The Authenticity and Integrity of Soil and Foundation of Bayon Temple in Angkor, Cambodia

Yoshinori Iwasaki1,a,*, Mitsuharu Fukuda2,b, Mitsumasa Iizuka3,c, Robert McCarthy3,d, Takeshi Nakagawa4,e, and Vanna Ly5,f

1FGeo Research Institute, 2-1-2, Otemae, Chuo-ku, Osaka, 540-0008, Japan
2Taisei Geotech, 1174-10, Nishi-machi, Kurume, Fukuoka-Pref, 830-0038, Japan
3JASA, #56, Gr6, Phum Tropeang Ses, Khum Kokchork, Srok, Siem Reap, Cambodia
4Waseda University, 3-4-1, Ohkubo, Shinjyuku, Tokyo, 169-8555, Japan
5Cambodia National Committee for World Heritage, Phonon Penh, Cambodia

*a yoshi-iw@geor.or.jp, b fuku564b@xug.biglobe.ne.jp, c mtms0709@gmail.com, d mccarthy2004@yahoo.com, e nakag@waseda.jp, f vanna1357@gmail.com

*Corresponding author

Abstract. The heritage structure of Bayon in Angkor stands upon a shallow direct foundation. The high main tower stands upon thick human-made fill without special supporting elements for such a foundation as piles. The strong strength of the human-made fill that supports heavy stone structure is one of the characters defining aspects of the authenticity of the foundation of Bayon in Angkor Thom. Several methods of restoration of retaining foundation structures in Angkor in the past are reviewed in terms of authenticity.

Keywords: Authenticity of foundation; integrity; main tower of Bayon; Angkor; filled mound; shallow direct foundation

1. Introduction

Geotechnical engineering plays an essential role in safeguarding cultural heritage and has made many key contributions, such as in the restoration work for the inclined Pisa Tower. In the past, foundations are generally considered simply nothing more than an element to support the heritage structures and were not considered a part of the heritage. However, the recent trend of conservation of heritage indicates that a foundation system has begun to be regarded as one of the heritage structure's basic components. In 2010, the international standard of ISO 13822 on assessing structural safety was renewed and added an Annex “Heritage Structures” and stressed the importance of the foundation [1].

2. Authenticity

2.1 The authenticity of cultural heritage

Authenticity was defined in the Venice Charter of 1964 as heritage composed of original material, original position, original design, and original procedure [2]. The concept of the Venice Chapter is called “anastylosis (Greek),” which means “take column back to the original position.” Anastylosis implies that original stone columns spread over a historical ruin shall be rebuilt at their original positions. The principle of anastylosis was developed based on the conservation of stone structures in Europe and did not give any heritage values to such repaired materials as often seen in Japan's wooden structures. Later in 1994, the concept definition of authenticity was expanded by the Nara Document on Authenticity to cover various methods characterized by the region to which the heritage belongs. Region-specific
methods that were developed in some areas are also accepted as the characteristic of authenticity [3]. Character-defining elements are defined as historical materials, forms, locations, spatial configurations, morphology, concept and details, structural design, uses, and cultural associations that contribute to the heritage value of a structure that shall be retained in order to preserve its heritage value.

2.2 Authenticity of Soil and Foundation

In 2005, ISO 13822 (Bases for design of structures—Assessment of existing structures) was reviewed for renewal. ISCARSAH (International Scientific Committee on the Analysis and Restoration of Structures of Architectural Heritage under ICOMOS) had proposed to include heritage structures in the standard and worked together for five years to develop. The ISO 13822 has been updated in 2010 and added an Annex-I (informative) Heritage Structure, which has expanded the heritage structure to include the foundation as a part of structures. The Annex I clearly state as in paragraph of I.5.3 Authenticity of foundation that “From the point of view of conservation, foundations are not different from the rest of the structure and should be assessed and rehabilitated taking into consideration their heritage value. This involves the requirement to identify their authenticity and character-defining elements” [1].

