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International Journal of Architectural Heritage
Conservation, Analysis, and Restoration

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/uarc20

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INTERNATIONAL JOURNAL OF ARCHITECTURAL HERITAGE
2022, VOL. 16, NO. 9, 1366–1381
https://doi.org/10.1080/15583058.2021.1884319



# Damage Assessment and Guidelines for Restoration Methods of Ancient Brick Structures at Sambor Prei Kuk, Cambodia

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**ABSTRACT**

Many ancient brick structures have been recorded in the archaeological site of Sambor Prei Kuk. Most of these structures were considered to be built in the 7th century as religious facilities of royal city Isanapura and abandoned in the 15th century. Since then, the brick structures in this site had been covered by dense forest and suffered severe damage due to the tropical climate. This archaeological site was inscribed on the World Heritage List in 2017, and proper intervention is needed to preserve the remaining brick structures. The Sambor Prei Kuk Conservation Project carried out comprehensive research on the state of conservation for all 286 brick structures in this site. This project has developed a risk map, and carried out the survey of structural deformation and diagnosis of deterioration. Based on these surveys, the main causes of damage were identified: outward deformation of the base and foundation; thrust caused by the roof of the corbel arch; structural weakness at the door opening; fragmentation of brickwork by invasive vegetation; and impact of fallen tree. Finally, appropriate and acceptable restoration methods which can effectively stabilize and consolidate the brick structures to prevent further destruction while not negatively affecting the authenticity were discussed.

**ARTICLE HISTORY**
Received 9 November 2020
Accepted 28 January 2021

**KEYWORDS**
Angkor; authenticity; brick; deformation; restoration; Sambor Prei Kuk; tropical climate

## 1. Introduction

A large number of stone and brick monuments were built by the ancient Angkor empire in what today is Cambodia and neighboring countries. Most of the monumental architecture that was built in the pre-Angkorian period, before the 9$^{th}$ century, was made of brick. Today, many of these brick structures located in remote areas are left to the harsh tropical climate without proper conservation and management.

The archaeological site of Sambor Prei Kuk is located almost in the center of Cambodia and is identified as the capital of the Chenla kingdom which flourished in the late 6$^{th}$–7$^{th}$ centuries. This site is one of the most representative series of brick monuments of the pre-Angkorian period. Numerous religions and living facilities are thought to be constructed in Sambor Prei Kuk mainly in the first half of 7th century. A part of the archaeological site, Sambor Prei Kuk, was inscribed on the UNESCO World Heritage List in 2017 under the title of “Temple Zone of Sambor Prei Kuk, Archaeological Site of Ancient Ishanapura”. This ancient city consisted of a Moated City Zone in the west and Temple Zone in the east (Figure 1). Moated City Zone is on the western side of the river O Krou Ke, and surrounded by a moat on three sides and measures about 2 km per side. In the Temple Zone, there are three large-scale temple complexes enclosed by multiple enclosure walls. Additionally, many temples of a single shrine or combination of several shrines were located around large complexes. In addition, many earthwork elements, including banks, roads, and ponds, have been constructed in and around these zones (Shimoda and Shimamoto 2012).

A total of 286 brick structures has been recorded in the entire area of this archaeological site. Most of them are thought to be shrines dedicated to Hindu deities. Many structures have been severely damaged during a prolonged period of abandonment, and the deterioration is progressing today. However, about 70 brick structures remain in a relatively good state of condition. However, they require appropriate interventions including continuous maintenance and minimum restoration.

The aim of this article is to identify the causes of damage to these structures and discuss the restoration methods for stabilizing the fragile structures

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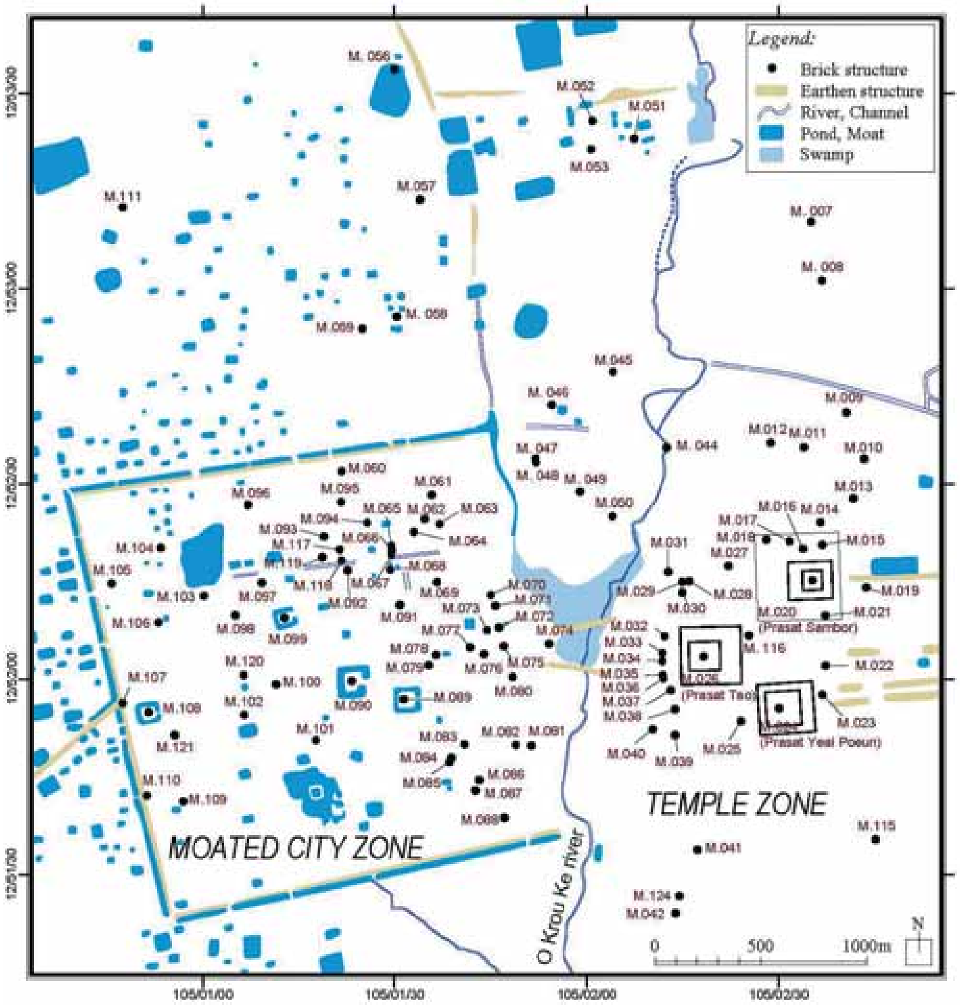


Figure 1. Distribution map of the brick structures in the main area of archaeological site of Sambor Prei Kuk.

effectively, while not negatively affecting the authenticity of their brickwork.

