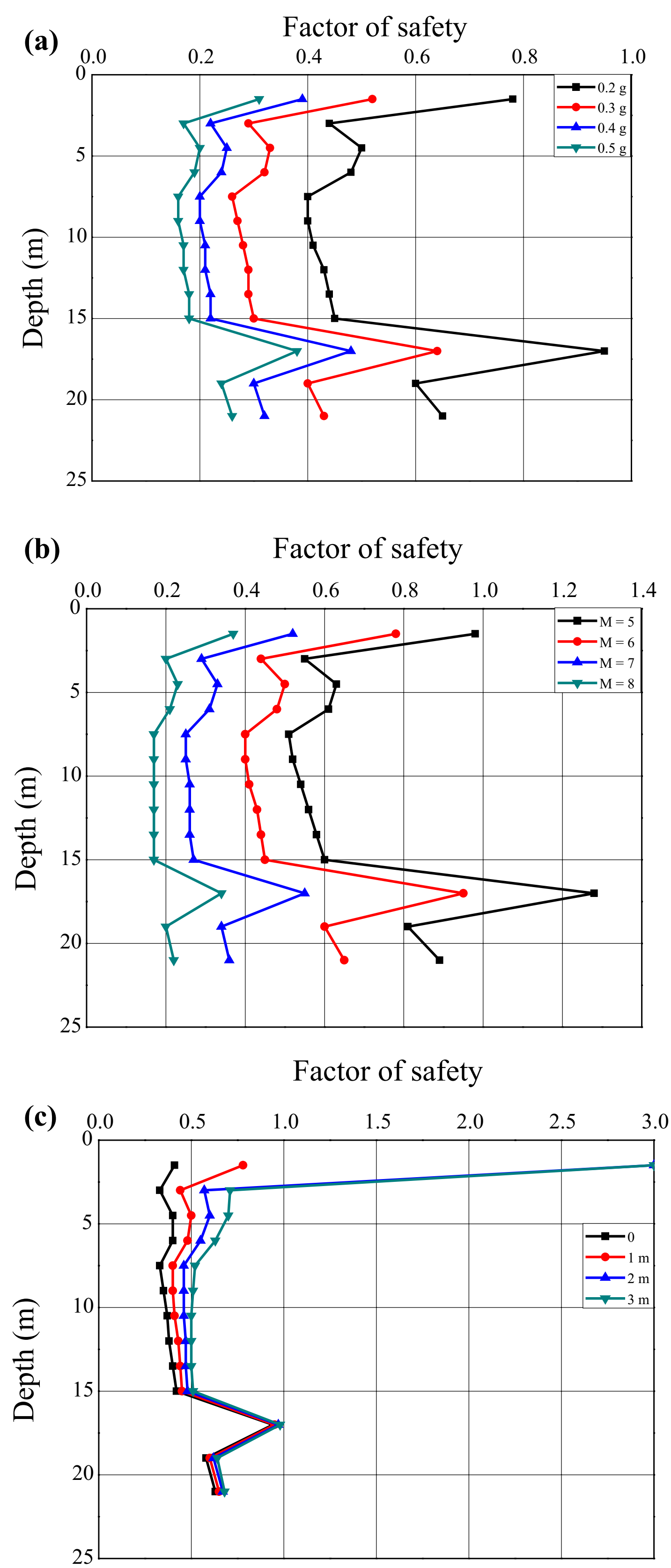
