Liquefaction resistance evaluation of soils using artificial neural network for Dhaka City, Bangladesh

Abul Kashem Faruki Fahim1 · Md. Zillur Rahman1 · Md. Shakhawat Hossain1 · A. S. M. Maksud Kamal1

Received: 26 April 2021 / Accepted: 21 March 2022 / Published online: 13 April 2022
© The Author(s), under exclusive licence to Springer Nature B.V. 2022

Abstract
Soil liquefaction resistance evaluation is an important site investigation for seismically active areas. To minimize the loss of life and property, liquefaction hazard analysis is a prerequisite for seismic risk management. Liquefaction potential index (LPI) is widely used to determine the severity of liquefaction quantitatively and spatially. LPI is estimated from the factor of safety of liquefaction that is the ratio of cyclic resistance ratio (CRR) to cyclic stress ratio calculated applying simplified procedure. Artificial neural network (ANN) algorithm has been used in the present study to predict CRR directly from the normalized standard penetration test blow count (SPT-N) and near-surface shear wave velocity ($V_s$) data of Dhaka City. It is observed that ANN models have generated accurate CRR data. Three liquefaction hazard zones are identified in Dhaka City on the basis of the cumulative frequency (CF) distribution of the LPI of each geological unit. The liquefaction hazard maps have been prepared for the city using the liquefaction potential index (LPI) and its cumulative frequency (CF) distribution of each liquefaction hazard zone. The CF distribution of the SPT-N based LPI indicates that 15%, 53%, and 69% of areas, whereas the CF distribution of the $V_s$ based LPI indicates that 11%, 48%, and 62% of areas of Zone 1, 2, and 3, respectively, show surface manifestation of liquefaction for an earthquake of moment magnitude, $M_w$ 7.5 with a peak horizontal ground acceleration of 0.15 g.

Keywords Earthquake · Liquefaction · Liquefaction potential index (LPI) · Simplified procedure · Artificial neural network (ANN)

1 Introduction
Liquefaction occurs when granular, loosely compacted or cohesionless, saturated or partially saturated sediments lose their shear strength and transform from solid to liquid state at or near the ground surface resulting from cyclic loading or other abrupt alteration of stress conditions (Castro 1969; Castro and Poulos 1977; Castro et al. 1982). The loss of

*A. S. M. Maksud Kamal
maksudkamal@du.ac.bd

1 Department of Disaster Science and Climate Resilience, University of Dhaka, Dhaka 1000, Bangladesh
strength takes place in cohesionless soil due to reduction in effective stress resulting from increased pore water pressure caused by rapid, usually cyclic loading exerted by strong ground shaking (Marcuson 1978).

During an earthquake, liquefaction can be devastating incurring widespread damage, which was revealed by Niigata Earthquake in 1964, Alaska Earthquake in 1964, Loma Prieta Earthquake in 1989, Chi-Chi Earthquake in 1999, and Sulawesi Earthquake in 2018 (Seed and Idriss 1967; Ku et al. 2004; Lee et al. 2007; Chao et al. 2010; Sassa and Takanawa 2019; Hossain et al. 2020). Therefore, in a seismic hazard-prone area, liquefaction resistance evaluation is an integral part of site characterization.

Both in situ tests (e.g., SPT, $V_s$, Cone Penetration Test (CPT) data) and soil laboratory tests (e.g., cyclic triaxial test) can be used to evaluate soil liquefaction resistance during seismic loading. Good-quality undisturbed soil samples are essential to assess the soil liquefaction resistance by the laboratory tests. However, collecting such samples from degraded loosely compacted silty or sandy soils are sometimes difficult and expensive. Due to these drawbacks of the laboratory tests, geotechnical engineers widely use in situ tests as it is simple and economical (Seed and Idriss 1971, 1982; Seed et al. 1983, 1984, 1985; Seed and de Alba 1986). Over the last five decades, the Simplified Procedure, developed initially by Seed and Idriss (1971), has been used in liquefaction resistance evaluation of soils. Since its inception in 1971, many researchers have updated, modified, revised, and validated this method (e.g., Juang et al. 2003, 2000; Olsen 1997, 1988; Olsen and Koester 1995; Robertson and Wride 1998; Stark and Olson 1995). To assess liquefaction resistance by this procedure, the corrected SPT-N is widely used as input (Seed and Idriss 1971, 1982; Seed et al. 1983, 1984, 1985; Kayen et al. 1992; Juang et al. 2000; Youd et al. 2001; Idriss and Boulanger 2004).

Using field $V_s$ measurement, a method of liquefaction resistance estimation was introduced by Andrus et al. (2000) and Andrus and Stokoe (1997). The use of the $V_s$ data has more advantages than the SPT-N and CPT data as the $V_s$ data can easily be collected from stiff and gravelly soils. The soil profile can be easily obtained and the analytical procedures that analyze the small-scale shear modulus for evaluating soil-structure interaction and dynamic soil response are related to $V_s$ value of the soil materials.

In Bangladesh, most of the subsurface lithology is characterized by unconsolidated, sandy and clayey floodplain sediments. In alluvial deposits of Bangladesh, following the Srimangal Earthquake in 1918, Great Indian Earthquake in 1897, and the Bengal Earthquake in 1885, the evidences of widespread liquefaction were documented (Middlemiss 1885; Oldham 1899; Stuart 1920; Hossain et al. 2020). In the north and northeast areas of the country, the evidences of liquefaction were observed during paleoseismic studies, which are considered to be triggered by a series of earthquakes along the Dauki fault (Morino et al. 2011, 2014a, b). In addition, the country is sitting close to the tectonically active Himalayan orogenic belt and Arakan megathrust where there are at least five major active fault zones, which have shown evidence of large magnitude earthquakes (Aitchison et al. 2007). Steckler et al. (2016) claimed a locked megathrust exists along the Indo-Burman mountain ranges, which reinforces the notion of the resistance future for major earthquakes. Therefore, it is an absolute necessity for the country to further study the liquefaction resistance evaluation of soils for the major cities.

Rahman et al. (2015) and Rahman and Siddiqua (2017a, b) have conducted liquefaction potential studies based on simplified procedure for Dhaka, Chittagong, and Sylhet cities in Bangladesh using limited standard penetration test blow count (SPT-N), cone penetration test (CPT), and shear wave velocity ($V_s$) data. The studies observed that the Holocene alluvium of these cities is susceptible to liquefaction. In those studies, the empirical equations

\[ \text{Liquefaction Potential Index} = \frac{SPT_N}{\text{Corrected SPT-N}} \times \frac{V_s}{\text{Corrected } V_s} \]
of Youd et al. (2001) were used to calculate the factor of safety (FS) of liquefaction, cyclic resistance ratio (CRR), cyclic stress ratio (CSR), and magnitude scaling factor (MSF). The equations of Iwasaki et al. (1982) were used to calculate liquefaction potential index (LPI).

However, in the present study, the ANN models were incorporated based on Juang et al. (2002, 2000) to predict the CRR where a variant of performance function (Seed and Idriss 1971, 1982) termed as limit state function (LSF), was considered. This mechanical process of defining LSF has remarkably reduced drawbacks of simplified method, used by Rahman et al. (2015) and Rahman and Siddiqua (2017a, b). Those drawbacks primarily are reliance on engineering judgement in drawing limit state curve and giving limited consideration to all possible interaction among different type of soil and load parameters. Additionally, the ANN models are useful particularly for studying multivariate nonlinear relationships. The scope of this study does not allow for a comprehensive discussion of the ANN methodology. The fundamental architecture of ANN has been extensively discussed in Rumelhart et al. (1986, 1988), Lippmann (1987), Eberhart et al. (1990), Flood and Kartam (1994), Krogh (2008), etc. The ability to detect complex nonlinear relationships between independent and dependent variables without requiring much formal statistical training, the availability of multiple training algorithms, and the ability of detecting all possible interactions between predictor variables are some of the advantages of ANN models (Hammerstrom 1993a; Flood and Kartam 1994; Tu 1996; Krogh 2008). The effectiveness of ANN methods in classifying field performance cases have been found in many studies (Goh 1994, 1995, 1996; Agrawal et al. 1997; Ali and Najjar 1998; Juang and Chen 1999; Juang et al. 2000, 2001, 2003). Thus, this study utilizes an improved, robust, and promising method in assessing liquefaction resistance of soils for Dhaka City.

The SPT-N and $V_s$ data from Dhaka City have been used in the assessment of liquefaction resistance of soils for an earthquake of moment magnitude, $M_w$ 7.5 with a peak ground acceleration (PGA) of 0.15 g. According to the proposed Bangladesh Nation Building Code (BNBC), the PGA value for Dhaka City is 0.2 g for the maximum considered earthquake (MCE), which is equivalent to 2% probability of exceedance in 50 years (2475-year return period). The PGA of the design basis earthquake (DBE) is equal to the 2/3 (two-third) of the MCE. Therefore, the PGA of DBE in Dhaka City is 0.13 g. It is observed from historical record of earthquakes that more than $M_w$ 7.0 earthquakes occurred beyond 50 km radius from city center of Dhaka (Middlemiss 1885; Oldham 1899; Stuart 1920). Therefore, the magnitude of earthquake is considered as $M_w$ 7.5 with PGA of 0.15 g in this study.

