The use of dynamic probing tests and cone penetration tests to verify the effectiveness of expanding polyurethane resin injections for ground improvement

Cone Penetration Testing 2022 – Gottardi & Tonni (eds)

The use of dynamic probing tests and cone penetration tests to verify the effectiveness of expanding polyurethane resin injections for ground improvement

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ABSTRACT: Injection of expanding polyurethane resins is a popular method to improve both the stiffness and the shear strength of the ground below existing foundations. The effect of the polyurethane resin expansion is to increase the soil confining stress and density around the injection holes. An estimation of the horizontal stress and volumetric strain changes that are induced within the ground is derived from the theory of cavity expansion in elasto-plastic materials. A series of case-histories is presented to document the feasibility of different *in*-situ tests to evaluate the achieved ground improvement. The tests have been performed before and after the injection of polyurethane resins and the obtained results have been compared with theoretical predictions. The considered investigation methods include the dynamic probing tests and the cone penetration tests. The preliminary results that have been achieved using an experimental miniature cone penetration test are also illustrated. The advantages and limitations of different test methods are discussed and practical indications for conducting such verifications of polyurethane resin injection effectiveness are provided.

1 INTRODUCTION

The use of polyurethane expanding resins is a widespread technique adopted to solve ground-related engineering problems. Due to their significant swelling capacity, polyurethane resins are currently deployed successfully in the following cases (Dominijanni and Manassero, 2014):

- filling and stabilization of underground cavity;
- reduction of soils hydraulic conductivity;
- heaving of pavement and foundations in settlements problems;
- ground improvement and compaction.

Ground improvement and compaction with expanding polyurethane resins aim to increase soil density and soil mechanical parameters such as stiffness and strength. This type of treatment, often performed below existing foundations, can be considered part of the treatment methods related to compaction grouting techniques. However, this type of treatment is different from conventional compaction grouting techniques due to the physical and mechanical processes governing the expansion of the expanding polyurethane resin in the subsoil. The cavity expansion theory represents a relatively simple and reliable approach for modelling the changes in the stress state and the density of the soil induced by the expansion of the resin (Yu, 2000; ASCE, 2010; Dominijanni and Manassero, 2014).

Despite the possibility of using well-established design methodologies, the assessment of the success of the ground treatment with expanding polyurethane resins still represents a major challenge. When the ground treatment is performed before the construction of structures and buildings, it is possible to carry standard in-situ tests, such as cone penetration tests (CPT), to evaluate the achieved ground improvement. However, when the treatment is performed below existing structures, the use of standard in-situ testing equipment might not be feasible due to the space required for this type of equipment.

DOI: 10.1201/9781003308829-135

A solution to this issue is provided by the performance of reduced scale in situ testing, such as mini-CPT and small dynamic probing tests. This paper illustrates some examples of using these types of testing equipment, besides the adoption of CPT testing, to evaluate the effectiveness of the ground improvement with expanding polyurethane resin.

2 GROUND TREATMENT WITH POLYURETHANE RESINS

Polyurethane resins are obtained from the exothermic reaction occurring by the mixing of a polyol and an isocyanate. The swelling capacity is the key feature of this material, and it is responsible for a volume increase under unconfined conditions (null mechanical stress) of about thirty times (Dei Svaldi et al., 2005; Buzzi et al., 2008). When the resins are injected underground, the expansion process occurs in confined conditions leading to a compaction of the soil surrounding the injection point until a mechanical equilibrium between the resin and the soil is achieved. The injection can be performed at different depths using either several injection tubes with single-point injection at the bottom end of the tube or a single tube with several lateral injection points (multi-point). In both cases, the injections are performed with small tubes (external diameter of about 10-15 mm) and equipment, reducing the treatment's impact on the existing structure as much as possible.

From a design point of view, the cavity expansion theory represents an efficient tool that can be used by engineers (Yu and Houlsby, 1991; Shrivastava et al., 2018). In this framework, spherical cavities expansion can be considered when single point injection tubes are adopted for the treatment. On the other hand, when multi-point injection tubes are used, it is possible to consider a cylindrical cavity expansion (Figure 1). This design approach allows engineers to estimate the amount of a specific type of resin to be injected to obtain a given increase of the soil density and mechanical parameters.

