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INVESTIGATION OF DIFFERENTIAL SETTLEMENT OF PAGODA FOUNDATION USING 3D FINITE ELEMENT METHOD

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ABSTRACT: It is important to predict the future behavior of historic buildings to avoid potential problems. Wat Khao Sukim Pagoda is situated on a hill slope and has different types of foundations. These foundations include both shallow and pile foundations representing different stages of construction and having different loadings. Although the structure meets the design criteria for the current loading, in the future overloading may occur. Therefore, an analysis of additional loading was undertaken using the 3D finite element method (FEM). In particular, the effects of differential settlement and its mitigation were investigated. Changes in the groundwater level were simulated after major rain events and compared to dry conditions. Overall, the concept of staged construction (preloading) is a useful technique to minimize the risk of differential settlement associated with different types of foundations. In addition, the current results showed that the average differential settlement value at each stage was lower than in previous work. Furthermore, the new model reduced the differential settlement value by more than 50%. These results showed that the concept of preloading can better solve the differential settlement problem in this type of construction. The PLAXIS 3D model showed that the groundwater level increase did not affect Pagoda settlement, indicating that the Pagoda was stable and could withstand a large load without undergoing any major structural deformations and that it was suitable structurally for a variety of applications, even in wet conditions.

Keywords: Preloading method, 3D finite element method, Differential settlement, Groundwater table

1. INTRODUCTION

Historic buildings are a prominent indication of a city's status. However, the limited options to address major damage to these structures while maintaining their historical authenticity are critical problems confronting city management today [1].

It is possible to minimize future damage by enhancing preventative efforts and initiating conservation research. In this sense, it is essential to examine the behavior of historical buildings such as the Pagoda to detect and prevent future damage caused by foundation collapse or movement [2].

The current study investigated the Wat Khao Sukim Pagoda foundations and their geotechnical characteristics as an essential step in developing future conservation strategies. Furthermore, these studies could contribute to any necessary preventive actions.

The 3D finite element method (3D FEM) has been applied to examine the settlement of different types of foundations, with the PLAXIS 3D software being one available computer package to model the soil and foundations. In previous analysis [3], the design period applied 100% loading for all zones since the initial construction.

The Pagoda building site is in the foothills on the east side of Wat Khao Sukim. It is a reinforced concrete structure with six main floors and a mezzanine, measuring 99 m in width, 99 m in length, and 119 m in height [4] as shown in Fig.1.

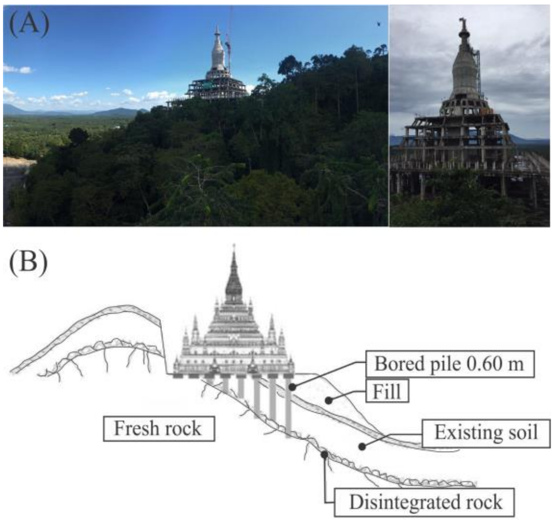

Fig.1 (a) Location of the Wat Khao Sukim Pagoda and (b) sketch of the foundation layers [4]

Frequently, the preloading or precompression concept is used to reduce the total settlement of a permanent load, which is defined as compressing the soil under applied stress prior to placing or completing the structural load [5].

In a previous study [3], the assumption was that the foundations were constructed at the same time, and the differential settlement was then established by comparing the final settlement of each area, and the structure was still considered safe based on the regulations [6,7]. For the current study, as in the actual construction, a preloading concept was adopted using 3D FEM to minimize the effect of differential settlement and to investigate the approach's advantage in reducing differential settlement.

Rainfall is a major source of groundwater recharge [8] and has been identified as the most influential factor for groundwater levels [9,10]. Consequently, landslides may occur and cause major damage to structures [11]. To address this issue, the current paper simulated the change in groundwater level after major rainfall events and compared the impact to dry conditions.

2. RESEARCH SIGNIFICANCE

In the construction period, the engineer can propose improvements or reduce the differential settlement using several phases of construction. In this respect, several construction phases have been updated to follow the real construction phase. Thus, it can be used as a more reliable source for Pagoda safety. Additionally, the results can also be utilized in engineering design and any future loading applied to the Pagoda foundations. Furthermore, the groundwater level change in the case of high-intensity rainfall can cause many problems. In conclusion, this study is an important step toward a better understanding of problems associated with the settlement and damage prevention of the Pagoda.

