

Potential areas susceptible to Liquefaction in National Capital Region, India

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ABSTRACT

Liquefaction is a phenomenon triggered by the vibrations of earthquake tremors in saturated loose soil. It is a major seismic risk particularly for the urban areas with large number of buildings and infra-structures, which are likely to be collapsed or toppled down due to destruction of foundation by this phenomenon. An attempt has been made here to identify the potential areas susceptible to liquefaction in the National Capital Region of Delhi (NCR). Geological set up shows that a large part of the NCR is covered with Older and Newer Alluvium, and seismically the NCR falls under High Seismic Zone – IV. Further, Yamuna River flows through the NCR that shows water table at shallow level at most of the places particularly along the river channel. All these are favourable for the possibility of liquefaction in the region. It is, thus, important to delineate the areas that are susceptible to liquefaction so that risk due to liquefaction may be reduced, especially where high rise buildings and mega infra-structure are already existing and even coming up in different places of the NCR. Accordingly, field and laboratory data from various parts of NCR was collected to study the geotechnical parameters of the sub-surface strata and water table, which are the conditioning factors for the occurrence of liquefaction. Data from 182 boreholes was collected and generated covering a large part of the NCR up to the depth of 30 m. Field test, viz. Standard Penetration Test (SPT) was conducted, and soil samples collected from each borehole were tested in the laboratory to understand the physical, strength and deformation (behavior) properties leading to assess the bearing capacity. Liquefaction analysis was carried out on the soil at different depths in all the 182 boreholes using the method as given by Seed et al. (1983, 1985), leading to delineate the potential areas where soil is susceptible to liquefaction. These areas as suggested by the analysis include a large part of East Delhi, area along Noida-Greater Noida Expressway, and some part of Rohtak, Jhajjar and Sonapat.

1. Introduction

Liquefaction is one of the key factors that leads to the destruction of the structures during earthquakes, which has caused major damage during the earthquake events in the past over the years. The damages due to liquefaction include failure of the buildings foundation, slope failures, ground settlement, and floatation of the light buried structures. Earthquake vibrations cause seepage of water through ground cracks to mix up with sand deposits making the sand over saturated so much so that the soil loses its strength and bearing capacity.

In India, Bihar Earthquake of M 6.6 in 1988, Latur Earthquake of M 6.4 in 1993, Bhuj Earthquake of M 7.7 in 2001, Kashmir Earthquake of M 7.6 in 2005, and other earthquake events have caused damage to the foundation of several building due to the soil liquefaction (Pande and Kayal, 2003; Kandpal et al., 2007; Malik et al., 2007).

2. The study area

The National Capital Region (NCR) of India, which is a hub of political, social, economic and various national and international issues, has a concern of liquefaction phenomenon as a large part of the NCR is covered by loosely to moderately dense alluvium sand. It is more so important because urbanization is increasing fast in the NCR with already existing and yet coming up a number of high rise buildings and mega infra-structure at different places. Rao and Neelima (2007)

pointed out the need for assessment of liquefaction potential in Delhi region.

The studies on probabilities of liquefaction in the National Capital Territory (NCT) of Delhi has been carried out in the past by many researchers, however, much have been done in isolation and in different parts of Delhi for different purposes (Roy and Neelima, 2007; Gupta et al., 2008, 2017; Thoithoi et al., 2013, 2016; Mittal et al., 2014). In addition, some work on liquefaction studies have also been carried out while delineating the seismic micro-zonation of the Delhi region (Sharma et al., 2003, 2004; GSI, 2011; MoES, 2014).

Gupta et al. (2008) worked out liquefaction susceptibility study at Commonwealth Games Village, near Akshardham in New Delhi. They concluded that soil to a depth of about 9.5 m is susceptible to liquefaction hazards. Later, Gupta et al. (2017) investigated an area of over 500 acres in Greater NOIDA designated for construction of a university. They encountered loose to medium grained dense Yamuna River sand deposit, locally named as 'Khadar' susceptible to liquefaction at about 8-12 m depth.

