Impact of Shear Strength Degradation on Raft Foundation Performance in Clay Shale

Andryan Suhendra
Bina Nusantara University, Indonesia
asuhendra@binus.ac.id (corresponding author)

Riza Ainul Hakim Suwondo
Bina Nusantara University, Indonesia
riza.suwondo@binus.ac.id

Natalia Vincensia
Bina Nusantara University, Indonesia
natalia.vincensia@binus.ac.id

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ABSTRACT

The construction of structures on clay shale soils presents significant challenges due to the soils' propensity for water absorption and associated volumetric changes. These problematic soils are characterized by weak bond structures and expansive clay minerals that can lead to severe structural damage and foundation instability. This study investigates the performance of raft foundations under varying conditions of shear strength degradation and different thicknesses of degraded clay shale layers. The study employs numerical simulations using the finite element software PLAXIS 3D, which allows the detailed modeling of soil-structure interactions. Various scenarios were analyzed, considering shear strength degradation and clay shale thickness variations ranging from 0.5 m to 2.5 m. The findings indicate a clear trend of decreasing safety factors and increasing settlement with both the degradation of shear strength and the increased thickness of the degraded clay shale layer. These results emphasize the critical impact of soil degradation on foundation performance and highlight the necessity for rigorous soil assessments and the implementation of mitigation strategies to ensure long-term structural stability. The study's insights and recommendations contribute to advancing geotechnical engineering practices, thus promoting safer and more resilient foundations in challenging soil conditions.

Keywords-clay shale soil; shear strength degradation; raft foundation; finite element analysis; soil-structure interaction

I. INTRODUCTION

Constructing structures on problematic soils, such as clay shale, presents significant challenges due to their propensity for water absorption and associated volumetric changes. The swelling and shrinkage of these soils, induced by variations to water content, stem from their weak bond structure, which is attributable to a deficiency of cementitious materials between soil particles and the presence of expansive clay minerals [1-3]. Consequently, structures erected on clay shale soils are susceptible to severe damage and cracking if appropriate precautions are not taken [4-6]. Clay shale is a fine-grained sedimentary rock formed geologically through the compaction of layered clays over thousands of years, subjected to prolonged pressure deep underground. Over the years, geological processes have brought clay shale formations closer to the surface. In its unweather state, clay shale typically exhibits high Standard Penetration Test (SPT) blow counts of 60 blows per foot or higher [7]. However, upon exposure to weathering conditions, it rapidly degrades, crumbles, and experiences a significant loss of shear strength within days or weeks [8-10]. Consequently, structures built on clay shale are particularly vulnerable to severe damage and cracking if appropriate measures are not taken. This inherent instability underscores the importance of understanding and mitigating the effects of shear strength degradation in clay shale when designing foundations. A range of studies have explored the behavior and the properties of clay shale. Authors in [11] reported that the unweather clay shale can exhibit effective cohesion up to 85 kPa and an internal friction angle as high as 41°. However, upon exposure to atmospheric conditions, the clay shale weathers rapidly, leading to a dramatic decrease of shear strength, with cohesion dropping to zero and the internal friction angle reducing to merely 9°. Authors in [12] investigated the shear strength of soaked and unsoaked clay shales from the supporting clay layer of California's San Luis

