Assessment of Liquefaction Potential of Allahabad, India: A Future Smart City

Keshav Kumar Sharma, Kumar Pallav, Manjari Singh, Ashhad Imam, and Alvin Harrison

Abstract In the present work, seismic hazard assessment is performed for Allahabad city in terms of liquefaction potential index (LPI) for a hypothetical earthquake along the Allahabad fault of magnitude Mw 6.7 for different surface peak ground acceleration (PGA) levels (0.06, 0.1, 0.15 and 0.2 g). Factor of safety against liquefaction (FS) has been estimated using modified semi-empirical process from Idriss and Boulanger (Soil Dyn Earthq Eng 26, 115–130, 2006 (Mogami, T., Kubo, K.: The behaviour of soil during vibration. In: 3rd International Conference on Soil Mechanics and Foundation Engineering, pp. 152–155 (1953))) for all depths of 116 boreholes across Allahabad. Estimated FS values are used for computing LPI (deterministic) valuwheres. Liquefaction potential hazard contour maps are shown in terms of spatial distribution of FS and LPI indices. It is observed that a large part of Allahabad is safe against FS for lower PGA values (0.06 and 0.1 g) but has a potential to liquefy under high intensity shaking of 0.15 g and 0.2 g PGA at depth 15 m or more. In terms of LPI, most places have "low" to "very low" liquefaction severity (i.e. LPI < 5) for (0.06 and 0.1) g. It gets modified to "high" (i.e. LPI b/w 5–15) for (0.15 and 0.2) g at Naini, Jhalwa, Sangam area, near railway station and Jhunsi region.

Keywords Liquefaction · Cyclic stress ratio · Peak ground acceleration · Lateral spreading · LPI

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1 Introduction

Earthquakes accompanying liquefaction have been detected for several ages. Detailed records dating back hundreds of years have described failures during earthquakes that are now thought to be related to liquefaction. Even though the impacts of liquefaction have long been known but it more thoroughly grabbed the attention of engineers and researchers after the 1964 Alaska (USA) and Niigata (Japan) earthquake.

Initial studies described the strength loss in loose sands leading to flow failures in the form of liquefaction [1]. It can be defined as a development in which saturated/partially saturated soils, in response to stress, lose their strength and stiffness [2]. The effective stress of soil reduces to zero, resulting in a complete loss of shear strength and it start behaving viscous liquid rather than a solid [3]. Liquefaction potential relies upon the susceptibility of a soil deposit to liquefy and the level of shaking to exceed the threshold value required for liquefaction to occur.

In India, liquefaction analysis was performed on various regions such as Ahmedabad [4], Kolkata [5], Bangalore [6], Imphal [7], Roorkee [8], Mumbai [9], NCR Region [10], Agartala [11], Kanpur [12]. Naik et al. [13] presented liquefaction potential studies for Allahabad using FS and laboratory investigations, but they did not performed site specific analysis to determine liquefaction severity. Vijay et al. [14] used ANN technique and compared results with Idriss and Boulanger method [15], Vijay et al. [16] and Yaseen and Bind [17] used neuro-fuzzy techniques for the same, but they too do not talk about probability of liquefaction failures at specific locations. Moreover, liquefaction hazard maps have also not been yet prepared for the region. Estimation of liquefaction potential with depth at a specific site will be important in earthquake hazard planning and mitigation. Comprehensive research on liquefaction damage due to scenario earthquakes for Allahabad has not been done in accordance with the best of found knowledge. Within the confines of this study, Idriss and Boulanger's [18] semi-empirical method which is based on standard penetration test data is used to compute liquefaction potential of Allahabad city in terms of FS and LPI for a hypothetical earthquake of magnitude Mw 6.7 and for different surface PGA levels (0.06, 0.1, 0.15 and 0.2 g). Liquefaction potential hazard contour maps are also prepared to show geographic variability of liquefaction severity in Allahabad.

2 About Allahabad City and Its Development

Allahabad city (25° 28′ N, 81° 54′ E) is situated in Indian state of Uttar Pradesh at an elevations of 98 m above sea level and lies at the confluence of two rivers, Ganga and Yamuna [19]. It is among the biggest cities of north central India with metropolis area of 70.5 km^2. Allahabad is the most-populous district in the state of Uttar Pradesh with estimated population of about 6 million [20].

Past earthquake histories indicate that, the area is low to moderate seismic. The region has been assigned Zone II in the seismic zoning map of India [21].

