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An Over Review of Post-Grouted Piles

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ABSTRACT

Post-grouting of piles after construction becomes popular because it effectively increases axial capacity under serviceable displacements. Lately, pile construction has been utilized for several well-established deep foundation installation techniques. Piles are built with a method suitable for soil conditions, and once the concrete gets hardened, grout is injected under pressure under the pile tip. Base-grouted piles have been used successfully all over the world as they could increase axial pile capacity resulting from high tip resistance at relatively low displacements. Geotechnical specialists debate when to use post-grouting of a pile base because grouting the pile tip will cause an extra cost of pile construction. For consideration of post-grouting, the designer should estimate the load-displacement performance of both grouted and un-grouted piles to assess post-grouting as a feasible alternative. This paper summarizes the state of practice for post-grouting piles, assesses the effectiveness degree of various improvement mechanisms, and presents suggestions derived from this research.

1. Introduction

Pile foundations are widely used to support different building types under different loading conditions. In majority of cases, the construction methods are bored piles and continuous flight auger (CFA) piles [1–3].

To increase the overall pile capacity, grouting the pile tip is utilized to these methods to increase the tip resistance. Injecting grout under relatively high pressure beneath the pile tip is referred as post-grouted piles [4,5]. It has been effectively used for the past few decades all over the world. Since the early 1960s, this method has been widely applied in Asia and Europe [6–8]. However, the grouting effect on pile stability is still fully uncertain [9,10].

This paper aims to explore the different techniques of post-grouting piles and assess various mechanisms for post-grouting pile improvement. The conclusions derived in this paper include recommendations for more research to evaluate post-grouting techniques and create a more economical pile foundation system.

2. Grouting Techniques

One of the earliest applications of post-grouting for piles was recorded by Bolognesi et al. (1973) [6]. Post-grouting was carried out across some stages to enhance the pile performance for two South American bridges over the Paraná River. The sand-based piles had a diameter that varied from 1.0 to 2.0 m and a length of 75.0 m. The grouting tool consists of a basket filled with uniformly coarse gravel and two steel

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plates. A rubber sheet is attached to the end of the steel cage as shown in Fig. (1) to provide strength for the basket end. 40 holes were strategically drilled into the rubber sheet and steel plates to avoid grout backflow. The basket was made to work as a pressure chamber and a grouting chamber. As the grout filled the basket gaps, the pressure inside the basket began to build, pulling on the steel plates. The pile's weight and the lower side resistance prevented the higher plate from rising, while the soil beneath the basket prevented the lower plate from moving down.

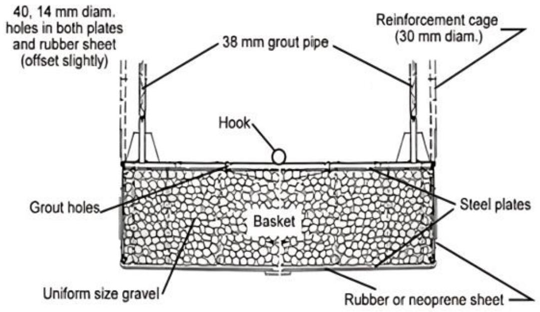

Fig.1. Grouting tool used by Bolognesi et al. (1973) [6].

Bolognesi et al. (1973) [6] mentioned that post-grouting has two main advantages. The first one is concerned with the "grout penetration" created by pile construction, which strengthens the soil near the pile tip. The second advantage is the precompression of the soil beneath the pile base, which significantly reduces settlement.

Lizzi et al. (1981) [11] proposed a grouting distribution system termed a "pre-loading cell," as shown in Fig. (2) consisting of two plates of steel spaced apart by steel mechanical spacers, as an alternative to consistent gravel. This system was fastened to the bottom of the reinforcement cage and covered with an interior canvas envelope and an impermeable PVC membrane on the outside. When pressurized grout was added, it functioned as a "flat jack with an unrestricted flow," consistently compressing the soil below the base of the pile and pushing the pile upward. Since the grout spreads smoothly throughout the pile tip, Lizzi et al. (1981) [11] assumed that the grout pressure provided a highly upward force acting on the pile tip.

