CONSTRUCTION OF UNDERGROUND STRUCTURES IN URBAN AREAS

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ABSTRACT:

The aim of this paper is to emphasize the significance of underground structures in urban areas by exploring specific requirements and limitations related to their planning, construction, and utilization in comparison to structures outside urban areas. The paper provides insight into various methods of constructing underground facilities through an analysis of the advantages and disadvantages of individual methods. Using practical examples, it highlights potential issues that may arise during different phases of construction. Furthermore, the research focuses on identifying possible solutions to enhance safety. Some positive examples from practice are also presented in the paper.

KEYWORDS:

underground structures, urban areas, construction, risks in construction, construction methods, examples from practice

1 INTRODUCTION

Cities are facing increasing traffic congestion, which negatively impacts the quality of life for citizens. This has led to a noticeable growth in the number of underground structures in the last few decades. One of the main advantages of constructing underground structures in urban areas is the maximum utilization of limited space [1]. Cities are becoming denser, and surface space is becoming more expensive and less available. Therefore, the underground structures provide the possibility of creating additional space below the surface, which can be used for residential, commercial or infrastructure purposes. Underground parking spaces, subway stations, and storages are just some examples of underground facilities. Another advantage is preserving the visual identity of the city, especially for parts of the city with cultural and historical significance. By building underground structures, space is left for the possible creation of green areas on the surface, which has a positive impact on the environment.

However, the construction of underground structures in urban areas also brings a number of challenges. One of them is geotechnical - properly assessing and preparing the soil for the construction of underground structures can be a challenging process. The impact on existing buildings and infrastructure must be taken into account. When planning underground structures, it is important to keep in mind that their construction permanently changes the characteristics of the soil, which can affect the groundwater regime and the state of stress in the soil [2].

Underground structures can be divided into tunnels, where one dimension is significantly longer than the other two, and underground spaces where the length is not so emphasized in relation to width and height. Table 1 shows the application of underground structures.

The aim of the paper is to emphasize the significance of underground structures in urban areas, explore specific requirements and limitations related to their planning, construction, and utilization in comparison to underground structures outside urban areas. Additionally, the goal is to highlight and discuss potential problems that may arise during the construction process.

Table 2: Application of underground structures

Underground spaces	Tunnels
- Parking lots - Metro stations - Storages - Shopping centres - Bunkers and shelters	- Road tunnels - Railway tunnels (metros) - Water and sewer tunnels - Tunnels for power supply - Tunnels for natural gas supply - Tunnels for communication cable networks

2 SPECIFICS OF THE CONSTRUCTION OF UNDERGROUND STRUCTURES IN URBAN AREAS

When planning the underground structures, it is necessary to consider numerous factors. This is especially important when planning construction in urban areas, as it usually takes place in the immediate vicinity of other buildings that may be of cultural or historical significance.

Considering the fact that the excavation is most often carried out directly next to or beneath other buildings, it is necessary to secure the excavation in order to prevent settling of those buildings. These settlements are often not uniform, especially when the excavation is carried out only under a certain part of the existing building. Often, these buildings were not originally designed to withstand such stresses, so it is necessary to make a plan for their protection [3]. This can be achieved by installing retaining walls. In addition, it is important to take into account the impact on the existing infrastructure during construction, such as water and electrical installations, in order to prevent any damage.

The dimensions of the building, characteristics of the soil, level of groundwater and the method of soil excavation play a significant role in the stability of the structure [4]. For example, building in rock is usually easier to control deformations and groundwater levels compared to building in soft soil [5]. In urban areas, where the instability of the structure can cause serious consequences, special attention is paid to these factors. The stability of underground structures requires constant monitoring during construction and usage. This implies the implementation of a system for monitoring displacement and deformations of underground structures. Because of these risks, it is necessary to collect detailed information about the geological conditions of the soil [6].

The presence of groundwater can significantly affect the process of building underground structures. Groundwater can cause excavation instability and soil erosion, which can potentially lead to damage to adjacent structures [2]. To prevent this, it is necessary to install water drainage systems. Additionally, great attention must be paid to the suffusion potential of the soil. Specifically, during the construction and exploitation of the building, the pumping of percolated water can cause soil settling, and thus a negative impact on neighbouring buildings.

The construction of underground structures in urban areas significantly affects the environment and the daily life of residents. While the underground structures themselves have a positive impact on the environment, construction activities often generate noise and vibrations, which can disturb residents in the area. The dust released during construction activities can be harmful to human health and the environment. Additionally, construction may require the temporary closure or slowdown of roads, leading to traffic congestion and increased travel times. To mitigate these negative impacts, it is important to implement appropriate measures for noise, dust and vibration control.