The efficiency of the treatment depends on several factors, such as the type of soil, the presence of groundwater, the soil stiffness and strength, the injection layout, the amount and type of injected resin. When compaction is the aim of the treatment, the efficiency of the treatment is higher under drained conditions (Kovacevic et al., 2000).

In fact, under drained conditions, the mean effective stress increases monotonically, and the soil compresses along a compression curve for first loading, with a consequent increase in density, stiffness and shear strength.

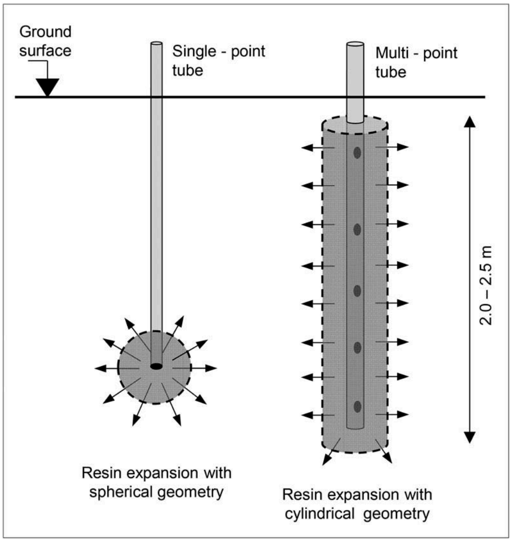

Figure 1. Schematic layout of the two types of tubes usually adopted for the injection of polyurethane resins, along with the expansion process of the injected resin.

Instead, under undrained conditions, the soil is not allowed to compress, and the mean effective stress decreases due to the formation of excess pore pressures. During the subsequent consolidation phase, the soil follows an unload/reload compression curve until the original mean effective stress is reached. However, because of the higher rigidity of the unload/reload compression curve with respect to the curve for first loading, the amount of compression is lower than that achieved under drained conditions.

Therefore, the use of polyurethane has to be firstly considered either in coarse-grained soil or in partially saturated fine-grained soil.

The evaluation of the soil geotechnical parameters is often performed with in-situ tests, such as dynamic and static penetration tests, using empirical correlations available in the scientific literature. Moreover, penetration tests may also be adopted to evaluate the efficiency of the treatment by comparing the results of the tests performed before and after the treatment in the soil surrounding the injection points. The role of in-situ testing is, therefore, fundamental not only for the design of the ground treatment but also for the assessment of the treatment efficiency.

3 IN-SITU PENETRATION TESTS

Beside the standard CPT test, the use of smaller equipment is often required to evaluate the effectiveness of the ground treatment with polyurethane resins. In the following two subsections, a brief overview of the miniature cone penetrometer (mini-CPT) and the medium-light dynamic probing penetrometer

(DPM 30-20) are introduced. These types of penetrometers have the advantage of being easy to transport, install, and use.

3.1 *Mini CPT*

The miniature cone penetrometer is a reduced scale cone with a diameter of 18 mm and an apex angle equal to 60°. Examples of the use of the mini cone penetrometer can be found in Squeglia and Lo Presti (2010), where this equipment has been adopted to develop an innovative methodology for the evaluation of the compaction degree of earth works, and in de Vries et al. (2018) where a comparison with standard CPT tests is illustrated. The cone is pushed downward in the soil at a constant rate equal to 2 cm/s by an electric motor. The tip resistance (q_c) is evaluated by a load cell placed above the penetrometer with maximum load of 5 kN and accuracy of 5 N.

The performance of mini-CPT tests is not common for soil geotechnical characterization. Therefore, this test method suffers of a lack of empirical correlations to estimate geotechnical parameters, as well as a direct comparison with the standard CPT test. To face this issue, mini-CPT tests are often carried out along with standard CPT or, in case this is not possible, with dynamic probing tests.

3.2 *Dynamic penetrometer DMP 30-20*

Dynamic probing tests (DP) consist of driving into the soil a steel cone located at the end of a set of driving rods by blowing the upper end of the rods with a specific hummer (Cestari, 2012). DP tests can be classified in different category (light, medium, heavy, super-heavy), depending on the hammer weight, falling height, cone size and geometry, rods size, etc.