Firstly, a liquefaction indicator function was formulated for predicting the occurrence of liquefaction, then points at the limit state surface (Juang et al. 2000, 2002) were generated to determine the CRR through simulation of borehole data of the city in neural network models that were trained using the derived points at the limit state surface. The CSR was estimated on the basis of simplified procedure (Seed and Idriss 1971). The factor of safety (FS) of liquefaction was calculated at selected locations of Dhaka City using estimated CSR and CRR values. Even though the FS may provide an idea of the resistance of soils, it is not enough to represent the state of the liquefaction severity of any location (Sonmez and Gokceoglu 2005). Therefore, the FS values up to the depth of liquefiable layers, which is considered as 20 m depth, were used to determine the LPI of all selected locations of Dhaka City for both datasets (SPT-N and $V_s$) based on the developed method of Iwasaki et al. (1982) to prepare liquefaction hazard maps for calculating LPI values of the areas where SPT-N and $V_s$ data were not available. For each geological unit, the liquefaction hazard is also predicted from the cumulative frequency (CF) distribution of the LPI according to Holzer et al. (2006).
2 Surface geology of Dhaka City

Dhaka City, the capital of Bangladesh, located is on the bank of the Buriganga River, is now one of the world’s megacities. The city is encircled by the rivers of Buriganga, Balu, Turag, and Tongi Khal. It occupies an area of about 321 square kilometers with a population of about 14 million. Dhaka City has an average elevation of 6.5 m ranging between 2 and 14 m (above the mean sea level) with many depressions (Rahman et al. 2015). Dhaka is situated in the central part of Bangladesh bounded by the Shillong Massif in the north, Precambrian Indian Shield in the west, the Indo-Burman Folded Belt in the east and it is open to the Bay of Bengal in south. Bangladesh covers most part of the Bengal Basin with the maximum sedimentary thickness of 22 km (Alam 1989; Reimann 1993). Dhaka City is developed partly on the Madhupur Terrace of the Pleistocene age and partly on the low-lying floodplains of the Holocene age. The sediment of the Pleistocene terrace has been deposited on the older floodplains, whereas the Holocene alluvium has been deposited on the recent floodplains of the Ganges–Brahmaputra River Systems (Morgan and McIntire, 1959).

In Dhaka City, six surface geological units have been identified based on the geomorphological, geological, and geotechnical properties. These units are Artificial fill (af), Holocene Alluvial channel deposit (Qhc), Holocene Alluvial valley fill deposit (Qhav), Holocene Alluvium (Qha), Holocene terrace deposit (Qhty), and Pleistocene terrace deposit (Qpty) (Fig. 1) (Rahman et al. 2015).

The Pleistocene terrace deposits exposed in the central part of the city are primarily comprised of a 6–8 m thick layer of reddish to yellowish-brown, medium stiff to stiff silty clay that is underlain by a layer of medium dense to very dense silty sand and sand down to the depth of investigation of 20 m. The Holocene alluvium deposits composed of very loose to loose sand, silt, and very soft to soft silty clay that are present down to the depth of investigation in northwestern, southeastern, and eastern parts of the city (Rahman et al. 2021). Gray sand, silty sand, and clayey silt make up the artificial fills that are emplaced to the west and east portions of the city. For the emplacement of the artificial fills, both hydraulic dragging from the river and trucks from the land were used, but the ground was not compacted properly during filling, which creates the area prone to liquefaction (Rahman et al. 2015).

3 Seismotectonics of the region

The Bengal Basin is in the northeastern part of the Indian plate and bordering the Indian-Eurasian convergent plate boundary where the Himalayan ranges in the north and Indo-Burman ranges in east have been created due to the collision between these plates (Curray et al. 1982; Aitchison et al. 2007). Besides Bangladesh, the Bengal Basin also contains portions of Assam, Tripura, and West Bengal.

Dhaka is seismically vulnerable due to its proximity to the Eurasian and Indian convergent plate boundary (Rahman et al. 2020, 2021). Bangladesh, Myanmar, Nepal, and northeastern India experienced several historical earthquakes (Table 1) that occurred along this plate boundary and associated faults. The Himalayan and the Arakan subduction-collision systems (Fig. 2) also generated many devastating earthquakes in these regions (Fig. 3).
The Dauki Fault (DF) and the Himalayan Frontal Thrust (HFT) are the main seismo-tectonic elements of the Himalayan system, while the Arakan subduction-collision system manifests itself through the Indo-Burman Folded Belt along with the megathrust beneath (Steckler et al. 2008; Wang et al. 2014).

Bilham and Hough (2006) anticipated that a large earthquake with a magnitude ranging from $M_w$ 7.5 to 8.5 may occur in the Himalayan system because of the movement of the Indian

---

**Legend**
- Locations of SPT and Vs
- $af$: Artificial fill
- $Qhav$: Holocene Alluvial valley fill deposit
- $Qha$: Holocene Alluvium
- $Qhc$: Holocene channel deposit
- $Qhty$: Holocene terrace deposit
- $Qpt$: Pleistocene terrace deposit

**Fig. 1** Surface geological map of Dhaka City with locations of the boreholes (modified from Rahman et al. (2015))
| Date          | Earthquake              | Moment magnitude ($M_w$) | Number of casualty | Structural damage                                                                 |
|---------------|-------------------------|--------------------------|--------------------|----------------------------------------------------------------------------------|
| April 2, 1762 | Bengal-Arakan Earthquake | 8.5<sup>a</sup>          | 500 in Dhaka<sup>b</sup> | The earthquake was very strong in Dhaka and Chittagong.<sup>b</sup>              |
| July 14, 1885 | Bengal Earthquake       | 6.87<sup>c</sup>         | Not reported       | The highest damage was reported in Sirajganj, Bogura, Jamalpur and Mymensingh. In Dhaka, the damage was very low compared to other areas located at similar distance from the epicenter.<sup>d</sup> |
| June 12, 1897 | Great Assam Earthquake  | 8.03<sup>c</sup>         | 545 in Sylhet<sup>b</sup> | The highest damage was reported in Shillong, Assam (India). In Dhaka, almost all masonry buildings were badly damaged, and some were entirely collapsed. In Sylhet, most of the masonry buildings were severely damaged.<sup>e</sup> |
| July 08, 1918 | Srimangal Earthquake    | 7.10<sup>c</sup>         | Exact numbers were not reported | Most of the tea factories and bungalows at Srimangal (Moulvibazar) were destroyed. Significant damage was reported in Kishoreganj, Sylhet, Habiganj, Agartala (India). In Dhaka, several buildings were slightly cracked.<sup>f</sup> |

Based to <sup>a</sup>Wang et al. (2014);<sup>b</sup>Banglapedia (accessed on 06 August, 2018);<sup>c</sup>Ambraseys and Douglas (2004),<sup>d</sup>Middlemiss (1885);<sup>e</sup>Oldham (1899); and<sup>f</sup>Stuart (1920)
plate at a rate of 4 cm/year towards the north and at a rate of 6 cm/year towards the northeast. The 2015 Gorkha Earthquake ($M_w$ 7.8) occurred in Nepal along the subduction interface of the Himalayan System (Goda et al. 2015). It has been revealed by recent paleoseismological investigations that the Dauki fault was activated three times during last thousand years (Yeats et al. 1997; Morino et al. 2011, 2014a) The convergence of the tectonic plates and increasing frequency of earthquakes with large magnitude are, therefore, the indication of active seismic activities in these regions (Rahman and Siddiqua 2017a).

![Fig. 2 Typical borehole profiles of SPT-N and $V_s$ at BH-52](image)

| Depth (m) | Lithology | SPT-N | $V_s$ (m/sec) Curve |
|-----------|-----------|-------|--------------------|
| 1.5       | Reddish Brown Medium Stiff Silty CLAY/ Clayey SILT |       |                   |
| 3.0       | Reddish Brown Stiff Silty CLAY/ Clayey SILT |       |                   |
| 4.5       | Reddish Brown Medium Stiff Silty CLAY/ Clayey SILT |       |                   |
| 6.0       | Reddish Brown Stiff Silty CLAY/ Clayey SILT |       |                   |
| 7.5       | Yellowish Brown to Brown Medium Dense Fine to Medium SAND little Silt/Clay |       |                   |
| 9.0       |                   |       |                   |
| 10.5      |                   |       |                   |
| 12.0      |                   |       |                   |
| 13.5      |                   |       |                   |
| 15.0      |                   |       |                   |
| 16.5      |                   |       |                   |
| 18.0      |                   |       |                   |
| 19.5      |                   |       |                   |
| 21.0      |                   |       |                   |
| 22.5      |                   |       |                   |
| 24.0      |                   |       |                   |
| 25.5      |                   |       |                   |
| 27.0      | Brown Very Dense Medium to Coarse SAND |       |                   |
| 28.5      |                   |       |                   |
| 30.0      | End of Boring |       |                   |
4 Material and methods

4.1 Database establishment

The SPT-N and $V_s$ data from sixty-five (65) boreholes including relevant geotechnical properties of soils were used to assess soil liquefaction resistance of Dhaka City in terms of the FS, which was estimated using ANN incorporated (Juang et al. 2000, 2002) Simplified Procedure of Seed and Idriss (1971). Fifty (50) borehole profiles were obtained from the Comprehensive Disaster Management Programme (CDMP) while the most of the authors were present during data collection, and the remaining fifteen (15) borehole data were collected by all the authors. Typical borehole profiles of SPT-N and $V_s$ are shown in Fig. 2. Then, the LPI of each borehole profile was estimated using all FS values of each borehole that were estimated at every 1.5 m interval to a depth of 20 m below the ground surface according to the method introduced by Iwasaki et al. (1978). The borehole sites were selected considering the variation of the geological units in the city (Table 2). The surface geological map (Fig. 1) shows the borehole locations.

For training purpose, artificial neural network (ANN) requires the SPT-N and $V_s$ data of the sites where the historical data of liquefaction and non-liquefaction cases are available to find liquefaction indicator (LI) function and points of the limit state function (LSF).
The SPT-N data of the historical cases for liquefaction and non-liquefaction were primarily collected by Fear and McRoberts (1995) and later summarized by Idriss and Boulanger (2010). The $V_s$ data were compiled by Andrus et al. (1999). After screening as per the ANN model applicability criteria of used parameters as described in Juang et al. (2000), total 225 SPT cases (127 cases liquefied) and 225 $V_s$ cases (97 cases liquefied) from 26 earthquakes over 70 sites identified by Andrus et al. (1999) were used for the analysis of the present study.

