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Generation of Liquefaction Potential Map for Kanpur City and Allahabad City of Northern India: An Attempt for Liquefaction Hazard Assessment

Sambit Prasanajit Naik · Nihar Ranjan Patra

Abstract Kanpur City and Allahabad City are the most populous city and the largest urban agglomeration among other north Indian cities. Both the cities are situated along Ganga and Yamuna River. The study areas are one of the growing urban centers in Northern India. Two large Himalayan earthquakes experienced by this area during 1803 A.D. and 1934, and large-scale liquefaction was reported in and around the area along with the recent 2015 Gorkha earthquake which caused severe shaking. As per the IS-1893–2002, the study area lies in seismic zone III and the soils from the above cities are prone to liquefaction. However, no such attempt has been made so far for the detailed liquefaction potential map for the study area. The present study is an approach towards evaluation and preparation of spatial distribution map of liquefaction potential for the Kanpur City and Allahabad City using several bore hole data collected from the study area. The PGA used for the liquefaction potential analysis was taken from the ground response analysis of Kanpur soil and Allahabad soil. The PGA values are 0.25 and 0.18 g for Kanpur soil and Allahabad soil respectively. The results are presented in the form of factor of safety contour map at a depth of 7, 15, 24 and 30 m below the ground surface. The map indicates that most of the sites in Kanpur City and Allahabad City area are susceptible to liquefaction and hence this aspect has to be considered in earthquake-resistant design of foundations/structures in Kanpur City and Allahabad City.

Keywords Liquefaction · CRR · CSR · PGA · Spatial distribution

1 Introduction

Liquefaction induced damage along the sedimentary basins of the world due to occurrence of large magnitude earthquakes around the globe viz. 1934 Bihar–Nepal border earthquake, 1957 Abant earthquake, Turkey, 1960 Chile earthquakes, 1964 Niigata Earthquakes, 1964 Alaska earthquakes, 1989 Loma Prieta earthquake, 1995 Kobe earthquake, 2001 Bhuj earthquake, 2004 Chūetsu earthquake, 2005 Kashmir earthquake, 2011 Christ Church earthquake, 2011 Tohoku earthquake raises the concern of both engineering geologists and geotechnical engineers towards proper evaluation of liquefaction susceptibility. Ground failure due to liquefaction causes severe engineering problems like large displacements of

S. P. Naik
Department of Civil Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India
e-mail: sambitprasanajit_naik@yahoo.in

N. R. Patra (✉)
Geotechnical Engineering Division, Department of Civil Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India
e-mail: nrpatra@iitk.ac.in

earth dams, damage to various life line structures, landslides in hilly regions etc. Keeping in mind the devastation caused by recent earthquakes like 2011 Christ Church earthquake, 2011 Tohoku earthquake, it is necessary to evaluate the liquefaction potential of a city or a region having seismic threat. Several cities of Indo-Gangetic Plain are having seismic threat from the Central Seismic Gap and comes under zone III and IV as per IS: 1893 (2002). Some parts of the Indo-Gangetic Plain have undergone liquefaction during great 1934 Bihar–Nepal earthquake (Naik 2015; Naik et al. 2014), whereas the cities like Kanpur, Allahabad, Lucknow, Agra undergo severe damage and liquefaction due to 1803 AD earthquake (Rajendran and Rajendran 2005; Jishnu et al. 2013; Naik 2015; Naik et al. 2014). Damage observed along cities of Indo-Gangetic Plain during that period was less which might be due to the infrastructural facilities and population density but now days the region like Indo-Gangetic Plain which covers one of major part of Indian population and undergone significant development. For the region like Kanpur, Allahabad Lucknow, few major cities along IGP and having seismic threat from the Himalayan Frontal Thrust (HFT) will undergo severe damage. The population of Kanpur City is 2.551 million whereas the population of Allahabad City is 1.17 billion and having several educational institute, multistoried buildings, and flyovers and many huge structures. Therefore, it is important to evaluate the liquefaction hazard of these cities, which will take a step ahead towards proper seismic hazard assessment of the city and will guide the architect and structural engineers to take up suitable measures to provide a safer and better society. Liquefaction potential evaluation was carried out using twenty six (26) number of borehole data from Kanpur City and seventeen (17) number of borehole data from Allahabad City. The liquefaction potential estimation and mapping have been carried with keeping in mind the criteria specified in IS-1893 (2002), ASTM E2557–16a and ASTM E2026–16a. Also the methodology adopted for the present study were followed as per the criteria specified by the recommended criteria for delineating liquefaction zones in California, USA (Bobrowsky 2002). Twelve (12) and ten (10) boreholes were carried out at Kanpur City and Allahabad City respectively during the present research work. Fourteen (14) borehole data for Kanpur City were collected from central public

works department (CPWD), Lucknow and Public work Department, Kanpur (PWD) whereas seven (7) bore hole data for Allahabad City were collected from CPWD Allahabad. Liquefaction zonation map are presented by preparing the contour map for 7, 15, 24, and 30 m depth to represent the liquefaction potential variation spatially for the city with depth.

2 Estimation of Liquefaction Potential

After 1964 Niigata and Alaska earthquake, the study on effects and causes of liquefaction was accelerated. The liquefaction potential of soil deposits depends upon the intensity of seismic loading and the resistance of the soil deposits. There are several approaches are available towards estimation of liquefaction potential of soil susceptible to liquefaction. The liquefaction potential approaches can be divided into two broader groups. The first method compares the seismic demand of the soil layer i.e., CSR and the resistance of liquefaction i.e., CRR and assumes that the earthquake scenario which will generate certain stress level within the soil layer (Seed and Idriss 1971; Idriss 1999; Seed 1979; Seed et al. 1975, 1983; Seed 1983). This is mainly analytical approach. The second group includes the field data and historical seismicity. It includes the SPT or CPT test collected from the sites and develops empirical correlations which are used for new sites.

