Diaphragm Wall Support Deep-Excavations for Underground Space in Bangkok Subsoil

Zaw Zaw Aye, Thayanan Boonyarak
Nutthapon Thasnanipan and Nutthachai Prongmanee
Seafco Public Company Limited
E-mail: zaw@seafco.co.th

ABSTRACT: Diaphragm wall support deep excavation works of some major projects including Bangkok first subway project are presented in this paper. Available literatures related to diaphragm wall and deep excavation works in Bangkok are summarized together with recent research works. Problems and difficulties in construction of diaphragm walls and deep excavation works in early days are reported. The areas of development in diaphragm wall construction and main factors contributed to these are also presented. An attempt is also made to briefly discuss the future trend of diaphragm wall construction and deep excavation works in Bangkok. This paper is intended to serve as a source of reference for the practitioners in the construction industry with regard to the application of diaphragm walls in deep excavation works in urban area of Bangkok.

KEYWORDS: Diaphragm wall, Deep excavation, Underground structure construction, Bangkok

1. INTRODUCTION

As in other major cities, growing land price and need of underground space for commercial and infrastructure developments necessitated deeper underground excavation works in Bangkok. Diaphragm wall as embedded earth-retaining structure is one of the most suitable solutions to facilitate the deep excavation works in urban area of the growing metropolis. The common thickness of diaphragm wall in Bangkok ranges from 0.80m to 1.20m. Though not very common, in some cases, thick diaphragm wall of 1.50m and thin diaphragm wall of 0.50 to 0.60m were also constructed. Toe depths of diaphragm walls are in the range of 16m to over 30m depths depending on the final elevation of the excavation. This paper aims to provide the summaries of the technical data on diaphragm wall construction and deep excavations in Bangkok with particular focus on the progressive development in past decades. Literatures published throughout past 20 years are summarized along with the recent research works. The information and data presented in this paper are based on the author's personal experience, observation from other completed projects and from published literatures.

2. GEOLOGY OF BANGKOK AND SUBSOIL CONDITION OF MRT PROJECT

Bangkok is located in Gulf of Thailand, approximately 40km from the sea. Geologically it is located in the Lower Central Plain also known as Chao Phraya Basin. Lowe Central Plain begins at Chainat, where the Chao Phraya River flows southward through a flat and featureless plain, until it reaches the Gulf of Thailand at Samut Prakarn province with the distance of about 200 km. The wider part of the plain in an east-west direction is about 180 km and the total area is approximately 36,000 km^2 Block faulting in Late Pliocene-Pleistocene formed deep horsts and grabens in the Lower Central Plain basements where thick deposits of Quaternary sediment overlain the basement rocks. The Quaternary sediments are classified into Pleistocene and Holocene deposits. Upper sediments were influenced by sea level fluctuation - deposited alternating layers of clays and sands. Gravel formation can also found in deeper depths. The exact configuration of bedrock of the Chao Phraya Basin is not known. Through the aeromagnetic data and a few wells drilled down to the deeper depths revealed that bedrocks consist of quartzite, gneiss and granite gneiss, gently dipping southwards to the Gulf of Thailand. Subsurface geologic profile of Bangkok is presented in Figure 1.

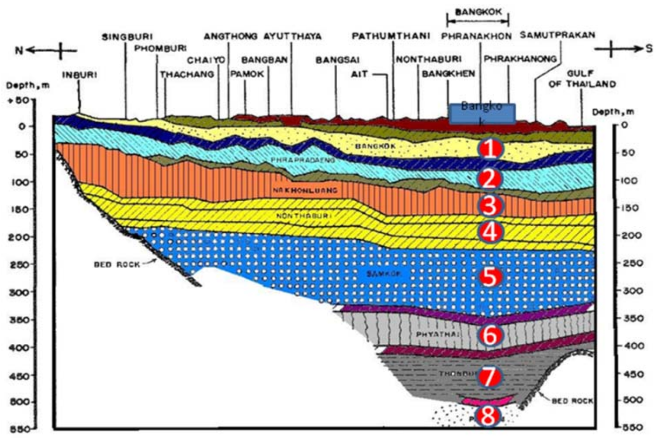

Figure 1 Subsurface geologic profile of Chao Phraya Basin showing location of Bangkok [Layers 1 to 8 are eight main aquifers (sand and gravel formation) beneath Bangkok]

3. SUBSOIL AND PIEZOMETRIC PROFILES IN BANGKOK

Subsoil profile and the present piezometric drawdown condition of Bangkok are presented in Figure 2 below. A typical subsoil profile is relatively consistent in different localities in Bangkok. It is characterized by alternating layers of clay and sand deposits as shown in the Figure 2.

4. THE NEEDS OF DIAPHRAGM WALL FOR DEEP EXCAVATIONS IN BANGKOK

Generally, requirement and selection of basement retaining walls are based on the following factors.

- Depth of final excavation of basement – shallow or deep excavation
- Subsoil condition
- Construction sequence and permanent condition of basement structure
- Environmental conditions and constraints – effect of retaining wall installation and basement excavation to neighbouring properties and structures
- Constructability – availability of space and physical condition of existing site

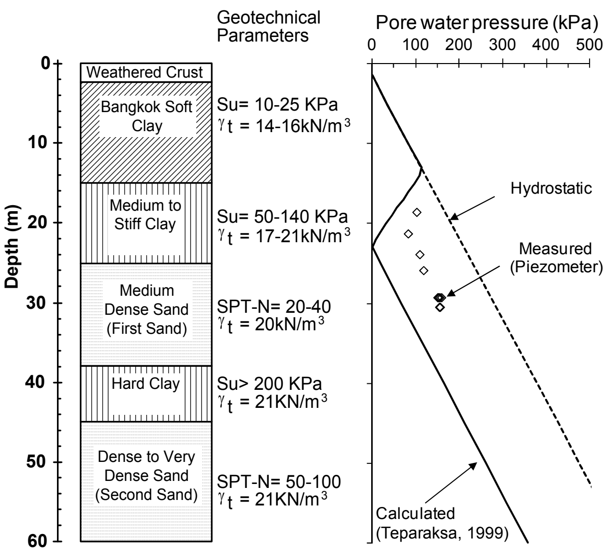

Figure 2 Subsoil and piezometric profile of Bangkok

Peck et al. (1977) defined that deep excavations are those whose depths are deeper than 6m. Sheet piles, contiguous-pile walls, secant pile walls and sinking caisson are alternative retaining structures available in Bangkok for deep excavations. Prevailing subsoil (existence of very soft to soft clay) and ground water condition are the main factors for using diaphragm walls for deep basement excavation in Bangkok. For most of the deep excavation works in urban environment, advantages offered by diaphragm walls weigh more favourably for both technical and economical reasons while other methods have distinct limitations. Major advantages of diaphragm wall are listed below.

