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Flood Protection of Prague Metro after the 2002 flood

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ABSTRACT: About one third of the length of operating lines of the Prague Metro found in the central area of Prague were inundated during the flood in August 2002. The construction of a new flood-protection system commenced immediately, when the damage caused by the flood had been repaired and the metro lines operation had resumed. Analyses and the assessment of the flood impacts showed that the flood wave threatens most of all cut-and-cover structures of the metro lines which are founded near to the surface, namely by increased external hydrostatic pressure and/or the hydrodynamic effects of this pressure. Mined metro sections are virtually unthreatened in these cases. Protection of the cut-and-cover structures is provided by several basic types of traditional construction measures. The structural parts found in the flooded zone are reinforced or thickened, permanently anchored, braced or supercharged. Structures which are selected with respect to their design and local hydrogeological conditions are provided with elements relieving the hydrostatic pressure on the outer surface of stations and concourses. This paper describes the function of the relieving elements in detail.

1 INTRODUCTION

The oldest line of the Prague Metro has been in service since 1974. Since then, 54 stations have brought into service, on three lines. Before 2002, all threatened sections of the Prague Metro had been protected against inundation from the surface up to the level of the Vltava River peak flood calculated in a 100-year cycle. The water surface level exceeded the 100-year flood level by more than 2 metres in the vicinity of some stations during the August 2002 flood. The metro entrance spaces were inundated by surface water; it was impossible then to prevent the water from rushing into the stations. At the same time, the flood wave was running through the metro tunnels. This is how the inundation affected the total of 17 stations (6 stations – primary inundation, 11 stations – subsequent inundation through running tunnels and cross-passages). Even though the flood wave did not affect integrity of structures, it caused extensive damage to the structural parts and equipment of the metro.

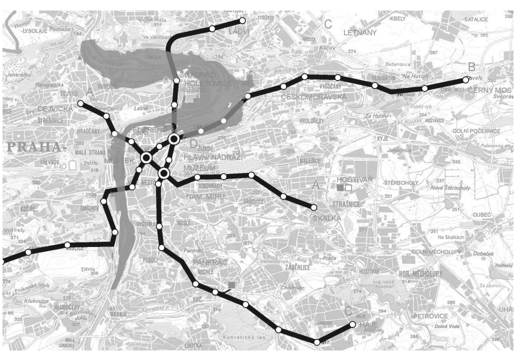

Figure 1. Plan map of the Prague Metro showing the extent of the surface inundation during the 2002 flood.

2 HYDROLOGICAL CAUSES OF THE FLOOD

The flood that passed through Prague in August 2002 had not been recorded before since 1827 when systematic hydrological monitoring started. It was probably the greatest flood in the history starting in 1432, when a flood destroyed five pillars of Charles Bridge, which was at that time the only stable connection between the Vltava River banks in Prague.

The peak flow was assessed statistically as a 500-year recurrence flood. Nearly 3 km^3 of rainwater fell during a single August week in 2002 in southern and south-western Bohemia. The amount of precipitation exceeded the precipitation totals for many months in some locations. The ground, which had been saturated by previous rains, did not receive other water, therefore nearly all this amount flew directly to streams and rivers. Virtually the entire above-mentioned area is part of the Vltava River catchment basin, therefore this amount of water had to flow through Prague in the course of several days.

The volume rate of flow, which is referred to as "100-year flood discharge" in statistical terms ($3700\,m^3\,s^{-1}$) was exceeded roughly by $1500\,m^3\,s^{-1}$.

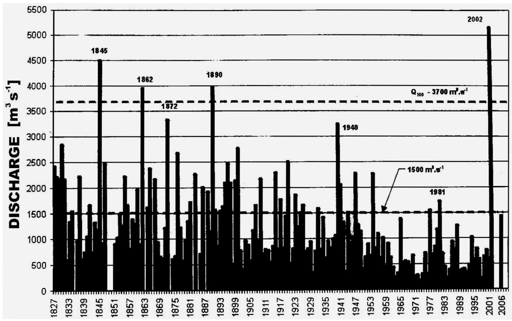

Figure 2. Time series of culmination flow capacity on the Vltava River – maximum annual flow capacity.

