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Non-Destructive Investigation Methods for Stone Materials at Angkor Monument

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Abstract: *The Angkor monument in Cambodia was constructed between the 9th and 15th centuries, and consists of a group of masonry structures. The monument was inscribed on the UNESCO World Heritage List in 1992. While bricks were used in some of the older temples, most of the temples in the Angkor monument were built using sandstone and laterite. Since its construction, the site has undergone structural collapses and material deterioration owing to various factors. This study primarily focused on sandstone and examined the following non-destructive investigation methods related to stone deterioration: (1) visual inspection using a percussion rod, (2) measurement of rebound value, (3) measurement of P-wave velocity, (4) measurement of magnetic susceptibility, (5) surface temperature measurement using a thermal infrared camera, (6) crack investigation using a ground-penetrating radar, (7) measurement of moisture content, and (8) chemical composition analysis using a portable X-ray fluorescence (pXRF) analyzer.*

Keywords: Non-destructive investigation methods; Angkor monument; Sandstone; UNESCO World Heritage; Cambodia

1. INTRODUCTION

The Angkor monument was inscribed on the UNESCO World Heritage List in 1992. It consists of a group of Hindu and Buddhist temples constructed by the Khmer people—modern-day Cambodians—between the 9th and 15th centuries. The site was later occupied by the neighboring Ayutthaya Kingdom and, except for a few temples, was abandoned to the forces of nature, resulting in the collapse of structures and the deterioration of stone materials. In the early 20th century, restoration work was initiated by the École française d'Extrême-Orient (EFEO). In recent years, restoration efforts have involved teams from Japan, Germany, India, China, the United States, South Korea, Italy, and other countries. In 1994, the Japanese government organized the Japanese Government Team for Safeguarding Angkor (JSA), which has since carried out restoration work at Angkor Wat temple, Prasat Suor Prat, and Bayon temple. As a member of the JSA, the author has studied the stone and brick materials used in the Angkor monument [1–2], and investigated their deterioration [3–4]. Because the Angkor monument is a valuable cultural heritage site, non-destructive investigation methods are employed as a fundamental principle in all research activities. Accordingly, this paper reports on the non-destructive investigation methods used in studies conducted by the author's group on the stone and brick materials in the Angkor monument [5].

Bricks were mainly used in the early temples constructed during the 9th to 10th centuries [6], whereas sandstone and laterite were employed more extensively in later structures. This study focused primarily on non-destructive investigation methods for sandstone. Sandstone can be classified into gray sandstone (gray to yellowish brown), red sandstone, and greenish graywacke, with gray sandstone being the most widely used [1, 7]. The gray sandstone was quarried from the southeastern foothills of Kulen Mountain, located approximately 35 km northeast of the Angkor monument, and transported to the site through canals [8–9]. The first capital of the Angkor dynasty, Mahendraparvata, was established on the summit of Kulen Mountain, where Jayavarman II was enthroned as the first king of the Angkor dynasty in 802 AD [6, 10–12]..

2. NON-DESTRUCTIVE INVESTIGATION METHODS

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This paper discusses the following eight non-destructive investigation methods used—primarily for sandstone—to study the stone materials and their deterioration: (1) visual inspection using a percussion rod, (2) measurement of rebound value, (3) measurement of P-wave velocity, (4) measurement of magnetic susceptibility, (5) surface temperature measurement using a thermal infrared camera, (6) crack investigation using a ground-penetrating radar, (7) measurement of moisture content, and (8) chemical composition analysis using a portable X-ray fluorescence (pXRF) analyzer.

2.1 Visual inspection using a percussion rod

The simplest method for investigating stone deterioration is visual inspection using a percussion rod (Figure 1). The tapping sound produced by the percussion rod varies depending on the presence of internal cracks or the surface delamination of the stone.



Fig. 1. Percussion rod.

With this method, the degree of stone deterioration can be generally classified into four ranks (A to D):

Rank A indicates that the stone has no or little deterioration; Rank B indicates slight deterioration that does not require repair; Rank C indicates the presence of cracks or deterioration that requires repair; Rank D indicates severe deterioration, where repair is not possible and replacement with new material is necessary (Figure 2).

