Principles of the integrated development of Moscow City underground space

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Abstract. Moscow is the most dynamically developing metropolis in the Russian Federation. This is a city with almost a thousand-year history, where about 12.65 million people live on an area of 2.5 thousand km². The economic efficiency of the underground space utilization is characterized by the ratio of the area of the underground part of the structure to its total area. Said ratio on average is less than 8% for the city of Moscow. From 2011 to 2019, 50 new metro stations and about 82 km of new metro lines were built in Moscow. By the end of 2027, it is planned to build 329 km of new lines and 151 stations. The housing renovation program provides for the renovation of 5175 residential buildings with maximum utilization of the underground space to ensure a comfortable living for people. The report considers the basic principles, goals and objectives of the integrated development of the underground space of Moscow, indicated in the Code "High rise buildings and complexes. Regulation of urban planning". A review of accumulated experience in the construction and operation of residential areas of Moscow, built on the autonomous principle of "city in city". Methods for ensuring the integrity and technological safety of existing buildings with integrated development of the underground space are considered.

1. Introduction

The pattern of the modern stage of development of the underground space is the continuous increase in the importance of underground construction throughout the world. More and more governments and municipal authorities around the world are realizing the need and benefits of using the underground space. The 2017 World Tunnel Congress and the 43rd General Assembly of the International Tunneling Association (ITA) showed that the total investment in tunneling and the development of underground space in the world reached 86 billion euros in 2016. Tunneling is growing in the Middle East, where investment in the industry amounted to 10.2 billion euros, which is comparable to all European countries combined (9.7 billion euros). China remains the leader in global tunneling, occupying about 50% of the market. The International Tunneling Association predicts growth in the global tunneling market to 680 billion euros by 2024, while 75% of the total tunneling volume will be concentrated in India, Southeast Asia and China [1].

Moscow is the most dynamically developing metropolis in the Russian Federation. It is a city with almost a thousand-year history. Here about 12.65 million people live on an area of 2.5 thousand km². About 12.1 million of them are located in the territory of “old Moscow” with an area of about 0.9 thousand km².
2. Analysis of the experience of underground construction to Moscow

An analysis of the foreign experience of underground construction in urban agglomerations, similar to Moscow in accordance with such indicators as the population, the number of vehicles per inhabitant, the area occupied, the ratio of historical and modern buildings, shows that the optimal conditions for ensuring sustainable development and comfortable living are achieved with a share of underground facilities of 20-25% of the total area of constructed facilities [6].

The current situation in Moscow with the usage of underground space in the construction of structures for various purposes as a whole can be described as follows (Fig. 1).

![Figure 1. Accommodation of objects of various functional purposes in the underground space of Moscow](image)

The implemented projects and experimental proposals in the central area of Moscow are characterized by the active use of the underground space with the placement of various enterprises and institutions in it, most often unconnected.

The peripheral area is characterized by insufficient use of the underground space and an increase in the number of elevated levels. At the same time, underground infrastructure facilities are, as a rule, monofunctional.

According to purpose, underground structures within the city are distributed as follows. The most widespread are car parking lots and utility facilities. Next are unloading yards and warehouses, trade and public catering facilities. A special place is occupied by pedestrian connections with public transport (primarily with the metro). There are cases of the location in the underground space of spectating, social and administrative institutions.

The economic efficiency and prospects of using the underground space is demonstrated by the percentage ratio of the area of the underground part of the structure to its total area. Within the city limits, it varies from 4.0% to 87.5% for civil engineering projects and up to 100% for transport and engineering facilities (Fig. 4). The most active use of the underground space is observed in the central area, where this ratio is close to 30%. In peripheral areas, this ratio is quite insignificant. Generally, it is less than 8% in the city.

In 2012, the Government of Moscow adopted the Resolution “On the Approval of the List of Perspective Construction Facilities of the Moscow Metro” [2]. It was planned to build 329 km of new lines and 151 stations by the end of 2027. To service the newly constructed lines, 19 metro depots should be put into operation (Fig. 2). This will reduce the load on the existing metro network, as well
as provide “step-by-step access” to stations for 93% of the population of Moscow. In total, from 2011 to 2019, 50 new metro stations were built in Moscow, about 82 km of new lines and 10 metro depots.

