Top-Down excavation system, an integral solution for challenging deep excavation projects with complex surroundings and difficult geotechnical conditions.

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ABSTRACT Edification projects in Vancouver are each time more complex and challenging. A clear example is the construction of high rises in relatively small surfaces that require a considerable amount of basement levels, reaching substantial excavation depths. In addition, these projects may have sensitive surroundings such as tunnels from the metro system and buildings with a significant number of basement levels. To make these types of projects a reality, this article presents an integral solution where the earth retention system is accomplished by means of a diaphragm wall. Whereas the excavation is achieved by implementing the Top-Down system, so that the basement slabs are the elements that react against the lateral earth pressure, eliminating the need for any other type of additional shoring or anchoring. Moreover, the deep foundation consists of large diameter circular or rectangular piles supported in the competent material. The article highlights the analysis and design of diaphragm walls, referencing the validation against data obtained from inclinometer measurements. It also discusses the construction aspects of this solution and suggests its feasibility for Metro Vancouver. Furthermore, it presents a selection of relevant case studies where the Top-Down excavation system has been successful.

Basic Principles

Definition

The Top-Down excavation system is a solution that successfully integrates the earth retention, deep foundation, and excavation works.

This approach incorporates a watertight definitive structural element as the earth retention system, i.e., a diaphragm wall, also known as D-Wall. Eliminating the need for an additional basement wall constructed in front of the temporary earth retention works. Furthermore, the basement slabs are the elements that react against the lateral earth pressure, eliminating the need for additional shoring or anchoring. Whereas the deep foundation elements are leveraged to embed vertical beams that will support the basement slabs. Once the final excavation level is reached, the deep foundation and the entire basement for underground parking have been built. In addition, it may be possible to simultaneously build a portion of the superstructure.

Applicability

Challenging deep excavation projects with complex surroundings and difficult geotechnical conditions are becoming the norm. Large cities continue to expand, and property is becoming scarce. To maximize land use, high-rise buildings are preferred. These require deep foundations and tend towards increasingly deeper basements. Experience with this specialized technique has shown an average of 6 basement levels. However, there have been projects with 8, 10, 12, and up to 16 basement levels for underground parking where the Top-Down excavation system proved to be an efficient and effective solution.

Some of the most common challenges that designers and contractors face in such projects are:

- Complex footprint geometry and limited surface
- Deep and sensitive neighbouring structures
- Nearby utilities, e.g., electrical, and gas
- Tunnels from the metro or sewer systems
- High water table
- Soft soils, e.g., expansive clay and organic soil

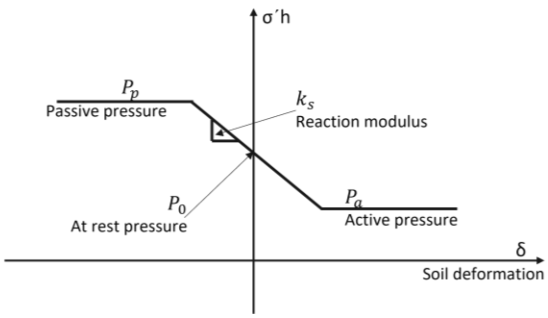
Analysis and design

Earth retention

One of the most common earth retaining structures used for the Top-Down excavation system is the diaphragm wall or D-Wall, Chadeisson (1961). This is a watertight and definitive cast-in-place reinforced concrete structure, built with very strict verticality, and drilling mud control. Meeting the design criteria specified by EN1997-1 (2004) and EN1998-5 (2004).

