

## Research Article

# An Alternative Method for Long-Term Monitoring of Thai Historic Pagodas Based on Terrestrial Laser Scanning Data: A Case Study of Wat Krachee in Ayutthaya

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This article presents an alternative method for the long-term monitoring of heritage pagodas in Thailand. In this method, terrestrial laser scanning (TLS) is used in combination with permanent survey markers. The Wat (temple) Krachee in the Ayutthaya Province of Thailand was chosen as a case study. This temple has several fantastic elements, including an inverted bell-shaped pagoda, two intertwined trees growing within it, and a chamber inside the pagoda. The preservation team working on the pagoda encountered a challenging problem and faced a decision to trim or not to trim the tree since it has a long-term effect on the pagoda's structural stability. A high-accuracy terrestrial laser scanner was used to collect three-dimensional point cloud data. Permanent survey markers were constructed in 2018 to be used in long-term monitoring. The 3D surveying of the temple and the monitoring of the pagoda were carried out in five sessions during a period ending in 2020. A point cloud data analysis was performed to obtain the current dimensions, a displacement analysis, and the pagoda leaning angle. The results revealed that the terrestrial laser scanner is a high-performance piece of equipment offering efficient evaluation and long-term monitoring. However, in this study, permanent survey markers were also required as a benchmark for constraining each monitoring session. The 3D point cloud models could be matched with the assumption model elements to evaluate the damaged shape and to determine the original form. The significant elements of an inverted bell-shaped pagoda were investigated. Trimming the tree was found to cause the leaning angle of the pagoda to decrease. An equation was developed for predicting the leaning angle of the Wat Krachee pagoda for preservation and restoration planning in the future. From the results of this study, it is recommended that periodic monitoring should continue in order to preserve Thai pagodas in their original forms.

## 1. Introduction

The cultural heritage sites of Thailand are considered an invaluable resource for the nation. Over time, the heritage sites have been inevitably affected by natural disasters and damage by humans. For this reason, assessment and monitoring of the historical structures are essential to prevent future damage. In traditional surveying methods, the surveyors or engineers must collect information by hand, which is a time-consuming process with low precision. It also requires a surveyor's specific expertise to investigate the

anomalies of this historic structure. Today, the most effective instrument for surveying and monitoring is the terrestrial laser scanner (TLS). It has been used for the massive collection of three-dimensional data for structures in their current condition. An advantage of this technology is the relatively short time and its high accuracy in digitizing real-world objects [1]. This information can be processed and developed for the assessment and risk management of historic buildings [2–4]. Previous research has reported the application of the terrestrial laser scanner in engineering, architecture, and various other fields, such as prototyping

[5], geomorphology [6], and characterization of slope instability [7]. In terms of the conservation of historical buildings, surveying based on TLS technology has various applications, such as roof deformation analysis [8], deformation monitoring of structures [9–11], geometric anomalies analysis [12, 13], and leaning angle analysis [14].

Many researchers have utilized terrestrial laser scanners for data collection to assess structural stability and conduct seismic analyses of historical buildings. For example, Jiao et al. [15] carried out a building damage analysis from earthquake loading by acquiring data from 3D laser scanners. The results revealed that the three-dimensional information from TLS provides enough data for the analysis of building damage. Fortunato et al. [16] studied the seismic vulnerability of San Giovanni in Tumba (Italy) by surveying with a 3D laser scanner to develop a shape model for structural analysis under seismic loading. Quagliarini et al. [17] reported that the risk assessment of historical buildings in their current condition using the 3D laser scanner for data collection provided a fast, low-cost, and safe methodology. Moreover, Micelli and Cascardi [18] presented a drone-based survey of a historic bell tower in Italy for the generation of geometry for structural assessment and seismic analysis. The results showed that drone-based surveys can reduce the time-cost. However, for data collection in a lightless area or small chamber, it may be essential to use TLS technology.

Point cloud data from TLS can accurately provide the geometrical shape of a structure for its current surface condition. In the literature, there are related reports on the point cloud analysis of historic structures. For example, Bertacchini et al. [19] described the monitoring of three historical towers in Italy. The data obtained from TLS was used to determine that the maximum displacements and tilt angles of the three towers were in the range of 0.71–2.38 meters and 1.04–1.51 degrees, respectively. Jo and Lee [20] presented the displacement analysis procedure to evaluate the structural stability of a stone pagoda in Korea. The results showed that the stone pagoda had moved in the northeast direction. Moreover, the authors suggested that continuous monitoring of the pagoda's deformation should be required to preserve its original form. Fregonese et al. [21] presented the use of TLS technology for surveying and monitoring an ancient building. The results demonstrated that such technology could accurately detect the displacement of the ancient structural movements. Teza and Pesci [22] presented the results of a survey of an old bell tower in Italy. The point cloud data analysis was able to evaluate the wall inclination of the bell tower.

In Thailand, TLS technology is relatively new for engineering applications, especially for the assessment and structural health monitoring of building structures. Leelataviwat et al. [23] have pioneered the preservation of many important historical sites in Thailand, and they recommended that continuous assessment and long-term monitoring are the best ways to preserve cultural heritage. One of the most well-known cultural heritage sites in Thailand is Ayutthaya Historical Park, which has been declared a World Heritage Site by UNESCO. In this historical park, there are

many important temples that need to be preserved. One of these is the Wat Krachee. This temple is dominated by two intertwined trees growing and entrancing inside the pagoda chamber. Over time, the Wat Krachee has been damaged by deteriorating materials, and the tree growth may have affected the pagoda's structural stability. Accordingly, in 2018, the Wat Krachee Conservation Project was started with the cooperation of the Fine Arts Department of the Ministry of Culture and UNESCO Bangkok of Thailand [24, 25]. However, the project faced the challenge of how to preserve the pagoda with two intertwined trees growing inside it and becoming part of the pagoda's structure. For this reason, long-term monitoring of the pagoda was required to protect it against damage.

The primary problem for the long-term monitoring of historic buildings using terrestrial laser scanners is to ensure that the point cloud data has been obtained correctly. This is not always the case due to errors in referencing the position in fieldwork and data processing. Abellán et al. [26] reported the monitoring of rockfalls based on the use of a terrestrial laser scanner for detection and spatial prediction. They noted in the results that the registration process was carried out through the visual identification of homologous points. In practice, it is challenging to choose the exact point of reference in the data processing for each monitoring session. To reduce the error in this process, a new method must be developed. Quagliarini et al. [17] identified the alignment error in each dataset as one of the main issues. Reducing this error would help to improve the technique. From the aforementioned studies on fieldwork monitoring using TLS, it was found that errors might occur in the data processing when using point-by-point referencing in manual operations.

Consequently, to reduce the errors in the long-term monitoring of Thai historic pagodas, the purpose of this study is to present an alternative method based on TLS in combination with permanent survey markers. The permanent survey markers are constructed to constrain the point cloud data for each monitoring session. This procedure is essential for the long-term monitoring of Thai pagodas to ensure that the registration corresponds to the real-world coordinates, and these should not be moved so that they can be used for future reference. The five monitoring session results for the Thai pagoda over a period of approximately two years and six months are reported. The significant elements are investigated, including the dimensions of the inverted bell-shaped pagoda, the chamber inside the pagoda, the leaning angle, and the horizontal displacement. The effect of trimming the tree is evaluated. Moreover, a prediction equation for the leaning angle of the Wat Krachee pagoda is proposed for future preservation and construction planning.

## 2. A Case Study of Wat Krachee in Ayutthaya

Wat Krachee is located in Ayutthaya Historical Park in Phra Nakhon Si Ayutthaya Province, as shown in Figure 1. Ayutthaya Historical Park is one of the most important archaeological sites in Thailand and was declared a UNESCO

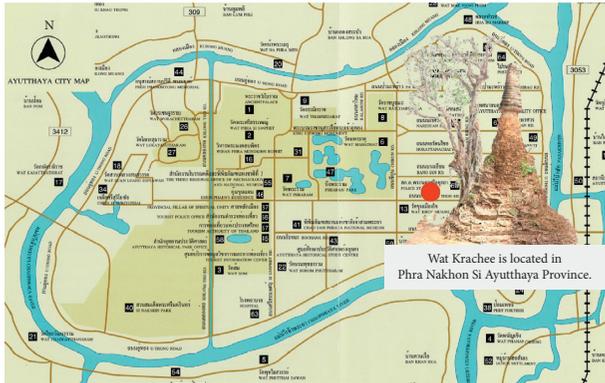


FIGURE 1: Location of Wat Krachee, Phra Nakhon Si Ayutthaya Province, Thailand.

World Heritage Site in 1991. Figure 2 shows the differential environment of Wat Krachee at three points in time, namely, AD 1987, AD 2005, and AD 2018. It can be observed that the remaining shape of the pagoda is an inverted bell shape. Moreover, this temple has a dominant pagoda with two intertwined trees growing inside it and an entrance into the pagoda chamber, as shown in Figure 3. According to archaeological assumptions, the Wat Krachee pagoda was constructed in the middle period of Ayutthaya, in approximately AD 1550 (2093 BE), meaning that the Wat Krachee pagoda is almost 470 years old [19, 20]. At present, the material deterioration and the growth of the two intertwined trees may be affecting the stability of the Wat Krachee pagoda. In 2018, the Wat Krachee Conservation Project was started through cooperation with the Fine Arts Department of Thailand's Ministry of Culture and UNESCO Bangkok. This conservation project has brought together a multidisciplinary group of engineers, architects, materials scientists, archaeologists, arborists, craftspeople, and professionals from other related fields. Therefore, this study provides supporting information for the Wat Krachee Conservation Project.

