Flooding of the Prague metro during the August 2002 floods

SVATOSLAV CHAMRA[1]

[1] *CTU Prague, Faculty of Civil Engineering. (e-mail: chamra@fsv.cvut.cz)*

Abstract: In August 2002, Southern Bohemia was affected by extremely heavy rainfall, which lasted for two weeks. Because of two flood tides, the storage capacity of the drainage area and the capacity of the system of the dams were exceeded.

On August 14, 2002, the Vltava River and the Berounka River converged simultaneously in their confluence area near Prague. As a result, Prague was struck by a catastrophic flood. The worst in some 500 years. Some districts of the capital city, as well as approximately one third of the Prague metro system was flooded. This caused the artery of the public transport system - the metro - to be out of service for a long time. In the flooded tunnels and metro stations there were approximately 1.2 million cubic metres of water.

The Prague metro flooded, firstly due to the anti-flood protection being insufficient. The surface protection was only designed for the one-hundred-year flood. Secondly, there were also some structural defects from the date of construction.

This paper will mainly concentrate on the identification of the problems that influenced the flooding; on the different geological structures and also on the tunnel lining stability.

Résumé: En août 2002, le sud de la Bohème a été éxposé à des pluies extraordinaires pendant deux semaines. Lors de deux crues, la capacité de rétention de bassin de la rivière ainsi que du système de barrages de la Vltava a été complétement épuisée.

Le 14 août 2002 deux rivières, Vltava et Berounka, ont culminé simultanément devant Prague. Prague a été frappée par une crue catastrophique, la pire dans les derniers 500 ans. A part de quelques quartiers de la ville capitale, environ un tiers du système de métro a été inondé, et ainsi cette artère de transport de la ville a été mise hors service pour longtemps. Il y avait environ 1,2 million mètres carrés de l´eau dans les stations de métro et dans les tunnels inondés.

Premièrement, le métro de Prague a été inondé parce que la protection contre l´inondation n´a pas été suffisante. La protection de surface n´a été conçue que pour une crue centennale. Deuxièmement, il y avait des défauts structuraux, provenants dès la construction du métro.

Cet article va porter sur l´identificaton de problèmes liés à l´inondation, sur les diverses structures géologiques et aussi sur la stabilité de voûte de tunnel.

Keywords: floods, geotechnical engineering, geological hazards, tunnels.

INTRODUCTION

In August 2002, we were witness to an event unprecedented in the Czech lands that will long remain in the memories of our people. Prague was struck by a catastrophic inundation, which, apart from flooding vast areas of the capital city, shocked both experts and common citizens by one more blow of immense consequences – by flooding one third of the Prague Metro system and putting this vital transportation artery of the city out of operation for a long time. Let us go back in time bringing back the causes of the triumph of the elements over technology and the reasons why the Prague Metro was flooded.

PRAGUE METRO

Brief history of Prague Metro

The design of the traffic flow in Prague at two vertical levels started practically as early as 1898, when a Prague entrepreneur Ladislav Rott submitted the first proposal for building an underground railway to improve the traffic connection in the historic district of the city. In 1912 – 1941, a series of designs of new routes of the underground railway were developed, which, however, were never implemented (Figure 1). Starting from 1958, the design of an underground railway using a system of subsurface tram with a subsequent transition to metro trains was under development. In 1967, the final decision for the construction of the Metro was made. On the 20th January 1969, driving operations on the first underground tunnel were launched, and on the 9th May 1974 regular passenger operation on the first line of the Prague Metro (line I.C – 6.570 km in length, 9 stations) was started. The last Metro section put in operation to-date was the extension of line C as far as Ládví Station with 2 stations and a length of 3.981 km. The highlights of this section are the first double-track driven Metro tunnel (Figure 2) and the first Prague single-nave driven Kobylisy Station, which is, at the same time, the deepest station on line C being situated 31.5 m below ground.

The Prague Metro system presently operates 3 lines (A, B, C) with 53 stations and a total length of 53.7 km. Line A has 12 stations and is 10 km long, line B is the longest with 24 stations and a length of 25.6 km, and line C has 17 stations being 18.1 km in length.

