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Sandy Soils Improvement in Brazil

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Abstract

Designing geotechnical projects requires greater attention due to the importance of sustaining the building and transmission of loads to the ground. In this way, geotechnologies have been developed toward guaranteeing security and lowering cost for a building, as some methods of soil improvement to make shallow foundations feasible. The objective of this work is to present selected methods of sandy soils improvement in Northeastern Brazil, verifying the most common compaction columns in the region. Furthermore, this work demonstrates the technical feasibility of a new method of compacting sandy soils: terra-probe without material introduction. As a result of applying this technique, the treated massif obtained an increase in resistance and, consequently, an increase in its load capacity, as well as reduced the foundations settlements significantly.

Keywords: Soil improvement; Compaction Columns; Terra-probe.

1. Introduction

Soil is considered an element with the purpose of supporting a structure, making the understanding of its characteristics and properties an essential part of foundation projects. Because of the high diversification of the subsoil in regions of the world, it is necessary to give due importance to geotechnical prospecting, for foundation projects and to laboratory tests on soil samples, field tests, and load tests. Several research works have been developed in the last decades regarding the superficial sandy layers. Generally, these deposits have medium to fine granulometry with variable depth and a state of soft to little compressed. Therefore, these layers have been considered appropriate for the execution of soil improvement with compaction columns, increasing the resistance to the penetration of the soil and reducing its level of deformability. Soil improvement means the densification of the soil by dynamic methods, which depend on the transmission of energy to the soil, and it can be divided into two categories: impact compaction and vibration compaction [1]. Some soil improvement methods use the impact to compact the massif, using equipments like the pile driving.

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Those techniques necessarily perform the injection of material on the ground. However, there is another method that uses only the vibration as compaction, with or without introducing material in the soil. There are several factors responsible for choosing the foundation of a construction. When the relation between the applied load and the permissible soil tension is very high, the use of the shallow foundation may not be viable [2]. One suitable solution would be to increase the load capacity of the soil through compaction columns. The choice of the land improvement technique can be determined according to the soil granulometry for a given situation. The most used method in the Northeast of Brazil is by compaction columns, which are restricted to sandy soils because when the soil exhibits a number of fines that exceeds 20% to 25%, the soil compaction methods become less efficient [3,4,5]. The operation principle of the compaction columns is in the displacement of the natural soil, through the introduction in localized points, reducing the settlements and increasing the load capacity of the treated land [6]. Implementing the improvement on the surface layer through compaction columns, can make shallow foundations feasible and significantly reduce foundation costs [7]. The author in [7] pointed out that foundations in Northeast Brazil are driven by the geological and geotechnical characteristics of the subsoil, although other factors influence the choice. The soil improvement technique using compaction columns is widely used in cities like Recife, João Pessoa, Natal and Aracaju. The general objective of this work was to present selected methods of improvement of sandy soils by compaction columns. In addition, was evaluated the efficiency and effects of the new terra-probe technique without material introduction, which showed to be superior to the other methods for a given initial soil resistance.

2. Standard penetration test (SPT)

Standard Penetration Test (SPT) is the most common geotechnical investigation process employed in most countries. It constitutes a measure of dynamic resistance combined with a simple recognition test. According to the author in [8], the executive SPT process can be divided into two stages: one for drilling and the other for sampling/testing. In the first stage, drilling is realized with an auger or washing burr with the aid of water circulation or bentonitic mud. In the second stage, the standard sampler is introduced, initiating the sampling test, which consists of three consecutive measures of blows necessary to drive 15 cm segments to a total of 45 cm. The blows are performed by free fall using a weight of 65 kg, falling to a height of 75 cm. The result of the penetration resistance index (N-value) is the sum of the 2nd and 3rd measurements, that is, the number of blows needed to introduce the last 30 cm of the sampler. The authors in [9] states that the SPT is the most common resource for evaluating the conditions of compaction of sandy soils in situ. The important aspects provided by the standard penetration test are: obtaining the sample, penetration resistance index (N-value) at each meter, and observing the water table level. The samples can be used for laboratory tests such as natural humidity, plasticity limit, liquidity limit, granulometry, and organic matter content [8]. Typically, comparisons of SPT results are made before and after soil improvement. To establish the type of foundation for any project, it is necessary to investigate the properties of the soil. Likewise, due to the specificities of the terrain acquired by SPT, it is decided whether or not to use the soil improvement technique by compaction columns to make shallow foundations feasible.

