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Enhancement Of Uplift Capacity Of Shallow Foundation On Cohesionless Soils Using Geotextile Reinforcement

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Abstract
The uplift resistance of soil is critical in geotechnical engineering, especially for foundations subjected to upward forces induced by wind, wave action, or seismic activity. This study investigates the enhancement of uplift capacity of shallow foundations embedded in cohesionless soil, under varying moisture conditions and compaction levels. A comprehensive experimental program was conducted using woven geotextile reinforcement and a trench-anchor system. The uplift behaviour was analyzed by varying the embedment depth to footing width ratios (D_f/B = 0.5, 1, 2, 3) and relative compaction levels (65%, 80%, 95% of MDD), under dry, OMC, and submerged conditions. Results revealed a significant improvement in uplift capacity with geotextile reinforcement, particularly at higher compaction levels and embedment depths. Cohesionless soils displayed the highest uplift resistance at OMC, while submerged conditions reduced resistance, albeit mitigated by geotextiles. The study contributes valuable insights for optimizing foundation designs in uplift-critical applications, offering a cost-effective and sustainable approach to improving safety and performance in civil engineering structures.
Keywords: Shallow foundations, uplift resistance, geotextile reinforcement, trench-anchor, cohesionless soil, moisture conditions.

INTRODUCTION

The surge in global population and rapid urbanization has necessitated a significant expansion in infrastructure development [1]. For civil and geotechnical engineers, this boom presents substantial challenges, primarily due to the heterogeneity of soil strata that underpins these structures [2][3]. Foundations, acting as the crucial load-transferring component of any superstructure, must be meticulously designed to accommodate not only vertical compressive loads but also complex upward forces [4]. The proper selection and construction of foundations are influenced by a combination of factors including superstructure type, load intensity, and subsurface conditions [5][6]. In modern engineering, the demand for high-rise buildings and expansive offshore platforms has escalated [7]. These structures often face substantial uplift forces due to wind pressures, hydrostatic actions, or seismic disturbances [8][9]. Examples include transmission towers, tall chimneys, floating marine platforms, and suspension bridges, where uplift forces frequently exceed the structure's self-weight [10][11]. To counteract these forces, foundations with enhanced uplift resistance are indispensable [12]. Traditionally, solutions have involved deep foundations such as piles or innovative systems like belled piers, pyramid footings, or grillage foundations [13][14]. However, these methods often demand extensive equipment, specialized expertise, and result in increased project costs [15].A promising alternative lies in the use of soil reinforcement techniques employing geosynthetics [16]. Geotextiles, as a member of the geosynthetic family, have emerged as effective solutions for improving the mechanical behavior of soil under various loading scenarios [17][18]. These materials, predominantly made from polymers like polypropylene or polyester, offer high tensile strength, durability, and flexibility [19][20]. When introduced within soil masses, geotextiles enhance uplift resistance through mechanisms such as shear strength augmentation, load redistribution, and improved soil confinement [21]. The concept of soil reinforcement is not entirely new. Historical applications trace back to ancient civilizations [22], but it was not until the systematic studies by Henri Vidal in the 1960s that the science of reinforced earth gained significant traction [23]. Vidal's introduction of the "Terre Armee" or mechanically stabilized earth (MSE) systems revolutionized the approach to earth structures, particularly in retaining walls [24]. Since then, extensive research has explored the bearing capacity improvements achieved through soil reinforcement [25]. However, comparatively fewer studies have delved into the enhancement of uplift capacity—a critical parameter for foundations subjected to tension forces [26].

