

ORIGINAL CONTRIBUTION

## A Comprehensive Geotechnical Evaluation of Subsoil Engineering Properties Including Index, Compaction, Shear Strength, and Compressibility Characteristics for Foundation Design and Overall Construction Suitability Assessment

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**Abstract**— The project provides a comprehensive geotechnical evaluation of the geotechnical characteristics of the underground engineering that is relevant to the foundation design and constructability assessment. Edafic samples were sampled at multiple locations and underwent controlled laboratory tests characterized to outline index parameters, compaction behaviour, shear strength coefficients, compressibility traits, consolidation reactions, settlement tendencies, as well as hydraulic permeabilities. The index testing revealed that the soils are mostly under the CH, CL, CI, and NP categories of the Unified Soil Classification System, indicating the large proportion of highly plastic clays, low to intermediate plasticity clays, and non-plastic granular assemblages. Compaction tests produced the best moisture levels between about 6% and 20% and the highest dry densities of between 1777 kg/m<sup>3</sup> and 2341 kg/m<sup>3</sup>. Parameters of shear strength indicated cohesion values to 111 kPa, and friction angles of 49°, thus indicating heterogeneous bearing-capacity regimes. The compression indices of consolidation tests (0.035-0.070) and settlement projections were moderate, with an overall settlement that falls within the acceptable limits of shallow foundations. Determinations of permeability emphasized a high degree of variability, and in correspondence with the range of grain-size distribution. Overall, the findings highlight the existence of a heterogeneous subsurface, whose strength and compressibility are moderate, which requires site-specific foundation plans to maintain the structural integrity and assure the sustainability of the performance in the long term.

**Index Terms**— Geotechnical investigation, Subsoil properties, Shear strength, Consolidation, Settlement analysis, Compaction characteristics, Permeability, Foundation design, Soil classification, Bearing capacity

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### I. INTRODUCTION

The essential initial process of ensuring that foundations transfer structural loads to the ground safely without undue settlement, distortion, or failure is done by geotechnical evaluation of subsoil engineering properties. In varying geological conditions, research continuously demonstrates that improper or a lack of subsoil characterization is a key inherent factor of building distress and collapse in rapidly urbanizing territories and structures constructed on troublesome soils like soft clays, organic layers, or heterogeneous fills [1, 2]. Strict evaluation is a combination of geological, geophysical, and geotechnical data to establish the subsurface stratigraphy, measure strength and deformation parameters, and associate them with suitable and cost-effective foundation solutions [3, 4, 5, 6].

### A. Key subsoil properties and their engineering significance

Load-bearing capacity and settlement are controlled by subsoil strength and stiffness. The most common parameters are standard penetration test (SPT) *N*-values, cone penetration resistance, undrained cohesion, friction angle, Uniaxial Compressive Strength (UCS), and moduli calculated in the laboratory and in-situ tests [7, 3, 4, 8, 9]. UCS in residual sandstones can be between 200-1200 kPa, and bearing capacities are several tsf based on the method applied to the analysis [3]. Conversely, soft to firm clay, peats, and highly plastic soils can have low strength, large compressibility, and, therefore, lower foundation competence [10, 2, 11, 5]. Grain size distribution, Atterberg limits, plasticity index, and specific gravity are all index properties, which cannot be done away with when it comes to classifying soils and making inferences about their behavior. High compressibility and shrink-swell potential are commonly identified by high plasticity clays (e.g., A-7-6 or CL-CH groups), and are commonly considered as fair to poor as sub-

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grade or foundation materials [10, 2, 12, 5]. The indices of plasticity exceeding 2025% and high liquid limits often indicate the presence of low resistivity and low foundation competence [10, 2]. On the other hand, the sands and silty sands, which have low-mediocre plasticity and good density, tend to offer moderate-high engineering competence of shallow foundations [2, 4, 13]. Design is also affected by hydrogeological conditions and chemical conditions. Effective stress can be reduced by shallow groundwater or thick saturated clays, or by environments that are aggressive to chemicals, and may encourage consolidation settlement, or introduce durability and corrosion issues [14, 4, 15, 5]. In areas where they exist, expansive clays or large ratios of free swell may cause foundations and pavements to heave and crack [14]. Evaluation of environmental radioactivity may be used to supplement geotechnical activities by eliminating radiological risks at deep foundations, as in Cairo, where the effective doses calculated were less than the acceptable limits [14].

### B. Investigation methods and integrated characterization

Strong assessment of the subsoil properties is based on the combined geophysical and geotechnical methods, and this combination offers spatial coverage and quantitative engineering parameters. The most common tools to map layer continuity, thickness, fractures, and areas of weak or clayey material are electrical resistivity, Vertical Electrical Sounding (VES), resistivity tomography, Very-Low-Frequency (VLF) electromagnetic surveys, and magnetic profiling [1, 2, 4, 13, 16], 2 Clay-based, organic, and saturated layers with low resistance are compressible, weak, and may be corrosive in nature, and associated with low-resistance horizons [1, 2, 15, 11, 5, 17]. Bear-

ing capacity and settlement properties are then measured using geotechnical techniques, such as borings, SPT, Cone Penetration Tests (CPT), laboratory strength, and consolidation tests. As an example, geophysical and geotechnical joint testing on Lagos Island revealed clayey and water-laden units and suggested deep pile foundations that ended below 13 m of competent strata [1]. In basement foundation, VLF-EM, resistivity, and index testing were used in combination to define highly weathered and plastic clays over fractured basement rock, and it was found that poor-to-low subsoil competence is necessary and indicated in the classification of the material [11, 18].

### C. From subsoil properties to foundation design

Stratigraphy and properties defined, bearing capacity and settlement analysis lead to the guidance of the type of foundation and depth. Strength parameters or SPT/CPT relationships are used to estimate ultimate and allowable bearing capacities using such approaches as Terzaghi, Meyerhof, and Bowels [7, 3, 4, 13, 16, 9, 5]. Residual sandstone with SP-SP-SM profiles have been reported to have bearing capacities of 2.8 to 8 tsf, and reaction coefficients of subgrade favor the use of concreteness and a uniform distribution of loads when the raft foundations and stiffness need to be taken into account [3, 19].

### D. Subsoil and foundation design examples

Several case studies illustrate how evaluation of subsoil properties leads to tailored foundation solutions and construction suitability assessments:

TABLE I  
SUMMARY OF REPRESENTATIVE CASE STUDIES AND RECOMMENDED FOUNDATIONS

Site/Setting	Dominant Subsoil & Key Properties	Recommended Foundation / Suitability	Citations
Urban district (Pakistan)	Variable sands and clays; SPT-based zoning and bearing capacity maps	Shallow spread footings with allowable bearing capacity accounting for shear, settlement, seismic effects	[7]
Lagos Island, Nigeria	Clayey, compressible near-surface soils; geoelectrical mapping of weak layers	Deep piles founded in competent strata >13 m	[1]
Residual sandstone site	Poorly graded sands, silty sands with clayey layers; UCS 217–1238 kPa	Raft foundation suitable; site generally appropriate for buildings	[3]
Stadium complex, Akure	Clay-rich, low-resistivity layers and fractures; high-plasticity samples	Soils classified from poor to good; zones with high plasticity unsuitable for shallow foundations	[2]
Cairo deep foundations	Fill over clays and sands; friction angle 35–41°, non-aggressive chemistry; variable swell	Pile design with computed $Q_u$ , $Q_{all}$ and settlement; site suitable and non-hazardous radiologically	[14]
Coastal sands, Ilaje & Ode Irele	Moderately thick, high-resistivity coastal sands; bearing capacity 150 kN/m <sup>2</sup> ; settlements <25–50 mm	Shallow strip/raft foundations at 0.8–1.6 m; driven and bored piles sized for higher loads	[4, 13]

These examples show that even within the same regional geology, local variations in plasticity, density, groundwater, and structure can shift recommendations from shallow strip footings to rafts or deep piles [1, 3, 4, 13, 5].

### E. Uncertainty, spatial variability, and reliability

The subsoils are naturally unpredictable both horizontally and vertically. The analysis with random field modeling and probabilistic analysis shows that the parameters of settlement-related phenomena are strongly spatially autocorrelated, and variability is frequently a more important factor influencing the estimation of subsidence than correlation structure [20, 21]. The approaches based on reliability are thus recommended to measure the probability of failure and to define the safety factors and design margins, particularly in sensitive or heavily loaded projects [20, 6].

The current research also highlights the concept of transforming legacy geotechnical study reports into geostatistical soil maps through the optimization of SPT N-values, soil types, and seismic velocities interpolation to construct depth-dependent bearing capacity to build regional geotechnical zoning [7]. These models permit less costly initial layouts and faster elimination of unfeasible areas, which do not need unnecessary repeat investigations, though the final design must be site-confirmed.

