

# ANALYSIS OF COMPLEX FOUNDATION ON HISTORICAL PAGODA IN THAILAND USING 3D FINITE ELEMENT METHOD

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\*Corresponding Author, Received: 02 Aug. 2022, Revised: 07 Sept. 2022, Accepted: 10 Oct. 2022

**ABSTRACT:** This paper presents a three-dimensional foundation numerical model of Thailand's historical building, the Wat Khao Sukim Pagoda. The Pagoda's high reputation is due to the fact that it was constructed through donations from the public. The purpose of the research is to analysis the differential settlement and define the capable layer to transmit the load from structure. Numerical analysis will significantly contribute to the construction and mitigate the impact of any potential differential settlement. The present study is using PLAXIS 3D to model the ground surface and to analyze the settlement of the complex foundations of the Pagoda, which is loaded by varying column load. Back-analysis of the single pile load test was performed to verify the soil parameters and the results of the numerical simulations were in good agreement with settlement data reported in the field. The numerical analysis showed the settlement values in Zone 1 (shallow foundation) were in the range 0.05-0.43 mm, in Zone 2 (short pile foundation) were in the range 0.42-1.98 mm, while Zone 3 (long pile foundation) had a settlement range of 0.82-1.25 mm. These results were considered acceptable due to the modes differences in values that the differential settlement did not exceed 0.75 ins or 19 mm as recommended by ACI, 2017 and ASCE/SEI 7-02, 2013. Also, Weathered Granite layer is determined as an effective layer capable of transmitting a significant load of higher than 50%.

*Keywords: Differential settlement, Shallow foundation, Pile foundation, Historical building, 3D finite element method*

## 1. INTRODUCTION

Many historical buildings suffer from structural damage caused by differential settlement and inclination [1]. The geological profile of the soil and the type of foundation that carry the load have a dramatic effect on the superstructure.

The factors that influence the type of foundation selected to support the structure, in this case the Pagoda, are ground conditions and location of rock strata. The Pagoda is located in the foothills with uneven ground surface, the strong rock strata can be found at depths ranging from 0 m (on the surface) to 26 m below the ground level, which is likely to be weathered with a deep thickness. As a result, in the beginning of construction when the pile load test was performed, the pile was unable to carry the maximum load. As a reason of that, the whole foundation was newly design.

The problem might arise because of the loads from the superstructure that are transferred to the non-uniform foundation can lead to differential settlements. When differential settlement occurs, foundations with sufficient stiffness will cause the building to tilt as a rigid body and will consequent serious damage to the structure of a building [2] or remain within the safe according to allowable differential settlement values under specific building regulations [3,4].

This paper presents a simplified three-dimensional finite element study of complex foundations. PLAXIS 3D is used to generate the numerical model and a project of Wat Khao Sukim Pagoda selected as case study. The analysis focus on the varying column loads applied on the different types of foundations and define the capable layer of soil to transmit the load. All the finite element model are compared with several tests that have been conducted, including eight boreholes, SPTs, and eight static pile load tests. In 2021, six samples were collected from Fill and Weathered Granite Layer and tested in the laboratory. Field investigations also conducted to evaluate the present situation of the research area.

## 2. RESEARCH SIGNIFICANCE

The findings of this research will redound to the construction project of the Pagoda. Since the Pagoda was surrounded by small temple in the foothills and community area, any risk should be avoided. The structure is located on the ridge of the hill. Thus, it can create the stresses and movements in any directions. In this case, modeling in 3D has a clear benefit over 2D models. The importance of this research is showing the amount of settlement value resulting from different types of foundation and to understand the possible causes of differential

settlement. Also, in 3D model can predict the direction of its lateral movements when it happens and to mitigate their impact. Furthermore, in the near future, some of buddha statue also will be placed inside the Pagoda. This research can be used as a reference for the proper location of the statues.

### 3. LOCATION AND PROJECT HISTORY

Chantaburi province is located 245 km east of Bangkok. Granitic rocks and metamorphic rocks dominate most of the area, with recent quaternary deposits in lower part of the slope.

The Pagoda construction site is on the east side of Wat Khao Sukim, in the foothills. 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 [5]. The first phase of construction began in 1995 with clearing the area and blasting the rock to form a flat base. During this time, a pile load test was performed, and it was discovered that most of the bored piles did not meet the criteria for carrying the maximum load because of spheroidal weathering caused by the floating rocks—the pile tip of the bored pile rested on these floating rocks rather than on the bedrock. It should be noted that the Pagoda foundations are embedded into granite rock on the slope with both shallow and pile foundations, as shown in Fig. 1 that can lead to differential settlement.

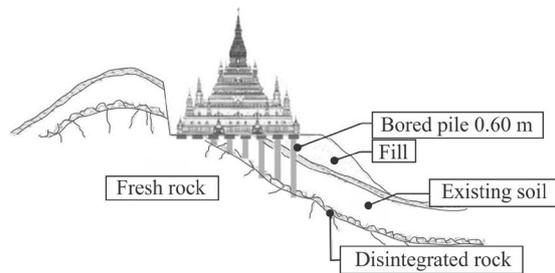


Fig.1 The sketch of Wat Khao Sukim and the foundation laid on the rock [5].

Subsequently, the project was delayed for several years after first construction; these problems still have not been solved. In 2005, Kasetsart University's GERD (Geotechnical Engineering Research and Development) was mandated to resolve the outstanding issues. Representatives from Kasetsart University analyzed the old foundations by excavation and checking the slope stability. During this period, additional piles were installed in this area.

