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INHIBITORY EFFECT OF GROUND IMPROVEMENT ON THE SETTLEMENT OF THE LEANING PAGODA

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ABSTRACT: The Wat Krasai pagoda in Ayutthaya, Thailand, leans mainly toward the north. Soft clay sediments of foundation ground and the deterioration of the bricks and mortar that compose the pagoda are the main causes of the pagoda's deformation. In 2013, the surface of the lower part of the pagoda was restored and the base was reconstructed using new bricks. Since 2014, field surveys were conducted twice a year and we confirmed that there are cracks and irregularities in the reconstructed structures in addition to a gap between the reconstructed base and the pagoda at the southside. Based on the measurement of the inclination and our surveys, we deduced that the pagoda has been continuously sinking toward the north and this settlement will continue in the future. In this study, ground improvement was proposed as a countermeasure for differential settlement and the settlement inhibitory effect of the ground improvement was evaluated through a numerical simulation. The results of the analysis indicated that the weight of the bricks installed during the restoration in 2013 exacerbated the settlement and inclination of the pagoda. Additionally, ground improvement has an inhibitory effect on settlement, and the rapid restoration-induced settlement was found to decrease in the case where ground improvement was conducted from the surface of the ground to the bottom of the second soft clay layer. The restoration work of historical brickwork buildings that need additional bricks should therefore consider the possibility and consequences of settlement owing to its new weight.

Keywords: Differential settlement, Consolidation analysis, Ground improvement, Deterioration of brick

1. INTRODUCTION

Ayutthaya in Thailand was the capital of the Ayutthaya dynasty, which was established in 1350 and lasted for 417 years, and is located approximately 90 km north of Bangkok. Ayutthaya was recognized as a World Heritage Site in 1991 owing to the criterion that is "The Historic City of Ayutthaya bears excellent witness to the period of development of a true national Thai art". The Ayutthaya ruins are characterized by tall pagodas and Buddhist monasteries of monumental proportions [1]. Some historical brick buildings, such as pagodas, and the walls of some temples have tilted or collapsed, as shown in Fig. 1. This study examines the Wat Krasai pagoda, one of the cultural assets, particularly focusing on methods to conserve it and cease its continued inclination. In addition, we aim to provide useful information that will facilitate restorative projects and ensure that historical assets remain in good condition in the future. We have been observing the condition of the pagoda and its surrounding assets twice a year since 2014, began monitoring groundwater fluctuation from 2016, and have been measuring the angle of the pagoda since 2018. The results indicate that the pagoda continues to sink and lean over time. Therefore, a countermeasure to stop the inclination of the pagoda is needed. In this paper, simulation results are reported for cases in which different levels of ground improvement are conducted as a countermeasure for the differential settlement.

Fig. 1 Brickwork at Wat Mahathat
(Photograph taken on March 1, 2016)

2. HISTORY OF WAT KRASAI

We surveyed when the Wat Krasai pagoda was built in order to set the period of consolidation analysis. According to the signboard at the Wat Krasai site, there is no evidence pertaining to its period of construction. However, it is surmised that

Wat Krasai was built prior to the second Burmese-Siamese War in 1767, because during which it was used as a Burmese army base. Additionally, in the Late Ayutthaya Period, Wat Krasai was mentioned as the burial site of Phra Si Sin, who was charged with treason against King Narai the Great, who ruled between 1656 and 1688. Assuming Wat Krasai was erected during the reign of King Narai, it can be inferred that it was constructed approximately 360 years ago.

When the Wat Krasai temple was built, it was surrounded by walls. The principal pagoda, Chedi, was bell-shaped and built on an octagonal foundation, which was a popular Chedi style in the early Ayutthaya period. The principal pagoda was surrounded by four auxiliary Chedis. However, we cannot confirm the existence of the walls and four auxiliary Chedis as of 2010, based on data from Google Earth [2]. The surface bricks of the principal pagoda have deteriorated and the octagonal foundation has collapsed or was buried underground, as shown on the left in Fig. 2.

