Restoring the foundation of a historic Viennese building using injections of expanding polyurethane resins

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ABSTRACT

During the investigations conducted prior to the construction of an underground railway, it became clear that the foundations of a listed event building, erected in 1887, were severely deteriorated and no longer load-bearing. The timber pile foundations, which were originally positioned above the groundwater level, had completely rotted away, leaving only voids where the original foundations once existed. As a result, the load-bearing capacity could no longer be verified, and in some areas, the foundations were entirely hollow. Refurbishment was necessary, as constructing an underground railway beneath a building in this condition was impractical. The building had recently undergone renovation, including refurbishments in the basement, so a minimally invasive solution was required. The chosen soil improvement method involved using hand drills to reach the base of the foundation and injecting an expanding two-component urethane resin to fill the voids. The expanding material creates a friction-locked connection; although it is technically possible to lift the building, this is not desirable. After the injection, exploratory excavations were conducted at two test pits. It was found that the cavities had been successfully filled and that the injection material permeated through the loess clay in fine veins, demonstrating the effectiveness of the method. The treatment was then extended to the entire foundations of the building to restore the uniform distribution of the loads to the foundation soil.

Keywords: Vienna, foundations, polyurethane resins, injection, timber piles

INTRODUCTION

The WUK is one of Vienna's most vibrant cultural institutions, hosting concerts, exhibitions, workshops, and community events. It is considered a symbol of independent culture and it is an example that historic spaces can reinvent themselves for modern needs while keeping their unique character intact. The WUK building (Figure 1) originally served as a factory for machines and locomotives, operating from 1855 until the mid '80s. Like many businesses of the time, it suffered during the stock market crash of 1873. It managed to survive for another decade thanks to prestige projects, including producing the stage machinery for the Vienna State Opera and ironwork for the Votivkirche. For almost 100 years after that, the building housed the Technologische Gewerbemuseum (TGM), functioning as both a technical school and a small museum. In 1979 the TGM moved out and the building was about to be demolished. However, civil protests and local action groups stepped in, claiming to preserve the space as a social and cultural institution for the community. As a result, the Verein zur Schaffung offener Kultur- und Werkstättenhäuser (WUK), or the Association for the Creation of Public Cultural and Workshop Houses, was founded in 1979. The building was saved, renovated, and presented as it is today, an alternative cultural space dedicated to music, art, and community engagement.

During the recent site investigation performed in 2024 for the construction of the new U5 underground railway line (Wiener-Linien), the foundations of the WUK building were found in critical conditions. Specific excavations (Figure 1) to investigate the state of the building foundations highlighted the presence of large voids beneath the foundations where there was no contact with the soil and significant discrepancies compared with the originally approved structural design were found. These conditions prevented a satisfactory verification of the building's global stability in accordance with structural design standards and the need for a reinforcement intervention of the foundations was required to allow the project development of the underground line.

This paper presents the work carried out to reinforce the foundations of the historic WUK building located in the city of Vienna, focusing on the ground treatment with the injection of expanding polyurethane resins. The performed renovation work was therefore intended to restore continuity between the soil and the building's foundations by filling the underground voids and cavities such that the structural integrity and overall stability of the building can be reliably evaluated according to the Eurocode requirements.

