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Underground Structures During Floods

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ABSTRACT

In many parts of the world, flood situations with extreme devastating consequences on people's lives, buildings, and the natural environment occurred in 2023. During the floods, water levels rose up to 5 meters above ground level. One cannot forget the flood in 2002 in Prague, during which 18 metro stations and 19.6 km of track tunnels were flooded. In Bratislava, in the immediate vicinity of the Danube, a four-story underground garage with an unburdened surface was built in front of the Carlton Hotel. There are several lighter objects with multiple basements near the Danube. During extreme floods, these structures can be seriously damaged or destroyed. This contribution provides an overview of the development of extreme flow rates in the Danube, failures and the measures aimed at protecting underground structures during floods.

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Introduction

Underground structures, or underground parts of construction objects, can be affected by floods at various stages of their construction. Important documents include information on the development of flood flows and levels in nearby streams. The ideal solution to the problems should ensure, at all stages of the construction and operation of the buildings, flood protection measures that would prevent any damage. However, such a solution cannot be achieved in principle, so it is necessary to focus on minimizing possible damage.

However, the stability of finished buildings cannot be compromised, so the most unfavorable flood levels (for example, thousand-year floods) and hydrodynamic effects should already be considered in the projects. During floods, limited use of the interior spaces of buildings cannot be ruled out. Even in spite of this, it is necessary to exclude inflows of water from the surface of the territory with appropriate closures of the buildings. Appropriate surface treatment of the ground-floor parts of building structures will make it possible to remove the consequences of floods very quickly.

The intensive development of motoring after 2000 also required the creation of numerous parking spaces in our large cities. In Bratislava, separate underground garages were created near the Danube, and three to four underground floors of other buildings, especially tall buildings, were also used for parking or shopping. The effects of flood protection measures on the left bank of the Danube were positively reflected in the central parts of Bratislava. In this contribution, we present more detailed information about the underground garages in front of the Carlton Hotel. Similar problems were also solved on other construction sites near the Danube. These are the underground garages of the Centrum, the Opera and the underground spaces of the Eurovea complex.

At the Department of Geotechnics of the Faculty of Civil Engineering of the Slovak Technical University in Bratislava, special attention was paid to the problems of flooded environments, particularly between 1999 and 2001, during the project of the Scientific Grant Agency of the Ministry of Education of the Slovak Republic, titled "Geotechnical problems of flooded environments". The most important findings and recommendations are summarized in the book publication and in several publications and presentations from the department at scientific and professional conferences here and abroad [1].

Development of Flood Levels and Flows

Time developments of water levels and flows during some floods in Bratislava are shown in Figure 1. In 1954, several dams broke in Hungary, while in 1965 the dams in our country near Cicov and near Patinci also broke. In 1991, the Gabčíkovo water project was practically completed, but it was not yet put into operation. In 2002, the maximum water level was at the maximum recorded in 1954. Figure 1 also shows the development of water levels in the Danube during the flood in 2024. The figure provides information about the surface level of the area in Bratislava near the Slovak National Gallery and near the underground garages of the Carlton Hotel (approximately 138 m above sea level) and the level at the thousand-year water level (140 m above sea level). Flood conditions in the Danube with different courses usually occur in the summer months.

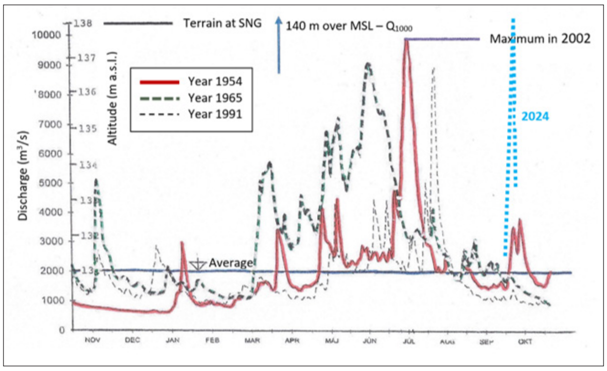

Figure 1: Development of Characteristic Flood Flows of the Danube in Bratislava According to SHMU Documents

In Figure 2 is a photograph showing the position of the water level on the wall of the Old Town Hall in Bratislava in February 1850, when approximately a thousand year flood occurred in the Danube. Approximately the same surface level also occurs at the site of the underground garages in front of the Carlton Hotel. At that time, there were no anti-flood measures in Bratislava, so water was present in a large part of the old city. Currently, Bratislava has built permanent embankment walls with sealed subsoil in the lowest locations and has mobile fences at its disposal, which can be used to protect the city from thousand year floods.