Thoithoi et al. (2013) evaluated the liquefiable subsurface soil in part of Delhi University North Campus and found that the average depth of liquefiable sub-surface soil is more than 8 m, and that the North Campus of Delhi University as a whole, and the area between GTB Nagar Chowk to Vishwavidyalaya Metro Station, in particular, is highly susceptible to liquefaction during earthquake. Thoithoi et al. (2016) further analyzed liquefiable

sub-surface soil data from 750 boreholes from different places of Delhi region.

Since Delhi region has been extended to the NCT and subsequently to National Capital Region (NCR) comprising 25 districts, the present study has been attempted to demarcate the potential areas susceptible to liquefaction covering the entire NCR.

It is clear from the above discussion that the NCR is imposing high risk of earthquake related disaster, primarily the liquefaction phenomenon, causing large scale damage to buildings and infra-structure. Although the earthquakes cannot be stopped to occur, but mitigation measures can certainly reduce the impact of the liquefaction during earthquake tremors. This is possible through identification of liquefaction prone areas in the region. Accordingly, an effort has been made to carry out this study in the entire NCR of Delhi to demarcate potential areas susceptible to liquefaction.

To begin with, it is important to understand the geology and the seismicity of the NCR.

Geology of the NCR

In general, the NCR forms a part of the Indo-Gangetic Plains predominantly towards the northern and eastern parts. Towards the west and south-west the NCR forms the extension of the Thar Desert, and towards the south it forms a part of the Aravalli Hill Ranges. The topography is generally flat to slight undulating, with a low lying ridge in the south-central part of the region, named as Delhi Ridge that trends NNE–SSW.

Geologically, the NCR is occupied by the rocks of Delhi Supergroup, comprised of quartzite with intercalations of micaceous schist, phyllite and slate, which protrude out in the form of Delhi Ridge, represented by the denudational / structural dissected hills and valley. These rocks are also exposed in form of some isolated hill mounds especially in south-south central part of the NCT, and further represent pediment pediplain features. The Quartzite is light grey to brownish grey coloured, fine to coarse grained, massive to thickly bedded, hard, compact and highly jointed. The quartzite rocks are intercalated with thin beds of slate, phyllite and schist, and often intruded by pegmatite and quartz veins.

In the slope portion of the ridge and isolated hill mounds that merges with the ground, these rocks are overlain by Quaternary sediments comprised of Older Alluvium and Newer Alluvium.

The Older Alluvium comprises of yellowish and reddish sand, silty clay, with kankar and small ferruginous concretions. The Newer Alluvium is represented by Flood Plain and Channel Alluvium of Yamuna River. The Flood Plain Alluvium is represented by grey sand, coarse grit, pebbles and clay deposited by the periodic flood in the Yamuna River. The Channel Alluvium, on the other hand, is represented by sand mixed with silt, clay, grit and gravels.

A number of faults and lineaments have been reported in the NCR (Kachroo and Bagchi, 1999; GSI, 2000; Thussu, 2006). These are :

- (i) Great Boundary Fault (GBF),
- (ii) Mahendragarh-Dehradun Sub-surface Fault (MDSSF),
- (iii) Delhi-Moradabad Fault,
- (iv) Delhi-Sargodha Ridge (DSR),
- (v) Sohna Fault, and

(vi) Mathura Fault.

In addition, Dubey et al. (2012) identified two major faults in Delhi Region, one named as Faridabad-Mehrauli-Rohtak Fault; and another named as Yamuna-Timarpur–Sonapat Fault, both are trending sub-parallel to the Himalayan thrust systems.

The NCR is further characterized by intricate tectonics because of faults and folded belts of the basement rocks forming the ridges (Verma et al., 1995; Chauhan et al., 1998; Kaul and Pandit, 2004; Shukla et al., 2007). These include Delhi-Haridwar Ridge, Delhi-Sargodha Ridge (DSR), and Delhi-Lahore Ridge.

