ACCSCIENCE PUBLISHING

Journal of Chinese Architecture and Urbanism

ORIGINAL ARTICLE

Parametric investigation of a geotechnical survey: A case study of the central wing of a stadium foundation

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Citation: Alalade, G.M., Emetere, M.E. & Aigbe, F. (2026). Parametric investigation of a geotechnical survey: A case study of the central wing of a stadium foundation. *Journal of Chinese Architecture and Urbanism*, 8(2):025090021. https://doi.org/10.36922/JCAU025090021

Received: February 25, 2025

Revised: April 1, 2025

Accepted: April 24, 2025

Published online: July 30, 2025

Abstract

Stadium foundations constructed in geologically sensitive areas require careful geotechnical evaluation to ensure structural safety and longevity. This study presents a sectional analysis of geotechnical results from building sites located near significant geological faults that may compromise structural integrity. This proposal stems from the excessive vibrations or collapses in some stadiums around the globe, often resulting from inadequate assessments of geological fault extensions and unexpected ground movements. To investigate this issue, three boreholes were drilled, and soil samples were collected at specific depths and tested. It was observed that some proposed stadium locations lie above active geological faults, necessitating the use of a hybrid footing design. A sectional analysis of the central wing of a proposed stadium was conducted to demonstrate that the foundation design is best understood when examined in discrete sections. Settlement predictions at the proposed site indicated significant activity between depths of 9 and 10 m. These results further corroborate the adoption of a hybrid footing system. Accordingly, this study proposes the implementation of a hybrid footing system incorporating circular, rectangular, and continuous footings, with estimated bearing capacities of 332.32 kN/sqm, 311.04 kN/sqm, and 586.01 kN/sqm, respectively. The findings underscore the critical role of sectional geotechnical analysis in foundation planning and highlight the effectiveness of hybrid footing systems in mitigating risks associated with underlying geological faults.

Keywords: Stadium; Geotechnic; Geology; Foundation; Bearing capacity

1. Introduction

The design and construction of a stadium are a complex and often time-consuming process that demands solutions ensuring the comfort and safety of users (Losi *et al.*, 2021). Given the massive scale, specialized construction methods, and various functions of a stadium, it is necessary to locate the structure on land with appropriate geotechnical properties. Hence, geotechnical surveys are a critical component of the early planning process. These investigations represent the first step in the preliminary stage of building design and construction.

Structures such as buildings, bridges, tunnels, and dams are economically and technologically demanding, and these challenges are further intensified when constructed on poor soil conditions (Jazvin, 2019). Regardless of soil conditions, stadiums, such as all other structures, require stable foundations (Roy & Bhalla, 2017). Comprehensive geotechnical surveys conducted before stadium construction contribute to the complexity and duration of the project. These surveys are essential for gathering information on surface and subsurface features required for structural design and construction planning. The advantages of geotechnical surveys are well-documented, making them a common practice during the preliminary stage of design. Various studies, such as that by Sherwood (2011), highlight that failures in small- and medium-scale engineering works are often due to human factors and poor application of existing knowledge. Similarly, Losi *et al.* (2021) emphasized the importance of foundation design in large-capacity stadiums, reinforcing the need for thorough geotechnical evaluations.

In most cases, stadiums are key sports facilities that serve as the epicenter of broader sports centers (Chang & Xue, 2019). While primarily designed for sporting events, stadiums can also function as semi-enclosed spaces for other events (Losi *et al.*, 2021). Globally, there are over 4,000 stadiums, with 54 located in Nigeria. Of these stadiums, majority are used for football, which is the most popular sport in the world. The construction of large-capacity stadiums is relatively rare and typically undertaken for major international events, such as the Olympic Games or the FIFA World Cup.

During the design and preliminary planning stages of a stadium project, multiple factors, including safety, comfort, and structural stability, must be taken into consideration. Therefore, inputs from various professionals are required to ensure the smooth delivery of the project. Among these experts, the geological surveyor or engineer plays a vital role in recognizing and evaluating landforms and surface geological features. Geology, the scientific study of the solid Earth, comprises subfields such as petrology, mineralogy, and crystallography (Imashev *et al.*, 2024). Surface geology deals with the superficial parts of the Earth. In engineering, "soil" is the general term used to describe any surface deposit that can be excavated without blasting.

The application of geological, geophysical, and hydrological scientific principles to solve engineering issues on or within the Earth is known as geotechnical engineering. It is a broad field that covers a wide range of applications, including foundation design, earthworks, ground improvement, slope stabilization, and retaining wall construction (Dhir *et al.*, 2017; Sherwood, 2011). One of the biggest challenges in stadium construction is selecting an ideal site. Even after a suitable location is chosen, its properties must be thoroughly assessed to ensure compatibility with the proposed land use. At this phase, the geotechnical engineer is introduced into the project for geotechnical surveys (Kauffman, 2012; Olofinyo *et al.*, 2019).

To carry out a geotechnical survey in a specified area, comprehensive geotechnical exploration is needed, especially when dealing with virgin land where no prior systematic exploration or construction has occurred. To avoid geotechnical failures, the established engineering procedures within the code of practice should be followed during the geotechnical survey process (IvyPanda, 2019). Systematic site exploration may involve up to five procedural stages, from preliminary investigation to testing to the geotechnical survey report (Al-Amoudi *et al.*, 1992; Gupta, n.d.; Imashev *et al.*, 2024; IvyPanda, 2019). The first step in conducting a geotechnical survey is gathering existing knowledge of the proposed site, which includes conducting a literature review and collecting data from relevant authorities (Hussain *et al.*, 2022). The process ends with reporting the findings of soil testing, aimed at determining the chemical and physical properties of the site's soils. This analysis helps assess the suitability of the site for construction and informs potential ground improvement strategies where necessary.

