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Use of Compaction Grouting as Ground Improvement Technique in Compressible Solid Waste Landfill

Utilisation de Compactage par Injection Solide comme une technique d'amelioration des sols, dans une décharge de déchets solides compressibles

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ABSTRACT: Ground improvement methods are increasingly being used as means to control settlements and improve the shear strength of foundation soils. The compaction grouting (CG) method is a ground improvement method that is used as means to mitigate or even remediate excessive settlements in existing structures. The use of this method causes minimum disturbance to the structures; therefore, it is an appropriate application for those structures. The objective of this publication is to investigate the advantages and limitations of CG as a repair solution in situations where the foundation soil is composed of very compressible solid waste landfill material. The investigation is conducted by means of a case study that includes a 40.000 square meter (m^2) commercial centre founded on a previous compressible material and subjected to excessive differential settlements. It includes description of the installation as well as monitoring during and after construction of 1800 CG columns, each having a depth of 15 meters. The data collected from the monitoring systems are used to determine the rate, pressure and volume of injected grout required to achieve the target amount of densification of the foundation soil for a selected treated area.

RÉSUMÉ: Les méthodes d'amélioration des sols sont de plus en plus utilisées pour contrôler tassements et améliorer la résistance au cisaillement des sols de fondation. La méthode de Injection Solide (IS) est une méthode d'amélioration des sols utilisée comme moyen d'atténuer, voire de remédier aux tassements excessifs dans les structures existantes. L'utilisation de cette méthode provoque une perturbation minimale des structures; c'est donc une application appropriée pour ces structures. L'objectif de cette publication est d'examiner les avantages et les limite de la IS en tant que solution de réparation dans les cas où le sol de fondation est composé de matériau de décharge de déchets solides très compressible. L'investigation est menée au moyen d'une étude de cas comprenant un centre commercial de 40 000 mètres carrés (m^2) fondé sur un matériau tres compressible et soumis à des tassements différentiels excessifs. Il comprend la description de l'installation ainsi que la surveillance pendant et après la construction de 1800 colonnes IS, chacune ayant une profondeur de 15 mètres. Les données collectées à partir des systèmes de surveillance servent à déterminer le taux. la pression et le volume de coulis injectés nécessaires pour atteindre le niveau de densification du sol de fondation pour zone traitée.

Keywords: Compaction grouting; Ground improvement; Settlements; Differential settlements; Compressible soils

1 INTRODUCTION

The typically used grouting methods for improving or sealing loose soils are based on the use of grouts, which penetrate and fill existing voids, or voids that are created during soil fracturing. In this process the injected grout is being mixed with the soil. Nevertheless, in many instances, dispersion of the grout material in the vicinity of injection and mixing with the natural soil should be avoided [5], hence alternative ground improvement methods must be used.

The above objectives may be achieved using solid grouts, which can displace and compact the soil, without traveling far from the injection point, thus compacting/densifying the natural soil. Compaction Grouting (CG), Low Mobility Grouting and Solid Injection are the terms, which are most commonly associated with the use of solid grouts.

Due to their composition, solid grouts expand in the soil as a homogeneous mass forming bell-shaped grout bulbs [1]. In addition, they behave as globular masses whose movement can be controlled; hence, their continuous injection into the soil is suitable for treating problems of differential settlements in existing structures.

The method of compaction grouting is an effective, low-disturbance solution for existing structures founded on poor foundation soils, which are susceptible to large (differential) settlements ([2], [6]). In the execution of the method, the low mobility mortar grout is injected at a slow and controlled rate, but under large pressure into the ground. It is important that the injection pressure is closely monitored so that the natural ground is not fractured, or the grout permeates the surrounding soil. The grout is a soil-cement mixture with a sufficient silt component, which provides plasticity, together with a sufficient proportion of sand, which helps to develop internal friction [4].

The typical execution sequence starts by drilling a hole, with proper support, to the desired depth. In the sequel, the grouting starts from the bottom towards the soil surface. The stiff grout is injected while gradually removing the grout casing. Injection is achieved by means of a pump with capacity greater than 40 atmospheres. Uniform compaction of the soil is achieved by using primary and secondary grids.

