International Journal of GEOMATE, March, 2017, Vol. 12, Issue 31, pp. 105-111
Geotec., Const. Mat. & Env., ISSN:2186-2990, Japan, DOI: http://dx.doi.org/10.21660/2017.31.6529

3-D NUMERICAL ANALYSIS OF CONSOLIDATION EFFECT ON PILED RAFT FOUNDATION IN BANGKOK SUBSOIL CONDITION

Kongpop Watcharasawe [1], Pastsakorn Kitiyodom[2] and *Pornkasem Jongpradist [3]

[1,3] Department of Civil Engineering, King Mongkut's University of Technology Thonburi, Thailand;
[2] Geotechnical & Foundation Engineering Co., Ltd. (GFE), Thailand

*Corresponding Author, Received: 30 June 2016, Revised: 25 July 2016, Accepted: 30 Nov. 2016

ABSTRACT: This study focused on the investigation of influencing factors on behaviour of piled raft foundation in Bangkok subsoil. To evaluate the possibility of implementing this system in Bangkok subsoil condition, this research performed the consolidation analysis of piled raft foundation systems for low-rise (8-storey) and high-rise (25-storey) buildings with basement levels in clay soil, using coupled three-dimensional (3D) mechanical and hydraulic numerical model. The soils are modelled with Hardening Soil model and Mohr-Coulomb model. Evaluations of piled raft foundation, i.e., the load sharing ratio of piles, settlement behaviours in the foundation system are performed. The parametric study on the effect of raft depth, and load carried by piles of piled raft was done. The consolidation had a strong influence on the load carried by piles of the piled raft foundation in Bangkok. The load shared by piles can increase by up to 12% and 6% for low rise and high-rise buildings, respectively due to the consolidation effect. Therefore, the design of the piled raft foundation system in Bangkok subsoil essentially consider the consolidation effect.

Keywords: 3D-FEM, Bangkok subsoil, Consolidation, piled rafts, Piled-raft load sharing, Softs soil

1. INTRODUCTION

In Bangkok, there are many building projects constructed on soft soil. As the subsoil of this area consists 13-16 m thick soft clay and stiff clay interspersed with sand [1], the pile foundation must be used to transfer the load to stiff soil layers. Normally, the design and construction of foundation system on soft ground have posed various problems to geotechnical engineers, such as consolidation, excessive settlement, negative skin friction and bearing capacity failure. To avoid these problems, the structure of foundation in this area are relatively expensive.

In Thailand, the designers prefer to consider the pile group to support a structure [2]. The pile groups mostly focus on pile capacity and group settlement without considering the presence of the raft or mat. In fact the foundations are built using concrete and their bottom surfaces are attached to the soil beneath. Therefore, in most cases end up with overdesign of the foundation.

Typically, new office or residential buildings require 2 or more basements (depth10-20m.) for utilizing as a car park space. Meanwhile, the foundation has constructed in deeper level. This means that the mat foundations is placed on the stiff soil. Therefore, the soil bearing capacity are increasing at the bottom of the mat foundations. In recent years, the foundation engineers tend to combine these two separate systems (between shallow foundations (rafts) and deep foundations (piles)). Such a foundation system is referred to as piled raft foundation.

Recent years, the "Piled Raft Foundations" (PRF) have been widely accepted as one of the most economical methods of foundation systems [3], [4]. Thus, the piled raft systems have been used extensively in many parts of the world e.g. England [5], Japan [6], Germany [7], [9], [10]. The application of piled rafts on soft ground is becoming a significant issue in foundation design. A few successful applications and analysis of piled rafts on soft ground have been reported [8]–[13]. However, the behaviour of piled raft foundation supporting the structure in clay soil was found that the long-term effect (consolidation) increases the load carried by piles and decreases raft contact pressure [5]. This means that the effect of consolidation in clay has influence on piled raft foundation system. Previous studies on numerical analysis of piled raft foundation in Bangkok subsoil condition indicated the potential of using PRF in Bangkok subsoil [2], [14]. However, they considered only short term behaviour.