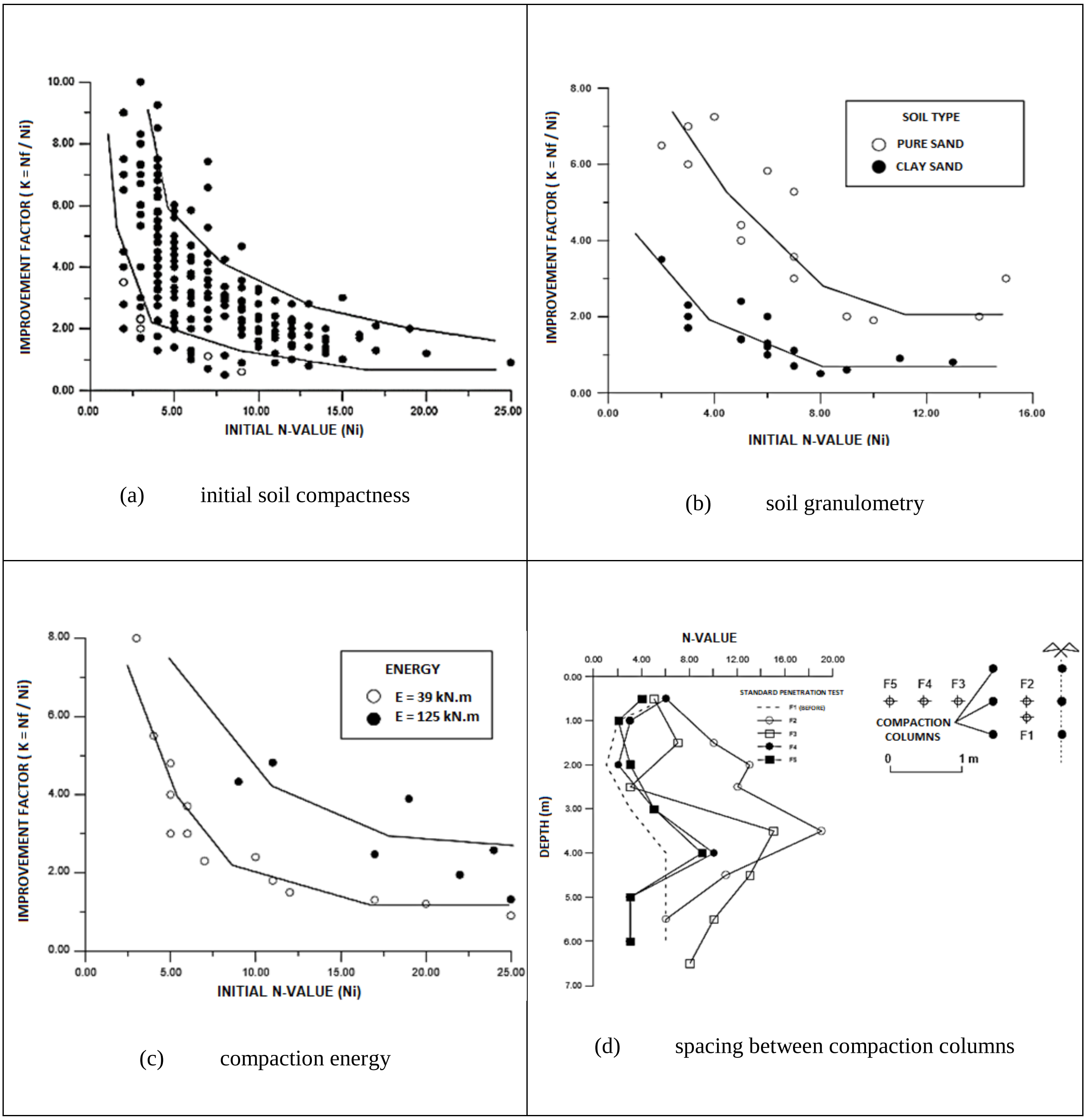
3. Influencing factors in soil improvement by compaction columns

There are some factors that affect the efficiency of soil improvement with compaction columns, as the initial soil compactness, granulometry, compaction energy, and spacing between columns. It is noteworthy that the initial soil compactness is determined by its index of resistance to penetration (N-value). According to the author in [10], another important factor, is related to the minimum depth from which the effects of the compaction columns appear. For depths up to 1,50 m, the improvement effect is negligible, that is, no efficient compaction of the surface layer of the terrain. The increase in soil resistance can be evaluated by the improvement factor, which is a constant defined by the relation between the final N-value (Nf) and the initial N-value (Ni), shown in Equation (1). It is worth mentioning that the larger the improvement factor (K), the greater the efficiency of the compaction technique.

$$K = Nf / Ni \qquad (1)$$

The Figure 1 shows the graphs of influencing factors in the technique of compaction columns: (a) initial soil compactness, (b) soil granulometry, (c) compaction energy and (d) spacing columns.