Prior to the application of the method, the design parameters should be determined. This includes the composition of the grout (material sources, types of grout, aggregate material and their proportions), injection rate, volume and injection pressure. Furthermore, for the case of existing structures, the limits for allowable uplift as well as a detailed monitoring program must be specified. If compaction grouting is used for soil improvement, a verification testing program before and after the works is also essential.

This paper focuses on a case study that includes a 40,000 square meter (m^2) commercial centre founded on compressible material. Due to the high compressibility of the fill material, eight years after construction, the structure was still settling excessively, posing a great risk to its structural integrity. The accumulation of excessive settlements required the improvement of the subsoil, using the compaction grouting method. The method was applied while the commercial centre remained in operation and involved the installation of approximately 1800 vertical and inclined grout columns, each having a depth of 15 m. The works took place between 2011 and 2017. A detailed monitoring system provided data on the column installation (mortar volume, drilling and injection time, applied pressure), as well as on the response of the foundations of the structure (uplift and subsequent relaxation) [3].

2 CASE STUDY

2.1 Project description

The commercial centre of the presented case study has a footprint of 40.000 square meters. It is a one-story industrial structure, constructed of prefabricated elements. Foundations consist of isolated 3 x 3 meter footings designed for a pressure of 200 kPa. The slab on grade, reinforced with dispersed reinforcement, supports maximum loads of 25 kPa and is designed to assure that the columns work together and the generated gases are controlled (by means of special collecting pipes throughout the floor area). Finally, a layer of compacted granular material was placed below the slab on grade.

2.2 Geotechnical conditions

The structure is located in an area, which was used as a ballast borrow pit from 1960 to 1967. As a result of the pit activities, the top meters of the natural soil were gradually replaced by spoils from the local industry, including leather, rubber, textiles, but also bricks, glass, metal, concrete and other fill materials.

Based on a detailed evaluation of the available soil borings, the soil conditions in the area of the project consist of layered soils, including a layer of non-homogeneous fill of varying thickness followed by layers of sand, with some gravel and stiff clay. The groundwater table was measured at 11.60 m below ground level. Figure 1 presents drilling samples from different depths and locations underneath the structure; hence, providing a qualitative display of the subsurface conditions.

The fill material is encountered throughout the footprint of the structure under consideration and has a varying thickness ranging between 2.8 and 14 meters. It has a very high proportion of organic material, in state of decomposition; thus, presents high compressibility. In addition, traces of methane gas emission have been reported in the fill layer by 13 borings. In fact, for 100 m^2 of ground surface, emissions ranged between 0.2 and 2 m^3/day. Organic content ranged between 5.3 to 35 percent. Specific weight γ (kN/m^3) ranged between 10 and 19 kN/m^3, moisture content (w) from 10 to 49% and porosity (n) from 45 to 75%.

The project is located in the vicinity of a seismograph station, which in the past has recorded maximum ground acceleration ranging between 0.19g and 0.21g.

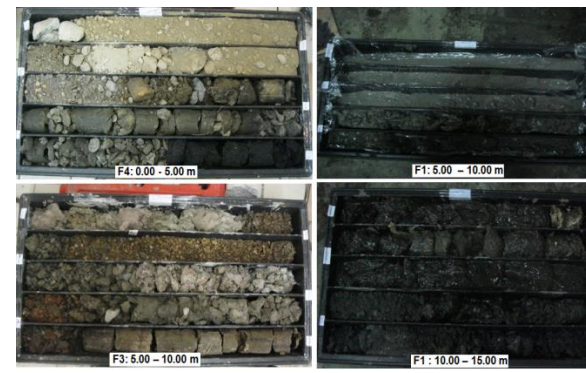

Figure 1. Soil samples from 0 to 15 meters.

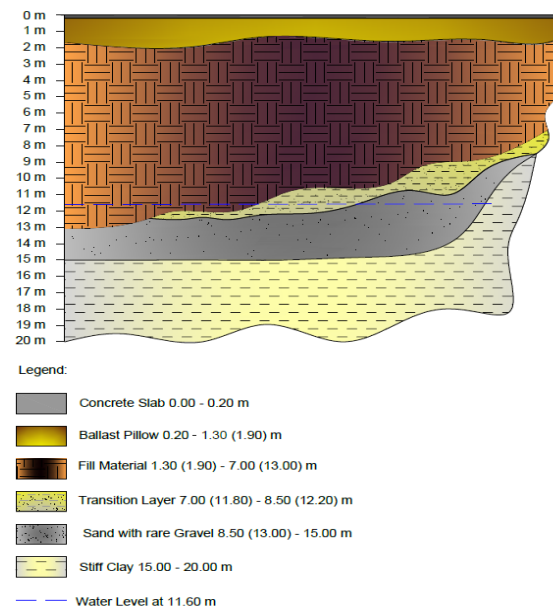

Figure 2. Soil profile at the site under consideration.