3 FLOOD PROTECTION SYSTEM DESIGN

3.1 *Parameters specified for the new flood protection system*

The catastrophic effect of the flood brought about a need for development of a new system of the Prague Metro flood protection. This is why the city authorities subsequently decided that the height of flood barriers be raised up to the level of the inundation experienced in 2002 in the given profiles of the particular stations, with a safety margin of 0.6 m. This level was further considered to correspond to the design protection height $Qn_{2002+0.6\,m}$.

The underground railway protection system is designed as a system independent of the systems protection individual districts of Prague; it protects the underground railway even in the case of the water spilling over barriers installed along the Vltava River. The primary task of the project is to prevent a flood wave from getting inside the metro spaces from the surface, in the case of inundation, to prevent water from spreading into other spaces of the metro, and to provide resistance of load-bearing structures of the metro against hydrostatic and hydrodynamic effects of the flood wave; The load bearing capacity of the metro structures is adequate to the height of all completed barriers.

3.2 *The summary of implemented measures*

The inundation of metro entries is prevented at the surface level by fixed walls and new lines where mobile barriers can be erected are prepared. When the flood wave is stemmed by barriers surrounding a metro station, the hydrostatic pressure on the station envelope will increase. Individual expansion blocks of cut-and-cover structures founded near the surface are, with respect to hydrogeological conditions threatened by heaving due to the buoyancy forces, or by a structural failure due to the hydrostatic pressure. The mined sections of the underground railway are not directly threatened by the flood.

The recently completed system of flood protection of the stations consists of implementation of several basic types of traditional construction measures. The load-bearing structures found in the flooded zone are reinforced or thickened, permanently anchored, braced and supercharged. Elements relieving the hydrostatic pressures on the outer surface of envelopes of stations and concourses are installed in some parts of the structures in the flooded zone, with respect to the design of these parts and local hydrogeological conditions. The construction measures that are implemented either remain hidden from passenger sights or they are incorporated into the architectural design of the stations.

The work on the flood protection system was carried out without any interruption to the underground railway operation. If the design protection height ($Qn_{2002+0.6\,m}$) is exceeded, the internal spaces of the metro stations found in the flooded zone will be automatically inundated. Elements of the civil defence system of the metro, namely pressure-resisting gates and other barriers, are also incorporated into the system preventing a flood wave from spreading.

In two cases (Florenc interchange station and the concourse of Invalidovna station), the implementation of the complete set of protection measures to reach the unified level is so complex and difficult that it will require much longer time than that required at the other stations. In the short run, organised inundation of the internal space of the metro is designed for these stations, to begin when a lower water surface level is reached for which the load-bearing capacity of the structures has been verified. The inundation of the internal space of the protected structure is a simple flood protection method. In this case, the pressures are equalised, thus damage to the structures is prevented. It has been proven that the damage due to the forced organised inundation would be lower by an order of magnitude and significantly faster to be compensated for than the damage resulting from contingent destruction of load-bearing structures.

4 TYPES OF THE CONSTRUCTION MEASURES IMPLEMENTED

4.1 *Permanent fixing of a concourse structure with anchors*

The system of protection against inundation from the surface level was provided for the concourse of Vltavská metro station, which had been originally built in an open trench. A line of permanent walls and mobile barriers up to 1.8 m high as a maximum was erected at the surface level. The barriers were

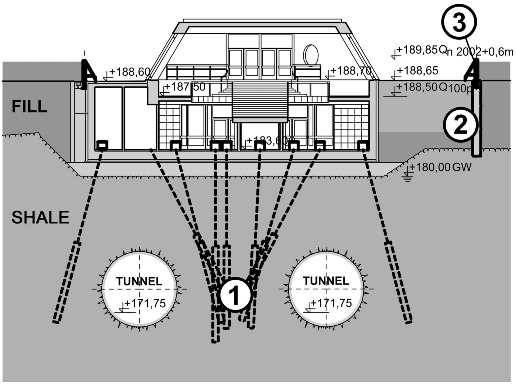

Figure 3. Permanent anchoring of Vltavská station to the bedrock. 1. Permanent anchors, 2. Jet-grouted pillars, 3. Mobile barriers.

