Assessment of operating environment of concrete lining of sewage collector tunnels

E Yu Kulikova

Department of Construction of Underground Structures and Mining Enterprises, National University of Science and Technology NUST "MISiS", 4, Lennsky Prosp., Moscow 119094, Russia

E-mail: fragrante@mail.ru

Abstract. The most important task in the field of design and construction of urban underground structures is the durability of their lining, which is a failure-free operation of the structure for a given period at a minimum cost of its construction. The quality of building processes, service life of underground structures and capital costs depend on the type of lining and technology of its construction. In this paper, on the basis of collector tunnels examinations the conditions of their work were revealed. Studies showed that the failure of the lining of sewers or its partial destruction occurs under the influence of the following factors: water-abrasive wear of the tunnel tray; gas and chemical corrosion, caused by the aggressiveness of the media flowing through the tunnels; biological corrosion; leaching of free lime from concrete under the influence of external groundwater, etc. It is revealed that the collector tunnels are subject to erosion of the tray associated with the abrasion effect of solids characteristic of the masses flowing through the tunnel. The effect of abrasives is exacerbated by the presence of “fistula”, cracks and chemical effects, which leads to weakening of the material and the tray design.

1. Introduction

Currently, the main material of collector tunnels lining is concrete. The technological section and the internal structure of the tunnel depend mainly on its purpose. In Russia, there are four types of technological sections and internal designs for the sewer and drain tunnels [1-8]:

- type I. For construction under highways, urban roads and open areas. The lower tray part of the inner lining is made of precast concrete products or monolithic concrete;
- type II – for construction on curved sections;
- type III – for construction under railways, subways and in difficult hydrogeological conditions;
- type IV – for construction under railway tracks, underground and urban highways in difficult hydrogeological conditions with hydrostatic pressure of groundwater or with a pressure in the tunnel up to 0.2 MPa (at the level of the tray).

Lining of tunnels of all types is two-layered: large-block external (primary) and internal (secondary). The primary lining consists mainly of blocks and tubes, going into rings. Seams
reconceived by expanding cement. Trapezoidal tubes, rectangular with a lock block, rectangular without a lock block and with radial connections, trapezoidal blocks with spherical ends, etc. are used in practice. The most perfect are rectangular enlarged blocks, which are becoming increasingly common in the construction of Moscow. The structural dimensions of the considered types of concrete blocks are given in table 1 [4,5].

| No. | Block type                             | Tunnel diameter, m | The dimensions of the lining | Filtration characteristics $K_f$, m/day |
|-----|----------------------------------------|--------------------|----------------------------|----------------------------------------|
|     |                                        | External           | Internal                   | thickness | the width of the block | average block length along the arc |                                      |
| 1.  | Concrete trapezoidal                    | 2,0                | 1,7                        | 0,15      | 0,32                  | 0,58                           | 0,085-10^{-5}                       |
| 2.  | Rectangular with a locking unit         | 3,6                | 3,2                        | 0,20      | 0,72                  | 1,07                           | 0,078-10^{-5}                       |
| 3.  | Rectangular with radial ties without lock block | 2,1             | 1,8                        | 0,12      | 0,70                  | 1,02                           | 0,078-10^{-5}                       |
|     |                                        | 3,6                | 3,2                        | 0,20      | 1,00                  | 1,07                           | 0,078-10^{-5}                       |
| 4.  | Enlarged unit                          | 2,1                | 1,80                       | 0,12      | 0,70                  | 1,005                          | 0,078-10^{-5}                       |
|     |                                        | 2,6                | 2,25                       | 0,15      | 0,70                  | 1,256                          | 0,072-10^{-5}                       |
|     |                                        | 3,2                | 2,80                       | 0,17      | 0,80                  | 1,554                          | 0,076-10^{-5}                       |
|     |                                        | 4,0                | 3,55                       | 0,20      | 0,80                  | 1,963                          | 0,076-10^{-5}                       |

In order to improve the waterproofing properties of the lining and the corrosion resistance of concrete in recent years coating based on epoxy resins are used, which are mechanically applied to the upper layer of the secondary lining. It is also used “shirts” constructed of concrete in a mechanized way.