In 2006, all the piles were subjected to a load test to check the settlement. The result was acceptable. Six hundred forty-five piles and thirty-six shallow foundations supported the total load of the Pagoda around 80,000 t or 797,121 kN. After the piling work had been completed, construction

commenced on a new structure while, concurrently the old structure was demolished. In 2009, the 2nd to 4th floors were completed. Currently, the pagoda construction project is still ongoing.

## 4. MODELLING APPROACHES

### 4.1 Mohr-Coulomb Model

The Mohr-Coulomb model (MC) is used to approximate the general behavior of soils. The linear elastic-perfect plastic model is the simplest with the fewest parameters to input [6]. It is recommended as a starting point for analyzing the current problem. The model's principal strengths are that the input parameters define stiffness, such as the modulus of elasticity and Poisson's ratio. Five input parameters are required in PLAXIS 3D: the elasticity modulus (E), Poisson's ratio ( $\nu$ ), cohesion (c), angle of friction ( $\phi$ ), and angle of dilatancy ( $\psi$ ).

### 4.2 Embedded Beam and Plate Element

In PLAXIS 3D, an embedded beam is composed of beam elements with embedded interface elements that describe the interaction of the pile skin (skin friction) and the pile tip (end bearing) with the soil [7]. In this case, piles can be analyzed in three dimensions by characterizing them as embedded beams.

Table 1. Pile parameters input in PLAXIS 3D

Structure	Shallow Foundation	Pile Foundation	
	Zone 1	Zone 2	Zone 3
Model	Plate	Embedded Beam	
Element	Plate	Embedded Beam	
Thickness (m)	1-1.5	-	
Pile Length (m)	-	11	18,24,26
E (kN/m <sup>2</sup> )	30,000,000	30,000,000	
$\gamma$ (kN/m <sup>3</sup> )	24	24	
Beam type	-	Circular-Square	Square
T <sub>shaft</sub> (kN/m)	-	148.2	34.55
T <sub>base</sub> (kN/m)	-	1,097	3,097
F <sub>max</sub> (kN)	-	12,700	20,700

The plate element was chosen to simulate a pile cap since this allows a completely compatible connection with the embedded pile element. At the same time, both parts have three translational and rotational degrees of freedom that help avoid numerical issues [8]. The parameters [7,9] are provided in Table 1.

## 5. 3D MODELLING SOIL

### 5.1 Soil Strata

In general, stratigraphy plays an important role in soil and pile analysis. In most cases, only a limited amount of data is available. For that reason, the stratigraphy must be simplified during the modeling process [10]. Indeed, it is common to overlook relatively thin or discontinuous layers, which can be corrected with proper parameter calibration based on monitoring data or field observation [11]. Therefore, without a doubt, calibration and validation are delicate and critical stages of the modeling process.

Site investigation boreholes were used to reveal the subsoil conditions. For brevity, all the boreholes are not presented here; instead, a simplified stratigraphy profile of the soil is shown in Fig.2.

The simplified stratigraphy profile was created using interpolation of 39 boreholes and five sampling points. The subsoil is composed of fill (approximately 1–2 meters thick), clayey sand (about 1–3 meters thick), silty sand (approximately 2–3 meters thick), weathered granite (approximately 3–8 meters thick), and underlying bedrock (granite). The parameters were chosen carefully to ensure that the model accurately simulated the actual soil behavior.

### 5.2 3D Model and Soil Parameters

Modeling the 3D soil to create a more realistic slope model as illustrated in Fig.3, required numerical analysis using Google Earth contour data to develop the topographic surface, with the borehole data used to generate the soil stratigraphy based on interpolation.

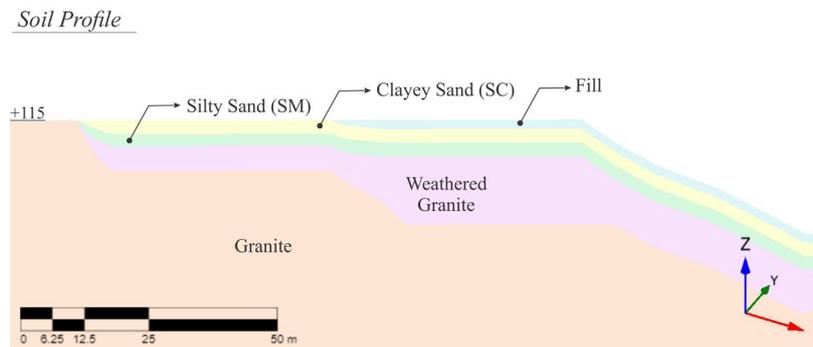


Fig.2 Soil stratigraphy profile in Wat Khao Sukim area.

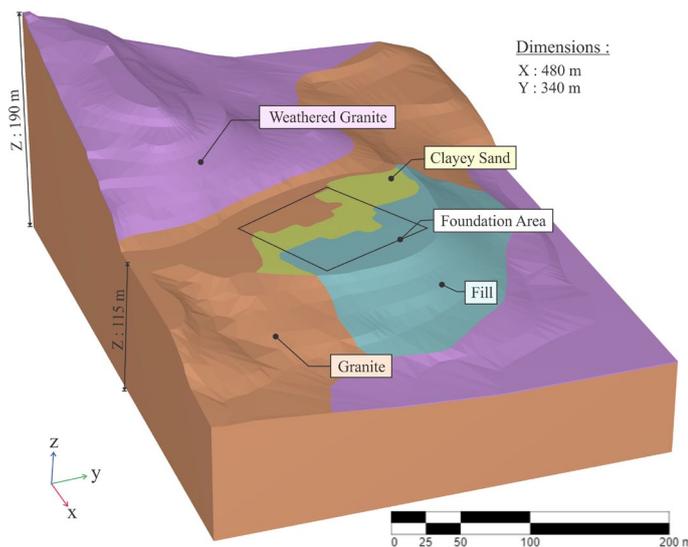


Fig.3 3D Soil model using PLAXIS 3D.