2.3 Ground improvement objectives

The objective of the performed works was to stop excessive settlements, which were ongoing for several years and varied in some areas between 5 and 24 cm. Works were scheduled in night shifts, in order to minimize disturbance, given that the commercial activity could not cease during the project. The columns' injection was generally performed on a primary and secondary grid to achieve optimum confinement. Underneath the concrete slab of the structure, grout columns were injected at a centre-to-centre distance of 2 meters, whereas around the footings, 8 columns were injected in total, 4 vertical and 4 inclined by 6 degrees. The total volume of the injected mortar exceeded 5,000 m^3 and the minimum and maximum mortar injected in one column ranged between 3 m^3 and 12 m^3 respectively, which indicates a highly non-uniform soil. In Figure 3 typical views of the performed works are presented.

Monitoring of the settlements started in 2003 (immediately after construction) for 60 columns of the structure, making up almost 25 percent of the total number of columns of the building. Significant settlements were measured already from the first year, which were analogous to the thickness of the fill material and reached up to 45 mm in the areas of the maximum thickness of the compressible layer. Then in 2010, settlements had accumulated to 160 mm in the same location with 0.5 – 0.8 mm settlement being added per month at the critical columns. This was a clear indication of the emergency of the situation. The above measurements from 2003 and 2010 are shown in Figure 4, as a function of the fill thickness, from where a direct link between the thickness of the fill and the magnitude of the settlements is observed. Namely, at the locations where the thickness of the fill material was 14 m, the settlement increased by a scale of 2 to 4 times reaching the level of 80 to 160 mm.

The most problematic area of the building was located in a zone where the fill layer had a thickness of about the previous thickness and spread over an approximate area of 250 square meters (m^2). This area started being monitored in 2007 after observing large deformations in the vicinity, which increased at a constant rate of 2 mm per month. From May to August of 2011 the reported settlements in the same area, reached 36 mm, leading to 24 cm in total.

In the present paper, the data from works performed during the last intervention that took place in 2017, are used. The particular intervention covered an area of 361 m^2, where smaller settlements accumulated. In total 74 CG columns were injected for the stabilisation of 5 spread footings (Figure 5).

Figure 3. Views of the injection works inside the structure.

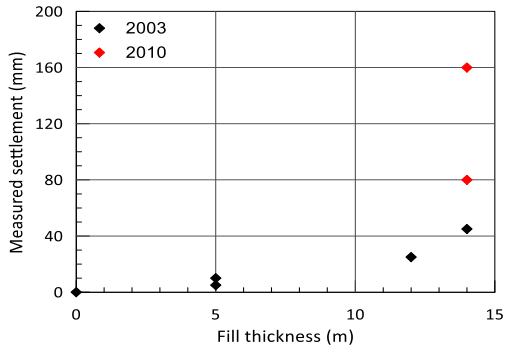

Figure 4. Measured settlements in 2003 and 2010, as a function of the fill thickness.

3 DATA PROCESSING

The available data from the site include the following (i) column logs, which provide information on the drilling and injection time, injected mortar volume, the minimum and maximum injection pressure, were registered every 1.5 m, and (ii) monitoring data of footing displacements, as explained previously. Based on the soil profile, the analysis was divided into three distinct soil zones; namely, 0 – 3 m, 3 – 12 m, and 12 – 15 m.

