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Ground Improvement Techniques for Problematic Soils: A Review of Stone Columns and Granular Anchor Piles

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Abstract: Construction on problematic soils, including loose sands, soft clays, expansive soils, and collapsible soils, poses significant challenges that can affect the stability, durability, and economic feasibility of structures. Such soils often exhibit inadequate strength and poor load-bearing capacity, which can result in issues such as excessive settlement, differential settlement, slope instability, and, in extreme cases, structural failure. To mitigate these risks, various ground improvement techniques have been developed to enhance the engineering properties of weak soils, ensuring that they can safely support structural loads. Ground improvement methods are crucial in modifying soil characteristics to increase its strength, reduce compressibility, and improve overall stability. These techniques can be broadly classified into mechanical, chemical, and inclusions-based methods. Mechanical methods, such as compaction and vibroflotation, enhance soil density. Inclusions, such as stone columns and granular anchor piles, provide reinforcement by replacing or mixing weak soils with stronger granular materials, increasing their strength and stiffness. Among these approaches, stone columns and granular anchor piles have proven highly effective in stabilizing weak soils and improving their load-bearing capabilities. Stone columns function by redistributing loads, accelerating consolidation, and enhancing drainage, making them particularly useful in soft clay and loose sand conditions. Granular anchor piles, on the other hand, provide additional anchorage and confinement, preventing excessive deformation and settlement. This review explores the characteristics of problematic soils, highlights the importance of ground improvement, and examines the role of stone columns and granular anchor piles in addressing foundation-related challenges.

Keywords: Problematic soil, Ground Improvement Technique, Granular Anchor Pile, Pullout Resistance.

I. INTRODUCTION

Problematic soils refer to soils with unfavourable properties that can cause issues in construction, such as low strength, high compressibility, or expansive behaviour (e.g., clays, silts, and loose sands). To address these challenges, stone columns and granular anchor piles are commonly employed ground improvement techniques. Stone columns involve replacing weak soil with compacted gravel or crushed stone to enhance load-bearing capacity, reduce settlement, and improve drainage. Granular anchor piles are specialized piles filled with compacted granular material, designed to resist uplift forces and provide additional stability in weak or expansive soils. Both techniques are cost-effective solutions for improving soil properties in challenging geotechnical conditions.

A. Problematic Soil

Problematic soils, such as soft clay, silty sand, peat, and loose granular soils, pose challenges for construction due to their poor strength, high compressibility, and low load-bearing capacity. These soils can lead to differential settlement, structural instability, and even failure of foundations. Addressing these challenges requires effective ground improvement techniques to enhance the engineering properties of the soil, making it suitable for construction. Problematic soils are very significant challenges for construction. These can difficulties in terms of stability, water retention, and bearing capacity, often requiring special attention or treatment. Problematic soils such as Expansive soil (swelling clay), collapsible soil, unconsolidated soil (sandy soil), etc. it is major difficult for construction in expansive soils. Expansive soils are those that expand when wet and shrink when dry. When building foundations on such soils, geotechnical engineers often face challenges related to heaving and shrinking [27]

B. Soil liquefaction

Soil liquefaction which is usually known as sudden loss of shear strength in soil due to ground shaking followed by a rapid increase in pore water pressure, generally occurs in loose to very loose saturated granular soils.

Soil is a complex material that exhibits various problematic behaviors under dynamic loading conditions. One of the most common and complex phenomena is liquefaction, which occurs in loose sandy deposits following an earthquake. The larger the magnitude of the seismic load, the greater the generation of excess pore pressure, leading to increased soil deformation. [2, 23]

Liquefaction at a vulnerable site can result in one or a combination of several hazardous effects, including: (i) lateral spreading, (ii) flow failures, (iii) a reduction in bearing capacity leading to increased settlement of structures, (iv) heightened lateral pressure on retaining walls, and (v) ground oscillations that alter ground motion characteristics such as amplitude, frequency content, and duration. Any of these effects, individually or collectively, can lead to ground failure and, consequently, the failure of overlying structures. Additionally, liquefaction can significantly diminish or even eliminate the vertical load-bearing capacity of piles by reducing both skin friction and end-bearing resistance, depending on the depth of the affected zone. It also weakens the lateral load resistance of piles, further compromising structural stability.[19].

C. Clay

Many types of plastic clay experience significant swelling when exposed to water, followed by shrinkage as they lose moisture. Foundations built on these clays are subjected to considerable uplift forces due to the swelling, which can lead to heaving, cracking, and the deterioration of both the foundations and slab-on-grade structures. Expansive soil refers to any soil that undergoes harmful volume changes due to fluctuations in moisture content. These soils typically go through cycles of wetting and drying, swelling when they absorb water during wet periods, and shrinking as water evaporates in dry conditions. Such soils are considered natural hazards, presenting significant challenges to civil engineers, construction companies, and property owners. Several methods can be used to minimize the effect of the damage caused by expansive soils. These include soil replacement, physical & chemical treatment and use of special techniques. The application of these methods will keep intact over a long period of time.[12].

Building structures on problematic soils, such as expansive clays, presents significant challenges due to their capacity to absorb water and undergo volumetric changes. These soils swell and shrink with fluctuations in water content, making structures vulnerable to severe damage and cracking if proper precautions are not taken. Jordan, a country rich in clay minerals, has a diverse range of clay deposits formed over different geological periods, from the Paleozoic era to the present day. Among the key clay deposits in Jordan are kaolin, bentonite, and palygorskite, along with other mineral-rich clays such as illite and smectite. To mitigate the risk of cracking caused by the volume changes of expansive clays, local authorities in Jordan strongly recommend the use of piles and raft foundations instead of shallow footings, although this solution is both costly and time-consuming.[20].

D. Peat soil

Its natural state, exhibits significant compressibility, similar to other soft soils, making it unsuitable for construction due to its poor geotechnical properties. It is characterized by low shear strength, high moisture content, high compressibility, a high organic material content, and limited load-bearing capacity. The vegetable-based grout liquid used as a soil stabilizer was derived from decomposed vegetables such as long beans, spinach, and cucumber. The peat soil samples exhibited a soft, fibrous texture with a slightly organic, musty odor and a dark brown color. This peat soil was moderately organic and moderately moist, with an organic content ranging from 70% to 73.5% and a moisture content of 337%. The addition of vege grout enhanced the strength of peat, with an optimal dosage of 15% yielding the highest strength improvement. Compared to untreated peat, vege-grout-treated peat demonstrated brittle behavior, which became more pronounced as its strength increased over the curing period. However, excessive vege grout led to a decline in strength over time due to the increased brittleness. As vege grout was introduced into the soil, the liquid filled the pore spaces within the peat. Throughout the curing period, continuous evaporation and mineral precipitation contributed to soil binding and accumulation. This treatment resulted in a peat soil strength of 260 kPa, achieving a 449% increase in UCS strength [10]

II. GROUND IMPROVEMENT IN SUBSURFACE

Among the various techniques available, stone columns and granular anchor piles are prominent solutions that improve soil properties through reinforcement and compaction. Both methods are particularly effective in addressing soft and loose soil conditions. Stone columns, also known as granular piles, are vertical columns of compacted granular material, such as crushed stone or gravel, installed in the ground. These columns enhance the load-bearing capacity of the soil, reduce settlement, and provide drainage paths, making them effective for stabilizing soft soils. The construction process typically involves driving a steel casing or mandrel into the ground, filling it with granular material, and compacting it either by vibration or static methods. The structural loads more evenly, reducing stress on the surrounding soil. In seismic-prone areas, stone columns dissipate excess pore water pressure, reducing the risk of liquefaction. By creating drainage paths, they accelerate the consolidation process in saturated soils.