In PLAXIS 3D, the software automatically interpolates the boreholes and generates the thickness of each soil layer when many boreholes are inputted. In this case, misinterpretation may

occur while working with a complex 3D model, so that sometimes the model created does not represent the actual field conditions. The actual surface model may be obtained from several sources, including

Google Earth from which surface topography information may be transformed into contour data. Using this contour data as a reference, the dummy boreholes may be inserted along the contour data line to help create the 3D surface. This strategy was used to assist the software in interpolating the soil as planned.

The results of the 3D model should be checked to ensure the model boundaries are sufficiently extended far enough that they do not influence the analysis results. Then, the volume of the model is created using geometric processing in PLAXIS 3D.

The definition of the geometry in PLAXIS 3D requires that the soil properties be assigned appropriate values. Afterward, the proper value for the parameter is determined through a back-analysis test, which is used to calibrate a set of reasonable soil parameters, as shown in Table 2.

Furthermore, the surrounding ground level in this model was set at 115 m above sea level. Once the soil 3D model has been constructed, the structure, including the plate and embedded pile, was inserted into the model, as demonstrated in Fig.4.

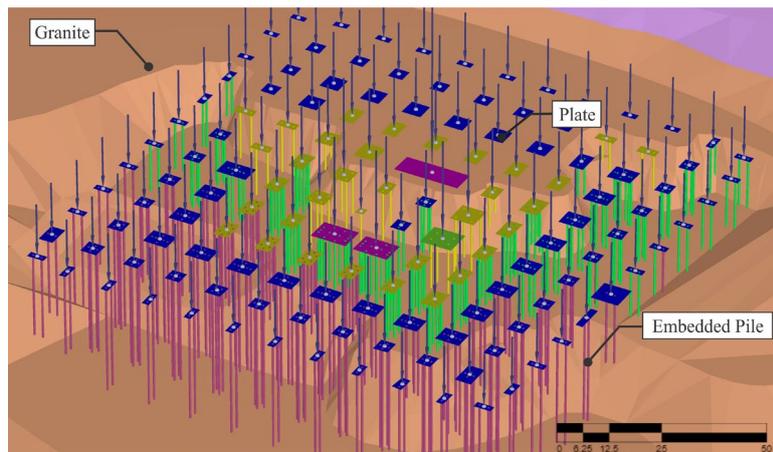


Fig.4 Plate (shallow foundation) and embedded pile (pile foundation) illustration in PLAXIS 3D.

Six samples were tested in laboratory to get the cohesion and friction angle values by performed the direct shear test. The testing results from two samples that get from fill layer were used to input the parameter the fill layer. On the other hand, the uniaxial test revealed that a realistic soil parameter was  $E = 46,686,620 \text{ kN/m}^2$  [9] for the granite layer. In addition, another value in Table 2 was derived from the work of another researcher [7,12,13,14].

### 5.3 Back-analysis of Pile Test

A back-analysis of the single-pile load tests is frequently performed to improve the accuracy and to validate the reasonable soil parameters to be used in the PLAXIS 3D model [15]. Eight static pile load tests were conducted in this case, with their locations shown in Fig. 5.

Table 2. Parameter of Soil 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
$\gamma_{\text{unsat}}$ (kN/m <sup>3</sup> )	15	19	20	20.5	26
$\gamma_{\text{sat}}$ (kN/m <sup>3</sup> )	15	19	20	20.5	26
$E'$ (kN/m <sup>2</sup> )	70E3	90E3	180E3	-	-
$\nu'$	0.30	0.30	0.30	-	-
$c'$ (kN/m <sup>2</sup> )	15	5	8	-	-
$E_u$ (kN/m <sup>2</sup> )	-	-	-	15E6	46E6
$\nu_u$	-	-	-	0.495	0.495
$S_u$ (kN/m <sup>2</sup> )	-	-	-	10E6	20E6
$\phi'$ (°)	29	30	37	0	0
$\Psi'$ (°)	0	0	0	0	0