In the framework of ground treatment with polyurethane resins, the use of a medium-light penetrometer, the DPM 30-20, is particularly considered in Italy. This equipment is based on the measurement of the blow number required for a penetration of the cone equal to 10 cm (N_{10}). Although this equipment is not included in any standard, its main features are similar to the standard light and medium dynamic penetrometer. The mass of hammer is 30 kg and falling height is 20 cm. The cone has a base diameter equal to 35.7 mm and an apex angle equal to 60° (Cestari, 2012).

Although the possibility to correlated the DPM 30-20 test results (N_{10}) to the standard penetration test (N_{SPT}), the main disadvantage of this type of test is represented by the absence of the measurement of the skin friction during the penetration of the cone. Therefore, the measured penetration resistance might be overestimated due to the missing contribution of the skin friction.

4 CASE STUDIES

In this section a series of case studies are presented, where the assessment of the effectiveness of the ground treatment with polyurethane resins is evaluated by performing standard CPT, mini-CPT and DPM 30-20 in situ tests. The examples refer to ground treatment works related to resin injections below shallow foundations of residential buildings.

4.1 *Case a)*

The first case study refers to the ground treatment performed below the plate foundation of a residential building that experienced differential settlements during construction. During the design phase, an in-situ testing investigation composed of four CPT tests was carried out. The map of the building is presented in Figure 2, along with the location of the four CPT tests. Figure 3 illustrates the tip resistance (q_c) profile obtained from the tests CPT-1 and CPT-2. From this outcome, the foundation soil can be roughly divided in a shallow layer of granular soil (mainly sand) with thickness equal to 3 m overlaying a deeper layer of fine-grained soil with a thickness equal to 7 m.

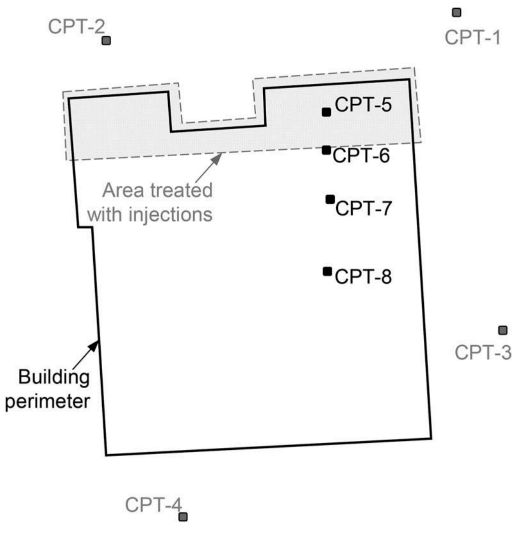

Figure 2. Map of the building along with the position of the four CPT tests (n.1 to n.4) performed before construction, the treated are with resin injections, and the four CPT tests (n.5 to n.8) performed after ground treatment.

As illustrated in Figure 2, the ground treatment was performed on the north side of the building, which was subjected to major settlements. The injection points were placed on a regular squared grid with spacing equal to 1 m, and they were performed first in correspondence of the building perimeter and then below the building. Moreover, the resin was injected first at a depth between -5 and -7 m with

