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[†]Review Paper

Review of methods to enhance the geotechnical and structural capacity of existing footings

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ABSTRACT

Enhancing and retrofitting existing structural components is a critical process that aims to restore or improve the performance, safety, and durability of constructions. Foundations in particular can be susceptible to damage, failures, or differential settlements for a number of different reasons, including improper design parameters, lack of soil investigations, additional weights produced by story extensions, lateral loads resulting from seismic events, or changes to the structure's purposes post-construction. Thus, the need for effective and economic strengthening methods is essential. Available techniques used to increase the structural and geotechnical foundation capacity are discussed in detail in this review paper. The geotechnical underpinning techniques involve soil improvements by piling, micro-piling, grouting, helical piers, and geosynthetic reinforcements, as well as structural enhancement approaches including concrete jacketing and footing enlargement. In terms of geotechnical improvement, micropiles were found to be the most effective in enhancing and stabilizing the foundation, and helical piers were the fastest and easiest to install in the soil. On the other hand, enlarging the footing offered better load distribution and enhancement to the shear capacity.

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1. Introduction

Foundations are the most important component of the structural system, as they are designed to safely transfer and distribute loads from structural elements to the soil, ensuring long-term performance of the structure. When a foundation can no longer carry its intended loads, it must be strengthened to prevent further damage and to increase its load bearing capacity. The need for strengthening arises due to many factors, including the increase in the structural floors above the foundation, which causes the transfer of additional vertical and lateral loads to the soil , [1, 2] Fig. 1, the fundamental changes to the design or remodeling of old buildings that can alter the loads carried by foundations and often require enhancement to the structure [3], and the existence of a problematic soil under the foundation, such as an expansive soil that can exhibit rapid shrinkage, creating heaves or movements in the soil, resulting in the loss of capacity to withstand the design loads, causing damages or even partial collapse [4]. Other factors affecting the foundation failure are seismic loads caused by earthquakes that can inflict inertial forces arising from the lateral forces acting on the structure, soil degradation, liquefaction, and changes in the distribution of pore water [5]. Thus, earthquakes can inflict considerable damage, particularly on structures not designed for seismic resistance. Figure 2 shows some types of damage the structures can be susceptible to. Strengthening aims to increase the structural capacity of the footing and improve its interaction with the soil. This leads to the enhancement of the overall soil-foundation system and stabilizes it against movements such as settlement or tilting. Unlike new construction, strengthening existing foundations requires working with structures already in place, often under the effect of loads, and that can be challenging. Several geotechnical methods are available to strengthen weak or damaged foundations, such as piled underpinning using driven or sand piles, micro-piles, grouting by injecting cement slurry, jet grouting by employing a high velocity jet fluid [6].

Figure 1. Example of additional weights on a structure's foundation during reconstruction [2].

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Nomenclature

BC	Bearing Capacity (kPa)	*P*	Pressure (MPa)
B	Width (m)	*RC*	Reinforced Concrete
D	Diameter (m)	*FEM*	Finite element Method

Compaction grouting involving the process of displacing and compacting the soil, and geosynthetic reinforcement by polymer-based materials such as geogrids, geocells, or geotextile reinforcement. As well as structural enhancement approaches, including footing enlargements, that work by increasing the contact area and the depth of foundation by utilizing a concrete jacket or an overlay. Additionally, multiple researchers have adopted the use of non-displacement underpinning techniques called helical piers; they consist of steel screw piles with helical plates connected to a hollow or solid body [7]. The primary objective of this study is to provide a rigorous overview of the strengthening methods used on existing foundations.

2. Theoretical background of soil improvement techniques

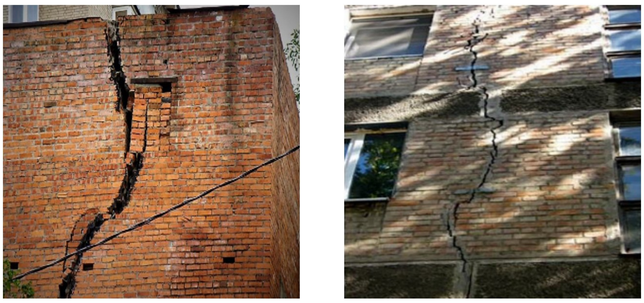
This section provides a general outlook on the theory of each technique used and their failure modes.