3. METHODOLOGY

In the preliminary stage of the methodology, critical data from prior studies was compiled, specifically addressing parameters such as soil composition, characteristics of piles, data on soil layers, and the classification of pile types [3,4].

Second, the soil beneath the Pagoda was evaluated to determine the depth of each layer and its geotechnical properties. Consequently, an accurate description of the subsurface profile was made taking into account various geotechnical studies affecting the building's foundation and surroundings. In this context, the several strata of the geotechnical model of the Pagoda and its surroundings were carefully portrayed in a 3D model based on boreholes in the building's foundation [3], as shown in Fig.2.

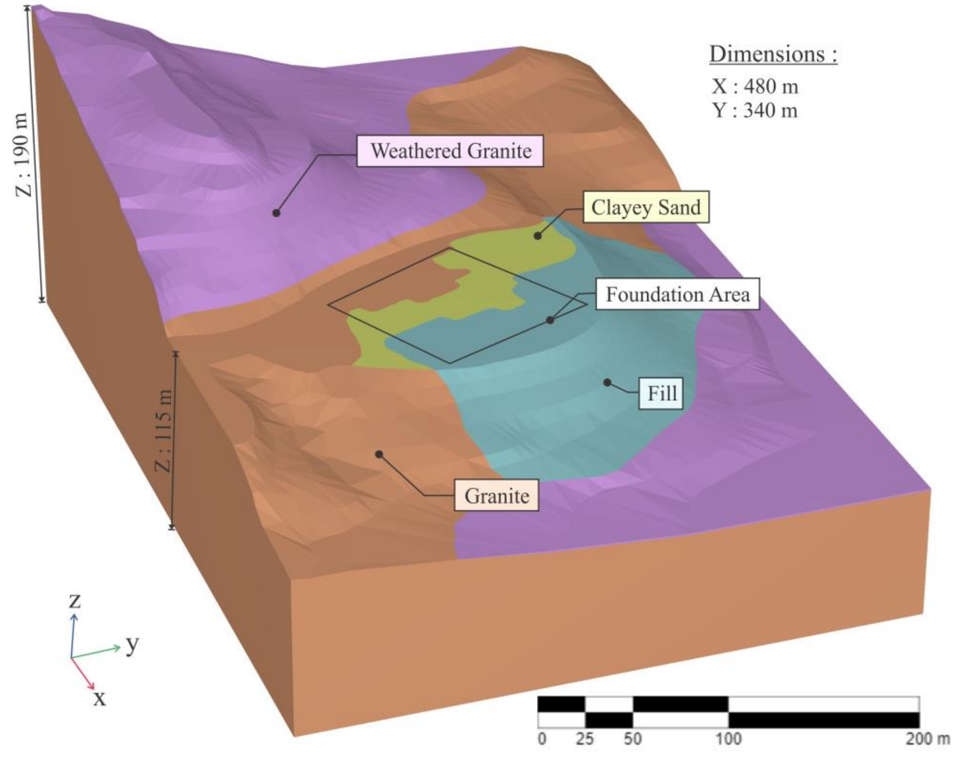

Fig.2 3D soil model of Wat Khao Sukim Pagoda [3]

The phases of construction were defined to carry out a detailed assessment of any settlement. Considering these phases is important in developing the model and the associated calculations as the Pagoda's building load has substantially increased through the different periods.

The analysis incorporated the Mohr-Coulomb model [13] to define soil behavior in the FEM, with a need for only five parameters—two for stiffness and three for strength—[14]. The reliability and accuracy of the Mohr-Coulomb model were substantiated through a previous study that conducted back-analysis [3]. This validation process revealed a satisfactory alignment between numerical predictions and field observations, establishing the suitability of the selected soil parameters for integration into the PLAXIS 3D model.

Shallow foundations were modeled as plates, while pile foundations were modeled as embedded beams, as shown in Fig.3 and 4. An embedded beam in PLAXIS 3D consists of beam components with embedded interface elements that represent the interaction of the pile skin (skin friction) and pile tip (end bearing) with the soil [9]. In this situation, piles can be evaluated in three dimensions by defining them as embedded beams.

The results obtained in the analysis of the 3D FEM were compared with previous work [3]. Consequently, accurate conclusions about the foundation differential settlements were obtained.