Often, the final decision on underground construction is made on the basis of an economic analysis. Although the initial costs of underground construction can be high, in the long run, such facilities often prove to be more economical than surface facilities of the same purpose. In particular, lower total costs during the lifetime of the facility (life cycle cost) should be emphasized, because underground structures usually require fewer regular repairs and renovations, which makes them more economical in the long term. During the economic analysis, it is important to take into account the impact on the environment in addition to the construction costs and the costs incurred during usage [7].

When designing, special attention must be paid to fire protection, escape routes, and the implementation of an efficient ventilation system to ensure the safety of the facility and people [8]. Table 2 shows some of the differences when designing in urban and non-urban areas.

Table 2: Differences in designing underground structures in urban areas and outside urban areas

Underground structures in urban areas	Underground structures outside urban areas
- Detailed geotechnical investigations are necessary to ensure soil stability during construction - Noise, vibration and dust control during construction - Preservation of existing water and electrical installations - Plans to secure existing buildings from settling and damage - Initial costs may be higher due to land prices and geotechnical investigations	- Soil stability is also important, but there is typically less emphasis on geotechnical investigations - Less concern about noise, vibrations, and dust during construction - Lower risk of damage to existing installations - Reduced need for securing existing buildings - Lower initial land and investigation costs, but possibly higher transportation costs

3 CONSTRUCTION METHODS

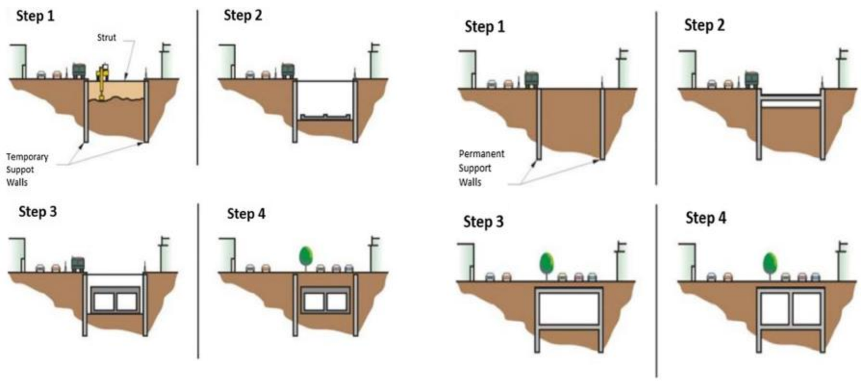
The choice of the construction method depends on the groundwater level, water permeability of the geotechnical environment, the dimensions of the underground structure, the position, and characteristics of neighbouring buildings [9, 10]. Some of the most commonly used methods for underground construction include construction in open excavation (cut and cover), excavation by tunnel boring machines (TBM), New Austrian Tunnelling Method (NATM), excavation by drilling and blasting.

The cut and cover method is often used for the construction of underground garages, metro stations and drainage channels. Open pit construction involves digging a trench on the surface of the terrain, placing solid retaining walls around the excavated area, and then placing an underground structure within that space, after which the upper structure is placed on the retaining walls and the excavated area is filled in to create a functional surface. This method is used in shallow excavations [11]. It is often used in urban areas, because it can be economically more profitable than other methods for excavation depths of up to 15 m [12, 13] and for shorter tunnels [14]. Still, it is not uncommon to witness cut and cover tunnels as deep as 20 or 30 m. *As a perhaps more specific determinant, it is also pointed out that if the overburden above the tunnel opening is less than or equal to twice the equivalent diameter of the tunnel, the advantage will probably be given to cut and cover method in comparison to one of the tunnel excavation methods.* This method is also often chosen for its potential safety advantages compared to other construction methods [14].

The disadvantage of this method is reflected in the need to temporarily stop and detour traffic and other surface activities in the area, and creation of significant noise and vibrations [12, 15]. There are several variations of this method, including the bottom-up method and the top-down method.

In the bottom-up method, a pit is first excavated on the surface, then retaining walls are placed around the pit and finally the upper structure is built (Figure 1a). This method is often used when geological conditions are favourable and do not require additional soil stabilization. Sometimes this approach is more difficult to perform due to the need to stop traffic for a while, which can be a problem in urban areas [13].