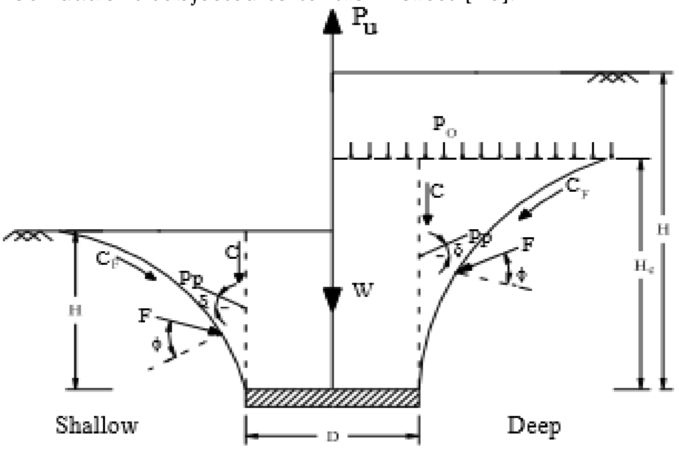


Figure 1 Shallow and Deep Anchor Under Uplift Load

Recent investigations underscore the necessity of addressing uplift resistance, especially in shallow foundations located in areas prone to high winds, waves, or seismic activities [27][28]. Shallow foundations are often preferred due to their cost-effectiveness and ease of construction, but they become vulnerable under uplift scenarios [29]. Integrating geotextile reinforcement within these foundations not only mitigates such vulnerabilities but also allows engineers to design safer and more economical systems [30]. This study builds upon these needs by examining the role of geotextile reinforcement in improving the uplift capacity of shallow foundations placed on various soil types under different moisture conditions and compaction states. It particularly focuses on the combined system of geotextiles and trench-anchoring—a novel method intended to further stabilize the reinforced soil mass. Through rigorous experimental investigations, this research aims to bridge existing knowledge gaps, providing empirical data and design insights that can guide the development of uplift-resistant foundation systems in diverse geotechnical environments [6][12][24].

LITERATURE SURVEY

The quest to enhance the uplift capacity of foundations has been an area of growing interest among geotechnical researchers [1][3]. As early as the 1930s, Marston et al. proposed models to calculate the uplift resistance of underground conduits, assuming simplistic vertical slip surfaces [5]. While pioneering, these models often conflicted with experimental observations, underscoring the complexity of uplift mechanisms [7]. Through the mid-20th century, studies by Mors (1959) and Balla (1961) offered more nuanced models, introducing failure surfaces shaped as truncated cones or circular arcs [9][11]. These approaches sought to better approximate the stress distribution in soil under uplift loads [13]. Meyerhof and Adams (1968) further refined this understanding by experimentally investigating circular and strip plate anchors in sands, identifying thresholds beyond which the breakout factor stabilized—a critical insight for designing uplift-resistant systems [14][15]. The advent of geosynthetics brought a paradigm shift. Krishnaswamy and Parashar (1994) were among the first to systematically study the impact of geosynthetics on uplift behavior [17][19]. Their work revealed that parameters such as type of geosynthetic, embedment depth, and soil density substantially influenced uplift capacity [20][21]. Subsequent studies by Mahmoud and Arash (2008) on geogrid-reinforced sandy soils demonstrated how reinforcing layers could significantly enhance bearing capacities and alter shear strain distributions [23][24].The exploration of geotextiles specifically for uplift resistance gained momentum in the 2010s [25]. Ghosh and Bera (2010) experimentally demonstrated that geotextile ties improved the uplift capacity of anchors embedded in sand, especially with optimal embedment ratios and tie configurations [27]. Similarly, Choudhary and Dash (2013) employed geocell systems, noting uplift capacity enhancements by factors up to 2.28 when combined with planar geogrids [28][29]. Recent research continues to validate and expand these findings. Shahin et al. (2017) used advanced finite element modeling to corroborate laboratory experiments, showing how geotextile positioning and anchorage conditions critically affect uplift performance [30]. Dharmesh et al. (2017) and Dasha and Choudhary (2018) extended this by exploring natural fibers like coir geotextiles, highlighting not only performance improvements but also environmental benefits [8][10]. Innovations such as grid-geotextile systems, investigated by Venkatesh et al. (2023), introduced punctured openings to optimize interlocking with soil, achieving uplift capacities comparable to traditional reinforcements with less material [12][14]. Meanwhile, Kumar et al. (2023) emphasized that geotextile placement directly above anchor plates maximized improvement, reducing required embedment depths [16][18].Despite these advances, literature identifies notable gaps [22][23]. Few studies rigorously examine the combined effects of moisture variation, compaction levels, and embedment ratios across different soil types [25][27]. Moreover, the role of trench-anchoring systems in tandem with geotextiles remains underexplored [29]. This research thus addresses these deficiencies, systematically investigating uplift behavior under controlled laboratory conditions [30]. The findings not only enrich theoretical frameworks but also provide practical guidelines for engineers seeking to design uplift-resilient foundation systems in varied geotechnical settings [2][4][6].