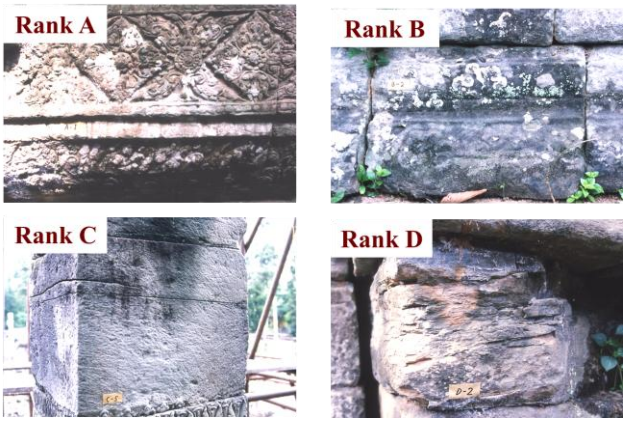


Fig. 2. Classification based on degree of sandstone deterioration: photographs of typical sandstone blocks classified from Rank A to Rank D.

Figure 3 shows the classification of stone deterioration ranks on the south face of the Northern Library at Bayon temple. Creating such figures facilitates the sharing of information on stone deterioration with restoration workers.

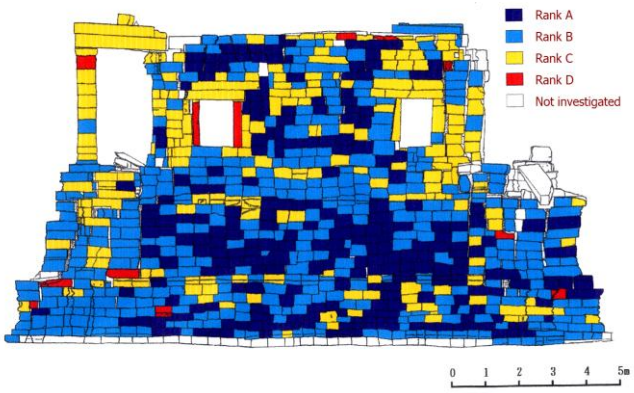


Fig. 3. Deterioration rank of sandstone blocks used at the south face of the Northern Library of Bayon temple.

2.2 Measurement of rebound value

One method for quantitatively measuring the degree of stone deterioration is the use of a rebound hardness tester. This method is based on the principle that the stronger the stone, the greater the rebound of the hammer after striking the stone surface. Representative devices include the Schmidt hammer (N-type) by PROCEQ Co., Ltd. (Switzerland) and Hardmatic tester (HH-401) by Akashi Co., Ltd. (Japan; Figure 4). A notable feature of the Hardmatic tester is its significantly lower impact energy compared with that of the Schmidt hammer.



Fig. 4. Rebound hardness testers. Left: Schmidt hammer (N-type) by PROCEQ Co. Ltd., and right: Hardmatic tester (HH-401) by Akashi Co. Ltd.

Figure 5 shows the results of gray sandstone deterioration measurements conducted on a pillar inside the Northern Library of Angkor Wat temple, obtained using both types of rebound hardness testers mentioned above. The measurements made with the Schmidt hammer, conducted by the Geotechnology team of JSA [13], clearly indicate severe deterioration of the gray sandstone at the lower part of the pillar. In contrast, the results obtained with the Hardmatic tester, which applies lower impact energy, reveal a less distinct deterioration pattern compared with those obtained with the Schmidt hammer. In this regard, the

Schmidt hammer is superior to the Hardmatic tester. However, the Schmidt hammer is considered unsuitable for investigating cultural heritage sites, because its impact energy is relatively high and leaves visible marks on the sandstone surface (Figure 5).

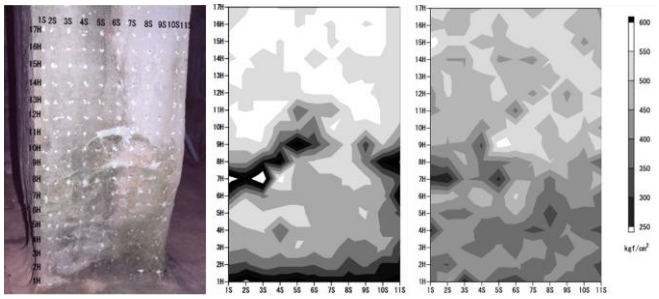


Fig. 5. Rebound value measurement results using hardness testers. Left: pillar where rebound hardness tests were conducted in the Northern Library at Angkor Wat temple; middle: results obtained using Schmidt hammer [13]; right: results obtained using Hardmatic tester.

2.3 Measurement of P-wave velocity

The P-wave velocity is proportional to the stone's strength. Therefore, by measuring the P-wave velocity, it is possible to assess the stone's strength or degree of deterioration. Figure 6 shows the results of P-wave velocity measurements conducted on a pillar inside the Northern Library of Angkor Wat temple [5]. The measurements were carried out using the portable ultrasonic non-destructive digital indicating tester (PUNSIT) manufactured by C.N.S. Electronics Ltd. (England).

