Liquefaction studies for seismic microzonation of Delhi region

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After the devastating 2001 Bhuj earthquake, the national capital region of Delhi has attracted major attention with several scientific studies in recent times. This region, being in zone-IV, has experienced many earthquakes in the past and recent times. It also faces the danger of severe seismic threat from the central Himalayan seismic gap. Seismic microzonation, which is a subdivision of an area into micro zones depending upon site-specific seismic response, is an effective mitigation method. During an earthquake, soil can fail due to liquefaction with devastating effects such as land sliding, lateral spreading, or large ground settlement. The phenomenon of liquefaction of soil had been observed for many years, but was brought to the attention of engineers after the Niigata (1964) and Alaska (1964) earthquakes. Since Delhi falls in the area with high seismic probability, there is need for the assessment of liquefaction potential. An extensive geotechnical borehole database has been prepared after compiling more than 1200 boreholes at various locations of Delhi, along with geological and seismological details. In this article, with the collected borehole data an attempt is made to assess in detail the liquefaction potential of soils using SPT-based methods and also to present a liquefaction hazard map.

Keywords: Liquefaction, microzonation, standard penetration test, seismic hazard.

MICROZONATION is the subdivision of a seismic zone into smaller zones according to a certain criterion to facilitate the implementation of seismic measures. This exercise requires more site-specific geological, geotechnical and ground responses to earthquake motions. The essential step in microzonation is the determination of seismic motion characteristics which are dependent on the maximum possible earthquake expected in the area, the probability of its occurrence, source of the fault, attenuation characteristics of the terrain and soil amplification, interaction of structures to seismic forces, and assessing the hazard and risk levels, on a site-specific perspective. Microzonation can be attempted in several stages depending upon quality of the input data and the scale required.

The State of Delhi occupies an area of 1485 sq. km spreading between lat. 28°24’01”–28°53’00”N and long. 76°50’24” and 77°20’37”E. Delhi is bound in the north, south and west by Haryana and in the east by Uttar Pradesh. The population of Delhi based on a recent census is around 16 million. Delhi is situated in a highly-earthquake prone belt near the active Himalayan region. The heavily populated city with a number of man-made structures could be prone to damage due to an earthquake of considerable magnitude (>6) from near-field sources. India has experienced some of the strongest earthquakes, viz. Assam 1897 (M = 8.7), Kangra 1905 (M = 8.6), Bihar-Nepal 1934 (M = 8.4), Assam-Tibet 1950 (M = 8.7), Uttarkashi 1991 (M = 6.5), Latur 1993 (M = 6.4) and Chamoli 1999 (M = 6.8) in the recent past.

The recent Bhuj earthquake of 2001 (M = 7.7) devastated many areas in Gujarat, causing extreme damage. Several areas in Rann of Kutch had experienced liquefaction, sand and salt boils, and severe ground-cracking. Delhi has a typical geological set up, which can sustain large amplified shaking not only due to earthquakes in and around the region, but also due to strong earthquakes in the Himalayas. This imposes high risk of an earthquake disaster in Delhi, resulting in casualties and damage to properties. The losses due to damaging earthquakes can be mitigated through a comprehensive assessment of seismic hazard. Damages caused by liquefaction of saturated soil showed that after liquefaction the ground failed, sand boiling occurred and the structure subsided unevenly causing tilting, cracking or even collapse. Therefore, conventional seismic measures of reinforcing the upper part of the structure in such situation are entirely in vain. Recognizing the potential hazard imposed by liquefaction, a detailed study was undertaken to map the likelihood of liquefaction within Delhi region.

Liquefaction and its mechanism

Several investigations have been made for understanding the phenomenon of soil liquefaction in the last four decades. From these it was observed that a vast majority of liquefaction occurrences were associated with sandy soils and silty sands of low plasticity. It is necessary to understand the mechanism of soil liquefaction; where and why it occurs so often during earthquakes. Figure 1 clearly depicts the
mechanism of soil liquefaction. Liquefaction of soil is a process by which sediments below the water-table temporarily lose shear strength and behave more as a viscous liquid than as a solid. The water in the soil voids exerts pressure upon the soil particles. If the pressure is low enough, the soil stays stable. However, once the water pressure exceeds a certain level, it forces the soil particles to move relative to each other, thus causing the strength of the soil to decrease and failure of the soil.

