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ORIGINAL PAPER

Geotechnical Characterization of Lacustrine Material of Kathmandu Valley, Nepal

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Abstract Kathmandu Valley, the capital region of Nepal, is a heavily populated, rapidly growing and haphazardly urbanized metropolis of the country, primarily seated upon lacustrine and fluvial origin deposits. The valley is situated in an earthquake-prone zone with a long history of catastrophic earthquakes, so the valley deposit is vulnerable to intense ground shaking and wide-area liquefaction during mid to major earthquakes. Although a few localized geotechnical studies have been conducted in the valley, holistic understanding, modelling, and geotechnical soil characterization are not well documented. In this study, based on the geotechnical properties of a large number of borehole materials, we put efforts in characterizing the Kathmandu Valley soil, 3D modelling of subsurface lithology and stratigraphy, mapping the geotechnical properties, and finally shedding light on the geotechnical characteristics of the valley subsoils. For this, we collected and analysed more than 400 borehole-based geotechnical investigation reports, and also specifically investigated 10 new test borehole locations and measured the standard penetration test (SPT-N) values along with the required laboratory tests. The methods for geotechnical characterization and result interpretation include Rockworks 3D model of lithology and stratigraphy and graphical and statistical presentation of the index properties (i.e. grain size distribution, dry unit weight, plasticity parameters, natural moisture content, Atterberg limits, etc.), consolidation parameters, shear strength, SPT-N value, and shear wave velocity. We basically focus on highlighting the statistical and spatial variations of the above soil properties with the depth. Moreover, a few correlations of the geotechnical properties are also established. We expect the findings of this study will aid structural and foundation engineers in studying foundations, cost estimation of geotechnical investigations, and planning and implementing various civil engineering projects.

Keywords Index properties · Shear strength · Three-dimensional modelling · Kathmandu Valley

Introduction

Kathmandu Valley covers 665 km^2 and is located at 1340 m average ground elevation. It receives an average annual rainfall of about 1500 mm per year, possessing an average humidity of 75% [64]. Kathmandu Valley is characterized by lacustrine and fluvial deposition in origin with a maximum thickness of 650 m [45]. The deposited sediments consist of interbedded clay, silt, sand, and gravel [32, 53] with a temporal and spatial variable shallow groundwater table [56].

With a more than 5 million population in total, the population density in urban areas exceeds 13,225 inhabitants per km^2 [29]. To cope with the growing population and increase economic and commercial needs, large-scale infrastructure development occurs at a high speed. The valley's urbanization has been fast, and all of the urban communities exhibit rapid expansion on their peripheral [12]. Additionally, the Kathmandu Valley is located in an earthquake-prone zone with a long history of deadly earthquakes. Being formed of

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lacustrine sediments with a strong capability for amplifying seismic waves [12], the valley is highly susceptible to damage if not given proper care during geotechnical investigations or subsoil characterization of the site.

Subsoil characterization is vital for geotechnical and geological designing associated with earthworks, structure foundations, forecast and comprehension of natural hazards, and environmental issues [2, 6, 27, 46]. Due to inadequate or incompetent subsurface characterization and assessment of soil strength, possible foundation-related failures or structure collapses may occur [15]. As a result of the variety and variance in subsurface conditions, thorough geotechnical evaluations of a building site are required in designing earthworks and structural foundations [36].

The trend of subsurface investigations has been expanding due to infrastructure construction in these years in the valley. Although the government and non-government sectors have carried out studies on subsoil's geotechnical characteristics for particular construction or research purpose, the geotechnical properties of Kathmandu soil are poorly documented. Dahal and Aryal [17] and Neeru and Dahal [33] have investigated the soils at different locations in Kathmandu Valley. However, both studies were limited in small areas, and research was confined to investigating few index properties of soil. De Risi et al. [19] and Gilder et al. [23] have presented the SAFER/GEO-591 containing data from groundwater wells and boreholes commissioned for research and commercial reasons. They described the variation of V_s and other geotechnical parameters with depth and geological cross-sections of the valley. Other studies include experimental investigation on the mechanical and physical behaviour of Kathmandu clay by Dahal et al. [16] and analysis and zoning of bearing capacity for shallow foundations by Danai and Acharya [18]. None of the previous studies has significantly characterized and modelled the valley subsoil in terms of geotechnical properties. Despite peak ground acceleration (PGA) being low (about 0.18 g) in Kathmandu Valley during the 2015 Earthquake, the damage level in some parts of the valley was extremely high. Several reconnaissance studies [14, 34, 50–52] conducted immediately after the earthquake reported that the damage was caused mainly by building mistakes and poor soil conditions. Though, no relevant geotechnical map based on a considerable amount of data was available at the time. Sharma and Deng [50] have also highlighted the lack of geotechnical information on the soil in the valley.

The building construction or development of any infrastructure needs an extensive soil investigation, which is expensive and time-consuming [62]. To reduce costs and shorten the time, geotechnical maps can be prepared using the data collected from several projects. Geotechnical map and soil properties data are often considered vital information for a construction project or infrastructure development and can be used in several ways and programmes such as urban planning and geohazards management [55]. Moreover, geotechnical maps can describe fast and easy access to bearing capacity, liquefaction potential, vertical settlement, and later spreading, which are unavoidable in foundation design [38, 39]. Few studies on the geotechnical properties of soil in Kathmandu Valley have been done. However, no study has ever used this volume of data, which increases the precision of the results and the trust in their application. Moreover, with propels in technology, the representation of 3D models is arising to beat the unpredictable nature of the subsurface soil [22]. In the past, Tonini et al. [65], Lelliott et al. [30], and Royse et al. [44] have utilized three-dimensional geological and geotechnical models at a variety of scales to suit the requirements of a variety of civil engineering applications. But, in the case of Nepal, the practice of 3D subsurface geological and geotechnical modelling is rare [60].

This research aims at collecting and analysing more than 400 previous geotechnical investigation data from different projects and boring 10 SPT-N boreholes with laboratory experiments. Correlations between the properties of statistical variability and histogram analysis are presented to get an overall perspective of the geotechnical properties of soil. Rockworks 2016 was used to prepare 3D models, lithology and stratigraphy of Kathmandu Valley subsoil. GIS mapping was used to show spatial variation of soil properties along different depths. The data presented and map prepared in this study can help urban planning, preliminary and feasibility studies, and land-use policies. This research also assists the geotechnical engineers beforehand to plan the comprehensive geotechnical investigation based on the provided geotechnical map and soil properties data. The presented work may serve as a basis for preliminary studies; however, it cannot replace the detailed investigation necessary for a project.

Study Area

Geology

The bowl-shaped Kathmandu Valley is mostly flat on its terrain except for some gorges created by river networks within the valley. The basement of Kathmandu Valley is formed by Bhimphedi and Phulchoki group (see Fig. 1). The Phulchoki group consists of un-metamorphosed or weakly metamorphosed sediments, predominantly limestone and underlain fluvial–lacustrine basin sediments; whereas, the Bhimphedi group is composed of metamorphic rocks with a reasonably high grade. Precambrian forms these to Devonian rocks [57]. Together, these rocks comprise the Kathmandu complex, which is tectonically interpreted as a thrust mass.

Kathmandu Valley basin's quaternary sediments are divided into three groups: Southern Group, Northern group,

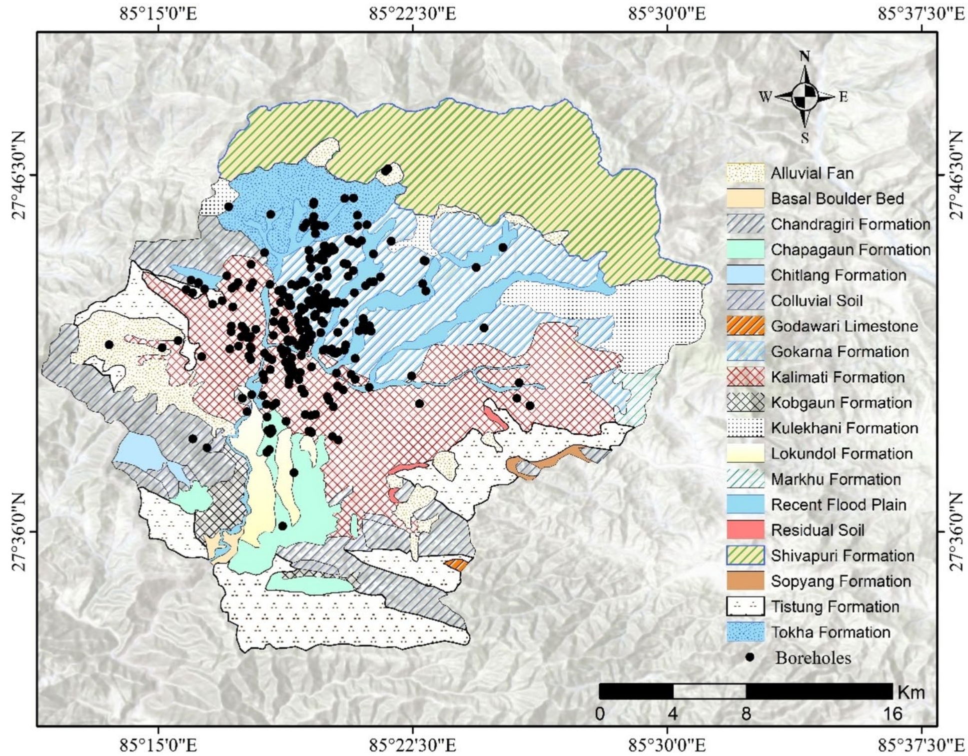


Fig. 1 Geological formation map of Kathmandu Valley (modified after Dhital [20]) with borehole locations

and Central group. Yoshida [67] confirms that the southern group comprises a steep terrace that dates from the Pliocene to the mid-Pleistocene. They are exposed along terraces and riverbeds and are classified as the Tarebhir, Lukondol, and Itaiti formations (Fig. 1). The core group may be split approximately into three sections. The bottom section is composed of the Bagmati formation, which was produced due to sediment deposition by the Bagmati River. The middle part consists of the Kalimati formation, predominantly dark grey carbonaceous and diatomaceous beds [45]. Additionally, the top section of the Patan formation is composed of medium to fine sand–silt that is mixed with fine gravels and clays in specific locations. And finally, the northern region consists of a terrace of sands from fluvial–deltaic or fluvial–lacustrine origins and consists of Thimi and Gokarna formation [45].

Seismic Setting

Kathmandu Valley lies within a seismically active region where the Indian and Eurasian tectonic plates meet, making it particularly susceptible to earthquake hazards [61]. The valley has a history of being affected by major earthquakes, such as the 1934 Bihar–Nepal earthquake (Mw 8.4) and the 2015 Gorkha earthquake (Mw 7.8), both of which resulted in widespread destruction of structures [1, 11]. The unique geotechnical features of Kathmandu Valley, such as soft, lacustrine deposits with low shear strength, lead to peak ground accelerations reaching up to 0.18 g, as observed during the Gorkha earthquake [51, 52]. With average shear wave velocities (V_s) in the upper 20 m typically below 200 m/s, the valley's soils are classified under NEHRP Site Class D or E. This classification highlights the susceptibility of valley to seismic amplification resulting from the combination of soft and stiff soil types. Additionally, the presence of silty sand and clay layers in the valley makes the soil prone to liquefaction, which was evident in various locations following the Gorkha earthquake [59]. Comprehensive evaluations of seismic effects in Nepal underscore the difficulties presented by geotechnical weaknesses, exacerbated by swift urban growth and infrastructural advancement [42]. Considering the seismic risks, it is important to carry out detailed geotechnical studies especially in areas of urban expansion to improve earthquake resilience and mitigate potential damage [23, 47, 48].