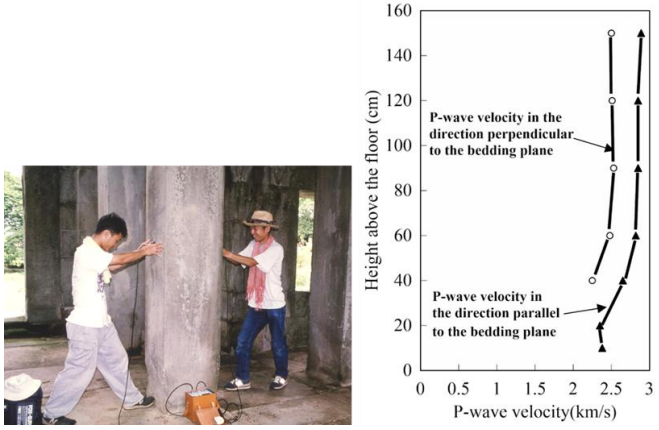


Fig. 6. Results of P-wave velocity measurements (right) conducted on the pillar inside the Northern Library at Angkor Wat temple [5]. The measurements were carried out using PUNSIT (left) by C.N.S. Electronics Ltd. (left).

In the pillars of the Angkor monument, the bedding planes of the sandstone are oriented vertically. Therefore, it is necessary to measure the P-wave velocity separately in directions parallel and perpendicular to the bedding planes. Generally, the P-wave velocity is faster in the direction parallel to the bedding planes than in the perpendicular direction. This trend is evident in Figure 6, where the P-wave velocity in the parallel direction is approximately 15% faster than that in the perpendicular direction. In both directions, the P-wave velocity tends to decrease below a height of 60 cm from the floor, indicating that salt weathering, caused by bat excrement, is progressing in the lower part of the pillar [3].

2.4 Measurement of magnetic susceptibility

In the gray sandstone primarily used in the Angkor monument, significant differences have not been observed in the constituent minerals or chemical composition [1], making it impossible to estimate the construction sequence or period of the temples based on these factors. However, as noted by Uchida et al. [14–15], the magnetic susceptibility of gray sandstone varies depending on the period, which allows for the estimation of the construction sequence and period of the temples based on magnetic susceptibility. The magnetic susceptibility of gray sandstone is believed to be proportional to the amount of magnetite it contains. Magnetite transforms into goethite, which has significantly lower magnetic susceptibility owing to deterioration. In other words, as the sandstone deteriorates, its magnetite transforms into goethite, resulting in a decrease in magnetic susceptibility. This principle can be used to estimate the degree of deterioration of sandstone. Figure 7 shows the results of magnetic susceptibility measurements conducted on a pillar inside the Northern Library at Angkor Wat temple, similar to those shown in Figure 6. The magnetic susceptibility meter used was the SM30 by ZH Instruments (Czech Republic). Each measurement took approximately 2–3 seconds, with a measurement accuracy of approximately 0.001×10^{-3} SI units.

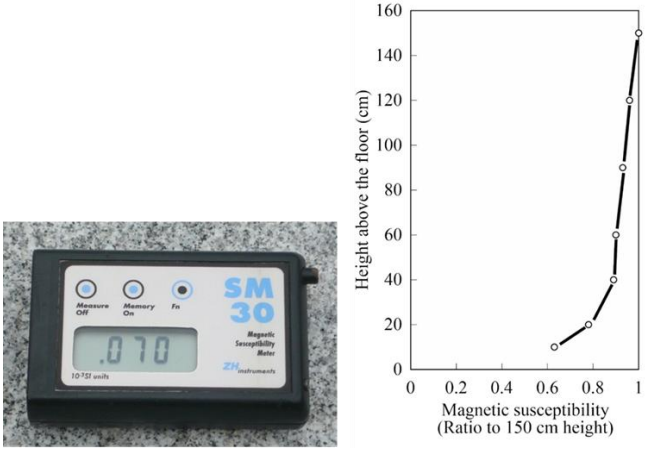


Fig. 7. Results of magnetic susceptibility measurements (right) conducted on a pillar inside the Northern Library at Angkor Wat

temple [5] using magnetic susceptibility meter SM30 by ZH Instruments (left).

In Figure 7, the results are presented as a ratio relative to the magnetic susceptibility at a height of 150 cm on the pillar [5]. The measurements clearly show that the magnetic susceptibility decreases below 150 cm above the floor. At a height of 10 cm, the magnetic susceptibility is approximately 40% lower than that at a height of 150 cm, indicating that the deterioration of the sandstone material is more advanced in the lower part of the pillar. These results are consistent with the P-wave velocity measurements.