More detailed information on the development of flood levels in various countries of the world in 2023 is not available. Probably the most devastating consequences were the floods in China, where the highest levels reached up to 5 m above the ground surface (in Beijing). At such levels, maximum flood levels have also occurred in other world cities. Significantly higher levels occurred near broken dams and leves. Large cities have massive underground sewage systems, which during intense rainfall can bring considerable amounts of water to the surface.

Figure 2: A Sign on the Wall of the Old Town Hall in Bratislava, which Indicates the Maximum Water Level in the City During the Flood in 1850 (Photo by Hulla).

Stability of Structures During Floods

For underground structures and underground parts of construction objects during floods, it is appropriate to analyze three basic stages of construction: the creation of a construction pit, the construction of underground parts of objects, and the operation of objects.

Construction Pits

The construction pit and the initial stages of the construction of underground garages in Bratislava, in front of the Carlton Hotel, are captured by Figure 3. Up to a depth of 3 m, the stability of the almost vertical walls above the groundwater level was ensured by steel mesh and shotcrete. The vertical retaining and sealing walls were created from reinforced concrete prefabs, which were inserted into the self-hardening suspension up to the surface of the impermeable subsoil. Gaps with a reinforced suspension were left between the prefabs [2]. The stability of the walls was ensured in the first level by anchoring, in the second level by steel spacers [3]. Drainage of the pit was ensured by drilled wells inside the pit; according to the project, the amount of water was expected to be 5.3 l/s, but in reality, only around 3 l/s was pumped for a long time [4].

Figure 3: Construction Pit for Underground Garages in Bratislava, in Front of Carlton Hotel (Photo by Hulla)

During the entire construction period of the underground garages, the groundwater level did not rise above the upper level of the underground retaining and sealing walls. Further comments related to the occurrence of floods will therefore be hypothetical. If there had been a flood with a level above the surface of the territory during the creation of shoring and sealing elements, the work would be interrupted. Similarly, the construction pit would be flooded with flood water from the surface even during the digging of the pit. But the most important task would be to get people to safety. Problems would arise only if the flood water were to fall from the surface of the territory to the surface of the bottom of the construction pit. The subgrade of the garages would be eroded and its properties would have to be artificially improved before the foundation slab was created, or deep foundations (probably micropiles) would be used.

Construction of Underground Parts

In the event of a sudden inflow of flood water into the construction pit from the surface during the construction of the underground parts of the garages, positions with unhardened concrete would deteriorate. Violated positions would need to be removed and supplemented.

Operation of Underground Garages

Here we will only consider underground objects that are not loaded by the above-ground structure. The diagram of the garages in front of the Carlton Hotel is shown in figure 4. With closed water inlets to underground spaces, the flood level above the garage ceiling would be a stabilizing factor against buoyancy due to its load on the building. However, the garage ceiling should reliably transfer the increased water load.

The critical stage for the stability of the building would be the flood level of the groundwater at the level of the ceiling of the highest floor. The isolation of the object between its external walls and the underground walls, which ensure the stability of the construction pit, creates a sliding surface with reduced friction, so that the stability of the object against buoyancy is ensured practically only by its own weight. An increase in stability can be achieved by pumping water from the gravelly soil between the base plate and the impermeable subgrade, which reduces the overall buoyancy. For this purpose, several drilled wells were permanently left, which were used to lower the water level inside the construction pit.

