Proactive Countermeasures against Global Warming

for the Central Tower of Bayon Temple, Angkor, Cambodia

-How to keep the tall masonry structure by shallow direct foundation upon manmade thick sandy filled mound for 700 years-

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Brief History

Angkor is the one of the world cultural heritage in Cambodia, which is the remains of ancient Khmer Empire from the declaration of the Empire (802) to the invasion by Siamese (1432) of 600 years in in South East Asia.

The conservation of Angkor started in 1907 by EFEO(*École française d'Extrême-Orient) of an* organization of French government.

Figure_1 Bayon temple, Angkor Thom, Camobodia

EFEO adapted the "Anastlylosis" as the basic method of cosevation for Angkor remains.

In 1943 the north eastern side of the slope of Baphuon temple in Angkor Thom had failed in 1943 by a heavy rain. The Baphuon temple was constrcuted by manmade sandy fill as a mountain temple in 34m in height.

In 1960', reconstruction of the manmade mound started, but, failed when the height reached at 5m. EFEO tried three times with the same results in failure and introduced a reinforced

concrete retaining wall structure to support the soil mound, which was originally stone masonary wall strcuture. Since then, the RC wall became a common countermeasure in Angkor without any question of the authenticity until at present.

In 1992 the Angkor was registered as the World Heritage and added in the List of "Heritage in Danger." Conservation system was reorganized in 1993 as ICC(Intrnational Coodrdinating Comittee) to approve the member to join and control the proposed countrmeasurs.
Japanese Government Team for Safeguarding Angkor (JSA) was established in 1994 and consists from varius fields from archaeology, to strcutural engineering including geotechniques.
Bayon temple is the one of the major sites which JSA has been workong with.

Multidiciplenary Approch to characterize the heritage
Archaeological trench along the base of the foundation with horizontal core-sampling underneath the base stone, it was confirmed neither additional stones beneath nor piles are found. The central tower is suppoted by shallow direct foundation.
The basic foundation structure of Bayon is trenched foundation with filled mound of about 14m from the natural ground as shown in Figure-2.

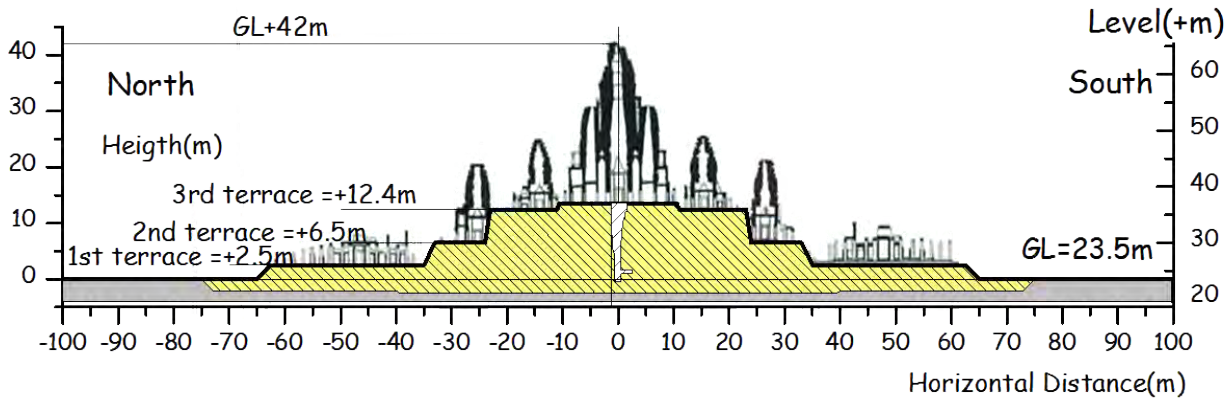

Figure_2 Vertical Section of the sand filled mound, Bayon Temple

If modern structural engineer has a chance to construct such a high masonry tower over 30m in heigt upon manmade sandy fill, he never selects direct foundation to support in sandy fillt. It was mystery for us to realize the fact that the central tower has been standng for more than 700 years without foundation failure in heavy rain condition of squal
EFEO excavated a vertical shaft with a diameter of about 2.5m at the center of the base of the cental tower .in 1933. The shaft was backfilled without compaction.

