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ESTIMATION OF INITIAL VOID RATIO OF CONSOLIDATED CLAY BASED ON ONE-DIMENSIONAL CONSOLIDATION THEORY

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ABSTRACT: Many stupas located within the sacred historical site of Ayutthaya, Thailand are inclined. It is important to understand their ground conditions and causes of inclination in order to design appropriate conservation countermeasures for these precious cultural assets. Soil investigations were conducted at four points around the inclined stupa of Wat Krasai, located outside the World Heritage Site ”Historic City of Ayutthaya” in 2013 and 2016. Three key soil layers appear to be responsible for the inclination of this stupa: the second soft clay layer, the third loose silty sand layer, and the fourth hard clay layer. The inclination of this stupa increased as the thickness of the second soft clay layer. Thus, we assumed that the cause of stupa inclination and disproportionate settlement of the stupa was only the second soft clay layer. The amount of settlement and the initial void ratio of this second layer were estimated using the consolidation calculation formula based on Terzaghi's one-dimensional consolidation theory. The results of this study indicate that the amount of settlement is not exactly proportional to the thickness of the second soft clay layer, or that the void ratio is inhomogeneous in the layer. The calculation is conducted in four directions, north, south, east, and west, and the maximum settlement and the initial void ratio of the second soft clay layer are estimated at approximately 6.9 m and between 1.46 and 2.48 at the north side of the stupa, respectively.

Keywords: Consolidation, Differential settlement, Void ratio, Inclined cultural assets

1. INTRODUCTION

The Phra Nakhon Si Ayutthaya Historical Park is located 86 km north of Bangkok and is surrounded by three rivers: the Chao Phraya, Pa Sak, and Lopburi. This park is one of the most famous World Heritage Sites in Thailand, attracting around one million visitors every year. This important historic city was registered as a UNESCO World Heritage Site in 1991 and encompasses a total area of 289 ha.

The Kingdom of Ayutthaya included one of the largest cities in Southeast Asia, and was an important regional power for 417 years, between 1350 and 1767. During the 16th century, this kingdom encompassed present-day Laos, Cambodia, and Myanmar. Three palaces and more than 400 temples were built during this time. Many of these structures, however, were subsequently almost completely destroyed by Burmese invaders. Many surviving ruins have been painstakingly restored, and two kinds of architecture are visible in Ayutthaya. The first of these comprises cactus-shaped obelisks called prangs that are indicative of Khmer (from the 9th to the 13th century) influence, while the second is more pointed stupas that exhibit Sukhothai (from the 13th to the mid-15th century) influence. Because stupas consist of weathered bricks, some of them have collapsed, and many are inclined at an angle.

In this study, we focus on the causes underlying the inclination of stupas, which are in need of conservation. The research was carried out on the leaning stupa of the Wat Krasai temple (indicative of Sukhothai influence), located within the World Heritage expansion planning area, with the permission of the 3rd Regional Office of Fine Arts.

Fig. 1. Location of Ayutthaya and Wat Krasai

2. PREVIOUS STUDIES AND OUR STUDY OBJECTIVE

Several studies have been conducted investigating the weathering conditions and restoration of cultural assets made of brick, including the stupas in Thailand. For example, Hatanaka et al. (2013) surveyed the weathered brick stupas at Wat Som and Wat Chaiwatthanaram within the Ayutthaya Historical Area and developed a restoration method that uses a surface toughening agent [1]. Kuchitsu (1998) surveyed stones used to build historic monuments in Thailand and concluded that salt efflorescence and bio-deterioration were the causes of brick deterioration [2].

Fujii et al. (2015) monitored the inclined stupa at Wat Langkhakhao using photogrammetry and confirmed that there was no deformation over the course of approximately 2 years [3]. The National Research Institute for Cultural Properties, Tokyo, investigated the 2011 flood damage of cultural properties in the Ayutthaya Historical Park, and they reported that the 2011 flood did not impact the inclination of these properties [4].