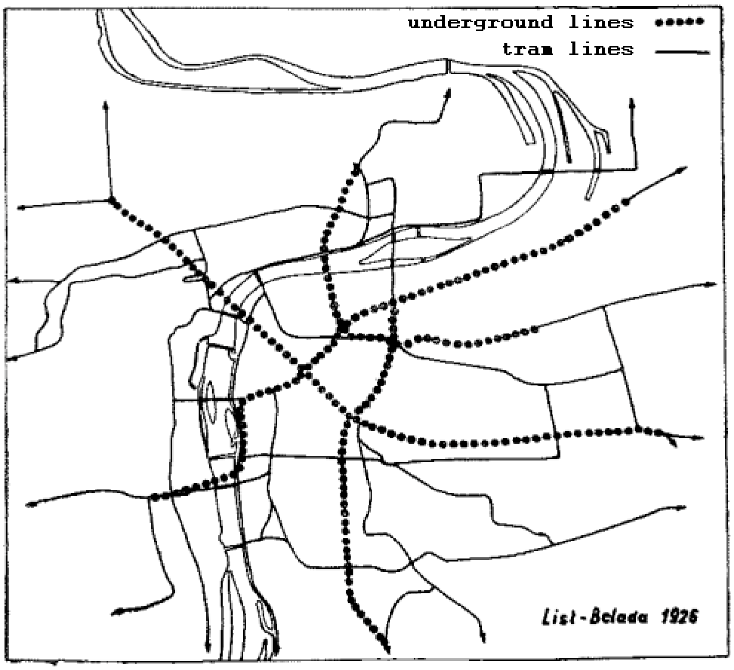

Figure 1. Project of underground railway network designed by Ing. Vladimír List and Ing. Bohumil Bellada in 1926

Engineering geological conditions of Prague Metro

The area of interest in the vicinity of metro lines A, B and C is predominantly formed by sedimentary rocks of the bottom Paleozoic era (Ordovician period), partly of the top Proterozoic era, which are overlaid by soils of quarternary superincumbent formations and made-up ground.

Figure 2. Double-track Metro tunnel on line IV.C

Bedrock rock masses

The tunnelled sections of the Prague Metro pass through a vast complex of sedimentary rocks of the Barrandien, from the top Proterozoic to the bottom Paleozoic era, with the most numerous positions of various formations of the Central Bohemian Ordovician period. The entire succession of strata shows predominance of clayey, silty to sandy shales and siltstones with different physical and mechanical properties and a varying degree of tectonic failure. The bedrock is also rich in sandstone to quartzite rock types, with a sporadic occurrence of subsurface forms of paleovolcanic activity. The whole area was intensely folded and tectonically deformed. An example is M stek Station in the city centre, a point of a prominent tectonic failure – so-called Prague fault (Figure 3), where clayey to sandy shales of Šárka strata and quartzites and siliceous sandstones of Skalka strata are found. This area was subject to intensive tectonic failures, and the rocks are heavily fragmented into chips or cuts. The tunnelling operations here had to face many difficulties.

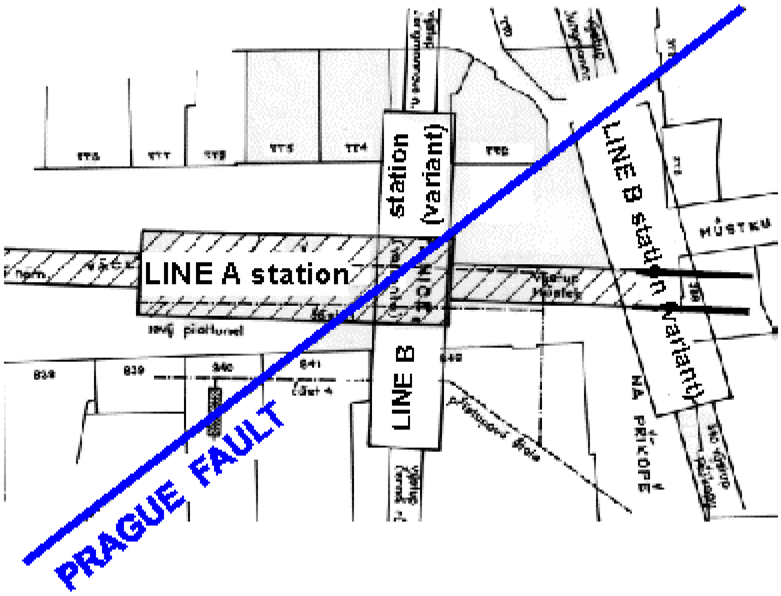

Figure 3. Unimplemented design version of M stek interchange station

Superincumbent formations

On the whole territory, the bedrock rock mass is overlaid by soils of superincumbent formations. In the central part of the city, in flood plains, these are mostly fluvial terrace deposits of the lowest Vltava River terrace benches, which are composed of sands and sandy gravels. Their thickness ranges from 6 to 12 m, sporadically up to 18 m.

The overlying stratum of terrace deposits contains Holocene alluvial plain deposits. They take predominantly the form of fine sandy, loamy and clayey sediments, at places with humous positions and separate horizons of redeposited sandy gravels. The thickness of this alluvium is mostly of 1–3 m (exceptionally up to 8 m).

Outside flood plains, in areas located mainly on the periphery of the city, there are eluvial, deluvial and deluvial-fluvial sediments, consisting predominantly of clayey to sandy loams, often with fragments of underlying rock.