## 2. Background and research aim

A part of this site was explored at the end of the 19th century. More recently, archaeologists of the École française d'Extrême-Orient carried out surveys in the first half of the 20th century. The temple zone where brick structures are concentrated was covered with dense forest, and each structure was damaged by a significant amount of vegetation including trees. Some of the brick structures, mainly in the temple complex Prasat Yeai Poeun, were stabilized by new brick fillings to large cracks, adding supports to door openings and other structural support measures (Golouvew 1927). This archaeological site was again abandoned in the 1960s due to civil and international conflicts in Cambodia. After the situation was stabilized in the 1990s, the Angkor Conservation Office, a Cambodian government institute, implemented restoration work mainly at one of the most symbolic brick structures of the site identified as the central shrine in Prasat Tao (Tranet 1997/1999; Vorn 2001). Since 2001, the Ministry of Culture and Fine Arts of the Cambodian government and the Laboratory of Architectural History in Waseda University established the Sambor Prei Kuk Conservation Project (hereafter SPK Conservation Project in this article) and began the safeguarding activities.

This site is located in a tropical climate with a rainy season of high temperature and humidity occurring from May to October. Most of the annual rainfall, approximately averaging 1,500 mm, is concentrated in the rainy season, and vegetation rapidly grows on and around the brick structures (Figure 2). The SPK Conservation Project has been carrying out conservation activities such as removing vegetation, pruning branches, and felling dangerous trees close to the

Figure 2. One of the brick structures with growth of tree (N18 shrine, Prasat Chrey, M.17).

remains, removing sediment, and installing temporary supports in and around the temple remains (Figure 3).

However, even during these activities, several brick structures have partially collapsed due to heavy rain and fallen trees. Therefore, SPK Conservation Project made a thorough examination of the restoration work required to stabilize and consolidate the fragile and unstable brick structures. Prior to the restoration work, the following studies and discussions were carried out.

*1) Comprehensive survey on the state of preservation of the brick structures*:

An exhaustive survey on the state of preservation of the brick structures in the entire area of this archaeological site had been implemented. All brick structures were inventoried and classified according to their current condition.

*2) Development of a risk map*:

Developing a risk map of selective structures which are in a relatively well-preserved state and deemed of significant historical value in order to consider the priority of the restoration work.

*3) Identification of the causes of structural damage*:

Identifying the ongoing causes of damage based on the measurements of the structural deformation and diagnosis of structural stability.

*4) Study on the consolidation method with pilot restoration work*:

In order to develop and verify the appropriate consolidation method, and capacity building of the field conservators, a pilot restoration work was carried out at a small structure, N14-1 shrine, in the temple complex of Prasat Sambor.

*5) Implementation of the full scale of restoration work*:

Based on the results of the pilot restoration work, full-scale restoration work was carried out at the central shrine of Prasat Sambor. This building was recognized as one of the highest risk structures by the risk map assessment. During the restoration work, the actual state of damaged brickwork was observed and led to improvements in the restoration techniques.

Based on the results of the identified causes of the structural damage and the restoration work for stabilizing and consolidating at the two brick structures, it is elucidated the appropriate and acceptable guidelines for restoration method of brick structures at Sambor Prei Kuk in this article.

## 3. Brick structures in Sambor Prei Kuk

Most of the brick structures in the Sambor Prei Kuk are considered to be shrines for the dedication of statues of Hindu deities. Some temples were the complex of multiple structures in a precinct, such as shrines, enclosure, gate, pond, and so on. However, most of the structures were stand-alone or a combination of a small number of shrines. The plan of each shrine is either square, rectangular, or octagonal. Most of the shrines face east and

Figure 3. Removing vegetation on the brick structure as the periodical maintenance activities at N15 shrine.

open only in this direction. However, there are several shrines that have a different orientation with two or four door openings. Central shrine (S1) in the temple complex Prasat Yeai Poeun is the largest brick structure of all standing monuments at Sambor Prei Kuk. The length of the long axis in the east-west direction is approximately 14 m; the short axis in a north-south direction is approximately 10 m, and the height of the remaining structure is approximately 22 m (Figure 4).

The common elevation of the shrines is composed by three elements: base, wall, and roof. The style of roof is classified as two types: high-tier type which the decorative motifs on the wall are repeated in each story of roof (S1 shrine), and low-tier type which the small decorative motif called chaitya arches are engraved on each story of roof (N7 shrine). The brickwork of the roof part utilizes the technique of corbel arch that is employed in other ancient mason architectures throughout the long span of Khmer history.

Sandstone material was used on many occasions at door frames, steps, decorative lintel, colonnette, and pavement. The exterior walls are richly decorated by carvings. Decorative finishing plaster is also observed on the exterior of some shrines. Some shrines have the projecting wall of false ante-chambers on each side as in the S1 shrine, and some are flat walls with simple pilasters as in the N7 shrine (Figure 4).

The size of the brick elements is not unified and differed by the individual structure, but the average size of the brick material of main buildings ranged from 253–289 mm in length, 130–152 mm in width, 57–69 mm in thickness, and the ratio of the length: width:thickness is approximately 4:2:1. Bricks are generally composed of detrital quartz grains with irregular grain sizes (about 0.2–1.8 mm) and a matrix made of quartz, hematite, feldspar, trace amounts of zircon, etc. As a result of analyses with an X-ray microanalyzer, the matrix of the brick was found to be composed of mainly Si and Al. As the result of bulk chemical composition analysis, the main component of brick is SiO2, which occupies 81–92 wt%. Al2O3 accounts for 5–12 wt%, and Fe2O3 accounts for 0.8–2.2 wt%.

The brickwork of the exterior surface appears to have been layered very carefully by rubbing the bricks together, and probably joining them with an organic adhesive. Although the adhesive material has not been identified at Sambor Prei Kuk, an analysis at the brickwork of the ancient Cham architecture at Po Klong Garai revealed the adhesive to be tree resin belonging to the genus Dipterocarpus (Fujiki 1996). The brickwork of the inner wall is also densely layered, but not rubbed together like the exterior brickwork and gaps between bricks were filled by mortar.