However, destruction caused by these earthquakes are not readily available. Such incidents happened at a time when Allahabad was confined in scope to its population and infrastructure. With population growth in recent times, several important infrastructural projects viz., multi-storey buildings, bridges, rail and road links, etc., have been taken up in the area. Allahabad city is also selected for smart city project, Government of India with the collaboration of USA [22]. New infrastructure projects such as roads, railway, bridges and utility lines will be taken up in the city under the smart city plan, and thus the vulnerability to the damages of earthquake has also been increased. Hence, assessment of liquefaction severity has become more important in order to mitigate damages.

3 Geology and Seismotectonic Setup

Allahabad lies in between the Faizabad and Munger-Saharsa ridge, which signifies the prolongation of Bundelkhand and Satpura massif. As per Dasgupta et al. [23], the study area may be characterized into Ganga, Yamuna alluvial plain and Vindhyan Plateau.

The area lies in the E–W tectonic basin, which has many concealed faults and ridges at the basement of Gangetic basin [24, 25]. The various faults around the study area with their features are gathered from various publications [23, 26] as shown in Fig. 1. Such subsurface faults have an oblique and transverse orientation around the tectonic pattern of the Himalayas [27, 28]. Past seismic data have shown that many of these faults are neotectonically active, with the possibility of large earthquakes in the near future [29]. Out of the various faults, Allahabad fault (Bhairwan Fault) is the one nearest to the study area and most critical from analysis point of view. Lucknow–Faizabad fault lies near Allahabad continuing towards the Himalayas in Nepal, and this fault has been sedentary for more than 350 years and under heavily stressed and would be originate great earthquake in future [30].

4 Standard Penetration Test Data

Extensive borehole data with detailed soil investigations and standard penetration tests (SPT) values has been obtained from various public/private organizations and engineering firms (MNNIT Allahabad, Allahabad Engineering Consultants (Allahabad), Ashok and Associates (Allahabad) and Universal Test House (Lucknow)) involved in soil investigation projects across Allahabad. These tests were performed following Indian Standard code of practice [32]. Data from 116 boreholes across 35

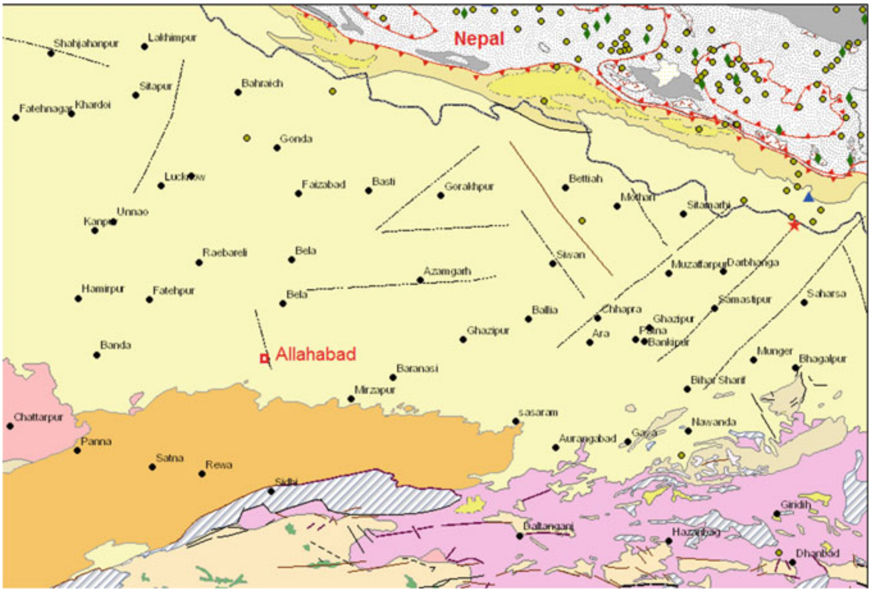

Fig. 1 Location of various surface and subsurface faults around Allahabad city [31]

sites in Allahabad is used in the study. These locations are scattered all over Allahabad (Fig. 2). At 1.5 m depths intervals, the N values were measured. SPT has been measured to a depth of more than 20 m for several significant building sites.

5 Determination of Peak Ground Acceleration for Allahabad

Ground motion is a significant parameter for estimating the FS against liquefaction. The size of the largest earthquakes that might be produced by a particular fault or earthquake source can be estimated from fault rupture parameters. On the basis of a worldwide data base of source parameters compiled from 421 historical earthquakes, Wells and Coppersmith [33] suggested relations among earthquake magnitude and the fault parameters. For "ALL" type of "subsurface" faults, the relation is

$$M_{\mathrm{w}} = 4.38 + 1.49\log(\mathrm{RLD}), \tag{1}$$

where M_{w} = moment magnitude, RLD = sub surface rupture length (km).