- Can be used as permanent structural wall
- Water retainable
- Can be installed to deeper depths and for load bearing element
- Less temporary propping needed
- Can be applied for top-down construction method
- Rigid structure so that ground movement induced by basement excavation is less than other flexible retaining wall
- Vibration and noise generated from installation of diaphragm wall is less than other methods

Key limitations of diaphragm wall can be summarized as follows:

- Diaphragm wall itself is water retainable structure but not 100% water-proof. Additional measures are required if basement required high-grade water-proof wall
- Availability of limited numbers of specialist diaphragm wall contractors
- Finished wall surface is influenced by the subsoil

5. KEY GEOTECHNICAL ISSUES IN CONSTRUCTION OF TUNNEL AND DEEP UNDERGROUND STRUCTURE IN BANGKOK

Key geotechnical issues in construction of deep underground structures in Bangkok are:

- Prevailing subsoil condition
- Groundwater changes
- Ongoing land subsidence
- Tunnelling and excavation induced ground movement

5.1 Prevailing subsoil condition

Prevailing subsoil condition in Bangkok poses some impacts on the project. Table 1 summarizes key geotechnical features of prevailing subsoil and their impact on design and construction of deep underground structures.

5.2 Ground Water Changes

Figure 1 shows eight main aquifers (sand and gravel formation) with combined thickness over 500m. As a result of long term excessive groundwater extraction in the past, from aquifers mainly from 2nd and 4th aquifers (between 100m and 200m), the piezometric pressure has been drawn down from the original hydrostatic profile as shown in Figure 2. Though lower pore water pressure is beneficial to tunnelling and deep excavation works by having less risk of water ingression, careful consideration for long term ground water condition had to take account in design as shown in Table 2.

Comparison of measured and calculated pore water pressure (Teparaksa, 1999) is given (see Figure 2). Measured pore water pressure from pneumatic piezometers indicated that the initial pore water pressure distribution was larger than the calculated one suggested by Teparaksa (1999) but was still smaller than the hydrostatic condition. This is because the assumptions of the calculated initial pore water pressure were based on measurements taken in 1999. A reduction in ground water pumping during year 2000-2011 (Paveenchana and Saowiang, 2012) caused an increase in pore water pressure compared with that in 1999. Physical evidence of recovery of piezometric drawdown was observed in recent deep excavation projects as presented in later section of this paper.

Table 1 Summarized geotechnical features due to prevailing subsoil condition affecting design & construction of deep underground structures

Key Geotechnical Features	Impact on Design & Construction
Thick quaternary deposits (inter-bedded layers of clays and sands up to 400m below existing ground). Presence of thick very soft to soft marine clay	- Need of rigid retaining wall for deep underground structure - Need more attention on ground movement induced by deep excavation
Relatively uniform soil profile	- Less soil boring and testing required - Less complicated in geotechnical design
Ongoing consolidation of soft to very soft clay	- Significant differential settlement between structure with shallow foundation and deep foundation - Need to consider negative skin friction

Table 2 Summarized geotechnical features due to ground water changes affecting design & construction of deep underground structures

Geotechnical Feature	Impact on Design & Construction
Current Condition Drawdown piezometric profile (originated from deep well pumping)	- Less problem with uplift water pressure at base of deep excavation during construction such as need of dewatering
Future Consideration Drawdown piezometric profile will recover to hydrostatic condition	Needed to consider ; - change of effective stress in foundation design - design for floatation of deep

Geotechnical Feature	Impact on Design & Construction
(stopped deep well pumping)	underground structures from higher uplift pressure in future

5.3 Ongoing Land Subsidence

Bangkok is one of the sinking metropolises similar to other major cities situated on thick soft marine clay. Land subsidence of regional settlement has been playing key role in design of buildings and various superstructures – no exemption in design and construction tunnel and underground subway stations as summarized in Table 3.

Table 3 Summary of geotechnical features due to land subsidence affecting design & construction of tunnel and station boxes

Geotechnical Feature	Impact on Design & Construction
- Thick highly compressible very soft to soft clay - Large consolidation settlement in top soft clay layers and less settlement in deeper layers	- Large differential settlement between station box supported by deep foundation and floating tunnel - Large differential settlement between station entrance and surrounding surface - Large differential settlement between deep underground structures, buried utilities and roads, etc.

The decline in piezometric head in the First Sand layer triggered the decline in porewater pressure of the overlying clay layers at the surface. The drawdown gradually propagated upward in the clay layers, and by early 1980s it was well in the lower part of the soft clay layer. Consequently, large consolidation settlement of the clay occurred, which in long term it may constitute a considerable portion of the overall surface subsidence. Monitoring data indicated that approximately 30 to 50% of the total land subsidence in the inner city area was from the compression of the soft and stiff clay layers overlying the first sand layer (Duc, 1999 and Phienwej, 1999).

5.4 Excavation Induced Ground Movement

Deep excavation works generally induced ground movement in different magnitude especially in soft ground. Therefore, in congested urban environment of Metropolitan Bangkok, a systematic process of ground movement prediction, building risk damage assessment and protection are required. Comprehensive procedure of ground movement prediction and building damage assessment applied in the first Bangkok Subway project was reported by Aye et al. (2006) and briefly presented in later section of this paper.

6. DIAPHRAGM WALL CONSTRUCTION METHOD

The diaphragm wall construction method allows for the formation a reinforced concrete wall beneath the ground surface. The construction of the diaphragm wall is carried out from ground level, panel by panel forming series of cast-in-place underground RC walls. RC Guide walls of 1m to 1.5m deep are mainly used to assist the trenching operation. Each panel is excavated by using cable operated mechanical clamshells suspended from crawler cranes or by more modernized hydraulic grabs. Throughout the excavation Bentonite slurry is maintained at the top of the excavated trench for wall stability. On completion of excavation, the Bentonite slurry which may have become contaminated with soil is cleaned by recycling through de-sanding equipment. The reinforcement cages are then lowered into the slurry filled trench, with each unit spliced to the other, to form a continuous cage to the required depth. Tremie pipes are then installed to the base of the panel and concrete is cast from the panel toe up to the required cut-off. During casting the displaced Bentonite slurry is drawn off and stored for reuse. Adjacent panels are then excavated using the same procedure. Stop-ends are used to provide the formation shear-key and continuity between adjoining panels. Figure 3 is a summarized demonstration of process involved in diaphragm wall construction. The selection of panel width is mainly depending upon the available grab size, ground condition and geometric constraints of the basement footprint. Panel width of 3m to 6m are commonly use in Bangkok. Where practical, it is advisable to use same panel width for the ease of preparation and handling of the reinforcement cage.

