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Improvement of foundation soil behavior for Gründerzeit buildings in Austria using polyurethane resin injections

A. Dominijanni
Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Torino, Italy

M. Gabassi
Uretek Italia SpA, Bosco Chiesanuova (VR), Italy

F. F. Kopf
Chiari & Partner ZT GmbH, Wien, Austria

A. Minardi
Geotechnical Engineering, Torino, Italy

A. Pasquetto
Uretek Injektionstechnik GmbH, Vienna, Austria

ABSTRACT: The second half of the XIX century signed a period of comprehensive industrial and cultural development in Austria known as Gründerzeit. The architecture was deeply influenced during this epoch by the construction of large masonry buildings, called "Gründerzeit Häuser", which represent today the historical heritage of the most important Austrian cities. Due to the increasing demand for apartments in the centre of these cities, renovations and adaptations of existing buildings has been performed in the last decades. These modifications of the buildings structure represent, besides a business opportunity for the real estate economy, an increase/variation of the load for the foundations. Hence, the renovation and preservation of this architectural heritage often involve the improvement of the foundation soil. This article illustrates how the soil treatment with expanding polyurethane resin represents an efficient solution to achieve this goal. A case study of a historic building in the city of Salzburg is presented.

1 INTRODUCTION

The period from 1840 until the First World War in 1914 is known in Austria as the "Gründerzeit". During this period, residential constructions in Vienna, and other major cities in the country, developed significantly and the typical buildings of Vienna were built (e.g. buildings on the *Ringstrasse*), which still characterize the cityscape today and give the city its special flair.

During the "Gründerzeit", residential constructions also became interesting for the middle classes. This changed the shape of the houses. The plots of land, which had previously comprised an entire street block, were divided because the middle-class builders could not afford to build an entire block. This so-called "edge block development" characterized residential buildings until about 1918, with the individual houses being completely independent of each other. Entire neighbourhoods were built with this architectural concept in the major Austrian cities starting from 1840. Vienna's population grew exponentially, exceeding the two-million mark at the turn of the last century. In 2019, Statistics Austria counted about 32,400 buildings built before 1919, the vast majority from the Gründerzeit era, that is about 20 per cent of all Viennese buildings.

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Some of the Gründerzeit houses were built in "Jugendstil" (Art Nouveau style), which was all the rage at the time. First and foremost, the architects Otto Wagner and Josef Hoffmann shaped the image of the Austrian capital. These names alone cover a large part of Vienna's Art Nouveau architecture. The facade decoration is typical for Viennese houses. However, the facade design was relatively independent of the standard of the houses. Above all, the size of the apartments, the lighting, the sanitary and technical equipment differed greatly. The magnificent facades were intended to conceal the low standard.

The typical Gründerzeit house consists of 4 to 6 floors with large room heights (3.5–4.5 m), whereby the ground floor (parterre) was often executed higher than the other floors. The first floor was often dedicated to the lord of the house or wealthy residents and was particularly sumptuously executed, had higher rooms and sometimes a balcony on the street side. It was therefore a prestige to live on the "first floor". Often, however, it was only the second floor that was executed in a stately manner. In this case, the floor below was only called "Mezzanin" (mezzanine) and only the second floor was considered "first floor". The walls were made of brick masonry with different thickness (gradation over the floors). The floor ceilings are wooden truss ceilings (wooden beam ceilings) and stretched across the street between the perforated façade, the middle wall and the courtyard façade.

The design of the Viennese Gründerzeit houses was regulated by law in the building code, which contained many construction features. For example, the permissible foundation loading was also specified in the building code in 1902. Considering the different types of ground (e.g. loose or dense gravel) values between 350 kPa and 600 kPa were considered.

Today, renovations, adaptations and additional loads represent a much greater problem. After the Second World War, damaged houses were often provisionally rebuilt and, from the 1970s onwards, many ground floors were stripped of their bracing walls and converted into commercial premises. In recent decades, attic conversions and raising of the structures have been made, leading to further additional loads for the foundation soil. Almost all cases of failure in the foundations of Gründerzeit houses can be traced back to such adaptations and usually occur during improper construction activities.

It has been shown that careful handling of the historic buildings is necessary in order to preserve this cultural heritage. Therefore, it is appropriate to proceed with the right methodology and with the appropriate expertise also in the renovation and reinforcement of foundations of the Gründerzeit buildings.