Of particular note is the lining from monolithic pressed concrete. Thus, the use of pressed concrete in St. Petersburg provides the strength of concrete at the age of 7 days 170-200 kg/cm², at the age of 28 days – 400 kg/cm² [6-8].

2. The role of “fistulas” in the durability of the tunnel lining
The basis of trouble-free operation of the collector tunnels is the durability of the lining.

The working conditions of the collector tunnels are the whole complex of factors, both chemical and physical and mechanical, in which the destruction of the concrete lining occurs [2,4].

In order to identify the main factors, a number of collectors were examined and the available information about failures was analyzed. 9611 m operated collector tunnels, passed by TBM, fixed with concrete blocks with a reinforced concrete secondary shirt were considered. At the same time, information about the defects of more than 600 m of reinforced concrete secondary lining of tunnels under construction was collected.

The results of examination are shown in table 2, from which it follows that the failure (by the factor of waterproofing) of 30-35 % of the lining makes it impossible to further operation, although in general the lining remains stable and, basically, in the necessary strength. Significant influence on violations of waterproofing properties of bearing structures of underground objects have fistulas, the diameter of which ranges from 0.5 to 5 cm. Fistulas are active conductors of water-sand mixture in the collector.
During the flow of the sewage mass in the manifold tunnel unacceptable leakage through the “fistula” may occur. Calculations, carried out by the method of V. M. Nasberg, showed that when the number of “fistulas” corresponds to the table 2 and their diameter of 0.5 mm, leakage in the tunnel, laid in highly waterproof soils ($K_f = 30-100$ m/day) is from 30 to 121 m$^3$ per 1 km of the route, and in slightly permeable soils ($K_f = 0.1-10$ m/day) – 3-12 m$^3$/day [7]. With a fistula diameter of 5 cm, these figures increase respectively to 600-1200 m$^3$/day (62-260 m$^3$/day per 1 km of tunnel). Comparison of the calculation results with the requirements for permissible leakage shows that leakage through the “fistula” is much higher than the permissible (50-100 m$^3$/day per 1 km).

The area of the fistula is also characterized by the weakening of the concrete. The weakening of concrete occurs as a result of leaching of calcium oxide hydrate (CaO) from concrete. So, laboratory tests of samples of a lining of one of the Moscow collectors showed a significant weakening of concrete: $R_p = 100$ kg/cm$^2$ against the project $R_p = 400$ kg/cm$^2$. It is characteristic that the majority of “fistulas” is confined to the places of technological seams, because it is noted that they are arranged in multiples of 3 or 5 m, which corresponds to the length of the formwork used [4,7,9].

The study of the results of collectors’ examination also showed that already during the construction of the lining, there are “fistulas” and leaks, stains affecting 8-10 % of the area of the lining, and, basically, these defects are also confined to the places of technological seams.

Therefore, the specified defects, despite the subsequent efforts of isolators, are further the most vulnerable place of linings and the place of formation of operational fistulas.

### Table 2. Results of tunnel lining investigation.

| No. | Service life at the time of examination | Dimensions, m | Lining material | Violation of the outer part, % | Defects (average values) |
|-----|----------------------------------------|---------------|----------------|------------------------------|--------------------------|
|     |                                         | Diameter      | Length of the examined area | Primary lining | Secondary lining | Fistula, numbers | Tray abrasion, % |
| 1.  | 4                                      | 2,0           | 1,4             | 728 | Reinforced concrete blocks | -                        | - | - |
| 2.  | 6                                      | 2,5           | 1,5             | 2893 | Reinforced concrete blocks | 16,0 | - | 0,50 |
| 3.  | 7                                      | 1,6           | 0,8             | 15 | Ceramic blocks | 18,0 | - | - |
| 4.  | 12                                     | 2,0           | 1,4             | 45 | Ceramic blocks | 39 | - | - |
| 5.  | 13                                     | 3,6           | 2,75            | 3762 | Reinforced concrete blocks | 37 | - | 27 |
| 6.  | 19                                     | 2,0           | 1,40            | 800 | Ceramic blocks | 34 | 75 | 34 |
| 7.  | 21                                     | 2,0           | 1,4             | 1090 | Ceramic blocks | 29 | 23 | 37 |
| 8.  | 21                                     | 2,0           | 1,4             | 200 | Ceramic blocks | 40 | 30 | - |