To pay special attention to the consolidation effect, a coupled three-dimensional (3D) mechanical and hydraulic numerical model is used to analysis the behaviour of piled raft in Bangkok subsoil. The model considers the dissipation of excess pore water pressure in saturated clays. Two different building sizes, i.e., low-rise (8-storey) and high-rise (25-storey) buildings with basements are considered in this study to evaluate the potential of using the piled raft system in Bangkok subsoil condition. The main factor to be investigated its influence is the level of raft under long-term condition.

2. PILED RAFT WITH CONSOLIDATION

The PRF is a complex design of foundation that combines the bearing effect of both foundation elements (piles and raft) [11]. In Bangkok subsoil condition the characteristics of soft soils are high compressibility, low shear strength and high water content.

The consolidation is a procedure by which soils decrease in volume. Generally, it is the process in which reduction in volume takes place by eviction of water under long term static loads. When the consolidation settlement occurs, the soil at the bottom of the raft are deformed. Therefore, the consolidation may have a strong influence on the load carried by raft, which consequently affect the load carried by piles. In this study, only the settlement due to consolidation is of interest. The value of incremental of consolidation settlement "ΔS_{end}" is defined as shown in Fig.1.

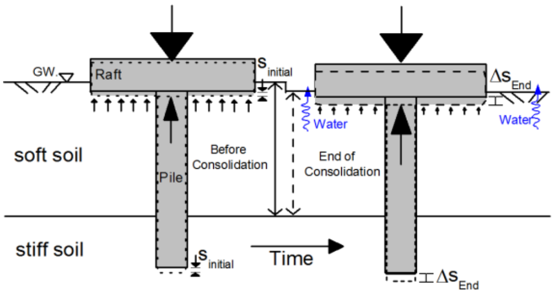

Fig. 1 Concept of piled raft foundation with consolidation.

Both, piles and raft are considered in the load distribution process:

$$P_{tot} = P_p + P_r \tag{1}$$

where P_{tot} = total load of the building; P_p = load carried by the pile group; P_r = load carried by the raft.

The bearing behaviour of the piled raft is commonly described by the piled raft coefficient or the load sharing ratio of piles α_{pr} which is defined by the ratio between the sum of load carried by pile and the total load of the building:

$$\alpha_{pr} = \frac{\sum R_{pile,i}}{R_{tot}} \tag{2}$$

where α_{pr}= the load sharing ratio of piles; $\sum R_{pile,i}$ = the amount of the pile loads; R_{tot} = total load of the structure. α_{PG} = the load sharing ratio of pile group.

For the pile group concept which does not take the advantage of raft into consideration, the α_{PG} is therefore equal 1 and defined in this study as

$$\alpha_{PG} = 1 \tag{3}$$

$$\alpha_{\Delta} = \alpha_{final} - \alpha_{initial}$$

(4)

The effect of consolidation settlement is considered in load sharing ratio of pile. As mentioned previously α_{final} = the load sharing ratio of pile at end of settlement; $\alpha_{initial}$ = the load sharing ratio of pile before consolidation.

3. NUMERICAL MODELING OF PILED RAFT FOUNDATION ANALYSIS

3.1 Reference Case

A parametric study was considering 9 × 9 m, and 1 m. thick raft with 9 piles. The low-rise (8-storey) and high-rise (25-storey) buildings with basements are considered in this study. Both Low-Rise-Piled Raft (LR-PR) and High Rise-Piled Raft (HR-PR) having identical characteristics as shown in Fig.2 (a) and 2 (b), respectively.

The pile foundation in this study was designed following the pile group concept with a safety factor (FS) of 2.3 for each single pile, which is the current design in engineering practice. The raft level is varied from 0 to 10 m below the ground level. The bored piles have 1 m diameter (d) being arranged in the foundation with the spacing of 3 m. The level of pile tip is at 23 (1st stiff clay layer) and 36 m (2nd sand layer) below the ground surface for low-rise and high-rise buildings, respectively. Summary of the analysis cases is shown in Table 1.

3.1.1 Applied Load

Uniformly Distributed Loads (UDL) is used in this analysis. The weight of the structure and designed load were computed.