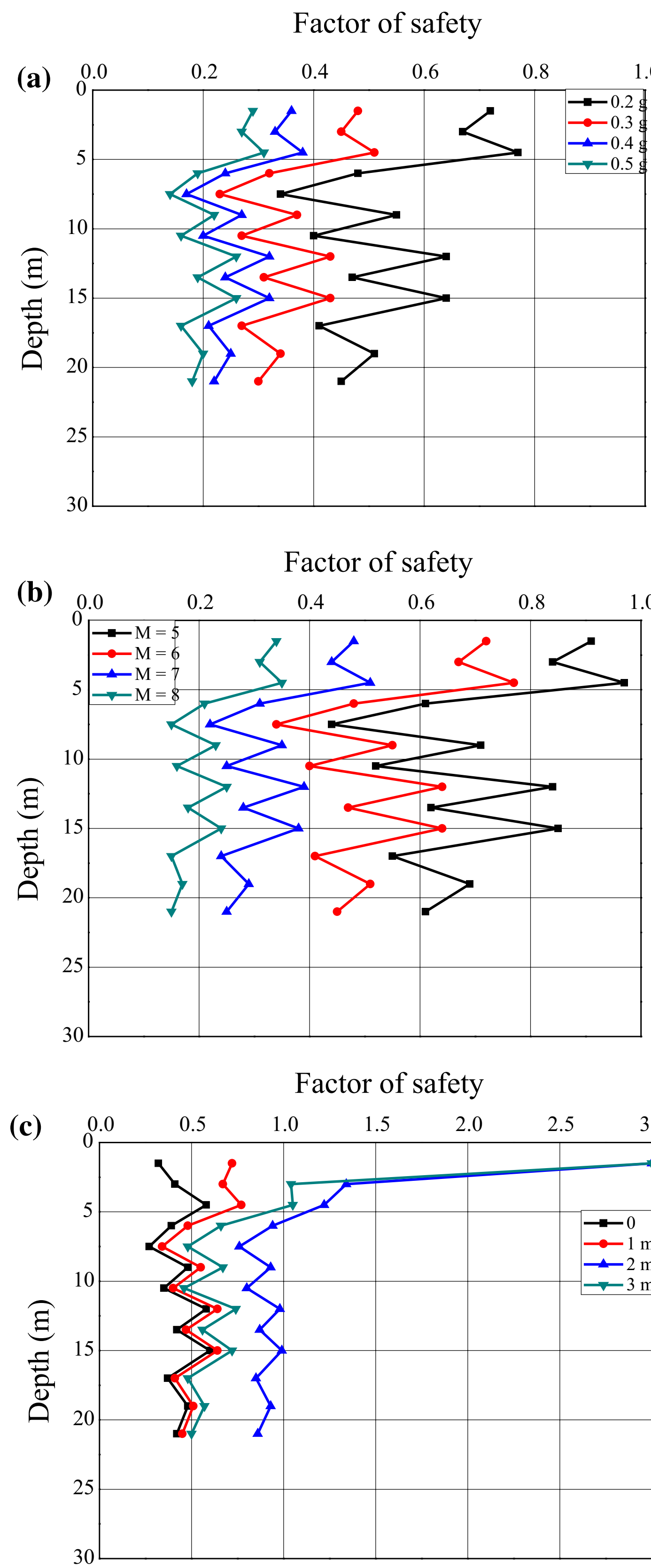


