Geomechanics and Engineering, *Vol. 13, No. 3 (2017) 475-488*
DOI: https://doi.org/10.12989/gae.2017.13.3.475

Spatial interpolation of geotechnical data: A case study for Multan City, Pakistan

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(*Received January 13, 2017, Revised March 28, 2017, Accepted March 30, 2017*)

Abstract. Geotechnical data contributes substantially to the cost of engineering projects due to increasing cost of site investigations. Existing information in the form of soil maps can save considerable time and expenses while deciding the scope and extent of site exploration for a proposed project site. This paper presents spatial interpolation of data obtained from soil investigation reports of different construction sites and development of soil maps for geotechnical characterization of Multan area using ArcGIS. The subsurface conditions of the study area have been examined in terms of soil type and standard penetration resistance. The Inverse Distance Weighting method in the Spatial Analyst extension of ArcMap10 has been employed to develop zonation maps at different depths of the study area. Each depth level has been interpolated as a surface to create zonation maps for soil type and standard penetration resistance. Correlations have been presented based on linear regression of standard penetration resistance values with depth for quick estimation of strength and stiffness of soil during preliminary planning and design stage of a proposed project in the study area. Such information helps engineers to use data derived from nearby sites or sites of similar subsoils subjected to similar geological process to build a preliminary ground model for a new site. Moreover, reliable information on geometry and engineering properties of underground layers would make projects safer and economical.

Keywords: site investigation; standard penetration resistance; spatial interpolation; geographic information systems; soil mapping

1. Introduction

In spite of the rapid technological developments in construction industry, urban underground remains an unknown space (Angin 2016, Abdel-Kader 2011). A huge amount of geotechnical database is gathered for a municipality with decades of field and laboratory soil investigations. Nevertheless, at the feasibility stage of a largescale engineering project, our information on the underground mostly come from the disordered accumulation of geotechnical investigation reports, instead of an organized database (Yoo 2016, Oda *et al*. 2013, Akgun 2012). In such situations, Geographic Information System (GIS) proves to be a powerful tool for collecting, storing, retrieving at will, transforming, and displaying spatial data from the real world (Schweckendiek *et al*. 2015). The data can be presented in the form of three distinct but overlapping views: database,

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http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

Table 1 Studies on spatial interpolations of geotechnical data

Outcomes of the study	Reference
Coding and analysis of soil data to build representative sections or for geostatistical purposes	Orhan and Tosun 2010, Antoniou *et al*. 2008, Rozos *et al*. 2006
Earthquake hazard zonation of urban areas, commonly referred to as seismic micro-zonation	Shiuly *et al*. 2015, Roy and Sahu 2012, Kienzle *et al*. 2006
Engineering geological, geophysical and geotechnical surface mapping	Dasaka and Zhang 2012, Pradhan and Youssef 2010, Kolat *et al*. 2006
Geotechnical and environmental risk management	Tan *et al*. 2015, Augusto *et al*. 2010, Chung and Rogers 2010
GIS as a tool in Geotechnical Engineering	Hellawell *et al*. 2001
Managing site investigation data for an early identification of geotechnical problems in urban infrastructure planning	Abdelfattah and Pain 2012, Mendes and Lorandi 2010, Player 2004
Site investigation data management	Zhang and Daska 2010, Kunapo *et al*. 2005
Slope stability problems	Manzo *et al*. 2013, Xie *et al*. 2006

spatial analysis, and map (Hennig *et al*. 2013). Table 1 lists recent studies on spatial interpolations of geotechnical data as well as some practical applications of GIS in geotechnical engineering. GIS-based coding and analysis of soil data to build engineering geological, geophysical and geotechnical maps can act as guidelines for design, construction, and building regulations. As a result, considerable saving in site exploration program can be realized because the existing information is readily available regarding subsoil conditions for the site under consideration. Moreover, geotechnical maps can be prepared showing spatial diversity of soil types and their properties at any scale of interest. These maps are extremely useful in suggesting solutions of anticipated geotechnical problems prior to construction. Nevertheless, a comprehensive site investigation is eventually needed for final ground characterization and geotechnical design.

With the growing infrastructure developments in Pakistan, there is a strong need to prepare geotechnical maps for its megacities. In this paper, an effort has been made to develop zonation maps for the soil type and stiffness in Multan city, Pakistan. This will help to reduce the cost of soil investigation or at the very least to have an initial concept of the soil properties in the proposed project site. The geotechnical modelling presented in this study is limited to the near-surface layers (0-10 m depth range) as these layers are more concerned with majority of the infrastructure and their spatial variability has important consequences on design and construction. Nevertheless, the continuous development of Spatial Data Infrastructures (SDI) provides a favorable context for project management and planning (Georis-Creuseveau *et al*. 2017). Thus, this paper aims to furnish sufficient and reliable database such that the nature of underground layers and range of soil stiffness (standard penetration resistance number) at any point in the study area can be easily established.

