Diaphragm Walls:
A Solution For Deep Excavations In Difficult Soil Conditions With Superficial Water Table

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ABSTRACT This paper will describe and summarize the definitions, application, construction processes and, briefly, the design methods for Slurry Walls/Diaphragm Walls.
This excavation support system has not yet been used in BC or in the Lower Mainland for residential projects even though perfect soil conditions, for this technology, are present. A typical example is Richmond, where deep underground parking is not generally used.
Slurry Walls/ Diaphragm Walls can provide economic solutions where temporary and permanent support can be integrated into one retaining structure, or they can provide the only possible solution in extreme soil conditions with the presence of a high water table. .

Introduction

A Slurry Wall (SW), also called -especially in Europe- a Diaphragm Wall (DW), is a cast insitu structural underground concrete wall excavated from the surface, with the aid of stabilizing fluids (generally bentonite mud -or polymers- to keep the excavation stable), and constructed in contiguous elements (panels). It is generally reinforced (steel cages) and combines into a single foundation unit, a temporary earth support system, a permanent basement wall, a hydraulic (ground water) cut-off and, usually, a vertical support element.

A single element of SW/DW, called a "barrette", can also provide high capacity deep foundation elements as an alternative to piles. "Barrettes" have higher shearing and horizontal bending moment resistance in comparison to piles. It is typically 0.5 to 1.5 meters wide and, if used for excavation support, is typically anchored or braced. Solutions without anchoring or bracing are possible using "T" or "Y" shapes or circular or elliptical plans. Another common, non structural, use of DW/SWs is for water cut-off usually in dams. In this case plastic concrete or self-hardening grout mix is used instead of reinforced concrete.

Some definitions, from EN 1538 (European Standard for execution of special geotechnical works- Diaphragm Walls)- Ref (1):

- Cast in situ concrete Diaphragm Wall: wall made of plain concrete or reinforced concrete which is constructed in a trench excavated in the ground.
- Slurry wall: wall made from a self-hardening slurry. In most cases, the excavation is carried out using a self-hardening slurry as the supporting fluid.

As it is possible to see in Europe there is a very clear distinction between the definition of Slurry and Diaphragm Walls, as is not the case in NA.

One should be aware that SW/DWs are totally different from Slurry Trenches, where the excavation is <u>NOT</u> done per panel, but continuously with a backhoe, and where the filling material is <u>NOT</u> engineered. Misleading use of these terms is, unfortunately, still present in our industry.

Fig. 1. Diaphragm Wall

Historically the first SW/DW was carried out, privately, in Italy by Impresa Costruzioni Opere Specializzate (ICOS) in 1948 and in 1950 the first SW/DW was performed in Fedaia Power Plant. The system was subsequently patented.

Bentonite mud / Polymers

The basis of the development of the SW/DW was the study of bentonite mud in excavation.

In the early 1920's bentonite was discovered. The first significant advancement to fluid based earth stabilization came from technology developed in East Texas for the drilling of oil and gas. Bentonite, a unique naturally occurring swellable hygroscopic clay with unique electrochemical properties, allows for the control of fluid migration into the formation.

Bentonite dispersed in water creates a slurry (mud) with colloidal and tixotropic properties. The bentonite platelets, small brick-like objects in structure with one end of the brick carrying a positive charge and the other end of the brick carrying a negative charge, are transported to the formation interface with the initial migration of water into the formation. However instead of moving into the formation with the water, these clay particles begin to build up on the formation interface. And due to their unique electro-static charge characteristics they start to orient in an organized fashion, end-to-end, or positively charged end to negatively charged end. Within minutes, the bentonite platelets build a wall, or cake, and significantly slow down or stop the flow of the excavation fluid into the adjacent porous formation. Ref (2). See Fig. #2.

The hydrostatic pressure of the bentonite slurry in the trench creates a stabilizing action on the internal walls of the excavation preventing its collapse.

