Some aspects of open-face shield tunnelling in Moscow.

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Abstract: Several tunnels for communications and services were constructed over the past five years in the historical part of Moscow with the usage of open-face shield technology. Protection of buildings from potential damage was in the focus of research works conducted by NIIOSP. Special approach was provided to solve this problem. It combines studies for classification of masonry structures damage, FEM simulation of ground movements and settlements of buildings, design of protective measures and in-situ monitoring.

Tunnelling at Nikolskya street was performed at the depth about 8 m in loose partially saturated sands. The predicted ground surface movements reached more then 10 cm with corresponding settlements of buildings about 4 cm. Special complex of protective measures was conducted to prevent such settlements. The monitoring data showed the efficiency of these works and gave a good correspondence with numerical prediction.

Another site of open-face shield tunnelling located at Large Dmitrovka street. Tunnelling depth exceeds 20 m. The tunnel was excavated in hard clay though the predicted settlements of historical buildings were negligible. Protective measures were undertaken in the vicinity of shafts only. Nevertheless the serious collapse has happened during tunnelling works when the shield met ancient buried channel . The mistakes in geological data interpretation occurred to be the main reason for induced damage.

Keywords: open-face shield tunnelling prediction, monitoring, building settlements.

1. Introduction

The redevelopment of the central part of Moscow city was conducted last years. It involved new buildings construction, complex reconstruction of old brickwork buildings, construction and refurbishment of water supply and sewage communications. Several new tunnels for engineering purposes were constructed over the past five years in the historical part of Moscow. Here in the results of studies for buildings protection associated with the tunnelling   at Nikolskya and Large Dmitrovka streets are presented.

Nikolskya and Large Dmitrovka streets are located in Moscow historical center. In this part of the city there are a lot of historical and original constructed buildings, theatres. The business offices of parliament and the public prosecutor   are also situated there. The most of   the buildings was constructed in 18-20th centuries. This part of Moscow is characterized by variety of communications that use here below-ground services and complicated geological conditions.

The monitoring and measures for building protection during communications construction are complex and complicated work on which the shield type occurs the great influence. It was obvious that open-face shield technology in soft ground can cause unsuspected consequences, but this type of shield was chosen because of economical reasons.

2. Geological conditions

According to the investigations geological profile of Moscow center is complicated**.** The subsoil mainly consists of 3-10 m fill. The fill in this part of Moscow is presented by sand, crushed stone, pebble and even the debris of old foundations. The fill is followed by alluvial sand, Jurassic clays and loams. Moskwa and Neglinka rivers caused great influence on geological conditions of this part of Moscow.

Tunnelling at Nikolskya street was performed at the depth about 8-10 m in fill and partially saturated sands.The subsoil mainly consists of a 3-7 meters of filling material followed by alluvial sand and Jurassic clays.

The tunnel on large Dmitrovka street was performed at the depth 23-26 m in hard clay. Typical geological conditions are shown in Fig 1.

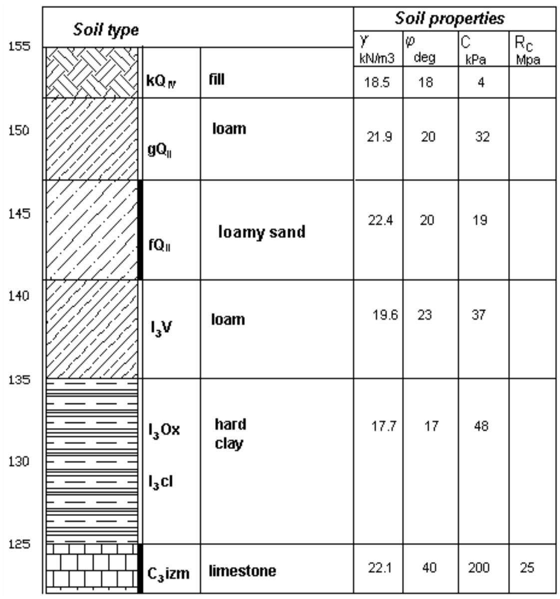
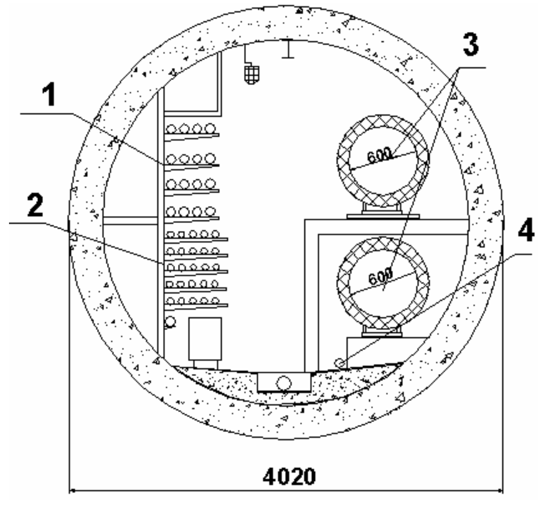


