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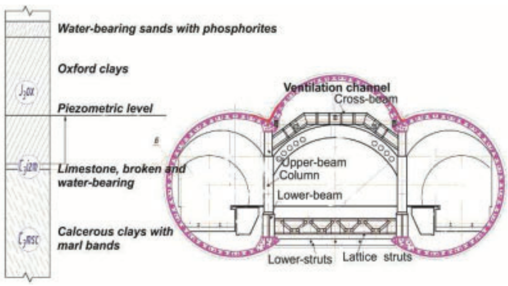

Figure 2. Geology in the area of Mayakovskaya station. Station Cross-section.

Figure 3. Regular multiple leakages caused deterioration of station finishing.

surrounded by filament lights; the niches are decorated with mosaics by Alexander Deyneka, one of the most prominent painters of the time.

This entire splendor hides the station skeleton: cast iron lining and steel structures lined with reinforced concrete, rendered and painted.

Waterproofing quality of any deep underground structure primarily depends on the quality of caulked joints between the lining segments as well as filling of the gap behind the lining with cement-sand grout through cementing ports. In terms of waterproofing the critical point is the contact area between the central and side tunnels. There specially designed cast iron segments were installed as well as drainage system comprising ducts and pipes embedded into the reinforced concrete inner lining.

Another factor which defines the quality of waterproofing is the geological environment of an underground structure. Moscow is located in the centre of the so-called Russian platform which has a vast crystalline foundation covered by a layer of basic sediments, upper part of which is represented by man-made soils, loams, clay sands, and unstable water-saturated sands. Deeper these are followed by clays with bands of limestone. Station structures lay mainly in this layer. It shall be noted that the vault of the station is located in Oxford clays with bands of water-bearing sands and phosphorites, the presence of which had not been known and hence accounted for at the design stage (Fig. 2).

2 PROBLEM BACKGROUND

Generally, about 90% of underground and subsurface structures show waterproofing failures, many of which appear quite soon after putting into operation (Shilin 2010).

As years of operation resulted in multiple failures of lining watertightness, ground water came directly to steel framework structures and reinforced concrete. Original drainage system failed as well: metal ducts were fully corroded, drainage pipes were completely mudded.

Intensive corrosion of metal structures and concrete reinforcement caused deterioration of finishing materials. There appeared water leaks and drips in passenger passage areas.

For years metro operation personnel tried to solve the problem by way of local repairs, however they didn't succeed in doing this.

Things kept growing worse, until the solution of complex rehabilitation of station waterproofing was proposed. It included detailed diagnostics with subsequent structural state assessment; project planning and designing based on the diagnostics results; implementation of the repair works.

3 INSPECTION OF STRUCTURAL STATE AND STATION WATERPROOFING

In 1986, 1997, and 2008 samples of leaking water were taken for analysis at the station, in the traction equipment chamber and in the escalator tunnel. Test results showed that the composition of water was altered greatly by various man-made activities in surrounding media. High chloride content made water aggressive towards concrete and steel reinforcement, whereas considerable quantities of calcium coming with water filtering through cement-sand grout from behind the lining caused drainage pipes blocking. The graph in Figure 4 demonstrates how chloride content in

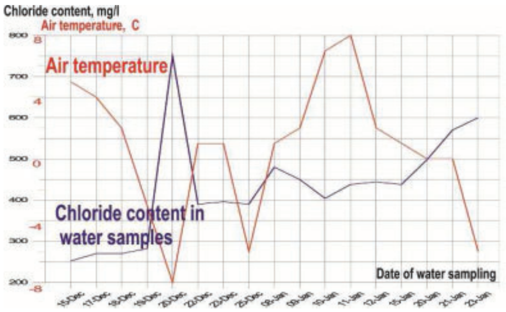

Figure 4. Relationship between chloride content in water samples and temperature fluctuations above ground.

Figure 5. High permeability of concrete caused leakages and structural deterioration.

water grew as temperatures went down in winter, and chloride-based de-icing salts were used in the streets.

Concrete tests confirmed high degree of water penetration: W2, whereas current norms state W4 as the standard value (Kirilenko 2013). Concrete around the leaks was wetted to different extent (Fig. 5).

