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# The Analysis of Support Systems of Underground Stormwater Basin Using a Multi-Criteria Analysis and Modeling

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## ABSTRACT

This paper illustrates the importance of integrating buried stormwater ponds into underground development plans using a multi-criteria analysis and modeling for the selection of support in urban underground constructions, applied to the case study of buried stormwater ponds. This study underlines the importance of careful planning and the use of the technique for order of preference by similarity to ideal solution (TOPSIS) in the selection of support for underground stormwater basins in urban environments. The TOPSIS method led to the selection of diaphragm walls as the optimum solution, illustrating its effectiveness in evaluating alternatives based on a variety of criteria. diaphragm wall modeling using robot structural analysis (RSA) software validated this choice and accurately predicted the structure's behavior, underlining the importance of numerical tools in engineering decision-making. The analysis of wall displacements, carried out using these tools, confirmed their compliance with standards, validating the choice of cast walls and highlighting the need for continuous monitoring to guarantee the stability of the structures.

**Keywords:** cast walls, RSA modeling, underground basins, underground planning, TOPSIS.

## INTRODUCTION

Accelerated population growth and unprecedented urban development over the last few decades have given rise to a series of complex problems relating to the management and planning of space. Cities, in particular, are subject to increasing densification, giving rise to the problems with infrastructure, mobility, housing, and the environment. This situation is particularly striking in Morocco, where urban transformation has undergone rapid, often uncontrolled expansion, giving rise to numerous challenges. Faced with this situation, innovative solutions are being sought to make cities more sustainable, resilient, and liveable. This is the context for this article, which explores a new planning approach: underground urbanism.

Underground urban planning is an innovative concept that proposes the use of space beneath the Earth's surface for urban development. This approach offers interesting prospects for responding to the densification of urban areas by providing new development opportunities. However, its implementation and adoption are complex processes requiring in-depth reflection and precise knowledge of the specificities of the urban and underground context.

The key question is: how can underground urban planning be introduced and adopted in Morocco? To answer this question, the previous research conducted by the authors focused on three main areas. The first was to assess the potential of urban undergrounding for urban planning, through an in-depth analysis of geological, technical, and environmental aspects (Bouchaqour et al., 2022a). The second focused on the study of methods for integrating underground urban planning into the existing urban fabric. Finally, the third axis aimed to define the criteria for optimizing the choice of underground structures, taking into account budgetary, technical, environmental, and social constraints (Bouchaqour, 2023). In this article, the case study of an underground structure that meets the theory of the three predefined axes was illustrated. In this context, the authors delved into the world of underground stormwater basins as an emerging component of underground operations. These subterranean reservoirs offer an innovative response to the growing needs of cities in terms of water management, water-based recreation, and strengthening urban resilience. Their strategic use optimizes the use of the urban subsoil while meeting the essential needs of the modern urban community.

In this article, the geological challenges, economic, environmental, and social benefits, as well as urban planning considerations that shape how buried stormwater ponds can integrate harmoniously into the urban fabric, were explored. By analyzing these aspects, the authors hoped to discover how in-ground basins are becoming a key part of sustainable urban subsoil management, helping to create more resilient, efficient, and livable cities for their inhabitants.

## THE NEED TO USE URBAN UNDERGROUND SPACE

### Historical background to the use of the urban underground – setting a timeline

The use of urban underground space has a long and varied history, responding to demographic, economic, and technological needs. Motivations include protection, exploitation, and space constraints (Audi, 2016; Pan et al., 2019). Underground practices differ from country to country (Bouchaqour et al., 2022a). The first uses date back to religious purposes in India, Egypt, and Spain, and to Roman water galleries dating back 2,700 years (Guoguang et al., 2015). Underground cities already existed, as in Cappadocia, Turkey (Xie et al., 2021). In France, defensive underground chambers date back to the Middle Ages. In the 19th century, with the rise of engineering, the use of underground structures expanded (Ménard, 2022). In the 20th century, the underground was mainly used for rail transport. Today, the Paris underground is home to various networks such as water, electricity, gas, sewage, and telecommunications, with building foundations occupying around 50% of underground space by the end of the 1980s (Bobylev, 2009; Labbé, 2016).

### The use of underground space

The use of urban underground space is essential to support urban development. Despite its often underestimated potential and its absence from urban development plans, the integration of this resource needs to be strengthened (Bobylev, 2009, 2016a). Underground exploitation is sometimes considered a last resort, even if historical examples exist, as it is not always taken into account in urban development plans (Audi, 2016; Mavrikos and Kaliampakos, 2021). The use of urban underground space is not limited to the lack of surface space, but also responds to the needs of energy management and environmental protection, with a growing demand for these services and innovative technical solutions proposed by engineers (Guoguang et al., 2015) .

The integration of urban underground space into urban development plans is essential for long-term urban planning, requiring authorities and planners to be aware of this dimension(Bobylev, 2016b, 2010, 2009). Economic considerations favor underground operations, offering cost advantages over surface alternatives and improving public safety by moving potentially hazardous equipment underground (Guoguang et al., 2015).