Fig 1. General description of geological conditions at Large Dmitrovka sreet



1.High tension cables
2. Communication cables
3. Hot water system
4.Oxygen supply line

Fig 2. Collector on Large Dmitrovka sreet

Before the works beginning special complex of geological and geophysical investigations were conducted. A traditional soil exploration as well as in-situ investigation program were performed to obtain reliable estimation of the tunnel behavior and the accompanying soil movements.

3. Original design and construction

The tunnels had almost similar construction. Outside diameter of the tunnels was nearly 4 meters. The tunnel length on Large Dmitrovka street was nearly 750 m and nearly the 400 m at Nikolskya street. The thickness of tunnel lining was 325 mm. The typical tunnel profile is shown in Fig 2.

The maximum predicted value of ground settlement at Nicolskya street was 15 cm. The predicted values of brickwork buildings settlement were 2-35.2 mm. Special protective measures were undertaken to ensure buildings safety. They included the fabrication of special cut-off wall made of bored cast-in-place piles. The pile length was 9-13 m, pile diameter 23 cm and spacing 50 cm. The piles were located at the distance 1.5-2.0 meters from the tunnel. In this case the FEM analysis predicted the values of settlements less then 1 cm due to concentration of ground settlement inside cut-off wall contour.

The predicted values of buildings settlements on Large Dmitovka street were less than 2 cm. That is why no special protective measures for buildings were planned. Only few buildings located near vertical shafts were strengthened by bored-jet-grouted piles.

4. Monitoring program

Protection of buildings from potential damage was in the focus of research works conducted by NIIOSP. Before the beginning of tunnelling works technical state of buildings located in surrounded area was established. The categories of buildings state were determined according to Moscow Code (Recommendations, 1998). This local Code was worked up by NIIOSP and other organisations due to the analysis of buildings settlements in the centre of Moscow at almost 50 years period. Admissible values for additional deformations of buildings are presented in Table 1.

There are 4 categories of buildings state in Table 1. The buildings of the first state are in a good condition. They have no cracks and no indications of building damages. The buildings of the second category are in satisfactory condition, but local repair is needed. The are local thin cracks in constructions of the building. The buildings of the third category are in a bad state. Immediately repairing is needed for this type of buildings. The are cracks with width less then 5 mm. For the buildings of the fourth category any small differential settlement can cause building collapse.

A special measurement program was performed to verify the design concept, to ensure the serviceability requirements and to fulfill the quality control. It included leveling measurements on the ground surface, convergence measurements in the tunnel, measurements of buildings settlements, visual and instrumental control of the cracks behavior . An extensive extensometer and inclinometer measurements were not planned because of economical considerations.

Table 1.