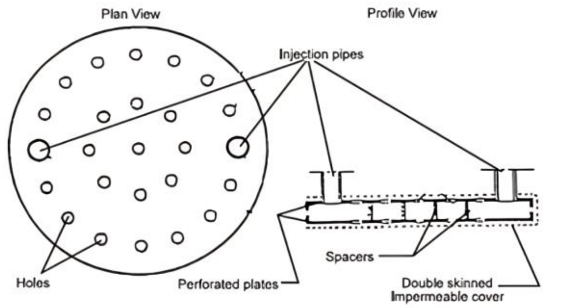

Fig.2. Grout distribution system or "Pre-loading Cell", Lizzi et al. (1981) [11].

Bolognesi et al. (1973) [6] and Lizzi et al. (1981) [11] described the "flat jack" devices. The devices have slightly different components and geometrical arrangements but typically include some form of membrane to contain the grout and/or to distribute the grout across the pile tip. Such membranes are frequently made of rubber, but geotextiles have also been used to provide separation between the concrete pile and the grout injected during post-grouting.

Sliwinski et al. (1984) [12] provided a "U-shape" grouting delivery system as an alternative to "flat jack" grouting techniques, which inject grout through holes in pipes at the pile tip as shown in Fig. (3). In this system, when the grout injection pressure overcomes the restricted force given by the rubber sleeves and surrounding soil or concrete, grout flows through the holes in the pipes and into the soil.

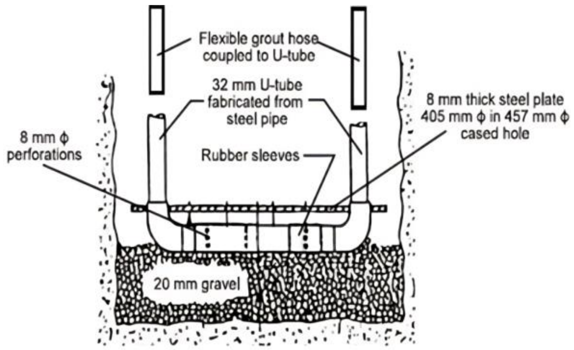

Fig.3. The “U-Shaped Grouting Cell”, Sliwinski and Fleming (1984) [12].

Lin et al. (2000) [13] detailed a sleeve-port system for grouting technique as described in Fig. (4). In this system, sleeve-port grout permits direct contact between the grout and the surrounding soil. The soil becomes more stressed as the grout is pressurized, which causes the soil to be compressed and possibly cemented. Pile's own weight and side resistance oppose upward movement, while the soil below and around the grouting device resists downward and radial movement of the grout.

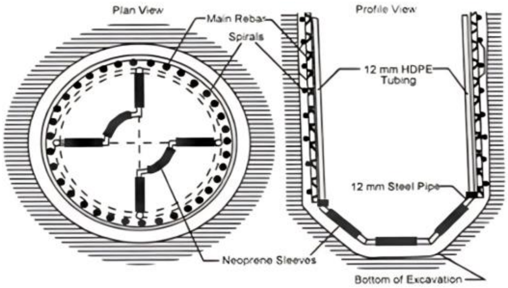

Fig.4. The sleeve-port grouting distribution system, Lin et al. (2000) [13].

Lin et al. (2000) [13] also mentioned using a high-pressure device to make a cavity under the base of the pile. Sleeve-port systems were used for the Sutong bridge pile foundation in China, Bittner et al. (2007) [14] as shown in Fig. (5a) and the Paksey bridge pile foundation in Bangladesh, Castelli et al. (2004) [15], as shown in Fig. (5b).