Dam. Drained direct shear tests were conducted compared to these two conditions. The results indicated that the unsoaked peak strength exhibited cohesion as high as 5500 psf (260 kPa) with a friction angle of 39°. In contrast, the soaked condition showed a near-total loss of cohesion, and the residual friction angle decreased as low as 15°. The design of foundations on clay shale presents a complex challenge due to the unique properties of these materials, which significantly influence stability and consolidation behavior [13]. At Sydney region, specific design loadings for foundations on shale and sandstone have been proposed, considering their classification and the allowable values for end-bearing pressure and socket shear stress [14]. However, the prevalence of smectite-rich shales in southeastern Nigeria has been associated with frequent foundation failures, underscoring the necessity for soil modification and appropriate foundation design [15]. Additionally, a new design approach for embankments on soft clays has been developed, incorporating critical state concepts to provide a comprehensive guide for the design and construction of such foundations [16]. Authors in [17] employed small-scale physical modeling to investigate the long-term behavior of two vertically loaded Piled Raft Foundation (PRF) models on saturated clay. The model ground was prepared by consolidating a slurry clay mixture. The results indicated that the piles were effective in reducing PRF settlement when the applied load was less than 70% of the piles' estimated ultimate capacity. Authors in [18] assessed the shear strength and durability characteristics of a weathered clay shale mixture treated with Portland Cement (PC). The percentage of PC used varied, not exceeding 20%, and the mixing material was compacted according to the Proctor Standard procedure. Results indicated that the weathered clay mixture treated with 10% PC and 8% larger Optimum Moisture Content (OMC) exhibited a significant increase of normalized shear strength and durability index, approximately 300% and 24%, respectively, compared to the original clay shale. These findings highlight that the optimal shear strength and durability of the shale mixture were achieved with 10% PC and 8% larger OMC.

Authors in [19] investigated the degradation of the axial bearing capacity of bored piles in clay shale due to the installation processes. Clay shale samples were prepared to simulate wetting and drying cycles over a weathering period ranging from 0 to 6 hours. Each hour of weathering represented one cycle of wetting and drying. Then the samples are tested using direct shear test. The results demonstrated that shear strength degradation, measured at peak, residual without stress release, and residual with stress release, respectively reached 87%-62%, 28%-20%, and 25%-14% after 1 to 6 hours of weathering. Authors in [20] studied the effects of Waste Marble Dust (WMD) and Corncob Ash (CCA) on the engineering and microstructural properties of expansive soils. Various laboratory experiments were conducted to the natural soil to determine its characteristics. The results indicated that the combined use of WMD and CCA significantly enhances the engineering properties of the soil, such as strength parameters and swell potential, demonstrating their potential as effective soil stabilizers. While there has been significant research conducted on foundation design and soil stabilization techniques, there remains a notable gap in the understanding of the specific effects of shear strength degradation on raft foundations in clay shale soil. Given the prevalence of clay shale in certain geological regions and the increasing demand for construction on these soils, it is imperative to address this knowledge gap. The lack of comprehensive studies focusing specifically on the impact of shear strength degradation on raft foundations in clay shale soil limits the ability to develop effective design methodologies and construction practices tailored to these conditions. The primary objective of this research is to comprehensively investigate the impact of shear strength degradation on raft foundations in clay shale soil. By subjecting clay shale samples to controlled weathering processes and varying degrees of shear strength degradation, the study aims to quantify the extent to which soil deterioration affects the stability and load-bearing capacity of raft foundations. Through this comprehensive investigation, the present study seeks to contribute to the existing body of knowledge on foundation design in problematic soils and offer valuable insights for the development of more robust and reliable engineering practices.

II. METHODOLOGY

This study investigates the behavior of a reinforced concrete raft foundation under varying soil conditions. The raft foundation, as shown in Figure 1, is composed of concrete with a compressive strength of 30 MPa. Its dimensions are 73 m in length and 26 m in width, with a depth of 1 m. This foundation size is adjusted according to the planned building dimensions and land availability. The foundation is designed to support the service load of 12 t/m^2. The investigation is involved to a comprehensive series of geotechnical tests aimed at characterizing the soil properties pertinent to the foundation design. The soil conditions at the construction site are characterized by silty clay layers extending to a depth of 2 m. These layers are dark gray, highly plastic, and moist. Below this, the soil transitions to clay shale, which is also dark gray but exhibits a hard consistency and remains moist. These tests provide essential data on the physical and mechanical properties of the silty clay and clay shale soil, which are summarized in Table I.