In 2013, extensive restoration work was conducted at Wat Krasai to reconstruct the walls surrounding the precinct and the foundation of the auxiliary Chedis. Additionally, the lower part of the deteriorated surface of the principal pagoda was restored with new bricks, and the octagonal foundation and square base were reconstructed, as shown on the right in Fig. 2. Bricks were bonded by lime mortar, but apparently, individual blocks moved flexibly owing to the weak binding. Sand was filled inside the reconstructed square brick base of the pagoda. Many bricks were used during this restoration work, which resultantly added to the weight that the pagoda was exerting on the ground. This additional weight has been accounted for in the consolidation analysis.

3. PROBLEMS OF BRICKWORK BUILDINGS IN AYUTTHAYA

3.1 The problem of Ground Deformation

Historical brick buildings face issues owing to the softening of the ground they are built on. In a study that nondestructively investigated the deterioration of stone materials at the Angkor ruins, Uchida indicated that the differential settlement of the ground and the deformation of the platform had a significant influence on the structure [3]. Kuchitsu indicated that the structural problem of the brick buildings due to the differential settlement was greater than that due to the weathering of salts and biodeterioration by moss and lichens [4].

Since 2014, we have been observing the restored pagoda, the reconstructed wall, and bases of the Chedis at Wat Krasai twice a year. The deformation of the reconstructed wall due to the softening of the ground during the rainy season of 2017 was confirmed, as shown in Fig. 3. Several cracks were found at the reconstructed base of the Chedi and the pagoda. In addition, we observed a gap between the main body of the pagoda and the adjoining reconstructed square base in 2019, as shown in Fig. 4. An increase in the width of this gap was confirmed in February 2020. Based on these surveys and measurements of the pagoda's incline, we speculate that the main body of the pagoda and the reconstructed base that surrounds it has been moving separately.

Standard penetration tests (SPTs) were conducted ahead of the restoration in the southeast and northwest regions of the pagoda in March 2013 and additional tests were conducted in the southwest and northeast regions in March 2016. Based on these investigations, we confirmed that the thickness of the second layer, which is composed of soft cohesive soil, was greater on the northern side than that on the southern side. Moreover, the increase in the thickness of the second soft clay layer and the direction of the pagoda's tilt are considered the possible chief causes for the pagoda's northward tilt [2]. The cause of the settlement of the pagoda was assumed to be the weight of the new bricks that were added during the restoration and the lack of countermeasures against the soft clay layer, such as ground improvement.

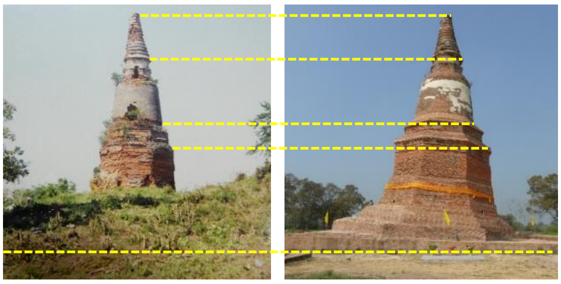


Fig. 2 Left: Principal pagoda before the restoration (Photograph taken in 2013)

Right: Principal pagoda after the restoration (Photograph taken on February 22, 2014)

Fig. 3 Deformation of brick wall at Wat Krasai (Photograph taken on May 17, 2017)

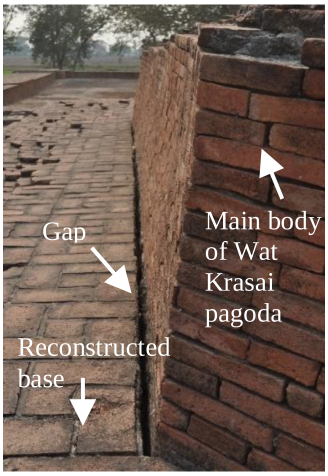


Fig. 4 The gap between the main body and the reconstructed base of the pagoda (Photograph taken on August 20, 2019)