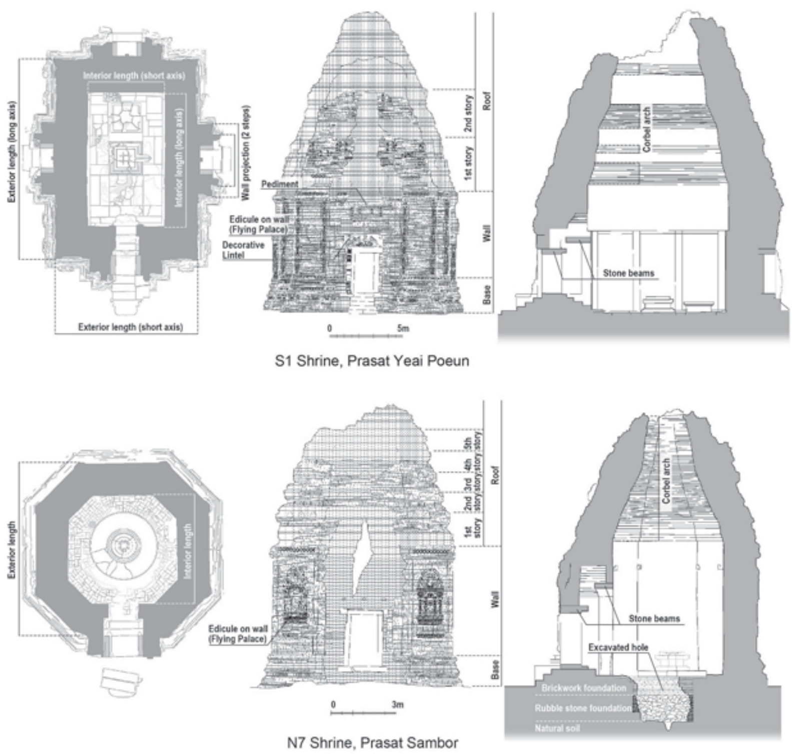


Figure 4. Plan, elevation, and section drawings of the representative brick structures in Sambor Prei Kuk (above) S1 shrine (high tier roof type structure) and (below) N7 shrine (low tier roof type structure).

The foundation structure of these brick structures has been confirmed during previous excavation and reconstruction work of the looted holes in the several shrines. In the case of the N7 shrine, brick layers about 1 m in thickness were confirmed below the floor level. Subsequently, a foundation layer of pebble stone and sand continued approximately 1.2 m in thickness until the natural soil layer was identified (Figure 4) (Shimoda, Nakagawa, and So 2004). The foundation structure by brickwork and sand with pebble stone is commonly found at several shrines. The thickness of the brick layer was about 1 m in N9 and N11 shrines, about 1.9 m in N22 shrine, and about 2.4 m in N1 shrine. The thickness of the pebble and sand layer has not been verified in each shrine because most of the excavation surveys did not reach the bottom of the artificial foundation structure. As a result of the excavation 9 m east of the N7 shrine, the natural soil layer was found at 2 m depth from the undisturbed ground level. Therefore, it is theorized that the site of the temple complex of Prasat Sambor was raised above ground level around 2 m and leveled, and the artificial foundation structure for each shrine were constructed solidly at least to this thickness. In addition, laterite blocks as part of the foundation structure were also often confirmed at collapsed brick structures in the city zone.

## 4. Identification of the causes of damage

### 4.1. State of preservation of the all brick structures in this archaeological site

To date, a total of 134 sites with 287 brick structures have been recorded in the archaeological site of Sambor Prei Kuk (Figure 1). The state of preservation is varied from relatively well preserved to the top of the original structure to entirely collapsed. The state of preservation was comprehensively investigated at all brick structures (Supplemental material 1). The state of the individual structure was classified into nine levels (Figure 5).

A1) Preserve to the top of the roof element: 13 structures

A2) Preserve to the upper half of the roof element: 18 structures

A3) Preserve to the lower half of the roof element: 3 structures

B1) Preserve to the upper half of the wall element: 13 structures

B2) Preserve to the lower half of the wall element: 16 structures

B3) Preserve to the low end of the wall element and platform: 10 structures

C1) Mound with a partial interior wall: 47 structures

C2) Mound with construction material: 157 structures

D) Scattering the construction material: 10 structures


Figure 5. Classification of the state of preservation (A1: S1 shrine in Prasat Yeai Poeun (M.24), A2: N15 shrine in Prasat Sambor (M.20), A3: N13 shrine in Prasat Sambor (M.20), B1: S6 gate in Prasat Yeai Poeun (M.24), B2: S17-1 shrine in Prasat Yeai Poeun (M.24), B3: N14-2 shrine in Prasat Sambor (M.20), C1: brick structure at M66-1, C2: brick structure at M68, D: C19-1 brick structure in Prasat Tao (M.26)).

There are 34 structures that have been preserved to the element of the roof (A1, A2, A3). Thirty-two are located in the Temple Zone, and only two are located in the Moated City Zone. There are 39 structures that have been preserved to the element of the wall (B1, B2, B3). It is possible with these structures to identify the original plan. Other structures are completely destroyed and it is difficult to estimate the original shape of structure (C1, C2, D). Within them, 47 structures partially retained the interior wall or the wall of underfloor space (C1), and 157 structures completely lost the original brickwork and are now brick mounds (C2). Among these mounds, some of them have been left with a quantity of brick material, but some have been left with only a small number of bricks. Ten sites consist of only the concentration of fallen bricks or laterite material which were elements of the foundation structure on the flatten raised ground (D). In addition, it is anticipated that other brick structures must be buried because previous archaeological excavation surveys unearthed many structures even though there were no traces of structure and scattering materials on the ground.

It is theorized that the religious function of Sambor Prei Kuk was maintained for a considerable time after the 9th century in the Angkorian period (Shimoda, Uchida, and Tsuda 2019). Therefore, the brick structures in the Temple Zone were most likely preserved in better condition than the structures in the City Zone. Nevertheless, it is unlikely that the religious significance, other than local significance, was not prolonged after the $15^{th}$ century due to the fall of the Angkor dynasty. Therefore, these brick structures were left to the tropical environment without any intervention for 500 years until this site was explored in some depth at the end of the $19^{th}$ century.

### 4.2. Preparation of the risk map

Although several structures are still preserved in relatively good condition, the deterioration of all brick structures has progressed gradually due to exposure to a harsh environment. As a result of the research on the state of preservation in the entire archaeological site, a more detailed risk map was developed for 47 seven structures which were in a reasonably well-preserved condition (A1, A2, A3, and B1 risk categories) in order to discuss the appropriate priority of the restoration work.