The shear resistance of cohesion-less soil is mainly proportional to the inter granular pressure and the coefficient of friction between solid particles, which is usually given by the following relationship

$$\tau_s = (\sigma - u)\tan \phi = \sigma' \tan \phi',$$

where $\tau_s$ is the shear resistance, $\sigma'$ the $(\sigma - u)$ effective normal stress, $\sigma$ the total normal stress, $u$ the pore water pressure and $\phi'$ the angle of internal friction in terms of effective stress.

The condition for liquefaction is $\sigma' = 0$, then $u$ will be equal to $\sigma$. The liquefaction phenomena that results from this process can be divided into two main groups, e.g. flow liquefaction and cyclic mobility\(^2\). Flow liquefaction can occur when the static shear stress is greater than the shear strength of the soil in its liquefied state. The deformations produced by flow liquefaction are induced by static shear stress. It occurs less frequently than cyclic mobility, but can cause more severe damage. Cyclic mobility occurs when the static shear stress is less than the shear strength of the liquefied soil. It can occur in a broad range of soils and site conditions. But the deformations produced here are caused by both cyclic and static stresses.

**Liquefaction hazard assessment and mapping**

The first step in liquefaction hazard assessment is the evaluation of liquefaction susceptibility. Liquefaction susceptibility was first coined by Youd and Perkins\(^6\) as a measure of inherent resistance of the soil to liquefaction, and can range from not susceptible to highly susceptible. Susceptibility can be estimated by comparing the properties of a given deposit to other soil deposits where liquefaction has been observed in the past. The primary relevant soil properties include grain size, fines content (i.e. amount of silt and/or clay), density, degree of saturation, and age of the deposit. The following incidences can be used as a general guide for assessing the liquefiable soils.

- Mean size, $D_{50} = 0.02$ to $1.0$ mm
- Fines $(d \leq 0.005$ mm) content $< 10\%$
- Uniformity coefficient $(D_{60}/D_{10}) < 10$
- Relative density $D_r < 75\%$
- Plasticity index PI $< 10$

Liquefaction susceptibility maps are the most basic levels of liquefaction hazard mapping. There are three different ways to predict liquefaction susceptibility of a soil deposit in a particular region. They are (a) Historical criteria, (b) Geological and geomorphological criteria and (c) Compositional criteria\(^7\). According to historical criteria, soils that have liquefied in the past can liquefy in future also. With the help of past earthquake records, liquefaction in the future can be predicted. The type of geological process that created a soil deposit has strong influence on its liquefaction susceptibility. Deposits formed by rivers, lakes and wind and man-made deposits, particularly those created by the process of hydraulic filling, are highly susceptible to liquefaction. It also depends on the soil type. Uniform graded soils are highly susceptible than well-graded soil deposits. Also, soils with angular particles are less susceptible than those with rounded particles. The liquefaction potential of any given soil deposit is determined by a combination of the soil properties, environmental factors and characteristics of the earthquake to which it may be subjected. Some of these factors cannot be determined directly, but their effects can be included in the evaluation procedure.

Liquefaction potential is represented as the ratio of stress induced to stress causing liquefaction. It also refers to the probability that the soil will actually liquefy at a given site, and therefore depends not only on the liquefaction susceptibility of the soil, but also on the level of seismic activity in the region. For example, loose, clean sand may be highly susceptible to liquefaction. However, if it exists in a region of negligible seismicity, then its liquefaction potential will be low. In contrast, denser soil may have a lower susceptibility and higher liquefaction potential because it is situated in an area of strong seismic activity. Liquefaction potential maps are therefore considered as the second level of liquefaction hazard mapping\(^7\).