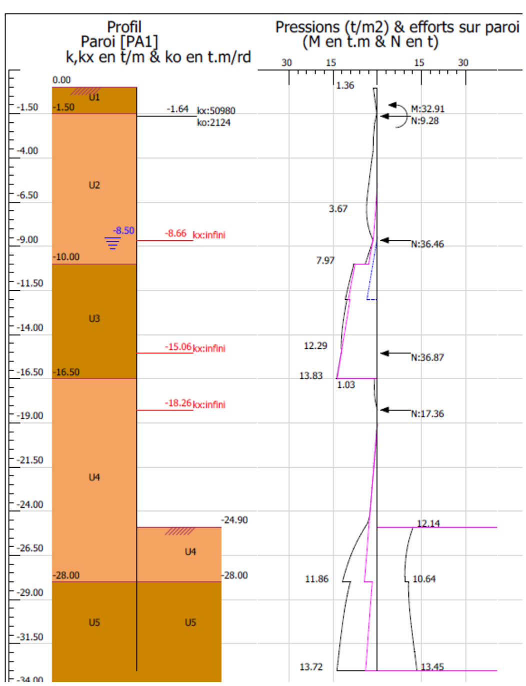
The site-specific geotechnical and piezometric conditions are considered within a D-Wall's corresponding soil-structure interaction analysis. This analysis is performed using the Reaction Modulus method or Finite Element method. In practice, Soletanche Bachy performs soil-structure interaction analysis using their proprietary software PARIS®. This tool can analyze a D-Wall's stress and deformation state throughout its multiple construction stages. In addition, it supports pseudo-static analysis based on the Mononobe-Okabe method, interpreted by Seed and Whitman (1970). The software represents soil-structure interaction using the elastoplastic behaviour of the soils, captured by the horizontal reaction modulus as illustrated in Fig. 1 and further discussed by Schmitt (1995).

Fig. 1. Stress and deformation behaviour considered in the analysis model for the Reaction Modulus method.



The software performs plane strain analysis, as depicted in Fig. 2. A major advantage is that the software can provide output for each construction stage. It provides active and passive earth pressures, as discussed by Dodel et al. (2002). In addition, it outputs horizontal deformation, as well as shear force and bending moment diagrams, as shown in Fig. 3. This is essential information to guarantee a tailor-made and economical structural design for the D-Wall, without overestimating these magnitudes.

Fig. 2. Reaction modulus analysis model in Soletanche Bachy’s proprietary software PARIS®.



On the other hand, there are projects where difficult geotechnical conditions may require analysis models using the finite element method which can capture complex soil behaviour, and where it is possible to introduce dynamic analysis through constitutive soil models under cyclic loading. For instance, Fig. 4 shows the deformation contours and mesh of a Top-Down excavation analysis model performed in the finite element software Plaxis 2D.

Fig. 3. Envelopes of horizontal deformation, shear force, and bending moment diagrams, PARIS® output.