Note: MC = Mohr-Coulomb Model

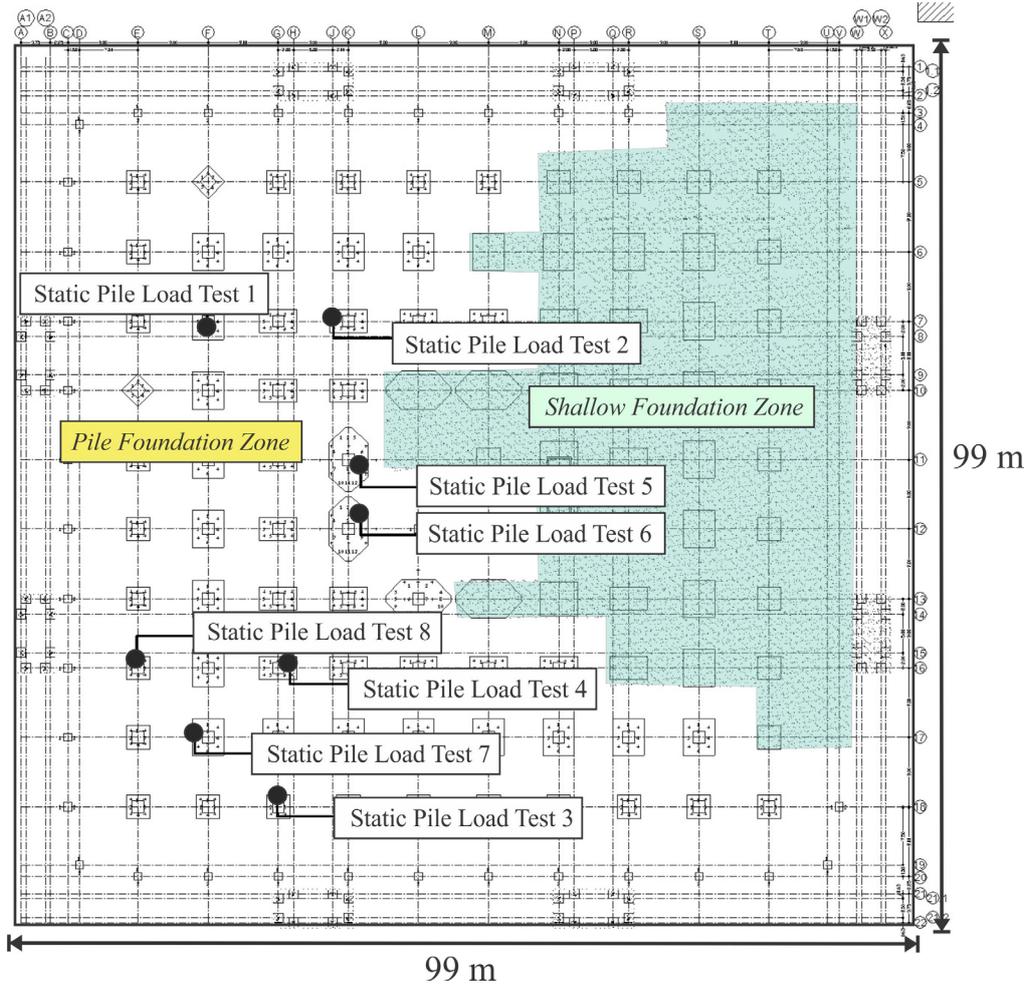


Fig.5 Location of static pile load tests [5].

The results of the static pile load test in the field are plotted in Fig. 6. The static pile load test results are presented as the circle for Zone 2 and as triangular for Zone 3. Reviewing the test results, the settlement of the pile in Zone 2 was higher (1.5-2.8

mm at 120 tons of load) than the pile in Zone 3 (1.2-2 mm at 120 tons of loads). These results show that the longer the pile is, the more settlement reduction can be achieved.

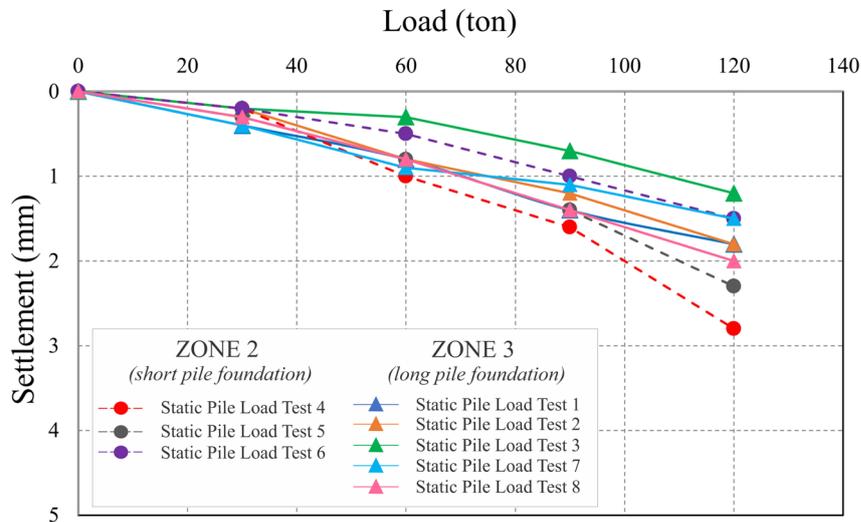


Fig.6 Static pile load tests result in the field.

The results presented in Fig. 7 were compared between settlement data from the actual and the single pile tests in PLAXIS 3D. The numerical simulations in PLAXIS 3D were compared with the settlement data reported in the field for single piles

shows the foundations were in good agreement. This result validated as reasonable soil parameters used for the three-dimensional soil model in PLAXIS 3D, as shown in Table 2.