The Housing Fund Renovation Program in Moscow provides for “a set of measures aimed at updating the living environment and creating favorable living conditions for citizens and public space in order to prevent the growth of emergency housing stock in Moscow, ensuring the development of residential areas and their improvement” (Fig. 2) [3]. Moreover, “the renovation of the housing stock is carried out taking into account the development of a network of infrastructure facilities, the creation of additional conditions for the development of human potential, the environment, which ensures the integrated development of the territory in accordance with modern requirements for the urban environment. When implementing the Renovation Program, it is necessary to ensure the creation of a comfortable living environment for citizens by establishing additional requirements for the improvement of the territory, the formation of a street-road network, parking space, sidewalks of the front area, and the organization of courtyard and intra-quarter green areas.”

Creating a comfortable living environment not only results in a “comfortable housing”, but a comfortable urban environment, which includes a combination of residential, transport, social, cultural, entertainment and natural clusters. Now, perhaps for the first time in its thousand-year history, Moscow is becoming a city convenient for life. There are wide sidewalks, bike paths, organized parking, landscaped parks, a network of roads and public transport is growing. It is very important to take this experience into account when renovating residential buildings and constructing new housing estates.

Comfortable housing without the organization of a comfortable urban environment will turn renovation blocks into new sleeping areas of mass residential development. The metropolis of tomorrow is an environmentally friendly, energy-efficient, affordable and people-centered city, in which priority is
given to the efficient use of natural resources, reducing environmental pollution and consumption. The use of the underground space allows to create a new, 4th dimension of the familiar urban environment, makes it possible to build compact infrastructure complexes in a limited area, minimize environmental damage from construction and improve the quality of life of the population. In theory, it is difficult to find opponents of the idea of developing the underground space of Moscow, including in areas of mass housing development. Everyone recognizes the social significance, rising real estate prices, the possibility of organized storage of transport and the organization of new transport communications, etc. However, in practice, every meter of the free surface is used instead, and the construction of underground structures is resorted to as the last resort, when all other possibilities have already been exhausted.

It should not be forgotten that when planning renovation areas and areas of mass residential development in New Moscow, we do not only solve everyday problems, but create a kind of urban development for at least the next 50-100 years. According to foreign researchers [4, 5], the creation of a new generation of urban infrastructure must be approached, first of all, from an environmental point of view.

3. The model of integrated use of the underground space of Moscow

The model of integrated use of the underground space of Moscow should take into account the following principles of long-term planning:

- complementarily – for example, the designed transport systems of a residential area should provide quick and comfortable movement of a person from the doors of his apartment to the doors of the subway car;
- interchangeability – in particular, civil defense facilities should be designed as parking lots, storehouses, fitness centers, library storages, etc.;
  - safety;
  - centralization of monitoring, control and maintenance systems;
  - social development.

The solution to these problems is possible only through the integrated development of the underground space. For this purpose, a regulatory document was developed that defines the main urban planning principles for regulating the development of underground space in Russia: the Code of Rules “Buildings, structures and complexes underground. Regulation of urban planning” The developers of the set of rules were using the following principles for creating a cost-effective, comfortable and safe ecological city:

- integrated, multiple use of the territory and underground space;
- compensation for a decreasing land resource by placing the engineering infrastructure and public services in the underground space of transport objects;
- the use of aboveground space primarily for housing, social infrastructure and green areas;
- synergistic effect from the use of energy and natural resources;
- the use of advanced construction technologies that have a minimal impact on the natural and technogenic environment.

Urban planning tasks for creating an underground space should include:

- the continuity of the historical development of cities, their spatial arrangement, ensuring their harmonious and compositional urban unity, creating a system of city-wide centers, including historically established city centers and centers of their peripheral areas, taking into account the maximum use of underground space;
- an increase in the share of territories of mixed and multifunctional use in the territories of cities, and an increase of territories of high-density public buildings and underground spaces;
- creation and development of centers of peripheral areas with underground spaces combined with transport and interchange hubs;
- creation of a system of public, commercial and business complexes concentrating significant flows of workers and visitors as a part of underground spaces in the periphery of the historical center.
The Code of Rules contains recommendations on the permitted use of capital facilities located in the underground space, on the degree of use of the underground space in cities with different population sizes, on the location of underground facilities in the territories of various functional areas of the city, on the functional composition of underground rooms.