According to the International Tunnelling Association (ITA), the implementation of an underground town planning scheme relies on two key elements: the establishment of a master plan and the analysis of geological ground conditions (Audi, 2016). The use of underground space in urban environments offers a response to growing demand while preserving the compactness of cities or creating new functional spaces without encroaching on the urban surface. This approach is supported by Broere (2016), highlighting several advantages, including space optimization, reduced environmental impact, road decongestion, disaster protection, and the creation of essential infrastructure.

Operations vary according to the type of underground structure. Underground public transport reduces traffic congestion, while underground hydrocarbon storage ensures a stable supply. The underground provides mechanical, thermal, acoustic, and hydraulic protection, camouflaging unsightly technical installations. While there are many advantages to exploiting urban underground space, there are also several constraints. These include the geological problems related to ground stability, high costs due to the complexity of underground works, technical challenges such as access, ventilation, and lighting, as well as potential interference with existing infrastructures, requiring careful planning (Bobylev, 2016b; Bobylev and Sterling, 2016a, 2016b). In addition, regular servicing and maintenance are essential to ensure the smooth operation of underground structures, which can entail additional costs. Gathering precise technical data on the subsoil and underground structures is often difficult and requires specific methods (Barles and Jardel, 2005; Barroca, 2019).

Finally, the concerns about comfort, safety, and social acceptability may influence the decision to adopt this approach, as citizens may have concerns in this regard. It is therefore crucial to consider these constraints when planning and implementing urban underground space projects.

## Integrating underground stormwater basins into the urban underground fabric

The concept of underground development is supported by the notion of urban efficiency, which aims to maximize the use of existing urban space to meet the multiple demands of modern society.

An underground stormwater basin is a stormwater management infrastructure that temporarily retains water during heavy rainfall to prevent flooding and sewer overflows. Located below ground, it optimizes the use of surface space. Constructed from various materials such as concrete or plastic, the choice depends on local needs and constraints. In addition to regulating flow, stormwater basins help improve water quality by allowing contaminants to settle before being released. It is an effective solution for managing stormwater while preserving urban space.

Integrating an underground stormwater basin into urban underground development plans offers several notable advantages. These basins enable efficient stormwater management, reducing the risk of flooding in dense urban areas. Moreover, by being buried, they preserve urban surface space, which can be used for other purposes, such as green spaces or buildings.

## Overview of underground stormwater basin construction

The implementation of an underground stormwater basin, while beneficial for urban stormwater management, presents several important challenges. Geotechnical soil conditions can complicate design and construction, particularly in the case of rocky or very wet soils, which can lead to waterproofing problems.

High construction costs, especially for in-ground basins, and the need for regular maintenance to avoid clogging by debris are financial constraints to be taken into account. Groundwater management is crucial, with precautions necessary where the water table is high to avoid infiltration. Accessibility for maintenance can be a challenge, as in-ground basins must allow easy access. In addition, environmental concerns arise, including the impact on wildlife during construction and the possibility of water pollution in the event of inadequate design or maintenance. Local regulations and permits add further complexity, requiring strict compliance. All in all, these challenges underline the importance of careful planning and professional execution to ensure the success of an underground stormwater pond project in an urban environment.

Certainly, the construction of buried stormwater ponds can be fraught with complications, as has been observed in real-life projects. The following are a few real-life examples taken from the literature. In New York, the city undertook a project to build buried stormwater basins to manage stormwater. However, the presence of rocky soils and high water table levels complicated construction and increased costs (Burns et al., 2005; McPhillips and Matsler, 2018).

In Australia, as part of the construction of the Melbourne Main Sewer Replacement, a large underground stormwater basin was built. However, the project faced numerous geotechnical challenges, including the management of contaminated soils and the need to work close to existing structures (Dayaratne, 2000; Walsh et al., 2005; Webber et al., 2020). Regarding regulatory constraints, the construction of an underground stormwater basin in Toronto's Amesbury Park was delayed due to complications in obtaining the necessary permits and the need to minimize the impact on the local environment, particularly the existing trees in the park (Drake et al., 2016; Johns, 2019; Kornelsen and Coulibaly, 2014).

The construction of London's "Lee Tunnel", a huge underground storm basin designed to prevent sewage from overflowing into the River Thames, encountered several challenges. The tunnel had to be dug through London's clay soil, which posed geotechnical problems (Stovin et al., 2013). In addition, the project was delayed by the complexity of obtaining the necessary permits and by environmental concerns (Yang et al., 2009). As part of Seattle's "RainWise" program, the city encourages homeowners to install stormwater ponds on their properties (Hammitt, 2010). However, implementation of this program has been complicated by the high cost of installations, the lack of space on some properties, and the need to manage a variety of regulations and permits (Gwilym et al., 2016).