1.1. Influence of geotechnical surveys on stadium architecture

The services of a geotechnical engineer are necessary in identifying potential failures and assessing risks associated with soil and its components at a construction site. Geotechnical engineers are constantly facing the challenges of geotechnical failures, as they may cause the loss of human life and significant economic losses (IvyPanda, 2019). In some cases, the failure to conduct a geotechnical survey or the reliance on falsified data can lead to catastrophic consequences. A geotechnical survey includes testing the chemical properties of the soil, such as the presence of sulfates and chlorides. The presence of high saline content in the soil or groundwater may lead to issues such as crystallization over time, which can compromise the structural integrity of buildings (Al-Amoudi *et al.*, 1992).

The consequences of failing to conduct timely geotechnical surveys are evident in a variety of case studies of structural failures. One such case was caused by salinity, affecting a building constructed on seemingly goodquality soil, located approximately 1 km from the coastline. The high salinity of the on-site groundwater, which was used in the concrete mix, ultimately compromised the structure. The saline content weakened the concrete, leading to structural failure (Ahmad *et al.*, 2022). In addition, the presence of chlorides and sulfates in soil is known to accelerate the corrosion of steel components or reinforcements, and can lead to general stability issues in concrete and steel structures (Al-Amoudi *et al.*, 1992)

In 2004, an engineer identified as J.C. from Plano, Texas, was suspended for 2 years and fined $1,850 for issuing a false certification for a foundation design that did not comply with necessary standards and failed to consider the soil data relevant to that site (Kauffman, 2012). This case illustrates the serious consequences of using falsified geotechnical soil data. Similarly, in 2012, another engineer in Texas had his license suspended and was fined $4,380 for negligence in design and analysis leading to structural failure. Various engineering firms and personnel have faced license suspensions, lawsuits, and financial penalties due to inaccurate or fraudulent geotechnical analyses.

These regulatory consequences are intended to ensure accountability among engineers during the pre-conceptualization stage of construction projects. They ensure that proper geotechnical analyses are carried out to prevent hazardous consequences throughout the building's lifespan. As illustrated in the previous case studies, it is evident that geotechnical surveys are essential for planning buildings and preventing the occurrence of disasters, including the loss of lives and property. Structural failure can often be identified through cracking and excessive deflection (Olofinyo *et al.*, 2019). Conducting geotechnical tests provides engineers with the data needed for accurate foundation design and assists architects in making appropriate design decisions. This is especially important for large-scale buildings, such as stadiums, which generally require deeper foundations compared to smaller buildings.

The construction phase of any structure is a critical period that significantly impacts the safety of the structure. In the construction of large-scale projects, such as high-capacity stadiums, several essential documents, tests, analyses, and assessments must be carried out, with geotechnical surveys being one of them (Erlingsson & Berglund, 1994). The absence of a valid geotechnical report may disqualify a project from advancing to the construction phase, as it may prevent the issuance of necessary construction licenses. Furthermore, in the case of dangerous substances or chemicals present in the soil, a geotechnical survey can reveal their content in the soil. Such knowledge can be used to determine safety measures during and after construction.

China's architectural concept of stadium design integrates innovative technology, traditional cultural elements, sustainability, and monumental scale. For example, the Beijing National Stadium design was drawn from the cultural symbolism of a bird's nest that represents home, family, and new beginnings. Another motivation is to display China's technological prowess and global influence. One of the most profound Chinese stadium designs is the conceptualization of unique multipurpose stadiums. However, these ambitious designs come with notable challenges. Overly artistic or abstract designs can compromise essential factors such as sightlines, acoustics, and spatial efficiency. Other issues include high construction and maintenance costs, insufficient revenue-generating events, prioritizing esthetic innovation over local climate, available materials, or user behavior, and the uncertainties of futuristic geological complications. Given that China has vast and geologically diverse terrain, stadium construction must account for complex subsurface conditions, seismic risks, and uneven soil bearing capacity. Moreover, many regions in China (e.g., Sichuan, Yunnan, Tibet, and parts of the North China Plain) lie along major seismic fault lines, necessitating that most Chinese stadiums have deep foundation systems, ground stabilization techniques, and soil improvement methods. Table 1 presents key solutions deployed to known challenges in the Chinese construction industry. To ensure safety, functionality, and quality, the construction industry in China is governed by several regulations, including GB 50009, GB 50017, and JGJ 31-2003. The partial collapse of Shenzhen Stadium in Shenzhen, Guangdong province, on July 8, 2019–during renovation and demolition work–further emphasizes the need for innovative building regulations (Skynews, 2019).

Table 1. Potential large-scale buildings' geological solutions

Challenge	Cause	Solution
Soft soils (coastal cities)	Saturated clay, low bearing capacity	Pile foundations, soil improvement (e.g., jet grouting)
Karst terrain	Underground voids	Grouting, deep piling, cavity mapping
Seismic zones	Fault lines across China	Base isolation, seismic joints, damping systems
High groundwater levels	River/delta systems	Waterproofing, dewatering, raft foundations
Variable subsoil	Large site area	Zoned foundation design, differential settlement control
Tight construction timelines	Event-driven projects	Advanced modeling, phased construction, risk buffers

1.2. Bearing capacity: Theory of footing determination

The gross bearing capacity of soil, whether cohesionless, cohesive, or mixed soil, is determined for different footings, as listed in Equations I-IX. Based on the borehole profile, it can be deduced that the gross bearing is composed of different soil types. Circular footings in cohesionless, cohesive, and mixed soil are defined, respectively, as:

$$qu = \gamma D(N_q) + 0.6\gamma R(N_\gamma) \quad \text{(I)}$$

$$qu = 1.3C(N_c) + \gamma D \quad \text{(II)}$$

$$qu = 1.3C(N_c) + \gamma D(N_q) + 0.6\gamma R(N_\gamma) \quad \text{(III)}$$

The square or rectangular footings in cohesionless, cohesive, and mixed soil are defined, respectively, as:

$$qu = \gamma D(N_q) + 0.4\gamma B(N_\gamma) \quad \text{(IV)}$$

$$qu = CN_c\left(1+\left(\frac{0.3B}{L}\right)\right)+\gamma D \quad \text{(V)}$$

$$qu = CN_c\left(1+\left(\frac{0.3B}{L}\right)\right)+\gamma D\left(N_q\right)+0.4\gamma B(N_\gamma) \quad \text{(VI)}$$