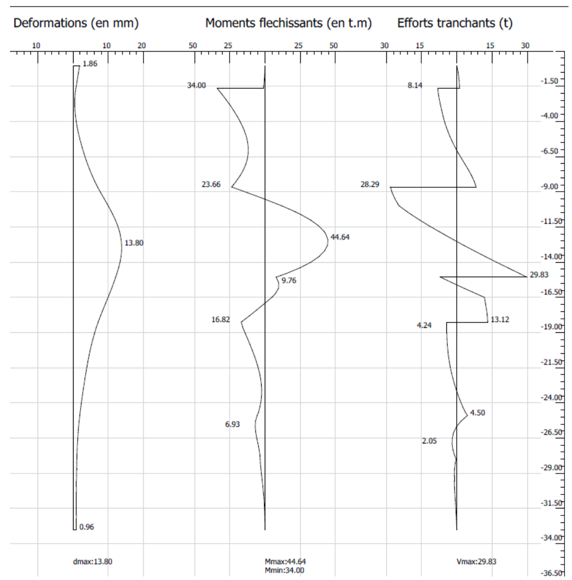
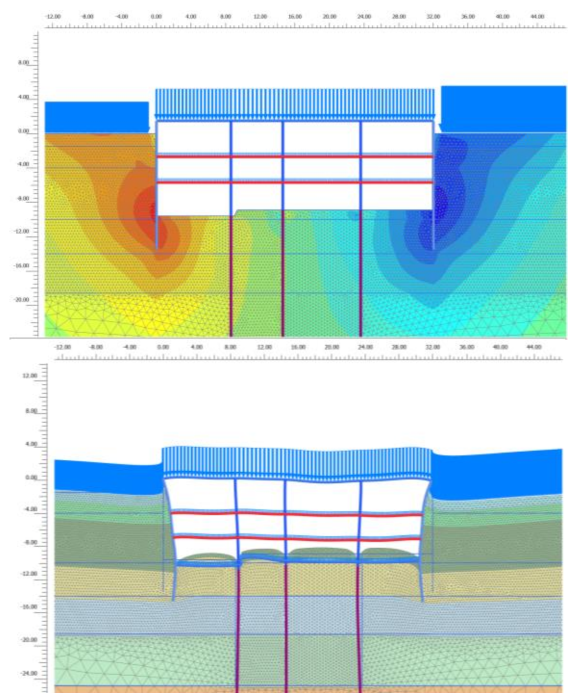
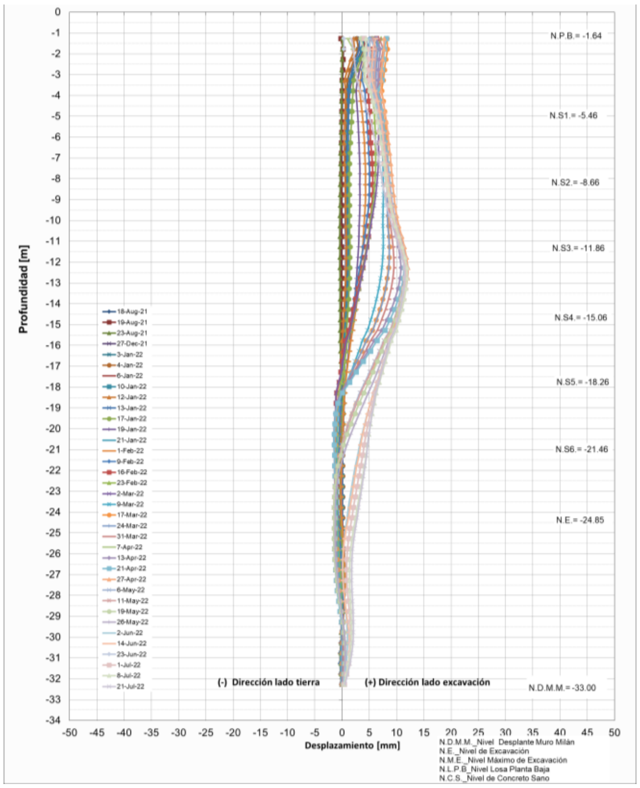


Fig. 4. Deformation contours of a Top-Down excavation, from a finite element method analysis model in Plaxis 2D.



Results from both the reaction modulus and finite element method models have been validated against real data obtained from instrumentation and monitoring, Gutjahr et al. (2003). This is illustrated in Fig. 5, which shows the horizontal deformations of a D-Wall during a Top-Down excavation, Rodriguez et al. (2022). Note that these observations are recorded during all excavation stages and compared against the theoretical deformation obtained from the analysis models. This is valuable information to calibrate values of both reaction and elastic modulus.

Fig. 5. Horizontal deformations in a D-Wall for a Top-Down excavation, from inclinometer data.



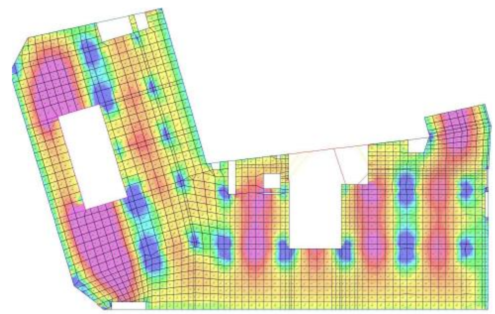
Moreover, considering that current practice for the design of basement walls in Vancouver is conservative, as suggested by Amirzehni, E. et al. (2015 and 2018), and that a D-Wall is a more robust structural element compared to a standard reinforced concrete basement wall. Therefore, the Top-Down excavation system alongside a D-Wall represents an attractive and feasible alternative.

Slabs

As previously stated, the basement slabs are the elements that will react against the lateral earth pressure, eliminating the need for additional shoring or anchoring on the D-Wall. These slabs are commonly analysed in structural analysis software, as depicted in Fig. 6, where the excavation shafts are also visible. With these models, it is possible to obtain deformations, bending moments, shear, and stress distribution, which are all required for design.