METHODOLOGY

The present study investigates the uplift capacity of shallow foundations on reinforced soils, focusing on material selection, experimental setup, scheme of testing, and data acquisition. The primary soil type was chosen to capture a broad spectrum of geotechnical conditions: well-graded sand (SW), classified per the Unified Soil Classification System (USCS). Soil type was characterized through comprehensive laboratory tests to determine essential properties such as grain size distribution, Atterberg limits, specific gravity, maximum dry density (MDD), and optimum moisture content (OMC). These tests were performed following IS:2720 specifications. For instance, the SW soil had an MDD of 1.82 g/cc with an OMC of 8.3% and an angle of internal friction of 38.3°. These diverse soil characteristics were selected to evaluate how geotextile reinforcement performs under varying granular and cohesive conditions, which are representative of typical field scenarios.

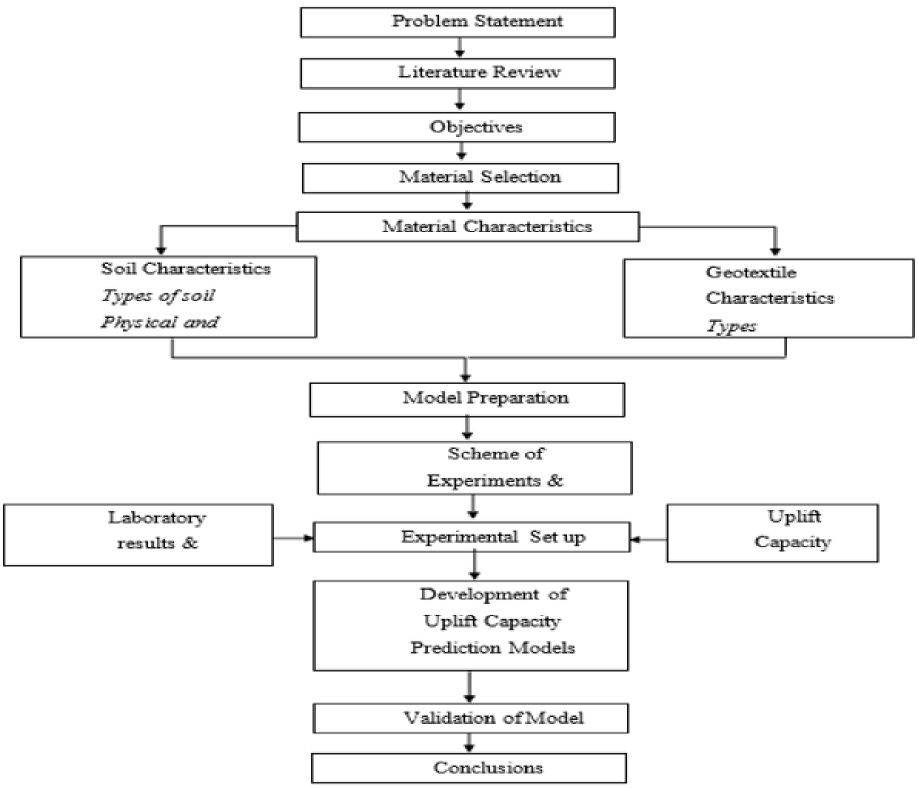


Fig 2. Proposed flow chart of study methodology

The reinforcing material employed in this research was a woven geotextile, specifically SKAPS W315. This geotextile was selected due to its high puncture resistance (533 N), burst strength (4134 kPa), tensile strength (1400 N), and moderate permeability (163 l/min/m²), which make it suitable for enhancing uplift resistance by improving shear strength, confining soil particles, and distributing loads over a larger area. The geotextile's apparent opening size (0.425 mm) was also deemed appropriate for effective soil interlock without excessive loss of fines. Prior to placement in the test bed, the geotextile was cut to a length corresponding to L/B = 5 (where B is the footing width), ensuring adequate development length to mobilize tensile forces. It was installed horizontally at a height above the footing base to achieve a placement ratio of $v/D_f = 0.3$ (where D_f is the embedment depth), which literature identifies as an effective positioning to optimize the uplift capacity in reinforced foundations. A series of laboratory model tests were conducted in a rigid steel tank of internal dimensions 500×500×600 mm. The model footing, fabricated from mild steel, measured 100×100 mm in plan area and 25 mm in thickness, with dimensions carefully chosen to minimize boundary effects (being less than one-fifth of the tank's width). The soil was placed in the tank in layers, each compacted to achieve target dry densities corresponding to 65%, 80%, and 95% of the soil's MDD, reflecting loose to dense field conditions. For tests under submerged conditions, the tank was filled with water after specimen preparation, ensuring saturation before applying uplift loads. The geotextile was anchored by trenching along two sides of the tank and backfilled to provide secure anchorage, mimicking field installations that prevent pullout during uplift loading. The experimental program was designed to systematically investigate the influence of embedment ratio (D_f/B), soil compaction, and moisture conditions on uplift capacity, both with and without geotextile reinforcement. Tests were conducted by varying the embedment depth ratios D_f/B = 0.5, 1, 2, and 3, thereby covering shallow to moderately deep foundation scenarios. For each embedment