2. Study area

Multan is Pakistan's fifth largest city by population and third largest city by area located (71.5° Longitude, 30.2° Latitude) on the banks of Chenab river (Fig. 1). The area around the city is a flat

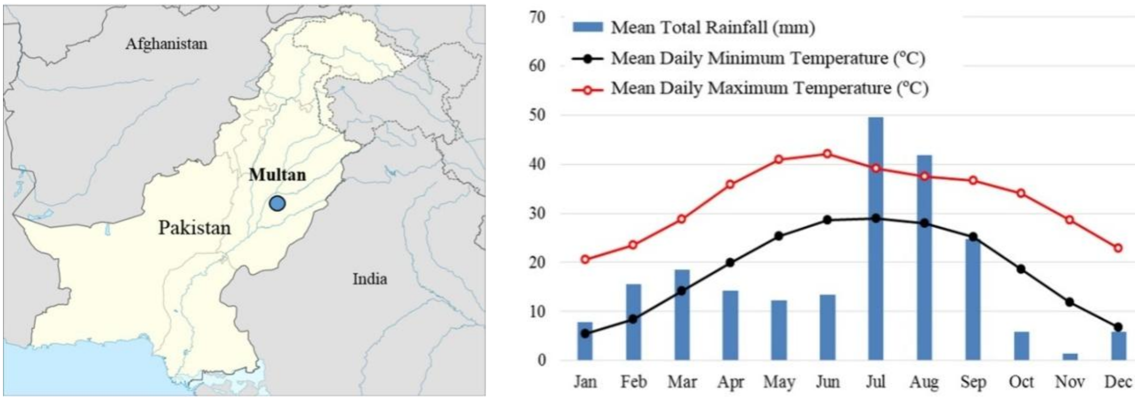


Fig. 1 Location and average climate of the study area

alluvial plain featuring an arid climate with very hot summers and mild winters. The city witnesses some of the most extreme weather in the country with the highest and lowest recorded temperatures of 52°C and −1°C respectively, and the average rainfall is approximately 186 mm per year. Due to the rapid industrialization and infrastructure developments across the city, the authorities have realized the importance of readily available subsoil information as an essential part of cost-effective construction planning and this study is a step forward.

3. Database description

Different types of information that can be retrieved from geotechnical investigation reports are listed in Table 2. These types of geographical, geological or geotechnical data can generally be both numerical and alphanumerical (Antoniou *et al*. 2008).

Table 2 Retrievable information from a geotechnical investigation report

Information	Description
Borehole ID	Includes identification number and general information of the investigation in the borehole log (i.e., project, location, depth of borehole, contractor, etc.).
Groundwater table	The fluctuation of the water table during drilling or its depth during the monitoring period.
Lithology	The detailed description of each stratum (i.e., thickness, color, consistency, etc.). Additional data needed for rock formations are: spacing, roughness, degree of weathering, aperture, and filling material of discontinuities
In-situ tests	Information obtained from tests carried out inside boreholes. In general, in situ tests are very reliable and many empirical correlations between their results and mechanical properties of soils have been developed worldwide
Lab tests	Includes data from laboratory test results for soil and rock specimens. Besides the depth, sampling method and quality of soil sample, the physical and mechanical properties of specimens are also recorded.

