NATIONAL UNIVERSITY OF SINGAPORE

BU2483

CONSTRUCTION TECHNOLOGY 2

INNOVATIVE DIAPHRAGM WALL SYSTEM AT 'THE SAIL @ MARINA BAY'

Submitted by:

Azlifah Binti Sarmidi	U054907E
Diana Lai Ngiik Chui	U054840L
Ho Bee Lan	U055009N
Jiang Ping Ping	U054867P
Lee Sing Yee	U054857M
Li Sai Ting Wayne	U054863M
Nur Aliyah Bte Khamis	U054909A

Table of Contents

Section I: Introduction

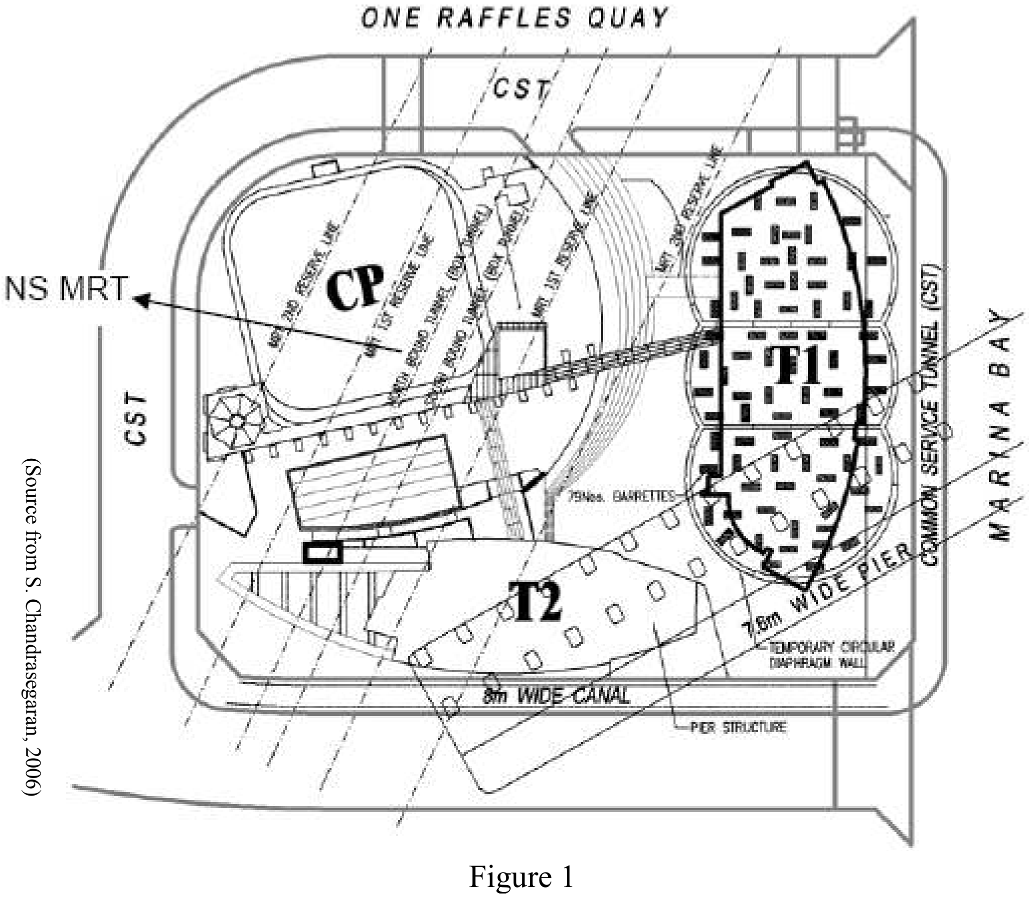
Singapore, a small city island with limited land space poses various challenges for the development of the Sail @ Marina Bay. This paper will focus on the innovative peanut-shaped diaphragm wall construction in the basement of the Sail, which has not yet being applied in the history of Singapore construction industry. Moreover, we will analyse and justify the use of peanut-shaped diaphragm wall construction. Furthermore, we will also discuss some constraints that were encountered in the construction of this innovative diaphragm wall construction technique.