Construction Practice

In Kathmandu Valley, construction practices have considerably relied on shallow foundations because of their affordability, and there has been little emphasis on enforcing advanced geotechnical standards. However, rapid urbanization and population growth have led to an increased number of structures built in the valley. Most of the buildings are constructed on very loose or soft soil conditions with low SPT-N values, commonly under 10 [54]. Many foundations are also too shallow and do not include important ground strengthening techniques, such as vibro-compaction or soil mixing, which are often used in earthquake-prone areas. As a result, these buildings are more likely to experience uneven settlements and damage from liquefaction. Around 70% of the buildings damaged in central Kathmandu had shallow foundations. The post-Gorkha earthquake survey emphasizes the need for deeper foundation types and soil improvement methods. It is crucial to implement stronger regulations and standards to strengthen the resilience of valley to future earthquakes [26, 34].

Urbanization Trend

In recent decades, Kathmandu Valley has experienced rapid urban growth, with some areas now having over 13,225 people per square kilometre [29]. This expansion has led to the transformation of rural and peri-urban areas into densely populated zones. However, much of this development has occurred without adequate consideration of the underlying geotechnical conditions and creating potential risks. The subsoil of the valley present significant challenges for construction, primarily due to the mixture of silt, sand, and clay found in the area. This combination of soil type's results in a bearing capacity that ranges between 100 and 200 kN/m^2, and this issue is observed in approximately 43% of the mapped areas. The presence of this mixture of silt, sand, and clay significantly impacts the bearing capacity, making construction more difficult in these regions. With the rapid urban expansion in these areas, issues such as settlement, liquefaction risk, and soil–structure interaction have become increasingly significant [64]. In the central regions, 85% of borehole logs indicate weak subsoil profiles, with shallow SPT-N values below 20, emphasizing the prevalence of fine-grained, liquefiable soils [33]. To address these geotechnical challenges, urban planning should use soil data to guide land use based on stability and strength, helping prevent issues as the area develops [14].

Methodology

Data Collection

In Kathmandu Valley, the standard penetration resistance test (SPT) is the most often utilized in situ test. In Nepal, other approaches such as the cone penetration test (CPT) have not been deployed due to resource and technical constraints [52]. Thus, for this study, most of the data include borehole logs prepared for a different purpose. The uncorrected SPT numbers are corrected using the strategy proposed by Robertson and Wride [43]. For this study, both primary and secondary data were used. As primary data, geotechnical investigations (boreholes and SPT test) were conducted at ten different locations in Kathmandu Valley, five boreholes from the core city area and five from the 2015 Gorkha earthquake-induced liquefaction zones. As secondary data, about 400 soil investigation reports for various projects, including residential and public buildings, bridges, slope stability works, etc., were collected. The total number of boreholes collected for this study was more than 1500. All these boreholes were up to 20 m from ground surface. The locations of field investigation spread all over the valley are shown in Fig. 1. In addition to 1500 shallow borehole, 403 deep borehole data were collected from the Department of Mines and Geology and Nepal Water Supply Commission (NWSC). Out of 403 deep borehole data, 84 boreholes drilled up to the bedrock of Kathmandu Valley with maximum depth 577 m.

Moreover, several laboratories work on Kathmandu soil (e.g. particle size distribution, Atterberg's limits, dry unit weight, natural moisture content, triaxial tests, and ring shear tests) were analysed for the geotechnical characterization of Kathmandu soil. In addition, 108 shear wave velocity data and 26 primary wave velocity data were collected and presented.

Data Analysis

The data analysis involved a thorough examination of soil samples and borehole logs from over 400 investigations across Kathmandu Valley. We used statistical tools such as mean, standard deviation, and coefficient of variation to analyse the depth-wise trend of soil properties such as bulk density, specific gravity, and shear strength, and corrected the standard penetration test (SPT) N-values by Robertson and Wride [43] to account for overburden pressure differences, ensuring consistency in soil strength assessments. This adjustment enabled a uniform evaluation of soil strength characteristics across different locations. Additionally, we utilized GIS for geospatial analysis and mapped the key soil parameters such as fines content and plasticity indices using inverse distance weighting (IDW). This approach enabled the visualization of the spatial distribution of critical geotechnical properties to identify areas prone to liquefaction and settlement which are crucial for geotechnical risk assessment in urban planning.

Properties Investigated

The investigation aimed to measure and analyse important soil properties to better understand the geotechnical conditions of Kathmandu Valley especially in terms of construction and seismic risk. Firstly, the bulk density of the soil was measured, which helped us understand its consistency and identify how the density changes with depth. By performing specific gravity tests, following ASTM standards, we were able to evaluate the mineral content of the soil and determine its void ratios, which are essential for understanding the compressibility of soil. In addition, plasticity tests were conducted, including liquid limit (LL) and plasticity index (PI) measurements, to assess the behaviour of soil under seismic loading and to understand its potential for liquefaction during an earthquake. The strength properties of soils were assessed by measuring undrained shear strength (Cu) and conducting ring shear tests. These tests provided us with crucial data on cohesion and friction angles, which are vital for designing stable foundations and ensuring slope stability [41]

Shear wave velocity (V_s) measurements were another important part of the study that helped classify the soil and evaluate its potential for seismic amplification. To understand how the soil would compress under pressure, consolidation tests were performed, which gave a valuable information on the soil's compression index (Cc) and other related properties. By combining all these measurements, a detailed geotechnical profile of Kathmandu Valley's soils were created, which is essential for designing safer and more resilient infrastructure that can withstand seismic events.

Results and Discussion

Groundwater Table

Groundwater table (GWT) directly affects the stability structure and their foundations due to change in mechanical properties of soil, pore pressure, and effective stress beneath the foundation. For this study, the GWT was obtained from borehole log information. In addition, the GWT map prepared by Shrestha et al. [56], as shown in Fig. 2, was also considered. The average depth to GWT was 6.85 m, with a maximum GWT of 0.5 m and a minimum GWT of 30.5 m. Additionally, elevated GWT was reported along the valley's major rivers. Seasonal change in groundwater level indicates that the Kathmandu Valley has a high GWT during the monsoon season in September [26]. The valley's elevated GWT during the Monsoon season (June to September) implies a heightened danger of liquefaction in the event of an earthquake between June and September. The dry season's low GWT (October–May) might be attributable to limited and localized liquefaction caused by the 2015 Gorkha Nepal earthquake [51, 52]. In Fig. 3, GWT is

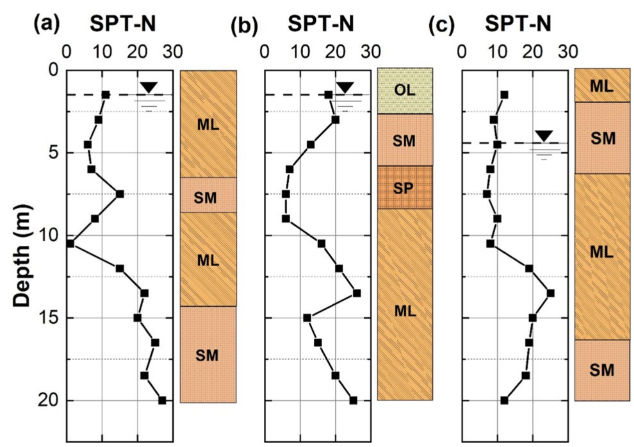


Fig. 3 Typical stratigraphy profiles observed GWT and SPT of **a** Manamaiju, **b** Ramkot, and **c** Tundikhel

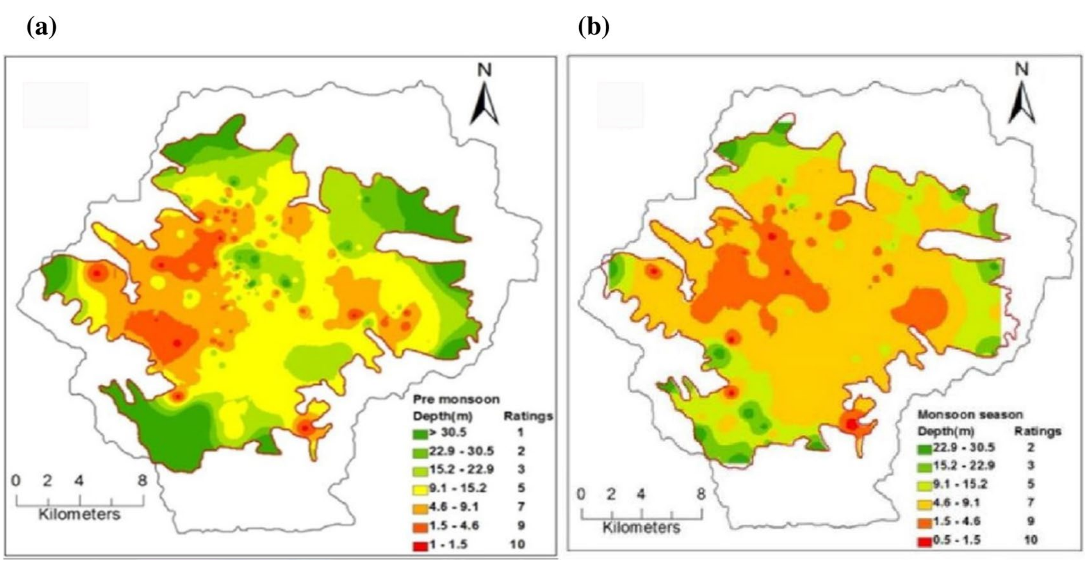


Fig. 2 Groundwater table maps of Kathmandu Valley for **a** pre-monsoon period and **b** monsoon period [56]

observed as 1.5 m, 3 m, and 4 m for Ramkot, Bungmati, and Tundikhel, respectively.

Stratigraphy

The geotechnical investigations reveal that the top 20 m of soil in the valley contains a complex and stratified profile. A depth up to 20 m was considered for this study as this depth is good enough for the shallow foundation for residential buildings and low story commercial or public buildings. Mostly grey to dark, silty sand and clayey silt are abundant throughout the valley, with wide variations in soil characteristics [51]. Up to 1 m depth, organic clay, fine sand beds, and peat layers are commonly termed a crust layer on the surface. Dark grey sandy silt dominates the majority of the investigation locations just under the crust layer. Below this layer comes silt with low plasticity followed by silt with medium plasticity; the resultant layer is often composed of stiff clay with low-to-medium plasticity. Typical soil profiles with SPT-N values are presented in Fig. 3. The borehole at Manamiju consists of a layer of silty sand and low plastic silt. The case mostly looks similar to both Ramkot and Tundikhel, as shown in Fig. 3. In all scenarios, the SPT value increases with depth. Thus, the top 5 m depth soil is observed as stiff and then becomes very stiff and hard with increased depths.