A part of the territory is also covered by eolian deposits, reaching up to several metres in thickness – loess and loess-like loams.

Close to the surface of the territory, materials deposited by man are often found (backfill, made-up ground, remains of structures), with a thickness of 1 – 2 – 5 m, sporadically even greater.

The hydrogeological situation

The hydrogeological situation directly reflects the complex geological composition of the Prague underlying bed. There are groundwater horizons with distinctively different characteristics of the hydrogeological regime. In the sands and gravels of the lowest Vltava River terraces with a considerable pore permeability, there is a continuous horizon of groundwater that may be called alluvial water. In other covering formations, groundwater of pore type with unconfined level is found. Another groundwater horizon is found in the bedrock of predominantly Ordovician sedimentary rock mass. This is mostly a very poorly permeable to impermeable medium with fissure permeability. Here, the water also tends to show increased aggressiveness, mainly of sulphate type.

SEQUENCE AND CAUSES OF PRAGUE METRO FLOODING

Rise and development of flood events

The first spell of rainfall struck parts of the territory of the Czech Republic on the 6th to 7th August 2002 – affecting mainly Southern Bohemia, and to a lesser extent west and central Bohemia and Southern Moravia. The highest precipitation amounts were measured in the south part of the Šumava Mountains and the Nové Hrady Mountains (130 – 200 mm). The extreme values recorded were up to 254 – 277 mm.

In the period from the 8th to 10th August 2002, local showers and storms occurred in Southern Bohemia with daily precipitation amounts of 30 – 55 mm, exceptionally up to 98 mm.

The second spell of rainfall came between the 11th and 13th August 2002. This time, the entire territory of Bohemia was struck, and on the 13th August there was heavy rainfall mainly in Eastern Bohemia, including the Orlice Mountains and parts of Northern Moravia. The highest precipitation amounts for these three days were recorded in the Krušné Mountains (200 – 300 mm), with peak values in Klínovec (400 mm). In Southern Bohemia, the average rainfall was 130 – 190 mm, exceeding at places 200 mm (Prachatice region, Slavkov). In other locations of Bohemia as well, the rainfall exceeded the value of 100 mm – in the Jizera Mountains, the Orlice Mountains, the Czech-Moravian Highland.

The precipitation total falling on the territory of the Czech Republic on the 6th – 13th August 2002 is displayed in Figure 4. Looking at this figure and knowing the morphology of the Czech Republic, we can make a clear conclusion that the major part of the territory most severely hit belongs to the Vltava River watershed, and that it was only a question of time when and how all these water masses would get as far as Prague.

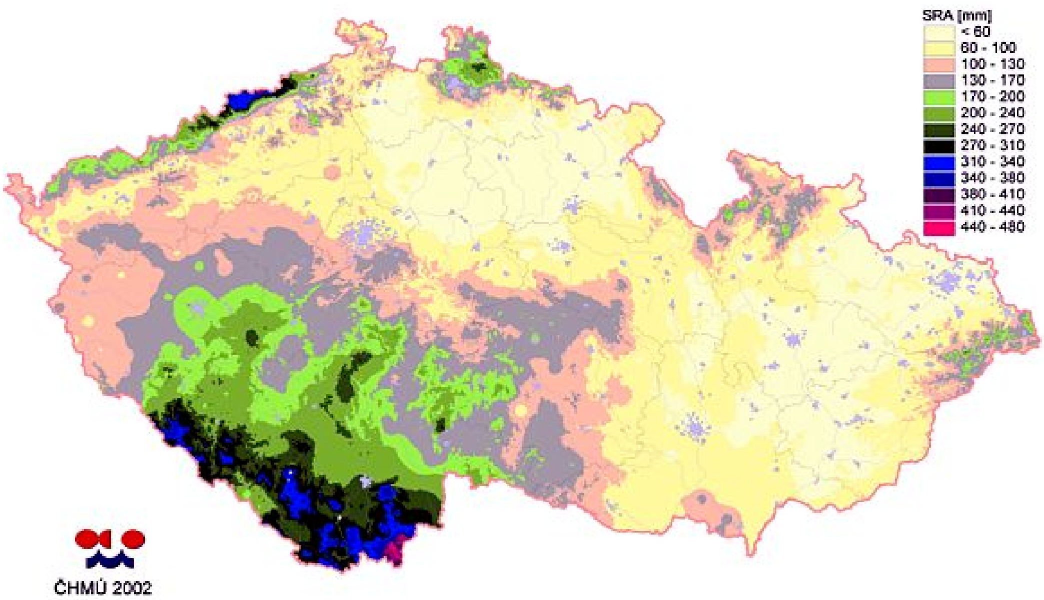

Figure 4. Precipitation total [mm] in August 2002 from 06 to 13 (Czech Institute of Hydrometeorology, 2002)

The August flood in the Czech Republic took a relatively atypical course unprecedented in the past. During a relatively short time, two flood tides were generated.