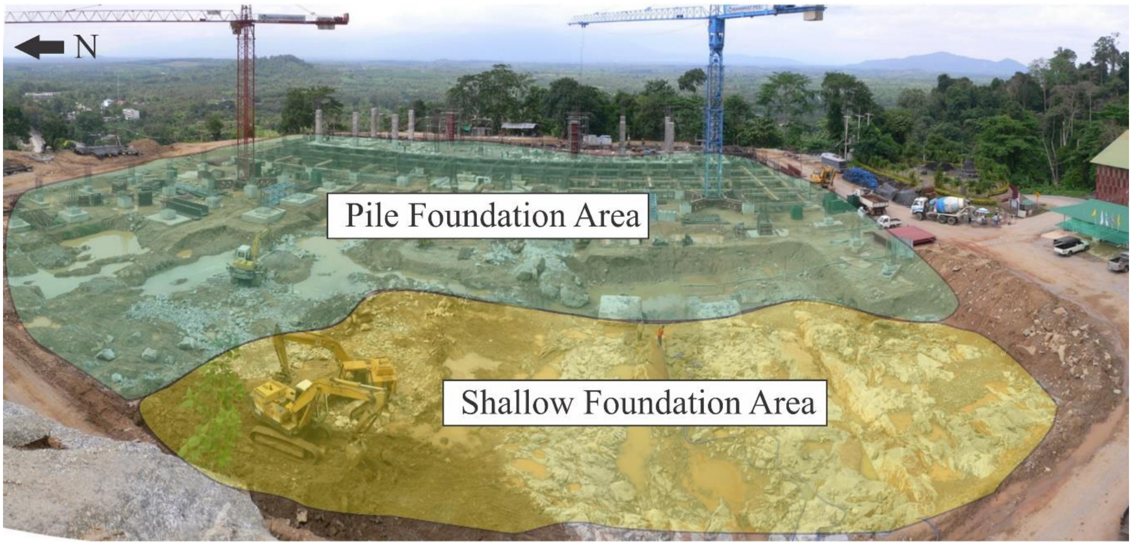

Fig.3 Different types of foundations in Pagoda area

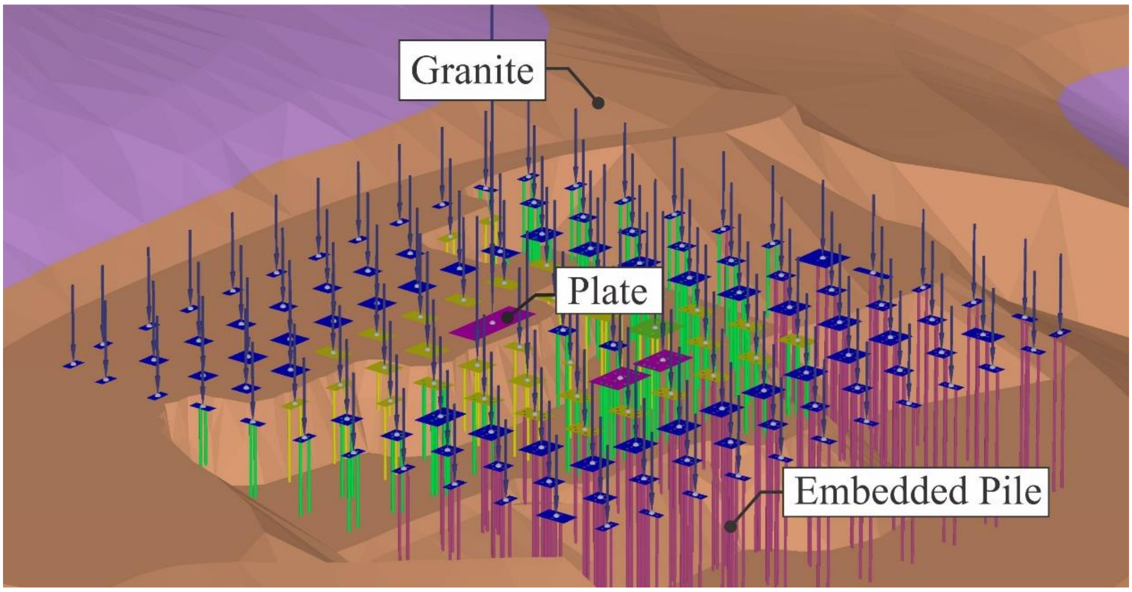

Fig.4 Different types of foundation model in PLAXIS 3D

4. CONSTRUCTION HISTORY OF WAT KHAO SUKIM PAGODA

In 1995, the first phase of development began with soil removal and rock blasting to create a flat base. During this time, a pile load test was carried out and it was determined that most bored piles did not meet the requirements for carrying the maximum load.

In 2005, GERD (Geotechnical Engineering Research and Development) at Kasetsart University, Bangkok, Thailand, was charged with addressing the unresolved challenges. Representatives from Kasetsart University investigated and evaluated the slope stability of the old foundations. Throughout this period, additional piles were installed. In 2006, each pile was subjected to a load test to determine settlement. The test results were satisfactory, indicating that the piles could support the total load of around 80,000 t or 797,121 kN. The second through the fourth floors were finished in 2009. The pagoda construction project is currently progressing.

The Pagoda foundation is composed of 645 piles and 36 shallow foundations. The foundations have been embedded in granite rock. Notably, the uneven ground surface and the location of granite rock have led to different types of foundations in this structure.