### 4.2 Factor of safety of liquefaction (FS)

In this study, an updated simplified procedure proposed by Youd et al. (2001) is used in calculating the factor of safety (FS) of liquefaction that is the ratio of the cyclic resistance ratio (CRR) to the cyclic stress ratio (CSR).

#### 4.2.1 Calculation of CSR

The CSR defines the cyclic loading characteristic of soils, by which the seismic demand of the soil layer is determined on a level ground condition. It is the ratio of the cyclic loading-induced average cyclic shear stress to the initial vertical effective stress on the soil particles (Robertson and Campanella 1985). The following equation of Seed and Idriss (1971) that was slightly adjusted by Juang et al. (2003) has been used to estimate the CSR at $z$ depth from the ground surface due to earthquake loading:

$$CSR_{7.5} = \frac{\tau_{av}}{\sigma'_{v}} = 0.65 \left( \frac{a_{max}}{g} \right) \left( \frac{\sigma_v}{\sigma'_v} \right) \frac{r_d/MSF}{0.65 \cdot r_d \cdot S_L}$$

where $CSR_{7.5} = CSR$ adjusted to an earthquake magnitude of $M_w$ 7.5 using a magnitude scaling factor (MSF); $\tau_{av} =$ average cyclic shear stress exerted by an earthquake, $\sigma_v =$ total vertical stress, $\sigma'_v =$ effective vertical stress at a depth of question ($z$); $g =$ gravitational acceleration; $a_{max} =$ peak horizontal ground acceleration (PGA); $R_p =$ overburden pressure ratio ($\sigma_v/\sigma'_v$); $S_L =$ seismic loading parameter ($a_{max}/g$)/MSF; $r_d =$ stress reduction coefficient that represents soil flexibility that depends on $z$. The calculation formula of $r_d$ according to Youd et al. (2001) is as follows:

### Table 2

| Geological unit                               | Number of boreholes | USCS soil type |
|-----------------------------------------------|---------------------|----------------|
| Artificial fill (af)                          | 6                   | SM, SP, MH     |
| Holocene Alluvial valley fill deposits (Qhav) | 7                   | SM, MH, CH     |
| Holocene terrace deposits (Qhty)              | 4                   | SM, SP, CL     |
| Holocene channel deposits (Qhc)               | 0                   | SM, SP         |
| Holocene Alluvium (Qha)                       | 10                  | SM, CL, MH, CH |
| Pleistocene terrace deposits (Qpty)           | 38                  | SM, SP, MH, CH |

The SPT-N data of the historical cases for liquefaction and non-liquefaction were primarily collected by Fear and McRoberts (1995) and later summarized by Idriss and Boulanger (2010). The $V_s$ data were compiled by Andrus et al. (1999). After screening as per the ANN model applicability criteria of used parameters as described in Juang et al. (2000), total 225 SPT cases (127 cases liquefied) and 225 $V_s$ cases (97 cases liquefied) from 26 earthquakes over 70 sites identified by Andrus et al. (1999) were used for the analysis of the present study.
The MSF is the magnitude scaling factor used in liquefaction resistance adjustment to the $M_{W\text{ 7.5}}$ reference magnitude earthquake (Youd et al. 2001).

$$\text{MSF} = \left(\frac{M_{W\text{ 7.5}}}{7.5}\right)^{-2.56}$$

where $M_{W\text{ 7.5}} = \text{moment magnitude}$.

### 4.2.2 Calculation of CRR using ANN

The ability of soil to resist cyclic stress is denoted by the CRR. In the present study, Juang et al. (2000, 2002) recommended procedures were used for calculating CRR from LSFs derived using the SPT-N and $V_S$. Initially, the LI function was produced by training with the cases of actual field performance using neural network. The LI function is a trained neural network capable of predicting liquefaction or no liquefaction occurrences with high precision. In general, the LI function (Eq. 4) is a multi-dimensional and highly nonlinear function. It can be developed using a neural network model of three layers:

$$LI = f_T\left[B_0 + \sum_{k=1}^{n} \left\{ W_k f_T\left(B_{HK} + \sum_{i=0}^{m} W_{ik} P_i\right)\right\}\right]$$

where $B_0$ refers to the output layer bias (consisting of one neuron only); $W_k$ is the connection weight between $k$th neuron in the hidden layer and the only one neuron of output layer; $B_{HK}$ refers to the bias at neuron $k (k = 1, n)$ of the hidden layer; $W_{ik}$ is the connection weight between input variable $i (i = 1, m)$ and the neuron $k$ of the hidden layer.

Secondly, a search mechanism is established using the LI function for searching points at the surface of the limit state. Thirdly, the LSF is specified collectively by the generated points. Finally, neural network models were trained for both datasets (SPT-N and $V_s$) to determine the CRR for the selected locations of Dhaka City using these generated data points. Conceptually, the LI function of the SPT-N and $V_s$ data may take the following ANN model forms, respectively, as suggested by Juang et al. (2002, 2000):

$$LI_{\text{SPT}} = f\left(\left(N_1\right)_{60}, \text{FCI, } \sigma', R_p, S_L\right)$$

$$LI_{\text{Vs}} = f\left(V_{s1}, \text{FCI, CSR}_{7.5}\right)$$

In this analysis, critical CSR = CRR = $f$ (indices of soil properties) defines the limit state. The LSF, conceptually illustrated in Fig. 4, is defined based on a robust but simple system that was introduced by Juang et al. (2000). For each case in training data, either by increasing normalized soil strength (path B showed in Fig. 4) or by lowering seismic load (path A shown in Fig. 4), the limit state could be reached when liquefaction has been observed. Using path A, as an example, by lowering seismic load while keeping soil resistance unchanged, a new data pattern is created. With a new input pattern, the LI function would generate a new output. Initially, it is expected that the output would remain the same with a slight lowering of the seismic load. Nonetheless, if this cycle continues to decrease seismic load, ultimately no-liquefaction will be implied by the output. In the given soil condition, the critical load determining
the limit state (also called critical CSR), is the upgraded seismic load resulting in a shift in the LI function. Likewise, when any case shows no liquefaction, critical CRR values of the LSF can be generated either by raising the seismic load (path C showed in Fig. 4) or by lowering the value of normalized soil strength parameters (path D showed in Fig. 4). Note that, in some cases, critical CSR searches might not be effective. It occurs when the upper limit of a normal load range is exceeded by seismic load using Path C in Fig. 4 for example. As a result, the liquefaction output of the LI function remains the same.

From each search that would be successful, a data point on the surface of the limit state, which is multidimensional is produced. Since \( \text{CRR} = \text{CSR}_{7.5} \) or critical CRR defines the limit state boundary surface by its definition, an LSF is defined through \( \text{CRR} = f(\text{indices of soil properties}) \) once enough data points were obtained. Figure 4 illustrates the described searching mechanism.

After generating the boundary surface points based on the algorithm mentioned above, by training those points with a feed-forward, three-layer neural network, connection weights and biases can be produced, that would then be used in CRR estimation:

\[
\text{CRR} = f_T \left[ B_0 + \sum_{k=1}^{n} \left\{ W_{ik} f_T \left( B_{HK} + \sum_{i=0}^{m} W_{ik} P_i \right) \right\} \right]
\]  
(7)

This equation is the same as Eq. 4.

Conceptually, the LSF from the SPT-N and \( V_s \) data may take the following ANN model forms, respectively, as suggested by Juang et al. (2002, 2000):

\[
\text{CRR}_{\text{SPT}} = f\left( (N1)_{60}, \text{FCI}, \sigma'_V, R_p \right)
\]  
(8)

\[
\text{CRR}_{V_s} = f\left( V_s, \text{FCI} \right)
\]  
(9)

Tables 3 and 4 show all specifications of the ANN model for training that were implemented using the neural network toolbox of MATLAB for LI and LSFs, respectively.
Table 3 Specifications for artificial neural network (ANN) models of liquefaction indicator (LI) and limit state functions (LSFs)

| Network type               | Training Function (both hidden and output layers) | Transfer function       | Adaption learning function          | Performance function          |
|----------------------------|---------------------------------------------------|-------------------------|-------------------------------------|------------------------------|
| Feed-forward Backpropagation | Levenberg–Marquardt (TRAINLM) | Hyperbolic Tangent Sigmoid (tansig) | Gradient descent with momentum (LEARNNGDM) | Mean squared error (MSE) |
MATLAB offers an immersive computational platform with numerous built-in algorithms, along with a programming language. It provides a network neural toolbox containing source code for all such algorithms for training neural networks including the LM algorithm (Levenberg–Marquardt) that could be adjusted according to the circumstances provided (Beale et al. 2017).

### 4.2.3 Calculation of FS

The FS was calculated using Eq. 10 from the CSR, CRR, and MSF for earthquake magnitude other than $M_w$ 7.5. The CSR was calculated for all data points of two datasets (SPT-N and $V_s$) using Eq. 1 and the CRR was predicted from the simulating normalized data (SPT-N and $V_s$) of Dhaka City using the developed ANN models of LSF.

$$F_s = \left( \frac{\text{CRR}_{7.5}}{\text{CSR}} \right) \text{MSF}$$  \hspace{1cm} (10)

If $F_s \leq 1$ it is considered that liquefaction occurs; and if $F_s > 1$ liquefaction is not likely to occur.