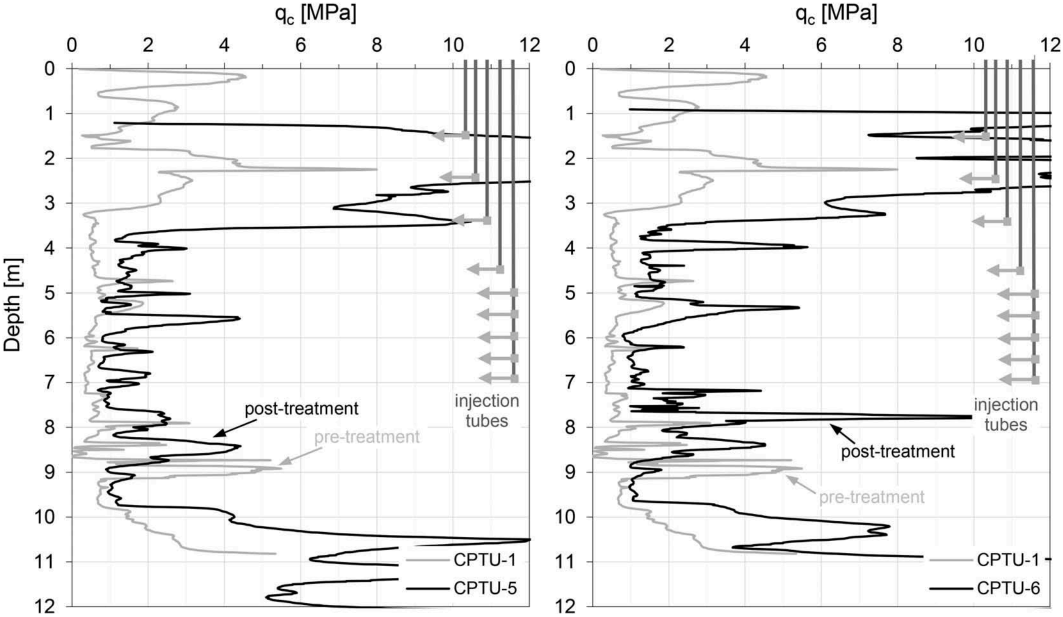

Figure 3. Comparison of tip resistance (q_c) profile between the CPT tests performed before (CPT-1) and after (CPT-5 and CPT-6) the ground treatment with polyurethane resins.

multipoint injection tubes. A second set of injection was then carried out at a shallower depth between -2 and -5 m with single-point injection tubes every 1 m.

A second series of in-situ tests, composed of four standard CPT, was performed after the ground treatment to evaluate the achieved improvement. The position of these tests is illustrated in the Figure 2 where the tests are numbered from 5 to 8. In particular, the CPT-5 and CPT-6 are carried out close the treated area, while the CPT-7 and CPT-8 are further and, therefore, less influenced by the injections.

Figure 3 shows a comparison between the tip resistance profiles obtained from the test performed before the treatment (CPT-1 is taken as a reference) and the tests performed after treatment (CPT-5 and CPT-6). In the shallow soil layer below the foundation (down to -3 m depth), a pronounced increase of the tip resistance is highlighted by both CPT tests (CPT-5 and CPT-6). The average value of q_c referred to this layer is higher than 10 MPa. On the other hand, in the in the depth range between -3 m and -7 m, the increase of the tip resistance exhibited by the two CPT tests is less pronounced. On average, the q_c value obtained from the two tests carried out after treatment is more than twice the average value measured before treatment.

4.2 *Case b)*

The second case study refers to the work carried out for the ground consolidation below an office building with dimensions equal to 15x7 m. The injections are performed along the building perimeter underneath the foundation starting from of a depth equal to 1.2 m. A combination of multi-point tubes and single point tube is adopted to treat a thickness of the ground equal to 3 m (from -1.3 m to -4.3 m). The injection points along the perimeter are spaced of 1 m.

Figure 4 shows the map of the building along with the location of the in-situ tests carried out to assess the efficiency of the treatment. Due to the presence of the existing structures, mini-CPT tests were adopted and performed in three different points. In each point, two tests were carried out one before and one after ground treatment. The two tests of each point were located close to each other to minimize the possible influence of different ground conditions.

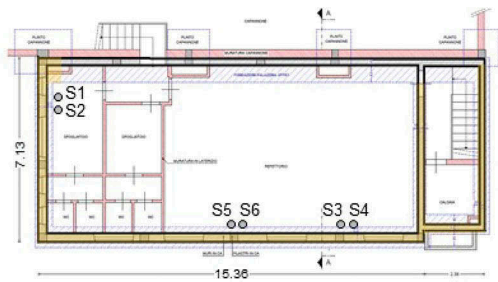

Figure 4. Map of the building illustrating the location of the mini-CPT tests performed evaluate the efficiency of the ground treatment.