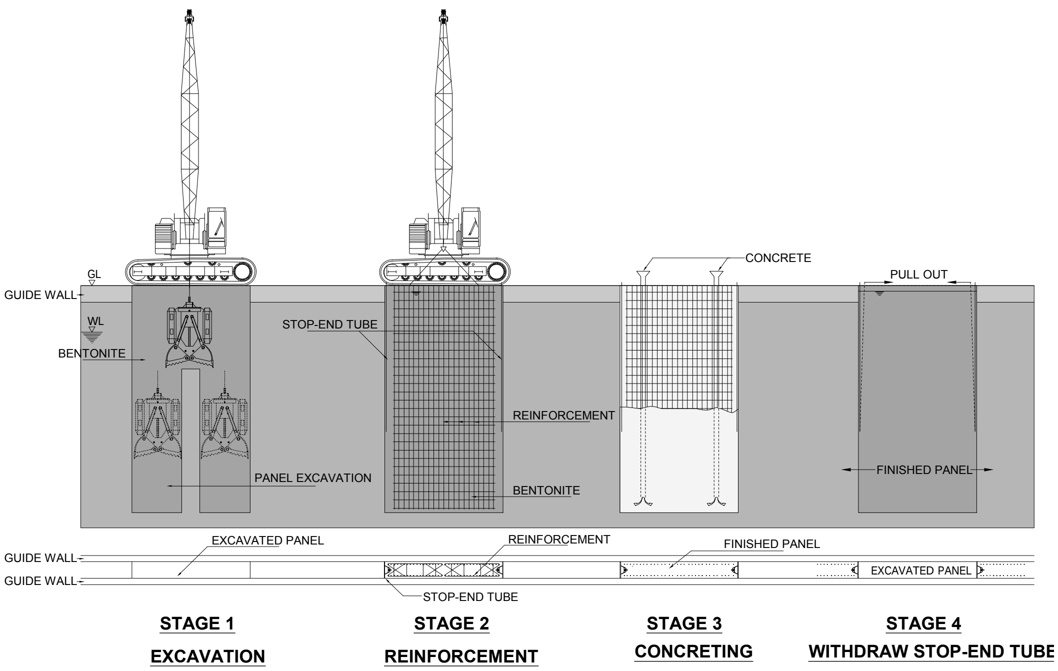

Figure 3 Diaphragm wall construction process

7. OVERVIEW OF DIAPHRAGM WALL PROJECTS IN BANGKOK

The first diaphragm wall in Bangkok was believed to have been constructed in the late 1970s for the basement retaining walls of the Bangkok Bank Head Office Tower on Silom Road. Table 4 summarizes the diaphragm wall projects constructed in the early days.

Table 4 List of the early diaphragm wall projects in Bangkok

Project Name	Diaphragm Wall Dimension (m)		Excav. Depth (m)	Year of construction
	Thk.	Depth		
Bangkok Bank HQ	0.50	14.00	7.00	1977
International Trade Center	0.82	26.00	18.50	1985
Srivara Hightech Tower	1.02	26.00	17.20	1991
Silom Precious Tower	1.02	28.00	20.00	1992
Jewelry Trade Center	0.82	28.00	15.60	1992
Oriental Tower	0.82	28.00	15.50	1992
Sukhumvit 33 Tower	0.82	26.00	14.00	1992
Tharmasat University Library Building	0.80	28.00	12.70	1994

Figure 4 illustrates the embedded length of diaphragm wall in relation to the excavation depth of the projects listed in Table 4. It is to be noted that except shallow excavation required for Bangkok Bank Head Office, diaphragm wall embedded deeper into hard clay layer in all projects constructed in the early days. Figure 5 shows the embedded length of diaphragm wall in relation to the excavation depth of the projects listed in Table 5.

From 1991, with the booming construction industry, usage of diaphragm walls for deep basements of the high-rise buildings in Bangkok has been significantly increased. In year 1997, due to the economic crisis, with significant decline of property sector, diaphragm wall construction was concentrated only for infrastructure projects.

Extensive application of diaphragm wall for deep excavations can be observed between 1997 and 2001 for the first Bangkok subway project where 18 deep stations and associated structure plus some sections of cut-and-cover tunnels were constructed by diaphragm wall. Phienwej et al. (2006) discussed the difference between the length of diaphragm wall and depth of excavation from two contracts of the first Bangkok subway, Chaloemratchamongkhon Line. The authors cited that it is partly due to the difference in design criteria adopted. Figure 6 illustrates the embedded length of diaphragm wall in relation to the excavation depth of MRT Stations. Excavation depth over 30m carried out in Silom Station set the deepest excavation ever done in Bangkok subsoil.

8. DIAPHRAGM WALL CONSTRUCITON PROBLEMS IN THE EARLY DAYS

Basic but extensive problems were experienced in early stages of diaphragm wall construction as summarized below:

- Lack of experienced engineers and foremen
- Limited availability and capacity of equipment
- Lack of skills in operation of equipment
- Limited knowledge and less advanced techniques in the control of bentonite slurry
- Limited knowledge and experience in construction method and related negative impact
- Quality of concrete used for tremie concreting
- Improper construction and quality control specifications and guidelines for local soil
- Improper design for constructability
- Limited availability of performance monitoring equipment (e.g. efficient and reliable inclinometer and other instruments)

Table 5 List of some diaphragm wall projects constructed from 1997 to 2008 in Bangkok (Basement Excavations Deeper than 10m)

Project Name	Diaphragm Wall Dimension (m)		Excav. Depth (m)	Year of construction
	Thk.	Depth		
Charoen Pump Station	0.80	20.00	16.50	1997
Sathorn Pump Station	0.80	20.00	16.20	1997
MWA GMC-7A	0.80	21.00	16.00	2002
Bank of Thailand	0.80	20.00	15.20	2003
Hampton Condominium	0.80	20.00	12.20	2003
Central World Plaza	1.00	18.00	9.00	2004
Boe Bae Bumrung Meung Plaza	0.80	24.00	19.00	2004
Esplanade	0.80	18.00	10.00	2005
Por Teck Tung Office	0.80	16.00	8.00	2006
Noble Remix	0.80	20.00	13.00	2007
Life@Sathorn	0.80	18.50	10.50	2008
Royal Maneeya	1.00	30.00		2005
Sathorn Square	0.80	21.00	15.50	2007
Renaissance				2008
The Sukhothai Residences	1.00-1.20	20.00-22.00	17.80	2008
Bangsue Wastewater Treatment	1.20-1.50	24.70	13.00	2009
Grand Rama 9 Square	1.00-1.50	22.00-25.00	20.15	2010
MahaNakhon Hill & Tower	0.60-0.80	16.00-18.00	15.40	2011
MahaNakhon Retail Cube	0.80	22.00	18.10	2011
UBC III & EM2	0.80-1.00	18.00-22.00	8.00-18.00	2011

9. DEVELOPMENT IN DIAPHRAGM WALL CONSTRUCTION

Over the past three decades, along with the development of diaphragm wall construction technology in other parts of the world, equipment, construction technique and design methods as well as better understanding of construction impact on the performance of embedded retaining wall have significantly improved in Thailand. Table 6 summarizes the areas of improvement in diaphragm wall construction and main factors contributed to these developments.

