SELECTION CRITERIA FOR CONSTRUCTION METHODS OF MULTI-STOREY UNDERGROUND BUILDINGS

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Abstract:

Multi-storey underground buildings are commonly constructed for commercial or service purposes. Construction of such structures involves unique construction methods due to various characteristics like soil condition, cost, constructability, resources and time. This paper covers different methods of construction of multi-storey underground buildings and provides a comparative analysis to show when to use every method of construction according to the conditions available. Two projects in which multi-storey underground buildings were constructed with different sizes, from two different countries and with different project conditions were studied and examined against the developed selection criteria in order to evaluate the validity of the applied construction methods in each case.

Keywords: Ground Stabilization; Shoring; Underground Structures; Construction Engineering; Deep Foundations.

1 INTRODUCTION.

Multi-story underground structures are several floors under the Earth's surface, which enable extra accommodation to the structure, in addition to protecting environmental and space limitation factors. These underground structures have become increasingly common in developed and developing countries, especially since space is becoming a progressively demanded resource in the 21st century. Therefore, the greater surface area of a structure the more economical it is considered to be. Underground structures are demanded for nearly every type of industry. Power plants use basement structures as shelters from destructive weather or environmental conditions in general, where the vulnerable electronic equipment is often kept. There are also commercial uses, for instance, underground car parking and even cities. Underground malls and commercial buildings provide better insulation against the cold, and are cheaper to heat.

Multi-story underground buildings incorporate several aspects of construction, where the main ones are the dewatering and/or soil stabilization of the site, pre-construction process and the choice of construction method. First, the dewatering and soil stabilization phase is highly dependent on the level of the ground water table at the site and the type of soil, which leads us to the preconstruction phase of understanding the site soil conditions, permeability, type, size, as well as the topography. Next, the depth of the foundation and structure purpose must be determined, in order to pick the most appropriate construction method. Finally, the construction of underground buildings is basically using one of the three approaches:

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open-cut, top-down or bottom up. The processes within the construction methods revolve around ground water control, wall installation, lateral bracing and excavation (ASUC plus, 2013).

The construction methods for these multi-storey substructures could be also classified according to the side support system into three main categories. The first category is the open excavations with no side supports, the second option is to have temporary side supporting systems while the third system depends on constructing permanent walls to act as side supports prior to the excavation. Several factors determine the level of difficulty of the multi-storey underground buildings. These factors include the neighbors' legal rights, location, ground conditions, proposed depth of the substructure under construction, the proposed design and the optimal usage of the available site volume (SCI, 2001). This paper illustrates the various construction methods used in the process of constructing multi-story underground structures. It will weigh the pros and cons of each method in order to develop a set of election criteria and apply these criteria in two case studies to evaluate the methods applied within each case.