Infrared thermography was used to locate wetted areas which could not be defined visually, though clearly seen as "thermal spots" on structural surface (Fig. 6). Besides, it helped to create general map of heat distribution within the structures (Shilin et al. 2015).

The following conclusions were drawn upon the inspection results:

- contamination of water, mainly with chlorides coming from de-icing salts, caused active corrosion process in metal structures and reinforcement. Only complete leakage elimination could stop the process;
- concrete of tunnel lining was highly permeable due to high porosity, which led to quick and extended structural wetting and spoilt finishing and decorative elements (Fig. 3);
- quite a number of areas were located where surface wetting could not be identified visually, though present inside the structures; those areas demanded urgent restoration of waterproofing;
- it was stated that water came mainly via the escalator tunnel which crossed water-bearing layers of soil.

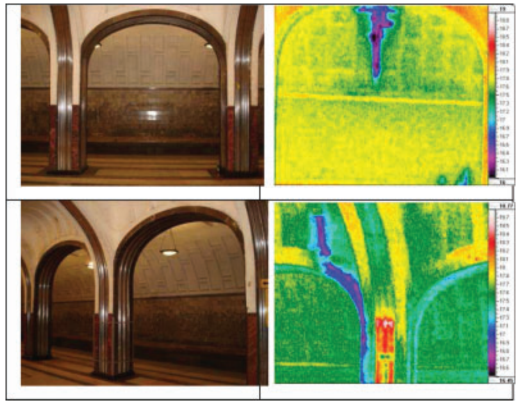

Figure 6. Station structures in visible and infrared ranges.

Based on the above mentioned conclusions, the decision was taken to perform complex reconstruction and waterproofing works. The project was divided into three stages: 1) injections from the escalator tunnel and traction equipment chamber to stop water leakages; 2) injections in the contact area between the central and side tunnels, which was most critical from the viewpoint of leakages; 3) restoration of waterproofing and drainage. Combigrouting injections were executed (Shilin 2009) when various products were used and combined in accordance with particular job conditions. The decision was backed up by the analysis of the world expertise in similar applications as well as our own experience of more than 25 years, including specialized techniques and products and qualified personnel.

4 EXECUTION OF RECONSTRUCTION AND WATERPROOFING WORKS

4.1 *Project characteristics*

Reconstruction of Mayakovskaya station was carried out with regard to EN 1504 principles and comprised diagnostics, design and planning, repair works and subsequent quality control (EN 1504, 2004-2013). Prior to starting the job, we had to decide upon possible injection techniques. To be able to inject behind the lining, we must have access to cementing ports in cast iron segments which were hidden behind the inner reinforced concrete lining. The only section with direct access was found in the vent shafts of the central station tunnel, however that was not enough. To perform the job, we had to locate cementing ports in other

Figure 7. Locating and correcting positions of cementing ports.

structures, which we did with the help of endoscopes in the following way. First we drilled small holes (dia. 18 mm) in the places shown at the design drawings and inserted rigid endoscopes into them (Fig. 7). The images we got from inside the structures allowed to make corrections – if necessary – to drill afterwards holes of bigger diameter (80–100 mm).

It should be also noted that in the side tunnels injections could be done only from the tracks, so actually the working period was maximum 2 hours per day, during the night break. There were most stringent requirements for moisture and dust content, noise and vibration limits, absence of specific odour, because the station was open to passengers in day-time.

Works were executed according to the specially developed design. Besides injections to waterproof the lining, there was a lot of work to be done to refurbish – where possible – old drainage system or – where refurbishment was not possible – to install a new one.

4.2 *Stage 1. Elimination of water filtration through the lining in the escalator tunnel and traction equipment chamber*

To fulfill the task stated for the first stage, we planned injections of hydro active polyurethanes behind the lining.

The works were to be done from upper semi-perimeters of the chamber and the escalator tunnel.

