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Restoration of retaining structures for steep pyramid temples in Angkor and disclosed soil conditions allowing construction of high rise manmade fill of 800 years old and still standing

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ABSTRACT

Temples in Angkor, Cambodia, are made of stone masonry structure and have been studied and treated for restoration work by EFEO, France, since 1907. Anastylosis was introduced in 1930 as the major guidelines for preservation work. The pyramid slope of Baphuon temple in Angkor Thom failed in 1943. EFEO studied the ancient structure of the stone masonry retaining wall and reconstructed the filled embankment with steep slopes. However, it had failed three times. Then EFEO introduced reinforced concrete retaining walls which support the embankment earth pressure and the loads transmitted by the foundations of the galleries and towers standing on top of the retaining walls, The retaining walls provided with a drainage chimney allowed to drain the earth embankment. Being interrupted in 1972 by civil war, the restoration was continued from 1994 and completed in 2011. How ancient Khmer engineers could have built such steep mound on which the high rise towers like Angkor Wat have been standing for many centuries? The mystery was disclosed in 2010 by geotechnical boring by JASA through the embankment of the central area of Bayon temple.

Keywords: Baphuon; Angkor; restoration; steep mound

1 INTRODUCTION

Angkor is one of the most important archaeological sites in South-East Asia. Stretching over some 400 km2, including forested area, Angkor Archaeological Park contains the magnificent remains of the different capitals of the Khmer Empire, from the 9th to the 15th century. They include the famous Temple of Angkor Wat and Angkor Thom where the Bayon Temple and Baphuon Temple were constructed.

Figure 2 Angkor Region in Cambodia

2 BAPHUON AND BAYON TEMPLE

The Angkor temples were generally constructed on top of natural hill or manmade embankment with tower at the top center surrounded by moat, which is considered as symbolizing the sacred mountain Sumeru center of the earth and surrounded by the milk ocean.

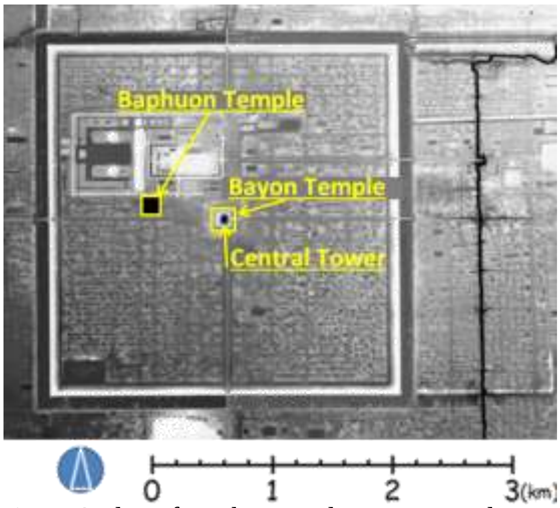

Figure 2 Plan of Baphuon and Bayon Temple

Angkor Thom, meaning “great city,” is an almost square area surrounded by 8 meter high walls and by a 100 meter wide moat as shown in Fig.2. King Jayavarman VII constructed Angkor Thom as the new capital of Khmer Kingdom after the war against the

Chams in the late 12th century. Recent lidar study (Evans, 2013) has revealed the precise geomorphology of the area that shows the existence of basic elements of schematic orthogonal division areas within Angkor Thom. What is highly surprising however, is the extent to which the rigorously conceived geometric spaces of urban landscapes extend far beyond the existing “enclosed” areas. it shows an orthogonal, cardinally aligned grid pattern of linear features (either canals or city streets) defining city blocks containing occupation embankments and ponds.

Within Angkor Thom, the Baphuon temple was constructed in the mid-11th century while the Bayon temple was constructed as the state temple at the center in the 12th century as shown in Fig.2.

Baphuon temple is shown in Fig. 3 and the plan and section are shown in Fig.4.