Geotechnical Properties

Three-dimensional Modelling

Boreholes ranging in depth from 15 to 20 m were used to model the lithology and stratigraphy of the Kathmandu Valley using Rockworks 2016. Vertical exaggeration (VE) 15 shows the three-dimensional lithological and stratigraphic models in Fig. 4. The 3D lithological model is constructed using the litho mix solid modelling methodology, while the 3D stratigraphic model is built using the inverse distance weighted (IDW) interpolation approach. The unified soil classification system is used to classify soil types (USCS) [5]. The Kathmandu Valley's 11 major lithologic categories (CH, CL, GM, GP, GW, MI, ML, SC, SM, SP, and SW) are depicted as spatially repeating sequences with substantial geographic variation in terms of their occurrence, the thickness of individual categories, and top and bottom elevations of each layer.

The lithological model's results (Fig. 4a) demonstrated a diverse variety of lithologic categories that change spatially following the presence of SM and ML litho layers. As a result, a lithologic model depicts the subsurface in three dimensions. Visualization of subsurface data is a critical use of 3D modelling for sustainable development planning. This model, in particular, directly captures heterogeneity in three dimensions. Due to the model's dependence on interpolation approaches to fill the gaps between the boreholes, it is worth noting that the lithologic representation between the boreholes may not accurately reflect reality. It is advised that additional boreholes be utilized for prediction purposes to attain a finer resolution and more accurate findings. Thus, the suggested model aided in conceptualizing the subsoil characterization of the studied area, which will be utilized to locate, define, and identify geo-objects of various types and shapes and their lateral and vertical expansions in the subsurface.

Additionally, it is critical for future research in geotechnical property modelling, settlement analysis, liquefaction evaluation, picking an appropriate foundation kind, groundwater flow modelling, contaminant transport modelling, and choosing a relevant geotechnical exploration towards parameters of geologically weak areas [21, 63] (Ozcelik and

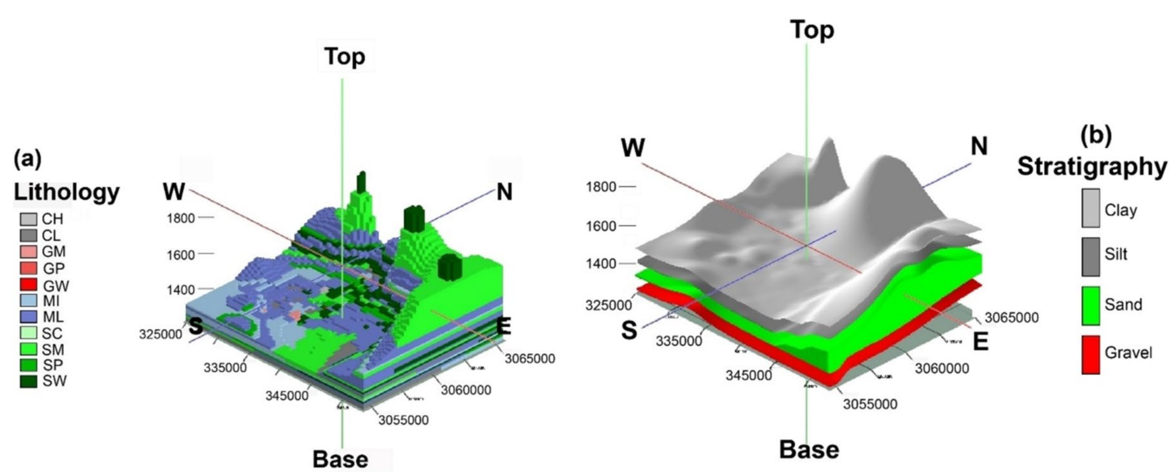


Fig. 4 **a** Lithological and **b** stratigraphic model of Kathmandu soil up to 20 m depth using Rockworks 2016 (VE:15)

Yeniceli 2015). Similarly, the soil was classified generally into clay, silt, sand, and gravel for the stratigraphy model. According to the model, the Kathmandu soil comprises a clay and silt layer up to a few metres below the ground level, followed by sand and gravel (Fig. 4b).

Statistical Analysis

The soil in Kathmandu Valley is diverse and layered at shallow depths. The heterogeneity results from lithological variation, natural soil variability, and exposure to varying overburden forces in different places. Thus, if the probability distribution for any measurable characteristic is known, it is critical to do statistical analysis to identify their geotechnical properties. According to prior research, the normal distribution fits most of the index, consolidation, and shear strength parameters of many natural soils [3, 28]. As a result, the current analysis used the standard distribution to provide a general characterization for Kathmandu soils. The number of data (n), minimum value, maximum value, mean value (μ), standard deviation (σ), and coefficient of variation (COV) were calculated for each soil property. The list of geotechnical properties, number of data, minimum and maximum value with *μ, σ, and* COV are summarized in Table 1.

As illustrated in Fig. 5, the statistical details and histograms were created with depth to determine the variance of soil with depth. We utilized Weibull and lognormal distributions to describe the statistical behaviour of soil parameters, informed by their data characteristics and applicability as stated in the previous studies. The Weibull distribution, recognized for its adaptability in modelling skewed data, was utilized for undrained shear strength (Cu) and plasticity index (PI), in accordance with Chen and Wang [13], where it successfully represented analogous dataset patterns. The lognormal distribution was employed for bulk density (γ), natural water content (w_n), and liquid limit (LL), as these characteristics had positively skewed distributions, consistent with the results of Griffiths and Fenton [24], which demonstrated that lognormal models effectively captured geotechnical variability. Goodness-of-fit tests confirmed the selected models, and Fig. 5a–l demonstrates their correspondence with the respective histograms, underscoring the justification for their selection. These models improve the characterization and prediction comprehension of the soils in the Kathmandu Valley.

Figure 5k presents a dataset of primary wave velocity (V_p) consisting of merely 26 data points, hence constraining the statistical robustness for fitting a lognormal distribution. The lognormal distribution was utilized because of its theoretical appropriateness for positively skewed data; nevertheless, the limited sample size presents validation issues. To resolve this, supplementary investigations contrasted the lognormal distribution with alternative distributions, such as normal and Weibull, employing goodness-of-fit measures. The results demonstrated that the lognormal distribution offered the most accurate fit, notwithstanding the constrained dataset.

Table 1 Variability and statistical representation of geotechnical properties of Kathmandu soils

Property	Number of data (n)	Min	Max	Mean (μ)	Standard deviation (σ)	COV (%)
Bulk density, γ (kN/m^3)	166	9.8	22.34	18.14	1.83	10.09
Specific gravity, G_s	302	1.89	2.89	2.59	0.15	5.79
Natural water content, w_n (%)	455	5.38	98	39.94	20.08	50.28
Plastic limit, PL (%)	239	15.2	50.98	29.12	7.84	26.91
Liquid limit, LL (%)	239	22.8	69.12	44.29	11.29	25.49
Plasticity index, PI (%)	239	1.73	34	15.13	6.26	41.34
PL/LL	239	0.34	1.14	0.67	0.11	17.08
Standard penetration test, SPT (N)	1167	0	50	15.5	11.14	71.87
Undrained shear strength, C_u (kPa)	119	1.3	178.48	61.50	33.65	54.72
Cohesion, C (kPa)	102	0	29	11.63	7.11	61.17
Friction angle, ϕ (°)	120	6.2	40	22.60	8.42	37.26
Compression index, C_c	59	0.033	0.95	0.284	0.193	67.82
Coefficient of compressibility, m_v (cm^2/kg)	53	0.00013	0.417	0.109	0.117	106.33
Coefficient of consolidation, C_v (cm^2/s)	67	0.0002	1	0.18	0.271	150.34
Recompression index, C_r	5	0.025	0.08	0.047	0.023	50.32
Shear wave velocity, V_s (m/s)	108	65	432	208.37	88.72	42.58
Primary wave velocity, V_p (m/s)	26	246	1677	999.58	449.29	44.95
Fines content (%)	933	0	100	52.24	36.69	70.24

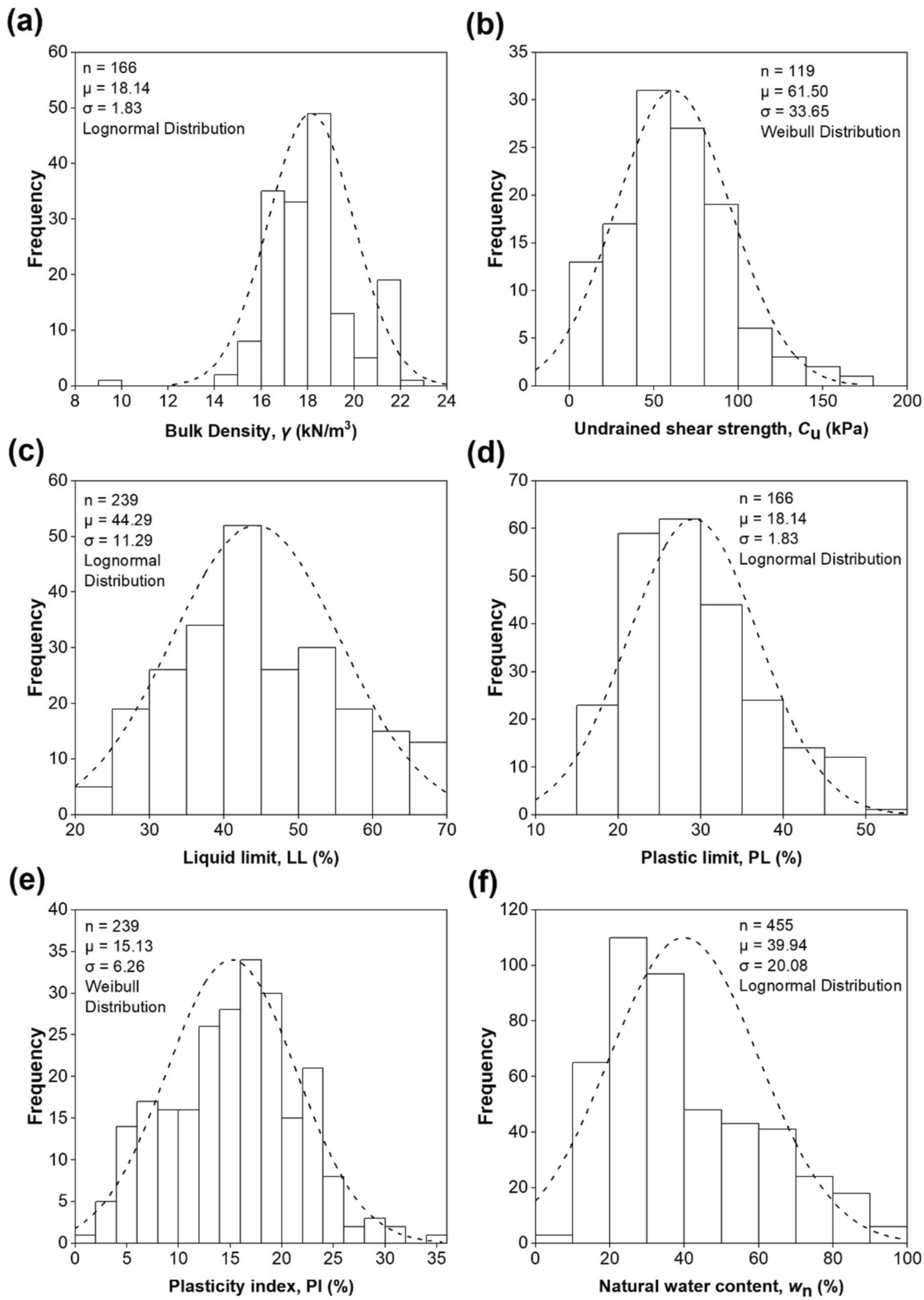


Fig. 5 Histogram and distribution function of the Kathmandu soil properties, **a** γ, **b** C_u, **c** LL, **d** PL, **e** PI, **f** w_n, **g** G_s, **h** C, **i** ϕ, **j** V_s, **k** V_p, and **l** C_c