2.1 Pilling

It is the oldest and most well-known soil improvement method. It involves the installation of piles in the soil by jacking or drilling in order to transfer the loads to high depths, reaching better and stronger soils, and stabilizing the structure. The modeling of load transform mechanisms works by incorporating T-Z and Q-Z curves that represent the end bearing and side surface behavior, respectively, for axially loaded piles, and failure of piles includes tip bearing, side friction, and buckling [8].

2.2 Micro-pilling

Smaller diameter and more modernized variant of piles that are installed in predrilled holes bonded by grout. Although their cost is high, their smaller size and high-strength capacity make them an increasingly popular underpinning method, particularly in places where precision is essential. The load transformation theory of micro-piles is mostly by soil-grout skin friction, and due to their slenderness, the effect of end bearing is significantly lower than the skin friction [9]. The main failure modes for the micro-piles are shear and flexural failures that mostly occur near the slipping surface [10].



(a) (b)

Figure 2. Examples of some types of structural damage that occure in buildings [2].

2.3 Grouting

It involves the injection of special materials in the soil below the foundation to lower the porosity, filling the gaps and reducing the voids, which increases soil stiffness, reducing its permeability, and preventing settlements, hence improving its capacity. Various types of grouting exist, such as cement slurry grouting, jet grouting, and compaction grouting. Their theoretical behavior is affected mostly by the pressure (P) and the rate of grout pumping, as fluid theories such as Darcy's law can't be directly applied to grouts, and their failure is mainly fracture failure [11].

2.4 Geosynthetic reinforcements

Geosynthetics are polymer-based materials such as geogrids, geocells, or geotextiles used as reinforcement under the footing that interact with the soil and enhance its bearing capacity (BC) without resorting to more expensive underpinning methods. The most common theoretical approach that predicts the reinforced bearing capacity is the limit equilibrium analysis models. These models work by the concept of membrane and confining effect, while the modes of failure were observed above and between the reinforcement layers as well as punching shear mode [12].

2.5 Helical piers

Giant screw piles with helical plates connected to their bodies were installed in the soil under the foundation by screwing them in using hydraulic machines. The theoretical assessment of the helical piers depends on the bearing capacity theories, cylindrical shear predictions, and limit state analysis, with the failure modes consisting of body bending and plate bearing failure [13].

2.6 Sectional enlargement methods

These methods employ direct modification to the foundation. They work by incorporating structural approaches to enhance the foundation, most commonly by increasing its dimensions to spread loads onto a higher area. The capacity increase of these methods can be determined theoretically by using Terzaghi or Meyerhof equations that account for soil type, foundation width, depth, and shape. Their main failure types are punching shear and soil bearing failure [14].

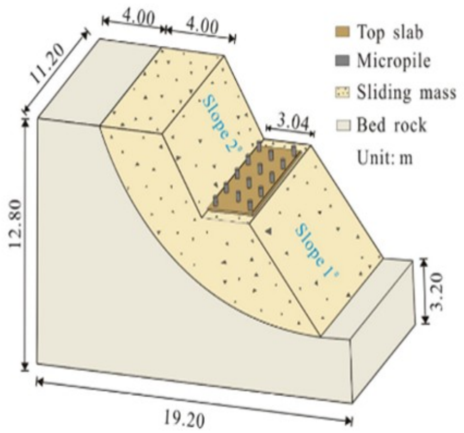
3. Literature review on enhancement methods to increase the geotechnical capacity of existing foundations