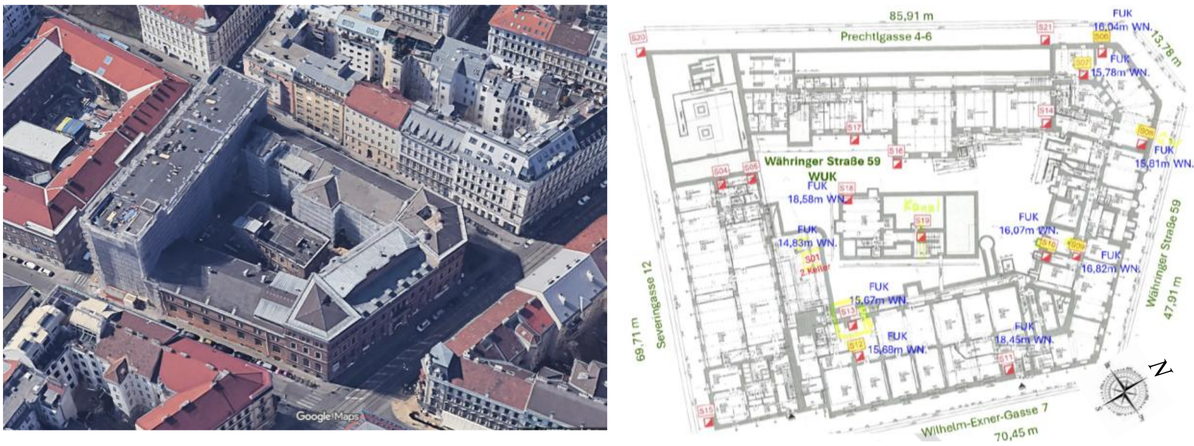


Figure 1. *Aereal view of the WUK building (left). Plan of the excavations for the investigation of the foundations (right)*

GROUND TREATMENT WITH EXPANDING POLYURETHANE RESINS

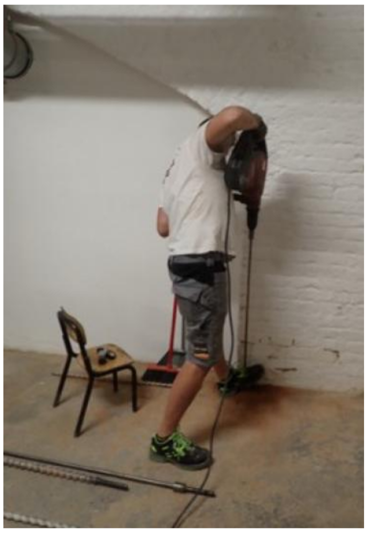
Injection of polyurethane resins can be performed to provide solutions to several geotechnical problems, such as filling of underground cavities, soil compaction, reduction of hydraulic conductivity and recovery of buildings' settlements. Polyurethane resins are obtained from the exothermic reaction 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 is achieved between the resin and the soil (Dominijanni and 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 (multipoint). 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 2 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.

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 (Yu and Houlsby, 1991; Yu, 2000; Dominijanni and Manassero, 2014; Shrivastava et al., 2018; Dominijanni et al., 2020). In this framework, spherical cavities expansion can be considered when single point injection tubes are adopted for the treatment. On the other hand, when multipoint 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. 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.

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, Linz. The main motivation for these works is the improvement of the foundation soil for the raising of buildings with the construction of additional floors and/or for the construction of the new underground spaces such as metro lines. 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 beneath the foundations, in order to prevent possible settlements induced by the new construction activities. In the following WUK case study, however, the primary goal of the injections was the filling of the cavities resulted from the degradation of the timber piles foundation, although a compaction of the soil foundation always occurs due to the expansion of the polyurethane resin.



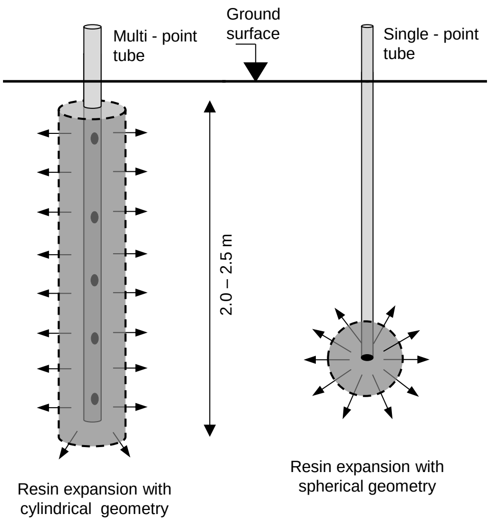


Figure 2. *Example of drilling operations (left). Schematic layout of the two types of injection tubes (multi-point and single-point) adopted for the injection of polyurethane resins, along with the underground expansion process of the injected resin (right)*

CASE STUDY

State of the WUK building foundations

A review of numerous historical documents indicates that the WUK site was formerly occupied by a brick factory, which used the local loessic loam as brick clay. Historical plans indicate that, prior to the construction of the existing buildings (in 1887 and 1891, respectively), the site of WUK, Währinger Straße 59, was occupied for over 100 years (since at least 1773) by a clay pit associated with a brickwork.