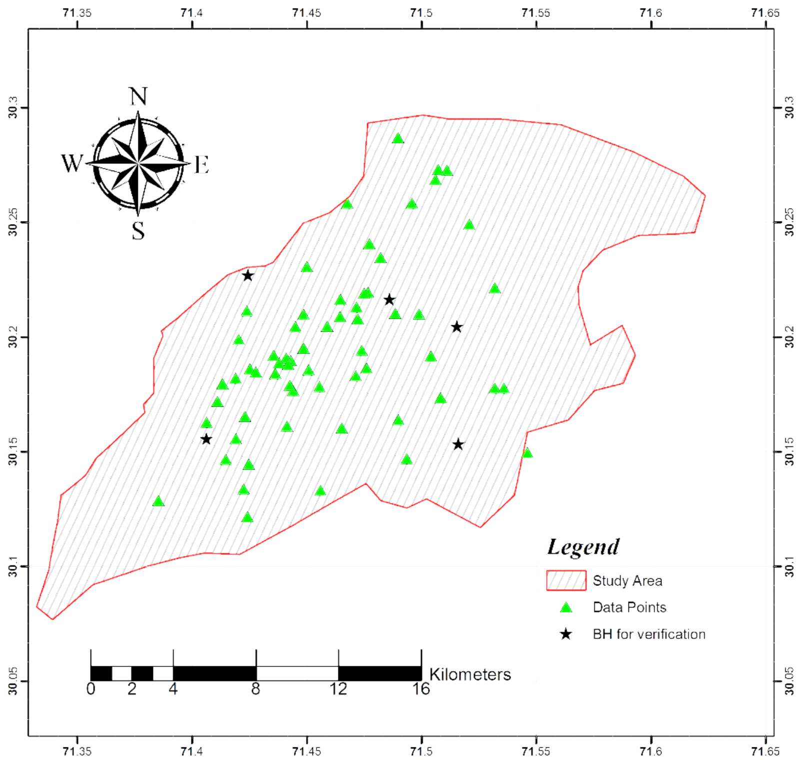


Fig. 2 Study area with locations of data points

Table 3 Statistical descriptors of SPT-N Data

Depth, m	1.5	3.0	4.5	6.0	7.5	9.0
Mean value	6.6	8.6	10.3	12.1	13.8	15.5
St. deviation	2.4	3.1	3.1	3.5	4.5	5.3
Minimum	3	4	3	7	7	7
Maximum	14	18	18	19	29	31
Data count	65	66	67	65	66	54

In this study, geotechnical investigation reports of 68 different construction projects in Multan area were collected. The location of each project site has been marked in Fig. 2 which clearly shows that data points are regularly distributed within the domain of investigation. The subsoil information retrieved from each borehole was thickness and location of each stratum along with standard penetration number (SPT-N value) at various depths. A total of 63 boreholes which provide accurate lithologic and stratigraphic information of each project site were used to prepare zonation maps of Multan city and the remaining five boreholes were used for validation purpose.

For the SPT-N datasets at various depths (i.e., 1.5 m, 3.0 m, 4.5 m, 6.0 m, 7.5 m and 9.0 m below existing ground surface), important statistical descriptors are given in Table 3 and analysis of variance is presented in Table 4. The frequency distribution of SPT-N values at various depths is plotted in Fig. 3. The comparison of frequency distributions as shows in Fig. 4 illustrates that the mean SPT-N values and its standard deviation increases with depth.

Table 4 Analysis of Variance (ANOVA) of SPT-N Data

ANOVA: Single factor

Groups / Depth	**Count**	**Sum**	**Average**	**Variance**
1.5 m	65	429	6.6	5.62
3.0 m	66	569	8.6	9.35
4.5 m	67	687	10.3	9.40
6.0 m	65	788	12.1	12.02
7.5 m	66	911	13.8	20.59
9.0 m	54	835	15.5	27.99

Source of variation	***SS***	***df***	***MS***	***F***	***P-value***	***Fcrit***
Between groups	3345.21	5	669.04	48.71	7.85E-39	2.238
Within groups	5178.70	377	13.74			
Total	8523.91	382				