3.2 Problems Caused Due to Brick And Mortar Deterioration

Bricks are mainly made of clay or mud, shaped into a rectangular parallelepiped, and then sun-dried or fired in a kiln. Thereafter, owing to their repeated wetting and drying due to insolation and rain, they eventually degrade and return to the soil. The deterioration of bricks is a common problem for historical brick buildings worldwide. Several studies on historical brick structures have focused on the deterioration of bricks. Based on their measurement of the diurnal alteration of temperature and humidity, Nishiura et al. mentioned that the Egyptian adobe brick deteriorates because condensation occurs throughout the year [5]. Since some stucco remained on the surface of the historical brick buildings in Ayutthaya, it is possible that the entire surface was protected by stucco when it was first constructed. However, when the plaster on the surface wore away due to deterioration over time, it exposed a means for water penetration, which melts the clay mortar, weakens the structure, and possibly results in an eventual collapse. Therefore, ICOMOS (International Council on Monuments and Sites) Thailand reports that the deterioration of bricks and mortar due to water is one of the risks faced by Thai monuments [6]. Ishizaki et al. conducted moisture measurements, precipitation salt surveys, and meteorological observations on historical brick buildings in Ayutthaya and resultantly determined the relationship between brick deterioration and moisture migration in brick materials [7]. In addition, Ishizaki et al. conducted a moisture migration analysis before and after the surface layer waterproof strengthening treatment of the Sukhothai Brick Buddha. The results indicated that the water content of the sediment decreased due to the waterproof treatment, which was consistent with their measurements [8]. Yoshida et al. created an analytical model for heat and moisture transfer in the Sukhothai Brick Buddha. Additionally, they showed that the possible cause of its discoloration was the movement of the components of the stucco and bricks to the surface associated with the internal moisture, which led to evaporation [9].

The deterioration of the brick block of the Wat Krasai pagoda that was restored in 2013 was identified in 2017, as shown in Fig. 5. The restored bricks are piled up in accordance with the inclination of the original bricks; therefore, water gathers through the joints on the north side. In fact, bricks on the northwest side, which have a larger inclination, deteriorated significantly. When the brick deteriorates and collapses, the voids of the brick block are compressed and the volume decreases. The pagoda resultantly suffers from distortion. We infer that bricks that have partly broken due to deterioration can possibly contribute to the deformation of the pagoda, such as by causing inclination or distortion.

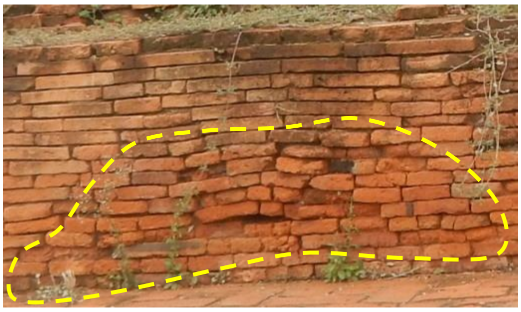


Fig. 5 Deterioration of bricks of the Wat Krasai pagoda (Photograph taken on May 17, 2017)

4. SETTLEMENT INHIBITORY EFFECT OF GROUND IMPROVEMENT BASED ON FEM ANALYSIS

Ground improvement is a common countermeasure against the softening of the ground. A numerical simulation was carried out under the assumption that ground improvement was conducted on the ground under the pagoda during the restoration in 2013. The suppression effect of settlement and inclination of the pagoda until 100 years after the 2013 restoration was evaluated using consolidation analysis. The area of ground improvement was set to the reconstructed square base, 1.0 m on the outside. Four distinct cases of ground improvement thickness were examined to facilitate a comprehensive analysis. The ground improvement thickness for each case is shown in Table 1.

Table 1 Thickness of ground improvement

	Thickness of ground improvement
Case-1	0.0 (m)
Case-2	3.0 (m)
Case-3	6.0 (m)
Case-4	10.0 (m)

4.1 Numerical Simulation

The effect of the ground improvement in terms of pagoda inclination inhibition was evaluated by the two-dimensional, nonlinear finite element analysis program software—PLAXIS. The analysis was performed with the plane strain condition. The constitutive model of the sandy and clay soils were used as a linear elastic model and an elasto-plastic model as per the Sekiguchi–Ohta model, respectively. The Sekiguchi–Ohta model is prevalent used in the condition of stress accompanying the anisotropy of naturally deposited clay. The bottom surface was set as a non-drainage boundary condition. It was estimated that it took two years to build the pagoda by the expertise of the archeologists. The period from the construction of the pagoda until its restoration in 2013 was set to 360 years in the analysis. Additionally, the end period of the analysis was set to 2113, which would be 100 years post its restoration.