3.1 Piled underpinning

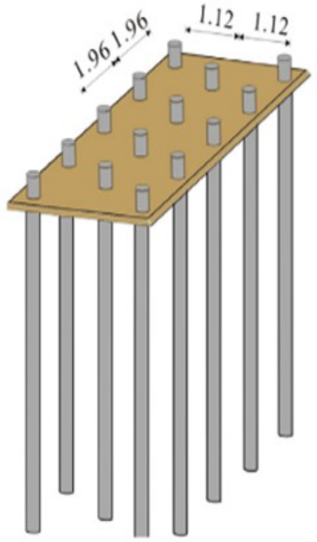
Makarchian [6] made a thorough review of the underpinning techniques, classifying them into permanent and temporary as well as minor categories, emphasizing the gained attention on piles with smaller diameters and criticizing the lack of pile designs prior to their application. In a related publication, Makarchian [15] did an experimental investigation on piled underpinning. By incorporating a laboratory test setup consisting of small footing models resting on kaolin clay soil underpinned by multiple length piles, and the test results were compared to a numerical model. He reported that employing piles resulted in reducing the soil settlement; the reduction was dependent on the length of pile used and the loading magnitude, although the development of creep was shown to affect the reliability of settlement estimation. Nazir and Azzam [16] used sandpiles to improve the soil under footing with skirting and without; the laboratory test consisted of a circular footing on clay soil with a sand bed underneath. It was reported that the capacity of footing increased with the addition of sandpiles for both cases. The skirted footing, however, had considerably better resistance to horizontal and vertical movement of soil. Samokhvalov et al. [17] performed an experimental assessment on enhancing the soil under a strip footing by making use of a widened end drill-injection pile. By analyzing the results, a 30% enhancement to the soil capacity and a 43% reduction in the settlements were observed. Polischuk and Petukhov [18] conducted a numerical analysis of the rehabilitation process of historical buildings' foundations using piles. The authors concluded that an examination of the loading, technical data, and soil condition is necessary to accurately model the foundation reconstruction. The technology of injection piles is necessary to take into account when strengthening the foundation. Although piles proved to increase the soil capacity and reduce its settlement, their disruptive installation and limited use in confined areas require additional considerations before properly employing them.

3.2 Micro-piles

Han and Ye [19] investigated the behavior of strengthening a raft foundation by incorporating micro-piles inserted in clayey soil using an in-situ test. The authors demonstrated that when adding new loads, 70-83% of the additional loads were carried by the micro-piles. Comparing their results to a loading test of a single micro-pile previously established in Han & Ye [20], it was noted that their capacity was similar. However, in the single pile test, the skin friction was higher and tip resistance was lower than in the micro-piled test. Hwang et al. [21] conducted an experimental and numerical test on the utilization of micro-piles and studied their confining effect. The use of micro-piles increased the capacity of the foundation by 1.5-2 times, and depending on soil type, their length needed to be at least 2.5-3 times the depth of failure for the effect of confining to work. It was noted that changing the angle of micro-piles contributed to extending the failure area of soil vertically or horizontally. Abbas et al. [22] demonstrated that the inclination angle and the spacing between the micro-piles have a great impact on the soil capacity. Changing the inclination angle of micro-piles by 15 ∘ is enough to improve the capacity of soil to an extent equivalent to reducing the spacing of micro-piles without increasing their numbers. Z. Li and Zhang [23] evaluated the use of centrifuge tests to model shallow foundations supported by micro-piles. The test proved the efficacy of micro-piles in capacity enhancement and settlement reduction. Due to a coupling effect between the micro-piles and the foundation, the enhancement in bearing capacity wasn't remarkable until later loading stages. El Kamash et al. [24] inspected the long-lasting behavior of micro-piles supporting a foundation on clay. The incorporation of finite element modeling allowed the prediction of consolidation for up to 60 months. Results showed that the consolidation in the long term increased the soil settlement as well as the load bearing capacity of clay due to the increase in the pore pressure dissipation in clayey soil and lowered the micro-piles' skin friction. Sun et al. [25] proposed a design procedure for micro-piles on ground slopes stabilizing. The design includes parameters such as micro-pile dimensions, spacings, and their location on the slope. A real-world application of the design proved its success in stabilizing the slope movement. N. Li et al. [26] outlined the performance of micro-piles in mitigating landslides caused by earthquakes. The authors implemented a shaking table test on a landslide model alongside a numerical simulation, see Fig. 3.



(a)



(b)

Figure 3. Accumulation landslide reinforced by micropiles: (a) dimensions of landslide model; (b) layout of micropiles [26].