3. **Water-jet wear**

When studying the materials of collector examination, water-abrasive wear of the tray was also found. As follows from the table 3, water-jet tray wear progresses as the life of the underground structure increases.
Table 3. Water-jet tray wear progress.

| No. | Service life (years) | % of blurred part of lining | Average washout depth | The average growth in cm per year |
|-----|----------------------|-----------------------------|-----------------------|---------------------------------|
| 1   | 2                    | 3                           | 4                     | 5                               |
| 2   | 6                    | 0,5                         | 8-9                   | 1,6                             |
| 5   | 13                   | 27                          | 10-15                 | 1,2                             |
| 6   | 19                   | 34                          | 7-10                  | 0,5                             |
| 7   | 21                   | 37                          | 30-40                 | 1,6                             |

This growth is characterized not only by an increase in the affected area, but also by an increase in the depth of abrasion of the tray. Abrasion of the tray helps to activate the fistula and weakening the strength of the tray. The formation of cavities in these conditions leads to the drawdown of the tray, which was recorded in a number of tunnels. According to statistics, an average of 1.2 cm of the tunnel tray is worn out per year [7]. In the result, corrosion can take place in the arch header and lead to delamination of sprayed concrete.

4. Results of examination

The study of the results of collectors examination and analysis of information about failures of bearing structures of underground structures allow us to draw the following conclusions.

Destruction of collector tunnels and their premature failure occurs as a result of the following factors:

- leaching, gas and chemical corrosion as a result of aggressive media flowing through the tunnels;
- mechanical wear by sediments;
- cracking under external loads.

Each of these factors separately or the combined effect of several of them destroy the lining of the underground structure, putting it out of service for a long time and reducing its service life. The above factors and their impact on the concrete lining of the collector tunnels are discussed in detail below.

4.1. The aggressiveness of the media flowing through the tunnels

By their nature, fecal masses flowing through the reservoirs are divided into mineral, organic and bacterial.

Mineral contamination includes sand, clay particles, ore particles, slag, salt solutions, acids and alkalis, mineral oils and many other substances.

Organic pollution are of plant and animal origin. Plant residues include residues of plants, fruits, vegetables and cereals, paper, vegetable oils, etc. The main chemical element of this pollution is carbon.

Animal contamination includes tissue residues, adhesives, milk sugar, etc. the Main chemical element is nitrogen.

Bacterial contamination includes microbes, algae, yeast and fungi.

The greatest impact on the concrete lining of the collector tunnels have mineral pollution. According to Professor S. N. Stroganov minerals in pollution contain 42 %, and organic – 58 %. In addition, a significant impact on the concrete has gas corrosion [9-15]. According to various experts, the content of minerals in wastewater reaches 30-40 %, and organic – 58-75 %.

Organic substances are the source of a number of substances that adversely affect the durability of tunnel lining materials.
The chemical composition of sewage sludge and manure (per cent from dry matter) is given in table 4.

**Table 4. The chemical composition of sewage sludge and manure.**

| Data                        | Nitrogen, N | Phosphorus, P2O5 | Potassium, K2O | Sodium, Na2O | Lime CaO | The ether extract (fat) |
|-----------------------------|-------------|------------------|----------------|--------------|----------|------------------------|
| **Sediment**                |             |                  |                |              |          |                        |
| According to the Russian Federation (Moscow) | 2,9         | 3,7              | 0,2            | -            | -        | -                      |
| According to Czech Republic  | 1,8-2,5     | 1,1-1,3          | 0,2-0,4        | 0,2-0,3      | 1,7-5,6  | 1,5-4,5                |
| According to the U.S.        | 1,8-2,6     | 1,3-3,2          | 0,4-0,5        | -            | -        | 4,8                    |
| **Manure**                  |             |                  |                |              |          |                        |
| Dry Content of % H2O        | 2           | 1                | 2,4            | -            | 2        | -                      |
| Manure Content of % H2O     | 75          | 0,5              | 0,2            | 0,6          | 0,5      | -                      |

A significant amount of harmful substances contained in industrial wastewater. For example, in table 5 the characteristics of wastewater coming to the pumping station from the collector, which receives wastewater from two plants, are given.