According to the geological map of the Geological Survey of Austria, the WUK site is situated within an area generally described as recent fluvial terrace deposits, overlain by loess and clay deposits. Due to this industrial activity, the ground was in a loose condition and significantly disturbed when the current masonry structure was subsequently constructed. According to the historical drawings, the building was indeed founded on timber piles and timber grillages. However, the timber piles were not permanently submerged as the groundwater table is usually located at a deeper level. During the trial investigations (pit excavations) within the WUK site conducted for the construction of the underground line U5 (Figure 1), no groundwater was generally encountered (with the exception of excavations 08 and 01). However, on the opposite side of Prechtlgasse, the buildings foundations were consistently found to be located directly within the groundwater table during comparable investigations. As a result, the timber foundations of the building have been completely damaged over time due to the persistently humid but non-saturated soil environment.

Among all the trial excavations and foundation exposures within the WUK site, a sandy silt classified as loess-derived loam was encountered at the foundation level. Within this stratum, evidence of the former pile foundation comprising timber piles was also observed. In most of the shallow excavations located in Figure 1 that provided meaningful results, problems with the pile foundations and the overlying timber grillage were identified. On the other hand, the excavations located in the stairwells (S04, S05, S11 in Figure 1) did not yield conclusive information; test pits S16 and S17 could not be executed and in the exterior test pits (S15, S20, S21) it was not possible to investigate the piles. Point-based investigations always have the risk that conclusions drawn by analogy may lead to misinterpretations. Nevertheless, based on the excavations results, it can be assumed that the entire building complex is founded on timber piles which are not only damaged but they are completely decomposed and now detectable only through the remaining voids. Similar considerations can be done for the beam grillages, that were often embedded into the foundation to distribute the building loads. In most cases, the foundation masonry is intersected by voids running longitudinally and transversely at various elevations, with only the soil (loess loam) between these voids able to carry the building loads. The situation in the excavation S13 may be cited as an extreme example. Here, the foundation appeared to be constructed on a full-area timber structure. Due to its complete decomposition, a continuous void with a height of approximately 30 cm was found beneath the foundation. Above this void, the entire foundation base was exposed (Figure 3). Beneath this void lied the soil material in an extremely loose state.

Despite the critical condition of the foundation soil, characterized by significant heterogeneity due to voids, the building structure did not appear to have any significant damage related to differential settlements at the time of the inspection. This evidence might indicate good overall compliance with the building's differential settlements prior to the intervention. However, renovation works recently carried out in the basement levels, and part of the west wing of the building, might have hidden the presence of fissures and cracks in the masonry wall. It was clear that an extensive structural assessment of the current building condition with respect to the foreseen construction of the new railway line was not possible, as the situation implied a high hazard level. Based on the current findings, it could be assumed that the entire structure, with regard to its foundations, no longer corresponded to its original as-built condition, and reinforcement work was therefore needed.

Figure 3. *Trial excavation S13 highlighting a large void beneath the masonry building foundation*

Description of the reinforcement works

A large part of the reinforcement work of the WUK building foundations was performed from the basement level in order to reduce the depth of the borehole to perform the injections and uniformly treat the foundation soil. As the basement rooms of the building were recently renovated, the choice of a treatment with polyurethane resins was particularly effective due to the light equipment required to perform the injections, in order to reduce the impact and damage to the existing structure.

The reinforcement intervention was carried out according to the following overall procedure: (i) investigation through shallow borings and excavations for the inspection of the foundation soil; (ii) filling the underground cavities with resin injection with single-point injection along with continuous monitoring of settlements and heaves of the building and the ground surface; (iii) assessment of the treatment with expanding resins through additional boreholes and endoscopic technique. It has to be considered that a complete filling of all existing voids was not possible. Therefore, the goal of the treatment was filling the most relevant voids in order to restore the contact between the building foundations and the soil and to ensure a uniform distribution and transfer of the loads to the foundation soil.

