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Soil stabilization and foundation restoration using an expandable polyurethane resin

Стабилизация грунтов и восстановление фундамента с использованием расширяющейся полиуретановой смолы

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Ключевые слова: осадка фундаментов; укрепления грунтов; технология инъектирования грунтов; жесткость грунта; подъем фундаментов; смоль полиуретана; уплотнение грунтов; консолидация грунта

Abstract. The settlement of foundation is one of the main existing problems which face construction engineers during the construction operation processes since the design of a project and through the whole construction life and it leads to bad consequences on the construction. Many methods have been implemented during the last decades to stabilize the soil, lift basements and reduce further settlements. Some of these methods are actively used and effective while others are less effective, have limitations of uses and/or expensive methods. Soil injection technology using an expandable polyurethane resin is an innovative technology which offers an efficient solution for the construction settlements and leads to the stabilization of the soil. The paper demonstrates the results of a full-scale experiment which was implemented in-situ to investigate the effect of the soil injection technology on the lifting of a concrete foundation and on the stiffness of the soil beneath the foundation (soil stabilization) at different soil depths. Dynamic cone penetration test DCPT was applied before and after the injection of the expandable resin in two different plots, one of the plots was injected (the soil has been treated) and the second plot considered as a reference plot where no injection was carried out (with no soil treatment). Results of the soil investigations before and after the injection of the expandable resin are achieved and analyzed. The graphs of DCPT before and after the injection process in different comparison points are incorporated and compared to the geological report of the investigated area. The injection process is explained, and the foundation lifting to the desired level is achieved and explored in this article.

Аннотация. Осадка фундаментов является одной из основных существующих проблем, с которыми сталкиваются строительные инженеры в процессе строительства: начиная от проектирования, на этапах строительства, а также в процессе эксплуатации. В течение последних десятилетий были реализованы многие строительные методы стабилизации грунтов, подъема фундаментов и сокращения их дальнейших осадок. Некоторые из этих методов активно используются и широко распространены, в то время как другие менее эффективны и имеют ряд ограничений в силу стоимости. Технология инъектирования грунтов с использованием расширяющейся полиуретановой смолы является инновационной технологией, которая является эффективным решением для стабилизации фундаментов и оснований подверженных осадке. В

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статье представлены результаты натурного эксперимента, который был проведён с целью исследования влияния технологии инъектирования основания расширяющимся полиуретаном на подъем бетонного фундамента и изменение жесткости (стабилизации) грунтов. Были достигнуты и проанализированы результаты исследования грунтов до и после инъектирования. Сравнены полученные графики зондирования до и после инъекции в различных точках, а также сопоставлены с геологическим отчетом исследуемой области. Описан и изучен процесс инъектирования, достигнут подъем фундамента до расчетного уровня.

1. Introduction

Polyurethane is a kind of polymer which can be implemented for different uses. In industry, the need to have homogeneous composition has led to investigating many ways for formation processes and investigation of the behavior of the polyurethane resin [1–3]. The resin is injected into the soil to undo settlements due to its expansion for foundation lifting [4–6]. Soil injection technology using polyurethane is the latest innovative technology used for constructions remediation, foundations lifting and other uses [7–9]. This technique can provide an effective and efficient solution for many differential settlements problem, it also can limit further settlements. Any soil treatment and settlement controlling must be designed well based on a comprehensive and integrated considering all factors which cause the problem, otherwise, the problem can be not solved in an integrated manner. Injection of an expandable polyurethane resin is an alternative way used for underpinning all types of structures such as small houses, commercial buildings and paving slabs and the solution of many differential settlement issues. The soil under pavement was stabilized after using the soil injection technology and at the same time, the pavement was remediated. When large or differential settlements of a foundation occur, action must be taken, to raise and level the foundation [10–13].