4.2 Soil layers and Parameters

The cross-section in the north-south direction is shown in Fig. 6. The ground is comprised of six layers based on the SPT and the thickness of each layer is shown in Table 2. Line-A and Line-B in Table 2 were set at the south and the north end of the pagoda, as shown in Fig. 6. Each layer is not an isopachous layer; hence, the thicknesses of the layers at Line-A and Line-B are different. The soil parameters are listed in Table 3. Soil parameters were determined by an examination of the soil sample obtained from Wat Krasai. The parameters γ, k, and I_p were determined from some soil tests. k and I_p are swelling index and plasticity index respectively. The parameters c, ϕ, E, and ν', were determined based on each N value. The parameters, M, Λ, K_0, ν', λ, e_0, and D, were estimated from I_p based on the chart shown in Fig. 7, which was developed by Iizuka et al. [10]. This chart illustrates the procedure to determine the input parameters of the Sekiguchi–Ohta model. M is critical state parameter, Λ is irreversibility ratio, K_0 is earth pressure coefficient at rest, λ is compression index, and D is coefficient of dilatancy. The parameters after ground improvement were set to following as enough stiff ground: the soil constitutive model is Mohr-Coulomb, γ_{unsat}=19.2kN/m^3, c=15.0kN/m^2, ϕ=26.5°, E=1.3*10^5 kN/m^2, ν'=0.4.

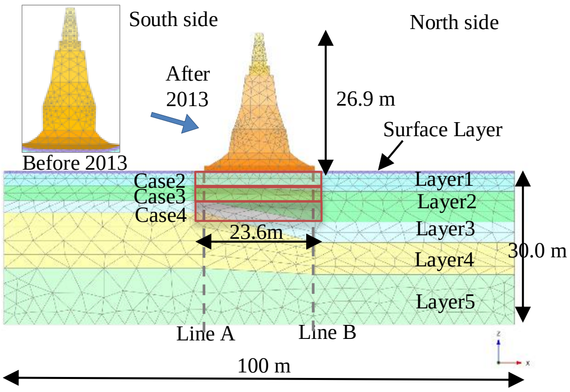


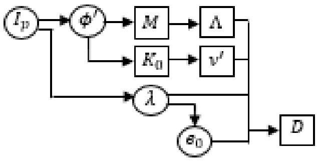
Fig. 6 The cross-section used for the analysis

Table. 2 Thickness of each soil layer

	Line A		Line B	
	Thickness (m)	Depth (GL-m)	Thickness (m)	Depth (GL-m)
Surface	0.50	0.50	0.50	0.50
1st Layer	2.35	2.85	3.48	3.98
2nd Layer	2.89	5.74	6.00	9.98
3rd Layer	2.42	8.16	3.99	13.97
4th Layer	10.84	19.00	6.26	20.23
5th Layer	11.00	30.00	9.77	30.00

Table. 3 Soil parameters of each layer

Layer	Surface	1st Layer	2nd Layer
Type of soil	CLAY	CLAY	CLAY
Condition of soil	Dried and solidified	Stiff to Very stiff	Very soft to Medium stiff
Constitution rule of soil	Mohr-Coulomb	Elasto-plastic (Sekiguchi-Ohta)	Elasto-plastic (Sekiguchi-Ohta)
M	-	1.035	1.009
Λ	-	0.5915	0.5764
D	-	0.0726	0.0726
ν'	0.2	0.358	0.362
K_0	-	0.559	0.568
e_0	-	1.223	1.324
I_p	-	38.2	42.0
E [kN/m^2]	8540	-	-
γ_{unsat} [kN/m^3]	19.2	19.2	17.1
γ_{sat} [kN/m^3]	19.2	19.2	17.1
c [kN/m^2]	80.0	-	-
ϕ [°]	6.0	-	-
k [m/day]	2.40E-06	2.40E-06	3.60E-06
Layer	3rd Layer	4th Layer	5th Layer
Type of soil	SILTY SAND	CLAY	SILTY SAND
Condition of soil	Loose to Dense	Stiff to Hard	Medium dense to Very dense
Constitution rule of soil	Linear elastic	Elasto-plastic (Sekiguchi-Ohta)	Linear elastic
M	-	1.128	-
Λ	-	0.6444	-
D	-	0.0611	-
ν'	0.3	0.344	0.3
K_0	-	0.525	-
e_0	-	0.940	-
I_p	-	27.5	-
E [kN/m^2]	15050	-	28560
γ_{unsat} [kN/m^3]	19.0	19.2	19.0
γ_{sat} [kN/m^3]	20.0	19.2	20.0
c [kN/m^2]	3.0	-	5.0
ϕ [°]	30.0	-	35.0
k [m/day]	2.00E-04	3.60E-06	1.20E-03