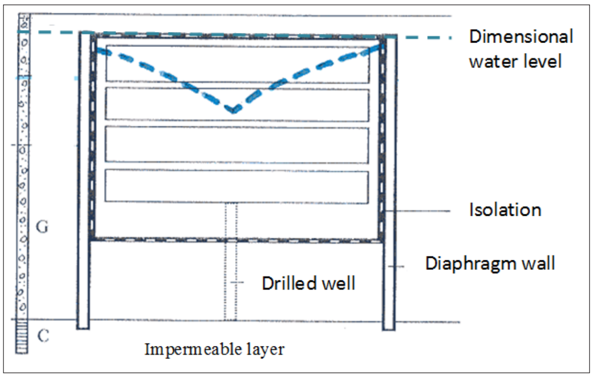

Figure 4: Scheme of the Underground Garages in Front of the Carlton Hotel in Bratislava

Failures and Protection

From the point of view of faults and their elimination, we will again distinguish between problems during the creation of construction pits and problems during the construction or operation of underground structures, respectively. underground parts of buildings. In the post, we also pay attention to flood protection measures.

Failures in Construction Pits

The basic prerequisite for trouble-free creation of construction pits is a high quality engineering geological, hydrological and hydrogeological survey, appropriate design and creation of construction pits. The hydrological prerequisites for the creation and development of flood levels are especially problematic. Flood situations in recent years show that historical knowledge of floods is not enough, and it is necessary to prepare for handling construction in extreme flood conditions, in which the water level will be above the surface of the terrain and water will flow into the constructed pits from the surface. Notes on such situations are provided in section 3.1.

In the case of pits with sealing walls tied into a natural impermeable layer, problems arise especially if the sealing walls are not deep enough. Under their lower ends, larger amounts of water can flow into the construction pits. It must be decided whether the increased inflows will be pumped out, or whether leaking areas will be located and additionally sealed, for example by injecting before the start of drainage and excavation of construction pits. If the permeable positions under the lower ends of the sealing walls are left, it is necessary to pay attention to the filtration stability of the gravelly and sandy soils under the base plate; more detailed information is provided in the paper [5]. When larger quantities of water are pumped from drilled wells, intensive hydrodynamic effects arise in their surroundings, during which sand particles can be removed from the pores of gravelly soils. Such soil then has lower shear strength and greater compressibility in the subsoil, which can adversely affect the stability of tall buildings.

Below Bratislava, the thickness of gravelly soils increases; near Cunovo, gravelly soils reach a depth of around 100 m, near Gabčíkovo up to 300 m, while the groundwater level is close to the surface of the territory. For greater depths of construction pits, it is therefore necessary to create an artificially impermeable layer under the lower ends of the sealing walls using injections. The amount of water that will flow into such construction pits is limited by the quality of the sealing elements. For the sealed construction pit of the Gabčíkovo hydroelectric power plant, the amount of pumped water was assumed in the project to be 1000 l/s; the sealing elements were created with high quality, the long-term pumped amount of water was around 250 l/s - [6].

The crawler and sealing system in construction pits must be stable. Vertical walls can be broken, for example, when the surface of the terrain in their vicinity is overloaded. Such failures require the creation of an additional spacer or anchoring system and sometimes also the sealing of the broken positions.

In the sealing elements of the construction pits in the walls and in the injected bottoms there can be failures in the form of "windows" filled with permeable gravelly soil, through which larger quantities of water flow into the construction pits. It must be decided whether such positions will be additionally sealed or left "open".

Failures During Construction and Operation

The pumping system inside the sealed space of the construction pits must ensure the stability of the gravelly soils in the foundation of the constructions under intense hydrodynamic effects, especially in the vicinity of wells and failures in the sealing elements. During the digging of construction pits, major problems will not arise when pumping is interrupted, e.g. due to failure of the pumps, or when the supply of electricity is interrupted. Inadequately loaded parts of underground structures could fail due to buoyancy during construction when the supply of electric current is interrupted. In critical stages for the stability of structural parts, it is therefore advisable to provide and connect a backup source of electricity (diesel units) to the pumping system.