Living in a rather monotonous city canopy, there is no tallest building ever built in the sea of tall buildings in Singapore till this global waterfront development of the Sail @ Marina Bay. It is a private residential development undergoing its construction in the marina bay area of Singapore. Overall, this development consists of 2 residential towers of 70 and 65 storey with 1 basement under Tower 1 for retail space Moreover, its site area is covered with hydraulic fill with a thickness ranging from 6m to 10m and up to 35m deep Kallang formation, which comprising very soft Marine Clay and fluvial sand underlain by Old alluvium or Fort Canning Boulder Bed. Initially, conventional methods are suggested for the basement, which requires the toe of the temporary or permanent retaining walls to be founded in the competent soil layer so as to achieve adequate mechanical stability as well as enough safeguard against basal heave (S. Chandrasegaran, 2006).

These methods of construction and technical solutions are even being stretched to the limits when the requirements on settlement of adjacent structures and deflection of the proposed retention systems are to be limited to small values (S. Chandrasegaran, 2006). However, the above methods were being rejected and the peanut-shaped diaphragm wall construction technique that was designed by Bachy Soletanche Singapore Pte. Ltd was used for the basement construction at the Sail instead. This was due to the fact that this innovative diaphragm wall construction eliminates the use of strutting, which in turn providing a safer and cleaner working environment, moreover, it saves time for the extremely tight construction schedule imposed by City Developments Limited & AIG J.

1.1 Site constraints

Various constraints are to be overcome during the construction of the Sail. Firstly, the existing NEL MRT line is built across the site, which in turn affecting the wall installation and excavation of the site. As clearly mentioned in the railway protection code, the effect of wall installation and the bulk excavation shall not be more than 15mm movement of the tunnels and 15 kPa stress change. (S. Chandrasegaran, 2006). Secondly, there is an old pier in use before the reclamation work was completed. The pier lies across the site under Tower 1 where the basement has been proposed. Thirdly, a nearly completed Common Service Tunnel (CST) Phase 1 is built near the sides of the site and an existing service tunnel about to be opened in one side of the site *(refer to the figure 1).* Fourthly, it has a restricted working area of 140,000m sq, this adds on the difficulty in carrying out the basement construction. Lastly, the main contractor has also encountered a difficulty in following up with the tight construction schedule which the project needed to be completed within 40 months (Dragages Singapore Pte Ltd, 2007) as required by its client. Due to all these constraints, the basement construction needs to carry out with undue care so as to avoid any disruption on the other services and infrastructures located around the site.



(Source from S. Chandrasegaran, 2006)

Figure 1

Section II: Justification & Evolution of Diaphragm Wall

2.1 Justification

2.1.1 Choice of Retaining Wall

There are a lot of choices of retaining walls to be used in a construction project for examples sheet piles, contiguous bored piles, secant piles and diaphragm wall. Here we will justify each method and explain the reasons of the decision made by The Sail @ Marina Bay.

First, sheet piles are constructed by driving steel sheets into a slope during the excavation stage. This is an economical choice especially when the retention of higher earth pressures of soft soils is required. However, sheet piles have low stiffness and water-tightness. It is not suitable to be applied in the marina bay area where both of these factors are crucial even though it involves low cost. Moreover, sheet piles will generate high vibration to the neighboring areas therefore this method is not appropriate given that The Sail is located in the Central Business District (CBD) area.

Contiguous bored piles (CBP) provide special advantages where available working space dictates that basement excavation faces be vertical. In comparison between these four methods as mentioned above, CBP has medium level of stiffness and water-tightness among the fours. Moreover, it generates low vibration. However, due to the critical working environment in the marina bay, this method is suitable but not the most suitable one to be adopted.

Secant piles come into The Sail's consideration. This method will generate medium stiffness but higher water-tightness among the fours. They are constructed in such a way that space is left between alternate 'female' piles for the subsequent construction of 'male' piles.

Construction of 'male' piles involves boring through the concrete in the 'female' piles in order to key 'male' piles between them. Secant piles generate low vibration and involve medium cost but there is another choice favored by The Sail – Diaphragm Wall.

Diaphragm walls come into The Sail's consideration because of its highest water-tightness. Besides that, the walls have high stiffness and generate low vibration during construction. The only disadvantage of diaphragm wall is its high cost. Nevertheless, due to the tight constraints in the marina bay area, this method is chosen by The Sail. Yet, there is still another decision to be made – the shape of the diaphragm wall.

