Southeastern Europe Tunnelling Conference (SETC-2025)
1-3 October 2025, Belgrade, Serbia

DOI: 10.5937/SETC25002D

Soil fixing technologies used in the construction of cross passages in the Moscow metro

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Abstract: In the city of Moscow, the construction of the subway is proceeding at a high pace. Over the past few years, almost 200 km of main line tunnels and more than 100 stations have been built. At the same time, it was necessary to overcome many technological difficulties associated with the construction of cross passages both between the main line tunnels and between them and the tunnel structures. The city of Moscow is located on a plain of fluvioglacial genesis, characterized by a marmorate, steep, lenticular interlayer of sandy, water-saturated and clay soils, as well as the presence of water-saturated fractured limestones. Main line tunnels and shafts are usually arranged in a mechanized way, which ensures the required predictability and quality of work. Failures have to be built in a mining way. In limestones saturated with cracks and cavities and water-saturated sandy soils, especially if they have the property of quicksand, the breakdown device is possible only under the protection of an array of fixed soil having the necessary strength and anti-filtration properties. At the same time, high-quality soil consolidation in such geological and hydrogeological conditions is a significant difficulty, especially with short construction time. During the construction process, various technologies were used to fix soils in Moscow: cementation, micro-cement impregnation, jet grouting, impregnation with organic resins capable of polymerization, as well as soil freezing. At the same time, radically different substances were used for fixation purposes. Each of the listed technologies has its advantages and disadvantages both in the nomenclature of the soils to be fixed, and in the availability of the equipment used, the availability of the substances used for fixing, the qualifications of the maintenance personnel, the time required for the work on fixing and the subsequent set of necessary strength. All of these technologies were applied in the production of construction works at different sites in accordance with the geological conditions and advantages of each technology, the quality of the fixed soil, the size of the array compared with the design values, and the manufacturability of the method were monitored. As a result, the limits of applicability of each technology were confirmed, reliability and degree of risk were determined, and environmental aspects were identified. Based on the experience of work in the construction of an array of fixed soil during the construction of buildings by mining, preferences were revealed when choosing the method of fixing, materials, and the method with the least risks with the best physical and mechanical characteristics of the fixed soil was recommended.

Keywords: antifiltration curtain; breakdowns; quicksand soils; soil anchoring; tunnel structures

1. Introduction

The construction of the Moscow metro is proceeding at a high pace – it is planned to open 3 stations in 2025, 11 stations in 2024, 14 stations in 2023, 69 stations in 2022, 12 stations in 2021, etc. Almost 200 km of subway tunnels have been built. Due to such a large volume of construction of metro facilities, many organizational, technological and technical difficulties have been overcome. This publication examines the technical and technological aspects related to the construction of cross passages, both between tunnels and between tunnels and tunnel structures. The special features of these works are the difficult soil and hydrogeological conditions.

The Moscow region is located on the Russian Plain of fluvioglacial genesis, far from mountain-forming sites. The geological structure of the region is characterized by multiple layers of sedimentary rocks formed by weathering and the transport of small particles over long distances or the separation of

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accumulated sedimentary rocks by watercourses. Thus, the geological section of the Moscow region is represented by clay and sandy soils in a mottled interlayer. The underlying rocks are limestones of varying degrees of weathering. The variegated layering of sandy and clay soils, together with the flat nature of the terrain and regular rains, ensures the presence of groundwater at several horizons, which, in turn, ensures the pressurized nature of groundwater in some water-bearing soils. But a special place in the geological structure is occupied by the fragmentary presence of watered fine sands with clay aggregate, the so-called ‘drift sand’. This type of soil is characterized by a special property – liquefaction under the influence of vibration. In its natural state, the specified soil is dense, water-saturated, and capable of successfully withstanding various types of loads, except for vibration. Under the influence of vibration (or when a watercourse is formed from this soil, for example, with a hole in the structure), this type of soil loses its structural strength and turns into a suspension under pressure in the ground column. Another feature of the geological structure of the Moscow region, which is a consequence of the rainy climate and the anthropological impact, are gullies filled with bulk soils. At the same time, bulk soils often represent the buried remains of substandard building materials and/or buried organic inclusions.

The ancient character of the fluvioglacial plain is emphasized by the presence of places where previous sediments were washed away by water, as a result of which the soil layers become especially mottled, precipitous, and lenticular (Fig. 1).