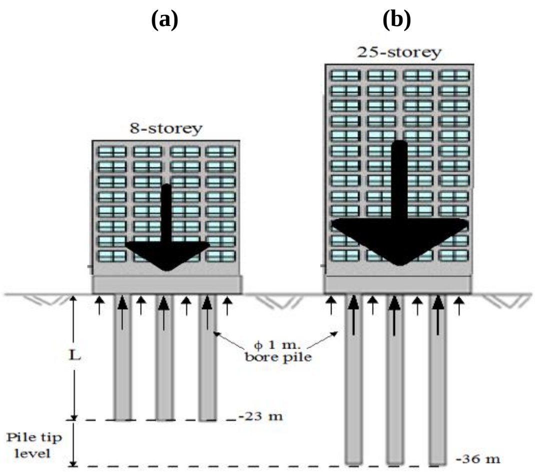

Fig. 2 Reference Case (a) LR-PR, (b) HR-PR

These UDL are applied on top surface of the raft in analysis of PRF. The basement is considered to apply the load of 50 ton per level. The total applied loads on each foundation are listed in Table 1.

Table 1 Summary of piled raft foundation of numerical analysis conducted

Building	Pile spacing	Pile tip level (m)	Raft level (m)	Total load (kPa)
Low-rise 8-storey	3*d**	23[f**]	0	140
			4	146
			8	152
			10	158
High-rise 25-storey	3*d**	36[e**]	0	350
			4	356
			8	362
			10	368

* *d* (pile diameter): 1 m.
** f: floating pile in clay; e: end bearing in sand layer.

3.1.2 SUBSOIL CONDITION

The subsoil profile in this study are referred from that in the north of Bangkok. The generalized profiles of the stratified soil at the considered location are shown in Fig.4 (a). The top 2.0 m thick layer is the weathered crust, -which is underlain by 6.0 m thick soft to medium clay layer. A medium clay layer is found at the depth of 8.0 m from the surface. Below the medium clay is stiff clay; the thickness is about 15m. The first sand layer is generally found at a depth of 25 to 30m. Below the upper first sand layer, there is stiff clay and further down alternating layers of dense sand and hard clay. The ground water table is below the ground surface at 1.5 m [14], [15]. The pore water pressure condition in Bangkok soft clay are hydrostatic from 1m below ground surface. Then the piezo-metric changed to drawdown near middle of clay layer as shown in Fig.4 (a) [22]. The piezo-metric drawdown pressure was considered in this study.

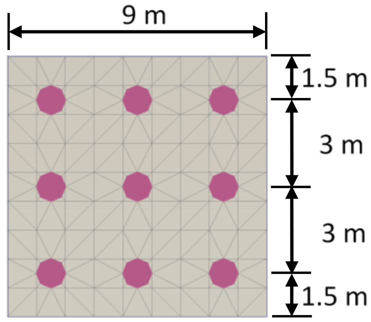

Fig. 3 Adopted piled-raft geometry.

(a) (b)

