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Hybrid Deep Foundation System for Collapsible Soils

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Abstract- The inherent strength of collapsible soils in their desiccated state is often compromised upon exposure to moisture. This poses a formidable challenge for foundation engineers when designing under such conditions. The intricacies of foundation design are exacerbated by the variability in treatment protocols, contingent on factors such as collapsible soil depth and the structural demands of the intended edifice. Deep foundations, often indispensable, facilitate the transfer of loads to more resilient strata beneath the collapsible soil matrix. This study pioneers the conception of an innovative foundation system calibrated to navigate the complexities of collapsible soils. Serving as an avant-garde foundation support mechanism, the novel system amalgamates raft foundations, steel cylindrical piles, and encapsulated and stabilized stone columns within an integrated framework. Employing sophisticated numerical analysis via Plaxis 3D, the performance of this hybrid system within collapsible soils is rigorously evaluated. Findings underscore the transformative potential of coupling reinforced stone columns with piles, culminating in a substantial augmentation of load-bearing capacity. Optimal performance is manifested when reinforced stone columns are judiciously positioned at the core of the raft foundation, complemented by peripheral pile deployment. Beyond load-bearing enhancement, the novel foundation system exhibits an unparalleled propensity for elevating ground quality and optimizing soil foundation performance. This innovation transcends the efficacy of traditional pile solutions and supersedes stone columns in terms of ground improvement. Moreover, the amalgamated foundation system is postulated to catalyze a transformative alteration in soil foundation dynamics, engendering a composite ground of elevated capabilities. The study further introduces a pioneering analytical model poised to prognosticate the carrying capacity of this integrated foundation system.

Keywords**:** Piles, reinforced stone columns, improvement, collapsible soils, carrying capacity.

1. Introduction

The phenomenon of soil collapse, characterized by significant volume reduction upon wetting with or without additional loading, leading to radical particle rearrangement, has been observed in diverse soil types including loess, alluvial, residual, aelion subaerial, colluvial, and gypsiferous silts (e.g. [1,2]). Despite limited historical emphasis on the study of collapsible soil susceptibility and the construction of modest, cost-effective structures, the contemporary landscape of urbanization and heightened water consumption necessitates a comprehensive examination of collapsible soil subsidence, especially with structures erected atop such substrates (e.g. [3]).

Research in the realm of collapsing soils has predominantly centered around identification methodologies and quantification of potential collapse magnitude; however, the current advancements, while noteworthy, are not yet at a level enabling engineers to confidently design structurally resilient and economical foundations on these soils (Among others, [4,5,6]). Designing foundations within collapsible soils poses significant challenges, wherein predicting settlement demands laboratory or field assessments. Pre-treatment strategies, aiming to either stabilize or intentionally induce collapse, can prove beneficial, contingent upon soil depth and structure support requisites. Various treatment methodologies, including stone columns, present themselves as promising alternatives to conventional techniques, particularly as construction costs escalate and environmental concerns escalate, albeit with certain limitations.

In this context, the encapsulation and stabilization of stone columns within geofabric emerge as a compelling ground improvement approach, particularly for collapsible soils subject to potential inundation ([7]). The integration of stone columns, steel cylindrical piles, and rigid raft foundations in a unified system stands as a novel contribution in addressing collapsible soil challenges, offering enhanced ground quality, superior performance, and improved carrying capacity. This innovative foundation system not only rivals conventional pile solutions in cost-effectiveness but also presents a more appealing option compared to traditional stone column methods. Additionally, it holds the potential to engender a composite ground upgrade, reshaping soil foundation behavior. Furthermore, the study introduces an analytical model for predicting the carrying capacity of this composite foundation system, encapsulating a holistic advancement in the realm of collapsible soil engineering.

2. Description of the New Foundation System

Utilizing numerical modeling, this study affirms and endorses the necessity for a novel foundation system tailored to accommodate heavy structures, specifically medium to high-rise buildings with over five floors, situated within collapsible soils. The innovative system entails the integration of a rigid raft foundation, steel cylindrical piles, and encapsulated, stabilized stone columns, offering a comprehensive foundation support solution for collapsible soils. The encapsulated stone columns are constructed using Terram T3000 geofabric, with stabilization achieved through the incorporation of 12% Ordinary Portland Cement (OPC), corresponding to 234 kg/m^3. The newly amalgamated foundation system is anticipated to not only enhance load-bearing capacity but also effect transformative improvements, reshaping the soil foundation into an upgraded composite ground profile, and concurrently optimizing geotechnical expenses (Fig. 1). Through meticulous investigation, this research ascertains that optimal system performance is achieved when piles are strategically positioned at the periphery of the rigid raft. Furthermore, a noteworthy augmentation in system performance is noted upon the introduction of supplementary piles at the raft's central zone.