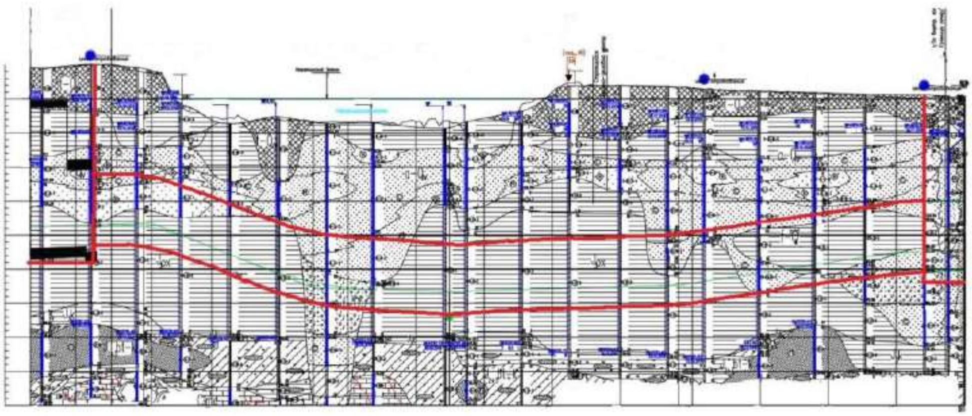

Fig. 1. Typical structure of the soil stratum of the Moscow region.

The described nature of the hydrogeological features of the ground conditions of the Moscow region dictates the specifics of the difficulties of building the Moscow Metro. Most stations are designed and built by subsurface method to allow the development of a relatively shallow excavation and, consequently, reduce capital costs. This is also more convenient for passengers – there is no need to spend extra time getting down/up from the surface to the platform. Usually, tunnels tend to be located in layers of cohesive soil. But this does not always happen due to the periodic presence of volumes of sandy soils along the tunnel route, usually shallow and water-saturated, i.e. having the properties of quicksand. Tunnels are built by means of mechanized tunnelling complexes (TBM), their construction is characterized by high speed and quality. In accordance with regulatory requirements, it is necessary to periodically arrange cross passages and near tunnel structures between tunnels, where drainage and ventilation installations are placed. Due to the fact that they require access to the surface, they must be positioned along the tunnel route in such a way that they do not fall into the footprint of existing buildings and have minimal impact on it. Thus, there is no rational choice of engineering, geological and hydrogeological conditions.

Cross passages both between interstation tunnels and between tunnels and tunnel structures built in vertical boots have to be arranged in a mining manner. This often occurs in water-saturated soils – fine sandy, even with clay aggregate (i.e. in quicksand), or, less often, in fractured and porous limestones. In any case, with a pressure level of groundwater, frequently several tens of meters. For the construction of buildings by mining in such geological conditions, it is imperative to arrange an array of fixed soil. A typical tunnel structure is shown in Fig. 2.