2.5 Surface temperature measurement using a thermal infrared camera

During the day, sunlight heats the stone surface, raising its temperature, while at night, the surface cools as temperature drops. The repeated cycle of these temperature changes causes the expansion and contraction of the stone, which is believed to contribute to surface delamination. A thermal infrared camera is the most effective tool for comprehensively monitoring the surface temperature of stone materials.

Using the Neo Thermo TVS-700 thermal infrared camera by Nippon Avionics Co., Ltd. (Japan), surface temperature measurements of the Southern Library at Angkor Wat temple were conducted from 7 a.m. to 6 p.m., at hourly intervals (Figure 8).

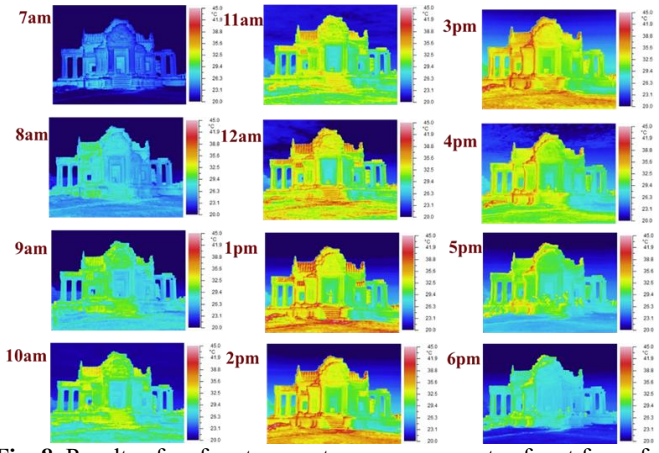


Fig. 8. Results of surface temperature measurements of east face of the Southern Library at Angkor Wat temple from 7 a.m. to 6 p.m. at hourly intervals.

The results revealed significant temperature variation throughout the day on surfaces exposed to sunlight, with the roof serving as a typical example (Figure 8). Extensive surface delamination of the sandstone on the roof is evident in multiple areas, with large temperature changes throughout the day considered as a contributing factor. Additionally, afternoon rain showers (squalls) rapidly cool the heated sandstone surfaces, which is believed to accelerate sandstone deterioration.

The thermal infrared camera is also an effective tool for detecting the surface delamination of sandstones. Figure 9 shows the results of using the thermal infrared camera to identify areas of sandstone surface delamination on the wall of the Northern Library at Angkor Wat temple [5]. Delaminated areas can be identified by their thermal behavior: they exhibit higher temperatures than the surrounding areas during temperature rise, and lower temperatures during temperature drop. This temperature difference between the delaminated areas and the surrounding surface enables detection.

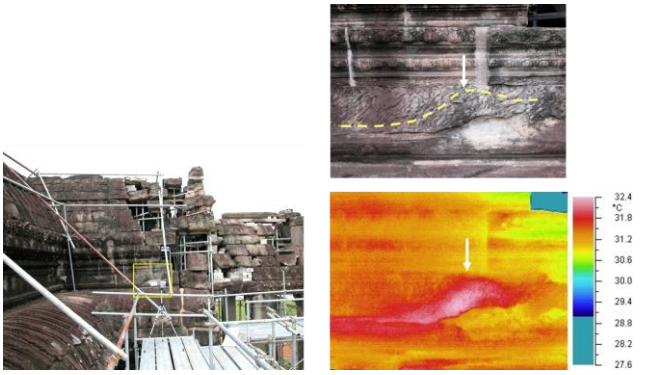


Fig. 9. Results obtained using a thermal infrared camera to identify stone surface delamination areas (lower right) on the wall of the Northern Library at Angkor Wat temple (left) [5].

2.6 Investigation using a ground-penetrating radar

Ground-penetrating radar (electromagnetic wave radar) is commonly used to investigate underground archaeological remains. This study used the Handy Search NJJ-95A, an electromagnetic wave radar by Japan Radio Co., Ltd. (Japan), to examine cracks in stone materials and investigate the arrangement of reinforcing iron bars in the concrete used to repair the stone.

Figure 10 (left) shows a pillar from the porch of the Northern Library of Angkor Wat temple [5]. This pillar has two large visible cracks. This study used the Handy Search NJJ-95A to determine whether these cracks could be detected.

