Identification and Quantification of Liquefaction- Induced Lateral Spreading Potential of Guwahati City Soil

Konathala Raghavendra [1] and Olympa Baro[2][56979284600]

[1] National Institute of Technology, Silchar, 788010, India
konathalaraghavendra@gmail.com
olympabaro@gmail.com

Abstract. An attempt is made in this study to understand and quantify the liquefaction-induced lateral spreading potential of Guwahati city soil in the Indian state of Assam. Past studies have shown that Guwahati city soil is prone to liquefaction. Liquefaction-induced lateral spreading in Guwahati city was reported during the 1897 Assam EQ (MW-8.1). However, no studies have been conducted to identify the probable locations or to estimate the displacement lengths of lateral spreading during similar future earthquakes. In this study contour maps developed by previous researchers for scenario earthquakes of 1869 Cachar EQ (MW-7.5) and 1897 Assam EQ are used to identify sites with high liquefaction potential. The identified sites are further classified as prone to lateral spreading based on sub-soil properties, layer thickness, fines content, depth of ground water table, ground slope, earthquake magnitude, and source to site distance. The aforementioned parameters are then employed in a Multiple Linear Regression (MLR) model to estimate the amounts of displacement at the classified locations. The displacement lengths are found to range between 0.02m to 0.11m. Based on case studies the flow direction of lateral spreading at some of the locations is also identified.

Keywords: Liquefaction-induced lateral spreading, Multiple Linear Regression model, Guwahati city.

1 Introduction

Earthquake is a phenomenon common to Indian subcontinent and specifically to the Himalayas and the north-eastern (NE) regions of the country. The NE part of the country is particularly prone to earthquakes because of the ongoing subduction of Indian plate below Eurasian plate in the north at a rate of 45 mm/year (Bilham 2004). At the same time towards east, the Indian plate is subducting under the Burmese plate. This subduction movement of the tectonic plates have led to the development of several faults within the region. Baro and Kumar (2017) have identified several of these faults lying across the length and breadth of the NE state of Assam. These faults have individually generated two great earthquakes ($M_W \geq 8.0$) and several major earthquakes ($7.0 \leq M_W \leq 7.9$). Some of the earthquakes are 1869 Cachar EQ (M_W - 7.5), 1897 Assam EQ (M_W - 8.1), 1930 Dhubri EQ (M_S - 7.1), etc. The source faults of these earthquakes are Kopili, Oldham and Dhubri faults respectively (Baro and Kumar 2015). Among these faults, Oldham and Kopili fault are noteworthy. The Kopili fault is an active fault which has generated two major earthquakes till date (Kayal et al. 2010). The Oldham fault is located approximately 67km from the densely populated Guwahati city (often called the "Gateway to NE"). The earthquakes generated by the above-mentioned faults have caused severe damages to the city of Guwahati and places located in its vicinity. During the 1869 Cachar EQ the damages spread across Dibrugarh in the north, Manipur in the east, Patna in the west and Kolkata in the south (Austen 1869; Oldham 1882). Recent studies have highlighted that apart from the structural damages, ground liquefaction had also occurred in the Barak valley during the 1869 Cachar EQ (Raghu Kanth and Dash 2010).

Compared to 1869 Cachar EQ, the intensity of shaking during the 1897 Assam EQ was much larger and consequently damages were also more. Liquefaction and ground fissures were observed at several locations during 1897 Assam EQ (Bilham 2008). Fissures of 18 to 30m ran parallel to the banks of the Brahmaputra River and sand vents were observed at various places (Oldham 1899). As per Raghu Kanth and Dash (2010) liquefaction and lateral spreading occurred along the banks and riverbed of the river Brahmaputra River. A major road of Guwahati city between Sukleshwar Ghat and Bhorolumukh had also reportedly undergone liquefaction (Raghu Kanth and Dash 2010).
Collectively based on the discussion above, it can be observed that Assam has experienced earthquakes which generated soil liquefaction. Taking this into account, several studies have evaluated the liquefaction potential of Guwahati city. These studies have also identified the probable liquefiable locations within the city. However, no studies have been conducted to identify the locations of probable lateral spreading as well as the amount of displacement or the direction. Thus, in this study, an effort is made to identify the probable locations of lateral spreading during a future earthquake of (M_W = 8.1), and also to estimate the displacements and the direction of flow.