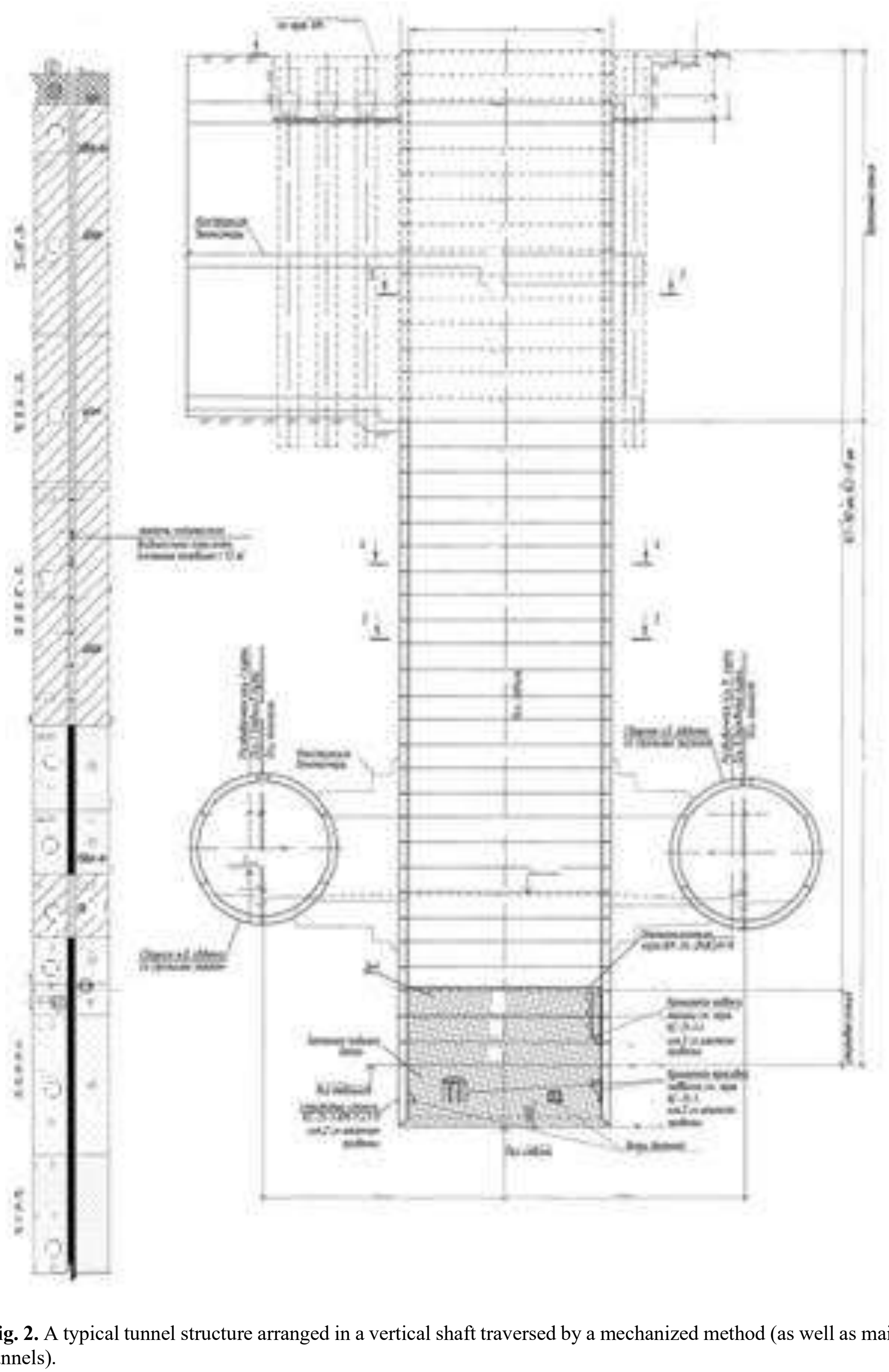

Fig. 2. A typical tunnel structure arranged in a vertical shaft traversed by a mechanized method (as well as main line tunnels).

The analysis of the possibility of solving the problem of soil consolidation consisted of a review of the positive practices of such work by contractors and an analysis of literary sources. Thus, Sokolovich (1980) described proven technologies for fixing soils using silicate solutions, organic resins, cement and cement-clay compositions. Rzhanitsyn (1986) developed technological approaches to soil consolidation and added the accumulated experience. Subsequently, when microcements appeared, soil stabilisation using them was developed by Garkavi et al. (2020), Ibragimov et al. (2016) have brought certainty to the limits of applicability. Guo et al. (2020) supplemented the description of methods for stabilisation sandy soils with polymer solutions, Shuplik and Nikolaev (2016) contributed to the introduction of artificial soil freezing.

2. Materials and methodology

When mining operations are carried out, as a rule, a borehole screen is first arranged to provide soil support in the arched part of the mine. After that, the lining of the tunnel or vertical boot is opened, the soil is worked out (usually first the upper ledge, then the lower one) and after each approach, temporary lifting frames are installed with temporary lining of the exposed soil (usually boards). Then, the next capture is developed and so, cyclically, the entire soil is extracted for the entire length of the stroke in the breakdown. Thereafter, reinforcement frames, formwork, and concrete permanent lining of the fault line are arranged.

All these works can be done only if:

- water supply in volumes that allow the work described earlier to be carried out with proper quality, especially concreting (water supply in volumes up to 5 m^3/hour);
- the strength of the soil must be sufficient to withstand the pressure of groundwater and mountain pressure.

In the presence of rocky and semi-horizontal soils, for example, fractured aquiferous limestone, the strength of the soil is sufficient for the development of traps. However, in the presence of sandy, water-saturated soils, it is necessary to consolidate the surrounding soil mass.

The criterion for satisfactory fixation of the surrounding soil mass, both according to the established practice of mining operations and according to the calculation justification, is mainly the strength of the fixed soil of 5-7 MPa with a thickness of at least 2.5-3 m. It should be borne in mind that the development of the soil is carried out with pneumatic jackhammers and the level of vibration loads at the excavation site is quite high. It is also necessary to take into account the creation of anti-filtration properties of a fixed ground mass, ideally not allowing groundwater to pass through completely or, in real conditions, ensuring an influx of water into an open passage of no more than 5 m^3/hour.