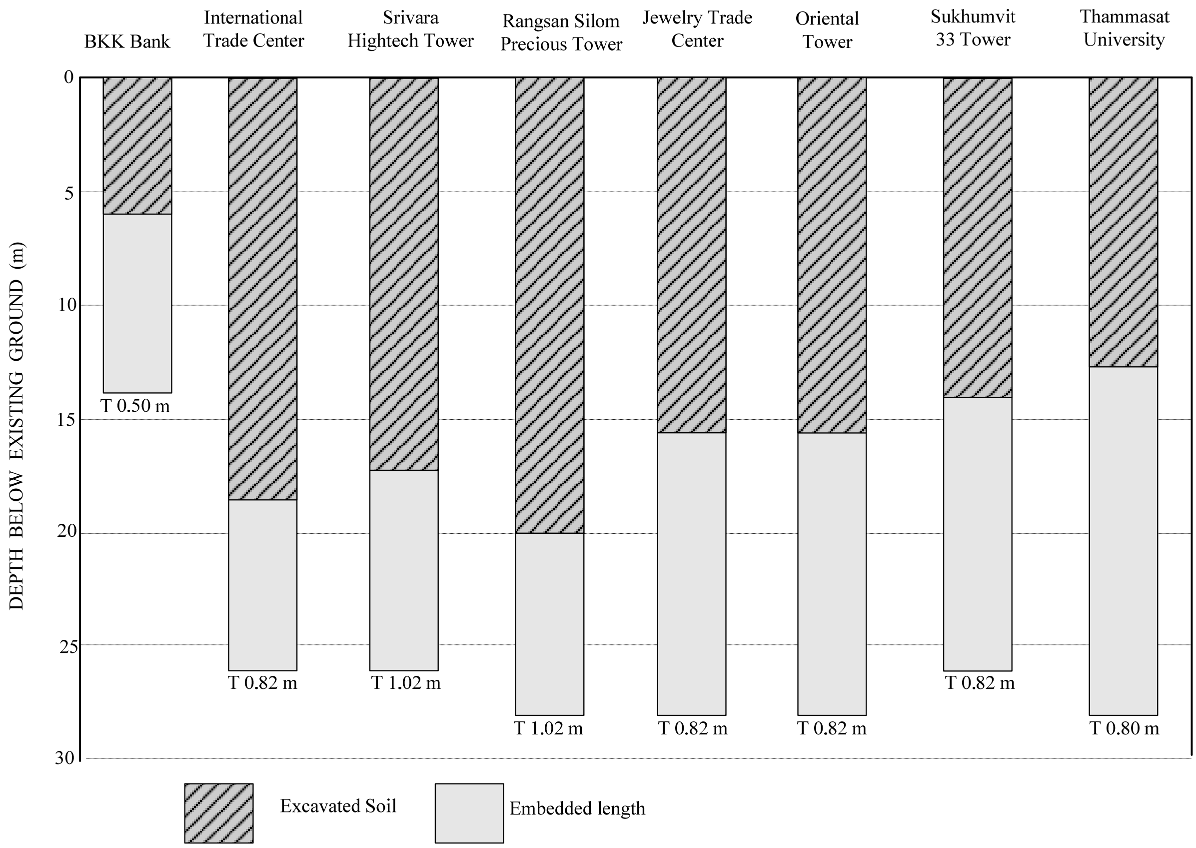

Figure 4 Diagram showing the excavation depths in relation to embedded length of diaphragm walls in early days (1977 to 1994)

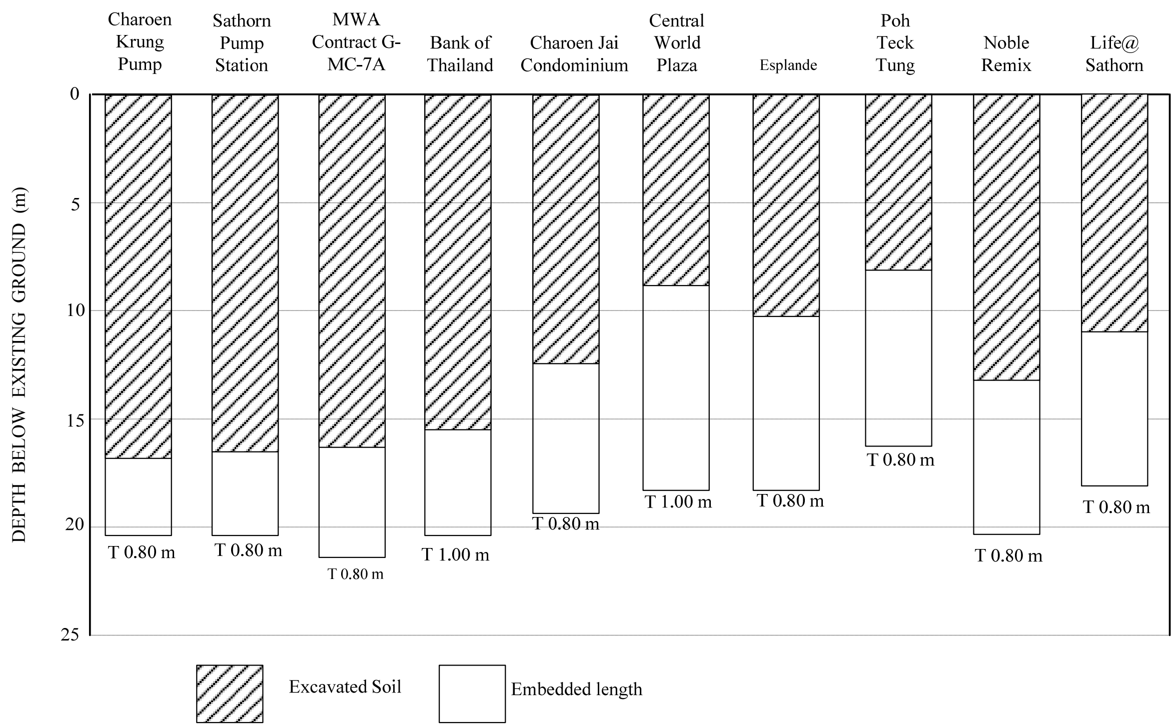

Figure 5 Diagram showing the excavation depths in relation to embedded length of diaphragm walls from 1997 to 2008