(1) $sin\phi' = 0.81 = 0.233 \log I_p$ Kenney(1959)
(2) $M = 6sin\phi' / (3 - sin\phi')$
(3) $\Lambda = M/1.75$ Karube(1975)
(4) $K_0 = 1 - sin\phi'$ Jaky(1944)
(5) $v' = K_0 / (1 + K_0)$
(6) $\lambda = 0015 + 0.007I_p$
(7) $e_0 = 3.78\lambda + 0.156$
(8) $D = \lambda\Lambda / [M(1 + e_0)]$ Ohta(1971)

Fig. 7 Procedure used to determine the input parameters of the Sekiguchi–Ohta model [10]

4.3 Structure Modeling

The shape of the Wat Krasai pagoda was modeled based on the cross-sectional drawing that was made during the restoration in 2013. The actual pagoda is hollow and has an approximate height of 26.9 m. However, the weight of the hollow part was reduced and the pagoda was reconstructed into 10 uniformly filled blocks in this analysis. These blocks were sequentially built up over the course of two years of construction. In the two-dimensional plane strain model, it is assumed that the same cross-section is continuous in the depth direction, and a unit width of 1 m is set in depth. Therefore, the unit volume weight of each block was reduced considering the block by block width to load the actual weight. We adopted the before-restoration shape model as the shape of the pagoda from its construction until 2013 and adopted the after-restoration shape model after 2013. The diameter of the bottom of the pagoda after the restoration is approximately 10.8 m and the width and depth of the baseare approximately 21.6 m. The total weight of the pagoda before the restoration was estimated to be approximately 19,600 kN, and the weight increased by approximately 7,000 additional kN owing to the restoration, as shown in Fig. 6. The parameters of the brick are listed in Table 4.

Table. 4 Material properties of bricks

Material model	Linear elasticity
Density (ρ)	1.546 g/cm^3
Young's modulus (E)	1.0×10^7kN/m^2
Poisson's ratio (ν)	0.18
Unitw eight (γ)	15.15 kN/m^3

5. ANALYSIS RESULTS AND DISCUSSION

5.1 Amount of Settlement and Inclination -from the Beginning of Construction until 2113-

The analysis output reference points of the pagoda are shown in Fig. 8. The amount of settlement was marked as “under” just below the center of pagoda base. The temporal change in the settlement of the pagoda in Case 1, in which ground improvement does not be conducted, is shown in Fig. 9. The results indicate that a rapid consolidation settlement occurred during the construction of the pagoda. Fig. 10 shows the amount of settlement of each layer on the center line shown in Fig. 8. The consolidation was promoted at the first, second, and fourth layers from the construction’s early stages. Following that, the settlement increment gradually increased. In addition, because the additional weight was loaded onto the ground by the restoration work in 2013, the settlement and the inclination of the pagoda were exacerbated. Furthermore, settlement speed increased after the restoration.