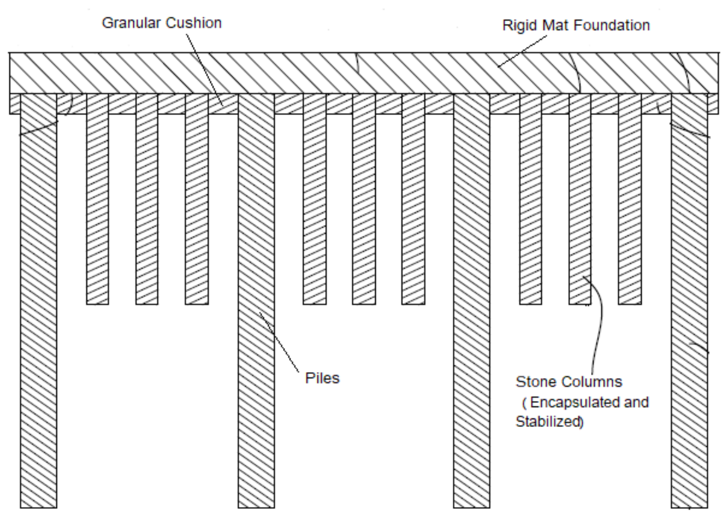

Fig. 1: Cross-section of the Combined Foundation System

In comparison to existing solutions, the new foundation system offers distinctive advantages that position it as a superior and more cost-effective option than traditional piles, and a more appealing choice than stone columns for enhancing ground quality and optimizing soil foundation performance (e.g. [6 and 8]). Notably, this innovative system demonstrates the ability to withstand tensile and lateral loads, endure high driving stresses, mitigate excessive noise during pile driving operations, and maintain a harmonious equilibrium between technological, environmental, and social costs. The key constituents of this pioneering foundation system are outlined as follows:

Piles, elongated steel elements, play a pivotal role in transferring structural loads to deeper rock or firm soil layers. Typically, steel pipe piles, often filled with concrete post-installation, are utilized; welding or riveting may be employed to splice steel piles where needed. To enhance durability, steel piles facing potential corrosion ($pH < 7$) may be augmented with increased thickness or epoxy coatings. The typical length of piles ranges from 15 to 60 meters, with load-bearing capacities ranging between 300 to 1200 kN (e.g. [9]).

Stone columns, comprising compacted granular material within cylindrical voids, are established through a vibroflot-assisted process that involves drilling a circular opening into the soil and subsequently filling it with gravel. The compacting action occurs during vibrator withdrawal, utilizing gravel particles ranging from 6-40 mm. These columns generally possess diameters of 0.5-0.75 m and are spaced at intervals of 1.5-3 m. Stone columns exhibit optimal effectiveness at depths between 6 to 10 m, though constructions reaching depths of up to 31 m have been realized (e.g. [10, 11,12,13]).

Terram, developed by ICI fibers, encompasses a spectrum of fabrics catering to the Civil Engineering sector. These materials, composed of 67% polypropylene and 33% polyethylene, are designed to serve diverse purposes including ground stabilization, drainage, reinforcement, and erosion control. Structural attributes include a maximum load (per 200 mm) of 2800 N, an extension at maximum load of 60%, a thickness of 1.0 mm, and a specific gravity (G_s) of 0.9. Notably, Terram exhibits resistance to natural soil alkalis, even with 10% sodium hydroxide exposure, as well as resilience against soil acids up to pH > 2 and general chemical interactions, such as water, oil, and petrol ([14]). This comprehensive analysis underscores the multifaceted advantages and distinctive elements that characterize the new foundation system, paving the way for enhanced construction practices in collapsible soil scenarios.