2 CONSTRUCTION METHODS.

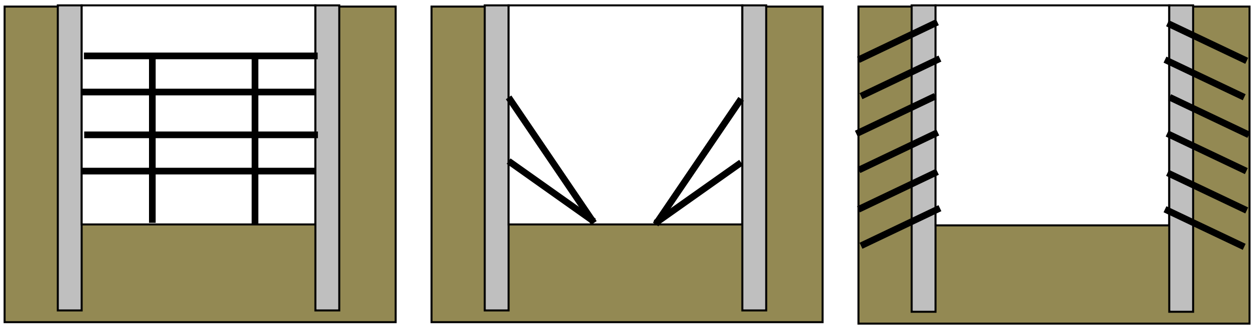
2.1 Open-Cut Construction

This is the simplest of all the multi-storey basement construction methods. As simply the excavation takes place before constructing the walls. This method entails a slope full open cut method that doesn't entail using retaining walls or struts while within cantilever methods (described later), the retaining walls stiffness is the source of stability with no temporary struts that would obstruct excavation activities. The slope method excavates the site with sloped sides, where the costs are very low due to no excavation obstruction by struts. However, if the excavation depth is deep, or the slopes need significant additional space, the amount of soil needed for backfilling would be large, therefore cost might not be that low. The cantilever method, on the other hand, requires the construction of side support walls, therefore making backfilling unnecessary, hence more economic than the slope method for some cases. This method is ideal when space is available as it is the most economical way to build a permanent basement. This requires sufficient right of way to guarantee safe slopes and access to excavation, dewatering, and backfill construction expertise. Hence, on applying such method it should be applied far away from the building footprint. It also may have restricted crane access due to the high area usage and could need dewatering that could be associated with detrimental settlements of surrounding properties. As the excavations go deeper, the costs associated with large volumes of earth located outside the building footprint significantly increase (Pearlman, Walker, & Boscardin, 2004).

2.2 Bottom-Up Construction

Within this method temporary or permanent walls and/or piles are constructed before the excavation should start (if any underground water is found dewatering should be done before the construction of the temporary walls). After that the site is excavated with temporary bracing members (if needed) installed as the excavation goes deeper. Then the construction of the structure starts from down to up and at the end of the construction the waterproofing should be done. After that, the ground level is restored (SCI, 2001).

Usually side shoring is temporary and is removed once the slabs/beams are capable of functioning however it may be left at times and it becomes permanent part of the building's structure this is usually done when it's too cost consuming to pull shoring out or if it's too close to the neighboring property line and there is no practical way of pulling it out without major disruption. The need of bracing members is mainly determined by the excavation depth and the stiffness of the walls (whether temporary or permanent). One type of bracing is the cross-lot bracing that utilizes temporary horizontal steel members spanning the site at one or more elevation. As shown in Figure 1a, temporary steel columns could be used to reduce the free unsupported length of these horizontal members to increase its critical buckling capacity. Another option is to use inclined bracings (also called rakers), as shown in Figure 1b, they are used when the excavation is too wide for cross-lot bracing, sloping rakers are used instead, bearing against heel blocks or other temporary footings. It is also common to see these two methods applied together. Another alternative to bracings is tiebacks that could be installed through the walls as shown in Figure 1c if the soil conditions permit its use. Tiebacks could be used with braces to reduce the number and/or size of braces. However, tiebacks are permanent and hence more costly than bracings (Santarelli & Ratay, 1996).



a. Cross-lot bracing of diaphragm walls.

b. Inclined bracing of diaphragm walls.

c. Tiebacks installed through diaphragm walls.

Figure 1: Different lateral protection methods applied within the bottom-up technique.

The bottom-up method is well known for the contractors, as it is most conventional. Within this method the construction equipment easily accesses the site. If underground water is found, drainage system could be constructed all over the site. On using such alternative the structure could be waterproofed from the outside. However, this method requires large construction area, the original ground surface level could only be restored at the end of the work. This method may require constructing temporary supports and change the locations of utilities. Dewatering should be done if underground water is found (SCI, 2001).

