Journal of Information Systems Engineering and Management
2025, 10(63s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Comparative Geotechnical Characterization of Subsurface Soils at Multiple Construction Sites in Northern Pakistan

Hafiz Muhammad Kamran Idrees*[1], Najmul Faris[2], Muhammad Imran[3], Muhammad Naveed Khalil[4], Muhammad Shaheer Rizwan[5]

[1] Department of Civil Engineering, National University of Technology Islamabad, Pakistan*
[2] Department of Earth Sciences, COMSATS University Islamabad, Pakistan
[3] Department of Earth Sciences, The University of Haripur, Pakistan
[4] National Centre of Excellence in Geology, University of Peshawar, Pakistan.
[5] Department of Civil Engineering, National University of Technology NUTECH
***Corresponding Author:** Hafiz Muhammad Kamran Idrees,*
Department of Civil Engineering, National University of Technology Islamabad,
Email: ranakami021@gmail.com

ARTICLE INFO

Received: 24 Oct 2025

Revised: 01 Dec 2025

Accepted: 12 Dec 2025

ABSTRACT

Background: Geotechnical properties characterization is a basic requirement to the design of safe and cost-effective foundations particularly in geologically diverse regions like in the northern part of Pakistan, whereby the accelerated infrastructure growth involves alluvial plains and hilly soils.

Purpose: The aim of this investigation is to carry out a comparative geotechnical analysis of the subsurface soil conditions in thirteen construction sites located in Rawalpindi, Taxila, Chakwal, Khushab, Murree, Khanpur (Haripur), Jhelum, and Mandi Bahauddin as well as to determine the implication of the outcome and how it can be used in the foundation design.

Methodology: The field investigation activities included percussion drilling, test pit construction, and hand augering, and Standard Penetration Tests (SPT) were carried out at specified depth periods. Laboratory tests included testing of natural moisture content, bulk density, particle size distribution and Atterberg limits. The outcome data were then coded as per Unified Soil Classification System (USCS).

Findings: At most of the locations the stratigraphy of the subsurface is dominated by silty clay (CL-ML) and clay (CL) with low to medium plasticity. At a deeper depth, particularly in hilly landscapes, silty sand (SM) and sandstone were found. The common Standard Penetration Test (SPT) N-values were reported to have a range of 5 to 18 and had an upward trend with depth thus showing the progressive increase in stiffness of soil. In most of the sites, groundwater was not met with; however, seepage features were observed at depths of above 35 40 feet or so in given places.

Conclusion: The results indicate a high spatial variation in the geotechnical properties controlled by geological and depth-based factors and hence the urgent need to carry out site-specific geotechnical research studies to facilitate the safe and cost-effective design of foundations in northern Pakistan.

Keywords: Geotechnical investigation; Standard Penetration Test (SPT); Soil classification; Subsurface stratigraphy; Foundation design.

1.1 Background

Geotechnical investigations represent an indispensable part of civil engineering works that provide essential information about the properties of soils and rocks under the ground, which to a certain extent affect the formation of foundations and structural performance (Oyeyemi et al., 2017). These tests are meant to determine the engineering and physical properties of the soil and rock layers that are located underneath a proposed construction site, hence allowing engineers to make quality decisions about the foundation type, bearing capacity, and settlement behaviour before the commencement of construction (Olusola et al., 2021). The adequate implementation of the geotechnical investigation contributes to increased safety, avoiding the structural failure and lowering the total project costs as it avoids over-design or unexpected conditions of the subsurface environment during the construction project (Amadi et al., 2024). The common field tests used to explore geotechnical sites include borehole drilling, excavation of test pits, and in situ tests like Standard Penetration Test (SPT) which provides an estimate of soil resistance and strength based on the number of blows to drive a sampler into the ground under controlled conditions (Fernandes et al., 2022). Particle size distribution, natural moisture content, and Atterberg limits are enumerated as some of the laboratory index tests commonly used to categorise soils and determine how they behave under different conditions of moisture and load (O'Kelly et al., 2021).