The chemical composition and physical properties of the cement (OPC) are summarized in the following table:

Table 1: Chemical Composition and Physical Properties of Cement OPC

Properties	**Characteristics**
Chemical Composition	Lime (CaO) = 60-67%, Silica (SiO_2) = 17-25%, Alumina (Al_2O_3) = 3-8%, Iron oxide = 0.5-6%, Alkalies (K_2O+Na_2O) = 0.2-1.5%, Magnesia = 0.1-1%.
Physical Properties	Specific gravity G_s = 3.15, consistency = 24, Blaine's specific surface (cm^2 /kg) = 2415, initial setting time = 1 hour , final setting time = around 10 hours.

3. Theoretical Development

Using the equilibrium method and the superposition approach, a new analytical model for the prediction of the carrying capacity of the combined foundation system was proposed, as follows:

$$Q_{g(u)} = \left[\frac{2(n_1+n_2-2)S+4D_p}{\pi n_1 n_2 D_p}\right]\left[n\left(\frac{\pi}{4}D_p^2\gamma' L_p N_q^* + \pi D_p L_p(1-\sin\varphi_s)\tan\left(\frac{2}{3}\varphi_s\right)\gamma'\frac{L_p^2}{2}\right) + m\left(\frac{\pi}{4}D_c^2\right)\left(\frac{2c\cos\varphi_c}{1-\sin\varphi_c} + \frac{2\sin\varphi_c}{1-\sin\varphi_c}(1-\sin\varphi_s)(3\gamma' D_c + \gamma' L_c)\right)\right]$$

Where:
D_p = Diameter of pile tip
D_c = Diameter of stone column
L_p = Length of pile tip
L_c = Length of pile tip
n = number of piles in the foundation system
m = number of stone columns in the foundation system
S = Minimum spacing between piles and/or columns
n_1 = Number of piles and columns in one row
n_2 = Number of piles and columns in one column
γ' = Effective unit weight of collapsible soil
c = Cohesion of stabilized stone column
φ_s = Angle of shearing resistance of collapsible soil
φ_c = Angle of shearing resistance of stabilized stone column
N_q^* = Bearing capacity factor (deduced from Meyerhof chart shown in Figure 2).

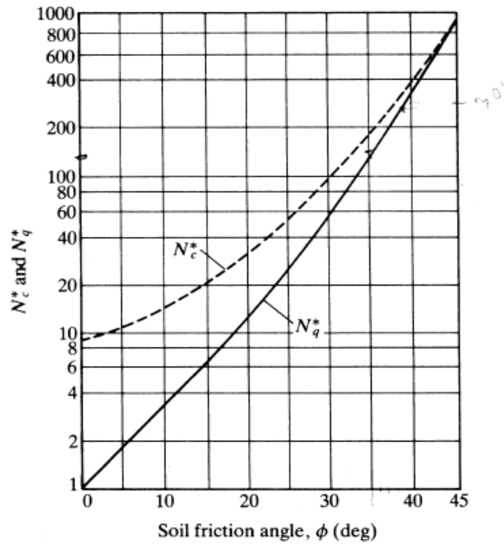

Fig. 2: Meyerhof Chart used for the determination of the bearing capacity factors ([15])

4. Conclusion

In response to the challenges posed by collapsible soils, a groundbreaking foundation system has been devised, seamlessly integrating a rigid raft foundation, steel cylindrical piles, and encapsulated, stabilized stone columns within a unified support structure. Employing Terram T3000 geofabric, the encapsulated stone columns are fortified with 12% Ordinary Portland Cement (OPC), equating to 234 kg/m3. This synergistic approach significantly enhances load-bearing capacity, with optimal performance achieved through centered reinforced stone columns and peripheral pile placement. Beyond bolstering load-bearing capacity, the system offers an enticing alternative to traditional pile solutions in terms of cost-effectiveness, as well as a more appealing option compared to conventional stone column methods for ground enhancement, thus improving ground quality and soil foundation performance. Moreover, the integrated foundation system holds the potential to usher in transformative advancements, shaping an elevated composite ground profile that enhances overall performance. Notably, this research yields an innovative analytical model, facilitating the precise prediction of the combined foundation system's load-bearing capacity and empowering engineering practitioners to make informed decisions for sustainable construction practices. The newly developed foundation system represents a remarkable advancement in geotechnical engineering, offering a versatile, high-capacity solution for collapsible soil scenarios while simultaneously raising the standards of ground improvement and structural integrity.

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