Present study estimates the maximum possible earthquake based on nearest seismic source, i.e. Allahabad fault. The maximum earthquake magnitude which can occur due to Allahabad fault is 6.27, obtained from Eq. 1 and rupture parameters of Allahabad fault.

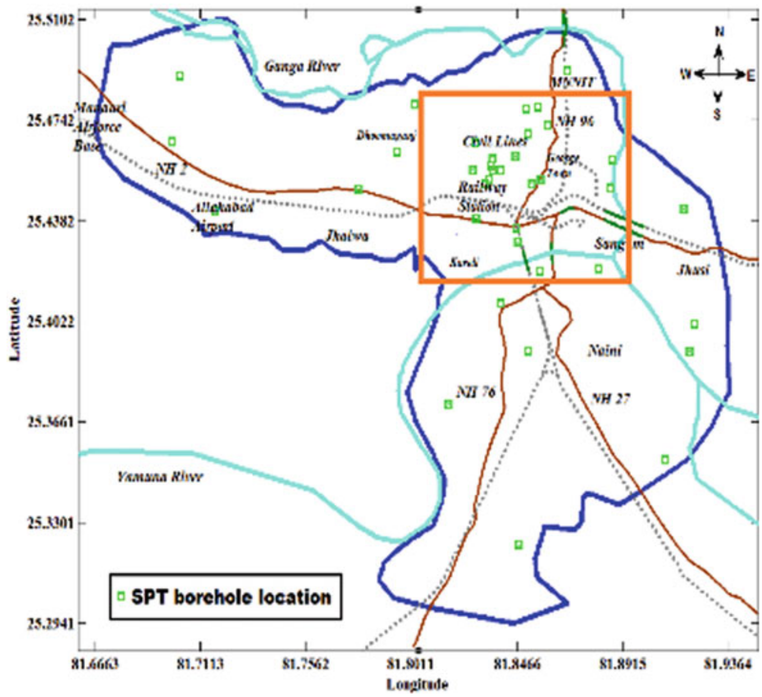

Fig. 2 Allahabad city with Borehole locations

As the region lacks recorded strong motion data, it is very hard to recommend a PGA value. So, an attenuation relationship recommended by Abrahamson et al. [34] can be used. They recommended a relation (Eq. 2) based on 585 records from 76 worldwide earthquakes:

$$\log(a) = -0.62 + 0.177 \times M - 0.982 \times \log\left(r + e^{(0.284\mathrm{M})}\right) + 0.132 \times F - 0.0008 \times \mathrm{Er}, \quad (2)$$

where

a	PGA
r (Km)	distance to closest approach of zone of energy release
M	arthquake magnitude
F and Er	dummy variables.

Note: ($F = 1 \rightarrow$ reverse/reverse oblique fault, $F = 0 \rightarrow$ otherwise) and ($\mathrm{Er} = 1 \rightarrow$ interplate, $\mathrm{Er} = 0 \rightarrow$ intraplate events).

Allahabad fault is most prominent and closest source for the study region. Thus, the design PGA value attained from Eq. 2, for a hypothetical earthquake of 6.27 Mw along Allahabad fault, is 0.057 g. Naik et al. [13] also estimated PGA ranging between 0.063 and 0.15 g for Allahabad city. Thus, it is found suitable to use PGA value of 0.06 g as the starting point to estimate LPI and LSI, which is further increased intermittently up to 0.2 g, where most of the sites are found to be liquefiable.

6 Methodology

In the present study, FS for each soil strata at all sites have been estimated from soil property and ground motion as inputs, as per Idriss and Boulanger's method [15]. Then, FS values are used to compute liquefaction potential of sites as LPI. The mentioned methods are based on SPT-N values and cyclic stress-based approach and briefly described in subsequent sections.

7 Semi-Empirical Approach

The semi-empirical approach is an updated technique of Seed and Idriss [35] and proposed by Idriss and Boulanger [15]. It is used for computing liquefaction potential. It, a methodology which evolved over years. In this approach, liquefaction potential of soil is defined in the terms of FS, which is a ratio of cyclic resistance ratio (CRR) to cyclic stress ratio (CSR), expressed in Eq. 3. At places where seismic loading exceeds the soil resistance, i.e. FS < 1.0, liquefaction is expected to be triggered.

$$\mathrm{FS} = \frac{\mathrm{CRR}}{(\mathrm{CSR})_{M_{\mathrm{w}=7.5,\sigma=1.0}}}, \tag{3}$$

$$\text{cyclic stress ratio : } (\mathrm{CSR})_{M_{\mathrm{w}=7.5,\sigma=1.0}} = 0.65\left(\frac{\sigma_{\mathrm{v}} a_{\max}}{\sigma'_{\mathrm{v}}}\right)\frac{r_{\mathrm{d}}}{\mathrm{MSF}}\frac{1}{K_\sigma}, \tag{4}$$

where $(\mathrm{CSR})_{M_{\mathrm{w}=7.5,\sigma=1.0}}$ corresponds to the equivalent uniform shear stress due to earthquake having a moment magnitude of $M_{\mathrm{w}} = 7.5$ and σ (overburden pressure) $= 1$ atmosphere.