In France, for the ZAC Clichy-Batignolles project in Paris, a large underground stormwater basin was built to manage stormwater (Gache et al., 2017). However, the project faced many challenges, including handling polluted soils, organizing the cohabitation of different underground works, and preserving the nearby environment (Nordmark, 2002). These examples show that although underground stormwater ponds are a valuable solution for stormwater management, their implementation can be complex as well as require careful planning and project management.

In most cases, the challenge lies in controlling wall displacement during excavation, which proves to be the main obstacle when building buried stormwater basins in urban environments. This displacement, if not properly managed, can have repercussions on neighboring infrastructures and compromise the overall integrity of the project (Falcon, 2011; Sebastian, 2013). When constructing buried stormwater ponds, various underpinning techniques may be required to stabilize the soil and prevent it from collapsing during excavation work. Table 1 summarizes the most commonly used methods.

The choice of support method depends on several factors, including soil type, excavation depth, surrounding loads, available space, time, and cost. A preliminary geotechnical study is generally required to help determine the most appropriate support method for a particular project.

## METHODOLOGY

### Presentation of the case study

As part of the urban development of Bouskoura, a 10000 m$^3$ retention basin is to be built. This underground reservoir is adjacent to residential buildings (Fig. 1 and 2). We are going to take a look at this specific case, which highlights the challenges associated with the construction of underground stormwater ponds in an urban environment. This example will enable to explore in concrete terms how engineering and project management techniques are applied to overcome these difficulties. In particular, it will highlight the importance of managing wall displacement during excavation, a crucial step that, if not properly managed, can have a significant impact on neighboring infrastructures and compromise the integrity of the overall project.

In addition, this case study will highlight the crucial importance of underground urban planning. In dense urban environments, the efficient use of underground space is not only a necessity but also an opportunity. Underground stormwater basins are an example of this innovative use of underground space, offering a solution for managing stormwater and reducing the risk of flooding while minimizing the impact on valuable surface spaces. By studying this case study, the complexity of these underground urban planning projects and the expertise required to bring them to fruition can be better appreciated. The technique for order of preference by similarity to ideal solution

**Table 1.** Most commonly used underpinning methods, based on bibliographic research

| Underpinning | Technique description | Preferred use |
|---|---|---|
| Moulded walls | Excavation of a trench stabilized by a retaining fluid, followed by insertion of a reinforcing cage and pouring of concrete. Mainly suitable for hard soils and confined urban areas (Puller, 2003) | Hard soils, tight urban spaces |
| Berliner walls | Spaced steel beams with wood or concrete lining installed as excavation proceeds. Commonly used in cohesive, economical soils (Kolymbas, 2005) | Coherent soils |
| Micropiles | Small reinforced concrete pillars drilled into the ground to support existing structures or stabilize the soil around the excavation (Dasgupta, 2021) | Support of existing structures, restricted areas |
| Nailed walls | Ground reinforcement with steel bars (nails) anchored with shotcrete. Often used on sloping or unstable ground (Olarewaju, 2010) | Sloping, unstable ground |
| Sheet-pile walls | Interlocking steel sections (sheet piles) are driven into the ground to form a continuous wall. Practical for temporary or permanent construction in soft or loose soils (Ouyang et al., 2020) | Soft soils, temporary or permanent constructions |

**Fig. 1.** In-ground basin adjoining

**Fig. 2.** Underground basin site

(TOPSIS) was used to select the most suitable support method. The procedure for applying this method was explained below.

## Presentation, process, and application of the TOPSIS method to the case study

The TOPSIS method, which stands for Technique for Order of Preference by Similarity to Ideal Solution, is a multi-criteria decision support technique. It was first developed by Hwang and Yoon in 1981. This method aims to determine the best alternative among a set of choices based on multiple criteria. In 1981, Hwang et al. defined TOPSIS as a multi-criteria evaluation technique that selects the option closest to the perfect solution and furthest from the least favorable solution (Hwang et al., 1981). In the same vein, Behzadian et al. developed TOPSIS as a multi-criteria evaluation approach that identifies the best solution by reducing the Euclidean distance to the positive ideal solution while increasing the distance to the negative ideal solution (Behzadian et al., 2012). Similarly, Yang and Hung describe TOPSIS as a multi-criteria decision analysis technique that orders different options according to their similarity to a perfect solution (Yang and Hung, 2007). It is important to note that these definitions vary slightly according to the authors' interpretations (Elhachmi et al., 2020; Gumus, 2009; Lima and Carpinetti, 2016; Méndez et al., 2009; Méndez and Galván, 2007; Seçme et al., 2009; Yezza, 2017; Zolfani et al., 2012), but all present TOPSIS as a technique for ranking alternatives according to their closeness to an ideal solution, taking into account several criteria at once. The TOPSIS application process is described in Table 2.