The rise of the first flood wave on the Vltava River was, to a large extent, eliminated by the reservoirs of the Vltava River cascade (Table 1) so that the flood flow recorded in Prague reached only a five-year maximum. At the same time, considerable saturation of the afflicted territory occurred during this first flood wave leading practically to the exhaustion of its retention capacity.

Table 1. Subdivision of storage belonging to the Vltava River cascade (mil. m^3)

Reservoir	Permanent storage	Effective storage	Flood-control storage	Total capacity
Orlík	288.00	374.43	62.07	716.50
Kamýk	8.32	4.652	0	12.98
Slapy	68.80	200.50	0	269.30
Štěchovice	6.236	4.208	0	10.44
Vrané	8.58	2.523	0	11.10
In total				1020.32

That is why the start of the second flood surge was followed by a rapid rise in the water levels on water courses and in reservoirs. Due to the synchronous rise of flood waves on individual water courses, the maximum inflow went into the Orlík water reservoir (the only one fitted with flood-control storage) reaching a level of a one-thousand-year flood discharge. The Orlík reservoir got in unmanageable condition on the 13th August 2002 at 1 p.m. when the maximum water level in the reservoir had been exceeded and uncontrolled water runoff over the top emergency spillways occurred.

The subsequent development of the flood on the Vltava River was the result of a collision of the flood wave from the Vltava River cascade and the flood wave from the Berounka River. The unfortunate fact was that the flood waves on both streams culminated almost simultaneously on their confluence just outside Prague (Figure 5). The resulting culmination on the Vltava River in Prague, in Velká Chuchle, occurred on the 14th August 2002 at 12.00 a.m. with a water level of 782 cm and a discharge of 5130 $m^3.s^{-1}$, which is a value corresponding approximately to a five-hundred-year flood. It was the largest flood event recorded in Prague in the period 1827 to 2002 (Figure 6).

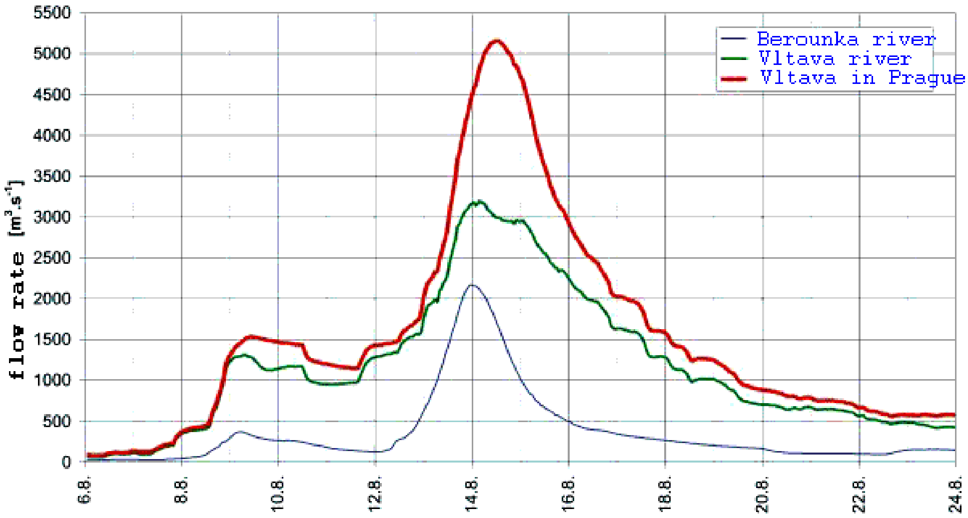

Figure 5. Critical flood flow in Prague (Czech Institute of Hydrometeorology, 2002)