To reduce the impact of soil expansion on lightweight structures, various remedial measures have been proposed in the literature, including pre-wetting, soil replacement, the sand cushion method, and chemical stabilization using materials like lime, cement, fly ash, and pozzolan. In foundation engineering, several design alternatives have been employed for structures built on expansive soils, such as micro-piles, stiff mat foundations, drilled pier foundations, and spread footings placed below the depth of seasonal moisture variation. the utilization of steel slag materials as granular columns to improve problematic soils. Steel slag is a solid waste in steel-making operations from either the conversion of iron to steel in a basic oxygen furnace (basic oxygen furnace slag (BOF)), The inclusion of steel slag or sand column in soil leads to an increase of the shear strength. The granular column has stronger effects when the column diameter is more than 20 cm (or A r larger than 54%). Geosynthetic encasement results in further enhancement of shear strength. The overall friction angle of granular column-soil composites increases when the column diameter increases which is almost independent of geosynthetic encasement A simple foundation technique in the name of GPA foundation system as a dependable solution to suppress or tolerate heaving developed by expansive soils. [12, 23 ,27]

A. *Ground improvement in loose cohesionless soils*

Ground improvement in loose cohesionless soils can be achieved through various methods, including excavation and replacement, compaction piles, compaction with explosives, vibro-flotation, well point systems, dynamic compaction, and grouting, among others. Chemical stabilization using traditional binders, such as Portland cement and lime, is a widely adopted technique to stabilize expansive soils and reduce their potential for heaving and shrinkage. These stabilizers have been shown to enhance strength, decrease compressibility, and improve the stability characteristics of problematic soils by creating artificial cementation bonds between soil particles [20].

Stone columns or granular piles are particularly effective and efficient for ground improvement, outperforming many other methods due to their ability to enhance the performance of various soil types, ranging from soft, loose sand deposits to waste fill sites. The behavior of laterally loaded piles is heavily influenced by the surrounding soil, with factors such as whether the sand is dry or fully saturated playing a critical role in pile-soil interaction. [20 ,11].

B. *Ground improvement in loose cohesive soils*

When a tunnel with a shallow overburden is excavated in challenging ground conditions, such as soft or unconsolidated soil, ensuring the stability and safety of the tunnel face becomes a primary concern. In soft ground, the loosened soil from excavation tends to expand into the surrounding area. In cases where there are no surface obstacles, the target ground was improved using either shallow or deep mixing stabilization methods before proceeding with tunnel excavation using the New Austrian Tunneling Method (NATM). This technique serves as a ground improvement strategy for excavating tunnels with shallow overburden. The addition of water increases soil cohesion. To prevent moisture from migrating into the unimproved ground, a guide wall is installed between the improved and unimproved ground. After the guide wall is in place, the improved ground is established. Once this is complete, the guide wall is removed, and the unimproved ground is then formed. The effectiveness of the pre-ground improvement method, as well as the influence of the width and height of the improved area, were analysed. Ground improvement techniques help prevent settlement of both the ground and the tunnel, with their effectiveness increasing as the width and height of the improved zone expand. Additionally, when the ground surrounding the tunnel lining cross-sections is improved, the area affected by tunnel excavation becomes narrower.[17]

C. *Deep mixing method*

In this study, the excavation and agitation processes within the target ground were successfully visualized using the DCS method. The excavation and agitation effects produced by the DCS agitating blades were accurately reproduced and evaluated through MPS-CAE analysis. The performance of ground improvement using the DCS method was assessed, demonstrating the feasibility of evaluating visual performance across various ground conditions and improvement techniques. Additionally, incorporating various external factors within the ground into the MPS-CAE analysis is expected to facilitate the investigation of the co-rotation mechanism, leading to the development of more effective ground improvement methods. A model experiment was also conducted using the DCS method with coloured pellets to simulate excavation and agitation. This experiment confirmed the mechanism of relative agitation in a three-dimensional and visual manner. The results showed that all pellets, regardless of colour, were agitated and mixed nearly uniformly. Furthermore, the agitating range could be clearly distinguished, using the outer blade diameter of the DCS agitating blades as the boundary. This suggests that the DCS method has minimal impact on the surrounding external ground. However, it is important to note that the effectiveness of this method may vary depending on geological conditions.[18]

D. Underground improvement for tunnel

In this study, the excavation and agitation processes within the target ground were successfully visualized using the DCS method. The excavation and agitation effects produced by the DCS agitating blades were accurately reproduced and evaluated through MPS-CAE analysis. The performance of ground improvement using the DCS method was assessed, demonstrating the feasibility of evaluating visual performance across various ground conditions and improvement techniques. Additionally, incorporating various external factors within the ground into the MPS-CAE analysis is expected to facilitate the investigation of the co-rotation mechanism, leading to the development of more effective ground improvement methods. A model experiment was also conducted using the DCS method with coloured pellets to simulate excavation and agitation. This experiment confirmed the mechanism of relative agitation in a three-dimensional and visual manner. The results showed that all pellets, regardless of colour, were agitated and mixed nearly uniformly. Furthermore, the agitating range could be clearly distinguished, using the outer blade diameter of the DCS agitating blades as the boundary. This suggests that the DCS method has minimal impact on the surrounding external ground. However, it is important to note that the effectiveness of this method may vary depending on geological conditions.[18]

E. Underground improvement for tunnel

The construction of underground infrastructure, such as new subway systems or extensions of existing ones, necessitates a thorough assessment of potential impacts on the surrounding environment. In urban tunnelling projects, the primary concern is the ground movements caused by excavation, which can have detrimental effects on nearby monuments and historical structures. Excavation for tunnels and deep open pits in urban areas inevitably leads to ground movements, making precise and reliable predictions essential during the design phase. In addition to forecasting excavation-induced subsidence, it is crucial to identify mitigation measures or corrective actions to prevent potential damage to adjacent structures. The extent of ground movements caused by tunnelling is influenced by several factors, including tunnel diameter and depth, excavation techniques, soil strength and stiffness, and protective measures implemented to minimize tunnelling effects. Upon completing the excavation of the two mini-tunnels, soil improvement was performed in the layers of alluvial sandy silt (CS-SS) and the sandy layer (SG), located directly beneath the tunnel invert. The conventional excavation of the main tunnels proceeded within the improved soil by expanding the mini-tunnels. Soil improvement was simulated in two stages: (i) a reduction in effective stress caused by borehole radial drilling in the surrounding soil and (ii) an increase in effective stress due to soil compaction resulting from grout injections, which enhanced the strength and stiffness of the treated soil. To replicate these effects, a non-uniform volumetric deformation was applied to the improved soil.[22]