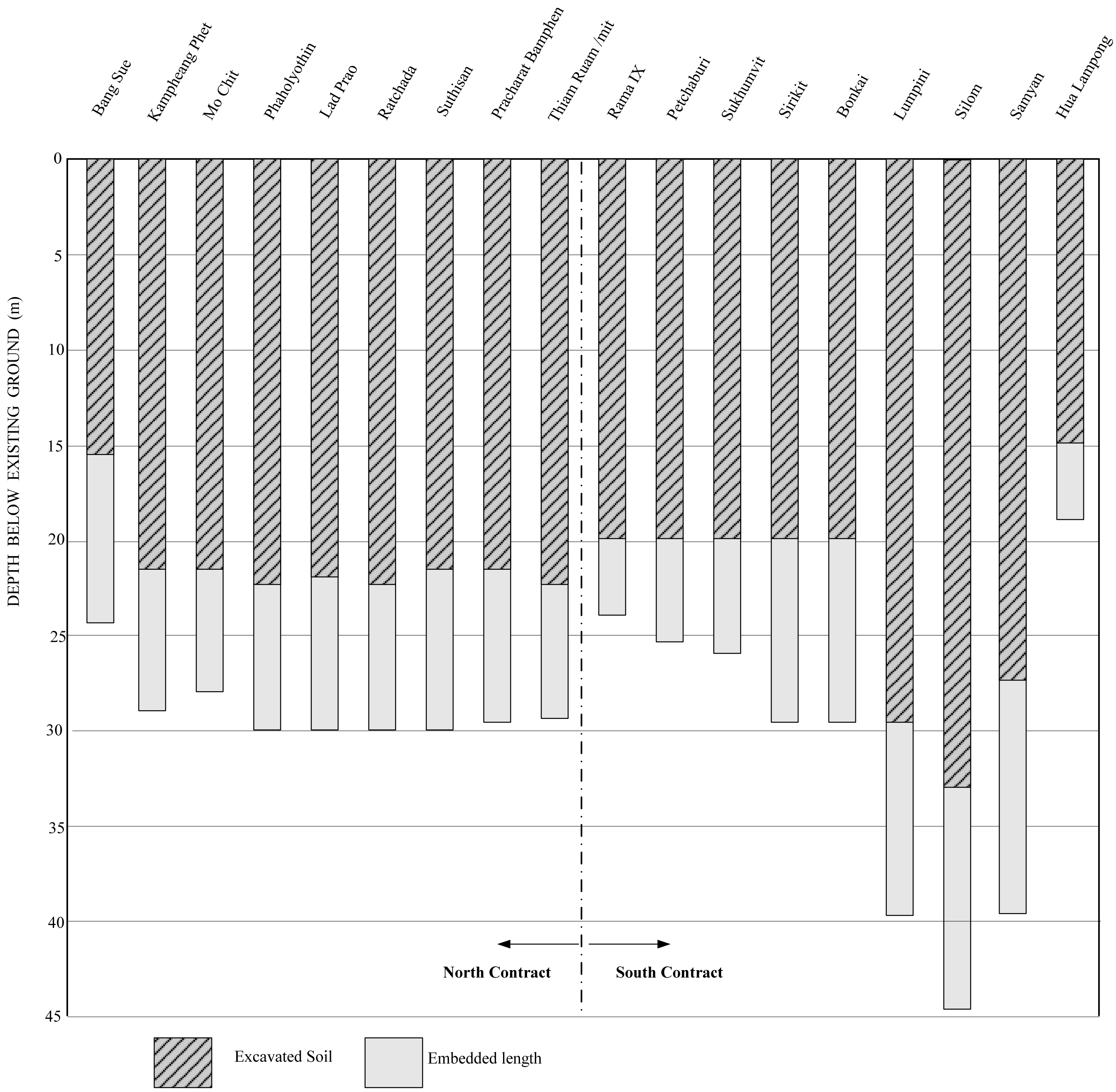

Figure 6 Diagram showing the excavation depths in relation to embedded length of diaphragm walls of 18 subway stations of the first Bangkok Mass Rapid Transit Project

Table 6 Summary of development in diaphragm wall construction in Bangkok

Area of development/ improvement	**Main factor contributed to development**
Speed of construction	Better equipment, operating skills as well as improved-knowledge in construction method, management and local soil condition
Size and depth of diaphragm wall	Better equipment, operating skills as well as improved-knowledge in construction method, management and local soil condition
Slurry management	Experience from past projects and research studies
Construction impact on quality and performance	Experience from past projects and research studies
Quality control in construction process	Experience from past projects and research studies
Quality control test method and interpretation	Advance equipment, experience from past projects and research studies

In some projects where headroom is limited, special diaphragm wall grabs and equipment were employed. Figure 7 shows the specially-designed diaphragm wall equipment used in the project with limited low headroom.

Figure 7 Specially designed baby-grab with short-boom for limited low-headroom area

Diaphragm wall is an ideal solution for deep circular shafts. Though alternative method such as sinking caisson may offer cheaper direct cost, significant time saving and maximum safety can be achieved by using diaphragm wall in construction of deep shafts. View of diaphragm wall support deep shaft is presented in Figure 8.

Figure 8 Deep circular shaft constructed by diaphragm wall

Diaphragm walls were only solution for deep excavations required for subway stations of the first Bangkok MRT. Thasnanipan et al. (2000) presented the construction of diaphragm wall for one of the largest subways stations of the MRT. Construction parameters and technical details of the diaphragm wall were reported by the authors.

10. DEVELOPMENT IN DEEP EXCAVATION SUPPORTED BY DIAPHRAGM WALLS

In Bangkok, most of the diaphragm wall support deep excavations are carried out by multi-propping or of braced-excavation. Depending on the excavation depths and sequence, bracing span-lengths commonly ranges from 4m to 8m. Improvements in diaphragm wall support deep excavation works are obvious and significant in past decade. Developments in the following areas are notable.