(a) (b)

Fig.5. Radial circuit arrangements for sleeve-port grout distribution systems at the (a) Sutong Bridge (Bittner et al., 2007) [14] and (b) Paksey Bridge (Castelli et al., 2004) [15].

Littlejohn et al. (1983) [16] described "linear" tube-á-manchette system as an alternative to the "flat jack" and sleeve-port systems, as provided in Fig. (6). In this technique, grout was injected through the system into the soil beneath the pile tip to limit the pile settlement.

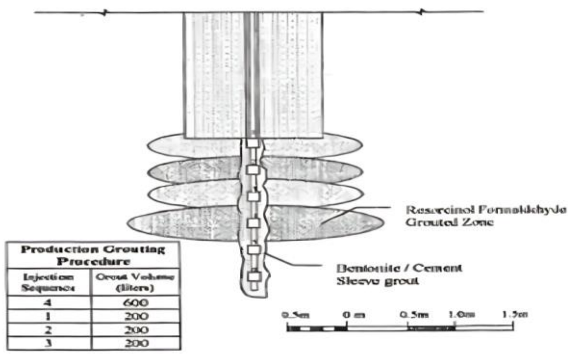

Fig.6. The "linear" tube-á-manchette system used, Littlejohn et al. (1983) [16].

Brusey (2000) [17] described a project in New York where piles were constructed by post-grouting the base and sides after drilling into sand and organic deposits. Circular grout pipes were inserted into the pile and fastened to the rebar cage without the need for a designated grouting instrumentation. Water was then pumped through the grout pipes 24 hours after the concrete was placed to fracture the concrete and provide paths for grout delivery.

3. Technical Guidelines for Post-Grouted Piles

The guidelines for designing and constructing post-grouted piles have been developed from case studies and researches.

Mullins et al. (2006) [5] presented a design method that estimates the ultimate base resistance for post-grouted piles found in cohesionless soil. The proposed method involves multiplying the tip resistance for an un-grouted pile by a tip capacity multiplier ($\boldsymbol{TCM}$) computed for the target settlement value and sustained grout pressure. The unit tip resistance for post-grouted piles is predicted as:

$$\boldsymbol{q_{p,gr} = TCM * q_p} \qquad \textbf{(1)}$$

where:

- $q_{p,\,gr}$ = Unit tip resistance for a post-grouted pile.
- TCM = “Tip Capacity Multiplier” reflecting improvement in the unit tip resistance for post-grouted piles compared to the unit tip resistance for an un-grouted pile. This parameter is taken to be a function of the maximum sustained grout pressure imposed during grouting and the displacement of the post-grouted pile.
- q_p = Unit tip resistance for an un-grouted pile.

Brown et al. (2010) [18] reported that post-grouting may be used in piles founded in sandy soil if there is sufficient side resistance able to develop the necessary grout pressure at the pile tip. Brown et al. found that post-grouting is not expected to improve base resistance for piles bearing in clay, as long as proper construction procedures and quality assurance are followed. Also, post-grouting piles is unlikely needed for pile bearing in rock because high tip resistance has already been achieved.

4. Improvement mechanisms for Post-Grouted Piles

Different mechanisms have been proposed to explain the capacity enhancement of post-grouted piles. The improvement of soil under the pile tip and pile tip enlargement are considered the most important improvement mechanisms affecting pile capacity [19]. To develop an appropriate and dependable mechanism, it is important to understand the actual performance of each mechanism in order to have the basis for conceptually assessing post-grouting in various situations and applications [19].

Loehr et al. (2017) [19] stated that during the grouting process, pre-mobilization occurs, which is only influenced by the amount of pressure created during grouting. Pre-mobilization is a result of mobilizing negative side resistance and positive tip resistance during grouting at the pile tip. Pre-mobilization has been found to have a minor effect on the ultimate axial resistance of post-grouted piles when compared to a similar un-grouted pile. It improves pile performance as it results in a "stiffer" pile response, meaning that under a given load or settlement, higher load capacities and lower settlements are attained [19].