Fig. 22 Parametric study results of BH 1—Kaloor. **a** Variations in the factor of safety against liquefaction due to change in peak ground acceleration; **b** variations in the factor of safety against liquefaction due to change in earthquake magnitude; **c** variations in the factor of safety against liquefaction due to change in ground water table

Fig. 23 Parametric study results of BH 19—Elamkulam. **a** Variations in the factor of safety against liquefaction due to change in peak ground acceleration; **b** variations in the factor of safety against liquefaction due to change in earthquake magnitude; **c** variations in the factor of safety against liquefaction due to change in ground water table



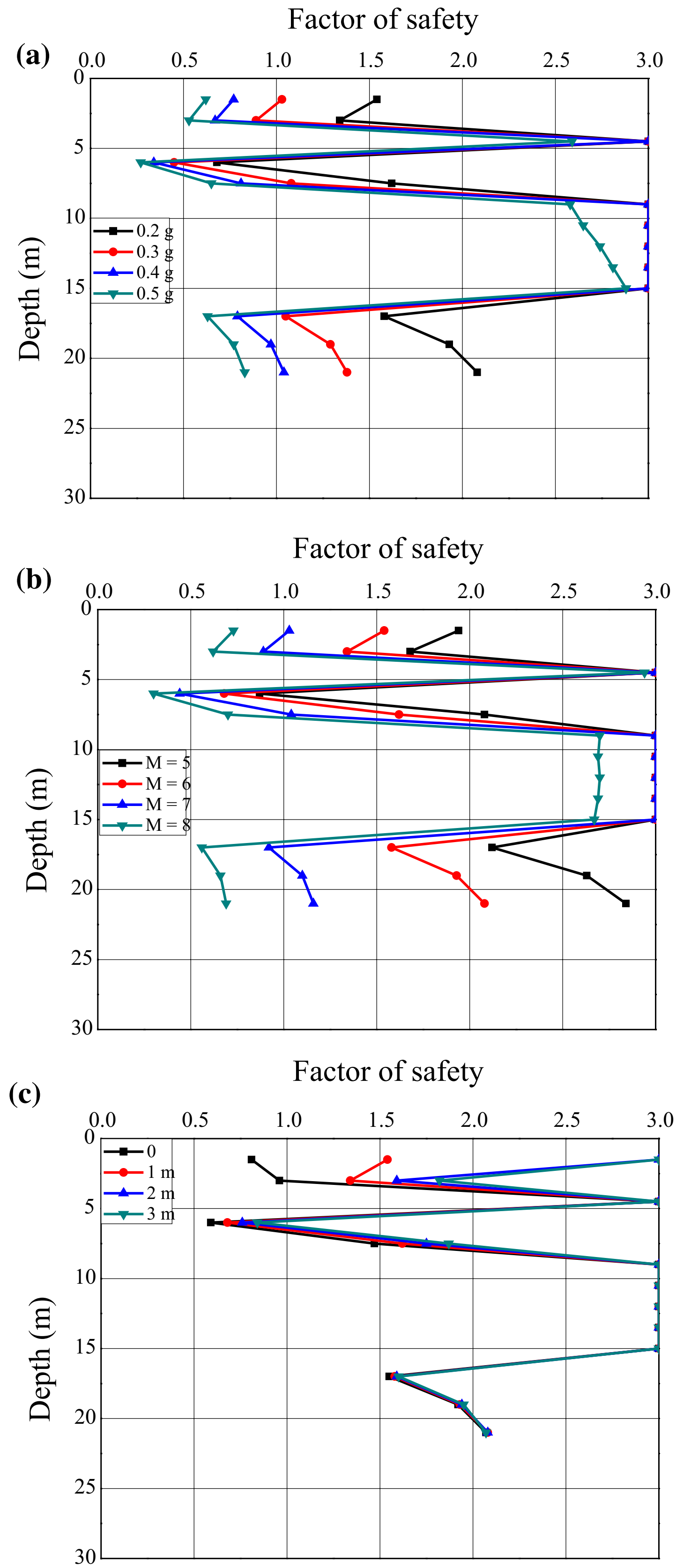


Fig. 24 Parametric study results of BH 33—Puthiyakavu. **a** Variations in the factor of safety against liquefaction due to change in peak ground acceleration; **b** variations in the factor of safety against liquefaction due to change in earthquake magnitude; **c** variations in the factor of safety against liquefaction due to change in ground water table

Table 9 Effect on liquefaction parameters (results of BH 1—Kaloor)

Input			Results			
M_w	PGA (g)	GWT (m)	PL (%)	LS (cm)	VS (cm)	LSI
6	0.2	1	72.76	11	6	3
5	0.2	1	45.13	2	1	1
7	0.2	1	96.33	482	63	33
8	0.2	1	99.60	743	70	80
6	0.3	1	75.20	318	50	3
6	0.4	1	75.76	658	70	3
6	0.5	1	75.76	743	70	3
6	0.2	0	74.17	78	32	3
6	0.2	2	75.60	5	3	3
6	0.2	3	75.09	3	2	3

in this paper. It can be concluded that all areas are prone to liquefaction if an earthquake with PGA of 0.2 g and a magnitude of 6 hits the areas, except Manorama Junction, Puthiyakavu and some areas near Kacheripadi. The main reasons include the low SPT N values (which reflect the soil conditions) and low ground water table. The places like Kacheripadi, Puthiyakavu, etc. where soils are in dense conditions showed a high factor of safety against liquefaction. The presence of laterite also improves the liquefaction resistance. A detailed parameter analysis was also carried out to study the effect of PGA, earthquake magnitude and ground water table on liquefaction susceptibility and other liquefaction parameters. The obtained values of the factor of safeties can be used to find the factor of safety against liquefaction for an earthquake with other a_{max} and earthquake magnitude.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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