2.3 Top-Down Construction

This method involves the construction of succeeding basement levels from the ground downwards to the lowermost level. Like the bottom-up method, the construction starts by constructing the retaining walls and/or the piles (depending on the side support type). Interior piles are driven or bored to act as the interior columns until reaching the bearing strata. After that, the ground-floor slab is cast either on grade over unexcavated soil or on drop-down forms attached to the columns. This newly constructed slab will also act as a lateral brace against the perimeter walls negating the need for temporary bracing systems that could be needed in the bottom-up method. Then the soil beneath the slab is excavated and the slab construction process is repeated for the lower floors until reaching the lowermost level. Within this method and unlike the bottom-up method, the ground surface could be restored to its early stage before the end of the construction of the structure itself. It is useful in fast track projects as activities could start together in addition to saving time of constructing temporary walls and bracing members as they are not needed within this method. In addition to that small construction area is needed and the roof is easily constructed. However, waterproofing could not be applied to the outside of the structure and connecting the different floor slabs to the columns is not an easy task. Also, the accesses of the site need to be planned ahead due to the construction of different slab levels. Due to the construction of different slab levels, as the floor level goes deeper, its construction becomes more complicated with the lowermost slab being the most difficult to construct it in place (Basarkar, Kumar, Mohapatro, & Mutgi, 2013).

3 SIDE SUPPORT SYSTEMS.

3.1 Sheet Piles

This system consists of interlocking vertical steel sheet driven into the soil prior to excavation. Within this system the construction of the walls is significantly faster than that of reinforced concrete walls or secant piles as the driving process of sheet pile sections is significantly faster than all other side support systems in addition to the fact that it could immediately carry the loads after installation. It is suitable for almost all soils causing no ground disturbance as bored methods. In addition to all of that its components are of factory quality opposed to the site quality achieved within other methods. In addition to all of that it could be temporary as removing the sections after finishing the construction process is possible which makes it a cost-saving alternative. However, driving these sections causes significant noise which makes it not preferred in occupied areas. Sheet piles can't be driven for more than 15 – 20 meters therefore it can't be used for deep excavations in addition to the high possibility of water leakage between the different wall sections which necessitates the use of dewatering techniques on using this alternative. Another limitation is that this alternative can't be driven into rocky soil strata or the sheets will bend and deform (SCI, 2001).

3.2 Soldier Piles (Berlin Walls)

Within this system steel I-sections are driven vertically into the earth at small intervals around an excavation site prior to excavation. As earth is being removed wooden planks (or steel or RC panels) are placed against the flanges of the columns to retain the soil outside the excavation as shown in Figure **2**. It is very similar to sheet piling in terms of being fast, of good quality and causing noise while driving the steel piles and possibility of water leakage. However, this system is stiffer enabling it to reach deeper depths that could reach up to 20 – 25 m, anything deeper requires further side support. The larger member size, use of panels and the lower possibility of dismantling the system components after constructing the substructure makes it a relatively expensive system that is mostly used in large projects (Woolworth, 1996).

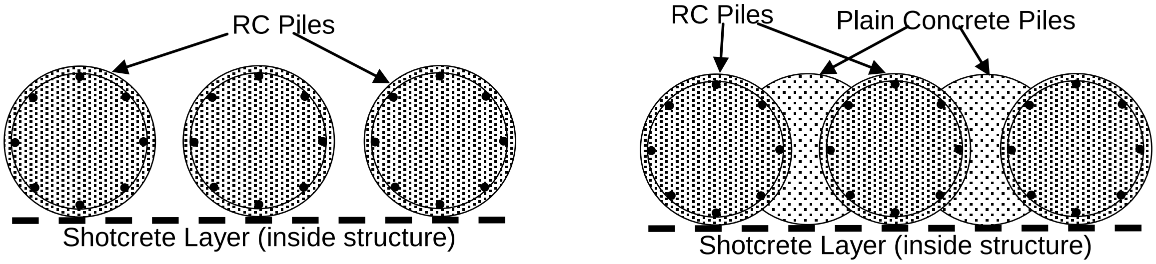
Figure 2: The Soldier piles utilizing wooden planks between steel piles (Mondayis, 2007).