Srivastava and Somayajulu (1966) identified two tectonic provinces, viz., Delhi-Moradabad Province and Kasganj-Ujhani Province separated from each other along the NE-SW trending Moradabad Fault Zone. This Moradabad Fault trending NE-SW is traceable on to the shield area as a tectonic boundary between the Delhi Fold belt and the Vindhyaans.

Seismicity in the NCR

The NCR is in juxtaposition to the geodynamically active domain of the Himalaya, and thus, falls under the seismotectonically vulnerable domain. Seismically, the NCR falls under the 'Seismic Zone IV' of the Seismic Zoning Map of India (IS 1893, Part 1 : 2002), whereas from intensity point of view it falls under high risk zone, i.e. 'Intensity VIII' on Modified Mercalli Scale. The NCT has remained seismically active and has experienced several earthquakes in the historic past in and around Delhi (Srivastava and Somayajulu, 1966; Tandon, 1975; Kamble and Chaudhury, 1979; Srivastava and Roy, 1982; Verma et al., 1995; Parvez et al., 2004; Wyss, 2005; GSI, 2006).

The Delhi region has also been affected by several large scale earthquakes occurred in the nearby Himalayan Region and the Peninsular India, viz., Kangra Earthquake ($M > 8.0$) of 1905; Uttarkashi Earthquake ($M 6.6$) of 1991; Latur Earthquake ($M 6.4$) of 1993; Chamoli Earthquake ($M 6.8$) of 1999; and Bhuj Earthquake ($M 7.7$) of 2001, that caused substantial non-structural damage to several buildings in Delhi, particularly in trans-Yamuna area (GSI, 2000).

It is significant that large number of high rise and non-engineering buildings in densely populated and congested areas with poor quality buildings are all highly prone to severe damage in the event of moderate earthquake tremor. Similarly, illegal settlements with sub-standard construction are also likely to damage during earthquake of even medium intensity. In fact, seismic response is much dependent on local geologic conditions, particularly where heterogeneous layers of rocks prevail. It is well known that the ground acceleration is much more on the alluvium than the hard rock of the earthquake of same magnitude.

In the NCR, as already mentioned, a large part is covered by Older Alluvium where earthquake waves may propagate ground motion with severe intensity leading to damage buildings, particularly in the Alluvium Zone that too along the Yamuna River, where it may cause liquefaction leading to substantial destruction and collapse to the structures in this zone.

Mechanism of Liquefaction

Soil liquefaction is a complicated phenomenon. Many researchers have worked to understand the mechanism of

liquefaction, particularly where, when and why it occurs (Seed and Idriss, 1971; Youd, 1973; Youd and Perkins, 1978; Seed, 1979; Seed et al., 1983, 1985).

Liquefaction occurs in loosely compact and saturated granular material, mostly sand, under sudden ground shaking vigorously. During the earthquake vibrations the loose saturated sand grains tend to consolidate into compact packing, but water in the soil voids does not allow to change the volume. Rather keeping the volume of the loose sand constant, intergranular water in soil voids exerts pressure on the soil grains. As a result, pore pressure begins to increase up to the extent it becomes equal to the overburden pressure. Once the pore pressure further exceeds the limit, it forces the soil grains to move relative to each other and making the solid sand into viscous liquid state. With this, bearing capacity of the soil is suddenly lost, which damages the foundation of the structure built at this site and the structure gets collapsed. Such a situation is known as 'Liquefaction'.

The sandy soil has maximum potential for liquefaction. The field and laboratory tests have shown that the great majority of clayey soils will not liquefy during earthquakes (Seed et al., 1983). However, some clayey soils having less than 15 % fines smaller than 0.005mm, a liquid limit less than 35% and in situ water content greater than 0.9 times of the liquid limit, may be susceptible to liquefaction (Seed et al., 1983).

Similarly, packing of sand grains as well as the severity of earthquake activity has a profound effect on liquefaction. Thick soil deposit is generally considered to be highly susceptible to liquefaction, but it may be negligible if the seismicity is very low. On the other hand, in very dense sand where the residual pore pressure is not large enough to cause liquefaction (Seed et al., 1983), it may act differently in case of strong earthquake tremors.