The famous Leaning Tower of Pisa is constructed on three formations. In the past, the cause of creep had been widely attributed to the underlying soft sensitive marine clay, which is normally consolidated. This marine clay is the second layer extending from a depth of 10 m to about 40 m underground. The precision level measurements, which commenced in 1928, revealed the rotation of the tower based on the fact that the center of the foundation plinth had not been displaced vertically relative to the surrounding ground. The cause of the continual long-term rotation of the Tower lies in the first layer. In addition, the most likely cause of the progressive seasonal rotation was a fluctuating ground-water level due to heavy seasonal rainstorms [5]. These studies showed that the inclination of the Tower had multiple causes.

Our project team comprises researchers from Thammasat and Ritsumeikan Universities. We attempted to conduct two studies under the circumstances we are in the lack of accurate information on stupa construction, ground conditions, soil composition, and groundwater levels. Chijiwa et al. (2015) analyzed two cases in Ayutthaya using boring data of the other place in Ayutthaya prefecture, the first of which anticipated the occurrence of two floods over the next 100 years, while the second anticipated no flooding and subsequently compared the two results after 100 years. The result showed that the stupa is not likely to sink rapidly by floods [6]. Ishida et al. (2016) tried to reproduce the current inclined conditions using a consolidation analysis, working with the assumption that the inclination was caused only due to an imbalance in the stupa weight. The results showed that the cause of inclination does not depend only on the imbalance of stupa weight [7].

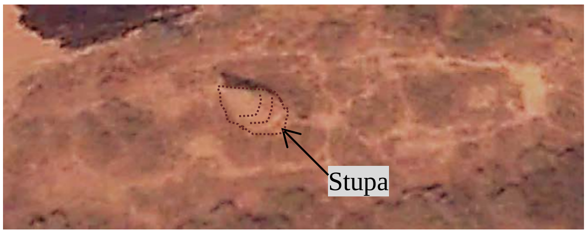
It is possible that the inclination of the stupa may have multiple causes, as in the case of the Leaning Tower of Pisa. However, in this study, we planned to first attempt to reproduce the current inclination using consolidation analysis from the time of construction of the stupa, assuming that the uneven thickness of the soft clay layer is the cause for inclination. Because physical properties of the soil are changing before and after consolidation in general, we have to estimate initial soil parameters. In this study, the methodology of estimating the initial void ratio, which is one of the parameters for consolidation analysis, based on one-dimensional consolidation theory is described. The uneven layer thickness and slope angle of the stupa were used in the estimation.

3. OVERVIEW AND INCLINATION ANGLE OF THE STUPA AT WAT KRASAI

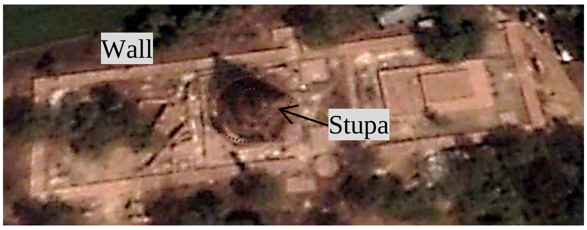
The Wat Krasai site is a long rectangle in the east-west direction. The temple was destroyed and only the stupa remains. The direction of the front of the stupa is rotated approximately 8° from east to north. The stupa consists of several parts, an eight-sided pyramid and conical body with a multi-layered structure. This entire structure is hollow, with an approximate height of 27 m and an approximate foundation diameter of 22 m. The stupa is bent, and the inclination of the top and bottom were different, and the base is tilted much more than the head.

Fig. 2 and Fig.3 show the stupa before and after restoration. Before restoration work, the base part of the stupa was in a state filled under the ground. Thus, it indicates that the stupa sank below the surrounding ground. The foundation of the stupa was excavated, and the octagonal and bottom quadrangular bases were added using a lot of bricks for reinforcement. Additionally, surrounding wall and base of the temple was reconstructed.