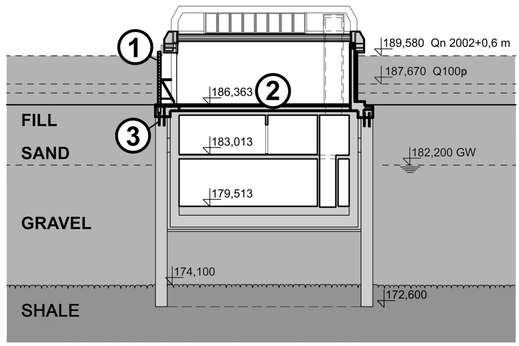

Figure 4. Incorporation of the weight of the diaphragm walls into the weight of concourse structure – Křižíkova metro station. 1. Mobile barriers, 2. Thickening of the roof structure, 3. Sills joining the diaphragm walls to the concourse structure.

founded on newly installed jet-grouted pillars keyed into bedrock consisting of shale.

The protection of the concourse structure against floating was provided by a system of permanent anchors (see Fig. 3). The structural analysis assumed full hydrostatic pressures exerted as a result of the design flood flow; the environment surrounding the concourse structure consists, according to the hydrogeological survey, of permeable man-made ground. The foundation slab of the concourse, which is found at a depth of 5.0 m under the surface, was tied to the bedrock with anchors; in terms of the structural analysis, this system even reduces the span of the slab carrying the hydrostatic forces. The ground plan of the grid of anchors was adjusted to operational requirements. The ends of the 500 (800) kN capacity anchors were provided with steel face plates. The openings where the anchors passed through the slab and the waterproofing layers were made watertight by grouting. The heads of the anchors found on the floor of the public area of the concourse were masked by visible benches. The hinged upper part of the benches allows an easy access to the anchor heads, where the pre-stress can be checked. The benches were incorporated into the architectural design of the concourse.

4.2 *Reinforcing and/or thickening of the structures; incorporation of diaphragm walls weight into the weight of the concourse structure*

The whole height of the original light-weight glazed external walls of the Křížíkova station concourse, from the floor to the roof, are designed to be replaced by 300 mm thick reinforced concrete walls. The walls will be structurally connected with the existing reinforced concrete underground part of the station and tied to the at grade steel structure of the concourse.

The newly constructed reinforced concrete sills are tied to the original diaphragm walls for the purpose of protecting the concourse structure against the buoyancy effects (spliced reinforcement bars). The incorporation of the weight of the diaphragm walls into the weight of the overall structure is shown in Fig. 4. Additional elements of the at-grade part of the concourse structure were built and this part of the structure was extended to cover the entire ground plan area of the underground part within the framework of the flood protection works. Openings and entrances to the concourse are protected up to the height of 3.0 m by means of mobile barriers. The architectural design maintains the features of the original design. The new external walls are a combination of stone cladding with opaque glazing.