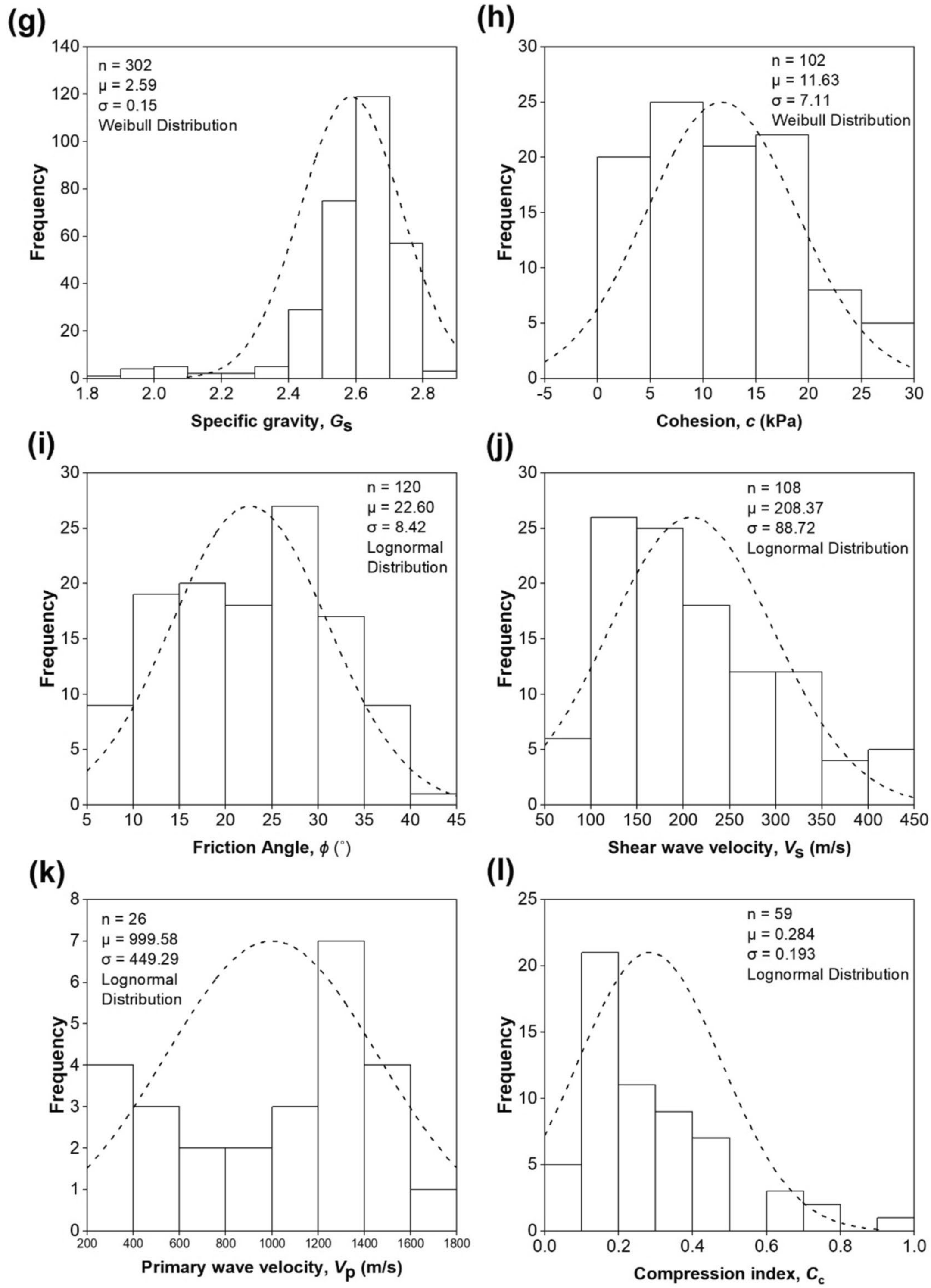


Fig. 5 (continued)

Particle Size Distribution

The percentage of various sizes of soil particles was determined utilizing particle size analysis. The particle size distribution graph shown in Fig. 6 shows that silty sand is abundant in Kathmandu soil. In addition to this, two sets of grain size curves showing the particle size distribution ranges for most liquefiable and potentially liquefiable soils

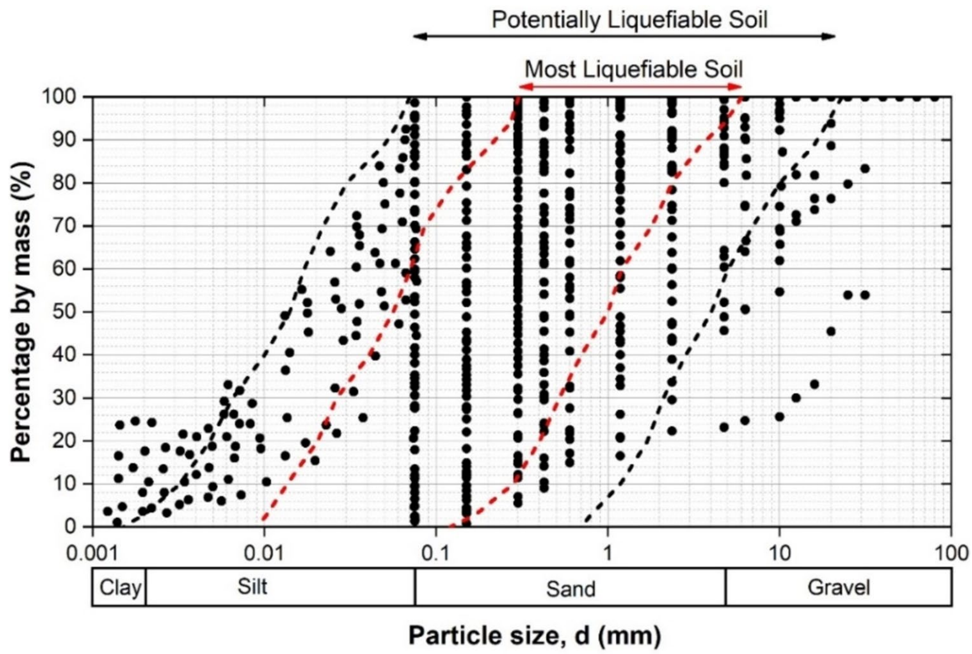


Fig. 6 Particle size distribution with a range of liquefiable soils given by Tsuchida and Hayashi [66]

proposed by Tsuchida and Hayashi [66] are also plotted. The majority of the gradation curves are seen to fall inside the border of possibly liquefiable soil. Figure 6 shows that particle size distribution is high inside the potentially liquefiable soil zone and highest inside the zone of most liquefiable soil. It strongly suggests that the soil in Kathmandu is highly susceptible to liquefaction considering high GWT.

Standard Penetration Test (SPT-N) Value

SPT-N is an in situ penetration test designed to provide basic information about the geotechnical properties of the soil. It is often used to determine the consistency of stiff or stony cohesive soils and weak rocks by repeatedly striking the ground with a hammer falling through 76 cm. The measured SPT blow count (N) is normalized for overburden stress at the test depth and adjusted to a standardized value of $(N_1)_{60}$ using Robertson and Wride [43] suggested correction parameters. This test is prevalent for the ground investigation in Kathmandu Valley. Averaging blow counts per 300 mm has been extensively utilized to assess the in situ state of Kathmandu soils. Corrections for overburden and high hammer energy were calculated later for the study using the formula given by Robertson and Wride [43].

Analysing SPT data from more than 400 projects with 1500 boreholes, the SPT-N values of soil layers lying in the central part were less than the outer part of the valley. The central part denotes the main urban areas—the geographical nucleus of the valley—primarily encompassing locations such as Kathmandu Metropolitan City and Lalitpur Metropolitan City, characterized by thicker sedimentary deposits and less compact soil. The outer section denotes the periphery regions of the valley, adjacent to the surrounding hills, where bedrock is more superficial, resulting in elevated SPT values. These disparities underscore the impact of geological factors on SPT-N values, with peripheral regions exhibiting more stable and compact soil profiles. Most of the shallow depth soil is silt and silty sand (Fig. 4). The SPT-N values of about 85% of the borehole test data were found less than 20, and more than 50% have SPT-N values less than 10 in shallow depth in the core area of the valley. The average SPT-N value of Kathmandu soil at depths 1.5 m, 3 m, 6 m, 9 m, and 15 m were 12, 15, 18, 20, and 23, respectively, with overall $\mu = 15.5$, $\sigma = 11.14$, and COV = 71.87%. Typical SPT profiles at three different locations in the study are presented in Fig. 3, whereas the distribution pattern of SPT in 1.5 m depth and 3.0 m depth is shown in Fig. 7. The variation of SPT-N with depth for Kathmandu Valley is shown in Fig. 8a.

Specific Gravity (G_s)

Specific gravity (G_s) is a critical parameter in evaluating the engineering behaviour of the soil. The value of G_s is used to calculate the void ratio, compressibility coefficient, degree of saturation, and other soil parameters. In general, a higher value of G_s indicates mineral soil and higher strength. In the study area, the value of the specific gravity of soil is between 1.89 and 2.89 ($\mu = 2.59$, $\sigma = 0.15$, and COV = 5.79%) (Fig. 8b). The low specific gravity (< 2.5) might be attributed to the organic soil at the top. The average value of G_s as 2.59 indicates the high presence of silty sand in the valley.

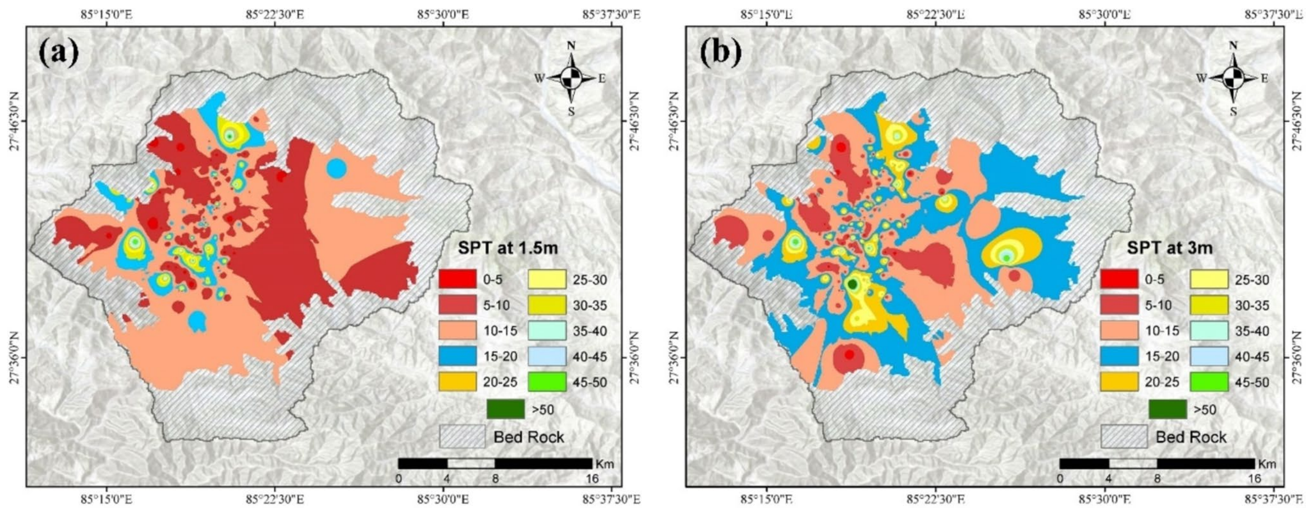


Fig. 7 SPT zoning map of Kathmandu Valley for **a** 1.5 m depth and **b** 3.0 m depth

Fines Content (FC)

The fines content (FC) of sandy soils is critical in the engineering design of geotechnical buildings, particularly in earthquake-prone areas [35]. The quantity of FC in soil has a considerable effect on its relative density and liquefaction potential [31]. The variation of FC with depth in Kathmandu soils is shown in Fig. 8c. The value of FC ranges from 0 to 100%, with a mean of 52.24, standard deviation of 36.69, and a coefficient of variation of 70.24%. Figure 7 shows that most parts of the valley have low FC in shallow depth. Sand and silt with low FC might be attributed to liquefaction at several locations in Kathmandu Valley during 2015 Gorkha Nepal, even though the peak ground acceleration (PGA) earthquake (~0.18 g) was much smaller than that expected (i.e. 0.30 g).