The restoration work was carried out on the missing part of the octagonal body, which was below the bell shape in 2013. The entrance of the stupa was closed using bricks, except for small windows on the body in four directions. We observed the internal structure of the small open windows on four sides and confirmed that the inclination angle of the original bricks and the bricks added during restoration has a harmonic relation. Therefore, the inclination of the bricks on the surface of the body can be considered the same as the inclination of the bricks before restoration. The inclination angle of the stupa was obtained by measuring the inclination of the bricks at the yellow and white lines (shown in Fig. 4), using a digital clinometer. Table 1 shows inclination angle measured at 3 points which are the left side, center, and right side in each face. The inclination toward to right is shown in plus and inclination toward to left is shown in minus. Data show that the northern side of the Wat Krasai stupa is the most sunken, followed by the eastern side.



Before repair（Google earth 2010.3.20 shooting）



After repair（Google earth 2013.2.20 shooting）

Fig.2. Wat Krasai before and after restoration work

Before restoration　　After restoration

Fig.3. Stupa before and after restoration work

Fig.4. Inclination measuring station

Table 1. Inclination angle in each face

Direction	Inclination angle (degree)					
	Yellow line			White line		
	Left	Center	Right	Left	Center	Right
North face	2	0	-3	2	0	-1
NorthWest face	-7	-9	-9	-3	-7	-7
West face	-3	-8	-11	-2	-9	-7
SouthWest face	-9	-9	-9	-7	-7	-7
South face	-4	-3	-4	0	0	0
SouthEast face	-2	0	0	2	1	0
East face	1	1	0	0	5	1
NorthEast face	0	1	2	5	5	5

4. SOIL INVESTIGATION

4.1 Standard Penetration Test at 4 points

The topography of the Bangkok plain reflects the fact that it was covered by a shallow marine sea from 3000 to 1000 B.C. Soft clay was deposited in the shallow waters near the shore, and which it is spreading to Ayutthaya [8]. In order to identify ground composition, soil investigations were carried out around the stupa at Wat Krasai. Standard penetration tests (SPTs) at Bor-1 and Bor-2 (shown in Fig. 5) were conducted by the government of Thailand in March 2013, and we carried out additional SPTs at two survey points within Bor-3 and Bor-4 in March 2016.

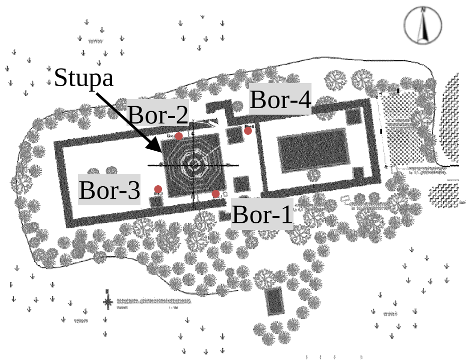


Fig.5. Four points of soil investigation

4.2 Relationship between the key soil settlement layer and stupa inclination

We produced four cross-section drawings (Figs. 6–9) of northern side, southern side, eastern side and western side, using data from our soil investigations. Layer thicknesses were prorated by the distance from boring points. These drawings illustrate the presence of three key settlement layers. Of these, the second and third layers are soft, while the fourth is hard.

This is illustrated in Fig. 6, where the second layer, a very soft-to-medium stiff clay layer, is much thicker on the northern side than the southern side, and the third layer, a loose-to-medium dense silty sand layer, is also much thicker in the north. In contrast, the fourth layer, a stiff-to-hard clay layer, is much thicker on southern side than the northern side, and it seems to support the stupa. Viewed from west-to-east, the top of the stupa is inclined at 2.4°, and the body is inclined approximately 2° to 11° towards the north.

The other orientations are analyzed in the same way and plotted the difference between the soft layers thicknesses at both end sides of the stupa base part as well as the degree of inclination (Fig.10). Results showed that inclination of the stupa correlates roughly with a thickness of the soft layers.