Along with horizontal zoning, it is proposed to use rational zoning of the underground space vertically. For this, a functional distribution of the underground space is proposed for four levels of depth, taking into account social and medical factors:

- **the first level** (low depth – up to 5 m): pedestrian zones and institutions gravitating towards them, retail enterprises, cultural and leisure centers and other retail and consumer services enterprises that are constantly operated and visited by an unlimited number of people;
- **the second level** (medium depth – 5-15 m): transport tunnels, garages and parking lots, utility warehouses, cargo yards, service communications, etc., facilities used for a short time by an unlimited number of people;
- **the third level** (increased depth – 15-30 m): industrial and energy enterprises with the constant presence of a limited number of qualified personnel;
- **the fourth level** (especially deep – more than 30 m): deep engineering communications, metro, special structures operated without the constant presence of a person.

At the same time, it is proposed to provide for the possibility of creating multifunctional underground spaces that may be operated without need for access to the surface.

The use of underground space should provide:

- rational placement of underground parts of buildings and underground structures for various purposes in the necessary places of the city, including ones in the conditions of dense urban development;
- improving transport services for the population through the use of off-street electrified modes of transport for high-speed mass transportation of passengers, the organization of high-speed and continuous traffic on main streets and certain sections of roads; the formation of transport hubs and the construction of interchanges using the underground space;
- formation of optimal conditions for the development, operation and repair of urban engineering networks through the installation of straight-way collectors, compact water and sewage treatment plants, electricity and gas supply facilities, pumping stations, etc.
- storage and parking of cars and other means of transport in the underground space;
- adaptation to the modern use of territories of cultural heritage sites, ensembles of architectural monuments, protected areas of cultural heritage sites;
- improving the comfort of staying in public, business and commercial areas, public service areas;
- protection of the population in protective structures of civil defense in wartime and emergency situations of a natural and man-made nature;
- creation of an urban environment friendly to people with limited mobility.

For this, a gradual transition from the use of the underground space of cities to accommodate individual objects to its integrated development, which makes the urban environment more comfortable for the life of the population, is assumed. At the same time, the Code of Rules in accordance with sanitary rules restricts the use of the underground space for the placement of:

- residential premises;
- educational facilities for children;
- educational facilities for adults with a stay of more than 4 hours;
- administrative premises with a constant operating mode.

4. Space-planning solutions and examples
The implementation of these principles and approaches with specific examples in considered next.

During the construction of main line tunnels and underground metro stations in the areas of mass residential development, it is proposed to use the area above the tunnels to place pedestrian and road
tunnels, parking lots and garages, as well as trade enterprises. In some cases, underground structures may be located under or near main line and station tunnels.

In areas where it is not planned to develop the network of the metro under construction and renovation does not imply a quarterly principle of development, it is proposed to use the existing street-road network to place underground parking lots and public amenities within walking distance. With the width of the parking space of 2.5 m, such a technical solution will allow to place up to 1,500 parking spaces (taking into account the entrances and exits and other technical premises) per 1 running km of parking lots. With an automated storage system, the capacity of the parking lot will increase to about 1,650 parking spaces per 1 running km.

Also, for the storage of personal vehicles of the population, the underground part of the shopping and entertainment complexes and transportation hubs under construction should be used. To do this, part of the parking spaces in parking lots must be used not only for hubs, shopping centers, visiting retail establishments, public catering, etc., but also for storing personal vehicles by employees of nearby administrative and office buildings during the day, and by residents of the surrounding area-at night.

For areas where the quarterly principle of development is expected, these same tasks can be solved in a fundamentally different way. In this case, in our opinion, it is advisable to build a common underground part of the micro-district including:

- underground car parking lots, including places for permanent and guest storage of vehicles;
- underground transport network, including:
  1. carriageway for cars and public transport;
  2. sidewalks for pedestrian traffic;
  3. public transport stops;
- access roads, unloading platforms and warehouses of trade enterprises, consumer services, catering, etc. ;
- enterprises of trade, consumer services, catering, etc. ;
- construction of the engineering infrastructure of the micro-district;
- civil defense facilities, etc.

Such a solution will almost completely separate the residential and engineering zones of the micro-district. The ground part will be given to housing, kindergartens, schools, hospitals, green spaces. Due to the transfer of all transport to the underground part of the district, maximum safety of residents, reduction in road accidents will be ensured, and the environmental situation will be improved.

An example of such a solution can be the experimental district Northern Chertanovo, built in the 1970s (Fig. 3). The district was designed as a “city in a city” and included local household, commercial, cultural, administrative zones. At the same time, a unified building maintenance system with underground parking lots, pneumatic garbage disposal and centralized control of engineering systems was implemented in the micro-district.