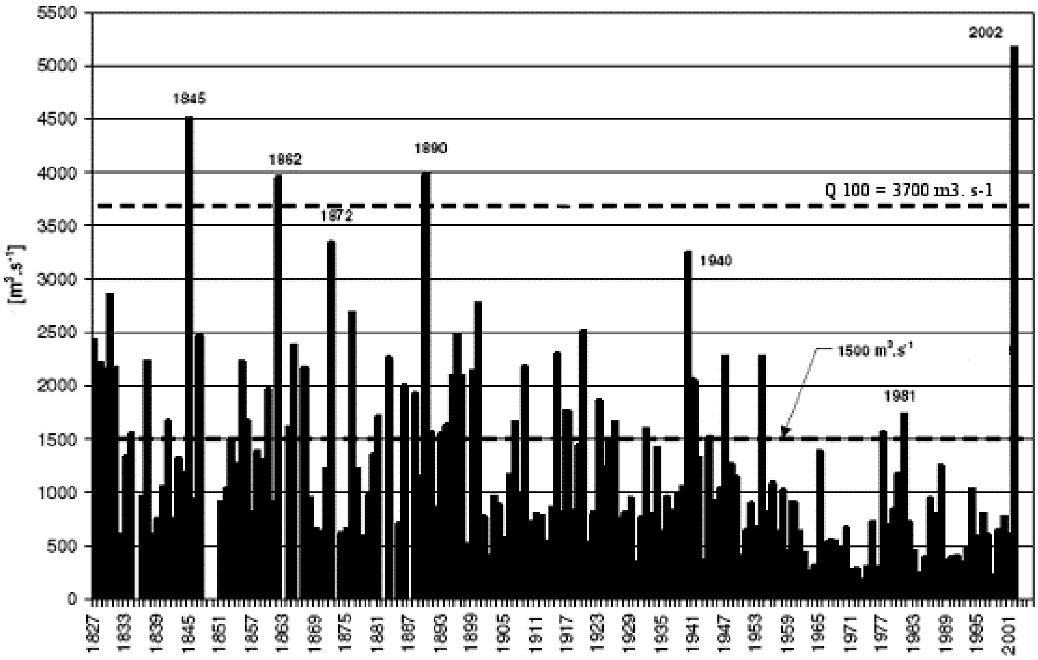

Figure 6. Floods on Vltava River in 1827 – 2002 (Czech Institute of Hydrometeorology, 2002)

Prague Metro systems

During the time of its construction, the Prague Metro was designed not only as the main arterial route of the city public transport, but it was also supposed to fulfil a vital role in the protection of the citizens of the capital in the case of war.

In terms of its functional aspect, the Prague Metro consists of two separate (but mutually interconnected) systems:

- **Metro transportation system (MTS)** – it is a transportation system servicing the city and providing passenger transport. The people using the Metro are quite familiar with certain parts of this system, though its greater (technological) part still remains hidden from their sight.
- **Metro protective system (MPS)** – it was designed and built as a shelter for civilians in the case of war to face the attack of the weapons of mass destruction, including protection against a break wave caused by the burst of the dams of the Vltava River cascade. Putting this system in state of full readiness for operation starts several months prior to the planned exploitation and is part of the state security strategy. During this time, all checks of the functioning of the system as a whole and of its individual elements, which are not used in the time of peace, would be performed. After this phase is completed, putting the MPS into operation may be achieved in up to 6 hours, and the final transition from the MTS into the MPS mode can occur within 13

minutes. The MPS is designed in such a way that in the case of exploitation it is controlled (and fed) from the inside, i.e. it should function autonomously, without external feeding, independently of the surface.

Protected spaces are separated from external spaces by pressure-proof and gastight divides in escalator tunnels and ventilation shafts, the inside protected spaces being further subdivided into individual protective sections by line pressurized divides.

Pressurized divides mostly consist of a highly resistant building construction, a pressure lock, cable grommets and some other auxiliary closing elements.

With a full activation of the MPS (Metro protective system), the MTS (Metro transportation system) function is completely disabled.

In this respect, it is necessary to raise a question that was often asked in those days (and later as well): Could the Prague Metro be saved by closing it several hours earlier? As the previous paragraph explains, we can give an unambiguous reply to it by saying that the condition in which the Metro was at that time implied that any earlier closure of underground spaces would have had no significant effect on its protection from flooding as no previous activation of MPS elements had been started.

The MPS was never designed or implemented as a system protecting the Metro against common floods. Despite this, however, some MPS elements were partially included in the Flood control plan of the Public Transport Company – Metro division (DP-Metro) as part of the second stage of flood-control measures.

The protection of the Prague Metro from floods was designed as a **two-stage system**. The first stage is represented by flood-control stop logs, which provide protection of the surface parts of the Metro (as well as of other structures situated on flood plains) against a one-hundred-year flood (+ a 50 cm reserve). In the case of exceeding this floodwater level, **some MPS elements** were supposed to be used as the second stage of protection. These were mostly escalator (station) and other pressure locks and cable grommet seals. Flood-control measures designed in this way provide efficient protection, but presume full efficiency and reliability of the MPS elements serving for this purpose.

Investigation of causes of Prague Metro flooding

The Prague Metro was flooded for approximately two days, from the evening hours of 13th August 2002 to the afternoon hours of 15th August 2002. The following sections of the Prague Metro were flooded:

- Line A – at a length of ca 3.8 km + 4 stations,
  (total operated length of 9.97 km + 12 stations)
- Line B – at a length of ca 11.2 km + 12 stations,
  (total operated length of 25.70 km + 24 stations)
- Line C – at a length of ca 2.3 km + 3 stations,
  (total operated length of ca 14.14 km + 17 stations)

At that time, the Metro had 53 stations in all, of which 19 were completely flooded (Figures 7, 8, 9). The total volume of water in the stations and tunnels was estimated at about 1.2 mil. m^3.