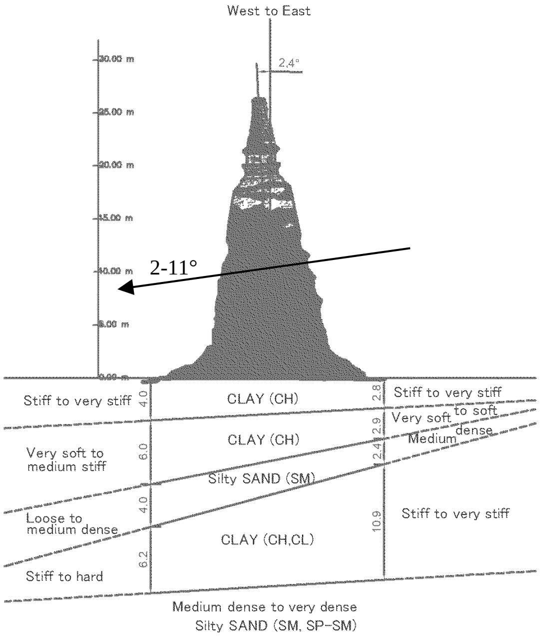


Fig.6. Cross-section drawing of western side

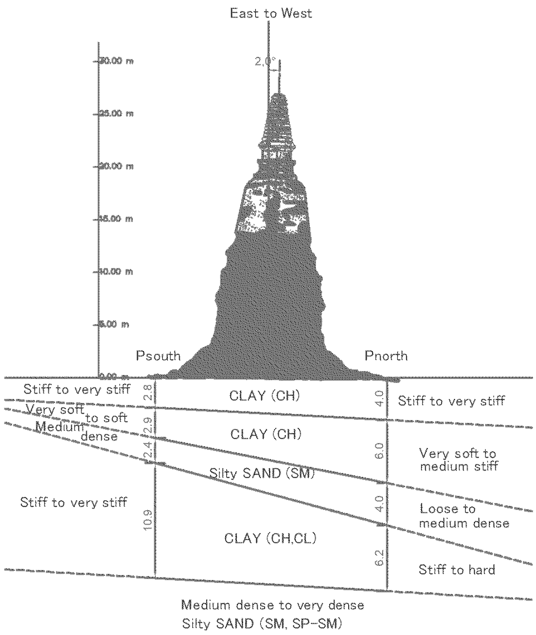


Fig.7. Cross-section drawing of eastern side

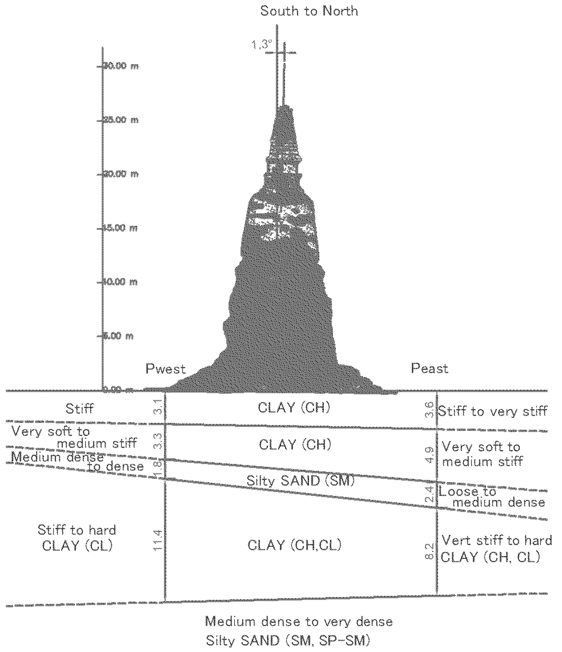


Fig.8. Cross-section drawing of southern side

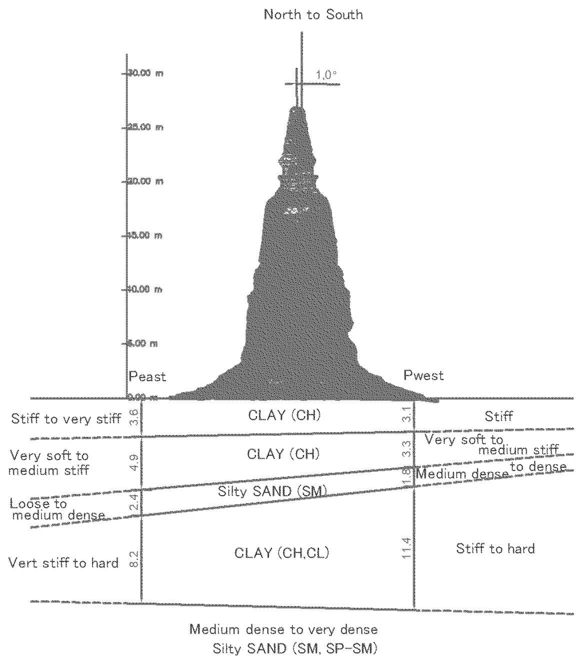


Fig.9. Cross-section drawing of northern side

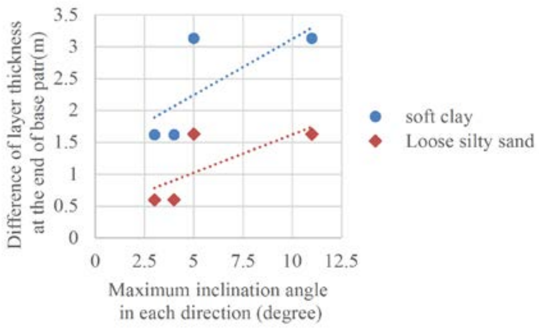


Fig.10. Correlation of layer thickness and inclination

5. ESTIMATION OF INITIAL VOID RATIO

We assumed that the cause of stupa inclination due to disproportionate settlement of the stupa were only the second

In addition, the amount of settlement due to consolidation and the initial void ratio of the second soft clay layer were calculated using the uneven layer thickness, the inclination angle of the stupa, and Eq. (1) based on one-dimensional consolidation theory.

$$S = H\frac{\Delta e}{1+e_0} = H\frac{e_0 - e}{1+e_0} \quad (1)$$

In this expression, S refers to the amount of settlement due to consolidation (m), H is the initial thickness of the soft clay layer (m), e is the current void ratio (0.62 based on our soil tests), and e_0 is the initial void ratio.

We focused on the difference in layer thickness and the amount of settlement at both ends of the stupa. It was assumed that ground level was horizontal when the stupa built. However, a difference in settlement had