Through the preparation of the risk map, damaged states and elements were broadly classified into five types:

A) collapse around the door opening and vertical crack above the door opening (Figure 6);

Figure 6. Collapse around and above door opening (N11 shrine in Prasat Sambor, M.20).

B) vertical crack of wall at the middle of the wall (Figure 7) and corner of the wall (Figure 8);

C) deformation, crack, and missing corner of the wall (Figure 9);

D) detachment and missing projected decorative element (Flying Palace, pediment, pilaster) (Figure 10); and

E) collapse and fragmentation of the brickwork of the roof and base elements (Figure 11)

In addition, the risk of further collapse and damages were classified into four levels by visual examination as follows:

Level 4) Element requiring urgent measures

Level 3) Element requiring high attention

Level 2) Element requiring the monitoring

Level 1) Element where the risk is a result of expansion due to plant settlement.

As a result of this risk map a total of 257 hazardous parts were identified (Supplemental material 2). The number of Level 4 is 41 parts, Level 3 is 75 parts, Level 2 is 99 parts, and Level 1 is 42 parts (Figure 12). Many high levels of the risk element were observed around the door opening. Deterioration at the roof and base was large in number, but the number of higher risks of further collapse was relatively smaller than the other deteriorated elements. It was revealed that the

Figure 7. Vertical crack at the middle of wall (N21 shrine in Prasat Sandan, M.10).

Figure 8. Vertical crack at the corner of wall (S7 shrine in Prasat Yeai Poeun, M.24).

Figure 9. Crack at the corner of wall (N10 shrine in Prasat Sambor, M.20).

deterioration at the door openings and walls were the critical elements which will trigger further collapse.

Based on the results of this risk map, the priority of restoration work was studied, and it was concluded that the brick structure with a high number of Level 4, N1 and N11 shrines in Prasat Sambor, S8 in Prasat Yeai Poeun, and T1 in the City Zone were in urgent need of restoration work.

### 4.3. Causes of damage

It is important to determine the cause of damage in order to plan and design the appropriate intervention. Restoration work based on a misinterpretation may lead to secondary incidences. The following factors were estimated as the cause of damage:

(a) deformation of the foundation structure (uneven subsidence and horizontal deformation);
(b) thrust of corbel arch on the top of the walls;
(c) vulnerable original structure around door opening;
(d) invasion of vegetation roots into gap openings and cracks;
(e) impact of fallen trees;
(f) biological deterioration (animals, termite, micro-organism, etc.);
(g) salt weathering of brick material; and
(h) vandalism.

**Figure 10.** Detachment of the projected decorative element, Flying Palace (S8 shrine in Prasat Yeai Poeun, M.24).

**Figure 11.** Loose and fragmentation of brickwork of roof part (W shrine in Prasat Kouktroung, M.41).

The detail of each factor is described below and attempts to identify the on-going causes that affect further deterioration and collapse.

### *4.3.1. Deformation of the foundation structure*

The foundation structure may be affected by the change of the underground water level due to a clear change of rainfall between the rainy season and dry season, as well as the excess pumping for agriculture, industry, and personal hygiene. By visual evaluation most of the brick structures in this site were observed with uneven subsidence, and the change of water level and concentration of the uneven load of the structure were deducted to be the main factors of this deformation. Survey of the structural deformation was carried out at 16 selected brick structures. Two types of survey were implemented: leveling the horizontal molding decoration at base and inclination measurement of the corners of wall. The leveling at the N11 shrine was unavailable because the base was covered by collapsed brick and sedimented soil. The inclination of the wall was measured at every corner of the exterior wall, but N1 and N15 shrine were measured at the interior wall because the exterior wall was severely damaged. The value of inclination was calculated by the dimension of horizontal displacement per 3 m in the height at the corner of the wall.

Table 1 shows the result of these surveys. Figure 13 shows the results of six brick structures (N1, N7, N9, N15, S9, and S10 shrines) which represent the tendency of several deformation patterns.

Most of the structures are subsided to one direction. However, the direction of sinking is different for each shrine even though they are located in the same temple complex. This result implies that the foundation of each shrine was constructed independently even though the ground level was artificially elevated about 2 m in the entire area of precinct. Most of the structures are inclined to the same direction of the subsidence. However, some structures show a different deformation pattern (S9 and S10 shrines). In other words, the walls of every side are inclining outward.

The largest value of uneven subsidence was measured at the N7 shrine. The northeast face of the structure is

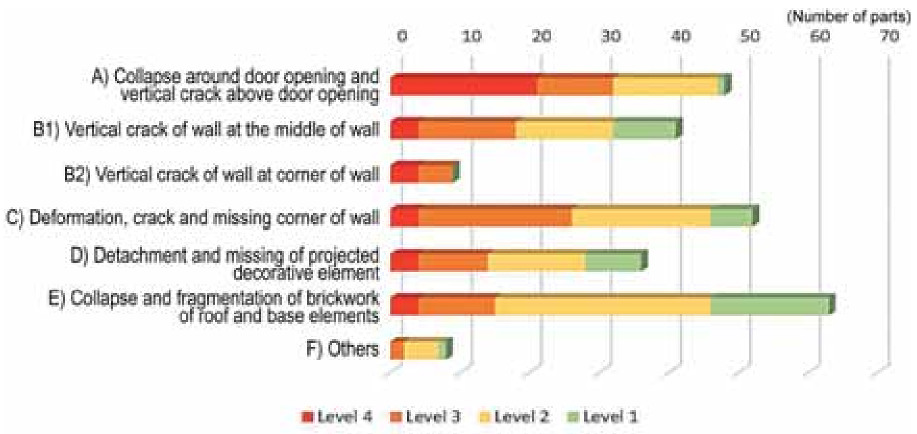


**Figure 12.** Number of deteriorated elements and risk levels, classified by deteriorated type.

the most deeply submerged at 304 mm. The sloping ratio is calculated at approximately 3% (submerged value 304 mm/width of structure 9.8 m). Each wall is also inclined to the northeast direction in conjunction with the uneven subsidence. The horizontal dimension at the largest corner is about 35 mm per meter. It means that the inclination ratio is 3.5%. Thus, the ratio of the subsidence and inclination are almost the same value at the N7 shrine. There are several small vertical cracks at the wall of this shrine. It is unlikely that these cracks were caused by uneven settlement because of the above result. Since the crack is closed at the upper part, it is predicted that these cracks have been caused by the outward deformation of the base.

N15, N9, and S9 shrines also measured largest value of uneven subsidence after N7 shrine. At two of them, S15 and N9 shrines, every wall is inclined to the same direction in conjunction with the subsidence. These structures have no vertical cracks because these structures were tilted in accordance with the subsidence.