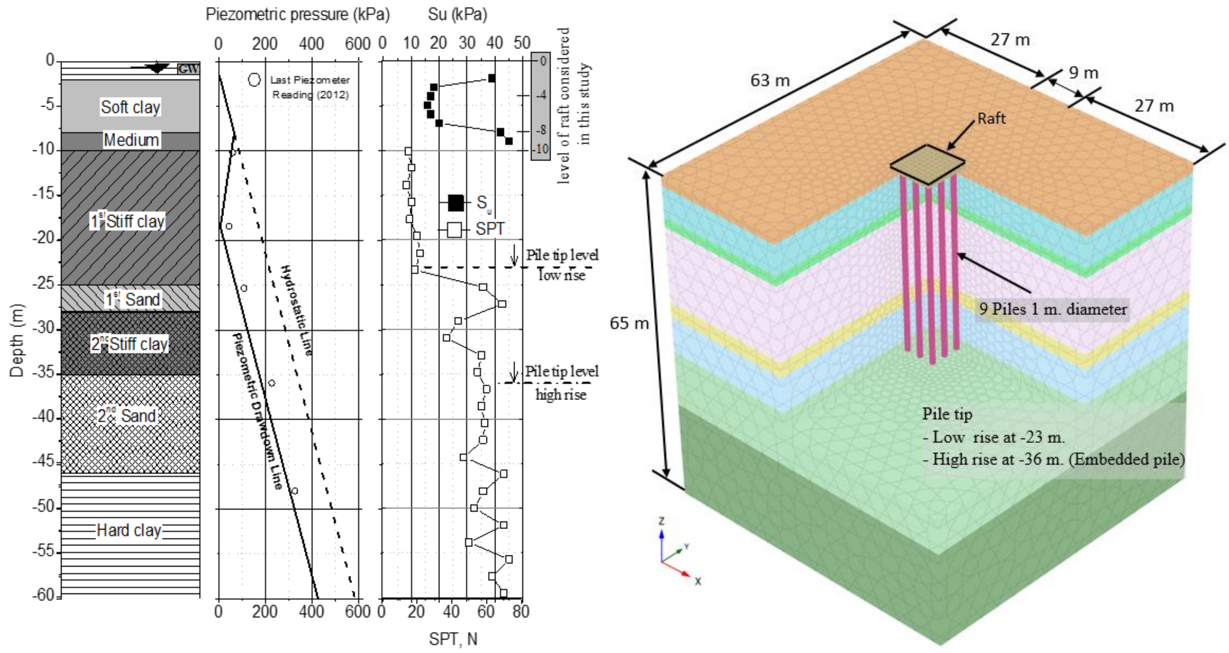

Fig. 4 Soil profile and Piezo-metric line (a), Geometry of the problem and 3D Finite element mesh used in this analysis (b).

Table 2 Constitutive models and model parameters used in analyses

Material		Model	γ_t (kN/m³)	Material behaviour	S_u (kPa)	C' (kPa)	ϕ (°)	E_u, E' (kPa)	E_{50}^{ref}, E_{oed}^{ref} (kPa)	E_{ur}^{ref} (kPa)	G_0^{ref} (kPa)	Permeability coefficient, k (m/d)	$\gamma_{0.7}$	m	p_{ref} (kPa)	ν, ν_{ur}
Subsoil	**Depth (m.)**															
Weathered clay	0-2	MCM	17	Undrained	40			6000				-				0.3
Soft clay	2-8	HSS	15.2	Undrained		0	23		7000	23280	8954	5×10^{-4}	1×10^{-4}	1	100	0.33
Medium clay	8-10	HSS	18.4	Undrained		0	24		10300	30900	22800	2.5×10^{-4}	1×10^{-4}	1	100	0.32
1st Stiff clay	10-25	HSS	19	Undrained		0	26		25400	83900	32270	2.5×10^{-4}	2×10^{-3}	1	552	0.32
1st Sand	25-28	MCM	20	Drained		-	36	85800				1.6				0.3
2nd Stiff clay	28-35	MCM	20	Undrained	192			96000				2.5×10^{-4}				0.3
2nd Sand	35-46	MCM	20	Drained		-	37	96200				0.8				0.3
Hard clay	46-60	MCM	20	Undrained	223			111500				2.5×10^{-4}				0.3
Foundation																
Bored Pile	Tip -23,-36	LEM	6-8	Non-porous				2.6×10^7								0.2
Raft	0,-4,-8,-10	LEM	24	Non-porous				2.8×10^7								0.2

HSS: Hardening Soil Model with small strain; MCM: Mohr-Coulomb model; LEM: Linear Elastic Model

3.2 Modelling and Boundary Condition

The geometry of the problem and FE mesh simulation of the piled raft foundation are shown in Fig.3 and Fig.4 (b). The 3D-FEA using PLAXIS 3D version 2013 was carried out in this study. A coupled mechanical and hydraulic model was used for the consolidation analysis. The 3D model included a rigorous treatment of the soil and raft which were represented by volume elements. The piles are modelled as embedded piles in which the pile is assumed to be a slender beam element. The boundary conditions adopted for analysis are displacement restraints with roller supports applied on all vertical sides and pin supports applied to the base of the mesh. The layer surface (upper and bottom side) is allowed to drain while the other sides are kept undrained by imposing closed consolidation boundary conditions.