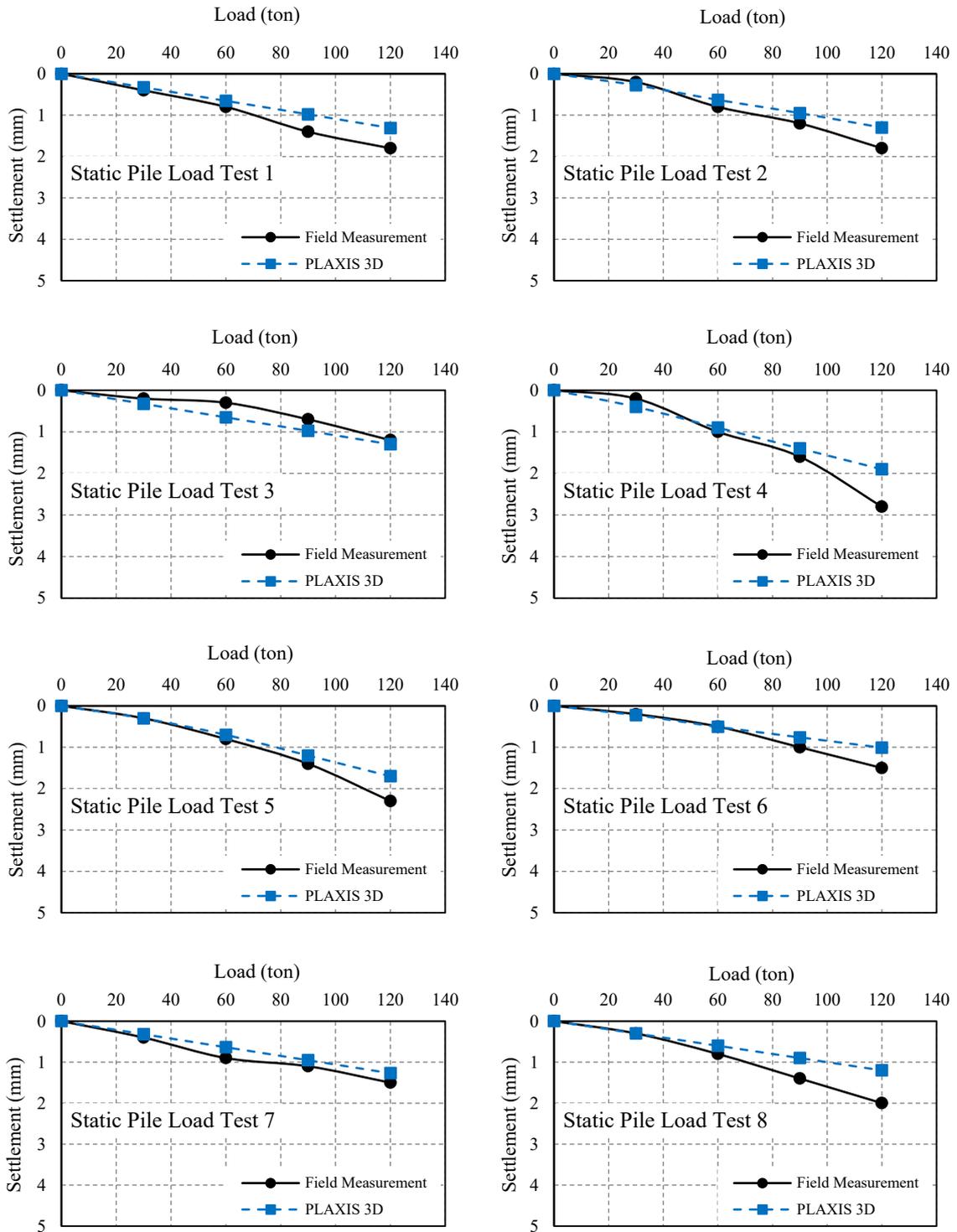


Fig.7 Load-settlement curves compared between settlement in PLAXIS 3D and static pile load test.