### F. Construction suitability assessment and sustainability

The suitability of a site during construction, based on the after selecting the foundation the right type, is determined by the characteristics of the subsoil which must meet the criteria related to the bearing failure, total and differential settlement, corrosion and durability risks, and long-term stability under environmental and seismic loads [7, 1, 2, 4, 15, 5]. In soils of

fair to poor consistency, such as high-plasticity clays, organic peats, weak fills, and so on, one may choose to either avoid the area, deep foundations, preloading and consolidation, stabilization, or some other ground improvement options [10, 2, 12, 11, 22]. In both the existing structures and the new infrastructure, like wind turbines and solar farms, geotechnical engineering will be used to provide the underground data necessary to enable safe location, the use of the most appropriate foundations, and resistance to natural disasters [12, 6]. Combined, methodical characterization of subsoil engineering qualities therefore continues to figure at the center stage in feasible foundation design and sound construction aptness evaluation. The design of the foundations should consider ultimate and serviceability limit states. The end limit state is that of failure caused by bearing capacity or shear collapse, and the serviceability limit state is the one in which settlement and deformation are limited by acceptable margins. Whether to use shallow foundations, which include strip and pad foundations, or deep foundations, which include piles, depends on the characteristics of the subsoil to a large extent. Where the soil is good and not deep in the ground, shallow foundations can be sufficient and cost-effective. Deep foundations or ground improvement methods are, however, needed where surface soils are weak, highly compressible, or expansive. The construction costs may be too high, or structural instability may occur without an adequate geotechnical assessment of the foundation. Environments and climatic aspects also affect subsoil behavior between the structural considerations. Fluctuations in the moisture content in the soil during different seasons can lead to expansion and contraction in the clay soils, and a change in effective stress conditions may also occur due to variation in the level of groundwater. Organic matter or deleterious materials, which weaken the soils and make them compressible, may also be present in certain areas. These factors need to be understood in order to have long-term performance. Green building, as well, places significant importance on the ability to design foundations according to the unique site soils as opposed to generalized methods. Coherent geotechnical analysis will eventually lead to lessening risks, reducing costs, and ensuring structural stability. With a careful study of subsoil engineering properties, the engineers will be able to foresee the likely difficulties and take some preventive measures even

before construction starts. This positive strategy will reduce the risk of distress of the foundation, structural damage, and the expensive corrective actions. Accuracy and completeness of subsurface investigation and laboratory tests can be considered to be the key to the reliability of any civil engineering project. Hence, a thorough evaluation of the index properties, compaction behavior, shear strength, compressibility, and permeability properties is the basis of responsible foundation engineering and guarantees that the basis of construction activities is conducted on an informed and safe platform.

## II. METHODOLOGY

### A. Research design

The research adopts an experimental and laboratory-based geotechnical investigation approach aimed at evaluating the engineering properties of subsoil for foundation design suitability assessment. This design involves the systematic collection of soil samples from the field, followed by detailed laboratory testing to determine physical and mechanical characteristics. The experimental approach ensures that measurable and reproducible data are obtained under controlled conditions. Laboratory tests are conducted in accordance with recognized geotechnical standards to ensure the accuracy and reliability of results. The properties investigated include index properties, compaction characteristics, shear strength parameters, compressibility behavior, and permeability. These parameters provide essential information regarding soil classification, load-bearing capacity, settlement potential, and drainage characteristics. Data generated from laboratory tests are analysed using standard geotechnical principles and empirical relationships to assess the suitability of the soil for foundation construction. The integration of experimental results with engineering analysis enables the determination of allowable bearing capacity and the prediction of settlement behavior. This structured research design ensures a scientific and systematic evaluation of subsoil conditions, thereby minimizing uncertainties in foundation design and enhancing the safety, durability, and performance of proposed structures.

TABLE II  
DETAILED RESEARCH DESIGN

S/N	Component	Description	Purpose	Expected Output
1	Research Type	Experimental laboratory investigation	To obtain measurable soil data	Quantitative soil parameters
2	Data Source	Field soil samples	Represent in-situ conditions	Representative soil specimens
3	Laboratory Tests	Index, compaction, shear, consolidation, permeability	Determine engineering properties	Soil classification & strength values
4	Data Analysis	Engineering calculations & interpretation	Assess foundation suitability	Bearing capacity & settlement estimates
5	Evaluation	Comparison with standards	Confirm construction suitability	Design recommendations

### B. Site description and soil sampling

The study area is carefully examined to understand its geological and environmental characteristics prior to sampling. This includes reviewing local geology, topography, drainage conditions, and land use patterns that may influence soil behavior. Site reconnaissance is conducted to observe surface features such as vegetation, existing structures, erosion patterns, and groundwater indications. Sampling points are strategically identified to ensure that collected samples accurately represent subsurface conditions. Soil samples are obtained using appropriate methods depending

on the required test type. Disturbed samples are collected for index and compaction tests, while undisturbed samples are obtained using sampling tubes for consolidation and shear strength tests. Samples are taken at predetermined depths to capture variations in soil layers. The depth of sampling depends on the anticipated foundation level and subsurface profile. After collection, each sample is properly labeled with location, depth, date, and sample number. Samples are carefully sealed to prevent moisture loss and transported to the laboratory under controlled conditions to preserve their natural state. Proper handling ensures the reliability and validity of laboratory test results for accurate engineering assessment.

TABLE III  
DETAILED SITE DESCRIPTION AND SAMPLING TABLE

S/N	Activity	Description	Equipment Used	Purpose
1	Site Reconnaissance	Visual inspection of terrain and surface conditions	Field notebook, GPS	Understand environmental & geological setting
2	Selection of Sampling Points	Strategic identification of test locations	Measuring tape, GPS	Ensure representative sampling
3	Sampling Method	Disturbed & undisturbed sampling techniques	Auger, sampling tubes	Obtain soil specimens for testing
4	Depth of Sampling	Samples collected at specified depths	Hand auger/drilling equipment	Capture soil layer variation
5	Labeling & Preservation	Proper identification and sealing of samples	Sample bags, labels, wax	Maintain natural condition
6	Transportation	Safe delivery to laboratory	Sample boxes	Prevent contamination & moisture loss

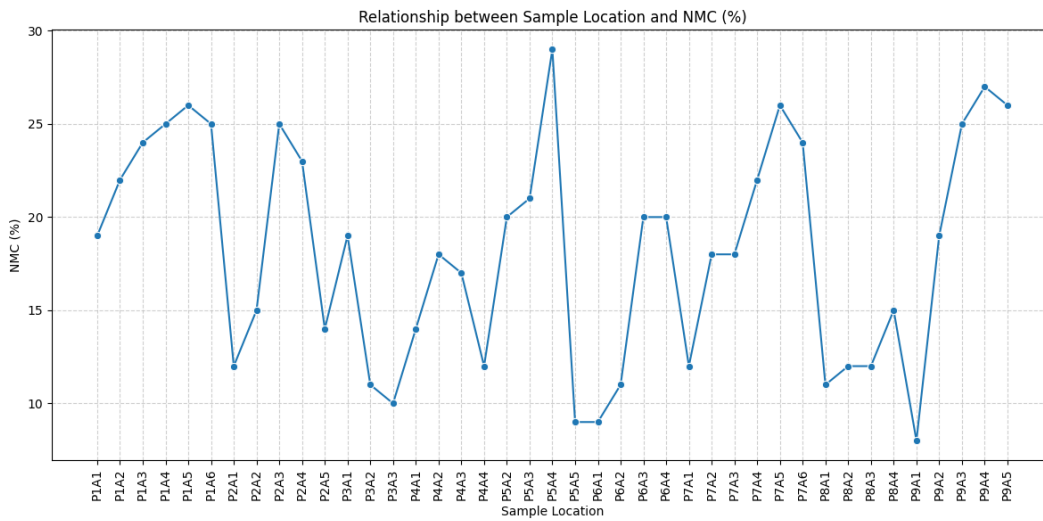


Fig. 1. Relationship between sample location and NMC (%)