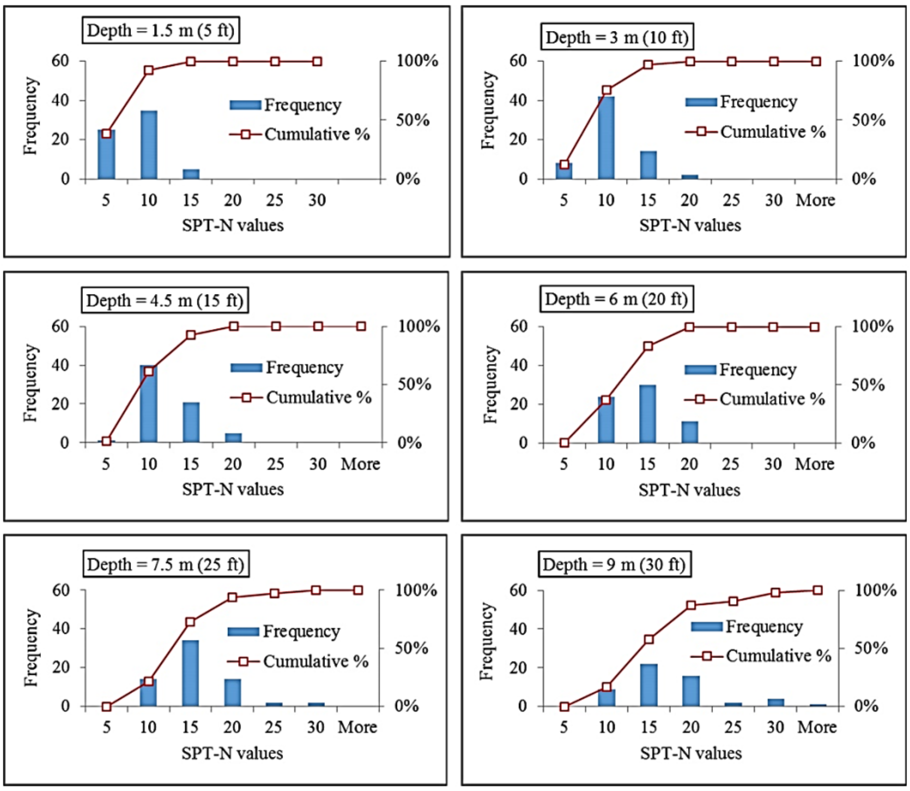


Fig. 3 SPT-N histograms at various depths

Table 5 presents linear regression analysis of SPT-N values with depth based on its statistical variations shown in Fig. 5. These correlations can reliably be used for quick estimation of strength and stiffness of subsoil during preliminary planning and design stage of a proposed project in the study area.

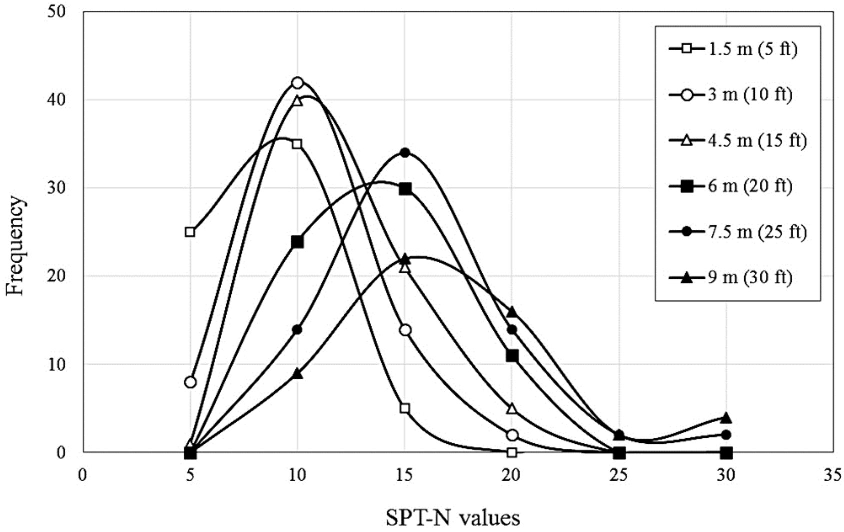


Fig. 4 Comparison of SPT-N distributions at various depths

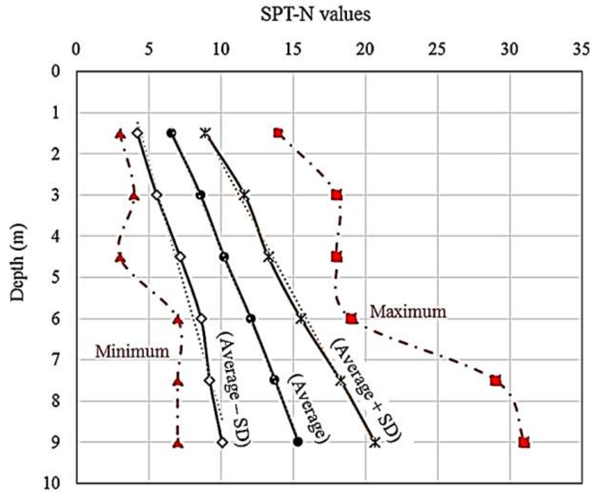


Fig. 5 Statistical variation of SPT-N values with depth

Table 5 Linear regression of SPT-N values with depth

Profile	Correlation	R^2
Average:	$N = \frac{D + 4.25}{0.86}$	0.9989
Average + Standard deviation:	$N = \frac{D + 4.28}{0.65}$	0.9960
Average - Standard deviation:	$N = \frac{D + 3.93}{1.23}$	0.9756

Where: N = SPT-N value, D = Depth (m)

4. Development of zonation maps

Data have been collected from 68 geotechnical investigation reports from the study area. The collected data at various depths and locations includes 389 SPT tests and 408 soil classifications. From the geotechnical reports, the site location (coordinates), elevation from mean sea level, SPT-N values and soil type at different depths were digitized and used as an input data in ArcGIS.

Zonation maps have been prepared by using ArcMAP software which is an important component of ArcGIS suite for geospatial processing programs. It is used mainly to sight, evaluate, form, and amend geospatial data. It also permits its users to search data within a data set, represent features, and generate maps. Various data interpolation techniques (spatial and geostatistical analyst extensions) in ArcMap10 are listed in Table 6.