1.2 Importance of Soil Characterization

The geotechnical parameters are fundamentals to comprehend the behaviour of soils under loading, and their response to loading is different depending on the composition of the soils, their moist condition and geological background (Onyelowe et al., 2023). Fine-grained soils, including that of clays and silts, have specific engineering properties in comparison to coarse-grained soils, including sands and gravels (Verma et al., 2020). As an example, the moisture contents of fine-grained soils between plastic and liquid can be measured using the Atterberg limits, which are the primary sources of essential data about soil consistency and plasticity directly affecting compressibility and shrink-swell potential (O'Kelly et al., 2024). The values of the standard penetration resistance (N -values) obtained through the SPT indicate the relative density and rigidity of soils and are often correlated with the geotechnical design parameters, e.g., bearing capacity and predicted settlement (Motahari et al., 2022). The reason behind the popularity of the SPT is that it is affordable, portable, and provides prompt field data that can be analyzed through the available empirical paradigms (Anbazhagan et al., 2022).

1.3 Research Motivation

Urbanisation and varying geology are rapid issues in the north of Pakistan, which make it difficult to rely on foundation design (Khan et al., 2021). The nature of the soils in the region is between alluvial deposits in the plains and variable soils in the areas with elevation, which, in turn, requires site-specific investigations of the construction projects (AbdelRahman et al., 2023). Despite the fact that single geotechnical reports give subsurface information of certain sites, there is a necessity to have a comparative, and integrated evaluation of various sites to enhance the knowledge of typical soil behaviours and engineering consequences (Martinez et al., 2022).

1.4 Study Objective

This study aims at carrying out a comparative assessment of geotechnical properties in the various construction sites in the north of Pakistan encompassing Rawalpindi, Taxila, Chakwal, Khushab, Murree, Khanpur (Haripur), Jhelum, and Mandi Bahauddin using a mixture of field SPT and laboratory soil index tests. The analysis that follows aims to determine the patterns on soil classification, strength parameters and parameters that are relevant to foundation in different geological environments, thus providing a powerful ground of enhanced foundation design and geotechnical planning.

2. Study Area and Site Descriptions

2.1 Geographic Setting

The location of the study area includes the variety of construction sites spread all over the North and central regions of Pakistan including Rawalpindi, Taxila, Chakwal, Khushab, Murree, Khanpur (Haripur), Jhelum and Mandi Bahauddin. All these locations are a representation of a range of physiographic provinces, which consist of alluvial plains, piedmont deposits and hilly lands. The geographical diversity of the target locations provides a chance to determine differences in the conditions of subsurface soils due to regional geology and geomorphology effects.

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Research Article

Figure 1: Location map of the investigated sites in Pakistan

Rawalpindi, Taxila, Jhelum and Mandi Bahauddin are located in the Upper Indus Plain which is typified by alluvial deposits which are of fluvial origin. The site of Chakwal/Khushab is found in the Potohar Plateau, having topographical undulations and uneven soil deposits. Murree and Khanpur (Haripur) are located in hilly and sub-mountainous areas, whose main features are shallow soil cover and erosion by rock formations.

2.2 Regional Geological Framework

Geologically, the study area spans three major tectono-stratigraphic zones of Pakistan:

1. **Indus Basin (Alluvial Plains)**

   The plains of Rawalpindi, Jhelum, and Mandi Bahauddin are underlain by Quaternary alluvial deposits consisting primarily of silts, clays, sands, and occasional gravels. These materials have been deposited by the Indus River system and its tributaries over thousands of years. The predominance of fine-grained soils in these areas is consistent with the silty clay (CL–ML) and clay (CL) layers identified in the borehole logs.

2. **Potohar Plateau**

   Chakwal, Taxila, and parts of Khushab fall within the Potohar Plateau, a tectonically active region composed of folded and faulted sedimentary rocks overlain by residual and colluvial soils. The plateau is known for variable soil thickness, interbedded clayey and sandy layers, and moderate cementation at depth, which explains the observed increase in SPT resistance values with depth at several sites.