In Eq. 5, $a_{\max}$ refers to maximum horizontal acceleration at the ground level σ_{v}, σ'_{v} is total and effective vertical stress at depth z, respectively. Factor (0.65) is used to modify peak cyclic shear stress ratio to a cyclic stress ratio that is representative of most significant cycles over the full duration of loading. The stress reduction factor (r_{d}) accounts for the flexibility of the soil column, and it measures the attenuation of peak shear stress with depth due to non-elastic behaviour of soil [15]. It is calculated as per Idriss [36] and Golesorkhi [37]

$$\begin{aligned}\ln(r_{\mathrm{d}}) = &-1.012 - 1.126\sin\left(\frac{z}{11.73} + 5.133\right) \\ &+ \left[0.106 + 0.118\sin\left(\frac{z}{11.28} + 5.142\right)\right]M_{\mathrm{w}}.\end{aligned} \tag{5}$$

If M_w larger or smaller than 7.5 is scaled by magnitude scaling factor (MSF) (Eq. 6) to modify CSR value to equivalent uniform shear stress caused by an equivalent earthquake of M_w of 7.5.

$$\mathrm{MSF} = 6.9 \exp\left(\frac{-M_w}{4}\right) - 0.058 \leq 1.8 \tag{6}$$

The efficient use of SPT blow counts as indicators for liquefaction characteristics requires the separation of the effects of soil density and effective confining stress on penetration resistance [18]. As the resistance to liquefaction rises with rising confining pressure, overburden pressure correction (K_σ) is implemented in such a manner that CSR values correspond to equivalent overburden pressure (1 atm) as shown in Eq. 7.

$$K_\sigma = 1 - C_\sigma \times \ln\left(\frac{\sigma'_v}{p_a}\right) \leq 1.0, \tag{7}$$

where the C_σ can be calculated as

$$C_\sigma = \frac{1}{18.9 - 2.55\sqrt{(N_1)_{60}}} \leq 0.3, \tag{8}$$

where p_a denotes atmospheric pressure (100 kPa)

$$(N_1)_{60} = (C_{N\times} N_{60}) < 37, \tag{9}$$

where N_{60} = SPT-N value after correction to an equivalent 60% hammer efficiency. C_N denotes correction factor for overburden pressure [18] is

$$C_N = \left(\frac{p_a}{\sigma'_v}\right)^{0.784 - 0.0768\sqrt{(N_1)_{60}}} \leq 1.7. \tag{10}$$

As shown in Eq. 10, due to their independence on each other, C_N and $(N_1)_{60}$ are computed by iterative process.

CRR based on SPT-N values for a cohesionless soil with any fine content (FC) can be calculated as [15]

$$CRR = \exp\left[\frac{(N_1)_{60_{cs}}}{14.1} + \left(\frac{(N_1)_{60_{cs}}}{126}\right)^2 - \left(\frac{(N_1)_{60_{cs}}}{23.6}\right)^3 + \left(\frac{(N_1)_{60_{cs}}}{25.4}\right)^4 - 2.8\right], \tag{11}$$

$$\begin{aligned}(N_1)_{60cs} &= \text{clean sand corrected SPT - N value} \\ &= (N_1)_{60} + \exp\left[1.63 + \frac{9.7}{FC + 0.1} - \left(\frac{15.7}{FC + 0.1}\right)^2\right].\end{aligned} \tag{12}$$

By combining these two factors (CSR, CRR), FS can be calculated by Eq. 3 for all depths of boreholes. If FS < 1, the soil is considered as liquefiable else non-liquefiable [15].