On the other hand, at the S9 shrine, all walls are inclined outward whereas the foundation was subsided in one direction. The southwest corner which has the largest subsidence shows the largest inclination (86 mm/m), but the northeast corner which has the smallest subsidence also shows the outward inclination (42 mm/m). One of the octagonal structures S10 shrine has no observable large subsidence. However, each wall of this structure is inclined outward.

As described above, each wall at most of the octagonal structures, S7, S8, S9, S10, and S11 shrines, is commonly inclined outward, while the exceptional structure, N7 shrine, shows different deformation. The reason for these differential is not obvious, but it is presumed that the causes of the difference lies in the brick layering technique or foundation structure, and the different history of the maintenance in each temple complex.

The outward inclination of walls most likely is caused by the horizontal outward stress by the corbel arch. This deformation is observed when the vertical cracks are largely expanded at the upper part. On the other hand, the cracks which have a wider gap at the lower part or almost parallel are also observed in many structures as well. These cracks were thought to have occurred as a result of the outward deformation of the base and foundation structure. Thus, uneven subsidence of the foundation structure is not the direct cause of structural damage, however the horizontal deformation may be a critical cause of damage.

### 4.4. Thrust of the corbel arch on the top of the walls

The technique of the corbel arch is the dominant method in ancient Khmer architecture including the brick structures of Sambor Prei Kuk. The load of this roofing structure is not transmitted vertically to the wall, but part of the load is transmitted horizontally to the top of wall (Croci 1998). There are several informative studies on the structural stability of the corbel dome of historic buildings in other regions (Cavanagh and Laxton 1981; Rovero and Tonietti 2012, 2014). In order to counteract this horizontal stress, the wall was constructed considerably thick at the brick structures of Sambor Prei Kuk. Nevertheless, the thrust of the corbel roof extrudes the walls outward, and causes the vertical cracks in the brickwork of the wall. These cracks often occurred at the corners of the wall of structures with an octagonal plan, and they occur in the middle of the wall of structures with a rectangular or square plan.

As shown in Table 1, the ratio of wall thickness against the interior length is varied from 32–50% depending on the structures. But the state of condition is not always better in the structures with higher ratio of

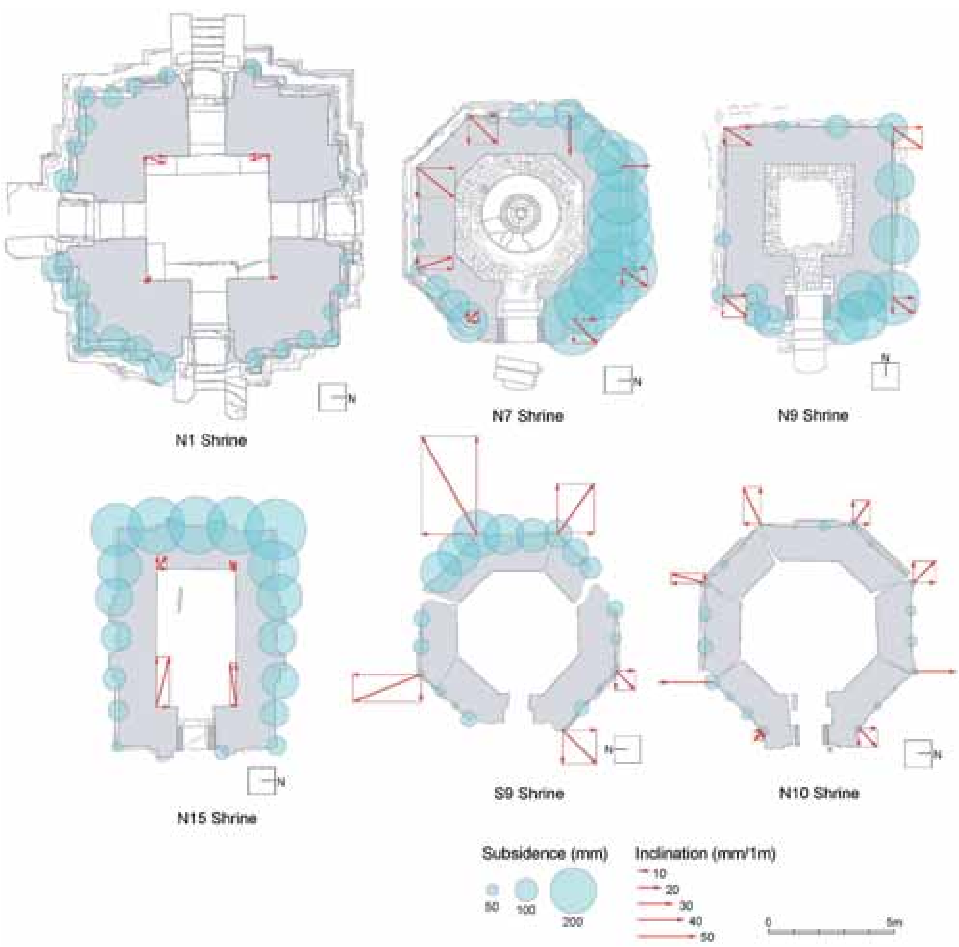


**Figure 13.** Uneven subsidence and inclination of brick structures: N1, N7, N9, N15, S9, and S10 shrines.

walls. As the square and rectangle shrines with stepped projection wall such as S1 shrine for increasing the thickness of the supporting wall as a buttress function are in better preserved condition than the shrines of flatten walls as N7 shrine (Figure 4). The projected wall plan at the middle of each side contributes to the structural stability.

As described above, the style of roof is classified into high tier type and low tier type (Figure 4). The thrust by the corbel arch of the low tier type might be larger than the structures of high tier type because the roof of lower tier type is a gentler slope. Because all octagonal shrines are low tier roof type and the thickness of the wall is relatively thin, the wall of octagonal shrines has suffered the damage of wider cracks by large inclination.

The width of these vertical cracks has not expanded since 1998 when the authors began the research at this site, and no behavior has been detected by the monitoring of the gap opening at several cracks. However, as the thrust by the load of roof accumulate for significant years, potential risk of further collapse due to the impacts of strong wind and heavy rain is highly probable.

#### *4.4.1. Vulnerable original structure around door opening*

Each shrine has a door opening in the front wall. Some shrine and gate structures have openings at two or four directions. The door opening is framed with sandstone material, and reinforced by stone beams and space for reducing the direct load to the opening (Figure 4). The number and position of stone beams and the structure around the door opening is different in each shrine. During the restoration work of N1 shrine, triangular hidden spaces were confirmed in the brickwork above the door opening. Thus, reducing the load to openings might be intended by the ancient constructors much like builders of other civilizations.