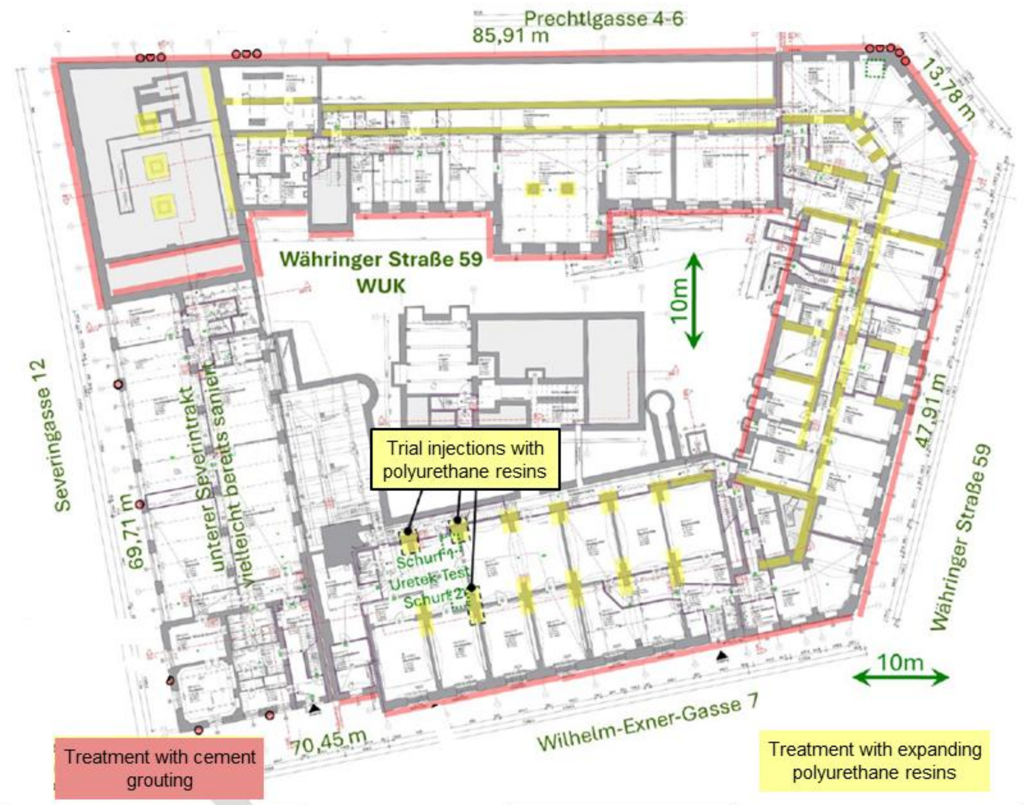


Figure 4. *Plan of the WUK building with positions (in yellow) of the trial tests and the overall area treated with injection of expanding polyurethane resins*

To assess the feasibility of the treatment concept with polyurethane resin from the basement level of the building and to establish an initial optimization of borehole location and injection technique, a trial test area was identified. In particular, three trial points were defined at three masonry columns (highlighted by the three dashed rectangle in Figure 4). Using handheld drilling machines, drilling was performed up to a depth of 2.8 m into the masonry in order to reach the foundation base and the voids underneath. The voids were inspected using an endoscopic camera. After the drilling operations, single-point injection tubes were used to inject a two-component polyurethane resin that was designed to have high mobility and a slightly delayed reaction time. In two of the three tested points, more than 300 kg (also corresponding to roughly 300 litres in unexpanded conditions) were injected at each location. Considering the heterogeneous underground conditions beneath the building, it is possible to estimate the injected resin expanded at least five times compared to its initial volume. The third trial injection was carried out into a borehole within the masonry that did not reach the foundation base. In this case, only 1.5 kg could be injected. These values of the amount of resin injected demonstrated that the injected volume is a good indicator of the presence of voids and fissures beneath the building foundations. Moreover, a further injection test was also performed by drilling a vertical borehole into the soil away from the masonry columns. After approximately 25 kg of injected material, a ground uplift of about 0.5 mm was observed, leading to the termination of the test. The monitoring system was therefore able to detect any undesirable uplift of the ground, allowing the operators to stop the injection. The red areas in Figure 4 indicate the zones of the building without basement levels which required the treatment to be made with a conventional grouting technique from the sidewalk outside the building instead of injecting polyurethane resins.

After the trial injections, shallow excavations were carried out at the two testing points where large amounts of resin were injected. These excavations highlighted the success of the treatment, as the injected material reached and completely filled the voids beneath the foundation, thanks to the expansion capability of the resin (Figure 5). Around the injection points, the resin migrated through available soil pathways (mainly fissures) and created a branched treated area. This evidence demonstrated that the resin could find preferential pathways adjacent to the voids and even create its own pathways due to its swelling capacity (Figure 5). It was also evident that the injection material expanded and formed a substantial injection body where voids were encountered. In the branched veins, expansion occurred only in isolated spots; elsewhere, the injected material remained as compact resin sheets (Figure 5).