Liquid Limit and Plastic Limit

The lowest water content at which soil transitions from a plastic to a fluid state is the liquid limit (LL). More than 40% of the borehole locations considered in this study have less or equal 35% with $\mu = 44.29$, $\sigma = 11.29$, and COV = 25.49%. Sandy soil with LL less than 35 indicates the high probability of liquefaction [7, 8, 37]

The plastic limit (PL) of soil is defined as the lowest water content at which it disintegrates (plastic behaviour). In comparison with silt, clay contains smaller particles and a higher PL. In Kathmandu Valley, PL values were found between 15.2 and 50.98% during the study ($\mu = 29.12$, $\sigma = 7.84$, and COV = 26.91%). The variation of LL and PL with depth is presented in Fig. 8d, e.

Plasticity Index (PI)

A measure of the range of water content within which soil behaves plastically is called the plasticity index (PI). If the plastic limit is equal to the liquid limit, the plasticity index is treated as zero. For most soils in Kathmandu Valley, PI value ranges from 10 to 20% ($\mu = 15.13$, $\sigma = 6.26$, and COV = 41.34%). The variation of the plasticity index (%) with depth (m) is presented in Fig. 8f. The average LL and PI values were found to be 44.29% and 15.13%. This clearly shows the abundance of medium plasticity soils in the Kathmandu Valley.

Additionally, 1.5 m, 3.0 m, and 6.0 m LL and PI values are imported into ArcGIS. To determine the spatial distribution of LL and PI, the values are interpolated over a selected area in Kathmandu Valley. The thematic maps (Figs. 9 and 10) illustrate the geographic variance in soil type at 1.5, 3.0, and 6.0 m depths in Kathmandu Valley. All of these maps are divided into six major zones, each with its distinct colour scheme. At 1.5 m deep (Fig. 9a), a large area of the map is covered with light green and yellow hues, indicating the presence of silt and clay content greater than 50%.

Similarly, at depths, 3.0 m and 6.0 m, the higher values LL of the soil are shown in Fig. 9b, c. The spatial variation of the plasticity index with depths is given in Fig. 10. It can be seen that with increasing depth, the sand and silt content in soils increases significantly.

Plasticity Chart

Figure 11a shows the plasticity chart based on Casagrande [10] of all cohesive soils taken for this study. Figure 11a reveals that most fine-grained soils are silt and exhibit

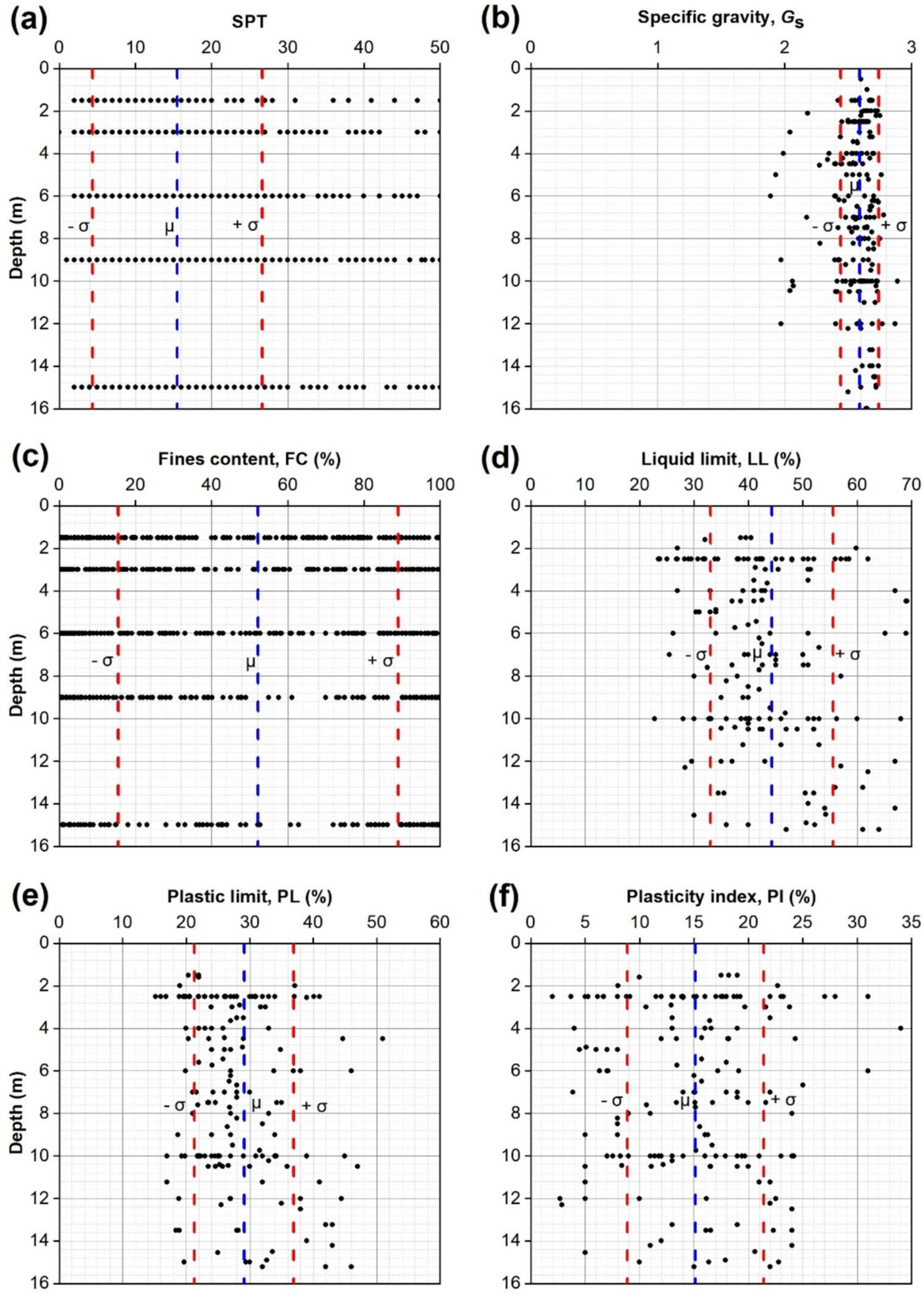


Fig. 8 Index and strength properties of soil versus depth: **a** SPT, **b** G_s, **c** FC, **d** LL, **e** PL, and **f** PI

medium to high swelling characteristics. This is essential information for liquefaction analysis, as low plasticity silts are mostly more susceptible to liquefaction during the earthquake [4, 7, 40]. The liquefaction susceptibility criteria suggested by Seed et al. [49] are also presented in the same figure.

The value of LL and PI for clayey soil (CL and CH) is plotted together in Fig. 11b to develop the relationship between PI and LL. The relation between PI and LL was obtained as follows, with an R^2 of 0.84.

$$\mathrm{PI} = 0.708\mathrm{LL} - 9.584,\ R^2 = 0.84 (n = 144)$$

Natural Moisture Content (w_n)

Natural moisture content (w_n) or water content of the soil is a vital soil parameter that significantly influences soil behaviour, particularly for cohesive soil. The mechanical behaviour of the soil substantially relies on the water content. Figure 12a presents natural moisture content versus depth.