The third level of liquefaction hazard mapping goes one step further and estimates the probable amount of permanent liquefaction-related ground displacement induced by a particular intensity of ground motion. These
maps are also referred to as ‘lateral ground displacement’ or ‘lateral spreading’ maps. The magnitude of ground displacement depends on the soil properties, local seismic activity and topology. Lateral spreading is defined as the horizontal displacement that occurs on relatively flat ground, with a slope of less than about 5°. On steeper slopes, the magnitude of liquefaction-induced soil movement could be much greater and large flow slides are possible. Figure 2 explains the steps involved and parameters considered in liquefaction hazard mapping.

Seismicity of the area

According to the seismic zonation map of India, Delhi is classified in the category of moderate to high earthquake-prone zone (IV), with intensity of VIII on modified Mercalli scale. The first scientifically recorded earthquake from this region was on 15 July 1720 with intensity IX. Other major earthquakes have been reported subsequently in the years 1803 (IX), 1825 (V), 1830 (V), 1831 (VII) and 1842 (VI). In the recent past, earthquakes of magnitude up to 6.2 have been reported in Delhi and nearby regions. Figure 3 shows the detailed lineamental map with faults and fractures. They are Bulandshahr earthquake (1956) of magnitude 6.2, earthquake near Sohna (1960) of magnitude 6.2 and Moradabad earthquake (1966) of magnitude 5.6. Similarly, as mentioned earlier, Delhi has far field sources (200 km) in the Himalayas, which can produce greater magnitude earthquakes. Figure 4 shows the epicentres ranging in magnitude from 2 to 6 with 10 and 100 years of probability. The distribution of earthquake epicentres in the Delhi region indicates that the clusters of seismic events are located to the west of Delhi, particularly between Sonipat-Rohtak and Gurgaon. These earthquakes are shallow focus events. The map also indicates that maximum concentration of epicentres occur along NNE–SSW direction and around the intersection of the margin of the Delhi-Lahore ridge and Mahendragarh–Dehradun fault. Several attenuation laws are available in the literature for assessing the seismic ground-motion parameters. Greater acceleration can be observed on a station located on alluvium compared to station located on hard rock for events of the same magnitude. For assessing the seismic hazard from seismic sources in and around Delhi region, Joyner and Boore’s attenuation law is used, which is valid for shallow sources. For seismic sources located in the Himalayas, McGuire’s law is used.

Geology of Delhi

The geology of Delhi is interesting on account of its being at the end of exposed ancient Aravali mountain ranges extending NE in this area. It is presumed underneath the river alluvium, the Aravalis might have extended as far as up to the Himalayas, which makes Delhi susceptible to seismic events in the Himalayas. Delhi and its adjoining region are surrounded in the north and east by Indo-Gangetic Plains, in the west by the extension of the great Indian Thar desert and in the south by the Aravali ranges. The terrain is generally flat, except for a low NNE–SSW trending Delhi ridge in the central portion of the region. The rocks of Delhi have undergone multiple folding and different phases of metamorphism. In addition, there are some transverse features like Delhi–Haridwar ridge, Faizabad ridge, Moradabad fault, Agra–Tilhar fault and perhaps other features hidden underneath the Indo-Gangetic alluvium. The quartzites are bedded and highly jointed with pegmatite intrusives. The trends of the faults and major shear zones, which
are generally steeply dipping (50–70° east) vary from NNE–SSW to ENE–WSW. The major faults, possibly tear faults trending northeast to south–west with steep dips, had been mapped on each side of the main ridge. The Alwar series and the post-Delhi intrusives are covered by Quaternary deposits in the form of aeolian and alluvial deposits. The alluvial deposits belong to the Pleistocene period – older alluvial deposits and of recent age, i.e. newer alluvium. Older alluvium deposits consists of mostly inter-bedded lenticular and inter-fingerling deposits of clay, silt and sand along with kankar. The detailed geological map of Delhi is shown in Figure 5.

