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Using Magnetic Susceptibilities of the Sandstone Blocks to Determine the Construction Period of the Revetment of the Surrounding Moat of the Angkor Wat Temple, Cambodia

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Abstract

In the Angkor monument located in Siem Reap Province, Cambodia, temples surrounded by moats are commonly seen. However, examples of surrounding moats protected with stone blocks such as sandstone (gray to yellowish-brown sandstone) and laterite are not common. The surrounding moat of the Angkor Wat temple, representing the Angkor monument, is one of the few temples surrounded by a moat revetted with sandstone and laterite blocks. The Angkor Wat temple is the pinnacle of the Khmer architecture, and was founded by King Suryavarman II in the first half of the 12th century. Sandstone and laterite blocks were mainly used in its construction. The Angkor Wat temple is surrounded by a moat 1.5 km long E-W, 1.3 km long N-S, and 190 m wide. Magnetic susceptibility measurements were carried out on the sandstone blocks that make up the revetment to clarify its construction period. The mean magnetic susceptibilities of the sandstone blocks at each area of the structures inside the surrounding moat are relatively high, ranging from 3.1 to 4.0 × 10^{-3} SI units. In contrast, the mean magnetic susceptibilities of the sandstone blocks at each area of the revetment of the surrounding moat, except for the central part of the revetment of the western surrounding moat, are lower, ranging from 2.0 to 2.9 × 10^{-3} SI units. These magnetic susceptibility values correspond to those of the sandstone blocks used in the early Bayon-style period, indicating that the moat revetment was likely constructed during this period (the late 12th century to the early 13th century), slightly later than the structures inside the surrounding moat. There is a clear discontinuity between the central part of the moat revetment on the west side and the rest of the revetment, and much of the latter has collapsed. Judging from the degree of collapse and the clear boundary between the two, the latter is presumed to have been built later than the former. Considering the limited number of the sandstone blocks still present along the inner side of the surrounding moat and the lack of stepped structures, revetment may not have been undertaken on the inner side of the surrounding moat of the Angkor Wat temple except for the central part in the western side.

Keywords

Angkor Wat Temple, Gray to Yellowish-Brown Sandstone, Magnetic Susceptibility, Revetment of Surrounding Moat, Construction Period

1. Introduction

The Angkor monument, located in Siem Reap Province, Cambodia, comprises temple complexes built by the Khmer people from the 9th to the 15th centuries. The Angkor monument is registered on UNESCO's World Heritage List and comprises nearly 50 major temples. Among them, the Angkor Wat temple, constructed by King Suryavarman II (1113-1150 CE), is representative of the complex and can be considered the pinnacle of the Angkor period in its elaborateness and size.

In the Sambor Prei Kuk monument, the capital city of Ishanapura built before 802 CE during the pre-Angkor period (the 6th to 8th centuries), most temples are constructed with bricks (e.g., Shimoda and Shimamoto, 2012). In the early Angkor period (the 9th century), a capital city (Mahendraparvata) was built on the summit of Kulen Mountain (Phnom Kulen), and the temples in this capital city were primarily made of bricks (e.g., Chevance et al., 2019). Subsequently, the capital city was relocated to Hariharalaya (the late 9th century), where the Roluos monument is located. Here, in addition to bricks, sandstone and laterite blocks started to be used. Later, the capital city was moved to the Angkor area (the late 9th century), where sandstone, laterite, and brick blocks became the primary building materials (Uchida et al., 1999).

The sandstone used for the Angkor monument is a fine- to medium-grained feldspathic arenite quarried from the Phu Kradung Formation of the Jurassic to Cretaceous periods, which forms part of the Khorat Group (Meesook et al., 2002). The feldspathic arenite used at the Angkor monument is referred to as gray to yellowish-brown sandstone because of its color (Uchida et al., 1999).