Loehr et al. concluded that, unlike pre-mobilization, soil improvement and pile tip enlargement techniques are likely dependent on the type of soil. Post-grouted piles tipped in clean, loose granular soils are expected to exhibit much better improvement than cohesive or rock soils.

Pile side resistance could be improved by injecting grout at specified points along a pile length and around its perimeter, which is known as "side grouting" [17, 19]. Post-grouted pile performance may also be improved by the increased side resistance due to the upward flow of grout during tip grouting [17]. The pile ultimate side resistance might be also increased, due to such an unintentional occurrence of grout along its length [20]. The upward distance over which grout will flow is likely dependent on the specific grouting apparatus, the grouting process used, the fluid grout's characteristics, ground conditions, in situ stresses, the method of pile drilling, and the placement of concrete [18]. For design purposes, it is therefore commonly preferable not to consider such improvements in side resistance as it is very difficult and complex to estimate [19]. When assessing load tests carried out on post-grouted piles, increases in side resistance should be taken into consideration to prevent incorrect assessment and increase performance to other improvement mechanisms [19].

Mullins et al. (2004) [20] and Muchard et al. (2010) [21] have reported cases of unintended upward grout flow around the pile perimeter for post-grouted piles that are subject to “tip grouting”, as seen in Fig. (7) [18].

Fig.7. Post-grouted pile showing grout flowing up the side of the pile, Brown et al., (2010) [18].

Loehr et al. (2017) [19] ensured that post-grouting main objective is to increase piles overall efficiency. It is difficult to distinguish the contributions of each mechanism separately, based on the load test results [20]. According to Muchard et al. (2010) [21], depending on these improvement mechanisms and load test results, it is possible to evaluate the effectiveness and the performance of post-grouting piles, and/or create plans to enhance the consistency and dependability of post-grouted piles performance.

4.1. Soil Improvement under the Pile Tip

Post-grouting can increase the pile capacity as a result of the soil improvement under the pile tip. This improvement could come from grout penetrating the soil at the pile tip, or it could come from the densification of the soil near the pile tip [22, 23]. Improving the soil might "stiffen" the pile tip's response to loading, leading to an overall stiffer response from post-grouted piles [24].

Densification usually happens quickly in highly permeable soils (like clean sand). While, in other soil types, densification may require a longer period, depending on the soil permeability, saturation level, and duration of grout pressure application [25]. Densification usually tends to increase the strength as well as stiffness of the soil, both of which will improve post-grouted pile performance, depending on the degree and volume of densification [26].

The initial density of the soil under the base of the pile as well as the magnitude of the grout pressure and the duration of its application, all likely influence the degree of densification [27]. Logically, larger piles and higher grout pressures should result in a larger improved volume [28]. The volume of soil improvement is likely to be limited by the details of the grout delivery system, the initial soil properties and the existing in situ stresses [29].

Similar to the densification effect, grout permeation into the soil below the pile tip will strengthen and stiffen the soil, thus, improving overall post-grouted pile performance [30]. The effect of densification and permeation are qualitatively similar, as it is generally difficult to distinguish between the two operations based on load test measurements alone. Therefore, improvement due to both operations is generally considered collectively as “soil improvement” [30]. The level of soil improvement is anticipated to be greatest in loose soil and less noticeable in cohesive soils or rock [31].

4.2. Pile Tip Enlargement

The enlargement of the pile tip could improve the performance of post-grouted piles in addition to improving the soil. The ultimate tip and axial resistances of a post-grouted pile tend to increase with the enlargement of the pile tip resulted from post-grouting [32].

An enlargement of the pile tip may not result in the stiffer reaction indicated by the soil improvement technique because the larger tip area extends the stresses to a greater depth below the pile tip [33]. The degree of tip enlargement will be greatly influenced by the grout material properties, in situ stress conditions, the relative density of the soil at the pile base, and grout pressure [34].