2.3 Bayon temple in Angkor Thom

As shown in Figure 1, Bayon is the central temple of Angkor Thom constructed around in late 12th to early 13th century. Figure 2 shows a section and plan view of the Bayon temple. Japanese Government for Safeguarding Angkor Team (JSA) performed an archaeological trenching study at the north-eastern corner as “Long trench” also shown in Figure 2 in blue.
3. Trenched foundation
The result of the long trench has revealed the following facts, as shown in Figure 3 [4].

- The first terrace's surface was covered with sandstone and laterite block, beneath which densely compacted sandy-filled layer was identified.
- The compacted sandy-filled layer continued with an additional laterite block layer to the original ground surface level.
- It was identified that the compacted sandy-filled layer continues from the original ground level to 2-3 meters in thickness.
- The compacted sandy-filled layer below the original surface was found to continue horizontally to about 10 m outside of the outer gallery plinth.

The archaeological study suggests that the foundation work for the Bayon is a “trenched foundation” and was systematically constructed by excavating the original ground 2-3 meters vertically as well as about 10 meters outside of the temple boundary of the outer gallery, as shown in Figure 4. The stone masonry structures were constructed upon terraces with three different levels of 2.95 m, 6.95 m, and 12.40 m.

![Figure 3. Long trench at the northern outside of Bayon [4].](image)

4. Foundation platform of Bayon

4.1 Ground condition of Bayon Temple
A boring survey was performed near the Bayon temple to study the ground condition. The results of the boring log with SPT (standard penetration test) N-values are in Figure 4. The upper 40 meters from the surface is mainly a silty and clayey sand layer of Quaternary deposit, which was transported a distance of 25 km to the north of Bayon from the weathered sandstone of Mt Kulen.

![Figure 4. Boring result near Bayon temple and foundation of Bayon temple.](image)
Weathered tuff stone was found to continue downwards. N-values of the standard penetration test show seasonal change for the uppermost layer of 5 meters from the surface, dependent upon underground conditions.

4.2 Seasonal Change of Soil Strength in the Top Surface
The boring was carried out in April 1995, and the underground water level was GL-5m. The N-value was about N=20 at the surface and decreased to N=10 at a depth of 5 m. In September, the surface condition was studied by a dynamic penetration test. The results are shown in Figure 4, and the N-value at the surface was almost negligible and increased with depth to GL-5 m. The underground level in September was found near the ground surface. Levels of the subsurface water change with rainfall. When the rainy season begins in May, the underground water begins to increase and reaches the highest level near the ground surface at the end of September. When the dry season starts in October, the underground water decreases and reaches the lowest level of around GL-5.0 m. Due to the water level change, the SPT N-value changes from N=20 at the top surface in a dry state and decreases to N=1 in the wet state.

4.3 High Mound Representing Mount Meru in a Mountain Style
A concentric series of walls typically encloses Temple Khmer temples, with the central sanctuary in the middle as shown in Figure 2; this arrangement represented the mountain ranges surrounding Mount Meru, the mythical home of the gods. There are three terraces: the first, the second, and the top of GL+2.5m, +6.0m, and 12.4m respectively in height. The Central Tower is constructed at the highest level of these terraces to represent Mount Meru. On the flat plain in Angkor, the human-made fill about 14 m in thickness was constructed to image Mount Meru.

5. Foundation structure of Bayon
5.1 Direct Shallow Foundation
A base stone is placed beneath the bottom of the Central Tower, as shown in Figure 5. JSA carried out archaeological trench excavation along the inside of the base stone and geotechnical hand auger sounding beneath the stone to determine if any special base structure was installed to support the heavy Central Tower. Horizontal hand auger tests were carried out at 5 points as shown in Figure 6 and have resulted in no supporting stones identified, but only very dense sandy fills beneath the base stone support.

Figure 5. Base Stone For Central Tower Bayon.

Figure 6. Hand auger soundings beneath the base stone [5].
5.2 Platform mound with vertical shaft at the center

EFEO, a France-sponsored organization, in 1933 excavated the center of the base of the main Central Tower below the pavement and found a disarticulated Buddha statue. It was recorded that the vertical shaft had been backfilled. Geotechnical boring was performed at the backfilled vertical shaft and at the original human-made filled mound as shown in Figure 7.