3.3 Grouting

3.3.1 Cement slurry grouting

The data revealed that the micropiles underwent shear and tensile failures. Furthermore, when compared to piles or retaining walls, micropiles provided little sliding enhancement against earthquakes. Micropiles are suitable for a variety of applications due to their high capacity and smaller size, making them especially beneficial in confined and tight spaces. Although micro-piles proved to work in stabilizing slopes, limitations arise due to their inefficient lateral load resistance, particularly during seismic loads. This method involves the injection of a cementitious grout into the soil to fill the voids, creating a hardened mass that enhances its mechanical properties. Van Duc et al. [3] studied the use of cement slurry grouting for strengthening a shallow foundation on sandy clay soil. A notable improvement to the foundation capacity was observed. The length, inclination, and diameter of the grouting had an impact on the enhancement. Yao et al. [27] reported that for a sandy soil, utilizing a superfine cement slurry enhanced the strength and consolidation of the soil compared to using normal cement slurry. It was also noted that at the same w/c of superfine cement, grouted sand exhibited higher dry/wet density and cohesive strength than grouted sandy soil.

3.3.2 Jet grouting

It is the most advanced grouting technique. It works by employing a high-pressure jet grout that mixes with the soil, forming jet grouting columns and reducing the settlements. Pinto et al. [28] investigated the ground enhancement of a cruise terminal in Lisbon situated on soft alluvial mud utilizing jet grouting combined with micro piles. A full-scale loading test on the jet grouting columns confirmed the increase in the ground capacity and reduction in settlements. Although the method provided a balance between efficiency and economic sustainability, an increase in the long-term settlement was observed, leading to the adoption of a different enhancement system. Górski et al. [29] used a numerical model to estimate the enhancement of jet grouting on the settlement of foundations. Jet grouting columns with diameters of 0.5, 1 and 2 *m* were injected under a spread footing with symmetrical and asymmetrical installations. The largest central column with a diameter of 2 *m* produced the maximum settlement of 2.8 *cm*, while minimum settlement was observed in the 0.5 *m* central column, where it functioned as a micro-pile stabilizing the soil. Modoni and Bzówka [30] incorporated field inspections and theoretical analysis to develop a design procedure for foundations reinforced with jet grouting. Using a 3D numerical load-settlement model calibrated by a collection of experimental and numerical results and applied to a raft foundation with evenly spaced jet columns demonstrated a significant enhancement to the settlement and bearing capacity. The effectiveness of jet columns is governed by their optimal length and the unpredictability of column properties. Chepurnova [31] evaluated the jet grouting effect on surrounding structures. A settlement caused by nearby underpinning can be introduced in buildings called technological settlement. By integrating a numerical model, the technological settlement for jet grouting was found to be no less than 2-3 *mm*. Makowski and Polańska [32] examined field applications on the use of jet-grouting to rehabilitate old buildings. Observations show that the grouting column is highly effective in increasing the strength of granular soil compared to fine or medium sandy soil. Ground conditions, soil type, and the jet grouting technique all affect the results. Njock et al. [33] constructed a review on jet grouting methods. Data showed that the twin-fluid jet method is twice as effective as the one-fluid method. Although the effectiveness and the economics of the twin-jet method are highly dependent on the water/cement of the grout.

3.3.3 Compaction grouting

It is the process of injecting the soil with a high pressure, thick grout that works on shifting and compacting the soil without merging with it, which increases its density. Gularte et al. [34] applied a compaction grouting system to reinforce the structural foundation of the University of California that was subjected to the effect of sinkholes. The grout was injected in 81 places beneath the foundation. Steady observations found that the grout increased the density and reduced the voids in the soil, limiting the total structure movement to 3 *mm*, which was lower than the limit placed on the total allowable lift of 6.4 *mm*. Chin et al. [35] studied the employment of compaction grouting to increase the capacity of a steel tank foundation placed on a soil vulnerable to earthquake events. They discovered that the compaction grouting minimized the soil liquefaction and improved its resistance to lateral movements. The soil movement after grouting was calculated to be smaller than 15 inches (38.1 *cm*), which is lower than the expected movement of 20 $feet$ (6.1 *m*) before injecting the grout. El-Kelesh et al. [36] field-tested the performance of compaction grouting at an airport in Tokyo. Based on the findings, a critical depth that separates deep and shallow grout injection was defined, the effectiveness of compaction grouting is highly dependent on the injection depth and its sequence. Shrivastava and Zen [37] carried out a laboratory investigation on the confining and densification of compaction grouting. The formed bulb was observed to be cylindrical, and its confining effect was highly dependent on the time and bulb distance from the soil-grout interface. While densification wasn't affected by bulb distance. In another paper, Shrivastava and Zen [38] implemented a numerical model to further explore the densification and confining of compaction grouting. The value of the vertical-to-radial stress ratio was lower at greater depths but higher at shallow depths relative to the experiment. The multiple applicable grouting techniques can target a wide range of soil and foundation problems and offer low vibration during installation. While compaction and cement slurry grouting focus mainly on specific soil types, jet grouting can be used in almost all types. Although, due to the variability of grouted columns obtained, it requires skilled installations and thorough site investigations.