depth, tests were performed at three relative compactions (65%, 80%, and 95% of MDD) and under three moisture states: dry, at OMC, and submerged. This comprehensive matrix enabled the assessment of how soil density and water content affect the mobilization of uplift resistance and how these effects are altered by geotextile inclusion. The experimental matrix led to a total of 72 tests per soil type (36 with geotextile and 36 without), ensuring robust comparative analysis. During testing, uplift loads were applied quasi-statically using a screw-jack mechanism connected to a force gauge, at a controlled displacement rate of approximately 0.625 mm/min. This slow rate ensured that the tests reflected drained conditions, minimizing pore pressure effects, especially critical under submerged tests. Load and corresponding displacement data were recorded until failure, typically defined by a peak in the load-displacement curve followed by a sustained drop or plateau. This data was subsequently used to plot uplift load versus displacement curves, from which peak uplift capacities were determined. Additionally, uplift capacity ratios were computed to quantify the improvement due to geotextile reinforcement across different test conditions. This methodical approach, combining careful material selection, a robust laboratory setup, and a detailed scheme of experiments, provided insights into the interaction mechanisms between soil and geotextile under uplift loading. It allowed for the evaluation of how variations in embedment depth, density, and moisture condition influence the effectiveness of reinforcement. The systematic data collection of uplift load versus displacement formed the basis for deriving conclusions on the benefits of geotextile reinforcement, validating its potential to significantly enhance the uplift performance of shallow foundations across diverse soil environments.

RESULTS & DISCUSSION

The experimental investigation presented clear uplift resistance versus displacement relationships under varied conditions. Across cohesionless soil the general trend showed an initial sharp rise in uplift resistance with small displacements, followed by a peak and a gradual decline with further displacement, indicating post-peak softening. For instance, in cohesionless sand at 65% MDD and without reinforcement, uplift resistance increased steeply to peaks of approximately 3.6, 6.8, 12.6, and 19.2 kN/m² at embedment ratios (D_f/B) of 0.5, 1, 2, and 3 respectively, occurring at displacements between 3–8.5 mm. This trend consistently demonstrated that deeper embedment has provided higher uplift resistance, corroborating classical uplift theory which links greater confining soil mass to increased resistance. With geotextile reinforcement, the uplift curves became noticeably stiffer; the same conditions yielded uplift resistances of approximately 4.2, 11, 22.2, and 42 kN/m² at similar displacements, revealing enhanced load transfer and delayed failure. The sharper rise and higher peaks in reinforced cases illustrate how geotextiles mobilize greater tensile resistance, thus modifying the load-displacement behavior to Favor more resilient uplift performance.

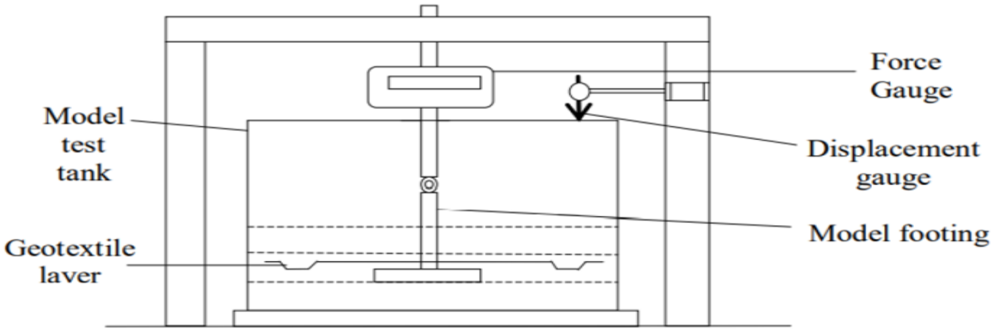
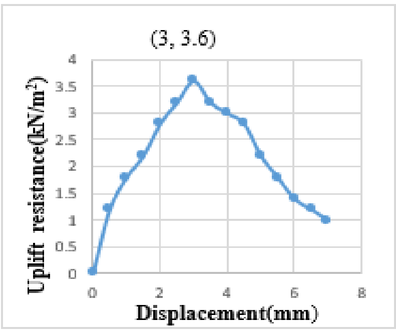
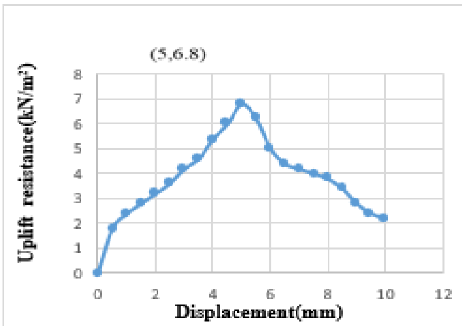