**Geotechnical characteristics**

Extensive borehole data were collected from various public and private organizations. These data points are spread throughout Delhi region, except in some parts of northwestern Delhi. Selected data from different sources have been brought to a common platform and located on the Eicher block map. Based on these data 18 different soil profiles were made covering almost the entire region to study the sub-soil heterogeneity. Figure 6 shows such typical soil profiles along with corrected N values at different depths. Figure 6 a is the horizontal profile from
Kakraula Gaon to Sec-7, Dwaraka. Since this is low-laying area, the water-table depth is above 10 m. Similarly, Figure 6 b is from Chanakya Puri to Sec-62, Noida with quartzite at Chanakya Puri and sandy silt with patches of silty sand, clayey sand and gravelly sand. Figure 6 c is along Sec-1 to Sec-61, Noida which has sandy silt and silty sand with patches of clayey sand and so on. Generally, in trans-Yamuna, silt is predominant. The silty soils have high apparent cohesion in the dry state, which reduces rapidly with increase in water content. The water-table is high in areas near the Yamuna. Grain size distribution (GSD) curves are also drawn at four different depths (3.5, 5, 7.5 and 10 m) for north, south, east, west and central blocks in Delhi. The GSD curves in the eastern block are steeper.
than those for the other blocks. In this block the soils are sandy silt/silty sand with high percentage of medium to fine sand (30–90). The percentage of silt is 10–80 with less percentage of clay (plasticity index, PI = 0–5%) i.e. non-plastic soils which are prone to liquefy, and $D_{50}$ ranges from 0.03 to 2 mm. The northern block has silty sand with $D_{50} = 0.002–0.1$ mm, sand = 20–75%, silt = 30–80%, clay = 0–10%, PI = 0–7% i.e. low plasticity. In the western block the soil has reasonable percentage of clay with PI = 0–20% (less prone to liquefy) with $D_{50} = 0.005–0.8$ mm, sand = 15–60%, silt = 50–80%. GSD curves of the northern and western blocks are almost similar. The south and central blocks have gravelly sands with percentage of gravel = 0–8, $D_{50} = 0.003–0.8$ mm. For a particular block, at shallow depths, the curves are steeper when compared to greater depths. Figure 7 shows the GSD curves of some of the places in trans-Yamuna region along with the limiting curves for the liquefaction to occur.

Standard penetration test based methods for liquefaction analysis

Standard penetration test (SPT) is widely used as an economical, quick and convenient method for investigating the penetration resistance of non-cohesive soils. This test is an indirect means to obtain important design parameters for non-cohesive soils. The use of SPT $N$ value for evaluation of liquefaction potential began from the 1964 Great Alaskan Earthquake ($M = 9.2$) and 1964 Niigata Earthquake ($M = 7.5$), both of which produced significant liquefaction-related damage.

In the standard penetration test, a standard split spoon sampler (Figure 8) is driven into the soil at the bottom of a borehole by giving repeated blows (30–40 blows per minute), using a 65 kg hammer released from a height of 75 cm. The blow count is found for every 150 mm penetration. If full penetration is obtained, the blows for the first 150 mm are ignored as those required for the seating drive. The number of blows for the next 300 mm penetration is recorded as the standard penetration resistance, called the $N$ value.

Seed and Idriss method

The shear stress developed at any point in a soil deposit during an earthquake appears to be due primarily to the vertical propagation of shear waves in the deposit. This leads to a simplified procedure for evaluating the induced shear stress. If the soil column above a soil element at depth $h$ behaved as a rigid body, the maximum shear stress on the soil element would be

$$ (\tau_{\text{max}})_r = (\gamma h/g) a_{\text{max}}, $$

where $a_{\text{max}}$ is the maximum ground surface acceleration and $\gamma$ is the unit weight of the soil. Because the soil column behaves as a deformable body, the actual shear stress at depth $h$, $(\tau_{\text{max}})_d$ will be less than $(\tau_{\text{max}})_r$, and is expressed as

$$ (\tau_{\text{max}})_d = r_d (\tau_{\text{max}})_r, $$

where $r_d$ is a stress reduction coefficient with a value less than 1.

The more generalized equation for $r_d$ is suggested by Shibata and Teparasaka as

$$ r_d = 1.0 - 0.015 z, $$

where $z$ is depth in metres.