5. Technological safety

It must be borne in mind that construction is carried out in a dense urban environment. For example, on average, 5-7 existing buildings and structures are located in the zone of influence of the excavation of the underground station (Fig. 4).

To ensure the safety of existing buildings, it is necessary to use modern advanced technical and technological solutions.

In particular, a ranking of modern underground construction technologies was conducted and 3 classes of “high” or “advanced” technologies were introduced with regard to their impact on the natural and technogenic environment (Table 1). The Table 2 shows the ranking of modern underground construction technologies that are most often used in Moscow, depending on the degree of influence on the prevailing geo-ecological environment.
Figure 3. Residential micro-district "Northern Chertanovo" in Moscow. Elements of the underground space: car parking lots, transport network, access roads, unloading platforms and warehouses of trade enterprises, construction of the engineering infrastructure.

Figure 4. View of the foundation pit of the Yugo-Vostochnaya metro station under construction and the perspective of the Nekrasovskaya metro line.
| Class   | Description                                                                                                                                                                                                 |
|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| I – Simple | The construction of structures with a reduced or normal level of responsibility is carried out in territories free from development and does not affect the geo-ecological environment                             |
| II – Moderate | The construction of structures of a normal level of responsibility is carried out in urban areas, it affects the geoecological environment, however, environmental safety requirements are secondary in comparison with economic efficiency or building safety |
| III – Complex | The construction of structures of a normal and increased level of responsibility, including especially dangerous, technically complex and unique ones, is carried out in the conditions of the historical part of the city. The urban development condition is dense. In the construction influence zone there are historical, cultural, architectural monuments, buildings and structures with increased requirements for noise and vibration, especially dangerous and unique buildings and structures. Environmental impacts should be minimized. |

| Table 2 |
|--------|
| I class |
| 1.1 | Driving of metal piles and sheet piles using pile driver |
| 1.2. | Diaphragm wall with electric discharge piles |
| II class |
| 2.1 | Hydraulic driving of metal piles and sheet piles |
| 2.2 | Diaphragm wall |
| 2.2.1. | Slurry wall using grappler |
| 2.2.2. | Using jet-piles |
| 2.2.3 | Using jet-piles with chemical additives |
| 2.2.4. | Using soil mixing technology |
| 2.3. | Long-term anchoring of retaining walls |
| 2.4 | Tunneling |
| 2.4.1 | NTM |
| 2.4.2 | TBM with active face loading |
| 2.4.2.1 | Air Balance |
| 2.4.2.2. | Combined Balance |
| III class |
| 3.1 | Vibratory driving of metal piles and sheet piles |
| 3.2 | Diaphragm wall |
| 3.2.1 | Slurry wall using hydromel equipment |
| 3.2.2 | Using secant piles |
| 3.2.3 | Combined precast and cast-in-situ with plate reinforcement |
| 3.2.4 | Combined precast and cast-in-situ with prestressed reinforcement |
| 3.2.5 | With a thin cutoff made by jet-grouting |
| 3.3 | Bracing of excavation pit with reusable prefabricated struts |
| 3.4 | Top-down construction method |
| 3.5 | TBM with active face loading |
| 3.5.1 | Hydraulic Balance |
| 3.5.2 | Earth Balance |
Thus, another major urban development objective of underground construction in Moscow is to ensure safe and trouble-free operation of the existing surrounding buildings, underground structures and utilities [7]. During underground construction, deformations of nearby buildings are caused by unavoidable effects associated with changes in the existing stress-strain state of the soil mass, as well as the so-called "technological" effects of working construction equipment. Domestic building codes stipulate the need for geotechnical forecasting, as a rule, using mathematical modeling methods. The geotechnical forecast should provide answers to questions about the safety of the planned underground construction and the degree of influence on existing buildings and structures. The results of the geotechnical forecast should be confirmed in the process of geotechnical monitoring [8], which should be carried out throughout the construction of the underground facility. In the event that the results of the forecast show that underground construction can have an unacceptable effect on certain existing capital structures, protective measures should be included in the design that reduce the degree of influence. The design of protective measures is regulated by the Code of Rules [9], recently developed in connection with the intensive development of the underground construction in the largest cities of the Russian Federation and, first of all, of course Moscow.

6. Conclusion
The experience gained by civil engineers and geotechnics of Moscow, innovative solutions for resource saving and energy efficiency, zoning of the territory, the organization of transport accessibility with the predominance of high-speed mass transportation of passengers, will create a city environment convenient for life and increase the safety and investment attractiveness of urban construction.

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