Special Characteristics of the Foundation Mound of the 700-Year-Old Bayon Temple in Angkor and Countermeasures against Anticipated Degradation

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ABSTRACT

Angkor heritage locates in the subtropical zone of Cambodia where half of a year is covered by rainy season with a squall in afternoon, every day. The Central Tower of Bayon in Angkor Thom 42m in height from the ground stands upon a thick mound with 15m in thickness.

Japanese Government Team for Safeguarding Angkor started in 1994 and carried general geotechnical study. In 2008, only sandy soil was found and identified as shallow direct foundation on thick sandy filled mound. Rainy season starts in May and continues half a year and brings heavy but short rain of Squall almost every afternoon in summer.

The direct shallow foundation on a filled sandy mound is considered as resulting in unstable condition in heavy rainy climate. The Bayon has been keeping stability for more than 700 years since the construction.

Several borings of vertical, horizontal, as well as inclined directions were carried out. The SPT, N-values were found to be as large as more than 100 to 200. By laboratory tests, it was discovered that unsaturated strength becomes very large in dry conditions. The in-situ monitoring of moisture content revealed the short duration of the heavy rain did not cause enough infiltration of water into the mound. In the coming global warming, which may bring continuous and long rain, some additional countermeasures shall be required to protect the Bayon Tower on thick sand foundation.

Keywords: Angkor, Bayon Temple, Sand Mound

INTRODUCTION

After the civil war in 1970 and the war against Vietnam from 1978 to 1989, the Japanese government organized an international meeting in 1990 titled the Tokyo Conference for Cambodia with the aim to discuss how to cooperate to keep the peace of the country. An international governmental meeting was held in Japan in 1992 by UNESCO to discuss how to safeguard the Angkor Monuments in Cambodia. The Japanese Government Team for Safeguarding Angkor (JSA) was organized in 1994 to study and to safeguard the Angor monuments. JSA started to study the topography, geology, construction, and monuments of Angkor. Among the many temples in the Angkor Archaeological Park, JSA selected Bayon Temple located at the centre of Angkor Thom as the primary focus of research. A thick foundation mound was identified as consisting of dense sandy soil supporting the Central Tower of Bayon of 42 m in height without special foundations as stone columns, pilings, or other support mechanisms. This paper describes a special character of the sandy soil that supported the Tower for 700 years, however the tower still needs additional countermeasures for safeguarding against the continuous rain in a potential global warming climate.

BAYON, ANGKOR

Bayon temple and geotechnical condition

Bayon temple was built in the late 12th or early 13th century and is located at the centre of Angkor Thom in the World Heritage site of the Angkor Archaeological Park. Figure 1 shows a photograph of Bayon temple. The height of the main tower is about 42 m from the surrounding ground surface.

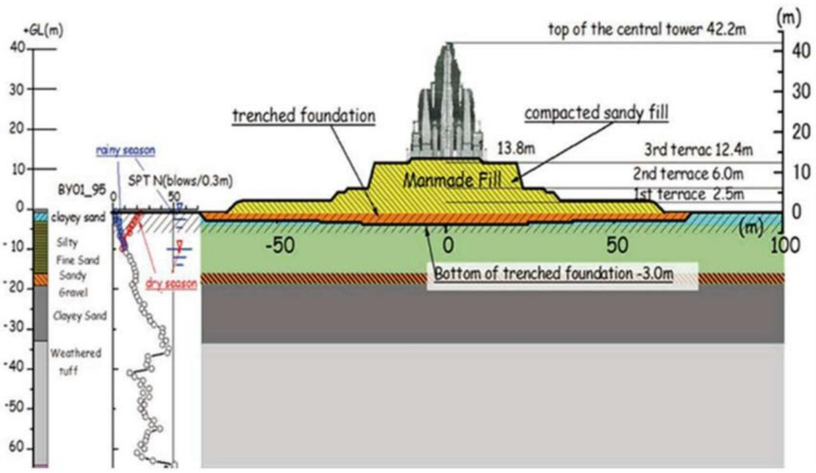

Figure 1. Bayon Temple, Angkor Thom ***Figure 2.*** Bayon Temple, Angkor Thom (JSA, 1995)

The vertical section is shown in Figure 2, and the results of boring revealed the ground consists of silty to clayey sandy soil down to GL-35m followed by weathered tuff.