The probability of a significant increase in the pile tip area is highest for loose soils and lowest for cohesive soils or rock [35–37]. The tip can be enlarged if the soil below the base of the pile has either become denser or the grout has penetrated through [38,39]. Despite the increased number of tested post-grouted piles, it is hard to determine, if the improvements for post-grouted piles are due to tip enlargement, soil improvement or a combination of the two mechanisms [40].

Therefore, the mechanisms for improving soil and tip enlargement are usually considered together, even though the improved performance achieved by other techniques might differ somewhat.

5. Conclusions

This paper presents a review of the research that is based on post-grouting techniques. An investigation and evaluation of post-grouting practices are presented to explain the factors contributing to the post-grouting of piles, and its techniques are summarized in Table (1).

The capacity of post-grouted piles cannot always be predicted with the same degree of accuracy as that of traditional piles during the design process. In general, the unresolved issues are the amount of accessible side and tip resistances and the degree to which the selected forecasting methods accurately represent efficiency. Although post-grouting can be used to explain that capacity or a portion of it, has been achieved, it does not reduce the uncertainty associated with capacity prediction during design. An overview and ideas for further research are given in the section that follows.

5.1. Future Research Recommendations

Several inquiries and concerns about the post-grouting of pile bases are addressed in this paper's conclusions. The study recommendations covered in this section are prioritized based on the expected influence on the post-grouting practice of each design or construction activity. They are meant to act as a basis for future investigations. To provide design and construction methods that will expand post-grouting processes, more studies and developments are required.

- Performing instrumented pile load tests to evaluate axial load distribution with depth. Such gages should be monitored throughout grouting operations and load testing to help develop a better understanding of load transfer mechanisms for post-grouted piles.
- Assessment of pile load tests for shaft grouting, base grouting, and un-grouted piles of similar size, soils, and configurations to gain results for comparison and develop a better understanding of the different mechanisms that contribute to improved performance of piles.
- Investigating pile load testing with the load-displacement reactions of the grouted and un-grouted piles simultaneously, along with comprehensive grouting records that display the properties for the grout, the grout pressure sequence, pile displacement data, and records of the axial force during the load testing and grouting.

Table 1. Summary of the main results.

Grouting Techniques		
1	Bolognesi et al. (1973) [6].	- Recorded one of the earliest applications of post-grouting for piles, which was carried out across some stages to improve pile performance. - Mentioned that post-grouting has two main advantages. The first one is concerned with the "grout penetration". The second advantage is the precompression of the soil beneath the pile base. - Described the "flat jack" devices. The devices incorporated a membrane to keep the grout in place and/or spread it evenly throughout the base of the pile.
2	Lizzi et al. (1981) [11].	- Proposed a grouting distribution system termed a "pre-loading cell". - Assumed that the grout pressure due to post-grouting provides a highly accurate approximation of the upward force acting on the pile tip. - Described the "flat jack" devices. The devices incorporated a membrane to keep the grout in place and/or spread it evenly throughout the base of the pile.
3	Sliwinski et al. (1984) [12].	- Provided a "U-shape" grouting delivery system as an alternative to "flat jack" grouting techniques.
4	Lin et al. (2000) [13].	- Detailed a system for grouting technique, which is sleeve-port grouting distribution system. - Mentioned using a high-pressure device to make a cavity under the base of the pile.
5	Bittner et al. (2007) [14].	- Mentioned using a high-pressure device to make a cavity under the base of the pile constructed for the Sutong bridge in China.
6	Castelli et al. (2004) [15].	- Mentioned using a high-pressure device to make a cavity under the base of the pile constructed for the Paksey bridge in Bangladesh.
7	Littlejohn et al. (1983) [16].	- Described one of the techniques, which is "linear" tube-á-manchette system as an alternative to the "flat jack" and sleeve-port systems.
8	Brusey (2000) [17].	- Described a project in New York where piles were constructed by post-grouting the base and sides after drilling into sand and organic deposits.
Technical Guidelines for Post-Grouted Piles		
1	Mullins et al. (2006) [5].	- Presented a design method that estimates the ultimate base resistance for post-grouted piles found in cohesionless soil.
2	Brown et al. (2010) [18].	- Reported that post-grouting may be used in piles found in sandy soil if there is enough side resistance to provide the necessary grout flow at the pile base. - Mentioned that post-grouting is not expected to improve base resistance for piles bearing in clay, as long as proper construction procedures and quality assurance are followed. - Concluded that post-grouting is unlikely to improve pile bearing in rock significantly because high tip resistance has already been reached.