3.2.1 Constitutive Models and Parameters

The soft clay, medium clay and first stiff clay layers were modelled with Hardening Soil Model with small strain [14]–[16]. The 1st -2nd sand, 2nd stiff clay and hard clay layers were modelled with Mohr–Coulomb model. The soil properties used in the analysis are mostly determined from comparing local investigated data with comprehensive in situ tests of MRT projects [17] and previous laboratory tests from Asian Institute of Technology (AIT) [18]–[20]. Table 2 summarizes the material parameters used in the analysis.

4. COMPUTED RESULTS

4.1 Effect of the Load Sharing Ratio of Piles against Time with Differential Raft Level

Fig.5 shows the load sharing ratio of piles for different raft levels below the ground surface and time for both building types. The analysis results show that when the raft was placed on deeper soil layer, the load sharing ratio of pile has been decreased significantly. For subsoil condition and problem characteristics in this study, before consolidation, the load sharing ratio of pile reduces from 95% to 80% and 98% to 91% with increasing raft levels (0-10 m.) for the low-rise and high-rise buildings, respectively.

At the end of consolidation, the load sharing ratio of pile increases 2% to 12% and 1% to 6% with increasing raft levels (0-10 m.) for the low-rise and high-rise buildings respectively. Significant changes of load sharing by raft are obviously observed. This leads to the long-term load sharing by piles of 92% to 98% and 97% to 99% for the low-rise and high-rise buildings respectively. This means that the consolidation has a strong influence on the load carried by piles of the PRF in Bangkok subsoil.

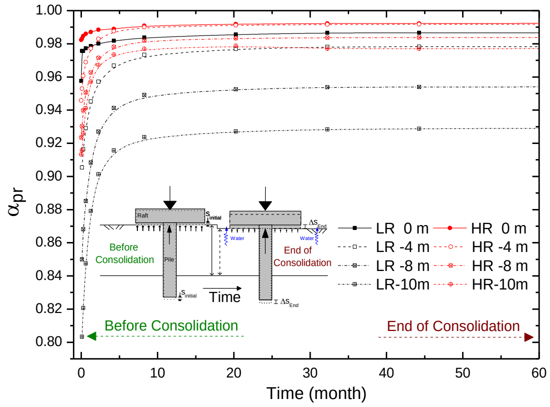

Fig. 5 Load sharing ratio of piles (α_{pr}) versus Time and raft level of different building types.

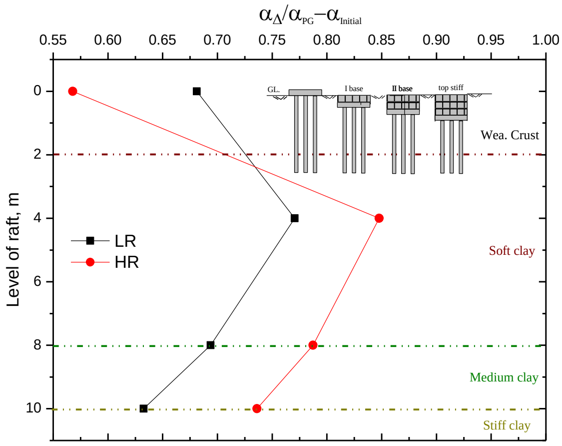

Fig. 6 Variation of load sharing ratio of piles versus raft level of different building types

Fig.6 illustrated the computed variation of load sharing ratio of piles versus raft level with different building types. The variation is the difference load sharing ratio of pile between short term and end of consolidation process ($\alpha_{\Delta} = \alpha_{final} - \alpha_{initial}$ in Eq. (4)). The variation of load sharing ratio of piles seems to decrease with increasing raft level between -4 m to -10 m.