2.1.2 Why Cellular Diaphragm Wall

The shape of the diaphragm wall plays an important role in deciding its retaining forces, stiffness, water-tightness and the other characteristics. Based on the investigation on the site and geometry constraints, the base stability in soft clays excavation is expected to be better to use circular walls compared to a rectangular wall. Cellular wall system consists of self-supported walls. This is the factor who contributes to its suitability to be used compare to rectangular diaphragm wall.

By using cellular diaphragm wall, the excavation will be strut-free. This will contribute to shorter construction time in the sense that earth removal, steel placement and concrete pouring will be faster compare to the conventional diaphragm wall construction. It saves cost and time on installing and removing steel struts as well.

Besides that, the cellular diaphragm wall will subject only to compression forces which consists mainly of the soil pressure which acting perpendicular to the 800mm thick walls. Therefore, this will further reduce the toe depth which not necessary to reach the firm soil. Cellular diaphragm wall will thus more stable and having less deflections. This is extremely important because of The Sail's location in close proximity to Common Service Tunnel (CST) and Rapid Transit Service (RTS).

Conventional diaphragm wall usually involves the usage of Jet Grout Slab. This is to control lateral deflection of the walls and against basal heave stability along with piles to anchor the forces imposed on them in deep excavations. By adopting the cellular diaphragm wall, the pressure used to cut the soil can be reduced so as not to cause damage to the adjacent structures. Moreover, cellular diaphragm wall will prevent the environment problems for disposal which will always occur in the conventional diaphragm wall construction.

2.1.2 Triple cellular diaphragm vs. Single cellular diaphragm wall

Due to the geometry of the site, triple cellular diaphragm wall is more suitable because of its shape which is more linear as compared with the single circular wall. The following figures will give clearer illustration.

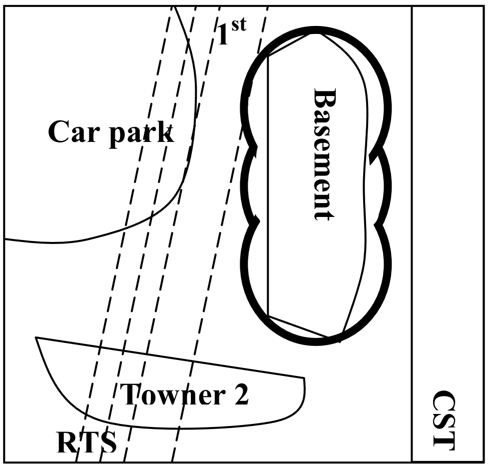


Figure 2

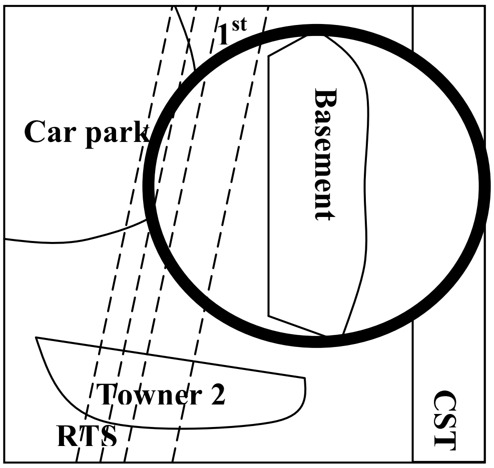


Figure 3

Remarks: RTS = Rapid Transit Services & CST = Common Service Tunnel

In Figure 2, if single circular wall is adopted, the area of the excavation needed is much higher in order to accommodate the linear shape of the basement at the Towner 1. However, if triple cellular diaphragm wall is adopted (shown in Figure 3), the area of excavation is much reduced and it's sufficient to contain the entire basement. In addition, if the area of excavation expanded, it may exceed beyond the MRT 1st reserve line and this is not permissible under the Regulation by LTA.

2.1.3 Bottom-up construction vs. top-down construction


Source from: http://www.skyscrapercity.com

Bottom-up construction will be more suitable in this project because the diaphragm wall which only acted as a retaining wall will not integrate into part of the permanent structure of the Towner 1. The shape of the basement will take the shape of the building but not the shape of the diaphragm wall as shown in the photo. Top-down construction has become impossible when the diaphragm wall is not used as the permanent structure.