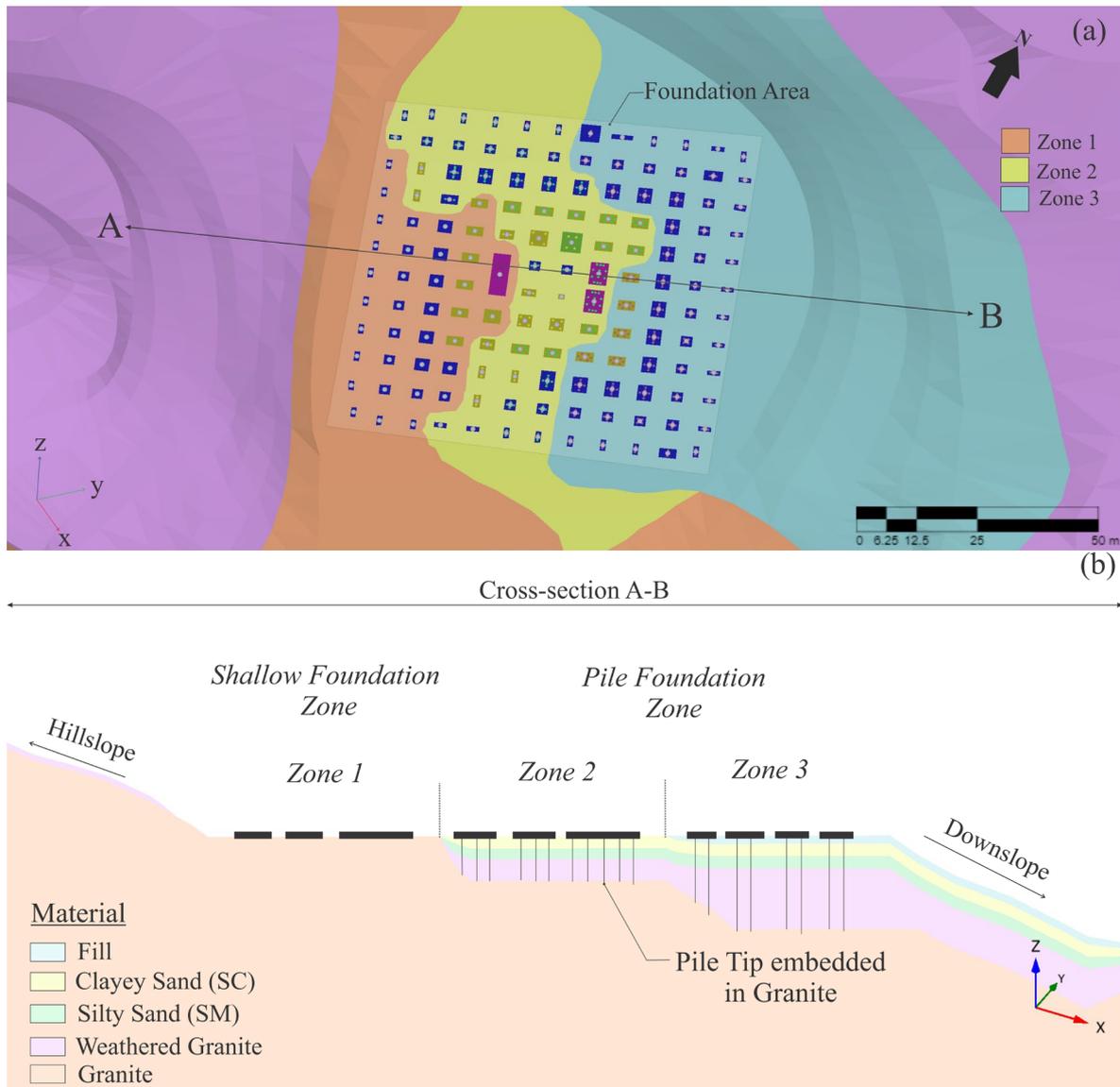


Fig.8 Output model for (a) location of foundation and (b) illustration pile on cross section A-B.

## 6. ANALYSIS OF THE FOUNDATION BEHAVIOR

### 6.1 Location of Foundation

Based on the stratigraphy, the group of foundation types can be classified into three zones, as illustrated in Fig. 8a and Fig. 8b. Zone 1 was the shallow foundation laid on top of the surface rock. Zone 2 consisted of the 11-meter driven piles and bored piles embedded in the rock, while Zone 3 consisted of driven piles embedded in rock ranging from 18 to 26 m.

### 6.2 Settlement in Shallow Foundation

The results of settlement in the finite element simulation are shown in Table 3. In general, assessing shallow foundations with varying column

loads and dimensions revealed relatively minimal settlement value (0.05–0.43 mm). These values indicated that the load in a shallow foundation is carried by the bearing of granite rock. In addition, the results indicated that the settlements were highly impacted by the load applied and the dimensions of the shallow foundation.

For example, as shown in Table 3, there was a high settlement value in the shallow foundation area N/11–N/12 with 0.43 mm. In this location, the column load applied was 24,164 kN. However, with the column load 3–6 times higher than other locations, the settlement value result was still low, and these was no large gap. This is because the foundation's dimensions were also important, resulting in a low settlement value. On the other hand, a small settlement value resulted when the column load applied was 2,177 kN and the dimensions of the foundation were 1.5x3 m.

Table 3. Settlement results in shallow foundation area

Location	Dimension (m)	Column Load (kN)	Settlement (mm)
N/10	4.8x4.4	7482	0.17
N/11-N/12	13.5X4.8	24164	0.43
R/5, S/5, T/5, T/6, T/7, T/10, T/11, T/12, T/13	3X3	4315	0.09-0.16
R/6, S/6, S/7, S/10, S/11, S/12, S/13	4X4	4786	0.11-0.15
R/7, R/10, R/11, R/12, R/13, R/16	4.8X3	5933-6374	0.14-0.18
S/3, T/3, U/4, V/5, V/6, V/7, V/10, V/11, V/12, V/13, V/16, V/17	1.5X3	2177	0.05-0.09

### 6.3 Settlement in Pile Foundation

The location of pile foundations in this research was separated into Zone 2 and Zone 3. Table 4 summarizes the settlement results using the finite element approach. Piles in Zone 2 had a slightly higher settlement value compared to piles in Zone 3 because the portion of loads applied in Zone 2, located near the center of the Pagoda, was higher than for the piles in Zone 3, as shown in Fig.9. However, the settlement values have remained mostly similar in Zone 3.

As illustrated in Fig.10 for the location of the column load applied, and in the settlement contour map, showed that the higher settlement values were distributed in Zone 3. Also, with the same column load, the settlement result in Zone 3 was higher than in Zone 1 because Zone 3 consisted of several soil layers, including fill on top, whereas Zone 1 only had a granite rock layer on top. This demonstrated that a smaller settlement value could be expected if the pile tip is laid on rock.

Table 4. Settlement results in pile foundation area

<i>Zone 2 (short pile foundation)</i>				
Location	Column Load (kN)	Pile Length (m)	Pile Size (m)	Settlement (mm)
G/13, G/16, K/10, K/13, K/16, L/5, L/6, L/7, L/16, L/17, M/5, M/6, M/7, M/16, M/17, M/18, N/16, N/17, N/18, R/17, R/18, S/16, S/17, S/18, T/18	4315-7482	11	0.52x0.52	0.88-1.68
K/11, K/12	11317	11	0.52x0.52	1.25-1.30
L/3, L/12, M/3, M/12, M/20, N/3, N/20, R/3, R/20, S/20, T/20, U/19, V/18	1589-2177	11	0.52x0.52	0.42-0.90
L/10, L/13, M/10, M/13	11317	11	0.8	1.55-1.98
L/11, M/11	1589	11	0.8	0.44-0.66
N/5, N/6, N/7, N/13, T/16, T/17	4315	11	0.8	0.82-1.56
<i>Zone 3 (long pile foundation)</i>				
Location	Column Load (kN)	Pile Length (m)	Pile Size (m)	Settlement (mm)
C/5, E/3, G/3, K/3, L/20	2177	18	0.52x0.52	0.82-1.10
C/6, C/7, C/10, C/11, C/18, D/4, D/19, E/20, F/3, F/20, G/20, K/20	2177	24	0.52x0.52	1.01-1.09
C/12, C/13, C/16, C/17	2177	26	0.52x0.52	1.07-1.10
E/13, E/16, G/5, K/5, K/7, K/17, L/18	4315	18	0.52x0.52	1.02-1.25
E/5, E/6, E/7, E/10, E/11, E/17, E/18, F/5, F/18, G/18, K/18	4315	24	0.52x0.52	1.17-1.24
E/12	4315	26	0.52x0.52	1.24
F/13, F/16, G/6, G/17	4786	18	0.52x0.52	1.01-1.08
F/6, F/7, F/10, F/11, F/17, K/6	4786	24	0.52x0.52	1.01-1.10
F/12	4786	26	0.52x0.52	1.10
G/7	5933	18	0.52x0.52	1.19
G/10, G/11, G/12	6374	18	0.52x0.52	1.22-1.25

