Problems and prospects for the development of the Saint-Petersburg metro system

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Abstract. The Saint Petersburg Metro was opened on 15 November 1955. It is the second largest subway in Russia after the Moscow Metro. The St. Petersburg Metro has stagnated since the early 2000s. This causes many problems for the transport network, such as high congestion of surface transport, especially in new areas of the city where there is no underground line. Also, the misallocation of underground traffic, the small number of regular and interchange stations per multi-million city. And what stops the development of the St. Petersburg metro is insufficient state funding, inefficient budget spending and poor construction quality. Development plans are shifted in terms of timing and in the end remain only on paper. The solution to these problems will allow Saint Petersburg to distribute the load on the surface and underground transport network, improving the quality of life of residents of St. Petersburg. Also, metro is a cultural heritage, and exclusive technologies were used to build it back in the USSR, and the central stations have their own design code.

1 Introduction

Major cities are often faced with the challenge of moving huge numbers of people within their boundaries and, unfortunately, land-based transport systems are far from always able to cope with this challenge. In a city like St. Petersburg, this problem is compounded by the large area of the historic centre and the large number of rivers and canals. In St. Petersburg, where 7 percent of the city's area is made up of bodies of water, the problem of load-shedding for public transport is most acute. O. Nikiforov states the following in his research: «Many large cities of the Russian Federation have to create a balance between different modes of passenger transport – public and private, electric, gasoline, and bicycles. It is necessary to wipe out the lag in the development of the road traffic network, reduce traffic jams, provide the required number of parking spaces, and, at the same time, create a public transport system that provides reliable and fast communication between central areas and external transport zones» [1].

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1.1 Relevance

The relevance of the study is determined by the fact that the Saint Petersburg Metro is developing slower than the city's growth rate requires, and ground transport is failing to cope with the load. On the outskirts of the city, motorways are congested and public transport is significantly behind schedule in the morning and evening hours. Over the years, the problem has worsened, which can lead to transport collapse. The pace of construction lags behind city plans by several years, and in some sections (Teatralnaya station) construction has been suspended. The new underground stations built between 2017 and 2021 are being repaired every year due to a large number of leaks, with walls crumbling and escalators breaking down in station lobbies. The city authorities send funds from the budget for current repairs of metro stations, but the problem is not globally solved, because the construction should initially provide for good waterproofing, use of quality materials, and control by chief engineers. The slow construction of new metro stations is due to the difficult geological conditions on the territory of Saint Petersburg, as well as irrational use of the budget.

1.2 Literature review

In order to identify the problems of the St. Petersburg metro system the works and sources presented in the list of literature were studied. The main points are described by Mikhalyuk M.A. in his paper The influence of the metro on the socio-economic development of the territories of St. Petersburg: history and prospects for the development of the St. Petersburg metro system. The author discusses the shortage of new underground lines to cope with the load on the current stations, and also touches upon the low density of stations in the city centre, citing the difficult geology. This implies a large financial investment, which the city does not have. The author specifically mentions the development of new areas of the city, which increases the load on surface transport from the lack of underground transport. The author considers this to be unavoidable, and this is why this work was decided to be the main course of action.

M.I. Amosov in his work "Development of the St. Petersburg metro network over 60 years and prospects for its further development" considered stages of St. Petersburg Metro development for 60 years. The author proposes to increase the efficiency of the transport system by linking the metro network with other types of non-metropolitan rail transport. This idea is quite global and the city authorities are unlikely to implement it. We partly agree with the author and think that such a project can be implemented only on the outskirts of the city, at underground stations under construction.

Yu H in his paper "Evaluation of water logging risk in an urban subway station //Advances in Civil Engineering" offers a method for assessing risks of leaks and waterlogging in underground stations. It is important for St. Petersburg because its territory is erodible and the method suggested by the author can significantly reduce the risk of leakage, especially on stations built near Gulf of Finland using shallow embedding method.

A.N. Styazhkina in her article "Prospects for the construction of the metro in St. Petersburg on the basis of a concession agreement" proposes to modernize the transport sector and the metro in particular, by attracting private capital (investors). This idea is quite progressive and widespread abroad. At this stage, the authorities of Saint Petersburg are not set on such a solution to the economic problem, but it is worth paying attention to. We support the author's opinion and think that involving private capital can help solve the problem of under-financing of metro construction.