2 Tectonic setting of Guwahati city

India's Northeastern region, encompasses parts of the Himalayan Mountain, the Mishmi Hills, the Naga Patkoi Mountain range, the Assam Valley, the Shillong Plateau, the Burmese arc, the Tripura folded belt, and some parts of the Bengal Basin. Guwahati city is situated in the Assam Valley and due to the presence of several seismic sources in its vicinity, the city has experienced damages during past earthquakes. Some of the seismic sources identified by past studies are Kulsi, Barapani shear zone, Kopili, Artherkhet, Dudhnoi, Main Frontal Thrust (MFT), Main Boundary Thrust (MBT), Himalayan Frontal Thrust, Brahmaputra, Oldham, Guwahati . Table 1 gives the locations of the above mentioned faults. Fig. 1 shows the tectonic map consisting of the various seismic sources located within a 100km radius of the Guwahati city. It has to be mentioned here that in this study a radius of 100km for identification of the seismic sources has been taken based on the past damage reports.

Table 1. Seismic sources located around Guwahati city within a 100 km radius

Sl.No	Fault Name	Latitude (ºN)	Longitude (ºE)	References
1	Kulsi	26.10 - 25.48	91.39 – 91.44	Mohanty et al. 2014
2	Barapani Shear	25.57- 25.88	91.64 - 91.99	Imsong et al. 2018
3	Kopili	26.78 - 26.10	92.16- 92.72	Mohanty et al. 2014
4	Atherkhet	26.72 - 26.80	91.09 - 92.40	Mohanty et al. 2014
5	Dudhnoi	26.03 - 25.80	90.80- 90.81	Mohanty et al. 2014
6	Main Frontal Thrust (MFT)	26.76 - 26.91	91.01 - 92.24	Mohanty et al. 2014
7	Main Boundary Thrust (MBT)	26.85 - 26.94	91.11 - 92.18	Mohanty et al. 2014
8	Himalayan Frontal Thrust (HFT)	26.74- 26.85	90.98- 92.30	Mohanty et al. 2014
9	Brahmaputra	26.48- 26.63	90.80 - 92.57	Imsong et al. 2018
10	Oldham	25.97 - 25.79	90.75 - 91.37	Imsong et al. 2018
11	Guwahati	25.49 - 26.25	91.04- 91.73	Imsong et al. 2018