2.1 Cyclic Shear Stress Ratio (CSR) Based Approach

Seed and Idriss (1971) and Seed et al. (1975) proposed the simplified approach for liquefaction potential estimation. In this method, it is assumed that the soil layer is a rigid body and the earthquake motion data is given in the basement of the soil layers. The earthquake taken into consideration by the present method is of Moment Magnitude. The shear stress due to the ground motion data was calculated for the entire soil column. However, in real the soil column is not rigid. To overcome this limitation a stress reduction factor (r_d) has been employed by the authors to the deformable body shear stress and measures the attenuation of peak shear stress with depth due to the non-elastic behavior of soil. The stress reduction parameter is 0.65 and it is used to get the 'equivalent

uniform cyclic shear stress'. The formula proposed by the authors to calculate the cyclic shear stress induced by an earthquake is given in Eq. 1.

$$\tau_{avg} = 0.65 \frac{a_{max}}{g} \sigma_v r_d \tag{1}$$

The uniform cyclic shear stress is normalized using the initial effective overburden stress to get the cyclic stress ratio (CSR) and can be estimated using Eq. 2

$$\text{CSR} = 0.65 \frac{a_{max} \gamma h}{g \sigma'_v} r_d \tag{2}$$

Since the earthquake magnitude values are different from Mw = 7.5, it is compulsory to modify the CSR values according to the magnitude of the earthquake used. So that the CSR values will give the exact CSR values for the earthquakes used for the present liquefaction potential analysis.

$$(\text{CSR})_{M=7.5} = \frac{\text{CSR}}{\text{MSF}} = 0.65 \left(\frac{\sigma_v a_{max}}{\sigma'_v g} \right) \frac{r_d}{\text{MSF}} \tag{3}$$

The CSR value for the earthquake of $M_w = 7.5$ is given in Eq. (3). Though the earthquake used for the present analysis is not of $M_w = 7.5$, the magnitude scaling factor (MSF) is used to get the equivalent cyclic stress ratio for an earthquake of $M_w = 7.5$ and given in Eq. (4).

$$\text{MSF} = \frac{\text{CSR}_M}{\text{CSR}_{M=7.5}} \tag{4}$$

The shear stress developed within a level ground due to earthquake shaking is due to the upward propagation of shear wave i.e., vertically to the surface and is dependent on earthquake characteristics, shear wave velocity of the soil, density, water table depth and the dynamic soil properties. Seed et al. (1983) suggests that the liquefaction potential of the soil depends upon the confining stress and also suggests that the liquefaction resistance increases with increase in confining stress. It follows the nonlinear trend. To overcome this, Seed et al. (1983) proposed the overburden stress correction factor K_σ for soil layers with overburden pressures >100 kPa from the laboratory tests on the sand specimen. CSR can be estimated using Eq. (5).

$$(\text{CSR})_{M=7.5, \sigma=1} = 0.65 \left(\frac{\sigma_v a_{max}}{\sigma'_v g} \right) \frac{r_d}{\text{MSF}} \frac{1}{K_\sigma} \tag{5}$$

The K_σ is being estimated using the formula given by Idriss and Boulanger (2006) and given in Eqs. (6) and (7).

$$K_\sigma = 1 - C_\sigma \ln \left(\frac{\sigma'_v}{p_a} \right) \le 1.0 \tag{6}$$

in which $C_\sigma = \dfrac{1}{18.9 - 17.3 D_R} \le 0.3 \tag{7}$

2.2 Cyclic Resistance Ratio (CRR) Based Approach

Towards a better understanding of the difference between liquefiable and nonliquefiable conditions, a semi-empirical approach has been adopted using SPT–N data collected (Seed and Idriss 1971; Seed et al. 1983; 1984; 1985). A boundary curve has been proposed to estimate the CRR values based on SPT–N data, which is one of the most widely, used approach towards estimation of liquefaction potential. The boundary curve has been modified by Idriss and Boulanger (2006) and proposed an equation (Eq. 8) for the determination of CRR based on SPT data, which can be used for the liquefaction potential evaluation of cohesionless soil.

$$\text{CRR} = \exp \left\{ \frac{(\text{N}_1)_{60cs}}{14.1} + \left(\frac{(\text{N}_1)_{60cs}}{126} \right)^2 - \left(\frac{(\text{N}_1)_{60cs}}{23.6} \right)^3 \right. \\ \left. + \left(\frac{(\text{N}_1)_{60cs}}{25.4} \right)^4 - 2.8 \right\} \tag{8}$$

where $(\text{N}_1)_{60cs}$ is the corrected SPT–N values. The SPT–N values were corrected using the NCEER report 1997 and 2001 (Youd et al. 2001). The measured N values were corrected for different corrections (Youd et al. 2001), such as Overburden correction (CN), Hammer energy (CE), Bore hole diameter (CB), Rod length (CR), presence or absence of Liner (Cs) and fine content. The corrected value $((\text{N}_1)_{60cs})$ is calculated using Eqs. (9) and (10).

$$(N_{160}) = N \times (CN \times CE \times CB \times CR \times CS) \qquad (9)$$

$$(N_1)_{60cs} = \alpha \times \beta \times (N_1)_{60} \qquad (10)$$

2.3 Factor of Safety Against Liquefaction

The liquefaction potential can be quantified based on factor of safety against liquefaction (FSL). The FSL values can be estimated from the Eq. (11).

$$F_{SL} = \frac{CRR}{(CSR)_{M=7.5, \sigma=1}} \qquad (11)$$

If the FSL value is <1 the soil is prone to liquefaction and if the FSL is >1 the soil is safe against liquefaction.