Figure 5 illustrates the tip resistance profiles of the three mini-CPT tests performed before ground treatment. From these findings, the soil can be mainly classified as sand-silt mixture. In particular, the test S5 exhibited the lower tip resistance, highlighting the presence of silt/clayey silt below a depth equal to -3 m.

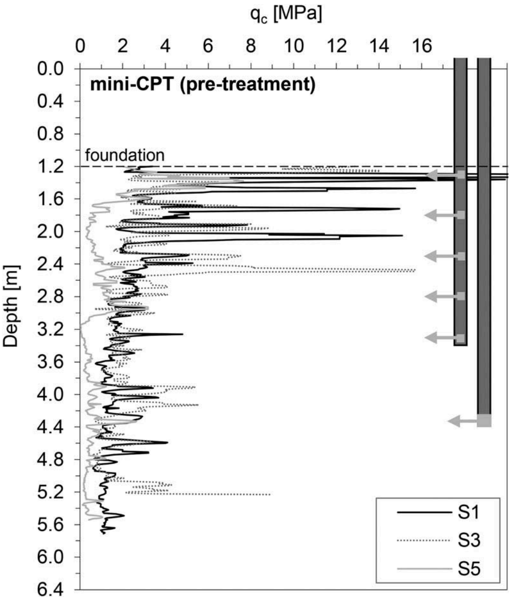

Figure 5. Tip resistance (q_c) profile of the three mini-CPT tests (S1, S3, S5) performed before the ground treatment.

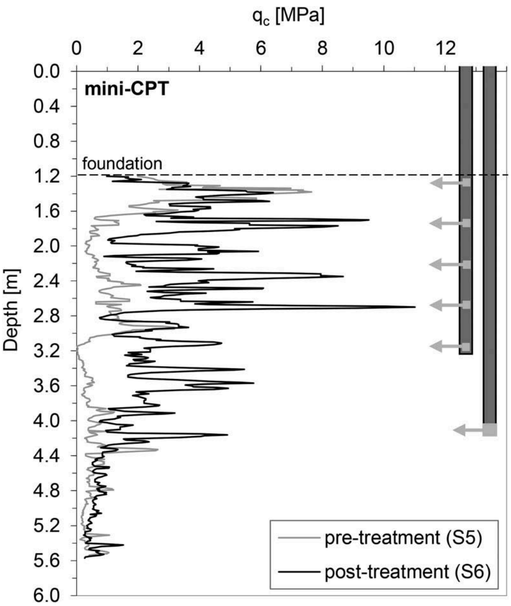

Figure 6. Comparison of the tip-resistance profiles obtained from the mini-CPT tests S5 and S6 performed before and after ground treatment.

The evaluation of the ground treatment is carried comparing the tip resistance profiles from two mini-CPT tests performed before and after treatment. In Figure 6 is illustrated an example obtained from the mini-CPT S5 and S6. The graph clearly highlights the increase of tip resistance measured at depths corresponding to the resin injection.

In the range between -1.3 m and -2.8 m the tip resistance increased from 1.6 MPa to 4.0 MPa, while in the range between -2.8 m and -4.3 m the tip resistance increased from 0.6 MPa to 2.4 MPa.

4.3 *Case c)*

The last case study illustrates the treatment with polyurethane resins of the ground foundation below an existing residential building. The treatment involved just part of the building as illustrate in the Figure 7. The injections were performed below the building foundation located at -1.2 m depth and along the perimeter of the building, with a spacing equal to 1 m, using multi-point tubes. The thickness of the soil layer treated is 2 m, from -1.2 m (depth of the foundation) to -3.2 m. The ground below the foundation is mainly composed of a mixture of loose fine soil and gravel.

In this example, the efficiency of the ground treatment was evaluated with dynamic probing tests, adopting the medium-light penetrometer DPM 30-20. As illustrated in the Figure 7, two DPM 30-20 tests were carried out: P1 before the treatment and P2 after the treatment.

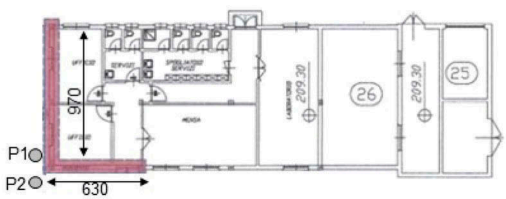

Figure 7. Map of the building along with the location of the treatment zone and the location of the DPM 30-20 tests performed before (P1) and after (P2) the ground treatment.