Figure 7. Flooded Florenc Metro Station

As part of investigation of the causes of the Metro flooding, all Metro sections which had been submerged were the subject of detailed examination and documentation by several groups of experts.

The main interest was focused on the following problems:

- What was the actual water volume in the flooded spaces of the Prague Metro?
- Did the Metro flooding cause damage to the principal load-bearing constructions of the tunnels, stations and other component parts of the Metro transportation and protective system?
- Could increased pressures during the flood produce new seepage paths through which larger amounts of groundwater can penetrate into the Metro spaces?
- Did water pumping from the underground result in an increased groundwater inflow from the rock mass into the underground Metro spaces (as compared to the situation of the years prior to the flood)?
- and others.

While investigating the causes of flooding of the Prague Metro, a need arose for dividing the whole surge into two events following one another:

- situation until reaching the one-hundred-year flood level – all flood-control measures on the territory of the capital city of Prague were designed and implemented to withstand this floodwater level
- situation at exceeding the one-hundred-year flood level when a natural disaster unprecedented in the modern history of the Czech basin was already under way, for which no alternative procedures had been developed and when numerous decisions were made more or less spontaneously.

Figure 8. Submerged metro train in Florenc Station

This classification was accepted due to the fact that the existing legislative system, implementing regulations, flood control plans and time schedules of operations, are all limited by the one-hundred-year flood level and do not include any measures concerning procedures and management of operations to be applied in a situation of reaching higher floodwater levels and flooding larger areas. All plans and measures, which had been developed and implemented, were prepared for the one-hundred-year flood water level. According to the data documented to-date, the so-called exceeding of the one-hundred-year flood water level in Prague occurred only four times (1845, 1862, 1890, 2002) in about 175 years – see Figure 6.

In order to understand the flooding mechanism of the Metro system, the causes investigated were further split into two categories:

- causes of water penetration from the surface into the Metro system
- causes of further water propagation in underground spaces of the Metro system.

Causes of water penetration into the Metro system from the surface

- **the floodwater level on the Vltava River** reached approximately 2 m above the level of the one-hundred-year flood. This cause is of primary importance and of the most significant nature. The successive overflow of floodwater over the flood-control gates protecting against the one-hundred-year floodwater level was the cause of surface flooding of the following stations:
  - Nádraží Holešovice, Vltavská, Florenc C on line C,

- Křižíkova, Invalidovna, Palmovka, Florenc B on line B.

  From these stations, water kept spreading through the underground spaces thanks to leaks, unsealed crawl spaces and some failures in constructions to other stations and line tunnels.
- **lack of coordination of the activation plan** of the Metro protective system with the flood control plan of DP-Metro and the flood control plan of the capital city of Prague
- **interruption of power supply** – pumping of seepage water from underground spaces of the Metro was stopped, triggering off their partial flooding
- **a serious point of water penetration** into the Metro system via a vertical member was a ventilation shaft near Invalidovna Station (Figure 10), where the external masonry protection structure of the air vent providing ventilation of the station hallway was overflowed and subsequently destroyed. From there, water penetrated through the ventilation hole into the air-conditioning chamber and through open slide valves further into line tunnels
- **a minor point of water penetration** into line tunnels was faulty steel insulation of ventilation shafts in Křižíkova and Štvanice Stations (Figure 11).