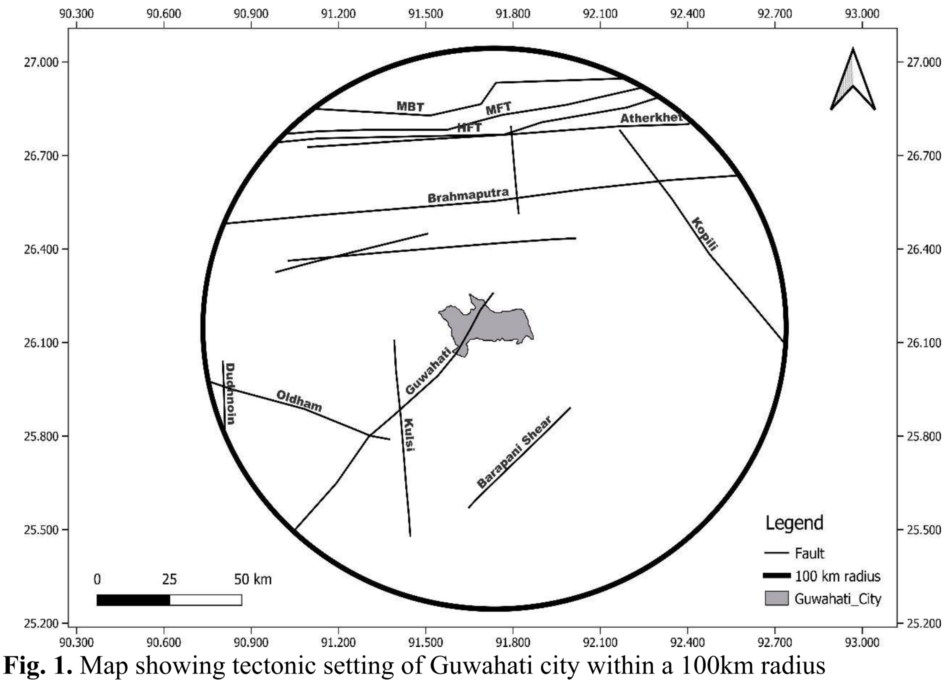

Fig. 1. Map showing tectonic setting of Guwahati city within a 100km radius

From Fig. 1, it can be observed that the Oldham fault is located very close (67km approximately) to the densely populated Guwahati city. It has been mentioned earlier that the Oldham fault is the source of the 1897 Assam EQ. Damage reports have clearly stated that liquefaction accompanied by lateral spreads had occurred in Guwahati city during the 1897 Assam EQ. Thus, the influence of this fault on seismic hzard studies of Guwahati city cannot be ignored In addition to this, the 1869 Cachar EQ had occurred on the Kopili fault which lies within the 100km radius around Guwahati city. It can be observed from past reports that damages had occurred in Guwahati city due to this earthquake. Though there are no reports of lateral spreads occurring in Guwahati city, Khan and Kumar (2020) have identified areas of high liquefaction potential index during this earthquake. Further, Kayal et al (2010) and Kumar et al. (2016) have highlighted that the Kopili fault is an active fault which has the potential to generate major earthquakes in the future. Hence, in this study an attempt is made to estimate the lateral spreading potential of the Guwahati city soil due future earthquakes similar to 1869 Cachar EQ and the 1897 Assam EQ.

3 Data & Analysis

3.1 Sub soil data:

For the estimation of liquefaction-induced lateral spreading potential of the Guwahati city soil, sub soil information is essential. To achieve this, subsoil data from 69 borehole locations has been obtained from the Guwahati Metropolitan Development Authority (GMDA). Fig. 2 shows the locations of the 69 bore holes superimposed over the geographical map of the Guwahati city. The bore logs revealed that the soil type of Guwahati city is mostly silty clay (CI to CH). However at some locations silty sand (SP/SM) and clayey sand are also present. It was observed from the report that some locations along the banks of the Brahmaputra River have a layer of filled up material up to a depth of 2-4 meters with very low soil strength. The depth of groundwater table at the borehole locations was found to lie between 0.6m and 6.7m.