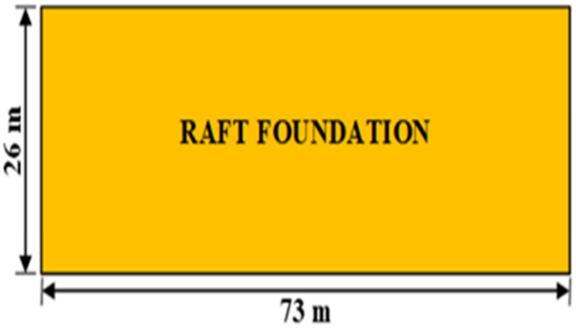

Fig. 1. Plan view of raft foundation.

In this study, both undegraded soil (Condition 1) and four distinct levels of degraded soil (Conditions 2-5) are examined. The soil parameters for each condition, including shear strength and other relevant characteristics, are detailed in Table II. These conditions represent varying degrees of degradation, simulating the effects of weathering and environmental exposure on the soil's structural integrity. In addition to the varying levels of soil degradation, the study also considers the impact of different thicknesses of the degraded clay shale layer, ranging from 0.5 m to 2.5 m. This variation in thickness is crucial for understanding how the volume of degraded material influences the overall performance of the raft foundation. The clay shale layer thickness originally is around 28 m.

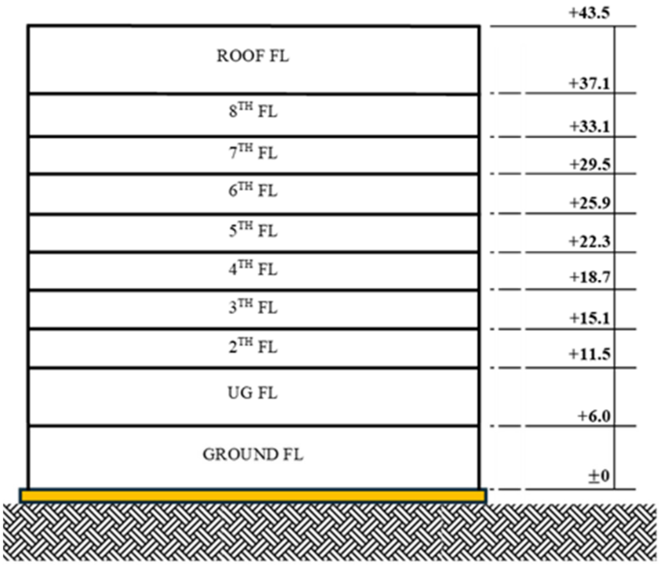

Fig. 2. Plan and cross section of building.cross section.

TABLE I. TYPICAL VALUES OF SOIL

Parameter	**Value**	
Lithology	**Silty clay**	**Clay shale**
Water content, %	5.06	5.08
Specific gravity	2.68	2.66
Porosity, %	21.95	17.65
Density, gr/cm^3	1.87	2.29

TABLE II. SILTY CLAY SOIL PARAMETERS

Soil parameter	**Silty clay**				
	Condition				
	1	2	3	4	5
Cohesion (c), kPa	12				
Friction angle (φ), °	20				
Modulus of elasticity (E), MPa	96	86.4	81.6	72	52.8
Poisson's ratio (μ)	0.35				

TABLE III. CLAY SHALE PARAMETERS FOR VARIUS CONDITIONS

Soil parameter	**Condition**				
	1	2	3	4	5
Cohesion (c), kPa	60	44	41	37	30
Friction angle (φ), °	20	13	11	8	5
Modulus of elasticity (E),	300	192	177	144	96
Poisson's ratio (μ)	0.30	0.31	0.33	0.34	0.35

Note: Condition 1: Undegraded Soil, Condition 2 to 5: Degraded Soil.

The numerical analysis was conducted using the finite element software PLAXIS 3D [21], known for its user-friendly interface and robust capabilities in modeling soil-structure interactions. This software enables detailed simulation of the complex behaviors associated with raft foundations on clay shale soil. The finite element model of the raft foundation, as evidenced in Figure 3, was developed to represent the actual conditions accurately. Soil properties, including shear strength parameters and other relevant characteristics, were input into the model based on soil characteristic value, as summarized in Tables II and III. Boundary conditions were defined to replicate actual constraints and interactions between the soil and the foundation. The model boundaries were set sufficiently far from the foundation to minimize edge effects and ensure accurate stress distribution.