Figure 6 presents the distribution of mortar volume with depth from various locations of the treated area. These are grouped based on their shape and the amount of mortar used, in order to obtain a better understanding of the nature and the response of the fill material to CG. Based on this figure, the highly non-uniform nature of the fill material becomes evident, as the used mortar volume presents a great variation between 3 and 12 meters. In addition, there is a direct influence of the soil layering on the column shape. Namely, in most cases the cross section of the column presents a significant bulging between 3 to 12 meters, implying the presence of a soft layer and in the sequel the cross section is reduced again, as compaction grouting progresses to the stiffer soil layers. This picture is also consistent with what is described in ASCE guidelines [1] and Figure 7. In the top 3 meters most of the column cross sections are rather narrow, implying the injection of low mortar volumes. This is expected, as due to the low overburden stress, the applied injection pressures need to be kept at low levels, to avoid damaging the superstructure. Based on the information from the entire database of the column logs (74 columns), it is estimated that the vertical columns absorbed from 0.79 to 3.94 m^3 of solid grout, giving an average of 1.43 m^3 with a standard deviation of 0.48. The inclined columns exhibited a higher consistency in terms of the absorbed volumes, ranging from 1.23 to 2.39 m^3, with an average equal to 1.87 m^3 and standard deviation of 0.40.

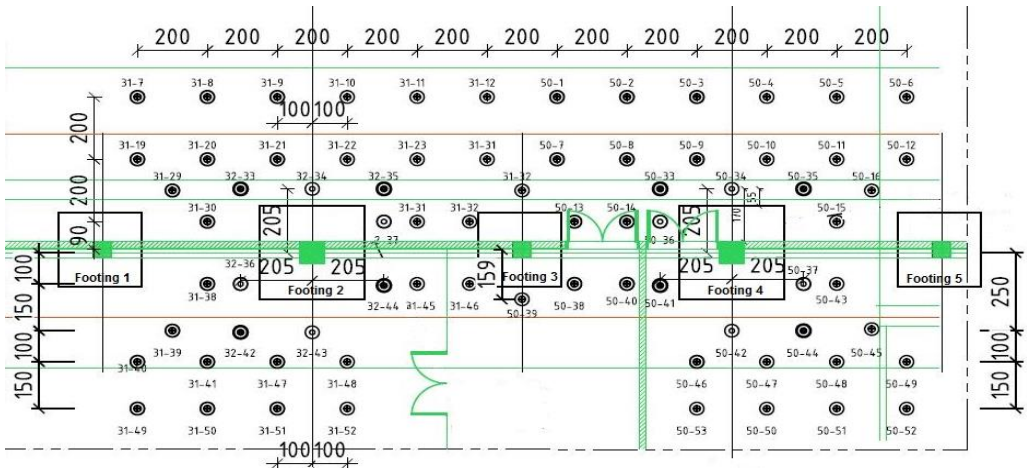

Figure 5. Plan view of the treated area in 2017.

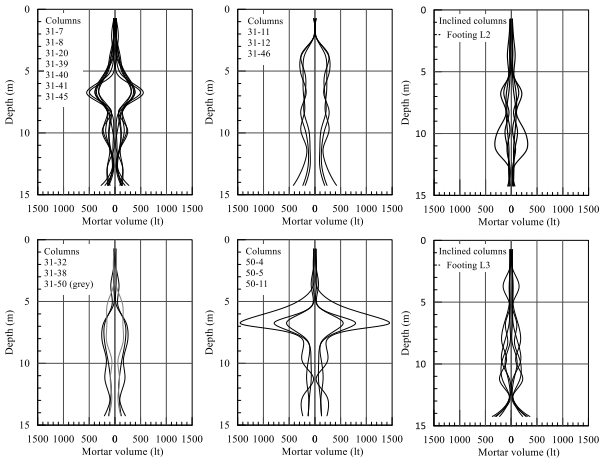

Figure 6. Mortar volume distribution with depth from selected locations from the treated area.

Figure 8 summarizes the distribution of the injection pressure with depth for selected locations of the treated area, including the inclined columns, which were constructed around foundations 2 and 4. It is observed that – on average and within the fill material (3 to 12 m) – the injection pressure remains constant and equal to 20 bar for all vertical columns. Regarding the inclined columns, a slightly higher injection pressure is recorded, which is equal to approximately 23 bar. Moreover, it is observed that in the top 3 meters, the injection pressures are significantly lower given the low overburden pressure.

Figure 9 illustrates the correlation between the normalized mortar volume and the normalized total injection time for each distinct soil zone (as explained earlier) and each column. It is observed that for all three zones there is a linear correlation between the injection time and the mortar volume. The performed normalization here, essentially does not reveal what is observed in Figure 6, namely that in the middle zone there is the highest absorption of material, due to its compressibility.