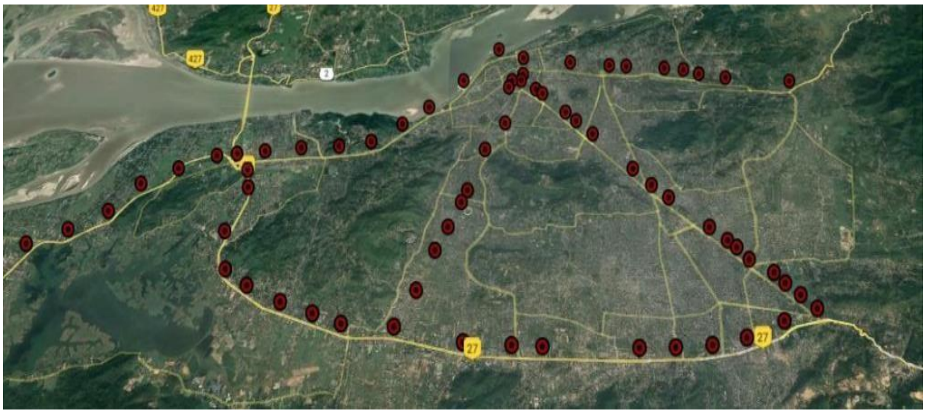

Fig 2. 69 borehole locations spread across Guwahati city

3.2 Identification of locations prone to lateral spreading

After the superimposition of the 69 borehole locations over the geographical map of Guwahati city, the liquefaction prone locations were identified. Khan and Kumar (2020) had developed Liquefaction Potential Index (LPI) maps of Guwahati city for the 1869 Cachar EQ and the 1897 Assam EQ. The locations with LPI>5 are considered for further analysis in this study. This classification was done based on the studies conducted by Iswasaki et al. (1982) and Sonmez (2003). As per Iswasaki et al. (1982) and Sonmez (2003) locations with LPI>15 have very high chances of liquefaction and those with LPI<5 have least possibility of liquefaction. It was observed from Khan and Kumar (2020) that for the 1869 Cachar EQ, out of the 69 borehole locations 3 are in the range of 5<LPI<15. Fig. 3 shows these 3 locations as red coloured circles. For the 1897 Assam EQ, 22 such locations have been identified which have a LPI value range of LPI>5. Out of these 22 locations, 5 are found to have LPI>15 and remaining 17 fall in the range of 5<LPI<15. Fig. 4 shows these 22 locations in red coloured circles.

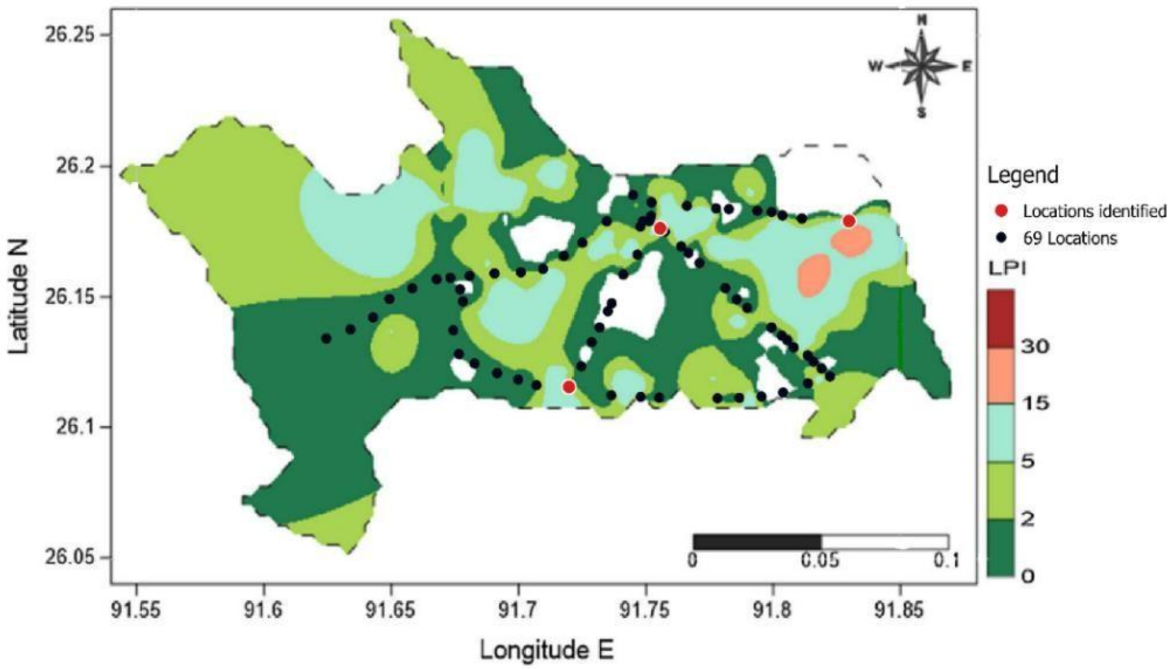

Figure 3. Showing locations with LPI>5 for 1869 Cachar EQ
(After Khan and Kumar 2020)