From the above mentioned justification, a triple cellular diaphragm wall is adopted at The Sail due to the advantages of using diaphragm wall as the site is with high water table, site constraints and geometry and project tight schedule. In addition, since the diaphragm wall will not become part of the permanent structure, which differs from usual practice, the choice of construction is bottom-up construction.

2.2 Evolution of Diaphragm Wall

The innovative concept of triple cellular diaphragm wall is actually an evolution of the conventional rectangular diaphragm wall. The following three construction projects would illustrate the process of evolution.

The 1997-2B Complex in Robertson Quay adopted the rectangular diaphragm wall constructions. It is the first generation of diaphragm wall where is adopted commonly. The diaphragm walls are supported by struts and this limit the working spaces moreover involves higher cost on the materials and labors.

(Source from :*Bachy Soletanche*, 2005)

The second generation of diaphragm is showed in the work site in Manjung, Malaysia. The diaphragm wall was built in semi-circle with a cross wall connected at the middle. However, since the cross wall is full-length which divide the basement into two parts, casting of basement slab has faced and need more time to cast.

(Source from S. Chandrasegaran, 2006)

The Storm Water Decontamination control basin in Lievin, France illustrates the third generation of diaphragm wall. They are multi cellular diaphragm walls connected by flying beam on top as showed in the picture. One significant characteristic is that the cross wall occupies a smaller portion compare to the construction in Manjung, Malaysia. This will provide extra working spaces for the convenience of workers as well as facilitating the material handling from one cellular workplace to the neighboring ones.

(Source from S. Chandrasegaran, 2006)

By adopting the concept of multi-cellular diaphragm walls mentioned above, a new type of diaphragm wall named "Peanut-shaped Diaphragm Wall" is applied in The Sail. It consists of triple cellular diaphragm wall connected by two flying beam in the middle points. Here we will explain why The Sail adopting a triple cellular instead of a single cellular diaphragm wall.

2.4 Construction sequence

The construction sequence for this innovative triple cellular diaphragm wall is similar to conventional diaphragm wall construction. However, due to the shape of the diaphragm wall, flying beams are constructed instead of struts to provide support for the walls.

"Peanut" shaped diaphragm wall

As mentioned earlier, cellular diaphragm wall is a good choice for this project. However, this project uses three-cellular diaphragm wall instead of single circular diaphragm wall. This is due to the shape of the building. Tower A of the Sail @ Marina Bay is rectangular in shape. This makes a single circular diaphragm wall impossible to be constructed. Three-cellular shape enables a longer span but more stable structure.

The construction steps explained as below:

1. First step is to install the three circular diaphragm walls, followed by installing of cross walls *(refer to Appendix, Figure A)* with cut off level at 94.5mRL. (S. Chandrasegaran, 2006) In general situations, the cross walls are constructed to the same depths as the main perimeter walls. However in this project, there is a cut off area in the cross wall to allow better and obstruction-free working space in the basement construction later on. The cut off area also prevents the obstruction of the pouring of the raft slabs. (S. Chandrasegaran, 2006)

Diaphragm wall installation:

I. First the cellular guide *walls (refer to Appendix, Figure B) are* installed to ensure the circular shape of the retaining wall.

II. Then excavation of trench for diaphragm wall starts. The excavation is adjacent to the CST ventilation shaft. As a result, there are several precaution measures to be taken to account during the designing and commencement stages of the excavation works.

III. The *clamshell (refer to Appendix, Figure C) is used* to cut and remove the soil to form a panel. There is a temporary structure constructed in site to allow the clamshell to lean against it so as to ensure the verticality of the excavation.

IV. Bentonite slurry is poured to stabilize the trench and to support the wall of excavation. (LTA, 2007)

V. Next, the reinforcement-bar *cages (refer to Appendix, Figure D) are* installed into the diaphragm wall. The crane is used to lift the reinforcement-bar cages and to place them within the panel.

VI. Lastly, concrete is poured into the panel to form the panel wall. The concrete is poured using tremie pipes. The location of the tremie pipes are shown in *Appendix, Figure E.*

2. Next, barrettes are installed. The barrettes are the effective rectangular piles that can be orientated to accommodate high horizontal forces and moments in addition to vertical load. (Shanska, 2007)

3. First stage of excavation work is commenced after completion of piling works. After excavation of 1.5 meters to 100.5mRL, capping beams and flying beams *(refer to Appendix, Figure F)* in line with the cross walls are casted (S. Chandrasegaran, 2006). The two flying beams are constructed to support the walls. They also acts as assess bridges in the site. According the information given by contractor, each flying beams are supported with three numbers of kingposts *(refer to Appendix, Figure G)* embedded in to the low cut off cross wall so as to reduce the 28m span.