The process described in Table 2 is initiated by applying its steps sequentially. After carrying out literature searches and consulting several experts in the field, the method was narrowed down based on four criteria, namely strength, installation and placement, speed of execution, and cost. The possible alternatives adapted to this case study include cast walls, Berliner walls, micropiles, nailed walls, and sheet-pile walls. Once this step has been completed, the evaluation matrix (Table 3) was created, where each criterion corresponding to each alternative is weighted in order of importance. The weighting values and their meanings are defined by Hwang, Yang, and Hung (Bennis and Bahi, 2016; ElHachmi, 2010; Yang and Hung, 2007). It was then necessary to normalize the judgment matrix (Table 4). Each matrix element was divided by the root of the sum of the squares in each column. In practical terms, for column j, each element of the normalized matrix aij is equal to (1):

$$aij = \frac{xij}{\sqrt{\sum_i (xij)^2}} \tag{1}$$

where: $xij$ is the element of the judgment matrix.

Assigning weights to the criteria in the TOPSIS method is a crucial step, as it reflects the relative importance of the criteria in the decision-making process. This approach relies on the judgment of the decision-makers or experts involved in the decision-making process. They assign weights to the criteria according to their perception of their

**Table 2.** TOPSIS application process

| Step | Description |
|---|---|
| 1 | Define criteria and alternatives |
| 2 | Create an evaluation matrix: each row represents an alternative, each column a criterion |
| 3 | Normalize the matrix to equalize criterion values |
| 4 | Assign weights to the criteria to reflect their relative importance |
| 5 | Calculate the positive and negative ideal solution for each criterion |
| 6 | Measure the distance between each alternative and the ideal solutions |
| 7 | Calculate the proximity score for each alternative, determining the best option |

**Table 3.** Judgment matrix-Bouskoura buried basin

| Underpinning | Strength | Installation and placement | Speed of execution | Cost |
|---|---|---|---|---|
| Cast walls | 8 | 6 | 8 | 6 |
| Berliner walls | 4 | 4 | 8 | 8 |
| Micropiles | 6 | 4 | 4 | 4 |
| Nailed walls | 7 | 5 | 5 | 6 |
| Sheet-pile walls | 6 | 5 | 6 | 8 |

**Table 4.** Normalization of the judgment matrix-Bouskoura underground reservoir

| Underpinning | Strength | Installation and placement | Speed of execution | Cost |
|---|---|---|---|---|
| Cast walls | 0.564 | 0.552 | 0.559 | 0.408 |
| Berliner walls | 0.282 | 0.368 | 0.559 | 0.544 |
| Micropiles | 0.423 | 0.368 | 0.279 | 0.272 |
| Nailed walls | 0.494 | 0.460 | 0.349 | 0.408 |
| Sheet-pile walls | 0.423 | 0.460 | 0419 | 0.544 |

importance. It should be noted that a stated preference analysis (or Analytic Hierarchy Process, AHP) was used in previous studies to weigh each criterion (Bouchaqour et al., 2022b; Mariame Bouchaqour, 2023). It involves collecting information from decision-makers on their relative preferences between criteria and using this data to calculate the weights of the criteria mathematically. Weights were 0.4; 0.25;0.1; and 0.25 for strength, installation and placement, speed of execution, and cost, respectively. The results of this step are shown in Table 5. When it comes to calculating ideal solutions, there are two types of ideal solutions in the TOPSIS method: the positive ideal solution ($Ei+$) and the negative ideal solution ($Ei-$). $Ei+$ is obtained by selecting the maximum value for each criterion, while $Ei-$ is obtained by selecting the minimum value for each criterion. For each alternative, the proximity to the positive ideal solution ($Ei+$) and the proximity to the negative ideal solution ($Ei-$) was calculated. Proximity is usually calculated using a distance measure, such as Euclidean distance or Manhattan distance. In fact, the calculation of vector $E+$ represents the distance between each option and the optimal solution $A+$, and the calculation of vector $E-$ represents the distance between each option and the least favorable solution A-, as presented in the following formulas 2 and 3:

$$E+i=\sqrt{\sum_{j=1}^{m}(Aj(+)-aij)^2} \quad (2)$$

$$E\ -i=\sqrt{\sum_{j=1}^{m}(Aj(-)-aij)^2} \quad (3)$$

The TOPSIS score for each alternative is obtained by dividing the $Ei$-value by the sum $Ei$-+ $Ei+$, as mentioned in the formula (4):

$$Si^{*}=\frac{Ei-}{Ei-+Ei+} \quad (4)$$

Alternatives are ranked according to their TOPSIS score. The higher the score, the better the alternative (Table. 6). A careful analysis of the information presented in Table 6 reveals that the use of diaphragm walls is the closest to the ideal solution for the specific conditions required to build a stormwater basin in an urban environment. However, this initial conclusion requires further exploration through numerical modeling. This modeling aims to decipher more precisely the behavior of cast walls, focusing particularly on their influence on the overall stability of the structure. In this context, the use of numerical simulation software such as RSA (Robot Structural Analysis) is essential. The purpose of this advanced modeling is not only to validate the conclusions deduced from Table 6, but also to provide more detailed information on the potential performance of cast walls in the specific context of this buried storm basin project