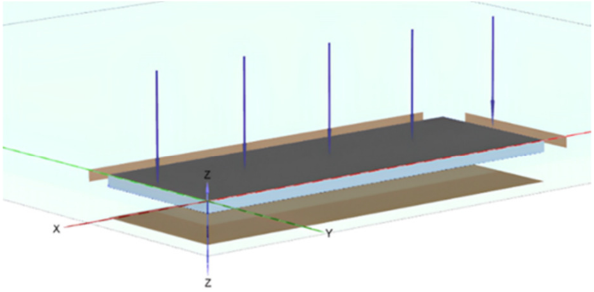

Fig. 3. PLAXIS 3D model.

This study focuses on investigating the safety factor and deformation of raft foundations. The analysis approach for determining the safety factor involves a gradual reduction of the soil shear strength parameters—tan φ (friction angle), soil cohesion, and tensile strength—until structural failure occurs. During this reduction process, the dilation angle (φ) remains unaffected by the phi/c reduction procedure. However, it is important to note that the dilation angle cannot exceed the friction angle. Once the friction angle has been reduced to a level equal to the dilation angle, any further reduction in the friction angle will correspondingly reduce the dilation angle. Similarly, the strength of interfaces, if utilized, will be reduced in the same manner. Additionally, the strength of structural components such as plates and anchors can be optionally reduced during safety calculations to simulate realistic failure conditions. The total multiplier factor ΣMsf is used to determine the value of the soil strength parameter at a specific stage in the analysis, as observed in the following equation:

$$\sum \mathrm{Msf} = \frac{\tan \varphi_{\mathrm{input}}}{\tan \varphi_{\mathrm{output}}} = \frac{c_{\mathrm{input}}}{c_{\mathrm{output}}} = \frac{\text{tensile strength}_{\mathrm{input}}}{\text{tensile strength}_{\mathrm{input}}} \quad (1)$$

On the other hand, the deformation analysis utilizes the fundamental principles of Hooke's Law within the PLAXIS 3D. Hooke's Law states that the magnitude of force exerted on an elastic object is proportional to the change in its length. This relationship is crucial for understanding the tensile stress and strain behavior of materials under applied forces. The basic equation governing this relationship is expressed as:

$$\sigma = E \times \varepsilon \quad (2)$$

where σ is the tensile stress, E is Young's modulus of elasticity and ε is the strain.

III. RESULTS AND DISCUSSION

Figure 4 presents the results of the safety factor analysis for the raft foundation under various conditions of shear strength degradation and different thicknesses of the degraded clay shale layer. The analysis reveals a clear trend of decreasing safety factor values as the degree of soil degradation increases and as the thickness of the degraded clay shale layer varies from 0.5 m to 2.5 m. The results also indicate that soil degradation significantly impacts the stability of the raft foundation. As the quality of the clay shale soil deteriorates due to degradation, the soil's shear strength diminishes, leading to a lower safety factor. This is particularly evident in scenarios where the thickness of the degraded layer is greater, suggesting that both the extent of degradation and the volume of the degraded material play crucial roles in determining foundation stability. The study demonstrates that variations in the thickness of the degraded clay shale layer contribute to the overall reduction in the safety factor. Thicker layers of degraded clay shale correlate with more pronounced decreases in the safety factor, stressing the compounded effects of degradation and increased layer thickness. This finding highlights the importance of considering both factors in the design and assessment of raft foundations on clay shale soils. The observed decrease in safety factors with increasing soil degradation and layer thickness has significant implications for geotechnical engineering practice. It requires rigorous assessment and monitoring of soil conditions, especially in regions prone to rapid degradation. These findings emphasize the importance of comprehensive soil investigations and tailored design approaches to address the challenges posed by degraded clay shale soils.