3.3 Bored Pile Walls

Bored pile retaining walls (also called column piles) are rows of bored concrete piles. These piles cause less noise and vibrations when compared to the installation of solider piles or sheet piles in addition to being stiffer. These systems include less excavation when compared to diaphragm walls and hence less ground movements. Continuous Flight Augers (CFA) are usually used to construct such piles with pile diameters ranging from 0.3 m to 1 m. CFA's can be used to bore in all soils except soft clays, weak organic soils and hard rocks. There are three different bored pile wall options: contiguous piles, secant piles and tangent piles. In general, bored pile walls are more economical than diaphragm walls when considering small to medium scale depths of excavations as these piles save cost and time of site operations (Godavarthi, Mallavalli, Peddi, Katragadda, & Mulpuru, 2011).

3.3.1 Contiguous Piles

Contiguous piles are bored piles with small gaps between them as shown in Figure 3a. The first step in the pile construction is to drill into the ground with a CFA. Then, concrete is injected under pressure through the auger's hollow stem during its withdrawal. The concrete pressure is maintained during the auger withdrawal in order to assist the auger extraction and exert a lateral pressure on the surrounding soils. Once the auger was fully removed and the pit is full of fresh concrete, a reinforcing cage is placed into the freshly poured concrete. Then capping beams are constructed at the top to distribute pressure equally on the piles. The diameter and spacing of the piles are decided based on soil type, ground water level and depth, as the gap size could increase with the increase in soil cohesiveness and should decrease as the depth increases. They are suitable in packed urban areas, where conventional retaining methods would affect neighboring structures as these piles have less vibrations and less ground motions. This system can only be used in scarcity of ground water or where grouting or dewatering techniques could be used to prevent leakage between the piles and it could be used for maximum excavation depths reaching 12 m however it is significantly cost-saving when compared to almost all other side support methods (except for sheet piling) (Godavarthi, Mallavalli, Peddi, Katragadda, & Mulpuru, 2011).



a. Contiguous piles. b. Secant piles.

Figure 3: Bored pile wall systems.

3.3.2 Secant Piles

Secant piles are basically bored piles intersecting with each other with significant over laps as shown in Figure 3b. This alternative is used to construct cut-off walls for the control of groundwater inflow and to reduce ground motions in weak and wet soils. This alternative is similar to the contiguous bored pile wall but the gap between piles is filled with other piles made of unreinforced cement/bentonite mix or weak concrete. The primary plain concrete piles are constructed first and then the secondary RC piles are constructed, cutting into the primary piles. The CFA is used in a manner similar to the manner applied in constructing contiguous piles except for the fact that the secondary piles are cut overlapping into the primary piles via heavy duty piling rigs fitted with special cutting heads. Although this alternative is more expensive than contiguous piles, the major limitation of contiguous piles which is the lack of water tightness could be solved by the interlocking nature of secant piles. Tangent piles are very similar to secant piles however the piles do not overlap and they are just touching each other which gives them lower permeability than secant piles however they don't need special equipment attachments as these used in secant pile wall construction (Godavarthi, Mallavalli, Peddi, Katragadda, & Mulpuru, 2011).

3.4 Diaphragm Walls

Within this system, a vertical concrete guide wall is being constructed by excavating through the ground and using bentonite slurry to retain the excavated pit sides from failing. The excavation process is done either through using specially fabricated rectangular clamshell buckets or through the use of a boring machine specially designed for this purpose called the hydrofraise. After the excavation is finished and the bentonite slurry is filling the excavated pit, tremie tubes are used to pour concrete. After that, a steel cage is bored into the concrete acting as reinforcement (in some cases the steel cage is placed into the bentonite slurry pit before pouring the concrete). This method is usually done when there is a high groundwater table and deep basements (up to 40 m) as the constructed walls are of significantly higher stiffness and higher permeability when compared to all other methods. However, this process is more expensive and more time consuming than other alternatives due to the use of bentonite slurry and the need to have a slurry refining unit on site (Pearlman, Walker, & Boscardin, 2004).

