The Use of Diaghragm walls to Reduce Risk in Deep Excavation

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SUMMARY Failure in deep excavation can be divided into two main categories: - Lateral Failures, - Bottom Failures. The paper will show how the use of diaphragm walls minimizes the risk in both conditions because this construction system results in a very rigid and watertight perimeter wall that can be extended below the intended bottom of the excavation. Furthermore all construction is done from the ground level, so that when the excavation is carried out the retention system is already in place. A detailed description of application of this technique in circular structure is offered, with design considerations. A brief explanation of the construction method and equipment is offered to help in understanding how the stated results are achieved.

1. INTRODUCTION

Construction, as we all know is one of the riskiest industries, and its foundation segment is at the leading edge.

When we talk about risks we talk about a subject which is neither good nor bad, it is a fact, which properly understood, can be reduced (at a cost) to acceptable levels; and while there is no practical way of eliminating it, risk management consists in finding an acceptable area within the risk/cost curve where an acceptable increase in cost produces a substantial reduction in risk.

Risk in foundation construction does not only have economical implications but, unfortunately, can often be measured in human lives, and while one could make risk-reward calculations when only economic factors are involved, one cannot knowingly consider a construction system which inherently exposes human lives to danger no matter how cost effective such a system might be.

Hence, from time to time, new techniques can become prevalent, not because they are cheaper, but because they are safer. To give but just two examples: The practical disappearance of hand dug compressed air tunnelling in favour of mechanical moles and the gradual reduction of timber sheeted excavation for utilities and pits in favour of trench boxes, hydraulic shoring systems and the like.

The tendency, in essence, is to remove the worker from being in harms way as much as possible and rely on technology to make conditions safer in advance of each construction phase.

In order to illustrate how those principles come to bear in diaphragm wall construction, I shall briefly describe for those who are not familiar with the technology how the work is accomplished.

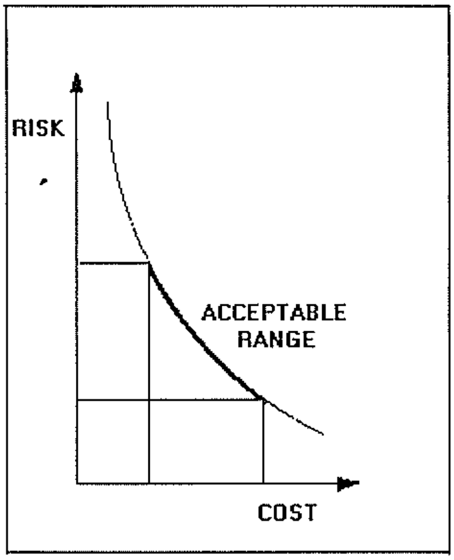

Figure 1 Risk vs Cost

2. DIAPHRAGM WALL

A diaphragm wall is an excavation in unstable soil, supported by a fluid which is constantly kept at ground level, in which a reinforcing cage is introduced, and which is later backfilled with concrete. The resulting reinforced concrete wall segment, a "panel" in the diaphragm wall lexicon, has been constructed to any practical depths (several examples in excess of 100 metres have been built) through any type of soil (ranging from soft organic to hard rock), with various planimetrical shapes (linear, cross, L.T. etc) in thickness ranging from 600 mm to 1500 mm and length of panel ranging from 2.5 to 10 metres.

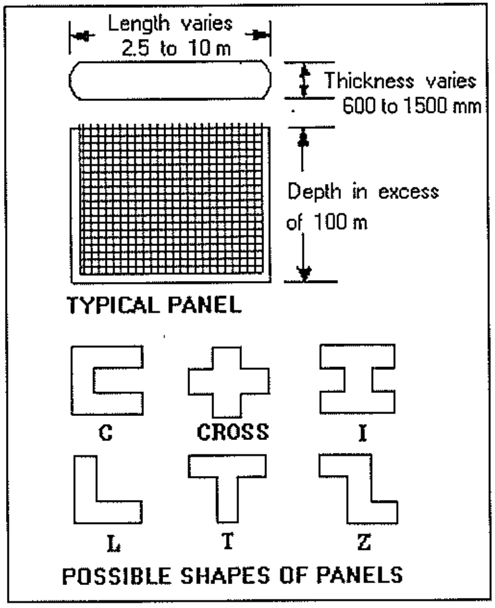

Figure 2 Diaphragm Wall

The planimetric flexibility of the wall allows for irregular contours and innovative designs and solutions.

The construction of those walls is done in the following manner:

3. GUIDE WALLS

Two guide walls are constructed at grade, fulfilling the following functions:

a. Guide the excavating tool
b. Avoid superfical ground unravelling
c. Provide support as well as vertical and horizontal bench marks for the reinforcement cage.
d. Provide reaction for the hydraulic jacks which pull the end pipes.

