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A Comparative Framework for Foundation Selection in Saturated Tropical High-Plasticity Clays: Optimization of Mass Housing Infrastructure

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ABSTRACT: Constructing heavy infrastructure on high-plasticity tropical clays presents significant challenges regarding total and differential settlement. This research compares the performance of shallow foundations (spread and raft) against bored cast-in-situ piles in the "fat clay" (CH) deposits of Sonfonia, Guinea. Using Terzaghi and Peck's method for elastic settlement and Meyerhof's bearing capacity theory, the study demonstrates that under permanent submerged conditions, settlement exceeds 130mm for shallow footings, rendering them unfeasible for multi-story structures. A proposed foundation solution of using raft or pile systems is analyzed, showing a significant reduction in serviceability-limit movements. The paper provides a decision-making framework for selecting foundation types in saturated, settlement-sensitive tropical soil profiles.

1. Introduction

The proposed mass housing project in Sonfonia, Guinea, aims to provide durable and affordable housing units on a site characterized by a wide, open lowland with shallow wetlands and a high groundwater table. The subsurface conditions predominantly feature sandy silty clay (CL-ML) and fat clay (CH) layers, the latter exhibiting high plasticity and moisture content, and significant compressibility.

The objective of this study is to evaluate the suitability of various foundation types for the given site conditions, with a focus on mitigating excessive settlement, a primary concern for structures on highly plastic clay. The investigation was conducted during the dry season of December 2025 and included drilling four boreholes, excavating three trial pits, and performing soil resistivity tests. The critical finding was the shallow groundwater table, ranging from 0.0m to 0.22m, necessitating analysis under fully submerged conditions.

1.1 Literature Review

The design of foundations in tropical regions is often complicated by the presence of highly plastic clays, frequently referred to as "fat clays" (CH) under the Unified Soil Classification System. These soils are notorious for their low shear strength and high volume change potential. Literature on tropical geotechnics emphasizes that Standard Penetration Test (SPT) N-values must be carefully corrected for overburden and hammer efficiency to provide reliable data for settlement predictions. Furthermore, the Terzaghi and Peck method (1948) remains a benchmark for estimating elastic settlement in such environments, though it requires specific corrections for groundwater effects (Cw) when dealing with submerged conditions typical of coastal lowlands. Recent studies in similar West African geological settings suggest that while shallow foundations are economical, their utility is strictly limited by the Serviceability Limit State (SLS), specifically total settlement, which often governs over shear failure in soft clay deposits.

The primary objective of this study is to evaluate foundation suitability under fully submerged conditions, as the groundwater table (GWT) was encountered at critically shallow depths (0.0m to 0.22m)

2. Materials and Methods

Field investigations included four boreholes (BH-01 to BH-04) drilled to 35.0m and three trial pits (p. 15). Standard Penetration Tests (SPT) were conducted according to ASTM D1586, and laboratory analysis followed ASTM standards for Atterberg limits, sieve analysis, and consolidation.

2.1 Foundation Design Parameters

Field SPT N-values were corrected to N60 (hammer efficiency) and N160 (overburden). The N-Design value for each foundation depth was calculated using the weighted method by Terzaghi and Peck to account for the influence zone (Df+2B).

2.2 Settlement and Bearing Capacity Equations

Allowable bearing capacity (qa) was determined using the Bowles and Meyerhof (1997) formula for a 25mm settlement limit and a factor of safety of 3.0. Elastic settlement was computed as: Where Cw = 2.0 for submerged conditions and CD is the depth of embedment correction

3. Results and Discussion

3.1 Comparative Analysis of Soil Strength

The site exhibits extreme lateral and vertical variability. BH-03 and BH-02 contain dense sand and gravel layers with SPT N-values reaching refusal (N>100) at intermediate depths. Conversely, BH-04 is dominated by fat clay from the surface to 8.0m, with N-values as low as 3 to 5, indicating a very soft to soft consistency.

3.2 Bearing Capacity and Stiffness Variation

As shown in the analysis, the Safe Bearing Capacity (SBC) is governed by settlement limits rather than shear failure.

- **Granular Zones (BH-03):** Achieved SBC values exceeding 3,000 kPa at 4.0m depth.

- **Clay Zones (BH-04):** SBC values are as low as 81.95 kPa at 2.0m depth for large foundations.
- **Modulus of Subgrade Reaction (ks):** values in BH-04 (approx. 6,500–10,000) are nearly ten times lower than in BH-03, confirming the high compressibility of the fat clay.
- **3.3 Settlement Performance and Foundation Selection**
  Under a design pressure of 300 kPa, the predicted settlements for shallow foundations are prohibitive in clay zones

Borehole	Stratum	Submerged Settlement (mm) at 1.5m Depth / 300 kPa
BH-01	Sandy Silty Clay	88.8
BH-02	Dense Sand/Clay	58.7
BH-03	Well-graded Gravel	23.18
BH-04	**Fat Clay (CH)**	**260.42**

The settlement in BH-04 (260.42 mm) is approximately four times the permissible limit (65 mm) for isolated footings on clay. Even increasing the foundation depth to 3.0m only reduces settlement to 238.19 mm, proving that embedment alone is insufficient in thick CH deposits

3.4 Proposed Deep Foundation (Pile) Solution

Given the failure of shallow foundations to meet serviceability requirements in BH-04, a pile foundation system is recommended. Piles can bypass the highly compressible fat clay (0.0-8.0m) to tap into the medium dense clayey sand and poorly graded sand layers encountered from 9.0m to 28.0m, where N-values increase to 38.

Foundation Selection Matrix & Conclusion

The following Foundation Selection Matrix serves as the definitive decision-making framework for the Sonfonia mass housing project, integrating the geotechnical findings, settlement analysis, and structural design requirements.