- Application of top-down construction method in diaphragm wall support deep excavation works
- More complex excavation works to deeper depths
- More understanding on excavation induced ground movement and risk of damages to adjacent structures
- Application of ground improvement method to minimize the ground movement
- Application of observational method integrated with value engineering option and comprehensive instrumentation program
- More understanding on water-retainable capacity of diaphragm wall

Application of top-down construction method in urban area of Bangkok was presented by Thasnanipan et al. (2006). Along with technical aspects of the top-down application for 19.10m deep excavation works, the authors highlighted the cost saving gain from shorter construction period and minimum usage of material for temporary bracing works. View of excavation process with permanent slabs having braced the excavation can be seen in Figure 9.

Figure 9 Application of top-down method for deep excavation work in Bangkok (Thasnanipan et al., 2006)

All 18 deep underground stations of the first Bangkok MRT Subway were constructed between 1997 and 2000 by top-down method using diaphragm walls as permanent structural support. Figure 10 shows the view of subway station construction with application of top-down method. Skeleton slabs provided large openings for which offered logistically significant advantage in deep excavation works.

Figure 10 View of subway station construction with application of top-down method

Complex and challenging deep excavation works at Silom MRT Station was reported by Hall et al. (2001). The authors demonstrated the complicated construction sequence involved in the deepest excavation works in Bangkok subsoil supported by

NS-Box Diaphragm Wall. The process involved in underpinning of existing flyover was also described by the authors.

Ground movement prediction and building risk damage assessment for the deep excavation works can be found in the works of Aye et al. (2006). With demonstration of the procedure used in staged assessment on risk of damage by excavation induced ground movement, the authors proposed a simple method to predict both vertical and horizontal surface and subsurface ground movement based on the deflection profile of diaphragm wall. Figure 11 shows the proposed method for prediction of subsurface ground movement.

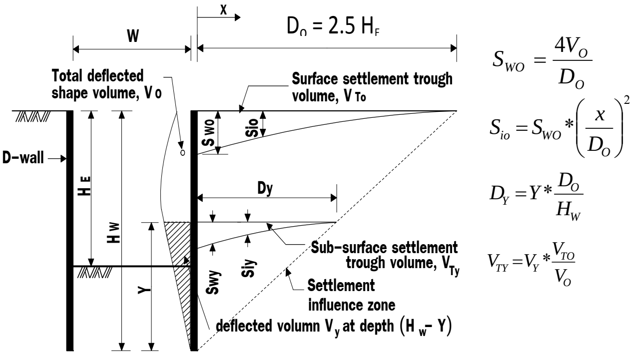

Figure 11 Demonstration of subsurface settlement prediction from diaphragm wall deflection values proposed by (Aye et al., 2006)

Thasnanipan et al. (2006) reported an unprecedented case on use of soil-cement columns as ground improvement to minimize ground movement induced by diaphragm wall support deep excavation adjacent to existing Bangkok MRT tunnels (as shown in Figure 12). The authors presented the technical requirement of the deep excavation work in the protection zone of MRT tunnels along with actual monitoring results of similar projects in other parts of the world. This integration of ground improvement application to diaphragm wall deep excavation works is expected to be more popular in the future as need of basement facilities are increasing along the existing MRT tunnels. The performance of diaphragm wall and impact on tunnels meeting all technical criteria required imposed by the Metropolitan Rapid Transit Authority of Thailand (MRTA) was subsequently reported by Teparaksa et al. (2006)

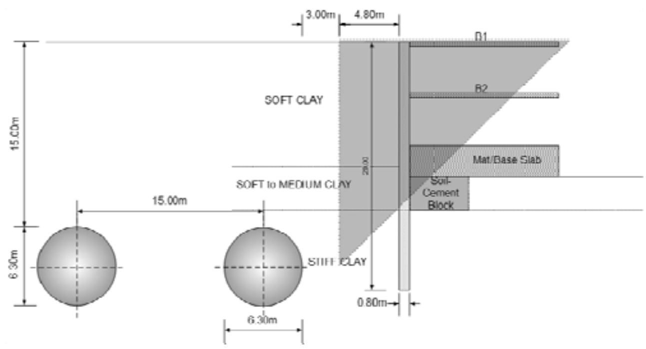

Figure 12 Typical section of diaphragm wall support deep excavation adjacent to MRT tunnel showing protection zone (Thasnanipan et al., 2006)

Application of observational method integrated with value engineering and risk management for deep excavation works was demonstrated by Aye et al. (2006) as shown in Figure 13. The authors concluded that well organized plan with systematic approach of observational method backup by extensive instrumentation and close cooperation among the involved parties were the key factors contributed to successful completion of the reported projects.

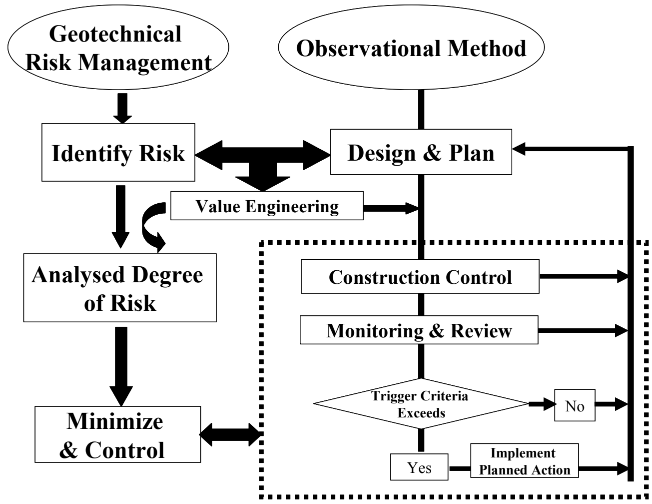

Figure 13 The elements of observational method and risk management with integration of value engineering in deep excavations, (Aye et al., 2006)

Thasnanipan et al. (2008) presented the comprehensive study of water-resisting deep basement in Bangkok soil. The authors highlighted the preventive measures for water leakage commonly occurred in basement with reference to BS8102. The authors also recommended the designers to consider additional measures to prevent water leakage and dampness for diaphragm wall support excavation as diaphragm wall itself is not fully water-proof.

Pongrujikorn (2006) reported the development of underpass construction in urban area of Thailand with emphasis on the projects in Bangkok. The author stated that diaphragm wall has been proved to be a reliable option for most cases in underpass construction.

11. IMPROVEMENT IN DESIGN PARAMETERS

In the initial stage of introducing diaphragm wall in Thailand, the design concepts and parameters were mainly based on the available literature from research carried out in other parts of the world. With the passage of time, design method and selection of parameters for local subsoil were improved as a result of research works carried out in 1990s. Differences between the behaviour of flexible pile walls and diaphragm walls were well realized from these studies. Development in powerful computer facilities and commercially available FEM programs are key factors contributed to the advancement in analysis of diaphragm wall support deep excavations.