Cavities located by thermography and test drilling as well as sections of water filtration behind the tunnel lining were first injected with rigid hydro active polyurethane with expansion ratio of $K = 10$, and then with rigid/flexible hydro active polyurethane with expansion ratio of $K = 3\text{-}4$. Such scheme allowed to begin with creating a waterproofing membrane and further to increase its reliability by filling the majority of minor irregularities, such as caverns, cracks

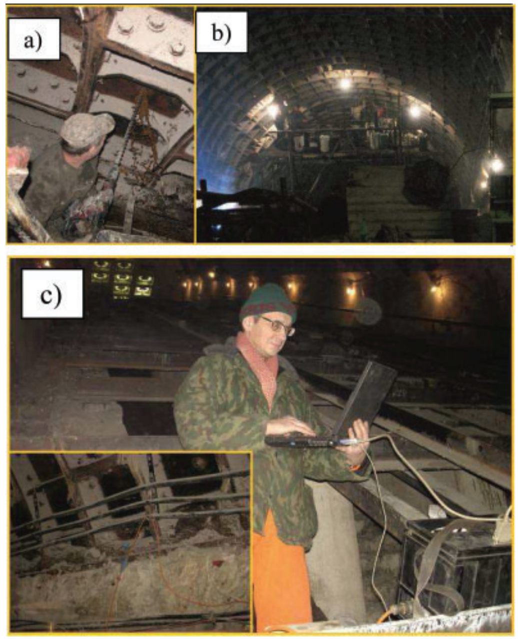

Figure 8. Drilling of a borehole through a cementing port in the segment (a), injections from the trolley-based rig (b), impact echo tests for quality control of injections behind the lining (c).

etc. Both one- and two-component polyurethanes were used, depending on water saturation of soil behind the lining at a particular tunnel section.

In the traction equipment chamber injections were carried out from the existing running bridges, in the escalator tunnel a special trolley-mounted rig was assembled for the purpose. Plugs from cementing ports were pulled out; through the ports boreholes were drilled to the depth of 500 mm crossing the layer of concrete plugging injected at the time of construction (Fig. 8a).

Quality of injections was controlled visually, by impact-echo tests (Fig. 8c), and also with the help of rigid/flexible endoscopes inserted into specially drilled boreholes. Besides, selective water tests were carried out, as well as continuous infrared thermography in the end.

Injection works were supported by laboratory testing to be able to co-adjust injection parameters and resin properties. Setting time was the most critical parameter when injecting rigid/flexible products.

Outcome of the first working stage can be formulated as follows. Plugging injections into surrounding soil as well as filling the gaps behind the escalator tunnel lining with HA polyurethanes allowed to eliminate active water leaks around its perimeter and to large extent cut one of the major sources of water filtration to the station. The results of thermography prior and after the injection works (Fig. 9) confirmed the effectiveness of the work done.

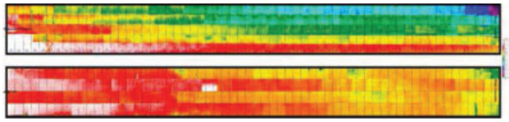

Figure 9. Results of infrared thermography in the escalator tunnel prior (up) and after (bottom) the injection works.

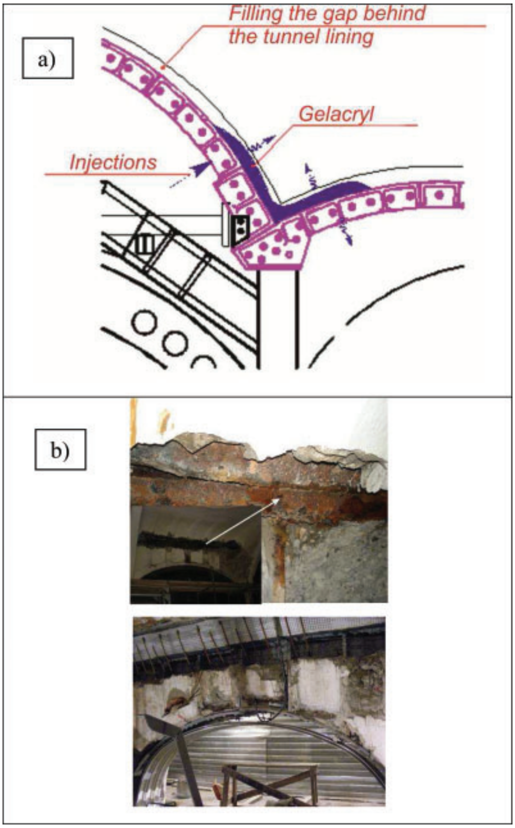

Figure 10. Scheme of polyacrylate gel injections (a), refurbishment of the failed drainage system (b).