The categories of buildings state used for analysis at Nikolskaya and Large Dmitrovka streets

Types of buildings	Category of buildings state	The values of extra deformations	
		Maximum allowable extra settlement s (cm)	Maximum allowable differential settlement $\Delta s / L$
Multi-storied prefabricated concrete buildings	I II III	4,0 3,0 2,0	0,0016 0,0008 0,0005
Multi-storied brickwork buildings without reinforced masonry	I II III	4,0 3,0 1,0	0,0020 0,0010 0,0007
Multi-storied brickwork buildings without reinforced masonry	I II III	5,0 3,0 2,0	0,0024 0,0015 0,0010
Single-store or historical brickwork buildings	I II III	1,0 0,5 0,2	0,0005 0,0003 0,0001
Notation : L (cm) – distance between reference points			

5. Numerical analyses

A two-dimensional finite element analysis was conducted to model the tunnel behavior using isoparametric triangular elements with 15 nodes and beam elements. PLAXIS FE code was used for prediction of building settlements. Elastic-perfectly plastic analysis using the advanced Mohr-Coulomb model was carried out to detect the tunnel performance and the accompanying deformations.

2-D FE schemes were defined for all buildings in tunnel influence zone, the settlements and tilt values for all buildings were predicted. This type of calculations is very complicated because great amount of factors that can influence on calculation results. It was the reason not to make 3-D calculations. Only 2-D calculations were used for the prediction.

Beam elements were used to simulate the upper part of the building. It is a problem to find true values of rigidity of these beams during the simulation. We gained some experience in finding these values and have received good results for settlement prediction for a variety of buildings in Moscow.

Figure 3 shows the used finite element mesh with the applied boundary conditions and soil layers.

The value of ground loses for open-face shield tunnels was initially assumed 4-10 % at the first stage of research and was reduced to 2-7 % according to monitoring data.

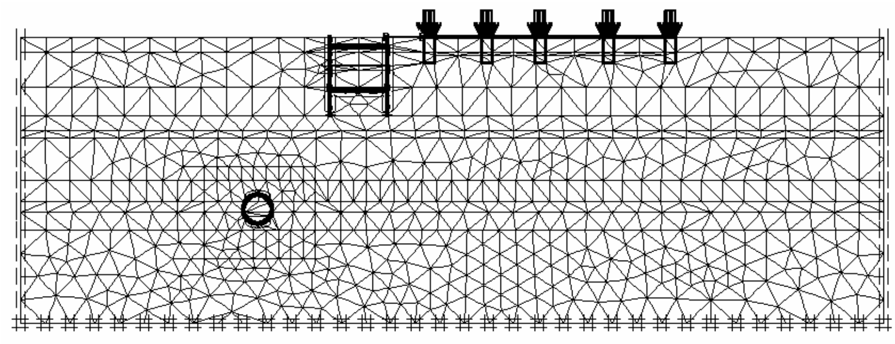


Fig 3. FEM mesh for analysis tunneling at Large Dmitrovka street.

During this work the vertical shafts influence on buildings was also in consideration. Predicted magnitudes of buildings settlements caused by shaft construction were often higher than induced by tunneling.

6. Monitoring results

Leveling measurements of ground surface settlements along Nikolskaya street gave the values of 60-130 mm. The surface settlements mainly developed over the tunnel trace within 4 to 5 m of the face. The maximum values of buildings settlements on Nikolskaya street were much less and consist between 2 and 8 mm. The monitoring of the buildings state did not reveal new cracks and serious damages in the buildings**.** Due to monitoring data significant amount of buildings settlements (over 80% of total values) was mostly developed in the tunneling excavation stage. The measurements showed that settlements didn't develop after one month since tunnelling works were finished.

At the first stage of works at Large Dmitrovka street the buildings settlements were from 2 to 3 times less then predicted values. Nevertheless the serious cave-in collapse took place during tunnelling works when the shield met an ancient buried channel . The mistakes in geological data interpretation occurred to be the main reason for induced damage. The thickness of clay layer above the tunnel was too thin and it was punctured by upper layer of saturated sand. As the result the sand penetrated into the tunnel. A subsidence crater appeared at ground surface with dimensions 20x30 m in plan and the depth more then 6 m. Approximately 2500 m^3 of sand-water mass penetrated into the tunnel. At the period of 10 minutes 245 m of tunnel length were filled. Several buildings were severely damaged. The shield was also damaged and buried at the depth more then 20 metres. Fortunately there were no human victims during the accident.