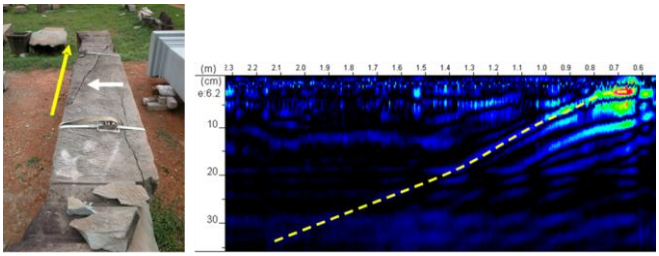


Fig. 10. Pillar with two large vertical cracks (left). Scanning was conducted along left side of the pillar, in direction indicated by

yellow arrow. As indicated by yellow dashed lines in right figure, a crack in the pillar was successfully detected [5].

The results of scanning along the left side of the pillar are shown in the direction indicated by the yellow arrow in Figure 10 (left). As indicated by the dashed lines in Figure 10 (right), the cracks in the pillar were successfully detected. This result demonstrates that the Handy Search NJJ-95A can identify cracks located at depths of at least 30 cm.

Figure 11 (left) shows the wall surface on the north side of the Inner Gallery of Bayon temple [5]. Within the area shown in Figure 11 (left), a tapping inspection of the sandstone blocks using a percussion rod suggests the presence of internal cracks in sandstone blocks (a), (b), and (c). In sandstone block (b), the left end of the crack is visible on the surface. A scan was conducted on sandstone block (a) using the Handy Search NJJ-95A (Figure 11, upper right). The results are shown in Figure 11 (lower right). As indicated by the dashed lines in Figure 11 (lower right), a crack was detected at a depth of 3 cm on the right end, and at a depth of 12 cm on the left end.

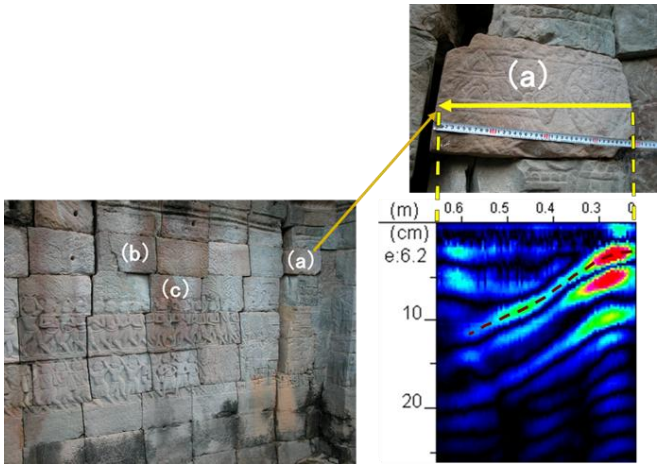


Fig. 11. Wall surface on the north side of the Inner Gallery of Bayon temple (left). Tapping inspection of sandstone blocks using a percussion rod indicated presence of internal cracks in sandstone blocks (a), (b), and (c). Scan was conducted on sandstone block (a) using the Handy Search NJJ-95A (upper right). Crack was detected at depth of 3 cm on right end, and at depth of 12 cm on left end (lower right) [5].

Figure 12 (left) shows the top surface of a beam inside the Northern Library of Angkor Wat temple [5]. Mortar has been used to reinforce this beam by EFEO. To investigate the condition of the reinforcing iron bars within the mortar, a scan was conducted using the Handy Search NJJ-95A in the direction indicated by the yellow arrow in Figure 12 (left). The result is shown in Figure 12 (right), confirming that two reinforcing iron bars are present at a depth of 7.5 cm along the scanned direction.

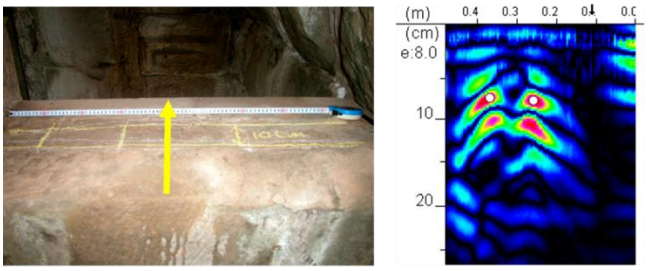


Fig. 12. Top surface of a beam inside the Northern Library at Angkor Wat temple [5]. Scan was conducted using the Handy Search NJJ-95A in direction indicated by yellow arrow left). Two reinforcing iron bars were detected at depth of 7.5 cm along scanned direction (right).

2.7 Measurement of moisture content

Water plays a significant role in the degradation of stone materials. Therefore, understanding the moisture content of stone is crucial for preventing its deterioration. Three methods can be used to measure the moisture content of stone non-destructively: measuring infrared absorption, measuring electrical conductivity, and measuring the dielectric constant.