3. **Sub-Himalayan and Hilly Terrains**

   Murree and Khanpur (Haripur) are part of the Sub-Himalayan foothills, dominated by sandstone, shale, and claystone formations. Weathered rock and shallow soil cover are common in these areas. The encounter of sandstone strata at shallow depths and drilling refusal in some boreholes directly reflects the regional geological setting.

2.3 Site History and Land Use

The sites that have been investigated include residential housing schemes, commercial buildings, and religious buildings, industrial and institutional developments. A number of urban sites show disturbed or filled surface layers, which are likely due to some previous grading, excavation, or construction. On the contrary, sites located in rural and hilly settings also have relatively natural soil profiles with minimal anthropogenic disturbance (Mekonnen et al., 2022). The soil behaviour is determined by historical land-use patterns in combination with geological conditions with a decisive influence. Soils that are filled usually have less stiffness and strength when they are shallow, and natural deposits and weathered rock formations tend to have a greater bearing capacity (van der Meij et al., 2020).

2.4 Relevance to Geotechnical Design

The wide geographic and geological area that the chosen locations offer makes this study representative of the usual construction conditions in north Pakistan. This heterogeneity in terms of the soil type, depth to the competent strata, and conditions in the groundwater table reflects the urgent need to examine the sites of geotechnical tests instead of making generalized assumptions in designing foundations.

3. Materials and Methods

3.1 Field Investigation Program

Geotechnical investigations for the selected sites were carried out in accordance with standard engineering practice to evaluate subsurface conditions relevant to foundation design. The field investigation program included subsurface exploration, in-situ testing, and soil sampling. All field activities followed internationally recognized standards such as ASTM and AASHTO.

Subsurface exploration was conducted primarily through borehole drilling using percussion machines. At selected locations, particularly where shallow investigation was sufficient or where hard strata restricted drilling progress, test pits and hand augers were employed. Boreholes were advanced to depths ranging from approximately 9 ft to 50 ft, depending on project requirements and subsurface resistance. During drilling, soil strata were visually examined and systematically logged with respect to soil type, colour, moisture condition, texture, and relative consistency.

3.2 Standard Penetration Test (SPT)

Standard Penetration Tests (SPT) were performed at regular depth intervals in accordance with ASTM D1586 (PAUL et al., 2023). The test was conducted using a standard split-spoon sampler driven into the soil by a 63.5-kg hammer falling freely from a height of 760 mm. The number of blows required to drive the sampler through the final 300 mm of penetration was recorded as the SPT N-value.

The obtained N-values were used as indicators of relative soil density, stiffness, and strength, and to evaluate variations in subsurface conditions with depth. Groundwater conditions were observed during drilling, and the depth of seepage or water table, where encountered, was recorded.

3.3 Soil Sampling and Laboratory Testing

Laboratory analysis was done on disturbed soil samples acquired during drilling and SPT operations. The moisture content was measured in order to determine in-situ moisture conditions and the bulk density was determined to determine the soil compaction and unit weight properties. The size distribution of gravel, sand, silt, and clay portions were measured by analyzing the particle-size distribution of mechanical sediments using a sieve. In Fine-grained soils, the limits tests were done in terms of liquid limit, plastic limit and plastic index to explain the behaviour of the soils in terms of consistency and plasticity.

3.4 Soil Classification and Data Interpretation

According to the laboratory data, the soils were categorized according to the Unified Soil Classification System (USCS). Combination of borehole logs, SPT resistance values and Index property of laboratory reports added a comprehensive scheme of assessing subsurface variability and the determination of the geotechnical status with respect to foundation design in each site.