Regarding the initial soil compactness (Figure 1a), the author in [11] states that the load capacity of soft sandy soils can double after improvement with compaction column. Also, according to the author, when the soil is already dense, the execution of the columns promotes an opposite effect, there is a decrease in compactness and elevation of the ground level. In this case, the soil improvement factor decreases as the initial compactness rise. The presence of a fraction of fines in the soil to be compacted develops a reaction to the vibrations imposed, besides the increase in soil permeability [12]. The improvement efficiency is reduced because it generates a greater damping effect on fine soils over induced horizontal vibrations. The author in [4] experimentally demonstrated that when the number of fines exceeds 20% to 25%, the vibro-compaction become inefficient since the vibrations imposed on the ground are more effective in granular soils, as shown in Figure 1b. Another important factor in the efficiency of the technique is the equipment's compaction energy (Figure 1c). The compaction energy is directly proportional to the improvement efficiency. However, there is a limit of soil compaction, after which the soil compaction energy no longer influences the compaction column technique. Figure 1d curves show that the execution of a column provides soil compaction with a radius of influence of 2,0 to 2,5 times the diameter. In sandy soils, the deformation process takes place under drained conditions with a reduction in the volume of voids in the soil equal to the volume of the column, with the reduction of voids being maximum near the column, decreasing with the detachment from the axis, until it is null [13]. The author, also, stated that the deformations were predominantly horizontal, except for the regions close to the top and bottom.



(a) initial soil compactness

(b) soil granulometry

(c) compaction energy

(d) spacing between compaction columns

Figure 1: Influencing factors in soil improvement by compaction columns [12]

4. Compaction Column: Vibro-displacement

In underdeveloped countries, especially India and Brazil, a technique has been made in which the granular columns are executed by pile driving equipment. In this method, as the name suggests, the lateral displacement of the natural soil is caused by the insertion of a closed-end pipe. According to the authors [14], in the Northeast of Brazil, the vibro-displacement method has been used since the 1950s, with satisfactory results. Granular columns are widely used in foundation projects in the Northeast, when the objective is to densify sandy soil. In the specific case of sandy soils, the increase in the compactness of the massif, due to the compaction with columns of sand and gravel, gives the improved layer a great rigidity, ensuring better stability to the shallow foundation [6]. According to the authors in [2], this type of column is suitable for sand with good granulometry, without many fines. The author in [3], in turn, proposed an ideal range for the improvement by vibration, characterized by a percentage of fines less than 20%. The construction process of the granular column is initiated by the positioning of the coating tube and the formation of the soil plug at its base (bushing). The tube is dynamically inserted by repeated impacts from strikes of the pestle on the bushing to the design depth. Then, the bushing is removed and the granular material is added that will be compacted by the free fall of the pestle. Simultaneously with the introduction of the material, the tube is removed, reaching maximum densification and finishing the compaction column. During the insertion of the column, the location controls depth reached, equipment and energy used, pipe driving diagram, amount of material needed in the base and shaft must be performed [12]. The demonstration of the executive process of improving the land by columns of sand and gravel is shown in Figure 2.

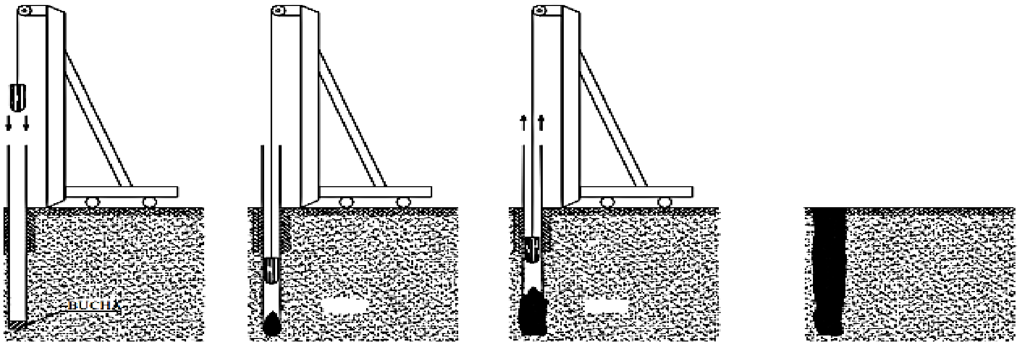


Figure 2: Executive process by columns of sand and gravel [15]

The author in [16] says that the densification of the soil is achieved due to the displacement of the material on the ground with a volume equal to that of the column and, also, to the effects of vibration resulting from the executive process. In addition to these causes, the introduction of compacted material on the ground [7]. After the execution of the granular columns, a control must be accomplished through a standard penetration test to verify the increase in soil resistance due to the execution of this technique.

5. Methodology

The methodology of this research consisted of the compilation of several theoretical references, from the oldest to the most recent ones, about the terra-probe technique that started to be used in the United States and expanded to the Northeast of Brazil. In addition, was analyzed the evolution of this method in previous case study [17], which verified the progress of the terra-probe technique without the introduction of material on the ground. The soil improvement was analyzed in this case study from the geotechnical point of view with the increase in soil resistance was verified by the standard penetration tests (SPT) performed. Furthermore, a comparative study of the soil was made [17] based on the obtained results of SPT before and after the execution of the terra-probe technique, developing the improvement factor (K) to analyze the optimization of the soil. Accordingly, was prepared an initial N-value graph as a function of the improvement factor (K) to investigate the influence of the initial soil compactness in the execution of the method, also structuring a diagram that evaluates the method statistically. The author [17] produced graphs relating the results obtained by the terra-probe research without material introduction to the diagrams developed by the authors in [18], between the conventional compaction columns and a traditional terra-probe. Therefore, based on the diagrams in this research, it was possible to compare the three methods, verifying the most satisfactory one.