Quarries of the gray to yellowish-brown sandstone remain on southeastern foothills of Kulen Mountain (Garnier, 1873; Delaporte, 1880; Delvert, 1963; Boulbet, 1979; Carò and Im, 2012; Uchida and Shimoda, 2013; Evans, 2016; Uchida et al., 2020). Constituent materials of this sandstone are quartz, plagioclase, potassium feldspar, biotite, muscovite, and rock fragments, with small amount of chlorite, zircon, calcite, garnet, and magnetite (Uchida et al., 1998). Calcite is a secondary mineral and is thought to have been formed during the alteration process of the sandstone. Chlorite is also thought to have been formed by the alteration of biotite, which also produced the goethite responsible for the yellowish-brown color of the sandstone (Uchida et al., 1998). The chemical composition of the garnet is close to that of almandine, containing up to 40 mol.% spessartine. Based on the chemical composition of the garnet, the source rock of the gray to yellowish-brown sandstone is inferred mainly to be metamorphic rocks of upper amphibolite to granulite facies (Uchida et al., 1998). There are no differences in constituent minerals of the sandstone among the temples. In addition, no difference in chemical composition of the sandstone, including minor elements, was found among the temples (Uchida et al., 1998). Because no differences were found in the gray to yellowish-brown sandstone used for each temple, it is impossible to distinguish the construction period and construction sequence of the temple based on the gray to yellowish-brown sandstone.

However, systematic differences in magnetic susceptibility of the gray to yellowish-brown sandstone blocks related to the construction period have been recognized; thereby, differences in the construction periods and construction order of the temples could be deduced using these measurements (Uchida et al., 2003, 2007). Differences in the magnetic susceptibilities of sandstone blocks are mainly attributable to magnetite. Although magnetite is a minor constituent mineral of the sandstone, it has extremely strong magnetic susceptibility. Unlike other constituent minerals, magnetite has a relatively high specific gravity. The specific gravity of magnetite is 5.2, while that of major constituent minerals such as plagioclase, potassium feldspar, quartz, biotite, and muscovite are in the range of 2.7 - 3.3. The differences in specific gravity may have caused differences in the degree of magnetite concentration during the sedimentation process in rivers and streams, resulting in differences in the magnetic susceptibility despite a lack of differences in mineral or chemical composition. In addition, differences in sandstone supply sources may also contribute to differences in magnetic susceptibility. Uchida et al. (2003, 2007) used the magnetic susceptibility of the gray to yellowish-brown sandstone to estimate the construction sequence and construction date of each temple at the Angkor monument, and identified the quarrying sites of the sandstone blocks (Uchida and Shimoda, 2013; Uchida et al., 2020). Thus, using magnetic susceptibility measurements of the sandstone blocks was a breakthrough in the understanding of the construction period and construction order of the Angkor monument.

The gray to yellowish-brown sandstone blocks were major construction materials in the Angkor Wat temple (**Figure 1(a)**), in addition to the laterite blocks. Laterite blocks are often used for surfaces and interiors of platforms, surrounding walls, approaches, bridges, and other structures. Sandstone blocks tend to be used in important parts of the Angkor monument instead of laterite blocks.

Figure 1. Photographs of the Angkor Wat temple. (a) The main structure inside the surrounding wall of the Angkor Wat temple, (b) the central part of the outer revetment of the western surrounding moat built of the gray to yellowish-brown sandstone blocks (the upper part) and laterite blocks (the lower part), (c) the central part of the inner revetment of the western surrounding moat built of the gray to yellowish-brown sandstone blocks (the upper part) and laterite blocks (the lower part), and (d) the northwestern corner of the outer revetment of the surrounding moat in better preserved condition than elsewhere.

The Angkor Wat temple was constructed mainly from gray to yellowish-brown sandstone blocks that are characteristically larger than those used in other temples, and have less color variation with less pronounced bedding. The magnetic susceptibility of the sandstone blocks in the Angkor Wat temple varies little, with mean magnetic susceptibilities for the 50 sandstone blocks at each area ranging from 3.1 to 4.0×10^{-3} SI units (Uchida et al., 2007). The mean value of the magnetic susceptibility for all the buildings within the surrounding moat is 3.49×10^{-3} SI units.

Within the Angkor monument, many temples surrounded by moats exist, such as the Preah Ko, Bakong, Chau Srei Vibol, Angkor Wat, Beng Mealea, Angkor Thom, Preah Khan, and Ta Prohm temples. In many of these temples, the surrounding moats are not protected by stone blocks, but by laterite blocks in the Preah Ko temple or by sandstone blocks in the Angkor Wat temple. The use of valuable sandstone in the revetment of the surrounding moat demonstrates the significance of the Angkor Wat temple as a crucial temple. The Angkor Wat temple is a pyramid-shaped temple, representing Mount Meru, the sacred mountain where the gods reside. The moat surrounding it symbolizes the sea, and the Angkor Wat temple represents ancient India worldview as a whole.