It is important to note that the working platform during the Top-Down excavation will be one of the definitive slabs. Furthermore, it will be subjected to temporary loading that in most cases is higher than the service loading for the slab and thus should be considered in its design. Meanwhile, the rest of the basement slabs should be analysed and designed according to their respective service loads.

Fig. 6. Stress distribution in basement slab.

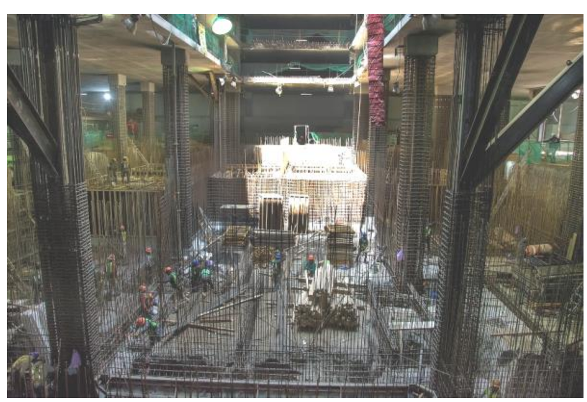


The bottom slab plays an equally important role in this excavation system. This slab needs to be designed to distribute all the stresses that reach the base of the excavation while also resisting any possible water pressure. Likewise, it should be designed considering soil-structure interaction in both static and dynamic conditions.

Vertical beams

Another essential component for the Top-Down excavation system is the vertical beams or plunge columns that will support the working platform and the rest of the slabs that are built as the excavation advances. The vertical beams, shown in Fig. 7, are pre-embedded within the deep foundation elements. These sections are designed for buckling and require mechanical and welded connections accordingly.

Fig. 7. Vertical beams pre-embedded in deep foundation.



With each excavation stage, the vertical beams are uncovered and the node that connects them with the slab can be built. This node, commonly referred to as stump and depicted in Fig. 8, also serves to prevent punching shear failure. Therefore, the plunge columns along with the stumps constitute the load transfer mechanism from the slabs to the foundation. In addition, the definitive columns can potentially be built as the excavation progresses, as seen in Fig. 9.

Fig. 8. Vertical beams and stumps for load transfer.

Fig. 9. Definitive columns built while excavating.

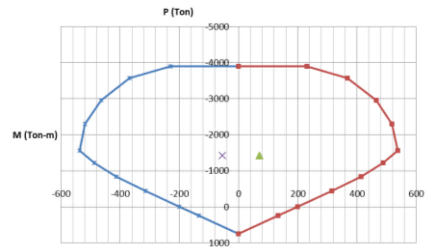
Foundation

The deep foundation elements are regularly large diameter piles or barrettes. These are designed considering the loads from the structure in its various combinations for the static and dynamic conditions, as well as the corresponding load factors.

The bearing capacity should meet local codes and guidelines. Similarly, it is crucial to account for the vertical deviation during the construction of these elements. The structural design of the deep foundation should consider axial compression resistance, minimum or tension reinforcing, and the possibility of flexural compression, as depicted in the interaction diagram in Fig. 10.

Finally, in terms of quality assurance, it is advised to perform pile integrity testing in accordance with the requirements of local practice and codes.

Fig. 10. Interaction diagram of a deep foundation element.



Construction

Diaphragm Wall

A D-Wall is an impervious reinforced concrete wall cast in panels. To build a D-Wall, guide walls are necessary. These serve as alignment, as guide for the excavation tool, and to support the reinforcing cages. The required equipment to build a D-Wall is illustrated in Fig. 11. Namely an excavation tool such as a mechanic grab, hydraulic grab, or hydro-fraise. In addition to a desander, a service crane, a tremie rack, return pumps, drilling mud silos, and a mud central. The standard thicknesses for D-Walls are 0.5, 0.6, 0.8, 1.0, 1.2, 1.5, and 1.8 m. Furthermore, Fig. 12 illustrates a hydraulic grab excavating a diaphragm wall panel.

Fig. 11. Common equipment for D-Wall construction.