6. Results

6.1. Terra-probe

It consists of a method of soil compaction that uses as main tools a vibrator and a tube of a specific diameter, which, through vertical vibrations, introduces the tube into the ground to densify the soil [10]. According to the authors in [1], the employment of the vibration process in compaction has significant benefits. Around the 1970s, in the United States, a technique for executing compaction columns, called Terra-Probe, was initiated. This method has been used for the past 10 years in the Metropolitan Region of Recife for geotechnical land improvement projects [19]. In the United States, this technique is performed using a metal tube approximately 0.75 m in diameter and 15 meters high, connected to a vibrator, often with a frequency of 15 Hz [20]. The terra-probe method performed at high frequency it is used to stabilize geotechnical conditions. The conventional executive method of terra-probe proceeds with the introduction of a metal tube into the ground using the vibrator attached to the hydraulic excavator arm. The vibration imposes vertical impulses on the tube that make it penetrate the soft sand. Water jets are used initially to aid penetration but are interrupted during compaction. This execution process becomes more effective in saturated sands since it does not use water injection during the process. The improved material is introduced at the top of the metal tube, then the procedure is completed by removing the tube with vibration, leaving the compacted material on the ground. The spacing between the columns is 0.80 m to 0.90 m, depending on the required compaction. Wrongly, it is assumed that in the case of the introduction of the pipe vertically, there will only be vertical vibrations transmitted to the ground. However, horizontal movements also occur, due to the shear waves emitted in the vertical penetration. Horizontal vibrations are caused by friction between the metal tube and the ground during insertion, adding lateral pressure to the ground [1]. In order to assess the efficiency of the soil improvement technique by terra-probe, the authors in [18] developed a diagram showing the improvement factor (K) for this method, based on the standard penetration tests. Despite being a process with higher productivity, the soil compaction efficiency decreases as the value of the initial soil compactness increases. The diagram showing the influence of the initial soil resistance on the improvement factor of this technique is shown in Figure 3.

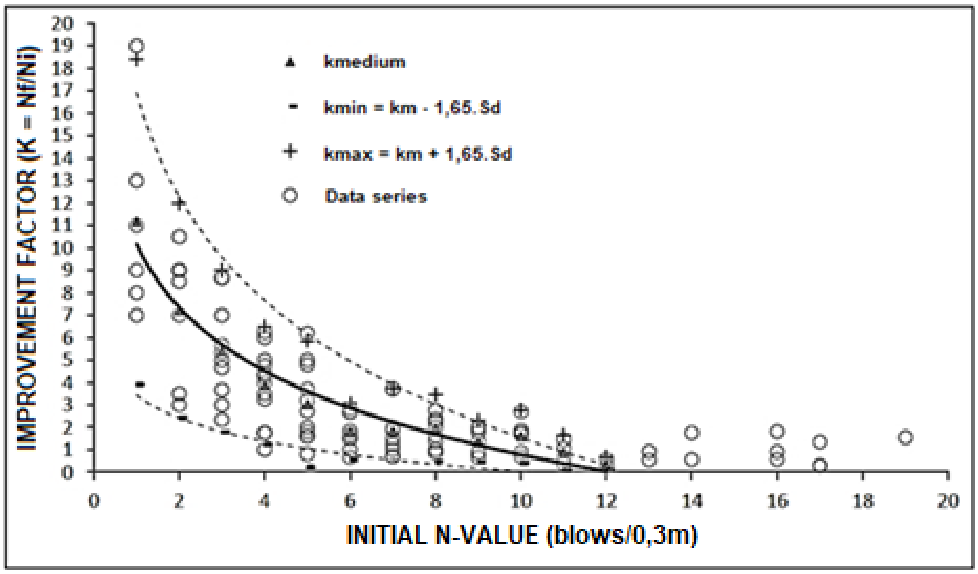


Figure 3: Influence of the initial compactness of the soil for the terra-probe technique [18]

In the graph prepared by the authors, the traditional terra-probe technique is efficient for an initial soil resistance of 0.9 blows/0.3 m. Therefore, the method proves to be efficient for soft or less compact sandy soils. According to the author in [10], to verify a good compaction performance by the terra-probe method, a series of tests must be performed before and after the execution. Generally, the standard penetration test (SPT) is the most used test to obtain the initial relative densities, establishing the criteria of densification of the terrain and proving that the desired density has been reached. For monitoring the compaction control, it is recommended that the results of the SPT before and after the improvement are compared in the same diagram, analyzing the resistance of the soil as a function of depth, to verify if the compaction of the soil was enough. Despite the large amount of information about the N-value before and after the improvement, there is little data available for an analysis of the work's performance, such as plate tests and settlement measurement, making it difficult to a greater understanding of the effects of soil improvement [12].