4 CONTROLLING WATER LEVEL.

The presence of ground water within the excavation site could cause migration of fine particles through the side supports, loss of soil bearing capacity and significant changes in the soil properties. While removing water via pumping as it accumulates in the pit or shaft is an alternative however this process does not solve the ground stability problems as the fines will still come in through the side supports and the soil in the site will still be saturated and its bearing capacity will be reduced, hence this option isn't valid for deep underground structures. Seepage cut-off and/or dewatering methods are typically needed if the groundwater table is high and the walls are constructed using a technique that could not prevent water and fines from seeping into the site (ASUC plus, 2013). Hence, seepage cut-off and/or dewatering are needed mainly when using sheet piles, soldier piles or contiguous piles as side supporting systems.

4.1 Dewatering Techniques

Wellpoints are one of the most commonly used dewatering techniques. Within this system a number of vertical tubes (50 mm – 100 mm in diameter) with screening openings at the bottom are placed into the ground outside the site to suck the water out even before entering into the excavated location. This system also keeps the soil particles out. This water suction process is done via pumps. As the pumps depress the water table, the excavation can take place in dry condition. For excavations deeper than 6 m this process isn't sufficient and an additional two ring of well points may be required. However, this conventional form of wellpoints is not that successful in sucking water within soils of permeability that is less than 0.01 mm/s (silts and silty sands). For suction within such soils the use of more sophisticated vacuum wellpoint systems which are basically conventional well systems with partial vacuum maintained within the sand filter surrounding the wellpoint and its riser pipe. On the other hand, developments within well point systems facilitated the addition of an eductor hence creating a jet-eductor wellpoint system. This system consists of an eductor installed within a small diameter wellpoint screen that is attached to a jet-eductor fitted at the end of double riser pipes, one of them is a pressure pipe to supply the jet-eductor and the other pipe is to discharge from the eductor pump. This development enables the suction of waters from elevations as deep as 10 m (US Army Corps of Engineers, 2004).

On the other hand, deep wells are very similar in concept to wellpoints however larger in scale (150 mm – 600 mm in diameter). They are principally designed for to dewater large excavations that need high pumping rates. These deep wells could dewater excavations and shafts as deep as 90 m. Such large dewatering tasks are performed by pumping from deep wells with turbines or submersible pumps. Like wellpoints they are fitted around the borders of an excavation leaving the construction space free of dewatering equipment (US Army Corps of Engineers, 2004).

In the presence of certain soil conditions, vertical sand drains could be an ideal solution as they are used when a stratified semi-pervious layer that is nearly impermeable in the vertical direction is above a permeable layer and the groundwater table has to be lowered in the two layers. Vertical sand drains could be used to lower the water table in the upper layer as these sand drains will intercept seepage in the upper layer and transfer the water to the lower layer that could be dewatered using wells or wellpoints. These sand drains are columns of pervious sand allocated in a drilled pit. Additionally, installing a slotted 50 mm pipe inside the sand drain could increase its capacity and make it more efficient in conducting the water down to the more pervious layer (US Army Corps of Engineers, 2004).

Certain types of soils, such as silts, clayey silts, and clayey/silty sands, are very difficult to dewater using wellpoints or wells. These soils can be dewatered using wells or wellpoints in combination with a flow of direct electric current passing through the soil towards the wells, this system is called “Electra-osmosis”. Pumping from the wells or wellpoints creates a hydraulic gradient that together with the passage of direct electrical current through the soil forcing the water trapped within the soil voids to move from the positive electrode (anode) to the negative electrode (cathode). By making the cathode a wellpoint, the water that is moved to it could be sucked using vacuum or eductor pumping (US Army Corps of Engineers, 2004).