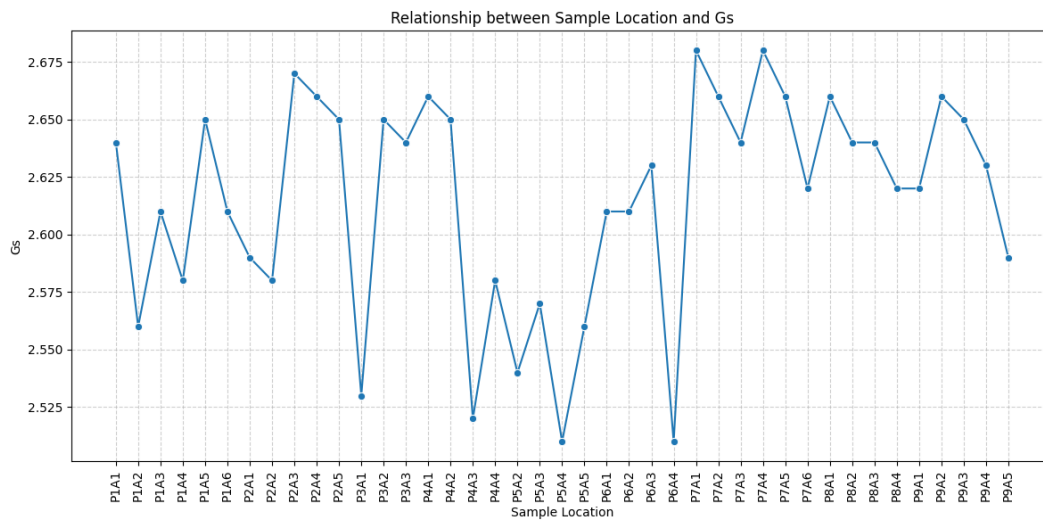


Fig. 2. Relationship between sample location and Gs

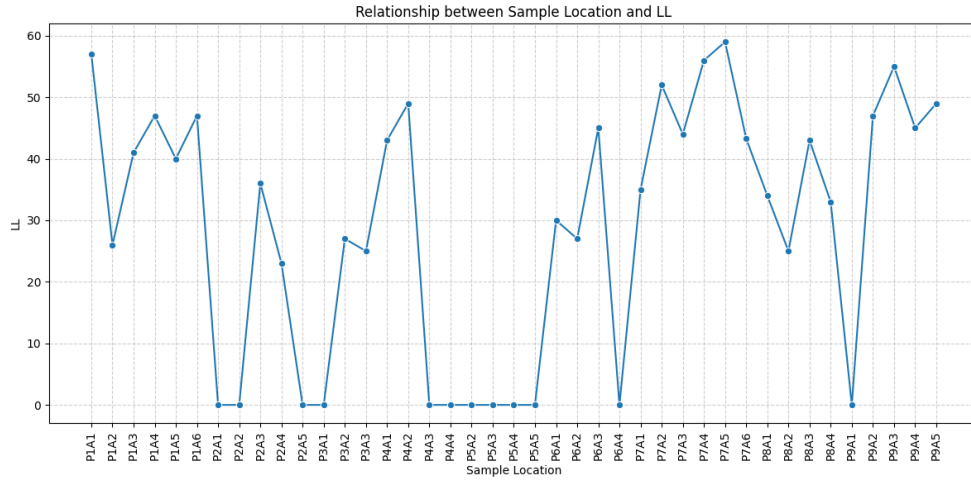


Fig. 3. Relationship between sample location and LL

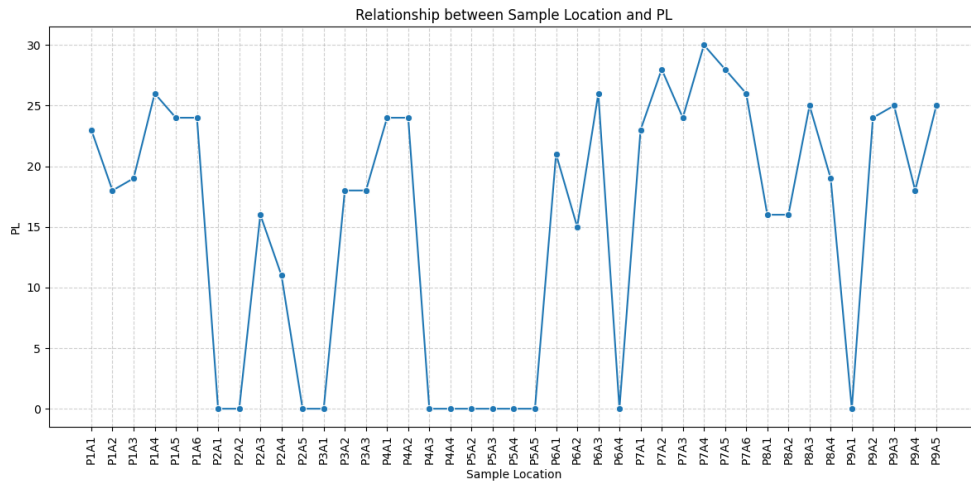


Fig. 4. Relationship between sample location and PL

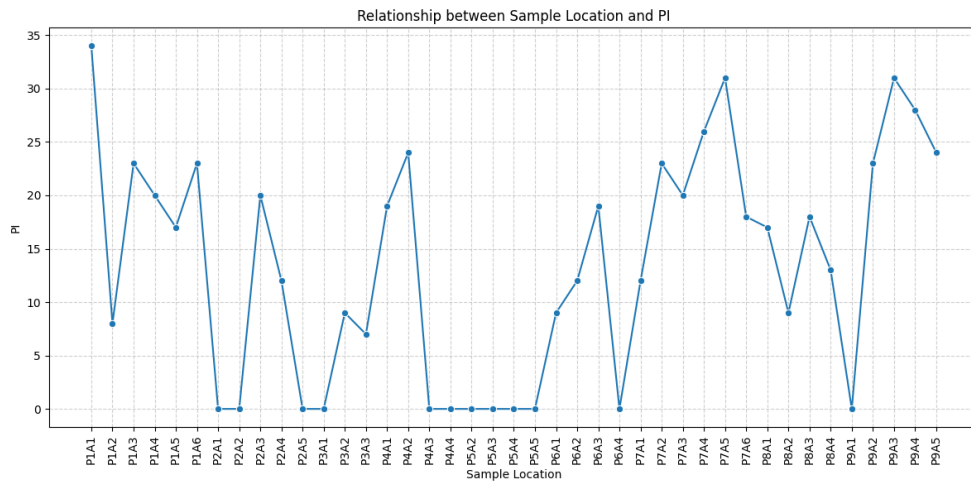


Fig. 5. Relationship between sample location and PI

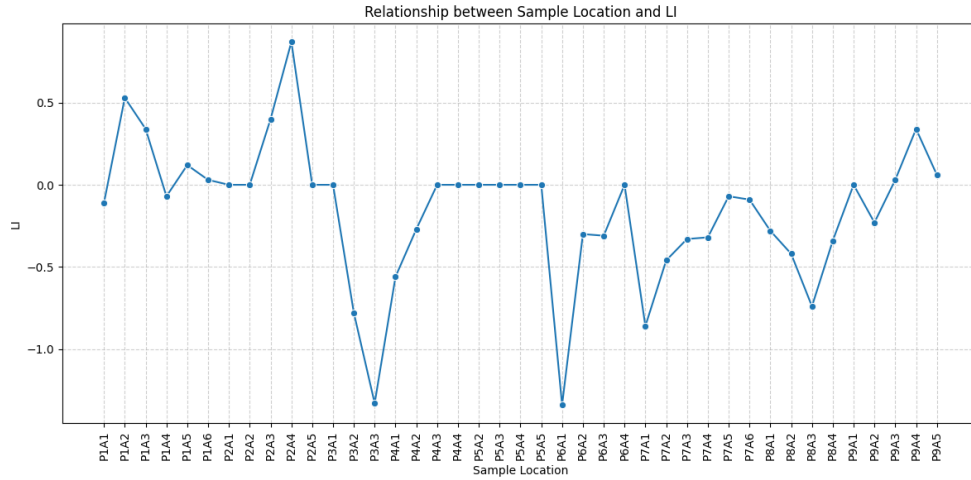


Fig. 6. Relationship between sample location and LI

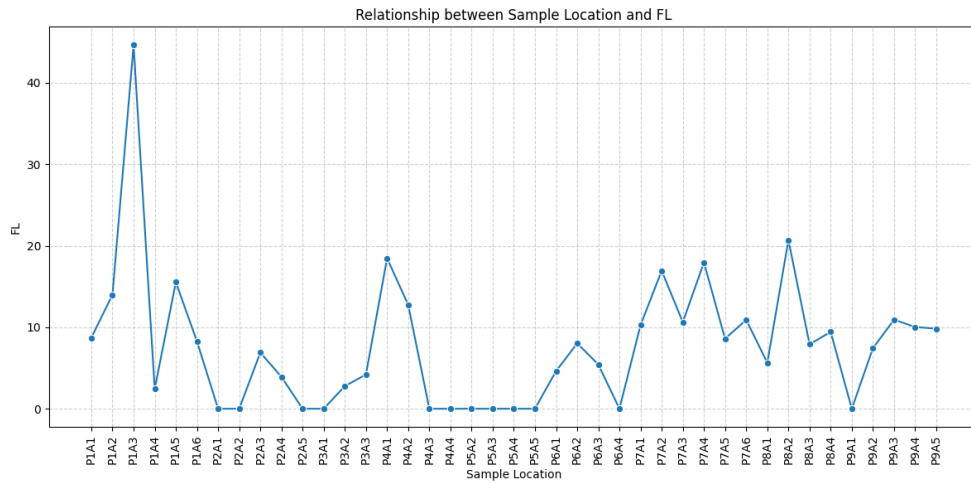


Fig. 7. Relationship between sample location and FL

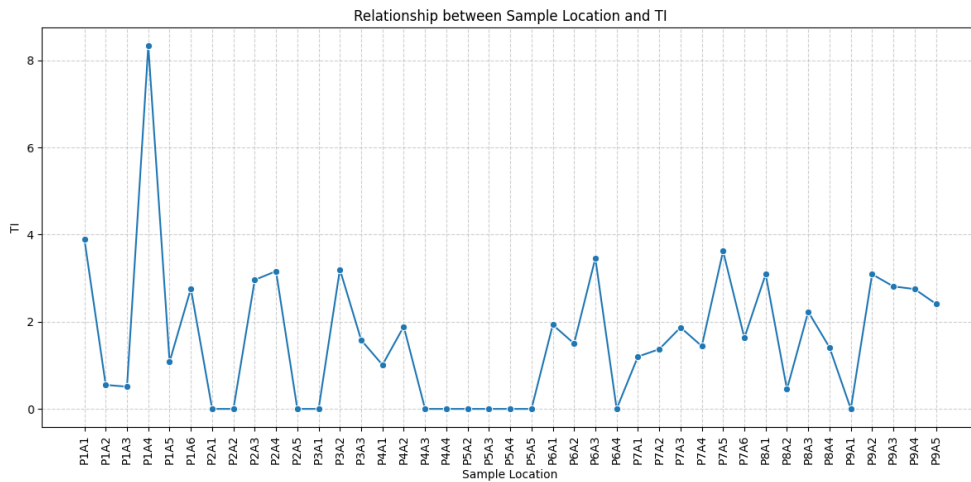


Fig. 8. Relationship between sample location and TI

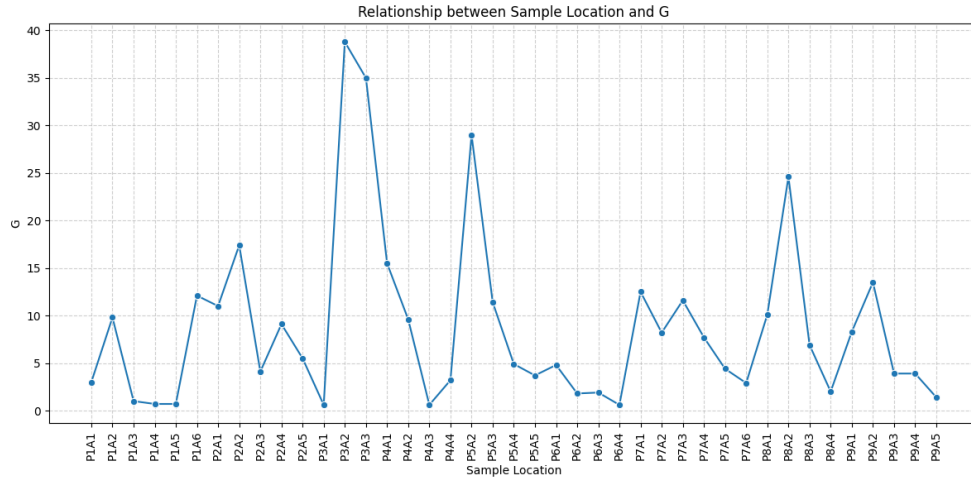


Fig. 9. Relationship between sample location and G

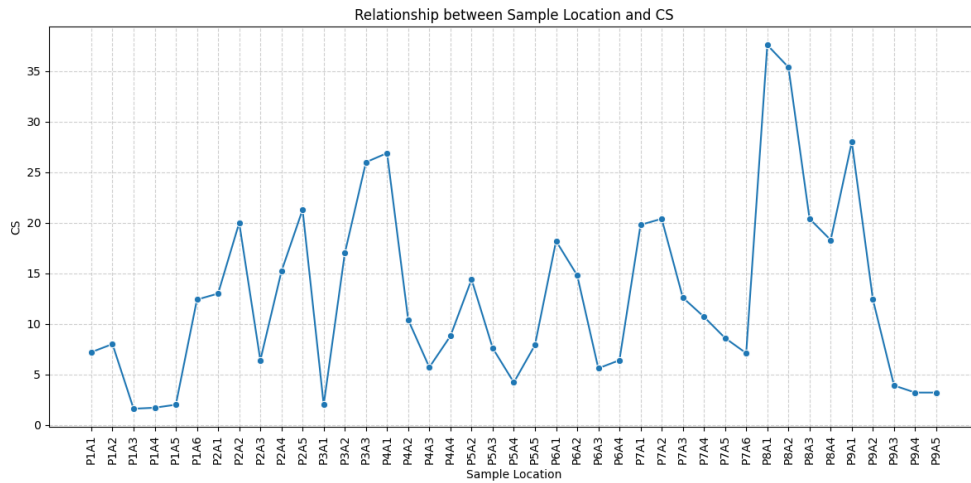


Fig. 10. Relationship between sample location and CS

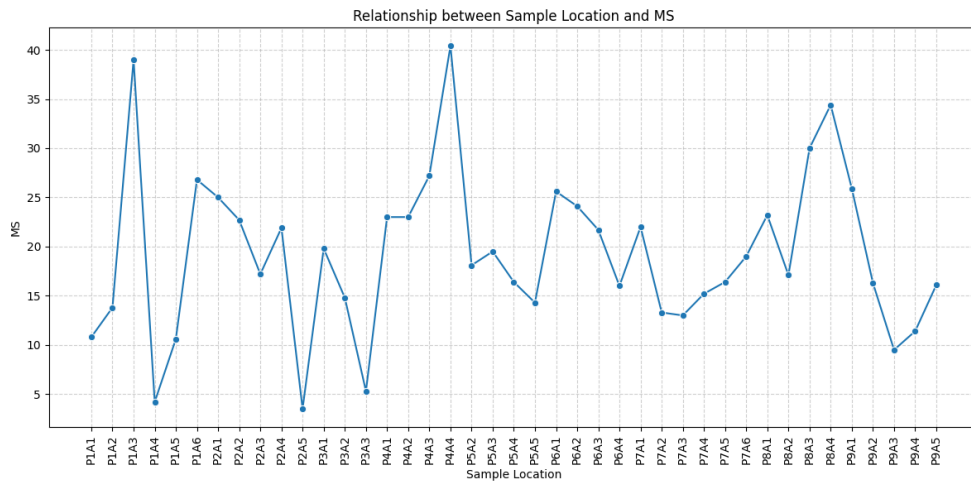


Fig. 11. Relationship between sample location and MS

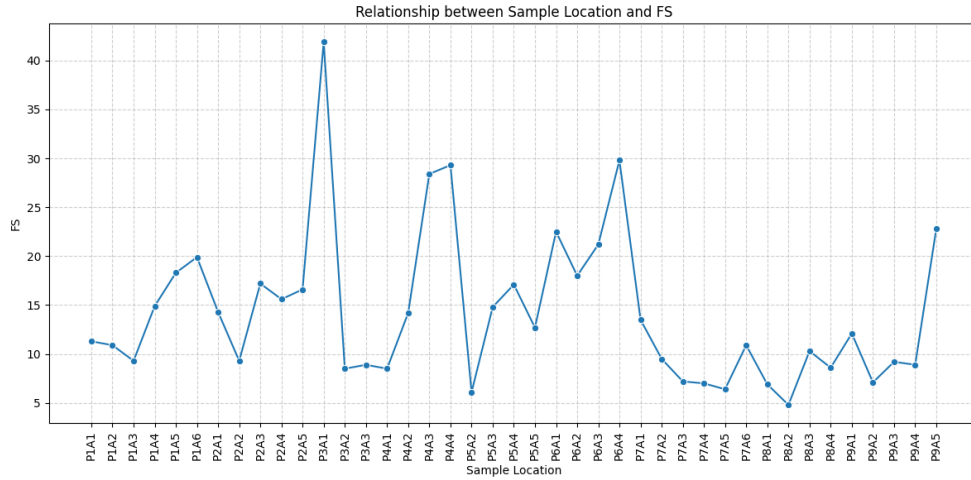


Fig. 12. Relationship between sample location and FS

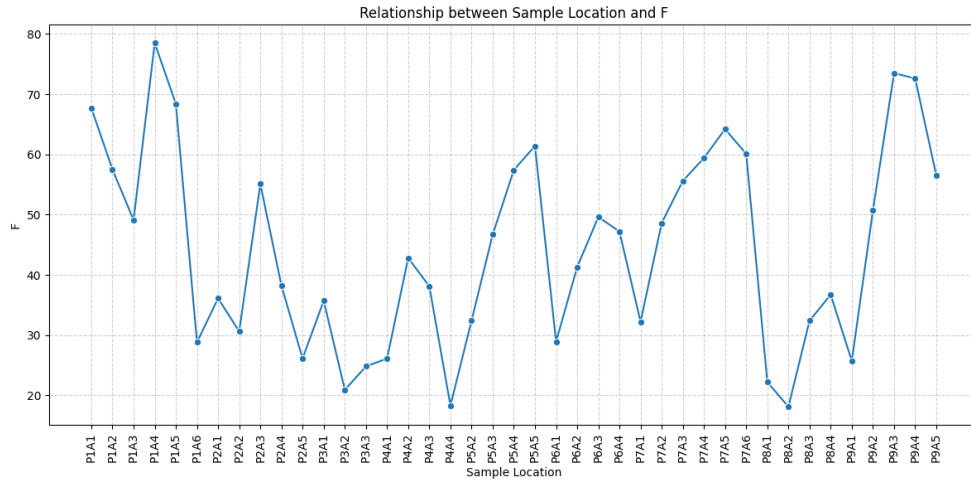


Fig. 13. Relationship between sample location and F

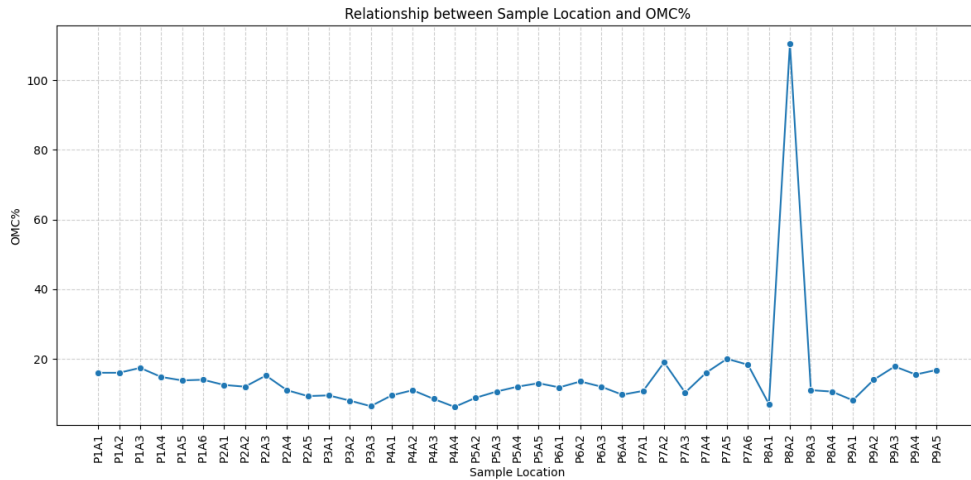


Fig. 14. Relationship between sample location and OMC%

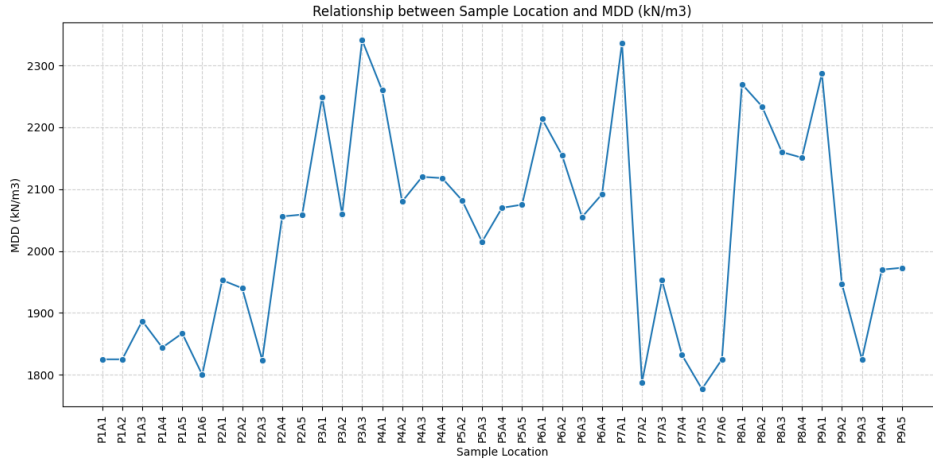


Fig. 15. Relationship between sample location and MDD (KN/m3)