Figure 3 Baphuon Temple

completed. The side slopes of the pyramid are very steep with an angle around 45 degrees. EFEO (École Française d'Extrême-Orient) made great efforts to reconstitute the Baphuon temple which suffered serious landslide in 1943. The reconstruction of the temple begun in 1950 and was completed in 2012. The design of the reconstruction is based upon reinforced concrete retaining wall keeping the slopes stable.

3 RESTORATION WORK AT BAPHUON

Baphuon temple stands upon a high pyramid mound of 132 m in width east-west, 107 m north-south.

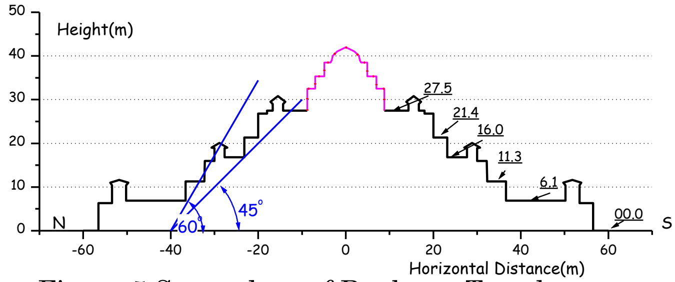

Figure 5 Steep slope of Baphuon Temple

Vertical section in N-S direction is shown in Fig.5. There are five steps from the ground to the top floor standing 27 m above the original ground level. The upper four floors are connected with very steep stairs (55° to 60° slope) located at the central axis of the four sides.

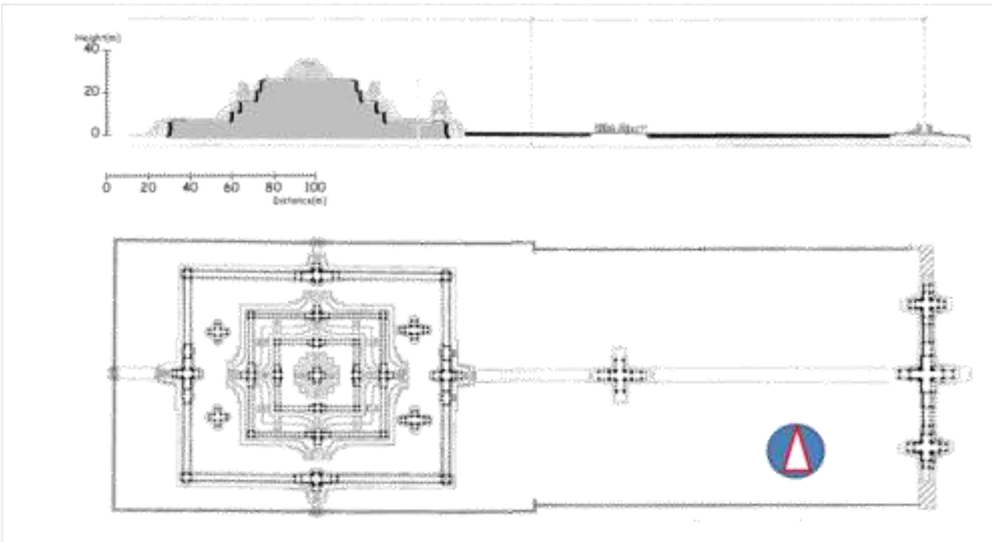

Figure 4 Section and Plan of Baphuon Temple

The Baphuon temple was built by king Udayadityavarman II in the second half of 11^{th} century. The pyramid of the base is 107 x 132m with an estimated height of about 50m when

The northeastern side of the slope of the Baphuon temple failed in 1943 (Fig.6). Borings were carried within the collapse zone which suggested circular failure line. Back analysis

resulted in the possible parameters of soil strength as C=50kPa and ϕ=25°.
The sampled soil was tested and classified as silty fine sand based upon the results of grain size distribution as shown in Fig.10.