Konykhov D. S., Kolybin I. V. in their paper "Principles of the integrated development of Moscow city underground space" reveal the principle of Moscow metro construction, when residential quarters are built around the metro station on the outskirts and city residents, buying real estate, immediately have access to the metro network. We fully agree with the authors that this principle of construction not only ensures comfortable living conditions for residents, but also corresponds to the pace of the city's growth. The authors also cite important statistics on the pace of construction of the Moscow metro and the city budget, which were used in our study for comparison with the pace of construction and financing of the metro in St. Petersburg.

1.3. Problem statement

The main problems in the development of the Saint Petersburg Metro are: insufficient state funding for the construction of underground transport in the city, the slow pace of tunneling due to the difficult geology, the need to introduce new technologies (building a double-track tunnel, abandoning the construction of deep-bottom stations).

1.4. Aim, objectives and hypothesis

The aim of the study is to identify the key problems in the field of geology and construction financing that hinder the development of the St. Petersburg Metro, as well as to analyse the prospects for its development.

The above-formulated goal requires the following tasks: analysis of historical experience in construction of St. Petersburg metro, collection and analysis of statistical data on construction and budget, identification of problems in construction and problems of metro development, comparison of experience of metro construction with Moscow and with other countries, as well as characterization of future prospects of this type of transport.

Research hypothesis: current financing of metro construction projects is not enough, it's necessary to increase construction budget and to invest in high-quality materials, which will eliminate the need of annual repair of stations. Annual subsidy to SUE "Moscow Metro" is 30 billion rubles, and in St. Petersburg in 2021, 7.4 billion rubles were allocated for the construction of the underground, in 2022, it is planned to allocate 11.9 billion rubles. It is necessary to increase the annual funding to at least 15 billion rubles. It is possible to reduce underground construction costs by using a double-track tunnel technology and excavating it using the shallow method.

2 Methods and materials

Relevant material from various sources was selected for this paper. Based on these, the problem was analysed, the solutions were identified and conclusions were drawn. Empirical-theoretical research methods were used, in particular the method of analysis, the method of analogy, the method of comparison and induction. In order to analyse the current state of St. Petersburg Metro and identify existing problems, materials from different sources were found. Based on the data obtained, the problems were identified and analysed, the ways to solve them were determined and the conclusions were drawn.

3 Results

On the basis of empirical-theoretical methods of research and analysis, the current state of the Saint Petersburg Metro, problems, development prospects and solutions are considered.

3.1 History of the construction of the Saint Petersburg metro

In the 20th century, St. Petersburg's population grew past 3 million. The time was ripe for the construction of a metro. In 1814, English engineer Mark Brunel proposed to Russian Emperor Alexander 1 to build a tunnel under the Neva, but he preferred a bridge. World War I and the October Revolution halted construction of the metro in St. Petersburg, and it began in 1941. Two lines of the first stage were planned, and Moscow and Leningrad metro builders were involved in its construction. Over half a year it was built: 15 shafts; 700 m of tunnels. But plans were interrupted by the Great Patriotic War, work was suspended until 1947.

Many parts of the city were in ruins, ground transport could not cope with the movement of people, there was a need for new technology to pass the difficult ground. The first underground line opened in 1955: from Vosstaniya Square to Kirovsky Zavod. As of 2021, St. Petersburg has 5 lines, 72 stations, 6 depots.

3.2 Features of the construction and current state of the Saint Petersburg Metro

All watercourses in Saint Petersburg have erodible soils underneath, which easily crumble and shrink. Good soils: clay and sand have a high density. But as the researchers Qixiang Yan, Minghui Sun, Chaofan Yao, Hongyue Liu, Wang Wu & Jingchuan Duan state "Boulders can cause serious damage to the cutting heads of shield machines and even lead to the failure of shield tunnels during the excavation of subway tunnels in granite formations" [2]. Consequently, any soil has problems during excavation.

Cambrian clays that hold back water to a depth of 50 meters were suitable for the construction of the underground. "Lenmetroproekt" constantly offered exclusive solutions: cast iron was replaced by steel, the idea of freezing the ground. The diameter of the tunnels was smaller, 5.5 m instead of 6 m, and the thickness of the cast-iron tubing was reduced.