The comparison methodology was to identify the advantages and disadvantages of using certain methods to create an array of fixed soil with antifiltration properties relative to the nomenclature of soils to be fixed (fractured limestones, sands of various sizes, sands with clay filling), availability of equipment and the fixed substance (scarcity, price), the qualifications of maintenance personnel, the required time, the size of the anchoring array (actually achieved relative to the design values), environmental aspects (residues of unreacted substances, the duration of the fixed array's existence).

However, technologies capable of creating an array of water-saturated soil that has the properties of antifiltration protection and the necessary strength (at least 5 MPa) are limited in number. The set of these technologies, as well as the advantages and disadvantages of each of them, are presented in Table 1.

Table 1. Advantages and disadvantages of the adopted technologies of soil fixation

Soil consolidation technology	Advantages	Disadvantages
Grouting works	• Relative ease of work execution; • Availability and simplicity of equipment; • Availability and low cost of materials.	• Can be used only in coarse and gravelly sands without fine aggregate; • Can be used only in semi-horizontal (rocky) soils with sufficient crack opening width; • It takes time to gain strength; • Fixed array remains as such forever (environmental interference)
Micro-cement impregnation	• The possibility of application in gravelly, coarse, medium-sized and small sands with fine (but not clay) aggregate; • Possibility of application in semi-horizontal (rocky) soils, even with very small crack opening width; • Gentle method – there is no physical impact on the surrounding soil.	• Highly qualified staff is required; • Complexity and non-proliferation of equipment (pumps with strictly controlled pressure/volume supply); • Often the presence of residual water occurrences in the fixed soil; • It takes time to gain strength.
Jet grouting	• Physical mixing of the soil with the hardening compound, higher uniformity and quality of the fixed soil; • Greater reliability of the fastening process; • The use of cheap general construction cement; • The prevalence of equipment; • High-quality fixing of the boundary of sandy and clay soils.	• The risks of delamination of the soil – concrete mixture and, as a result, the risks of lowering the quality; • Difficulties in organizing a pilot site for testing injection parameters; • The effect of high pressure on surrounding building structures; • The complexity of application in rocky (semi-horizontal) fractured soils; • There are great difficulties with the uniformity of the fixed soil in quicksand soils.
Impregnation with organic resins capable of polymerization	• The possibility of application in any sandy soil without restrictions on the size of its particles; • Greater reliability of the fastening process; • Gentle method – there is no physical impact on the surrounding soil; • The prevalence of equipment; • High-quality fixing of the boundary of sandy and clay soils.	• Risks of non-reaction (polymerization of not the entire volume of resin), with a decrease in the quality of fixation; • Difficulties in organizing a pilot site for testing injection parameters; • The use of expensive hardening materials; • Ecological contamination of the fixed soil with polymerization products and organic resins.
Ground freezing	• Guaranteed uniformity and continuity of the fixed soil; • Gentle fixing of the soil without changing the type and format of its natural composition; • Absolute ecological cleanliness.	• The time required for soil freezing is long enough (30-40 days) for brine freezing; • Limited number of enterprises producing 'dry ice' and liquid nitrogen on the required scale; • The construction site is cluttered with equipment and pipelines for the entire duration of the soil freezing work.

3. Results and discussion

It should be noted that cementation with ordinary cement is performed only in rocky and semi-rocky soils, as a rule, in limestones with a sufficiently large crack opening width. For this purpose, ordinary general construction cement with a grinding fineness of about 3000 cm^2/g is used, and 95 % of the grains of such cement should be less than 100 microns. If there are not only cracks in the rock, but also cavities or hollows, then sand is added to the slurry to reduce cement consumption by up to 2/3 by volume, depending on the absorption of the injection material by the cavity. Conversely, if the fracturing of the rock is expressed by small cracks, then up to 10 % finely ground cement with a grinding fineness of about 9,000 cm^2/g is added to the cement slurry to seal even small cracks.

If the creation of an array of fixed soil is carried out using microcement, then impregnation technology is used. Injection into the soil is carried out by a cement-water suspension, while water is a transport system and its flow transports microcement particles into the pores of the soil at a distance of 0.3 to 0.6 m from the injector (depending on the type of sandy soil and the presence of clay aggregate). Unfortunately, in the case of this technology, it is impossible to achieve complete waterproofness of the fixed soil due to the heterogeneity of the natural composition of the soil and, as a result, the deposition of more microcement grains in the volume of soil with relatively greater permeability. As a result, when drilling a cross-passage in a body of such soil, there are almost always spot water occurrences that form in a chaotic manner. The total water inflow from these water events is nevertheless acceptable for failure concreting work.