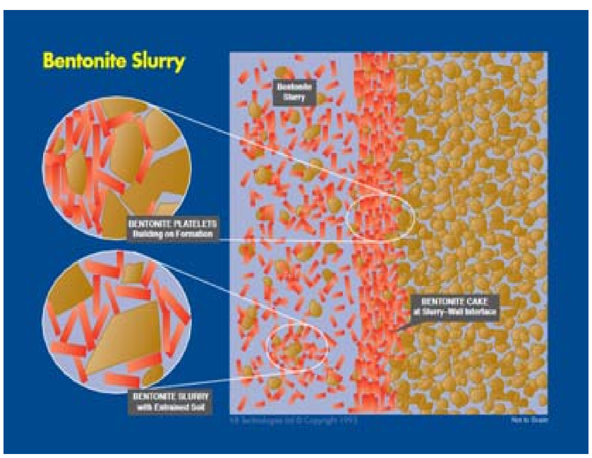

Fig. 2. Bentonite Slurry.

Today, more and more frequently, depending on the type of soil to be excavated, and due to potential disposal problems, the bentonite can be substituted by polymers.

Sequences, Procedures and Equipment.

The typical sequences in the construction of SW/DWs are:

1) Guide Walls

Before the construction of SW/DWs, guide walls around the perimeter of the area are constructed.

The reasons for the guide walls are:

- to have a containment of the bentonite slurry that guarantees the presence of a sufficient hydraulic head at the depth in which the slurry start to be necessary,
- to have a stable starting point of the excavation, assuring the stability of the superficial soil,
- to easily survey and guarantee the location of the SW/DW and panels,
- to have a rigid structure to support the rebar cages,
- to guide the beginning of the excavation tool or equipment chosen for the project .

See Fig. #3 with an example of the guide walls.

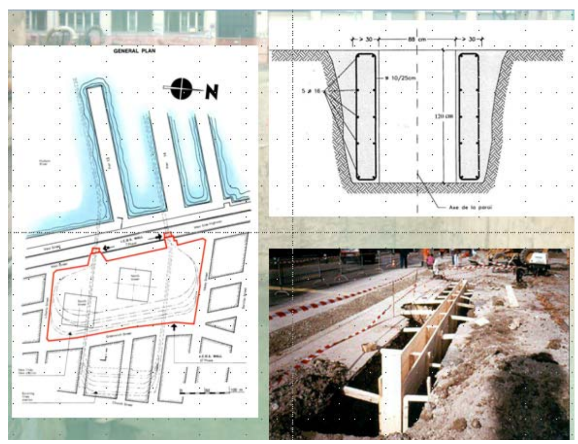

Fig. 3. Guide walls.

2) Excavation.

The excavation can be carried out with the aid of several pieces of equipment, such as (in increasing order of cost):

- Mechanical clam-shell,
- Hydraulic clam-shell,
- Kelly bar
- Hydromill

Basically any of these excavation tools are mounted on a crane with different characteristics that vary for each tool. See Fig. #4 with the pictures of some equipment.

Fig. 4. Typical excavation equipment for SW/DW.

The choice of the equipment depends mainly on the characteristics of the soil to be excavated and on the depth to be reached.

The excavation is done typically per panel, with, usually, a Primary and Secondary sequence, alternative or successive.

The length of each Primary panel is usually the maximum opening of the clam-shell (or wheels for the hydromill), typically 2.5 to 2.8 meters. In this case the primary panel is done in a single pass 2.5 to 2.8 meters, or so called "single bite". Depending on the type of soil, stability of the excavation, existence of adjacent building, etc, "multiple bites" can be constructed to obtain a bigger Primary panel of a maximum of 6.0 meters.
Secondary panels are usually done in a "single bite". See Fig. #5.

2.1) Excavation with mechanical clam-shell, hydraulic clam-shell or Kelly bars.

In this case the site installation is quite simple. In addition to the bentonite plant (silos or tank for stocking, mixing unit, re-circulation pumps, pipes for distribution to the panels, de-sander and tanks for treatment of the bentonite) and the crane for the excavation, on site it will be necessary to have a service crane that can be used for the installation of the rebar cages, tremie of the concrete and installation and removal of the joints.

The simplest tool for excavation is the mechanical clam-shell that is manoeuvred with the free fall cable of the crane. The limitation is in its weight, and to be effective should be quite heavy (6 to 10 tons). An alternate to the mechanical, is the hydraulic clam-shell, more powerful, with the same weight.