3. Methodology adopted for present study

Extensive field investigations were carried out in the entire NCR to understand the alluvium and to identify sites for boreholes to get requisite data. Overall 181 sites were identified in all the 25 districts of the NCR. These include 32 sites in Delhi; 23 sites in Gautam Budh Nagar (NOIDA); 13 sites in Ghaziabad; 4 sites each in Bulandshahr, Hapur, Muzaffarnagar, Shamli and Bagpat; 5 sites in Meerut; 9 sites in Gurgaon; 10 sites in Faridabad; 3 sites in Palwal; 4 sites each in Nuh (Mewat) and Rewari; 8 sites in Jhajjar; 7 sites in Sonapat; 4 sites in Panipat; 5 sites in Karnal; 4 sites in Jind; 6 sites in Rohtak; 3 sites each in Bhiwani and Charkhi Dadri; 4 sites in Mahendragarh (Narnaul); 10 sites in Alwar; and 4 sites in Bharatpur districts.

Data from each borehole was obtained up to a maximum depth of 30m, including level of the water table wherever available. Further, disturbed and undisturbed soil samples, which were preserved in standard poly packs as specified in IS : 1892-1979, at different depths were subsequently tested in the laboratory to determine the engineering characteristics. The laboratory tests were conducted in accordance with IS:2720. It included bulk density, natural moisture contents, grain size analysis, Atterberg's limits, specific gravity, gradation, triaxial shear, and direct shear tests.

Subsequently, liquefaction analysis for each bore-hole was carried out. The basic parameters used for estimation of

liquefaction potential include depth wise 'N' values obtained from Standard Penetration Test (SPT); % fines, depth of ground water; and Peak Ground Acceleration (PGA) value. As already mentioned, Liquefaction is the sudden loss of shear strength of the loose fine-grained sands due to earthquake induced vibrations under saturated conditions. Liquefaction generally takes place in loose fine-grained sands (fines < 10 %, D_{60} , 0.20 mm to 1.0 mm and C_u between 2 to 5) with 'N' value < 15. In case of soil strata having 'N' values > 15, liquefaction of soil will not take place normally.

SPTs were conducted in the boreholes as per the provisions of IS :2131-1981, during drilling. The data of % fines (Grain size and shape) and depth of ground water was obtained from the borehole data. The surface PGA values were used as given in IS: 1893 (Part-1) – 2016. The study area falls in Seismic Zone - IV. Considering the history of past earthquakes and available seismic data, an earthquake of Magnitude 7.5 having peak ground acceleration $a_{max} = 0.24$ g is considered in the present analysis.

Preliminary assessment of liquefaction potential of sub-surface soil is made by simplified approach as proposed by Seed et al. (1983, 1985) using the SPT data and peak ground acceleration, which is likely to occur at the site for a horizontal ground surface.

In this method, Cyclic Shear Stress likely to be induced in the foundation strata by Design Basis Earthquake (DBE) is first evaluated. Next threshold Cyclic Shear Stress, which is good enough to cause liquefaction, is determined from SPT data and the empirical relations. Finally, comparison of these two stresses is used in the estimation of liquefaction susceptibility of the foundation strata.

Cyclic Stress Ratio (CSR)

The equivalent average of shear stress τ_{av} likely to be induced in the foundation material due to an earthquake is calculated by using the equation :

$$\tau_{av} = 0.65 * \gamma * h * (a_{max} / g) * r_d$$

Where,

τ_{av} = Equivalent average of shear stress to be induced by DBE

γ = Unit weight of foundation material

h = Depth at which cyclic shear stress is calculated

a_{max} = Maximum surface acceleration

r_d = Stress reduction factor

$$= 1.0 - 0.00765 * h \text{ if } h < 9.15 \text{ m}$$

$$= 1.174 - 0.0267 * h \text{ if } h = 9.15 \text{ m to } 23 \text{ m}$$

$$= 0.744 - 0.008 * h \text{ if } h = 23.0 \text{ m to } 30.0 \text{ m}$$

$$= 0.50 \text{ if } h > 30.0 \text{ m}$$

If the equivalent average of shear stress τ_{av} is normalized with the initial effective overburden pressure (σ_o), the term is called seismic demand of soil layer or cyclic stress ratio (CSR).