### 4.2.4 LPI Calculation

The calculation of the LPI uses the FS derived from the CRR and CSR. Iwasaki et al. (1978) suggested the LPI, which can be estimated using the FS values calculated from the SPT-N, $V_s$, and CPT over the top 20 m, as follows:

$$\text{LPI} = \int_0^{20} F(Z)W(Z)dz$$  \hspace{1cm} (11)

where $W(z) = \begin{cases} 10 - 0.5z; & z < 20 m \\ 0; & z > 20 m \\ \end{cases}$ $z =$ Depth in meters and $F(z) = \begin{cases} 1 - \text{Fs}; & \text{Fs} < 1.0 \\ 0; & \text{Fs} \geq 1.0 \\ \end{cases}$

Iwasaki et al. (1982) mentioned that, if the LPI of a site is greater than 15, it is highly prone to severe liquefaction and if the LPI of any site is lower than 5, the liquefaction is not expected to show surface manifestation.

### 5 Results

Based on the approach discussed above, initially using 225 field performance cases (85% for training and 15% for testing) for the SPT-N and $V_s$ were used separately to train the LI function for each data set. One of the most effective ways to assess the ANN

| Table 4 Numbers of layers and hidden neurons in artificial neural network (ANN) model of liquefaction indicator (LI) and limit state functions (LSFs) |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
|                                | LI<sub>SPT</sub> | LI<sub>V_s</sub> | CRR<sub>SPT</sub> | CRR<sub>V_s</sub> |
| Number of layers               | 3               | 3               | 3               | 3               |
| Number of hidden neurons       | 8               | 6               | 5               | 4               |
model efficiency is by observing the coefficient of determination (R) value. In the case of the ANN model for the LI function, the R-value for the SPT-N data training was 0.886 and testing 0.92, and the R values for the $V_s$ data training and testing were 0.89. Next, points were generated in the limit state boundary with the help of the respective LI functions for different datasets using the searching mechanism shown in Fig. 5.

From the searching, total of 143 and 236 points have been generated for the SPT-N and $V_s$ datasets, respectively, on the limit state surface. Then, to approximate the LSF for the respective datasets (Eqs. 8 and 9), these data points were then used in training neural networks. The trained neural networks approximate the unknown but real functional relation between the output (CRR) and the inputs (indices of soil properties).
Plotting the output values from training against the actual field performance value (or targeted value) also shows the performance of an ANN model. Figures 6 and 7 show such plots for the training and testing according to Eqs. 8 and 9 of generated data points at limit state surface from the SPT-N and \( V_s \) data. Tables 6 and 7 are showing the weights and biases of connections obtained the trained ANN models for SPT-N and \( V_s \) data, respectively.

The FS values were calculated from the CSR and CRR values that were derived from simulating trained ANN models for the LSF using normalized parameters (as in Eqs. 8 and 9) of each location. The LPI values were calculated using Eq. 11 from the FS of the SPT-N and \( V_s \) datasets are shown in Table 8.

The surface geological units of Dhaka City is divided into three liquefaction hazard zones based on the LPI values (Table 9). For each zone, the cumulative frequency (CF) distributions of the LPI values of the SPT-N and \( V_s \) data are shown in Figs. 8 and 9, respectively.

The LPI values of sixty-five (65) borehole profiles along with the contour of LPI values (0, 5, 10, 15, and 20) are shown on the maps to visualize the spatial distribution of liquefaction severity in the city (Figs. 10 and 11). The contours of the LPI values have been drawn using inverse distance weighting (IDW) interpolation technique in ArcGIS software considering the surface geological units and depth of the Pleistocene deposit below the Holocene deposits and artificial fillings. Therefore, biases of dense boreholes and sparse boreholes in some geological units have been removed justifying the liquefaction potential based on geological units, e.g., Holocene deposits and artificial fillings are likely to be liquefy during a strong ground motion that is reflected in the liquefaction hazard maps. One the basis of the LPI values, the liquefaction hazard of different areas of Dhaka City is classified according Iwasaki et al. (1982) (Table 10).

Liquefaction hazard of each surface geological unit was also classified by the cumulative frequency (CF) distribution at the LPI value of 5, which can be used to define the threshold for observing liquefaction surface effects (Holzer et al. 2006). The map of the SPT-N data shows that 15%, 53%, and 69% areas, whereas the map of the \( V_s \) data shows that 11%, 48%, and 62% of areas of Zone 1, Zone 2, and Zone 3, respectively, will exhibit liquefaction surface effects.

![Fig. 7 Performance of CRR\(_{Vs}\) model](image-url)
Table 6  Weights and biases of connections in CRR\textsubscript{SPT}

| Hidden neuron (HN) no | Weight | Bias |
|-----------------------|--------|------|
|                       | Weight |      |
|                       | $W_k$  | $W_k$| $B_k$| $B_o$ |
|                       | Input 1 ($i = 1$) | Input 2 ($i = 2$) | Input 3 ($i = 3$) | Input 4 ($i = 4$) | Output neuron | Hidden layer | Output layer |
| HN 1 ($k = 1$)        | $-1.9681$ | $1.2399$ | $0.93542$ | $-0.71182$ | $-36.1196$ | $1.8671$ | $-46.7613$ |
| HN 2 ($k = 2$)        | $0.52733$ | $0.94369$ | $-1.2764$ | $1.735$ | $20.171$ | $-0.53251$ |               |
| HN 3 ($k = 3$)        | $-1.663$ | $0.98884$ | $1.0491$ | $-0.56474$ | $82.5362$ | $2.175$ |               |
| HN 4 ($k = 4$)        | $-4.7013$ | $-2.7607$ | $30.4863$ | $-44.1878$ | $0.28948$ | $-33.1536$ |               |
| HN 5 ($k = 5$)        | $0.42838$ | $0.93002$ | $-1.2782$ | $1.7321$ | $-20.1837$ | $-0.60614$ |               |
A comparison between the LPI values derived from the SPT-N and $V_s$ is illustrated in Fig. 12. In most of the cases, the LPI values of the SPT-N data are higher than that of the $V_s$ data.

### 6 Discussion

The liquefaction hazard map offers an opportunity to quantitatively estimate the liquefaction susceptibility of Dhaka City. The spatial liquefaction potential was determined by calculating the LPI values from the liquefaction FS estimated from both SPT-N and $V_s$ at each 1.5 m interval of a borehole down to a depth of 20 m. The contour lines of equal LPI values were drawn to represent the LPI values of the locations where there was no borehole. Three liquefaction hazard zones were identified in the city based on the CF distribution of LPI of each geological unit to determine the percentage of the area of these zones that are likely to liquefy in a defined earthquake.

Rahman and Siddiqua (2017a, b) have conducted liquefaction potential study for Dhaka, Chittagong, and Sylhet cites in Bangladesh using limited SPT-N, cone penetration test (CPT), and $V_s$ data. Only seven (7) SPT-N and $V_s$ profiles and three (3) CPT profiles in Dhaka city were used in that study. Though this study effectively showed a comparison among LPI derived from three (3) different in-situ tests and give an idea of liquefaction of the Dhaka City, but number of SPT-N, $V_s$ and CPT data were not sufficient enough to illustrate the heterogeneity of the subsurface of the city. Rahman et al. (2015) also studied liquefaction potential of Dhaka City using SPT-N values of fifty-three (53) borehole profiles. In this study, more SPT and $V_s$ profiles have been used to characterize the subsurface heterogeneity with more accuracy. A statistical comparison between the current study and Rahman et al. (2015) is shown in Table 11.

It has been observed from the resultant LPI that there are some differences in the outputs derived from SPT-N and $V_s$ data (Fig. 12 and Table 11). From the observed differences, in many cases LPI calculated from SPT-N has been found to higher than LPI from $V_s$ (e.g., BH-8, 11, 12) and the opposite was also observed (e.g., BH-3, 4). Such differences have also been found in other studies (Ateş et al. 2014; Rahman and Siddiqua 2016, 2017a, b). These differences could occur due to inherent uncertainties in data retrieval procedure of SPT-N and $V_s$. Due to the varied energy efficiency of various components of the standard penetration test (SPT) equipment, there is uncertainty in estimating SPT-N (Mayne et al. 2009). And the uncertainties in estimating $V_s$ include the expertise knowledge and skill of the personnel doing the test, the type of casing used in the borehole, the type of instrument...
Table 8 The SPT-N and $V_s$ based LPI values of each borehole for an earthquake of $M_w$ 7.5 with a PGA of 0.15 g. At each borehole, the SPT-N value and $V_s$ measurement were taken at each 1.5 m interval down to a depth 21 m