F. Seismic Resistance in embankments

The seismic resistance of existing embankments has become a critical concern, as embankment failures frequently occur during earthquakes. Embankments situated on inclined terrains, such as valley-filled embankments, have been identified as high-priority areas for improvement. The replacement/counterweight fill method effectively reduced the shear strain area by over 30% and helped suppress embankment deformation. However, in the case of Material A, more than 30% of the shear strain was concentrated near the boundary between the top of the counterweight fill and the existing embankment, indicating that the shear strain was primarily localized at the interface between different materials. Implementing the replacement/counterweight fill method enhanced seismic resistance by increasing the mean effective stress within the embankment, reducing specific volume (thus increasing density), lowering the stress ratio (q/p’), and minimizing plastic deformation. This reduction in plastic deformation was attributed to an increase in the over consolidation ratio (1/R) resulting from significant unloading during the earthquake. Additionally, increasing the height of the counterweight fill was found to be more effective in limiting embankment deformation than increasing its width, as it expanded the area of reinforcement influence.[36]

G. Vertical drains

Composite foundation technology is widely used to improve soft soils with high compressibility and water content. This study develops a theoretical model and analytical solution for the consolidation of composite foundations reinforced with vertical drains and gravel piles, considering the effects of radial flow within medium to high replacement ratio gravel piles. Findings indicate that the presence of two vertical drainage elements significantly reduces the horizontal drainage distance of pore water, making vertical flow in soft soils negligible. Ignoring radial flow within gravel piles leads to considerable errors in consolidation calculations, especially as the replacement ratio increases, though this effect remains unaffected by factors such as the number of vertical drains or the pile-to-soil modulus ratio. To accelerate consolidation efficiently, installing vertical drains around the perimeters of gravel piles is a faster and more cost-effective solution than increasing the pile-to-soil modulus ratio or replacement ratio.

Vertical drains, such as prefabricated vertical drains (PVDs) and sand drains, enhance drainage efficiency by providing pathways for water escape, improving load-bearing capacity, and reducing settlement time. These drains are widely used in land reclamation, highway embankments, and construction projects on soft ground, offering a practical and economical solution for soil stabilization.[43] Ground improvement techniques are widely used to enhance the strength and stiffness of soft soils, ensuring sufficient support for infrastructure. Among these methods, the combination of prefabricated vertical drains (PVDs) and preloading with fill surcharge or vacuum pressure is commonly employed to accelerate soil consolidation. Closely spaced vertical drains shift the dominant pore water flow direction from vertical (without drains) to horizontal (with drains), significantly shortening the drainage path and expediting consolidation. However, installing vertical drains creates smear zones, where soil disturbance reduces hydraulic conductivity. Modeling these smear zones in a finite element analysis can be computationally intensive, particularly in 3D simulations. To address this challenge, the Diameter Reduction Method (DRM) based on Hansbo's solution is proposed to account for the smear effect without physically modeling the smear zone. The classical Hansbo solution for average excess pore water pressure (uave) is extended to determine excess pore pressure (**u**) at any location in the soil domain, with validation from numerical results. The DRM introduces a diameter reduction factor (RF), demonstrating that the smear effect can be represented by reducing the vertical drain's diameter. The accuracy of DRM improves with radial distance, and the error in the smear zone becomes negligible at its outer boundary. To maintain constant discharge capacity, the hydraulic conductivity of the reduced drain must be adjusted. The effectiveness of DRM is independent of soil properties, and its strong performance is validated through numerical tests and a field case study. The method simplifies finite element modeling by using reduced-diameter drains without explicitly modeling the smear zone, making it a practical approach for simulating multiple drains in real-world conditions.[44]

H. Vibro compaction

Vibratory probe compaction is an innovative technique for deep compaction of granular soils. It involves a specially designed steel probe with a heavy vibrator attached to its top, generating vertical oscillations. The soil is compacted through repeated insertion and withdrawal of the probe, utilizing the amplified ground response that occurs when a soil layer is excited at its resonant frequency. This effect is achieved by adjusting the vibrator's frequency to match one of the resonant frequencies of the soil-probe system, ensuring optimal transfer of vibration energy to the surrounding soil. The influence range of a single compaction probe was assessed using standard penetration tests (SPT) conducted at various distances from the vibration point, 60 days after compaction. The highest compaction effect was observed at the vibration point, with a slight increase at 1 meter but no significant improvement at 2 meters. SPT blow counts at the grid center were slightly lower than at the probe point. The overall improvement significantly exceeded what would typically be expected at an equivalent distance from a single probe.

The soil strength showed the greatest increase at the vibration point, with only a minor enhancement at 1 meter and no improvement at 2 meters. The radial influence range and effective reinforcement radius were determined to be 2 meters and 1 meter, respectively. The most substantial settlement occurred within a zone approximately twice the probe diameter. Major settlement took place immediately after compaction and continued to increase slightly over time. [40]

Vibro-compaction is a ground improvement method that enhances the density and stability of granular soils such as loose sand and gravel by using vibrations to rearrange soil particles. This study investigates the effect of oscillator frequency on compaction using a rubber-tracked vehicle with an attached oscillator. Tests on an 80 cm deep decomposed granite sandy soil stratum showed that lower frequencies and increased compaction passes led to greater densification. The highest ground depression occurred at 16Hz, close to the natural frequency of the vehicle-ground system, causing over-compaction at deeper layers, with maximum dry density observed at 9.2 cm depth. The system's natural frequency was determined as 4.96, 8.46, and 9.85 Hz for 4, 8, and 13 passes, respectively. Vibro-compaction is widely used in foundation preparation, land reclamation, and infrastructure projects, as it improves load-bearing capacity and reduces settlement risks. Its effectiveness depends on soil type, vibration frequency, depth, and moisture content, making it a cost-effective and environmentally friendly method for soil improvement.[41]

This study examines the variation of random field model parameters in a liquefaction-susceptible site improved by vibro-compaction. The cone tip resistance was normalized for vertical overburden stress and used to identify homogeneous layer boundaries using the RI approach. The inherent variability in both vertical and horizontal directions was assessed through normalized cone resistance data. Weak stationarity and correlation length in the vertical direction were evaluated using the MBSR method, while a less rigorous approach was applied for the horizontal direction due to the larger distance. The removal of the linear trend in **qc1N** improved data stationarity, as confirmed by MBSR testing before and after vibro-compaction. No single ACF model was universally applicable for random field modeling in both conditions.

After vibro-compaction, vertical and horizontal coefficients of variation (COVw,v and COVw,h) increased, while the associated vertical correlation length (δv) also increased, but the horizontal correlation length (δh) decreased. The CPTU data revealed significant anisotropy, with the liquefaction-susceptible layer showing an uncertain change in the vertical direction but becoming more homogeneous in the horizontal direction. However, no clear trend in **COVw,h** and **δh** with elevation was observed.[42]

III.STABILIZING BY STONE COLUMN

The installation of stone columns in soft ground offers several advantages, such as enhanced bearing capacity, faster consolidation, improved slope stability, and control of liquefaction [35]. The primary benefit of stone columns is their adaptability to applied loads, allowing them to redistribute stresses effectively when load concentrations occur. This flexibility results from increased deformation due to bulging once the critical vertical stress threshold is surpassed [33]. Encased stone columns offer further advantages over traditional stone columns:

- The encasement prevents the column from intruding into the soft soil
- It helps maintain a consistent diameter along the column; and
- It enhances shear capacity due to the tensile strength of the encasing material, which provides additional confinement to the sand or gravel.