Many methods were used for solving the settlement problems and stabilization of the soil beneath foundations, but these methods sometimes cannot solve some existing problems [14–16]. A comparison between silicate method and cementation method was done. Cementation method was applied for a five stories brick building in Rostov on don city in Russian Federation. The dimension of the building is 12*39 m and deferential settlements occurred in this building. Cementation method was applied to stabilize the soil (increasing of the bearing capacity) and to lift the settled parts of the foundation. The injected depth was designed to be at the depth of 12.2 m under the foundation and on different depth levels and the water in the soil was located at 3 m depth under the foundation. Cementation method was not success firstly because of the migration of cementation particles. Thus, it was decided to insert drilling piles into the soil around the perimeter of the building's foundation to stop the migration of cementation particles. The soil was treated using cementation method and the project was succeeded using two different methods for soil stabilization and lifting the settled foundation. The author claimed that combination between methods can be the best solution for lifting the settled basements, soil treatments and for the reasons of increasing the bearing capacity of the soil after treatment in some cases where the traditional methods are difficult or not beneficial to be used [17]. Soil injection technology was used in the airport Rostov-on Don in Russian Federation and the results have shown the ability to lift an aerodrome even under a dynamical loading when airplanes are landing, and it did not require closing the airport as it's a vital airport [18, 19]. According to [20] it is difficult to accurately assess the nature of the earthquake in advance because the same field records may vary according to the local soil conditions and other features. Moreover, the stiffness of the soil and other factors affect the dynamic properties of the structure, which directly affect the response of the structure during an earthquake and the assessment of the structure remediation. [21, 22] investigated the effect of the soil beds density on the design of foundations. It was found that more compacted soil beds and reinforced soil beds lead to decrease the required dimensions of foundations and increase the weak soil bearing capacity which leads to minimizing the time and the cost of the construction. It leads to control the operating conditions of an artificial foundation and plate effect of foundations can be noticed. [23] studied problems of sub-mountains area development associated with collapsing loess soil. In general, a slope of the soil has a huge effect on the foundation design which can be noticed especially where constructions are built on mountains and hilly areas like in Tajikistan where the mountains cover around 90% of the areas. In such cases, the soil is exposed to high strains conditions and the soil properties might be collapsed effecting on the whole construction. The authors suggested that the combination of soil piles and compacted soil beds can offer an efficient solution to eliminate the collapse of the soil properties and to ensure the stability of the slope within territories under development.

A relatively new way to stabilize the soil and restore the settlement of foundations is the soil injection technology which can provide an optimum solution for the settlement of the basements in many applications due to the simplicity of the use and the less labor and equipment need to perform it from a side and the efficiency of the results obtained using this technology from another hand. Thus, an experiment was conducted in a field to investigate the effect of injecting two components of an expandable resin with high pressure on the lifting of a foundation and increasing the stiffness of the soil beneath.

2. Methods

2.1. The aim of the experiment

An experiment was conducted to investigate the efficiency of an expandable Polyurethane resin on lifting and elevating a concrete plate which was designed to be under load (to behave like a real foundation) and to investigate the effect of the injected resin on the stiffness of the investigated soil (soil compaction and stabilization).

2.2. The location of the experiment and the type of the investigated soil

The investigated soil is an open storage area located in the western part of the factory of the company “MC-Bauchemie-Russia” in Kirovsk, Leningradskaya region. Russian Federation as shown in Figure 1. The type of the investigated soil is non-cohesive sand according to the geotechnical report of the factory.

Figure 1. The layout of the object (the red Line highlighted the boundary of the plant; red fill indicates the test area)

The soil was investigated in September 2014 and the experiment was conducted based on the given geological report given to the factory. According to the geological report of the factory, the soil being investigated in this experiment consists of the following layers: a first layer is a technogenic layer represented by Bulk sand of different sizes grading (from small sand to gravels, with gravel, pebbles and building debris) within a depth up to (2 m) and the sediment layer is (1.5–2 m). The bulk sand is heterogeneous in composition and addition, having uneven density and compressibility. The second layer is a glacial soil layer widespread under the bulk sand consist of fine sand medium density and medium degree of saturation. Sediment power is from (3.5-6 m). In the period of geological surveying in September 2014, drilling up to 8m in depth, it was found that the water ground level located within (2.2–2.5 m). The properties of the investigated soil as given in the geotechnical report of the factory are shown in the table (1).

Table 1. The properties of the investigated soil as given in the geotechnical report of the factory. * According to laboratory investigation data, ** According to Russian Set of Rules SP 22.13330.2011 [24].

Geological Index	Soil Name (type)	Layer No.	Density t/m³	Porosiy factor e	Strength indicator		E, MPa	Calculated resistant R0, kPa	Filtration coefficient, m/day
					C, kPa	Φ, grad			
t IV	Bulk sand different sizes	1	R0=100 kPa						
lg III	Fine sand, medium density and medium degree of saturation and fully staturated	2	1.94	0.65	4**	30**	18**	200**	4,47*

2.3. The description of the experiment and the test site

In the test site, two plots, each measuring 3 m per side, were chosen, covering a total surface area of (3*3 m) as shown in Figure 2. Treatment of the soil and the injection process using the soil injection technology were applied in one plot while the second plot assumed as a reference plot (no injection was carried out in this plot) for the comparison of the results. The experiment was divided into three stages, the investigation of the soil before the injection process, the injection process and finally the investigation of the soil after the injection. After the site preparation, dynamic cone penetration test was carried out in both plots. A total of 10 comparison points was chosen for performing dynamic cone penetration test DCPT, five points were chosen in each plot (in the reference and the injected area). The points were placed symmetrically and numbered in the four corners and one point in the center of each plot, as shown in Figure 3.