SPT, N-values decreases at the depth near the surface in the rainy season compared to dry season. The N-values at the top surface increase from N=0 (rainy season in blue) to N=20 (dry season in red). This is caused by the increase of strength by decreasing water content by natural drying and run-off. Preliminary study of the existence of laterite blocks surrounding the base of the Tower is shown in Figure 3.

Foundation of Main Tower Bayon

The Central Tower is supported by the base stones of laterite as shown in Figure 4. Archaeological survey was performed in 2008. Hand auger boring was done below the base stones at 5 points. No stones were found beneath the base stones. Only densely compacted sandy soil was found. This implies the Main Tower has been supported by shallow and direct foundation of a sandy mound for more than 700 years without any special problems.

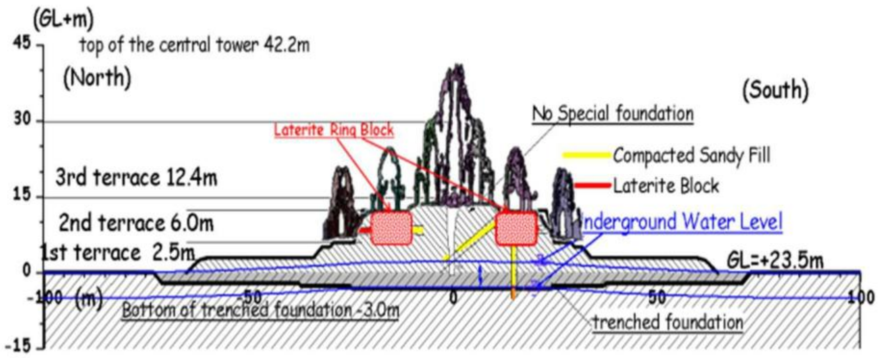

Figure 3. *Foundation Mound of Bayon Temple (JSA, 2012-2013)*

Boring Study of the Foundation Mound of Central Tower Bayon

EFEO (a French organization) excavated a vertical shaft with a diameter of about 2.5 m in 1933 and found Buddha statue fragments, and fragmented architectural elements. Backfilled soil was studied by geotechnical boring in 2009.[8] Another boring was performed at the top terrace in 2010.[9] Among the results, Standard Penetration Test and water content of the samples are shown in Figure 5.

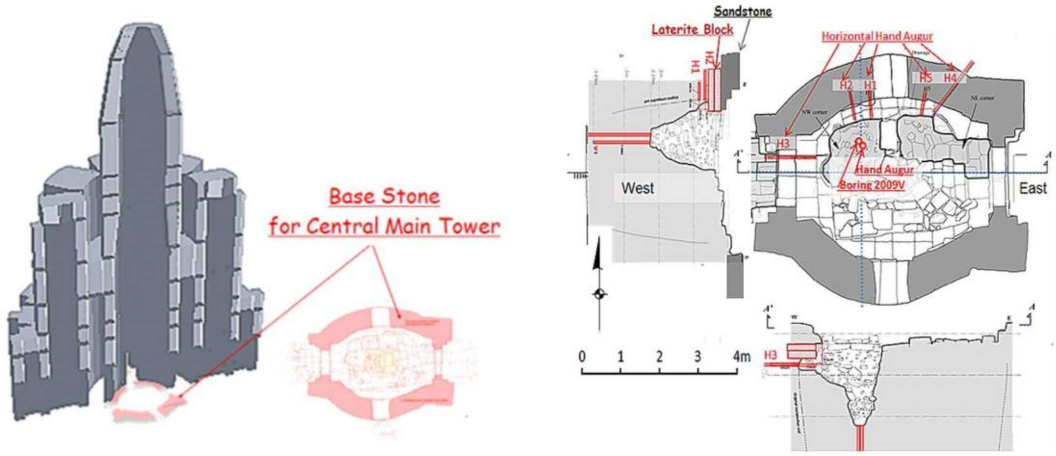

Figure 4. *Direct foundation identified by trench study beneath the base stone (Iwasaki et al.,2022)*

