Recent experience in solution of geotechnical problems during subway tunneling in Moscow

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Abstract. Moscow subway is one of the world’s leaders in transportation. Moscow subway extension is a vital and urgent task for the authorities and engineers. Subway tunnelling requires using new design solutions, techniques and careful planning. However, widespread application of progressive construction methods does not always allow to achieve reliable efficiency in underground subway construction, mostly because of geotechnical risks impact. Mitigation of geotechnical risk becomes an actual task during subway tunnelling, providing security and saving costs and time. The most effective action to avoid geotechnical risk is scientific maintenance, which allows using the previous experience and making careful analysis, to choose the proper construction methods or develop an effective strategy during accidents.

1. Statistics of the Moscow subway construction
Moscow subway is a system of the urban rapid railway transport, segregated from general traffic and servicing more than 56% of all passengers. The 13 of lines of Moscow subway are mostly placed underground. The total length of Moscow subway lines is 327 kilometers with 228 stations. Some of the stations work at the limits of their carrying capacity, transporting over 50,000 passengers every day and more than 85,000 – 150,000 at the peak. The average speed of the trains in Moscow subway is 40 – 60 kmph, which allows to maintain frequency of the traffic 90 seconds and 30 seconds in peak hours. This makes Moscow subway being a world leader in transportation.

The 2018 was a year of record rate of subway extension, when large number of stations and tunnels had been taken into operation:
- 33 km of the lines;
- 17 stations had been completed;
- 3 more train depots had been prepared completely.

During 2010 – 2018, when the program of Moscow subway development was being fulfilled, the following successes were achieved:
- 45% extension of metro lines;
- 136 km of metro lines were built, including Moscow Central Circle;
- 73 subway stations, including Moscow Central Circle;
- 9 depots.

The program of subway double-extension was declared by Moscow city authorities. This program assumes to some of the existing lines being extended and construction of the new lines, densifying the
network of underground rapid transport within the inhabited city areas and creating it in new districts at the periphery.

2. Lines depth and construction methods
There are two main construction schemes of subway lines in Moscow:
- Deep lines construction, when stations and tunnels are built by mining and boring methods without ground surface disturbance;
- Shallow lines construction, when stations are built by cut and cover method and tunnels are driven by cut and cover or bore methods.

![Example of deep line profile.](image1)

![Example of shallow line profile.](image2)

The parameters of the line plan and profile, as far as the suitable choice of construction scheme, in every specific case depends from a few factors:
- ground conditions, including possible geotechnical risks;
- urban development of a neighborhood, including the presence of buildings, structures and utility communications;
- transport overload and perspective development.

Fast speed of Moscow subway construction becomes possible only by reason of implementation of contemporary construction techniques in practice.

During the construction of cut and cover subway structures the following methods are used:
- slurry wall;
- bored and CFA piles;
- modern waterproofing systems and materials;
- anchoring systems;
- jet–grouting;
- special methods of ground improvement: water lowering, ground freezing, grouting, underpinning, etc.

Figure 3. Cut-and-cover construction method.

When deep structures without surface disturbance are constructed, the following methods are often used:
- tunnel driving with TBM using precast waterproof tunnel segments;
- sprayed concrete with sprayed sealing membranes;
- special methods of ground improvement: ground freezing and grouting, when cross-passages, sump and ventilation stations are constructed;
- shaft driving with use of vertical shaft machines (VSM);
- construction of cross-passages with use of small-diameter TBM.

Figure 4. Conventional tunneling of deep subway station.

3. Geotechnical aspects of underground construction and tunneling in Moscow

However, the widespread application of progressive construction methods does not always allow to achieve reliable efficiency in underground subway construction, not only due to the so-called ‘human factor’, but also as a result of geotechnical risks impact [2], [3], [4].
The geotechnical situation in Moscow region is rather complex, mentioning the subway extension and underground structures development, as a result restraining their essential potential.

The main factors, which have negative influence on the underground space development in Moscow geological conditions are:
- Ground properties degradation: decompaction and structure transformation;
- Ground settlements due to new construction;
- Water level rising due to the action of manmade factors: utility leakage, barrage effect and etc.;
- The presence of thixotropic (liquid sands) and frost-heaving soils;
- Water pollution, modern tectonic shifts, errant electricity and other anthropogenic impacts;
- Landslides and erosion;
- Karst and suffusion processes, aggravated with utility leakage, water lowering during underground construction and their use.

4. Implications of the risks
As a result of the action of the abovementioned factors, 30% of the structure operation costs are expended on current repairs: waterproof sealing, construction strengthening, stabilizations, grouting and etc.

![Figure 5. Map of construction cost increase [1].](image)

The Russian science academy [1] after the study of ground conditions over the entire city territory made a zoning of underground construction cost increase from 3 to 6 times comparing with original cost-estimation without detailed risk-analysis. The result of these studies showed that nearly a half (48%) of the city territory is in the geological risk zone, the other parts of the territory are in potential risk zone (12%) and safe zone (40%).

Though, the incidents during underground construction is unusual case, they were often an occasion for analyzing the reasons of their occurrence and mitigation of their impact. Most of the cases are the result of poor geological survey, deviations during underground works caused by ‘human factor’, inconsistency of design solutions and many other factors and etc.
Figure 6. Examples of accidents: surface settlement and building damage induced by unexpected geological anomaly along the axis of TBM tunnel (a). Undetected karst voids during the mining of escalator tunnel (b).

Sometimes the risk situation causes a great damage, making problematic the operation of the structures above or below the ground, as shown in fig. 6.