To study the inside structure of the soil mound of the platform, several borings were carried out by JSA. Some results of SPT, N-values at the vertical shaft and the sandy filled mound are shown in Fig.3.

SPT in the vertical shaft, SPT, N-values are less than 4, N<4, which means very loose sand of the refilled sand. However, the original manmade fill shows extra-ordinally large number of N=100-200.

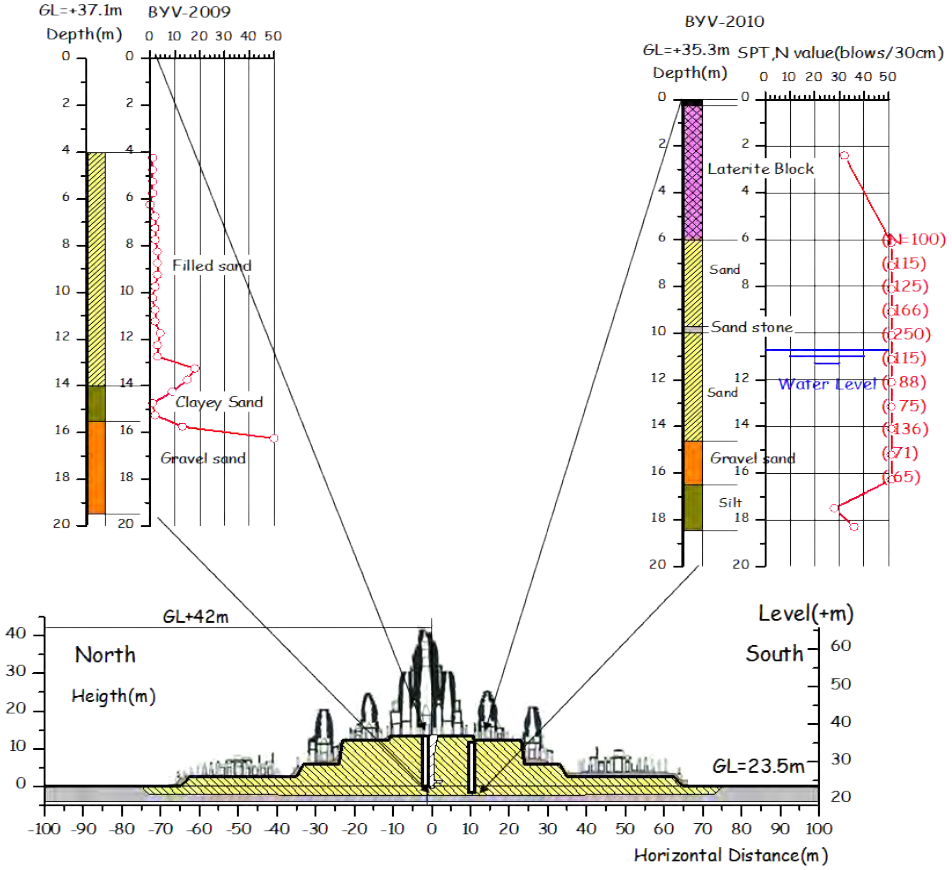

Figure 3 Boring logs for the vertical shaft filled back by French and Original fill

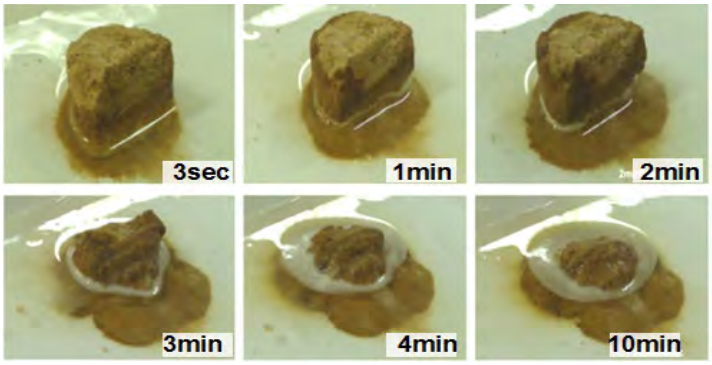

Figure 4 Collapse of stiff sand in water less than 10 min.