4. Draw the water table down to 93.50mRL. (S. Chandrasegaran, 2006) Second stage of excavation is commenced down to 94.0mRL after the lowering of water table.

5. Then a three meters thick base slab is casted. This base slab acts as the floor slab and waterproofing for the basement. According to the project manager, the waterproofing of basement in this project is not a crucial element even though the site is located on a reclaimed land. The reasons for it are the three meters thick concrete slab and the high quality diaphragm wall.

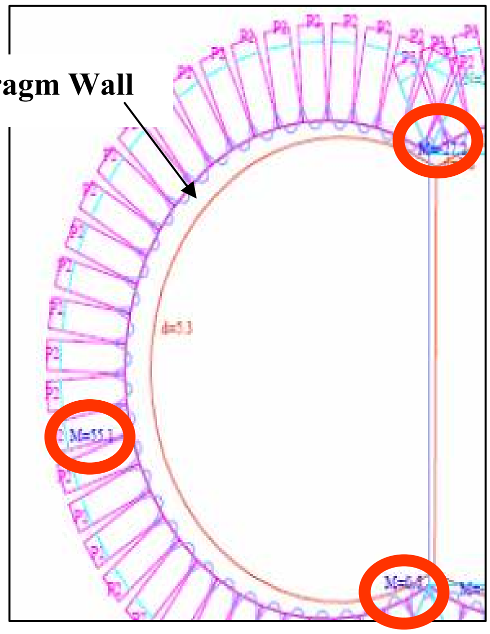
6. Tarpaulin *(refer to Appendix, Diagram H)* is installed and tent is put on top of it. When the base slab is casted, the site is covered with tent to protect the concrete base from direct sun-light and rain.

7. The last step of the construction is to remove the flying beams to facilitate the basement construction.

Section III: Analysis

3.1 Equilibrium of Forces[1]

The equilibrium of forces in the triple cellular diaphragm wall system is analysed using the software developed by Bachy Soletanche which are PAROI 2 and PARIS. The two equilibrium forces which were analyzed are the horizontal and plan view equilibrium. During the analysis of the horizontal equilibrium, the software has shown that a new equilibrium is reached after the removal of the flying beam.



(Source from S. Chandrasegaran, 2006)

As the plan view equilibrium is analysed, it is found that the diaphragm wall is subjected to two non-symmetrical pressures. The sources are from the soil condition, excavation as well as slight difference of water table throughout the site. The following diagram which is stimulated by the software is evidence that different degree of forces are acting on the wall. The moment at both Y junctions are M=27.2 and M=0.5 and on the curved part is M=55.1. Moment is directly proportional to stiffness which the resistance to deflect.

Therefore, different location, the wall is subject to different degree of deflection. However, those deflections are kept less than 10mm which is much lower than the regulation specified by LTA.

The last effects which are analysed are basal heave and water uplift. In order to accommodate the force by basal heave and water uplift and movement in barrette, the top level of the diaphragm wall is increased to +73.50mmRL.