4.2 Seepage Cut-Off

Ground stabilization is usually done to stabilize and decrease the permeability of weak or highly permeable soils. It is done through, either, injecting a chemical or cementiscious based material into the sub-base. Basically, such material goes through the process of hydration inside the soil and makes the weak sub-soil much stiffer. The chemical injection operates by shrinking the voids in the soil thus making the soil much denser and less permeable. On the other hand, the cementiscious based material consists of Portland Cement mixed as a slurry similar to bentonite, it acts as filler by filling the voids in the soil, however it has pretty much the same output of the chemical material. The benefit of the cementiscious slurry is that additives such as fine aggregates; expansion, polymers, fibers and accelerators can be placed to increase consistency and reduce waste produced by washout of the grout. The stabilized impermeable soil will act as a barrier that prevents ground water from seeping in the site. A major difference between the cementiscious and chemical method of grouting is the duration, strength yielded and the difficulty in construction. For instance a typical compressive strength for cement grouts range from 20-35 MPa. On the other hand, good quality chemical grouts yield 3 to 4 times the strength of cement grouts. Both methods are done in a period of hours or few days and the strength of the grout is gained over time after injection. However the problem with the chemical grout is that it is injected by a pump since it tends to be more viscous than the cement slurry, problems tend to arise due to inconsistency in flow creating harder workmanship on site (US Army Corps of Engineers, 2004).

Conceptually, soil freezing performs the same function performed by soil stabilization techniques which is creating a barrier that prevents ground water from seeping into the excavation site however the major difference is that this technique has a temporary effect while the effect of soil stabilization is permanent. Within this method a line of vertical piles similar to well points are immersed into the ground and continuously circulate a coolant at a very low temperature, low enough to freeze the soil around an excavation area. Of course the higher is the temperature in the site more number of freezing piles will be needed and the process will be more expensive. Hence, this method is rarely used in hot countries and it is more common in cold countries (US Army Corps of Engineers, 2004).

5 CONSTRUCTION METHODS SELECTION CRITERIA.

Based on the discussion of the different construction methods presented in section 2, a selection criteria could be developed to aid the decision making process concerning the construction methods. The excavation size, time frame, cost, level of risk, and constructability are the main factors governing the method choice. The open-cut method is the simplest, fastest and most economic when used in shallow excavations in neighboring conditions that allow the soil to slope. From a project schedule perspective, due to its ability to house several simultaneous activities and due to the fact that it doesn't need temporary bracings, the top-down alternative is the fastest and most economic method especially when it comes to constructing large projects. However, this type needs experienced contractors hiring skilled labors who are able to excavate below the slabs in narrow, damp and dark areas and have the experience of how to construct strong slab-column and slab-wall connections. The bottom-up method is more conventional and a lot of contractors have the expertise to apply it however the use for bracing members or tiebacks increases the project duration and the project cost and makes this method not that suitable for wide excavations as bracing such excavations would be significantly uneconomic due to the use of significantly large bracing members. A summary of the selection criteria could be found in Table 1.

Table 1: Selection criteria for Multi-storey underground building construction alternatives.

	Open-Cut	Bottom-Up	Top-Down
Temporary Bracing	Not needed	Needed	Not needed
Allowed Machinery Size	Large	Small – Medium	Small – Medium
Project Duration	Short in shallow depths	Longest	Shortest
Cost	Efficient (shallow cases)	High	Moderate
Suitable Locations	Open areas	Any	Any
Constructability	Easiest	Known for contractors	Needs experience
Construction Risk	Small in shallow depths	Medium	Medium
Suitable Project Size	Small	Deep but narrow site	Large

Based on the discussion of the different side support alternatives presented in section 3, a selection criteria could be developed to aid the decision making process concerning these alternatives. The excavation depth, water-tightness, neighbor rights and soil type are the main factors affecting the choice of the alternative to be used for a certain specific case. Additionally, the construction time frame, cost, level of risk and constructability are significantly important factors that should be considered when choosing between the different alternatives. Sheet piling is the simplest, fastest and most economic (as it could be removed after construction) when used in shallow excavations, with scarce ground water and in unpopulated areas to avoid noise pollution and avoid harming neighboring structures due to vibrations.