8 Liquefaction Potential Index

LPI was formerly developed in Japan by Iwasaki et al. [31, 38, 39] to evaluate the liquefaction potential of soils to cause foundation damage at a site. The vulnerability of region to liquefaction may be stated as a cumulative impact of layerwise liquefaction potential across overall depth of soil under consideration. LPI is defined as thickness of the liquefied layer, its proximity to ground level and FS values of each layer of soil. LPI can be defined as shown in Eq. 13 [39]

$$\mathrm{LPI} = \int_0^{20} F(z) \times w(z)\mathrm{d}z, \tag{13}$$

$$F(z) = 1 - \mathrm{FS}(z); \quad \mathrm{FS} < 1, \tag{14}$$

$$F(z) = 0; \quad \mathrm{FS} \geq 1, \tag{15}$$

where

$$w(z) = 10 - 0.5z; \quad z \leq 20\ \mathrm{m}, \tag{16}$$

$$w(z) = 0; \quad z > 20\ \mathrm{m}, \tag{17}$$

where z denotes depth from ground level (m).

Liquefaction susceptibility is classified into 4 classes given by Iwasaki et al. [39] depending on the value of LPI. LPI values can range from zero at a site with no potential for liquefaction to a maximum value of 100 at a site which has zero FS over whole 20 m depth range. The simplified procedure only estimates performance of a particular soil element, whereas LPI calculates the overall liquefaction resistance of entire soil column up to 20 m depth. Iwasaki et al. [39] proposed that severe liquefaction is very likely at sites with LPI greater than 15 and it is unlikely at sites with LPI less than 5. Toprak and Holzer [40] correlated observations of liquefaction occurrences with LPI for Loma Prieta (1989) earthquake and concluded that both sand boils and lateral spreading primarily occur at the locations where LPI ranges between 5 and 12.

9 Results and Discussions

SPT-N values and variation in FS against liquefaction with increase in PGA at one sample site (George Town) are shown in Fig. 3. Furthermore, FS variation for 1.5 m, 4.5 m depth (shallow foundation level) and 15 m depth (deep foundation level) is plotted for all PGA values of 0.06, 0.1, 0.15 and 0.2 g, at Allahabad city. Figure 4a–d shows FS for 1.5, 4.5 and 15 m depth for all the events. Following observations can be made from the plots.

For 1.5 m depth, areas near George Town, Tagore Town, Colonel Gang, Allahabad University, Jhalwa, Kareli and Manauri are critical to liquefaction failures at 0.2 g PGA, as evident from Fig. 4d.

At the depth of 4.5 m and PGA 0.15 g, areas near rivers like Sangam area, Arail ghat, Gaughat and Mahewa east are susceptible to liquefaction (Fig. 5c). Being close to river, this area has coarse sand to non-plastic silty sand with low compressibility clay in its soil profile, thus making it critical to liquefaction failures at the time of seismic shaking. As evident from Fig. 5d, areas near Jhalwa, Kareli, Allahabad high court, Sangam area, Chowk, Rambagh and Cheonki railway station are susceptible to liquefaction at 0.2 g PGA.

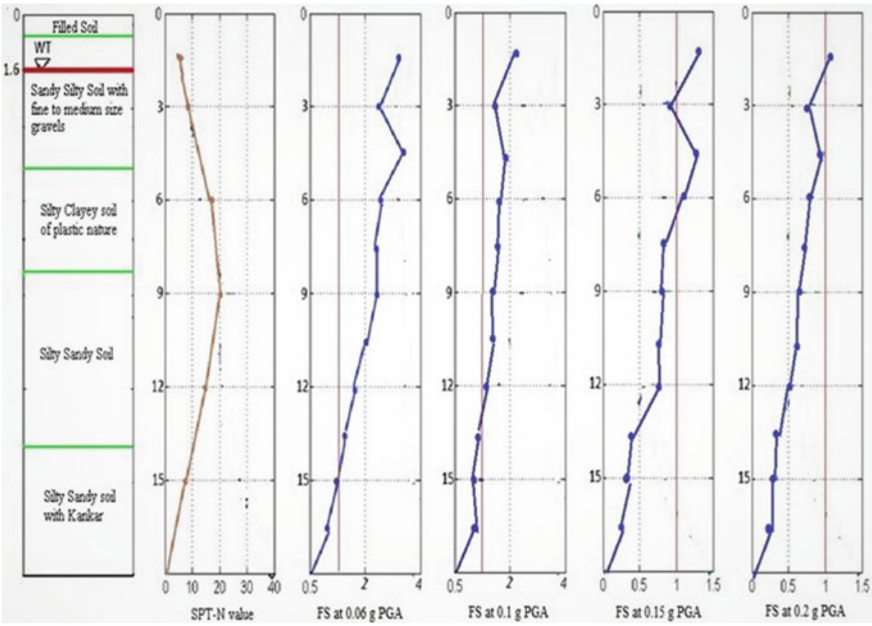

Fig. 3 Soil profile with SPT-N value along with FOS against liquefaction at different PGA levels (at George Town)