4. Results

4.1 Subsurface Stratigraphy

The borehole records of the thirteen sites scraped in the investigations indicate that the situation of the subsurface differs among the geographic position but shows homogenous regional pattern. The subsurface profile is mostly made of silty clay (CL–ML) and clay (CL) layers up to the depths explored in the urban and alluvial plain parts of Rawalpindi, Jhelum,

Journal of Information Systems Engineering and Management
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e-ISSN: 2468-4376
https://www.jisem-journal.com/
Research Article

Mandi-Bahauddin, Chakwal and Khushab. These soils are mostly brown and reddish in colour, and show mildly-increasing hardness as the depth is advanced.

However, sites in hilly and sub-mountainous areas, e.g. Murree and Khanpur (Haripur), found sandstone strata at relatively shallow depths, meaning that many boreholes were rejected during drilling. Notable filling or disturbance of soils was also observed at shallow depths in urbanised areas specifically at residential and commercial sites which reflects activities that preceded land-development activities.

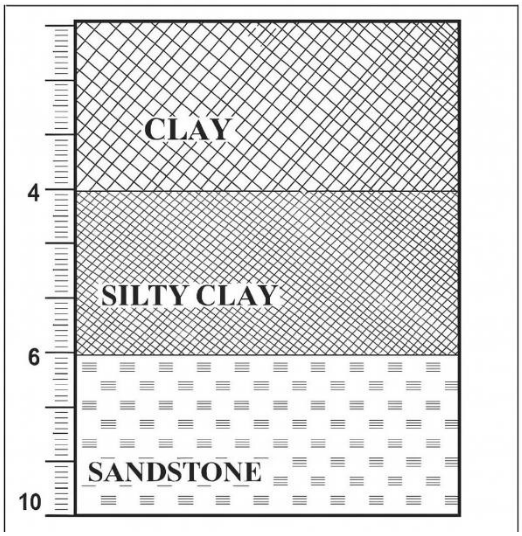

Figure 2: Typical borehole log illustrating clay, silty clay (CL–ML), and sandstone stratigraphy with depth profile.

4.2 Soil Classification Results

Laboratory testing and USCS classification show that fine-grained soils dominate the investigated sites. Table 1 summarizes the soil classifications observed across all locations.

Table 1: Soil Types Identified at Investigated Sites

Region / Site Type	Dominant Soil Type (USCS)	Remarks
Rawalpindi (Urban Sites)	CL–ML	Low to moderate plasticity
Taxila & Chakwal	CL–ML / SM	Variable strata with depth
Khushab	CL–ML	Alluvial deposits
Jhelum & Mandi Bahauddin	CL / CL–ML	Fine-grained soils
Murree	CL / Sandstone	Shallow rock strata
Khanpur (Haripur)	CL / Sandstone	Weathered rock at depth

These classifications are consistent with particle size distributions showing a high percentage passing the No. 200 sieve, confirming the dominance of silt and clay fractions in most locations.