In this framework, the treatment of the foundation soil with expanding polyurethane resins represents a valid solution. This method can be considered part of the compaction grouting techniques (ASCE 2010). However, compared to conventional technologies based on the use cement grout, the use of polyurethane resins is significantly less invasive. The small size of the equipment adopted to perform the injections of resin in the subsoil allow operators to carry out this treatment in narrow spaces, such as building basement, with a minimal impact on the people living in the building. This feature of the treatment technique makes it very suitable in a large variety of works due to the reduced impact on the existing structure. This article presents an application of this compaction grouting technology to a historic building in Austrian city of Slazburg for the improvement of the foundation soil. An overview of the treatment methodology based on the use of polyurethane resin and design approach is initially illustrated, along with some general examples of works carried out on Gründerzeit buildings in the city of Vienna, the Austrian capital. Then, the case study is presented in detail, to highlight the key aspects of the design and execution of the foundation soil treatment with expanding polyurethane resins.

2 GROUND TREATMENT WITH EXPANDING POLYURETHANE RESINS

2.1 *Description of the technology plus the method*

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 (Buzzi et al. 2008; Dei Svaldi et al. 2005). 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 is achieved between the resin and the soil (Dominijanni & Manassero 2014). 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 impact on the existing structure as much as possible. Figure 1 shows an example of the drilling operations carried out with a portable drill, and the equipment adopted to perform the injection of the resin in the installed tube from the ground surface.

Figure 1. Example of operations: a) Drilling of the borehole; b) Equipment for the injection of the expanding polyurethane resin.

From a design point of view, the cavity expansion theory, either in an infinite or in a finite medium, represents an efficient tool that can be used by engineers (Dominijani & Manassero 2014; Dominijanni et al. 2020; Shrivastava et al. 2018; Yu 2000; Yu & Houlsby, 1991). 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 assume a cylindrical cavity expansion (Figure 2). This design approach allows engineers to estimate the amount of a specific type of resin to be injected and achieve 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 injections, the efficiency of the treatment is higher under drained conditions (Kovacevic et al. 2000). Indeed, 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.

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.

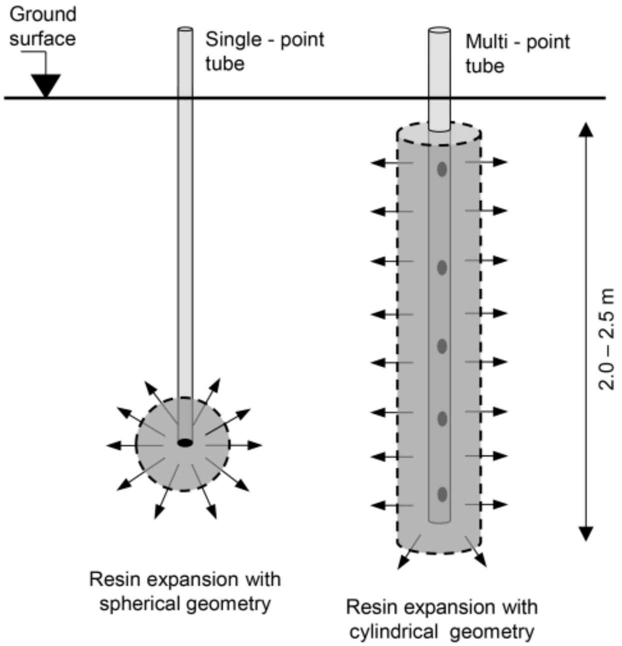

Figure 2. Schematic layout of the two types of injection tubes adopted for the injection of polyurethane resins, along with the underground expansion process of the injected resin.

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

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.

2.2 *Examples related to historical buildings in Austria*

In the last 15 years, the soil treatment methodology with polyurethane resins has been adopted for several historical buildings located in the most important Austrian cities, such as Vienna, Salzburg and Linz. As stated in the introduction, the main motivation for these works is the improvement of the foundation soil to cope with additional loadings due to renovation works and, in some cases, raising of buildings with the construction of an additional top floor. In most of the cases, the ultimate goal of the treatment is the compaction of the ground and the filling of fissures, fractures and cavities in the soil below the foundation, in order to prevent possible settlements induced by the modifications of the buildings structure.

An example of four historical buildings in Vienna, constructed during the Gründerzeit period, which have been subjected to soil foundation treatment with polyurethane resins for the construction of attics and/or renovation works, is illustrated in Figure 3. In all of the four cases, the buildings have shallow foundations at a depth in the interval 0.6–2.0 m below the ground surface. In this framework, the injections have been performed underneath the foundation beams. For the building in the image a) (Figure 3), about 260 m linear of strip foundations at a depth interval of 1.3–1.5 m were treated in 20 days of work. For the building in the image b), about 350 m linear of strip foundations at a depth of 2.0 m were treated in 25 days of work. These two works were performed for the construction of an additional attic floor. For the buildings in the images c) and d) (Figure 3), about 200 m linear and 50 m linear of strip foundations were treated in 18 and 5 days, respectively; in these two last cases, the treatment aimed at the improvement of the foundation soil for settlements mitigation occurred during and after renovation works of the structures. In all the illustrated examples, the foundation soil was mainly composed of a silty sand/gravel. This feature has made the treatment of polyurethane resins extremely attractive. The performed works allowed the stabilization and improvement of the foundation soil, which is usu3ally assessed through settlements monitoring system.