### 3. Methods

A method for the long-term monitoring of rockfalls was reported in the research by Abellán et al. [26]. The registration process was carried out through the visual identification of homologous points before starting the Iterative Closest Points (ICP) procedure. However, it was difficult to choose the homologous point in each monitoring period, which may cause an alignment error in each dataset. Moreover, Quagliarini et al. [17] found that the alignment error was the main problem for assessing the position of the measuring point. They suggested that this process should be improved to increase the accuracy of the data analysis.

To alleviate the error from the target-less registration process, the present study proposes an alternative method for the long-term monitoring of pagodas in Thailand based on terrestrial laser scanning technology in combination with permanent survey markers. A flowchart of the monitoring procedure is presented in Figure 4. In the initial phase, the

planning and surveying were set up and the permanent survey markers were constructed to define the coordinate system for long-term monitoring. A terrestrial laser scanner was then used, together with spherical targets, to generate the initial coordinate system. The purpose of using the permanent survey markers was to reduce (or minimize) the error from the registration process by constraining the coordinate system of the monitoring period in three-dimensional space.

In the monitoring phase, the data acquisition of the pagoda was first carried out using TLS together with the initial coordinates and spherical targets. Then, the point cloud data were processed using FARO Scene software [27]. In this process, point cloud data were transformed into the control coordinates. Next, the preparation of the point cloud data involved cleaning and removing noise to reduce the amount of data. Then, the postprocessing results of the point cloud data were exported as an RCP file. In the last step, the data analysis procedure, the geometrical properties, the dimensions, the inclination direction, and several essential elements of the pagoda were investigated using Autodesk Revit software [2]. The monitoring phase was repeated for each monitoring session until the data analysis was complete.

**3.1. Planning and Surveying.** Five sessions were completed as part of the long-term monitoring of the Wat Krachee pagoda, as shown in Figure 5. The operations were carried out in February 2018, March 2018, July 2018, July 2019, and August 2020.

The surrounding area of the Wat Krachee is soft soil, which has the potential to subside due to the surveying. Therefore, it was necessary to create permanent survey markers to ensure a registration corresponding to the real-world coordinates, which should be kept in place for future reference. In this study, four permanent survey markers were constructed on-site for the sake of monitoring, as shown in Figure 6. These survey markers were made of reinforced concrete with a drill hole diameter of 0.1 meters and a depth below the surface of approximately 15–20 meters. In addition, a steel pin was attached to the survey markers to support the spherical targets.

In the procedure for the creation of coordinates for the long-term monitoring of the pagoda, the essential equipment for defining the reference coordinates are standard spherical targets with a radius of 0.0695 meters. These spherical targets were installed on the survey markers, as shown in Figure 7. Then, TLS was used for collecting the coordinates of the four spherical targets. After that, the Scene software was used to automatically detect the spherical targets, as shown in Figure 8. The obtained coordinates ( $X$ ,  $Y$ ,  $Z$ ) were derived from the center points of the spherical targets. These coordinates, listed in Table 1, will be used as the reference coordinates for future monitoring.

**3.2. Data Acquisition with Terrestrial Laser Scanning (TLS).** TLS technology is a high-performance technology that is used to collect massive amounts of point cloud data for

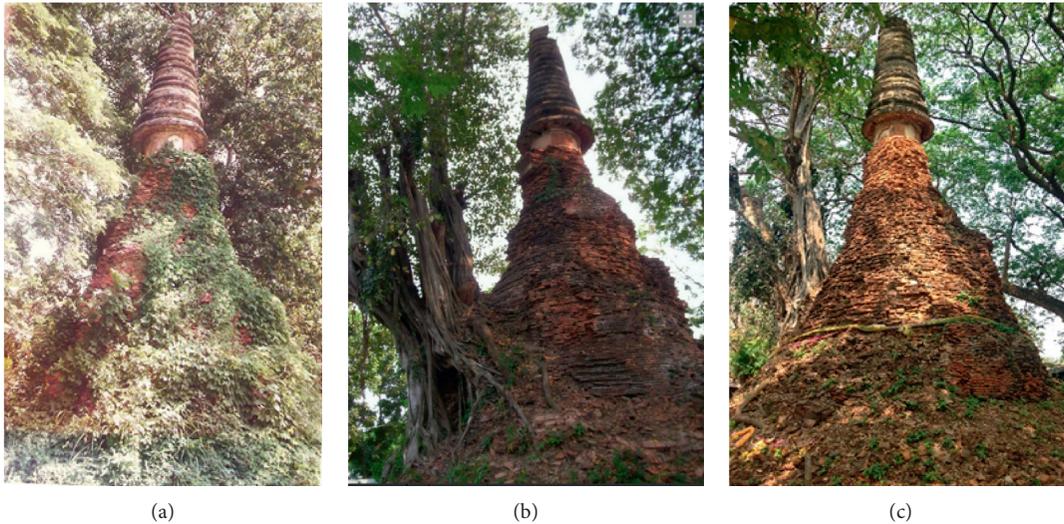


FIGURE 2: Images of Wat Krachee pagoda at three points in time. (a) AD 1987 [24]. (b) AD 2005 [25]. (c) AD 2018.

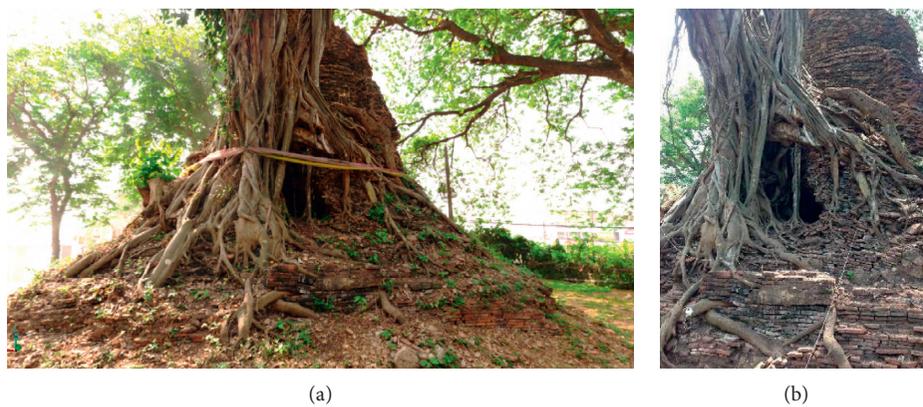


FIGURE 3: The two intertwined trees and the entrance to the chamber inside the pagoda.

objects with a complex surface [14]. In this study, TLS technology by FARO Focus3D X-330 [27] was applied for the data collection in each monitoring session. This TLS model uses phase-shift technology to measure distance, recording the vertical and horizontal angles simultaneously with the associated distance measurement. The fields of view in the vertical and horizontal directions are 300 degrees and 360 degrees, respectively. These angles and distances are transformed into Cartesian coordinates ( $X$ ,  $Y$ ,  $Z$ ). Moreover, terrestrial laser scanners have important sensors to help with the registration process, consisting of an inclinometer (dual-axis compensator), a compass, an altimeter, and GPS. The performance specifications of the terrestrial laser scanner are shown in Table 2.

The TLS technology was applied to attain the 3D point cloud data of the Wat Krachee pagoda for each monitoring session, as displayed in Figure 9. Pueschel [28] noted that parameters such as scan resolution and scan speed had an influence on obtaining point cloud data. Therefore, for each monitoring session, these parameters were controlled using

a resolution of 28.2 million points and a speed scan of 122,000 points per second for the whole scan. Furthermore, the color photograph mode was enabled to save eighty-five images per station. With these parameters (scan resolution, scan speed, and capturing the image), it took TLS approximately eight minutes for each scanner position together with the survey markers and the standard spherical targets.