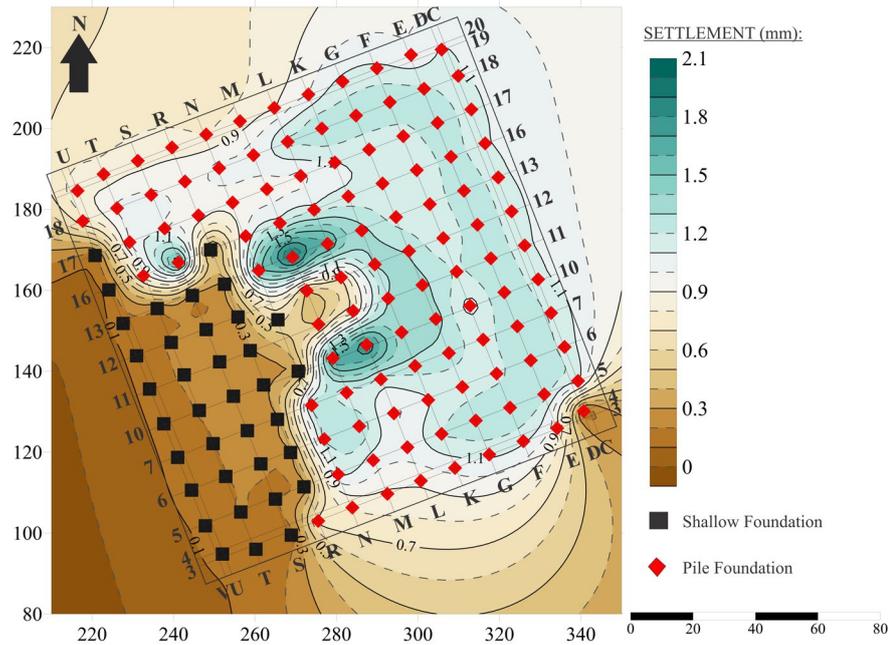


Fig.9 Settlement contour map.

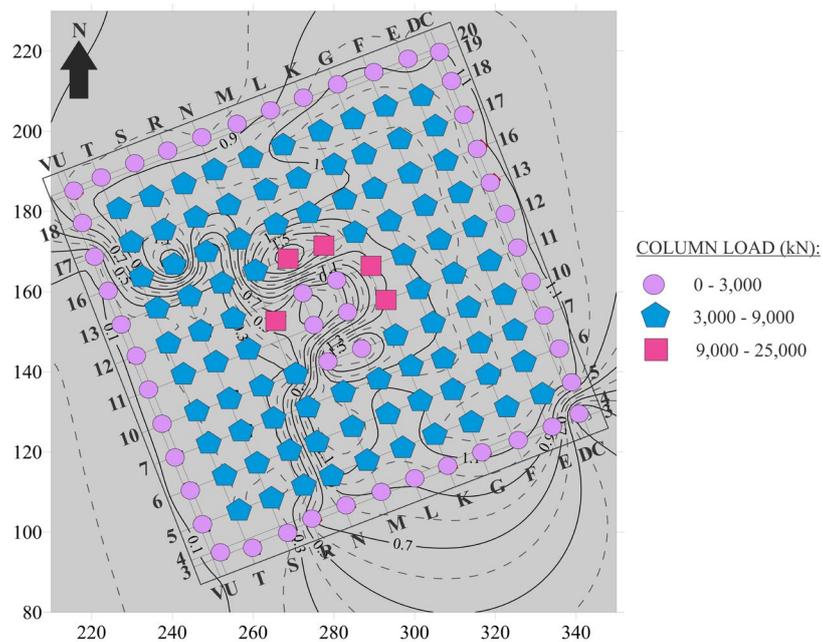


Fig.10 Column load location map.

#### 6.4 Load Distribution in Pile

Several piles have been chosen as representative piles based on pile size, pile length, and load applied. Fig.11 shows the axial force distribution when a load is applied in Zone 2. As a result of the thick layer of soil, the axial force of the pile shaft gradually decreased from the pile top to the pile tip along the depth direction. In Zone 2, especially for the pile location at T/17 with a pile diameter of 0.8 m, the axial force substantially decreased down to

106 m depth and reached zero at the pile tip. A pile size of 0.52 x 0.52 m had a similar trend of axial force distribution because the load applied did not differ by much and all pile tips were embedded to the same depth (104 m).

The axial force distribution in Zone 3 is shown in Fig.12. In this zone, the pile tip was embedded to different depths. For example, the pile tips at G/6, F/11, and F/12 were at depths of 97 m, 91 m, and 89 m, respectively. In general, the trend of axial force distribution was similar because it was applied with

the same load; when it was close to the pile tip, the axial force substantially decreased.