3.4 Geosynthetic reinforcement

El-Attar and El-Latief [39] performed a study on multiple geogrid reinforcement layers placed in a clayey soil under a square footing using experimental and numerical models. Findings confirmed that when the depth of geogrid is $1.5B$ (B is the ooting width) and the layers are $0.15B$ apart, the bearing capacity increased by 25% and the settlement was reduced by 12.6%. To reduce consolidation settlement of soil, the geogrid layers should be at least 3B long, particularly when placed at a depth exceeding $1.3B$. Dash et al. [40] analyzed the performance of strip footing on sand with geocell reinforcement. A linear pressure-settlement pattern was observed in the strip footing up to$0.5B$ of the settlement value, with 8 times higher loads than unreinforced soil. For optimal performance, the geocell reinforcement length was proposed to be $4B$, with the depth being no more than 2B. Kazi et al. [41] suggested employing wrap-around ends geotextile reinforcement in different sand densities under a strip footing. According to the author, for the dense and very dense sand cases, the wrapped-ends geotextile greatly enhanced the subgrade reaction and the bearing capacity in comparison to normal geotextile reinforcement, whereas in the medium density sand, the wrapped ends yielded no advantages. Raja and Shukla [42] showed that making use of wrap-around geosynthetic reinforcement resulted in a 45% reduction in settlements compared to unreinforced soil, relative to a 41% reduction in settlements when utilizing a double-layer planar reinforcement, with double the materials and 1.5 times the area usage. Latha and Somwanshi [43] highlighted the effect of geosynthetic reinforcement layers supporting a sand bed under a square footing through experimental and numerical analysis. The study revealed that the depth of reinforcement should be twice the footing width (B) with the ideal reinforcement spacing and width being 0.2B and 4B, respectively. [44] established a numerical and experimental method to capture the behavior of geosynthetic reinforced granular soil under a circular footing with a soft clay soil underneath. The improvement in the bearing capacity was related to the thickness of the granular soil and the number of geogrid reinforcement layers. An enhancement of 90% and 230% was noted when using 1 and 2 layers of reinforcement, respectively, when the granular fill thickness was about $0.67D$ (D is the footing diameter). Carlos et al. [45] measured the effectiveness of geosynthetic reinforcement on increasing a fine sand's strength. By incorporating laboratory testing, the data revealed that the bearing ratio increased with a decrease in the stiffness of the stress-strain system. The soil water content and the number of reinforcement layers had a major impact on the bearing ratio response. Geosynthetics provide enhanced capacity and stability to the soil. The enhancement was more noticeable in higher density soils when compared to lower density ones, as the high-density soil provides better confinement and friction between the soil and geosynthetics as well as reduced settlements.

3.5 Helical piers

Mohajerani et al. [46] conducted a review analysis on the design parameters of screw piles. Findings indicated that the optimal shape of plates is circular to increase load resistance; the main factors affecting its design are plate numbers, spacing, properties of soil, and the embedment depth. Elkasabgy and El Naggar [47] used a full-scale experimental investigation on helical piers and driven piles. The authors concluded that an 18% improvement in the capacity was obtained with a single-helical pier compared to a driven pile with the same length, whereas a double-helical pier exhibited a 45-85% increase in the load capacity. Venkatesan and Mayakrishnan [48] formulated a numerical model to predict the lateral and uplift loading conditions of a helical piled foundation situated on clay soil. The analysis confirmed that the number of helical plates and depth of embedment affected the lateral and uplift resistance of the helical pile. Figure 4 shows an illustration of the most important components of helical piers. Bian et al. [49] made use of a centrifuge test to evaluate the use of grouted helical piers for foundation underpinning. The experiment observed the formation of a grout bulb 0.6-1.9 times the diameter of the helical pile. Furthermore, the size of the bulb depended on the water/cement ratio, embedment depth, rotation of the piers, and injection pressure.