4. EXCAVATION

Excavation is begun between guide walls, while supporting fluid is pumped into the hole and kept always within 600 mm of the surface. The supporting fluid most commonly used is bentonite mud, although recently the use of polymers, with or without bentonite added, is gaining increasing popularity. The excavation is carried out with a variety of tools, most commonly mechanical and hydraulic clamshells. These tools provide a continuous sampling of the soil around the perimeter of the site, which is helpful in performing a safer and more economical mass excavation.

4.1 When excavation has reached the desired depth, the fluids are thoroughly desanded, stop-end pipes are positioned and a reinforcing cage, fabricated on the ground in advance, is lifted and inserted by a crane into the excavation.

4.2 High slump concrete is placed by tremie from the bottom up, displacing the fluids, and the stop-end pipes are pulled after the end of the pour to create joints with the adjacent panels.

This schematic and necessarily simplified description of the technique shows how a "panel" is constructed and gives the necessary elements to develop the consideration which are the main subjects of this paper. Obviously, a technique which has spawned an industry existing for over 40 years has branched in many directions and developed many aspects that are outside the scope of this presentation, but the bibliography gives several references which the reader can consult to deepen his or her understanding of this construction method.

4.3 Risks in Deep Excavation

Deep excavations fail by lateral failure or bottom failure. The following will discuss both failure modes and how the use of diaphragm walls is a valuable tool to minimise risks.

4.3.1 Lateral Failures

Lateral failures can in turn be divided into two main categories

a) Failure of the lateral support system
b) Failure due to loss of ground outside the excavation.

4.3.2 Failure of lateral support system

Lateral support systems are numerous, but in essence they consist of one of the following :

A Permanent or temporary systems totally installed from the ground level (e.g.diaphragm walls, sheet pile and, tangent or secant pile walls).

B Systems installed as the excavation is advanced (e.g soil nailing).

C Combination systems (e.g "H" beam and lagging).

From a safety standpoint, any system which can be totally constructed from ground level, resulting in an excavation which is protected and insulated from the surrounding area while being performed is inherently superior to a system which needs to be built as the excavation proceeds downward.

Indeed, in situations where there is a high water table that cannot be lowered economically (high flows) or practically (high settlements around the perimeter) B or C systems may not be possible. Of systems constructed from ground level precedence will go to a system which is more rigid (Diaphragm wall and tangent or secant piles vs sheet piles) as these minimise lateral movements and the need for closely spaced supports and one which also gives a better guarantee of continuity and watertightness (Diaphragm wall vs. secant or tangent pile wall).

Needless to say a perimeter wall needs to be supported in some fashion or other and here too the Diaphragm Wall offers the best advantage in the choice of the support system available. Its internal rigidity allows for the use of longer unsupported spans both horizontally and vertically, thus minimising the number of braces and/or tiebacks which cluttter or slow down the excavation. Its horizontal rigidity eliminates the need of horizontal distribution walers needed with other construction methods. The structural and planimetric characteristics of the wall allow for design where the wall (straight or built with T-sections) can act as a cantilever for high unsupported spans. Its capacity for absorbing sizable compressive loads lends itself to design solutions of circular or eliptical walls which are self-supporting and need no bracing or distribution rings during excavation. It is this particular application which epitomizes all that can be gained by using slurry walls. It is well known that, shafts, especially in difficult soils or under water and carried out to considerable depths, are complicated and potentially dangerous structures to construct. This is why structures are designed and built by the slurry wall method. A circular slurry wall offers the advantage, as do all types of slurry walls, of being in place prior to commencement of the excavation. The soil support system does not need to be continuously constructed during the excavation making both operations simpler and safer from a site management perspective.

Perhaps the most attractive feature of a slurry wall in such cases is that these structures can be designed to be fully self supporting. Once the slurry wall has been built from ground level, the excavation can proceed within the wall, completely uninterrupted, with a dewatering operation limited to pumping out only the water trapped within the volume enclosed by the shaft.

While the excavating equipment used to build slurry walls lends itself to the construction of rectilinear structures, proper planning and design can create circular structures comprised of many short straight chord elements. Such structures come very close to perfect circles and, in fact, within the thickness of the wall, a perfect circle of concrete can be delineated.

Consequently these structures can be designed as cylinders with the majority of the loads taken in compression.

The methods used to design the shafts vary and depend on the diameter and depth of the shaft as well as on the length of the chords used to approximate a circle. Obviously, the larger the shaft, the larger the compressive loads in the wall. The concrete in the walls may or may not require reinforcing for these axial loads; agin; this is primarily a function of the shaft size.