Figure 2. The selected experiment plots

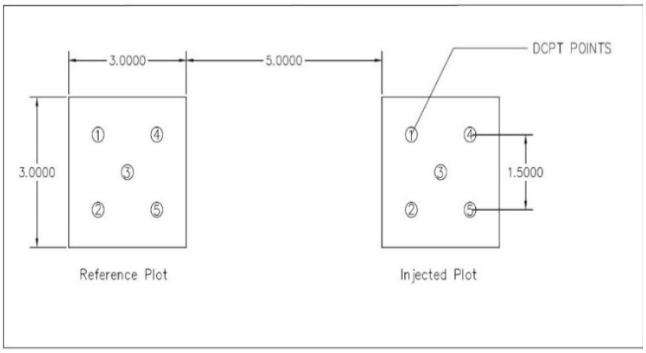

Figure 3. The locations and numbering of the dynamic cone penetration test DCPT selected points

Then, the results of the DCPT before the injection process in both plots were analyzed and compared to the geotechnical report of the factory to ensure the coherent of the results in both plots and for the accuracy of the comparison with the results after the injection of the expandable resin. After that, the concrete plate of the injected plot was cut, along the 12 m of the plot using an electrical cutting machine (up to 30 cm) as the thickness of the plate was approximately (20 cm) to separate the concrete plate and lift it as shown in Figure 4. Then, the injected process was carried out for elevating and lifting the foundation and finally the DCPT test was repeated after the injection of the resin into the injected plot and the results were compared.

(A) Cutting process (B) section of the injected plot after cutting

Figure 4. The cutting process of the injected plot. (A) The cutting process, (B) A Section of the injected plot after cutting

2.4. The injection process

Soil injection technology using polyurethane resin is based on injecting two-components of an expandable polyurethane resin into the zones where the soil needs to be treated or the lifting is required. The aim was lifting the injected plot while an actual load is applied on it to ensure that the concrete plate acts like a real foundation. Therefore, after the Cutting process, a total load (materials bags) of 11 ton (1.2 ton/m^2) approximately including the estimated self-weight of the plates was placed symmetrically as shown in Figure 5.

Figure 5. The injected plot under the load during the injection process

The injection of the expandable resin was carried out according to the following procedure:

1. Drilling holes with a diameter. The diameter of the holes is various according to the equipment used for injection. Mostly, the diameter ranges from 12–30 mm. The diameter of the holes used for this experiment was 12 mm.

2. The injection tubes were inserted into the soil zones as shown in Figure 6. The injected soil zones were pre-designed and selected before the injection process.

3. Then, two components of an expandable polyurethane resin (with a high coefficient of expanding) was injected incrementally into the soil through the holes made in advance using the special pistol for injection. The injected resin used in the experiment named (MC-MONTAN INJEKT-LE) produced by the company MC-BAUCHEMIE.

4. The process was monitored during the injection process until reaching the desired level of lifting and elevating of the foundation.

The injection process is very fast. The physical process of the expandable polyurethane resin of the soil injection technology is based on the chemical reaction of the injected foam in the soil. The chemical reaction of the resin is carried out within (10–15) seconds and the foam propagates through the cavities of the soil and hardened. It either propagates through existing cracks hardening fast in the soil massive or it creates new cracks and expands in the soil. The injection process was divided into stages into different soil levels and the injection process was done in, “shots” to control the lifting process and till reaching the desired results of lifting and/or the soil stabilization. Also, the injection process was repeated within an interval along the treated soil zones.

A digital laser level instrument with high accuracy was used for monitoring the lifting process. Different levels of injections were designed, and the soil was treated at different depths and different layers (the first and the second soil layer according to the geotechnical report of the factory). The injection started at the middle point (point number 3) and then moved around the other four points in consequence. Every point in the injected plot was injected at depths (0.5, 1 and 2 m) respectively. Beside of each DCPT point, one injected point was selected in the injected plot as shown in Figure 6.