Figure 3. Overview of Gründerzeit buildings in the city of Vienna that undergone foundation soil treatment with expanding polyurethane resins.

3 CASE STUDY OF A BUILDING IN SALZBURG

In this section, the case study of a building constructed in the XIX century, during the Gründerzeit period, in the Austrian city of Salzburg is presented in detail. The building, heavily damaged during the Second World War, was subjected to significant renovation works in 1961. Beside the renovation of the structure, the building foundations were also reinforced in the southern part with the installation of piles. However, the foundations of the northern part of the structure did not undergo any type of reinforced. Hence, the treatment with polyurethane resin has been foreseen to improve the foundation soil in the north part of the building, with the final aim of stopping the settlements and stabilizing the fissures network that have been occurred in this area of the building after the renovation works. Currently, this building has not been considered for the construction of an additional top floor and the treatment has not been designed to support a possible increment of the load.

3.1 *Description of the building*

4The structure of the building is composed of four floors above the ground and one underground floor. In Figure 4 are reported some pictures of the building from the main street, named Schwarzstrasse. The level of the basement is placed at a depth equal to 2 m from the ground surface (418.60 m a.s.l.). The strip foundations of the building have a width equal to 1 m and are located 1 m below the basement level (i.e. 3 m below the ground level). The foundations are composed of rock blocks obtained from the dismantling of the historical boundary wall of the old city.

Figure 4. Overview of the building in Salzburg: a) north side of the building; b) west side and main entrance of the building; c) south side of the building.

Before starting the treatment, the foundation soil has been investigated by performing a geotechnical survey until a depth equal to 12 m from the ground level on the north side of the building. Moreover, a shallow trench has been excavated until a depth of 3.70 m from the ground surface and nine dynamic penetration tests have been performed with the DPM 30-20 penetrometer (Cestari 2012) on the entire area of the north part of the building. Overall, the subsoil is mainly composed of the Salzach gravel until a depth equal to 10 m. In some areas, this course material shows the presence of significant lenses of fine soil (main silt and sandy-silt). From the geotechnical survey the stratigraphy of the subsoil has been reconstructed as follows:

- from to ground surface to a depth equal to 2.8 m the ground is mainly composed of a backfill soil used during the construction of the whole district close to the Salzach river;
- from 2.8 m to 5.8 m there is a sandy-gravel (Salzach gravel);
- from 5.8 m to 7.2 there is a silty-sand soil with gravel;
- from 7.2 to 10 m there is a sandy gravel (Salzach gravel).

A layout of the subsoil stratigraphy along with the foundation and basement scheme is presented in Figure 5. The additional results of the nine dynamic penetration tests have highlighted the heterogeneity of the foundation soil. Indeed, the tests carried out on the north-west side (of the north part) of the building have exhibited the presence of a fine soil (mainly silty lenses) from the ground surface until a depth equal to about 6–7 m on top of the underlying gravel layer. On the east and south sides (of the north part) of the building, the penetration tests have highlighted the presence of a stiffer material also at a shallower depth, from 1.5 m to 6 m. This heterogeneity of the subsoil between the east and west sides can be considered among the main causes responsible for the differential settlements of the building that mainly occurred on the north part of the building.