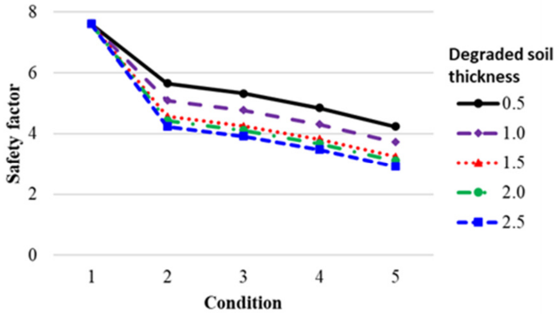

Fig. 4. The safety factor of raft foundation under different conditions.

To validate the analysis results, it is necessary to perform calculations deploying conventional methods. One manual method for evaluating the safety factor of a raft foundation is the Meyerhof method, with reference to SNI 8460: 2017. The following manual calculation addresses a scenario involving degraded clay shale soil. Given that the clay shale, initially a rigid base, has undergone physical changes and degradation, this calculation considers a special case involving layered clay soils. Specifically, there are two types of clay: a weaker soil layer supported by a stronger one. This can be shown by the ratio of $q_2/q_1 > 1$. The modeling of this special case, particularly in condition 2, with a degradation thickness of 0.5 m, can be seen in Figure 5:

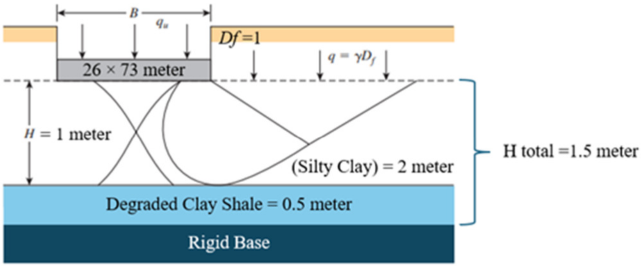

Fig. 5. Special case modeling of layered soils for condition 2, with a degradation thickness of 0.5 m (modified from [22]).

The following stage is the manual calculation for condition 2, with a degradation thickness of 0.5 m. Based on the bearing capacity factor graph with the value of cu(2)/cu (1) = 44/12 = 3.667 and H/B = 1/26 = 0.038, using extrapolation the value of Nc is obtaine. The calculation can be conducted as:

$$N_q = \frac{N_c}{\cot \phi'} + 1 = \frac{11}{\cot 20^\circ} + 1 = 5.004.$$

$$N_\gamma = 2\left(N_q + 1\right) \tan \phi' = 2(5.004 + 1) \tan 13^\circ = 2.772.$$

Meanwhile, based on the variation graph of m_1 and m_2, with the value of H/B = 0.038 and the value of ϕ' = 20°, the values of m_1 and m_2 are:

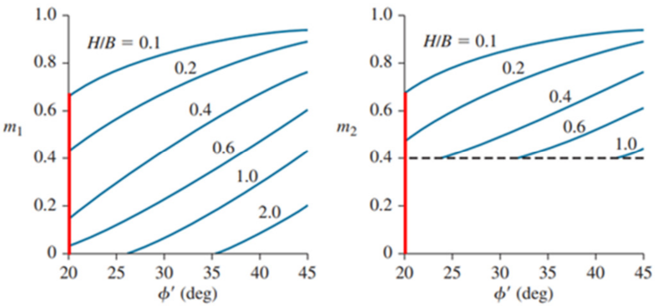

Fig. 6. Values of m_1 and m_2 [22].