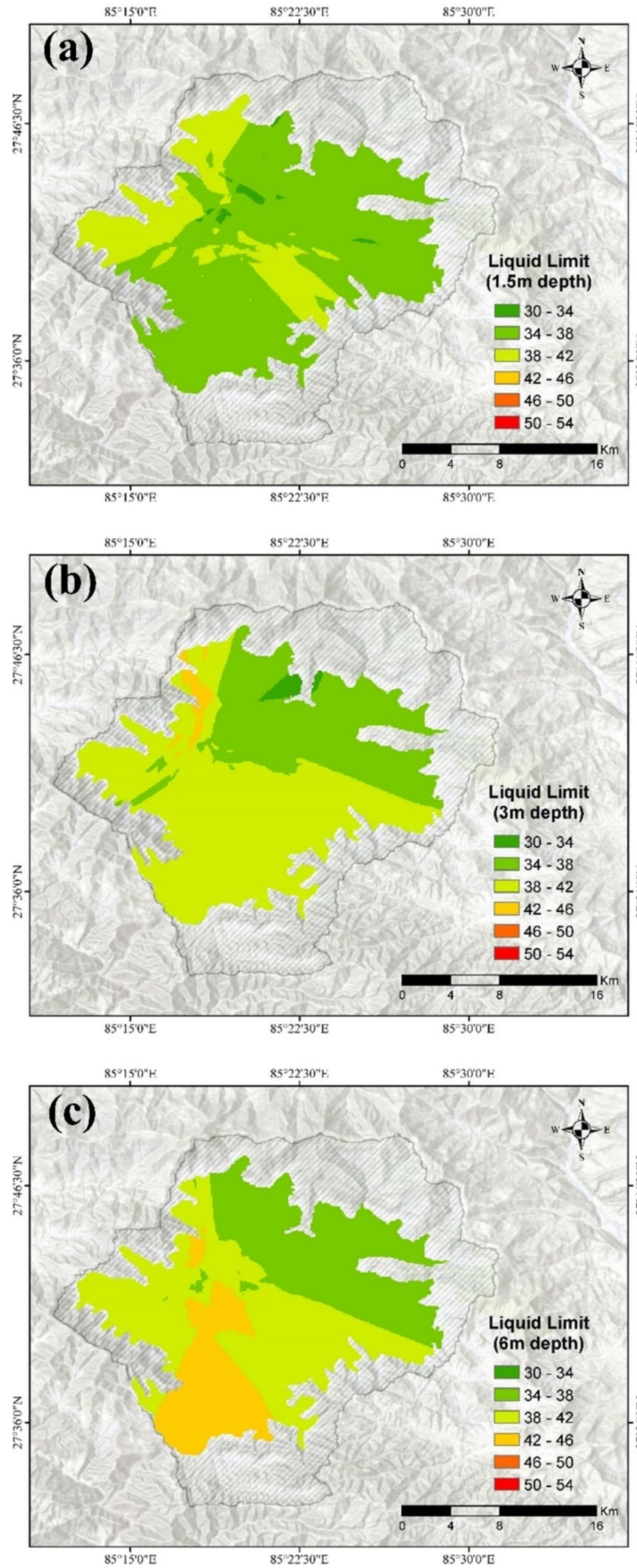
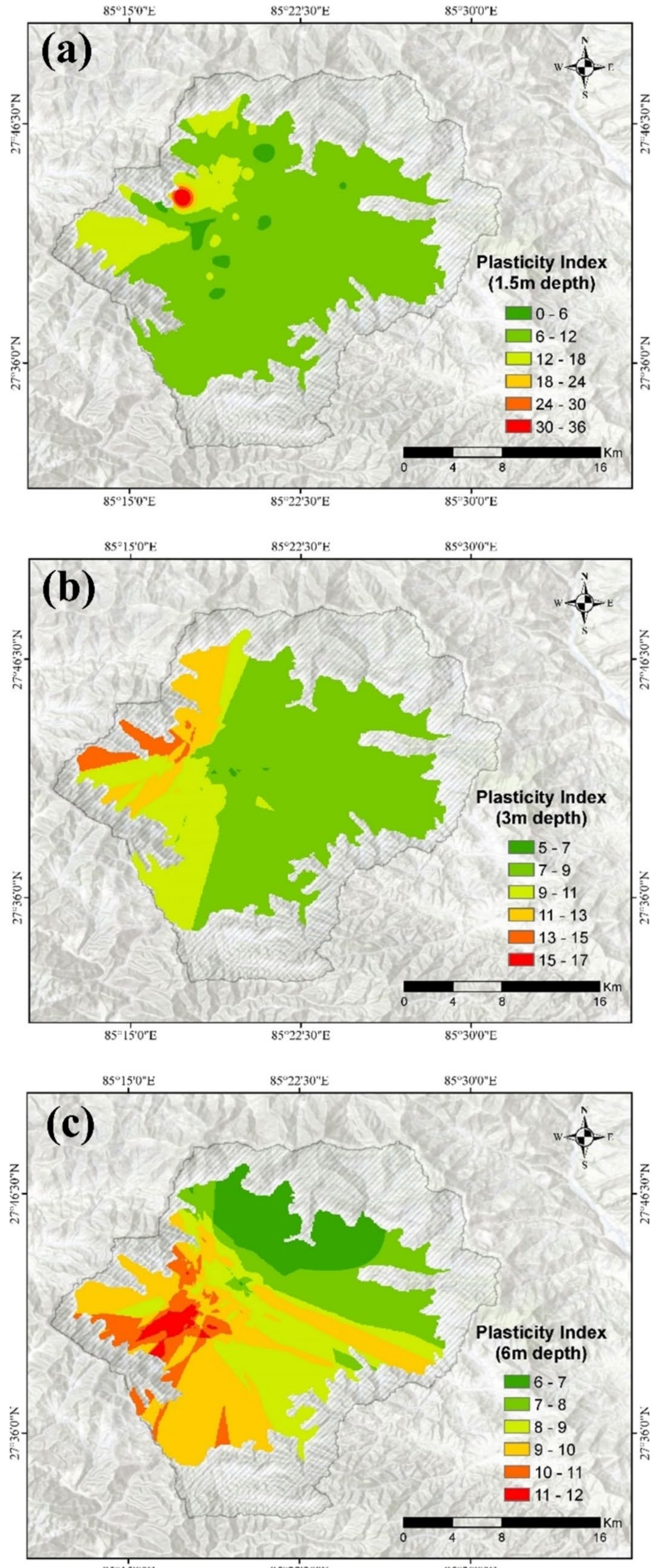


Fig. 9 Spatial variation of LL with depth, **a** 1.5 m, **b** 3.0 m, and **c** 6.0 m

Fig. 10 Spatial variation of PI with depth, **a** 1.5 m, **b** 3.0 m, and **c** 6.0 m



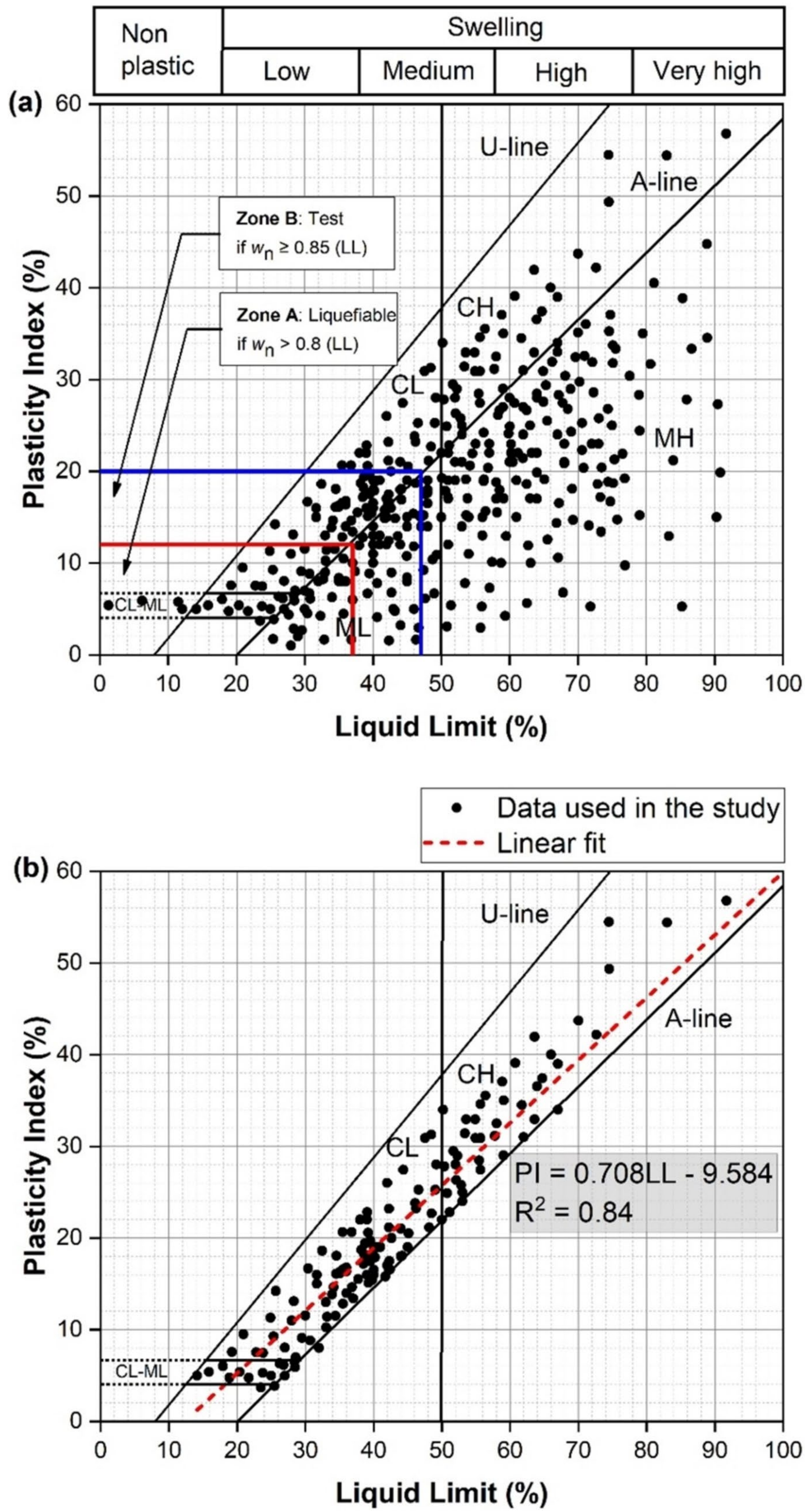


Fig. 11 **a** Fine-grained soils plotted in Casagrande's plasticity chart with liquefaction criteria by Seed et al. [49] and **b** linear variation of PI and LL for Kathmandu clay

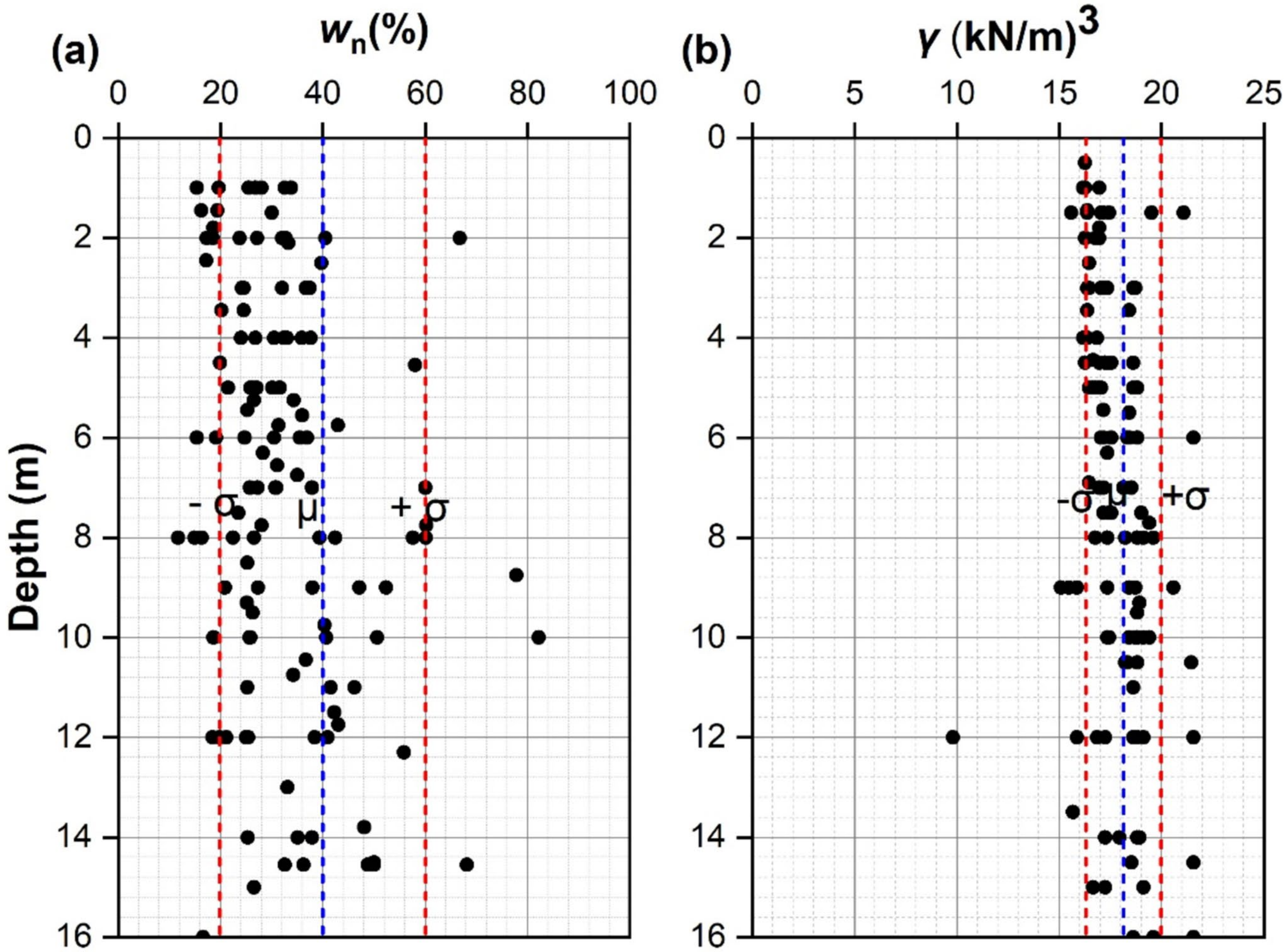


Fig. 12 **a** w_n and **b** γ versus depth (m)

The data show that most samples have a moisture content ranging from 20 to 40% (Minimum = 5.38, Maximum = 98, $\mu = 39.94$, $\sigma = 20.08$, and COV = 50.28%). The natural moisture content of the soil can be changed throughout the year, similar to the temporal variation of GWT in the valley.