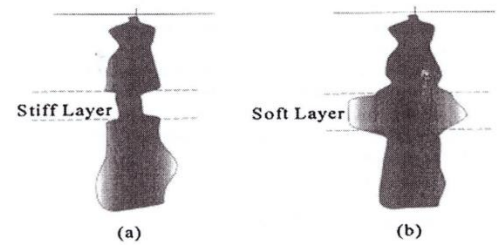

Figure 7. Effect of soil layering on column shape: (a) stiff layer leads to a reduced cross section (b) soft layer leads to enlargement (ASCE, 2010)

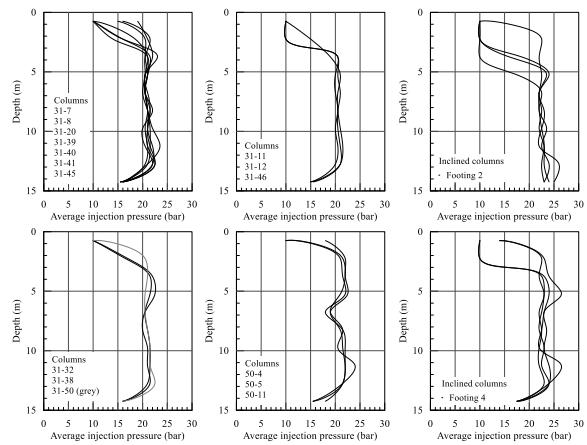

Figure 8. Average injection pressure with depth for selected columns of the treated area.

Figure 10 shows the vertical relative displacements (Δz) of footing 2 as recorded by the monitoring instrumentation, performed by total stations and prisms. It is observed that three separate sections of uplift are recorded. Part I of the heave measures approximately 1.5 mm and occurs from the beginning of the works until July 28, 2017. During this time period, there were no ground improvement works taking place in the vicinity of footing 2, hence this is attributed to works performed in adjacent footings. The second part of uplift measures roughly 3 mm and was recorded from 4 – 12 of August of the same year. During that time, records from the columns logs show that columns 31-20, 31-21, 31-22, 31-23, 31-31, 31-48, 31-47, 31-41 and 31-40 were

injected. The final part of uplift, measures approximately 4 mm and was recorded between 19 – 23 August, when columns immediately neighboring the footing were injected, that is, 32-33, 32-34, 32-35, 32-36, 32-37, 32-42, 32-43 and 32-44. The conclusion was that the columns located closer to the footing have caused the greatest uplift. Horizontal relative displacements were insignificant.

Figure 11 summarizes the vertical relative displacements (Δz) of footing 4. It is observed that the recorded uplift reaches up to 6 mm between 26 - 29 of July. During that time, columns 50-33, 50-34, 50-35, 50-37, 50-42, 50-41, and 50-36, located in the vicinity of the footing were injected.

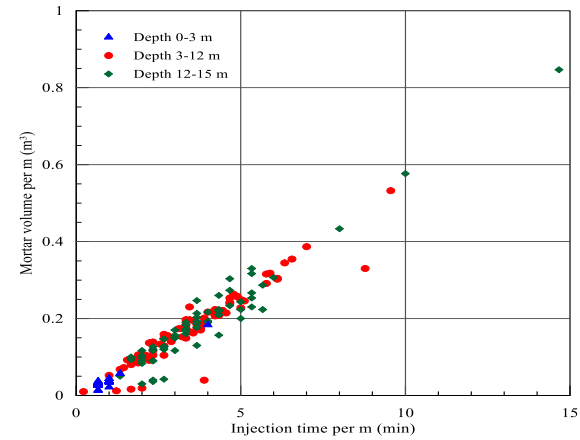

Figure 9. Normalized mortar volume against normalized injection time.