Detailed advance FEM analyses of diaphragm wall support deep excavations in Bangkok subsoil can be found in the work of Balasubramaniam et al. (1992). The authors demonstrated the FEM simulation for both top-down and conventional braced excavation with temporary support. The authors concluded that behavior of supported excavation in soft clay is mainly controlled by the cantilever mode of deformations and it is 80% of the maximum deflection of diaphragm wall.

With the peak of construction-boom in Thailand, particularly in Bangkok, large numbers of diaphragm wall support deep excavations were systematically monitored by geotechnical instrumentation throughout 1990's which provided better understanding on behavior of this type of embedded retaining wall. Researches focused on the design parameters and methods were published based on these data. With improved construction and design methods, diaphragm wall came to be regarded as reliable excavation support retaining structure in the construction industry of Thailand. With more confidence on soil parameters selection and better understanding on behaviour of diaphragm wall, significant cost savings were achieved by more efficient design. This can be seen by shorter embedded depths of diaphragm walls in recent projects than those in early days as shown in Figure 5 in comparison with Figure 4.

Teparaksa et al. (1999) back-analysed the soil stiffness parameters of the soft and stiff Bangkok clay for diaphragm wall support excavation based on three cases studies. The authors proposed the soil stiffness values for soft and stiff clay in terms of Young modulus in relation to undrained shear strength which provided useful reference for the design engineers involved in diaphragm wall and deep excavation works.

12. IMPROVEMENT IN APPLICATION OF INSTRUMENTATION

In early days, use of instrumentation in diaphragm wall support excavations was limited. Increasing needs of deep excavation works adjacent to sensitive buildings and structures called for more comprehensive instrumentation and monitoring program.

Thasnanipan et al. (1998) reported the use of inclinometer, tiltmeter, vertical beam sensor, vibrating wire strain gauge, settlement plate and earth pressure gauge in monitoring of diaphragm wall support deep excavations and adjacent sensitive buildings at the bank of Chao Phraya River. The important role of instrumentation for deep excavation in presence of unbalance loading condition was emphasized by the authors.

Ignorance of instrumentation data resulted in catastrophe collapse of deep excavation for Inlet Pumping Station was discussed by Teparaksa et al. (1999). The authors presented the findings of investigation into the causes of failure showing excessive movement recorded by inclinometer prior to the collapse.

Extensive application of geotechnical instrumentation was more evident in construction of 18 deep subway stations for the first Bangkok MRT between 1997 and 2001. Aye et al. (2006) summarized the instrumentation program used in monitoring of ground movement induced by deep station excavations. The authors discussed the systematic approach of damage risk assessment of adjacent existing buildings and structures with application of extensive instrumentation.

Thasnanipan et al. (2004) reported the effective application of inclinometer monitoring data in construction of underground car park in the historical area of Bangkok. The authors described that thin diaphragm wall with buttress support (see Figure 14) applied in this project was the first of its kind in Bangkok as described by the authors.

Figure 14 View of thin diaphragm wall supported by buttress (Thasnanipan et al., 2004)

The authors presented a good data set of diaphragm wall movement profile showing time-dependent progressive deflection pattern due to softening and deformation of soft clay caused by delay in installation of raker support as shown in Figure 15. The authors demonstrated by comparing actual monitoring results with pre-establish trigger levels contributed to the understanding of the condition of the excavation as work progressed. This approach served as the basis to judge whether contingency actions are to be implemented. To ensure the safety of the excavation, the contingency measures exercised upon diaphragm wall deflection reaching preset trigger levels were reported by the authors.

The actual monitoring data of different type of instrumentation presented in above literatures served as valuable information and technical references for all parties involved in diaphragm wall and deep excavations industry.

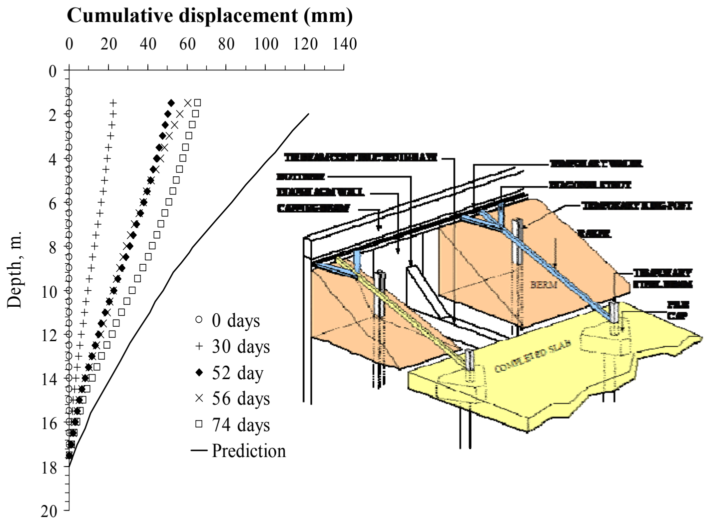

Figure 15 Time dependent wall deflection of diaphragm wall – diaphragm wall was supported only by soil-berm for 52 days before completion of raker installation (Thasnanipan et al., 2004)

13. OBSERVATION OF GROUNDWATER CONDITION IN RECENT PROJECTS

Recently, deep excavations deeper than 18.0m in depth at two projects for basement constructions being 5.25km apart in Bangkok subsoil encountered presence of groundwater after reaching about 17.5m as shown in Figure 16. Subsoil information obtained by soil boring in these projects indicated a series of stiff silty and sandy clay between 15m and 24m, overlying a dense sand layer. Construction progress was significantly affected by presence of groundwater in silty clay. Fully saturated silty clay turned liquid when disturbed by excavation activities, causing difficulties in casting a concrete blinding layer for foundations construction. Dewatering and ground improvement to the subgrade layer below foundation mat and footings needed to be carried out. Bearing capacity of disturbed silty clay with high water content is very low so that cobble size concrete blocks and crushed rocks to be compacted in to the soil for improving the subgrade. Then a lean concrete blinding layer was cast on the subgrade part by part while dewatering.

A general piezometric profile in Bangkok shown in Figure 2 indicates a drawdown at -20m. Additional piezometric readings from the piezometers installed at depths in the range of 28.0m to 33.0m and at 40m from other sites in Bangkok indicate that piezometric levels are around -15.0m and -23.0m respectively. Piezometers installed at depths 28.0m to 33.0m shows piezometric levels increase to -12.0m within six months. However, the groundwater encountered in the above mentioned sites was considered to be perched water in semi permeable soils layer being vertically cut off by diaphragm walls, with an assumption that the groundwater level was reduced gradually by pumping out.