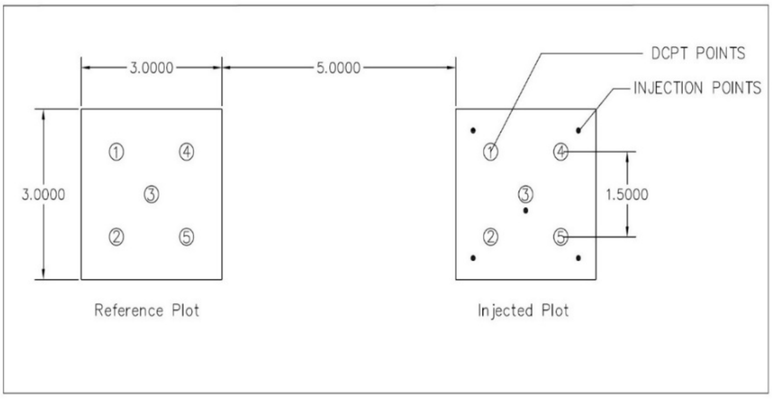

Figure 6. The locations of the injection points as placed in-situ

The injection process designed to elevate the whole injected plot more than (1 cm) beside improving the properties of the investigated soil such as the stiffness and the bearing capacity (soil stabilization). Thus, it was decided to stop the injection process by exceeding the value of (1 cm). The depth of the injection was designed to cover the whole volume of the treated soil in the injected plot up to a depth of (2 m). Therefore, the examined soil was injected at different depths (2, 1, 0,5 m) respectively at every point. The injection carried out from the bottom layer moving towards the upper layer (subsurface layer) because the resin propagates vertically from the bottom to the top. A hydraulic system with high pressure was used to control the mixing of the two- components of the resin. The temperature of mixing the components was around (15 °C) and the pressure more than 100 bar. The consumption of the resin which injected in the massive of the investigated soil was around (180 liters) to fulfill the aim of the experiment (lifting to the pre-designed level). The concrete plate had a different elevations levels in each of the corner points and the elevation of each point differ to each other and the center differs too. Thus, a high quality of control was required for elevating and monitoring the whole concrete plate to one desired level. Figure 7 shows the geological section of the investigated soil in this experiment, the concrete plate, and the injection zones.

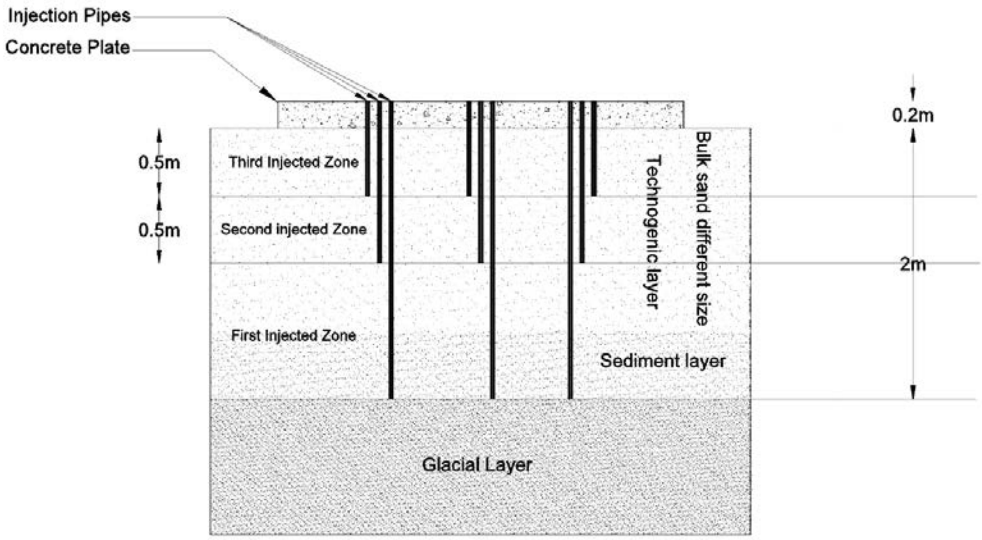

Figure 7. The geological section of the investigated soil including the injection pipes and the injection zones. (Approximately 180 liters of the resin injected to the soil massive under pressure more than 100 bar and temperature mainly 15 °C)

Finally, the dynamic cone penetration test DCPT after the injection of the resin was repeated in the injected plot where the resin was injected. The locations of DCPT points after the injection of the resin were selected close to the same points before the injection of the resin in the injected plot to investigate the dynamic resistant of the sand after the injection of the resin.

3. Results and Discussion

3.1. Results of the DCPT comparison before the injection process

The test was done according to the international standard GOST (19912-2001) [25]. According to this standard, the investigated soil is soft if the dynamic resistant (PD) less than (2.3 MPa), medium dense soil if it is between (2.3–6.6 MPa) and dense soil if (PD) value is greater than (6.6 MPa).

The main reasons behind investigating the mechanical properties of the reference plot were to ensure the accuracy and to verify the results of the investigated soil properties (more comparison points are used for the analysis of the results before the injection of the resin).