In the past, at the initial stages of the construction of the Moscow Metro, jet grouting technology was used to create blocks of fixed soil. After gaining relevant work experience, this technology, which was quite common, was gradually abandoned due to the identification of numerous problems with its implementation in quicksand soils (fine water-saturated sands with clay aggregate). The issues were the lack of continuity of the solidified soil. Quicksand soil is characterized by almost instantaneous liquefaction under the action of vibration. And the jet grouting erosion jet seems to create just such a vibration, at least near the working body of the monitor. As a result, stable erosion does not occur, and the soil is not secured in the required quality. It is necessary to combat this phenomenon by repeatedly installing each jet element in the same place. Nevertheless, the creation of an block of stabilized soil was carried out mainly from the daytime surface using: jet-1 (cement-water suspension only), jet-2 (air jet and cement-water suspension), jet-3 (water jet, air jet and cement-water suspension jet). Sometimes a preliminary washout was used. But, in addition, there was also the creation of a block of stabilized soil horizontally from a tunnel or boot using jet-1. When working from the surface, where the geological conditions were particularly difficult, jet grouting was used, followed by impregnation with microcement. This increased the quality of the stabilized soil, reduced the heterogeneity of water occurrences and increased the strength of the ground concrete. The impregnation was carried out through injection tubes, which were lowered into the ground concrete immediately after the manufacture of the jet element. Micro-cement impregnation was carried out after setting the soil-concrete and gaining the necessary strength.

To a first approximation, the most technologically advanced and most reliable way would be to stabilize the soil by impregnation with organic resins capable of polymerization. Indeed, these substances do not have a solid fraction in their composition, which means that in the presence of a pressure gradient they can easily penetrate even the smallest pores of sand with clay filler and, polymerizing, create high-quality solidified soil blocks even at large distances from the injector. Unfortunately, objective reality has made its own adjustments, and the use of organic resins has been reduced to a very small scale due to their very high price and a rather poorly predictable percentage of polymerization under field conditions with temperature variability, soil acidity, etc. In addition, both unreacted resin and polymerization reaction products, decomposing over time, pollute the soil and groundwater for many years.

The technology of soil freezing to create a block of stabilized soil was in demand at the very beginning of the construction of the Moscow metro. In those days, only brine freezing with $CaCl_2$ aqueous brine was used, pre-cooled in the heat exchanger of a refrigerating machine to minus 25 °C. Heat extraction in this way from a soil mass saturated with water occurs rather slowly. In addition, the movement of groundwater, which contributes to the constant removal of cold and the influx of heat, can further prolong this process, and at different horizons in different ways. The use of ‘dry ice’ with a lower gas formation temperature, up to minus 78 °C, significantly accelerates the process of soil freezing and reduces the impact of groundwater movement. However, the CO_2 released in the case of improperly arranged ventilation and inappropriate attitude towards this phenomenon on the part of construction workers can lead to death if it displaces oxygen to the surface on the lower marks of the shaft and the opened cross passages. The use of a refrigerant, liquid nitrogen, with an even lower temperature, down to minus 196 °C, can further accelerate the process of soil freezing. However, there is limited experience in its use in the Moscow region due to technological difficulties.

4. Conclusion

Thus, numerous technologies in soil and hydrogeological conditions of varying degrees of complexity have been tested for ground stabilization in the construction of buildings, including those with tunnel structures, during the construction of the Moscow Metro. The limits of applicability of each technology are revealed, reliability and degree of risk are determined, environmental aspects are revealed.

Based on the experience of constructing blocks of stabilized soil during the construction of cross-passages by mining during the construction of the Moscow Metro, the following conclusions can be drawn:

1. The installation of cross-passages is a very risky and particularly responsible stage in the construction of the subway, excessive water leakage (as well as the release of quicksand masses) in which it threatens the loss of both tunnel structures and sections of interstation tunnels.
2. The making of a block of stabilized soil with anti-filtration protection properties around the cross-passage under construction minimizes the risks of excessive water occurrence and their consequences.
3. Currently, many technologies are known and tested in practice to create a block of stabilized soil with anti-filtration protection properties. Their areas of applicability, advantages, and disadvantages have been identified.
4. As the practice of the work shows (the authors tracked the effectiveness and reliability of each individual technology for fixing the soil mass according to key indicators such as guaranteed continuity, properties of anti-filtration protection, nomenclature of types of soil to be stabilized, changes in natural composition, environmental aspects, compliance of the actual size of the stabilization with design values), according to the authors, as well as a combination of such fundamental characteristics as durability and overall reliability of stabilization, the best method of stabilization soils in the construction of cross-passages is the method of water-saturated soils freezing.

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