However, the openings were still one of the critical structural weakness, and extensive failures are observed at most structures. Looting of the decorative lintel above the door might also be one of the causes of collapse around the door opening. Unfortunately, most of the decorative lintel has been lost by past looting. The decorative lintel was supported by an element of projected decorative brickwork pediment above the door opening.

The partial collapse of the pediment by the looting of the decorative lintel led to the chain of collapse around the door opening. The instability around the door openings is still a significant cause of further failure today.

#### 4.4.2. Invasion of vegetation roots into gap openings and cracks

When the temples lost their religious function, vegetation growth would be quickly expanded in the precincts of the brick structures. Plants on the structure thrive in the rainy season and generally die in the dry season, but they accumulate on the structures and create an environment for further infestation. Root of these plants invade the brickwork and open and widen the joints, then rainwater carries soil into these opening gaps. Old photographs in the early 20$^{th}$ century show the severe condition by large grown trees on each structure. Although many of these trees were removed by the activities of École Française d'Extrême-Orient in the first half of the last century, some large trees remain on several structures, such as the N18, S3, and Y1 shrines.

During the restoration work at the N1 shrine, it was confirmed that several dozen layers of brickwork from the top surface of roof had lost their structural strength. Thus, even if the vegetation on the structure is removed periodically, the brickwork is fragmented to a considerable thickness and there is a loss of stability.

Plant invasion is also the significant cause of the damage at the projected decorative element such as Flying Palace and pediment. The upper surface of the projected decorative element is a good place for the plant settlements and their roots detach the projective brickwork. Fragmented brickwork reduced the stability and risk of the collapse by heavy rain and strong winds are increased.

The vegetation which survived during the dry season and especially trees and shrubs expanded the gaps caused by structural deformations. In addition, vegetation shaken by strong winds generates the occasional stress to the deeply root-infested brickwork.

#### 4.4.3. Impact of fallen trees

The temple zone is in a dense forest, and many trees stand near brick structures. It is estimated that direct hits of fallen trees and branches to the structures pose a significant risk of damages such as cracks, collapses, and deformation. In addition, vibrations caused by fallen trees near the structure may also cause damage of partial failure and fragmentation of brickwork.

In fact, currently, a part of the brickwork at N7 shrine had collapsed due to the impact of a fallen tree, and the west gate of the outer enclosure in Prasat Yeai Peoun was also collapsed by a fallen tree. In addition, several large trees fell in the precinct of Prasat Sambor with no direct hits to the remains. Thus, fallen trees are one of the most immediately dangerous factors in damaging the structures.

All trees should be diagnosed as their condition and placement, and trees that pose a risk should be removed. Tree roots have had a tremendous destructive effect on buried structures. Although tree planting programs have been implemented in the temple zone in the past, no planting should be carried out in this zone in consideration for the protection of underground remains.

#### 4.4.4. Other risks of biological activities, salt weathering and vandalism

Biological causes and salt weathering are also the possible cause of destruction. However, these effects are relatively long-term and moderate. Although there are various researches on the biological impact to stone materials at the Angkor monuments in Cambodia (Bartoli et al. 2014; Kusumi et al. 2013; Meng et al. 2016), no significant impact is observed at the bricks of Sambor Prei Kuk. Exfoliation of brick surface by salt weathering is partially observed on the interior walls of several structures as the same the brick monuments of other regions in Southeast Asia (Kuchitsu, Ishizaki, and Nishiura 2000; Siedel, Wendler, and Ullrich 2019). White crystals precipitated on the brick samples were collected from some structures, N9, S1, S7, and C1 shrines, and analyzed by a powder X-ray diffractometer and an X-ray microanalyzer. Formation of gypsum and alunite were confirmed from each sample. However, the salt weathering is also not the serious cause of the damage of these buildings for leading the structural collapse or loss of artistic value of decorative elements. The deformation by termite nesting in the cracks was pointed out by the restoration team of the brick structures in Phnom Bakheng, at the Angkor monuments (World Monuments Fund (Architectural Unit) 2012). Fortunately, this kind of phenomenon was not observed at the brick structures in Sambor Prei Kuk.

Past looting must also be considered as one of the significant causes of the destruction of structures in this site. Foundation deposits under the floor would be dug out and decorative stone elements on the wall were removed from each shrine in the past. This vandalism had a significant impact on the structures. SPK Conservation Project carried out the reconstruction work of looted holes between 2006 and 2008, and foundation stability were restored at most of structures.

Figure 14. North elevation of the Central Shrine in Prasat Sambor, before restoration.

Figure 15. North elevation of the Central Shrine in Prasat Sambor, after restoration.

## 5. Discussion on the restoration methods for stabilizing the brick structures

Based on the results of the studies on deteriorated conditions and cause, restoration methods for stabilizing the structure and consolidating the fragmented brickwork were discussed.

The following approaches are the possible ways for preserving the brick structures:

(1) installation of structural support outside the structure;
(2) insertion of reinforcement inside the original brickwork;
(3) partial dismantling and reassembling of the fragmented brickwork;
(4) consolidation and protection of the deformed brickwork; and
(5) installation of reinforcement structure with the dismantling and reconstruction.

In the 20th century, the above fifth approach of installation of reinforcement structure with dismantling and reconstruction was often adopted in the Angkor monuments. The restoration project of Prasat Kravan, brick temples of the 10th century, was the representative work of this method. Five brick shrines and the platform were almost fully dismantled, and an RC structure was installed inside the foundation and walls. The original brick material, along with new brick, were assembled on the surface of this reinforcement structure. This method was approved at the time because the most important value of this temple was thought to be the bas-reliefs on the interior wall. However, it is now difficult to adopt this method today because our understanding of the authenticity was largely revised from the past through the long discussions (Athens Charter 1931; Charter of Venice 1964; ICOMOS Charter 2003). In addition, the restoration method and policy were also developed in Cambodia after the Angkor monument was inscribed on the UNESCO World Heritage List (Angkor Charter 2012). Therefore, the other four approaches that are acceptable options today were carefully discussed and the current restoration work of the Central Shrine of Prasat Sambor was applied (Figures 14–16).