Bulk Density (γ)

The density of soil can be related to the mechanical properties of soil. Generally, the higher the density of soil, the lower the void ratio and higher the strength. The bulk density (γ) of Kathmandu soil was observed in between 9.80 and 22.34 kN/m^2. The mean, standard deviation, and coefficient of variation values are 18.14, 1.83, and 10.09%. The variation of γ with depth is demonstrated in Fig. 12b.

Shear Strength Test

Unconsolidated undrained (UU) and unconfined compressive strength (UCS) tests are two commonly used strength tests in Nepal. Consolidated drained (CD) and consolidated undrained (CU) are used rarely because of technology and cost constraints. Both UU and UCS tests were conducted on the undisturbed samples collected during the geotechnical investigation. Most of the soils in this study possess undrained shear strength at failure (s_u) ranging from 30 to 90 kPa (Fig. 13). The overall strength values range from 1.3 to 178.48 kPa ($\mu = 61.50$, $\sigma = 33.65$, and COV = 54.72%).

Moreover, the values of s_u were inserted in GIS, and interpolation was performed. The spatial variation of s_u at depth 3.0 m is shown in Fig. 14. Undrained shear strength estimation is a critical issue for geotechnical engineers [68].

Ring Shear Test

Ring shear tests are used to determine the drained residual strength at large displacement. The cohesion and friction angle values obtained from the ring shear test are plotted against depth, as shown in Fig. 15. The value of c found between 0 and 29 kPa ($\mu = 11.63$, $\sigma = 7.11$,

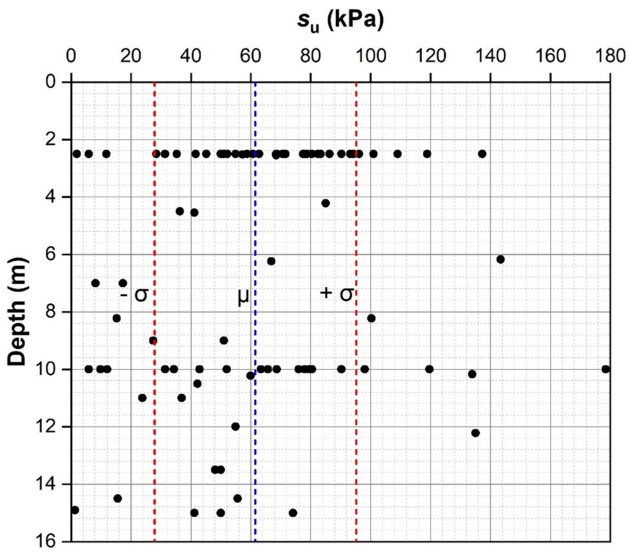


Fig. 13 The variation of s_u versus depth (m) in Kathmandu Valley

and COV = 61.17%), and ϕ varied from 6.2° to 40° with $\mu = 22.60$, $\sigma = 8.42$, and COV = 37.26%).

Primary and Shear Wave Velocity

Primary and shear wave velocity are critical soil parameters for seismic analysis and design. A total of 26 primary wave velocity (V_p) and 108 shear wave velocity (V_s) data used in this study were adopted from Gilder et al. [23]. Shear wave velocity is a mechanical feature of soil that may be advantageously studied in both natural and controlled conditions. The value of V_s can be used to determine the shear modulus of soil and evaluate the liquefaction potential of the soil. Table 2 shows the soil types based on shear wave velocity given by National Earthquake Hazards Reduction Program—NEHRP [9]. The measured V_s values are generally used in conjunction with other in situ (e.g. SPT test) and laboratory (e.g. adequate confining pressure) measurements to create a significant number of V_s-based correlations that could later be utilized to enhance designated testing [25]. Figure 16a shows that most of the soil samples have shear wave velocity within the range of 75–360 m/s, indicating soft to stiff

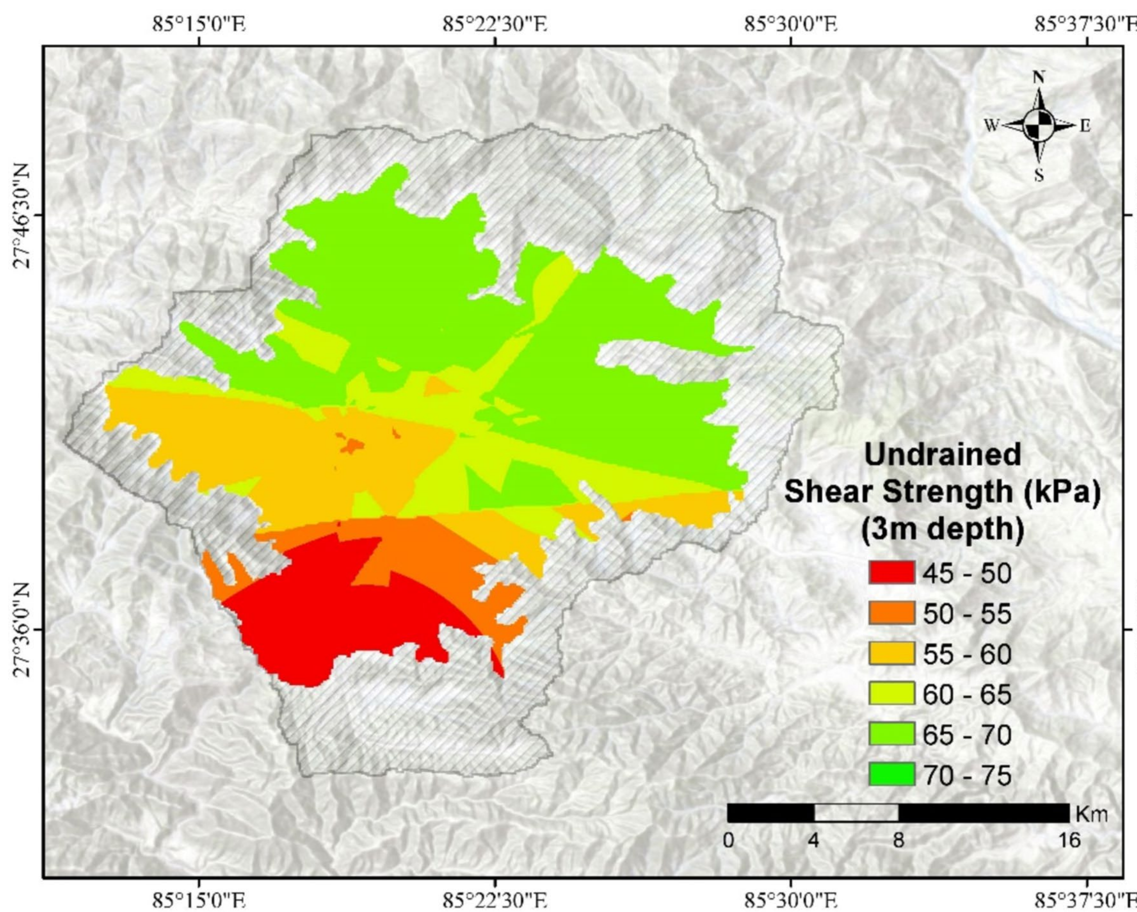


Fig. 14 Spatial variation of s_u of the Kathmandu soil at a depth of 3.0 m

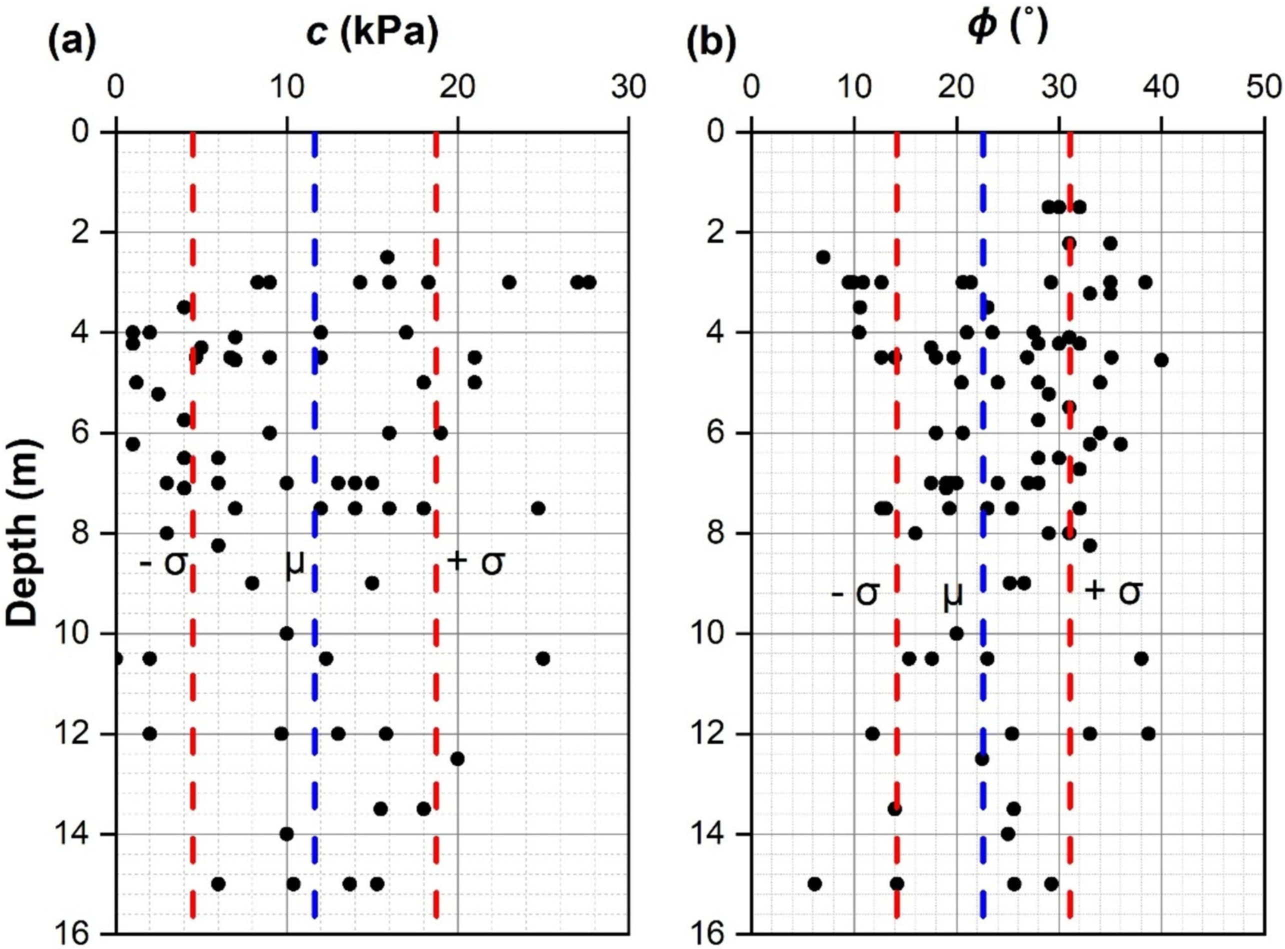


Fig. 15 Variation of **a** c and **b** ϕ with depth (m)

Table 2 NEHRP soil types based on shear wave velocity of upper 30 m

Soil types	Rock/soil description	Average shear wave velocity (V_s) m/s
A	Hard rock	> 1500
B	Rock	760–1500
C	Dense soil/soft rock	360–760
D	Stiff soil	180–360
E	Soft soil	< 180
F	Special soils requiring special evaluation	

type layers as shown in Table 2 [9]. Moreover, the value of shear wave velocity at a shallow depth less than 200 m/s. This might be attributed to several liquefactions observed at shallow depth during the 2015 Gorkha earthquake [51, 58]. Regardless of depth, V_s ranges from 65 to 432 m/s ($\mu = 208.37$, $\sigma = 88.72$, and COV = 42.58%). Whereas primary wave velocity has minimum and maximum values of 246 m/s and 1677 m/s, respectively, with $\mu = 999.58$, $\sigma = 449.29$, and COV = 44.95%. The variation of V_p with depth is shown in Fig. 16b.