**C. Laboratory testing program**

The laboratory testing program was made in order to effectively test the engineering behavior of the collected soil samples based on a set of standardized geotechnical tests comprising index properties, compaction properties, shear strength parameters, compressibility behavior, and permeability. Index property calculation was initiated by the Natural Moisture Content test that was performed to determine the in-situ water content of each soil sample, which has a significant impact on strength and compressibility. A specific gravity test was conducted to estimate the density of solids in the soil, which is a necessary parameter when calculating the void ratio, level of saturation, and other phase relationships. The Grain Size Analysis was done through sieve analysis of coarse-grained soil and hydro meter analysis of fine-grained soil to establish the size distribution of the particles, and the soil was classified according to the gradation. Atterberg Limit Liquid Limiting (LL), Plastic Limiting (PL), and Plasticity Index (PI) tests were done on fine-grained soils in order to assess their consistency and plasticity properties. They were the basis of classifying the soils as per the Unified Soil Classification System (USCS) or the AASHTO system to give a platform upon which to predict engineering performance. To determine the correlation between the moisture content and the dry density, the Standard Proctor or the Modified Proctor compaction test was

conducted to determine compaction characteristics. The results of this test were the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD), which are very important parameters to be considered in the control of field compaction and foundation subgrade preparation. The direct shear test or triaxial compression test was used to determine the parameters of shear strength depending on the type of soil and the condition of the sample. These tests gave the values of cohesion (c) and angle of internal friction (Philadelphia geotechnical laboratories, 2014), without which the bearing capacity is impossible to determine, and the slope stability is not possible to evaluate. The compressibility properties were determined by conducting the Consolidation (Oedometer) test, which observed the performance of the soil under load in small steps. This test has resulted in the determination of the Compression Index (Cc), Coefficient of Consolidation (Cv), and pre-consolidation pressure, which make it possible to estimate the size and rate of settlement. The analysis was followed by a settlement analysis that was done using parameters of consolidation to forecast foundation performance during applied loads. Lastly, to establish the hydraulic conductivity (k), the method used to determine coarse or fine-grained soils included Constant Head or Falling Head tests, respectively, to determine the respective hydraulic conductivity of these soils. The combination of these tests offered an all-inclusive assessment of the subsoil suitability in terms of foundation design and construction.

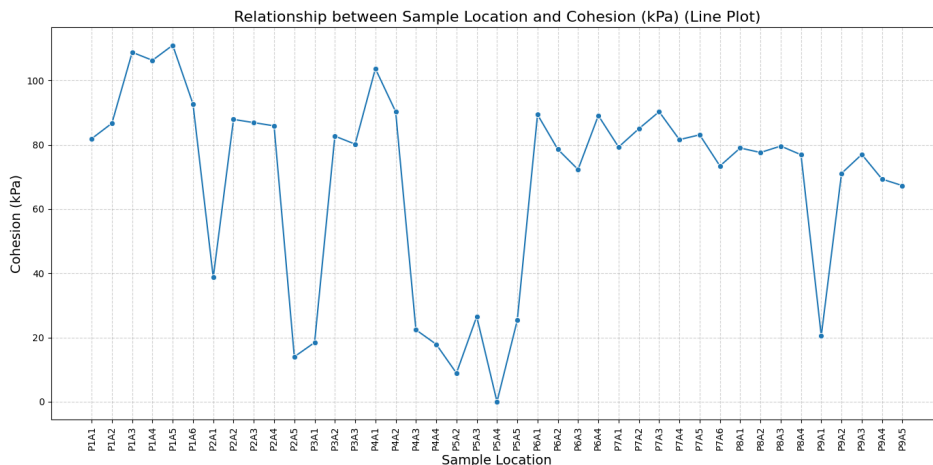


Fig. 16. Relationship between sample location and Cohesion (kpa) (Line plot)

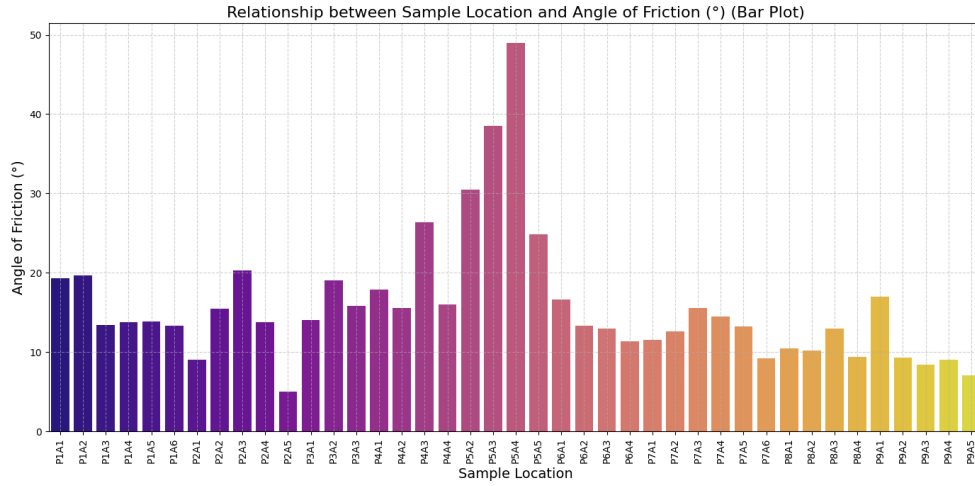


Fig. 17. Relationship between sample location and Angle of friction (°) (bar plot)

