Application of Jet Grouting technology for the renovation of historic buildings

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Abstract. Renovation and restoration of historic buildings to appropriate functioning is a big challenge for the designer. In the case of this type of buildings, providing them with a new function usually requires the creation of new technical areas for installations and parking spaces. However, the change of function cannot be associated with a fundamental change in the image of the modernised building. In such case, additional areas are obtained by building in the underground spaces under courtyards, streets and often also under existing structures. In certain situations, the mere change in the function of existing underground levels forces an increase in their usable height by deepening of the foundation. Subsequent problem encountered during modernisation is the change in load of individual foundation elements, which is related to the rebuilt static system of the historic structure. In such case, the fragments of foundations require reinforcement that can be implemented by their deepening. One of the methods that enables improvement of the usable properties of basements by increasing their height, as well as reinforcement of the foundations of historic buildings, is jet grouting. This technology resolves many problems associated with limitations in the scope of size of used equipment and access to the place of formation of soil cement elements. Its application allows to significantly facilitate and accelerate the works at the construction site. This study presents the selected examples of the implementation of specialised geotechnical works in the scope of modernisation of historic buildings in Poland, as well as dependence of the strength of soil cement composite on the soil type.

1. Introduction - principles of Jet Grouting Technology

Jet grouting is a jet injection technology that has been used in geotechnical works since the 1970s [1,2,3], while in Poland it has been applied for about 30 years [4]. There are many possibilities of using this technology, among others to pick up the foundations. A series of publications [5-9] also document the experiences of applying this technology in order to secure the excavations, by creating a palisade of overlapping or contacting elements, repairing old foundations, as indirect foundations, as well as fulfilling the function of sealing and anti-filtration partitions. In the case of palisades, it is necessary to embed the reinforcement at least in part of the columns – in order to transfer the bending moments and horizontal forces. Reinforcement is also introduced into the columns performed as elements that are subjected to tensile forces (anchor piles), or significant compressive forces, which exceed the strength of soil cement material. Also structural sections (e.g. IPE or HEB) are used as reinforcement, while in the case of limited space, the bolted systemic reinforcement is used. Jet injection can be performed in almost any soil conditions.
Jet grouting is a process consisting of the destruction of soil structure with the use of grout pressed under very high pressure. This results in the improvement of soil properties, while the created composite gains a strength in the range from 2 to 20MPa.

Among others, it depends on the w/c ratio, amount of grout provided per linear metre of the column, as well as the type of soil with the use of which the column was made. In this manner, the soil-cement columns are formed with irregular shape, which depends on the properties of the soil, injection grout pressure, injection time, nozzle diameter, as well as density of injection grout. One of the main advantages of jet grouting is adaptation to the condition of the existing structure and conditions prevailing at the construction site. The process unit requires appropriate spaces at the construction site and the possibility of supplying materials, however it can be located at a substantial distance from the place of works. Only the drilling rig is introduced into the region of performed drilling-injection works, which is connected to the process unit with the use of wires. Such drilling rigs can have the sizes allowing for the performance of works in spaces with limited height, or in places with limited access resulting from the necessity of accessing it via staircase or narrow tunnel.

2. Application examples of the jet grouting technology
The most common field of application for jet grouting technology is the creation of underground structures in the course of performance of deep excavations, which are associated with hazards in relation to buildings and structures in the immediate vicinity [10-12]. Regardless of the used measurement techniques [13-16], there is always a risk that the conducted works will lead to damage in the neighbouring buildings [17-19].

2.1. Service and residential building complex ANGEL STRADOM
The jet injection technology was applied in order to renovate the front building belonging to the new service and residential complex at Stradomska Street in Kraków. The construction was started in XIV century, while its final shape was achieved after many reconstructions in XIX century.

![Figure 1. Jet grouting columns (Kraków).](image1)

![Figure 2. Service and residential building Angel Stradom](image2)
From the top view, this building is in the shape of the letter T. Its front part runs along the street, while its the middle wing, which once served as a church, is protruding towards the yard. Basement walls and load-bearing walls are made of solid brick. The front part includes three blocks, which are parallel to Stradomska Street, with spans in the wall axes (subsequently from Stradomska Street) amounting to approx. 6.2m, 2.6m and 4.5m. These walls are mostly load-bearing walls and their thickness is variable in height. The middle block constitutes a corridor on each floor. Thickness of external walls of the aboveground storeys in the front part range from approx. 80 cm to 120 cm, while in the church part up to 150 cm.

In the ground at the construction site, the surface layer consists of uncompacted anthropogenic embankments with variable composition and condition, and with a thickness from 0.1m to 5.7m. Mainly unsorted sands, gravels and locally sandy clays are accumulated below. In some places, the pockets of alluvial soils and organic alluvial soils with a thickness of approx. 1.8m are accumulated. The layer of loams occurs at the lowest level, while their ceiling is at a depth from 5.5m to 9.8m. The building is mainly placed on medium sands and sandy clays. Below there is a continuous layer of medium-compacted gravels with a thickness of approx. 2.0-3.0m, lined with hard plastic loams.