The continuous footings in cohesionless, cohesive, and mixed soil are defined, respectively, as:

$$qu = \gamma D(N_q) + 0.5\gamma B(N_\gamma) \quad \text{(VII)}$$

$$qu = CN_c + \gamma_D \quad \text{(VIII)}$$

$$qu = CN_c + \gamma D(N_q) + 0.5\gamma B(N_\gamma) \quad \text{(IX)}$$

The first term in Equations III, VI, and IX is the cohesion term, the second term is surcharge, and the third term is friction.

1.3. Objectives of the study

In this study, a geotechnical survey was conducted on the central wing of a proposed stadium. The key objectives were to investigate the influence of subsurface conditions on the central wing, compare field data with remote sensing datasets, evaluate the bearing capacity of the central wing, and determine the most suitable types of footings for the structural requirements of the central wing. Ultimately, the investigation sought to determine the maximum allowable load that can be safely supported in the central wing of the stadium.

2. Methodology

The project site is situated primarily within coastal plain sands and lies near the border of the Ewekoro Formation. D'Almeida *et al.* (2016) geologically classified the extensive cohesive, sandy clayey materials and poorly sorted sands found beneath more recent alluvial deposits as part of coastal plain sands. However, this nomenclature may be misleading, given the clayey nature of the materials, which is widespread across the depositional formations of the southwestern Dahomey basin.

Coastal plain sands consist of clayey sands, sandy clays, poorly sorted sands, and rare thin lignite layers. The color of these materials is usually rust-brown, though mottled gray/rust-brown and gray shades can occur, particularly near the surface, as observed at the project site. While some areas within this formation contain soft to very soft organic clays as part of some recent intervening poor alluvial deposits, this is not the case on the current project site. Here, the subsurface is characterized predominantly by very stiff to hard silty clays, interspersed with layers of dense to very dense, well-graded sands.

An investigation of the fault lines identified through Landsat images (Figure 1) was conducted to determine

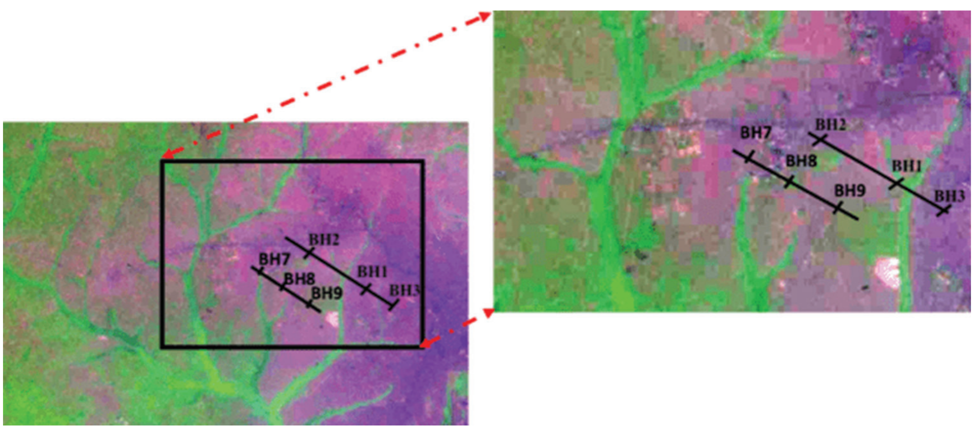

Figure 1. Surface geology of the research area
Source: Images from Landsat.

the potential load requirements in the central section of the proposed stadium. For structural load distribution, the main construction was divided into three sections: central, left, and right wings. The right wing has most of the supporting beams. Figure 2 illustrates the layout of the proposed stadium with the size of the proposed wings and the number of geotechnical tests. Three boreholes (BH7, BH8, and BH9) were drilled in the right wing. BH7 was terminated at a depth of 35 m, while BH8 and BH9 were terminated at 30 m. The elevations at BH7, BH8, and BH9 were given as 98.56 m, 97.47 m, and 96.01 m, respectively. During drilling, soil sampling and testing were conducted in accordance with BS 5930:1990–Code of practice for site investigation. Soil samples were collected progressively throughout the drilling process. Samples from the cutting shoe and split spoon barrel were collected as disturbed samples and were used for evaluating parameters relevant to undisturbed sampling testing.

Laboratory tests were conducted on selected soil samples to determine soil types and strength parameters critical for foundation design and construction at the project site. The testing procedures followed relevant parts of BS 1377:1990–Methods of test for soils for civil engineering purposes–with corresponding equivalents in th American Society for Testing and Materials standards. Two types of tests were performed: classification and engineering tests. Classification tests included liquid limit and plastic limit (Atterberg limits) analysis, sieve grading with hydrometer analysis, moisture content determination, and specific gravity determination. Engineering tests included a quick undrained triaxial test conducted on selected undisturbed samples and an oedometer consolidation test performed on selected undisturbed samples. A summary of key test results used in the calculation of bearing capacity for the footings is displayed in Table 2.

Finally, different models for bearing capacity were evaluated based on the acquired information, including the Terzaghi and Hansen methods for cohesionless, cohesive, and mixed soil conditions.