| Borehole no. | Coordinates | Geomorphological unit | Unit symbol | Depth of GWT (m) | FS from SPT-N | FS from $V_s$ | LPI from SPT-N | LPI from $V_s$ |
|--------------|-------------|------------------------|-------------|------------------|---------------|---------------|---------------|---------------|
|              | Easting     | Northing               |             |                  | 6 m depth     | 9 m depth     | 6 m depth     | 6 m depth     |
| BH-01        | 543,326.921| 639,885.898            | Lower Madhupur Terrace | Qpty       | 7              | 1.32          | 1.52          | 6.60          | 6.81          | 0             | 0             |
| BH-02        | 543,376.105| 621,458.48             | Upper Madhupur Terrace | Qpty       | 5              | 1.59          | 1.57          | 8.63          | 4.66          | 0             | 0             |
| BH-03        | 550,687.573| 623,127.326            | Flood Plain | Qha        | 3              | 0.65          | 0.77          | 0.35          | 0.68          | 11.94         | 19.19         |
| BH-04        | 543,419.417| 637,327.45             | Deep Alluvial Gully | Qhav       | 5              | 0.75          | 0.65          | 0.58          | 0.25          | 12.76         | 16.11         |
| BH-05        | 545,603.314| 638,709.462            | Lower Madhupur Terrace | Qpty       | 3              | 1.82          | 1.48          | 10.16         | 6.55          | 0             | 0             |
| BH-07        | 535,839.846| 632,035.635            | Upper Madhupur Terrace | Qpty       | 18             | 3.02          | 1.94          | 16.13         | 9.00          | 0             | 0             |
| BH-08        | 535,484.452| 628,074.969            | Swamp/Depression | af        | 4              | 0.63          | 1.18          | 1.80          | 2.27          | 8.93          | 2.49          |
| BH-09        | 546,532.2  | 625,777.363            | Upper Madhupur Terrace | Qpty       | 4.5            | 1.43          | 1.09          | 7.43          | 4.08          | 0             | 0             |
| BH-10        | 539,212.98  | 624,091.499            | Upper Madhupur Terrace | Qpty       | 1.5            | 0.91          | 0.73          | 3.97          | 4.74          | 2.34          | 0.34          |
| BH-11        | 537,885.386| 622,550.343            | Point Bar | Qhav       | 4.5            | 0.85          | 0.69          | 2.27          | 1.48          | 12.76         | 0             |
| BH-12        | 538,449.42 | 623,412.903            | Upper Madhupur Terrace | Qpty       | 5.5            | 1.44          | 0.87          | 5.61          | 3.85          | 4.46          | 0             |
| BH-13        | 539,212.98  | 624,091.499            | Upper Madhupur Terrace | Qpty       | 1.5            | 0.91          | 0.73          | 3.97          | 4.74          | 2.34          | 0.34          |
| BH-14        | 543,787.064| 627,948.675            | Deep Alluvial Gully | af        | 1.5            | 0.59          | 0.70          | 0.33          | 2.14          | 19.99         | 13.57         |
| BH-15        | 546,267.801| 631,123.967            | Swamp/Depression | Qha        | 1.5            | 1.15          | 1.06          | 6.51          | 4.68          | 9.79          | 7.78          |
| BH-16        | 548,501.53  | 631,684.808            | Upper Madhupur Terrace | Qhav       | 4.5            | 0.87          | 0.94          | 0.61          | 6.32          | 2.79          | 9.95          |
| BH-17        | 546,282.102| 635,521.81             | Lower Madhupur Terrace | Qhav       | 1.5            | 0.68          | 0.72          | 0.77          | 1.02          | 23.08         | 17.16         |
| BH-18        | 551,367.994| 621,269.109            | Flood Plain | Qha        | 4              | 0.83          | 0.90          | 0.60          | 0.96          | 6.66          | 16.73         |
Table 8 (continued)

| Borehole no. | Coordinates       | Geomorphological unit | Unit symbol | Depth of GWT (m) | FS from SPT-N 6 m depth | FS from SPT-N 9 m depth | FS from Vs 6 m depth | FS from Vs 6 m depth | LPI from SPT-N | LPI from Vs |
|--------------|-------------------|-----------------------|-------------|------------------|--------------------------|--------------------------|----------------------|---------------------|----------------|-------------|
| BH-20        | 547,143.988      | Flood Plain           | Qha         | 1.5              | 1.16                     | 1.31                     | 6.38                 | 6.14                | 0              | 0           |
| BH-21        | 544,049.881      | Upper Madhupur Terrace| Qpty        | 6                | 1.56                     | 1.16                     | 5.15                 | 3.12                | 0              | 0           |
| BH-22        | 541,835.945      | Upper Madhupur Terrace| Qpty        | 2                | 0.50                     | 0.81                     | 3.14                 | 6.24                | 9.1            | 0           |
| BH-23        | 542,752.243      | Shallow Alluvial Gully| Qhav        | 2.5              | 0.96                     | 0.83                     | 3.85                 | 6.05                | 1.3            | 2.89         |
| BH-24        | 539,372.339      | Shallow Alluvial Gully| Qhav        | 3                | 1.27                     | 0.93                     | 8.37                 | 1.21                | 2.38           | 0.69         |
| BH-25        | 540,158.18       | Upper Madhupur Terrace| Qpty        | 4                | 1.38                     | 0.77                     | 6.32                 | 3.46                | 6.39           | 0           |
| BH-26        | 537,796.56       | Shallow Alluvial Gully| Qpty        | 4                | 1.27                     | 1.07                     | 5.42                 | 4.43                | 3.54           | 0           |
| BH-27        | 537,132.08       | Deep Alluvial Gully   | Qhav        | 3.5              | 0.74                     | 1.08                     | 0.36                 | 1.74                | 6.56           | 11.65        |
| BH-28        | 544,802.623      | Lower Madhupur Terrace| Qpty        | 3                | 1.38                     | 1.01                     | 0.90                 | 3.46                | 0.67           | 1.03         |
| BH-29        | 540,012.645      | Point Bar             | Qhty        | 6.7              | 1.25                     | 1.26                     | 1.53                 | 1.56                | 0              | 0           |
| BH-30        | 537,251.312      | Point Bar             | Qhty        | 5.5              | 1.02                     | 1.32                     | 0.86                 | 2.09                | 0              | 2.46         |
| BH-31        | 538,385.375      | Upper Madhupur Terrace| Qpty        | 4                | 0.90                     | 0.94                     | 4.57                 | 3.91                | 2.93           | 0           |
| BH-32        | 538,594.907      | Swamp/ Depression     | Qha         | 1.5              | 0.64                     | 0.61                     | 0.55                 | 0.39                | 20.7           | 21.1         |
| BH-33        | 536,272.23       | Madhupur Slope        | af          | 1.8              | 0.76                     | 0.63                     | 0.97                 | 0.39                | 19.36          | 21.13        |
| BH-34        | 546,042.619      | Flood Plain           | Qha         | 1.5              | 0.83                     | 0.73                     | 1.17                 | 3.11                | 11.96          | 3.23         |
| BH-35        | 545,583.954      | Flood Plain           | Qha         | 3.7              | 0.86                     | 1.01                     | 0.81                 | 3.14                | 4.53           | 4.43         |
| Borehole no. | Coordinates | Geomorphological unit | Unit symbol | Depth of GWT (m) | FS from SPT-N 6 m depth | FS from SPT-N 9 m depth | FS from Vs 6 m depth | FS from Vs 9 m depth | LPI from SPT-N 6 m depth | LPI from SPT-N 9 m depth | LPI from Vs 6 m depth | LPI from Vs 9 m depth |
|--------------|-------------|-----------------------|-------------|----------------|------------------------|------------------------|----------------------|----------------------|------------------------|------------------------|----------------------|----------------------|
| BH-36        | 545,193.435 626,097.174 | Deep Alluvial Gully | Qhav        | 1.5 | 0.69 | 0.65 | 0.76 | 0.53 | 20.86 | 18.98 |
| BH-37        | 541,583.654 623,635.279 | Upper Madhupur Terrace | Qpty       | 3.7 | 0.80 | 1.01 | 0.59 | 3.14 | 3.84 | 6.12 |
| BH-38        | 538,537.681 625,718.273 | Upper Madhupur Terrace | Qpty       | 2.3 | 1.14 | 1.03 | 5.67 | 4.54 | 3.1 | 0 |
| BH-39        | 539,424.733 641,648.101 | Upper Madhupur Terrace | Qpty       | 1.5 | 1.01 | 1.35 | 5.14 | 6.41 | 1 | 0 |
| BH-40        | 546,755.248 620,173.641 | Flood Plain | Qha       | 1.5 | 1.25 | 1.70 | 1.96 | 1.67 | 0.08 | 0 |
| BH-41        | 534,707.013 636,900.28 | Back Swamp | Qha       | 1.5 | 0.64 | 0.73 | 0.44 | 1.00 | 17.63 | 7.45 |
| BH-42        | 539,861.182 635,008.868 | Lower Madhupur Terrace | Qpty       | 2.1 | 1.20 | 0.80 | 6.48 | 7.91 | 2.76 | 0 |
| BH-43        | 546,001.183 624,015.105 | Swamp/Depression | af         | 2.7 | 0.41 | 0.87 | 0.45 | 2.46 | 18.69 | 18 |
| BH-44        | 538,455.075 631,081.218 | Upper Madhupur Terrace | Qpty       | 1.5 | 1.21 | 1.28 | 2.78 | 3.97 | 0.5 | 0 |
| BH-45        | 536,010.634 626,431.552 | Back Swamp | af         | 2.5 | 0.86 | 0.90 | 1.74 | 2.75 | 3.63 | 0 |
| BH-46        | 547,379.066 635,489.77 | Swamp/Depression | af         | 1.5 | 0.89 | 0.78 | 0.60 | 0.70 | 16.11 | 19.57 |
| BH-47        | 537,745.941 641,488.616 | Upper Madhupur Terrace | Qpty       | 1.5 | 1.06 | 1.03 | 6.38 | 6.66 | 1.21 | 0 |
| BH-48        | 546,481.069 641,160.514 | Lower Madhupur Terrace | Qpty       | 1.5 | 1.25 | 1.11 | 5.14 | 5.65 | 1.95 | 4.77 |
| BH-49        | 550,146.733 624,520.859 | Natural Levee | Qhty       | 2.4 | 0.71 | 0.70 | 1.65 | 2.78 | 14.19 | 0 |
| BH-50        | 541,657.054 638,301.25 | Upper Madhupur Terrace | Qpty       | 1.5 | 1.16 | 1.40 | 7.56 | 6.66 | 0 | 0 |
| BH-51        | 547,661.889 635,503.001 | Lower Madhupur Terrace | Qpty       | 2.3 | 1.09 | 1.00 | 1.32 | 1.13 | 6.47 | 0 |
| Borehole no. | Coordinates | Geomorphological unit | Unit symbol | Depth of GWT (m) | FS from SPT-N 6 m depth | FS from SPT-N 9 m depth | FS from Vs 6 m depth | FS from Vs 6 m depth | LPI from SPT-N | LPI from Vs |
|-------------|-------------|-----------------------|-------------|-----------------|--------------------------|--------------------------|---------------------|---------------------|----------------|------------|
| BH-52       | 540,194.154 | 633,499.907           | Deep Alluvial Gully | Qpty            | 15                       | 1.31                     | 2.19                | 1.98                | 4.31           | 0          |
| BH-53       | 548,533.328 | 620,405.182           | Swamp/ Depression  | Qha             | 3                        | 0.80                     | 1.30                | 3.55                | 2.02           | 3.07       |
| BH-54       | 541,203.960 | 623,742.6556          | Upper Madhupur Terrace | Qpty         | 2.27                     | 1.04                     | 1.00                | 1.23                | 1.16           | 0          |
| BH-55       | 540,863.678 | 623,812.543           | Upper Madhupur Terrace | Qpty         | 3.05                     | 1.01                     | 1.85                | 1.03                | 0.57           | 0          |
| BH-56       | 540,556.790 | 624,114.3428          | Upper Madhupur Terrace | Qpty         | 2.74                     | 1.98                     | 1.95                | 1.49                | 2.10           | 0          |
| BH-57       | 540,271.199 | 624,531.228           | Upper Madhupur Terrace | Qpty         | 4.72                     | 1.89                     | 1.26                | 3.24                | 0.88           | 0          |
| BH-58       | 540,259.423 | 624,184.6964          | Upper Madhupur Terrace | Qpty         | 4.27                     | 1.30                     | 1.18                | 0.69                | 3.30           | 0          |
| BH-59       | 539,964.354 | 624,346.724           | Upper Madhupur Terrace | Qpty         | 4.27                     | 1.25                     | 1.20                | 3.79                | 2.43           | 0          |
| BH-60       | 539,751.221 | 623,952.3698          | Upper Madhupur Terrace | Qpty         | 3.36                     | 1.05                     | 1.07                | 2.52                | 3.27           | 0          |
| BH-61       | 539,696.542 | 624,307.4642          | Upper Madhupur Terrace | Qpty         | 1.98                     | 1.01                     | 1.43                | 1.24                | 2.95           | 0          |
| BH-62       | 539,769.114 | 624,526.079           | Upper Madhupur Terrace | Qpty         | 2.59                     | 1.07                     | 1.06                | 3.04                | 2.07           | 0          |
| BH-63       | 539,771.998 | 624,849.2276          | Upper Madhupur Terrace | Qpty         | 3.36                     | 1.20                     | 1.16                | 6.47                | 5.64           | 0          |
| BH-64       | 539,976.272 | 625,051.2678          | Upper Madhupur Terrace | Qpty         | 3.36                     | 1.20                     | 1.29                | 1.56                | 2.14           | 0          |
| Borehole no. | Coordinates | Geomorphological unit | Unit symbol | Depth of GWT (m) | FS from SPT-N | FS from Vs | LPI from SPT-N | LPI from Vs |
|-------------|-------------|-----------------------|-------------|-----------------|---------------|-------------|----------------|-------------|
|             | Easting     | Northing              |             | 6 m depth       | 9 m depth     | 6 m depth   | 6 m depth      |             |
| BH-65       | 540,148.5704| 624,838.1984          | Upper Madhupur Terrace | Qty | 3.81 | 2.25 | 1.68 | 6.62 | 3.19 | 0 | 0 |
| BH-66       | 538,908.2739| 623,661.4842          | Upper Madhupur Terrace | Qty | 3.05 | 1.27 | 1.05 | 5.38 | 2.47 | 0 | 0 |
| BH-67       | 538,906.2905| 624,477.1336          | Upper Madhupur Terrace | Qty | 8.23 | 1.39 | 2.12 | 1.59 | 4.43 | 0 | 0 |
| BH-68       | 537,608.7915| 624,440.5012          | Upper Madhupur Terrace | Qty | 4.57 | 1.88 | 1.38 | 1.84 | 3.36 | 0 | 0 |
Table 9  Liquefaction hazard zones along with their respective number of SPT-N and $V_S$ profiles