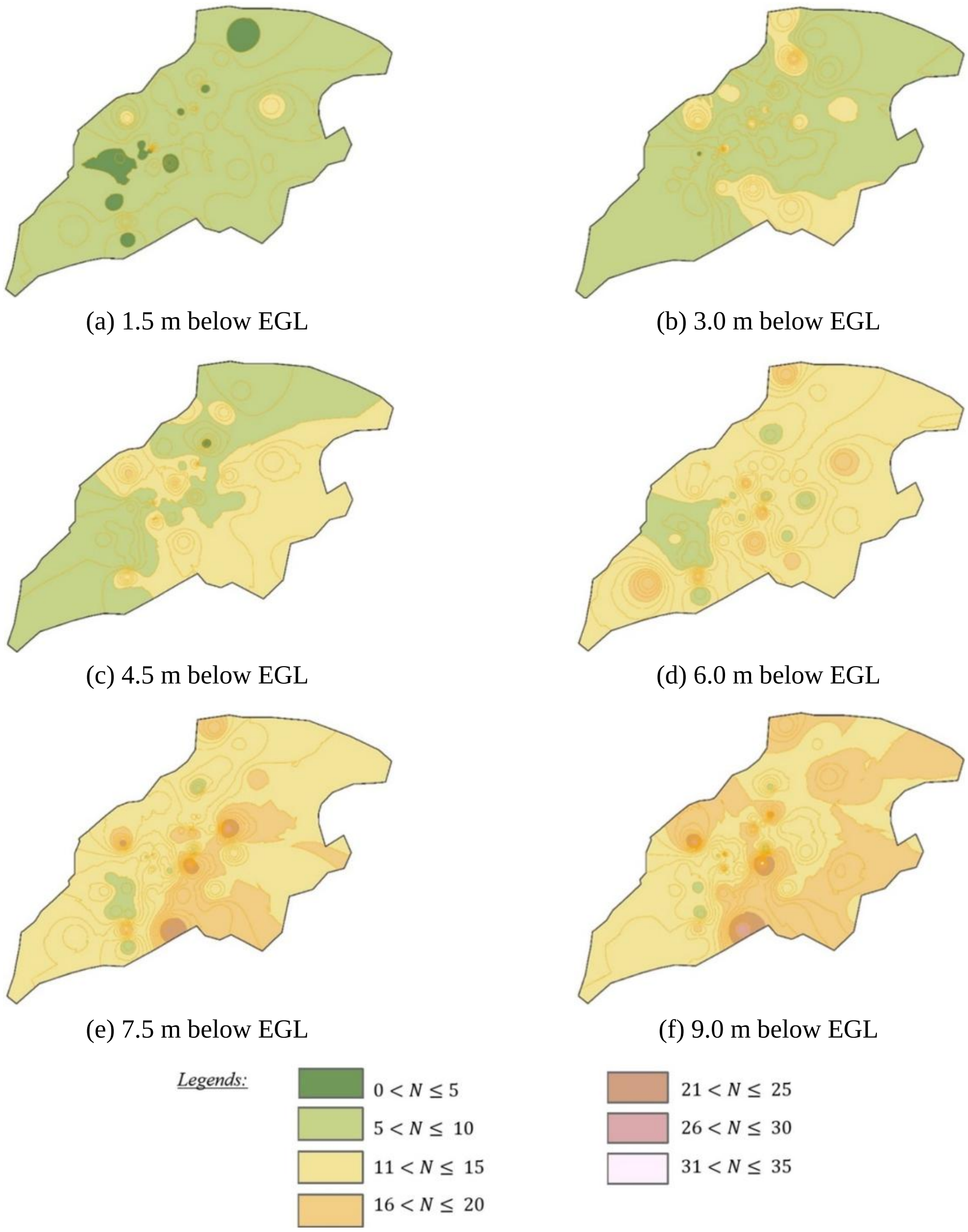
4.1 Zonation maps based on SPT-N values

Coordinates of each site were located using ArcMap. Zonation maps at depths of 1.5 m, 3.0 m, 4.5 m, 6.0 m, 7.5 m and 9.0 m below existing ground level (EGL) have been established from the SPT-N data by using the Spatial Analyst Inverse Distance Weighting (IDW) interpolation technique. IDW is one of the simplest and most readily available methods based on an assumption that the value at an unsampled point can be approximated as a weighted average of values at points within a certain cut-off distance, or from a given number of the closest points (Masser and Crompvoets 2015, Grunwald *et al*. 2011).