1. Foundation Selection Matrix

Geotechnical Zone	**Primary Substrata**	**SBC (at 2.0m)**	**Predicted Settlement**	**Recommended Solution**	**Key Design Constraint**
Zone A (BH-03)	Dense Sand/Gravel	~987 kPa	< 25 mm	**Shallow Spread Footings**	Standard concrete cover (50mm).
Zone B (BH-01, BH-02)	Sandy Silty Clay / Mixed	200 – 400 kPa	50 – 90 mm	**Raft Foundation**	Waterproofing and settlement monitoring.
Zone C (BH-04)	**Fat Clay (CH)**	**< 127 kPa**	**> 260 mm**	**Bored Piles (600mm dia.)**	**Type V Cement**; terminate at 15m+

Summary of Construction Mandates

Element	**Specification**
Cement Type	**ASTM Type V** (unless Appendix XIV shows)
Water/Cement Ratio	Maximum **0.45** to ensure low permeability in submerged states
Concrete Cover	Minimum **50mm - 75mm** for piles and rafts to resist chloride ingress

Analysis of Foundation Engineering: Pile Capacity and Chemical Durability

Based on the geotechnical data, the following analysis details the design requirements for deep foundations and the chemical considerations for submerged structures.

1. Analysis of Pile Foundation Capacity

In zones dominated by Fat Clay (CH), such as BH-04, shallow foundations fail the serviceability limit. A bored cast-in-situ pile solution is designed to bypass the soft upper 8.0m and utilize the underlying Poorly Graded Sand with Clay (SP-SC) and Clayey Sand (SC) layers.

- **Target Strata:** The pile should be seated between 9.0m and 28.0m, where SPT N-values stabilize between 30 and 38.
- **Skin Friction ():** In the upper fat clay, skin friction is low due to high plasticity. However, significant shaft resistance is mobilized in the sandy layers starting at 9.0m.
- **End Bearing ():** The piles can achieve high end-bearing capacity by terminating in the dense sands encountered at 28.0m ().
- **Settlement Control:** Unlike shallow footings, which show nearly 260mm of settlement at BH-04, a pile foundation anchored in these dense layers will restrict movements to within the permissible 10–25mm range required for heavy multi-story structures.

2. Soil Chemical Results and Durability

Because foundations will be permanently submerged (GWT at 0.0m–0.22m), the chemical environment is critical for concrete durability.

- **Corrosivity Potential:** The investigation included soil chemical testing to identify sulfates and chlorides that could degrade reinforcement or concrete.
- **Sulfate Resistance:** If laboratory results (Appendix XIV) indicate high sulfate concentrations, Sulfate-Resisting Cement (Type V) is mandatory to prevent the

formation of expansive ettringite, which causes concrete spalling in submerged conditions.

- **Chloride Protection:** Given the coastal lowland context of Sonfonia, high chloride levels would necessitate increased concrete cover and potentially the use of corrosion inhibitors to protect the steel reinforcement in piles and rafts.

Summary of Recommendations

Parameter	**Recommendation**
Foundation Type	**Bored Piles** for heavy loads; Rafts for moderate loads in non-clay zones.
Pile Termination	Minimum **15.0m - 20.0m** to bypass soft fat clay.
Cement Type	**Type V** or **Type II** depending on specific sulfate levels in Appendix XIV.
Waterproofing	Required for all basement or ground-contact elements due to zero-depth GWT.

Chemical Analysis and Cement Selection Strategy

Based on the geotechnical investigation's focus on permanently submerged conditions at Sonfonia, the chemical properties of the soil and groundwater are the primary drivers for concrete durability. While Appendix XIV contains the full laboratory dataset, the engineering summary establishes the following critical parameters:

1. Numerical Chemical Indicators

- **pH Levels:** The groundwater and soil at the site are strongly influenced by the tropical wetland environment. Standard reinforced concrete requires a pH of 6.0 to 8.5 for mixing water. Lower values (acidic conditions) would lead to the decalcification of the cement paste and rapid corrosion of steel reinforcement.

- **Sulfate Content ():** The "fat clay" (CH) and sandy layers are being analyzed for sulfate ions.

- **Low Exposure:** in soil or ppm in water.
- **Moderate Exposure:** in soil or ppm in water.
- **High Exposure:** in soil or ppm in water.

2. Finalized Cement Selection

Due to the zero-depth groundwater table (0.0m–0.22m), all foundation elements are in constant contact with the subsurface chemical regime.

- **Option A: Moderate Sulfate Exposure**
  - **Recommendation:** Use Type II Portland Cement.
  - **Constraint:** Tricalcium Aluminate () content must be limited to 8% to prevent moderate sulfate attack.
- **Option B: High Sulfate Exposure (Draft Recommendation)**
  - **Recommendation:** Use Type V High Sulfate-Resistant Cement.
  - **Constraint:** content must be restricted to 5% or less. This is the most likely requirement for the fat clay (CH) zones to prevent expansive ettringite formation that causes cracking and spalling.
- **Maximum Cement Content:** For all Reinforced Cement Concrete (RCC) used in these foundations, the content is capped at 450 kg/m³ to mitigate shrinkage and durability issues in the waterlogged environment.

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Data Availability Statement

The datasets generated during and/or analyzed during the current study, including borehole logs (Appendix I), corrected SPT N-values (Appendix II), and detailed laboratory results for Atterberg limits and consolidation (Appendices VIII & XIII), are derived from the Geotechnical Investigation Draft Report for Sonfonia, Guinea Conakry. Due to the proprietary nature of the infrastructure project and the sensitivity of the local subsurface data, full access to the raw data is restricted. However, anonymized data summaries and the computation methodologies for bearing capacity and settlement are available from the corresponding author upon reasonable request and with the approval of the project stakeholders.

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