Improvement Mechanisms for Post-Grouted Piles		
1	Brusey et al. (2000) [17].	- Stated that the practice of “side grouting” is a technique that specifically targets improvement in side resistance by injecting grout at discrete locations along the length and around the perimeter of a pile. - Mentioned that post-grouted pile performance may also be improved by the increased side resistance due to the upward flow of grout during tip grouting.
2	Brown et al., (2010) [18].	- Mention that, it is difficult to predict the upward distance over which grout will flow which most likely depends on the particular grouting apparatus, the grouting process used, the fluid grout's characteristics, soil conditions, in situ stresses, and the method of pile drilling. - Reported a case study, where post-grouted piles subjected to “tip grouting” cause some unanticipated occurrences, which explains some of the observed improvements.
3	Loehr, J. Erik, et al. (2017) [19].	- Stated that the improvement of soil under the pile tip and pile tip enlargement are considered the most important improvement mechanism. affecting pile capacity. - Ensured that it is important to understand the actual performance of each mechanism in order to have the basis for conceptually assessing post-grouting in various situations and applications. - Stated that when grouting occurs at the base of the pile, negative side and positive base resistances are generated, which results in pre-mobilization, which is a phenomenon that occurs in all types of soil and is only influenced by the amount of load created during grouting. - Defines pre-mobilization, which has a minor effect on the ultimate axial resistance of post-grouted piles when compared to a similar un-grouted pile. - Mentioned that pre-mobilization improves pile performance as it results in a "stiffer" pile response, meaning that under a given load or settlement, there is less deformation and more resistance is mobilized. - Concluded that, unlike pre-mobilization, soil improvement and pile tip enlargement techniques play a main role in increasing post-grouted pile capacity. - Mentioned that the mechanisms of tip enlargement and ground improvement are likely dependent on the type of soil. - Concluded that post-grouted piles tipped in clean, loose granular soils are expected to exhibit much better improvement than cohesive soils or rock. - Concluded that side resistance improved because of unexpected grout upward flow over the pile perimeter - Stated that it is commonly preferable not to consider such improvements in side resistance as it is very difficult and complex to estimate for design purposes. - Ensured that during load tests carried out on post-grouted piles, increases in side resistance should be taken into consideration to prevent incorrect assessment and increase performance to other improvement mechanisms. - Ensure that improving the total efficiency of piles is the main goal of post-grouting.
4	Mullins et al. (2004) [20].	- Recorded that, in certain case studies, when post-grouted piles were subjected to “tip grouting” only, there is some unintended upward flow of grout around the pile perimeter generated. - Mentioned that, it is difficult to distinguish the contributions of each mechanism separately, based on the load test results.

