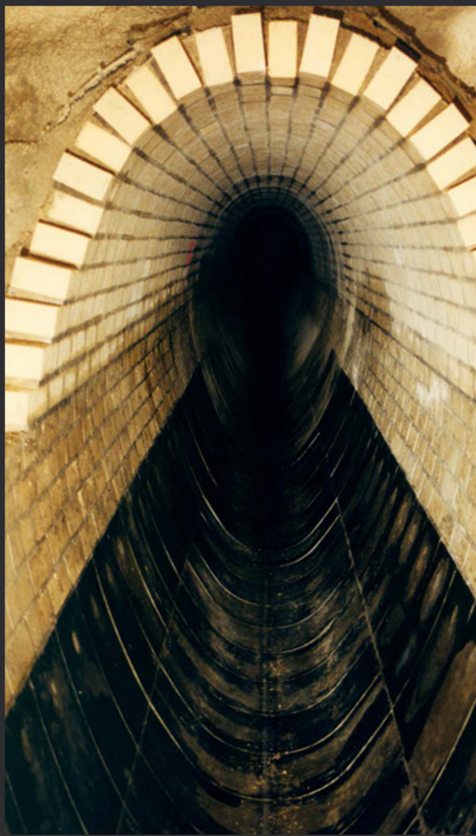
Repairing the dramatic collapse of the Trojsky header

beneath Trojská Street Prague



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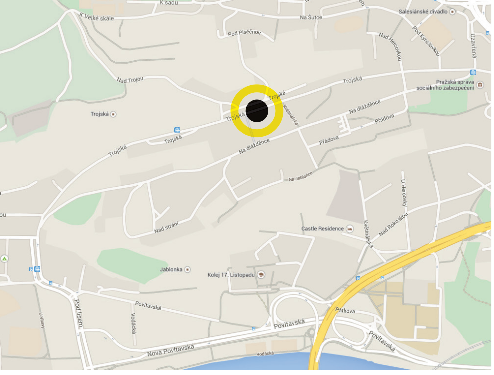

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THE HISTORY

In 1939 the city of Prague completed the initial construction of the first part of the Trojský header. Following this original phase, a further 695 meters of oval shaped sewer was built and installed beneath Trojská Street.

It was not until 1972 to 1975 that the next staged development of the construction of the headers in the Trojská Street area took place. At that time, there was a need to upgrade capacity because of the planned construction of multi-storey, high-rise, prefabricated buildings in the Kobylisy area.

A preliminary geological survey identified and foresaw very difficult conditions for the actual construction implementation because of the required depth of the sewer varying between 4m and 12m. In October 1971, the building authority issued a permit for the construction of the waterworks, and work began in March 1972. However work was constantly blighted by extremely adverse weather conditions.

Despite a reassessment of the route enabling the avoidance of any contact with saturated alluvial sediment, the enormous inflow of groundwater seriously affected the stability of the rocks and pressure on the sewer's lining. Over breaks or voids were created that were not always filled resulting in lack of solid contact between the new sewer lining and the rock the sewer was going through.

By October 1975, around 1.9 kilometres of the sewers had been constructed. The construction work involved creating 33 manholes, 27 of which were in brick sewers. 54% of the length of the newly built Trojský header had a gradient between 2.2% and 5%, while 27% of the route's length had a gradient of between 5% and 6.5% and the remaining 11% reached extreme values between 9.1% and 9.8%. In the lowest part of the header, the designed rainwater flowrate amounted to 10,404 m^3/sec.

The header was built as a brick sewer, using conventional sewerage bricks for the base and designed to incorporate circular earthenware segments. The 'Prague frame method' was used for carrying out the excavation.

The header's construction was approved in June 1976 and subsequently put into operation. One issue that further inhibited project execution was that the planned construction of the Trojská exit road was cancelled and therefore the largest part of the header, including its associated manholes, was located on now difficult-to-access private land. As a result of this unanticipated issue, checks on the header's construction were only carried out sporadically.

THE COLLAPSE OF THE TROJSKÝ HEADER

The collapse of an entire section of the Trojský header occurred at the beginning of July 1996. An earlier sign of what was to come happened in late June of that year when sewerage bricks were found in the Trojská rainwater separator. However, a period of high rainfall prevented any inspection of the header following the discovery of the bricks.