The results of DCPT in each tested point in both plots before the injection of the resin are shown in figures (8–12). The results of DCPT in both plots were mostly similar in both plots and close to the geological report of the tested area showing that the sand resistant mainly was ranging from weak to medium dense sand in both plots while it was approaching to a dense sand with a dynamic resistant up to (6–8 MPa) in some points at depth (1.5-2 m). The non-coherent of the results in points (3, 4) at depth (0.9, 1 m) was due to the loss of the rod-cone at these depths while digging it into the soil in these points. Thus, the dynamic resistant was high in these points at the mentioned depth. Also, as mentioned in the geotechnical report of the factory that the investigated soil layer consist of heterogeneous bulk sand contains gravels which might lead to some errors in results in some places and the density of the sand is variable. However, an outcome of the diversity of the selected points and the analysis of comparison of the dynamic cone penetration test DCPT to the factory geotechnical report has confirmed that the soil being investigated is mostly medium dense sand. Furthermore, according to the DCPT results the sand density in both plots was mostly ranging within medium dense sand at the depth of (1.5- 2 m) where the sediment of the soil layer is located approaching to dense sand in the bottom of this layer. However, the results of the dynamic resistant in all tested points in both plots mostly did not exceed the value of (8 MPa) except in the mentioned points and depths where the cone of the rod was lost in the soil during the digging process. The average results of the dynamic resistant in both plots show that the density of the investigated sand is ranging from weak to dense sand depending on the depth of the sand layer but mostly within medium density according to the results of the DCPT before the injection process.

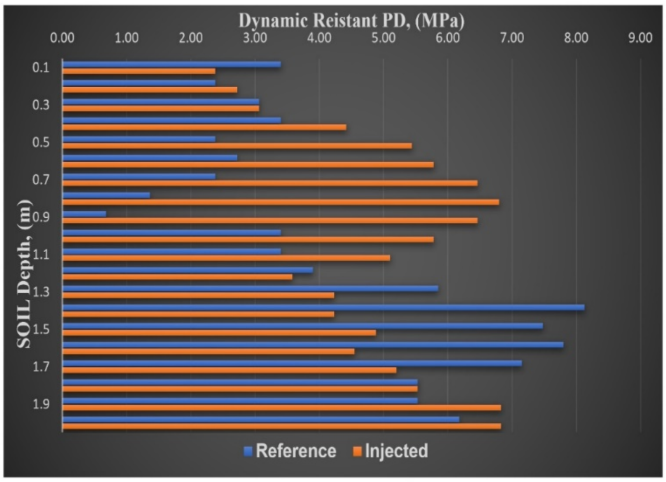

Figure 8. The DCPT results of the reference and the injected plot before the injection of the resin at point number (1)

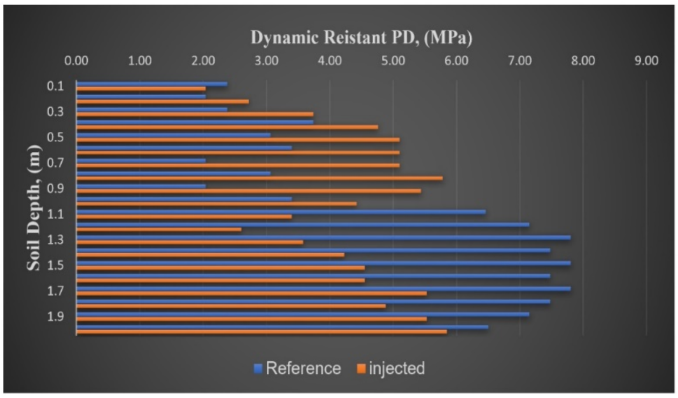

Figure 9. The DCPT results of the reference and the injected plot before the injection of the resin at point number (2)

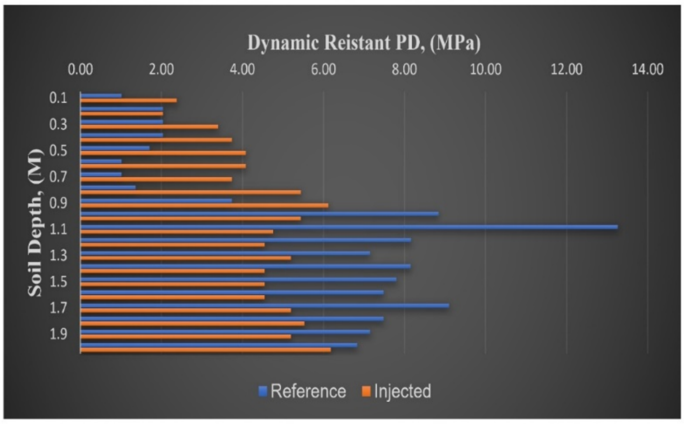

Figure 10. The DCPT results of the dynamic cone penetration test of the reference and the injected plot before the injection of the resin at point number (3)

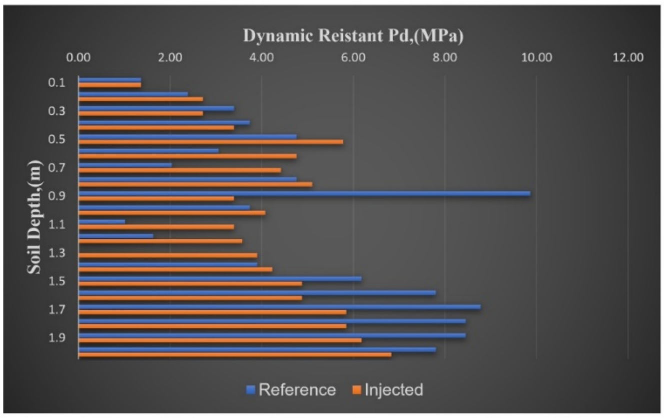

Figure 11. The DCPT results of the reference and the injected plot before the injection of the resin at point number (4)