Fig 3. Schematic Representation of The Test Model

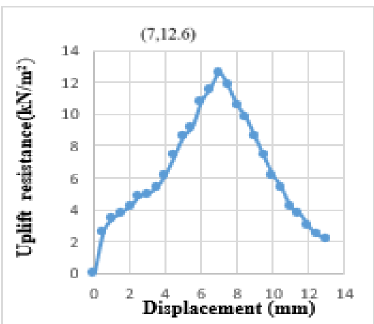
Comparisons between unreinforced and reinforced conditions unequivocally confirmed the beneficial role of geotextiles in improving uplift resistance. At 65% MDD, the uplift capacity enhancement was profound: for instance, uplift resistance improved by factors of approximately 1.17, 1.61, 1.76, and 2.18 respectively across embedment ratios from 0.5 to 3. The magnitude of improvement became even more pronounced at higher densities and embedment's, underscoring the synergy between soil compaction and reinforcement. Among all the conditions sand exhibited the highest uplift resistance due to its granular interlock, (under OMC and submerged states) showed relatively lower capacities owing to reduced shear strength under submerged condition. The geotextile layers had a notable impact across all conditions, but the degree of improvement varied: in sands, the interfacial friction and mechanical interlock were maximized, leading to uplift capacity ratios (reinforced/unreinforced) exceeding 2.5 at Df/B = 3,



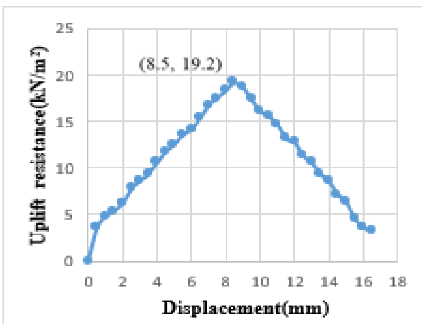
Graph for M.D.D=65%,D_f/B=0.5, without Reinforcement



Graph for M.D.D=65%,D_f/B=1, without Reinforcement



Graph for M.D.D=65%,D_f/B=2, without Reinforcement



Graph for M.D.D=65%,D_f/B=3, without Reinforcement

Fig 3. Uplift Resistance Vs Displacement Curve for Dry State with Different Dry Densities

The embedment depth to width ratio (D_f/B) was a critical parameter influencing uplift performance. As seen in the plots (e.g., Fig. 4.14), both with and without geotextiles, uplift resistance increased linearly with D_f/B, with the slope significantly steeper for reinforced cases. For example, regression lines for sand at 65% MDD yielded equations of $y = 6.19x + 0.49$ without reinforcement ($R^2 = 0.9992$) and $y = 14.77x - 4.16$ with reinforcement ($R^2 = 0.9821$), highlighting a substantial gain in uplift resistance per unit increase in embedment depth when reinforced. Moreover, increasing dry density from 65% to 95% MDD resulted in uplift resistance improvements by roughly 25-40%, owing to enhanced particle packing and frictional resistance. In submerged conditions, uplift capacities dropped by nearly 20-30% compared to dry or OMC states, yet geotextiles mitigated this reduction by maintaining interlock and providing tensile restraint, thereby sustaining higher uplift loads even under adverse moisture conditions.
A critical metric examined was the uplift capacity ratio (UCR = reinforced/unreinforced), which consistently increased with embedment and compaction, reflecting the reinforcement efficiency. For example, at $D_f/B = 3$ in sand (unreinforced) at 65% MDD, UCR approached 19.2 kN/m^2, while at $D_f/B = 3$ in sand (reinforced) at 65% MDD, UCR approached under similar conditions it was approximately 42kN/m^2. Tables summarizing these ratios across soil and densities reveal clear trends, indicating that geotextiles effectively redistributed stresses, delayed peak mobilization, and transformed local shear failures into more extended general failures, as supported by load-settlement curves showing broader peaks and larger displacements at maximum load. This shift from local wedge-type failures to more distributed bulb-shaped failure surfaces, especially at higher embedment's, demonstrates how reinforcement alters the mechanism of resistance mobilization, thereby enhancing the foundation's ability to sustain uplift without abrupt drops in resistance.