Uchida et al. (2007) measured the magnetic susceptibility of the gray to yellowish-brown sandstone used for the construction of the gopuras of the surrounding enclosure in the Angkor Wat temple, as well as the structures inside it. The central sanctuary (tower) has a height of 65 m and is surrounded by three tiers of galleries: the inner, middle, and outer galleries. The outer gallery measures 200 m east to west and 180 m north to south.

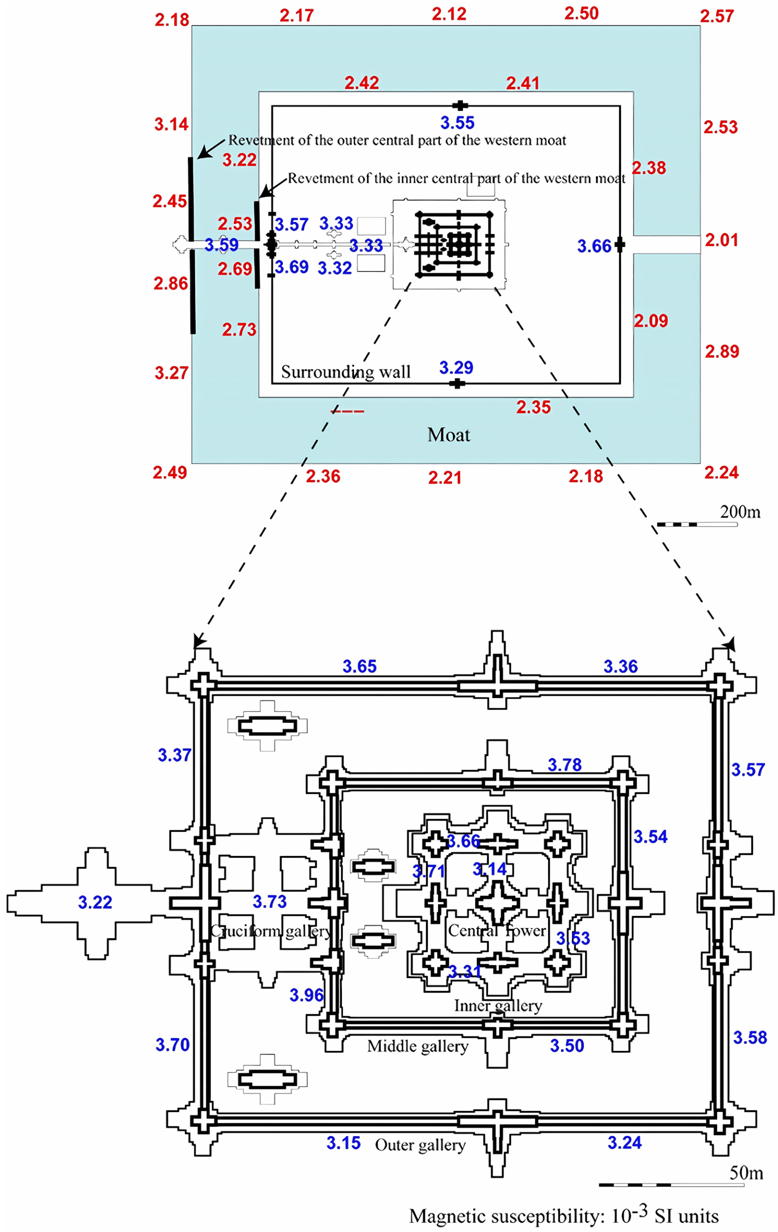

Figure 2. Map of the Angkor Wat temple showing the distribution of the mean magnetic susceptibilities of the 50 gray to yellowish-brown sandstone blocks at each area in the revetment of the surrounding moat, gopuras of the surrounding wall, libraries, causeways (top), and central structures (bottom) inside the surrounding moat.

However, the magnetic susceptibility of the gray to yellowish-brown sandstone blocks used for the revetment of the surrounding moat, which is 1.5 km long from east to west, 1.3 km long from north to south, and 190 m wide (Figure 2), has not been investigated. Therefore, we measured the magnetic susceptibility of the sandstone blocks used for the revetment of the surrounding moat and sought to establish its construction period in this study. No study has existed to verify whether the main structures of the Angkor Wat temple and the surrounding moat were built at the same time. Therefore, the purpose of this study is to verify whether or not the surrounding moat was constructed at the same time as the main structures of the huge Angkor Wat temple by measuring the magnetic susceptibility of the sandstone blocks used for the revetment of the surrounding moat.