occurred over a long period time, caused by the weight of the stupa. It is assumed that the inclination of the stupa is equal to the amount of differential settlement at both ends of the stupa as shown in Fig. 11. In this figure, *B* refers to the width of the octagonal base part and θ is the inclination angle of each face of the stupa. This hypothesis follows Eq. (2), (3), (4), (5), (6), (7).

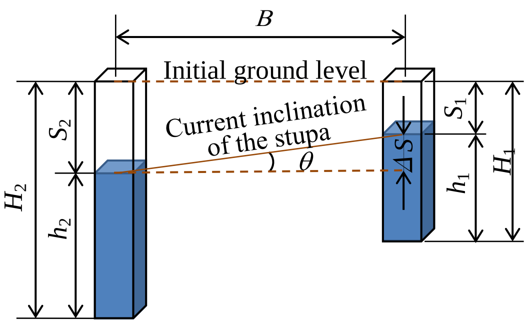


Fig.11. Degree of inclination

$$S_1 = H_1\frac{e_0 - e}{1+e_0}, \quad e_0 = \frac{S_1 + H_1 e}{H_1 - S_1} \quad (2)$$

$$S_2 = H_2\frac{e_0 - e}{1+e_0}, \quad e_0 = \frac{S_2 + H_2 e}{H_2 - S_2} \quad (3)$$

$$S_2 = S_1 + \Delta s, \quad \Delta s = S_2 - S_1 \quad (4)$$

$$\Delta s = \tan\theta \cdot B \quad (5)$$

$$H_1 = S_1 + h_1 \quad (6)$$

$$H_2 = S_2 + h_2 = S_1 + \Delta S + h_2 \quad (7)$$

In this expression, S_1 refers to the amount of settlement of the thin layer at the end of the stupa (m), S_2 refers to the amount of settlement of thick layer at the end of the stupa (m), H_1 refers to the initial thin layer thickness at the end of the stupa (m) , H_2 refers to the initial thick layer thickness at the end of the stupa (m) , h_1 refers to the current thin layer thickness at the end of the stupa (m) , h_2 refers to the current thick layer thickness at the end of the stupa (m), and θ is the inclination angle of the stupa.