The inclination of the pagoda was calculated from the south and north points of the pagoda body––marked as “south” and “north” in Fig. 8. The temporal change of the inclination of the pagoda in the south-north direction in case 1 is shown in Fig. 11. The increasing tendency of the inclination is similar to the degree of settlement. It is inferred that if consolidation settlement measures are taken during restoration, it will be possible to prevent any additional settlement and inclination of the pagoda that may result from the additional weight of the repair bricks. The inclination of the pagoda will gradually increase in the future. The measured actual partly inclination of the pagoda was approximately 2° to 11° [2]; therefore, the analysis result may be underestimated. The problem about the difference between the two-dimensional and three-dimensional analysis result about the inclined tower is discussed in some papers [11] [12]. It is considered that the undervalued causes of settlement and inclination are three-dimensional effects or the uncertainties related to the soil parameters, soil layer model, and the time elapsed since the construction of the pagoda. Additionally, the numerical simulation solely considers uneven foundation settlement when calculating the degree of inclination, however, the actual partly inclination of the pagoda results from not only differential settlement but also the deterioration of bricks and mortar. The results of the inclination monitoring of the pagoda indicate different fluctuation at the two measurement points, therefore it has possible the pagoda has complex movement actually. It is desirable that the conditions of settlement, inclination, and deterioration of the pagoda will be monitored in the future in order to do effective conservation.

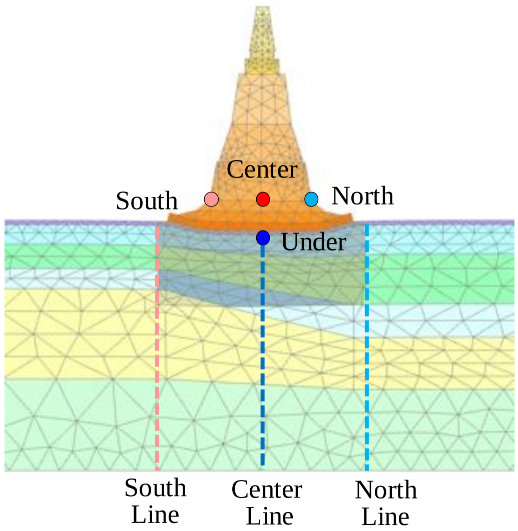


Fig. 8 Output reference points

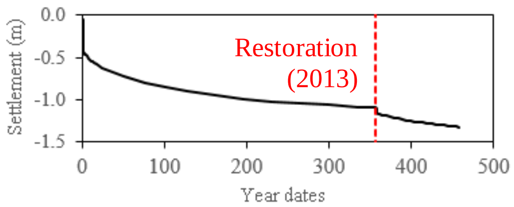


Fig. 9 Temporal change of settlement (Case 1)

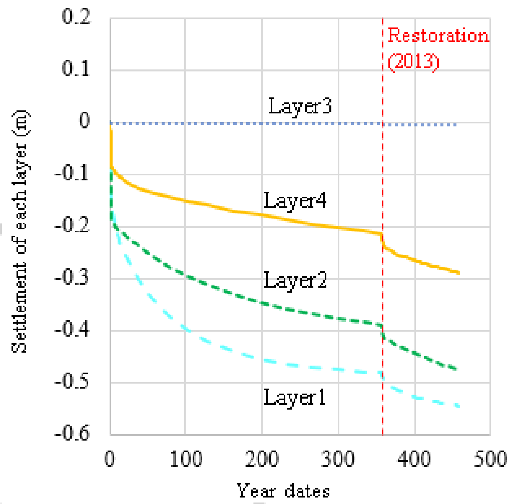


Fig. 10 The amount of settlement of each layer

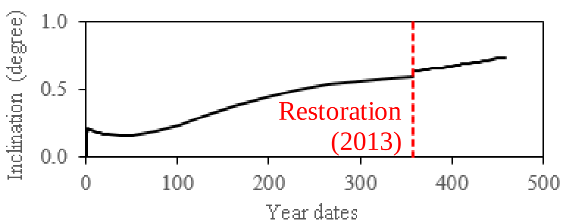


Fig. 11 Temporal change of inclination (Case 1)

5.2 Effect of Ground Improvement

Figures 12 and 13 show the temporal change of the amount of settlement of the first layer at the south and north lines after the 2013 restoration. At the south line, the settlement almost does not occur in cases 2, 3, and 4. Furthermore, at the north line, the obvious settlement does not occur in cases 3 and 4, but occurs in case 2. Since the thickness of the first layer increases northward, the 3 m of ground improvement in case 2 is less than the thickness of the first layer on the north line, which results in the settlement in the section of the first layer that is excluded from the ground improvement. The results thus indicate that ground improvement deters settlement.