**Table 5. Characteristics of wastewater.**

| Pollution index                      | Concentration, mg/l | Header 1 | Header 2 |
|--------------------------------------|----------------------|----------|----------|
| pH                                   | 3,4-8,5              | 2,7-5,1  |
| Total nitrogen                        | 10-150               | 12-210   |
| Phosphorus                            | 20-160               | 40-110   |
| Suspended solids                      | 94-400               | 120-481  |
| Chlorides                             | 8-177                | 8-161    |
| Biochemical oxygen demand             | 14-126               | 15-138   |

As a number of experts point out, domestic wastewater is less dangerous for concrete lining of sewer tunnels than industrial. In the latter, there may be a noticeable amount of sulfates, various acids, carbon dioxide, etc., predetermining the development of corrosion of I, II and III species. The content of sodium and potassium oxides, in turn, leads to the development of alkaline corrosion.

The resistance of the lining along with the action of sodium and potassium oxides is affected by carbon dioxide resulting from the decomposition of urea. With a slow flow of sewage through the collector, the concentration of CO₂ can reach dangerous limits.

Thus, the analysis of wastewater flowing through the collector shows that there are all necessary conditions for the destruction of the lining of aggressive components. It is known that alkaline fecal water partially neutralizes the acidic wastewater of industrial enterprises. However, the depth of this neutralization is often insufficient and practically do not exclude the aggressiveness of wastewater.

### 4.2. Mechanical wear by sediments

Along with the harmful effect on the lining of aggressive media flowing through the collector, special attention should be paid to pollution that causes water-abrasive wear of the collector tunnel tray.
All kinds of dirt occurring in sewers, divided into particulate, colloidal, dissolved and truly dissolved.

In domestic wastewater according to S. N. Stroganov contains approximately 40 g of coarse (suspended), 10 g of colloid-dissolved and 50 g of truly dissolved substances per person per day [15-20].

Coarse substances consist of particles larger than 0.1 mm in diameter. As part of the sediment in the sewer network has organic substances – 3%, by volume and mineral 97% [4]. Consequently, most of the sediment substances of mineral origin. These include sand, stones, brick, glass, etc. (heavy sediments).

Characteristics of heavy sediments by mechanical composition are given in table 6.

| Particle size (mm) | % by volume | Mineral content | Sediment composition       |
|-------------------|-------------|-----------------|---------------------------|
| Over 10           | 3.5         | -               | Broken glass, gravel, brick, etc. |
| 5-10              | 3.5         | 70.6            | Glass, coal, bones        |
| 3-5               | 4.5         | 79.17           | Glass, coal, bones        |
| 2-3               | 3           | 83.24           | Glass, brick              |
| 1-2               | 7           | 90.2            | Sand, brick, coal         |
| 0.5-1             | 9           | 95.9            | Sand, fragments of individual minerals |
| 0.25-0.5          | 35          | 98.14           | Sand                      |
| Up to 0.25        | 36          | 98.33           | Sand                      |

The data show that the sewage system receives mainly fine fractions of sand. For example, only in 2018 at the Lyubertsy aeration station sand fractions larger than 0.25 mm – 12207 m3 at 7.6% humidity were detained. At the Lublin aeration station, 2878 m3 of sand was detained at 31.4% humidity [6].

When sewage moves through the collector, coarse substances and erase the walls of the lining, especially in their lower part. In this regard, the materials of the lining of the tunnel should be subject to the requirement of increased resistance against abrasion.

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