4.2 Settlement of PRF and Load Sharing Ratio

The incremental settlement of consolidation ΔS_{end} and load sharing ratio of pile between short term and end of consolidation process (α_{Δ}) with different raft levels are shown in Fig.7 The analysis results show that the incremental consolidation settlement "ΔS_{end}" has significant influence on the incremental load sharing ratio of piles "α_{Δ}". For subsoil condition and problem characteristics in this study, the incremental consolidation settlement "ΔS_{end}" increases with increasing raft level. The incremental load sharing ratio of pile in consolidation process (α_{Δ}) increase with increasing incremental consolidation settlement ΔS_{end}. For low-rise building, the ΔS_{end} increase from 8.6 to 10.4 mm. with increasing α_{Δ} from 3% to 12% when increasing raft (0-10 m.). For the case of high-rise building, the ΔS_{end} increase from 8.6 to 10.4 mm. with increasing α_{Δ} from 1% to 6.5% with increasing raft level.

5. CONCLUSION

This article presents the results of numerical analysis of the PRF in the subsoil condition of north Bangkok, using 3-D FEM to investigate the effect of raft level on load shared by piles in Bangkok subsoil condition and paying special attention to the consolidation effect.

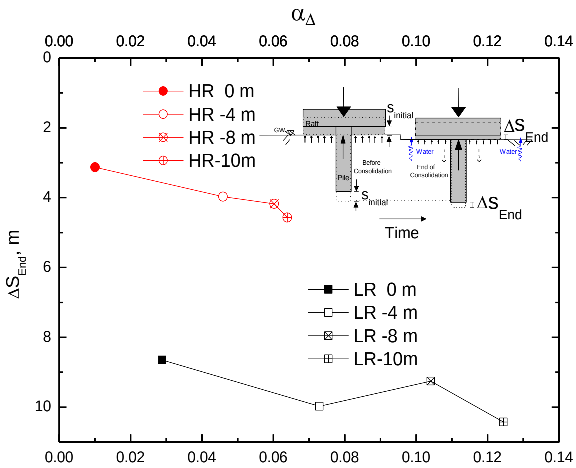

Fig. 7 Incremental settlement at end of consolidation ΔS_{end} versus the load sharing ratio of, α_{Δ}

The analysis result in terms of load shared by piles with consolidation effect for the PRF case in this study in Bangkok subsoil condition can be summarized as follows:

- The consolidation had a strong influence on the load carried by piles of piled raft foundation in Bangkok. The load shared by piles can increase by up to 12% and 6% for low rise and high-rise buildings, respectively. Therefore, the design of the piled raft foundation system in Bangkok subsoil should consider the consolidation.
- The incremental consolidation settlement "ΔS_{end}" has significant influence on the incremental load sharing ratio of piles "α_{Δ}". The incremental load sharing ratio of pile in consolidation process (α_{Δ}) increase with increasing incremental consolidation settlement ΔS_{end}.

Since the pile foundation was designed using the pile group concept with high FS. The raft is not considered in the design of which the FS of the pile can be smaller. Higher efficiency of the system can be expected. Further study with less FS of pile should be done, to confirm effectiveness of PRF.

6. ACKNOWLEDGEMENT

The authors gratefully acknowledge financial support by Thailand Research Fund (TRF) and Geotechnical & Foundation Engineering Co., Ltd. (GFE) through the TRF-Rri Project under Contract No 58I0050. Thanks are also extended to the National Research University (NRU) project.

7. REFERENCES

[1] Thasnanipan N, Aye Z, Submaneewong C, and Teparaksa W, "Performance of Wet-Process Bored Piles Constructed with Polymer-Based Slurry in Bangkok Subsoil" Deep Foundations 2002, pp. 143-157.

[2] Amornfa K, Phienwej N, and Kitpayuck P, "Current practice on foundation design of high-rise buildings in Bangkok, Thailand", Lowland technology international, 2012, Vol. 14, pp. 70-83.

[3] Randolph M.F, "Design methods for pile groups and piled rafts" In Proceedings of the 13th International Conference on Soil Mechanics and Foundation Engineering, New Delhi, 1994, Vol. 5, pp. 1–82.

[4] Poulos H. G., "Piled raft foundations: design and application" Geotechnique, 2001, Vol. 51(2), pp. 95-113.