3 Liquefaction Potential of Kanpur City and Allahabad City

For the present study total twenty six (26) borehole data from Kanpur City and seventeen (17) borehole data from Allahabad City were considered for the liquefaction potential evaluation. The boreholes are scattered over the Kanpur City and Allahabad City. The map showing the borehole locations from Kanpur City and Allahabad City are shown in Fig. 1. The SPT–N values were collected as per the IS-2131 standard at 1.5 m interval up to a depth of 30 m. To show the SPT–N methodology adopted correctly, the SPT–N values were plotted with lithology according to depth. Figure 2 showing the variation of SPT–N values with depth for some of the sites from Kanpur. The SPT–N values were used to classify the soil according to International Building Code 2000. According to IBC 2000, D and E types, soils are prone to liquefaction, which covers most of the parts of the Kanpur and Allahabad City (Table 1). Since most of the area of Kanpur City and Allahabad City are prone to liquefaction proper liquefaction potential evaluation is required. Kanpur and Allahabad cities are part of the Indo-Gangetic Plain and having a seismic threat from the Himalayan region, therefore, Himalayan earthquake ground motion data were taken for the liquefaction potential estimation. Three Himalayan earthquakes such as Chamba (M_w 5.1), Chamoli (M_w 6.1) and Uttarkashi (M_w 6.5) were taken for the liquefaction analysis with the recorded SPT–N

values at each depth using SHAKE 2000 software. The selection of Himalayan earthquake was on the basis of historical records that Indo-Gangetic plain underwent liquefaction during 1803 AD, 1934 Bihar–Nepal border earthquake and 2015 Gorkha and Kodari earthquakes (Thakur 2004; Malik et al. 2010; Kumahara and Jaygondaperumal 2013; Malik et al. 2016). The farthest occurred liquefaction during 2005 Kashmir earthquake was more than 250 km far from the epicenter (Malik et al. 2007). The liquefaction due to 1803 A.D. earthquake in Mathura was about 320 km away from the source, in the Indo-Gangetic plains (Ambraseys and Douglas 2004). This justifies the consideration of Himalayan earthquake ground motion data for liquefaction potential estimation of Kanpur City and Allahabad City. Kanpur City is situated about 250 km away from the Himalayan Frontal Thrust (HFT). Allahabad City is nearly 200 km away from the Himalayan Frontal Thrust (HFT). The parameters used for liquefaction potential analysis are density, soil type, SPT–N values and V_{s30} for the base layer, PGA, and the input ground motion parameters. The PGA values were taken from the ground response analysis of Kanpur soil and Allahabad soil (Naik et al. 2012; Jishnu et al. 2013; Naik 2015). For the collection of the soil sample from greater depth wash boring technique and thin walled sampling techniques were adopted. The wash boring technique was adopted for making the bore hole to reach the desired depth and the thin walled sampling techniques were adopted for the collection of undisturbed soil samples. The density and soil type were derived in the laboratory from the undisturbed soil samples collected from the borehole whereas the shear wave velocity was measured using the seismic downhole test in the field at 1.5 m interval up to 30 m. For the borehole which is not having recorded shear wave velocity, the empirical correlations developed by Naik et al. (2014) for the alluvial soil of Indo-Gangetic Plain have been used to estimate the shear wave velocity of soil. The correlations between corrected SPT–N values and shear wave velocity values developed by Naik et al. (2014) are given in Eqs. (12), (13) and (14).

$$V_s = 73.53 N_{60}^{0.400} \quad \text{for all soil} \qquad (12)$$

$$V_s = 77.49 N_{60}^{0.39} \quad \text{for silty soil} \qquad (13)$$

$$V_s = 85.49 N_{60}^{0.412} \quad \text{for clay soil} \qquad (14)$$

Fig. 1 Locations of borehole taken for liquefaction potential analysis: **a** Kanpur City; **b** Allahabad City
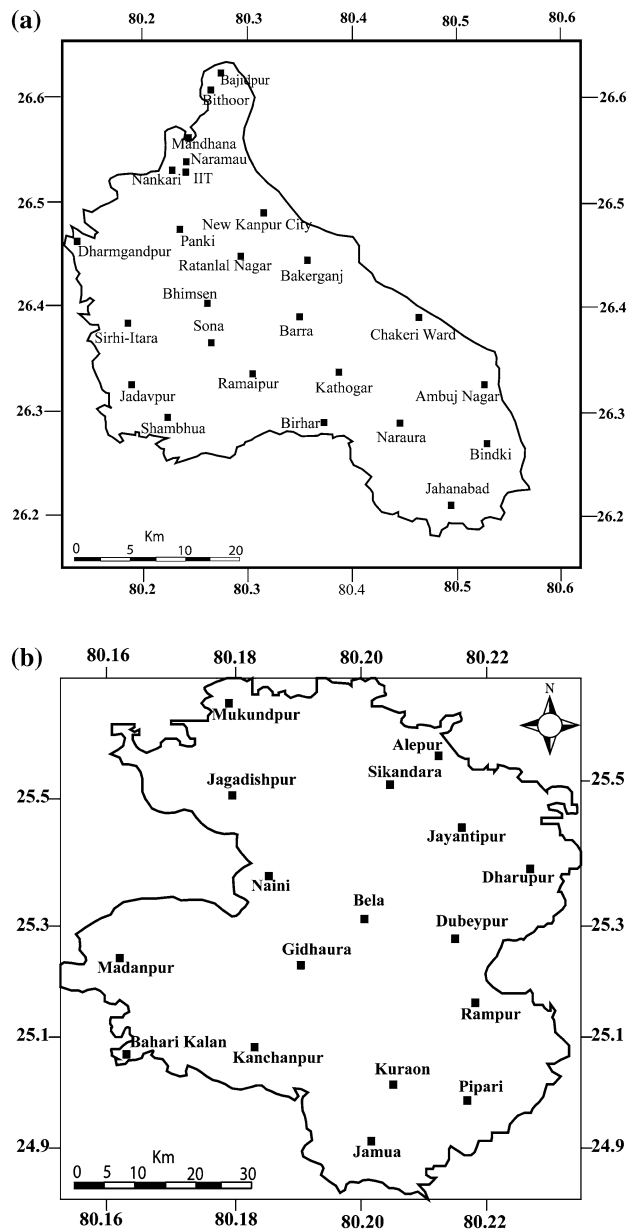
The factors of safety against liquefaction for all the locations were determined using Seed et al. (1975; 1983). The FSL values were evaluated using all three earthquakes for all the boreholes. After getting the FSL for all the three earthquakes an average value of FSL were estimated and used for the preparation of contour map using ArcGIS 9.2 software to show the distribution of FSL for Kanpur City and Allahabad City. The liquefaction map of Kanpur City and Allahabad City are having scale of 1:50,000. The FSL values for different locations from Kanpur City and Allahabad City along with latitude and longitude from GPS were plotted in ArcGIS 9.2. The SP line method has been used for the preparation of factor of safety against liquefaction map of the area. Also, the depth-wise variation of the FSL values were plotted spatially with depth i.e., at 7, 15, 24, and 30 m. Typical table showing FSL values for Allahabad City is shown in Table 2.