The method for measuring infrared absorption determines the amount of water present on the stone's surface, but it does not necessarily reflect the moisture content inside the stone, making it an ineffective method for measuring moisture content. Additionally, the method of measuring electrical conductivity faces challenges owing to the large contact resistance between the stone surface and the electrodes, making it difficult to measure the moisture content accurately. In contrast, the method for measuring the moisture content using the dielectric constant is considered effective because, unlike the two methods mentioned above, it reflects the moisture content inside the stone.

The relative dielectric constant of water is high at room temperature and pressure, with a value of approximately 80. In contrast, the relative dielectric constants of typical rock-forming minerals are low, generally ranging from approximately 3 to 5. As the moisture content increases, the dielectric constant of the rock also increases. One example of a moisture meter based on this principle is the HI-500, a mortar, concrete, and ALC moisture meter manufactured by KETT Electric Laboratory (Japan) (Figure 13). This device can measure moisture content up to approximately 4 cm beneath the stone surface. Prior to the measurements, the device was calibrated using a gray sandstone sample measuring 10 cm × 10 cm × 5 cm, collected from Angkor Wat temple.

Figure 14 shows a floor plan of the Inner Gallery of Bayon temple [4]. The areas shaded in yellow indicate sections where the platform is lower (Figure 15(a)), while the areas shaded in blue indicate sections where the platform is higher (Figure 15(b)). A significant difference in the

degradation of the reliefs carved on the walls can be observed between these two areas.



Fig. 13. Mortar, concrete, and ALC moisture meter (model HI-500 by KETT Electric Laboratory, Japan).

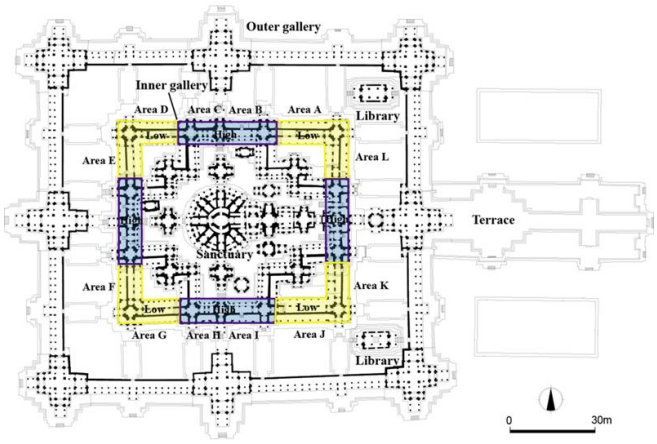


Fig. 14. Floor plan of Bayon temple showing Areas A–L, where moisture content measurements were conducted [4].

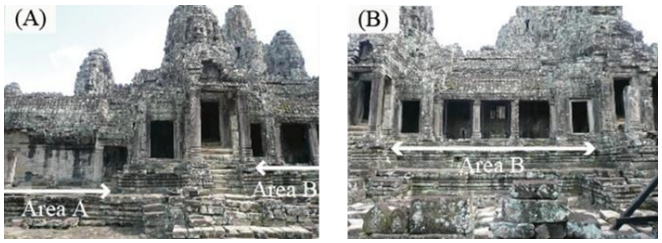


Fig. 15. Area A has lower platform while Area B has higher platform [4].

In areas where the platform is lower, there is an empty void behind the relief-decorated wall [4] (Figure 16(A)), and the reliefs on the wall exhibit little to no deterioration. In contrast, in areas where the platform is higher, a platform raised approximately 1.5 meters above the floor exists behind the relief-docorated wall (Figure 16(B)). Below this 1.5-meter level, noticeable deterioration of the reliefs can be observed, whereas the deterioration is significantly less pronounced above this height (Figure 17).

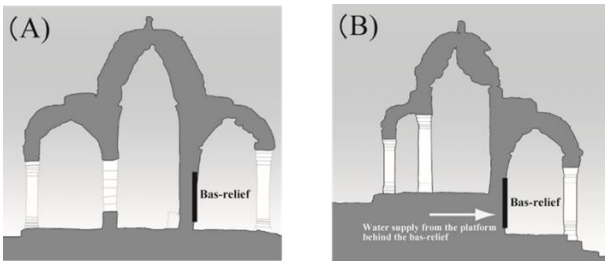


Fig. 16. In areas where the platform is lower, there is an empty void behind the relief-decorated wall (A); in areas where the platform is higher, a platform exists behind the relief-decorated wall (B) [4].



Fig. 17. In areas with a higher platform, a platform located approximately 1.5 meters above the floor exists behind the relief-decorated wall. The deterioration of the reliefs is noticeable below this 1.5-meter level, and less pronounced above it [4].