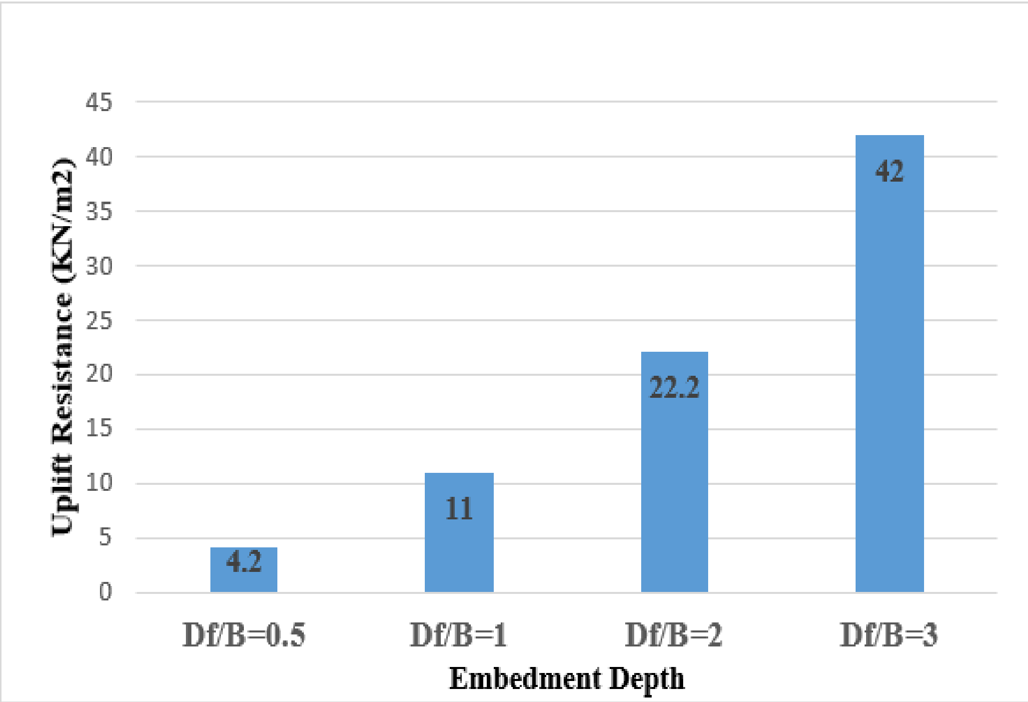


Fig 4. Bar graph for uplift resistance value for M.D. D=65%, dry condition with reinforcement
Collectively, the graphical and tabular analyses across all test series underline several practical insights. First, the effectiveness of geotextile reinforcement grows markedly with embedment ratio and compaction level, suggesting that in design practice, pairing higher D_f/B ratios with quality compaction can maximize uplift performance.