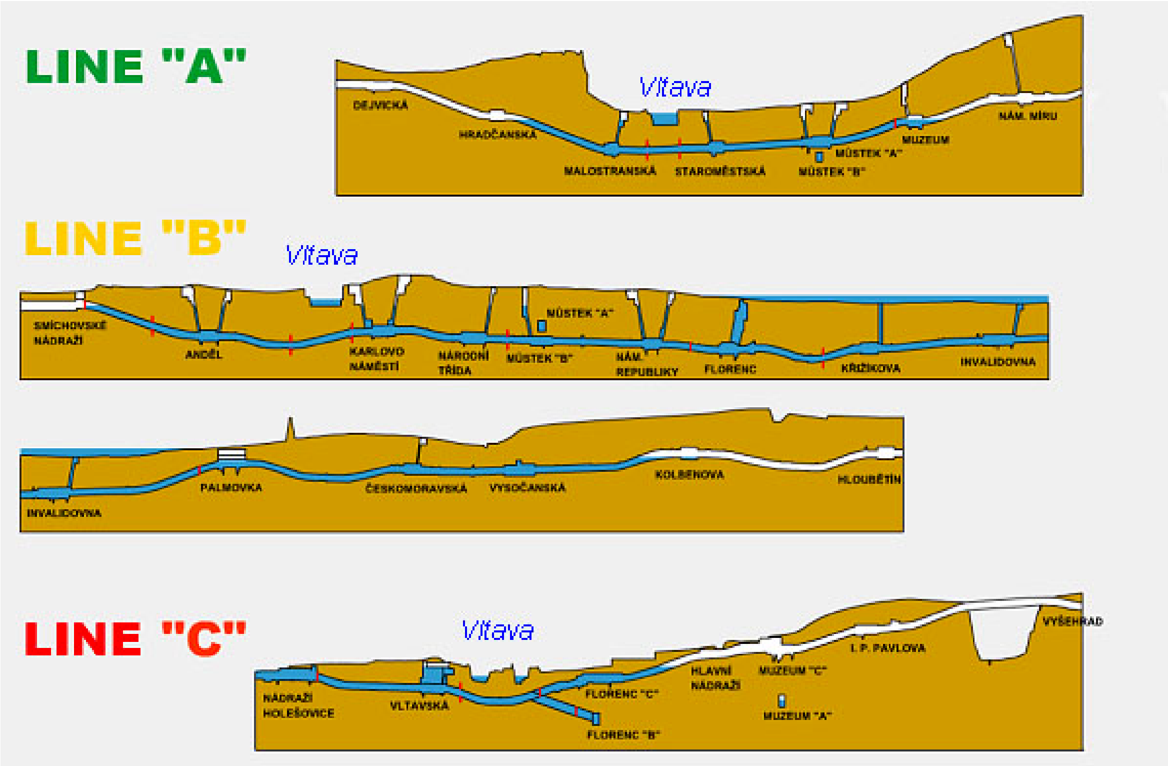

Figure 9. Flooded stations and tunnels of Prague metro

Figure 10. Damaged ventilation shaft near Invalidovna Station

Figure 11. Faulty steel insulation of ventilation shaft in Štvanice

Causes of water propagation in the Metro system

Among the causes of gradual flooding of underground spaces of the Metro system there are failures of some other members of building constructions, faulty cable grommets, some unclosed line closing devices and crawl spaces. These factors contributed to the extent and speed of water propagation in the underground.

Faulty members of building constructions

- destruction of a pressure plug of the air-conditioning chamber between line tunnels in Invalidovna Station, which showed workmanship defects
- pulled out concrete block in the pressure divide between Florenc B – Námestí Republiky Stations (Figure 12), damaged (lifted) concrete sills in pressure divides of both tunnels between stations Florenc C – Vltavská Stations

- broken cross member in the cable gallery between line B and A in M stek Station (Figure 13). According to the project there should have been a reinforced concrete pressure divide instead.

All these defects were caused by a serious lack of performance discipline, and their poor workmanship quality is in contradiction with both the project drawings and the set of record drawings.