On the 4th July 1996, close to a tram stop and about 20 metres from the tram track itself, a large 16 metres wide funnel sinkhole appeared. At the site where the 12 metre deep sinkhole now sat, the sewer had been completely destroyed and washed away. The collapse had also created a 10 metre long cavern downstream (P1), which was now directly connected to the sinkhole.

The sewer would continue to degrade and ten days later a large 2.5 metre wide circular sinkhole (P2) appeared in a garden adjacent to a family home. This downthrow was closely linked to the collapse of the entire lateral part of the sewer.

Detailed exploration of the header would continue to list the extent of damage as well as the status of the rock mass behind the extrados of the sewer.

The survey identified the existence of additional caverns behind the sewers extrados that until then had not caused further damage in the flow-profile of the header nor on the surface, but which, if undetected, would for certain cause additional failures if not repaired.

To determine the extent of the actual damage to the sewer an inspection of the entire sewer in Trojská Street was carried out in several stages, including photographic documentation and surveying of the caverns.

The survey, which was carried out in unstable and very difficult conditions, nevertheless provided sufficient basic information concerning the degree of stability to enable the project engineer to design a method for implementing the stabilisation of the rock mass.

The results of these surveys were discussed with Prof. Ing. J. Barták, DrSc. from the Faculty

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of Civil Engineering of the CTU, who had also directly participated in the inspection and in the assessment of the stability of the individual caverns.

PROJECT DOCUMENTATION

Immediately after the accident had occurred and following the first local investigation, a design and engineering firm was selected to prepare documentation which would guide and determine the reconstruction of the header. The selected company, Ingutis s.r.o. had extensive experience in designing many of Prague's most important underground engineering projects.

The project documentation took into account the varying degrees of damage to the header; from the complete absence of certain sections of the header to the partial wear of the brickwork of the upper sections.

The investors and the operator's input conditions for the preparation of the project documentation were challenging.

They required:

- Limiting the hydraulic capacity to the least possible.
- Designing the bottom part of the header to ensure long-term resistance to the effects of abrasion and high flow rates.
- Achieving perfect contact between the extrados of the sewer and the rock.
- Minimising construction costs.
- Implementing the construction within a period of two years.
- Preferred when choosing the building materials were:
    - A structurally sound lining system made of cast basalt, which the operator had tested and proven in previous construction projects for its suitability for handling sewerage.
    - The use of basalt oval-shape profile gutters of Prague Normal (PN) dimensions also had the advantage of easy adhesion to the concrete walls they were bedded to.
    - The large basalt liners significantly reduced the number and the length of joints needed in comparison with standard brick masonry.
    - Basalts excellent abrasion resistance also represented a key selection premise for the operation of long-lasting repairs.
- High-quality sewerage bricks for the arch of the header.
- Easily-processed concrete mixtures with the prescribed compactness and grain-size, which provided perfect performance, especially in regard to the bottom of the header.

The project engineer proposed four basic technology solutions for the renovation of the header:

1. In the extensively damaged sections, and in those sections in which the sewer construction was completely destroyed, the engineer recommended excavating the sewer along its original route. This excavation would be coupled together with the removal of the remaining structure of the header, which would be replaced by a completely new structure. The engineer also proposed installing cast basalt gutter segments at the bottom and sides of the sewer, along with installing cast basalt interlocking side panels. Despite basalt being more than suitable for direct adhesion to concrete, it was decided for extra security that the side panels be tied into the surrounding rock with anchor bolts. The remaining part of the structure was designed and built as a traditional brick sewer.
2. In the areas in which it was mainly only the bottom part of the header that was damaged, the project engineer proposed the demolition of the entire bottom part of the header. The existing masonry would be underpinned alongside the installation of an entirely new bottom part for the header. This installation would again utilise cast basalt gutters and side panels.
3. The section of the header with the 100/175cm flow profile and the highest gradient between 5 and 9.8% was designed to be renovated by using the sewer-in-sewer technology. This technology consists of lining the existing sewer with cast-basalt gutters and segments that are interlocked across the entire flow profile. The space between the basalt liners and the existing sewer construction was designed to be back filled with concrete, whilst the roof was filled with shotcrete. Although this technology decreased the flow profile, it was selected due to its hydraulic conveying benefits.
4. The upper sections of the header that suffered from either normal wear and tear or minor defects were designed to be repaired in-situ. After milling the joints, the brickwork was repointed and the damaged stoneware gutters at the bottom of the sewer were replaced with cast basalt.