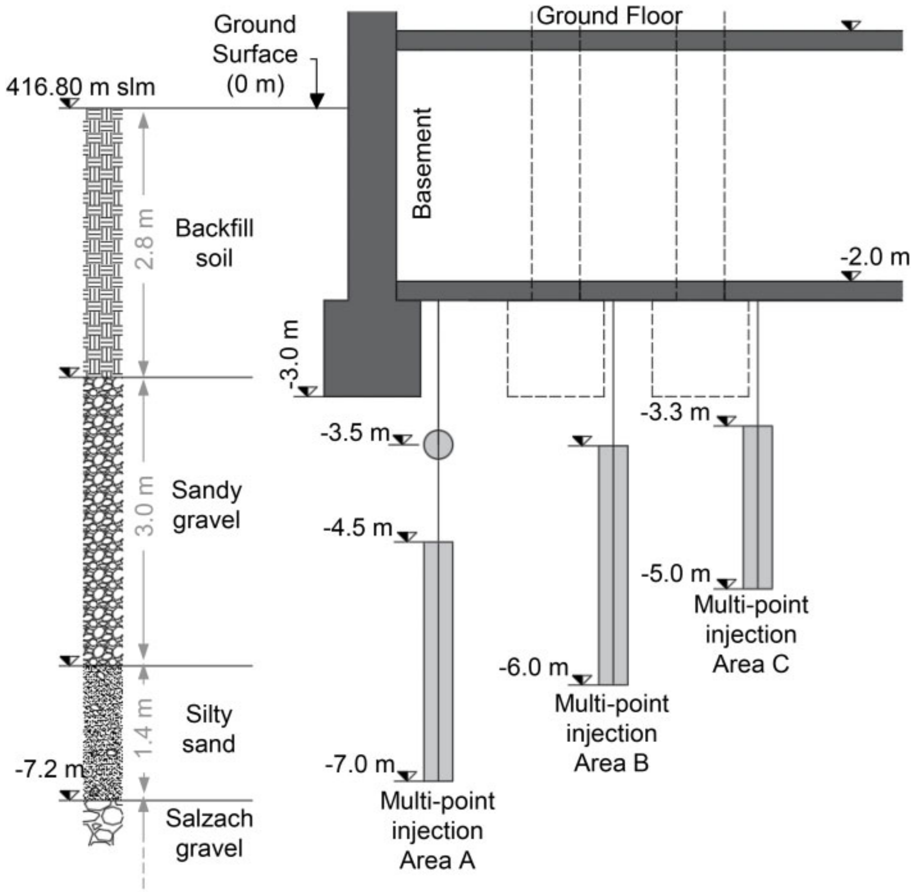

Figure 5. Schematic layout of the building strip foundations, along with the stratigraphy of the subsoil and the layout of the polyurethane resin injections performed in the different areas of the building.

Direct measurements of settlements have not been performed, neither in the past nor in recent time. However, evidence of these settlements has been given by the fissure network observed in the masonry walls and pillars of the basement level of the building, with openings in the order of several millimetres to centimetres (Figure 6). Some of these fissures have been filled in the past with cement, although most of them have been subjected to reopening. This aspect has suggested the progressive occurrence of settlements of the building during years, probably starting after the renovation works performed in 1961. A further contribution to the settlements of the building has been given by the deepening of the Salzach riverbed of about 3 m, which has been induced by the increase of the river flow starting from 1959. This factor has been responsible for a progressive lowering of the water table in the surrounding soil and the consequent consolidation settlements of the fine soil layers. Currently, the water table has been monitored with a piezometer installed in the performed geotechnical survey and its level, highly influenced by the Salzach river located about 100 m away from the building, has been found to oscillate in the interval −5 to −6 m from the ground surface.

Considering the combination of these two possible causes of settlements, the subsoil heterogeneity between the east and west side and increase of the effective stress due to the lowering of the water table of 3 m, a simple back calculation of the building differential settlements has been made adopting the theory of elasticity. Considering a stiffness of the fine soil layer equal to about 1/10–1/20 of the stiffness of the sandy-gravel layer, the differential settlements between the east and west sides are estimated in the interval 1.5 to 5 cm. This evaluation has to be considered as lower limit because it does not take into account the settlements that occurred after the renovation work performed before 1961, for which there are no information and data available.

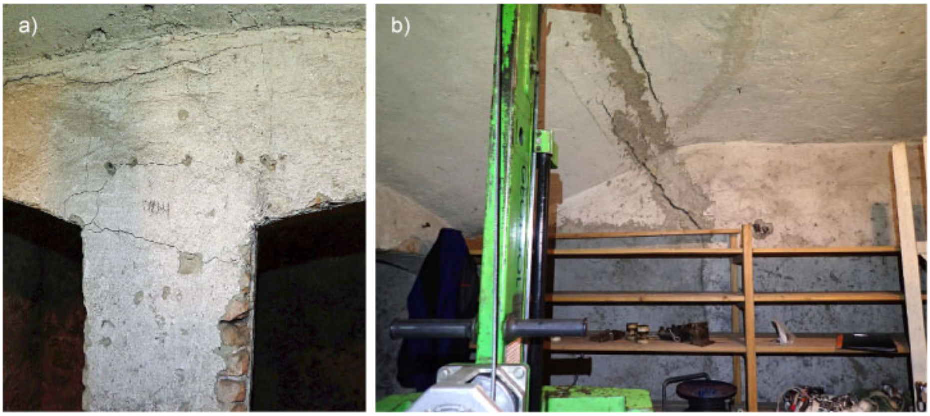

Figure 6. Examples of fissures in the masonry walls and pillar of the building structure in the basement.