| Zone | Geological units                                      | Number of SPT-N and $V_S$ profiles |
|------|-------------------------------------------------------|------------------------------------|
| Zone 1 | Pleistocene terrace deposit                           | 38                                 |
| Zone 2 | Holocene terrace deposit Holocene and Alluvial valley fill deposit | 11                                 |
| Zone 3 | Holocene Alluvium and Artificial fill                 | 16                                 |

Fig. 8  Cumulative frequency (CF) distribution of LPI values of SPT-N data for each liquefaction hazard zone of Dhaka City

Fig. 9  Cumulative frequency (CF) distribution of LPI values of $V_S$ data for each liquefaction hazard zone of Dhaka City
used in measurement, etc. Furthermore, these tests are influenced by fines content, soil type, test methods, and their accuracy. Therefore, it is more reliable to estimate both SPT-N
and $V_s$ in the same location and then compare the findings for an accurate evaluation of liquefaction resistance.
In Zone 1, up to 6–8 m depth is formed of stiff to hard, reddish- to yellowish-brown Pleistocene clayey soils that is underlain by the medium to very dense, yellowish-brown Plio-Pleistocene sandy soils up to the depth of investigation of 20 m. In the case of the SPT-N data, the liquefaction potential in Zone 1 ranges from low to very low with the LPI values from 0 to 4.46, except boreholes BH-22 and BH-25 with the LPI values of 9.10 and 6.39, respectively. The cumulative frequency (CF) distribution of the SPT-N based LPI values of Zone 1 suggests that fifteen percent (15%) of the area of this zone would have liquefaction surface effects (Fig. 10). For the $V_s$ data, the liquefaction potential in Zone 1 is also from very low to low with the LPI values from 0 to 4.77, except boreholes BH-37 with the LPI value of 6.12. The CF distribution of the $V_s$ based LPI values of Zone 1 suggests that eleven percent (11%) of the area of this zone would have liquefaction surface effects (Fig. 11). In case of outliers, the SPT-N based LPI values of boreholes BH-22 and BH-25 are 9.10 and 6.39, respectively, but the $V_s$ based LPI values are 0 for both boreholes, which seems more accurate as these two boreholes are in the Pleistocene terrace (Madhupur terrace) that is not likely to liquefy. On the other hand, at borehole BH-37, the $V_s$ based LPI value is 6.12 while SPT-N based LPI is 3.84 and it is also in the Pleistocene terrace, therefore, the LPI value of 3.84 from the SPT-N data seems more accurate.

Zone 2 includes the Holocene terrace deposits and alluvial valley fill where the terrace deposits are formed of sandy and silty gray soils which include point and channel bars and natural levees of the existing rivers. The valley-fill deposits that have been deposited in the depressions and valleys of the Pleistocene terrace, are comprised of gray sandy soils and gray to dark gray clayey soils. In Zone 2, the SPT-N based LPI values range from 0 to 23.08, which imply a range of no potential to very high potential of liquefaction. The surface effects of liquefaction will be exhibited in fifty-three percent (53%) area of Zone 2. The $V_s$ based LPI values are from 0 to 18.98, which also imply a range of no potential to very high potential of liquefaction in Zone 2. The surface effects of liquefaction will be exhibited in forty-eight percent (48%) area of this zone. At boreholes BH-11 and BH-49 of this zone, the SPT based LPI values are 12.76 and 14.19, respectively, whereas the $V_s$ based LPI values are 0 at these boreholes. BH-11 is located on point bar and BH-49 is on the natural levee and both are usually more prone to liquefaction. Therefore, the SPT-N provides a more accurate result in this case.

Zone 3 contains artificial fills and Holocene alluvium that are comprised of gray sandy and clayey soils. The SPT-N based LPI values of this zone vary from 0 to 20.70, which indicate a range of no potential to very high potential of liquefaction. The CF distribution of the SPT-N based LPI values suggest that the surface effects of liquefaction will be exhibited in sixty-nine percent (69%) area of this zone. The $V_s$ based LPI values of this zone range from 0 and 21.13, which also indicate a range of no potential to very high potential of liquefaction. The CF distribution of the $V_s$ based LPI values suggest that the surface effects of liquefaction would be exhibited in sixty-two percent (62%) area of this zone. In case of Zone 3, the SPT-N based LPI values of boreholes BH-8, BH-19, BH-34, and BH-41 are 8.93, 6.66, 11.96, and

| LPI         | Liquefaction hazard |
|-------------|---------------------|
| $LPI > 15$  | Very High           |
| $5 < LPI ≤ 15$ | High               |
| $0 < LPI ≤ 5$ | Low                |
| $LPI = 0$   | Very low            |

### Table 10 Classes of liquefaction hazard on the basis of LPI values (after Iwasaki et al. (1982))
Borehole BH-8 is in the swamp, so the SPT-N based LPI value (8.93) appears more reliable. Borehole BH-34 is in a floodplain, which is more likely to have an LPI value of more than 5, therefore, the SPT-N based LPI value (11.96) appears more reliable than the $V_s$ based LPI (3.23) value. Borehole BH-19 and BH-41 are in the floodplain and back swamp, respectively, and in both cases for both datasets their LPI values are greater than 5, but it cannot be reliably said either of these will be greater than 15 or not as the output differs.

From the historical earthquake records of Bangladesh, it was observed that liquefaction occurred in silty and sandy alluvium of the Holocene floodplains during the 1885 Bengal earthquake ($M_w$ 6.87), 1897 Great Assam earthquake ($M_w$ 8.03), and 1918 Srimangal earthquake ($M_w$ 7.2) (Middlemiss 1885; Oldham 1899; Stuart 1920). The results of the present study also suggest that severe liquefaction may occur in the silty and sandy alluvium of the Holocene floodplains and the Pleistocene terrace deposits are not likely to liquefy during an earthquake of $M_w$ 7.5 having a PGA of 0.15 g. It can also be mentioned that during the 1995 Kobe earthquake in Japan, severe liquefaction occurred in loose fills (Hamada et al. 1995). Holzer et al. (2006) have also identified that the Pleistocene deposits have low liquefaction potential and the artificial fills and alluvium have high liquefaction potential.