The details of the data collection process during fieldwork are as follows. First, the four standard sphere targets were installed on the permanent reference steel pins that had previously been constructed. TLS scanning was then carried out to collect the four spherical target positions, including the surrounding conditions of the pagoda. Next, the terrestrial laser scanner was moved to a new position, and scanning was performed while considering the overlap of the environment of the previous position to reduce alignment error in the registration process. Then, the scanner was relocated to the next position and the scanning process was repeated until the plan was completed. This process was

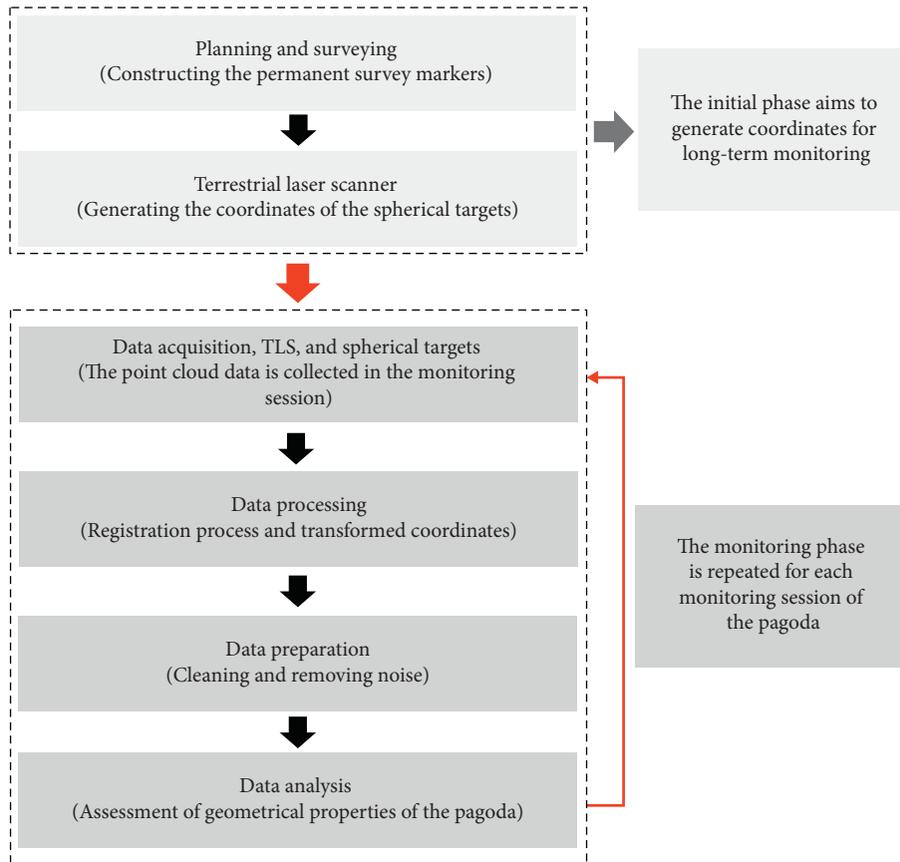


FIGURE 4: Method for long-term monitoring of Thai historic pagoda.



FIGURE 5: A schedule for the long-term monitoring of the Wat Krachee pagoda.



FIGURE 6: The four survey markers for the long-term monitoring of the Wat Krachee pagoda.

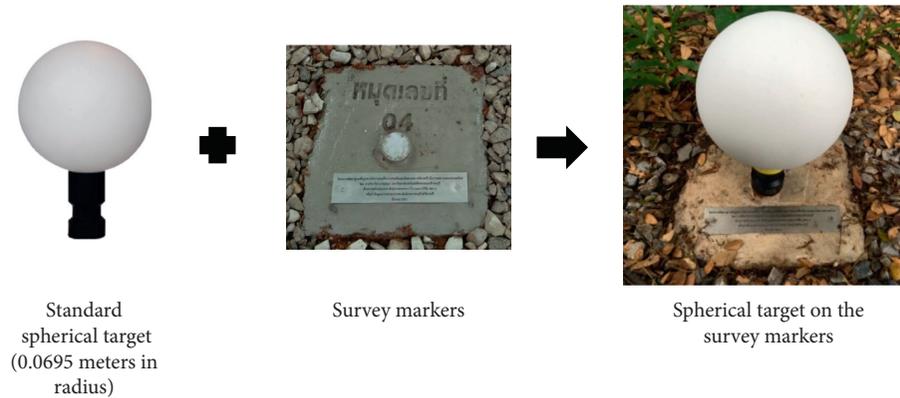


FIGURE 7: The combination of standard spherical targets and survey markers.

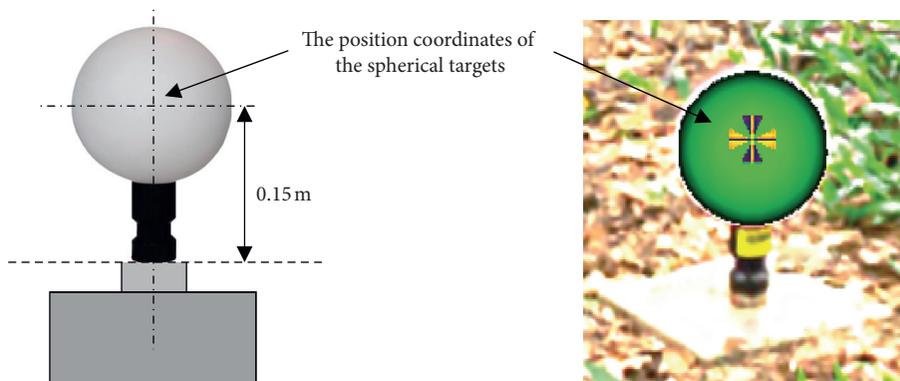


FIGURE 8: The position coordinates of the spherical targets on the survey markers.

TABLE 1: The coordinates of the spherical targets on the survey markers.

Survey markers	X (east)	Y (north)	Z (up)
SM 01	30.0000	30.0000	5.0000
SM 02	25.1550	21.9685	5.0215
SM 03	24.7339	10.0152	4.9913
SM 04	25.5419	25.0275	5.4381

TABLE 2: Performance specifications of the terrestrial laser scanner used in this study.

Effective range	0.6 m to 330 m
Field of view (vertical/horizontal)	300°/360°
Measurement speed	Up to 976,000 points per second
Laser class	Laser class1
Wavelength	1550 nm
Beam diameter at the exit	2.25 mm
Ranging error	±2 mm at 25 m
Resolution	Up to 710.7 million points per scan

applied for collecting field data during five monitoring sessions to assess the changes in the Wat Krachee pagoda structure.

On February 12, 2018, a survey of the surrounding conditions of the Wat Krachee temple was performed. It was found that this temple has some fantastic features, such as an inverted bell-shaped pagoda, two intertwined trees growing within it, and a chamber inside the pagoda. From a visual inspection, the pagoda clearly tilts; this may be due to the growth of the intertwined trees on the north side, as shown in Figure 10(a). Furthermore, a small chamber was constructed in this pagoda. The survey of this area required multiple scans of the data, and eight scan positions were collected during the first monitoring session. The second session was carried out on March 6, 2018. The environmental conditions of Wat Krachee had changed. Excavations had been made for archaeological exploration in some areas surrounding the pagoda. The two intertwined trees had been trimmed significantly in comparison to the first session, as shown in Figure 10(b). The data collection for the second monitoring session required sixteen positions to cover the archaeological excavation site. The third monitoring session took place on July 19, 2018, approximately five months after the first period. The critical problem for collecting data this time was that the surrounding pagoda was obscured by scaffolding, as shown in Figure 10(c). Moreover, the survey showed that one of the essential components of the Wat Krachee pagoda is a small chamber inside the pagoda. In this session, fourteen scans, including ten scans outside and four scans inside the pagoda, were carried out. One year and six

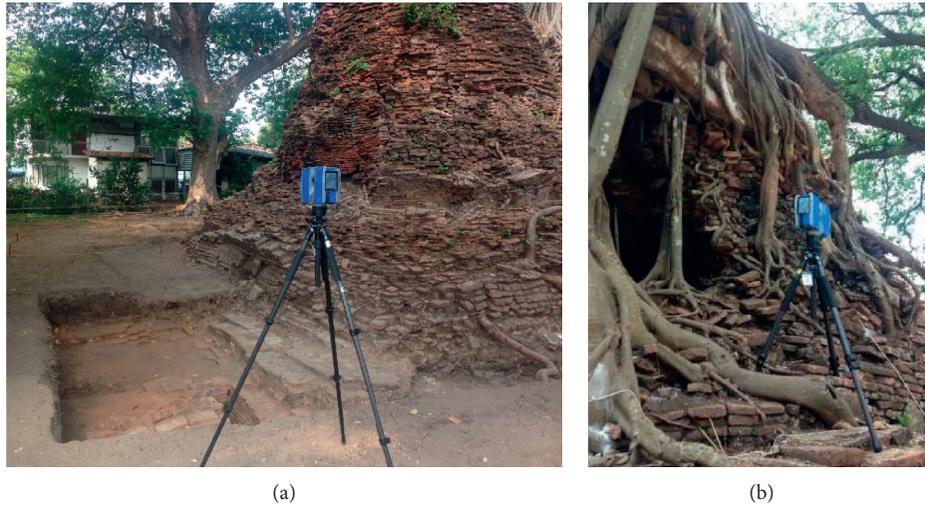


FIGURE 9: Fieldwork at the Wat Krachee temple using a terrestrial laser scanner.