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Research Article

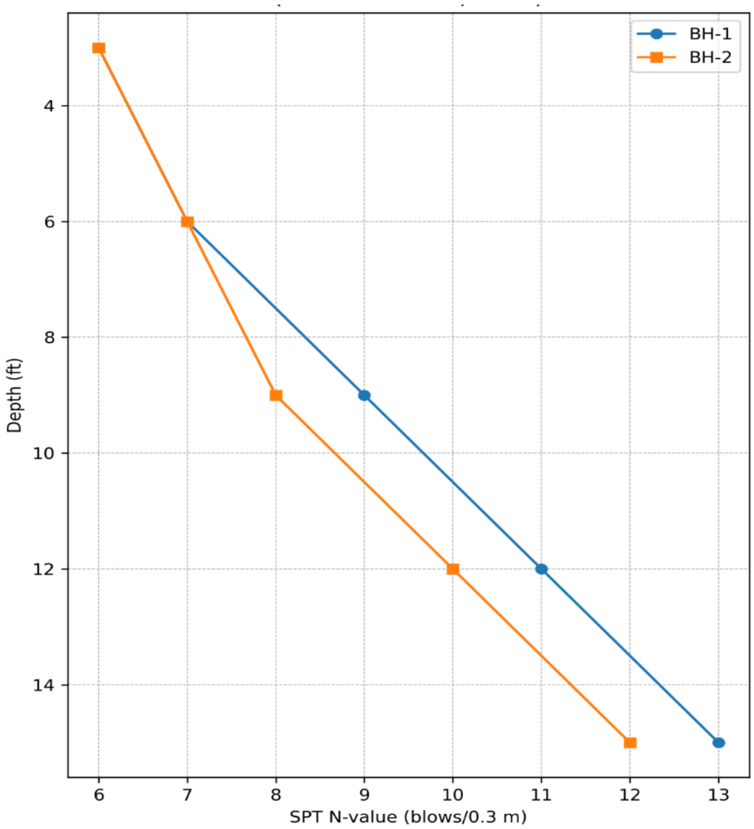

Figure 3: Variation of SPT N-values with depth for Faisal Hills Villas, Taxila (BH-1 and BH-2).

Figure 3 shows the change in the Standard Penetration Test (SPT) N-values with depth of Boreholes BH -1 and BH -2 at Taxila Faisal Hills Villas. Both boreholes indicate that the SPT N-values increase monotonic with depth indicating a successively increasing soil density and stiffness. The strata near the surface have relatively low N-values that are aligned with the loose to medium-dense soils, and the deeper strata have a high penetration resistance. The similarity of trends in BH -1 and BH -2 suggests that the conditions at the site are comparatively homogenous at the subsurface. However, the N-values are always higher in BH-1 at the depths of the same depth as compared to those in BH-2, indicating that the soil layers are slightly denser or stiffer on the BH-1 profile. The increase in penetration resistance with depth is in agreement to the characteristics of natural silty clay and clayey field which experiences consolidation with time. Overall, the SPT profiles indicate that the strength of soil in the Faisal Hills Villas location increases with depth, which supports the appropriateness of shallow foundation system to be used at the relevant depths, provided that the bearing-capacity and settlement analysis is conducted in detail.

4.3 Standard Penetration Test (SPT) Results

The N-values SPTs of field testing enlighten on the stiffness and strength of the soil. The N -values in all sites are mostly between 5 and 18 and the depths show a steady and even rising pattern. The near-surface soils had lower N-values with specific reference made to the filled or loose soils and the deeper natural soils and dense strata recorded higher values.

Journal of Information Systems Engineering and Management
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Research Article

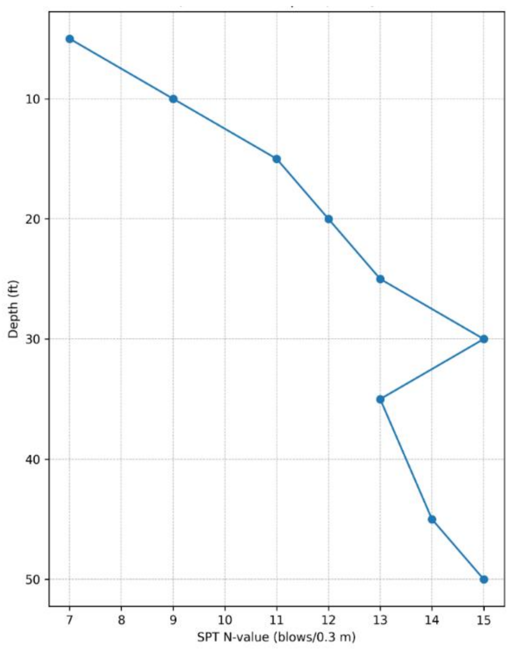

Figure 4: Variation of SPT N-values with depth for FOECHS Rawalpindi (BH-1).

Figure 4 shows the change of SPT N-values as a function of depth of FOECHS Rawalpindi (BH -1). There is an overarching upward trend in the SPT N-values, which indicates the change in the relatively loose near-surface soils to medium-stiff and stiff soil strata at more depths. The small oscillation of the N-values at the intermediate depths indicates the natural variation in the layering of soils. In general, the increasing penetration resistance overtime implies that the soil at the site is getting stronger and stiffer as the depth increases.