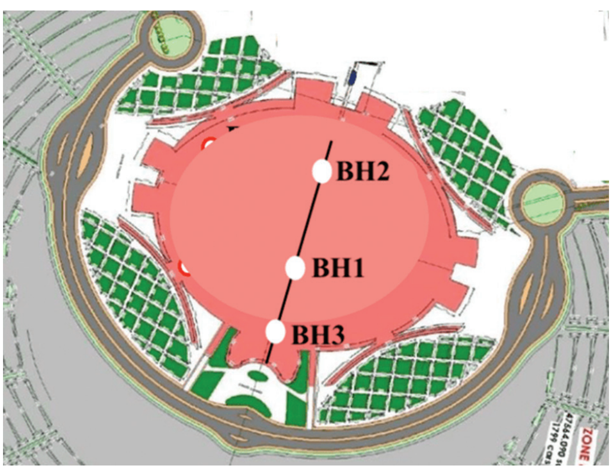

Figure 2. Layout of the proposed stadium
Source: Drawing by the first author.
Abbreviation: BH: Borehole.

3. Results and discussion

The combined analysis of samples from the three boreholes aligns with the geology of the area down to a depth of 35 m, as illustrated in Figure 3. However, the presence of underlying geological faults, as identified in the surface geology, may significantly influence the foundation design, such as those to avoid ground movement or vibration. The vertical profiling in BH1, when compared to BH2 and BH3, clearly indicates an extensive geological layer shift. This shift appears to result from vertical and horizontal faulting, angular unconformities, and disturbances to the Earth's magnetic field. What does this signify for construction professionals? It underscores the critical need to re-examine soil samples along the vertical profiles of large-scale buildings, such as stadiums.

As re-grouped and illustrated in Figure 3, essential geotechnical parameters were tested to ensure that the bearing capacities were adequately addressed in foundation design and settings. It was observed that in the first layer across the three boreholes, cohesion values ranged from 63 to 214 kN/sqm, coefficients of volume compressibility (Mv) ranged from 0.043 to 0.078 sqm/MN,

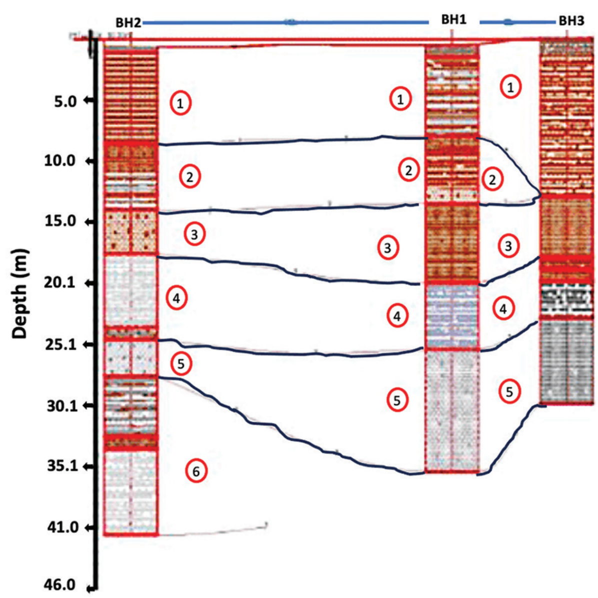

Figure 3. Comparative depth profiles of boreholes (BH) 1, 2, and 3
Source: Diagram by the authors.

vertical pressures ranged from 200 to 400 kN/sqm, and N-values were approximately 20. In the second layer, the cohesion ranged from 63 to 184 kN/sqm, Mv ranged from 0.077 to 0.096 sqm/MN, vertical pressures ranged from 200 to 400 kN/sqm, and N-values were approximately 20. The third and fifth layers, consisting of sand deposits, had N-values of 30 and 40, respectively. The fourth layer, situated between these sand layers, recorded cohesion ranged from 69 to 138 kN/sqm, Mv ranged from 0.083 to 0.291 sqm/MN, vertical pressures ranged from 200 to 400 kN/sqm, and N-values ranged from 20 to 30.

The N-value provides an indication of the relative density of the subsurface soil. It is used in empirical geotechnical correlation to estimate the approximate shear strength properties of the soils. The implication of this test is that the foundation design of a stadium facility should be in accordance with the soil profile of each section. The current findings ultimately support the use of a hybrid footing system. Moreover, Figure 3 further confirms that the fault lines presented the remote sensing image in Figure 1.

It was observed that the sixth layer, which only applies to BH3, had cohesion ranging from 165 to 184 kN/sqm, Mv ranged from 0.069 to 0.083 sqm/MN, vertical pressures ranged from 200 to 400 kN/sqm, and N-values were approximately 38. These results are of concern because a proper investigation is essential to provide insights into the impression load on the soil and identify potential abnormalities. Based on these findings, bearing capacities were determined for depths ranging from 0.75 to 17.5 m. A principal component analysis (PCA) was conducted on the large spectrum of ultimate bearing capacities to identify potential patterns in stadium loading. Furthermore, the average ultimate bearing capacities derived from the Terzaghi and Hansen approaches at the defined depths were used to generate contour plots to validate the PCA results.

The ultimate bearing capacities for circular footings at a depth of 6 m were calculated, with the results, as presented in Table 3. It was observed that within 6 m depth, the mixed soil exhibited the highest ultimate bearing capacity at 996.944 kN/sqm. To obtain the allowable bearing capacity at this depth, a factor of safety of 3 was used. Therefore, the maximum allowable bearing capacity at 6 m depth is 332.32 kN/sqm. This implies that, within a mixed soil profile, the maximum allowable bearing capacity for a circular footing is 332.32 kN/sqm. This result is significant as it is professionally sensible for the construction of stadium structures within the geological conditions of the proposed site.

The PCA of the ultimate bearing capacities at a depth of 17.5 m was performed, as demonstrated in Figure 4.