4.3 *The drainage system for lowering of the ground water table during a flood emergency*

The technical solution to the flood protection system around Malostranská station is based on the idea of preventing inundation of the underground railway from the ground surface by means of mobile barriers and, at the same time, lowering of the ground water table in the immediate proximity to the concourse structure to a level specified by a structural analysis. The at-grade atrium space will be closed during a flood from all sides: from three sides by means of new lines of mobile barriers; from the west, the barrier is provided by the building of the Waldstein Riding-School built in 1630. The mobile barriers are founded on jet-grouted pillars. There are drainage galleries in the area surrounded by the barriers driven along the external wall of the concourse. Dewatering wells are at the ends of the galleries (see Fig. 5). The gallery houses a DN 250 mm horizontal drainage pipeline installed

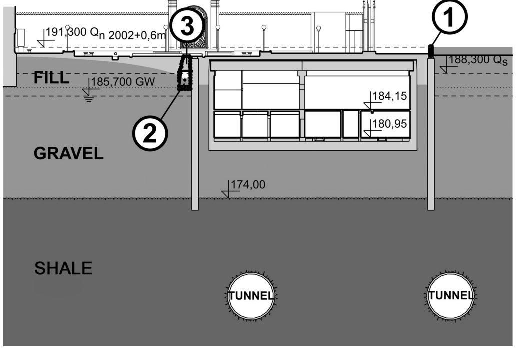

Figure 5. The drainage system along the concourse of Malostranská metro station. 1. Mobile barriers, 2. Drainage gallery, 3. Dewatering pump.

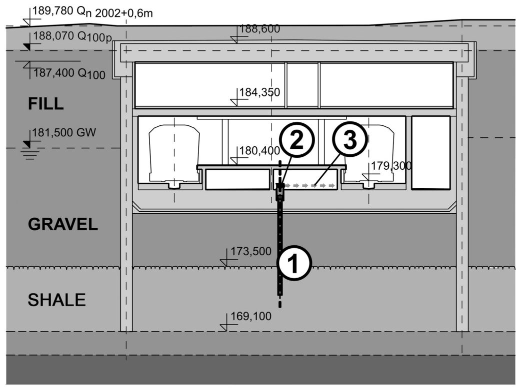

Figure 6. The pressure-control element passing through the foundation slab of Florenc metro station. 1. The cased hydrogeological borehole, 2. The head of the pressure-control element, 3. The pipeline draining water away.

on a 1 per cent gradient falling toward the dewatering well. The remaining space of the gallery around the pipeline is filled with gravel-sand, which guarantees that the stability of the environment being dewatered will remain unimpaired. The ground water that will seep to the galleries during a flood will be collected by the drainage and led to the wells; it will be pumped from the wells behind the barrier line, to the raised Vltava River. Thus the ground water table level in the atrium will be lowered and the hydrostatic pressure on the concourse structure reduced. The design has allowed for requirements for the stability of the Waldstein Riding-School subbase to be secured. The flow of water in the closed atrium space was verified by a hydrogeological survey and mathematical model.

4.4 *Pressure-control elements passing through the foundation slab*

The inventive solution to the problem of protecting the foundation slab against the buoyancy effects is based on pressure-control elements passing through the foundation slab of Florenc interchange station on the Line C (Fig. 6). The station was cut-and-cover top-down box excavation between slurry diaphragm walls. The foundation slab of the station consists of a single 221.0 m long expansion block. The design of the station (diaphragm walls braced with the bottom and roof slabs) does not allow overloading during the design flood.

The original structural analysis from 1970 assumed the 100-year flood level to be lower by 2.38 m than the current design level of the flood wave. This criterion is hard to satisfy by implementation of the above-mentioned traditional measures because of the existing intensity of operation of the interchange station. This is why a non-traditional solution to the problem of protection of the station substructure was adopted.

Figure 7. Drilling of the hydrogeological borehole through the hermetically embedded gate of the pressure-control element, with the seeping water drained away to a branch pipeline. A temporary extension piece is attached to the pressure-control element making it possible to cope with the inflows during the drilling operation.

Two hydrogeological boreholes passing through the foundation slab and reaching the bedrock were carried out inside the station to be used for pumping tests; additional two monitoring boreholes were drilled. As described in detail below, the drilling rods passed through special gates hermetically embedded in the foundation slab, with an intention to use them after the completion of the hydrogeological survey as parts of the pressure-control elements (see Fig. 7).