### 5.1. *Installation of structural support outside the structure*

Installation of structural support is an effective approach for stabilizing against the deformed and collapsed brickwork, in particularly around door openings and lacunas of brickwork at roof and wall. Several materials are an option for the supporting structure, such as timber, metal pipe, and new brickwork. Supporting of timber and metal pipe would be reversibility and they can be replaced or adjusted to size as needed. However, these supports very often have a negative impact to the appearance and landscape. In addition, it is necessary to solve several issues including the evaluation of the structural capacity, ways of periodical maintenance, and method for safely replacement. On the other hand, reinforcement with the additional brickwork to the missing element is more harmonizing to the original structure, while it is essential to distinguish the additional element from the original structure. Although the additional brickwork is not fundamental for the reconstruction, the form of the additional element should be studied and follow the original profile if the original form was

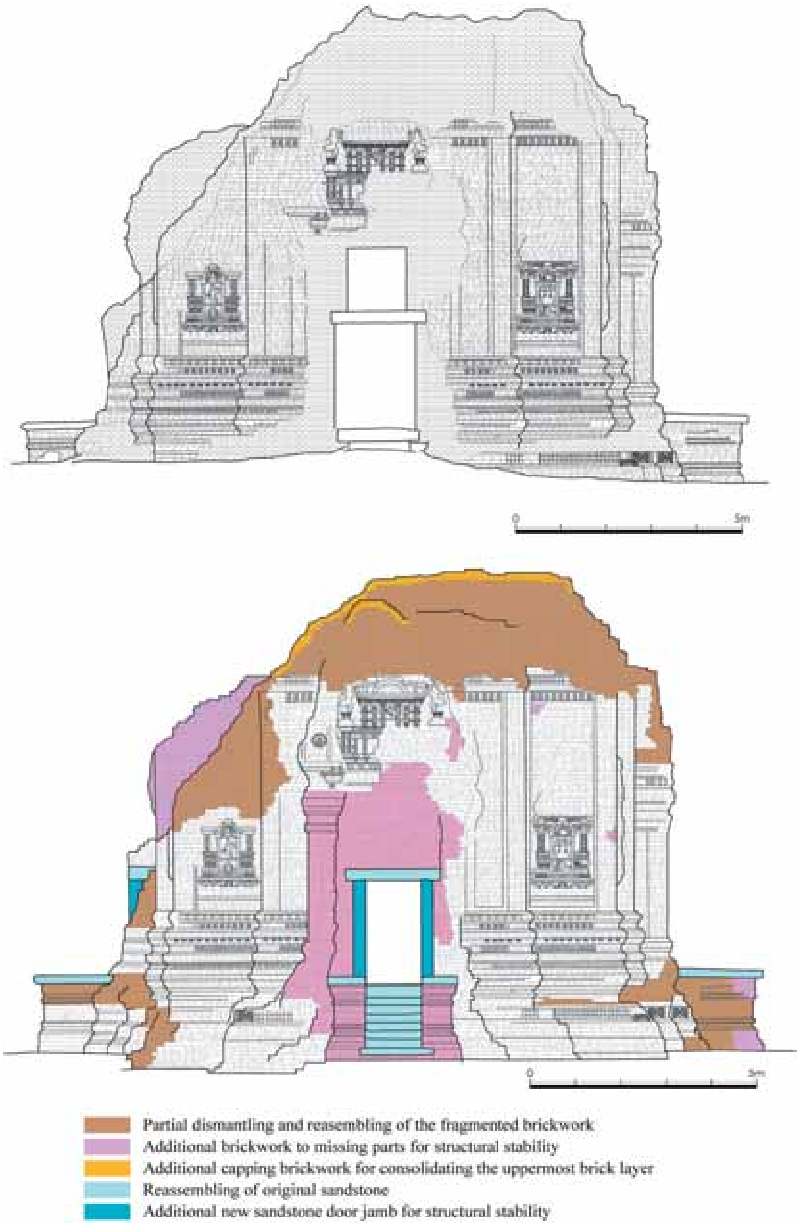


**Figure 16.** North elevation of the Central Shrine in Prasat Sambor (above: before restoration, below: after restoration).

identified. Decorative curving on the new brickwork should be engraved so as to be distinguishable from the original element.

Reinforcement of wire tying and installing diagonal support is a possible way for stabilizing inclined walls. The contact surface between the support and brick structure should be used as elastic material for absorbing the minor periodical deformation and vibration, and to ensure the considerable contact area not to concentrate the stress in a small brickwork area.

During the current restoration work of N1 shrine, the missing part of the wall around the door opening was filled by the new brick masonry, and the sandstone door frame was newly added for stabilizing the structure (Figures 15 and 16). The form and dimension of these additional parts carefully duplicated the other remaining parts, but the finishing work of additional brick and sandstone were intentionally differed from the original surface due to distinguish the preserved original brick and sandstone.

### *5.2. Insertion of reinforcement inside the original brickwork*

Insertion of the reinforcement members inside the original brickwork is another option for stabilizing deformed structures. Recently, new stabilizing methods such as inserting resin anchor or steel-rod to drilled hole in brickwork have also become popular to the restoration of brick heritage. Installation of the aramid rods in the joints of brickwork is also a familiar method for stabilizing the structure, but this method is not applicable to the brick structures in Sambor Prei Kuk due to the fact that there are no brick joints on the surface. The technique of stabilizing by the inserted steel-rod was adopted at the restoration work of brick building of Pre-Rup temple at the Angkor monuments (Santoro 1999; Santoro, Gallinaro, and Fumagalli 2000).

In the case of brick structures, it is often uncertain whether the internal reinforcement by points or linear supporting will effectively work for the stabilization of the entire structure because the size of individual brick member is too small and rigidity of a structure is low. In particular, there is a risk of additional damage between directly reinforced members and other elements in case of a structural deformation such as uneven settlement or wall leaning. In addition, due consideration is needed on the reversibility and structural authenticity because the inserted material is generally difficult to be removed and replaced. Despite several issues to be solved as above, insertion of reinforcement members inside the brickwork is an effective method that can avoid adverse impact to the appearance and landscape, and it is considered to be one of the acceptable stabilizing methods for structures under severe deformation.

### 5.3. Partial dismantling and reassembling of the fragmented brickwork

Due to the invasion of plant roots in the masonry structure for significant years, brickwork has been fragmented from the surface members. It is essential to dismantle and reassemble these fragmented brickworks for stabilizing these fragile elements. If the original position of the displaced brick materials is identified, this material should be reassembled at its original position. Even if the original position is not identified due to disturbance of the brickwork, it should be acceptable to assemble them around the original position because they were not displaced significantly. This intervention can be considered as a part of anastylosis effort of brick structure restoration.

However, reassembling of the collapsed brick materials should not be accepted in the brick structure because the identification of the original position is too difficult to determine. In particular, as many of the brick shrines in Sambor Prei Kuk are difficult to conjecture the original form because of individually different architectural design, reassembling the collapsed material is highly risky to the authenticity of design and form.