Figure 3 shows the FSL distribution for Kanpur City and Allahabad City at 7 m depth respectively.
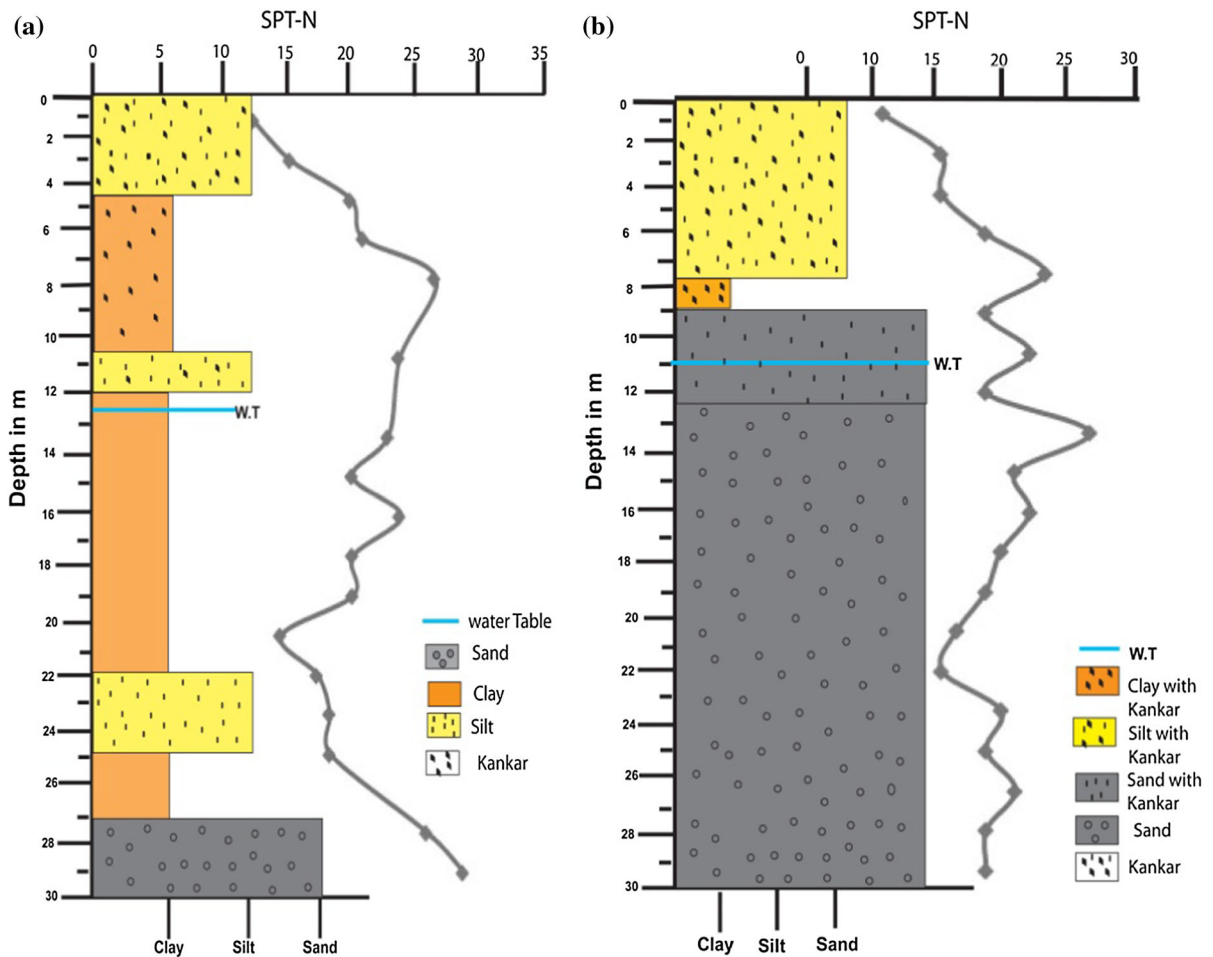
Fig. 2 Bore logs showing variation of lithology and SPT–N values with depth: a Nankari site; b Bithoor site (Jishnu et al. 2013)

Table 1 Site classification for seismic purposes (IBC 2000)

Range of N	Site class
N < 15	E
15 < N < 50	D
N > 50	C

From the figure, it is observed that the soil from most of the sites in Kanpur City the FSL values are higher than 1 except some of the sites in north parts of Kanpur i.e., Bithoor, Bajidpur sites. Whereas for Allahabad City the soils from all locations are susceptible to liquefaction with FSL values <1. This may be due to the presence of stiff clay of silty soil at shallow depth for all parts of Kanpur City. Whereas, the soils from Bithoor and Bajidpur sites are situated near Ganga

River having sandy deposits. The water table is located at shallow surface for Bithoor and Bajidpur sites. The FSL for soils from Bithoor and Bajidpur sites are <1 and hence will liquefy. However, the soils from Allahabad City are having a high percentage of sand.