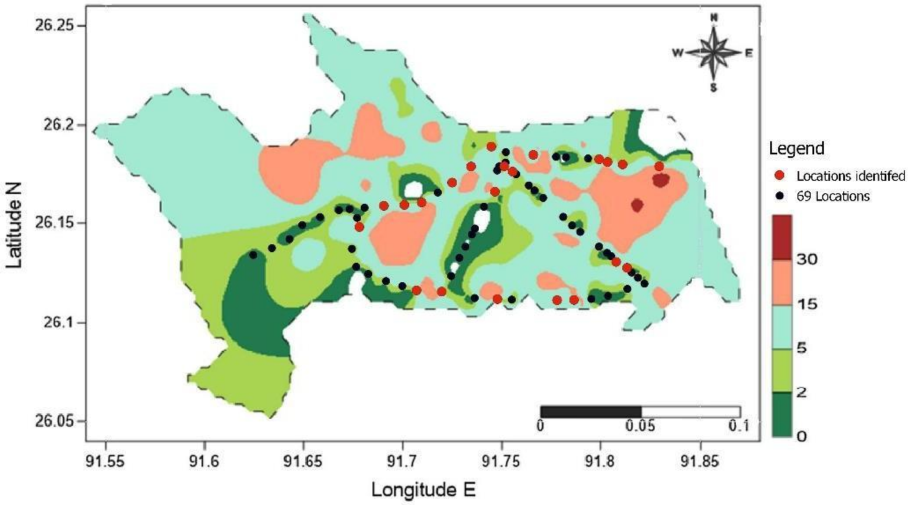

Figure 4. Showing locations with LPI>5 for 1897 Assam EQ (After Khan and Kumar 2020)

3.3 Analysis:

The LPI>5 locations identified in the previous discussion were further checked for lateral spreading potential with the help of empirical equations developed by Youd et al. (2002). Youd et al. (2002) had modified the empirical equations developed by Bartlett and Youd (1995) which were developed using Multiple Linear Regression (MLR). Bartlett and Youd (1995) had developed two empirical correlations using seismological, topographical and geological data obtained from Japanese and United States as case histories. The two empirical correlations were developed for free face of a river channel and gentle slopes without a free face. Later, Youd et al. (2002) observed proposed a revision stating that that Bartlett and Youd (1995) had developed the empirical correlations based on data from sites where free lateral displacement was hindered by the boundary effects. Further, Youd et al. (2002) incorporated data from additional sites and developed two revised correlations for free face and gentle slopes using on MLR as shown below:

For free-face conditions: -

$$\log D_H = -16.713 + 1.532M - 1..406\log R^* - 0.012R + 0.592\log W + 0.540\log T_{15} + 3.413\log(100 - F_{15}) - 0.795\log(D50_{15} + 0.1\text{mm}) \quad (1)$$

For gently sloping ground condition: -

$$\log D_H = -16.213 + 1.532M - 1.406\log R^* - 0.012R + 0.338\log S + 0.540\log T_{15} + 3.413\log(100 - F_{15}) - 0.795\log(D50_{15} + 0.1\text{mm}) \quad (2)$$

where,

D_H is the estimated lateral ground displacement, in meters; M is the moment magnitude of the earthquake; R is the nearest horizontal or map distance from the site to the seismic energy source, in kilometres; T_{15} is the cumulative thickness of saturated granular layers with corrected blow counts, $(N_1)_{60}$, less than 15, in meters; $F_{15}$is the average fines content (fraction of sediment sample passing a No. 200 sieve) for granular materials included within T_{15}, in percent; $D_{50}15$ is the average mean grain size for granular materials within T_{15} in mm; S is the ground slope, in percent, and W is the free-face ratio defined as the height of the free face divided by the distance from the base of the free face to the point in question, in percent