The average equivalent uniform shear stress, $\tau_{ur}$, is about 65% of the maximum shear stress, $\tau_{\text{max}}$.

$$ \tau_{ur} = 0.65 (\gamma h/g) a_{\text{max}} r_d. $$

The next step is to determine the liquefaction resistance (cyclic strength) of the soil. This can be achieved using SPT value along with the fines content of the soil. Em-
Table 1. Magnitude scaling factor values given by various researchers

<table>
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<th>Magnitude (M)</th>
<th>Seed and Idriss</th>
<th>Ambroseys</th>
<th>Distance based</th>
<th>Energy based</th>
<th>Andrus and Stokoe</th>
<th>P_L &lt; 20%</th>
<th>P_L &lt; 32%</th>
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The method is similar to the Seed and Idriss approach. In this soil liquefaction capacity factor $R$ is calculated along with a dynamic load $L$, induced in a soil element by the seismic motion, the ratio of both defined as factors which take into account the overburden pressure, grain size and fine content.

$$F_L = R/L,$$

$$R = 0.0882\left(\frac{N}{\sigma_0^* + 0.7}\right) + 0.225\log_{10}\left(0.35D_{50}\right)$$ if $0.02 < D_{50} < 0.6 \text{ mm}$.

$$R = 0.0882\left(\frac{N}{\sigma_0^* + 0.7}\right)-0.05L$$ if $0.6 < D_{50} < 2 \text{ mm}$, where $N$ is number of blows in SPT, $\sigma_0^*$ the effective overburden pressure in kgf/cm², $L$ the Dynamic load induced in soil element by seismic motion and $D_{50}$ the mean particle diameter (mm). $L = \frac{\tau_{max}}{\sigma_0^*} = \frac{(\sigma_0^*/\gamma)}{a_{max}}$, $a_{max}$ is the peak ground acceleration due to earthquake.

Then, $F_L$ can be calculated. If it is less than 1, liquefaction occurs in these strata. Liquefaction potential can be calculated as

$$P_L = \sum F(Z) W(Z) \, dz,$$

where $F(Z) = 1 - F_{L}$ if $F_{L} \leq 1.0$; = 0 if $F_{L} > 1.0$, $W(Z) = 10 - (0.5 \times Z)$.

Ranges for liquefaction potential are as follows: $P_L > 100$, Liquefaction catastrophic; $50 < P_L < 100$, Very severe; $15 < P_L < 50$, Severe; $5 < P_L < 15$, Minor; $P_L < 5$, Liquefaction unlikely.

Among several SPT-based methods, those by Seed and Idriss, Seed and Peacock and Iwasaki et al. are presently used for the analysis.

Results and discussion

Since Delhi falls in the high seismic risk zone, there is need for the assessment of liquefaction potential of the Holocene soils in trans-Yamuna region, where the depth of soil goes up to 150 m. Saturated sandy soils are susceptible to earthquake-induced liquefaction. Hence,
structures located especially on these areas that are not designed for earthquake forces are worst affected. Amplification of soil will be high on soft, saturated alluvium than on hard rock. The area has extensive tracts of Delhi silt and loose sand. Due to recurring seismic activity, there is a chance of the soil being subjected to liquefaction. With the collected bore-hole data, analysis for liquefaction is attempted using three SPT-based methods and a liquefaction potential map is prepared. A preliminary map\textsuperscript{31} prepared was modified with the additional analysis and is shown in Figure 11. The liquefaction potential is severe in the trans-Yamuna region, such as Yamuna Vihar, Geeta Colony, Mayur Vihar, Preet Vihar, Vinod Nagar. Some places at Noida, such as Udyog Vihar, Sec-62 Noida that are comparatively near the river also shows severe liquefaction potential but in Sec-1, 6, 12, 33, 61, Noida which are far have low probability. In the western side of Delhi like Punjabi Bagh, Paschim Vihar and Shahdra, the probability is moderately severe. In the northern side, Shahibabad, Vijay Vihar, Anand Vihar, Ritala, Haidarpur, the liquefaction potential is less but in few places like Lal Bagh the probability is severe. In the south of Delhi, Golf Link, Lodi Road, the probability is low and in some areas like Dhaula Kuan, C.P it is remote due to rock outcrops and presence of gravelly sands with high \( N \) value. The liquefaction hazard maps will help in selecting a suitable ground improvement technique and a foundation system for future constructions in the region.
7. DST Report, Geo-Scientific studies in and around Delhi, 2004, p. 74.

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