The internal friction angle of the stone column material was determined through direct shear tests on a mixture of gravel and sand, in a 70% to 30% ratio, under varying normal stresses.[33].The Leno netted bag was used as encased material to the stone columns. The thickness of the leno netted bag is 0.47 mm. The Leno netted bag was used as encased material. The load tests were conducted on single encased stone columns of diameter 7 cm and 6.5 cm using a loading plate of diameter 6 cm and 23.5 cm. the leno netted bag was filled with gravel and sand mixture at proportions of 70% and 30% respectively. The casing pipe was pulled out gently without disturbing the surrounding soil. [38] The most familiar characteristic of the soft soil is that it undergoes an excessive settlement on application of surcharge load. This is due to its low shear strength and high compressibility.[24].

A. Encasement in stone column

The performance of encased stone column in liquefaction and reliquefication under repeated shaking load. The generated excess pore pressure (EPP) and its corresponding pore pressure ratio at different depths for each incremental loading is compared and analyzed between unreinforced and reinforced conditions. The prepared samples with and without ESCs [31]. The aggregates primarily bear the applied load and transfer it to deeper layers through interconnected structures. Due to the high permeability of the column, pore water dissipates more quickly, thus accelerating consolidation. The natural lateral confinement for the granular column is provided by the undrained shear strength (cu) of the surrounding soil; however, this has a minimal effect in restricting axial stress. Three different column diameters, lengths, and footing sizes were selected to simulate both floating and end-bearing column conditions. Additionally, the stone column's effectiveness in addressing liquefaction and re-liquefaction was tested experimentally under repeated, incremental acceleration loading [2].

Crushed basalt aggregate was used as vertically installed stone column material. Stone column material in many practical cases is made of coarse sand, lime, crushed or natural aggregate. the columns extending beyond a depth of 15 m have to be encased so as to overcome the bulging failure. With regard to column diameter, the most commonly used diameters of stone pile are varying between 0.3 m and 1 m [4].

The influence of input motion frequency on the settlement behaviour of a square footing resting on a sand bed reinforced with stone columns was investigated through an experimental study. A model of a reinforced dry sand bed was constructed using a large laminar shear box mounted on a shaking table. The shear box has inner dimensions of 1000 mm × 1000 mm × 1000 mm (length × width × depth) and comprises 23 hollow aluminium layers stacked on top of each other. These layers are separated by linear roller bearings, allowing relative movement between them. The shaking table system is designed to simulate seismic vibrations with motion limited to a horizontal degree of freedom. The study revealed that the frequency of input motion significantly affects the settlement of the footing. In the unreinforced condition, where stone columns were not included, a noticeable change in both the slope of the displacement-time curve and the settlement magnitude was observed as the input motion frequency decreased. In contrast, in tests conducted under reinforced conditions, settlement was found to decrease by approximately 62% when the frequency was reduced from 1.73 Hz to 1.23 Hz.[28]

IV. GRANULAR ANCHOR PILE

Granular anchor piles (GAPs) are a variation of stone columns, enhanced with an anchoring mechanism. They consist of granular material packed within a geotextile or geogrid encasement and anchored to the subsoil. The anchor action helps resist uplift forces, making GAPs particularly suitable for structures subjected to tension, such as retaining walls or offshore platforms. It Provides stability against tensile forces, commonly experienced in submerged or uplift-prone conditions. It Supports shallow foundations in weak soils. Increases the shear strength of the soil mass.

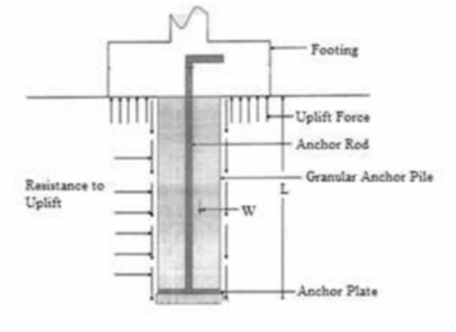


Fig 1 Diagram of granular anchor pile. [13]

Granular Anchor Piles (GAP) represent an innovative ground improvement technique that is increasingly used to enhance settlement and strength properties in cohesive soils for shallow foundations. In a granular anchor pile, the foundation is anchored at the base of the granular pile to a mild steel plate via a central mild steel rod. This anchoring system helps secure the granular material, preventing it from shearing away and thus enabling the mobilization of frictional resistance against uplift forces on the foundation.

In areas with weak soils, efficient and economical ground improvement methods like GAP are essential. Granular piles reinforce the surrounding soil, enhancing its engineering properties and facilitating effective drainage, which in turn increases resistance to liquefaction in loose, saturated soils. Additionally, this technique improves embankment stability, accelerates consolidation, enhances soil bearing capacity, and reduces settlement. To control heaving in shallow foundations over expansive soils, a promising solution is the granular pile-anchor (GPA) foundation system, which modifies the conventional granular pile (or stone column) approach [27].

The Granular Pile Anchor (GPA) system is an innovative foundation technique designed to reduce heave in expansive clay soils and enhance their engineering properties. It is an adaptation of the traditional granular pile, incorporating an anchor within the pile to provide resistance to tension. Granular piles are a widely used ground improvement method for decreasing settlement and increasing the load-bearing capacity of soft clay beds [10]. In the GPA system, various forces act on the foundation: the uplift force generated by the swelling pressure (Ps) of the expansive soil acts vertically upward on the foundation base, while the weight of the granular pile (W) provides a counteracting downward force to resist this uplift [12].

A. Various granular piles anchored in subsurface

This paper presents a systematic experimental investigation of the pressure dip phenomenon in a conical pile under various deposition conditions, including pouring rate, pouring height, and deposition jet dimensions. The findings indicate that, at a macroscopic scale, the base pressure distribution exhibits a central dip beneath the pile's apex, which is a consistent and repeatable occurrence for concentrated deposition. An increase in the pouring rate tends to amplify the magnitude of the dip while narrowing its width. However, within the studied range, variations in pouring height have minimal influence on the pressure dip. When the deposition jet radius is considerably smaller than the final pile radius, the observed dip at the center of the base aligns with findings from previous studies. Conversely, when the deposition radius is relatively large compared to the final pile radius, the dip shifts toward the edge of the deposition jet, accompanied by a partial recovery of the central pressure peak. It is suggested that particle movement down the conical slope during pile formation plays a significant role in the development of the pressure dip. Furthermore, the dip may be closely linked to the initial position, intensity, and characteristics of the downslope flows.[16].