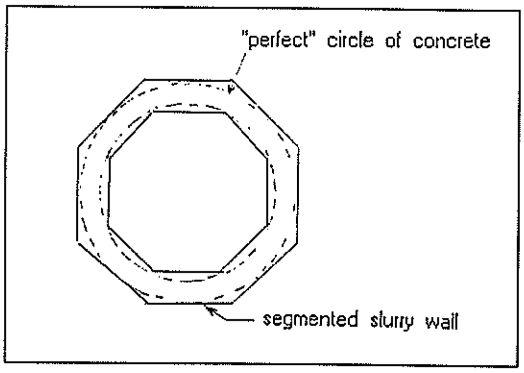

Figure 3. Circular Example

There are, essentially, two ways to place the slurry wall panel joints with respect to the chords. Either the panel joint can be located at the vertex of two chords and each chord is one slurry wall panel or, alternatively, the panel joint can be placed at the centre of a chord and each vertex is monolithic within a panel. For the second option, the chords tend to be longer as the clamshell bucket used in excavating must be able to take two "bites" in each chord. The choice of the panel joint layout again depends on the shaft size and the loads.

A perfect circle under a uniform load will act in pure compression. In a multi-sized polygon, like a slurry wall shafts bending moments develop within the chords in addition to the compressive forces. The design approach for carrying these moments depends on the location of the panel joint.

There are two approaches for a shaft with the joints at the chord vertices. Ideally, an arch can be inscribed in the panel, and the concrete designed to carry only compressive loads.

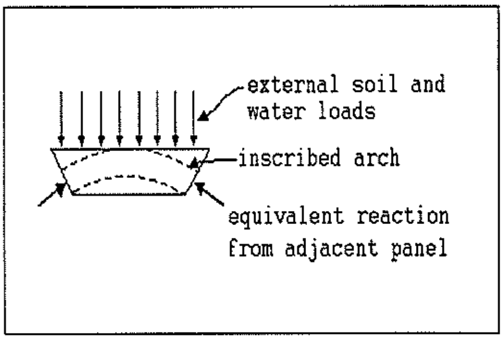

Figure 4 Shaft Joints

In such a case the stability of the panel must be considered, i.e. whether the angle at the vertex is large enough to ensure support of the panel. Alternatively, a more conservative approach will combine simple span bending moment with the axial loads, and the required reinforcing is detailed accordingly. For either approach, stability of the joint can be ensured by using wide flange sections or end stops at the joints, which become a part of the permanent wall.

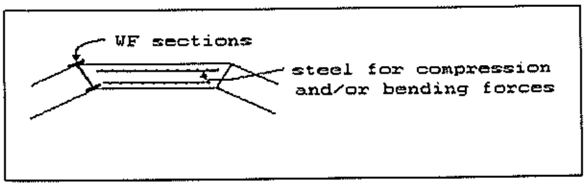

Figure 5 Panel Stability

If the panel joints are placed at the end of the chords, the analysis must consider these as pin connections. In a monolithic polygon moments develop at the vertices and at the center of the chords in the same proportion as moments in a fixed end beam.

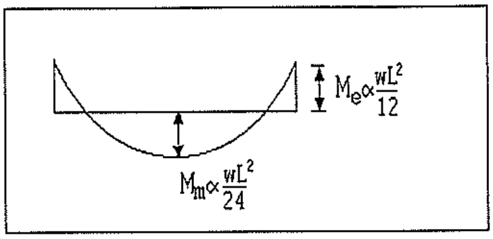

Figure 6 Panel F.E Moments

Depending on the shaft geometry, mainly the included angle of each chord, the unreinforced joint can be shown to carry a bending moment creating an equal and opposite stress to the compressive load.

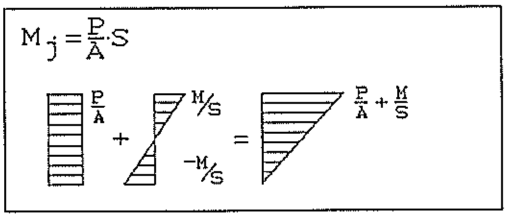

Figure 7 Joint Stresses

This moment capacity may exceed the center moment of a fixed beam, in which case it is assumed to carry only this moment (i.e 1/3 of the simple span moment). If the joint cannot carry the full one third of the simple span moment, excess moment will be redistributed to the vertex. Therefore, the vertex is designed to carry either two thirds of the simple beam bending or the entire simple beam moment less the capacity of the joint.

$$Mtot = \frac{wl2}{8} \qquad (1)$$

$$\text{at best } Mj = \frac{wl2}{24} \qquad Mv = \frac{wl2}{12} \qquad (2)$$

and in other cases

$$Mj = \frac{P}{A}.S \quad \text{and} \quad Mv = \frac{wl2}{8} - Mj \qquad (3)$$

The reinforcing for such panels is designed to carry the combined axial load and bending moment at the vertex.