Based on the results of the hydrogeological survey, the function of the pressure-control elements can be described in the following simplified way: In a flood emergency, the hydrostatic pressure in the closed space under the bottom of the station and in the vicinity will grow as a result of the rising ground water table level combined with an increased rate of seepage through the external diaphragm walls. The ground water table level around the station is bound to the level of the Vltava River surface. The installed pressure-control elements will allow controlled relieving of the hydrostatic pressure under the foundation slab of the station. When the valves installed on the heads of the pressure-control elements are opened, the pressure ground water will flow to the interior of the station and, at the same time, the hydrostatic pressure will be reduced in a controlled manner to the level verified by the structural analysis. Considering the completed measurements and on the basis of a model calculation, we can expect that the rate of the inflow which will be drained away into the existing sufficiently capacious non-faecal sump found in the metro station and pumped over back to the swollen Vltava River will amount to $5.0\,l.s^{-1}$. The efficiency of the protection of the foundation slab using the pressure-control elements was verified by hydrodynamic pumping tests within the framework of the survey activities, both in normal condition of the ground water table and, subsequently, using a mathematical model, which assumed the flow of the ground water during a flood emergency situation. The results of the model analysis resulted in addition of two elements to the existing four pressure-control elements so that gradual and steady process of reducing the hydrostatic pressure under the entire area of the foundation slab was possible. The filtration stability in the situation of ground water flowing from under the foundation slab of the station to the interior of the station is guaranteed owing to the hydraulically tested perforated casing of the boreholes and the fill around the casing pipes.

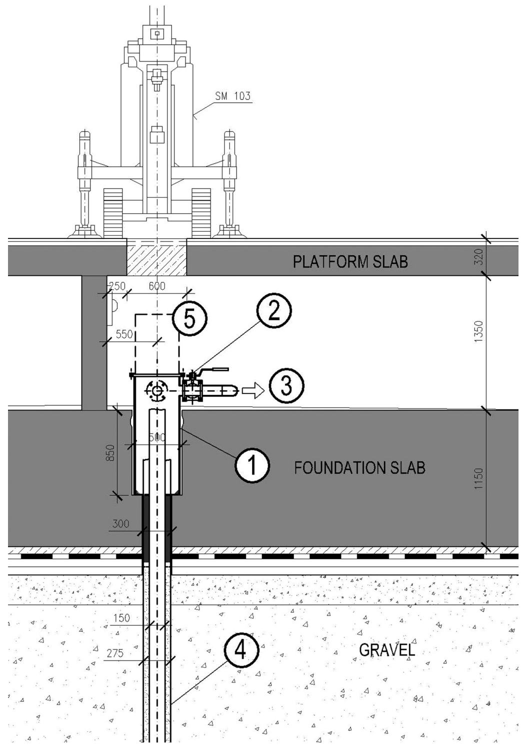

Figure 8. Vertical section through the pressure-control element. 1. The head, 2. The ball valve, 3. The pipeline draining water away, 4. The cased borehole, 5. The temporary extension piece allowing the drilling while ground water flows in.

5 SOME ASPECTS CONCERNING THE INSTALLATION OF THE PRESSURE RELIEVING ELEMENTS

5.1 *The design*

The additional incorporation of the pressure-control elements into the load-bearing structure is an innovative solution, which has been applied neither in Czech probably nor foreign construction practice. The design followed pre-set requirements to be met by the pressure-control elements, first of all the viability of drilling through the foundation slab, which is exposed to a permanent hydrostatic pressure, and handling the subsequent flow of ground water into the station space. Further, the elements had to allow installation of equipment necessary for the pumping tests to be carried out within the framework of the hydrogeological survey, waterproof embedment into the foundation slab, and had to meet requirements for long-term resistance against pressure.