Soldier piles are also not preferred in the presence of ground waters and populated areas but they could go deeper than sheet piles as they are stiffer however they are more expensive due to the difficulty of its removal after construction. Contiguous and secant piles produce negligible vibrations and minimal noise during construction which makes them good options within populated areas however they are slower than driven piles in construction and not suitable within all soils. However, the structural difference between contiguous and secant piles makes the first more permeable and unsuitable in ground waters while secant piles are stiffer and less permeable which makes them more suitable in the presence of ground water and in larger depths. These merits of secant piles are on the account of cost and speed which limits their use only when the need for them emerges. The stiffest, least permeable, slowest and most expensive alternative is the diaphragm wall system. However, it has high risk of the pit failure during the presence of the slurry in it or improper concrete pouring and its boring process could cause soil disturbance that could harm near substructures and foundations which needs high care from geotechnical engineers responsible for the design and monitoring processes. A summary of the selection criteria could be found in Table 2Table **1**. On the other hand, sheet piles, soldier piles and contiguous piles could be utilized in ground water presence if one of the techniques used to control the water level presented in section 4 is applied. In general, dewatering techniques are more economic than seepage cut-off techniques if the amount of ground water is within the capabilities of the dewatering methods and the depth of excavation are within the capabilities of the dewatering techniques. Additionally, proper hydrological and geotechnical analyses should be performed in case any of the dewatering or cut-off techniques are used.

Table 2: Selection criteria for side support construction alternatives.

	Sheet Piles	Soldier Piles	Contiguous Piles	Secant Piles	Diaphragm walls
Water Tightness	Seeps water	Seeps water	Seeps water	Water tight	Water tight
Suitable Soil Type	Not suitable for hard rocks		Not suitable for soft clays, weak organic soils and hard rocks		Any Soil
Maximum Excavation Depth	12 m	20 m	12 m	30 m	40 m
Suitable Locations	Avoid use in populated areas		Any	Any	Carefully used near structures
Speed	Fastest	Fast	Fast–Moderate	Moderate	Slowest
Cost	Lowest	Moderate	Moderate	High	Highest
Construction Risk	Low	Medium	Medium	Medium	High
Suitable Project Size	Small – Moderate	Moderate	Small – Moderate	Moderate – Large	Large

6 CASE STUDIES.

6.1 Tahrir Square Garage, Cairo, Egypt

Tahrir Square is located in the heart of Cairo, the capital of Egypt. It is a busy area, leading to downtown which serves as a connection to all the areas of Cairo. It is a crowded square with constant traffic during the weekdays. The consultant was the Arab Consulting Engineers and the contractor was the “Arab Contactors”. The project consists of two underground four-storey car parking garages, one located facing Omar Makram Mosque that could house 600 cars with an area of 5000 m^2 and another larger one facing the National Egyptian Museum that could house 1700 cars and 24 buses with an area of 76337 m^2. The construction of the both garages started in 1998, the smaller one was finished in 2002 (Abdel-rahman, 2007). However, political unrest and protests near the construction site have delayed the work in the larger garage that was only finished by the summer of 2014.

6.1.1 Applied Method

The site is located only 400 m away from the river Nile which creates a high groundwater table that is only 3 m deep while the depth of the excavation was 13.6 m. The project is only 6.5 m away from a major underground station connecting two perpendicular metro lines (at different depths). The first 4.5 to 6 m of soil was fill followed by a 48 m layer of dense sand that includes some intermediate layers of hard clays. Hence, a 27 m deep diaphragm wall with a thickness of 0.8 m was constructed in order to prevent water seepage. Before construction, a grout plug of about 2.5 m thick was injected around the garage circumference (outside the diaphragm walls) to assist the diaphragm walls in preventing the inflow of water towards the excavation site and to minimize the soil disturbance caused by the boring activities and the metro lines vibrations in the locations between the diaphragm wall and the neighboring structures minimizing the risk of any effect of the construction process on the soil between the project and the neighboring substructures. The top-down method was applied where the diaphragm walls were first constructed using the hydrofraise and the piles (columns) were constructed using bucket excavators and continuous flight augers. After that, the slabs were constructed and connected to the diaphragm walls and the piles (who act now as columns) in a process that went simultaneously with the excavation towards the foundation level to provide lateral supports to the diaphragm wall (Abdel-rahman, 2007).