Figure 7. Example of accident: Settlements of the segmental lining caused by the presence of poor bottom ground layer under the tunnel.

In other cases, the risk impact was remediable, allowing to make repair works creating safe conditions for the operation of the structure. One of these examples is presented in fig. 7, where the repairment works and ground stabilization of the bottom of the tunnel were performed.

5. Scientific maintenance of subway design and construction

In general, the interaction of subway structures with surrounding soil is determined by the stress-strain behavior of the soils and structures, including the following induced negative factors [7], [8]:

- Loading and unloading of soil during the excavations and further structure service, influencing on static conditions of soil-structure interaction;
- Hydrodynamic impact, caused by water level deviations;
- Technological impact, caused by additional loading during constructions and specific of geotechnical works.

Depending on the degree of geotechnical difficulties over the construction sites, three categories of geotechnical complexity of construction were introduced:

1 – including buildings and structures of lower responsibility level in simple ground conditions with little geotechnical risk probability;
II – including buildings and structures of normal and high responsibility level in simple and a medium difficulty ground conditions;

III – including buildings and structures of high responsibility level in difficult ground conditions with high probability of geotechnical risk. Subway structures are usually referred to that category. In this case the scientific maintenance of construction is an obligation.

When the scientific maintenance is performed, the following survey and analytical works are made:

- Site and route of the tunnel survey, as far as the buildings, structures and utilities, located in the zone of the influence of construction works;
- Geotechnical analysis of stress-strain behavior of soils and structures during the subway construction;
- Geotechnical risk assessment;
- Limit state analysis of underground structures and tunnel linings;
- Design and installation of monitoring systems;
- Buildings and structures underpinning;
- Optimization of construction and design solutions after detailing of geotechnical conditions of the site;
- Quality control during difficult geotechnical works.

**Figure 8.** Tunnel lining testing during scientific maintenance of subway construction [9].

**Figure 9.** FEM-analysis of tunnel lining shift in karst
6. Positive practice
The foregoing complex of geotechnical survey, scientific, applied and theoretical works are realized in the practice of Moscow subway tunneling. Several representative cases may impressively illustrate reasonable approaches of Moscow tunneling engineers during solving the complex tasks of geotechnical and underground engineering.

6.1. Double-track tunnels
Double-track tunnels are being constructed at Kozhuhovskaya line at the moment. That became a new challenge in Moscow [10]. The circular precast concrete lining with diameter of 9.6 / 10.5 m (internal / external) is used. The tunnels are being driven with large diameter EPB-TBM. The depth of the tunnel crown is 15 – 30 meters. The routes of the tunnel are passing through the built up districts in complex geotechnical conditions. The construction is being made without tunneling induced settlements. This became possible due to using of modern monitoring systems and underpinning methods – compensation grouting.

![Double-track tunnels construction](image1)

**Figure 10.** Double-track tunnels construction.

6.2. Construction of cross-passages and subway service tunnels with small-diameter TBM
This approach becomes necessary, when cross-passages or service (e.g. ventilation) tunnels have a rather big length, passing through the unstable and saturated soils. In that case a large amount of grouting works are cost-ineffective and risks are increasing. One of the examples of construction of two service tunnels with small-diameter EPB-TBM was accomplished on Lublinskaya line in 2019. The length of each tunnel is about 70 meters with tunnel diameter 3.6 meters.

![Construction of cross-passages and subway service tunnels with small-diameter TBM](image2)

**Figure 11.** Construction of cross-passages and subway service tunnels with small-diameter TBM.
6.3. Cut and cover solutions in complex geological conditions and built up areas

For cut and cover method many solutions are used in some difficult cases. One of the difficult cases is when installation chambers of TBM must be arranged. Usually slurry wall or bored secant piles are used for retaining walls. In some cases CFA secant piles and jet-grouting in the gap are used. Using the ground anchors instead of traditional struts sometimes it became possible to achieve much effect in speed and cost of construction.

![Figure 12. Construction of cut and cover subway station.](image)

6.4. Buildings and structures safety: monitoring and underpinning

In recent years the use of automated monitoring systems showed their efficiency [5], [6]. Especially in the cases, when the settlements may occur rapidly (e.g. TBM tunnel driving). Another solution, which showed its reliability is the compensation grouting with use of automated monitoring systems, allowing to avoid tunneling induced settlements during construction.

![Figure 13. Grouting works during under existing foundations to prevent tunnel induced settlements.](image)
7. **Perspectives**
The Moscow authorities have an approved program of subway extension. By 2022 the Second Ring Line (`Bolshaya Kol'tsevaya Line` - BKL) must be accomplished. Some stations are already in service, but 25 stations are under construction. The total length of the new line will be 69 kilometers with 31 change-stations, placed mostly in dense-populated districts. A new line is to be constructed in South-West by 2023, making the basis of transportation in 'New Moscow' - several districts, where mostly residential buildings are going to be situated. Kozhuhovskaya line will connect over-populated South-Eastern districts of Moscow with city-center by 2021. A half of the line will have stations with side platforms and double-track tunnels. In June 2019 a first part of this line – 7 km with 4 station were taken into operation. These are the main projects for the further 4 years of Moscow subway development.

8. **Conclusions**
The realization of the plans of Moscow subway development is responsible challenge. One of the keys of success is solving of geotechnical problems, which can occur in complex geological conditions. In combinations with use of modern construction methods it worth expecting a fine result of the work, which is in process nowadays.

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