Table 2. Vertical soil profile data

Depth (m)	γ (kN/m³)	ϕ (°)	c (kN/sqm)	k (MN/m³)	Dr (%)	N_{spt}
0	20.8	0	72.3	182.4	0.63	17
9.0	20.8	0	92.4	198.0	0.60	18
13.0	19.2	31.0	0	34.2	58.28	23
19.5	20.8	0	68.9	168.4	0.65	16
25.0	19.3	34.0	0	41.1	63.87	28
35.0	19.7	34.8	0	57.5	75.23	40

Notes: γ: Bulk unit weight; ϕ: Angle of internal friction; c: Cohesion; Dr: Relative density of soil; e_{50}: Secant modulus of elasticity at 50% of the maximum deviator stress; k: Modulus of subgrade reaction; N_{spt}: Standard penetration test blow count.

Table 3. Ultimate bearing capacities for circular footings in different soil types

Depth (m)	Terzaghi (kN/sqm)			Hansen (kN/sqm)		
	Cohesionless	Cohesive	Mixed	Cohesionless	Cohesive	Mixed
0.75	169.26	221.68	268.48	150.42	163.23	174.67
1.50	203.74	256.15	302.95	267.88	280.70	292.14
2.00	226.72	279.14	325.94	346.20	359.01	370.45
2.50	249.70	302.12	348.92	424.51	437.32	448.76
3.00	272.69	325.10	371.90	502.82	515.63	527.07
3.50	295.67	348.09	394.89	581.13	593.94	605.38
4.00	318.66	371.07	417.87	659.44	672.26	683.70
4.50	341.64	394.06	440.86	737.76	750.57	762.01
5.00	364.62	417.04	463.84	816.07	828.88	840.32
5.50	387.61	440.02	486.82	894.38	907.19	918.63
6.00	410.59	463.01	509.81	972.69	985.50	996.94

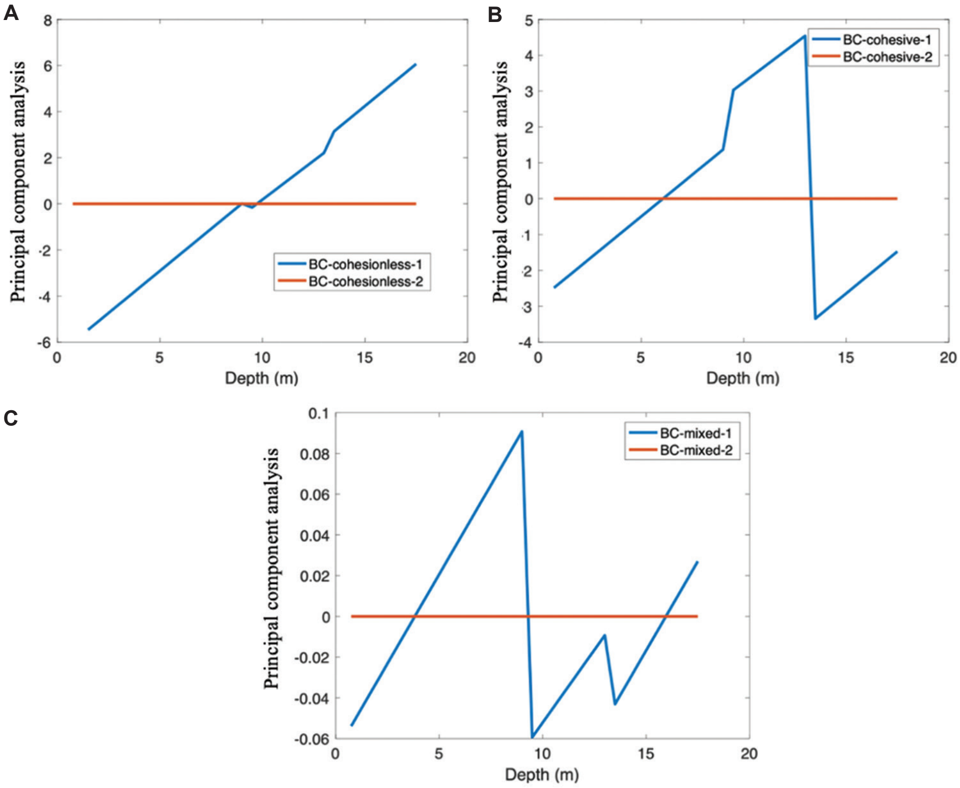

Figure 4. Principal component analyses of ultimate bearing capacities (BC) for circular footings: (A) Cohesionless soil, (B) cohesive soil, and (C) mixed soil
Source: Graphs by the authors.

Figure 4A illustrates the bearing capacity for circular footings in cohesionless soil. A comparative analysis of the Terzaghi and Hansen approaches was displayed. It was observed that the bearing capacity of circular footings of the Hansen approach was significantly lower compared to the Terzaghi approach. While the Hansen method generally provides more accurate bearing capacity estimates, particularly under non-ideal conditions, the Terzaghi approach reveals that at 10 m depth, the load on the foundation could withstand ground movements.

Ground movements can be caused by settlement, subsidence, or earthquakes (Bell *et al.*, 1988). Should there be significant ground movements due to an external factor, for example, an earthquake, consequential damage may occur. Previous studies have demonstrated cases where the Terzaghi approach yields better results compared to the Hansen method, especially for perfectly horizontal strip footings on homogeneous soils (Pandey *et al.*, 2023) or shallow foundations under simple loading (Vořechovský *et al.*, 2024). Figure 4B and C show relatively stable features for cohesive and mixed soils.

The contour plots, as shown in Figure 5, derived from the average and frequency distributions of ultimate bearing capacities using both the Terzaghi and Hansen approaches, suggest similar patterns of capacity across all types of soil. These results further shed light on the fact that the linearity of ultimate bearing capacities, which terminates around 9 m, is significant for settlement prediction in stadium design in the proposed site. To determine a depth that sustains the applied loads, moments, forces, and induced reactions, as well as to ensure desired settlement, a hybrid footing design, as proposed by Salunkh and Kuwar (2017), was recommended for the foundation of the proposed stadium. The hybrid foundation system combines different footing types to sufficiently support axial loads with an appropriate factor of safety and control settlement under working load conditions.