$$CSR = 0.65 * (\sigma_o / \sigma_o') * (a_{max} / g) * r_d$$

Cyclic Resistance Ratio (CRR)

It expresses capacity of soil to resist liquefaction. CRR is determined using correlation between corrected blow count $(N_1)_{60}$ and CRR for earthquake of magnitude 7.5. $(N_1)_{60}$ is the SPT blow count corrected to an effective overburden pressure of 100 kPa and to hammer energy efficiency of 60 %.

The corrected blow count $(N_1)_{60}$ is determined as follows.

$$(N_1)_{60} = N_m C_N C_E C_B C_R C_S$$

Where,

N_m = Uncorrected SPT blow count
 C_E = Correction factor for hammer energy ratio = 1.00

C_B = Correction factor for borehole dia = 1.05 for 150 mm dia borehole

C_R = Correction factor for rod length = 0.75 for 3.0 m to 4.0 m

= 0.85 for 4.0 m to 6.0 m

= 0.95 for 6.0 m to 10.0 m

= 1.0 for 10.0 m to 30.0 m

C_S = Correction factor for standard sampler = 1.0

Correction factor for effective overburden pressure (C_N) is given by the following relation.

$$C_N = \text{Sqrt} (P_a / \sigma'_v)$$

Where,

P_a = Atmospheric pressure

The value of SPT blow count for soil with fines content (FC) can be adjusted to the equivalent clean sand value of $(N_1)_{60CS}$ as follows:

$$(N_1)_{60CS} = \alpha + \beta (N_1)_{60}$$

Where,

α and β can be determined as follows:

$\alpha = 0.0$ and $\beta = 1.0$ for $FC \leq 5.0\%$

$\alpha = e_{xp} [(1.76 - (190/FC^2))]$ for $5.0\% < FC < 35.0\%$

$\beta = [0.99 + (FC^{1.5}/1000)]$

$\alpha = 5.0$ and $\beta = 1.20$ for $FC \geq 35.0\%$

$CRR_{M=7.5}$ is given by the following equation.

$$CRR_{M=7.5} = [1 / (34 - (N_1)_{60CS})] + [(N_1)_{60CS} / 135] + [50 / \{10 * (N_1)_{60CS} + 45\}^2] - [1 / 200]$$

Hence, the CRR for a particular earthquake magnitude is determined as

$$CRR = CRR_{M=7.5} * MSF * K_\sigma$$

The MSF value is 1.00 for earthquake of magnitude 7.5 K_σ .

The factor of safety against liquefaction, FS_L , is given as :

$$FS_L = CRR / CSR$$

The value of CSR and CRR are computed at different depth and depth susceptible to liquefaction is determined.

Liquefaction is probable when FS_L is less than 1.0.

4. Analysis of the data

The requisite parameters used for estimation of liquefaction potential, viz., SPT 'N' value, % fines, PGA value, depth of ground water, were analyzed in all the 182 boreholes to establish the susceptibility for liquefaction at every 1.5 m depth interval in each borehole.

The objective is to determine the possibility of soil liquefaction during earthquake. As shown above, it is determined by calculating the Factor of Safety (FS_L) by computing the values of Cyclic Resistance Ratio (CRR) and Cyclic Stress Ratio (CSR), as :

$$FS_L = CRR / CSR$$

Possibility of liquefaction is deemed when Factor of Safety is less than 1.0. In other words, the soil is considered resistant to liquefaction where the value of Factor of Safety is higher.

Although detailed analysis has been done individually in all the boreholes at different depths, it has not been given here in the paper for all the boreholes due to limitation of the paper size. However, a typical sample of data sheet showing various parameters of soil characteristics, SPT values, requisite calculations and FS_L at different depths have been given for one of the 30m deep boreholes in **Table 1**. Similar data and calculations have been carried out for all the 181 boreholes.