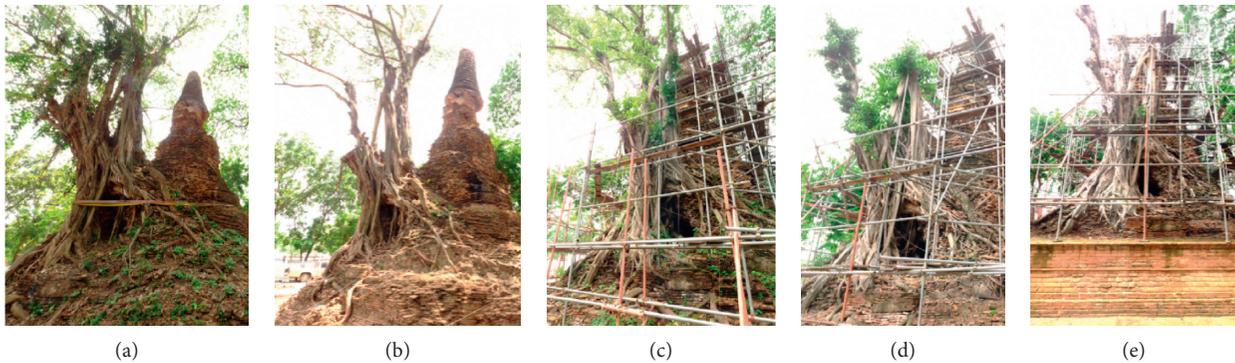


FIGURE 10: The surroundings of the Wat Krachee during the five monitoring sessions. (a) First survey. (b) Second survey. (c) Third survey. (d) Fourth survey. (e) Fifth survey.

months after the first survey, it was determined that tree trimming had slowed down the growth of the two intertwined trees, as shown in Figure 10(d). The scaffolding for preservation work was still attached to the pagoda. In this surveying session, thirteen stations of TLS were performed to gather the point cloud data. At this point, changes in the pagoda had been monitored for two years and six months from the first survey. In the fifth monitoring session, the Than Pra Thaksin section of the pagoda had been reconstructed based on archaeological assumptions, as shown in Figure 10(e). The other elements of the pagoda had not been restored. Therefore, the surveying teams carried out ten scan positions of the Wat Krachee pagoda surroundings.

**3.3. Data Processing and Data Preparation.** The FARO Scene software was used for data processing throughout the monitoring period. The data processing phase starts with importing the raw data into the local coordinate system from the laser scanner. Target-less registration (also referred to as cloud-to-cloud registration) was employed to combine the overlapping point clouds from each data scan. According to previous research by Wilson et al. [2], this registration

method can be applied for the data processing of historical buildings. Upon completion of this process, the 3D point cloud models are obtained. The results showed that the mean point error in each dataset from the five monitoring sessions was less than 8 mm. According to the manufacturer's [27] recommendation, the best mean error in the registration process should be less than 8 mm, for which the status is shown with a green light. An important process at this point involves constraining the dataset with the control coordinates before the data analysis, as seen in Table 1. To ensure the coordinates for each dataset were obtained through translation onto the survey control, the coordinates of the four spherical targets in each dataset were investigated. The results show that the coordinates of the spherical targets for each model were not significantly different compared with the survey control coordinates.

In the data preparation process before the point cloud analysis, it is necessary to clean the data obtained from the area surrounding the pagoda, such as scaffolding and unwanted objects. However, removing this point cloud data can only be done by filtering it out by hand, which takes a long time. The pagoda 3D models have been defined to conform to the realistic sites, as shown in Figure 11(a). The

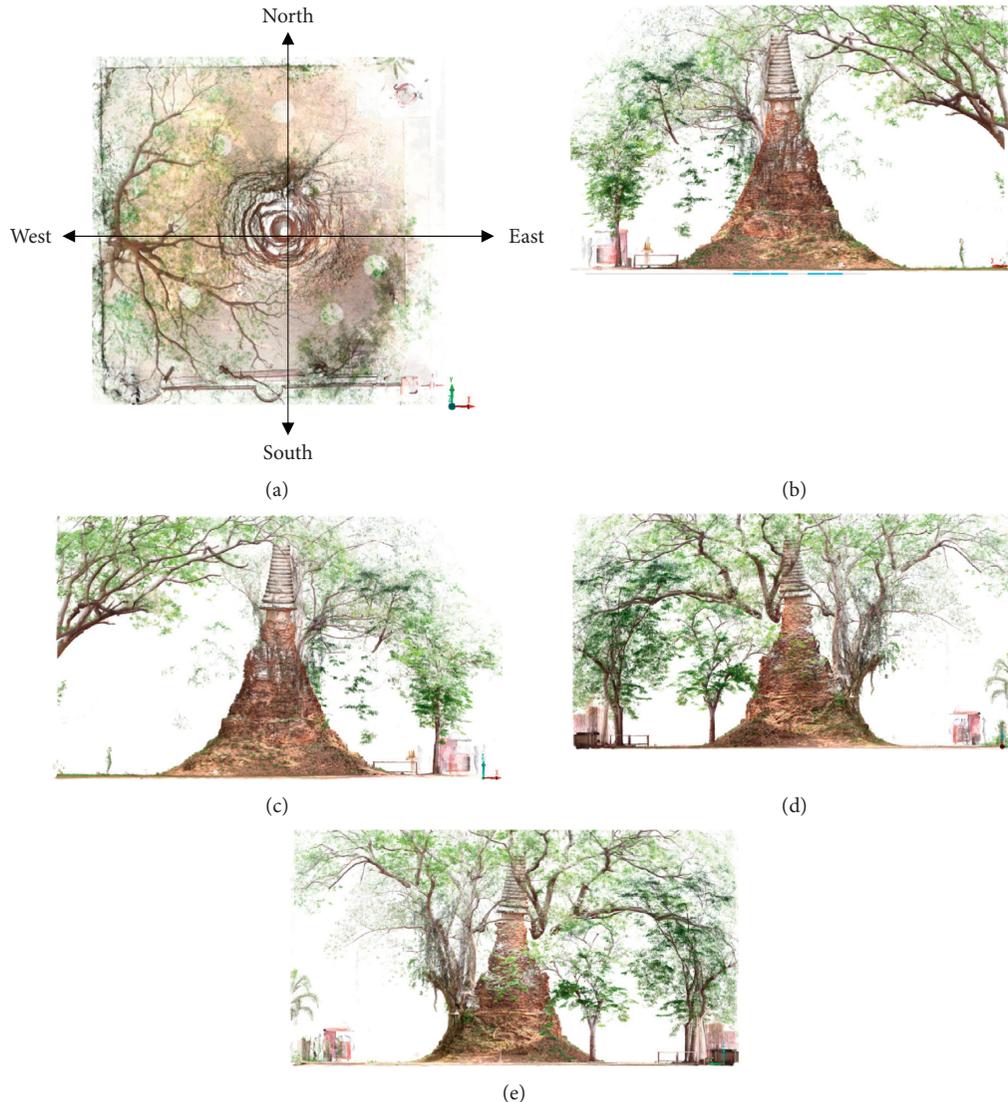


FIGURE 11: Plan view and side views of the point clouds collected in the Wat Krachee. (a) Plan view of the Wat Krachee. (b) South view. (c) North view. (d) West view. (e) East view.

side views of the four directions of the pagoda are illustrated in Figures 11(b)–11(e). The 3D point cloud models from the five monitoring sessions after passing the data processing and data preparation stages are shown in Figure 12. Finally, each model's point cloud dataset was exported as an RCP file and then transferred to Autodesk Revit software for the point cloud analyzing process.

**3.4. Point Cloud Analysis.** This section presents the procedure for the point cloud analysis. According to Korumaz et al. [14], the analysis of a tall building's verticality can be completed by cutting the point cloud and evaluating the obtained sections. In addition, Bertacchini et al. [19] have suggested that the trend of the vertical axis can be calculated by determining the center of each section and combining them. Therefore, this technique can be used to determine the

direction of the maximum inclination of the pagoda. The point cloud analysis of the Wat Krachee pagoda was investigated using tools in the Autodesk Revit software. The 3D point cloud models in the RCP file were inserted into the Autodesk Revit software. The point cloud dataset positioning was then selected using the origin-to-origin function so that the coordinate system was not changed. In this step, the pagoda dimensions and the change in the leaning angle for each monitoring session were assessed. Moreover, the effect of trimming the trees was investigated. A comparative analysis of the point cloud datasets was possible via CloudCompare software [7, 17]. The point cloud dataset for each monitoring session was compared with the first dataset before measuring the pagoda elements, as shown in Figure 13.

Before the assessment, the point cloud dataset required definitions for the inclination direction and the leaning angle