## Sounding and geological stratigraphy of the study site

In addition to the numerical modeling of these walls, a test borehole is necessary before starting to build them. The reinforced concrete diaphragm wall consists of a series of vertical reinforced concrete panels, cast into the ground from the

**Table 5.** The weighting of the judgment matrix-Bouskoura buried reservoir

| Underpinning | Strength | Installation and placement | Speed of execution | Cost |
|---|---|---|---|---|
| Cast walls | 0.226 | 0.138 | 0.056 | 0.102 |
| Berliner walls | 0.113 | 0.092 | 0.056 | 0.136 |
| Micropiles | 0.169 | 0.092 | 0.028 | 0.068 |
| Nailed walls | 0.197 | 0.115 | 0.035 | 0.102 |
| Sheet-pile walls | 0.169 | 0.115 | 0.042 | 0.136 |

**Table. 6** Calculation of the difference between the ideal solutions Ei+ and Ei- and the proximity factor-Bouskoura underground basin

| Underpinning | Ei+ | Ei- | Si* | Final ranking |
|---|---|---|---|---|
| Cast walls | 0.003 | 0.015 | 0.817 | 1 |
| Berliner walls | 0.017 | 0.003 | 0.143 | 5 |
| Micropiles | 0.004 | 0.010 | 0.715 | 3 |
| Nailed walls | 0.003 | 0.009 | 0.753 | 2 |
| Sheet-pile walls | 0.009 | 0.004 | 0.314 | 4 |

surface. It not only serves as a retaining wall but also plays a load-bearing role. The importance of test drilling lies in its ability to determine the method used to drill the cast wall, assess wall stability, and obtain a lithological profile of the various soil layers crossed by the borehole.

In addition, this test provides valuable information on the pace and duration of the project, helps define the soil on which the veil – or cast wall – will rest, and helps identify any problems encountered during drilling. It also provides an opportunity to assess the condition and capacity of the equipment used to install the diaphragm wall. Table 7 summarizes the depth and nature of the geological formations crossed (Figure 3) by the borehole. Given the poor quality of altered tuffs, sands, and shales encountered along the borehole, the use of bentonite-based drilling mud, such as Bentonil or equivalent, is necessary to ensure the stability of the borehole walls.

This bentonite mud plays a crucial role in maintaining the walls, suspending sand particles, and stopping groundwater infiltration into the borehole. The mud is prepared from Bentonil or similar bentonite and clean water, using an IPC turbo-mixer operating at 1,500 rpm. It is then stored in a metal tank before being transported to the drilling site. This approach ensures optimum drilling stability and promotes efficient, safe project execution. As a result, the condition of the borehole is satisfactory and the walls are relatively stable, making it easier to carry out the drilling work with the bentonite mud. To guarantee the integrity of the structure, the borehole must not be left open for more than one hour before work begins. In other words, once the borehole has been completed, it must be quickly concreted.

**Table 7.** Work site stratigraphy

| Depth | Nature of geological formations |
|---|---|
| 0 to 1 m | Whitish tuffs |
| 1 to 2.5 m | Sandy tuffs |
| 2.5 to 7.20 m | Fine sand |
| 7.20 to 10.20 m | Altered schists |

## RESULTS

As deduced from the application of the TOPSIS method, it is advisable to install diaphragm walls to provide both support and bearing capacity. This section presents the stability calculation for the Safaa project reservoir in Bouskoura and describes the strength of its structure. The basin is rectangular, 66 m long by 44 m wide, with an average depth of 4.34 m, and a 10.90×12.5 m drop at the pumping station (Figure 4). The enclosure comprises 134 cast walls 2.50 m wide, 0.40 m thick, and 9 m deep (Figure 5).The invert is 25 cm thick and the roof is 20 cm thick, laid on 50 × 30 cm transverse beams spaced 4.53 m apart and supported by 30×30 cm posts 4.52 m apart (Figure 4). A 0.25 m layer of topsoil is placed on top of the buried basin, to be used for sports fields. In addition, the water depth is encountered at around 3 m/TN (Figures 5 and 6), making it necessary to lower the water table to allow the access to the flooded excavation. Feedback is a valuable resource offering detailed lessons, as it enables engineers to understand the actual behavior of retaining structures by observing the movements caused in their immediate environment (Nejjar, 2019). Databases collecting wall deformations and ground subsidence are therefore essential to examine.