Table 1. Sample Data Sheet and computation for Liquefaction at different depths (using method as given by Seed et al., 1983, 1985)

Borehole No.	BH-37	Borehole Location	Sector-144, Noida (Long 28°49'75.1" N, Lat 77°44'03.3" E)
Borehole dia.	150 mm	Water Table below EGL (m)	5.80 m

COMPUTATION DEPTH (h)	SAT. DENSITY (t/cum)	FINE CONTENT (%)	STRESS RED. RATIO (σ'_d)	Total overburden σ'_v	Eff. overburden $\sigma'_{v'}$	Cyclic Stress ratio (CSR)	SPT Value (N)	C_N	C_E	C_B	C_R	C_S	SPT Corrected $(N_1)_{60}$	$(N_1)_{60CS}$	$CRR_{M=7.5}$	CRR	FS_L	REMARK		
1.50	1.98	70	0.989	2.97	2.97	0.154	4	1.833	1.0	1.05	0.95	1.00	7.3	5.00	1.20	13.8	0.15	0.148	0.96	L
3.00	1.98	22	0.977	5.95	5.95	0.152	5	1.296	1.0	1.05	0.95	1.00	6.5	3.93	1.09	11.0	0.12	0.122	0.80	L
4.50	1.98	26	0.966	8.92	8.92	0.151	6	1.059	1.0	1.05	0.95	1.00	6.3	4.39	1.12	11.5	0.13	0.127	0.84	L
6.00	1.98	20	0.954	11.90	11.90	0.149	8	0.917	1.0	1.05	0.95	1.00	7.3	3.61	1.08	11.5	0.13	0.127	0.85	L

7.50	1.98	10	0.943	14.87	13.97	0.157	10	0.846	1.0	1.05	1.00	1.00	8.9	0.87	1.02	9.9	0.11	0.113	0.72	L
9.00	1.98	11	0.931	17.85	15.45	0.168	12	0.805	1.0	1.05	1.00	1.00	10.1	1.21	1.03	11.6	0.13	0.128	0.76	L
10.50	1.98	6	0.894	20.82	16.92	0.172	22	0.769	1.0	1.05	1.00	1.00	17.8	0.03	1.00	17.9	0.19	0.190	1.11	NL
12.00	1.98	10	0.854	23.80	18.40	0.172	25	0.737	1.0	1.05	1.00	1.00	19.4	0.87	1.02	20.6	0.22	0.224	1.30	NL
13.50	1.98	8	0.814	26.77	19.87	0.171	28	0.709	1.0	1.05	1.00	1.00	20.9	0.30	1.01	21.4	0.23	0.234	1.37	NL
15.00	1.98	6	0.774	29.75	21.35	0.168	31	0.684	1.0	1.05	1.00	1.00	22.3	0.03	1.00	22.4	0.25	0.248	1.47	NL
18.00	1.98	20	0.693	35.70	24.30	0.159	37	0.642	1.0	1.05	1.00	1.00	24.9	3.61	1.08	30.5	NA	NA	>1	NL
21.00	1.98	24	0.613	41.65	27.25	0.146	42	0.606	1.0	1.05	1.00	1.00	26.7	4.18	1.11	33.8	NA	NA	>1	NL
24.00	1.98	18	0.552	47.60	30.20	0.136	45	0.575	1.0	1.05	1.00	1.00	27.2	3.23	1.07	32.2	NA	NA	>1	NL
27.00	1.98	74	0.528	53.55	33.15	0.133	48	0.549	1.0	1.05	1.00	1.00	27.7	5.00	1.20	38.2	NA	NA	>1	NL
29.55	1.98	10	0.504	59.50	36.10	0.130	50	0.526	1.0	1.05	1.00	1.00	27.6	0.87	1.02	29.1	0.42	0.415	3.20	NL

L = Liquefiable NL = Non-Liquefiable

Parameters Used in the above mentioned analysis are as follows :