Similarly, the FSL distribution map for Kanpur City and Allahabad City at 15 m depth is shown in Fig. 4. From the figure, it is clear that at 15 m depth almost all sites of Kanpur City and Allahabad City are having FSL values <1 except some of the sites in western part of Kanpur City and southern part of Allahabad City near Jagadishpur. This may be due to the presence of saturated silty sand and sandy soil in loose conditions. The sites showing FSL values near or =1 are having a high percentage of fines with Kankar.

Figures 5 and 6 show the FSL contour distribution at a depth of 24 m and 30 m for Kanpur City and

Table 2 Factor of safety against liquefaction for some of the sites of Kanpur and Allahabad City (Naik 2015)

FSL values for all sites for Chamba (M_w-5.1), Chamoli (M_w-6.4), Uttarkashi (M_w-6.5) earthquakes

Depth (m)	Panki (Kanpur City)			Naini (Allahabad City)			Kuraon (Allahabad City)		
	Chamba	Chamoli	Uttarkashi	Chamba	Chamoli	Uttarkashi	Chamba	Chamoli	Uttarkashi
1.50	–	–	–	–	–	–	–	–	–
3	–	–	–	–	–	–	–	–	–
4.5	–	–	–	–	–	–	–	–	–
6	–	–	–	–	–	–	–	–	–
7.5	1.9	1.93	1.96	0.67	0.81	0.90	0.81	0.86	0.92
9	1.87	1.89	1.92	0.64	0.85	0.93	0.84	0.88	0.93
10.5	1.82	1.85	1.78	0.69	0.87	0.95	0.98	0.92	0.90
12	1.78	1.76	1.6	0.74	0.89	0.98	0.89	0.87	0.98
13.5	1.70	1.73	1.53	0.78	0.85	0.89	0.82	0.88	0.94
15	0.82	0.79	0.74	0.88	1.00	0.87	0.93	0.92	0.91
16.5	0.81	0.74	0.69	0.96	0.98	0.82	0.91	0.89	0.86
18	0.72	0.69	0.64	0.78	0.96	0.79	0.94	0.99	0.88
19.5	0.70	0.67	0.61	0.74	1.02	0.71	0.92	0.96	0.89
21	0.72	0.69	0.67	0.84	1.01	0.96	1.00	1.02	0.94
22.5	0.69	0.64	0.60	0.78	1.00	0.98	1.09	1.02	0.96
24	0.62	0.60	0.58	0.89	1.05	1.00	1.06	0.98	0.96
25.5	0.63	0.57	0.54	0.83	1.06	1.00	0.99	0.94	0.90
27	0.67	0.69	0.72	0.93	1.09	0.99	0.97	0.95	0.92
28.5	0.64	0.67	0.70	0.95	0.98	0.93	0.94	0.92	0.89
30	0.72	0.75	0.81	1.01	0.95	1.01	0.96	0.99	1.02

Allahabad City respectively. From the figure, it is observed that at a greater depth almost all sites are producing FSL values <1 which indicates the soil from Kanpur City and Allahabad are prone to liquefaction at greater depth. This may be due to the presence of loose silty sand and sandy soil of fluvial origin. The soils from Kanpur City are having more silt fraction (more than 80%) at some locations and more sand fraction (more than 90%) at greater depth i.e., 10 m below ground surface. Whereas, the soils from Allahabad City are having more than 80% sand fraction. Almost all sites of Kanpur City are prone to liquefaction at a greater depth for a PGA of 0.25 g. Similarly, all sites of Allahabad City are prone to liquefaction at a greater depth for a PGA of 0.18 g. Hence, proper care should be taken for construction of the heavy structure, in selecting the foundation type or suitable soil improvement techniques can be adopted before construction of major structures in Kanpur City and Allahabad City.

4 Historical Liquefaction Data in Supports of Present Findings

For Kanpur City and Allahabad City, no liquefaction history is available during last century. During 1833 A.D. and 1934 Bihar–Nepal earthquakes there are evidence of liquefaction along Indo-Gangetic Plains. During 1934 earthquake, strong shaking caused extensive liquefaction from Motihari, Sitamarhi to Madhubani in Bihar (128 km long and 30 km wide area) resulting in most of the buildings totally collapsed in these regions (Rajendran et al. 2016). Rajendran et al. (2016) reported the paleo liquefaction features from north Bihar and one in eastern Uttar Pradesh. The paleo liquefaction features extended from the surface to 10 m deep or more. Joshi et al. (2009) reported the paleo liquefaction features along Yamuna Tear Fault in Indo-Gangetic Plains which also lies in the Central Seismic Gap area. The paleo liquefaction feature was about 13 m deep. So it can be elucidated that the alluvial soil from