Consolidation Properties

The data from the 1D oedometer test were collected to characterize the compressibility behaviour of the soil in Kathmandu Valley. Compression index (C_c) for Kathmandu soil was observed between 0.033 and 0.95 ($\mu = 0.284$, $\sigma = 0.193$, and COV = 67.82%), while coefficient of compressibility (m_v) values was in the range of 0.00013–0.417 cm^2/kg ($\mu = 0.109$, $\sigma = 0.117$, and COV = 106.33%). The value of Cc ranges from 0.033 to 0.95 indicates the highly compressible soil in the valley. Kathmandu soil had a coefficient of consolidation (C_v) values in the range of 0.0002–1 cm^2/s ($\mu = 0.18$, $\sigma = 0.271$, and COV = 150.34%). Recompression index (C_r) data ranged between 0.025 and 0.08 ($\mu = 0.047$, $\sigma = 0.023$, and COV = 50.32%). Variation of C_c, m_v, C_v, and C_r with depth is shown in Fig. 17.

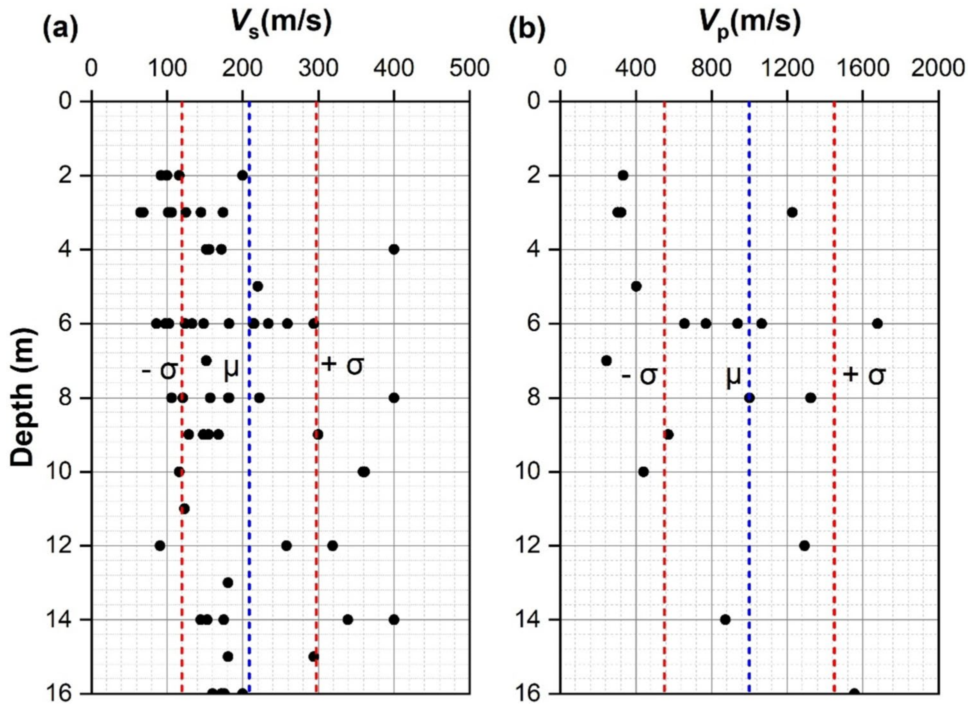


Fig. 16 Variation of **a** V_s and **b** V_p with depth (m)

Concluding Remarks

Following are the major conclusions of this study:

1. From ground surface to a depth of around 20 m, the Kathmandu Valley has a complicated and layered profile. The majority of the gathered database exhibited lithological heterogeneity. The valley was primarily composed of clayey silt and silty sand. Rockworks16 3D lithological and stratigraphy models of soil up to 20 m depth have also supported this result. Fine sand beds, organic clay, and peat layers were prevalent in the 1 m top layers.
2. Groundwater table was located at various depths ranging from 0.5 to 30 m, with an average of 6.85 m. After analysing particle size distribution and the plasticity chart, it was evident that Kathmandu soil deposits are very susceptible to liquefaction.
3. The SPT values of soil layers lying in the central part were much lesser than the outer. It might be due to the presence of hard rock bedding in the outer part of the valley. About 85% of the borehole test data had SPT less than 20, and more than 50% have SPT less than 10 in shallow depth in the core area of the valley. Most of the samples had a moisture content ranging from 20 to 40% with an average of 39.94%, whereas the specific gravity value was mainly between 1.89 and 2.89 with an average value of 2.59.
4. More than 40% of the boreholes locations taken for this study had a liquid limit (LL) less or equaled 35% ($\mu = 44.29$). Most of the soils in this study possessed undrained shear strength at failure (C_u) ranging from 30 to 90 kPa. After plotting a total of 120 ring shear tests, cohesion was found from 0 to 20 kPa ($\mu = 11.63$ kPa), and friction angle varied from 6.2° and 40° with an average of 22.6°. It was observed that most of the soil samples had a shear wave velocity lesser than 360 m/s, which indicates the extensive presence of stiff soil.

The analytical findings apply to future research and studies on the subsurface state of the Kathmandu Valley and civil engineering techniques. This work is the first comprehensive investigation on the geotechnical characterization of Kathmandu soil to the authors' knowledge. It will have a substantial impact on land-use planning. These study findings, 3D models, graphs, and maps of individual parameters of the Kathmandu Valley might help prioritize sites with geotechnical concerns or high total costs for civil engineering projects. It may aid in selecting more appropriate foundation types and building designs, as well as in the forecasting of changes in geological engineering conditions and the prediction of hazardous geological events. The work presented can be used for the preliminary investigations, it is in no way a substitute of the detail investigations required for a project. Finally, despite the abundance of boreholes in the Kathmandu Valley, direct shear wave observations are pretty rare. To better understand the Kathmandu soil's geotechnical properties, more investigations and studies are required to obtain more accurate results.

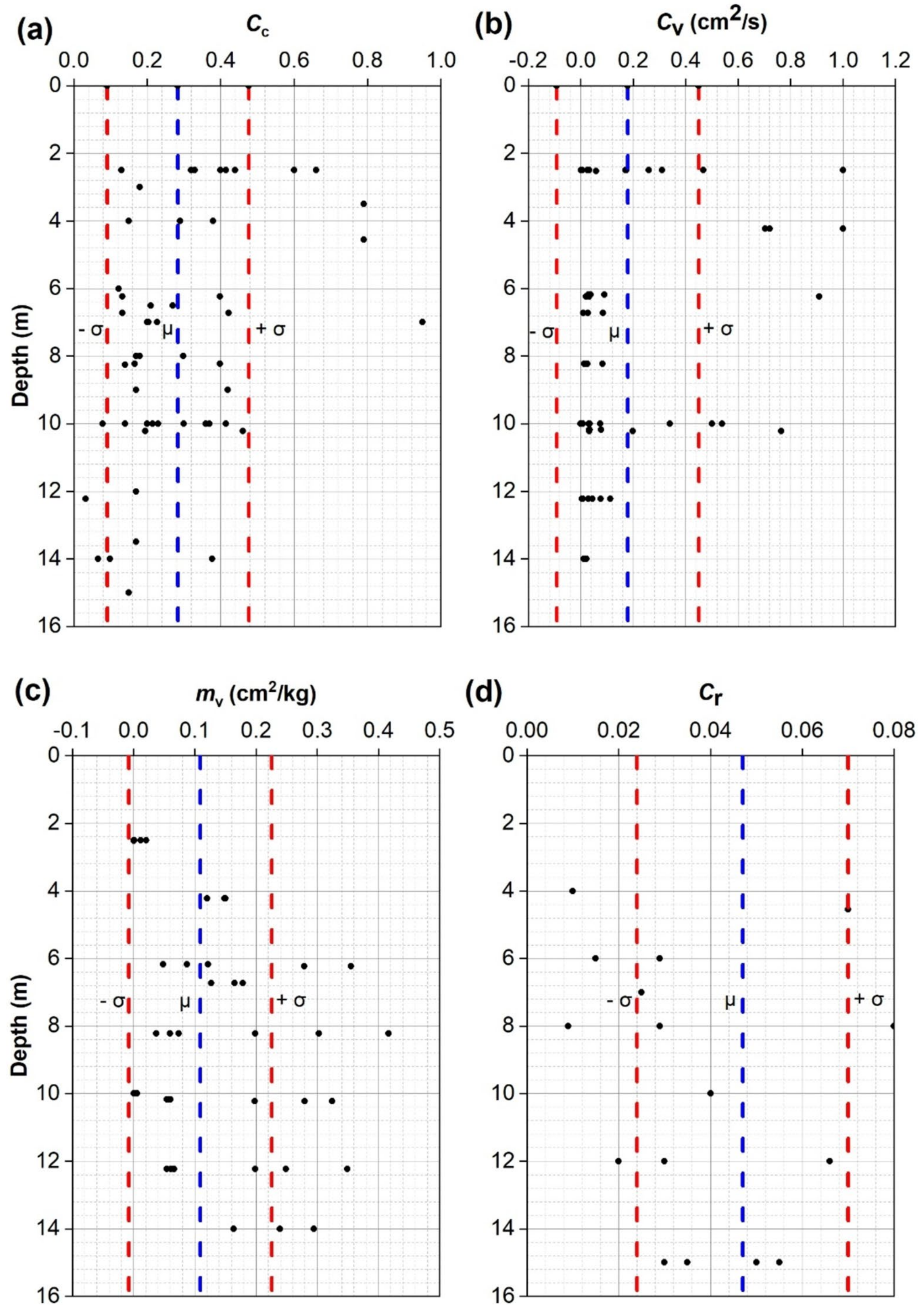


Fig. 17 Consolidation properties of Kathmandu soil versus depth: **a** C_c, **b** C_v, **c** m_v, and **d** C_r

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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