3.2 *Design approach*

The treatment of the foundation soil has been foreseen only for the north part of the building, as the south part of the building has been already subjected to the installation of piles. The Figure 7 shows the layout of the basement level along with the position of the strip foundations (grey areas) interested by the treatment with polyurethane resins (dashed lines). The injections have been carried out on the entire perimeter of the building, with a spacing equal to 0.7 m in most of the cases. Inside the perimeter of the building, the spacing of the injections is increased to approximately to 1 m. The injections have been performed from the basement level adopting the multi-point methodology, which allows the treatment of a given soil thickness with a single injection tube. In the area A (Figure 7) of the building, the multi-point method has been combined with shallower single-point injections.

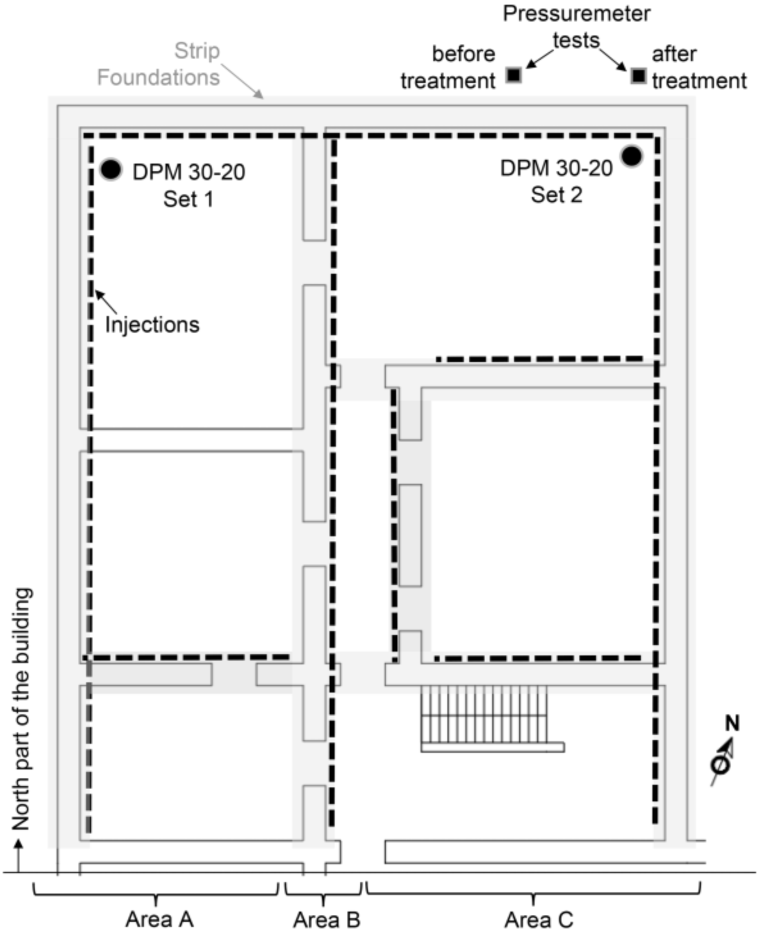

Figure 7. Layout of the basement level along with the position of the strip foundations (shaded areas), the location of the injections (dashed line) and in-situ tests (DPM 30-20 and pressuremeters).

As illustrated in the Figures 5 and 7, the maximum depth of the treatment is higher in the area A (-7.0 m from the ground surface), than in the areas B (-6.0 m) and C (-5.0 m), leading to different total thickness of the treated soil. In all the three areas, the injections have been designed to start the treatment underneath the strip foundations. Due to the higher depth achieved by the treatment in the area A, an additional shallow injection has been performed at a depth equal to 1.5 m below the basement level. This injection, carried out with the single point tube, is placed right underneath the foundation, and it has the main goal of filling voids and fissures at the interface between the foundation blocks and the ground to improve their contact. This difference among the injection schemes is related to the presence of softer soil (higher amount of fine soil) until a depth of 10 m on the west side with respect to the east side of the building. Overall, considering the underground stratigraphy highlighted by the survey and the dynamic penetration tests, the underground treatment with polyurethane resins mainly involved the gravel and sand layers below the foundations.

A series of in-situ tests has been performed to assess the efficiency of the treatment. Two sets of dynamic penetration tests have been carried out with the DPM 30-20 penetrometer. Each set is composed of two tests, one carried out before the treatment and the other performed after the treatment. The reduced size of this equipment has allowed the operators to perform these tests directly from the basement level close to the injection points (about 0.5 m). The tests are located in two points in the north side of the building, as illustrated in the Figure 7. The achievement of a 50% increase of the average N_{10} value, which represent the blow number for a penetration of 10 cm, over the treated layer of soil has been set as a goal for the treatment.

In addition to the dynamic probing tests, pressuremeter tests have been carried out to evaluate the efficiency of the treatment. These tests have been performed with the Ménard pressuremeter from the ground surface and are located outside the building perimeter on the north side (area C in Figure 7), as close as possible to the external wall. The tests have been performed at two depth levels below the ground surface: −3.5 m and −5 m. For each depth, one test has been carried out before the treatment and one after the treatment.