The selected range of SPT-N values for zonation were < 6, 6-10, 11-15, 16-20, 21-25, 26-30 and 31-35. Al-Ani *et al*. (2014) have presented a comparison among various interpolation techniques as listed in Table 6 and have observed that IDW interpolation technique with certain

Table 6 Data interpolation techniques and relevant parameters in ArcMap10

GIS tools	Interpolation technique	Parameters
Geostatistical analyst	Inverse Distance Weighting (IDW)	Output cell size, power, search neighborhood, major semi axis, minor semi axis, max. neighbor, min. neighbor, angle
	Diffusion	Output cell size, number of iterations, weight field, band width
	Global polynomial	Output cell size, order of polynomial, weight field
	Kernel	Output cell size, Kernel function, order of polynomial, output surface type
Spatial analyst	Ordinary kriging	Output surface raster, semi-variogram model (spherical, circular, exponential, Gaussian, linear), output cell size, search radius, number of points, max. distance
	Universal kriging	Output surface raster, semi-variogram model (linear with linear drift, linear with quadratic drift), output cell size, search radius, number of points, max. distance
	Spline	Output cell size, Spline type (regularized, tension), weight, number of points
	Inverse Distance Weighting (IDW)	Output cell size, power, search radius (fixed, variable), number of points, max. distance