Figure 5. *Images of the soil beneath the building foundation after the injection of expanding polyurethane resin*

After the positive outcomes of the trial tests, the treatment was extended to the entire building, as illustrated in Figure 4 by the yellow zones. The work was performed to minimize the impact and damage to the existing structure. Dust generation was mitigated by using “wet drilling,” which was already successfully applied during the test. Adequate suction of the return flow and drill cuttings was correctly ensured so that disturbances remain confined to the borehole and a few centimetres around it. The drilling method used to perform the injection was compatible with the restricted space on site (the building's basement). Drilling points were located near the column foundations (typically 2 to 4 injection points per column) to maximize the treatment's effect. The drill points were positioned approximately 3–4 cm from the wall, with an inclination angle of about 80–85°. Depths of about 3 m were achieved to ensure the resin injection beneath the building foundations. Endoscopic inspection with a camera was performed after drilling to evaluate the soil condition and the presence of fissures and voids. Settlements were continuously monitored to stop injections if excessive uplift occurred. A drilling log was kept, and the quantities of resin injected were precisely measured. Approval of each drilling location was required by an authorized representative of the WUK building management in order to assess the possible presence of underground utilities. The entire reinforcement work, including the injection of polyurethane resins, was completed in about two months. A total of 251 boreholes were installed, and 19,748.5 kg of resin was injected, resulting in an average injected resin mass per borehole of about 79 kg. Considering a resin density of approximately 1000 kg/m³ prior to expansion, the injected resin corresponds to a pre-expansion volume of roughly 20 m³. Under the given conditions, the resin expands by about a factor of five, so the resulting (expanded) filled volume can be estimated at approximately 100 m³.

When the building's uplift was detected by the monitoring system, the injection process was stopped to prevent possible damage. At three locations, local uplift of the floor occurred, as the resin spread flatly beneath the floor slab. One sewer pipe was affected by the resin. However, camera inspection after removal of the resin confirmed that the pipe was not damaged during the drilling operations, and the resin must have entered through an already existing leakage point. Unexpected uplift on the Wilhelm-Exner-Straße sidewalk was observed over an area of approximately 1 m², although the resin had been injected from the basement level at an additional depth of 2 m. However, given the total number of boreholes and the amount of injected resin, these damages can be classified as minor, demonstrating the capability of this treatment technique.

Figure 6. *Overview of the building plan showing, for each treatment zone, the range of resin mass injected beneath the foundations and the corresponding resin mass per borehole*

A more systematic method to assess the outcome of the treatment is represented by the locally varying quantities of injected resin, illustrated in Figure 6. The color-coded overview plan shows injection quantities ranging from less than 20 kg (green) to over 230 kg (purple) per injection point, providing a clear visualization of the foundation conditions throughout the building. This heterogeneous distribution of the amount of injected resin, showing a more critical condition for the east wing of the building, might be related to a lower level of the groundwater table, a lower relative density of the foundation soil, and, eventually, a different configuration of timber foundations (piles and grillages) with respect to the other wings of the building. However, the geotechnical investigations performed were insufficient to confirm these assumptions, and, given the shallow excavations carried out, more invasive investigations could not be conducted to preserve the serviceability of the building.

CONCLUSIONS

The application of a grouting technique based on the use of expanding polyurethane resins for the improvement of the foundations of the historical WUK building in Vienna was presented in this article. During the site investigation for the construction of an underground railway line beneath the WUK building, significant underground cavities and fissures were found beneath the building foundations, resulting from the degradation of the original timber grillages and piles. The injection of expanding polyurethane resins was performed to reinforce the building foundations. The treatment methodology restored contact between the building foundations and the soil, providing a uniform distribution of loads and correct stress transfer to the foundation soil. The amount of resin injected per borehole was a good indicator of the degree of damage to the foundations, as areas of the building previously reinforced required minimal resin, while damaged areas required larger volumes. Moreover, the reinforcement works were carried out without significant damage to the building, demonstrating the potential of this treatment technology to minimize disturbance. A system to monitor ground and building displacements during treatment is always recommended. After treatment with expanding polyurethane resins, the structural integrity and overall stability of the building can be reliably evaluated in accordance with the Eurocode requirements, providing a solid base for the development of the underground railway line. Based on the results of the presented study, the injection of expanding polyurethane resins can be considered a potentially effective technology for the preservation of historical buildings when new construction is planned around them.

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