6.2. Terra-probe without material introduction

The terra-probe method without material introduction was analyzed as a result of the recent application in Northeastern Brazil. The executive process of this technique is similar to the original process with material introduction. It consists of introduce a hollow metal tube with an open-end pipe using the vibrator attached to the hydraulic excavator arm. It was verified that all processes of this technique, such as driving and removing the metal tube, are performed with the action of vibration in the soil, without injection of water or improved material. Figure 4 shows the introduction of the pipe over the superficial layers of the sandy soil of the project under study.

Figure 4: Insertion of the tube using terra-probe method without material introduction [17]

A schematic drawing of the introduction of the hollow metal tube by the terra-probe method without material introduction was elaborated. The schematic representation of this technique is shown in Figure 5.

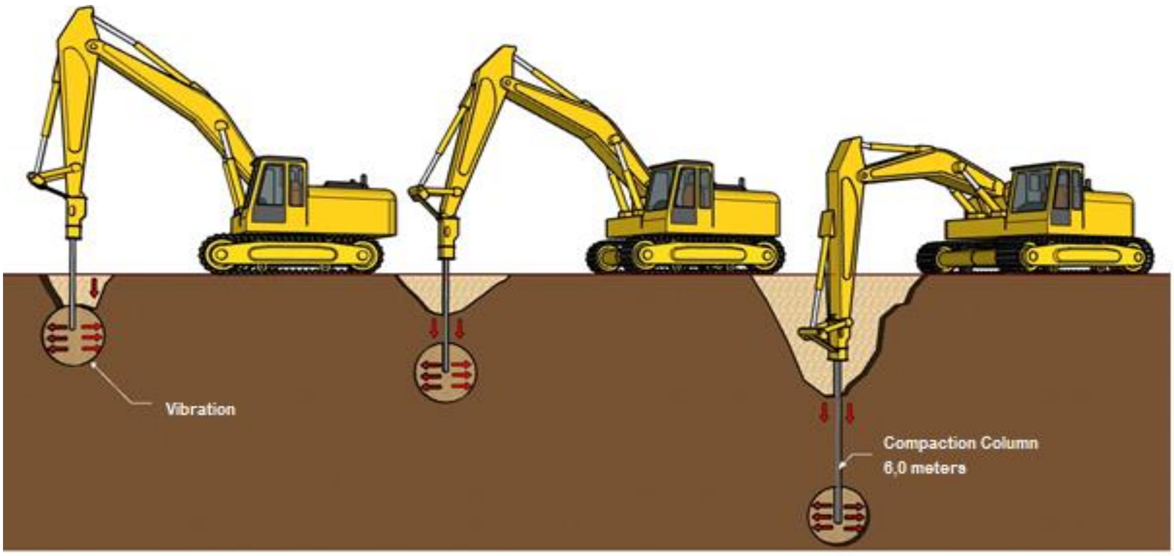


Figure 5: Schematic drawing of the execution of the terra-probe without introduction of material [17]

The gain of soil resistance from the technique arises through the basic mechanical compaction process with respect to the vibrations transmitted to the soil, causing a horizontal movement with frequency equivalent to the hydraulic vibrator and variable amplitude according to its power. The horizontal movements generated during the piping of the tube are caused by friction between the metallic tube and the soil, adding lateral pressure to the ground. The improvement of the soil by terra-probe allows an increase in the workability of the terrain, reducing the excavation and concrete volumes of the projected foundations. In this way, this technique reproduces an energy balance in the soil that generates the rearrangement of the particles, with a consequent decrease in the index of voids in the soil, without requiring the introduction of improved material [17]. The study [17] showed that after the introduction of the compaction columns, it was observed a settlement of approximately 0.50 meters, attributed to the volume of voids contained in the soil before the improvement. It is noteworthy that this settlement proves the reduction of the soil void index, since in the methods with introduction of material into the soil, there is an increase in the ground level, due to the injection of the material itself. Based on the data collected through the monitoring of standard penetration test and the development of the improvement factor (K), a diagram was elaborated by the author in [17] to analyze the influence of the initial compactness of the soil on the improvement factor by the terra-probe technique without material introduction. Figure 6 presents the mentioned graphic.