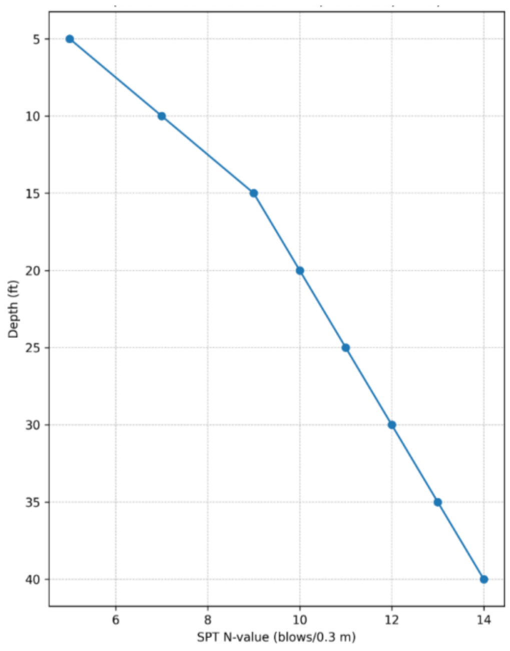

Figure 5**:** Variation of SPT N-values with depth for Sultan Flour & General Mills, Khushab (BH-1).

Figure 5 shows the SPT N-values variation with depth of Sultan Flour and General Mills, Khushab (BH -1). The SPT N-values show that there is a gradual increase in depth which indicates that the soil is becoming progressively denser and stiffer. The strata of shallow depth show lower N-values, which is typical of rather loose soil conditions, but the depths are higher, and N-values are higher, which is also typical of medium-stiff to stiff soil strata. The trend is homogeneous with the conditions being relatively uniform in the subsurface across the depth investigated.

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Research Article

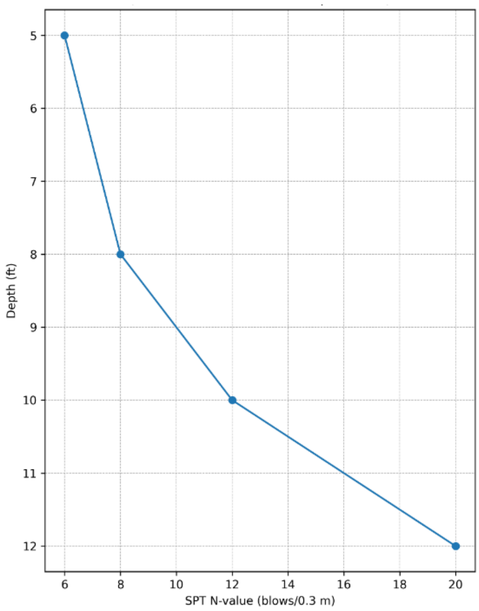

Figure 6: Variation of SPT N-values with depth for Farm House at Mouza Saradna, Khanpur

Figure 6 shows the SPT N-values versus depth of the Farm House at Mouza Saradna, Khanpur (BH -1). The values of the SPT N-values increase rapidly around the narrow depth range, suggesting there is a rapid change in comparatively soft, near-surface soils to very stiff soil or worn-out bedrock at shallow depths. This trend can be associated with the topography of the region, which is hilly, and it indicates the early discovery of competent strata during the process of drilling.

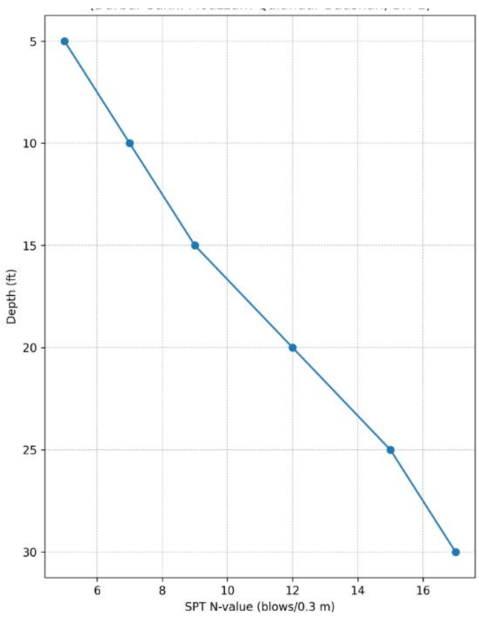

Figure 7: Variation of SPT N-values with depth for Darbar Sakhi Moazzam Qalandar Badshah (BH-1).