(a) 1.5 m below EGL (b) 3.0 m below EGL

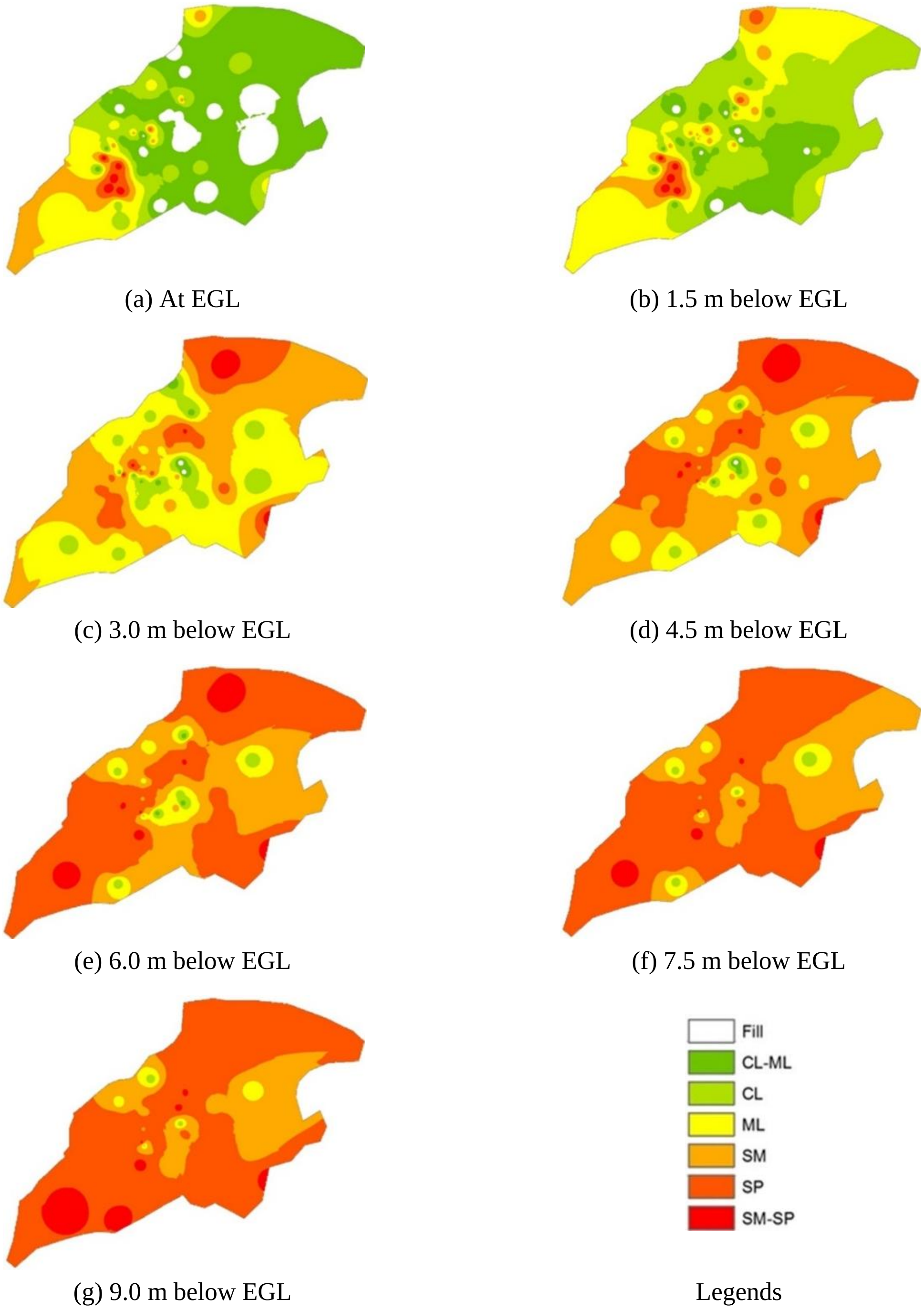
(c) 4.5 m below EGL (d) 6.0 m below EGL

(e) 7.5 m below EGL (f) 9.0 m below EGL

Fig. 6 Zonation maps of study area based on SPT-N values

parameters provides better representation of data for GIS-interpolated SPT-N zonation maps. The power of formula being used in mathematical computations of IDW technique is 2 which is a frequently used value (Lu and Wong 2008, Lloyd 2005, Ping *et al*. 2004, Bekele *et al*. 2003).

The zonation maps of study area based on SPT-N values at various depths below EGL are shown in Fig. 6. These maps show that the SPT-N values are generally below 15 for the upper 4.5 m layers and between 4.5 m to 9.0 m the values are increasing up to a maximum value of 35.



(a) At EGL (b) 1.5 m below EGL

(c) 3.0 m below EGL (d) 4.5 m below EGL

(e) 6.0 m below EGL (f) 7.5 m below EGL

(g) 9.0 m below EGL Legends

Fig. 7 Zonation maps of study area based on soil types

4.2 Zonation maps based on soil type

Based on unified soil classification system, zonation maps at depth intervals of 0 m (EGL), 1.5

m, 3.0 m, 4.5 m, 6.0 m, 7.5 m and 9.0 m below EGL have also been prepared. The numerical codes assigned to various soils types were: 1 (fill material); 2 (CL-ML, silty clay); 3 (CL, lean clay); 4 (ML, silt); 5 (SM, silty sand); 6 (SP, poorly-graded sand); and 7 (SP-SM, poorly-graded sand with silt). Fig. 7 presents the zonation maps of study area based on soil types at various depths below EGL. These seven zonation maps represent variety of soil classes at different depth levels. It can be observed that the upper 3.0 m layers mainly consist of cohesive deposits and below 3.0 m are sandy strata with some exceptional locations as shown in the maps.

4.3 Validation of zonation maps

From a total of 68 borehole logs in the study area, 63 were used to prepare zonation maps and the remaining 5 were used for validation purpose. For a given depth and location, the actual soil

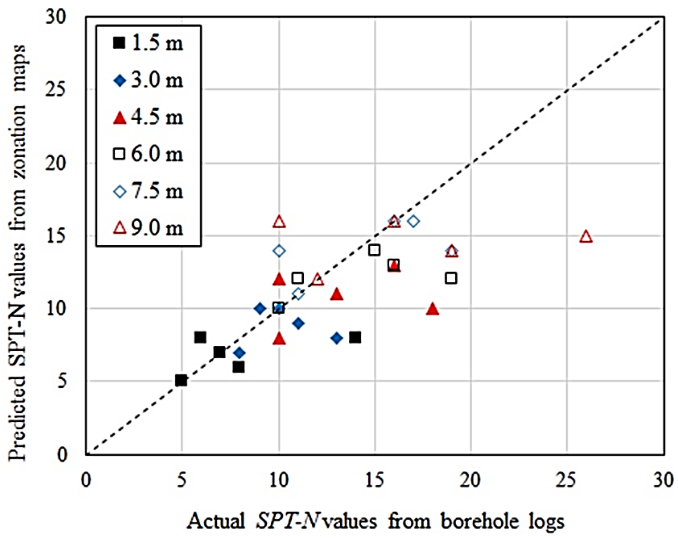


Fig. 8 Comparison of predicted and actual *SPT-N* values

Table 7 Comparison of predicted and actual soil types

Depth (m)	BH-10		BH-14		BH-18		BH-44		BH-64	
	A	P	A	P	A	P	A	P	A	P
EGL	CL	CL-ML	ML	CL-ML	CL-ML	CL-ML	CL-ML	CL-ML	CL	ML
1.5	CL	ML	SP-SM	CL	CL-ML	CL-ML	CL-ML	CL	SP	ML
3.0	SM	SP	SP-SM	ML	CL-ML	ML	SP	SM	SP	ML
4.5	SM	SP	SP-SM	ML	CL-ML	ML	SP	SM	SP	SP
6.0	SP	SP	SP-SM	SM	CL-ML	SP	SP	SM	SP	SP
7.5	SP	SP	SP	SM	CL-ML	SP	SP	SM	SP	SP
9.0	SP	SP	SP	SM	CL-ML	SP	SP	SM	SP	SP