When a core sample of the sandy fill was submerged, the stiff sandy soil was found to collapse within around 10min as shown in Figure-4.

Why standing for 700 years - Monitoring soil moisture

Several moisture sensors were installed in the platform mound and monitored the change during rainy season.

An example of the monitored records is shown in Figure 5, which shows the response of the installed sensors to a heavy rain of squall with a total of about 80mm.

The rainwater infiltrates into ground less than a hour with an sudden increase of the water contents in the soil. However, after the rain stop, the moisture gradually decreases and returns to the stable state.

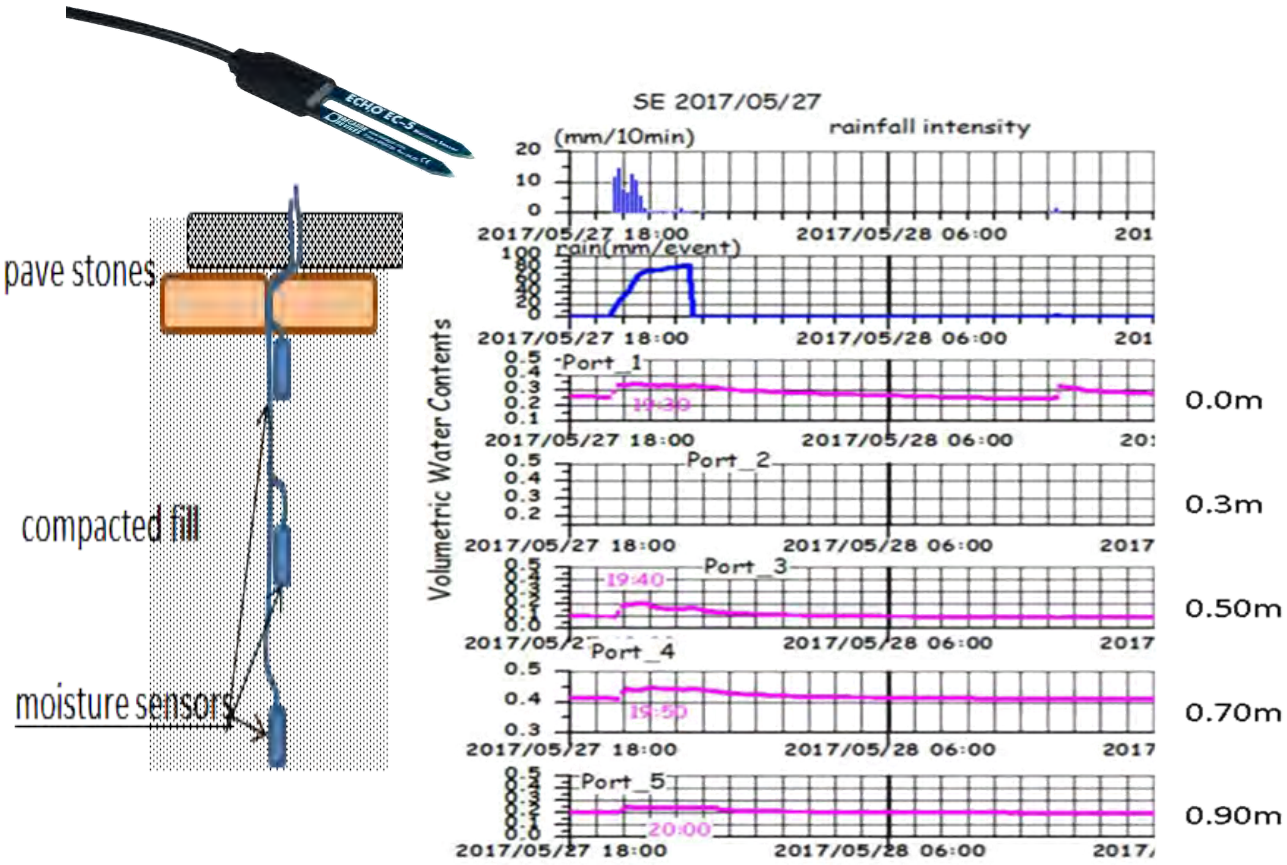

Figure 5 Moisture changes

Anticipated Collapse of the Sandy Filled Mound under Global Warming Climate

The pattern of rainfall in the Monsoon climate of South East Asia is called "Squall", which brings very heavy rain but continues only less than a few hours. This type of the rainfall causes the cyclic states from wetting and drying as shown in the monitored case.

In the coming global warming period, the much longer period of rain is anticipated and the

increase of the water contents continues much longer and finally becomes nearly saturated state of the sandy soil of the platform mound and inevitably reaches collapse of the ground failure of the sandy soil beneath the foundation of the tower, which shall cause the failure of the Central Tower of the temple.