The city became famous for having the deepest metro in the world. St Petersburg's geology offered energy-saving possibilities. Underground stations were built on slides: from a station, the train goes downhill, accelerates, and before the next station, it slows down. Currently, lines under construction will use double-track tunnel technology, where trains will run towards each other in a common tube-it's cheaper, reduces lead times, and is safer. There have been a number of major accidents in China, of which Yu H writes the following in his study: "On April 1, 2004, in the construction site of Lijiao Station of Guangzhou Metro Line 3 in China, the enclosure structure of underground continuous walls suddenly collapsed due to continuous heavy rain. A building only 30 m from the construction site leaned to the south for 60°, and the foundation pit by the side of the building collapsed, forming a hollow place with the area of more than 1,000 m2, which caused great losses" [3]. Liu W., Zhai S., Liu W. "A massive cave-in during the construction of Metro Line 1 near the Xianghu station caused 21 injuries and 24 deaths, and the direct economic loss amounted to 49.61 million Yuan. A more recent accident took place on May 14, 2017, in Nanchang [4]. Excessive surface settlement during the construction of Metro Line 2 near the Bayi square station caused a cave-in of more than 10 m in diameter and led to severe property losses. Yu H in his paper "Evaluation of water

logging risk in an urban subway station //Advances in Civil Engineering" said: "Therefore it is imperative to systematically access and manage the safety risks associated with shield tunnel excavation" [5].

3.3 Problems in the development of the Saint Petersburg metro system

Metro's revenue required for budgeting and maintaining the metro consists of: fare payments, advertising in cars and stations, and sales of advertising or souvenir products by subsidiaries. In Figure 1 we consider the metro budget over a 10-year period from 2010 to 2020.

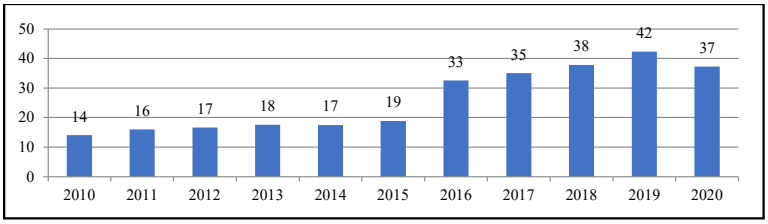

Fig.1. Revenue of St. Petersburg Metro from 2010-2020 in billion RUB.

Since 2010-2015, revenues have risen smoothly and declined by an average of 2%, but remain low. By 2016, passenger traffic was down by 15 million and rolling stock was 70% depreciated. However, revenue in 2016 increased by 14% to around 33 billion RUB. This was due to the Targeted Investment Programme to equip underground facilities with transport safety engineering equipment in the amount of RUB 62 million, the expansion of the fare selection of the concessionary fare programme and the signing of new contracts for the lease of underground premises. Attracting investment made it possible to lay broadband internet in 2017. The investment was made by Maxima Telecom NW Ltd. Thereafter, revenues grew until 2020. The downturn in 2020 is due to coronavirus restrictions.

Additional funding comes from state subsidies from the budget. The St. Petersburg metro is the most unprofitable in comparison with other metros in Russia. Consider Figure 2, which shows the state subsidy to the St. Petersburg metro from 2019 to 2020.

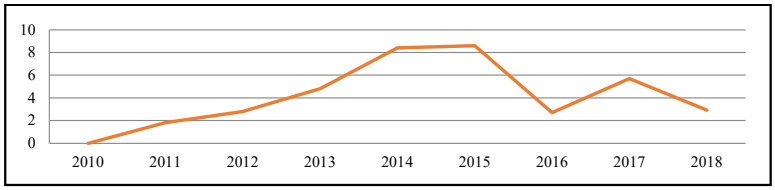

Fig. 2. State subsidy to Saint Petersburg Metro from 2010-2020 in million RUB.