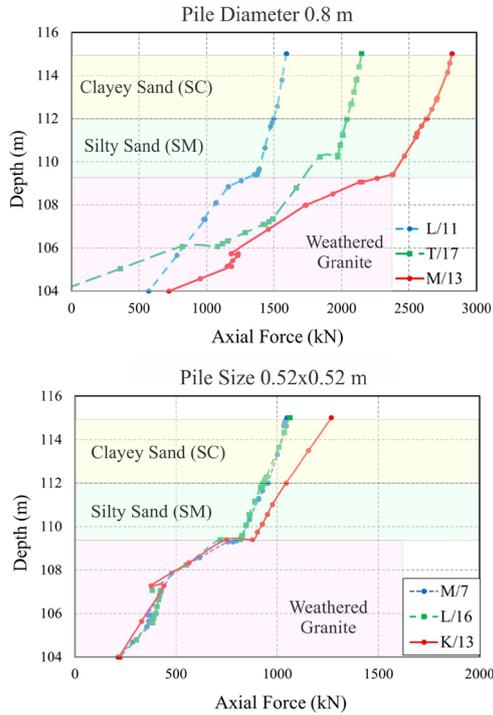


Fig.11 Axial force in Zone 2 with different pile diameters and size.

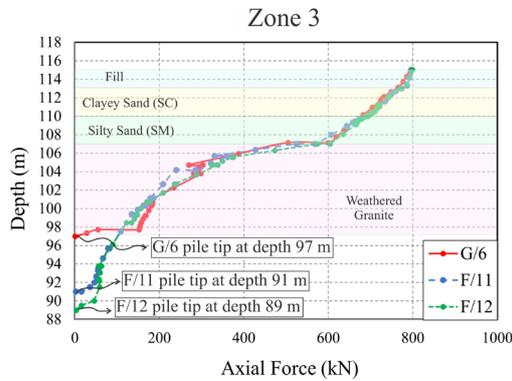


Fig.12 Axial force in Zone 3 with different pile tips.

In this case, skin friction often generates more resistance than end-bearing friction in driven piles. As a result, the soil layers have a more substantial portion on which to distribute the load before it reaches the rock, where the pile is embedded.

To identify a substantial layer capable of transmitting the applied load using representative piles, the percentage of load transfer is shown in Table 5 for Zone 2 and in Table 6 for Zone 3. In Zone 2, the layer of soil consisted of clayey sand, silty sand, and weathered granite with the pile tip embedded in the granite rock layer. As seen in the table, the weathered granite layer can transmit a load of more than 50% on average. This means the

part of the load was transferred to the surrounding soil through the frictional shearing action between the pile side and the soil.

Table 5. Percentage of load transfer in each layer Zone 2

Pile Diameter 0.8 m				
Layer	Load Transfer (%)			Average (%)
	L/11	T/17	M/13	
SC	6	5.1	8.8	6.6
SM	8.8	17.4	11.5	12.6
W.G.	49.2	77.5	77.3	69.5
Granite*	36	0	2.4	12.8

Pile Size 0.52 x 0.52 m				
Layer	Load Transfer (%)			Average (%)
	M/7	L/16	K/13	
SC	9.7	12.4	17.6	13.2
SM	12.3	20.1	13.1	15.1
W.G.	57.7	46.6	52.1	52.1
Granite*	20.3	20.9	17.2	19.5

Note: SC = Clayey Sand, SM = Silty Sand, W.G. = Weathered Granite, \*End-bearing

Table 6. Percentage of load transfer in each layer Zone 3

Zone 3				
Layer	Load Transfer (%)			Average (%)
	G/6	F/11	F/12	
Fill	3.9	2.8	3.5	3.4
SC	10.4	10.4	10.2	10.4
SM	22.4	20.9	14.4	19.2
W.G.	63.3	65.6	71.4	66.8
Granite*	0.1	0.3	0.4	0.3

Note: SC = Clayey Sand, SM = Silty Sand, W.G. = Weathered Granite, \*End-bearing

Furthermore, in Zone 3, the fill layer was added above the SC layer. And still, the load distribution for a layer in weathered granite was the most significant portion to transmitting 66.8% of the load.

## 7. CONCLUSIONS

Three-dimensional finite element model of the Wat Khao Sukim Pagoda area were performed using the PLAXIS 3D. The model allows the determination of settlement and stress distribution in the soil body below the structure to define the capable layer of transmitting the load. The numerical model has been calibrated based on Static Pile Load test data to determine the suitable parameters that show a fair agreement, which brings the simulation closer to real conditions.

The analysis results show in Zone 1, a shallow foundation, had settlement values in the range 0.05-0.43 mm. Zone 2, with various diameter piles and same length piles had a range of 0.42-1.98 mm. Furthermore, Zone 3, consisting of pile lengths of 18, 24, and 26 meters clearly had settlement values in the range 0.82-1.25 mm.

These results indicated that the differential settlement between Shallow Foundation Zone and Pile Foundation Zone was acceptable due to the modest differences in value between the two types of foundations, with none exceeding 0.75 ins (19 mm). This is important because their future work will focus on updating and extension of the superstructure, and the result can be used for future suggestions that any external load added, such as inserting some buddha statues into the Pagoda. Furthermore, the weathered granite layer was effective and capable of transmitting a substantial load, ranging from 52.1 to 69.5 percent.

## 6. ACKNOWLEDGMENTS

This research was funded by the Department of Civil Engineering and the Faculty of Engineering at Kamphaeng Saen Campus, Kasetsart University, Thailand. GERD (Geotechnical Engineering Research and Development) Kasetsart University and a previous researcher in Wat Khao Sukim Project provided the data for the study area.

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