Furthermore, the ultimate bearing capacities for rectangular footings at 6 m depth were calculated, as presented in Table 4, with the highest value reported for the cohesionless soil as 933.11 kN/sqm. Applying a factor of safety of 3, the maximum allowable bearing capacity becomes 311.04 kN/sqm.

When comparing the allowable bearing capacities of circular and rectangular footings, the advantages of adopting a hybrid footing system become evident.

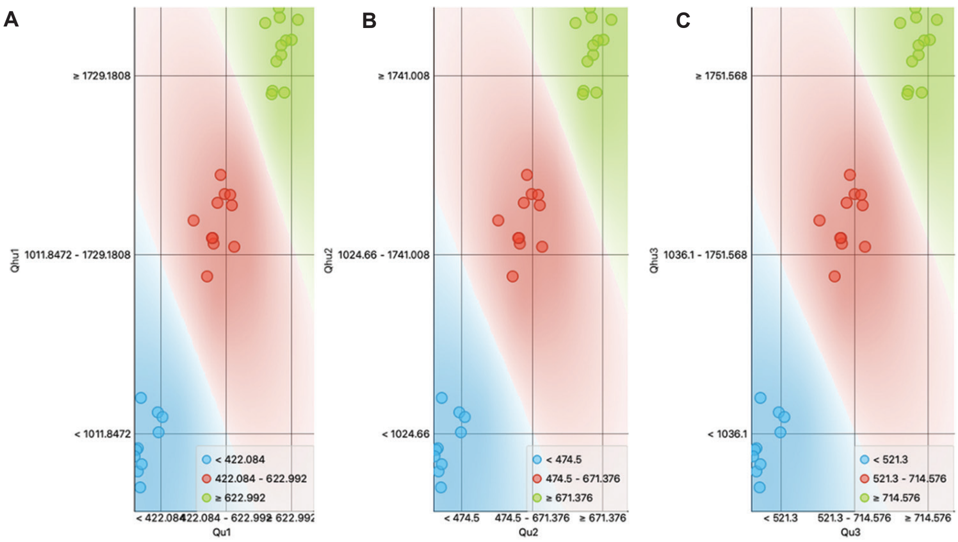

Figure 5. Contour plots of ultimate bearing capacities for circular footings: (A) Cohesionless soil, (B) cohesive soil, and (C) mixed soil
Source: Plots by the authors.

Table 4. Ultimate bearing capacities for rectangular footings in different soil types

Depth (m)	Terzaghi (kN/sqm)			Hansen (kN/sqm)		
	Cohesionless	Cohesive	Mixed	Cohesionless	Cohesive	Mixed
0.75	823.91	23.26	637.38	209.22	17.43	164.54
1.50	839.51	46.52	652.98	224.82	34.87	180.14
2.00	849.91	62.03	663.38	235.22	46.49	190.54
2.50	860.31	77.53	673.78	245.62	58.12	200.94
3.00	870.71	93.04	684.18	256.02	69.74	211.34
3.50	881.11	108.54	694.58	266.42	81.36	221.74
4.00	891.51	124.05	704.98	276.82	92.99	232.14
4.50	901.91	139.56	715.38	287.22	104.61	242.54
5.00	912.31	155.06	725.78	297.62	116.23	252.94
5.50	922.71	170.57	736.18	308.02	127.85	263.34
6.00	933.11	186.08	746.58	318.42	139.48	273.74

Figure 6A and C indicates that the predicted settlement depth is 9 m, consistent with the settlement observed for circular footings as shown in Figure 4. In contrast, Figure 6B shows a relatively stable settlement feature, with settlement at approximately 8 m depth. However, the contour plots of average and frequency distributions of ultimate bearing capacities, as derived from the Terzaghi and Hansen approaches (Figure 7), reveal that different patterns are expected to take place in rectangular footings. The applied loads, moments, forces, and induced reactions of the cohesionless and mixed soils exhibit an inverse relationship under this scenario. Meanwhile, Figure 7B shows similar features to those observed for circular footings (Figure 5). The ultimate bearing capacities for continuous footings at 6 m depth, their PCA results for 17.5 m depth, and their contour plots are presented in Table 5 and Figures 8 and 9, respectively.

The ultimate bearing capacities for continuous footings at 6 m depth were calculated, as presented in Table 5. It was observed that within 6 m depth, the highest ultimate bearing capacity was reported for the cohesionless soil, with a value of 1,758.042 kN/sqm. To determine the allowable bearing capacity at a depth of 6 m, the factor of safety of 3 was used, yielding a maximum allowable bearing capacity of 586.01 kN/sqm.

Figure 8A further confirms the predicted depth of the settlement to be approximately 9 m, consistent with earlier findings from other footings. Figure 8B shows a relatively stable trend for all types of soil. The contour plots (Figure 9) indicate that the width of footings should be wider in cohesive soils to withstand the predetermined load. In mixed soils, the footings are expected to be placed deeper than in cohesionless and cohesive soils to allow for extensive