Originally, water was drawn into the surrounding moat of the Angkor Wat temple from a canal leading to the Siem Reap River near the northeastern corner (Figure 3(a)). However, today, water is drawn from the surrounding moat of Angkor Thom, which is located approximately 0.9 km north of the surrounding moat of the Angkor Wat temple, near the northwestern corner (Figure 3(b)); this change could be because of a drop in the water level of the Siem Reap River. In contrast, drainage is conducted from the southeastern corner of the surrounding moat (Figure 3(c)). In this way, the water in the surrounding moat of the Angkor Wat temple was originally supplied from the northeastern corner and drained from the southwestern corner, utilizing the natural gradient from the Kulen Mountain, located approximately 35 kilometers northeast of the Angkor monument, toward the Tonle Sap Lake located to the southwest.

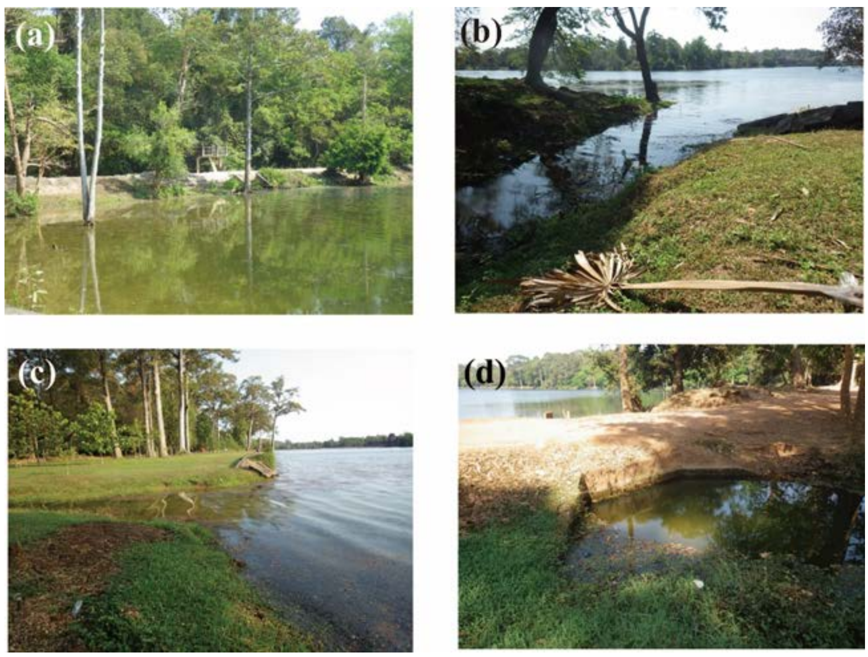

Figure 3. Photographs showing the water inlet and outlet for the surrounding moat of the Angkor Wat temple. (a) Water inlet from the Siem Reap River at the time of initial construction; (b) current water inlet from the surrounding moat of Angkor Thom, located 0.9 km north of the surrounding moat of the Angkor Wat temple; (c) drainage outlet located in the southwest corner of the surrounding moat; and (d) a waterway connecting the northern and southern surrounding moats in the eastern side.

Unlike many other temples, the Angkor Wat temple was built facing west. A main approach was built across the surrounding moat in the center of the western side of the moat, and the water of the surrounding moat is divided by this approach. While the build quality is inferior to that of the main approach on the western side, an approach was also constructed on the eastern side of the surrounding moat, beneath which lies a waterway connecting the northern and southern surrounding moats (**Figure 3(d)**). Water flows from the northern surrounding moat to the southern surrounding moat.