**Fig. 3.** Wooden box containing the geological formations of the borehole

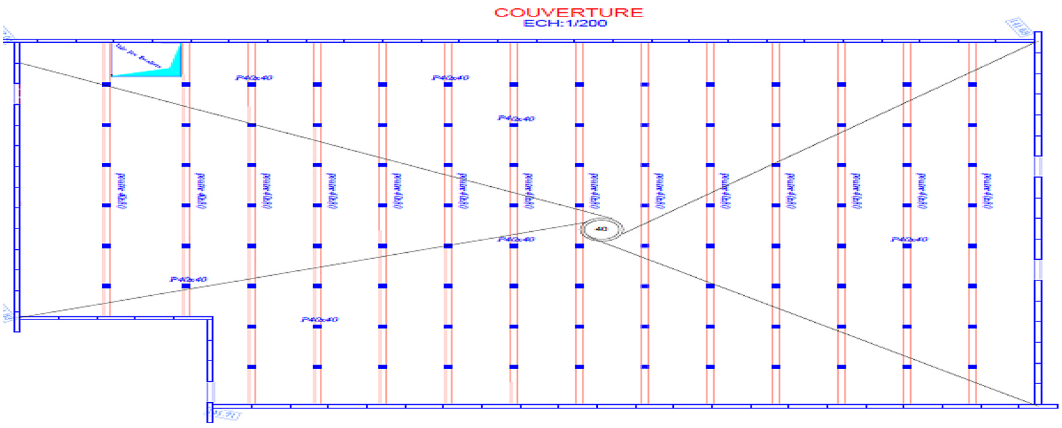


**Fig. 4.** Roof formwork plan

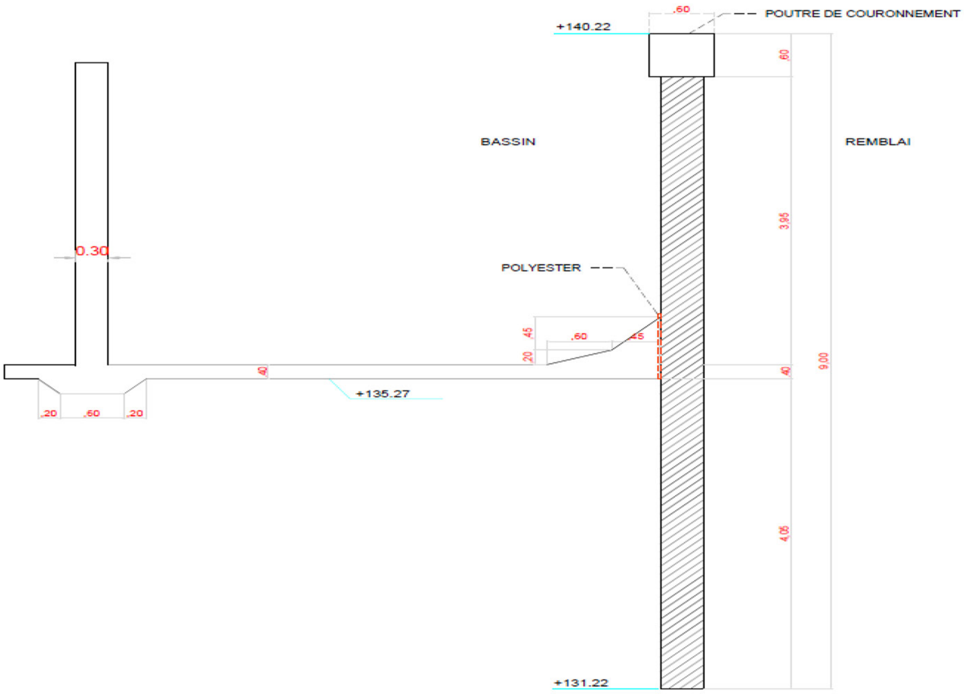


**Fig. 5.** Invert-wall junction

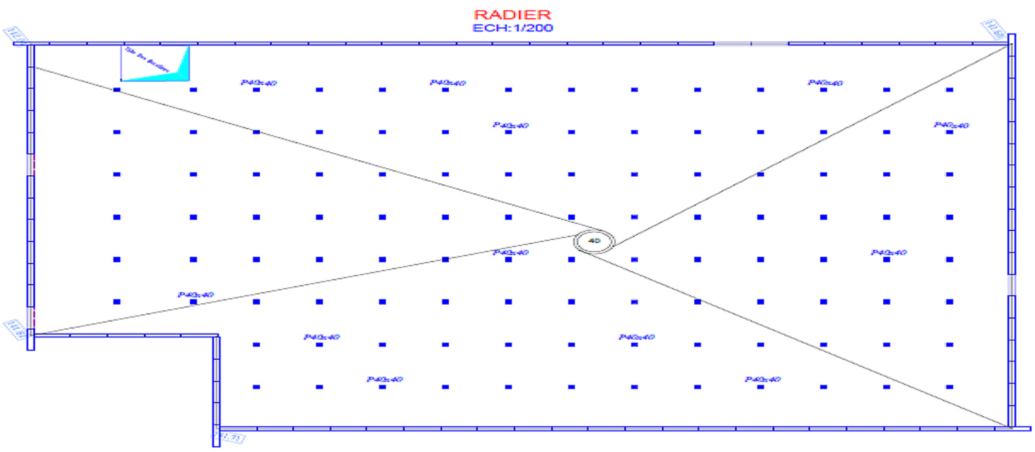


**Fig. 6.** Plan of inverted formwork

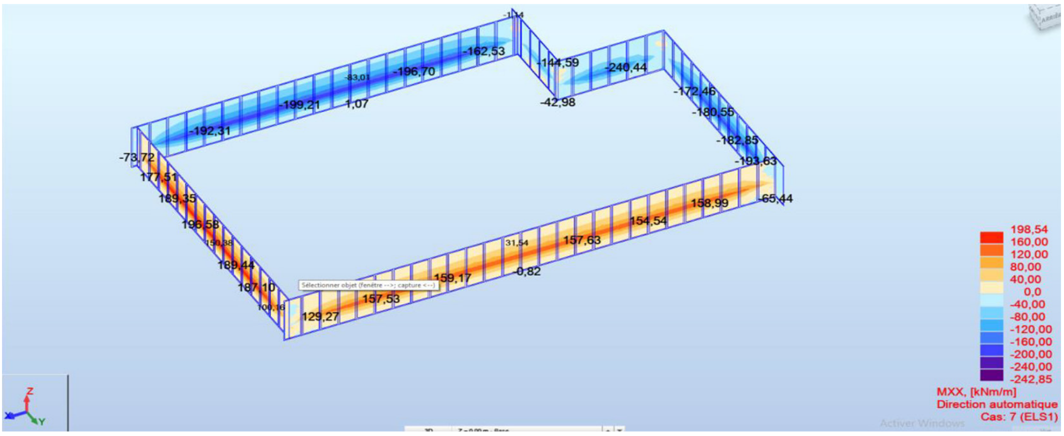

**Fig. 7.** Mapping of MXX moments at ELS wall level

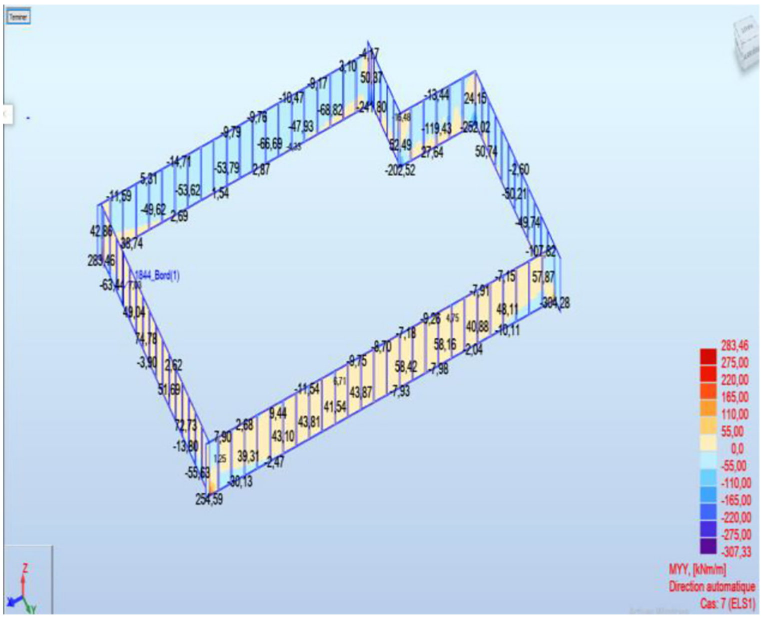

**Fig. 8.** Mapping of MYY moments at ELS wall level

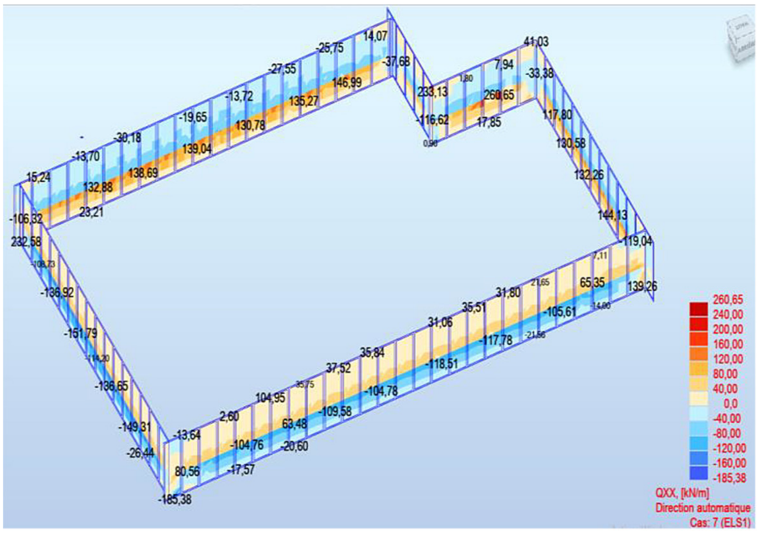

**Fig. 9.** Mapping of QXX wall reactions at ELS

In the case of excavation in rather stiff soil, such as dense clay or stratified mixed soil, the maximum wall displacement can generally be expected to be less than 0.25%, or even 0.1%, of the excavation depth. Furthermore, the ratio between subsidence and maximum displacement should be between 0.5 and 1. However, according to the French standard NF 92-282 relating to retaining structures (AFNOR, 2009), up to 1% of ELS displacements can be tolerated. Given that the maximum height is 9 m, the maximum value of tolerated displacements would be 0.09 m or 9 mm.  Calculations of wall displacements in civil engineering, particularly in the context of reinforced concrete structures, depend on the bending moments acting on the structure (Figures 7, 8, 9), at the Serviceability Limit State (SLS). Table 8 shows the maximum values for wall reactions and moments. The maximum moment applied to the wall is 244.78 kNm/m.

Using a simplified approach based on the principle of the finite element method for a wall of height H, subjected to a torsional moment M, the curvature k can be calculated by using the following formula 5.

$$k = \frac{M}{(E \times I)} \tag{5}$$

where: $M$ – the bending moment of the wall,
$E$ – the modulus of elasticity of the wall,
$I$ – will moment of inertia.

The maximum displacement δmax at the end of the wall can be estimated using relationship (6):

$$\delta max = k \times \frac{H}{2} \tag{6}$$