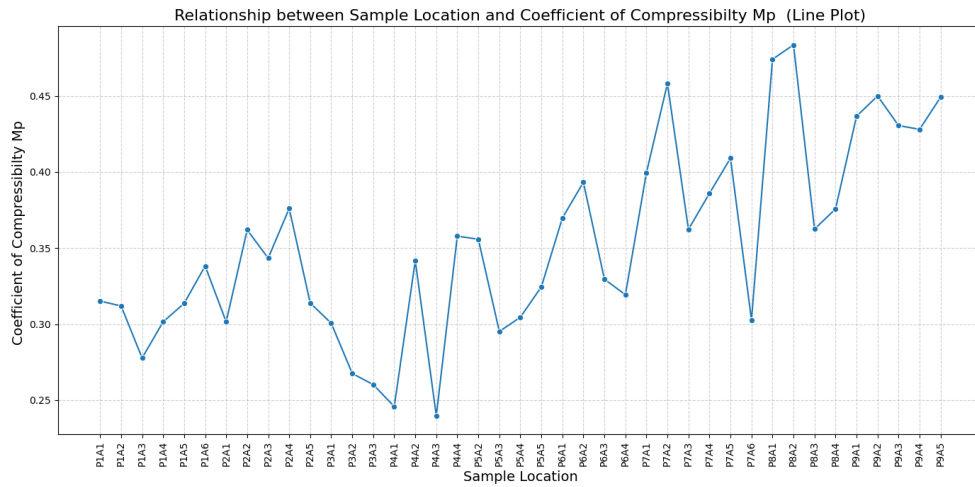


Fig. 18. Relationship between sample location and coefficient of compressibility Mp (line plot)

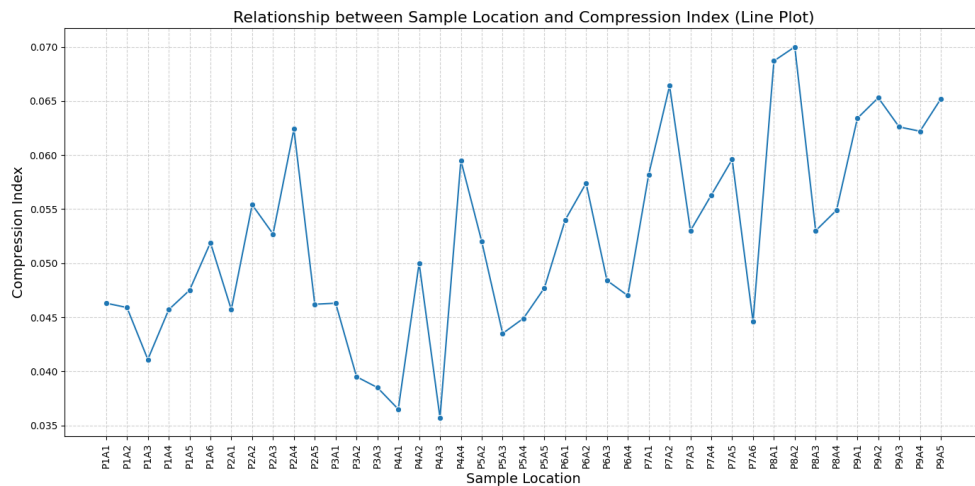


Fig. 19. Relationship between sample location and compression Index (line plot)

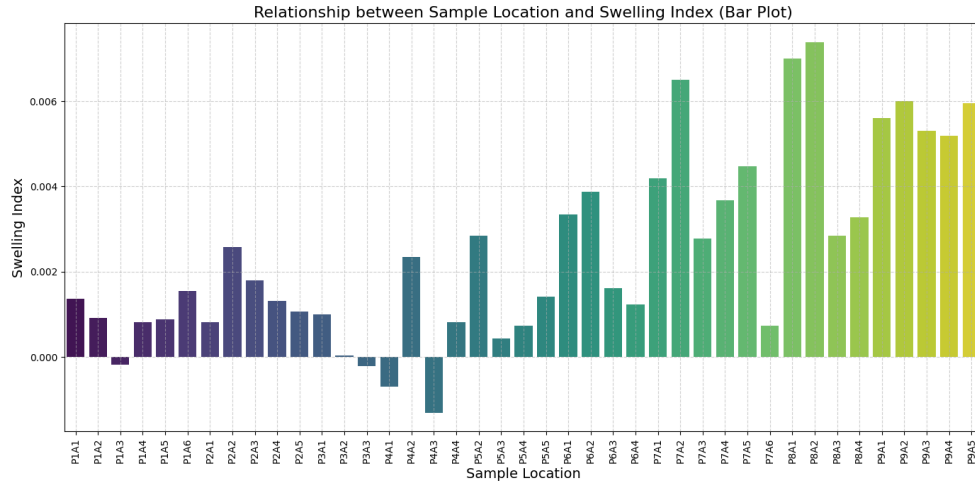


Fig. 20. Relationship between sample location and swelling Index (bar plot)

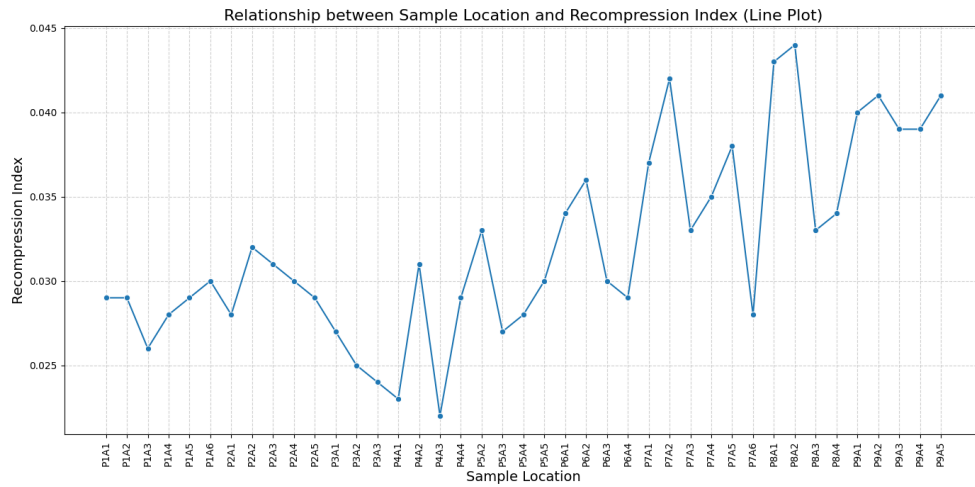


Fig. 21. Relationship between sample location and recompression index

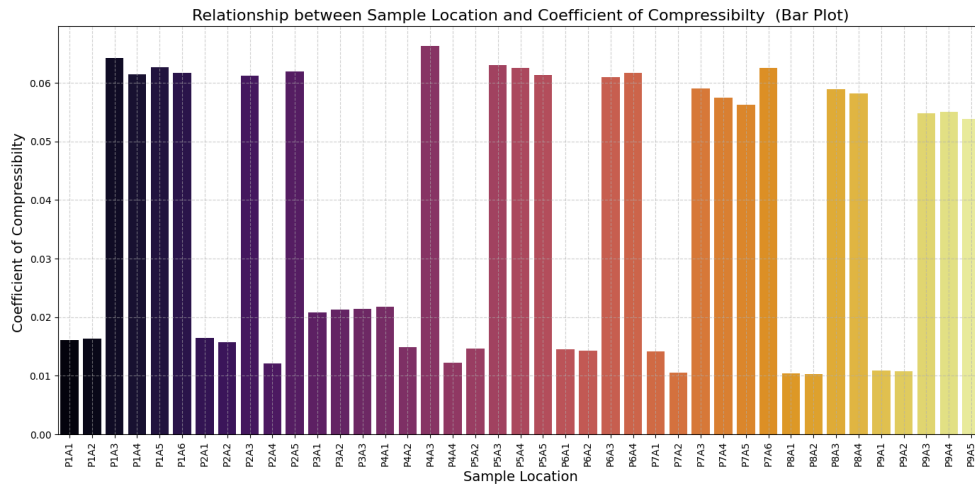


Fig. 22. Relationship between sample location and coefficient of compressibility (bar plot)

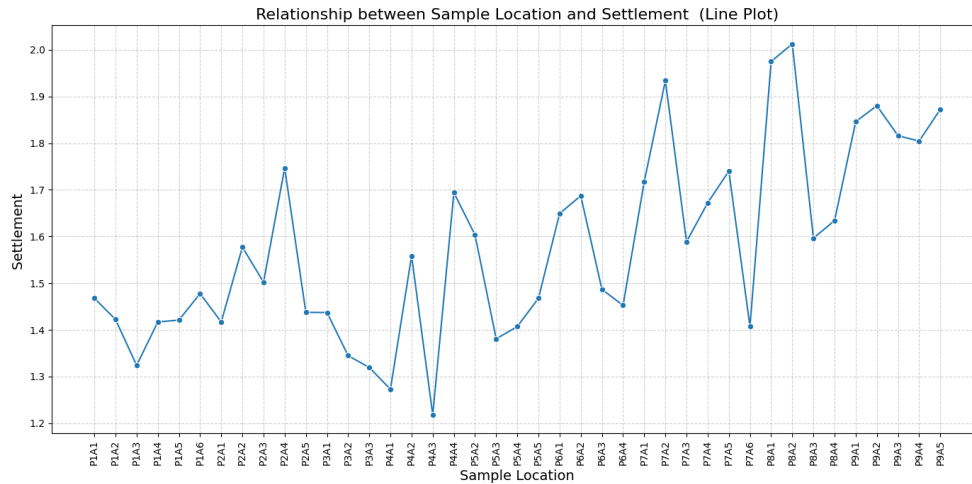


Fig. 23. Relationship between sample location and settlement (line plot)