2. Methods

To measure the magnetic susceptibility of the gray to yellowish-brown sandstone blocks, a portable magnetic susceptibility meter SM30 (ZH Instruments, Brno, Czech Republic) was used. For details on the principle and usefulness of magnetic susceptibility measurements, refer to Williams-Thorpe and Thorpe (1993) and Williams-Thorpe et al. (1996, 2000). The magnetic susceptibility measurement was conducted in situ and non-destructively. The measurement surface of the magnetic susceptibility meter has a size of 5 cm circle. Based on the user's manual for the magnetic susceptibility meter SM-30, a thickness of 10 cm accounts for 99.07% of the true value. Since magnetic susceptibility measurements were performed on sandstone blocks over 10 cm thick, we believe that a correction for the thickness of the sandstone blocks is unnecessary. The sandstone blocks of the Angkor Wat temple are larger than those of other temples, generally approximately 60 - 65 cm wide, 45 - 50 cm thick, and over 100 cm long. Magnetic susceptibility was measured exclusively on flat and non-deteriorated surfaces. The magnetic susceptibility measurement was first performed on the sandstone block surface and then in air (mode A); therefore, the measured values are the magnetic susceptibilities relative to air. The time required to measure the magnetic susceptibility at a single point is only a few seconds, and the measurement accuracy is high, approximately 0.001×10^{-3} SI units. In the gray to yellowish-brown sandstone blocks used for the construction of the Angkor monument, the magnetic susceptibility significantly varies with the measurement location; therefore, magnetic susceptibility measurements were taken at one point on 50 randomly selected sandstone blocks at each area, and the mean value was determined. The magnetic susceptibility measurements were taken at 17 areas along the outer revetment of the surrounding moat (**Figure 1(b)**) and at 9 areas along the inner revetment of the surrounding moat (**Figure 1(c)**).

3. Results

The detailed data of magnetic susceptibility measurements for the gray to yellowish-brown sandstone blocks used as revetment in each area of the surrounding moat of the Angkor Wat temple are summarized here:
10.13140/RG.2.2.29317.26088. There was a limited number of sandstone blocks remaining on the inner revetment of the surrounding moat, and they were not observed in the western part of the south side of the surrounding moat. **Figure 2**

(top) shows the mean magnetic susceptibility of the gray to yellowish-brown sandstone blocks at each area in the revetments of the surrounding moat, and the measured values range from 2.0 to 3.3 × 10^{-3} SI units. Conversely, the mean magnetic susceptibilities of the sandstone blocks at each area in the structures inside the surrounding moat (**Figure 2**; bottom) are higher, ranging from 3.1 to 4.0 × 10^{-3} SI units (Uchida et al., 2007).

The revetment in central part of the western surrounding moat (outer revetment with a length of 450 m, and inner revetment with a length of 225 m) has many steps. The southern revetment of the outer central part of the western surrounding moat (**Figure 2**) consists of seven layers of sandstone blocks at the top and three layers of laterite blocks below (**Figure 1(b)**). However, the northernmost part of the southern central revetment, which is approximately 9 m long, has the same structure as the northern central revetment. The northern revetment of the outer central part of the western surrounding moat (**Figure 2**) consists of four layers of sandstone blocks at the top and six layers of laterite blocks below. The thickness of the top layer of stone blocks is approximately 50 cm and the thickness of lower layers built of sandstone blocks and laterite blocks is approximately 30 cm. The revetment in the inner central part of the western surrounding moat consists of five layers of sandstone blocks at the top and five or six layers of laterite blocks below (**Figure 1(c)**). The thickness of the sandstone blocks in the top layer is approximately 42 cm, and the thickness of the other layers is approximately 30 cm. Most of the revetment has collapsed except for the outer central part of the western surrounding moat, but the presence of four steps of sandstone blocks on two steps of laterite blocks below have been confirmed. In the well-preserved outer northwest corner (**Figure 1(d)**), the thickness of the stone blocks is approximately 48 cm in the topmost sandstone blocks, and elsewhere the thickness is approximately 22 cm.

Apart from along the inner central part of the western surrounding moat, no steps are present, and the number of the remaining sandstone blocks of the moat revetment is extremely small. In the revetment on the inner side of the surrounding moat, only sandstone blocks are observed, and not a single laterite block has been found. One possible reason for this is that the sandstone blocks of the inner revetment were reused during the restoration of the Angkor Wat temple. In any case, it is speculated that the inner revetment of the surrounding moat was likely not in a stepped form.

Figure 4(a) is a histogram of the magnetic susceptibilities of the gray to yellowish-brown sandstone blocks at the Angkor Wat temple, excluding the moat revetments. The histograms of the magnetic susceptibilities of the sandstone blocks in the outer and inner revetments of the surrounding moat are shown in **Figure 4(b)** and **Figure 4(c)**, respectively. The shape of the histogram for the magnetic susceptibility of the sandstone blocks for the buildings inside of the surrounding moat is clearly different from that of the revetment of the surrounding moat. In contrast, the shape of the histogram for the sandstone blocks in the inner revetment of the surrounding moat is almost identical to that of the blocks in the outer revetment of the surrounding moat.