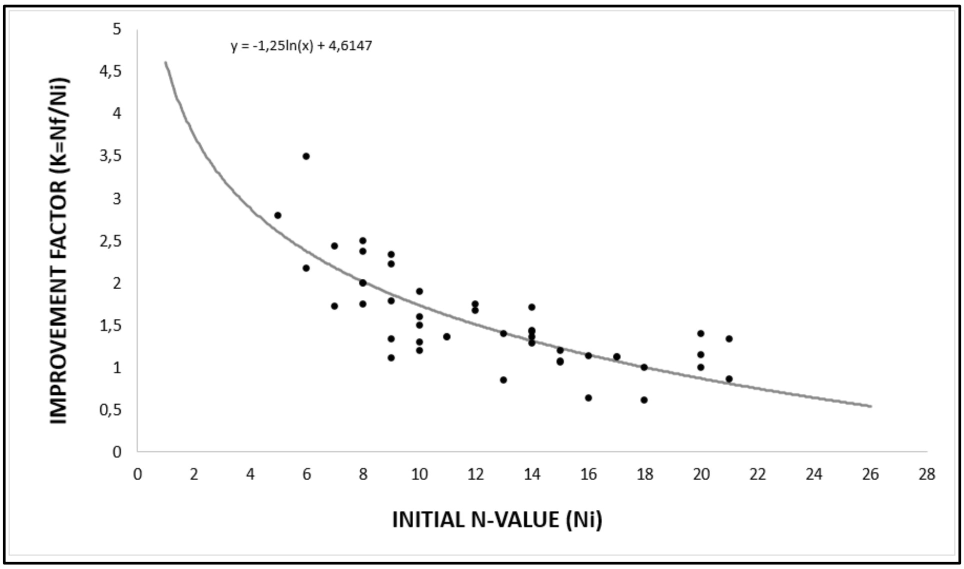


Figure 6: Influence of the initial compactness of the soil on the efficiency of the terra-probe technique without material introduction [17]

According to Figure 6, it was possible to observe the influence of the initial compactness of the soil, since the improvement factor decreased as the initial N-value increased. Therefore, the technique was efficient for soils with initial compactness until 19 blows/0.3 m, reaching sandy soils designated as soft, little compact and medium compact. Thus, the terra-probe technique without material introduction was more effective for low initial values of resistance to soil penetration. As a function of the values acquired with the execution of SPTs on the soil of the study [17], before and after the compaction of the land, it was observed that the growth of resistance to soil penetration was equivalent to 82.37%. However, it was verified that one region presented a lower carrying capacity, lacking a reinforcement in the improvement. Thus, the average increase in the soil resistance index (N-value) after the reinforcement corresponded to 30.59%.

6.3. Comparison between compaction columns methods

According to the exposed results of the soil improvement factor (K), a comparison was made between vibro-displacement, the original terra-probe, and the terra-probe without material introduction. Table 1 summarizes the differences between each method.

Table 1: Comparison between methods. Adapted from [17]

COMPACTION COLUMNS			
Column Type	Vibro-displacement (Sand and Gravel)	Terra-probe (stone powder)	Terra-Probe (without material introduction)
Equipment	Pile Driving Equipment	Vibrating Hammer	Vibrating Hammer
Diameter	300 to 400mm	301 to 400 mm	280 to 400 mm
Usual Length	4 to 6 m	5 to 6 m	5 to 6 m
Materials	Coarse sand and gravel 50 mm (trace 3:1)	Stone powder and gravel 50mm ou 75mm (trace 3:1)	-
Mesh spacing	90 to 110cm	80 cm	80 to 90 cm
Productivity	30 to 90m/day	266,4 to 349,4 m/day	300 to 420 m/day

The conventional technique and the original terra-probe perform the introduction of material on the soil, with the exception of the terra-probe in this study. Another important issue is productivity since the terra-probe method without material introduction has productivity exceeding the other methods. The author in [17] created a graph comparing the productivity between the methods, shown in Figure 7.

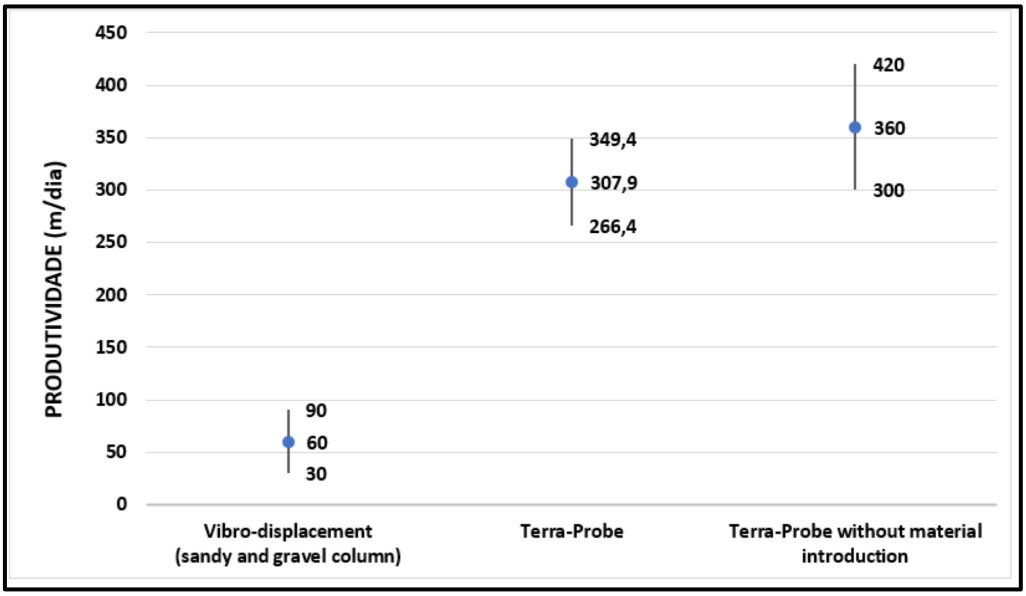


Figure 7: Comparison of productivity between methods [17]