In previous research [3], the analysis of differential settlement was considered acceptable as recommended by ACI, 2017, and ASCE/SEI 7-02, 2013. However, notably, in the previous work, the construction phase with preloading was not included in the calculation phase. On the other hand, in the current study, the construction phase with preloading was included in the calculation, which was a major improvement over the previous research.

4.1 Foundations of Wat Khao Sukim Pagoda

The foundations of Wat Khao Sukim were redesigned after Kasetsart University's GERD took over the project in 2005. The old foundation was excavated and new foundations were engineer-designed to be laid into the granite rock on the slope.

The Pagoda foundation was divided into two main areas: the shallow foundation area (Zone 1) and the pile foundation area, as shown in Fig.3. The pile foundation area was composed of piles having a length of 11 m in the middle part (Zone 2) and of 18–26 m in the northeast-southeast part (Zone 3).

In the Western part of Pagoda, the granite rock was located close to the surface, making it a logical choice for laying the foundation. In this area, the shallow foundation had a thickness of around 1–1.5 m.

The granite rock was slightly deeper toward the center of Pagoda until the eastern part. Once the excavation had been completed, it was leveled by adding fill to make a flat base for the construction. As can be seen in Fig.5, the foundation was attached to granite in the western part, with a piled foundation with fill on the top layer in the eastern part.

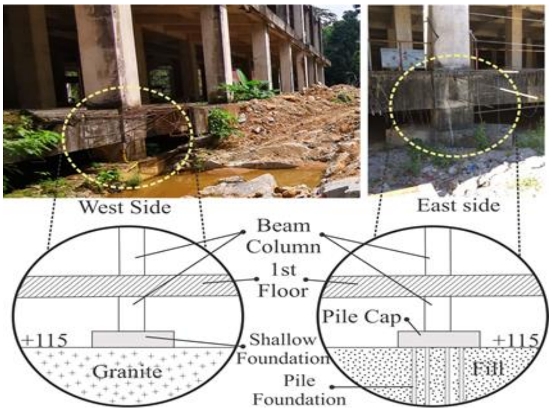

Fig.5 Foundations on west side and east side

4.2 Phases and Loads

In previous work, the phases included in the calculation only considered the phase of construction or installation of the pile and adding 100% of the column load in one phase. In contrast, the current work considered the actual construction period and adopted the preloading concept. Several phases have been specified to illustrate the various stages that the Pagoda has undergone. In the case of the Wat Khao Sukim Pagoda, foundation and base work began in 2008.

The calculations addressed the stages shown in Fig.6:

1) Phase 1. Construction of the long pile foundation with a length of 18–26 m in the eastern part (Zone A). Construction of pile caps and the first floor in this area was also included. The load applied for this phase was 20% of the total column load.
2) Phase 2. Construction was extended to the northwestern part. In this phase, the construction covered only a small area (Zone B). The load applied was 20% of the total column load. Elsewhere, the construction continued in the eastern part of the Pagoda (Zone A). The load applied was increased to 40% of the total column load because the 2nd floor had been constructed.
3) Phase 3. A small area in the northwestern part was extended from the center of the Pagoda to the southwest. The load applied varied in this area. In the center of the Pagoda (Zone C), the load applied was 20% of the total column load,