From the graph above, the value of m_1 = 0.663 and m_2 = 0.675. So, the calculation can be done as:

$$F^*_{cs} = 1 + \left(\frac{B}{L}\right)\left(\frac{N_q}{N_c}\right) = 1 + \left(\frac{26}{73}\right)\left(\frac{11}{5.004}\right) = 1.162.$$

$$F^*_{qs} = 1 - m_1 \left(\frac{B}{L}\right) = 1 - 0.663 \left(\frac{26}{73}\right) = 0.764.$$

$$F^*_{\gamma s} = 1 - m_2 \left(\frac{B}{L}\right) = 1 - 0.675 \left(\frac{26}{73}\right) = 0.760.$$

Considering that the load is vertical, the value of Fci = Fqi = Fγi = 1. In addition, because of the value Df/B ≤ 1 (0.038 ≤ 1 and of the value φ > 0 (20° > 0), for the calculation of the foundation depth factor the following formula can be used:

$$F_{qd\ (top)} = 1 + 2 \tan \phi' (1 - \sin\phi')^2 \frac{D_f}{B} = 1 + 2 \tan 20^\circ (1 - \sin 20^\circ)^2 \frac{1}{26} = 1.012.$$

$$F_{cd\,(top)} = F_{qd} - \frac{1-F_{qd}}{N_c \tan\phi'} = 1.012 - \frac{1-1.012}{11 \tan 20°} = 1.015.$$

$$F_{qd\,(below)} = 1 + 2\tan\phi'(1-\sin\phi')^2 \frac{D_f}{B} =$$

$$1 + 2\ \tan 13° \,(1 - \sin 13°)^2 \frac{1}{26} = 1.011.$$

$$F_{cd\,(below)} = F_{qd} - \frac{1-F_{qd}}{N_c \tan\phi'} = 1.011 - \frac{1-1.011}{11 \tan 13°} = 1.015.$$

$$F_{\gamma d} \quad = 1.$$

$$q_1 = \gamma_1 . D_f = 1.87 \times 1 = 1.87 \text{ ton/m}^2.$$

$$q_2 = \gamma_2 . D_f = 2.05\times1 = 2.05 \text{ ton/m}^2.$$

$$q_t = c'_1.N_{c(1)}.F_{cs\,(1)}.F_{cd}.F_{ci} + q.N_{q(1)}.F_{qs(1)}.F_{qd}.F_{qi} +$$

$$0.5.\gamma_1.B.N_{\gamma(1)}.F_{\gamma s(1)}.F_{\gamma d}.F_{\gamma i}$$

$$= (1.2\times11\times1.162\times1.015\times1)+(1.870\times5.004\times0.764\times$$

$$1.012\times1)+(0.5\times1.870\times26\times2.772\times0.760\times1\times1)$$

$$= 73.994 \text{ ton/m}^2.$$

$$q_b = c'_2.N_{c(2)}.F_{cs(2)}.F_{cd}.F_{ci} + q.N_{q(2)}.F_{qs(2)}.F_{qd}.F_{qi} +$$

$$0.5.\gamma_1.B.N_{\gamma(2)}.F_{\gamma s(2)}.F_{\gamma d}.F_{\gamma i}$$

$$= (4.4\times11\times1.162\times1.015\times1)+(2.050\times5.004\times0.764\times$$

$$1.011\times1)+(0.5\times2.05\times26\times2.772\times0.760\times1\times1)$$

$$= 121.113 \text{ ton/m}^2.$$

Authors in [23] state that for sand or clay soil types, the value of D ≈ B. So, the calculation can be performed as:

$$q_u = q_t + (q_b - q_t)\left(\frac{H}{D}\right)^2 = 73.994 + (121.113 - 773.994)\left(\frac{1.5}{26}\right)^2 = 74.151 \text{ ton/m}^2.$$