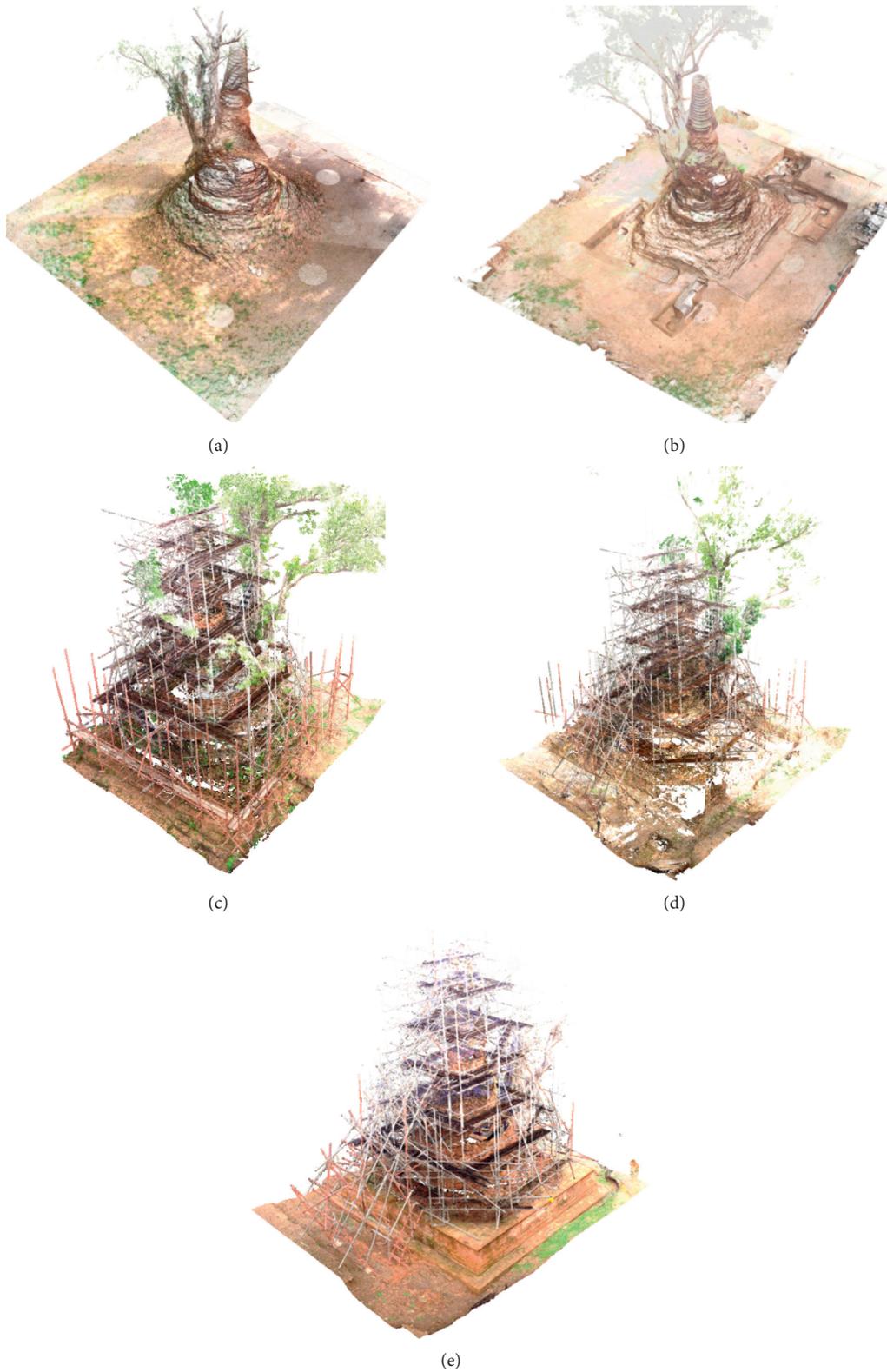


FIGURE 12: 3D point cloud models of the Wat Krachee from the five monitoring sessions. (a) February 12, 2018. (b) March 6, 2018. (c) July 19, 2018. (d) July 27, 2019. (e) August 5, 2020.

for ease of reference. Therefore, the beta ( $\beta$ ) angle was defined from the south axis and the alpha ( $\alpha$ ) angle was determined from the east axis as the inclination direction of

the pagoda, as shown in Figure 14(a). The pagoda leaning angle is defined as the zeta ( $\theta$ ) angle at the inclination direction plane, as shown in Figure 14(b).

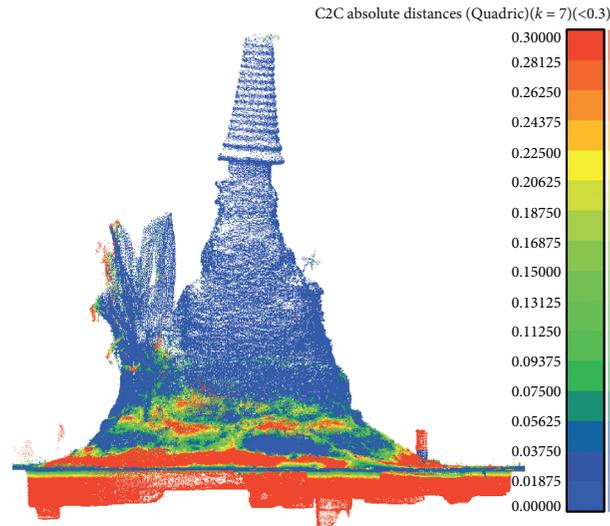


FIGURE 13: A comparative analysis between two datasets.

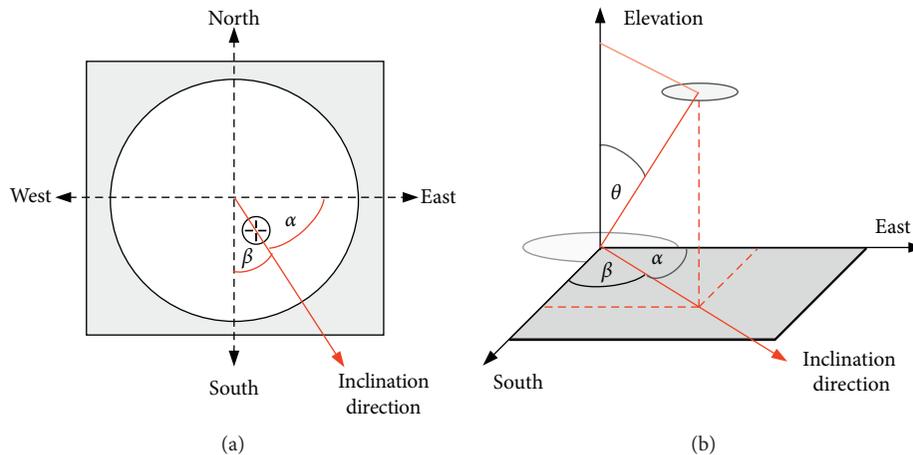


FIGURE 14: Side elevation of the pagoda with the central axis and inclination direction. (a) Plan view. (b) 3D view.

In the process of creating the geometry for the assessment of the pagoda, a level line for each component of the pagoda and a vertical axis were created, as shown in Figure 15. The Than Keang section of the pagoda was defined as a reference base for creating the vertical axis. The vertical line was generated based on the center of the Than Keang section. Afterward, a geometrical shape for each element of the pagoda was created using guidelines from the point cloud data. Then, the center of each geometric element was applied to find the pagoda inclination direction. The pagoda leaning angle could then be calculated by measuring the displacement differences between the center of each element's geometrical shape and the exact vertical line. This procedure will continue to be applied to assess the leaning angle for the long-term monitoring of the pagoda.

#### 4. Results and Discussion

Each session for monitoring the Wat Krachee pagoda over the period of two years and six months was assessed. The

benefit of the point cloud dataset is that it could be used to analyze the dimensions of the bell-shaped pagoda element, the dimensions of the chamber inside the pagoda, the thickness of the pagoda, and the effect of tree trimming. Moreover, the pagoda's changing leaning angle was investigated to develop a prediction equation for the pagoda's future leaning angle. Details are given in the following sections.

**4.1. Dimension Analysis.** The 3D point cloud models of the Wat Krachee pagoda for the first monitoring session are shown in Figure 16(a). According to a report by the Fine Arts Department [29], the assumption model for this temple pagoda is an inverted bell-shaped pagoda, which consists of the Than Pra Thaksin, Than Keang, Than Pat, Malai Thao, bell shape, Banlang, Kan Chat, Falami Lotus, Plong Chanai, and Pli Yod sections, as shown in Figure 16(b). A comparison between the bell-shaped pagoda elements based on the assumption model and the 3D point cloud models can be precisely matched for each pagoda element. It was observed

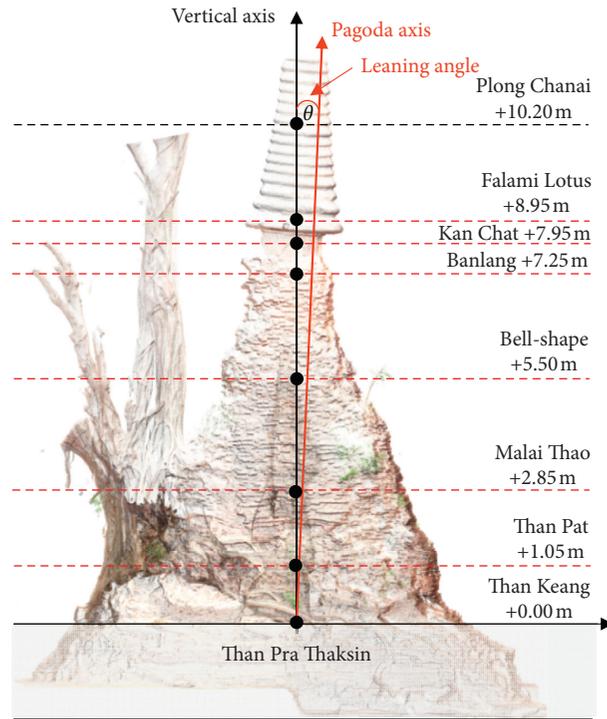


FIGURE 15: Section of the pagoda with the central axis and inclination direction.