It is noteworthy that the productivity of the terra-probe technique without introducing material was measured by the maximum and minimum value of the execution of columns per day. The days when the equipment failed due to the high energy imposed on the land were disregarded. Based on the comparative graph prepared by the authors in [18], between the traditional compaction columns and the original terra-probe, a new diagram was developed by the author [17], adding the data obtained by the research on terra-probe without material introduction, seen in Figure 8.

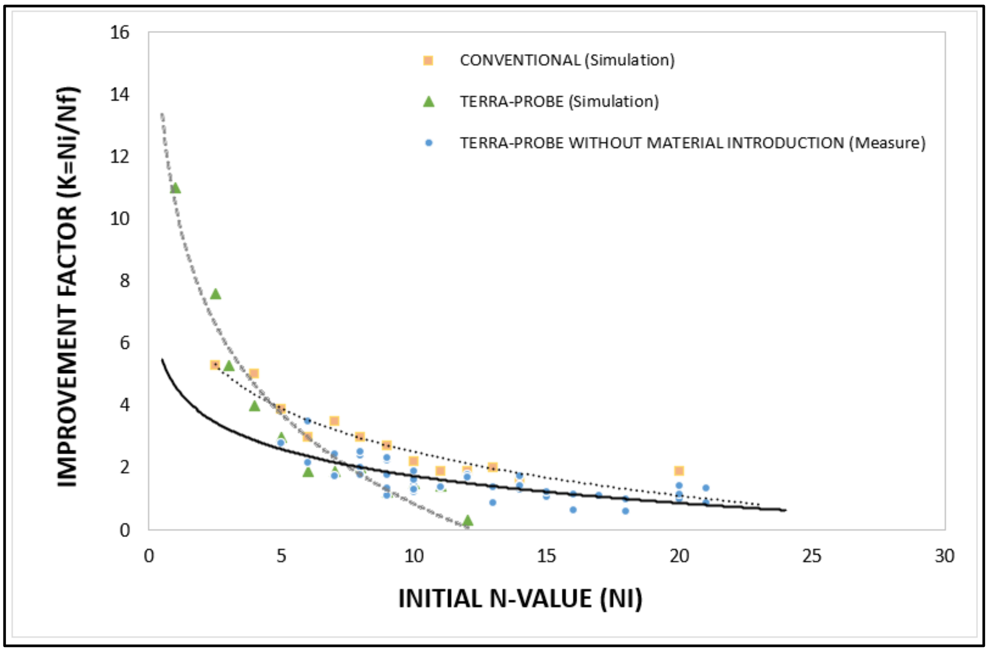


Figure 8: Comparative diagram between compaction columns [17]

It can be seen in Figure 8 that the traditional terra-probe method is more efficient in soils with low initial compactness. However, the database for the traditional terra-probe used by the authors was limited at that time, since this technique was a novelty in the Metropolitan Region of Recife. On the contrary, nowadays, this method has been used in abundance in the region, offering a more significant database. Therefore, due to the greater application of the technique in the region, there is, consequently, a better execution process and better training of the activity. Thus, it is clear that the original terra-probe method has improved over the past few years. This improvement made it possible to use this technique without depositing the material, as seen in the present study. For this study case, the evolution of this method - without introduction of material - is more effective in larger initial compactness, presenting results close to the conventional method of sand and gravel. In addition to the exposed, [17] prepared a diagram with soil resistances as a function of depth, shown in Figure 9. The graph was structured with the results obtained by investigating the terra-probe without material introduction and simulating the other compaction columns by the study from the authors in [18].