- 1) The project site falls in Zone - IV with peak ground acceleration $a_{max}/g = 0.24$ as per **IS : 1893 (Part-1) - 2016**
- 2) C_E = Correction for hammer energy ratio = $ER/60$, ER for Rope and pully System = 60 %, Hence $C_E = 1.0$
- 3) Borehole diameter = 150 mm , Hence $C_B = 1.05$
- 4) C_S = Correction for Standard sampler = 1.0
- 5) Magnitude scaling factor (MSF) = 1.00 for earthquake intensity of 7.5

5. Discussion and conclusions

Liquefaction is a major concern for the foundation of all structures, particularly those which are set up on soil rather than on the bedrocks. The need, thus, arises to assess the soil in the NCR for possibilities of liquefaction, so that disasters may be prevented by using safe and economical design.

It is found from the computations that the soil strata up to the explored depth, i.e. 30 m below existing ground level, is

generally not susceptible to liquefaction, however, at some places the soil strata has been found to be liquefiable. Location of all the investigated boreholes has been shown on the map designated as **Figure 1**. The boreholes marked as triangle show that these areas are susceptible to liquefaction, and hence should be given proper consideration during the foundation design in that area.

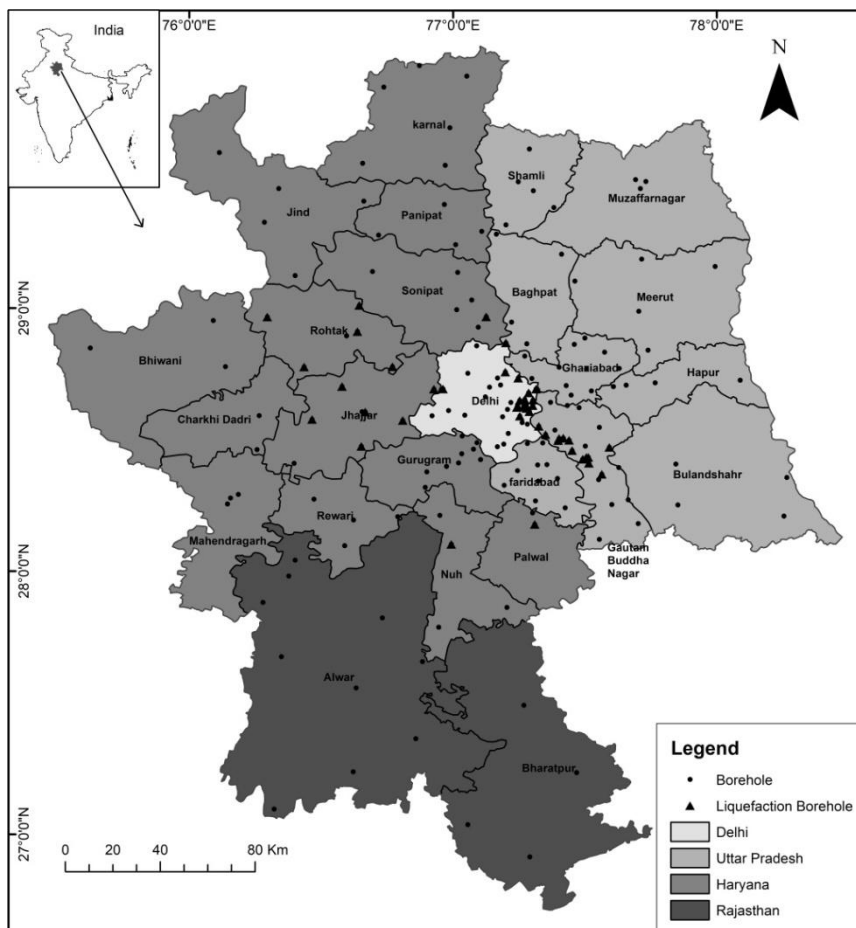


Figure 1. Map showing location of the boreholes. The boreholes marked as triangle show that the soil is susceptible to liquefaction.

The analysis shows that the areas susceptible to liquefaction in the study area includes a large part of East Delhi, area along Noida-Greater Noida Expressway, and some part of Rohtak, Jhajjar and Sonapat.

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