Figure 18 (upper) presents the moisture content measurements on the gray sandstone surface of the relief-decorated wall in Area A, where the platform was lower [4]. The moisture content tends to fluctuate with rainfall, being lower during the dry season (December to April) and higher during the rainy season (May to November). Figure 18 (lower) presents the annual variation in moisture content on the gray sandstone surface of the relief-decorated wall in Area B, where the platform is higher. On the wall surface, approximately 1.5 meters or higher above the floor, the deterioration of sandstone reliefs is relatively minor, similar to that observed in Area A. In contrast, for wall locations at approximately 1.5 meters or lower, the moisture content remains approximately constant throughout the year. This suggests that moisture is being supplied from the platform behind the relief-decorated wall, maintaining a consistently elevated moisture level.

In the Area B—below approximately 1.5 meters from the floor—measurements using a portable X-ray fluorescence (pXRF) analyzer (described later) indicate higher calcium (Ca) content, suggesting that calcium components from the sandstone dissolve into the moisture supplied from the platform behind a relief-decrated wall. When this moisture evaporates at the relief-decorated wall surface, the dissolved

calcium precipitates as $CaCO_3$ (calcite). The crystallization pressure of $CaCO_3$ is thought to contribute to sandstone surface deterioration.

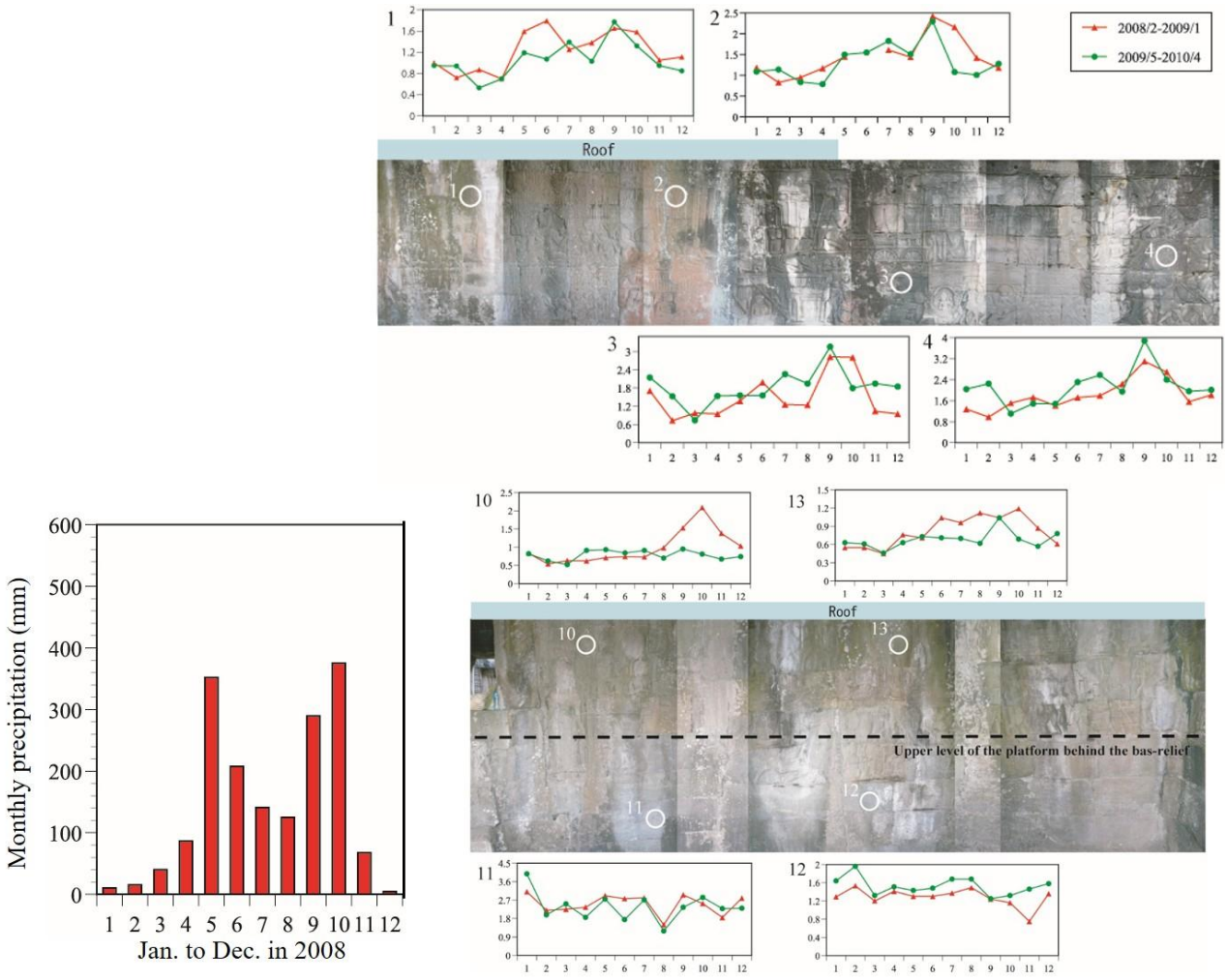


Fig. 18. Moisture content measurements of sandstone wall surface in Area A with lower platform (upper right) for 2008 to 2010 show seasonal fluctuations correlating with rainfall. In contrast, the wall surface in Area B with higher platform (lower right)—located approximately 1.5 meters or lower from the floor and backed by a higher platform—exhibits relatively stable moisture levels throughout the year, consistently maintaining higher moisture content [4].

2.8 Chemical composition analysis using a pXRF

Since around the year 2000, pXRF analyzers have become commercially available, enabling on-site chemical composition analysis of elements heavier than aluminum. In recent years, improvements in detection sensitivity have significantly increased measurement accuracy. The author has used the Delta Premium by Innov-X Systems Inc. (USA) to analyze the chemical composition of stone materials at sites such as the Angkor monument. The device weighs approximately 2 kg including a battery, and the typical measurement time is approximately one minute.