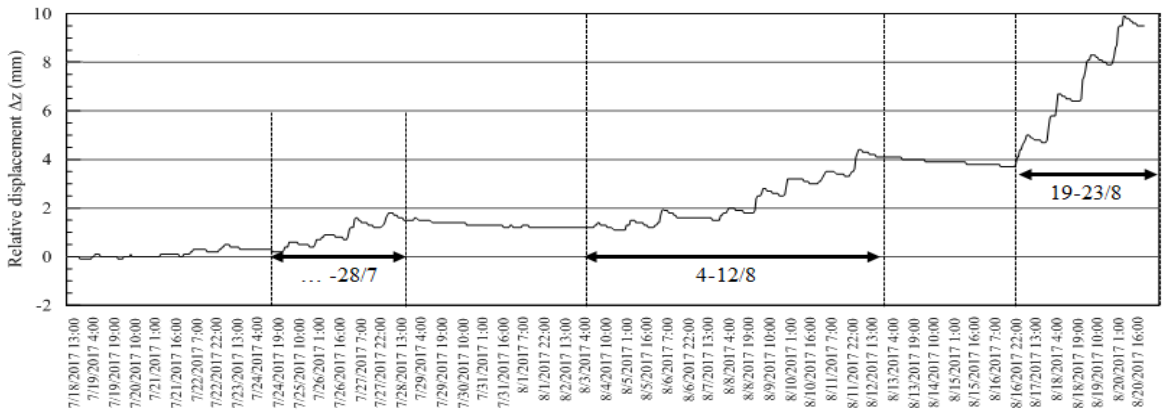

Figure 10. Relative vertical displacement footing 2.

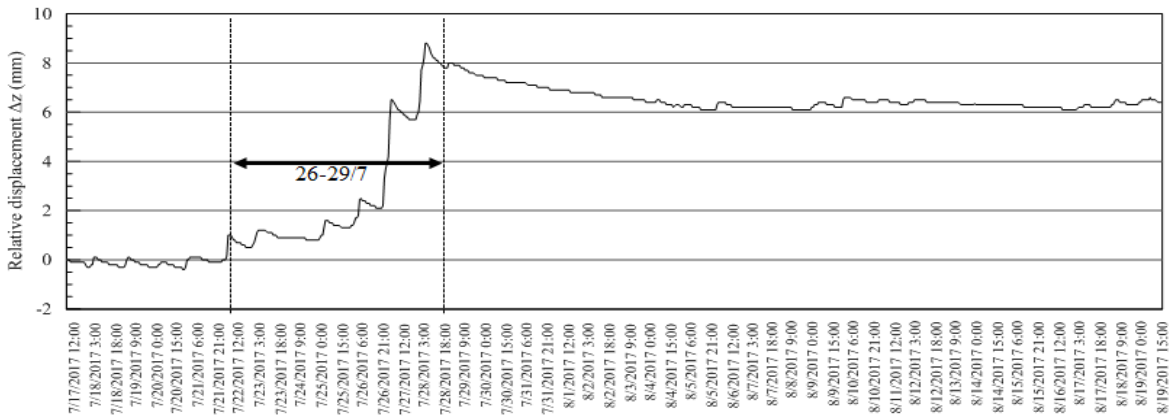

Figure 11. Relative vertical displacements for footing 4

4 CONCLUSIONS

In the present paper, a case study of a commercial centre, built on top of a highly compressible material is presented and the issue of the continuing settlements of the foundation system is addressed by means of ground improvement. The building was founded on top of a highly compressible fill material, rich in organic content. As a consequence, 8 years after the completion of the building, settlements were still accumulating, and significant differential settlements were threatening the building's structural integrity.

Compaction Grouting was proven to be an effective method to minimize settlement of fill materials with high organic content. The operation was conducted while the commercial structure remained operational at all times and without any need for structural modifications.

An extensive real-time monitoring network provided a large database of information. This included the column logs as well as settlement/heave data recorded at the columns of the footings.

Based on the presented data, the following conclusions are drawn:

The distribution of the absorbed mortar volume with depth demonstrated the highly non-uniform character of the fill material, as the volume required between depths of 3 to 12 meters was very different among columns. Another indicator, the shape of the presented cross-sections, indicated that the fill material was very soft and compressible.

Furthermore, a linear correlation was observed between the injection time and the normalised mortar volume throughout the depth of improvement. Generally, the normalised (per running meter) injection times, do not vary significantly between the compressible material and the stiffer underlying soils. Nevertheless, the total injection time per layer was significantly different, as the thickness of the fill is three times greater than the stiffer soil.

Based on the data from the monitoring system, the injection of the columns induced some jacking up of the footings, which was larger in magnitude as the columns were injected closer to the footing. The vertical component of displacement is much more pronounced compared to the horizontal one.

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