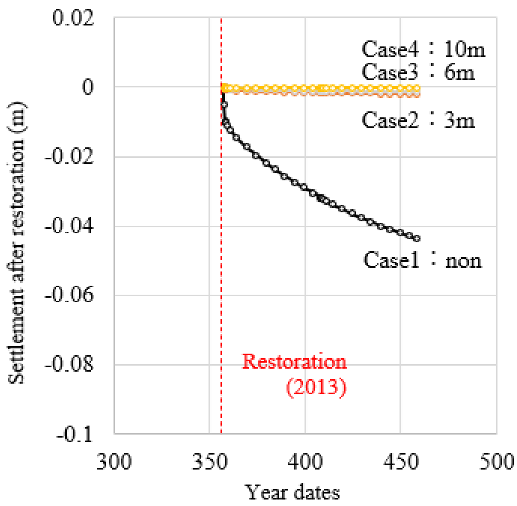


Fig. 12 The amount of settlement of the first layer at the position on South Line

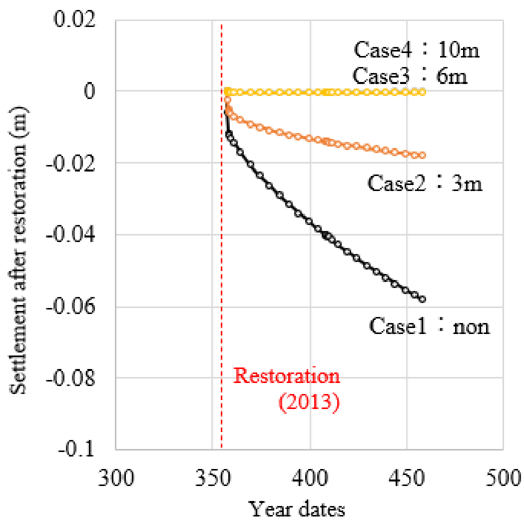


Fig. 13 The amount of settlement of the first layer at the position on North Line

5.3 Amount of Settlement on Each Layer

The temporal change until 100 years after the 2013 restoration in the amount of settlement of the center of the pagoda in all cases is shown in Fig. 14. The settlement of the pagoda tends to gradually increase in all future cases, which represent 0, 3, 6, and 10 m of ground improvement. Figures 15, 16, and 17 show the temporal change of the settlement amount of the first, second, and fourth layers at the center line marked in Fig. 8. The settlement does not occur in the ground improvement area in each layer but occurs in every layer that is excluded from the ground improvement. Therefore, the degree of settlement prevention increases with the thickness of ground improvement. In the case without the ground improvement, the greatest amount of settlement occurs in the second soft clay layer. If ground improvement is conducted from the surface to the bottom of the second soft clay layer, as in case 4, the rapid restoration-induced settlement can be reduced and the settlement rate after the restoration remains on par with the rate prior to the restoration.

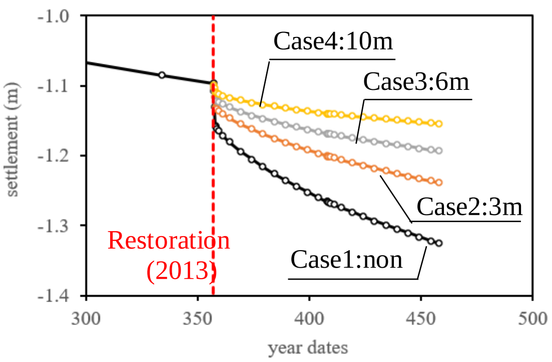


Fig. 14 Temporal change of settlement (all cases)