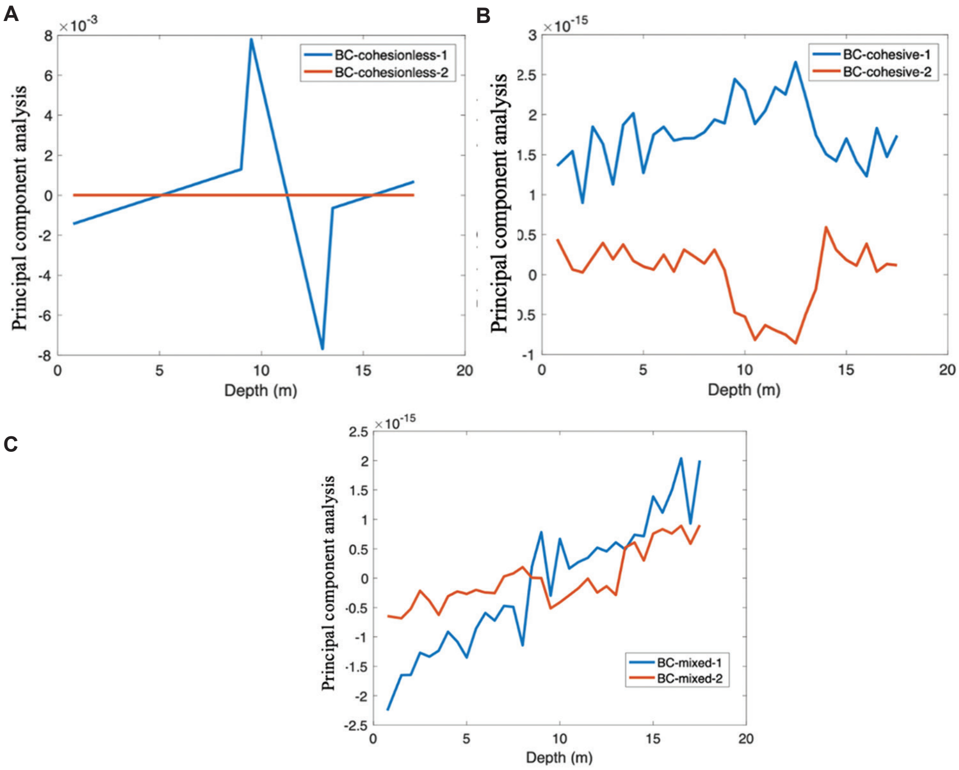

Figure 6. Principal component analyses of ultimate bearing capacities (BC) for rectangular footings: (A) Cohesionless soil, (B) cohesive soil, and (C) mixed soil
Source: Graphs by the authors.

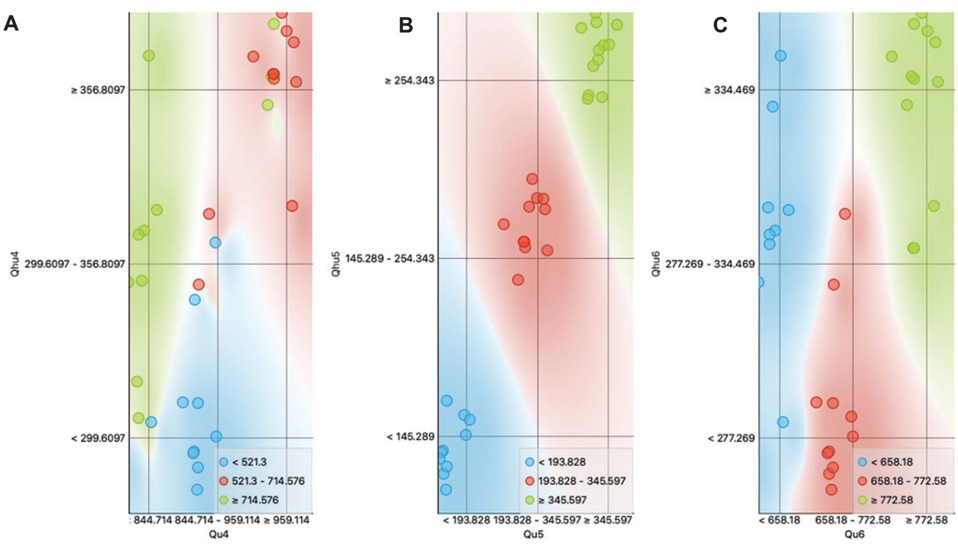

Figure 7. Contour plots of ultimate bearing capacities for rectangular footings: (A) Cohesionless soil, (B) cohesive soil, and (C) mixed soil
Source: Plots by the authors.

Table 5. Ultimate bearing capacities for continuous footings in different soil types

Depth (m)	Terzaghi (kN/sqm)			Hansen (kN/sqm)		
	Cohesionless	Cohesive	Mixed	Cohesionless	Cohesive	Mixed
0.75	1,516.71	960.04	890.26	475.82	340.09	323.61
1.50	1,551.19	994.52	924.73	593.29	457.56	441.07
2.00	1,574.17	1,017.50	947.72	671.60	535.87	519.39
2.50	1,597.15	1,040.48	970.70	749.92	614.18	597.70
3.00	1,620.14	1,063.47	993.68	828.23	692.50	676.01
3.50	1,643.12	1,086.45	1,016.67	906.54	770.81	754.32
4.00	1,666.11	1,109.44	1,039.65	984.85	849.12	832.63
4.50	1,689.09	1132.42	1,062.64	1,063.16	927.43	910.95
5.00	1,712.07	1,155.40	1,085.62	1,141.48	1,005.74	989.26
5.50	1,735.06	1,178.39	1,108.60	1,219.79	1,084.06	1,067.57
6.00	1,758.04	1,201.37	1,131.59	1,298.10	1,162.37	1,145.88