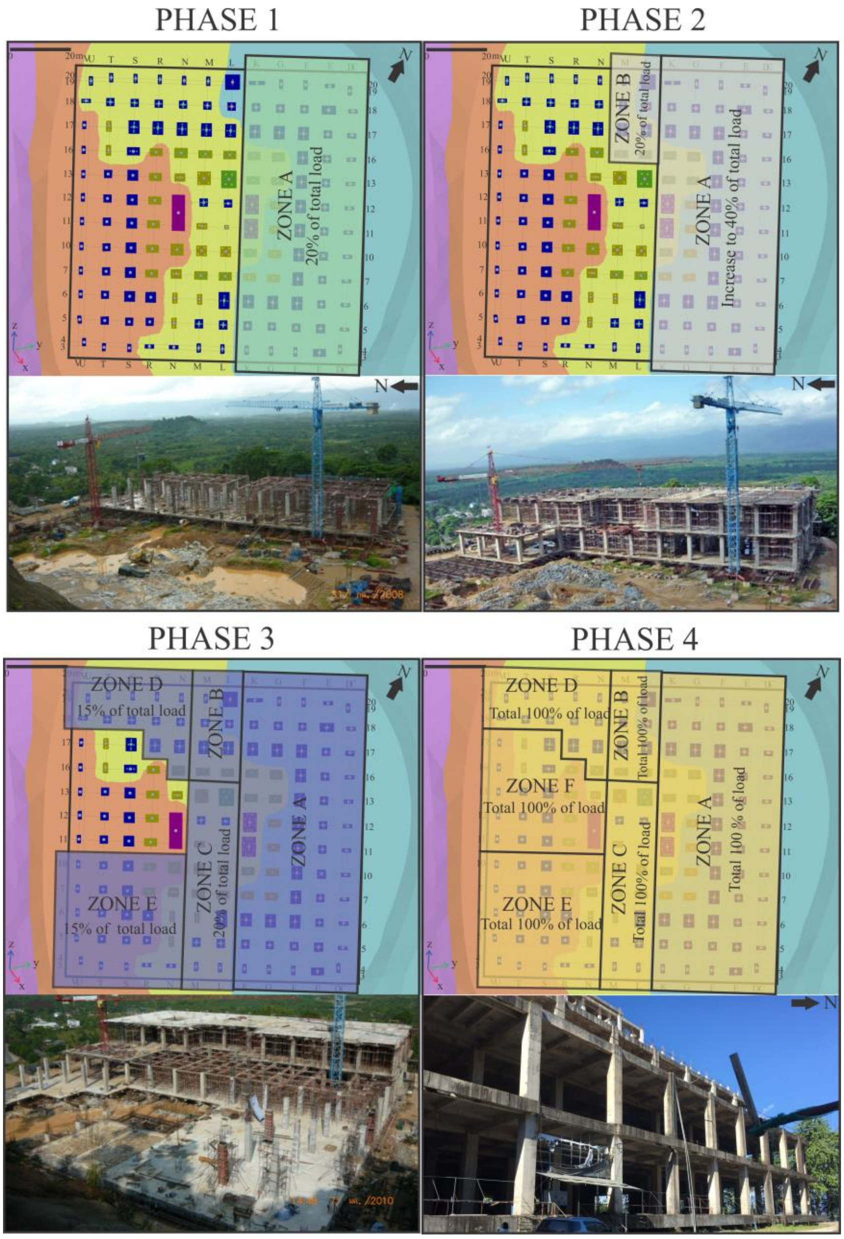

Fig.6 Phases of construction

4) whereas only 15% was applied in other parts (Zone D and Zone F) because the column needed to be entirely constructed. The areas in Zone A and Zone B had no applied load.
5) Phase 4. Construction was completed to the 5th floor. The rest of the column load was applied to the Pagoda area.

4.3 Geotechnical Model

The stratigraphy model beneath the Pagoda was composed of fill, clayey sand (SC), silty sand (SM), weathered granite, and granite. During the modeling process, this stratigraphy was simplified [3,15].

The soil properties of the strata used for the calculations are listed in Table 1. These were obtained from samples taken in the Pagoda area and from the work of other researchers [14,16–19].

An accurate definition of the 3D model of the Pagoda area has been done [3]. Notably, the depth of the Granite rock was not uniform.

The soil layer on the surface gradually changed from granite rock (in the shallow foundation area) to SC and fill (in the pile foundation area), which could have caused differential settlement.

The characteristics of the pile in PLAXIS 3D were determined according to previous work [3] and the parameters are provided in Table 2.

Table 1. Soil parameters in PLAXIS 3D

Materials	Fill	Clayey Sand (SC)	Silty Sand (SM)	Weathered Granite	Granite
Model	MC	MC	MC	MC	MC
Drainage Type	Drained	Drained	Drained	Undrained C	Undrained C
γ_{unsat} (kN/m^3)	15	19	20	20.5	26
γ_{sat} (kN/m^3)	15	19	20	20.5	26
E'(kN/m^2)	70E3	90E3	180E3	-	-
v'	0.30	0.30	0.30	-	-
c'(kN/m^2)	15	5	8	-	-
E_u (kN/m^2)	-	-	-	15E6	46E6
v_u	-	-	-	0.495	0.495
S_u (kN/m^2)	-	-	-	10E6	20E6
φ' (˚)	29	30	37	0	0
Ψ' (˚)	0	0	0	0	0

γ: Unit Weight, E: Young's Modulus, v: Poisson's ratio, φ: Friction angle, Ψ: Dilatancy angle, S_u: Undrained Shear Strength, MC: Mohr-Coulomb Model.

Table 2. Foundation properties in PLAXIS 3D

Structure	Shallow Foundation	Pile Foundation	
	Zone 1	Zone 2	Zone 3
Model Element	Plate	Embedded Beam	
Thickness (m)	1-1.5	-	
Pile Length (m)	-	11	18,24,26
E (kN/m^2)	30,000,000	30,000,000	
γ (kN/m^3)	24	24	
Beam type	-	Circular-Square	Square
T_{shaft}(kN/m)	-	148.2	34.55
T_{base}(kN/m)	-	1,097	3,097
F_{max} (kN)	-	12,700	20,700

γ: Unit Weight, E: Young's Modulus, T_{shaft}: Skin Resistance at the top, T_{base}: Skin Resistance at the bottom, F_{max}: Base Resistance.