Cracks and detachment due to partial deformation is observed at the corner of walls and projected decorative elements. Partial dismantling and reassembling of these deformed brickworks is the effective method for recovering the stability. This method is widely accepted in the brick restoration in Angkor monuments such as Phnom Bakheng and Preah Ko (Fajcsak and Renner 1996; Phet 1999). Installing stainless-steel pins for connecting the deformed elements and main body of the structure and adding the stainless-steel plates at the location of load concentration are also effective ways for long-term stabilization.

During the current restoration work of N1 shrine, fragmented brickworks on the upper layers of the remaining wall, corners of wall, and platform were partially dismantled and reassembled them for preventing further failures (Figures 15 and 16).

### 5.4. Consolidation and protection of the deformed brickwork

Preventive measure of plant infestation is essential for brick structures in a tropical climate. If it is difficult to eliminate the deformation by partial dismantling and reassembling, gaps of the brick joint and crack should be grouted or filled for preventing the invasion of vegetation. Appropriate filling material and techniques should be developed according to the size of the gap opening. Currently, three types of mortar are used at the restoration sites in Sambor Prei Kuk depending on the size of the filling gap openings: 5 mm or less, between 5 mm and 2 cm, and 2 cm or more. All of these injection or filling mortars are mixed of slaked lime, sand, brick powder, and water, and their proportion and grain size of sand and brick powder are adjusted for each mortar. Although it is effective to fill the large crack by brickwork and mortar, it should be distinguishable from the original brickwork.

To prevent the settlement of vegetation on the upper surface of the brick remains, adding a few layers of new brick is an effective acceptable method. In this case brick should be carefully placed in order to drain the rainwater smoothly. High duration and strength mortar is recommended to use for this brickwork. Newly added brick layers shall be distinguished from the original bricks and limited to a minimum volume. These kinds of capping brick layers were added on the reconstructed parts on the top of the wall or roof during the current restoration work of the N1 shrine (Figures 15 and 16).

New brick materials were used for the additional layers due to distinguishing the original brickworks.

## 6. Conclusion and further challenges

This article presents the results of a series of research on the preservation of the brick structures in the archaeological site of Sambor Prei Kuk. Based on the comprehensive study on the remaining condition of all brick structures, those structures that are in a well-preserved state and deemed of significant historical value were selected for the further studies. Subsequently, the risk map of selected structures was created for identifying the deteriorated condition and their causes to determine the priority of intervention. The main causes of further damage identified several factors: vulnerable original structure around door opening and corbel arch roofing; brickwork fragmentation by vegetation settlement; and impact of fallen trees. In addition, it was confirmed that the outward horizontal deformation of the base and foundation was a cause of structural damage at several structures, while the uneven subsidence was not a main cause because the upper structure was inclined in conjunction with the foundation subsidence.

Daily maintenance including the periodical removal of vegetation is indispensable to preserve the brick structures in a tropical environment where rapid vegetation growth is prevalent. However, the brickworks on which vegetation settled is weakened even after the removal of vegetation. Additionally, the brickworks with deformation and around collapsed elements have ineluctable risk of further deterioration. These fragile and unstable elements are at high risk of further damage by heavy rain, strong winds, and the impact of fallen trees. Therefore, appropriate interventions including consolidation and stabilization are required in addition to daily maintenance.

As a result of discussing the restoration method to enhance structural stability, it was determined that four approaches were effective and acceptable from the viewpoints of authenticity including form, material and structure for brick structures at Sambor Prei Kuk: (1) installation of structural support outside the structure; (2) insertion of reinforcement inside the original brickwork; (3) partial dismantling and reassembling of the fragmented brickwork; and (4) consolidation and protection of the deformed brickwork.

However, many issues still need to be considered for designing the comprehensive guidelines for restoration work of the brick structures in this site. The choice between external supports or inserting the reinforcement members inside brickwork is one of the issues. For large-scale deformations such as wall inclination and large collapse, installation of external supports will not reinforce them effectively and have a negative impact on the appearance and landscape. On the other hand, internal reinforcement is not easily reversible and requires a high level of design, technique, and verification as to the effect on the entire structure including foundation. A guideline for selecting alternative methods based on the damaged elements and condition is required.

Another issue is on the adding new brickwork in the lacuna for support and reinforcement of the structure. Although the main purpose of this approach is not reconstruction but to stabilize the structure, the form of the additional brickwork is always a critical point. If the element of additional brickwork enlarges, the authenticity of its form is a severe issue. The method of stabilizing by additional brickwork should be adopted only in the cases where the brickwork support is of an advantage over other materials and additional element will not lead to a misunderstanding of the form of architecture.

Scale of the dismantling and reassembling of deformed structures is also an issue to be defined clearly. The dismantling area should not exceed the considerable scale of brickwork. This method might be accepted if partial brickwork such as a corner of the wall and detached decorative element exist.

Countermeasures against settled vegetation on the structures is also a difficult issue. It is generally obvious that vegetation on and around the structures are one of the significant adverse effects. However, removing trees that have already grown with their roots invading deeply in brickwork is technically difficult. In addition, it is also necessary to evaluate the landscape of this archaeological site where monuments and nature are harmonized. The name of Sambor Prei Kuk means "shrines standing in forest" in Khmer. In other words, harmonious landscape and culture gives an important sense of place for local people. For visitors, monuments in a deep forest is the attractive visual image of this archaeological site. Thus, possible countermeasures to settled grown trees is limited to cut their branches for reducing the growth and minimizing the effect on the brick structures by strong winds.

SPK Conservation Project carried out the restoration work at the brick structure, N1 shrine, to date. Based on the monitoring of this structure after restoration work and further discussion on the above issues, standardized restoration methods should be established for the brick structures in the Sambor Prei Kuk. This challenge will contribute to the creation of a specific but flexible set of guidelines for brick restoration in tropical climates.

## Acknowledgments

The authors are grateful to all concerned experts and institutes for the conservation activities of the Sambor Prei Kuk, in particular to the Director of the Department of Culture and Fine Arts in Kampong Thom province, Mr. Hin Sophoarn, and the Director General of the National Authority for Sambor Prei Kuk, Mr. Phann Nady. In addition, we would like to express the deepest appreciation to the long-term supports to this restoration projects from The Sumitomo Foundation and Foundation for Cultural Heritage and Art Research.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Funding

This work was supported by the JSPS KAKENHI [17H01628,24686068]; Foundation for Cultural Heritage and Art Research; Sumitomo Foundation.

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