### Table 11

| Geomorphic Units | Current study | Rahman et al. (2015) |
|------------------|---------------|----------------------|
|                  | LPI from SPT  | LPI from $V_s$       | LPI from SPT |
|                  | Lowest        | Highest              | Lowest        | Highest              | Mean         | Lowest       | Highest      | Mean         |
| af               | 3.63          | 19.99                | 14.45         | 0.00                | 21.13        | 12.46        | 2.86         | 18.90        | 11.06        |
| Qha              | 0.00          | 20.70                | 8.64          | 0.00                | 21.10        | 7.99         | 0.00         | 18.77        | 8.05         |
| Qhav             | 2.38          | 23.08                | 10.87         | 0.69                | 18.98        | 11.06        | 1.09         | 19.33        | 7.58         |
| Qhty             | 0.00          | 14.19                | 6.74          | 0.00                | 2.46         | 0.61         | 0.00         | 13.16        | 6.19         |
| Qpty             | 0.00          | 14.42                | 1.63          | 0.00                | 6.12         | 0.32         | 0.00         | 8.66         | 1.15         |

17.63, respectively, whereas the $V_s$ based LPI values of these boreholes are 2.49, 16.73, 3.23, and 7.45. Borehole BH-8 is in the swamp, so the SPT-N based LPI value (8.93) appears more reliable. Borehole BH-34 is in a floodplain, which is more likely to have an LPI value of more than 5, therefore, the SPT-N based LPI value (11.96) appears more reliable than the $V_s$ based LPI (3.23) value. Borehole BH-19 and BH-41 are in the floodplain and back swamp, respectively, and in both cases for both datasets their LPI values are greater than 5, but it cannot be reliably said either of these will be greater than 15 or not as the output differs.
7 Conclusions

In this study, both SPT-N and $V_s$ data have been used to calculate the LPI for the preparation of liquefaction hazard maps of Dhaka City using simplified procedure considering an earthquake of $M_w$ 7.5 with a PGA of 0.15 g. In the present study, ANN model has been used to predict the CRR from the SPT-N and $V_s$ data, as it provides more realistic and reliable results using sufficient actual field performance cases. From the results, it is noted that the SPT-N based LPI value is higher than the $V_s$ based LPI value at most of the boreholes. Three liquefaction hazard zones are identified in the city based on the CF distribution of the LPI of each geological unit and the LPI contour lines 0, 5, 10, 15, and 20 have been drawn to demonstrate spatial distribution of liquefaction hazard in the city.

The map of the SPT-N based LPI values indicates that 15%, 53%, and 69% areas, whereas the map of the $V_s$ based LPI values indicates that 11%, 48%, and 62% areas of Zone 1, 2, and 3 exhibit surface manifestation of liquefaction for an earthquake of $M_w$ 7.5 with a PGA of 0.15 g. Therefore, it can be concluded that the CF distribution of the LPI of both SPT-N and $V_s$ data show almost similar severity of liquefaction in Zone 1, 2, and 3.

The uncertainties associated with the calculation of the LPI can be reduced by using more SPT-N, $V_s$ data, variation in groundwater level, accurate surface geological unit boundary delineation, and appropriate ground motion. Finally, this liquefaction hazard map of Dhaka City can be used as a guide for future urban development and planning to reduce the liquefaction associated damages and loss.

Acknowledgements The authors would like to thank the Comprehensive Disaster Management Programme (CDMP), Department of Disaster Science and Climate Resilience (DSCR), University of Dhaka, Bangladesh for providing the support to collect the data of this research. The authors are also thankful to the University of Dhaka for allowing them to conduct this research.

Funding The authors have not disclosed any funding.

Declarations

Conflict of interest The authors declare no conflict of interests.

References

Agrawal G, Chameau J, Bourdeau P (1997) Assessing the Liquefaction Susceptibility at a Site Based on Information from Penetration Testing. undefined

Aitchison JC, Ali JR, Davis AM (2007) When and where did India and Asia collide? J Geophys Res 112:1978–2012

Alam M (1989) Geology and depositional history of cenozoic sediments of the Bengal Basin of Bangladesh. Palaeogeogr Palaeoclimatol Palaeoecol 69:125–139. https://doi.org/10.1016/0031-0182(89)90159-4

Ali HE, Najjar YM (1998) Neuronet-based approach for assessing liquefaction potential of soils. Transport Res Rec 1633(1):3–8

Ambraseys NN, Douglas J (2004) Magnitude calibration of north Indian earthquakes. Geophys J Int 159:165–206. https://doi.org/10.1111/j.1365-246X.2004.02323.x

Andrus RD, Stokoe KH (1997) Liquefaction resistance based on shear wave velocity. In: Proceeding of NCEER workshop on evaluation of liquefaction resistance of soils. National Center for Earthquake Engineering Research, Sate University of New York, Buffalo, pp 89–128

Andrus BRD, Member A, Li KHS (2000) Liquefaction resistance of soils from shear-wave velocity. J Geotech Geoenviron Eng 126:1015–1025
Andrus RD, Stokoe KH, Chung RM (1999) NISTIR6277 Draft guidelines for evaluating liquefaction resistance using shear wave velocity measurements and simplified procedures

Ateş A, Keskin I, Tötğ E, Yeşil B (2014) Investigation of soil liquefaction potential around efteni lake in Duzce Turkey: Using empirical relationships between shear wave velocity and SPT blow count (N). Adv Mater Sci Eng. https://doi.org/10.1155/2014/290858

Beale MH, Hagan MT, Demuth HB (2017) Neural Network Toolbox TM User’s Guide.

Castro G, Poulos SJ, France JW, Enos JL (1982) Liquefaction induced by cyclic loading. Report by Geotechnical Engineers Inc., to the National Science Foundation, Washington, D.C

Castro G, Poulos SJ (1977) Factors affecting liquefaction and cyclic mobility. J Geotech Eng Div 103:501–516

Castro G (1969) Liquefaction of Sands. PhD Thesis. Harvard University, Cambridge.

Chao SJ, Hsu HM, Hwang H (2010) Soil liquefaction potential in Ilan City and Lotung Town. Taiwan J GeoEng 5:21–27. https://doi.org/10.6310/jog.2010.5(1).3

Chen CJ, Juang CH (2000) Calibration of SPT- and CPT-based liquefaction evaluation methods. In: Mayne P, Hryciw R (eds) Innovations and applications in geotechnical site characterization 97. Geotechnical special publication, ASCE, Reston, pp 49–64

Curry JR, Emmel FJ, Moore DG, Raitt RW (1982) Structure, tectonics, and geological history of the north-eastern Indian Ocean. The ocean basins and margins. Springer, Berlin, pp 399–450

Eberhart RC, Dobbins RW, Widrow B (1990) Neural network PC tools: a practical guide. Academic Press, Cambridge, p 431

Fear CE, McRoberts EC (1995) Report on liquefaction potential and catalogue of case records. Univ of Alberta, Edmonton

Flood I, Kartam N (1994) Neural networks in civil engineering. i: principles and understanding. J Comput Civ Eng 8:131–148. https://doi.org/10.1061/(ASCE)0887-3801(1994)8:2(131)

Goda K, Kiyota T, Pokhrel RM et al (2015) The 2015 Gorkha Nepal earthquake: insights from earthquake damage survey. Front Built Environ 1:1–15. https://doi.org/10.3389/fbuil.2015.00008

Goh ATC (1994) Seismic Liquefaction potential assessed by neural networks. J Geotech Eng 120:1467–1480. https://doi.org/10.1061/(ASCE)0733-9410(1994)120:9(1467)

Goh ATC (1995) Back-propagation neural networks for modeling complex systems. Artif Intell Eng 9:143–151. https://doi.org/10.1016/0954-1810(94)00011-S

Goh ATC (1996) Neural-Network Modeling of CPT Seismic Liquefaction Data. Journal of Geotechnical Engineering 122:70–73. https://doi.org/10.1061/(ASCE)0733-9410(1996)122:1(70)

Hamada M, Isoyama R, Wakamatsu K (1995) The 1995 Hyogoken-Nanbu Kobe earthquake-Liquefaction, ground displacement, and soil condition in the Hanshin area. Waseda University, Tokyo

Hammerstrom D (1993a) Neural networks at work. IEEE Spectr 30:26–32. https://doi.org/10.1109/6.214579

Hammerstrom D (1993b) Working with neural networks. IEEE Spectr 30:46–53. https://doi.org/10.1109/6.222230

Holzer TL, Bennett MJ, Noce TE el al (2006) Liquefaction hazard mapping with LPI in the greater Oakland, California area. Earthq Spectra 22:693–708

Hossain MS, Kamal ASMM, Rahman MZ et al (2020) Assessment of soil liquefaction potential: a case study for Moulibazar town, Sylhet. Bangladesh SN Appl Sci. https://doi.org/10.1007/s42452-020-2582-x

Idriss IM, Boulanger RW (2004) Semi-empirical procedures for evaluating liquefaction potential during earthquakes. In: 11th International Conference on Soil Dynamics and Earthquake Engineering, and 3rd International Conf. on Earthquake Geotechnical Engineering. Berkeley, pp 32–56

Idriss IM, Boulanger RW (2010) SPT-based liquefaction triggering procedure. University of California, Davis

Iwasaki T, Tatsuoka F, Tokida K -i., Yasuda S (1978) A practical method for assessing soil liquefaction potential based on case studies at various sites in Japan. In: Proc. of 2nd International Conference on Microzonation. San Francisco, pp 885–896