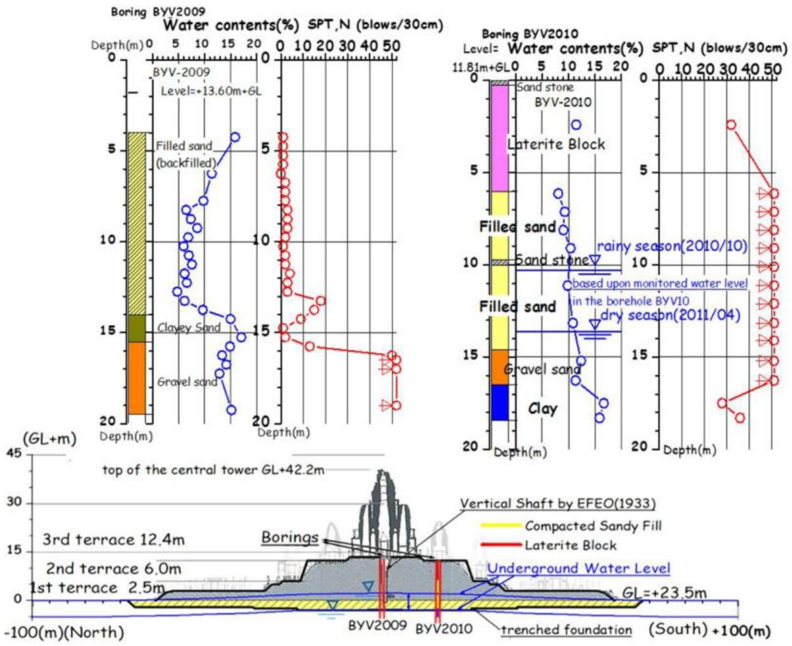

Figure 5. Borings at the centre and the outside of the foundation mound of Bayon (JSA, 1996)

Very small SPT, N values of N<=4 at the central shaft show the backfilled soil is in a very loose state without compaction. Another boring at the top terrace shows a layer of laterite blocks of about 6 m in thickness beneath the paved sandstone and followed by compacted sandy soil with extra ordinary large SPT, N-values larger than N>100~200, compared to the common values of N> 20~40 for compacted sand.

Additional study of horizontal as well inclined boring and electric survey was performed in 2011 and 2012, and the results are shown in Figure 6. After the construction of the second terrace mound, laterite blocks, capped with sandstone pavers, were installed for the construction of the top terrace, which was designed for the stability of the Central and sub-towers. The blocks do not support the load of the towers but prevent the horizontal displacement of the foundation soil beneath the direct base stones. This is one of the character defining elements of the authenticity of the foundation.