The final objective of the treatment with the injection of polyurethane resins is the stabilization of the fissures network, which will be evaluated during the months after the treatment.

4 RESULTS

During the performance of the entire treatment period, which lasted eight days, the building has been monitored with a topographic system to assess possible displacements induced by the injection and expansion of the polyurethane resin underground. This monitoring system allows the operators to stop the injection immediately in case of the occurrence of excessive displacements. No unwanted displacements have been observed during the injection process, confirming the potential of this treatment technique and the correct design and execution of the work.

The results of the in-situ tests have highlighted the efficiency of the treatment. The results of the dynamic penetration tests (DPM30-20), in terms of N_{10} (blow number for a penetration of 10 cm) versus depth, are illustrated in Figure 8.

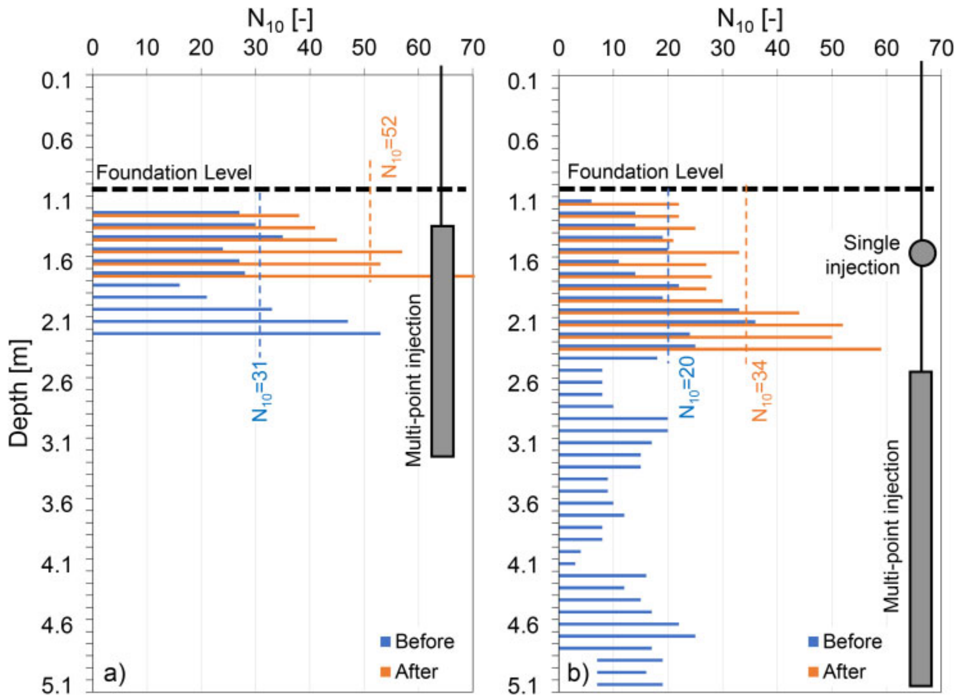

Figure 8. Results of the dynamic probing tests performed before and after the treatment with the DPM 30-20 penetrometer: a) Set 1 of tests on the north-east side; b) Set 2 of tests on the north-west side.

The first set of tests (Set 1 in Figure 8), carried out in the north-east side of the building, has investigated a relatively small portion of the subsoil. The test performed before the treatment achieved a depth equal to 2.2 m, corresponding to a thickness of soil of about 1 m. The average value of N_{10} in this interval is equal to 31. The test carried out after the treatment has been stopped at a depth equal to 1.7 m below the basement level, where $N_{10} = 81$ and the average value of N_{10} in the entire interval is equal to 52. Considering the soil layer thickness investigated after the treatment (from 1.1 m to 1.7 m below the basement level), the average increase of N_{10} is equal to 68% and, therefore, higher than goal set for the treatment (50%).

The second set of tests (Set 2 in Figure 8), carried out in the north-west side of the building, has investigated a larger portion of the foundation soil. The test performed before the treatment has achieved a depth equal to 5.1 m below the basement level, confirming the presence of a softer soil with respect to the east side. This finding highlights in particular the decrease of penetration resistance from 2.5 m below the basement level until the end of the tests at a depth of 5 m. The average N_{10} value until 2.4 m is equal to 20. The test carried out after the treatment has been stopped at a depth equal to 2.3 m below the basement level, where $N_{10} = 59$. A progressive increase of the penetration resistance with depth is observed in the soil after the treatment. The average value of N_{10} in this portion of the subsoil is equal to 34. Considering the soil thickness investigated after the treatment (from 1.1 m to 2.3 m below the basement level), the average increase of N_{10} is equal to 70% and, therefore, higher than the goal set for the treatment (50%).