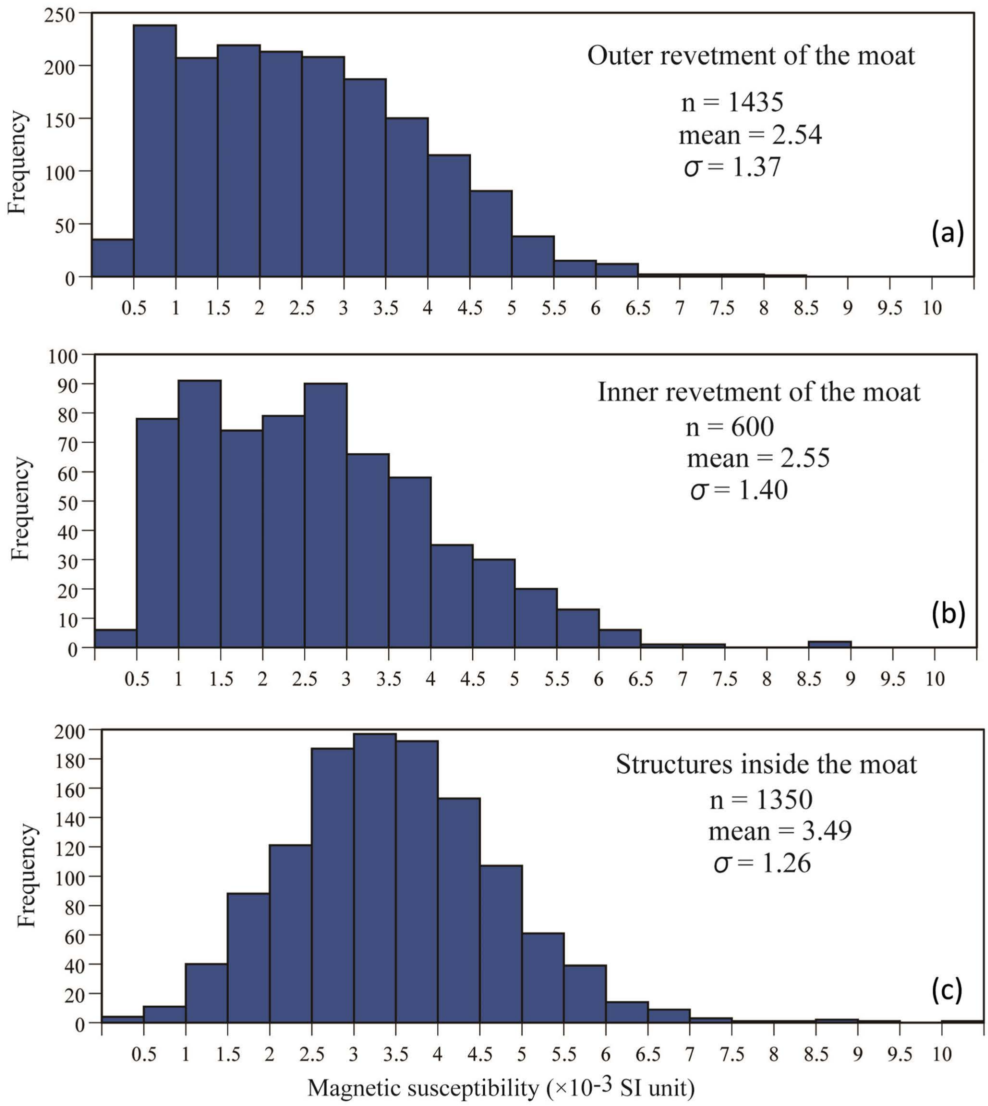

Figure 4. Histograms of the magnetic susceptibilities of the gray to yellowish-brown sandstone blocks in the outer (a) and inner (b) revetments of the surrounding moat, and central structures, gopuras of the surrounding wall, libraries, and causeways (c) inside the surrounding moat at the Angkor Wat temple.

We examined the junction between the revetment in the central part of the western surrounding moat and its surroundings with the aim of elucidating the differences in their construction periods. As a result, as shown in the photographs in Figure 5, while some sections of the revetment in the central part of the western side have been repaired, the junction with other sections is clear. Additionally, many parts of the revetment outside the central part of the western surrounding moat have collapsed. This indicates that the revetment in the central part of the western surrounding moat was likely constructed at approximately the same time as the structures inside the surrounding moat. In contrast, the remaining sections were likely constructed at a later period than the structures inside the surrounding moat and the revetment in the central part of the western side of the surrounding moat.