Figure 6 Failure of Baphuon in 1943

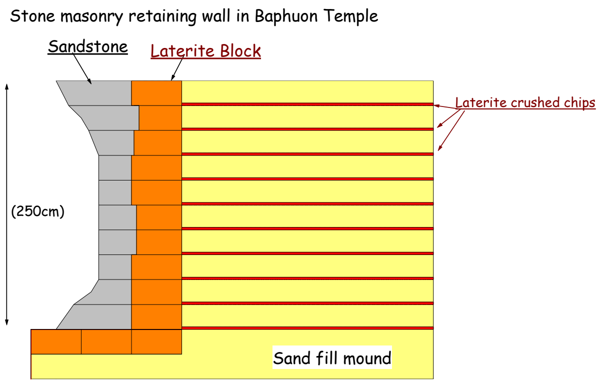

Figure 7 Original retaining structure of Baphuon

Fig.7 shows the original structure of the stone masonry retaining wall that was discovered at Baphuon. Thin layers of crushed laterite chips of 1-2 cm in thickness were embedded in compacted sandy layers for possibly drainage of infiltrated water, they extend some 4 to 5.0m behind the stone masonry rear face.
The failure mechanism was considered to related to build-up of water pressure linked to large quantity of infiltrated rain water into the fill behind the retaining wall. The decreasing drainage quality of the embankment with time (drains clogging) did not allow to avoid pore pressure to develop within the embankment with the well-known consequence of shear failure of the embankment slope
Unable to withstand the pressure of the inner fill saturated by rainwater, part of the retaining walls and the rear embankment had repeatedly collapsed (more severely in 1943) and were repaired on three occasions without success.
The high-water pressure behind the retaining wall had caused failure of the slope. In every case the key role is played by water. In a country of monsoon such as Cambodia, the regularity and thus the intensity of rains have to govern the rehabilitation design of these monuments.
The rain water flowing on the surface must be drained as well as the structures foundations in order to maintain dry conditions. Furthermore, the mistakes in the actual construction design must be eliminated as far as possible. In Baphuon, reinforced concrete structure was introduced to keep the steep slopes of the Baphuon temple (Launay, 1994).

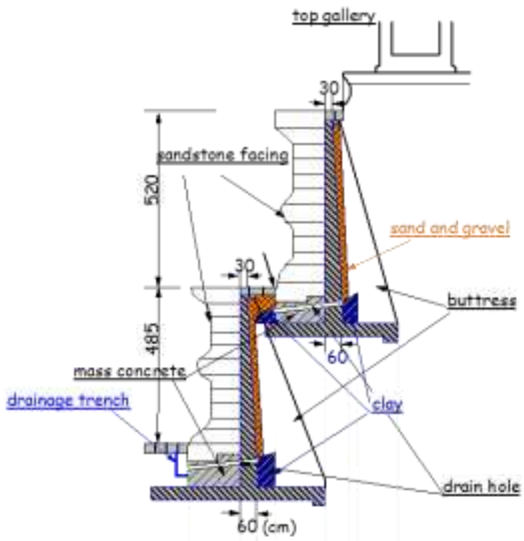

Figure 8 RC Retaining structure for Baphuon

As far as the retaining walls are concerned, they must be doubled by reinforced concrete walls able to sustain the various loads with their own dead weight including the sandstone facing. These retaining walls will be drained on their inside faces and weep holes will conduct the seeping water towards an outside covered drainage trench. When the rehabilitation of the monument is completed, the reinforced concrete wall which is not esthetic is totally invisible as it is covered by the original carved sandstone facing. This is the type of rehabilitation, which was begun in the 1955s with Mr Laure, then the Architect-conservator, and continued from 1965 till 1970 by Mr. POB. Groslier, then the Conservator of Angkor.

4 SECRETE POWER FOR THE STEEP SLOPE OF TEMPLE MOUND IN ANGKOR

In 2009, Japanese Government Team for Safeguarding Angkor performed a boring at the foundation at Bayon Temple, which showed very high SPT N values of N=100-200 for sand fill material of the same grain size characteristics as Baphuon temple as shown in Fig.10.