On the other hand, the top-down method involves building the upper structure directly on the surface, and then gradually excavating the soil below it (Figure 1b). This method is frequently conditioned by the need for ensuring stability in excavations for foundation pits and adjacent buildings, with the additional benefit of minimizing traffic interruption time.



a) bottom-up method b) top-down method

Figure 10: Phases of the cut and cover method [16]

TBMs are often used for the construction of deep and long tunnels. These machines allow the construction of tunnels with large diameters up to about 14 meters [11], where the cross-section of the tunnel is usually circular or semi-circular [9]. The use of TBMs results in minimal soil vibrations and does not disrupt surface traffic, a critical consideration in densely populated urban areas.

Various types of full profile excavation machines are used depending on the soil type and geological conditions. For example, Earth Pressure Balance (EPB) TBM is used for excavation of cohesive soil, while Slurry TBM is used for excavation of non-cohesive soil [9]. In addition to these, there are many other types of machines.

The principle of operation of these machines is based on gradual drilling and ejection of excavated material. Basic components include a drill, a conveyor belt for material transport, and building system. The TBM moves slowly, drilling into the ground and creating a tunnel, while the material is ejected to the surface.

NATM, also known as the Sequential Excavation Method (SEM), was developed in Austria during the 1960s by Pacher and Rabcewicz [17]. This method is based on the idea of stabilizing the tunnel itself using the surrounding rock mass. The procedure involves carefully digging tunnels in smaller sections, which are immediately reinforced with a layer of shotcrete and the installation of anchors or steel ribs [13]. This method can be applied in various geological conditions, making it commonly used in different tunnel construction projects. Another advantage of this method is its applicability in the construction of shallow tunnels. Rabcewicz [17] accentuated the importance of employing a thin shotcrete layer for lining, ensuring the prompt closure of the tunnel ring, and conducting systematic monitoring of deformations within the context of NATM.

The disadvantage of this method is that it requires highly trained workers for implementation and monitoring. Although this method was most often applied in urban areas, the analysis [18] showed that the greatest number of tunnel collapses occurred with this method.

Table 3: Advantages and disadvantages of different methods of building underground structures in urban areas

Methods	Advantages	Disadvantages
Cut and cover	- Cost-effective and practical for shallow tunnels (up to 15 m) - Suitable for constructing underground spaces - Safer compared to other methods	- Not suitable for deep excavation - Generates significant noise, dust and vibrations - Disruption of traffic
TMB	- Ideal for building deep and long tunnels - Low noise is generated - Low traffic disruption - Capability to construct large-diameter tunnels - Applicable in various geological conditions	- Fixed circular geometry - High initial costs
Drill and blast	- Applicable in diverse geological conditions - Allows for arbitrary tunnel cross-sections	- Generates significant noise and dust - Damage to the environment can be large
NATM	- Applicable in various geological conditions - Suitable for tunnelling in complex urban environments - Allows for arbitrary tunnel cross-sections	- Requires a highly trained workforce for implementation and monitoring

Excavation by drilling and blasting is another widely used method for constructing underground structures in urban areas. The advantage of this method is that an arbitrary cross-section can be achieved, unlike TBM, where it is either impossible or not economical [19]. Also, this method is particularly effective in very hard rocks where using other excavation techniques might be difficult or expensive. In addition, drill and blast method can be more economical for shorter tunnels compared to other methods [13]. However, the detonation of explosives creates noise and dust, which can be unpleasant for residents of urban area. Moreover, there is a risk of damage to surrounding buildings and infrastructure if adequate protection measures are not applied.

Table 3 shows the advantages and disadvantages of each mentioned method.

4 EXAMPLES FROM PRACTICE

The construction of underground facilities has a long history that goes back several thousand years. Archaeological research and historical records have established that the construction of underground structures was known in ancient Rome. The construction of underground structures accelerated from 1612 by the invention of gunpowder. During the second half of the 19th and the first half of the 20th century, due to the expansion of railway traffic, a large number of tunnels were built in Europe and America. By 1913, nine world cities had their own metro system [20].

The London Underground, one of the oldest and most extensive underground systems in the world, opened its first line in 1863, which stretched over a length of 6 km. Today, this subway system covers almost the entire territory of London with an impressive total length of 402 km [20]. Among the more challenging projects in the development of underground systems, Crossrail in London stands out. This project lasted more than 10 years and included the construction of a subway system that runs through central London, including many underground stations and tunnel sections. The total length of these tunnels is an impressive 118 km [21].

Apart from transportation purposes, the underground space is used for various commercial purposes. In urban areas, these spaces are often used for shopping centres, underground garages, restaurants or bars. In this way, it contributes to the functionality and aesthetics of cities.

Although there are many examples of successfully constructed facilities, challenges related to the construction still exist. Therefore, it is necessary to carefully plan and analyse risks, often relying on experiences from previous projects and learning from mistakes that occurred during construction. Given the different characteristics of each underground structure, it is crucial to consider all possible factors that may affect the stability and safety of both people and structures.