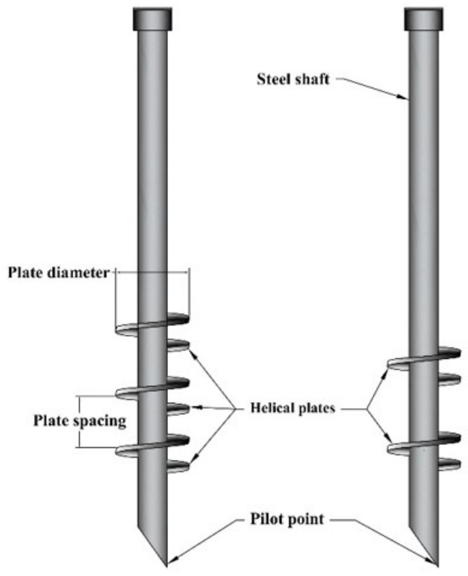


Figure 4. Layout and components of a standard helical pier used for soil strengthening.

Nagai et al. [50] investigated the influence of screw pile installation technique on its behavior. The study established that the installation method affected the residual load placement and the displacement pull-out relationship. While the pattern of the soil shear failure was cylindrical-shaped and unaffected by the installation technique. Helical piers are one of the easiest and least time-consuming methods to install; they require almost no excavation or curing, as they can be directly screwed into the soil, offering immediate effect. Although in hard or rocky soil, installation can be impaired. Other soil enhancement techniques include the use of additives to stabilize the soil. A paper by Turkane et al. [51] studied the influence of stabilizing and enhancing a high-plasticity soil using lime and fly ash additives. Results suggested that the use of these additives reduced the void ratio and compressibility of the soil, hence improving the soil bearing capacity. The authors reported that an optimum value used for fly ash was 25% which produced the best improvement.

4. Literature review of enhancement methods to increase the structural capacity of existing foundations

Fouda et al. [52] conducted an experimental study on the use of concrete jacketing connected to an isolated footing with and without dowel bars. When subjected to concentric and eccentric loads, findings showed that the jacketed footing had a similar load-carrying capacity compared to a control footing having the same dimensions. However, there were discrepancies in the contact stress distribution between the theoretical and experimental analysis. In a related paper, Fouda et al. [53] utilized numerical analysis to further assess the jacketing effect on footing. It was discovered that the contact stresses beneath the footing changed after cracking from saddle shape to parabolic, and dowels were shown to be ineffective in narrow jackets unless they were spaced 10-15 diameters apart. Moreover, the foundation without dowels displayed higher central contact stress, while the one with the dowels exhibited higher edge contact stress. Thermou and Elnashai [54] observed that seismic retrofitting of structures imposes additional loads on foundations, especially in old buildings, rendering them inadequate. Techniques like RC jacketing or footing enlargement were selected to improve the capacity and stability of the structure. Figure 5 illustrates the footing jacketing . Lu and Aboutaha [55] employed A numerical and analytical model to investigate a new strengthening method by enlarging a square isolated footing with circular prestressed concrete. Results demonstrated a significant enhancement to the punching shear strength; the increase in strength was proportional to the increase in the reinforcement ratio and the prestressing force. Strand eccentricity and notch length, on the other hand, exhibited minimal effect on the punching shear strength. Saiidi et al. [56] developed a seismic strengthening method for a bridge spread footing. It involves jacketing the column by enlarging the footing dimensions and incorporating a steel plate connection in the column-footing interface. It was found that the method enhanced the strength and ductility of the footing while minimizing its damage.

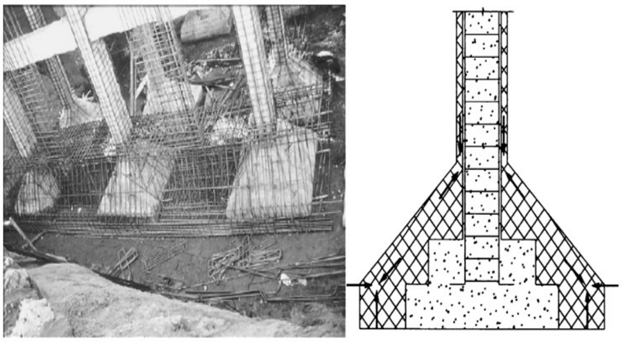


Figure 5. Strengthening of existing footings - RC jacketing [54]. (Reused after obtaining permission).