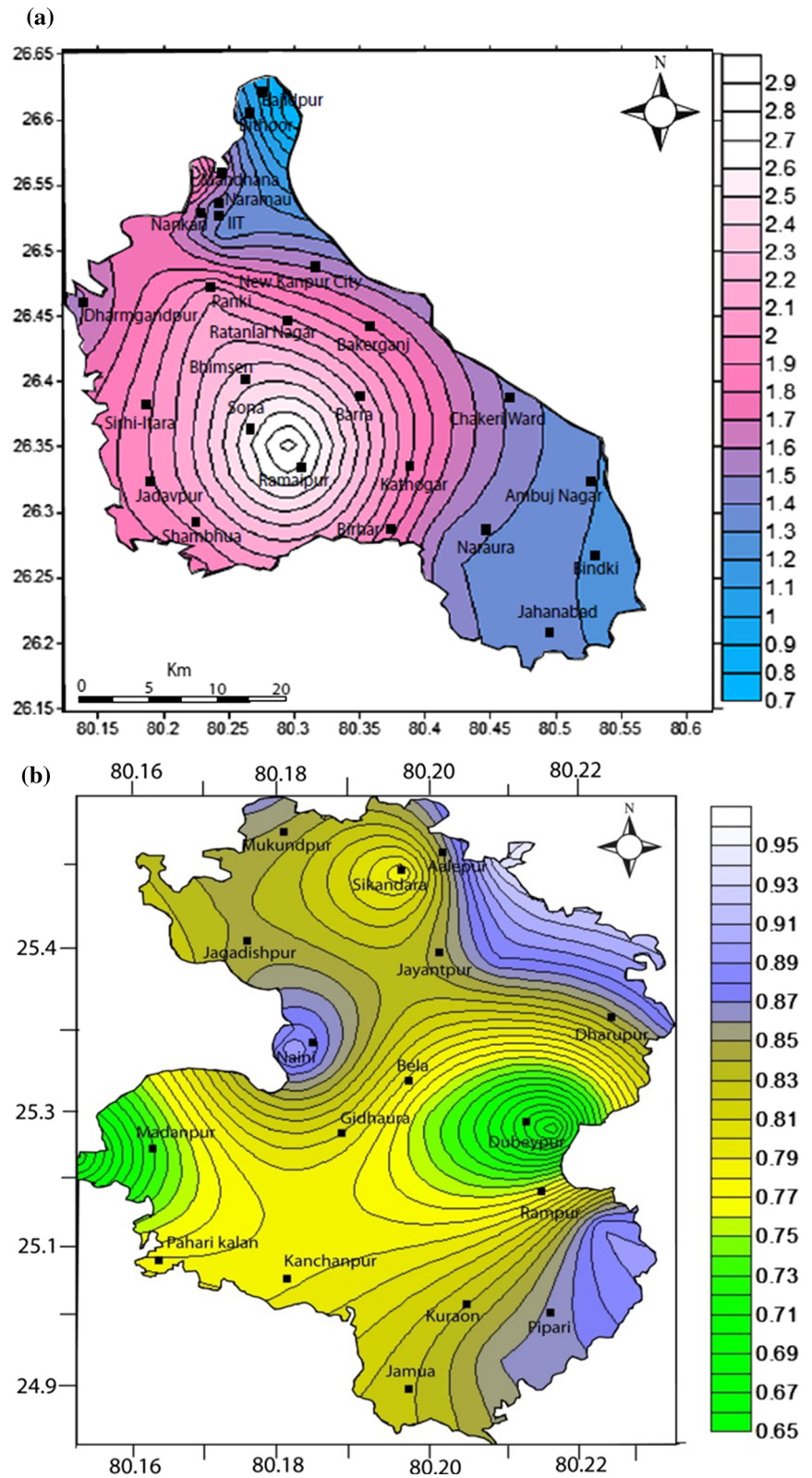**Fig. 3** FSL distribution contour map at 7 m depth: **a** Kanpur City; **b** Allahabad City

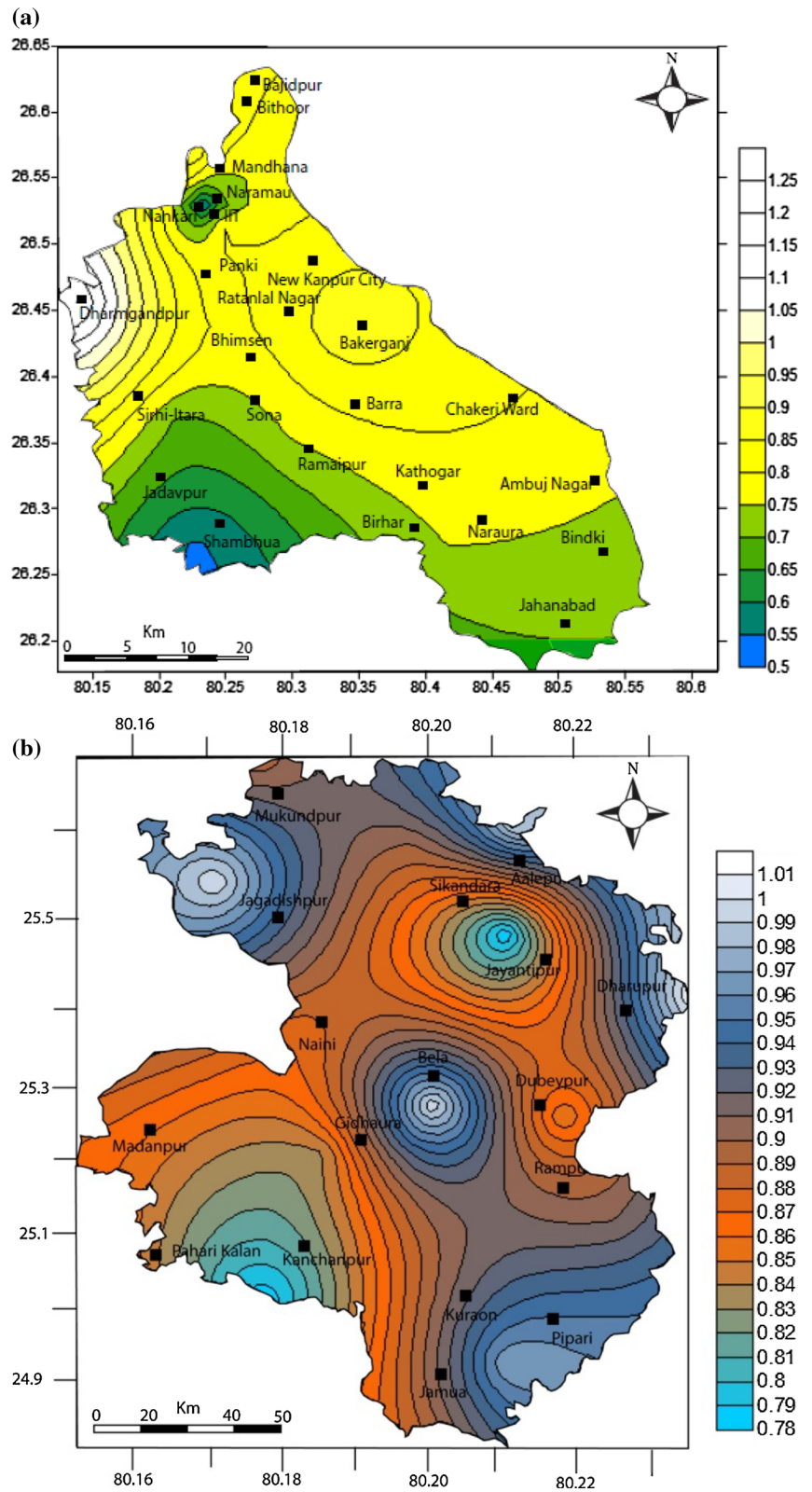**Fig. 4** FSL distribution contour map at 15 m depth: **a** Kanpur City; **b** Allahabad City