Problems with underground structures can be divided into those that occur during construction and those that occur after construction. Some of the problems that arise during construction can lead to demolition of the building. The analysis [18] shows that most tunnel collapses occur during the construction process itself, as much as 92% of the total number of incidents. [22] analysed tunnel collapses based on the construction method. From the analysis of 321 samples, it is evident that the largest number of accidents occurred with the application of the New Austrian Tunnel Method, reaching 48%. Meanwhile, collapse rates for the TBM, drill and blast and cut and cover method stand at 25%, 12%, and 3%, respectively. Working manually seems to be the safest, with only 1,5%

of all collapses. Factors affecting safety can be divided into several categories depending on their nature. These factors are shown in Table 4.

Table 4: Factors affecting safety during and after the construction of underground structures

	During construction	After construction
Natural environment	- Excavation speed - Excavation dimensions - Cross-sectional shape (for tunnels) - Excavation depth - Poor design of protective walls - Distance of neighbouring buildings	- Natural disasters (earthquake, tornado, floods) - Fire - Increasing the level of underground water - Soil erosion - Lack of maintenance during exploitation - Change in geological conditions - Improper use of the facility - Changing the object's purpose
Geological factors	- The appearance of water in the excavation - Change in bearing capacity of rocks - Ignorance of rock characteristics - The occurrence of soil instability	
Design and construction	- Precision of geological research - Excavation method - Stabilization of geological layers - Drainage - Ability of the workforce	
Organization and management	- Monitoring - Supervision on the construction site	

During construction works, contractors often encounter unforeseen challenges that require quick interventions to solve problems.

One such example is the construction of underground parking lot in Poland [3]. Construction took place in complex geotechnical conditions. Up to a depth of 1,5 m there was an anthropogenic layer, below that layer there was medium sands with a free water table, and deeper layers of hard clays. The height of the sheet piles varied from 8 to 10 m, depending on geological profiles. After the excavation was completed at the intended depth of 4,5 m, the contractor unexpectedly expanded the excavation for the foundation plate of a crane. This unplanned excavation led to large horizontal displacements of the sheet pile wall, in some places up to 0,5 m. Which further led to problems with the stability of the neighbouring buildings.

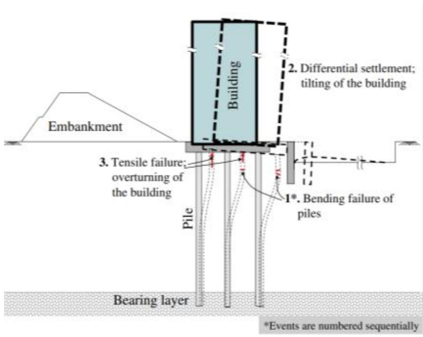
To mitigate the risk of ongoing horizontal displacement, a decision was made to construct an additional temporary support, employing steel pipe struts against combined piles driven inside the excavation (Figure 2). Afterward, work on the foundation slab continued safely.

The example of construction of an underground garage in Shanghai clearly shows the importance of adequate protection measures for neighbouring buildings. Unfortunately, the poor organization of the construction site in this case led to the overturning of the 13-story residential building number 7 (Figure 3a), located right next to the excavation. The incident occurred in 2009. The foundation of building number 7 consisted of 114 piles, which were supported on a bearing layer. The piles were prestressed, with an angular cross-section with a diameter of 0,4 m. Excavation was carried out on the south side of the building. The retaining wall was 0,7 m wide, additionally supported with soil nails 6.0 - 9,0 m long. The building overturned when the excavation reached a depth of 4,6 m.

Figure 2: Additional temporary support [3]

The analysis [23] using the finite element method indicates that the overturning of the building occurred after the appearance of cracks in the reinforced concrete piles (Figure 3b). The cause of this overturning was a combination of excavating the soil on one side of the building and temporarily dumping the excavated material on the opposite side of the building.

a) Overturned building number 7



b) Assumed fracture mechanism

Figure 3: Residential building number 7, Shanghai [24] and [23]

In 2004, another tunnel collapse occurred during the construction of the Nicoll Highway tunnel in Singapore. The tunnel was built using the cut and cover method. Although deformations of the diaphragms occurred during construction, exceeding the anticipated scale, further excavation continued. When the excavation reached a depth of about 30 m, the retaining walls collapsed, resulting in the complete destruction of a large part of the structure, with significant consequences for Nicoll Highway and other surrounding buildings (Figure 4).

A commission of inquiry formed by the Government of Singapore concluded that the collapse resulted from the inadequate design of the supporting walls, ineffective monitoring, and the constant pursuit of cost savings.