Granular Piles (GP) act as drainage channels, allowing for the rapid dissipation of earthquake-induced pore pressures due to their high permeability. The pore water pressure generated from repeated loading can dissipate almost as quickly as it forms. Additionally, during an earthquake, granular piles undergo dilation (bulging) as they are sheared. While seismic forces typically generate positive pore pressures in soil deposits, dense granular piles experience the opposite effect due to dilation.

A key advantage of ground improvement using granular piles is the densification of the in-situ soil, which enhances its shear strength and reduces seismic risks, particularly the potential for liquefaction. Furthermore, granular piles contribute to increased bearing capacity and significantly reduce settlement while also being a cost-effective solution. These advantages make granular piles a preferred choice for mitigating liquefaction hazards.[19].

Based on the results of 14 pile tests conducted on laterally loaded pile foundations in dry and fully saturated sand with varying densities, the following conclusions have been drawn; The relative density of the soil has a significant impact on the capacity of laterally loaded piles, leading to an increase of up to 168% in single-layered soil and 632% in two-layered soil when compared to loose sand. Soil layering plays a crucial role in pile capacity, resulting in a 52% increase compared to loose soil but a 46% reduction when compared to dense soil. Fully saturating the soil reduces the capacity of laterally loaded piles by 25% in single-layered soil and by 19% in two-layered soil. For both dry and fully saturated conditions in single-layered and two-layered soil, most models underestimated the capacity of laterally loaded piles. However, the API model overestimated capacity in loose and medium-density single-layered soil, as well as in two-layered soil when the L/D ratio was 2 cm. [26].

For the analysis of uplift capability, a granular pile anchor model with a range of lengths and diameters is created using the PLAXIS 3D. The soil that surrounds the GAP is considered to be loose sand and it reaches 600 mm below the surface of the ground. Cyclic reversal axial force due to excessive overturning moments induced by strong ground motions and/or wind-induced impact loading. Helical piles have been introduced and used in practice as a method to increase the bearing and pullout capacities without increasing the pile diameter. Helical piles are categorized into three types of steel pipe piles: (1) those with a single helical wing attached near the tip, (2) those with multiple helical wings, and (3) those with a continuous helical wing wrapped around the pipe shaft referred to as “single helix,” “multi-helix,” and “continuous helix” piles, respectively [39].

A classic problem in granular mechanics is the “sandpile,” where a noticeable dip in vertical pressure occurs at the base directly beneath the apex, even though maximum pressure might be expected there. This “pressure dip” phenomenon is also significant in the bulk handling of industrial solids, as various bulk materials are commonly stored in open stockpiles, particularly in the mining sector [29]. If a geogrid encasement with high tensile strength is applied around the GPA, the uplift resistance (PR) against the uplift force (Pu) would increase due to the friction generated along the GPA-geogrid-soil interface. This configuration can reduce heave, improve compressive load performance, and increase resistance to tensile or uplift forces [30].

This study explored the dependence of the granular friction coefficient (λ\lambda) on loading history by analyzing the deformation of surface profiles in a rotating granular pile. Specifically, surface profile changes were measured and examined to estimate λ\lambda. To investigate history-dependent behavior, profiles were systematically recorded during both increasing and decreasing CC phases. The results revealed that the surface profiles exhibited deformation influenced by their loading history. Notably, granular piles formed under rapid rotation (high CC) remained stable even when CC was reduced to approximately 1. To explain this history dependence, a force balance model was applied to both increasing and decreasing CC regimes, successfully reproducing the experimentally observed profiles. The measured friction coefficient λ\lambda demonstrated an increasing trend in the range 0.1≤C≤30.1 \leq C \leq 3, then either plateaued or slightly declined for C≥3C \geq 3. Additionally, when rotation ceased (C=0C = 0), λ\lambda was observed to be higher than its initial values. To estimate λ\lambda, an empirical model was formulated as λ(C)=λ0(1+c1log 10C)\lambda(C) = \lambda_0 (1 + c_1 \log_{10} C) with c1=0.69c_1 = 0.69 for 0.1≤C≤30.1 \leq C \leq 3 in the increasing CC regime. Furthermore, in this regime, λ\lambda and ϕ\phi appeared to increase alternately as centrifugal loading was applied.[37].

V. PULLOUT RESISTANCE IN GRANULAR ANCHOR PILE

Granular piles (GP), initially developed to resist compressive loads primarily through pile action, are also known as stone columns and have been widely used in soft clays and loose sands to improve geotechnical properties. They can be installed in a variety of soil types, from loose to medium sands, soft to medium clays, and organic soils, but are less effective at resisting uplift loads. Under uplift loads, GP typically fail as the granular material displaces outward from the pile-soil interface. The performance of granular anchor pile (GAP) foundations, with varying parameters, has been analyzed under pullout loads in cohesive soils. The effect of vertical pullout load and upward displacement is observed for GAPs of different lengths and diameters, considering the L/D ratio. In the GPA foundation system, the uplift force is generated by the swelling pressure of expansive soil. For shorter GAPs, uplift resistance is provided by both the shear resistance along the pile-soil interface and the weight of the GPA. At ultimate pullout loading, GPA may fail through one of two mechanisms: (1) "pile failure," occurring when the GPA length is less than a critical length; or (2) "bulging failure," where bulging occurs at the bottom of the GPA over a distance equal to three times its diameter.[23].

A. Pullout capacity in helix pile

The basic performance of the bearing and pullout capacities of continuous helix piles under cyclic loading conditions in both laboratory and field tests. Both the continuous helix and straight-sided piles, of the same diameter, were tested in the laboratory under monotonic compressive, monotonic tensile, and cyclic reversal loading conditions,.[29]. The behavior of pipe piles in partially saturated sand was analyzed at three different levels of matric suction: 6.0 kPa, 8.5 kPa, and 10.5 kPa. The ultimate load capacity of piles in unsaturated sand increased by 30% to 170% across various pile configurations compared to saturated conditions. Additionally, the uplift resistance of pile groups installed in cohesionless soil was investigated. It was observed that as the spacing between piles increased, their capacity to resist uplift decreased. The pullout capacity of piles is significantly affected by the slenderness ratio, with capacity increasing as the slenderness ratio decreases [3]. The pullout capacity of GPAs increased with increased number of geogrid layers and reduced spacing between them. Similarly, the load carrying capacity of granular piles or the uplift capacity of granular pile anchors depends on the lateral resistance offered by the surrounding soil [30].