A Kelly bar mounted clam shell, usually telescopic, has the advantage of being more rigid, providing better control of the verticality in 2 directions (parallel and perpendicular to the SW/DW axis).

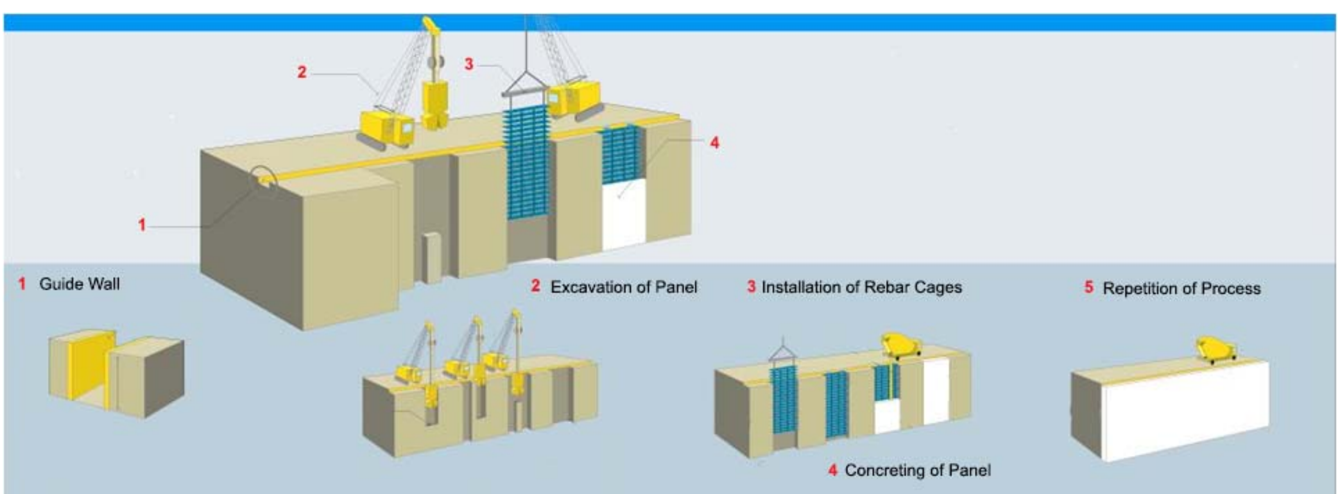

Fig 5. Sequence of SW/DW construction with multiple bites for the Primary panel.

The bi -axial verticality and tilting of the panel during the excavation is usually measured in real time with bi-axial inclinometers easily installed in the clam-shell. See Fig. #6.

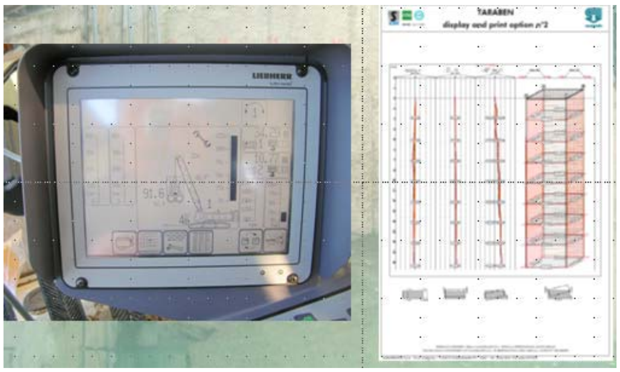

Fig. 6 Verticality display in real time and data graphs.

Generally the bi-axial verticality and tilting is guaranteed with long hull to assist with the correct balancing of the weight of the tool. Small verticality corrections are possible, adjusting the valves at the bottom of the excavation, or adjusting the number and shape of the teeth.

The excavation with clam-shell is carried out with the bentonite slurry "static" and not re-circulating as happens with the hydromill. During the excavation the level of the bentonite slurry is always kept close to the level of the working platform.

The clam is used to remove the soil, partially mixed with bentonite slurry, to the surface. Consequently its productivity, with respect to the hydromill, increasingly decreases with the depth.