5	Muchard et al. (2010) [21].	- Stated that post-grouted piles subjected to “tip grouting” cause some unanticipated occurrences and may increase the pile's overall side resistance, which explains some of the observed improvements. - Mentioned that, it is possible to evaluate the effectiveness and the performance of post-grouting pile based on load test results and/or create plans to enhance the consistency and dependability of post-grouted pile performance.
6	Zheng et al. (2021) [22].	- Stated that, post-grouting can increase the pile capacity as a result of the soil improvement under the pile tip and this improvement could come from grout penetrating the soil at the pile tip, or it could come from the densification of the soil near the pile tip
7	Ma et al. (2021) [23].	- Ensured that, the ultimate axial resistance of post-grouted piles increased as a result of improved soil at the pile tip rather than that of an un-grouted pile.
8	Z. Zhang et al. (2021) [24].	- Mentioned that, improving the soil might "stiffen" the pile tip's response to loading, leading to an overall stiffer response from post-grouted piles.
9	Wan et al. (2020) [25].	- Stated that, densification should quickly happen in highly permeable soils (like clean sand). - Ensured that, in other soil types, densification may require a longer period, depending on the soil permeability, saturation level, and duration of grout pressure application.
10	Z. Wan et al. (2018) [26].	- Ensured that, densification usually tends to increase the strength as well as stiffness of the soil, both of which will improve post-grouted pile performance, depending on the degree and volume of densification.
11	Z. Wan et al. (2017) [27].	- Mentioned that, the initial density of the soil under the base of the pile as well as the magnitude of the grout pressure and the duration of its application, all likely influence the degree of densification.
12	Y. Tan et al. (2017) [28].	- Ensured that, for larger piles and with higher grout pressures, it should result in a larger improved volume.
13	Zheng et al. (2017) [29].	- Mentioned that, the volume of soil improvement is likely to be limited by the details of the grout delivery system, the initial soil properties and the existing in situ stresses.
14	J. Zhou et al. (2017) [30].	- Stated that, like densification, grout permeation into the soil below the pile tip will strengthen and stiffen the soil, thus, improving overall post-grouted pile performance. - Ensured that, the effect of densification and permeation are qualitatively similar, as it is generally difficult to distinguish between the two methods based on load test measurements alone and the improvement due to both sources is generally considered collectively as “soil improvement”.
15	K. Fang et al. (2014) [31].	- Ensured that, the level of soil improvement is anticipated to be greatest in loose soil and less noticeable in cohesive soils or rock.
16	M. Zhang et al. (2013) [32].	- Stated that, the enlargement of the pile tip could improve the performance of post-grouted piles in addition to improving the soil. - Ensured that, the ultimate tip and axial resistances of a post-grouted pile tend to increase with the enlargement of the pile tip resulted from post-grouting.
17	H. Youn et al. (2010) [33].	- Ensured that, the enlargement of the pile tip may not result in the stiffer reaction indicated by the soil improvement technique because the larger tip area extends the stresses to a greater depth below the pile tip.

18	Kulhawy et al. (2010) [34].	- Stated that, the degree of tip enlargement will be greatly influenced by the grout material properties, in situ stress conditions, the relative density of the soil at the pile base, and grout pressure.
19	M. Zhang et al. (2009) [35].	- Ensured that, the probability of a significant increase in the pile tip area is highest for loose soils and lowest for cohesive soils or rock.
20	Ruiz et al. (2010) [36].	- Ensured that, the probability of a significant increase in the pile tip area is highest for loose soils and lowest for cohesive soils or rock.
21	C. E. Ho (2003) [37].	- Ensured that, the probability of a significant increase in the pile tip area is highest for loose soils and lowest for cohesive soils or rock.
22	Mullins et al. (2000) [38].	- Mentioned that, the tip can be enlarged if the soil below the base of the pile has either become denser or the grout has penetrated through.
23	Kulhawy et al. (1991) [39].	- Mentioned that, the tip can be enlarged if the soil below the base of the pile has either become denser or the grout has penetrated through.
24	Gouvenot et al. (1975) [40].	- Mentioned that, due to the increased number of tested post-grouted piles, it is hard to determine, if the improvements for post-grouted piles are due to tip enlargement, soil improvement or a combination of the two mechanisms.

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