$$R^* = 10^{(0.89M-5.64)} + R \quad (3)$$

Eqs. (1), (2) and (3) are used for the LPI >5 locations within Guwahati city to estimate the lateral spread displacements. For locations near the Brahmaputra River Eq. (1) was employed as these are free face conditions and for the remaining Eq. (2) was used. The concept of free face condition was explained by Bartlett and Youd (1992). The vertical distance between the free face's base and crest was defined as H, and the distance between the free face's base or toe and the desired location as L (see Fig. 5). As per Youd et al. (2002), T_{15} is the cumulative thickness of saturated granular layers with corrected blow counts $(N_1)_{60}$. Thus in this study the corrected N-values are calculated for locations with LPI>5 during 1869 Cachar EQ and 1897 Assam EQ. It has to be mentioned here that in a recent study conducted by Kumar and Srinivas (2017) a new empirical correlation was proposed for calculating the corrected N-values. As per Kumar and Srinivas (2017) the widely used empirical correlation developed by Idriss and Boulanger (2010) for estimation of Cyclic Resistance Ratio (CRR) using corrected N-values follows a cumbersome and iterative procedure. In order to remove this cumbersomeness, Kumar and Srinivas (2017) developed the equation given below:

$$N_{60} = N.C_R.C_B.C_S.C_E \quad (4)$$

where, C_E = Corrections for hammer energy, C_R = Short rod correction factor, C_B = Corrections for borehole diameter, C_S = Corrections for liners. In this study Eq. (4) is used for estimating N_{60} at locations with LPI>5. Within these locations, the ones for which N_{60}<15, are further considered for analysis. For granular materials included withinT_{15}, the parameter F_{15} and D_{5015} values are found.

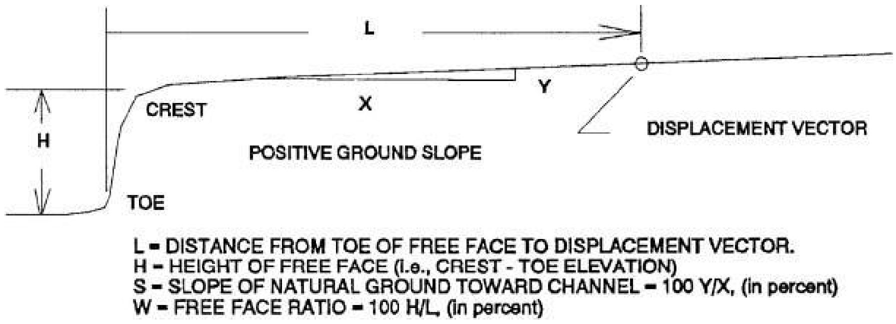

Fig. 5. Figure showing free face condition (after Bartlett and Youd 1992)

Results and Discussions

The empirical correlation developed by Kumar and Srinivas (2017) given in Eq. 4 is used to estimate the N_{60} values. The values for the parameters C_E , C_R , C_B , and C_S are considered as 1, 1, 1.05, and 1 respectively as proposed by Robertson and Wride (1998). It is found that for 1869 Cachar EQ none of the 3 LPI>5 locations have N_{60} <15 and hence are not considered for further analysis. However for the 1897 Assam EQ, out of the 22 LPI>5 locations, 7 have N_{60}<15. For these 7 locations T_{15} is calculated by taking the cumulative thickness of saturated granular layers. Out of those 7, at 4 borehole locations (C-1-13, C-1-20, C-1-21, and C-3-4) the loose granular material is in saturated condition. Thus the remaining 3 locations are not considered any further in the analysis. For the 4 selected locations F_{15} and $D50_{15}$ values are found. The borehole C-1-13 is located near the river front which is a free face condition, hence Eq. (1) is used. The value of M is taken as 8.1 as this the magnitude of the 1897Assam EQ. For R, 67km is taken which is the epicentral distance between the Oldham fault and Guwahati city. The lateral spread at C-1-13 is found to be 0.11m. The locations C-1-20, C-1-21 and C-3-4 are located on gently sloping ground, thus Eq. (2) is applied and the lateral spread displacements are found to be 0.02m, 0.07m and 0.08m respectively. The values of the parameters employed from Eqs. (1) to (3) and the lateral spread displacements found for the 4 borehole locations are given in tables 2 and 3. From table 2 and 3 it can be observed that the maximum and minimum lateral spread displacement occurs in borehole locations C-1-13 and C-1-20 respectively. Borehole C-1-13 is located near Kachari Ghat in M.G Road which lies along the Brahmaputra River front. Boreholes C-1-20, C-1-21 and C-3-4 are located near Unnati Bajaj showroom, Maniram Dewan Road; Indian oil petrol pump, Maniram Dewan Road and Regional Passport Office, Lalmati respectively.