6.1.2 Construction Method Evaluation

Concerning the consultant decision of using a 27 m deep diaphragm wall in this project, it was a correct decision. On referring to the selection criteria developed in section 5, using a non water-tight alternative would have needed a very large number of dewatering wells that would have worked continuously due to the high water flow at this location near the river Nile. That leaves only diaphragm walls and secant piles to be used in such a project however, the designer preferred diaphragm walls as they would be stiffer than secant piles.

Also concerning the decision of using the top-down method, according to the selection criteria developed in section 5, it is the most suitable method. The depth of the excavation and the presence of the ground water would make it impossible to use the open-cut method. On the other hand if the bottom-up method was used it would have been extremely expensive to place temporary bracing in this project as the two building sites were significantly wide and bracing such wide sites would have been a time-consuming process in addition to the need for large bracing members that would have been expensive, difficult to fabricate, difficult to transport to the site and also difficult to install. Hence, the only feasible option left was to use the top-down method.

6.2 Basement Car Park, Staines, UK

This project involved constructing a two-storey underground car park in an area where few buildings surround the project. The consultants were Andrews, Kent and Stone while the contractor was Kvaerner. The basement was 8 m deep, the soil was clay and the ground water table was only 2 m deep. The area of the site was approximately 3650 m^2 and the project was finished within the months of November and December of 1998 (SCI, 2001).

6.2.1 Applied Method

The consultant decided to drive 403 LX32 sheet piles with a depth of 14 m all over the perimeter of the site within two weeks using hydraulic pressing rigs. Well points were used to suck water just out of the site during the excavation. The bottom-up technique was used to construct the basement. This method was used with the aid of 80 tons of steel temporary bracing was installed to support the sides from failing during the excavation process. After the excavation process was finished, all the joints between sheet piles were welded to adjacent angle sections using continuous joint penetration welds and the voids were filled with a bituminous sealing material to permanently prevent water from seeping in the basement after the dewatering process is stopped. Then the raft foundation was constructed followed by the erection of steel columns and the two slabs were constructed before dismantling the temporary bracing members (SCI, 2001).

6.2.2 Construction Method Evaluation

According to the selection criteria developed in section 5 and due to the basement having a depth of 8 m which could be achieved by almost any side support construction alternative, this project is considered to be of that type of projects were nearly all construction alternatives could be used from a technical point of view however what would make one option more suitable than the others would be the construction speed and cost. Using secant piles or diaphragm walls would have saved the cost and effort of the dewatering and welding. However, these types of walls are significantly more expensive and slower than sheet piling taking into account that the additional cost of dewatering and welding the sheet pile sections is less than the difference in the cost of constructing such impermeable reinforced concrete walls and installing sheet piles. Hence, and as sheet piling is the fastest and least expensive alternative, choosing this alternative was the best choice available.

Also according to the selection criteria developed in section 5, the choice of the bottom-up construction method was valid. Excluding the open-cut method was a correct decision as although the depth was not considered significantly deep, the high ground water table would have caused side failures during excavations. On the other hand, the top-down method is more commonly used in larger projects were the space of the activities would not be over-congested and sufficient space to allow the entry and maneuvering of moderately sized excavation equipment would be available. If the top-down method was used in this project the construction areas would have been very limited to enter excavation equipment below the upper slab in addition to the fact that an additional set of activities of driving the middle steel columns before the excavation. Hence, the bottom-up method was a more practical method for a project of that size.

7 CONCLUSIONS AND RECOMMENDATIONS.

When examining the methods applied in the two cases discussed in section 6 of this paper against the selection criteria developed in section 5, the selection criteria proved that it covered the different aspects governing the selection of the most suitable multi-storey underground building construction methods and the different side support construction alternatives for different cases. The most governing factors of choice are the soil conditions, ground water table, excavation depth and neighboring site conditions and following that, comes the level of risk, constructability, speed and cost. Hence, it is highly recommended when using the selection criteria matrix to take all the factors governing the method selection into account as neglecting some of them could cause serious problems that are difficult in fixing.

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