However, the simplified approach is used to give quick and rough estimates of displacements. For a detailed and accurate analysis of displacements in reinforced concrete structures, it is recommended to follow detailed guidelines for the analysis of reinforced concrete structures based on Eurocode 2 or ACI318 (American Concrete Institute) (ACI, 2019; Eurocode2, 1992).  One should bear in mind that this study aimed to integrate the use of underground basins into urban underground development plans. Other manuals can be consulted to detail this approach (Darwin et al., 2016; Wight and MacGregor, 2012). From the application of formulae (5) and (6) to the modeled wall characteristics, a displacement δmax=0.015 m was obtained, which is well below the permissible limit displacements.

## DISCUSSION

The integration of structures such as underground parking lots, underground stormwater basins, and road hoppers into urban underground development plans is of considerable added value. It offers a more efficient use of available space, which is often limited in dense urban areas. It also helps to reduce the footprint of structures, preserving more green space and opening public surfaces for the population.

Underground parking lots are an effective solution for managing the high demand for parking in urban areas, minimizing the visual and spatial impact of open-air parking lots. Similarly, underground stormwater basins are an effective way of managing rainwater and preventing flooding, an increasingly important issue in the face of climate change. Finally, underground road hoppers can help reduce congestion, improving urban mobility and reducing greenhouse gas emissions.

In conclusion, integrating these structures into underground urban planning contributes to a more rational and sustainable use of urban space. It is a winning strategy for cities seeking to optimize the use of their space, improve the efficiency of their infrastructures, and strengthen their resilience in the face of future environmental challenges. The use of RSA and TOPSIS, in conjunction with modeling software such as Plaxis 2D, enables a deeper understanding of different underground urban development options and more informed, robust decisions. This is a valuable