Figure 8 shows the results of both the two DPM 30-20 tests. From the results of the test P1, two soil layers were identified: (i) from -1.2 m to -2.3 m with an average N_{10} value equal to 7 and (ii) from -2.3 m to -3.3 m with an average N_{10} value equal to 2.4. After the treatment, the performed DPM 30-20 test highlighted an increase of the average N_{10} value for both layers. In particular, the layer 1 exhibited an average value equal to 27, while the layer 2 exhibited an average N_{10} value equal to 21.

A design tool based on the cavity expansion theory in a finite medium (Uretek, 2021) was used to assess the achieved ground improvement in terms of increase in relative density and to verify the amount of resin injected. A perfect elasto-plastic Mohr-Coulomb model with a non-associated flow rule was adopted for the soil, considering two sets of parameters for the two different layers (Table 1). As the spacing of the injection

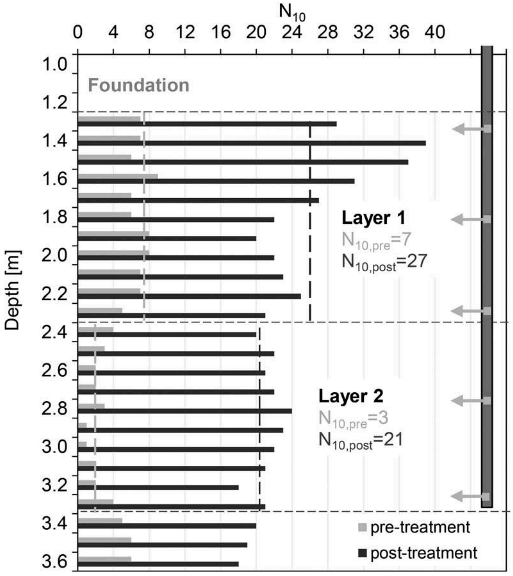

Figure 8. Comparison of the test results in terms of N_{10} obtained from the tests performed before (P1) and after (P2) the ground treatment.

holes was equal to 1 m, the radial distance of the fixed (no-displacement) boundary of the medium was set equal to 0.5 m, i.e. half of the injection hole spacing. The average increase in relative density obtained from the theoretical analyses was 12% for layer 1 (from 31% to 43%) and 21% for layer 2 (from 17% to 38%). The total amount of resin required to obtain such improvement resulted in being equal to 18.3 kg, which is in good agreement with the amount of resin injected in-situ (16.9 kg). This example highlights the potential of the cavity expansion theory to simulate ground behavior when treated with expanding polyurethane resins.

Table 1. Parameters of the soil adopted for the calculations.

Layer	1	2
Unit weight [kN/m^3]	18	18
Young modulus [MPa]	10	6
Poisson ratio [-]	0.25	0.25
Shear strength angle [°]	34	34
Cohesion [kPa]	0	0
Dilatancy angle [°]	-5	-8
Max void ratio [-]	0.65	0.65
Min void ratio [-]	0.30	0.30
Initial void ratio [-]	0.541	0.589

5 CONCLUSIONS

Expanding polyurethane resins represent a valid alternative to conventional grout for ground improvement and compaction. The effectiveness of the ground treatment can be assessed by performing in-situ tests with static and dynamic penetrometers. This paper presents a series of case studies where standard CPT, mini-CPT, and DPM 30-20 tests were adopted.

The main advantage of the standard CPT test is the possibility of using the test results not only for treatment performance evaluation but also for the geotechnical characterization of the subsoil. However, it is often difficult to adopt such equipment when the treatment is carried out inside an existing structure.

The reduced size of the mini-CPT and DPM 30-20 equipment represents their main advantage. On the other hand, the lack of well-established empirical correlations to estimate soil geotechnical parameters from these tests is their main drawback.

Based on the examples presented in this work, all three in-situ tests can be regarded as suitable tools to assess the efficiency of the ground treatment with expanding polyurethane resins.

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