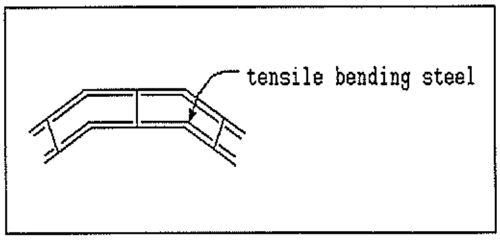

Figure 8 Reinforcing

The above description explains, on a very simple level, the design concepts of such circular structures. Detailed, three dimensional finite element computer models have been used to analyze such shafts. These models can precisely analyze the effects of unbalanced loads inside and outside the shaft due to uneven excavation and surcharges, respectively. The models can also be adapted to study the effects of verticality tolerances, i.e. if the overall structure becomes less than a "perfect" circle. These models can also allow for any vertical forces on the wall. While these models have shown slightly higher loads in some cases than those found in the rudimentary analysis outlined above, they have provided validation of these simple models. An actual design will use loads found in a computer analysis, but will detail the wall and reinforcing to carry the loads using the methods outlined above. Furthermore, comparisons of two and three dimensional models have often shown the vertical effects to be negligible, and, in fact, these structures can usually be designed fairly accurately using only two dimensions in the model. Again, the choice of the model will depend on the shaft geometry, specifically here the aspect ratio of the cylinder. A long thin cylinder can be modelled in two dimensions while a wide shallow shaft should be studied in three dimensions.

It has been shown that self supporting circular slurry walls present many advantages for constructability without presenting an overly complex design problem. These structures, by their nature, are highly indeterminate and the technique offers a safe and easy method for soil support.

Lastly, since the wall can be utilised as the permanent foundation wall, it lends itself to a top-down construction method (recently more and more popular in the U.S., Europe and the Far East) which allows for the simultaneous construction of the structure in elevation while the foundation is being excavated. Then the diaphragm wall is supported by the permanent floor system which is constructed as the excavation proceeds.

4.3.3 Failure due to loss of ground during excavation

Deep excavations, especially in unstable soils and in the presence of high water table, are particularly sensitive to loss of ground from outside the perimeter.

Thus a system which guarantees a watertight barrier around the site avoids the need for lowering the water table, with the often concomitant result of settlement of streets, movement of adjacent buildings and damage to utilities. It also gives a better chance of preventing sudden inflows of water or material which can happen when less reliable systems, allegedly watertight, fail (e.g sheet piles jumping interlock, secant or tangent piles having a gap between them.) This is not to say a diaphragm wall cannot have defects, but it is a technique inherently safer and easier to accomplish with good standards of workmanship.

Proof of this assertion is that in many European countries and frequently in North America, building codes accept that the use of a diaphragm wall obviates the need for underpinning adjacent structures which is a requirement when other construction methods are utilised.

5. BOTTOM FAILURE

Bottom failures are caused either by "heaving" or by untreatable water-carrying seams.

Diaphragm walls can easily be designed to obviate the first problem by embedding the wall below the bottom of the excavation for a length which creates a circumscribed mass of soil of sufficient weight to avoid blow up of the bottom.

In this respect, diaphragm wall watertightness and the ability to be built in different ground conditions are advantages over other systems. The capacity, for example, of going through boulder strata to reach the required depth is a characteristic that other systems have difficulty in matching.

As far as controlling water from a "leaky" bottom formation, a diaphragm wall is no better than any other watertight barrier carried to that level, except that it is easy to incorporate grout pipes. This allows drilling and grouting below the bottom of the wall and into the water carrying formation in an easy and cost effective manner.

6. CONCLUSIONS

A diaphragm wall is an excellent way to diminish the risk of a deep excavation in difficult soil conditions, especially in the presence of a high water table. The cost of such a superior retention system is more than justified when the diaphragm wall is designed to take advantage of all its properties:

It is a permanent retention wall, incorporated into the structure.

It can be loadbearing.

It is a waterproof system.

It obviates the need for underpinning adjacent structures.

It has inherent rigidity which results in an efficient support system.

It has planimetric flexibility lending itself to imaginative design solutions.

It is apparent that such a construction technique has earned its rightful place in the "bag of tricks" of competent designers, since it provides a safe and cost effective solution to the problem of difficult deep excavations for building foundations, subway cuts, pump stations, access shafts and other underground structures.

7. REFERENCES

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