IMPLEMENTATION

For the installation of the deep (H: 595 mm W: 888 mm) basalt gutter and subsequently of the basalt (H: 380 mm) side panels, the first requirement was to demolish the brickwork and surrounding concrete infill. This included the concrete base slab and associated drainage.

Progressing with the work in units of metres proved to be uneconomical or impractical because of the frequent alternating of working operations with the transporting of small quantities of the concrete mixture and in terms of the total time required for overall construction. It was therefore decided that retained parts of the brickwork would have 60/100 mm metal L basalt profiles anchored to the existing structure of the sewer and rock, by means of a bolt between 800 and 1000 mm long. Only then, with the protection of this underpinning did the demolition work commence. In tandem with the construction, new supporting vertical uprights made from Ø 40 mm steel pipes were installed. There was a maximum interval of 24 hours between the demolition work and the completion of a new drainage system with a concrete base slab. The next step was to install basalt bottom gutters onto the concrete along with the basalt side panels into a shoulder shaped cross-section of the sewer. This then allowed for the installation of metal M-20 anchor bolts to secure the positioning of the basalt side panels and their adherence to the surrounding concrete. The final phase of construction saw the completion of concreting to be level with the upper edges of the side panels, as well as dismantling the L profiles and finishing off the remaining space using sewerage bricks.

CONCLUSION

The collapse of the Trojský header represented a unique event in the history of Prague's sewers. The collapse was significant in terms of its wide structural impact, as well with regards to the technical and financial resources required for its repair. Indeed, the total costs associated with the job, including the design and survey works, exceeded CZK 120 million.

From a mechanical perspective, it was never entirely clear what caused the accident to occur. It was most likely that the collapse was started with either a tensile failure of the brick sewer due to internal tension, or due to forcible erosion. In addition, the sewer's local masonry was of poor quality, and it could be that that issue was compounded during the torrential storm flows flowing through the sewer at the time of the accident.

In either case it was undoubtedly true that the origination and continuing cause of this extensive accident was the void and free space behind the extrados of the sewer. These voids were caused through a lack of support for the lining causing damage due to overpressure, or the formation of space "pockets" behind the sewer. These 'pockets' enabled the damage to the lining to creep and cause further destructive erosion.

After the formation of the first large cavern and the appearance of a sinkhole (during which large volumes of material were suddenly transported into the sewer) potholes appeared both at the sides and bottom of the sewer. The pressure created by the process repeatedly ruptured the structure and created more caverns, whilst washed-up rocks moving through from faults in higher sections of the sewer accelerated the destruction.

Other factors that might have contributed to the accident to a greater or lesser extent were:

- The designed route of the header in accordance with the urban planning documentation. This took little account of the existing, very unfavourable, local physical and hydrogeological conditions which were highlighted in the geological survey.
- The fall and flow of the route matching the terrain morphology resulted in high flowrates.
- The use of common building materials that had proved satisfactory in Prague's sewer system but did not meet or match the extreme flowrate conditions.
- The original excavation only applying a temporary fastening of supports or anchoring during the underground works.
- The inconsistent filling of voids that inevitably emerged in the given conditions.
- Failure to link the parallel original header with the new header due to project changes and revisions.

During the two years following the accident, smaller, but similar mishaps with sinkholes and collapsed sewers occurred in Prague's sewer network. The reason for these accidents was similar to those leading to the collapse of the Trojský header.

As such, the PKVT State Enterprise adopted a number of measures and policies that it has been implemented gradually and now is being applied across Prague's sewer network:

During the project preparation and the construction of sewers of Prague Normal (PN) dimensions or their reconstruction special attention is paid to:

- The gradient and the flowrate conditions.
- The choice of building materials with a preference for the cast basalt liners, for which the manufacturer Eutit s.r.o and the PKVT State Enterprise processed the technical documentation, including the various dimensional categories of sewers.
- All the measures implemented towards the design of the bottom part of the sewers that determine downthrows and release of the arch support.
- The use of reinforcement for increasing the tensile strength of the arch in the event of pressure flow regimes.

The following companies and organisations participated in the resolution of the accident:

- Ingutis s.r.o
- Inset s.r.o
- Kankol s.r.o
- ČVUT
- Eutit s.r.o
- PKVT s.p
- MHMP

The Project Team:

- Prof. Ing. Jiří Barták, DrSc
- Ing. Štěpán Moučka
- Ing. Ludvík Hegrlík
- Josef Pastor
- Ing. Jiří Šejnoha