The graph shows the dependence of the decline and upturn on the subsidising of the metro development programme 2008-2020, which is regularly edited and not implemented. It foresees the construction of 70 km of new lines, 5 depots, 41 stations. The Frunzensky radius is due to be commissioned, and the first stage of the Krasnoselsko-Kalininskaya line was planned to be completed in 2015. Only the Frunzensky radius was completed on time. The extended program from 2011 to 2015 and the prospect for 2024 could not be

implemented in full. In 2013, because of the FIFA World Cup, the programme was adjusted, instead of the Krasnoselsko-Kalininskaya line, they focused on the Nevsko-Vasileostrovskaya section (Gazprom-Arena). Because of the lack of execution and poor implementation of the budget, Smolny had reduced funding. The credibility of the authorities was also undermined by a corruption scandal caused by abuse of power, as a result of which the metro was deprived of 466 million rubles. In an attempt to compensate for the losses, the cost of a single trip to the underground was raised to 45 rubles. Yinghan Zhu, Yu Zhang, Xiaosen Huo, Ya Wu, Liudan Jiao noted: "Among them, tariffs and quality of service are attributes of the metro system that can directly affect demand, since higher tariffs or worse quality of service will lead to a decrease in passenger traffic" [6].

In 2018, 2 Zenith and Begovaya stations were launched, with poor construction quality, causing operational problems. State subsidies covered concessionary travel, but the budget was not being utilised and the management did not give tenders in the right time. The company's net profits increased artificially, at the expense of higher fares, with passengers opting for ground transport. Maintenance and repair of rolling stock, stations, and tunnels ate up a huge amount of money. Metrostroy is currently in a pre-bankruptcy state. The total amount of debt is 15 billion rubles over 10 years. Nine stations have been commissioned with great delays.

Let us consider Fig. 3, it shows the built stations of St. Petersburg and Moscow subways from 2010-2020.

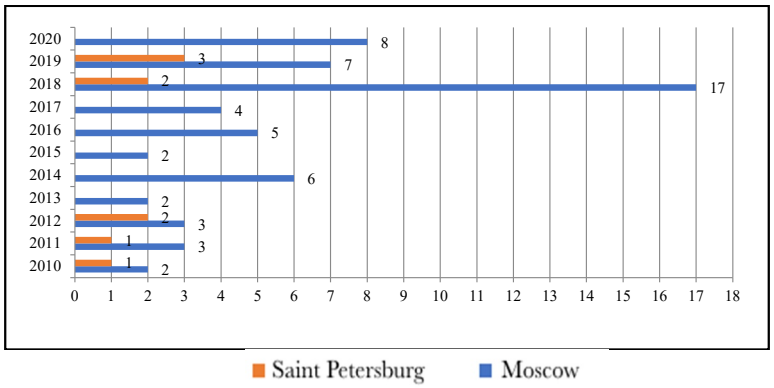

Fig. 3. Number of stations built in St. Petersburg and Moscow from 2010 to 2020.

Turning to the experience of the Moscow Metro, a tremendous difference in development can be seen. By 2010, there were 180 stations in Moscow. A total of 59 stations were opened in Moscow in 10 years, and 9 in St. Petersburg.

Figure 4 shows the revenue of the Moscow Metro from 2010-2020.

"Moscow is the most dynamically developing megacity in the Russian Federation. It's a city with an almost thousand-year history. There are about 12.65 million people living here, covering an area of 2.5 thousand km2. Of these, about 12.1 million people are located on the territory of 'old Moscow' with an area of about 0.9 thousand km2" [7]. as stated Konykhov D.S. and Kolybin I.V. in their paper "Principles of complex development of underground space in Moscow". It is also interesting that "In this study, I considered the parameters of architecture and network. The Berlin U-Bahn, the Moscow metro and the

Amsterdam metro, which can be considered tourist attractions themselves, recorded the greatest number of reviews on architecture", as Taecharungroj V. writes in his study. [8].

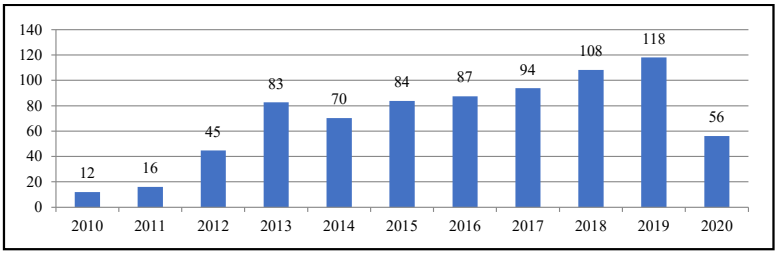

Fig. 4. Revenue of the Moscow Metro in the period from 2010 to 2020, in billion roubles.