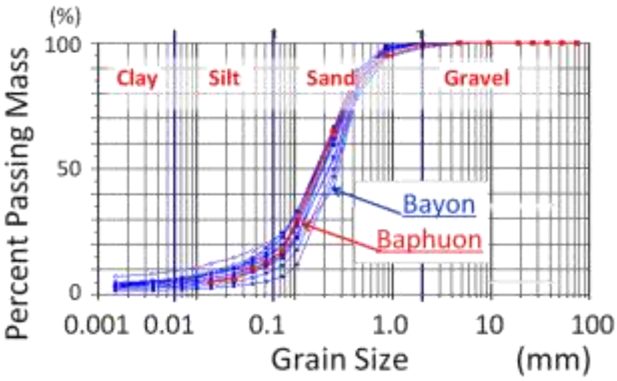

Figure 9 Grainsize Characteristics

The sampled soil looks like soft rock but easily collapsed under water as shown in Fig. 11

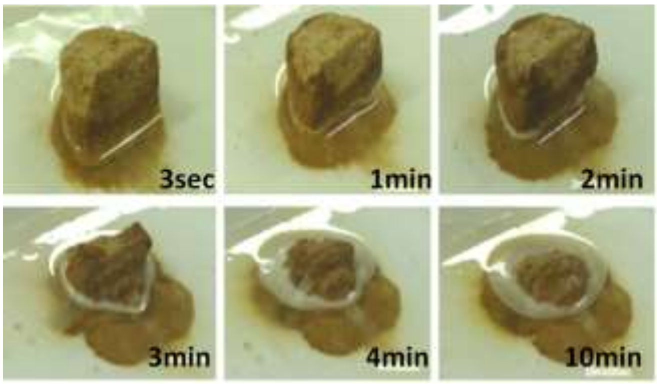

Figure 10 Sampled soil of filled mound in Bayon

The filled soil was compacted with the initial water contents of 15%. The change of the strength of the soil was studied by Yamanaka cone tester with the decrease of water contents with time by drying.

Figure 11 Strength test by Yamanaka Cone with time

The results are shown in Figure 13, which indicates amazing increase of strength of 60 times or 6 MPa of cone bearing strength.

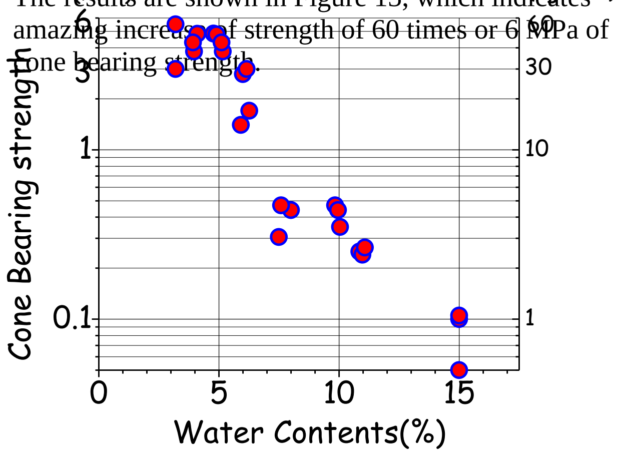

Figure 12 Increase of filled soil strength by drying

5 CONCLUSIONS

The original steep with the angle of more than 45 degrees was amazing to be kept for more than 800 years under heavy rains before 1943 when failed. The conservation work had been completed by introducing the reinforced concrete retaining wall. However, the authenticity of the original stone retaining structures was lost. There are many other such mountain temples as Angkor Wat and Bayon, whose retaining structures are estimated similar to Baphuon and are exposed to the much heavier rain in the coming global warming. We have two choices of conservation, repairing after the failure or some preventive measures before failure.

The preventive measures should be prepared and testified by laboratory and field experiments to keep the moil mound in dry condition.

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