![Figure 7. Boring BYV2009 at the backfilled shaft and Boring BYV2010 at the original mound.](image)

6. Characteristics of stiff platform sand fill

The obtained SPT, N-values are plotted against water contents of the sampled soils for both borings and shown in Figure 8. No relationship was found for BYV2009 of the backfilled soil; however, the decrease of water was found to increase the strength for boring BYV2010 [6,7]. Figure 9 showed the response of the dense sandy fill when it was submerged in water. Sampled soil looks like soft sandstone. However, it collapsed within 10 min when inundated, as shown in Figure 9. The grain size distributions of the sampled soil by the boring BYV2010 are shown in red color in Figure 10. The soil is clayey sand, and the entire samples of the filled soil show the same distribution, which implies very uniform filled soil.

![Figure 8. Relationship between SPT, N-values for B09(BY2009) and B10 (BY2010)](image)
Figure 9. Collapse of stiff sand underwater within 10 minutes.

Figure 10. Grain size distribution of BY2010 and BH.

7. Increase of strength by decreasing moisture
A series of laboratory tests were performed to see how much strength changes due to decreased moisture contents. More than 25 samples in containers were prepared with a water content of 15%, which almost creates a 100 % saturated condition.

Figure 11. Ymanaka Cone test.

Figure 12. Test results by Yamanaka cone test.
The samples were placed outdoor, and the water evaporates from the sample and the water content decreased day by day. Yamanaka cone penetration test was performed on these samples as shown in Figure 11. The test results in Figure 12 shows clearly an increase of strength more than 50 times due to the decrease of the water content.

8. Load of the Main Tower to Foundation
8.1 Load of the Main Tower
The main structure consists of the main tower and seven sub towers which are shown in Figure 13. Table 1 shows the estimated mass volume, total weight of the central tower, one sub-tower, and the contact load. The contact loading stress for the central and sub-tower is shown as 1482 and 470 kN/m² respectively. The averaged vertical stress in the foundation ground beneath the main tower base assuming the equivalent base with radius = 10.0 m is 150 kN/m² as shown in Table 1.

8.2 Comparable Structure with the Equivalent Load
Comparable to a present such common structure as RC building may be assumed as 12-15 kN/m² as a floor load for one floor. The contact load of the main tower of 150 kN/m² may be considered as comparable to a 10 story RC building. Figure 14 shows a situation of such a RC structure upon the same situation of the filled mound of 14 m in thickness.

| Item                              | Central tower | One sub-tower | Main tower  |
|-----------------------------------|---------------|---------------|-------------|
| Unit mass                         | 23 (kN/m³)    | 23 (kN/m³)    | 23 (kN/m³)  |
| Volume                            | 967 (m³)      | 156 (m³/unit) | 2059 (m³)   |
| Total weight                      | 22240 (kN)    | 3588 (kN/unit)| 475 (6kN)   |
| Contact area of base with a radius of 10 m | 15 (m²)      | 7.6 (m²/unit) | 314 (m²)    |
| Contact load                      | 1482 (kN/m²)  | 470 (kN/m²)   | 150 (kN/m²) |

Figure 13. Section and plan of Main Tower of Bayon.
9. Appropriate foundation for RC10 story building

Action systems are available. Two methods of direct and pile foundation are shown. When any structure is built on manmade fill, it may be common not to use the direct foundation except for one or two-storey buildings of minimal load. Since the building is 10 story RC structure, the expected load is about 150kN/m² and results in the foundation other than the direct foundation. The thickness of the fill is very thick at 14 m, and the natural layer of sandy formation of SPT, N increasing with depth. Another foundation system may be considered; such as pile foundation as in Figure 14.

10. Impossible design of foundation by Ancient Khmer Engineers

Japanese Government Team for Safeguarding Angkor studied from 1994 to the present, and it has revealed the exceptional design of the shallow direct foundation upon a manmade fill mound of 14 m in thickness to support the main tower of masonry stone structure with the load pressure of 150 kN/m² to the foundation base. The Ancient Khmer Engineers utilized the special character of the local sandy soil, which is very strong under dry conditions. The Bayon had been built in the late 12th early 13th century, and the main tower has been standing for more than 800 years in heavy rain under the tropical monsoon climate. The Angkor area belongs to the tropical monsoon climate zone with a rainy season from May to October.