Table 2: Values of parameters employed for free face condition

Locations (Borehole No.)	Soil type	M (M_W)	R (km)	R^* (km)	T_{15} (m)	F_{15} (%)	$D50_{15}$ (mm)	W (%)	Log D_h	D_h (m)
C-1-13	SM	8.1	67	104	1.3	40.1	0.2	5.2	-1.0	0.11

Table 3: Values of parameters employed for gently sloping ground condition

Locations (Borehole No.)	Soil type	M (M_W)	R (km)	R^* (km)	T_{15} (m)	F_{15} (%)	$D50_{15}$ (mm)	S (%)	Log D_h	D_h (m)
C-1-20	SM	8.1	67	104	0.4	32.6	0.3	0.9	-1.6	0.02
C-1-21	SP	8.1	67	104	3	26.6	0.4	0.8	-1.1	0.07
C-3-4	SM	8.1	67	104	4.5	51.0	0.1	2.4	-1.0	0.08

4 Comparison with case studies

In addition to the 4 borehole locations given in tables 2 and 3, a few other locations in Guwahati city might also be prone to lateral spreads. Past studies have shown that locations with fill materials are prone to lateral spreads especially in sloping grounds with shallow water tables. During the 1995 Kobe EQ (MW-6.9) lateral spreads were observed at the river front having fill material in sub soil layers (Chung et al. 1996). During the 1964 Niigata EQ (MW-7.6) surface cracks had appeared in loose fill material along the river side that caused lateral spreads (Hamada and Rourke 1992). Lithological sections obtained from the GMDA show fill material with gently sloping grounds and shallow water tables at 4 borehole locations (C-1-22, C-1-23, C-1-14 and C-3-7). At these borehole locations there are no N-value available for the fill material. Thus, the equations developed by Youd et al. (2002) cannot be used to estimate the lateral spread displacements. However, taking into account the similarity in the soil profiles of the past studies with the above mentioned borehole locations, possibility of occurrence of lateral spreads cannot be completely ruled out. Further in this study a scenario similar to the 1897 Assam EQ is considered which had a far greater magnitude than both the 1995 Kobe EQ and the 1964 Niigata EQ. Hence in this study it is postulated that these additional 4 borehole locations (C-1-22, C-1-23, C-1-14 and C-3- 7) are prone to lateral spread displacements. Fig. 6 shows the 4 borehole locations (C- 1-13, C-1-20, C-1-21, and C-3-4) given in tables 2 & 3 and the 4 postulated borehole locations (C-1-22, C-1-23, C-1-14 and C-3-7).

Furthermore, comparison with the 1995 Kobe EQ case study also provides an insight about the direction of lateral spread flow. It was observed that during this earthquake the ground near Osaka Bay in Japan had experienced lateral spreads and flowed towards the water. Later studies found that the soil profile in the bay area had fill material up to a depth of 10-12m and a shallow ground water table with unsupported river front lead to lateral spreads towards the water (Chung et al. 1996). It has already been mentioned that the soil profile in Guwahati city has fill material with gently sloping grounds and shallow water tables, which is similar to Osaka Bay. However to draw a conclusion, comparison of the ground slope between the two places is necessary. In this study, with the help of QGIS software the ground slope at the Osaka Bay, Japan is found. The ground slope at Osaka Bay ranges from 1.29^0 to 12.57^0. Similarly ground slope at borehole locations (C-1-13 and C-14) which are in river front areas with fill material the ground slope is found to be 3.00^0 and 5.68^0 respectively. Thus, at borehole locations (C-1-13 and C-14) during lateral spreads, the direction of flow will be towards the Brahmaputra River. Interestingly the above mentioned borehole locations are along the banks of the Brahmaputra River where, as per Raghu Kanth and Dash (2010) lateral spreads had occurred during the 1897 Assam EQ. This further solidifies the claim made in this study that sloping ground locations near river front are prone to lateral spreads with flow direction towards the river. Based on the study by Raghu Kanth and Dash (2010) it will not be wrong to say that more locations along the banks of Bahmaputra River might be prone to lateral spreads.