Let us compare the load per station in the St. Petersburg and Moscow metro per day.

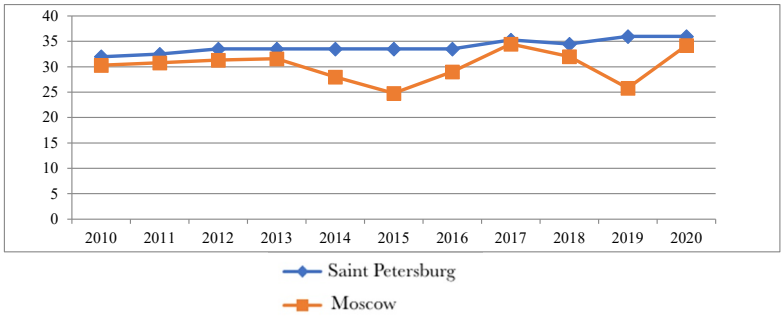

Fig. 5. Comparison of daily load per metro station in St. Petersburg and Moscow from 2010 to 2020 in million people.

The graph shows the load per underground station in St. Petersburg and Moscow on a daily basis. To be effective, this criterion needs to be reduced in comparison to the growth in passenger numbers.

Here the quote "The operation of a large underground space requires innovative designs and construction methods" from Application of a combined precast and in-situ-cast construction method for large-span underground vaults is appropriate" [9] because the priority is not given to the stations, as the priority is given to shallow stations and construction of stations by open-cast method is the most widespread and actual.

3.4 Priority for shallow stations and open pit construction.

Scandinavian technology is based on building stations in an open pit, using fixed shoots and typical, cast-in-place reinforced concrete structures. Open pit stations are located on the surface, where a train drives up to them and then goes back underground. This method is safer, primarily for the ground. And the work "Deformation analysis and safety assessment of existing metro tunnels affected by excavation of a foundation pit" is dedicated to this topic, but it should be remembered that "Previous studies have shown that excavation of

foundation pits can easily destroy the initial state of equilibrium of stresses in the soil of the site" [10].

Because of the ground, the Stockholm underground scheme is similar, where the "three-tier station" technology combines the green, red and blue line, there it is sufficient to cross the platform to the other side - a method called cross-platform transfer. An example in St Petersburg is the Tekhnologicheskiy Institut station. The advantages of stations are low cost and speed of construction (Table 1).

Table 1. Cost and terms of construction of deep and shallow stations.

	Cost per km in billions of roubles	Construction time
The method of deep-bedding	7	5-6 years
The shallow laying method	4.5	2-3 years

Table 1 shows the advantage of shallow stations. As the experience of Scandinavian countries with similar climate and soils has shown, it is not difficult to build an underground above ground, as it is always possible to 'insulate' the platform with walls and roofs, and the tracks can be laid much faster.

3.5 The pace of construction in Moscow and St. Petersburg

Moscow and Saint Petersburg budgets differ by a factor of 4, Saint Petersburg can only afford 2 stations a year. Maintenance and repair eat up a large part of the budget.

Table 2. Difference in the length of the underground.

City	The length of the underground	Number of stations
Moscow	2511 km^2	276 stations over 408 km
Saint Petersburg	1439 km^2	72 stations over 124 km

The capital has shallow stations, 31 surface MCC stations and 6 monorail stations. This feature accelerates station construction and passenger traffic. In his study Canca D. notes "One of the main issues to address in the analysis of a public railway rapid transit network construction project is the assessment of expected revenue and cost. On a network topology already defined, the problem considered in this paper consists on finding the construction schedule that maximises the project long-term net profit" [4].

The way of laying the Moscow metro is more progressive. The capital city first lays down an underground station in the project and only then builds a housing estate around it. This solves the problems of laying through the already existing urban communications, allowing not to go deep under the ground and to organise ground train traffic. Also, according to Aya Al Khereibi, Maryam Al Suwaidi, Reem Al-Mohammed, Shaligram Pokharel, Mohamed Ayari "This situation increases the waiting time, environ mental pollution in the area, unproductive use of fuel and loss of economic activity due to traffic jams" [11], and it cannot be denied.