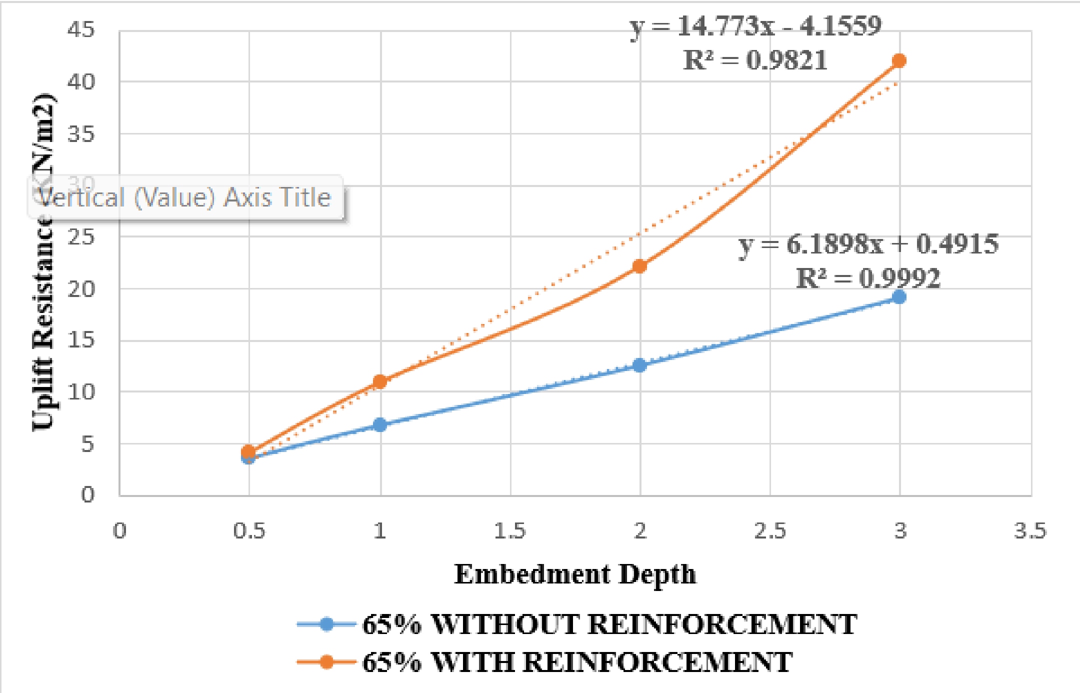


Fig 5. Linear regression graph for uplift resistance value of M.D. D=65%, dry condition with different embedment depth without and with reinforcement

Second, while all soil conditions benefitted from reinforcement, indicating that geotextile applications are particularly suited for such deposits. Third, under submerged conditions, geotextiles not only provided mechanical support but also improved the robustness of the foundation against water-induced weakening. These findings imply that for structures susceptible to uplift—such as transmission towers, pipeline anchors, and offshore platforms—incorporating geotextile layers could substantially enhance safety margins and reduce the need for overly conservative embedment depths, leading to material savings and construction efficiencies.

CONCLUSIONS

This study comprehensively investigated the uplift resistance of shallow foundations embedded in various conditions of cohesionless soils and reinforced with geotextiles. The experimental work demonstrated that incorporating geotextile reinforcement substantially enhances the uplift capacity of soils across different moisture conditions and embedment ratios. The major finding is that geotextile-reinforced soils consistently exhibited higher uplift resistance compared to unreinforced soils, with improvements becoming more pronounced at greater embedment depth-to-width ratios (D_f/B) and higher dry densities. The influence of the embedment ratio (D_f/B) was particularly notable. As D_f/B increased from 0.5 to 3, the uplift resistance improved significantly. This trend was observed across all tested conditions—sandy soils, Additionally, the benefits of geotextile reinforcement became more substantial with increasing dry density, underlining the synergistic role of soil compaction and reinforcement. At 95% of maximum dry density (MDD), uplift capacities were notably higher, reinforcing the importance of achieving proper compaction during field implementation. Moisture conditions also had a marked effect on uplift behaviour. Soil under submerged conditions showed reduced uplift capacities, emphasizing the vulnerability of foundations to elevated groundwater levels or flooding. However, even in such adverse conditions, geotextile reinforcement mitigated the loss of uplift resistance, demonstrating its robustness and adaptability in challenging environments. Thus, geotextiles not only contribute to higher uplift capacities in ideal dry conditions but also provide resilience under less favourable scenarios. From an engineering perspective, these findings have practical implications for the design of foundations subjected to uplift forces such as those experienced by transmission towers, offshore structures, and lightweight buildings exposed to wind and hydrostatic pressures. Incorporating geotextile reinforcement can lead to more economical designs by reducing required embedment depths or footing sizes while ensuring structural stability. This approach also facilitates easier and more sustainable construction practices, potentially lowering costs and environmental impact. Future work can build upon this study by exploring the performance of other geosynthetics such as geocells and comparing woven versus non-woven geotextiles to assess differences in uplift capacity enhancement. Moreover, extending investigations to full-scale field tests would provide valuable validation of laboratory-scale findings and address scale effects, enabling more confident adoption of these reinforcement techniques in diverse geotechnical projects.

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