A design approach based on the cavity expansion theory has been used to assess the performed treatment and verify the amount of resin injected. In the following, it is presented an example of a validation of the theoretical model based on the Set 2 of DPM 30-20 tests, for the shallow soil layer below the foundation, from a depth equal to 1.1 m to 1.9 m.

In this depth interval, the average value of N_{10} is equal to 15 before the treatment, which corresponds to a N_{SPT} value equal to about 14. The corresponding value of relative density, estimated according to Skempton (1986), is equal to 27%.

A perfect elasto-plastic Mohr-Coulomb model has been adopted for the theoretical estimation of soil densification. The soil parameters, obtained from the geotechnical investigation, have been assumed as follows: unit weight $\gamma = 18\,kN/m^2$, Young' modulus $E = 40$ MPa, Poisson's ratio $\nu = 0.3$, cohesion $c' = 0$ kPa, shear strength angle $\varphi' = 32°$, initial void ratio $e = 0.74$. Considering the treatment layout presented in Figure 7, the analysis has been carried out considering the expansion of a cavity in a finite medium with an external fixed boundary with a radius equal to 1 m. The analytical solution developed by Shrivastava et al. (2017) has been used to calculate stress and strain variation in the ground, following the procedure described in Dominijanni et al. (2020).

The results of the analysis are illustrated in Figure 9. The graphs show the evolution with radial distance from the injection point of the calculated relative density and N_{SPT} value. The relative density achieves a maximum value close to the expanded resin bulb equal to about 32%, and it decreases progressively to a value equal to 29% in the elastic region of the soil. The graph b) illustrates the evolution with the radial distance of the calculated N_{SPT} value. Also in this case, the maximum value is achieved close to the injection point ($N_{SPT} = 39$), and it decreases gradually to a value equal to $N_{SPT} = 20$ in the elastic region. At a radial distance equal to 0.5 m from the injection point, the N_{SPT} value is equal to 23. This value is in good agreement to the average N_{SPT} value, equal to 24, that has obtained for the same depth interval from the DPM 30-20 test performed in-situ after the treatment. This outcome has been obtained considering an amount or resin injected equal to 20 kg, which is equal to the average amount of resin injected in a single point for the treatment of 1 m of soil.

The increase of the penetration resistance (expressed int terms of N_{10} and N_{SPT}) is related to the increase of both the relative density and the mean stress in the ground. These factors are responsible for an increase in soil stiffness, which has been also evaluated with the pressuremeter tests. The results of the pressuremeter tests performed at a depth of 3.5 m are illustrated in the in Figure 10. The comparison of the two curves highlights an overall stiffer mechanical response of the soil after the treatment with polyurethane resins. In particular, the difference between the two tests can be

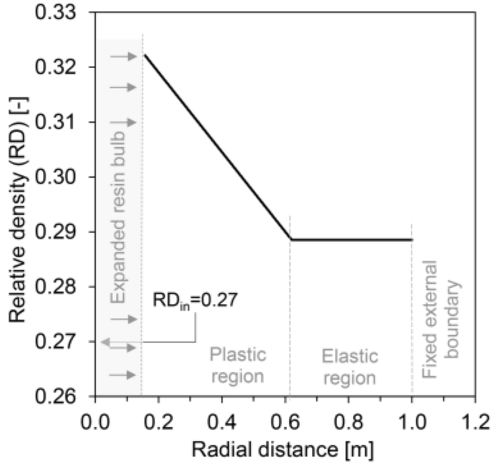

Figure 9. Results of the analysis carried out with cavity expansion theory in a finite medium to evaluate the increase of relative density (a) and blow number NSPT (b).

observed during the first loading of the curves (up to a pressure of about 0.8 MPa), as well as during the unloading phases of the stress cycle. During the first loading, the deformation modulus (E_{PMT}) has increased from 18 MPa to 26 MPa, while during the unloading phase the modulus has increased from 44 MPa to 66 MPa. Similar results have been observed for the pressuremeter tests carried out at a depth equal to 5 m below the ground surface (Figure 10). In this case, the deformation modulus has increased from 22 MPa to 24 MPa during the first loading, and from 46 MPa to 70 MPa during the unloading phase. With respect to the tests performed at a depth of 3.5 m, the lower increase of stiffness during the first loading is related to the higher stiffness of the natural soil at a depth of 5 m. In addition, it has to be considered that, in the area C the injections have achieved a depth equal to 5 m, therefore the influence of the treatment is expected to be less pronounced with respect to the shallow injection performed at a depth of 3.5 m.