In the case when boulders are found during the excavation, a chisel can be used to break them up. If the boulders are of unusual dimensions, explosives may also be used. In both cases delay in the excavation and over-consumption of concrete can occur.

2.2) Excavation with Hydromill

In the case of harder soils, or in the presence of frequent boulders, or soft rock, or when deep excavation with a high degree of verticality is required, a hydromill can be used.

Tests of SW/DWs 250 meters deep using a hydromill have been conducted and several case histories of SW/DWs 120 meters deep, mainly in dam cut-offs, are present in the technical literature. See Fig. #7.

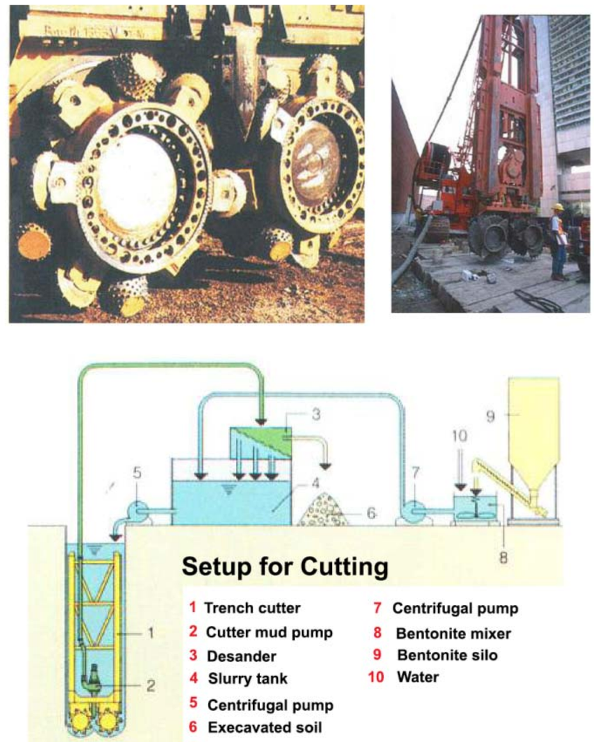

Fig. 7 Hydromill and typical site installation

The site installation is, in this case, much more complicated with respect to the use of a clam-shell. The material excavated is brought to the surface through the bentonite slurry (reverse circulation) and the bentonite slurry is always circulating during the excavation.

Numerous additional pumps, bigger de-sanding units and stocking tanks are in this case required.

Before the start of the excavation with the hydromill a pre-trench is required, usually done with a conventional mechanical clam-shell, to reach a sufficient depth so that the re-circulation pump (usually installed between the cutters) can start working.

Measurement of the verticality is guaranteed with similar bi-axial inclinometers used with the clam-shell tools and corrections can be done rotating the wheels of the cutter with different speeds. Verticality can be also corrected using special hulls installed on the body of the hydromill.

3) Concreting

Once the final designed depth is reached, after the removal of the clam/hydromill, the steps are as follows:

3.1) If bentonite is used, sand content in the slurry is measured and de-sanding of the panel may be necessary. See table #1, with recommended values of slurry.

	Fresh bentonite slurry	Bentonite slurry during excavation	Bentonite slurry before tremie of the concrete
Density (t/m3)	< 1.10	<1.25	<1.15
Apparent viscosity (Marsh-seconds)	32-50	32-60	32-50
Pressure-filtration (ml)	<30	<50	-
pH	7-11	7-12	-
Sand content (%)	<3	<6	<4

Table 1. EN 1538 proposal values of sand content for different SW/DW excavation phase.

The de-sanding is usually done with air-lifting and/or submersible pumps and/or through the tremie pipes. In cases where hydromill is used the de-sanding is done directly, keeping the cutter at the bottom of the excavation and pumping fresh bentonite slurry.

3.2) Joints.

One of the most delicate points of the final wall, in terms of impermeability, are the joints between Primary and Secondary panels.

Several possibilities are available to increase the possible path of the water between the part excavated and the part in contact with the soil, such as installation of sheet or H piles (to be recovered or left in place) with or without a plastic water-stop, or simple pipe, as shown in Fig. #8.