During construction, faults most often occur in insulating layers, which practically do not manifest themselves during their creation in a dry environment.

After the completion of the construction of underground structures, or at a suitable stage of construction, the pumping of water from drilled wells is stopped. The groundwater level will rise very quickly and the quality of the insulation will prove very quickly.

In Figure 5, two photographs from the fourth, lowest floor of the underground garage in front of the Carlton Hotel; in the left photo, inflows from the subsoil through the working joints of the base plate were clearly visible, and locally, water inflows through the walls of the underground garage were also visible. It was not possible to repair the insulation. Therefore, the work joints in the base plate were sealed with Bevedan - Bevedol polyurethane resins. Grooves have been created near the walls, which allow the water to be drained into a collection tank with a pumping system on the lowest floor. The right photo in Figure 5 testifies to the success of the sealing procedure. Insulation faults can therefore be removed by sealing the perimeter structures of the underground parts of the buildings. Essential findings are summarized in the contribution [7].

Flood Protection Measures

Flood protection measures can be regional or local in nature [8]. Regional measures will capture the intense effects of floods in reservoirs, half-pipes, and reliably fenced surface streams. Construction objects in such protected regions do not require special stabilization measures.

Figure 5: The Lowest Floor of the Underground Garage in Front of the Carlton Hotel After the Water Pumping has been Completed and the Working Joints have been Sealed (Photo by Hulla)

If regional measures do not exist or are not reliable, the stability of each object must be ensured by local measures. For these purposes, it is possible to use piles, anchors, structural or sealing underground walls, as well as improving the properties of the subsoil by compaction, injection or other means. The basic condition is the creation of a stable building structure under the most unfavorable flood level.

The maximum flood level, which is considered already at the design stage, is also problematic. Failures of dams, dykes and other construction objects abroad during extreme floods in recent years have shown that maximum flood levels were not considered correctly in many cases in the past, or were not considered at all.

Extremely heavy precipitation in recent years and the corresponding extremely high-water levels, even several meters above the surface of the territory, were practically impossible to predict. The existence of such situations in the future cannot be ruled out. Building structures in different locations and at different stages of construction can be exposed to extreme effects that will need to be dealt with. Some of them, as hypothetical, we also mentioned in this post.

Conclusion

For flood situations in large cities, water level developments in large rivers that flow through large cities tend to be authoritative. Protective measures (walls, dams, sealing walls) secure the surrounding areas and buildings so that they can perform their normal function even during floods.

Extreme rainfall and the corresponding high flood levels, as well as dam failures in recent years, have caused problems abroad that practically did not occur in the past. Such extreme events have not yet occurred in Bratislava. However, it cannot be ruled out that this will be the case in the future as well.

Using the example of the underground garages in front of the Carlton Hotel, in the immediate vicinity of the Danube, we have outlined several hypothetical problems that could arise if extreme flood situations with water levels above the current terrain surface were to occur at various stages of their construction and operation. We also stated how such problems could be solved during the creation of retaining and sealing structures, during the excavation of a construction pit, during the construction and operation of underground garages.

We highlighted the possibility of the existence of leaky spots, especially near the surface of the natural waterproof layer into which the sealing walls should be tied. If such positions are not additionally sealed, intense hydrodynamic effects can cause a deterioration of the mechanical properties of the soil under the base plate and threaten the stability of heavier structures. During construction, waterproofing failures cannot be ruled out, which will become apparent only after the pumping system for drainage of the construction pit is shut down. Faults in the insulation cannot be removed, but it is possible to seal the inflows of water through the working joints of the walls and base plate. In extreme floods, higher water levels would increase the loads and open additional pathways for water in the walls and foundation slab. Regional protection measures (such as dams, polders, and dykes) or local measures for each building object (piles, walls, anchors, improvement of soil properties) are available for the protection of construction objects from floods. Given the potential for extreme flood events that could occur in the future, the problem of the cost of additional protective measures (such as dams around construction pits) and the cost of damage that will occur in the case of an unprotected object must be solved.

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