Figure 12. Pulled out concrete block in pressure divide

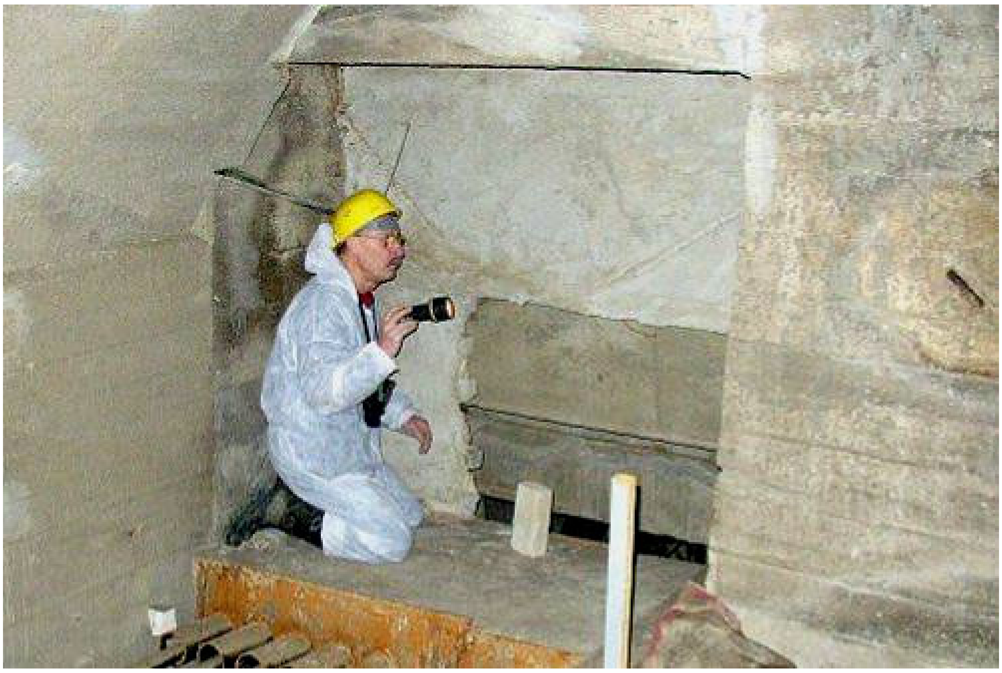

Figure 13. Cable gallery between lines B and A in Mustek Station

Unclosed pressure locks

- insufficiently closed station pressure lock in Florenc B Station – the lock closing direct entrance to the station to which water penetrated from the surface, most likely lost its leak tightness due to short circuit caused by water
- non-closing of some other line divides on line A and B was caused by the speed of water penetration into the underground and by power failure, and also by relying on the sealing function of closed divides. Further more, it was presumed that the operation of the majority of the Metro line sections would be restored in an immediate succession and therefore line divides were not closed at places where theoretically there was no

risk of water penetration from the surface of the station. After power supply was cut off and failures in the water-tightness of closed divides were detected, there was not enough time to close the neighbouring sections.

Unsealed cable grommets

- unsealed cable grommets (Figure 14) were the major cause of flood wave propagation in the underground – its share in flooding the Metro system was estimated at more than 44 % .

The significance of watertight sealing in cable grommets may be best understood by the following example: the amount of water passing through one unsealed (empty) cable grommet with a diameter of 100 mm under a given hydrostatic pressure (20-30 m of water head) equals approximately **125 – 150 l/sec**, so that this single grommet could fill up the volume of 1 linear metre of a line tunnel (ø 5.10 m) **in approximately 2.2 to 2.7 minutes**!

Figure 14. Unsealed cable grommets

To conclude, we may state that:

- surface flood-control barriers provided a reliable protection against water penetration into the Metro system up to the one-hundred-year flood water level. The Metro was flooded only after this level was significantly exceeded by the Vltava River culmination and a return flood wave surge by approximately 2 m above this height,
- the flooding of underground spaces was not caused by structural failures of the load-bearing constructions of the tunnels and the stations but by the failures of some constructions of the protective system, in which the specifications of the project documentation had not been observed or where low workmanship or technological discipline during their implementation had occurred,
- activated pressure locks reliably withstood the water pressures and their construction was not damaged,
- earlier closing of the Metro system without a previous activation of the protective system elements would not have resulted in any major effect in terms of protecting the Metro system from flooding,
- the airtightness of the rock mass and tunnel lining system has presently proved to be in suitable condition except for single details. No increased seepage volumes into the Metro system were recorded either during the flood or after successive pumping out of water. This fact leads to formulating a conclusion that no serious changes in the surrounding rock mass occurred and thus there is no higher risk of a significant increase in the seepage from the rock mass into the tunnels.

CONCLUSIONS: A FEW THOUGHTS CONCERNING FLOOD PROTECTION OF METRO

Restoration of the Metro service cost us nearly 7 billion CZK. This naturally brings up a question: To what floodwater level is it appropriate to protect endangered structures in flood plains? A hundred per cent protection from natural disasters is practically not feasible (or highly problematic and costly). Here, a reasonable compromise between the protection level of a structure and the resources spent on this protection must be made. At the present moment, flood-control barriers are being increased to the level of the flood of 2002 (+ 30 cm) and new ones are under construction. In this respect, the two-stage system of the Metro flood protection sounds logical and justified. By including several elements of the Metro protective system (in state of 100 % efficiency!), which would prevent water penetration into the Metro system and its further propagation in the underground in the case of overflow of external flood-control barriers, the system, to a reasonable extent, reduces the costs for the construction of extreme flood control measures.

In designing the flood control concept, we must, at the same time, take into account the fact that the protection of the Metro system cannot be approached independently, but in close coordination with the protection of the whole Prague and in a wider context and within the concept of the protection of the whole Vltava River watershed. New solutions must be sought and older ones must be restored, which would reduce the flood rise from the very beginning – e.g. construction of dry polders (flood release basins), optimization of the control code of the Vltava River cascade with a focus on flood protection of Prague, removal of obstacles in the inundation (flooded) areas etc.

Acknowledgements: The paper was written with support grants MSM 6840770005 and GACR 103/06/1257.

Corresponding author: Mr Svatoslav Chamra, CTU Prague, Faculty of Civil Engineering, Thakurova 7, Prague 6, 166 29, Czech Republic. Tel: +420 224 354 550. Email: chamra@fsv.cvut.cz.

REFERENCES

CHMU 2003. Preliminary summary report on the hydrogeological situation during the flood in August 2002. Czech Hydrometeorological Institute, Prague (in Czech)

FOJTÍK, P. 2004. 30 years of Prague Metro. Public Transport Company of Capital City Prague, Prague (in Czech)

KHMP 2003. Report on the investigation of causes of Prague Metro flooding during August floods in 2002. Final report of the Commission of Prague City Municipality, Prague (in Czech)