Figure 7 shows how SPT N-values change with depth in Darbar Sakhi Moazzam Qalandar Badshah (BH -1). The SPT N-values are shown to be gradually on the rise with depth and hence indicates that there is a change in relatively loose soils near to the surface towards medium and stiff soils layers further into the depths. The regular pattern shows the presence of homogenous conditions of the subsurface and increasing strength of the soil as the depth increases at the site.

Journal of Information Systems Engineering and Management
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https://www.jisem-journal.com/

Research Article

Table 2: SPT N-values with Depth at Investigated Sites

Site / Project Name	Borehole No.	Depth (ft)	SPT N-value (blows/0.3 m)
Darbar Sakhi Moazzam Qalandar Badshah	BH-1	5	5
		10	7
		15	9
		20	12
		25	15
		30	17
Faisal Hills Villas, Taxila	BH-1	3	6
		6	7
		9	9
		12	11
		15	13
	BH-2	3	6
		6	7
		9	8
		12	10
		15	12
FOECHS, Rawalpindi	BH-1	5	7
		10	9
		15	11
		20	12
		25	13
		30	15
		35	13
		45	14
		50	15
Sultan Flour & General Mills, Khushab	BH-1	5	5
		10	7
		15	9
		20	10
		25	11
		30	12
		35	13
		40	14
Farm House, Mouza Saradna, Khanpur	BH-1	5	6
		8	8
		10	12
		12	20

Table 3: Observed Range of SPT N-Values

Depth Range (ft)	Typical N-Value Range	Soil Condition
0 – 5	5 – 8	Loose to soft
5 – 15	8 – 12	Medium stiff
15 – 30	12 – 18	Stiff
>30 / Rock	Refusal	Sandstone strata

Journal of Information Systems Engineering and Management
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Research Article

4.4 Index Properties

Atterberg limits testing reveals that the fine-grained soils have low- to medium plasticity with the values of plasticity indices mostly being between 5 and 10. The values of natural moisture content and bulk density demonstrate the growing tendency in the direction of depth because the consolidation of the soil ground and the decrease of the values of the void ratio are observed in the deeper layers.

Table 4: Index Properties

Parameter	Observed Range
Natural Moisture Content	Low to moderate
Bulk Density	Increases with depth
Liquid Limit (LL)	~24 – 31
Plasticity Index (PI)	~5 – 10

4.5 Groundwater Conditions

The shallow depths at most locations did not find any groundwater at the investigated depths. Nevertheless, seepage or water-table would be found at depth more than about 35-40 ft at the specific sites, especially at the developments of Rawalpindi. This difference brings out the effect of the local hydrogeological conditions.

5. Discussion:

The outcome of the Standard Penetration Tests (SPT) carried out in the sites under examination indicates that the penetration resistance at depth does increase in general, though there was a gradual increase of the penetration resistance with the depth, which can be attributed to an upward trend of the soil strength and stiffness. This pattern can be observed in the majority of places, such as Darbar Sakhi Moazzam Qalandar Badshah, Faisal Hills Villas (Taxila), FOECHS Rawalpindi, and Sultan Flour and General Mills (Khushab) where SPT N -values change to a more shallow bottom gradually to deeper ones. This is characteristic of natural fine-grained soils that are experiencing the process of consolidation due to the pressure of overburden weight and is also in agreement with the preponderance of silty clay (CL-ML) and clay (CL) soils that were correctly identified through laboratory classification.