Another simple way to protect the joints is not to install any sheet-pile or pipe, but instead to carry out along the join (in the part not to be excavated) small columns of jet grouting. This system is more expensive but allows the penetration of the grout mix inside the joints guarantying their impermeability. Jet grouting outside the joints is also a common way to repair in case of defective execution of the joints.

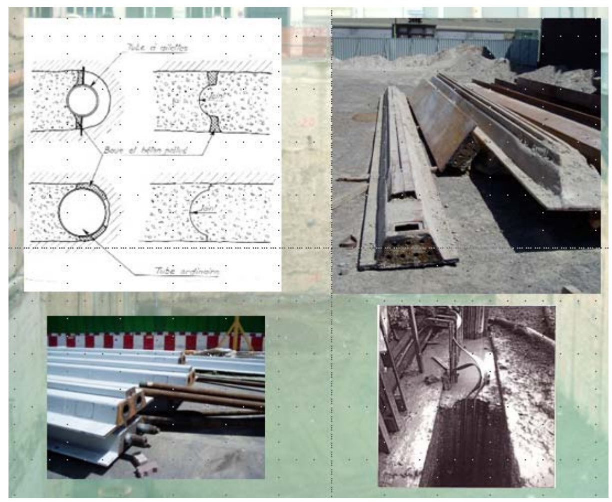

Fig. 8. Joints with simple pipes or sheet piles with or without plastic membrane.

3.3) Rebar cage installation.

Once the joints are installed, if required, the rebar cage is installed. The rebar cage is usually constructed in several sections, depending on the depth of the SW/DW, welded, tied or coupled.
It has been demonstrated and proven that the bond rebar cage/concrete is not affected by the bentonite slurry.

Particular attention should be paid to the design of the rigidity of the rebar cage that will be lifted and installed with the aid of a service crane. Centralizer should be installed to keep the rebar cage at the center of the excavated panel, and to avoid contact with the soil. See Fig #9.

Fig. 9 Lifting and installing a rebar cage.

3.4) Tremie of the concrete.

Tremie of the concrete is usually done from the bottom with adequate tremie pipes (25 to 35 cm diameters), with contemporary pumping of the bentonite slurry or polymer from the panel.

For a single bite panel one tremie pipe is sufficient, for multiple bites (approx 6 meters long), 2 or more tremie pipes would be required.

Concrete to be used for SW/DW shall follow the local standard CSA A23.1 / A23.2 – 04 (ENV 206 in Europe).

The maximum aggregate dimension shall be 32mm or 1/4 of the inter-space between the rebar. Usually the content of cement is between 350 kg/m3 or 400 kg/m3 for maximum aggregate dimension of 32 or 16 mm, respectively. Slump should be (recommended values) between 180 and 210 mm.

Depending on the type of soil and the correct tremie procedures the concrete surface may be not perfectly smooth and additional finishing of the face (milling, grinding, sacking or parging) may be required.

3.5) Demolition of the guide walls after the concrete has cured.

Fig. #10 shows a completed and excavated SW/DW.

Fig. 10 Example of a SW/DW excavated

QA/QC

Usual QA/QC procedures are used for this kind of work, such as:

- setting out of the position of the wall, guide walls and panels/joints,
- water, bentonite and concrete,
- fresh bentonite,
- excavation (continuous monitoring and recording of the excavation parameters with the hydromill) and verticality,
- bentonite slurry before installation of rebar cage,
- installation of sheet-piles or simple pipes for the joints,
- lowering reinforcement cages,
- concreting, procedures and samples.

Design

While it is not the object of this paper to enter into the details of the DW/SW design, below is a brief summary.

The analysis of a flexible diaphragm wall is a classic example of interaction soil-structure. The interaction between the soil and the structure depends on the applied load of the soil and the reaction of the structure.

Design of diaphragm walls requires experience and understanding of the principles of both soil mechanics and structural engineering.

A proper design must allow for the knowledge of the properties of the soil (geologic profile, groundwater, geotechnical parameters) and for the presence of whatever boundary conditions exist: neighbouring buildings, facilities and surcharge loads.

Other specific problems affecting deep excavations are given by risk of soil flows from the bottom in weak soils, hydraulic piping, and the risk of bottom excavation heave in the presence of an artesian aquifer. Only an experienced foundation specialist, in situations involving these topics, can make reliable estimates about the feasibility and affordability of the excavations.