S_1, S_2, and e_0 were calculated using Eq. (2) and (3) in each direction, north, south, east, west faces. These values are based on the conditions that the initial void ratio of the soft clay layer at both sides of the stupa, differential of the current layer thickness at both sides of the stupa, and settlement differences at both sides of the stupa are the same in each case.

6. RESULTS AND DISCUSSION

The results of settlement amounts, S_1 and S_2, as well as e_0 based on the maximum inclination angle of each face are shown in Table 2. As the same way, the inclination angle of 3 cases, average angle, yellow line measurement average angle, white line measurement average angle, were used for calculation. Figure 12 shows settlement amounts in 4 orientations, North, West, South, and East. The maximum settlement amount was estimated 6.90m at western side.

We estimated the initial void ratios in each orientation based on the maximum measurement angle to be within the range of 1.46 to 2.48 as shown in Fig.13. The values of results are in the range of general soft clay.

This estimation method includes some problem, for example in the case of little amount of difference of subsidence. We estimated the inclination angle by measuring on the body bricks. However, because bricks are not perfect shape, the bricks which consist the stupa wall have some minor deviations.

Table.2. Results of the consolidation settlement calculation based on the maximum inclination angle

	North	West	South	East
h_1(m)	3.28	2.87	3.28	2.87
h_2(m)	4.90	6.00	4.90	6.00
θ(°)	3.0	11.0	4.0	5.0
B(m)	18.50	18.50	18.50	18.50
ΔS (m)	0.97	3.60	1.29	1.62
S_1(m)	1.96	3.30	2.62	1.48
S_2(m)	2.93	6.90	3.91	3.10
H_1(m)	5.24	6.17	5.90	4.35
H_2(m)	7.83	12.90	8.81	9.10
e	0.62	0.62	0.62	0.62
e_0	1.59	2.48	1.91	1.46

In addition, because the inclination is different between top and bottom of the stupa, it is important to decide where sites as the inclination measurement location.

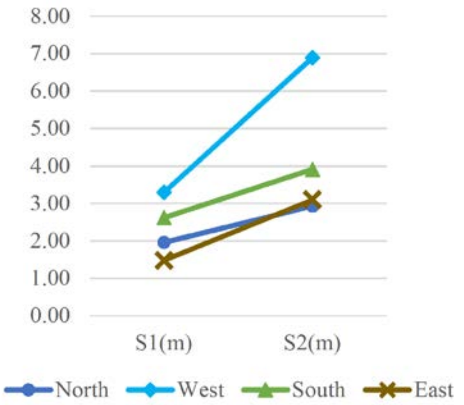


Fig.12. Amount of settlement in 4 orientations

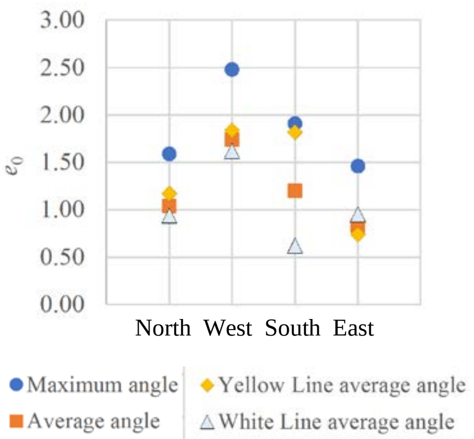


Fig.13. Initial void ratio (e_0) in 4 orientations

7. CONCLUSION

The settlement due to consolidation under the Wat Krasai stupa was analyzed in this study based on a soil investigation. The result of the soil investigation shows that it is possible that three key layers are responsible for the inclination of this structure, a second soft clay layer, a third loose silty sand layer, and a fourth hard clay layer. Especially, The inclination of this stupa increased as the thickness of the second soft clay layer.

We calculated both the amount of settlement and the initial void ratio of the second soft clay layer. Results indicate that maximum settlement was approximately 6.9 m at the northern end of the stupa, while the initial void ratio falls between 1.46 and 2.48.

In the future, consolidation analysis of a model including all soil layers will be required to determine the additional settlement details, and to consider the influence of the other layers.

8. ACKNOWLEDGEMENTS

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