Fig. 5 FSL distribution contour map at 24 m depth: **a** Kanpur City; **b** Allahabad City
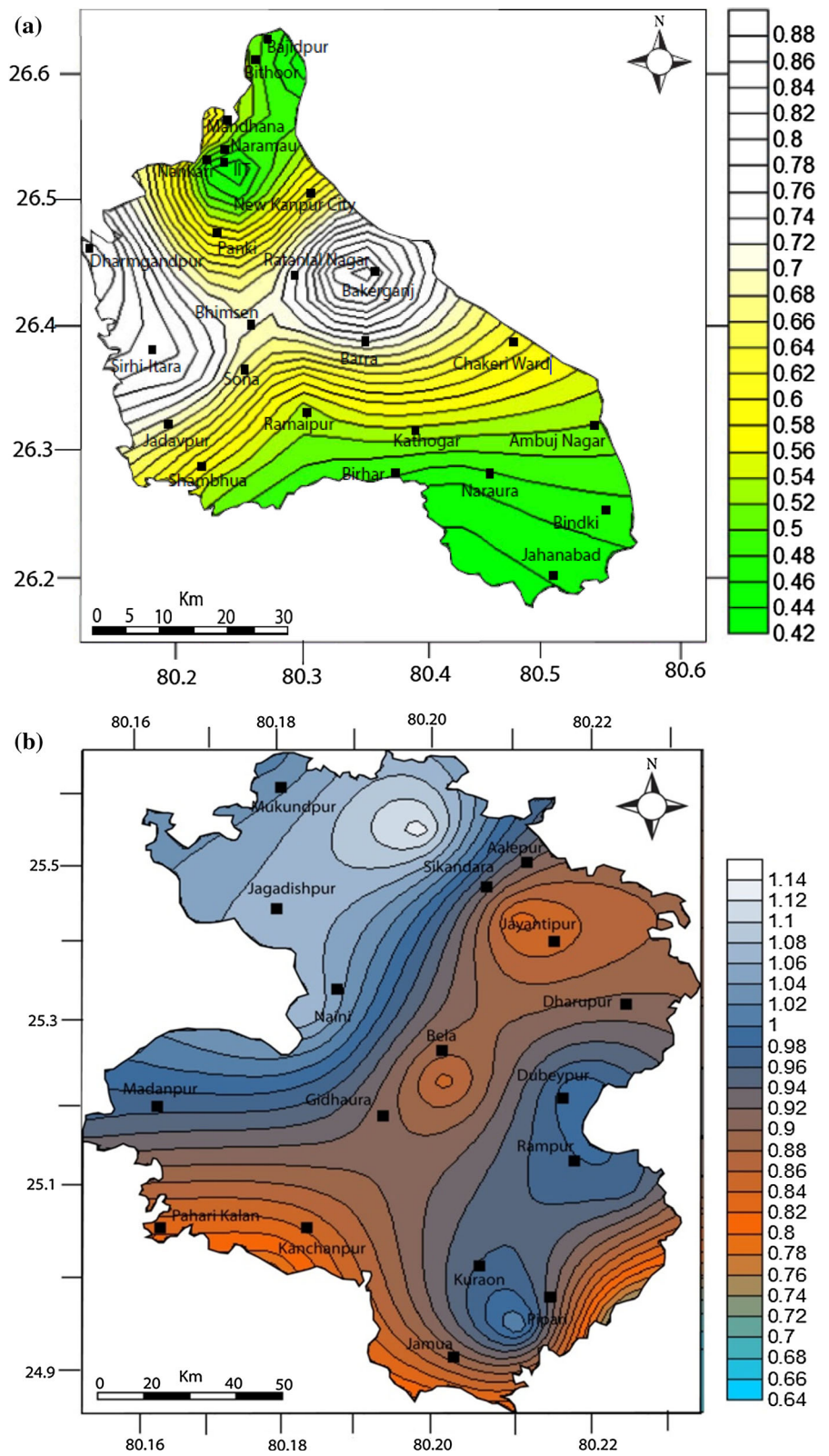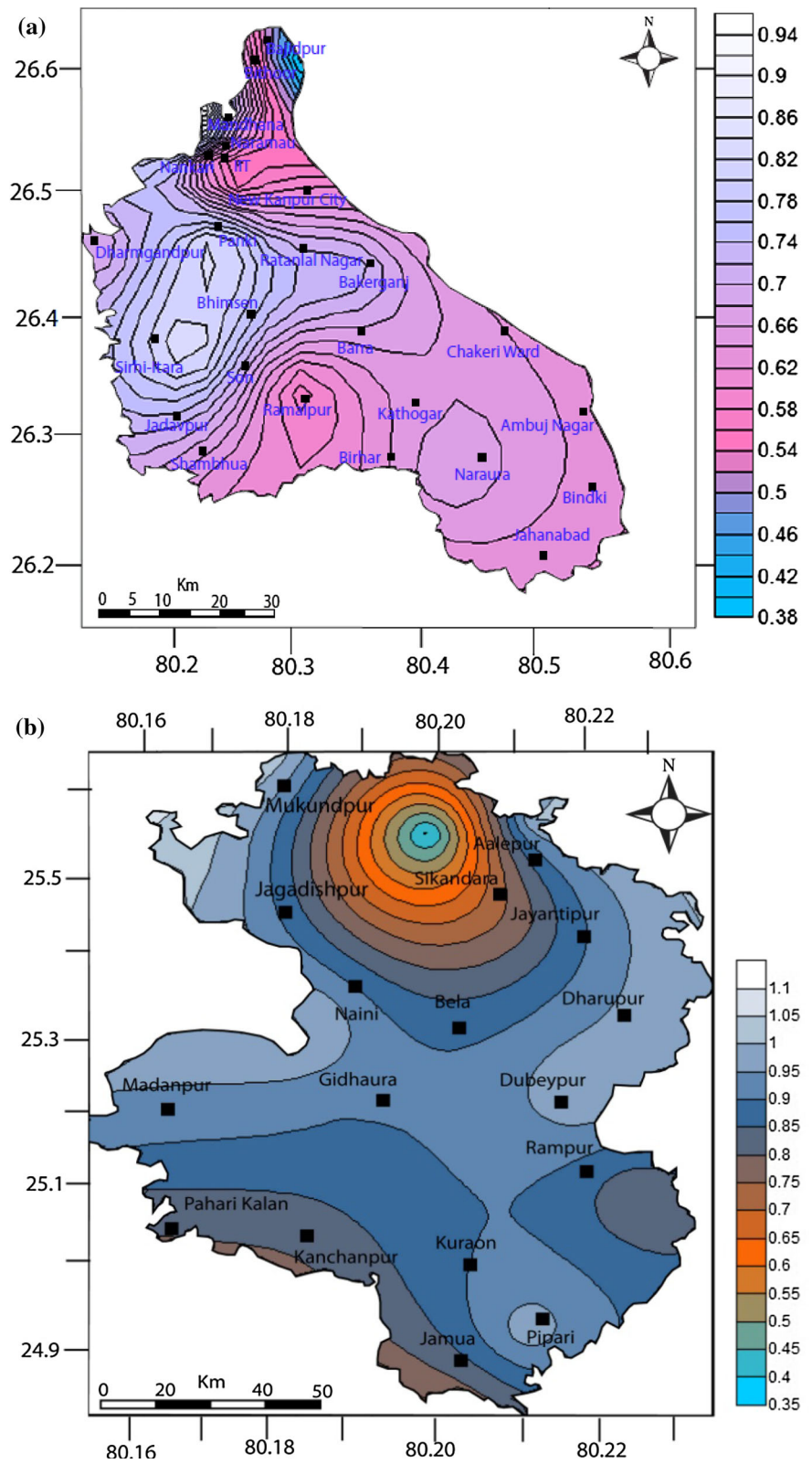
Fig. 6 FSL distribution contour map at 30 m depth: **a** Kanpur City; **b** Allahabad City