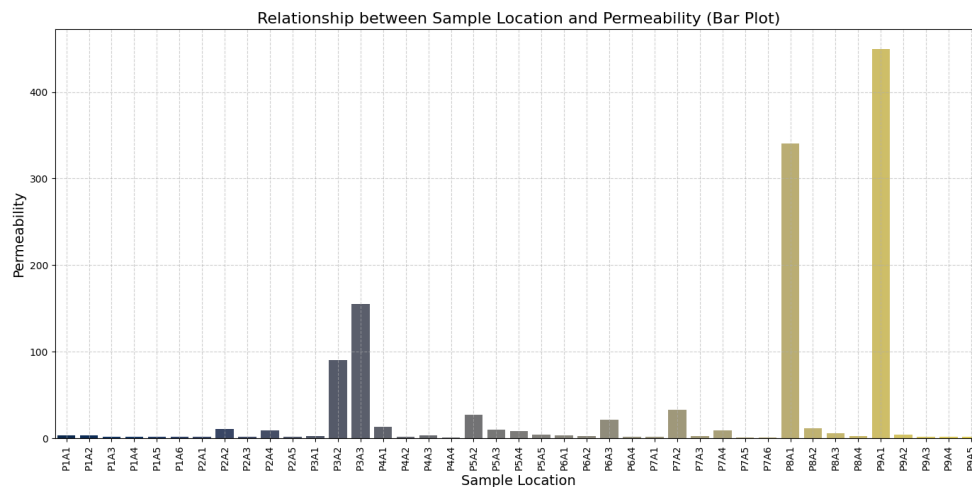


Fig. 24. Relationship between sample location and permeability (bar plot)

**D. Data analysis**

The data analysis phase includes systematized presentation, examination, and assessment of laboratory outcomes of the laboratory samples analyzed of the tested soil. The engineering behaviour of the soils is based on the input parameters which are Sample Locations, Natural Moisture Content (NMC), Specific Gravity (Gs), Liquid Limit (LL), Plastic Limit (PL), Plasticity Index (PI), Liquidity Index (LI), Flow Index (FL) and toughness Index (TI) and also on the grain size distribution constituents (Gravel-G, Coarse Sand-CS, Medium Sand-MS, Fine Sand -FS and Fines-F). These input outcomes are initially given as tabular and graphical forms, like grain size distribution curves and plasticity charts, to increase customer clarity and comparisons among samples. Based on the main test data, engineering parameters are calculated, and the output values are given. They are the Optimum Moisture Content (OMC%) and Maximum Dry Density (MDD) by means of compaction tests, soil consistency limits, and classification. Parameters of shear strength, such as Cohesion(kPa) and Angle of Internal Friction(°), are examined to determine the bearing capacity of the soil using the known equations of bearing capacity. The data presented through the consolidation tests is interpreted to provide compressibility characteristics, including Coefficient of Compressibility (Mp), Preconsolidation Pressure, Com-

pression Index (Cc), Swelling Index (Cs), Recompression Index (Cr), and Coefficient of Consolidation, which are used to estimate the extent and speed of settlement under structural loading. The values of settlement are computed and compared with the allowable limits of foundation performance. The results of permeability are analysed in order to determine the drainage properties and the possibility of dissipation of pore water pressure. Lastly, all the parameters assessed are compared to the standard engineering requirements and design guidelines in order to detect the appropriateness of the subsoil used in constructing the foundation. This combined method of analysis will guarantee that both strength and deformation properties are well evaluated to make a safe and cost-effective foundation design.

**III. RESULTS**

**A. Input parameters**

The data provided in the input parameters gives a full quantitative analysis of the physical and index properties of the soils under study that are the basis of further engineering assessment. Multiple sampling points (P1A1 to P9A5) were studied, and it was detected that there were significant changes in the moisture condition, plasticity, gradation, and classification

with space. Natural Moisture Content (NMC) is between 8 percent (P9A1) and 29 percent (P5A4), which means moderate to high levels of in-situ water in the various locations. The measurements that indicated increased moisture (over 24) of samples like P1A3, P1A4, P7A5, and P9A4 indicate relatively soft to firm clayey conditions, and this may affect the compressibility and shear strength behavior. Reduced moisture content (812) of the samples (P3A3, P6A1, and P8A1) implies a drier and possibly drier soil. The values of Specific Gravity (Gs) are 2.51 to 2.68, which is within the normal range of inorganic mineral soils. These values are indicative of mostly quartz-based and silicate clay minerals, and nothing to indicate unusually heavy or organic soils. The fairly stable Gs values are proof of mineralogical homogeneity with the change in gradation and plasticity. Atterberg Limits are highly variable. Liquid Limit (LL) takes values between 23% (P2A4) and 59% (P7A5), and Plastic Limit (PL) takes values between 11% and 30%. As a result, Plasticity Index (PI) varies between 7% (P3A3) to 34% (P1A1). When PI values exceed 25 percent (e.g., P1A1, P7A5, P9A3, P9A4), then there are highly plastic clays (CH classification), the presence of which is normally linked to a high compressibility and ability to shrink and swell. Moderate PI values (1524) are associated with intermediate plasticity clays (CI), whereas low PI values (less than 10) of P1A2, P3A3, belong to low plasticity soils (CL). Different samples denoted as NP (Non-Plastic) have the same value of LL, PL, and PI as 0, which proves the dominance of granular soil behavior. The values of the Liquidity Index (LI) are between -1.34 and 0.87. The negative values of LI (e.g., P6A1, P3A3, P7A1) denote the presence of soils in stiff or semi-solid form compared to the plastic limits, whereas the values of positive LI (around 1) (P2A4 = 0.87) denote the softer conditions of consistency. Toughness Index (TI) has a range of 0-8.33, with high values signifying increased resistance to deformation at and approaching the plastic limit. A lot of variability is seen in the grain size distribution. The content of gravel (G) is 0.6 -38.8, coarse sand (CS) is 1.6 -37.6, medium sand (MS) is 3.5 -40.4, fine sand (FS) is 4.8 -41.9, fines (F) is 18.1 -78.5. Clearly, fine-grained and clay-based samples like P1A4 (78.5% fines) and P9A3 (73.5% fines) are represented by samples like P3A2 and P3A3, which have higher percentages of gravel and sand, respectively. The existence of sand fractions in most of the NP classified soils proves their non-plastic nature as granules. The Compaction parameters indicate the Optimum Moisture Content (OMC) of 6.2% (P4A4) to 20% (P7A5) and the Maximum Dry Density (MDD) of 1777kg/m<sup>3</sup> -2341kg/m<sup>3</sup> (P3A3). A granular soil has a higher MDD value, whereas a fine-grained clay has less moisture demand and hence low density. Consistency characterizes mainly CH, CL, CI, and NP, whereas the description of the grain size (e.g., SL: CMS) characterizes mixed sand-clay systems in the greater part of the locations. In general, the data is representative of a non-homogeneous soil profile of high plastic clays, intermediate clays, low plastic clays, and non-plastic sandy soils, which implies fluctuating engineering behavior and requires assessment of the foundation on a case-by-case basis.

## B. Output results

### 1) Cohesion (kPa)

In soil bonding strength, cohesion values are between 0 kPa and 111 kPa, which means that cohesion varies greatly. A high cohesion value (greater than 80 kPa) found in several samples implies that there were strong interparticle attraction forces of the clay. Soil of moderate cohesion (4080 kPa) exhibits clayey-silty soils that have relatively good shear resistance. Very low values of cohesion (less than 25 kPa) are associated with sandy or non-plastic soils, whereby friction predominates shear strength. Cohesive soils of greater than 100 kPa (e.g., 108.8-111 kPa) have a high shear failure resistance, which adds positively to bearing capacity. Nonetheless, high cohesion usually goes hand in hand with increased compressibility and possible settlement issues.

### 2) Angle of Internal Friction (°)

Angle of internal friction ( $\phi$ ) is influenced by the content of granules and the interlocking of particles that are 5° - 49°. The low values (5-15°) are characteristic of the clay-based soils in which the frictional resistance is minimal. Moderate (15° -30°) values: The presence of a mixed sand-clay system associated with enhanced shear resistance. Friction angles that are high (greater than 30 degrees) to a maximum of 49 degrees are associated with granular soils that contain large proportions of sand or gravel. Soils having a high phi value help to increase the bearing capacity and slope stability. The extensive range of diverse variation supports the fact that the soil compositions are heterogeneous among sampling sites.

### 3) Coefficient of Compressibility (Mp)

The compressibility coefficient is between 0.239 and 0.484, with the range being between moderate and relatively high compressibility. The smaller Mp (approximately 0.24-0.30) indicates more rigid soils that show less deformation with load, and the larger ones (greater than 0.40) indicate softer, compressible clayey soils. Samples whose Mp is above 0.45 can be subjected to some apparent settlement during structural loading. The difference is in line with plasticity differences in index properties. In most cases, the data indicates medium compressibility, and special settlement analysis is needed in the very plastic areas.