B. Plate Anchor in Coarse Grains

The uplift capacity of anchors in granular soils depends on both the macroscopic strength parameters, such as internal friction angle, and the anchor to grains size ratio. the grain-size contribution on the anchor breakout factor is linearly increasing with the ratio d/B. models can be used to predict the pullout capacity of relatively small anchors in coarse gravels, pebbles and ballast, where the ratio B/d is small and the grain-size contribution is significant. They also confirm that the grain-size contribution is negligible for large anchors in sandy soils, characterized by large B/d ratios. In contrast, they indicate that grain-size effect can significantly contribute to the pullout capacity measured in small-scale laboratory testing, where anchors size is often limited to few centimeters [7]

C. Vertical anchor in granular pile

The failure displacement (suh) of a vertical anchor is defined as the pullout displacement corresponding to its ultimate load resistance. The variation of failure displacement, expressed as suh/h (%), was examined relative to soil friction angle for different embedment depths (H/h). For embedment ratios of H/h ≤ 7, anchor failure displacement consistently decreases as the soil's friction angle increases. The suh/H ratio decreases with increasing H/h for shallow anchors initially, but then begins to increase. A change in the slope of the response curve occurs at an embedment ratio of 7 for dense soils (RD = 75%), and at an embedment ratio of 5 for medium-dense and loose soils (RD = 50%, 30%). It was observed that the pullout capacity increases with an increase in GPA diameter, likely due to the greater weight and shear resistance along the pile-soil interface. The addition of GPAs with diameters of 30mm, 40mm, and 50mm resulted in pullout capacity increases of approximately 273%, 327%, and 393%, respectively, compared to the system without a granular pile. The variation of ultimate pullout load (Qu) with soil friction angle (ϕ) was also analyzed for different embedment ratios (H/h). Generally, the pullout load rises with an increase in the soil's friction angle, and this rate of increase further grows with greater embedment depth. At an embedment ratio of 1, increasing the friction angle (ϕ) from 32° to 39° raised the ultimate load by about 45%, while at an embedment ratio of 9, the increase was as high as 104% [6].

The friction angle of the GPA has a minimal impact on the probabilistic results, making its mean value suitable for deterministic analyses. The longest failure path is observed when the correlation length is zero. The reduction rate of GPA pullout capacity is influenced by both the coefficient of variation of undrained shear strength (COVSu) and the correlation length. The pullout capacity increases as COVSu rises and the correlation length decreases. However, with higher COVSu and correlation length, the safety factor must be carefully considered.

For a COVSu of less than 0.2, a safety factor of 1.5 is recommended, whereas for a COVSu greater than 0.2, a safety factor of 2 is more appropriate. [8] A mathematical modelling relates the heave of footing resting on reinforced expansive soil with a single (GPA) with three effective variables (L/D), (Df/D) and (L/H). The results of finite element analysis are merged and entered in a multiple linear regressions statistical analysis using SPSS Statistics 17.0 to develop a mathematical model that relates the ratio of (Hv'/Hvo) as a dependent variable to (L/D), (Df/D) and (L/H) as independent variables.[32]. The increased weight and shearing resistance along interface of the pile and the soil can be the reason for the increase in capacity.[15]

The uplift capacity of a GAP system mainly depends on soil and pile properties and also depends on the degree of compaction used for the granular pile. During the compaction of granular pile, the surrounding loose soil also undergoes compaction So the shear strength properties of the loose soil around the granular pile get modified. The uplift capacity of a pile increases as the L/D ratio increases for a given diameter. In the GAP system, uplift capacity improves by 30%. The uplift capacity significantly enhances with an increase in pile length up to a certain point, beyond which further lengthening has minimal effect. It has been observed that the group efficiency of a GAP system decreases as the number of piles in a group rises, due to interaction effects.

As the number of piles in the group grows, the load-carrying capacity of each pile may decrease due to stress overlap from adjacent piles transmitting to the surrounding soil [20].

VI. RESULTS

The results presented above highlight the effectiveness of granular pile anchors (GPAs) and related reinforcement techniques in mitigating the challenges posed by expansive soils, particularly in reducing heave and improving load-bearing capacity. Through various experiments and numerical analyses, it has been shown that the installation of GPAs significantly accelerates the stabilization of expansive soils by reducing the time required to achieve full heave and enhancing uplift resistance. Key findings include the impact of GPA length, diameter, and embedment depth on heave reduction, as well as the superior performance of encased piles in providing higher pullout loads compared to non-encased piles. Additionally, the study reveals the influence of stone column diameter on bearing pressure and settlement, highlighting the importance of proper design for optimal soil stabilization. Overall, the results confirm that GPA-based reinforcement systems offer a promising solution for improving soil stability, controlling heave, and ensuring the structural integrity of foundations in expansive soils.

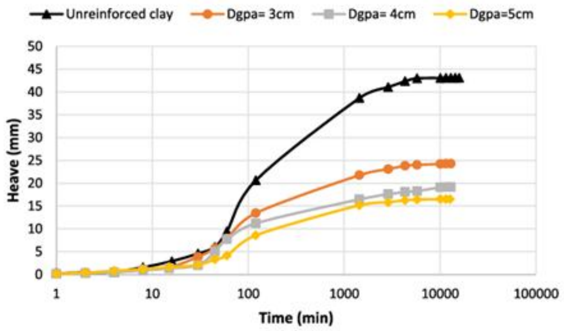


Fig 2. Measured heave with time for the model footing with GPA of length=20cm [27]

Figure 2 Generate plots of measured heave over time for the model footing with GPAs of lengths 20 cm, 30 cm, and 40 cm, respectively. For the unreinforced clay bed, full heave was achieved in approximately 11 days. When the clay bed was reinforced with GPAs, the time to achieve full heave was reduced to about 9 days.[27]

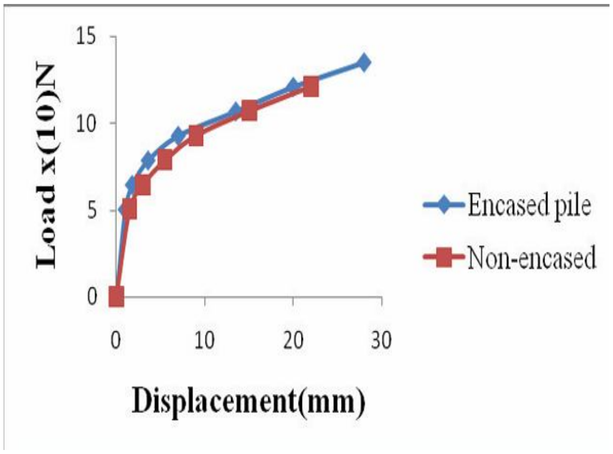


Fig 3: Load- displacement graph of 50mm granular pile for encased and non-encased pile [25]

Figure 3 shows the ultimate pullout load of the encased pile is higher than that of the non-encased pile. For the encased pile, the ultimate pullout load is 121 N, compared to 106.7 N for the non-encased pile, representing an increase of approximately 13.4%. Similarly, in another case, the ultimate pullout load is 149 N for the encased pile and 135 N for the non-encased pile, showing an increase of about 10.4%. This improvement is attributed to the higher interface friction between the non-woven geotextile and sand compared to the friction between soil and sand.[25]

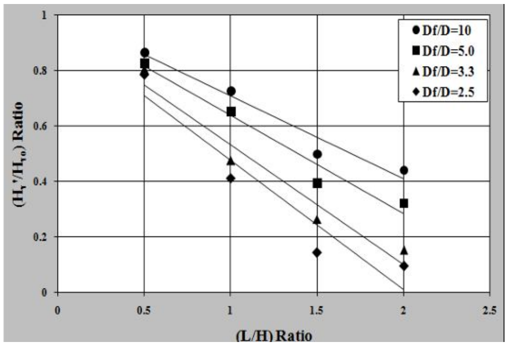


Fig 4: Relationship between the Normalized Maximum Heave (Hv'/Hvo) & (L/H) Ratio of (GPA) for Different Ratios of (Df/D) - (L/H) Ratio Effect [32]