4.4 Groundwater Level Change

The initial water table was not identified in the borehole data since it is in the hills. For the initial conditions, the Pagoda area was set to dry conditions.

For the wet condition, the water table was set from 2 m to 5 m depth, as illustrated in Fig.7, to test the stability of the Pagoda when extreme conditions occur, such as heavy rainfall. This was important to ensure the structure could remain stable and not collapse. This helped to identify any potential weak points in the structure.

5. RESULTS AND DISCUSSION

5.1 Differential Settlement Analysis

In this part, the most important results from the FEM model calculations are presented and analyzed. The settlements for each construction phase are shown in Fig.8. Notably, after each phase of construction, the option to reset displacements to zero was applied. Thus, all phases began with zero displacement.

In previous work, all the foundations were assumed to have been constructed at the same time. Then, the differential settlement was determined by comparing the final settlement of each zone. In the current work, after each phase construction with some building load, settlement of this phase occurred and the level of the foundation in this zone sank. Next, the foundation of the new zone was constructed and connected to the foundation of the previous zone. Therefore, the differential settlement between connecting zones was determined from only this phase and the settlement from the previous phase could be neglected in the differential settlement consideration.

Fig.8 shows that the phase of construction was divided into zones A–F. In phase 1, the value of the phase settlement in zone A was relatively small, with an average of 0.29 mm.

In Phase 2, the stage construction was extended to zone B. The average phase settlement in zone A was 0.22 mm and in zone B was 0.26 mm. In addition, the differential settlement between zone A and zone B was relatively small at 0.04 mm.