Figure 16 Groundwater encountered in basement excavations deeper than -17.50m

14. CONCLUSIONS

According to the authors' experience as deep-foundation contractors and observation as researchers, development in both construction and design aspects of diaphragm wall and deep excavations in Bangkok in past decades were significant. With recognition of technical and economical advantages of using this type of embedded retaining walls by local practitioners, it is expected that they will be more popular in the future construction industry of Thailand. However, in the authors' opinion, there is much work to be done with particular focus on constructability issues, concrete technology for diaphragm walls, reliable but cost-effective quality control testing and value-engineering. Starting from the planning stage, site investigation, design, construction and inspection should be integrated so that designers, contractors and construction inspectors can participate as a team with a common goal. Appropriate and practical specifications should be established jointly by these parties for local soil conditions and construction methods. As a commercial and political centre of the country with a rapidly growing population, Bangkok will continue to witness more underground construction for its infrastructure development in which diaphragm wall support excavation will clearly play a great role.

15. REFERENCES

Aye, Z. Z., Karki, D. and Schulz, C. (2006) "Ground Movement Prediction and Building Damage Risk-Assessment for the Deep Excavations and Tunneling Works in Bangkok Subsoil", Proc.s of the International Symposium on Underground Excavation and Tunneling, Urban Tunnel Construction and Protection of Environment, EIT, Bangkok, Thailand, pp. 281-297

Balasubramaniam, A.S, Longanathan, N., Fernando, G.S., Indraranta, B., Phien-wej, N., Bergado, D.T. and Hongjo, Y. (1992) Advance Geotechnical Analysis, "Finite Element Analysis Coupled with Critical State Theories Using CRISP Computer Program", Asian Institute of Technology, Thailand

British Standards Institution, (2009) BS 8102: 2009 "Code of practice for protection of below ground structures against water from the ground", London, BSI.

Duc N.A., (1999) "Updating and analysis of Bangkok land subsidence caused by deep well pumping with emphasis on shallow soil settlement", Master Thesis. Asian Institute of Technology, Bangkok, Thailand

Hall, J.T., Munson, S.R. and Sakai, K. (2006) "Silom Underground Station-Bangkok Design for Unusual Planning Challenges", Proceedings of the Symposium on Underground Construction of Bangkok MRT Chaloemratchamongkhon Line, EIT, MRTA, Bangkok, Thailand, pp. 58-68

Peck, R.B., Hanson, W. E. and Thornburn, T.H. (1977) "Foundation Engineering", John Wiley & Sons, New York

Phienwej, N., Photayanuvat, C., Suwansawat, S. and Mcconochie, D., (2006) "Geotechnical Aspects in Design and Construction of Chaloemratchamongkhon Underground MRT", Proceedings of the International Symposium on Underground Excavation and Tunneling, Urban Tunnel Construction for Protection of Environment, 2-4 February 2006, Bangkok, Thailand, pp. 171-180

Pongrujikorn, T., (2006) "Development and Use of Underground Strucutre as Underpass in Urban Area in Thailand", Proceedings of the International Symposium on Underground Excavation and Tunneling, Urban Tunnel Construction for Protection of Environment, 2-4 February 2006, Bangkok, Thailand, pp. 441-448

Paveenchana, T. and Saowiang, K. (2012) "The change of piezometric pressure in the subsoil strata affecting substructures in the Bangkok area", Proceeding in Seminar of soil mechanics and foundation engineering 2012. Engineering Institute of Thailand, Bangkok. pp 1-12 (in Thai)

Teparaksa, W. (1999) "Principle and Application of Instrumentation for the First MRTA Subway Project in Bangkok", 5th International Symposium on Field Measurements in Geomechanics, Singapore, pp 411-416.

Teparaksa, W., Thasnanipan, N., Maung, A. W. and Tanseng, P. (1999) "Lessons from the collapse during construction of an inlet pumping station: Geotechnical instrumentation aspect", 5th International Symposium on Field Measurements in Geomechanics, Singapore, p.p. 247-252.

Teparaksa, W., Thasananipan, N., and Tanseng, P. (1999) "Analysis of Lateral Wall Movement for Deep Braced Excavation of Bangkok Subsoils", Civil and Environmental Engineering Conference, Bangkok, Thailand, II-67 to II-76.

Teparaksa W., Boonsong C., Submaneewong C. and Wisuttipat N., (2006) "MRT's Tunnel Deformation due to Deep Basement Excavation in MRT's Protection Zone", Proceedings of the 11th National Convention on Civil Engineering, Phuket, Thailand (in Thai), pp. GTE-095

Thasnanipan, N., Maung, A.W., Tanseng, P. and Wei, S.H., (1998) "Performance of a Braced Excavation in Bangkok Clay, Diaphragm Wall Subject to Unbalanced Loading Conditions", 13th Southeast Asian Geotechnical Conference, Taipei, Taiwan, ROC, p.p.655-660.

Thasnanipan, N., Maung, A.W. and Ganeshan, B., (2000) "Diaphragm Wall and Barrette Construction for Thiam Ruam Mit Station Box", MRT Chaloem Ratchamongkhon Line, Bangkok, An International Conference on Geotechnical & Geological Engineering, Melbourne, Australia, 19-24 November 2000, pp. 157

Tanseng P., Aye, Z. Z. and Submaneewong, C. (2001) "Monitoring of Diaphragm Wall Displacement and Associated Ground Movement, Braced Excavation Adjacent to Historical Building at the Bank of Chao Phraya River", Proceedings of the Seventh National Convention on Civil Engineering, Bangkok, Thailand, pp. GTE-53-60

Thasnanipan, N. , Aye, Z. Z. and Submaneewong, C. (2004) "Construction of Diaphragm Wall Support Underground Car Park in Historical Area of Bangkok", Proceedings of Fifth International Conference on Case Histories in Geotechnical Engineering, April 13-17 2004, New York, U.S.A. pp. 5.66

Thasnanipan, N. , Aye, Z. Z., Submaneewong, C. and Boonyarak, T. (2006) "Application of Top-down Construction Method for Deep Excavations in Urban Area of Bangkok", Proceedings of the International Symposium on Underground Excavation and Tunneling, Urban Tunnel Construction for Protection of Environment, Bangkok, Thailand, pp. 383-396

Thasnanipan, N., Maung, A.W., Aye, Z. Z., Submaneewong, C. and Boonyarak, T. (2006) "Construction of diaphragm wall for basement excavation adjacent to tunnels in Bangkok subsoil", Proceedings of the International Symposium on Underground Excavation and Tunneling, Urban Tunnel Construction for Protection of Environment, 2-4 February 2006, Bangkok, Thailand, pp. 371-382