Indo-Gangetic plain is vulnerable to liquefaction at greater depth. The 1803 earthquake caused liquefaction about 320 km away from the source, at Mathura along Indo-Gangetic plains (Ambraseys and Douglas 2004). From the above evidence of paleo liquefaction along Indo-Gangetic Plain from Bihar to New Delhi, it can be observed that the Indo-Gangetic Plain is prone to liquefaction due to large magnitude Himalayan earthquakes. The soil type undergoes liquefaction during 1803–1833 A.D. and 1934 Bihar–Nepal earthquake is similar to the soil of the present study area. The present study area is about 200–300 km from the epicentral area of 1803 A.D. earthquake which caused liquefaction in Mathura. So if similar or large magnitude earthquakes occur in Central Seismic Gap, the present study area may undergo severe liquefaction. The present study indicates that the soil from Kanpur City and Allahabad City are prone to liquefaction at shallow to a greater depth which is in agreement with the paleo liquefaction features found from Indo-Gangetic Plains.

5 Conclusions

From the present study following conclusions can be drawn.

1. Considering the Himalayan ground motion data, it is observed that the soils from Kanpur City and Allahabad City are producing FSL values <1 at almost for every location. It is observed that the soils at greater depth are also susceptible to liquefaction. In general, the soils from Kanpur City and Allahabad City are prone to liquefaction for moderate to large magnitude earthquakes.

2. The developed liquefaction potential distribution map can readily be used to evaluate the liquefaction potential for major structural design, seismic hazard estimation in Kanpur City and Allahabad City.

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