Classic evaluations of earth pressure diagrams are used for the structural design of a SW/DWs, as well as prediction of its displacements. See Fig. #11 and 12.

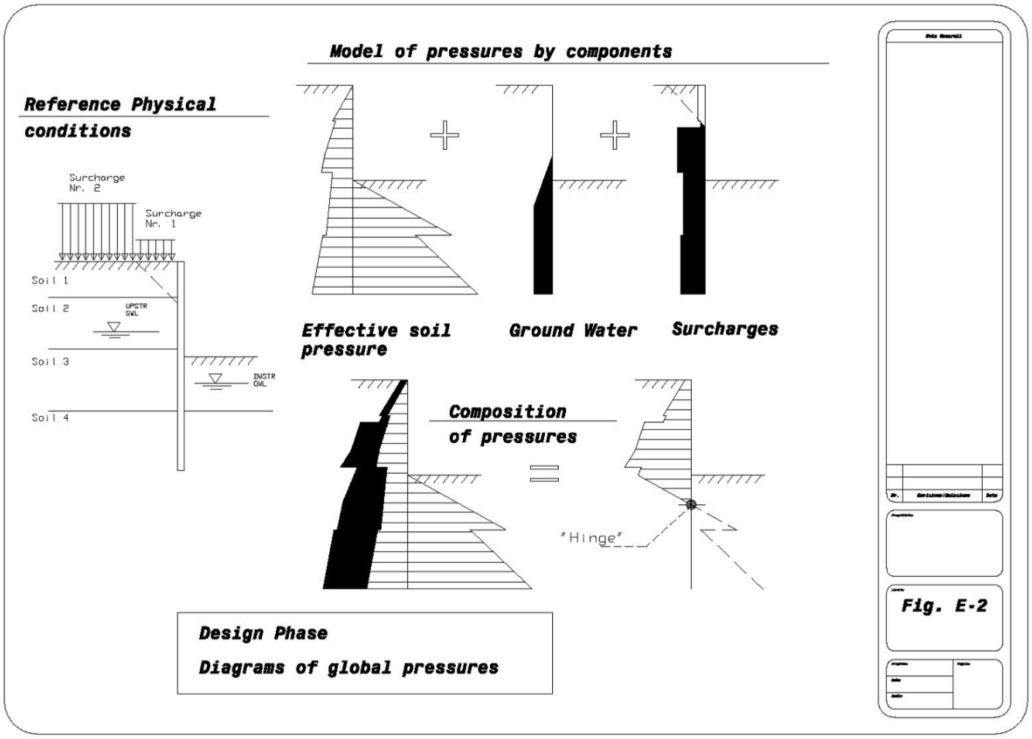

Fig. #11 Usual diagrams of pressures acting against a vertical wall.