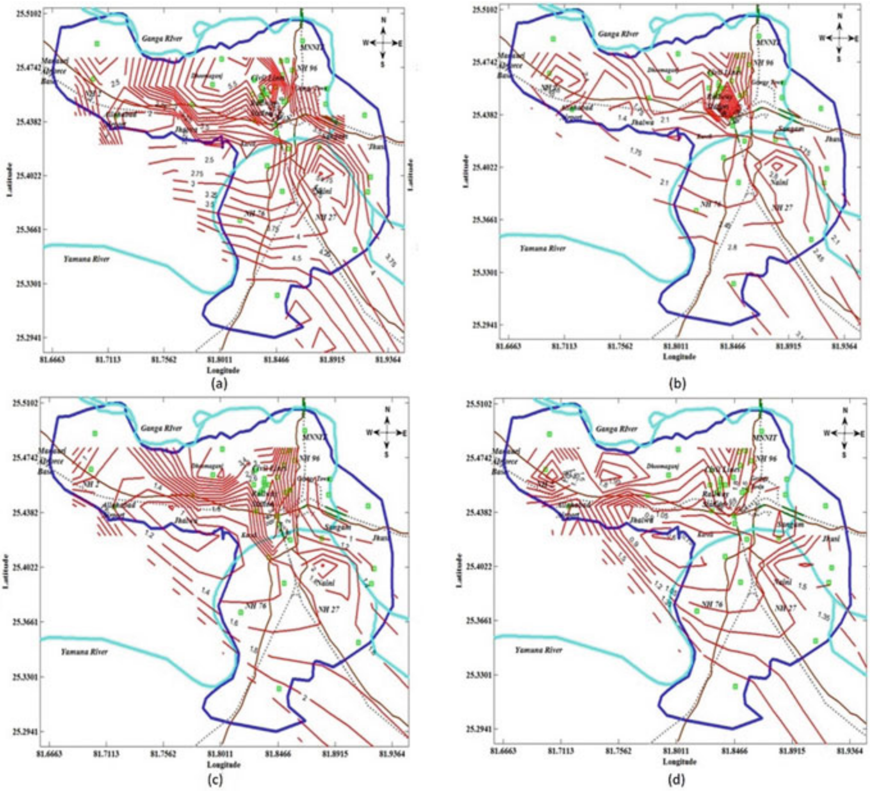

Fig. 4 Simulated FS against liquefaction at depth 1.5 m for PGA **a** 0.06 g, **b** 0.1 g, **c** 0.15 g and **d** 0.2 g

At 15 m depth, the situations are however observed to be more critical. Places such as Naini, Jhalwa, Kareli, Sangam area, Manauri, Chowk and area near Allahabad airport show liquefaction possibility at 0.15 g PGA, as evident from Fig. 6c. Figure 6d shows that most of the area of Allahabad including commercially important area of civil lines is also critical at 0.2 g PGA. Whereas other part of this region has low compressibility clay with gravels and sands at shallow depth and medium compressibility clay with gravel, sand, silt and kankar in lower layers, which make it quite safe against liquefaction at lower PGA values. Table 1 displays the FS-based liquefaction hazard for important areas in Allahabad.

It should also be noted that that FS does not state the extent of the liquefaction of a site, but it can be used as input parameter to assess liquefaction severity rely on 2 indices viz., LPI and LSI. Figure 7a–d shows the variation of LPI in Allahabad for different events. As evident from Fig. 7a, b, for PGA (0.06 and 0.1)g, LPI is less than 5 and therefore based on the LPI classification [39], liquefaction susceptibility of Allahabad city is "low" to "very low". It gets modified to "high" (i.e. LPI b/w 5