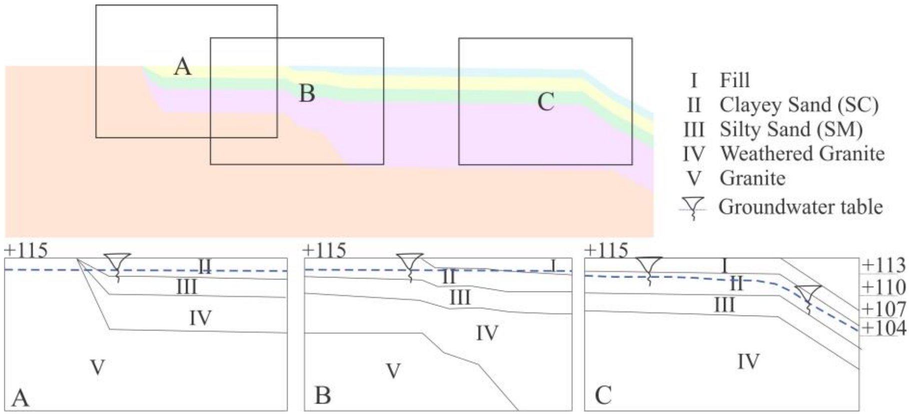

Fig.7 Illustration of groundwater table

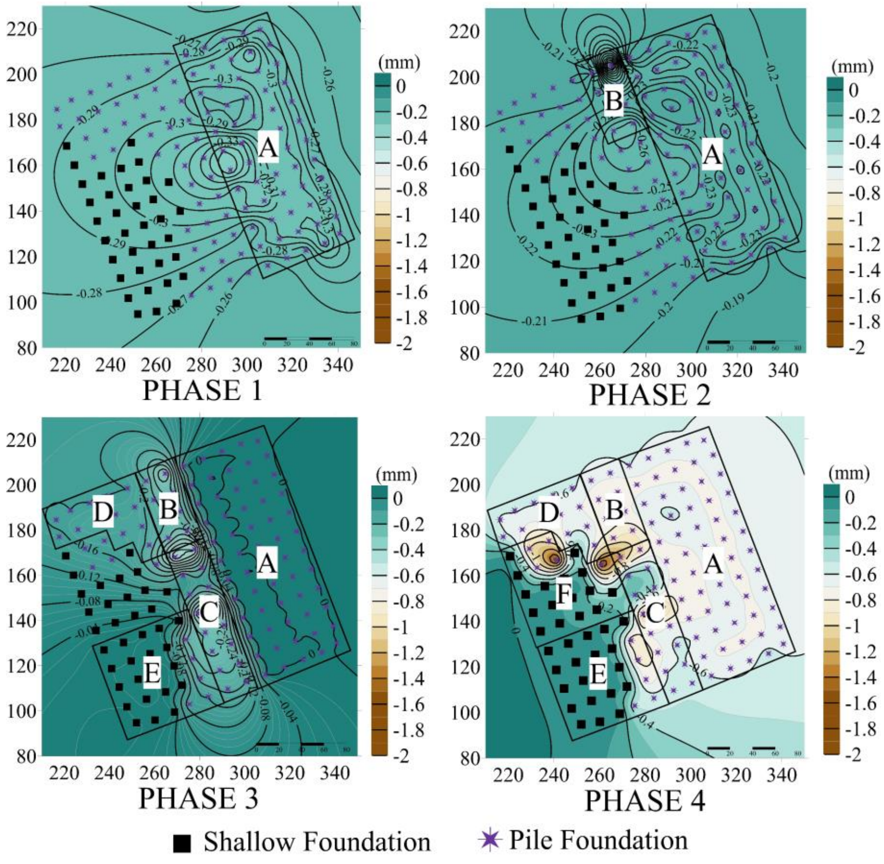

Fig.8 Settlement map of each phase

In contrast, in Phase 3, construction in zone A and zone B was not applied. It was extended, with the load being applied only to zones C, D, and E. The highest phase settlement was in zone C, followed by zones D and E because the load applied in zone C was higher than in any other zone. The average phase settlement values in zones D, E, and F were 0.26 mm, 0.17 mm, and 0.05 mm, respectively.

Furthermore, zone A has direct contact with zone C and zone B has direct contact with zone C and zone D. As mentioned before, no load was applied to zones A and B and the settlement in this zone was zero. Consequently, the differential settlement between zone A and zone C was 0.26 mm and the values for zone B with zone C and zone D were 0.26 mm and 0.17 mm, respectively. Variation in the values for differential settlement between the zones were as expected, with zone C experiencing the highest settlement due to the load applied.

The phase settlements in each stage of construction from Phase 1 to Phase 3 varied depending on the construction stage and area of application. The settlement in Phase 1 was higher compared to the other stages, with the settlement in Phase 3 being lower due to the absence of construction in zones A and B.

In Phase 4, the construction was extended to zone F, resulting in phase settlement values of 0.68 mm in zone A, 0.77 mm in zone B, 0.66 mm in zone C, 0.66 mm in zone D, 0.21 mm in zone E, and 0.38 mm in zone F. Overall, the range of settlement increased as the construction progressed and the range also increased as the load was applied to deeper foundations. The average settlement in each phase is summarized in Table 3.

Table 3. Average settlement in each phase

	Average Settlement (mm)				
Zone	Previous Work [3]	Current Work			
		Phase 1	Phase 2	Phase 3	Phase 4
A	1.12	0.29	0.22	0.00	0.68
B	0.98	-	0.26	0.00	0.77
C	1.07	-	-	0.26	0.66
D	0.90	-	-	0.17	0.64
E	0.29	-	-	0.05	0.21
F	0.39	-	-	-	0.38

The current result in Phase 4 was compared with previous work [3]. Overall, the analysis showed that the settlement values in the current model were lower than in the previous model, which showed the advantageous impact of the construction phase. Table 4 shows that the current model reduced the differential settlement value by more than 50%, indicating the advantageous optimization achieved during the construction phase across all zones. This reduction was expected to reduce any potential damage to structures in these zones, which may reduce the need for costly repairs in the future.

Table 4. Differential settlement in each zone

	Differential Settlement (mm)			
Zone	Previous Work [3]	Current Work		
		Phase 2	Phase 3	Phase 4
AB	0.14	0.04	-	0.09
AC	0.05	-	0.26	0.02
BC	0.09	-	0.26	0.11
BD	0.08	-	0.17	0.13
CE	0.78	-	0.21	0.45
CF	0.68	-	-	0.28
DF	0.51	-	-	0.26
EF	0.10	-	-	0.17

5.2 Groundwater Level Change

With wet conditions, the water table was 2 m below the ground level and gradually lowered to 5 m in the fill area. The maximum increase in the water level close to the ground surface was around 2 m depth.

The analysis showed initially, the maximum settlement in the Pagoda area for dry and wet conditions was 1.68 mm. This very small settlement value indicated that the soil in the Pagoda area for both dry and wet conditions was likely to remain stiff and strong.

The analysis of the stability of the Pagoda involved increasing the load to a level several times greater than the initial column load. The stability of the Pagoda was satisfactory for a maximum load of 5 times the initial column load for both dry and wet conditions, as shown in Fig.9, indicating that the Pagoda was stable and could withstand a large load without undergoing any major structural deformations and a variety of structural uses were suitable, even in wet conditions.

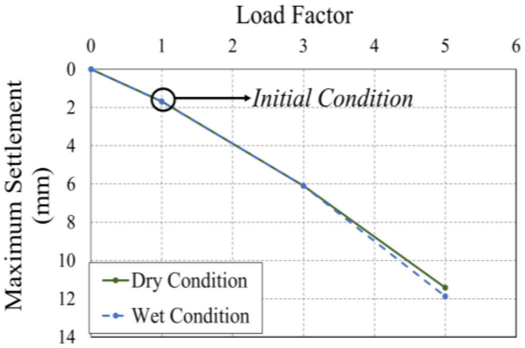

Fig.9 Maximum settlement results with increased load for dry and wet conditions

6. CONCLUSIONS

The evaluation of differential settlements in Wat Khao Sukim Pagoda, considering its construction phase, revealed significant insights. The application of the preloading concept emerged as an advantageous technique for minimizing the risk of differential settlement across diverse foundation types. Quantitative analysis showcased notable reductions, with average settlement values in each phase consistently lower than those reported in previous studies. Notably, the current model exhibited a commendable reduction of over 50% in differential settlement, underscoring the efficacy of the preloading concept in addressing the differential settlement issue in this specific area.