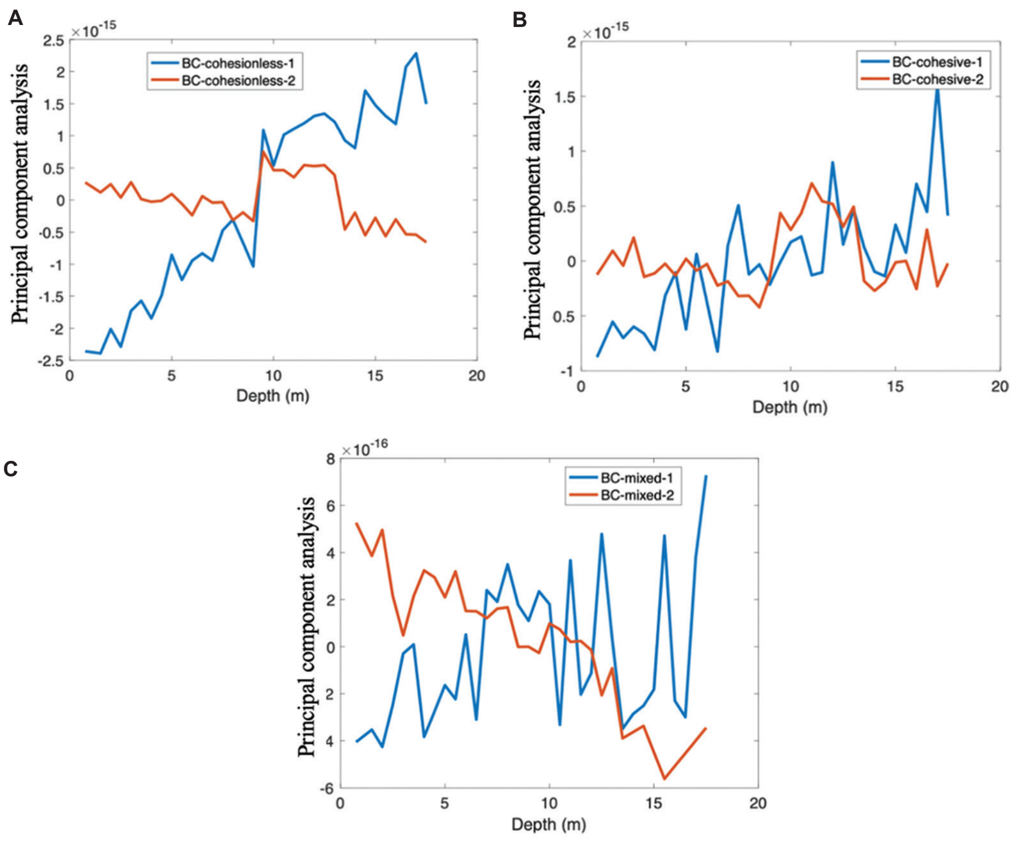

Figure 8. Principal component analyses of ultimate bearing capacities (BC) for continuous footings: (A) Cohesionless soil, (B) cohesive soil, and (C) mixed soil
Source: Graphs by the authors.

shear stress. Overall, continuous footings demonstrate more potential in the central section of the proposed stadium. Nonetheless, a hybrid footing system, incorporating circular, rectangular, and continuous footings, is recommended, with allowable bearing capacities of 332.32 kN/sqm, 311.04 kN/sqm, and 586.01 kN/sqm, respectively.

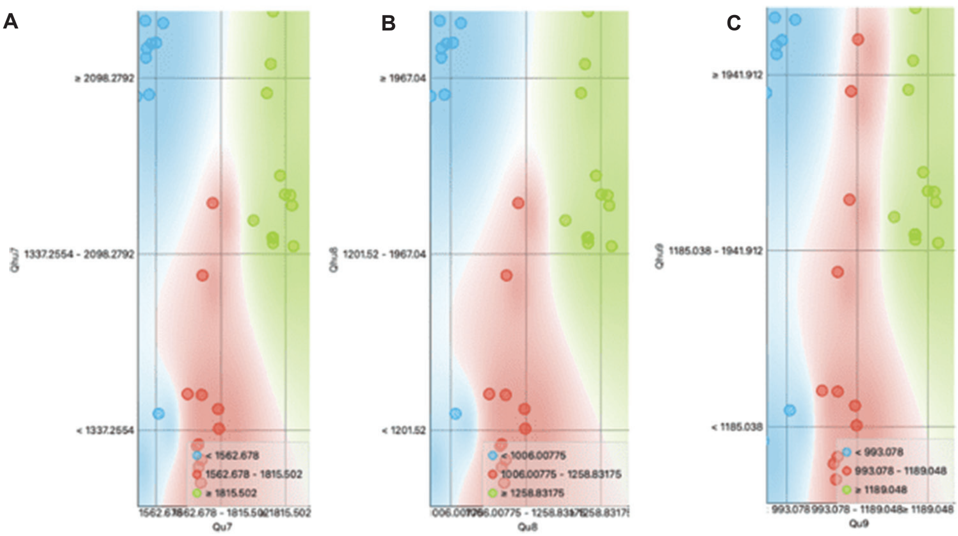

Figure 9. Contour plots of ultimate bearing capacities for continuous footings: (A) Cohesionless soil, (B) cohesive soil, and (C) mixed soil
Source: Plots by the authors.

4. Conclusion

The role of underlying geological faults, as identified in the surface geology from Landsat images, has been proven to significantly influence foundation design. Specifically, foundation design is critical to avoid issues such as ground movement and vibration. The vertical profiling in BH1, as compared to BH2 and BH3, clearly indicates an extensive geological layer shift. This shift is a result of the presence of vertical and horizontal faulting, angular unconformities, and disturbances to the Earth's magnetic field. The significant variation in N-values across soil layers underscores the need for foundation designs tailored to each section of the soil profile, particularly for large-scale buildings such as stadiums. Based on the calculations using the Terzaghi and Hansen bearing capacity methods (cohesionless, cohesive, and mixed conditions), the analysis confirms the necessity of a hybrid footing system. Hence, the idea of a hybrid footing system incorporating circular, rectangular, and continuous footings, with respective allowable bearing capacities of 332.32 kN/sqm, 311.04 kN/sqm, and 586.01 kN/sqm, is recommended in this study. In addition, this study further corroborated that a near-surface geology map from Landsat is a valuable tool to plan and validate results from fieldwork. However, a limitation of this study is the cost constraints associated with conducting a reverse traverse of the borehole spot to ascertain the extent of the fault lines between BH1 and BH3. Future research should integrate Landsat fault mapping in the field with cone penetration testing to better characterize the width of fault zones.

Acknowledgments

The authors would like to appreciate the host institutions and the Ark research cluster.

Funding

The study was supported by The Ark Project (grant no.: 202211).

Conflict of interest

The authors declare that they have no competing interests.

Author contributions

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Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Data will be made available on request.

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