The population of St. Petersburg is growing, new MABs are being built, there is an acute shortage of new metro stations, new metro stations are extremely expensive, so "It is well known that rail transit plays a key role in supporting spatial development and promoting the urban and regional economy", stresses in his study Lee J. K. [12] New districts are built every six months, and it takes 1-3 years to build a new station and the state of the transport infrastructure deteriorates.

3.6 Prospects for the development of the Saint Petersburg Metro

According to the General Development Plan, the following stations are planned to appear: "Gorny Institut" (end of 2022), "Shuvalovsky Prospekt" and "Bogatyrskaya" (by 2025), "Yugo-Zapadnaya" (by 2023).

A circular underground line has been in the government's plans since the 50s. Sportivnaya station was part of the circular line plan and was built with two lobbies, but the budget was not available for such a grandiose construction and the plans had to be frozen. At the moment, it is stated that the project is being implemented, but with significant amendments. The first phase of construction is scheduled for 2028-2030.

Unfortunately, such plans are unlikely to be implemented. Over the last 10-15 years, there has been a tendency to postpone many stations, postpone construction, as well as insufficient funding for construction and slow documentation, which tends to become outdated.

A few things can be taken from the experience of the Moscow metro construction to build the St. Petersburg metro faster and more economically. First and foremost is the method of laying stations ahead of building a residential area. Solving several problems in one smart move. This reduces the load on surface public transport. The second problem that is solved is the bypassing of utilities, as there are none. The next method that can be borrowed is shallow stations. Several of these have already been constructed, for example, Begovaya. The construction quality is not that high, but if this design is typified and refined, it will save a large amount of budget and speed up construction. Also the introduction of elevated stations. As the Parnas construction experience shows, such a method is applicable, just not widespread.

On August 31, 2021 Metrostroy was declared bankrupt, Smolny transferring people and equipment to a new venture between Smolny and VTB, Metrostroy of Northern Capital. Having obtained the status of sole builder and designer, the company will receive state contracts for underground construction. The contract provides for the construction and reconstruction of underground facilities and responsibilities for the preparation of necessary project documentation. For the construction of 37 underground facilities, 602.7 billion rubles is provided, this amount may increase.

"Metrostroy of the Northern Capital is going to use the production base of its predecessor. To increase the volume of construction, the staff will be expanded, new equipment and tunnelling equipment will be purchased. Works on continuation of existing lines of the underground, reconstruction of old and building of new entrance halls of the underground stations, and also building of new, Krasnoselsko-Kalininskaya line will be carried out.

The company's plans look promising, and with sufficient state funding, we can expect an increase in the pace of construction. In the next 3-5 years it is planned to finish the projects started: "Teatralnaya", "Gorny Institut", "Yugo-Zapadnaya", and other projects may be implemented sooner in the future.

4 Conclusions

In the course of this study, the problems hindering the development of the St. Petersburg Metro were analysed, construction and budget statistics were studied, a comparison of construction experience with other cities was given, and development prospects were suggested. On this basis, the following conclusions can be drawn:

1. Insufficient state funding for St Petersburg Metro development projects is hampering the construction of new stations, which are needed in the built-up areas of St Petersburg and

the Leningrad region to relieve the ground transport network. In 2018, Begovaya and Zenit stations were opened at a cost of 36.8 billion roubles, which is inexpedient given the need to build metro stations on the outskirts of the city, such as Kudrovo and Prospekt Veteranov. It is necessary to increase financing of metro construction by 5 billion rubles a year and set a fixed annual subsidy of 15 billion rubles.

2. Over the past 20 years, 13 metro stations were opened in St. Petersburg, and 79 in Moscow. The low pace of construction is due not only to complex geology and irrational use of budget due to tensions in Metrostroy, but also to investment in low-quality materials that require replacement after a few years, a clear example being regular leaks at Begovaya and Dunayskaya stations.

3. The double-track tunnel technology should be applied at the stations under construction to reduce both the time of commissioning and the cost of construction

4. Difficult geology and the cost of excavating a tunnel in a deep way are not practical; it is necessary to switch to more energy-efficient and cost-effective methods, such as shallow and above-ground stations, as the experience of Scandinavian countries and the example of Moscow show. But this is only possible if it is away from the centre and the wetland soils.

5. Increased pressure on the surface transport network in new areas of the city. The solution could be to build the metro system upfront, following the example of Moscow, i.e., to launch surface and underground transport first, and then to build residential buildings.

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