Furthermore, an examination of the influence of fluctuations in groundwater levels within the Pagoda area has indicated negligible impact on settlement. Moreover, structural stability has been confirmed under diverse load conditions, with the Pagoda exhibiting resilience even under a maximum load five times the initial load, both in dry and wet conditions. These quantitative findings underscore the strength of the preloading concept and its successful application in mitigating the risks associated with differential settlement in the studied context.

7. ACKNOWLEDGMENTS

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8. REFERENCES

[1] Sanchez E.R., Esteban A.M., and Casas, J.N., Analysis of Historical Settlements of the Giralda, International Journal of Architectural Heritage, Vol. 17, Issue 8, 2023, pp. 1312 -1330.

[2] Ito H., Ishida Y., Sansaard V., Takeyama T., and Iizuka A., Leaning Pagoda of Ayutthaya Analysis with Three-Dimensional Effects and Ground Uncertainty, International Journal of GEOMATE, Vol. 20, Issue 82, 2021, pp. 161-169.

[3] Pratama G.A.P., Amornfa K., Mairaing W., and Soralump S., Analysis of Complex Foundation on Historical Pagoda in Thailand Using 3D Finite Element Method, International Journal of GEOMATE, Vol. 23, Issue 98, 2022, pp. 125-135.

[4] Soralump S., Construction of a Building Foundation on A Hillside: A Case Study of the Construction of Wat Khao Sukim, Academic Seminars on Soil and Foundation Engineering, Bangkok, Thailand, 2009.

[5] Johnson S.J., Precompression for Improving Foundation Soils, ASCE, Journal of the Soil Mechanic and Foundation Engineering, Vol. 96, 1970, pp. 111-144.

[6] ACI, Building Code Requirements for Reinforced Concrete – ACI 318-89, American Concrete Institute, Detroit, Michigan USA, 2006.

[7] ASCE/SEI 7-02, Minimum Design Loads for Buildings and Other Structures, American Society of Civil Engineers, Reston, Virginia, USA, 2013.

[8] Jan C.D., Chen T.H., and Huang H.M., Analysis of Rainfall-induced Quick Groundwater-level Response by using a Kernel Function, Paddy and Water Environment, Vol. 11, 2013, pp. 135-144.

[9] Intui S., Soralump S., and Inazumi S., Behavior of Bearing Capacity on Pile Foundation During Fluctuating Groundwater Level, International Journal of GEOMATE, Vol. 22, Issue 90, 2022, pp. 24-31.

[10] Zhang M., Singh H.V., Migliaccio K.W., and Kisekka I., Evaluating Water Table Response to Rainfall Events in a Shallow Aquifer and Canal System, Hydrological Processes, Vol. 31, Issue 22, 2017, pp. 3907-3919.

[11] Troncone A., Pugliese L., and Conte E., Rainfall Threshold for Shallow Landslide Triggering Due to Rising Water Table, Water, Vol. 14, Issue 19, 2022, pp. 1-11.

[12] Labuz J.F., and Zang A., Mohr-Coulomb Failure Criterion, Rock Mechanics and Rock Engineering, Vol. 45, Issue 6, 2012, pp. 975-979.

[13] Nasr A.M., Elhakim A.F., and Amer M.I., Soil Stiffness from Back-Analysis of Pile Load Tests in Al Burrullus, Ain Shams Engineering Journal, Vol. 13 Issue 6, 2022, pp. 1-14.

[14] Plaxis, PLAXIS Material Models Manuals, Bentley, Netherlands, 2018.

[15] Bovolenta R., and Bianchi D., Geotechnical Analysis and 3D FEM Modeling of Ville San Pietro (Italy), Geosciences, 2020, pp.1-25.

[16] Noihome C., A Study of Behavior of Differential Settlement Between Shallow Foundation and Piles Foundation, Thesis Master Degree, Kasetsart University, Bangkok, 2014.

[17] USACE, Settlement Analysis, Engineer Manual No. 1110-1-1904, Washington D.C., 1990.

[18] Das B.M., Principle of Foundation Engineering, 9th Edition, Cengage Learning, Boston, 2019, pp.1-856.

[19] Thasnanipan N., Boonyarak T., Aye Z.Z., Chea S., and Roth C., Challenge in Deep Foundation and Underground Structure in Thailand, 11th International Conference on Extreme Engineering, 2019, pp.1-15.