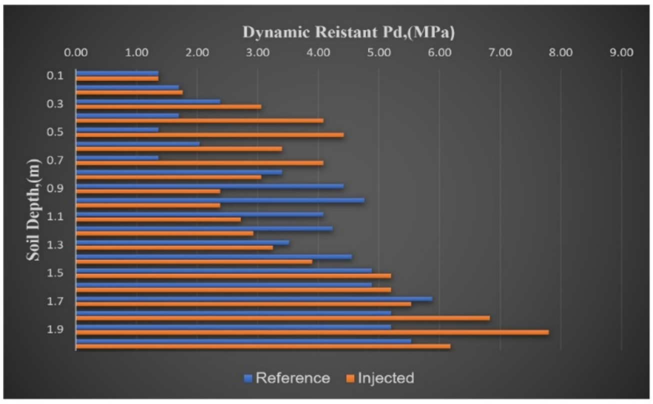

Figure 12. The DCPT results of the reference and the injected plot before the injection of the resin at point number (5)

3.2. Results of lifting and elevating

The concrete plate with the load was elevated and lifted to (12 mm) after the injection of the resin. The injection process was stopped by exceeding the value of (1 cm) of lifting (any value more than 10 mm) as pre-designed for this experiment. Thus, it was decided in-situ to stop the injection process at a level of lifting (12 mm) as it exceeded the pre-designed lifting level for this experiment. The results were carried out immediately in each point, then the last elevating of the whole plate was controlled through the middle point (point 3). The injection process proceeded until the designed level for this experiment was obtained. The temperature of mixing the components of the resin and the pressure of injection was variated depending on the elevating required for each point as the pressure of the injection plays important role in the elevating process. Figures 13, 14 show the results of lifting the concrete plate in the injected plot before and after the injection of the resin.

(A) Before (B) After

Figure 13. A side section of the concrete plate of the injected plot before and after the injection of the resin. (A) Before injection, (B) After injection

(A) Before (B) After

Figure 14. A side section of the concrete plate of the injected plot before and after the injection of the resin. (A) Before injection, (B) After injection

3.3. Results of the dynamic cone penetration test after the injection of the resin

After the injection of the resin, the dynamic cone penetration test DCPT was repeated in the injected plot only. Then, the obtained results of the test in the injected plot were compared to the results of the test in the same plot before the injection process. The analysis of the dynamic cone penetration test DCPT has shown a great increase in the dynamic resistant of the investigated sand after the injection of the resin. Figures 15, 16 shows different sections of the injected soil after the injection of the resin and the propagation of the resin in the injected plot.

Figure 15. A section of the injected plot after the injection of the resin (The investigated soil and the resin propagation)

Figure 16. A section of the injected plot after the injection of the resin (The investigated soil and the resin propagation)

Focusing on the results of the dynamic resistant of the middle-injected point (point 3) which shows a huge improvement in the sand dynamic resistant along the treated soil depth as shown in Figure 17. The sand resistant was mainly averaging within the medium dense sand with dynamic resistant less than (6.6 MPa) before the injection, while, it increased to a very dense sand after the injection of the resin and the dynamic resistant increased up to (16 MPa at the depth 2 m) showing the ability of the resin to compact and consolidate the surrounded injected soil. Moreover, more consumption of the resin was designed (more resin injected in this point) for the elevating process in this point in comparison to other points as it is the center of the plate and the injected started and carried out at this point and then moved around through the other points as mentioned. Therefore, the effect of the resin on the properties improvement of the investigated soil is noticed clearly in this point and covers the whole volume of the injected soil zone along the whole depth.

In fact, the soil depth at (1 m) was injected less comparing to the other injected depth (0.5, 2 m) because the injection starts at the depth of (2 m) where more resin consumption was required for the lifting process as well as the at depth (0.5 m) where the last elevating and monitoring was carried out through this depth in all injected points. Obviously, less consumption of the resin at depth (1 m) was required (less resin injected). Therefore, it can be noticed that the dynamic resistant of the investigated soil was increased along the whole treated depth and in every one of the injected points at depth (0.5, 2 m) respectively, as shown in the figures (18–21), while, the effect of the resin on the sand properties became less at the depth (1 m) due to less injection of the resin (less consumption) required for the lifting and elevating process at this depth.