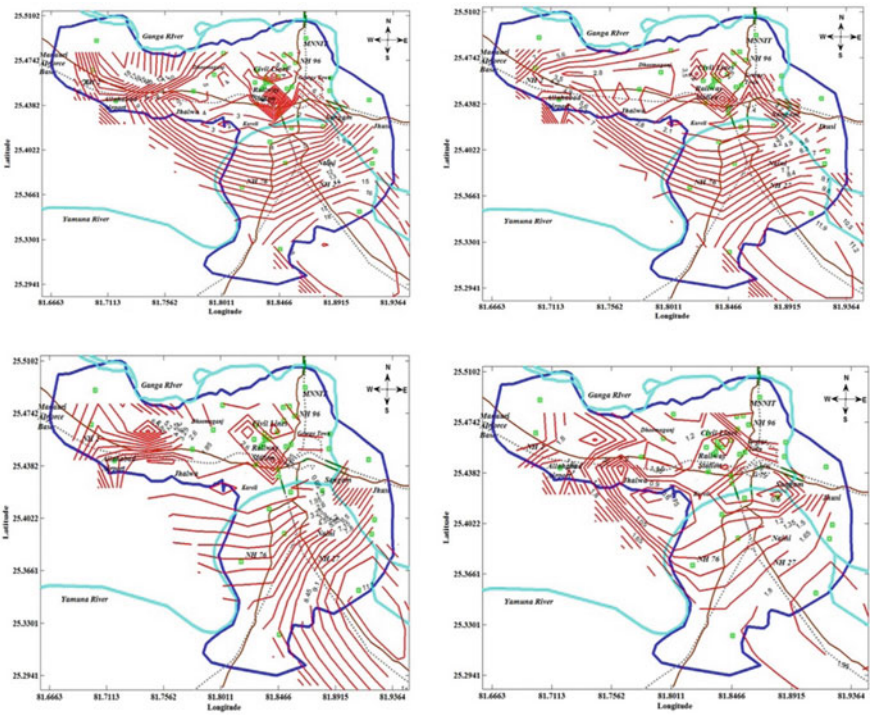

Fig. 5 Simulated FS against liquefaction at depth 4.5 m for PGA **a** 0.06 g, **b** 0.1 g, **c** 0.15 g and **d** 0.2 g

to 15) for PGA 0.15 and 0.2 g at Naini, Jhalwa, Kareli, Sangam area, near Railway station, Jhunsi, etc. (Fig. 7c, d and Table 2).

10 Conclusions

The geological structure of Allahabad city, proximity to active faults and seismically active regions of Himalayas make it susceptible to liquefaction. It has been established as per IBC [51] that mostly sites in Allahabad city belongs to E and D Type category, hence evaluation of their potential to liquefy under seismic loadings needs to be done. Liquefaction potential hazard studies have been done for a hypothetical earthquake along the Allahabad fault of magnitude Mw 6.7 and for different surface PGA levels (0.06, 0.1, 0.15 and 0.2 g), with the help of liquefaction potential index (LPI) [61], using factor of safety against liquefaction (FS) as input [10], for Allahabad city. The findings of liquefaction hazard for Allahabad city are provided in the form of a contour map. It has been observed based on FS studies that most of the areas in Allahabad city are liquefiable (FS < 1.0) for 0.2 g PGA. As per LPI studies,

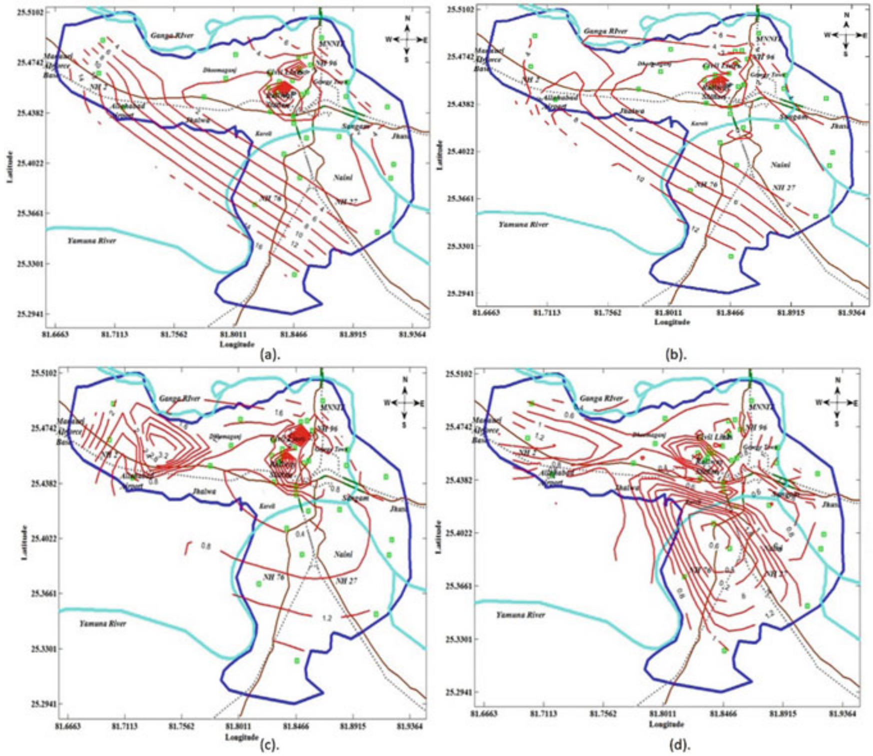

Fig. 6 FS against liquefaction at depth 15 m for PGA **a** 0.06 g, **b** 0.1 g, **c** 0.15 g and **d** 0.2 g