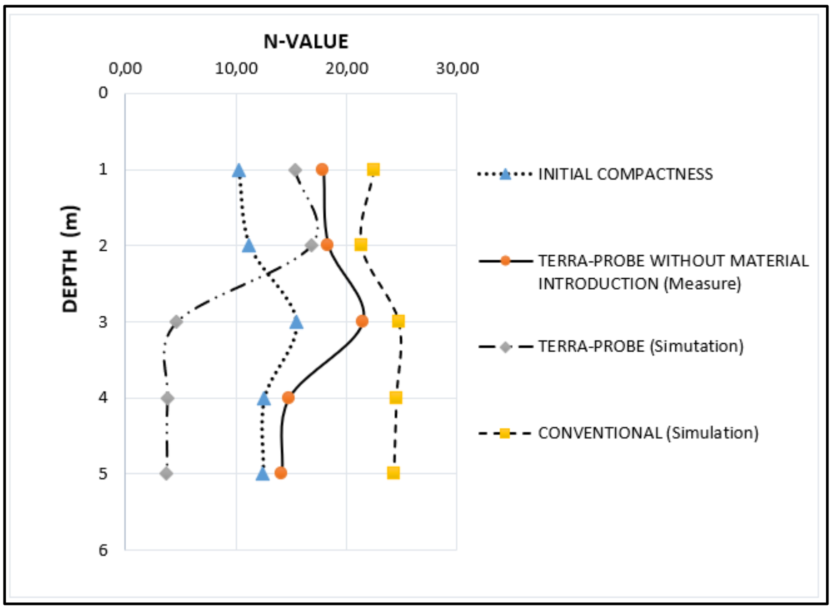


Figure 9: Comparison between traditional compaction columns and terra-probe without material introduction depending on depth [17]

Figure 9 presents the results of applying the compaction column methods to a natural soil studied, with relatively high initial compactness. The original terra-probe method is not so efficient because it is enhanced with high initial compactness values, causing an opposite effect, because it generates a softening in places where the sands are compact or very compact. It is noteworthy that at the time, the authors [18] did not have a significant database during the preparation of this study. Furthermore, the author in [17] also performed a statistical analysis that certified the importance of the initial resistance of the soil for this method. The graph was elaborated investigating the maximum and minimum improvement factor for each N-value with a 95% confidence level, shown in Figure 10.

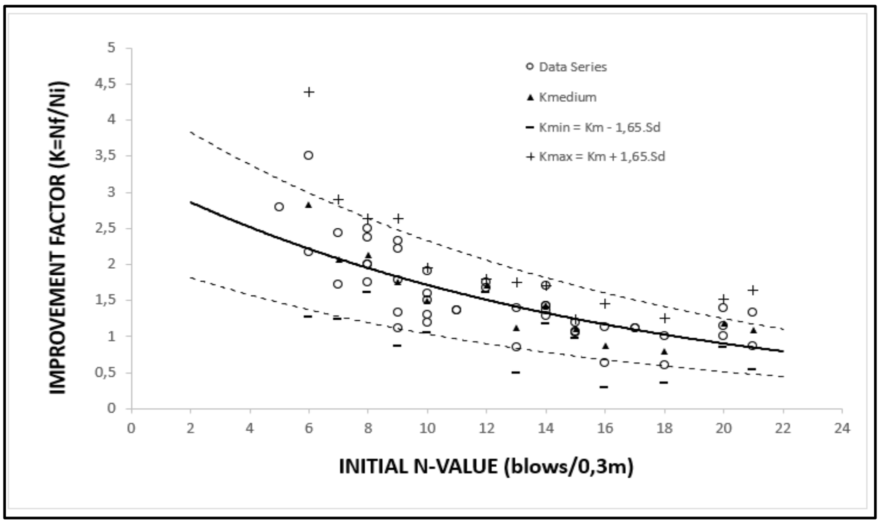


Figure 10: Statistical analysis of the influence of initial compactness [17]

The graph statistically checks the maximum and minimum improvement factor for each N-value with a 95% confidence interval. This level of reliability determines the maximum and minimum limits of a data set that is likely to understand within it the true result of the effect of the intervention under study. Thus, the use of the confidence interval allowed greater precision with the estimation of the upper and lower limit of the improvement factor. With this diagram, one can compare it with the graph developed by the authors in [18], shown in Figure 6. The diagram elaborates by the authors, exhibited that the original terra-probe method was effective for initial N-value up to 9 blows/0,3 m, that is, efficient for soft or little compacted sandy soils. However, the terra-probe method without material introduction (Figure 14) presented an efficiency for initial compactness of up to 19 blows/0,3 m, also covering medium compacted sandy soils. The use of the confidence interval allowed greater precision with the estimate of the maximum and minimum improvement factor. In this way, the evolution of the original terra-probe executive process to without the introduction of material manifested itself effectively with high N-value, initially as well as, the conventional compaction columns, connections in Figures 8 and 9.

7. Conclusion

The compaction columns are one of the types of soil improvement, being more suitable for sandy soils with a limited number of fines. The process is executed by introducing columns in low resistance soils, through the application of large compaction energies through dynamic or vibration efforts. The purpose of improving the terrain is to increase the load capacity of the soil, providing the stability of the building and the elimination of excessive settlements of the elements of the foundations. Due to the limitation of the database of the original terra-probe method observed by the authors in [18], this technique was used as an indicative. Currently, this method has a more significant database because it is used in abundance in the region of Northeast of Brazil. In the diagram that was developed by [17], it can be seen that the terra-probe method without material introduction is an improvement of its original method, showing itself to be more effective in higher initial compactness. In this case, the terra-probe technique without material introduction presented inferior results, but relatively close to the conventional compaction columns methods (vibro-displacement), with the exception of productivity, since its productivity is superior to the mentioned methods. Finally, based on the results presented on the previous study case [17], soil compaction based on the terra-probe method without introduction of material proves to be effective.

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