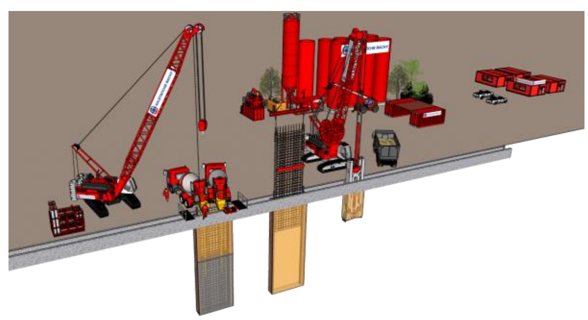


Fig. 12. Hydraulic grab excavating a D-Wall panel.

Panel joint

The water tightness between panel joints is achieved with a patented CWS formwork. In essence, a temporary steel stop end that allows the installation of a PVC or Neoprene water stop along the entire panel joint, as seen in Fig. 13. Furthermore, this formwork guarantees the contact between adjacent panels, thus forming a continuous concrete wall.

Fig. 13. CWS formwork for D-Wall panel joints.

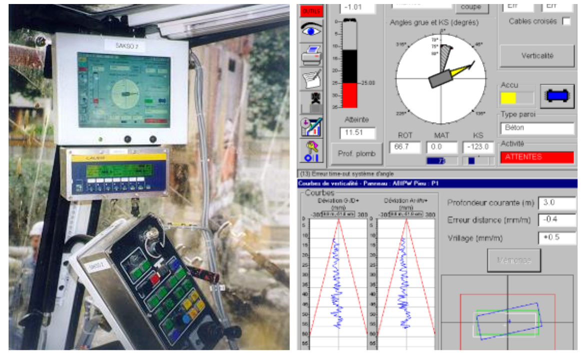
Verticality

Verticality control is rigorous and continuous for each diaphragm wall panel. D-Walls can be excavated with mechanical and hydraulic grabs, as well as with a hydro-fraise. Mechanical grabs were the first tool used for D-Wall excavation. Hydraulic grabs, on the other hand, benefit from its power and versatility in harder soils, allowing for higher productivity. Whereas the hydro-fraise can excavate harder soils due to its two counter-rotating drums with cutting teeth. In practice, the most used excavating tool is the hydraulic grab shown in Fig. 14.

With these tools, the tolerance of vertical deviation can range between 0.8% to 1%. In Fig. 15, the verticality controls available to the hydraulic grab operator are shown. In addition, real-time measurements of the alignment are monitored, and corrective action can be taken at any time during excavation. As a precautionary measure, the vertical accuracy of a panel can also be diagnosed and verified with an ultrasonic echo sensing system test.

Fig. 14. Hydraulic grab for diaphragm wall excavation.

Fig. 15. Verticality controls available to the grab operator.



Drilling fluid

One of the keys to the D-Wall technique lies in the stability of the walls during its excavation. This is achieved by using polymer or bentonite mud as drilling fluid, a material made on-site, regenerated, and de-sanded in one or more mud centrals. It is essential to constantly safeguard the quality of the drilling fluid on-site and throughout the various construction stages of a D-Wall, Fig. 16 shows drilling fluid control at an on-site mud central.

The drilling fluid maintains the stability of the excavation walls. As a reference, Table 1 displays a set of characteristic parameters for bentonite mud, differentiating between mud in its new state and mud before concreting a D-Wall panel.

Table. 1. Sample bentonite mud characteristics, for new mud and mud before concreting a D-Wall panel.

Parameter	New mud	Before concreting
Marsh viscosity (s)	33-40	33-50
Density	1.02-1.05	<1.15
Cake (mm)	<1	<3
PH	7-10	7-11
Sand content (%)	0	<3

Fig. 16. Drilling fluid control at on-site mud central.