However, at the depth of (1.5 m), there was no injection performed at this depth and this soil zone was assumed to be the average of the (1–2 m) of injection depth to examine the effect of the resin where no injection based on the injection at other depth. Thus, the results of the dynamic resistance of all points less improved at the depth (1.5 m) comparing to other depths where the injection was performed except in the middle point (point3) where an improvement of the soil resistance is noticed, although, there was no injection perform at this depth, more resin was injected as stated above.

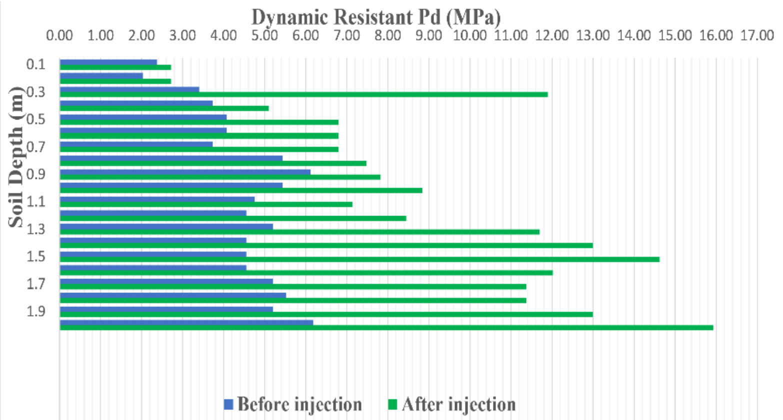

Figure 17. The results of the dynamic cone penetration test of the injected plot at point number (3) before and after the injection of the resin

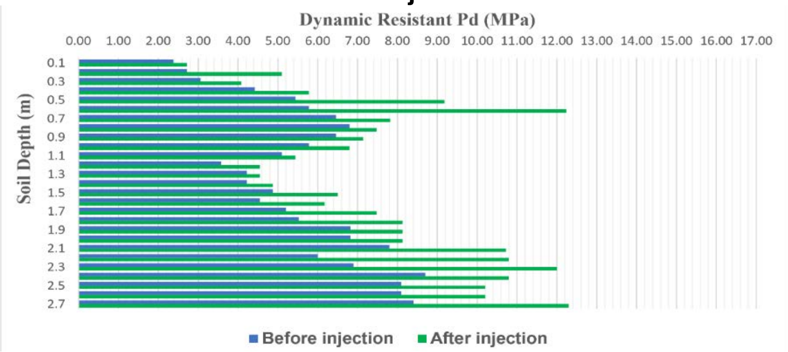

Figure 18. The results of the dynamic cone penetration test of the injected plot at point number (1) before and after the injection of the resin

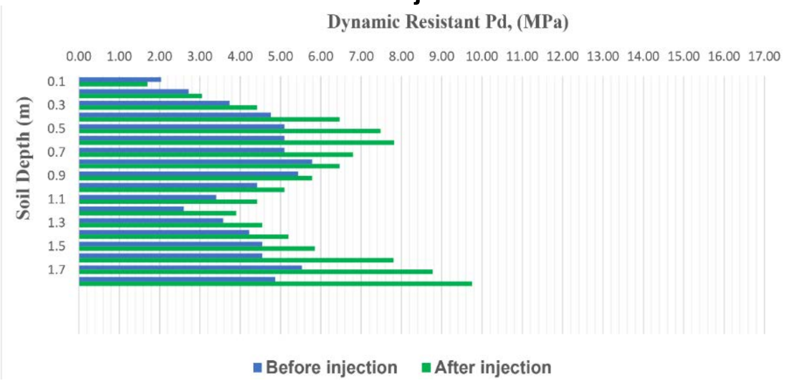

Figure 19. The results of the dynamic cone penetration test of the injected plot at point number (2) before and after the injection of the resin

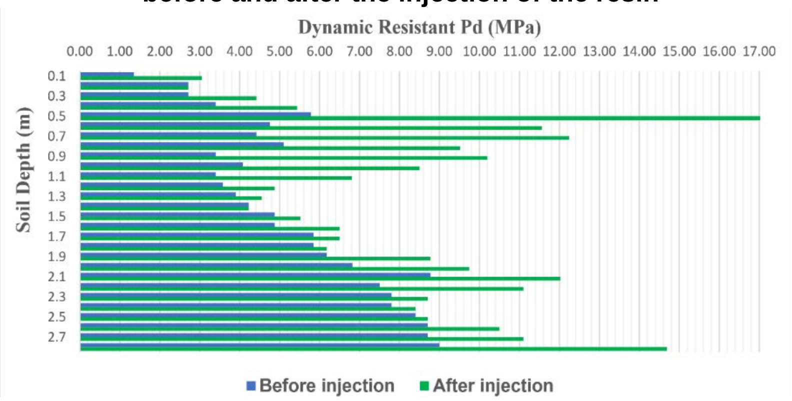

Figure 20. The results of the dynamic cone penetration test of the injected plot at point number (4) before and after the injection of the resin