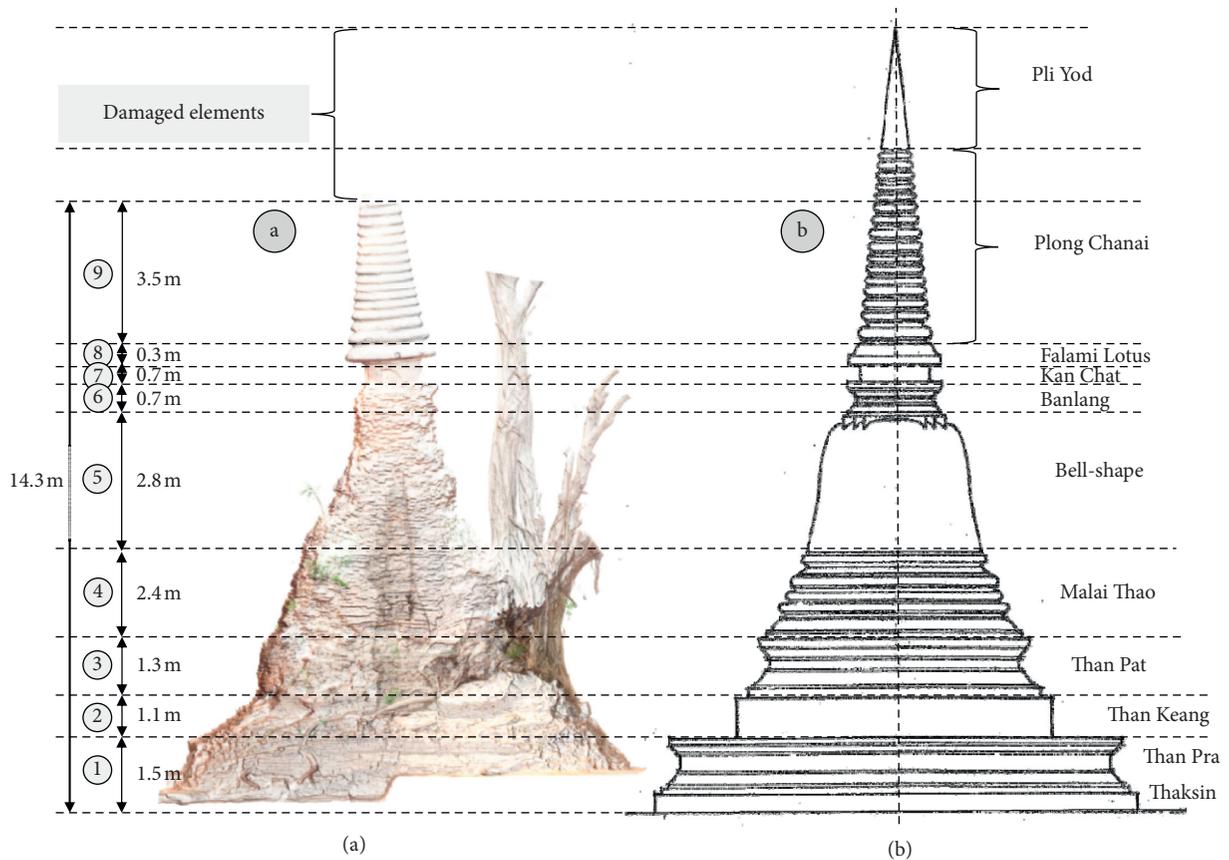


FIGURE 16: The comparison elements of the Wat Krachee pagoda. (a) 3D point cloud model. (b) Assumption model [29].

that the Pli Yod and some of the Plong Chanai sections were damaged compared to the assumption models. However, it was not clear when the damage occurred. Furthermore, the 3D point cloud models reported dimensions for each element based on the assumption model's pagoda elements.

The dimensions of each element of the realistic bell-shaped pagoda can be measured in terms of height, base dimension, and geometrical shape, as presented in Table 3. These results reveal that the point cloud data are useful for the preservation of the pagoda to its original form. The obtained dimensions of each element of the pagoda were applied to the reconstruction phase. In 2020, the Than Pra Thaksin section of the pagoda was entirely reconstructed using assumption models as a square base, as shown in Figure 17, and the other elements are in the process of being renovated.

One of the essential elements of the pagoda is the complexity inside the chamber. After postprocessing, the 3D point cloud data were utilized to investigate the complicated shape of the chamber inside the pagoda. Figure 18 shows cross-section A–A in the west direction and the measured dimensions of the pagoda. The results revealed that the entrance of the chamber is adjacent to the trees, and the height of the cavity is an average of 1.0 m. The total length of the chamber from the access point to the last chamber has a horizontal distance of 4.1 m. The smallest thickness of the pagoda in the west direction is equal to 1.0 m in the upper part of the chamber. Figure 19 displays cross-section B–B in the south direction of the pagoda, representing the detailed measurement. The findings showed that the dimensions of the chamber in the first layer are  $1.2 \times 1.2$  m. There are three layers of the chamber inside the pagoda. The first layer has a height of 1.75 m, the second has a height of 1.55 m, and the third layer has a height of 2.4 m to the top layer of the chamber; thus, the total height of the chamber is 5.7 m. The smallest wall thickness is 0.5 m, located at 6.0 m above ground level. The horizontal and vertical lengths of the cavity opening were measured at 0.7 m and 1.2 m, respectively. This method collected the point cloud data inside and outside of the pagoda. Therefore, the thickness of the pagoda could be precisely assessed.

The highlight of the Wat Krachee pagoda is the two intertwined trees growing within it. The changes in the trees surrounding the pagoda at the time of each monitoring session are represented in Figure 20. In 2018, surveying and evaluation found that the height of the main tree trunk was approximately 11.45 m, and the total size of the tree was 15.5 m with respect to the ground level. During a multi-department meeting, it was agreed that the growth of the trees might affect the structural stability of the pagoda in the long term. Therefore, in 2019, arborists carried out tree trimming to slow down the growth. The height of the trimmed area was 6.8 m so that the main tree remained at the height of 8.7 m.

**4.2. Monitoring Results.** In this study, long-term monitoring of the Wat Krachee pagoda was carried out over a period of two years and six months. The first pagoda

TABLE 3: The dimension of each element of the bell-shaped pagoda.

No.	Elements of the bell-shaped pagoda	Height (m)	Base dimension (m)	Geometrical shape
1	Than Pra Thaksin	1.5	$10.2 \times 10.0$	Square
2	Than Keang	1.1	7.5	Circle
3	Than Pat	1.3	7.3	Circle
4	Malai Thao	2.4	5.8	Circle
5	Bell shape	2.8	3.5	Circle
6	Banlang	0.7	$1.85 \times 2.0$	Square
7	Kan Chat	0.7	1.35	Circle
8	Falami Lotus	0.3	2.1	Circle
9	Plong Chanai	3.5	1.8	Circle

monitoring session revealed that the pagoda had leaned toward the southeast direction, in which the beta and alpha angles were 20.85 and 69.15 degrees, respectively. This inclination direction was applied to assess the distance from the vertical axis to the center of each element of the pagoda, as shown in Figure 21. The first monitoring session calculated that the maximum leaning angle of the pagoda was equal to 3.567 degrees. The second monitoring session of the pagoda found that the leaning angle had not changed significantly because the monitoring took place shortly after the first period, as represented in Figure 22. Four months later, the inclination direction and the horizontal displacement were determined, as displayed in Figure 23. From this monitoring, it was found that the leaning angle of the pagoda had increased by 0.019 degrees. Therefore, the leaning angle of the pagoda during the third monitoring session was equal to 3.586 degrees. Moreover, it was found that the beta angle had increased in the east direction when compared to the first monitoring. One year and six months after the first session, the assessment inclination direction and the leaning angle were determined, as shown in Figure 24. The results revealed that the leaning angle of the pagoda had become 3.618 degrees or an increase of 0.051 degrees from the first measurement. The beta angle continuously increased to 21.85 degrees. The results from the fifth monitoring session of the pagoda, two years and six months after the first one, are shown in Figure 25. The maximum distance of the vertical axis of 0.652 m was obtained on the Plong Chanai section of the pagoda, and the leaning angle was 3.655 degrees.

Furthermore, the assessment of the leaning angle for each monitoring session can generate the relationship between time and the leaning angle of the Wat Krachee pagoda, as shown in Figure 26. The results show that the leaning angle might have increased significantly if the recommendation to trim the trees had been ignored. Considering the actual monitoring, the results also indicate that time influences the leaning angle of the pagoda. However, a regression analysis was applied using the least-squares fit method with a linear trend line, as presented in equation (1). The result revealed that the slope ( $d\theta/dt$ ) and the coefficient of determination ( $R^2$ ) of this equation are 0.0001 and 0.99, respectively.

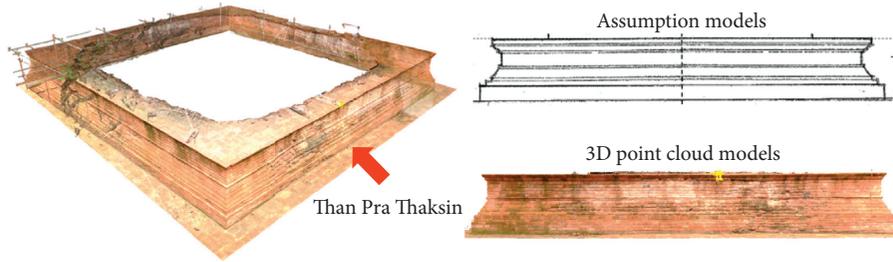


FIGURE 17: Addition of the Than Pra Thaksin section of the Wat Krachee pagoda.