![Figure 14. Foundation for RC 10 story building on the top terrace of the Bayon temple.](image)

11. Authenticity and Integrity

11.1 Ignored Foundation of Heritage Structure in Angkor

There have been no special character studies for the foundation system in Angkor in the past, only for the upper structures as usual conventional procedure. Japanese Government Team for Safeguarding Team was the first to establish the clarify of the value and character of cultural heritage for the foundation mound in Angkor.

11.2 Character Defining Element of the Authenticity

There are several elements of the foundation system of the Bayon temple as follows,

1) Trenched foundation for the entire structural temple zone
2) A densely compacted filled mound of 14 m in thickness
3) Shallow direct foundation to support the masonry stone tower of 30 m in height
4) Long stability of more than 800 years since 13 century to present
11.3 Integrity of the Structure
The above-mentioned characters must be maintained as one of the conservation of the heritage structures in Angkor. The most dangerous condition against the filled mound is the saturated state of water contents. If the filled soil mound becomes saturated, the strength of the fill will be lost, and the mound will have failed to result in the Central Tower of the Bayon's failure, the symbol of Angkor Thom.

11.4 Proactive Measures to Keep the Integrity
In the coming potential of global warming, much more rain is anticipated and will bring about the failure of the Bayon temple's main tower. Several proactive measures to keep the filled mound dry during the heavy rain weather are being prepared and will be arranged shortly.

12. Conclusions
The study of heritage structures in the past never focusses on the character of the structure's foundation. In Angkor, the situation was the same as in the other areas. However, the Japanese Government Team for Safeguarding Angkor had identified the character-defining elements of the authenticity for the foundation system for the Bayon temple. The character-defining elements of the Authenticity of the Foundation System in the Bayon temple are as follows,
1) Trenched foundation for the entire structural temple zone
2) A densely compacted filled mound of 14 m in thickness
3) Shallow direct foundation to support the masonry stone tower of 30 m in height
4) Long stability of more than 800 years since 13 century to present

- It was a fantastic practice of the ancient Khmer engineer to understand the special character of gaining strength in the local soil's dry state and introduce it into the base structure of the filled foundation in Angkor more than 800 years ago.
- It was a great pleasure to identify the special characteristics of the foundation of the Bayon in Angkor. Otherwise, the heavy stone structure's standing by the shallow direct foundation is not a mystery but a common structure upon a stone foundation.
- The amazing fact of the thick human-made fill of 14 meters should be understood as the mystery in of Bayon temple. The study should be extended to the other zone of the Angkor area and reference other international heritage sites constructed with similar defining characteristics.

References
[1] International Organization for Standardization ISO 2010, Bases for design of structures — Assessment of existing structures, (ISO 13822:2010), International Organization for Standardization.
[2] https://www.icomos.org › charters › venice-e
[3] https://www.icomos.org › charters › nara-e
[4] Narita, T., Nishimoto, S., Shimizu N., Akazawa Y., 2001. Trench Excavation of Outer Gallery, Bayon, Annual Report on the Technical Survey of Angkor Monument 2000, pp.3-18,317(2001)
[5] Shimoda, I., Yamamoto, N., Iwasaki, Y. and Fukuda, M., 2009. Excavation survey of the central tower chamber (pp. 67-88). Annual technical report on survey of Angkor monument 2008, JASA, Tokyo.
[6] Iwasaki, Y., Fukuda, M., Ishizuka, M., McCarthy, R., Shimoda, I., Nakagawa, K., Koyama, T., Nakagawa, T. and Ly, V., Preventive Conservation of the Central Tower of Bayon Temple under Global Warming: Case Study in Soil Filled Foundation and Character Defining Elements of Authenticity of Foundation in Angkor, Cambodia.
[7] Iwasaki Y., Fukuda M., Haraguchi T., Kitamura A. Ide Y., Tokunaga T.and Mogi K., 2014. Structural of Platform Mound of Central Tower Based upon Boring Information. Annual Technical Report on the Survey of Angkor Monument 2012-2013, Tokyo, pp.93-113.