Table 1 Liquefiable places in Allahabad city based on FS

Depth (m)	PGA			
	0.06 g	0.1 g	0.15 g	0.2 g
1.5	None	None	None	George Town, Tagore Town, Colonel Gang, Allahabad University, Jhalwa, Kareli and Manauri
4.5	None	None	Sangam area, Arail ghat, Gaughat and Mahewa east	Jhalwa, Kareli, Allahabad high court, Sangam area, Chowk, Rambagh and Cheonki railway station
15	None	None	Naini, Jhalwa, Kareli, Sangam area, Manauri, Chowk and area near Allahabad airport	Area near Allahabad high court, Civil lines, Georgetown, Sulem Sarai, Sangam area, Chowk, Jhalwa, Kareli, Rambagh, Naini, Manauri, Allahabad university, etc.

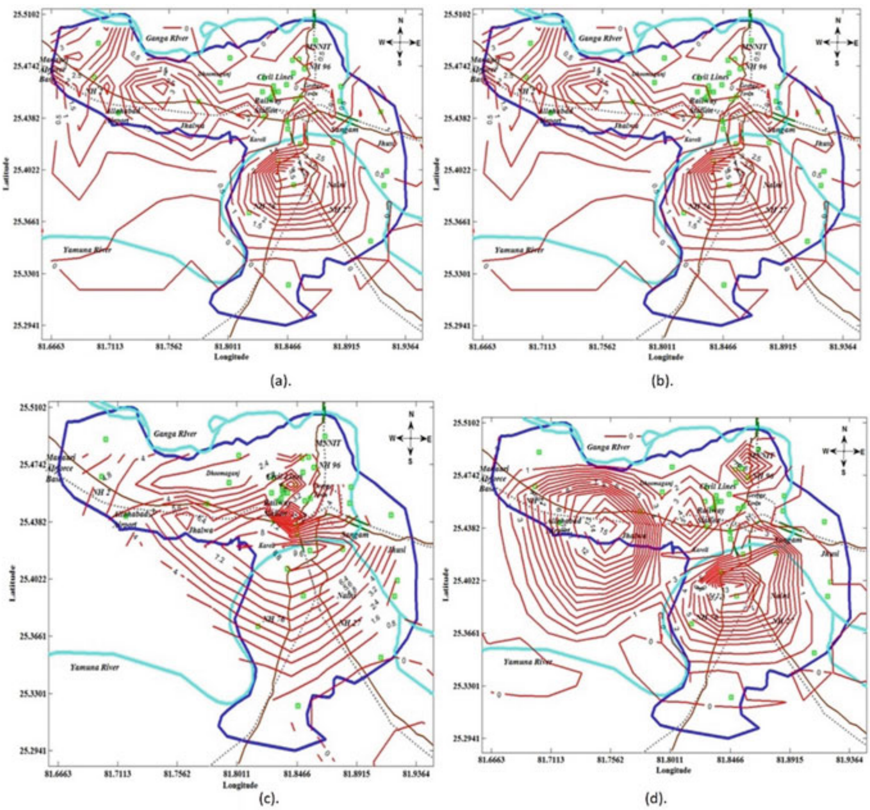

Fig. 7 LPI map for PGA **a** 0.06 g, **b** 0.1 g, **c** 0.15 g and **d** 0.02 g

liquefaction susceptibility of Allahabad city is "low" to "very low" at PGA 0.06 and 0.1 g. It get modified to "high" for PGA 0.15 and 0.2 g at Naini, Jhalwa, Kareli, Sangam area, near Railway station, Jhunsi, etc. This work offers an understanding of variation of liquefaction risk in the region. Contour maps may play a major role in the selection of a site and assist administration in planning and reducing potential risks from earthquakes.

Table 2 Results of LPI analysis for Allahabad

Places	PGA			
	0.06 g	0.1 g	0.15 g	0.2 g
Civil lines	Very low	Low	Low	Low
George town	Low	Low	Low	Low
Near railway station	Very low	Low	Low	**High**
Kareli	Low	Low	Low	**High**
Sangam area	Low	Low	Low	**High**
Naini	Low	Low	**High**	**High**
Jhalwa	Low	Low	**High**	**High**
Jhunsi	Low	Low	**High**	**High**
Manauri	Low	Low	Low	Low
Near Allahabad university	Very low	Low	Low	Low
Mahewa (East)	Low	Low	**High**	**High**
Near MNNIT	Very low	Low	Low	Low

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