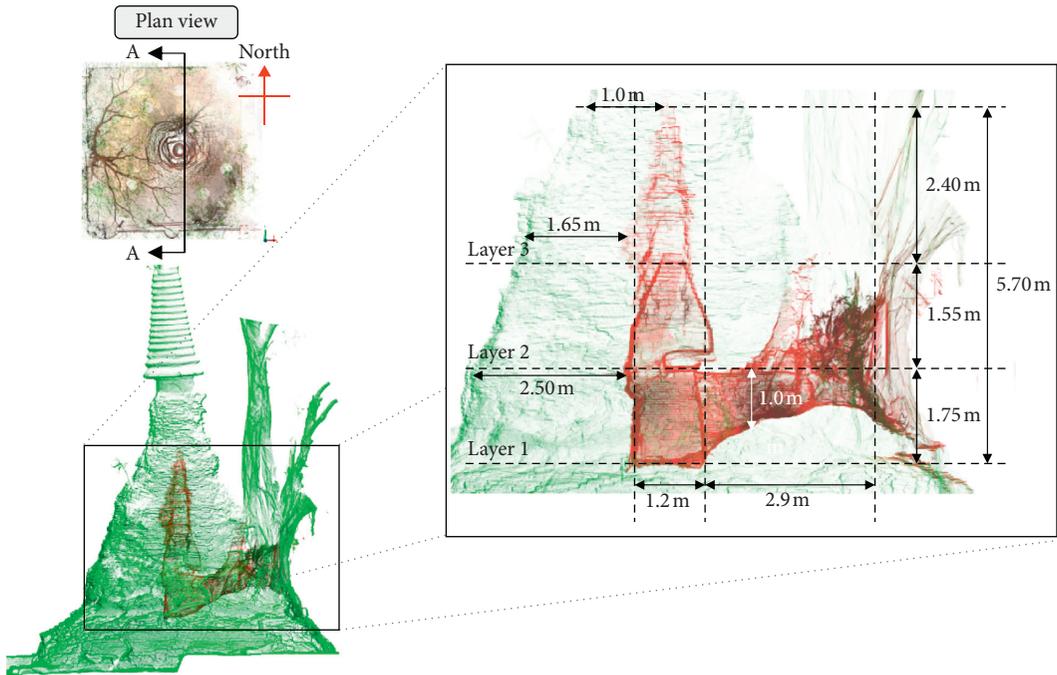


FIGURE 18: Section A-A in the west direction.

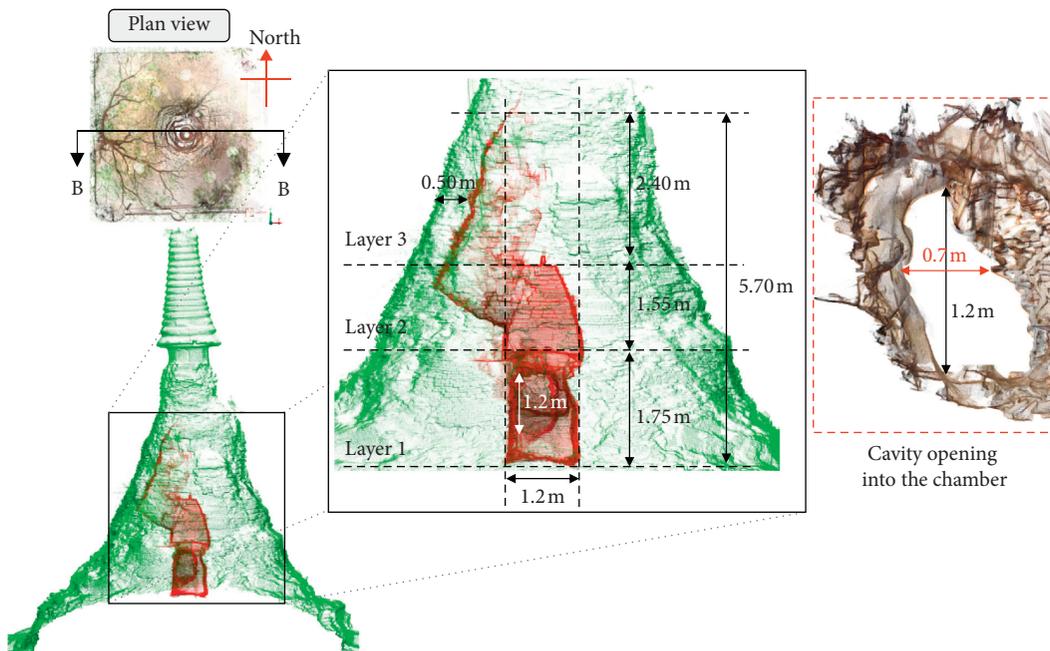


FIGURE 19: Section B-B in the south direction and a cavity opening into the chamber.

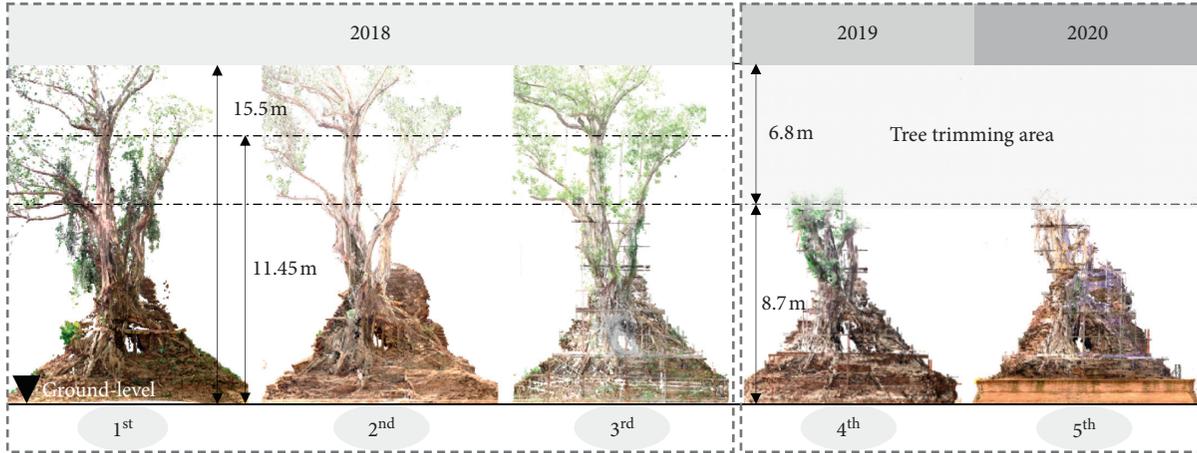


FIGURE 20: The changing of the trees surrounding the Wat Krachee.

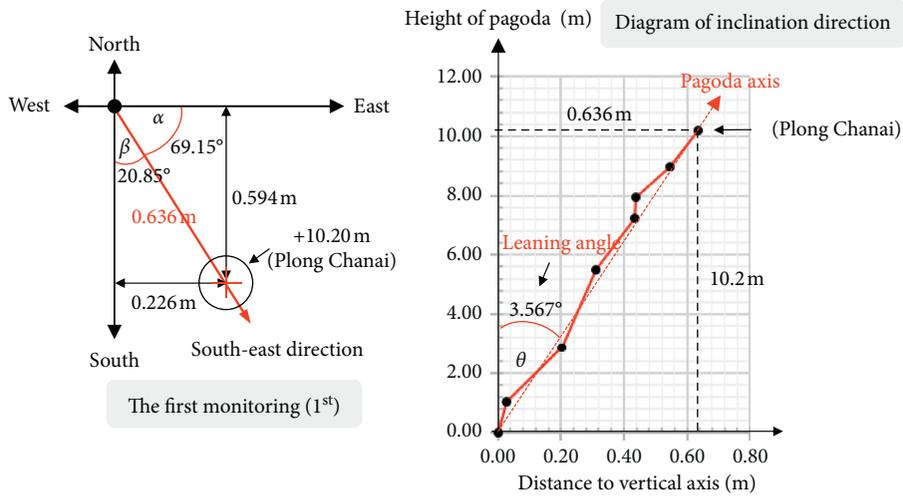


FIGURE 21: First monitoring session (February 2018).

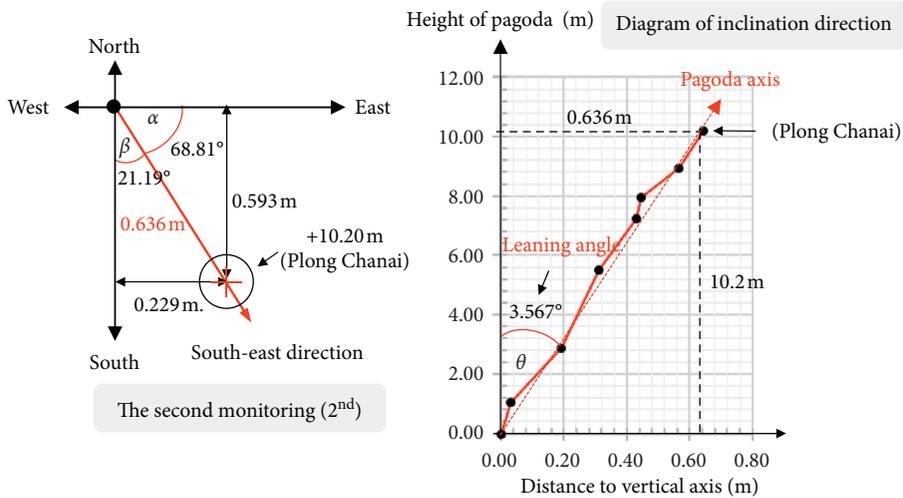


FIGURE 22: Second monitoring session (March 2018).