Character Defining Elements of the Authenticity of the Stone Structure in Angkor

Both high strength of the sandy soil of the mound in dry state and the shallow direct foundation of the tall masonry tower are the character defining elements of the authenticity of the stone structure in Angkor and shall be preserved.

Proactive Countermeasures against the Global Warming

The simplest yet the effective way is to insert an impervious layer beneath the pave stone and the existing soil mound to prevent the rainwater infiltrating into the foundation mound.

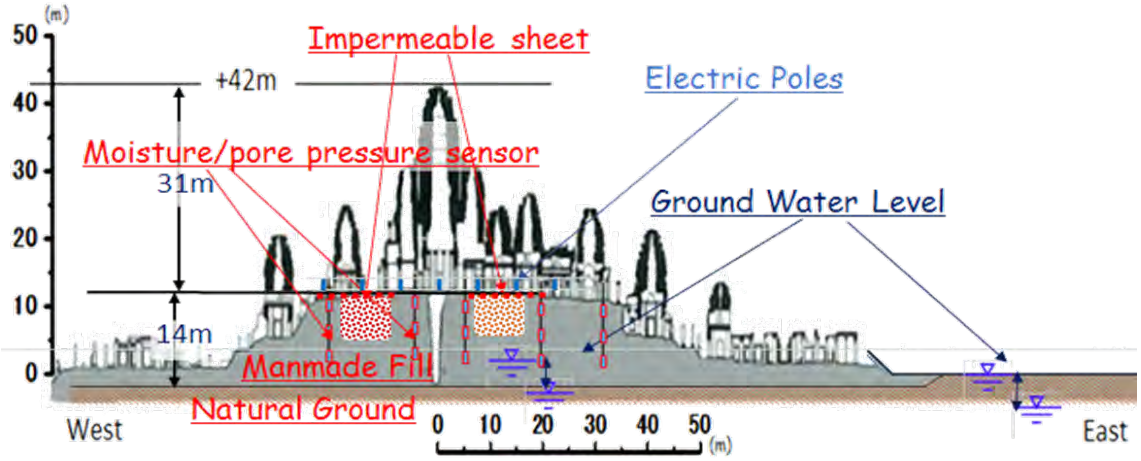

Figure 6 Countermeasures against the Global Warming

Conclusive Remarks

A. Foundations are not always regarded important elements of the heritage structures. However, the foundation is one of the important elements of the structures to support as in case of Angkor. Geotechnical engineering was the essential field to cope with for multi-disciplinary thinking.

B. Most of the conservation work starts after the failure of the heritage structure, however, proactive countermeasures should be prepared against the anticipated failures by such global warming as unavoidable situation.