Figure 5. Photographs of the central revetment of the western surrounding moat at the Angkor Wat temple, showing the end faces of the western central part of the revetment of the surrounding moat built of the gray to yellowish-brown sandstone blocks. There is a clear boundary between the outer and inner revetment in the central part of the western surrounding moat and the rest of the revetment.

4. Discussion

The histograms of the magnetic susceptibilities of the gray to yellowish-brown sandstone blocks used for the outer and inner revetments of the surrounding moat at the Angkor Wat temple exhibit a very similar shape to each other (mean magnetic susceptibility and σ for the outer and inner revetments: 2.54×10^{-3} SI units and 1.37×10^{-3} SI units, and 2.55×10^{-3} SI units and 1.40×10^{-3} SI units, respectively) (Figure 4). However, the magnetic susceptibilities of the gray to yellowish-brown sandstone blocks used for the revetments are clearly lower than those of the sandstone blocks used for the construction of the structures inside the surrounding moat (mean magnetic susceptibility and σ for the structures inside the surrounding moat: 3.49×10^{-3} SI units and 1.26×10^{-3} SI units). The above result is supported by the box plot diagrams in Figure 6, which also include mean values and standard deviations (σ and 2σ). A two-sample t-test was conducted to determine if there was a significant difference in the mean magnetic susceptibilities of the sandstone blocks (Table 1). The p-value for the sandstone blocks used in the outer and inner revetments was 0.41, which is larger than 0.05. Therefore, it was concluded that there was no significant difference in their mean values. In contrast, very small p-values were obtained for the sandstone blocks in the outer revetment and the structures inside the surrounding moat and for those in the inner revetment and the structures inside the surrounding moat, 9.78×10^{-79} and 1.53×10^{-42}, respectively. Therefore, it can be concluded that there is a significant difference in their mean values.

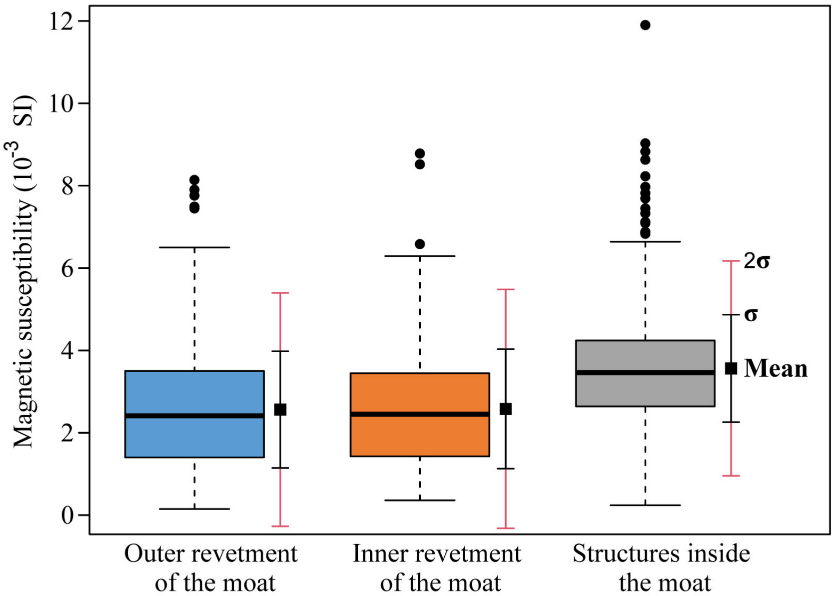

Figure 6. Box plot diagrams of the magnetic susceptibilities of the gray to yellowish-brown sandstone blocks in the outer and inner revetments of the surrounding moat and the buildings inside the surrounding moat at the Angkor Wat temple, accompanied with σ and 2σ standard deviations.

Table 1. Results of two sample t-test assuming unequal variances for sandstone magnetic susceptibilities (10^{-3} SI unit) in the Angkor Wat temple.