Truong et al. [57] performed several strengthening techniques to increase the punching shear capacity of isolated footings. The parameters considered consist of increasing the top or bottom reinforcement near the center of the footing, adding shear rebars, and casting high-strength concrete or fiber-reinforced concrete. The results showed that an enhancement to the shear capacity was achieved through using reinforcement or casting additional concrete near the footing center. Whereas the incorporation of shear rebars had no effect on the shear capacity of the footing. Rogers [58] discussed a case study of a building that required the addition of a new column above the foundation to assess existing footing modifications to accommodate new loads. A model of soil-foundation interaction was employed to evaluate and analyze the modifications used. It was suggested that a reinforced concrete overlay (cap) connected to the footing by shear dowels be used to enhance the capacity of the structure. Saunders et al. [59] investigated the seismic retrofitting of bridge pile foundations using various measures, including adding piles, jacketing columns, and utilizing a reinforced concrete overlay connected to the pile cap by shear dowels. The analysis determined that the concrete overlay enhanced the performance and shear capacity of the footing. In addition to that, enlarging the footing with the addition of piles resulted in overturning resistance. Another factor influencing the seismic response of the system is the structure's shape, as suggested by El-Sakhawy et al. [60], where using a finite element model (FEM), it was reported that the optimum shape of a bucket situated on clay soil is shell-shaped. Hence, it's possible to enhance existing structures by changing their shape, which can be suggested for further studies. These methods work directly on enhancing and enlarging the footing without needing heavy equipment, drilling, or deep excavations, which can be safer for old or sensitive structures. These techniques are slower and highly dependent on soil type, and they generate a lot of waste when compared to other methods.

5. Conclusion

This study included a comprehensive review of the main methods considered in enhancing the footing capacity, highlighting the importance of effective strengthening techniques in engineering practice. The analysis of the literature provided leads to the following conclusions:

- The utilization of piles proved to lower the settlement of foundations regardless of the confinement placed on the foundation, particularly when a better soil exists under a considerable depth. A widened end pile can effectively enhance the capacity and reduce the settlements.
- The efficiency of micro-piles depends on their design parameters, including their length, spacing, installation angle, and soil type. Although they are more complex compared to traditional piles, the flexibility in their installation makes them more reliable. Additionally, their smaller diameter gives them adaptability to most geotechnical problems.
- With regard to using grouting in soil under the foundation, the grouting column geometries, properties of grouting materials, soil behavior, and site condition, as well as the grouting technique used, have a significant impact on the degree of soil enhancements. The diversity in grout applications makes them useful in tackling a variety of different situations. However, certain challenges can arise due to their unpredictable nature in some soil types.
- The implication of employing structural enhancement approaches to improve the load capacity of footings through footing enlargements or jacketing works by increasing the footing area and depth, which increases its interaction area with the soil to better distribute loads. While they can be done traditionally without requiring heavy machinery, they have limited scope, are slower and depend on soil stability compared to other methods.
- The contribution of geosynthetic reinforcement to the soil-foundation enhancement is dependent on the soil type and condition, in addition to their design parameters, such as the depth of installation, length, diameter, and spacing. The use of wrap-around end geosynthetic is as highly effective as using a double-planer geosynthetic reinforcement with half the cost.
- When choosing helical piers to improve the load bearing capabilities of foundations, they perform better than driven piles with similar depth. The depth of embedment, spacing between the piers, and rotation are all factors impacting their effectiveness. Compared to other foundation enhancement methods, helical piers are unique due to their non-destructive insertion technique that doesn't require vibration or excavation, making them suitable to enhance foundations on unstable soils.
- Micro-piles can be considered the most common enhancement technique. They stand out from all other methods due to their high load capacity, wide range of applications, and their adaptability to all soil types. Although, they are high in cost and require careful design to maximize their effectiveness. While helical piers excel in their straightforward installation, speed, and waste minimization, they are however, not as effective in highly dense or rocky soils.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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