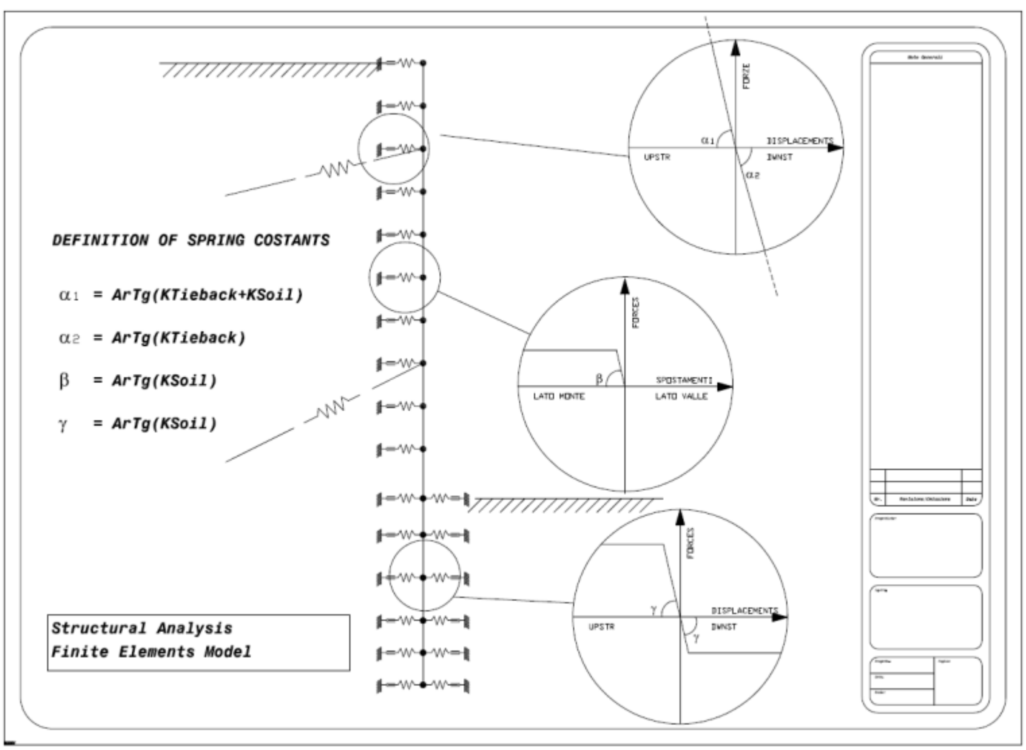

Fig. 12 FEM modelling of diaphragm walls

Applications

Multiple applications and case histories of SW/DW, around the world, are available both for permanent and temporary utilization, such as:

- underground basement or parking,
- subways,
- underpasses or overpasses,
- shafts,
- maritime applications such as piers and wharves,
- retaining walls,
- simple foundations (barrettes),
- impervious positive cut-off wall usually for dam and environmental purposes.

Shapes such as square, rectangular, circular or elliptical are possible. See Fig. #13.

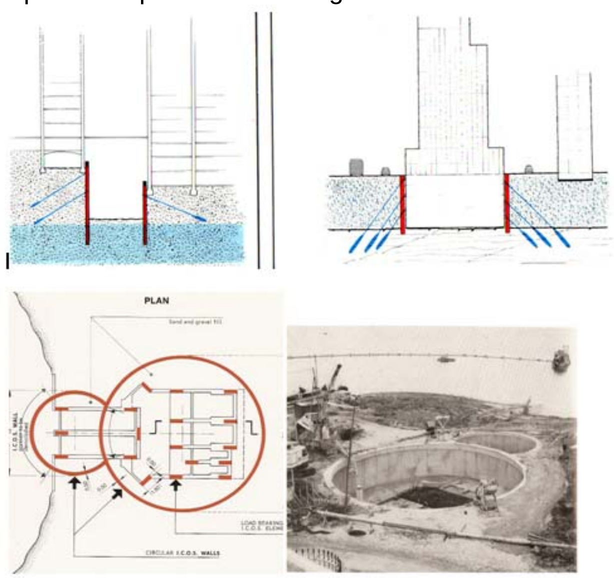

Fig. 13 Some application and shapes of SW/DW

Advantages and Benefits

There are multiple benefits in using SW/DWs for permanent excavation support, such as:

- Facilitating the excavation below groundwater while eliminating dewatering,
- Providing impervious watertight concrete walls,
- Eliminating vibro-densification in case of seismic conditions in some cases.
- Providing structural stiffness which reduces ground movements and adjacent settlements during excavation,
- Providing load bearing, transferring loads to the underlying layer. (3)

In addition Slurry Walls/Diaphragm Walls can:

- accommodate connection to the structure,
- be adapted to both anchors or internal bracing,
- be constructed to a depth up to 120 meters, through virtually all types of soils/rocks, with great control over geometry/continuity and without vibrations. (4)

SW/DWs:

- are installed before the excavation commences,
- are the basis of top-down, or cut and cover construction. See Fig. #14.

Cost

The cost of a DW/SW is, usually, in the order of 1,000/1,300 $/m2 and it depends mainly on the thickness, depth and quantity of anchor/bracing necessary for the excavated structure.

This cost can not be compared with any conventional British Columbia shoring application such as shotcrete/anchors, jet grouting/anchors or secant piles/anchors as all these systems are applicable in different soil conditions and they are not "permanent" earth retention systems.