The plot illustrates the relationship between the normalized maximum heave ratio (Hv'/Hvo) and the (L/H) ratio for various (Df/D) ratios. The results indicate that for a given (Df/D) ratio, heave decreases as the (L/H) ratio increases due to the extended length of the GPA. A significant reduction in heave was observed when the GPA penetrated sufficiently into the non-expansive clay layer. This suggests that extending the GPA into the stable zone provides adequate anchorage at its base, effectively mitigating heave. This behavior can be attributed to the increased shear resistance along the penetrated length of the GPA.The findings show that the GPA should extend into the non-expansive clay layer to a depth at least equal to the thickness of the expansive clay layer to ensure sufficient anchorage at its base. the heave decreased dramatically from 260 mm to 25 mm, representing a 90.4% reduction. In comparison, for the same GPA size, the heave reduced to 204 mm at \(L/H = 0.5\) (a 21.54% reduction) and to 81 mm at (L/H = 1\) (a 69% reduction).[32]

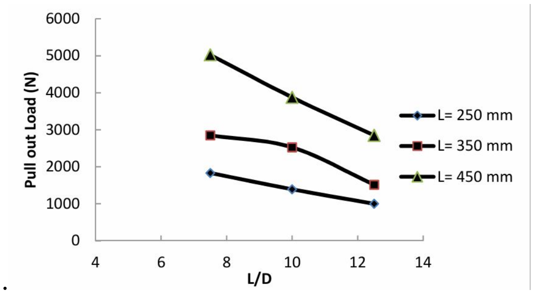


Fig. 5**.** Pullout deformation curve of L/D versus Pull-out load [13]

Figure 5 illustrates the pullout behavior of GAPs, highlighting the influence of diameter on pullout performance. The results show that the applied upward load increases with a larger GAP diameter at all testing stages, as the resistance to uplift rises with the increased surface area of the pile-soil interface. Additionally, it was observed that as the (L/D\) ratio of the GAP increases, the pullout load decreases. This indicates that uplift resistance is governed by the frictional properties and the surface area of the interface. A larger surface area enhances uplift resistance, as it increases both the frictional interaction and the anchor weight of the pile. Consequently, an increase in GAP diameter leads to higher uplift resistance and a greater ultimate pullout load.[13]

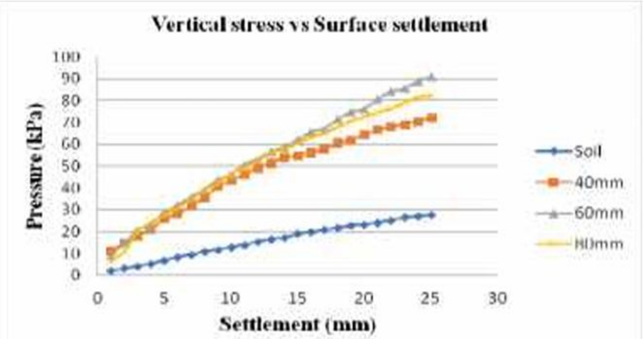


Fig. 6. Vertical stress vs Surface settlement on soil and soil having stone columns [34]

The figure 6 results demonstrate the impact of stone column diameter on bearing pressure. For a 25 mm settlement, the maximum bearing pressure of the soil was 91.23 kPa with a 60 mm stone column and 82.56 kPa with an 80 mm stone column. Initially, the bearing pressure increased with the diameter of the stone column. However, a further increase in diameter to 80 mm led to a decrease in bearing pressure, likely due to the bulging effect observed in larger-diameter stone columns.[34]

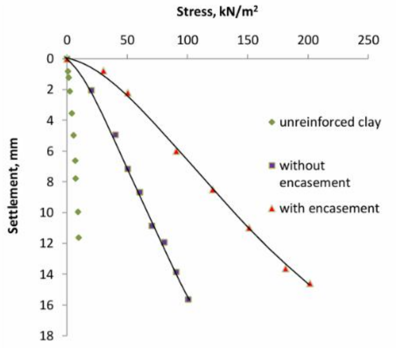


Fig 7 shows the comparison of stress-settlement curves. [32]

The figure 7 shows by applying Leno netted bag as encased material, the settlement of a stone column is decreased. The stiffness of an encased stone column increased by 2.37 times when compared with the stiffness of an uncased stone column.[32]

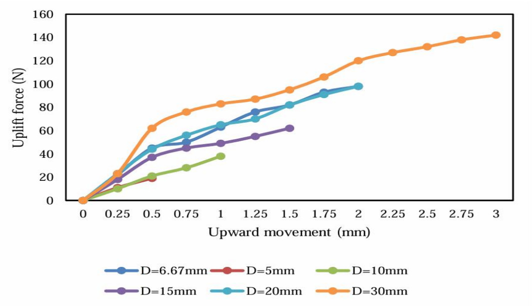


Fig 8 The effect of GAP diameter on GAP system uplift capacity [31]

Figure 8 shows a numerical study was conducted to evaluate the effect of GAP diameter on the pullout capacity of the GAP system. GAPs with various diameters and lengths of 100 mm, 200 mm, and 300 mm were modeled to investigate their uplift behavior. For a 100 mm length and a directed upward movement of 10%, the uplift resistance capacities were recorded as follows: 16.27 N for a 5 mm diameter GAP, 22.46 N for a 6.67 mm diameter GAP, 38.67 N for a 10 mm diameter GAP, 62.16 N for a 15 mm diameter GAP, 98.13 N for a 20 mm diameter GAP, and 142.16 N for a 30 mm diameter GAP. The percentage increase in uplift resistance capacity was approximately 40% when the GAP diameter increased from 5 mm to 6.67 mm, 72% from 6.67 mm to 10 mm, 60% from 10 mm to 15 mm, 57% from 15 mm to 20 mm, and 44% from 20 mm to 30 mm, all for a 100 mm length. The finite element analysis results indicate that the increase in pullout resistance is not solely due to the self-weight of the pile but also to the failure mechanism extending beyond the pile's surface, involving a significant mass of surrounding soil. A similar trend was observed for GAP lengths of 200 mm and 300 mm, with and without the construction effect.[9]

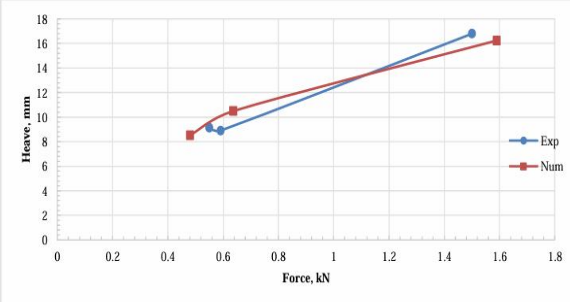
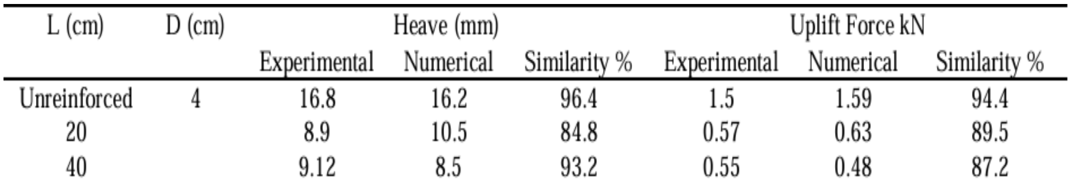