Concrete

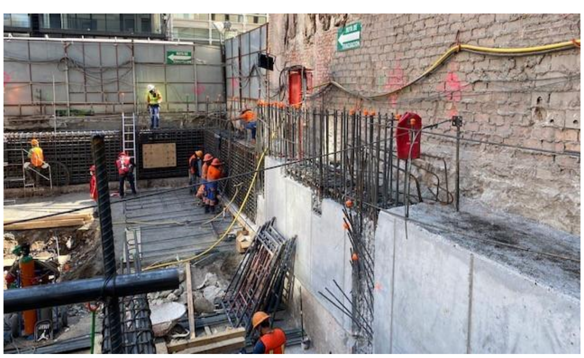
To guarantee the quality of the D-Wall, a special concrete mix designed specifically for diaphragm walls must be used. Similarly, concrete quality control is fundamental. Although D-Walls are built with structural concrete with a compressive strength varying from 30 to 40 MPa, they require a special concrete mix. This mix must be self-compacting and have a particular slump and placement time to guarantee its workability characteristics during panel concreting. Furthermore, concreting of a D-Wall must always be continuous and performed using one or more tremie pipes which are kept within the fresh concrete to avoid cold joints as the concrete rises.

Capping beam

Another fundamental and often overlooked element of a D-Wall is the capping beam. This continuous element ties all the panels together along the entire alignment. Its main purpose is to homogenize the displacements and forces at the top of the D-Wall. Moreover, considering that the maximum shear force under static or seismic conditions will occur at the ground-level interface, the depth of the beam and reinforcing can be designed to resist these forces in service conditions. See Fig. 17 and Fig. 18, which illustrate the geometry, size, and reinforcing that the capping beam for a diaphragm wall can have.

Fig. 17. Geometry and size of a D-Wall capping beam.

Fig. 18. Size and reinforcing of a D-Wall capping beam.



Working platform slab

The working platform slab is paramount for the Top-Down excavation system. As previously mentioned, this slab is definitive and will need to resist heavy loading from cranes, trucks, concrete mixers, construction materials, and all the equipment that may be required. See Fig. 19, which illustrates the use and common loading on the working platform slab, and where the excavation shaft is also visible.

Fig. 19. Working platform slab for Top-Down.

Successful projects

Project in actively seismic region

The Top-Down excavation system was implemented for a 50-story 235 m tall high-rise building located in Mexico City. The project has a 1 m thick D-Wall with a tip elevation at -55 m, a deep foundation at a depth of -64 m, and civil works for 7 basements with under slab excavation to a maximum depth of 25 m. The D-Wall capping beam, working platform slab, under-slab civil works, and simultaneous superstructure, are shown in Fig. 20, Fig. 21, Fig. 22, and Fig. 23, respectively. It should be noted that the maximum recorded Peak Ground Acceleration (PGA) after the inauguration of the project in 2016 has been 101, 314, and 305 cm/s2 in the NS, EW, and Z components, respectively, Lermo et al. (2020), which is approximately 0.10, 0.32, and 0.31 g.

Fig. 20. D-Wall capping beam.

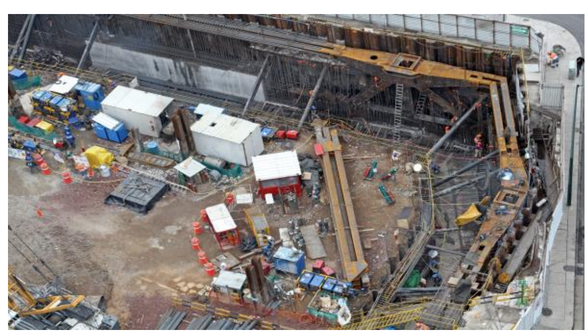
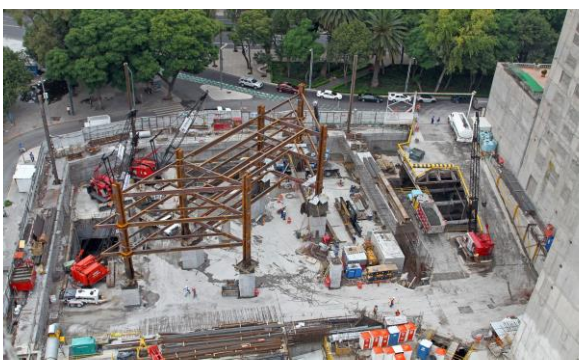


Fig. 21. Working platform slab.

Fig. 22. Civil works and under slab excavation.

Fig. 23. Simultaneous construction of superstructure.