[5] Hooper J.A., "Observations on the Behaviour of a Piled-Raft Foundation on London Clay", Proc. Instn. Civil Engrs, 1973, Vol. 55, pp. 855- 877.

[6] Yamashita K., Yamada T, and Kakurai M, "Simplified method for analyzing piled raft foundations" In Proceedings of the Third International Geotechnical Seminar on Deep Foundation on Bored and Auger Piles, 1998, pp. 457–464.

[7] Poulos H. G, and Davis E. H., "Pile foundation analysis and design" *New York: Wiley*. 1980.

[8] Yamashita K, Kakurai M, and Yamada T, "Investigation of a piled raft foundation on stiff clay" Proceeding of the 13th International Conference on Soil Mechanics and Foundation Engineering, New Delhi, 1994, pp. 543-546.

[9] El-Mossalamy Y, El-Nahhas F, and Essawy A, "Innovative Use of Piled Raft Foundation to Optimize the Design of High-Rise Buildings" 10th Arab Structural Engineering Conference, 2006, pp. 13-15 November 2006, Kuwait

[10] Randolph M. F., "Design of pile raft foundations" Recent Development in Laboratory and Field Tests and Analysis of Geotechnical Problems, Bangkok, 1983, pp. 525-537.

[11] Katzenbach R, Arslan U and Moormann C, "Piled raft foundation in Germany In H. J.A. (Ed.)", Design applications of raft foundations, London, Thomas Telford Ltd, 2000, pp. 323-391.

[12] Poulos H.G., "Piled raft and compensated piled raft foundations for soft soil sites. Advances on designing and testing deep foundations"

[13] Tan Y.C., Cheah S.W., and Taha M.R., "Methodology for design of piled raft for 5-story buildings on very soft clay" Foundation analysis and design: Spec. Publ. ASCE, 2006, Vol. 153, pp 226–233.

[14] Watcharasawe K, Kitiyodom P, and Jongpradist P., "Numerical Analyses of Piled Raft Foundation in soft soil using 3D-FEM", South-East Asian Geotechnical Society Journal, 2015, Vol. 46(1), pp. 109-116.

[15] Jamsawang P, Bergado D. T, and Voottipruex P, "Field behavior of stiffened deep cement mixing piles" Ground Improvement, 2010**,** Vol**.** 164(1)**,** pp. 33-49.

[16] Detkhong T, and Jongpradist P, "Impact of Constitutive model on the Numerical Analysis of Tunneling in Bangkok Clay", Conference on Advances in Civil Engineering for Sustainable Development, 2014, pp. 349-354.

[17] Prust R.E., Davies J, Hu S, "Pressuremeter investigation for mass rapid transit in Bangkok" Thailand, Journal of the transportation research board, Transportation research of the national academies, Washington, DC, 2005, pp. 207–217.

[18] Jamsawanga P, Yoobanpota N, Thanasisathita N, Voottipruex P, and Jongpradist P, "Three-dimensional numerical analysis of a DCM column-supported highway embankment", Computers and Geotechnics, 2016, Vol 72, pp. 42–56

[19] Bergado D.T, Youwai S, Teerawattanasuk C, and Visudmedanukul P, "The interaction mechanism and behavior of hexagonal wire mesh reinforced embankment with silty sand backfill on soft clay", Computers and Geotechnics, 2003, Vol. 30, pp. 517-534.

[20] Tanchaisawat T, Bergado D.T., and Voottipruex, P, "Numerical simulation and sensitivity analyses of full-scale test embankment with reinforced lightweight geomaterials on soft Bangkok clay",

Geotextiles and Geomembranes, 2008, Vol. 26, pp. 498-511.
[21] Sawatparnich A, Sunitsakul J, and Kanhasing P, "Numerical Analysis of DOH Bearing Unit Sitting on Soft Bangkok Clay by Finite Element Method", Report No. RD. 256 Bureau of Road Research and Development, Department of Highways, Thailand, 2009
[22] Department of Groundwater Resources, "A study on recovery of groundwater effect in Bangkok subsoil", Thailand, 2012