Regarding the gray sandstone commonly used in the Angkor monument, significant differences have not been observed in its chemical composition [1]. However, in deteriorated sandstone, variations in chemical composition have been detected. For example, in the deteriorated areas of the reliefs in the Inner Gallery of Bayon temple, as discussed in Section 2.7, elevated levels of calcium (Ca) were found, suggesting that the precipitation of calcium carbonate ($CaCO_3$) contributes to the deterioration [4].

At the Angkor monument—particularly at Angkor Wat temple—the deterioration of sandstone caused by bat excrement (guano) is also significant [3]. In such areas, elevated levels of phosphorus (P) and sulfur (S) have been

detected. Therefore, pXRF analyzers serve as valuable non-destructive tools for identifying factors contributing to stone deterioration.

In addition to sandstone, laterite is the second most used material in the Angkor monument. The trace element composition of laterite varies depending on the construction period [2]. Figure 19 shows the concentrations of arsenic (As) and strontium (Sr) in laterite, analyzed using the pXRF analyzer. These elements were found to vary over time, and the analytical results revealed that the laterite used in the Angkor monument temples was sourced from five different quarries.

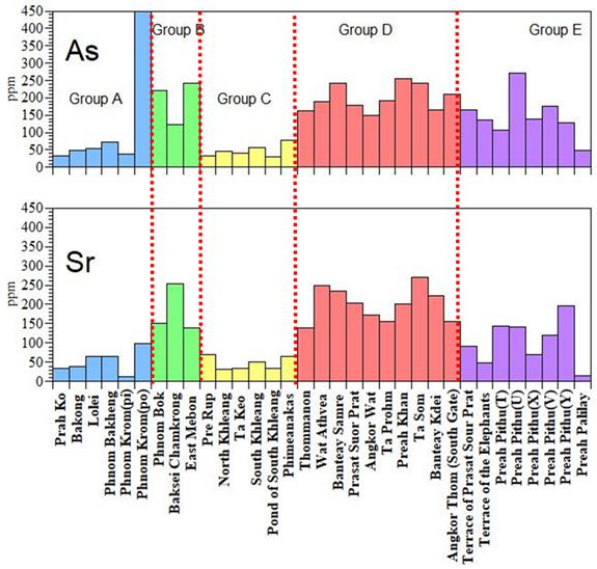


Fig. 19. Concentrations of arsenic (As) and strontium (Sr) in laterite used in temples at the Angkor monument, analyzed using the Delta Premium pXRF analyzer of Innov-X Syetems Inc. The analytical results revealed that the laterite used in the temples at the Angkor monument was sourced from five different quarries.

3. SUMMARY

In principle, cultural heritage should be studied using non-destructive methods. The Angkor monument in Cambodia, which is the focus of this study, was inscribed on the UNESCO World Heritage List in 1992, and its preservation and restoration are vital responsibilities entrusted to humanity. The Angkor monument comprises stone structures, making petrological investigations essential for describing and classifying the stone materials, and for identifying the causes of their deterioration. However, the destructive methods commonly used in petrological studies are inappropriate for investigating masonry cultural heritage. Therefore, this study summarized non-destructive investigation methods that are useful for examining both the stone materials used in the monuments and the processes of their deterioration. The author hopes that the methods presented here will prove beneficial not only for the Angkor monument but also for the study and conservation of other masonry cultural properties.

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