	Outer revetment of the moat	Inner revetment of the moat	Outer revetment of the moat	Structures inside the moat	Inner revetment of the moat	Structures inside the moat
Mean	2.54	2.55	2.54	3.50	2.55	3.50
Variance	1.87	1.96	1.87	1.59	1.96	1.59
Observations	1425	600	1425	1350	600	1350
Hypothesized mean	0		0		0	
Degree of freedom	1102		2771		1047	
t-value	−0.24		−19.36		−14.25	
p-value	0.41		9.78E−79		1.53E−42	

Uchida et al. (2003, 2007) divided the Angkor period into thirteen stages (Stages

I - III, IVa, IVb, V, VIa - VId, VII, VIIIa, and VIIIb) based on the magnetic susceptibility of the gray to yellowish-brown sandstone blocks. The mean magnetic susceptibilities of the sandstone blocks used for the outer and inner revetments of the surrounding moat are 2.55×10^{-3} SI units and 2.54×10^{-3} SI units, respectively, and the value for the structures inside the surrounding moat is 3.49×10^{-3} SI units. According to Uchida et al. (2003), the gray to yellowish-brown sandstone blocks showing mean magnetic susceptibilities ranging 2.0 - 2.9×10^{-3} SI units were used in each structure constructed in the early Bayon-style period (Stages VIa - VId), immediately after the main Angkor Wat-style period (Stage V). The magnetic susceptibilities of the gray to yellowish-brown sandstone blocks used for the revetments of the surrounding moat are nearly the same as those of the gray to yellowish-brown sandstone structures constructed in the early Bayon-style period. Consequently, it can be inferred that the moat revetment work was undertaken slightly later (the early Bayon-style period; Stages VIa - VId) than work on the structures (Stage V) inside the surrounding moat. However, this conclusion does not necessarily mean that the surrounding moat of the Angkor Wat temple itself was dug in the early Bayon-style period. Rather, the gray to yellowish-brown sandstone blocks with higher magnetic susceptibilities used in the western approach built over the surrounding moat suggests that the surrounding moat had already been dug when the western approach was constructed.

The central revetment on the western surrounding moat is well constructed (**Figure 2**), and there is a clear boundary between the central revetment and the rest of the revetment. From these facts, it can be inferred that the central revetment was completed first, and the revetments in the other parts were built later than the central revetment. Most of the revetment of the surrounding moat, excluding the western central part, was poorly constructed and severely collapsed. From these facts, it can be inferred that the revetment, excluding the western central part, was built in a later period than the western central part.

The Angkor Wat temple is one of the few temples in the Angkor monument where the surrounding moat is protected by a stone block revetment. The Angkor Wat temple is the only temple in the Angkor monument that uses precious sandstone blocks, which were transported from approximately 30 km away from the Angkor monument, for the revetment of the surrounding moat. In addition to this, the quality of the construction of many parts of the revetment of the surrounding moat is crude compared to the structures inside the surrounding moat. These facts, together with the difference in the magnetic susceptibility of the sandstone blocks, confirm that the revetments of the surrounding moat were built later than the structures inside the surrounding moat.

5. Conclusion

1) The Angkor Wat temple is surrounded by a moat, with the upper part of its revetment built of gray to yellowish-brown sandstone blocks and the lower part built of laterite blocks. Among the structures at the Angkor monument, only the

Angkor Wat temple used a large amount of precious gray to yellowish-brown sandstone blocks for the revetment of its surrounding moat, which indicates the importance of the Angkor Wat temple.

2) The outer revetment in the central part of the western moat consists of a total of 10 tiers of sandstone blocks (upper section) and laterite blocks (lower section). However, the rest of the outer revetment consists of a total of 6 tiers of sandstone blocks (upper section) and laterite blocks (lower section), and this part has collapsed significantly. The inner revetment in the central part of the western moat is composed of a total of 10 or 11 tiers of sandstone blocks (upper section) and laterite blocks (lower section). However, elsewhere, there are few sandstone blocks remaining, and none of them are tiered.

3) The magnetic susceptibility of the gray to yellowish-brown sandstone blocks used for the structures inside the surrounding moat is high, whereas the magnetic susceptibility of the sandstone blocks used for the revetments of the surrounding moat is low, suggesting that the latter could have been constructed in the early Bayon-style period (Stages VIa - VId).

4) There is a clear boundary between the outer and inner revetment in the central part of the western surrounding moat and the rest of the revetment, and judging from the degree of collapse and the clear boundary between the two, the latter is presumed to have been built later than the former.

5) The scarcity of gray to yellowish-brown sandstone blocks remaining on the inner side of the surrounding moat and the absence of stepped structures suggests that revetment was not carried out on the inner side of the surrounding moat at the Angkor Wat temple except for the central part of the western surrounding moat.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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