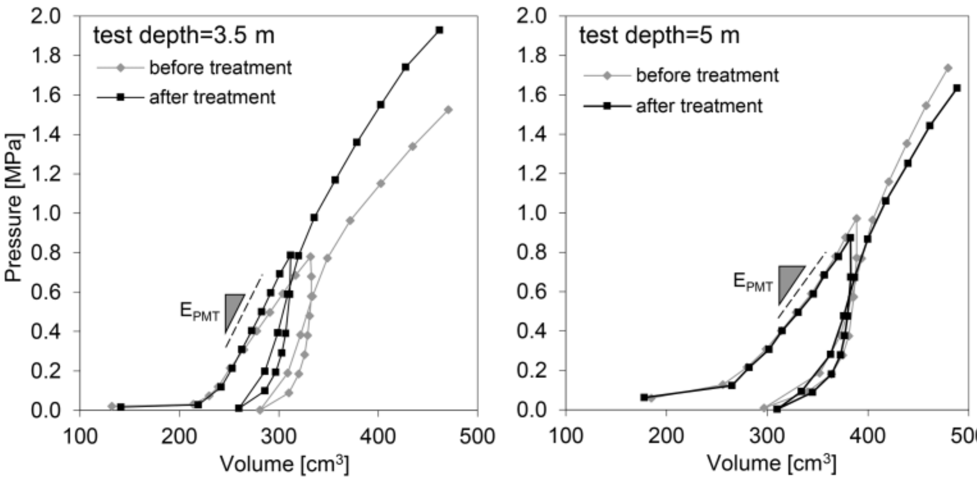

Figure 10. Results of the pressuremeter tests performed before and after the treatment with expanding polyurethane resins at depths of 3.5 m and 5.0 m.

5 CONCLUSIONS

The paper has presented the application of a compaction grouting technique based on the use of expanding polyurethane resins for the improvement of the foundation soil of historical buildings constructed in Austria during the Gründerzeit period.

A detailed case study of a building in the city of Salzburg has highlighted the key features of this ground treatment technology, including the application of the cavity expansion theory for the design of the treatment, and the use of dynamic probing tests and pressuremeter tests to assess the efficiency of the treatment. Beside the achievement of the goal set for the treatment in terms of penetration resistance, the success of the treatment is currently under evaluation with the analysis and monitoring of fissures network, observed in the basement level, that might develop again in the future due to the occurrence of further differential settlements.

The outcome of the presented case study, as well as of other works carried out for Gründerzeit buildings in the city of Vienna, have pointed out the potential of this treatment technology to improve the foundation soil behaviour. Therefore, the injection of expanding polyurethane resins can be considered as a potentially effective technology for the preservation of these historical buildings when subjected to renovation works, as well as raising with the construction of an additional top floor.

REFERENCES

ASCE (American Society of Civil Engineers). 2010. Compaction ground consensus guide, ASCE Standard ASCE/G-I 53-10. ASCE.

Buzzi, O., Fityus, S., Sasaki, Y., e Sloan, S. 2008. Structure and properties of expanding polyurethane foam in the con-text of foundation remediation in expansive soil. Mechanics of Materials 40,1012–1021.

Cestari, F. 2012. In situ geotechnical tests. Pàtron editore.

Dei Svaldi, A., Favaretti, M., Pasquetto, A., e Vinco, G. 2005. “Modellazione analitica del miglioramento del terreno attraverso iniezioni di resina ad alta pressione d’espansione.” 6th International Conference on Ground Improvement Techniques, Coimbra, Portogallo.

Dominijanni, A., Manassero, M. 2014. Consolidamento dei terreni con resine espandenti: guida alla progettazione. McGraw-Hill.

Dominijanni, A., Manassero, M., & Minardi, A. 2020. Codice di calcolo numerico per l’analisi di iniezioni con resine poliuretaniche espandenti mediante tubi multiforo, Uretek Italia SpA, technical report, 1–118.

Kovacevic, N., Potts, D. M., & Vaughan, P. R. 2000. The effect of the development of undrained pore pressure on the efficiency of compaction grouting. Geotechnique, 50(6), 683–688.

Shrivastava, N., Zen, K., Shukla, S. K. 2017. Modeling of compaction grouting technique with development of cylindrical cavity expansion problem in a finite medium. Inter-national Journal of Geosynthetics and Ground Engineering, 3(4), 1–12.

Skempton, A. W. 1986. Standard penetration test procedures and the effects in sands of overburden pressure, relative density, particle size, ageing and overconsolidation. Geotechnique, 36(3), 425–447.

Yu, H. S. (2000). Cavity expansion methods in geomechanics. Springer Science & Business Media.

Yu, H. S., Houlsby, G. T. 1991. Finite cavity expansion in dilatant soils: loading analysis. Geotechnique, 41(2), 173–183.