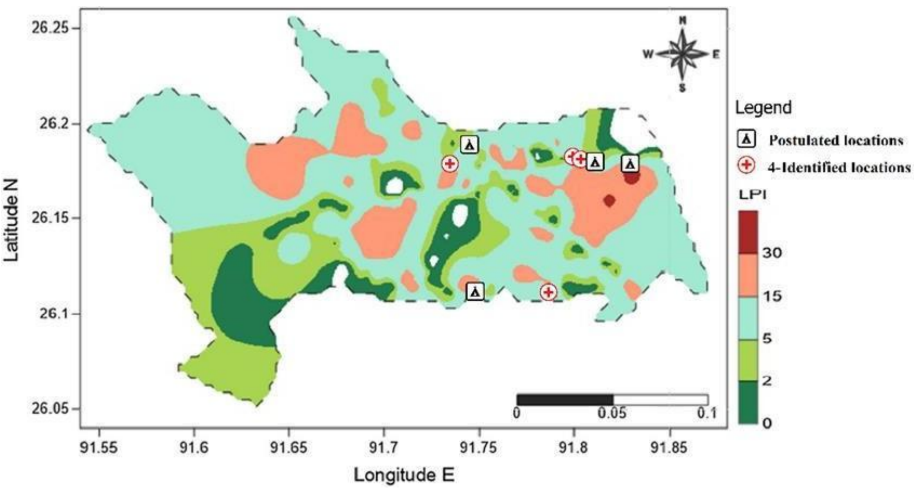

Figure 6. Identified and postulated locations for lateral spread displacements (After Khan and Kumar 2020)

5 Conclusion

Guwahati city located in the NE part of India is a seismically active region. Past studies have found that Guwahati city is prone to liquefaction and identified the high liquefaction potential areas. In this study an attempt has been made to find out if the previously identified high liquefaction potential areas are also prone to lateral spread displacements.

Permanent ground displacements were reported in Guwahati city during the 1869 Cachar EQ and the 1897 Assam EQ. In this study both the earthquakes were considered to check if the Guwahati city soil would undergo lateral spreading during similar events in the future. For the 1869 Cachar EQ, 3 locations of LPI>5 and for the 1897 Assam EQ, 22 locations of LPI>5 were considered. None of the 3 locations were found to undergo lateral spread displacements. Out of the 22 locations, 4 were found to be prone to lateral spread displacements ranging from 0.02m to 0.11m. The location on the banks of the Brahmaputra River showed the highest lateral spread displacement.

A comparison was done between the Guwahati city subsoil and the subsoil profile of areas in Japan which had undergone lateral spread displacements. This comparison showed that locations in Guwahati city which have fill material, shallow ground water table and sloping ground conditions are prone to lateral spreads. The locations on the banks of the Brahmaputra River satisfies this criteria and are thus prone to lateral spread displacements with flow direction towards the river. Interestingly several lifeline structures of Guwahati city such as the Saraighat Bridge, the Brahmaputra Bridge, railway lines, oil and natural gas pipelines pass over the Brahmaputra River and its banks. Baro and Kumar (2019) have reviewed the vulnerability of the oil and gas pipelines of Guwahati city towards lateral spread displacements. Thus, from the findings of this study it can be concluded that key locations in Guwahati city which house some of the life line structures are prone to lateral spread displacement.

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