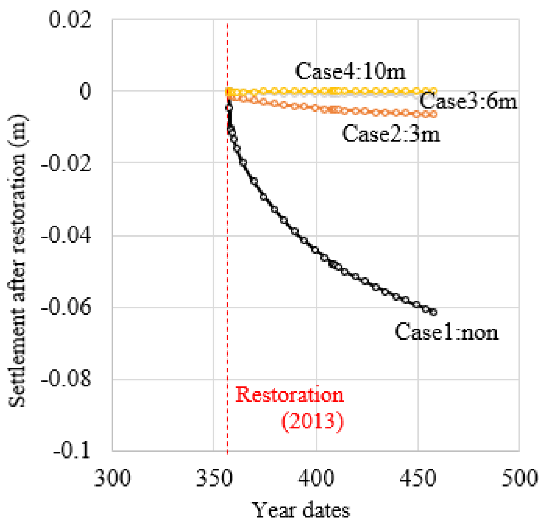


Fig. 15 Temporal change of settlement (Layer 1)

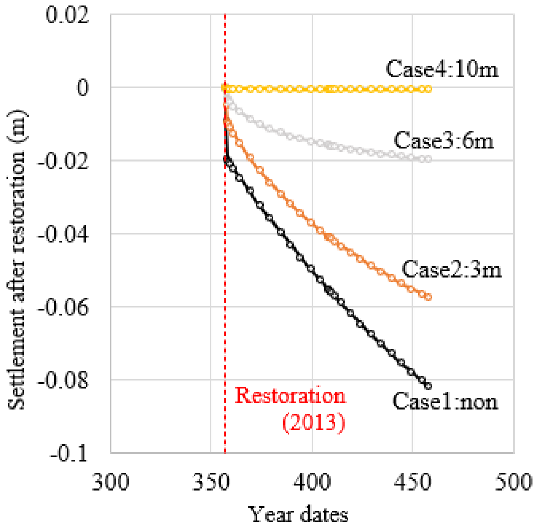


Fig. 16 Temporal change of settlement (Layer 2)

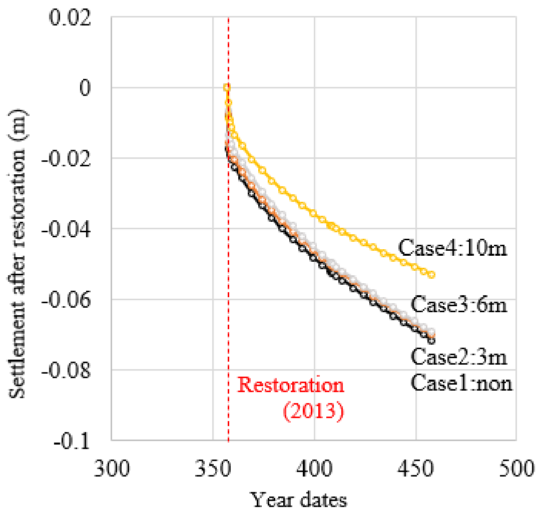


Fig. 17 Temporal change of settlement (Layer4)

6. CONCLUSION

In this study, the changing conditions of the pagoda and the surrounding ground were described based on observation. It is inferred that the main body of the pagoda and the reconstructed base that surrounds it has been moving separately. Additionally, a countermeasure for the settlement of the pagoda was also described.

In addition, a simulation was carried out, wherein distinct cases of ground improvement were considered as a countermeasure for differential settlement. The results indicate the following:

1. The settlement and inclination of the pagoda tend to increase in the future.
2. The possibility that the settlement and inclination of the pagoda are exacerbated by the restoration work, which utilized several bricks, is confirmed. This is consistent with the development of the gap

between the main body of pagoda and the reconstructed square base.
3. The degree of inclination of the pagoda that was gathered from the analysis may have been underestimated because it does not match the actual situation.
4. The effect of reducing settlement through ground improvement was confirmed by comparing it with and without ground improvement. Additionally, in Case 4, where ground improvement was conducted from the ground surface to the bottom of the second soft clay layer, the rapid restoration-induced settlement was reduced. Additionally, the settlement increment after the restoration was also reduced.

For conserving the Wat Krasai pagoda in a better manner, we should consider not only the behavior of the inclination of the pagoda but also its structural deterioration, which includes cracks, gaps, deformations, and brick deterioration. Moreover, restorative projects concerning historical brickwork buildings that need additional bricks should consider the influence of its new weight on settlement and the deterioration of bricks due to the accumulation of water.

7. ACKNOWLEDGMENTS

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