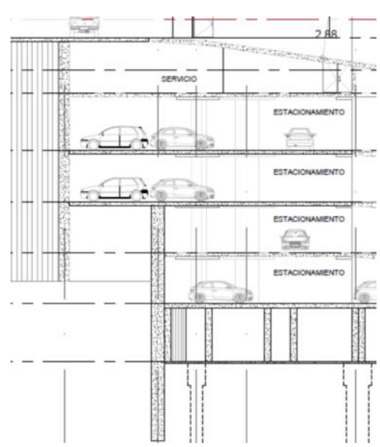
Project with complex surroundings

Another successful application in the same highly active seismic region was for two 30-story towers, with 6 and 8 basement levels, reaching 25 m and 33 m of depth, see Fig. 24 and Fig. 25 for pictures from the 8-basement excavation. These two deep excavations were performed simultaneously, being separated by a building in operation. To add to the complex urban environment, the projects are surrounded by a tunnel from the metro system and 2 high-rise buildings with 4 and 8 basements. The metro line alignment had drastic implications for the 6-basement excavation, forcing a reduction of the parkade surface from levels 4 to 6, and implicating an interior D-Wall, as seen in the elevation shown in Fig. 26. In both excavations, the earth retaining system is a 0.6 m thick D-Wall with tip elevations ranging from -27 m to -40 m. Meanwhile, the deep foundations are cast-in-place piles of 1 m to 2 m in diameter with tip elevations ranging between -33 m to -46 m within the cemented and compact tuff material. Although this solution guaranteed a negligible urban impact, it did require continuous collaboration among all disciplines.

Fig. 24. Working platform slab and excavation shafts.

Fig. 25. Top-Down excavation works for 8 basements.

Fig. 26. Reduction of parkade surface due to metro line.



Large urban excavation

Similarly, this solution has been applied to a project in New York City where the site covered two city blocks, see Fig. 27. In this case, the property line constraints and a rail line did not allow for a conventional open pit excavation with tiebacks. The major benefit of the Top-Down was the ability to progress with the 6-story high-rise superstructure construction while the basements reaching a depth of 18 m were excavated and built at the same time. Overall, this resulted in significant time and cost savings. In this project, the structural and watertight D-Wall had tip elevations ranging between -30.5 m and -45.7 m. While the deep foundation had a total of 96 piles ranging between 1.8 m to 2.1 m diameter, and tip elevations ranging from -37 m to -84 m. Note that the D-Wall and Pile works were simultaneously performed, as shown in Fig. 28. During these works, difficult drilling conditions were reported due to the encounter of boulders and cobbles, which affected productivity. In addition, the removal of debris and contaminated soil was an additional challenge during under-slab excavation, as seen in Fig. 29.

Fig. 27. Plan view of large urban excavation.

Fig. 28. D-Wall and Pile works for Top-Down.

Fig. 29. Under slab Top-Down excavation.

Top-Down projects worldwide

Worldwide, Soletanche Bachy and its subsidiaries have implemented the Top-Down excavation system for purposes of deep excavations for basements and underground parking garages, as well as for large cut and cover projects, at least once or multiple times in the following countries: Chile, Colombia, France, Mexico, Monaco, New Zealand, Poland, Singapore, Spain, USA, and Vietnam. Whereas other D-Walls have been successfully built in Australia, Hong Kong, Malaysia, UAE, and throughout Europe.

Conclusions

This paper presented an overview of the Top-Down excavation system, a robust solution that successfully integrates earth retention, deep foundation, and excavation works. Furthermore, it described its application in complex surroundings and difficult geotechnical conditions to overcome the challenges owners, designers, and contractors face in these intricate projects.

Consequently, this system effectively reduces urban impact and delivers a safe alternative to open-pit excavations. In addition, it can potentially reduce construction time because the excavation and basement slabs are built simultaneously. Moreover, it may also be possible to build a portion of the superstructure at the same time. Additionally, the earth retention, provided by a D-Wall is a watertight definitive structure that can have a dual purpose as both a bearing and retaining element.

Similarly, the document provided a high-level description of the analysis and design for the main components of this solution, i.e., earth retention, slabs, vertical beams, and foundation elements. Likewise, the most important construction aspects related to the D-Wall, panel joint, drilling mud, verticality, concrete, and capping beam were discussed. Finally, a brief and limited selection of successful Top-Down projects has been presented.

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