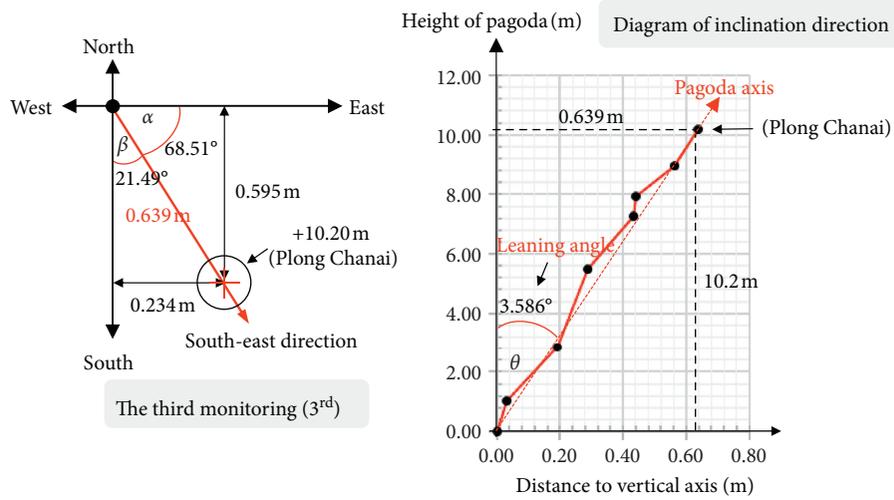


FIGURE 23: Third monitoring session (July 2018).

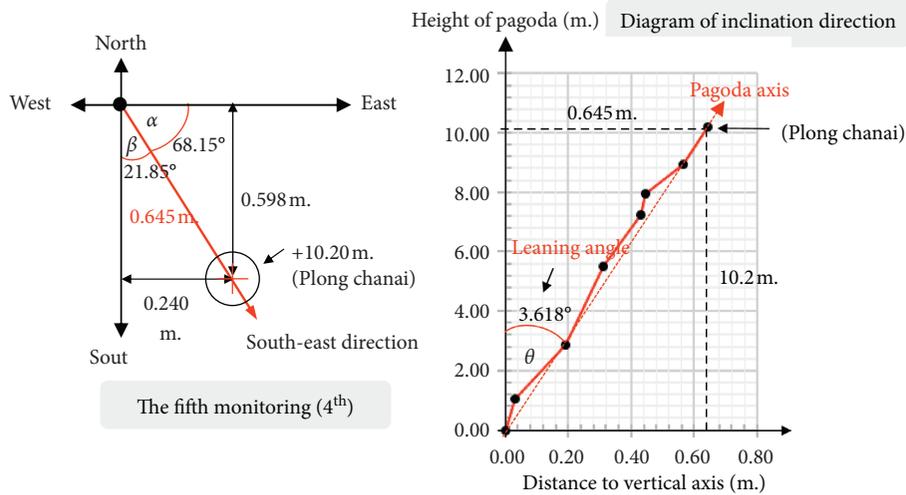


FIGURE 24: Fourth monitoring session (July 2019).

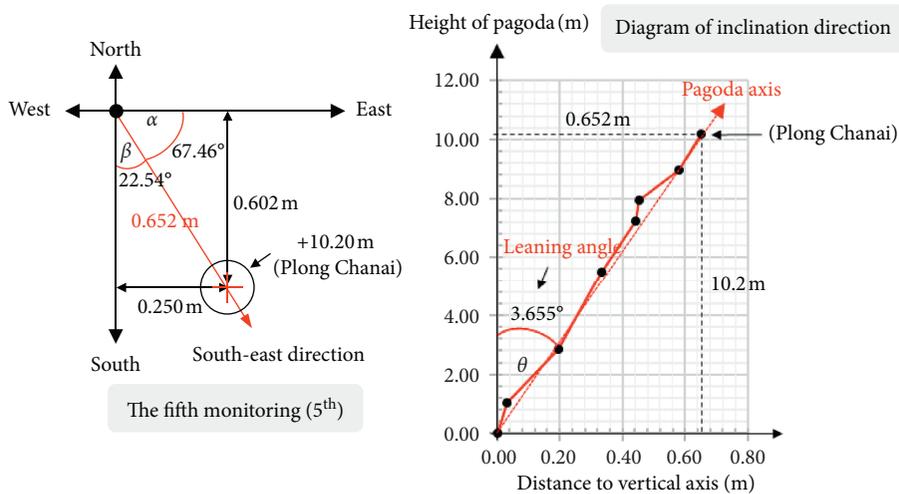


FIGURE 25: Fifth monitoring session (August 2020).

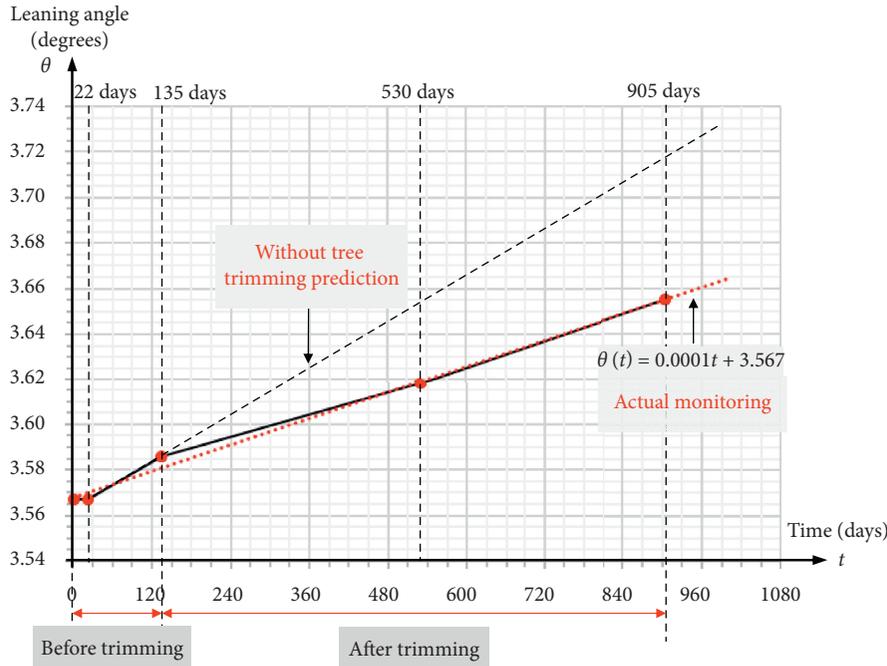


FIGURE 26: The relationship between time and the leaning angle of the Wat Krachee pagoda.

$$\theta(t) = 0.0001t + 3.567, \quad (1)$$

$$\frac{d\theta}{dt} = 0.0001, \quad (2)$$

where  $\theta$  is the leaning angle of the pagoda in degrees and  $t$  is the time in days. Equation (1) was used to forecast the leaning angle of the pagoda with the initial leaning angle equal to 3.567 degrees, as measured in 2018. This equation can also predict the increase in the leaning angle for the structural stability assessment of the pagoda and restoration planning in the future. Moreover, the rate of increase in the leaning angle of the pagoda can be predicted using equation (2).

## 5. Conclusions

This article has presented an alternative method for the long-term monitoring and preservation of Thai pagodas based on TLS combined with permanent survey markers. The Wat Krachee pagoda in the Ayutthaya Province of Thailand was selected as a case study because of the challenges presented by its geometric configuration and the two intertwined trees growing within it. The massive amount of three-dimensional data from TLS technology is valuable for structural stability assessment in the long term. Moreover, the permanent survey markers were constructed to constrain the point cloud dataset. This method significantly reduced the alignment error in the data processing and increased the accuracy of the data analysis process. Throughout the five monitoring sessions over a period of two years and six months, the results revealed that 3D point cloud models provide high-precision dimensions and geometric shapes for the current pagoda condition. The pagoda leaning angle was assessed to continue to protect it from damage.

Furthermore, a challenge of this project involved deciding whether to trim the trees or not. During a meeting, most of the individuals on the conservation project team agreed to recommend trimming the trees adjacent to the Wat Krachee pagoda. The results revealed that the tree trimming significantly decreased the leaning angle of the pagoda. For long-term monitoring, an equation was developed to predict the pagoda leaning angle for preservation and restoration planning. In addition, data from the terrestrial laser scanner were used to create a realistic drawing of the plan before the reconstruction phase. In 2020, this method was found to be beneficial to the conservation work of the pagoda, and the teams completely and successfully restored the pagoda's Than Pra Thaksin elements. Finally, the original forms of several Thai pagodas need to be preserved, and monitoring using a terrestrial laser scanner would be an efficient alternative method for this preservation work.

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

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