### 4) Compression Index (Cc)

The values of the compression index are 0.0357 to 0.070, implying that it has low to medium compressibility. The censor Cc (0.035 0.045) is more stable in soils that do not exhibit much change of volume, whereas higher values of censor Cc (greater than 0.06) indicate more compressible clays. Samples whose Cc is close to 0.07 are more vulnerable to the settlement of the consolidation. In general, the range displays moderate consolidation qualities of inorganic clays and clayey sands. The magnitude of settlement will be proportional to increased values of Cc in sustained loading.

### 5) Swelling Index (Cs)

The swelling index ranges between about -0.0013 and 0.0074, which represents low swelling potential. Minimally negative values possible can be attributed to variation in measurements, but in effect indicate insignificant expansion behavior. Beyond the positive value of -0.005, there is a slight swelling tendency, whereas a value near -0.007 is a positive indication of expansion in very plastic clays. In general, the swelling probability within the data range is low to medium, which means that there are not many risks associated with expansive soil issues in the presence of moisture changes.

### 6) Recompression Index (Cr)

The values of the recompression index are between 0.022 and 0.044, which are the behavior of soil in reloading conditions. A low value of Cr implies that the volume of the soil does not change much during unloading and reloading, as is the case with normally consolidated soils. The values are higher (above 0.04), which indicates somewhat higher elastic rebound properties. The range is quite small, which proves the moderate stiffness in the secondary loading stages. As would be expected, the values are much smaller than the Cc values because recompression behavior has smaller deformation increments.

### 7) Coefficient of Consolidation (Cv)

The coefficient of consolidation is in the order of 0.010 to 0.066 m<sup>2</sup>/year (or units), meaning that there is a variation in the rate of pore water pressure to dissipate. An increase in Cv value leads to accelerated consolidation

and completion of settlement, which is normally typical of soils of high drainage quality. A lower value of  $C_v$  shows that the process of consolidation is slower, especially in fine-grained soils. The sample indicates a moderate level of consolidation in general, i.e., settlements do not happen immediately.

### 8) Settlement (mm)

Settlements are estimated to vary between about 1.22 mm and 2.01 mm, which means that the settlements are predicted to be small at the loading conditions applied. The values are within the acceptable range for shallow foundation systems in most structural applications. The more the settlement values, the greater the compressibility index of the soil is, and the higher the  $M_p$  value of the soil is. The relatively low magnitude indicates that with controlled loading, most soils in the dataset can sustain foundations without undue deformation.

### 9) Permeability (k)

There is a considerable variation in the values of permeability, which are between about 0.516 and 449.908 (unit values taken). When the values are lower, it means that the soils are clay-based and therefore have low drainage ability, which slows down the process of consolidation. The increase in permeability is associated with sandy or granular soils that have good drainage and dissipation of their pores. For very high values (more than 100), one can be certain that it is granular soil behavior. The heterogeneous soil structure is attested to by the large variation in the composition as well as the drainage properties across the study area.

## IV. DISCUSSION

The wide range of the cohesion (0-111 kPa) and friction angles (5-49 degrees) indicates that it has a heterogeneous substrate profile ranging between loose sands and very plastic clayey materials, which is consistent with the regional records where the compression index,  $C_c$ , is ranging between almost zero in sands to over 150 kPa in stiff lateritic or overconsolidated clay formations [23, 24, 25]. Values of cohesion exceeding 80 kPa and low-moderate friction angles are similar to deposits of lateritic and compacted cohesion that provides sufficient short-term bearing capacity, but could suffer settlement over time, should the indices of compressibility be not negligible [26, 23, 27]. Conversely, near-zero cohesion having friction angles greater than 30° characterises dense granular strata that have frictional shear strength that is highly sensitive to grading and particle size [28, 29, 25]. Experimental data show that as the max particle size and interlocking are enhanced, so is the cohesion and angle of friction in coarse fill materials [28, 30, 25], which is in line with the high- $\phi$  subset of the data.

The values of compressibility parameters ( $M_p$  0.24-0.48;  $C_c$  0.036-0.07;  $C_r$  0.022-0.044) suggest low to moderate compressibility in general, which is less than many soft clays where  $C_c$  usually lies between 0.2 and 0.6 and  $C_r$  is a decade lower [26, 31, 32, 27]. These low values of  $C_c$  and  $C_r$ , combined with a comparatively low coefficient of consolidation ( $C_v$ , 0.01-0.066 m<sup>2</sup>/yr), indicate primary consolidation, which is both measurable but not extreme, as is typical of structured or overconsolidated sands and clays [33, 26, 34, 35]. The estimated settlements at 1.2-2.0 mm with design stress are far below the values recorded in highly compressible marine or organic clays that may yield settlements of centimetres to hundreds of millimetres [33, 31, 27, 36, 37]. Similarly, Artificial Neural Network (ANN) and Support Vector Machine (SVM) based regional models are evidenced to show that soils in this  $C_c C_r$ -envelope tend to produce small to moderate total settlements in case loading is not incompatible with bearing capacity [30, 32, 37, 38].

Non-expansive to slightly expansive inorganic clays such as the lateritic and ferrallitic ones with the free swell rate being less than 50% and with minimal heave potential are characterized by low to slightly positive swelling indices ( $C_s$  about -0.0013 to 0.0074) and recompression indices that are significantly lower than  $C_c$  [26, 23, 31, 27]. Therefore, the probability of differentiating heave under typical variations of moisture is low as opposed to expansive bentonitic materials, which exhibit far more swelling parameters and activity [26, 23, 31, 39]. Nevertheless, localized increased  $C_s$  or plasticity could still support the need to control the moisture or drainage where sensitive structures would be suggested [33, 26, 40, 41, 27].

Permeability is in a variety of orders of magnitude (approximately 0.5-450 in recorded units) and, therefore, proves the existence of alternating low- $k$  cohesive and high- $k$  layers of granular [33, 24, 31, 25, 36]. The research on soft and coastal soils demonstrates that such stratification is a significantly influential factor on the rate of consolidation: in high- $k$  sandy lenses, pore-pressure dissipation is faster, and in thick low- $k$  clays, long-term settlement is controlled [33, 24, 34, 42, 35]. The reported  $C_v$  and  $k$  combination is within the range of soft to medium clays and loose sands, where the process of primary consolidation is not instantaneous or too slow [33, 26, 31, 34, 35]. Layered foundation studies point out that the difference in  $k$  and compressibility between strata could cause non-uniform settlement and redistribution of stress, even when  $C_c$  and  $C_v$  averages are moderate [34, 35].

These data reflect overall patterns in the empirical literature, the high correlation between index properties and mechanical behaviour. Increases in clay content, as well as water content, raise cohesion in a systematic way, though it can raise the angle of friction above an optimal point [33, 26, 41, 36]. The predictors of cohesion show that clay fraction, organic matter, and suction best predict cohesion, whereas the predictors of friction angle are more sensitive to grading and density [41, 29, 36]. Those relationships justify the application of the simple index test to narrow spatial zoning of the given parameters and to train information-driven prediction tools of bearing capacity and settlement [30, 38]. The measured ranges, in general, show that the soils can be safely used to construct shallow foundations with the appropriate consideration of the locally more compressible or low- $\phi$  soils, provided that reinforcement, compaction, or drainage are optimised [33, 26, 40, 30, 24, 25, 27].

## V. CONCLUSION

The geotechnical sampling showed that the properties of the soils between the sampled sites were highly heterogeneous. Parameters of indices showed that there was a dominance of clayey soils with fluctuating plasticity in comparison to non-plastic sandy constituents. Compaction properties showed that most soils with well-managed moisture conditions can be compacted to reasonable levels and thus represent the presence of suitability in foundation subgrade, when properly compacted. Shear strength parameters showed moderate and high values of cohesion with variable friction angles, indicating that the bearing capacity of shallow foundations would be generally good in a number of sites. The consolidation parameters were found to be associated with moderate compressibility and projected settlement that is lower under the considered loading conditions. Generally, the risk of expansive soil behavior was reduced by the presence of low to moderate swelling potential. The obtained results on permeability revealed the difference in drainage properties, and clayey soils showed a lower rate of consolidation compared to granular soils. In general, when many places can be accommodated with shallow foundation systems, the changes in plasticity and compressibility require careful design and site-based evaluation.

### A. Recommendations

- Shallow foundations could be implemented in locations that have moderate to high shear strength and low projected settlement, subject to confirmation of the permissible bearing capacity.
- The foundation loads should be carefully controlled in highly plastic clay areas, which are categorized as CH, so that the settlement due to consolidation is minimized.
- To attain the Maximum Dry Density and to increase the subgrade performance, both accurate field compaction at Optimum Moisture Content and accurate field compaction at optimum surface must be strictly adhered to.
- In permeable areas, adequate drainage facilities ought to be installed in order to avoid the buildup of pore-water pressure.
- In the case of zones having high compressibility indices, ground-improvement methods, i.e., preloading or stabilization, can be applied.
- Prior to the final design of the foundations, a site-specific geotechnical study must be carried out in detail to consider the local variability of soil.

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