Iwasaki T, Tokida K, Tatsuoka F, et al (1982) Microzonation for soil liquefaction potential using simplified methods. In: Proceedings of 3rd International Earthquake Microzonation Conference. pp 1319–1330

Juang CH, Chen CJ (1999) CPT-based liquefaction evaluation using artificial neural networks. Comput-Aided Civil Infrastruct Eng 14:221–229. https://doi.org/10.1111/0885-9507.00143

Juang CH, Chen CJ, Jiang T, Andrus RD (2000) Risk-based liquefaction potential evaluation using standard penetration tests. Can Geotech J 37:1195–1208. https://doi.org/10.1139/t00-064

Juang CH, Chen CJ, Jiang T (2001) Probabilistic framework for liquefaction potential by shear wave velocity. J Geotech Geoenviron Eng 127:670–678. https://doi.org/10.1061/(ASCE)1090-0241(2001)127:8(670)

Juang CH, Jiang T, Andrus RD (2002) Assessing probability-based methods for liquefaction potential evaluation. J Geotech Geoenviron Eng 128:580–589
Juang CH, Yuan H, Lee D-H, Lin P-S (2003) Simplified cone penetration test-based method for evaluating liquefaction resistance of soils. J Geotech Geoenviron Eng 129:66–80. https://doi.org/10.1061/(ASCE)1090-0241(2003)129:1(66)

Kayen RE, Mitchell JK, Seed RB, et al (1992) Evaluation of SPT-, CPT-, and shear wave-based methods for liquefaction potential assessment using Loma Prieta data. In: Proceedings of 4th Japan-U.S. Workshop on Earthquake-Resistant Des. of Lifeline Fac. and Countermeasures for Soil Liquefaction. pp 177–204

Krog A (2008) What are artificial neural networks? Nat Biotechnol 26:195–197

Ku CS, Lee DH, Wu JH (2004) Evaluation of soil liquefaction in the Chi-Chi, Taiwan earthquake using CPT. Soil Dyn Earthq Eng 24:659–673. https://doi.org/10.1016/j.soildyn.2004.06.009

Lee YF, Chi YY, Lee DH et al (2007) Simplified models for assessing annual liquefaction probability—a case study of the Yuanlin area. Taiwan Eng Geol 90:71–88. https://doi.org/10.1016/j.engegeo.2006.12.003

Lippmann RP (1987) An Introduction to computing with neural nets. IEEE ASSP Mag 4:4–22. https://doi.org/10.1109/MASSP.1987.1165576

Marcuson WF (1978) Definition of terms related to liquefaction. J Geotech Eng Div 104:1197–1200

Mayne PW, Coop MR, Springman SM, et al (2009) Geomaterial behavior and testing

Middlemiss CS (1885) Report on the Bengal earthquake of July 14, 1885. Rec Geologi Surv India 8(4):200–221

Morgan JP, McIntire WG (1959) Quaternary geology of the Bengal Basin, East Pakistan and India. Bull Geol Soc Am 70:319–342

Moroino M, Kamal ASMM, Muslim D et al (2011) Seismic event of the Dauki Fault in 16th century confirmed by trench investigation at Gabrakhari Village, Haluaghat, Mymensingh, Bangladesh. J Asian Earth Sci 42:492–498. https://doi.org/10.1016/j.jseaes.2011.05.002

Moroino M, Kamal ASMM, Akhter SH et al (2014a) A paleo-seismological study of the Dauki fault at Jaffpong, Sylhet, Bangladesh: historical seismic events and an attempted rupture segmentation model. J Asian Earth Sci 91:218–226. https://doi.org/10.1016/j.jseaes.2014.06.002

Moroino M, Monsur MH, Kamal ASMM et al (2014b) Examples of paleo-liquefaction in Bangladesh. J Geol Soc Jpn. https://doi.org/10.5575/geosoc.2014.0032

Oldham RD (1899) Report on the great earthquake of 12th June 1897. Mem Geologi Surv India 29:1–379

Olsen RS, Koester JP (1995) Prediction of liquefaction resistance using the CPT. In: Proceedings of the International Symposium on Cone Penetration Testing, CPT’95, Linkoping, Sweden, Vol. 2. SGS. pp 251–256

Olsen RS (1988) Using the CPT for dynamic response characterization. In: Proceedings of the Earthquake Engineering and Soil Dynamics II Conference. American Society of Civil Engineers, New York, pp 111–117

Olsen RS (1997) Cyclic liquefaction based on the cone penetration test. In: Proceeding of NCEER workshop on evaluation of liquefaction resistance of soils. National Center for Earthquake Engineering Research, State University of New York, Buffalo, pp 225–276

Rahman MZ, Siddiqua S (2017a) Evaluation of liquefaction-resistance of soils using standard penetration test, cone penetration test, and shear-wave velocity data for Dhaka, Chittagong, and Sylhet cities in Bangladesh. Environ Earth Sc 76:207. https://doi.org/10.1007/s12665-017-6533-9

Rahman MZ, Siddiqua S (2017b) Evaluation of liquefaction-resistance of soils using standard penetration test, cone penetration test, and shear-wave velocity data for Dhaka, Chittagong, and Sylhet cities in Bangladesh. Environ Earth Sc 76:1–14. https://doi.org/10.1007/s12665-017-6533-9

Rahman M, Siddiqua S, Kamal A (2015) Liquefaction hazard mapping by liquefaction potential index for Dhaka City, Bangladesh. Eng Geol 188:137–147. https://doi.org/10.1016/j.engegeo.2015.01.012

Rahman MZ, Siddiqua S, Kamal ASMM (2020) Seismic source modeling and probabilistic seismic hazard analysis for Bangladesh. Springer, Netherlands

Rahman MZ, Siddiqua S, Kamal ASMM (2021) Site response analysis for deep and soft sedimentary deposits of Dhaka City. Natural Hazards, Bangladesh. https://doi.org/10.1007/s11069-021-04543-w

Rahman Z, Siddiqua S (2016) Liquefaction resistance evaluation of soils using standard penetration test, cone penetration test, and shear wave velocity

Reimann K-U (1993) Geology of Bangladesh. Gebruder Borntraeger Verlagsbuchhandlung Science Publishers, Berlin

Robertson PK, Campanella RG (1985) Liquefaction potential of sands using the CPT. J Geotech Eng 111:384–403

Robertson PK, Wride CE (1998) Evaluating cyclic liquefaction potential using the cone penetration test. Can Geotech J 35:442–459. https://doi.org/10.1139/t98-017
Rumelhart DE, McClelland JL, Group the PR (1988) Parallel distributed processing, volume 1 explorations in the microstructure of cognition: foundations. Bradf Book 1:576
Rumelhart DE, Hinton GE, Williams RJ (1986) Learning representations by back-propagating errors. Nature. https://doi.org/10.1038/323533a0
Sassa S, Takagawa T (2019) Liquefied gravity flow-induced tsunami: first evidence and comparison from the 2018 Indonesia Sulawesi earthquake and tsunami disasters. Landslides 16:195–200. https://doi.org/10.1007/s10346-018-1114-x
Seed HB, Idriss IM (1967) Analysis of Soil liquefaction: Niigata Earthquake. J Soil Mech Found Division 93:83–108
Seed HB, Idriss IM (1971) Simplified procedure for evaluating soil liquefaction potential. J Soil Mech Found Division 97:1249–1273
Seed HB, Idriss IM (1982) Ground motions and soil liquefaction during earthquakes. Earthquake Engineering Research Institute Monograph, Oakland
Seed HB, Idriss IM, Arango I (1983) Evaluation of liquefaction potential using field performance data. J Geotech Eng 109:458–482
Seed HB, Tokimatsu K, Harder LF, Chung RM (1985) Influence of SPT procedures in soil liquefaction resistance evaluations. J Geotech Eng 111:1425–1445. https://doi.org/10.1061/(ASCE)0733-9410(1985)111:12(1425)
Seed HB, de Alba F (1986) Use of SPT and CPT tests for evaluating the liquefaction resistance of sands. In: Clemence SP (ed) Use of in situ tests in geotechnical engineering. Geotechnical Special Publication 6; Houston, pp 281–302
Seed HB, Tokimatsu K, Harder Jr. LF, Chung R (1984) The Influence of SPT procedures on soil liquefaction resistance evaluations. Report No. UCB/EERC-84/15, Earthquake Engineering Research Center, University of California, Berkeley
Sonmez H, Gokceoglu C (2005) A liquefaction severity index suggested for engineering practice. Environ Geol 48:81–91. https://doi.org/10.1007/s00254-005-1263-9
Stark TD, Olson SM (1995) Liquefaction resistance using CPT and field case histories. J Geotech Eng ASCE 121:856–869
Steckler MS, Akhter SH, Seeber L (2008) Collision of the Ganges-Brahmaputra Delta with the Burma Arc: Implications for earthquake hazard. Earth Planet Sci Lett 273:367–378. https://doi.org/10.1016/j.epsl.2008.07.009
Steckler MS, Mondal DR, Akhter SH et al (2016) Locked and loading megathrust linked to active subduction beneath the Indo-Burman Ranges. Nat Geosci 9:615–618. https://doi.org/10.1038/ngeo2760
Stuart M (1920) The Srimangal earthquake of 8th July 1918. Mem Geo Surv India 46(1):1–70
Tu JV (1996) Advantages and disadvantages of using artificial neural networks versus logistic regression for predicting medical outcomes. J Clin Epidemiol 49:1225–1231
Wang Y, Sieh K, Tun ST et al (2014) Active tectonic and earthquake Myanmar region. J Geophys Res Solid Earth 119:3767–3822. https://doi.org/10.1002/2013JB010762 Received
Yeats RS, Sieh K, Allen CR (1997) The geology of earthquakes. Oxford University Press
Youd BTL, Idriss IM, Andrus RD et al (2001) Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. J Geotech Geoenviron Eng 127:817–833

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.