**Table 8.** Global extremes for cast walls

| Paremeter | mXX [kNm/m] | MYY [kNm/m] | MXY [kNm/m] | QXX [kN/m] | QYY [kN/m] |
|---|---|---|---|---|---|
| MAX | 244.78 | 66.37 | 98.25 | 167.09 | 198.61 |
| Panel | 1818 | 1818 | 1818 | 2039 | 1845 |
| Node | 36699 | 36699 | 1834 | 428 | 5646 |
| Case | 10 (C) | 10 (C) | 10 (C) | 7 (C) | 10 (C) |

advantage for the cities seeking to maximize the use of their underground space while meeting the needs and expectations of their citizens.

## CONCLUSIONS

This case study has highlighted the importance of careful planning and the use of decision analysis tools, such as the TOPSIS method, in the choice of support method for urban underground structures, in this case, buried stormwater basins. Application of the TOPSIS method led to the selection of diaphragm walls as the most appropriate support solution for this project. This demonstrates the effectiveness of this multi-criteria decision-support technique for evaluating various retaining alternatives based on varied and often contradictory criteria. Modeling this diaphragm wall solution using RSA software enabled us to validate this choice and accurately predict the behavior of the structure. This step demonstrated the importance of using modern numerical tools to refine and validate engineering decisions. Finally, the calculation of wall displacements, carried out using these modeling tools, revealed that these were within admissible limits. This confirms the relevance of using cast walls for this project while highlighting the importance of monitoring and controlling displacements to guarantee the stability and safety of the structure. Overall, this case study illustrates the importance of an integrated approach, combining decision-support techniques, numerical modeling, and deformability analysis, to ensure the success of underground construction projects in urban environments.

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