After the accident another shield was used and the works were continued. No serious accidents were marked. The buildings settlements outside collapse area were also lower then predicted values.

At the construction period settlements of buildings were measured weekly. Ground surface settlements were determined at the distance up to 50 metres from the tunnel during construction.

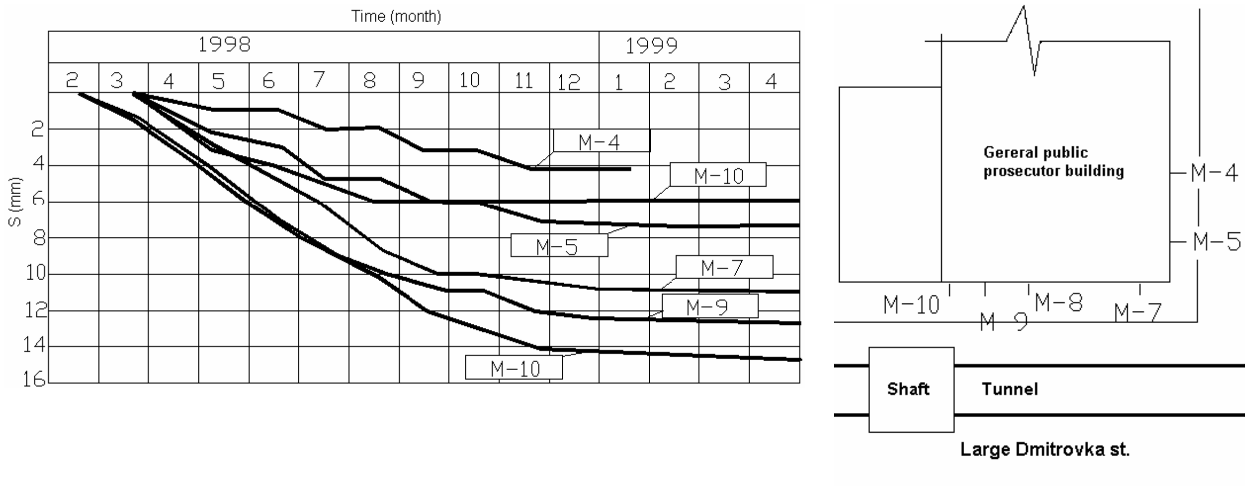


Fig 4. The time-settlement curves of the General public prosecutor building at Large Dmitrovka st.

Monitoring results at Large Dmitrovka st. can be illustrated by the instrumental settlement determination of the General public prosecutor building. The main settlements of the building took place on the main elevation. There were different reasons for the settlements of this building. Settlements were caused by tunneling, sewage communications repairing and vertical shaft construction. The III category of building state was associated with this building. Taking into account all factors the predicted maximum settlement magnitude was more than 1 cm, but the building owners decided not to strengthen it beforehand. The maximum final value of building settlement was 15mm. It exceeds admissible magnitude for this type of buildings. It was the reason for strengthening and repairing of the building after the tunnelling. In Fig. 4 the results of settlements measurements are shown.

The settlements of the other buildings at Large Dmitrovka street were lower and did not exceed 1 cm.

7. Conclusions

The usage of tunnelling with open-face shield technology in combination with special engineering measures for building protection is usually virtual when the works are performed at the depth less then 10 metres. Open-face shield technology at the depth more than 20 metres is more risky as it can cause serious ground moves and building settlements due to punching failure of saturated soils. In this case other up-to-date tunnelling technologies should be used.

The elasto-plastic analyses gives satisfactory estimation of buildings settlements. In the most cases values of building settlements obtained from two-dimensional finite element analysis are higher then measured values, i.e. the results of 2-D modeling can be used for development of monitoring program and design of special protective measures for buildings.

8. Acknowledgements

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9. References

Recommendations of MOSCOMARHITECTURE (1998). “Recommendations for survey and monitoring of the buildings situated nearby reconstructed buildings and new constructions” (in Russian)-Moscow, GUP NIAC.