Fig 9. Heave vs force relationship [5]



L (cm)	D (cm)	Heave (mm)			Uplift Force kN		
		Experimental	Numerical	Similarity %	Experimental	Numerical	Similarity %
Unreinforced	4	16.8	16.2	96.4	1.5	1.59	94.4
20		8.9	10.5	84.8	0.57	0.63	89.5
40		9.12	8.5	93.2	0.55	0.48	87.2

Table 1 Heave percentage [5]

The reinforced soil demonstrates a significant reduction in both upward force and heave compared to unreinforced soil. The relationship between upward force and heave is nearly linear for both experimental and numerical investigations, as depicted in Figure 5. Table 1 highlights the improvements and the percentage of similarity between the numerical and experimental models across all tests. The findings indicate a maximum heave reduction of 50% in reinforced soil compared to unreinforced soil. Additionally, the use of GPAs effectively mitigated the resulting upward forces, achieving a reduction of approximately 60%. Incorporating the anchor system enhances resistance to tensile forces induced by water absorption, further improving the system's performance.[31]

VII. CONCLUSIONS

The following conclusions from the review of the problematic soils, stone column, granular anchor pile;

1) The installation of granular pile anchors (GPAs) in expansive soils significantly reduces the time required for heave, leading to an accelerated rate of heave. Expansive soils reinforced with GPAs adapt more quickly to moisture changes due to the high permeability of the granular material. This permeability facilitates faster water circulation and absorption, thereby shortening the radial inflow path and enabling quicker attainment of the final heave. The time required to achieve final heave in GPA-reinforced soil is approximately three-sevenths of that for unreinforced expansive soil.

2) The observed heave decreased significantly when the clay bed was reinforced with granular pile anchors (GPAs). The reduction in heave ranged from 43% to 93%, depending on the diameter and length of the GPA. These results demonstrate that GPAs are an effective solution for controlling heave in shallow foundations constructed on expansive soils.

3) The ultimate pullout load of an encased pile is greater than that of a non-encased pile.

4) Additionally, as the size of the granular material increases, resistance to uplift load improves. This improvement is attributed to the formation of a larger pressure bulb in soils containing larger aggregates compared to soils with smaller aggregates.

5) The GPA system is a cost-effective foundation technique suitable for various soil types. It effectively counters uplift forces and minimizes heave. Field and laboratory studies suggest that the performance of the GPA system is comparable to or even superior to traditional tension-resistant foundation methods, such as concrete anchor piles and screw piles. Compression tests indicate that the GPA system exhibits behavior similar to a standard stone column in soft soils.

6) The ultimate uplift capacity of the GPA depends on its embedment ratio (length-to-diameter ratio), the relative density and elastic modulus of the surrounding soil and GPA material, the water table level, and the degree of saturation of the surrounding soil.

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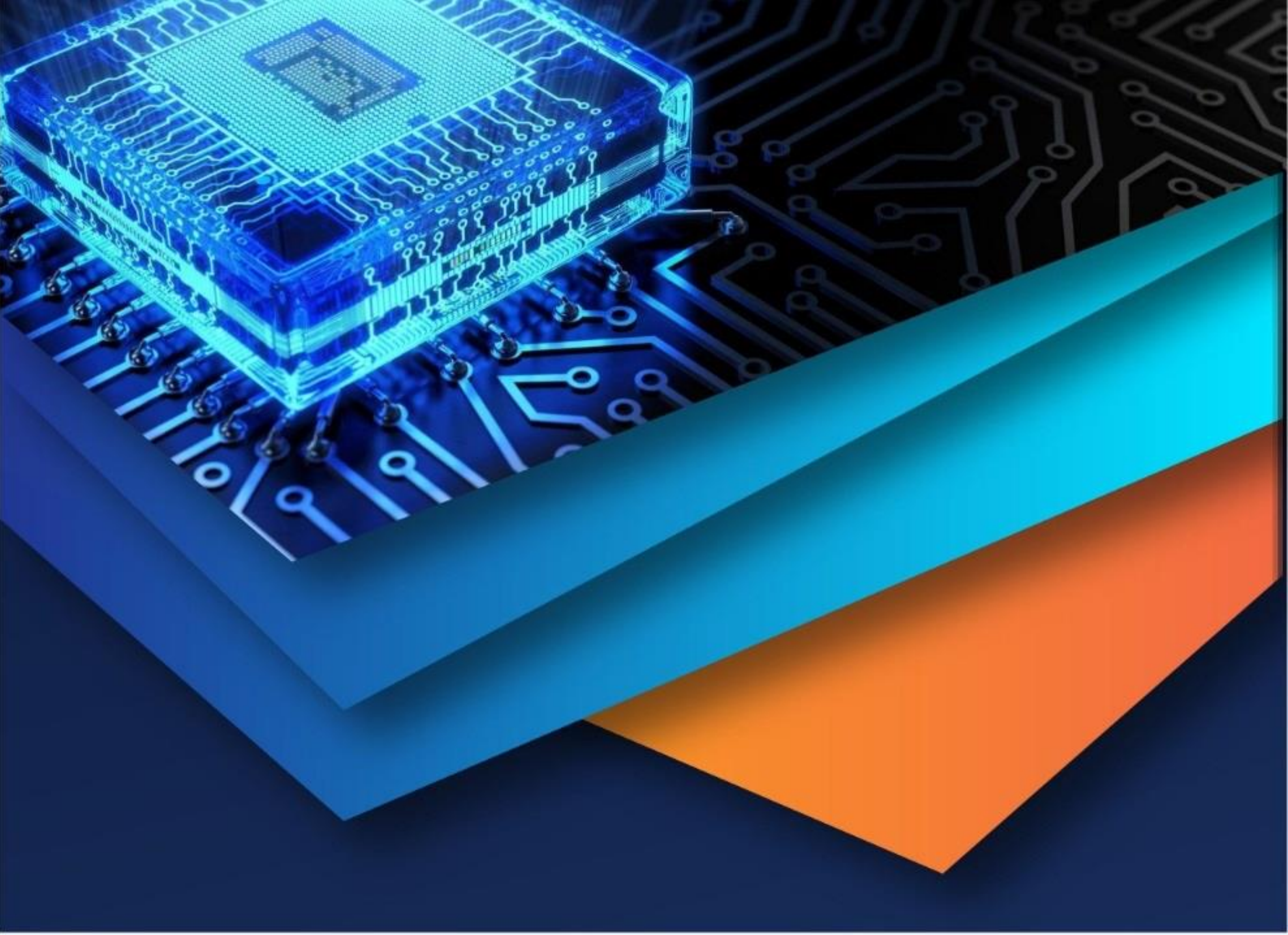

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