$$FS = \frac{q_{ult}}{q_{all}} = \frac{74.151}{12.7} = 5.839.$$

This factor of safety is quite like the result obtained from the analysis using the PLAXIS 3D program, as displayed in Figure 4, i.e. 5.652. Figure 7 portrays the results of the settlement analysis for the raft foundation under varying conditions of shear strength degradation and different thicknesses of the degraded clay shale layer. The analysis reveals a clear trend of increasing settlement corresponding with the degradation of the soil's shear strength. The results indicate that as the shear strength of the clay shale soil diminishes due to degradation, the settlement of the raft foundation increases significantly. This is attributed to the reduced ability of the degraded soil to support structural loads, leading to greater deformation under the same applied stresses. The relationship between shear strength degradation and settlement underscores the critical role of soil integrity in foundation performance. In addition to shear strength degradation, the analysis considers the impact of varying the thickness of the degraded clay shale layer. The findings show that settlement increases proportionally with the thickness of the degraded layer. This suggests that thicker layers of degraded soil exacerbate foundation settlement, likely due to the greater volume of compromised material affecting the overall stability and load-bearing capacity of the foundation system. The observed trends in settlement behavior have important implications for geotechnical engineering practice. The results emphasize the necessity for thorough soil investigations and careful consideration of soil degradation in foundation design. Engineers must account for the potential increase in settlement due to the degradation of shear strength and the thickness of the degraded layer. Mitigation strategies, such as soil stabilization or alternative foundation designs, should be considered to minimize excessive settlement and ensure structural stability.

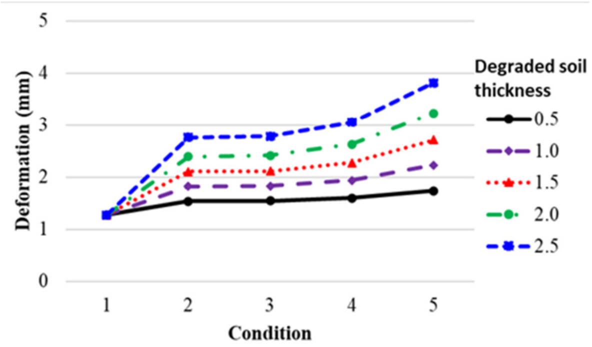

Fig. 7. Deformation of raft foundation under different conditions.

IV. CONCLUSIONS

This study provides a comprehensive analysis of the impact of shear strength degradation and varying thicknesses of degraded clay shale layers on the performance of raft foundations. The key findings and their implications are summarized as follows:

1) Shear Strength Degradation

The degradation of shear strength in clay shale soils significantly affects the stability and settlement of raft foundations. As the shear strength diminishes, the safety factor decreases, and settlement increases. This highlights the importance of maintaining soil integrity to ensure the structural stability of foundations.

2) Thickness of Degraded Clay Shale

The thickness of the degraded clay shale layer is a critical factor influencing foundation performance. Increased thickness of the degraded layer results in more pronounced reductions in the safety factor and greater settlements. This suggests that both the extent of degradation and the volume of degraded material must be considered in foundation design and assessment.

3) Extreme Settlements

The study identified extreme settlement values, particularly when the thickness of the degraded clay shale layer reached 2.5 m. The highest recorded settlement was 3.8 mm under the most severe degradation conditions. This underscores the compounded effects of significant shear strength loss and substantial layer thickness on foundation displacement.

4) *Engineering Implications*

The findings emphasize the need of rigorous soil investigations and continuous monitoring in regions with clay shale formations. Engineers must account for potential soil degradation over time and consider implementing soil stabilization techniques or alternative foundation designs to mitigate adverse effects. Practical mitigation strategies and tailored design approaches are essential to enhance structural resilience and ensure long-term performance.

5) *Guidelines for Practice*

Based on the study, it is recommended that geotechnical engineering practices incorporate detailed evaluations of soil conditions, including assessments of shear strength degradation and layer thickness variations. Developing comprehensive guidelines for the design and construction of foundations on clay shale soils is crucial for the unique challenges posed by these problematic soils to be addressed.

This research underlines the significant impact of shear strength degradation and thickness variations of clay shale layers on raft foundation performance. By providing valuable insights and practical recommendations, the study contributes to the advancement of geotechnical engineering practices, promoting safer and more resilient foundation designs in challenging soil conditions.

DATA AVAILABILITY

The utilized data can be accessed at: https://zenodo.org/records/13352763

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