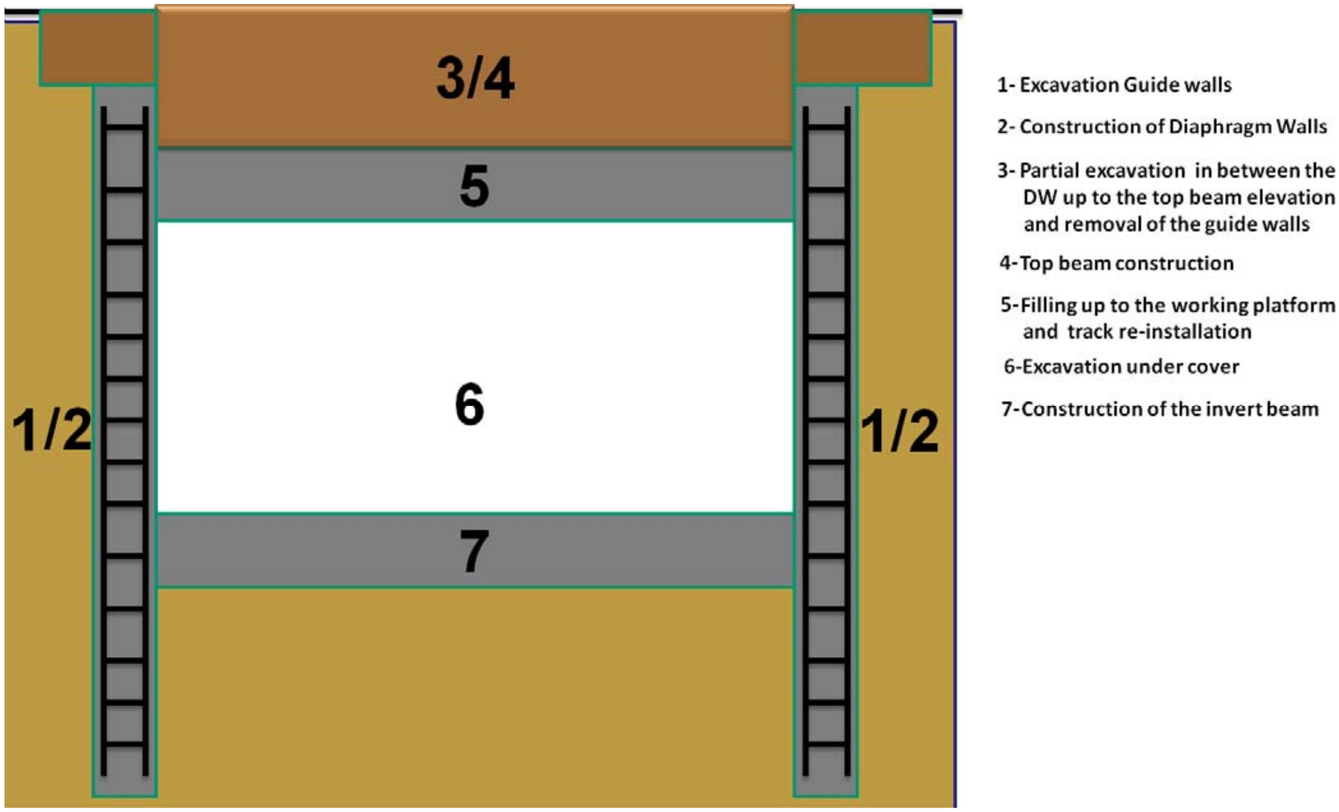

Fig. 14 Top down construction. "Milan System".

Conclusions

Several SW/DWs have already been constructed in the lower mainland mainly for cut-off walls for hydraulic purposes and/or shafts. No deep basements, as for example in Richmond, have been constructed yet, where the perfect conditions are present for this kind of specialty construction methodology: sand/silt/clay and very high water table.

Ref.

(1) - EN 1538 - Execution of special geotechnical works- Diaphragm Walls
(2) - KB International brochures
(3) - Diaphragm walls: standard, dimensioning and practical examples. Marco Russo- Lombardi SA, 2005
(4) - Diaphragm walls- Thomas D. Richards Jr. P.E. - Nicholson, 2006