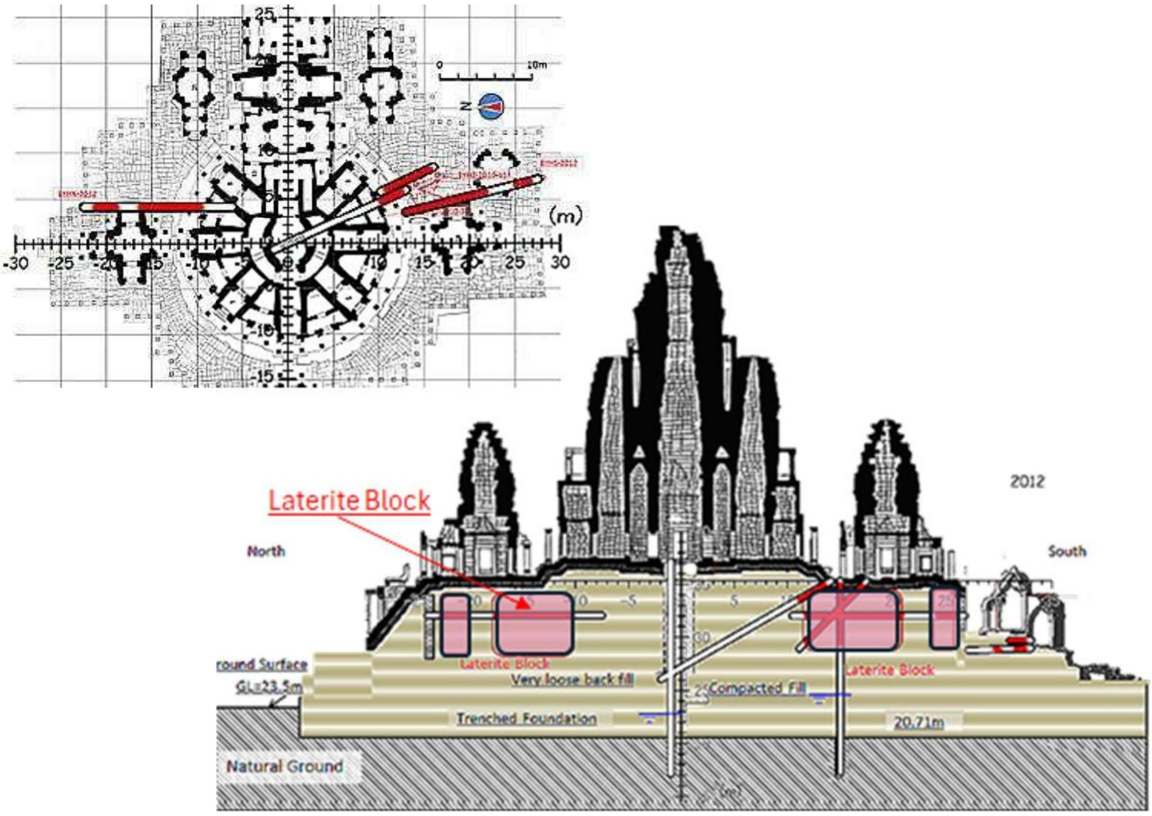

Figure 6. Borings at the centre and the outside of the foundation mound of Bayon (JSA[1], 2012-2013)

ANGKOR SAND

The foundation of the Central Tower of Bayon stands upon a thick sandy filled mound of 15 m in height by only simple direct shallow foundation. The standard penetration tests of the sandy mound show the value of SPT, N>100~200. Sampled soil looks like soft sand rock but collapses under submerged conditions within 10 minutes. as shown in Figure 7(JSA, 2012-2013).

The extra high strength is due to negative water pressure by the unique character of the grainsize distribution of the "Angkor Sand" shown in Figure 8(JSA[2]., 2012-2013). The unique character of the grainsize distribution resulted in the special capability of standing by the shallow direct foundation on thick sand mound under rainy climate conditions for more than 700 years. The grain size distribution is one of the characters defining element of the authenticity of the Angkor soil.

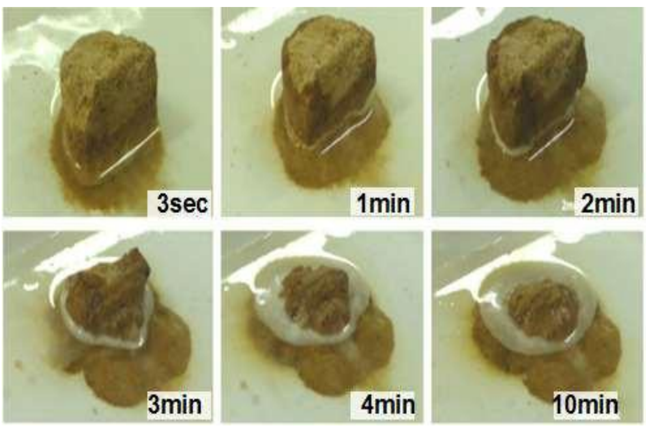

Figure 7. Collapse under submerged water condition

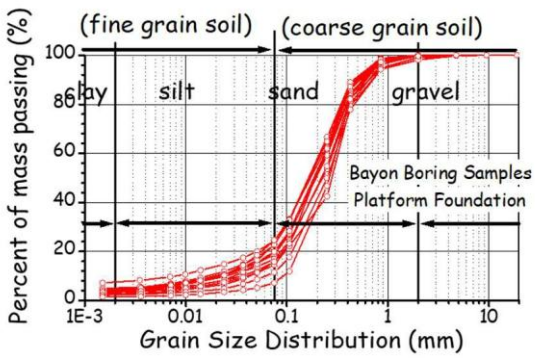

Figure 8. Grainsize distribution of Angkor Sand

Laboratory cone test for drying process

A series of cone bearing strength tests were performed for compacted Angkor Sand for different water contents. The soil was compacted with water content of around 15% in a plastic bowl. About 20 samples were prepared and placed outside of the laboratory for natural drying conditions.

Every day since the specimens were prepared, the bearing strength of each sample was obtained by Yamanaka Cone Tester as shown in Figure 9. The Yamanaka Cone Tester is uniquely designed and capable of obtaining strength from very soft to very hard soils.

The obtained changes of bearing strength with time as well as water contents are shown in Figure 10. The water contents gradually decreased from 15% to 5% for the first week and subsequently the decreasing rate became very small.

The bearing strength stays very low for the initial steps up to the 3rd to 4th days but, rapidly increases to high bearing strength. After one month, water was applied to the samples and, the bearing strength was found to become a very small value.