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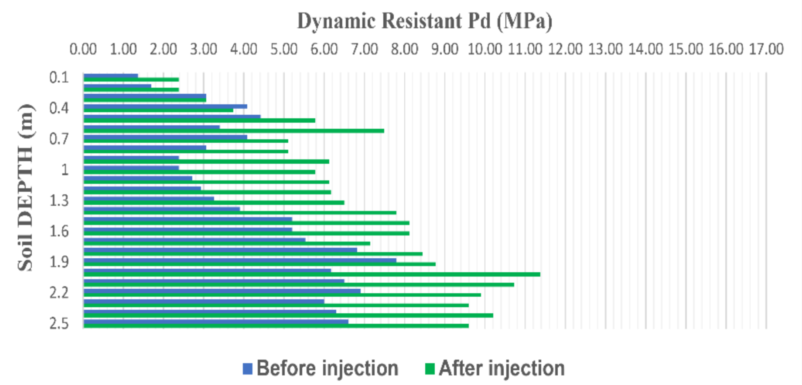

Figure 21. The results of the dynamic cone penetration test of the injected plot at point number (5) before and after the injection of the resin

According to the author opinion, after the treatment of the soil using the expandable resin, additional sufficient settlement does not occur in the treated soil (not in the injected layers of the soil nor in the layers beneath the injected layers) for many reasons. The technology works for existing construction where a soil needs to be stabilized and/or the foundation needs to be lifted and remediated. In this case, the settlement is known and can be solved using the injection of the resin. The injection zones and the injected layers are determined according to the bearing capacity of the construction and the conditions of the treated soil. Thus, no further settlement occurs after the treatment process. Moreover, the density of the treated soil is increased because of the additional volume of the injected expandable resin, while, the weight of the injected resin is small relatively. Therefore, it does not lead to more additional sufficient settlement. Furthermore, the resin pressure is more than the compressive strength of the resin itself and the resin propagates and expands towards the upper layers. Therefore, the soil located above the injected zones is compacted due to the outcome of the forces applied to the soil in opposite directions (the load of the construction facing the pressure of the resin vertically) beside the lateral pressure of the resin applied to the soil. additional settlements do not occur in the deeper layers due to the injection of the resin because there are no extra pressures applied to the soil layers beneath the injection zones. Finally, an assumption, the technology can be applied for non-existing constructions if applies a load equal to the pre-designed load of the construction while the practice shows that it is very difficult in many cases especially if the load of the constructions is huge. However, according to this assumption the settlement occurs due to the release of the load during the load replacing process (removing the applied load used for the injection process and building a construction which loads equal to the applied load through the injection process in assumption) is small relatively and can be calculated and controlled.

4. Conclusion

Results of the experiment have shown the ability to inject an expandable polyurethane resin into a non-cohesive sandy soil on the lifting of a concrete foundation as well as increasing the stiffness of the investigated soil. An outcome of the results has shown the great improvement of the sand dynamic resistant after the injection of the expandable resin. However, the improvement is varied and diverse depending on many factors, such as the type of the soil, the injected depth, the injection pressure, the amount of the injected resin and on the soil layer itself. Moreover, the soil injection technology can stabilize the soil even the dense sand as shown in the results of the DCPT beside lifting and remediation of the foundations. The stiffness of the soil was increased up to twice in some points in the injected plot showing the high efficiency of the resin on the improvement of the soil properties (soil stabilization). Furthermore, more stabilization was obtained in the injected zones where more consumption of the resin as the dynamic resistant of the investigated sand was increased enormously. The technology has many advantages such as the simplicity of the injection process and the ability to apply in any kind of construction beside the less labor and equipment required for the injection. The soil injection method using an expandable polyurethane resin can lift and elevate the foundations and the monitoring process is easy in comparison to many other methods besides the high accuracy of lifting which can be obtained immediately during the fast process of injection and with no inherent to the soil ecology or the soil groundwater level. The research is done in one type of soil (non-cohesive sand soil) and the properties of the investigated soil are demonstrated above. However, the obtained results are valid, actual and applicable to all similar types of non-cohesive sandy soil because the injection of an expandable polyurethane resin under high pressure increases the cohesion of the treated sand. Moreover, the outcome of the forces exerted on the soil (load-resin forces) in opposite directions beside the lateral pressure which applies on the soil during the injection process which leads to compressing the soil and the additional volume of the injected expandable resin added to the soil while the weight of the injected resin is small relatively which lead to increase the mass density of the soil (soil compaction) and it does not lead to additional sufficient settlement. Therefore, this method might also be applied to other soil types according to the author opinion.

The improvement of the investigated soil stiffness (soil stabilization) beside lifting and elevating of a concrete plate which was designed to carry a load like a real foundation to the desired level (pre-designed level) by injecting an expandable polyurethane resin was achieved.

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