P: Predicted soil type from zonation maps; A: Actual soil type from borehole log
Highlighted text shows the actual and predicted soil type doesn’t match

Table 8 Estimation of soil parameters from SPT-N values (Schmertmann 1975)

Granular soils						
Corrected SPT-N	0	4	10	30	50	
Relative density	Very loose	loose	medium	dense	Very dense	
Friction angle (deg.)	25-30	27-32	30-35	35-40	38-43	
Moist unit weight (kN/m^3)	11-15.8	14-18	17.3-20.4	19-22	20.4-23.6	
Cohesive soils (relatively unreliable, use for preliminary estimates only)						
Field SPT-N	0	2	4	8	16	32
Consistency	Very soft	Soft	Medium	Stiff	Very stiff	Hard
Unconfined comp. strength (kPa)	0	25	50	100	200	400
Moist unit weight (kN/m^3)	15.7-18.9	15.7-20.4			18.9-22.0	

information is obtained from borehole logs and the corresponding predicted values refer to the data retrieved from zonation maps. Fig. 8 presents the comparison of predicted and actual SPT-N values at various depths. The comparison between predicted and actual soil types is given in Table 7. Boreholes 10, 14, 18, 44 and 64 were selected randomly from the dataset keeping in view that the validation boreholes are scattered and representative of the study area. As far as difference between actual and predicted SPT-N values is concerned, while referring to Table 8, it can be observed that when estimating soil parameters, SPT-N is always a range (0-4, 4-10, 10-30, 30-50, > 50). Therefore, the scatter observed in Fig. 8 would make no difference to geotechnical design of foundations while selecting SPT-N design value from the proposed zonation maps. Moreover, these maps are for feasibility studies/initial design, a detailed site investigation would always be required for the final design. Regarding the difference between actual and predicted soil types (e.g., for BH-14 at 3.0 m and 4.5 m and for BH-64 at 1.5 m and 3.0 m) in Table 7, the engineering behavior of low-plastic silts is quite similar to non/low-plastic fine sands which as a result does not impact the feasibility designs.

5. Practical application

In foundation designs, SPT-N values are typically used to estimate shear strength properties of soils such as relative density and internal friction angle of granular soils, and consistency and undrained cohesion of cohesive soils. The properties listed in Table 8 are the basic input parameters for bearing capacity analysis of foundations, slope stability analysis and liquefaction studies, etc.

According to Tavakoli *et al*. (2016), geotechnical properties of shallow soil layers sometimes dramatically influence the characteristics of seismic waves during an earthquake because of the complex three-dimensional heterogeneities. Therefore, in regard to the surface mapping of soil properties, it is anticipated that by importing the data from soil stratigraphy and SPT blow counts zonation maps as presented in Figs. 6 and 7, additional maps can be generated based on estimated shear strength properties of soils which can be quite useful for geotechnical designs in the study area.

6. Conclusions

This paper intends to guide and indicate the potential suitable areas for the construction of shallow foundations, using an interpretative geotechnical maps produced by the Geographical Information System. Likewise, an attempt has been made towards development of spatial geotechnical data infrastructures to provide a favorable context for planning site investigations for proposed projects in the study area. The outcomes of this study are as follows:

- Zonation maps depict that the top 3 m soil deposits are mainly fill material, low-plastic clayey silts, and/or silty clays with average SPT-N values of less than 10 (i.e., very soft-to-stiff cohesive soils). Fill and soft clays are problematic soils and most of the infrastructure in the study area are supported by shallow foundations, therefore the depth and thickness of such soils should be taken into consideration for a suitable, economic, and safe design.
- Zonation maps of the study area based on soil types, reveal that the soil stratigraphy below 3 m are silty sands and/or sands with average SPT-N values of 10-15 (i.e., medium dense sands) which is considered as an suitable ground support for most of the engineering structures.
- The validation and reliability of zonation maps would be improved with densification of data points through addition of further geotechnical investigations conducted in the study area.
- It is anticipated that the zonation maps presented in this study will be useful for planning and preliminary design of construction projects by providing useful information on important geotechnical parameters required for foundation design and excavations. Nevertheless, a comprehensive site investigation is always needed for final ground characterization and geotechnical design.

Acknowledgments

The authors are grateful to Geotechnical Engineering Divisions of UET and NESPAK (Lahore, Pakistan) for their support and providing necessary data.

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