4.3 *Stage 2. Injections in the contact area between the central and side station tunnels*

At this stage a two-component polyacrylate gel was injected. This gel was capable to penetrate not only into the contact zone between the lining and surrounding soils, but also into fine cracks and pores in structures and soil (Fig. 10a). The job was carried out on a round-o'clock basis from the station vent channel.

Lab testing allowed to fine-tune gel viscosity and polymerization time. Special requirements were set for injection pressure and volume.

After the injections into the contact area were finished, we started to install the drainage system, which included both the refurbished existing parts and new ducts and pipes. The new part was fabricated from modern corrosion-resistant FRP materials; additionally PVC flashings were installed instead of old ones made of ruberoid (Fig. 10b).

Exposed metal elements were sand-blasted to remove corrosion deposits, then coated by a special primer and corrosion-resistant paint.

Figure 11. Waterproofing works in the side tunnel (a), installation of drainage sheets on the side tunnel wall (b).

4.4 *Stage 3. Waterproofing and drainage of water in the side tunnels*

In the side tunnels water leaked primarily through the joints between the lining segments and also through the plugs in the cementing ports and bolt connections.

Water came from the water-bearing stratum, piezometric level of which lay exactly at the elevation of the tunnel vaults. So decreasing or – ideally – eliminating water leaks could be achieved only by injecting of a cement-based grout behind the side sections of the tunnel lining.

As mentioned above, cast iron lining was covered by inner reinforced concrete lining (playing decorative part as well), and to preserve the original appearance of the station it was decided to make injections through the boreholes drilled around the plugged cementing ports from a specially assembled scaffolding (Fig. 7). Two rows of segments located above decorative marble panels were treated with injections. To be able to inject, plugs were removed from the ports.

Injections were made with the same polyacrylate gel as used for the 2nd stage of the project. Elevation of the injected screen was chosen to cut the water-bearing stratum and connect it with the injected contact areas between the central and side tunnels.

First the lower row was injected to get the screen protecting the lower part of the tunnel section from infiltrating water. After that the upper row was injected to connect this screen with the top screen at the contact zone between the tunnels.

To additionally protect decorative marble panels from moisture, dimpled drainage sheets were installed on the walls, thus creating a vented gap (Shilin et al. 2003). For this purpose marble panels were dismantled and the underlying wall surface was leveled. Then the dimpled sheets were installed, their bottom edges preformed as a drainage chute. Afterwards plaster was applied on top of these and marble panels were put in place. In the end final installations of the drainage system were done to remove residual water.

5 CONCLUSIONS

The strategy chosen for the project was outlined based on the results of structural diagnostics, examination of original construction plans, detailed investigation of geology – all the aspects known as a conformative approach to repair works (Shilin 2005, Shilin 2010), implying a thorough selection of techniques and products capable not only to solve the problem in general, but to fulfill particular requirements of a particular project.

Basically we succeeded in eliminating water leakages, to carry out required repair and reconstruction works, to maintain normal operation conditions and preserve original historic and architectural appearance of the station.

The works done allowed:

- to remove corrosion products from all metal structural parts and carry out corrosion protection of these parts to guarantee functional safety of load-carrying structures for long-term operation;
- to refurbish drainage system embedded into the concrete lining adding new elements made of modern corrosion-resistant materials;
- to install the reliable wall waterproofing and water draining systems in the side station tunnels with the total area of 838 m^2;
- to perform repairs of all decorative elements: ceiling mosaics, steel and stone columns, marble panels, granite floors; total repaired area (excluding the walls in the side tunnels) amounted to 6490 m^2.

It should be said as well that after the works were completed a special team was present at the station for a year to check the state of repairs done and eliminate minor water leaks which occurred due to seasonal temperature fluctuations. However, the time that passed since the end of that period confirmed that the repair strategy chosen was absolutely correct to provide sustainable operation of the whole station complex.

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