Ground water stabilises at a depth of 1.0-2.0m below the level of existing floors. The main structural changes of the building consisted of elimination or replacement of ceilings and construction of a bottom slab below the existing foundations. The main task of building tamping was increasing the usable height in the underground part by approx. 80cm. An additional issue resolved with the use of jet grouting technology was increasing the bearing capacity of foundations.

Necessity to make the changes resulted, among others, from a change in the manner of using the building and replacement of ceilings. The project envisaged the construction of a new foundation slab, along with pressure walls “coming out” to the columns. Such solution required the performance of a continuous tamping in the height range between the bottom of existing foundations constructed of brick and limestone, and the bottom of excavation for the new building slab. Neuralgic location of this building resulted in additional difficulties associated with the lack of consent for occupation of the
sidewalk and for the drilling and injection works from the side of Stradomska Street. Due to this reason, the columns under the front wall from the side of Stradomska Street were performed at different angles to make the construction more reliable concerning lateral forces.

Another issue was to secure a deep excavation for the new structure located in the yard. The designed excavation was in contact with the front part of the old building and was located approx. 2.0m away from the church part. Differences in the levels between bottom of the designed excavation and the existing foundation amounted to approx. 2.0m. Therefore, reinforcement of foundations of the building’s sacral part was performed with the use of columns, in spacing ensuring the transfer of loads and implementation of the slope. Under the front part, which was in the so-called "sharp border” with the excavation, it was necessary to implement a continuous tamping. As part of the described task, the works were carried out from inside and outside of the building. A system of columns with a diameter of approx. 800mm and with extension to 900mm under the foundation was implemented. Arrangement, diameters and lengths of the columns were adapted to the existing soil conditions and provided target loads.

They were implemented through drillings of foundations built of solid brick and limestone, which allowed for quite efficient performance of the works. The scope of jet grouting works included reinforcement of the foundation, transfer of the loads and securing the excavation. The following grout injection parameters were applied in order to implement jet grouting columns that meet the project requirements:

- cement grout density from 1.50 g/cm³,
- compressing of the medium to a pressure of 50MPa and 60MPa on the last metre of the column under the existing foundation,
- rod lifting speed from 4 cm/5 sec.
- rod rotation speed 20 rpm.

2.2. Branicki Palace in Warsaw

This building was constructed in the 1840s. During the Second World War, the building was completely destroyed. After the war, it was rebuilt with great accuracy.
In the middle of XX century, the left wing of the building was partially demolished due to the construction of the W-Z Route Tunnel. The demolished wing was rebuilt with great accuracy. This building has two aboveground storeys and one underground, as well as a usable attic. It consists of three parts - the main one from the side of Miodowa Street and two side outbuildings. From the top view, the building resembles the letter "U". Both outbuildings have a full basement up to level -1. External and internal walls were made of 7x13x27cm brick, obtained from the demolition of buildings destroyed during the war. Thicknesses of aboveground external walls range from 66 cm to 81 cm. Wall thicknesses of the underground storey amount to 91 cm. Foundation depth of lateral outbuildings is greater by approx. 1m compared to the foundation of the central part. Foundations of this building were constructed from full brick and pebble stones, and the oldest ones from the boulders.

Substrate in the described area in the surface zone consists of non-construction embankments, which contain silts, loams, debris and sands, while their thickness reaches up to 7m. Below, there are sands of various fractions and hard plastic clays. They are lined with a layer of loams, the ceiling of which occurs at depths from 9.5 m to 15.5 m below the ground level. The analysed building is placed on the layers of sands and clays. Two groundwater levels were drilled in the area of tamped building during the geological research. The first level (probably rainwater) stabilises at a depth of approx. 1.5-2.5m below the existing foundations. The second level of groundwater occurs at a depth of approx. 8.0-9.0 m below the existing foundations.

This building was intended for renovation and significant expansion. Due to the envisaged increase in the usable height of basements, the performance of continuous tamping (Fig. 7) of foundations in the jet grouting technology was planned. Moreover, technological ducts were placed in some walls under the designed floors, which resulted in a deepening of existing foundations even by approx. 3.0m (Fig. 8). The project assumed implementation of jet injection under a significant part of the building.

In addition, due to the changes introduced in the building structure, the loads increased that may exceed the ultimate bearing capacity of the foundations. Implementation of jet grouting columns strengthened the original foundations. The designed columns with diameters of approx. 800mm are loaded with a force reaching up to 650kN/m, i.e. approx. 230kN per one pile. Columns under the walls were designed in two rows and axial spacing amounting to 700mm (Fig. 9) and thanks to that, the overlapping columns constitute a continuous tamping. The works were performed from the outside from the ground level and from the inside from the basement level. The column lengths range from 1.5m (the ones performed from the basement level) even up to 5m (the ones performed from the ground level).