A comparative study of the SPT profiles indicates that there are site-specific differences that are dependent on the geological setting and the subsurface stratigraphy. The trends of the two boreholes (BH-1 and BH-2) at Faisal Hills Villas, Taxila seem to follow a similar pattern, which indicates that the subsurface environment is made of relatively homogenous conditions in the site. Minor differences in the N -values of the two boreholes indicates some local variations in the soil density that are typical of residual and colluvial deposits of the Potohar Plateau. The moderate rise of N-values on the whole endorses the existence of medium-stiff soils at the depth and which are favorable to shallow foundation systems with the relevant design considerations.

Variations in SPT N -values in the FOECHS Rawalpindi site are increasing steadily with depth and minor changes are noticed in the intermediate levels. Such differences are probably not due to sudden differences of material type, but rather to variations in the layering of soil. The lower strata are characterized by an increased penetration resistance which means better bearing conditions. The absence of sudden rejection in the depth that is being explored indicates that it has a fairly thick soil layer before reaching any hard layer which is characteristic of every alluvial plain in the area.

By contrast, the site of the Khanpur (Farm House at Mouza Saradna) indicates a steep rise in SPT N -values across a moderate depth range suggesting that the very stiff soil was encountered or weathered rock was discovered early. This activity is in line with the topography of the region which is hilly and sub-mountainous with shallow cover of soil overlaying competent sandstones. The conditions can impose a great impact on the foundation design where shallow foundations can rest directly on competent strata and settle slightly.

The N-values at Sultan Flour and General Mills at the Khushab site are relatively smooth and gradual increasing in depth implying that the soil is relatively uniform with alluvial soils at the site. The slow growth of the penetration resistance shows depth consolidation and the non-existence of sharp disparities in the soil type of the profile studied.

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Research Article

In general, the interpretation of SPT data and soil classification, as well as stratigraphic observations, combined, demonstrate the relevance of site-specific geotechnical tests. In spite of the fact that very similar soil types are observed in various sites, they exhibit engineering behavior which changes with their depth, geological location, and level of soil consolidation. These results reiterate the importance of such dependence on generalized soil properties and the significance of field and laboratory studies in the field of safe and cost-effective foundation design in a wide range of geological conditions in northern Pakistan.

Conclusion:

The current research paper conducts a comparative geotechnical evaluation of underground soil properties at various construction sites in the north of Pakistan using borehole logging, Standard Penetration Tests (SPT) and index testing on a lab. The results indicate that the ground profiles of most of the studied sites are mainly dominated by fine-grained soils, predominantly silty clay (CL-ML) and clay (CL) and there is evidence that both the strength and firmness of the soils show a general increase with the depth. The trends in Standard Penetration Test (SPT) N-values indicate a cumulative consolidation activity, which is accompanied by increasing bearing capacity with depth of the penetration. A comparative study of the SPT profiles highlights the high level of spatial variability of the subsurface conditions, which seems to be subjected predominantly to the influence of regional geology and topography. Sites located in alluvial plains, such as Rawalpindi and Khushab, show an increasing resistance to penetration by depth, which is a symptom of quite homogeneous deposits. Sites located in hilly and sub- mountainous conditions such as Khanpur show, on the other hand, rapid increases in SPT N-values at low depths which can be explained by the early appearance of hard soils or eroded rock layers. The similarity in the trends of SPT of adjacent boreholes at the chosen points, especially in Faisal Hills Villas, Taxila, suggests that there is laterally homogeneous subsurface regime, but small variations can reflect local changes in density of soil. These findings highlight the fact that despite the similarity in the occurrence of similar soil types in different locations, the engineering behaviour can vary significantly as a depth and geological setting. On the whole, the paper highlights the importance of site geotechnical investigations with regard to foundation design. A combined compilation of field and laboratory data provides a reliable base on which soil strength and hardness can be observed thus assisting in choosing secure and cost-effective systems of foundations in construction projects located in the diverse geological terrain of the north of Pakistan.

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