---

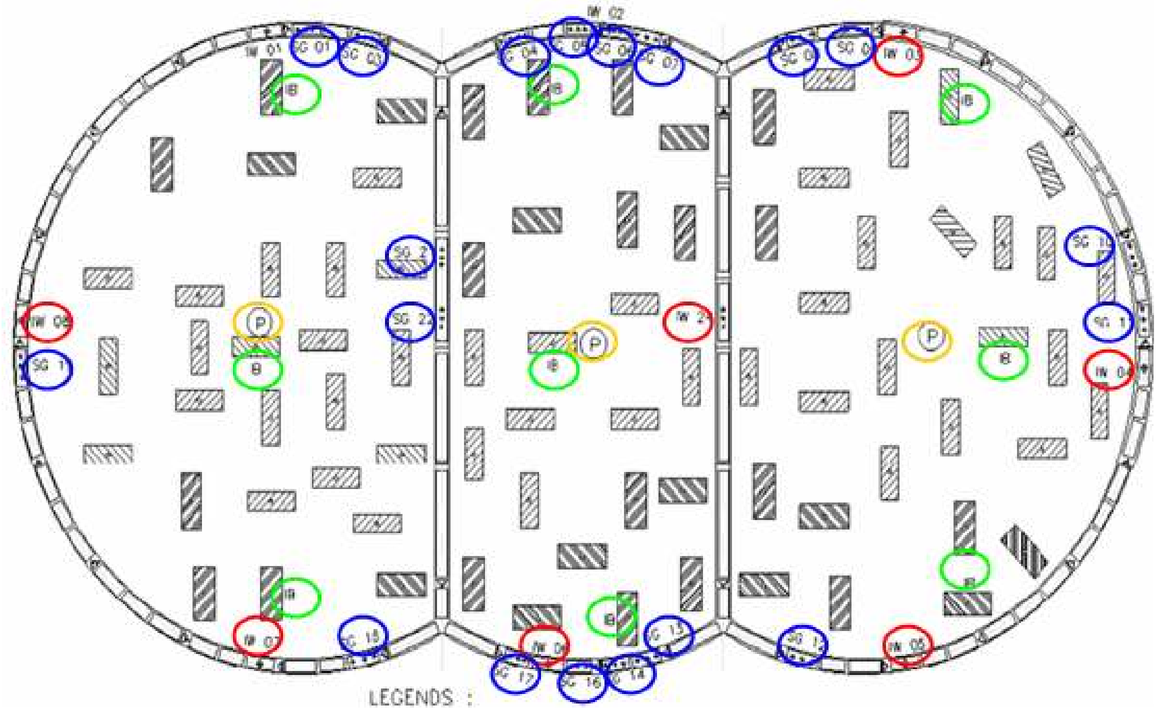
[1] S. Chandrasegaran, 2006 (For full citation please refer to bibliography)

Section IV: Instrumentation

The monitoring instruments used in this project are as same as the conventional method. The instrumentation process is crucial to monitor the excavation work as the site is located next to the MRT safety zones; the excavation was monitored for settlement, basal heave, deflection of the wall and change in pore pressures. Moreover, as this type of retaining wall system was new to Singapore and was installed without the conventional JGP slabs and struts, it was decided to place instruments in the wall, barrettes and the surrounding areas to understand the new system.

Table: Summary of instruments used during monitoring of the excavation

Instrument	Location	Purposes
Strain gauges	Perimeter of the wall	To measure the compressive force along the perimeter one on outer shear link near the soil face and another on the inner shear link closer to the excavation.
Inclinometers	In the wall and in the barrettes piles	To monitor the lateral movements in the wall and in the barrettes
Piezometers	Between the cellular diaphragm wall	To monitor the pore water pressure and manage dewatering
Settlement and Heave Markers	Placed within the excavation pit	To measure the soil settlement during the excavation work



1W= INCLINOMETER IN DIAPHRAM

1B = INCLONOMETER IN BARRETTES

SG = STRAIN GAUGES

(P) = PIEZOMETER

(Source from S. Chandrasegaran, 2006)

Section V: Conclusion

S. Chandrasegaran once commented about the project, The Sail @ Marina Bay in his conference paper that "*Constructing underground structures for buildings or infra-structure elements in very thick soft marine clay like the one encountered in this site is always going to pose challenges to the engineers. With the conventional techniques being stretched to the limits, there is genuine need to look for other alternatives.*" (S. Chandrasegaran, 2006) He has highlighted that whenever there are constraints, we should always do not limit by what we are familiar, but then always look for alternative.

Therefore innovation has become crucial in today's construction industry in finding alternative. No single construction project is identical; hence, we should be flexible and open to the new ideas. Just like from what we learn in this project, the concept of triple circular diaphragm wall is the evolution of the conventional rectangular one, i.e. from a rectangular diaphragm wall, into a circular diaphragm wall and finally use a TRIPLE cellular diaphragm wall as a solution for the construction project. Technology also plays a role to make a challenging design into a reality and thus architects' ideas can be realized. The build-ability and construct-ability of a building comprises the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives.

With the implementation of this innovative way of construction in Singapore, it is a milestone for more new innovative diaphragm wall system to be generated to accommodate different constraints and architectural design of the building. Construction industry is changing all the time and we have to keep ourselves on the track.