Implementation of injection columns was also intended to secure the initial excavation for implementation of guide ledges of the diaphragm walls, designed by the existing building. The manner in which the columns were implemented prevented the soil dusting and the performance of the above-mentioned ledges also in the spots below the original foundation level.

**Figure 7.** Tamping of internal wall in the left wing of the Branicki Palace (Warsaw)
As part of the described task, the works were performed from inside and outside of the building. A system of columns with a diameter of approx. 800 mm, which were adapted to the existing soil conditions and provided target loads, was implemented. They were implemented through drillings in brick and stone foundations. However, the occurrence of a significant amount of pebbles and field stones, which constitute a difficult material for drilling, significantly hindered the performance of works. The scope of jet grouting works included reinforcement of the foundation, transfer of the loads and securing the excavation inside the building in order to increase the usable height of the building, as well as outside of the building in order to implement an initial excavation for guide ledges of the diaphragm walls. The following grout injection parameters were applied in order to implement jet grouting columns that meet the project requirements:

- cement grout density from 1.55 g/cm³,
- compressing of the medium to a pressure of 50MPa,
- rod lifting speed 4 cm/4 sec.,
- rod rotation speed 20 rpm

3. Comparison of the sample strength results for both investments

Basic technological issues in the formation of soil cement columns with the use of jet grouting method is the certainty of mixing the soil with a hydraulic binder (strength) [20-22], obtained diameter [23], as well as the strength at the column-soil contact [24,25]. Particular attention should be paid to the dependence of soil type on the strength of tested samples. Portland fly ash cement CEM II/B-V 32.5 was used both in the construction of the service and residential building complex Angel Stradom in Kraków and in the construction of Branicki Palace in Warsaw.

During implementation of works at the construction sites, a soil cement sample was collected every day in order to test its strength after a minimum of 28 days. The results from individual days are presented below. Strengths of samples collected at the construction site in Warsaw range from 4.9MPa to 17.7MPa (average strength 9.36MPa), while the minimum strength required by the project amounted to 2.0MPa.
Strengths of samples collected at the construction site at Stradomska Street in Krakow range from 8.1 to 19.5MPa (average strength 12.75MPa), while the minimum strength required by the project amounted to 6.0MPa. It can be observed that as part of the construction at Stradomska Street, the limit values as well as average values of the tested samples are higher. This results from the contractor’s compliance with the higher strength parameters of the soil cement material required in the given project, by applying higher compressing of the medium to a pressure of 50MPa (60MPa at the last metre) and slower rod lifting (Warsaw = 4cm/4s, Kraków = 4cm/5s). In the scope of our comparison, also important are the differences in geology under both investments. Cohesionless soils - sands, gravels and sandy gravels dominated in Kraków, while in Warsaw, the columns were mainly implemented in cohesive soils. In order to perform more detailed analysis of relation between the soil type and the strength, it is necessary to focus on analysing the strength within one construction, in order to exclude the impact of project assumptions, which were different at both construction sites. Therefore, let's take a deeper look at the construction site in Kraków and the strength values of samples collected within specific geological openings. The below diagram shows the regions of occurrence of specific soils and average strengths obtained in them.
The highest strengths were noted closest to the test opening no. 6. This opening mainly included medium-compacted fine sands and sandy gravel. Samples collected near the opening no. 10 were also characterised by high strength, where medium sands lined with a thin layer of silty sands were located. The opening no. 12 included medium humus sands. The smallest strength values were noted near the test openings with the following numbers: A/A', 9, 11. It was mainly caused by the occurrence of cohesive soils, silts and clays. The list of average strengths is presented in table 1.

| section | compressive strength | original kind of grouted soil |
|---------|----------------------|------------------------------|
| OT6     | 15.41 MPa            | fine sands, sandy gravel     |
| OT10    | 13.22 MPa            | medium sands and silty sands |
| OT12    | 12.71 MPa            | medium humus sands           |
| A/A'    | 12.40 MPa            | sandy clay/coarse sands      |
| OT9     | 11.72 MPa            | silty clay/medium sand       |
| OT11    | 11.44 MPa            | Silts and clays/silty sands  |

4. Final remarks
The above-mentioned observations confirm the dependence of soil cement composite on the soil type, in which the column was implemented. The greatest strength is exhibited by columns implemented in cohesionless coarse soils, such as gravel and sandy gravel. Lower strength will be obtained in the case of implementing a column in medium and fine sands. The lowest results of soil cement tests were noted near the test openings, in which cohesive soils were dominating. Moreover, the strength was reduced by the occurrence of organic soils, which can be observed based on the test results within the opening no. 12 (in comparison to the openings no. 6 and 10, where the sands were also occurring).

The presented results can be helpful for planning of geotechnical works in the neighbourhood of deep excavations. It may be noticed that the results are highly dependent on ground conditions and grouting technology. The necessity of further examination and juxtaposing of the results in experience databases is recommended as the final conclusion of the presented study.

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