The preceding examples highlight the importance of considering not only final loads, but also changes in loads during the construction process. Also, we can conclude that most of the existing buildings were not designed for the loads that occurred during the excavation. In addition, we can note that the human factor plays a significant role in successful construction, including decision making on the construction site during the execution.

Figure 4: Location of collapsed tunnel and highway section [25]

One example of a successfully organized construction site is shown in [26] on the example of the construction of a residential and commercial building "Pupinova palata" located in Novi Sad. They presented the method of calculation and execution of the protective structure for a deep foundation pit and its surrounding buildings, in complex urban and geotechnical conditions with a relatively high level of groundwater. Excavation for a 9 m-deep foundation pit is planned. Based on the analysis, it was determined that the reinforced concrete diaphragms will be lowered to the marl, thus avoiding inflow of groundwater. Following the decision to perform deep diaphragms, various options for construction of bracing were analysed. A special challenge was the large width of the foundation pit, which reached as much as 36 m at the narrowest part. Three different solutions were considered.

The first one was the top-down method, which would require the production of a large number of piles with a large diameter, which would increase the cost of construction. The second options included the analysis of the excavation of the foundation pit with the parallel execution of pre-stressed anchors to ensure the stability of the diaphragm under large lateral pressures of the soil and groundwater. This option required that the investor asks for the written consent of the neighbours, which was not possible. In the end, the investor decided to implement the option of phased excavation of the foundation pit with phased expansion of the diaphragm with horizontal steel braces.

The works underground part of the building went without problems, and the measured displacements of the diaphragm were similar to the displacements obtained by calculation. Minor damage in the form of cracks in the walls and ceilings appeared on the old neighbouring buildings during the excavation, however, the level of damage was within the expected limits.

Problems with groundwater during the excavation of the construction pit were described in [27] using the example of building with two underground floors, 8,5 m deep. The work was complex because the excavation was carried out in dry gravelly soil with the excavation level below the level of groundwater, and in the immediate vicinity of neighbouring buildings.

The construction pit is protected by jet grouting of columns, which are connected by header beams. The first problems occurred during the excavation on the northern side of the construction pit, when the material collapsed and water entered the pit. This led to a weakening of the soil between the neighbouring buildings and the pit. In order to solve this problem, it was necessary to strengthen the protective structure. This was achieved by injecting the jetting material at the joints with the existing protective structure. In addition, in order to properly strengthen the structure, it was necessary to equalize the pressures on both sides of the construction pit. Because of this, the pumping of water was stopped, which resulted in the controlled sinking of the construction pit (Figure 5a). After the strengthening of the protective structure was completed, water pumping and excavation continued.

Despite the additional reinforcement, the problems with waterproofing and stability of the vertical protective elements were not completely solved. During further excavation, water continued to seep in intermittently. Therefore, mini talps were installed, which were sufficient to complete the construction work. (Figure 5b).

a) Controlled submersion of the pit

b) Application of mini piles to prevent water infiltration

Figure 5: Construction pit in different excavation phases [27]

5 CONCLUSION

Underground construction requires special attention when it takes place in dense urban areas, where it often needs to be harmonized with existing buildings. Underground facilities provide the opportunity to create additional space below the surface, which can be used for residential, commercial or infrastructure purposes. When planning these constructions, it is necessary to carefully consider all factors that can impact the stability and safety of people and neighbouring buildings.

When choosing a construction method, it is necessary to consider all options in order to achieve the optimal way of execution, taking into account the time period during which traffic will be restricted, as well as the impact on surrounding buildings and the environment in terms of vibrations and noise. Each of the analysed methods has its advantages and disadvantages when it comes to implementation in urban areas. Therefore, it is essential to choose the method that best meets the specified requirements. Proper consideration of geotechnical conditions, soil stabilization and risk management are key factors for achieving successful results.

Safety measures during underground construction have advanced significantly, however working in complex conditions is a challenging task without a standard solution. Each individual case requires detailed geotechnical investigation and innovative design solutions. The examples given in this paper emphasize that the challenges during construction and the potential risks after project completion should not be overlooked. Each phase, from design to construction, must be carefully analysed in order to reduce risks and ensure the stability and safety of both people and buildings.

Through all the mentioned aspects, it is clear that underground construction in urban areas requires a high level of expertise, planning and management. Continuous learning from previous mistakes and application of acquired knowledge is key to improving the safety and quality of these structures. The success of the specific project requires the maximum involvement of all participants, utilizing empiricism, analytics, and monitoring in all phases of project implementation and utilization.

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