The work was complicated by the fact that the drilling of the cored boreholes had to be carried out through the reinforced concrete platform slab, during overnight traffic closures. The pressure-control elements were incorporated into the foundation slab using the following procedure (see Fig. 8):

1. Ø500 mm core drilling down to a depth of three quarters of the foundation slab depth (approximately 850 mm),
2. gluing of stainless steel prefabricated head of the pressure-control element into the foundation slab using an epoxy sealant,
3. a check test of hardening of the epoxy sealant,
4. checking on the sealing of the head by means of a pressure test (see below),
5. Ø300 mm core drilling through the remaining portion of the slab and the waterproofing layers, drainage of ground water away to the pumping station,
6. the final hydrogeological borehole extending to the bedrock; a pumping test,

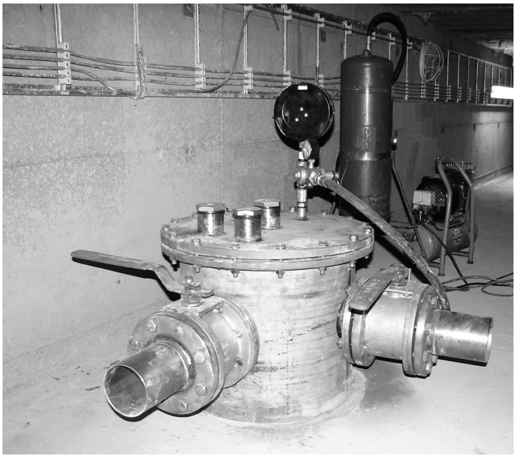

Figure 9. The complete pressure-resistant head embedded in the foundation slab.

7. installation of the equipment of the head, installation of closing ball valves,
8. closing of the pressure-control element

The valves are closed in the condition of common operation. These elements, which interconnect the external and internal environment, even allowcontinuous monitoring of the ground water pressure under the foundation slab.

5.2 *Testing of quality of the gluing and sealing of the heads of the pressure-control elements*

The tests carried out during the installation of the stainless steel heads of the pressure-control elements consisted of pull-out tests performed to verify the process of setting of the epoxy glue and pressure tests checking the tightness of the glued sealing and individual components (the valves, flanges) of the head of the pressure-control element. The testing set is shown in Fig. 9.

6 NOTES

6.1 *Other measures implemented within the framework of the flood prevention system*

The flood protection structures were built concurrently with installing permanent instruments monitoring the hydrostatic pressures in selected structures as a part of the survey operations. The load-bearing capacity of roof decks of the stations was tested using loads corresponding to the expected extent of the surface inundation. The services penetration points were inspected and the openings provided for the services in external walls were protected against leakage.

6.2 *Mined sections of the metro and the flood*

In terms of the condition of tunnel structures, we can say that the mined sections of the Prague metro survived the 2002 flood without any damage. The metro was in full service even during the initial hours of the flood while the water surface level had risen by several metres. No increased leakage was observed, let alone operational safety threatening defects caused by the adequately increased hydrostatic pressure on the tunnel lining. Despite the fact that speculative notions that the inundation happened due to a collapse or holing of the main load-bearing structures which were expected to withstand the water pressure, the inspection carried out after the water pumping had been completed and the condition of the structures checked conclusively proved that the tunnel lining passed this test undamaged.

7 CONCLUSIONS

The solutions described in this paper regarding the problem of protection of load-bearing structures are generally applicable to other structures located in a flooded zone or threatened by increased level of the ground water table.

The above-mentioned method of diminishing the hydrostatic effects by means of additional incorporation of the pressure-control elements can be conveniently utilised in other cases, after a thorough analysis of the condition of the lining and of the potential rate of water inflow from the outer environment. A hydrological survey of the outer environment and subsequent verification of the function of the pressure-control element are advisable.

Regarding the existing underground structures exposed to one-off effects of increased hydrostatic pressures, for instance during a flood, the application of the pressure-control elements is not only a highly effective but also highly economic solution compared with traditional conventional methods.

A catastrophic flood, similar to the flood which hit Prague and inundated the metro, can also affect other cities where underground railway lines are within the reach of a river. We can recommend a responsible solution of the flood protection system to be developed in such a case.

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