The mechanism of the high strength of sand in dry condition is show in Figure 11. Water films will be formed in dry conditions, and the meniscus of the free surface forms a concave shape due to capillary action and due to the negative pore pressure in strong suction. The shape of the grain-size distribution of Angkor Sand adds a unique character to maximize the strength.

Figure. 9 Yamanaka Cone Test

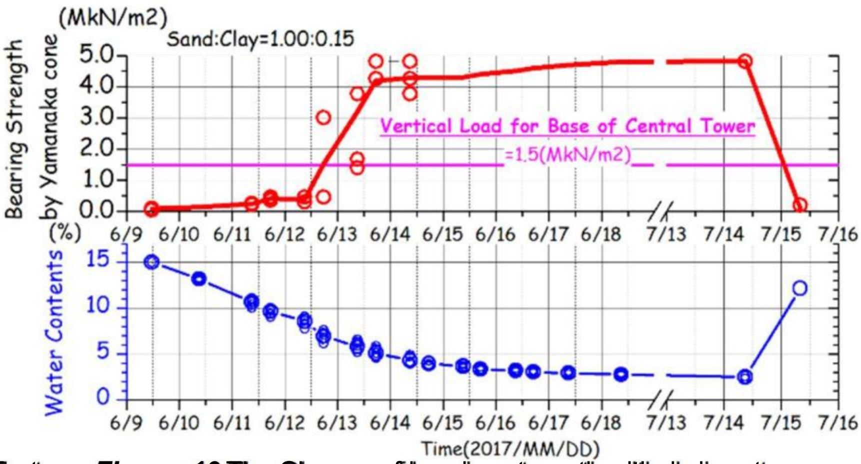

Figure. 10 The Change of bearing strength with drying steps (Iwasaki et al.,2022)

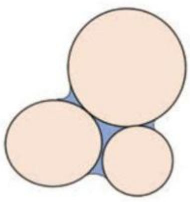

Figure. 11 Meniscus of water film

Table-1 Estimated vertical load on base rock foundation

	Cenral Tower	One SubTower
Unit mass(kN/m3)	23	23
Volume(m3)	967	156
Total mass(kN)	22,240	3,588
Contact area(m2)	15	7,64
Contact load(kN/m2)	1,482	470

The Central Tower consists of one Central as well as several sub-towers. The loads of these towers are estimated based upon the total volume of each tower assuming the unit weight of the sandstone as 23(kN/m3) as shown in Figure.11 and in Table-1. The averaged load of the Central Tower is estimated at about 1,500(kN/m2).

Characteristics of Strength of the Angkor Sand

Angkor Sand was compacted under saturated condition of water contents of W/C=15%. The sample was dried down to about W/C 4% and becomes self-standing as shown in Figure.13. A series of undrained triaxial tests was carried out with the results of friction angle =44.3^{o}, cohesion = 600 (kN/m2) as shown Figure.14.

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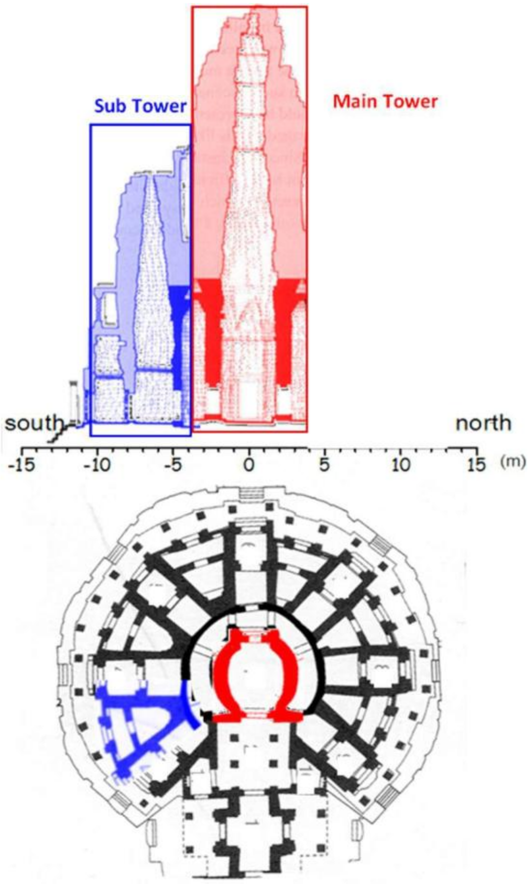


Figure. 12 **Foundation Base of the Tower**

Figure. 13 **Self Standing Specimen of the Sand**

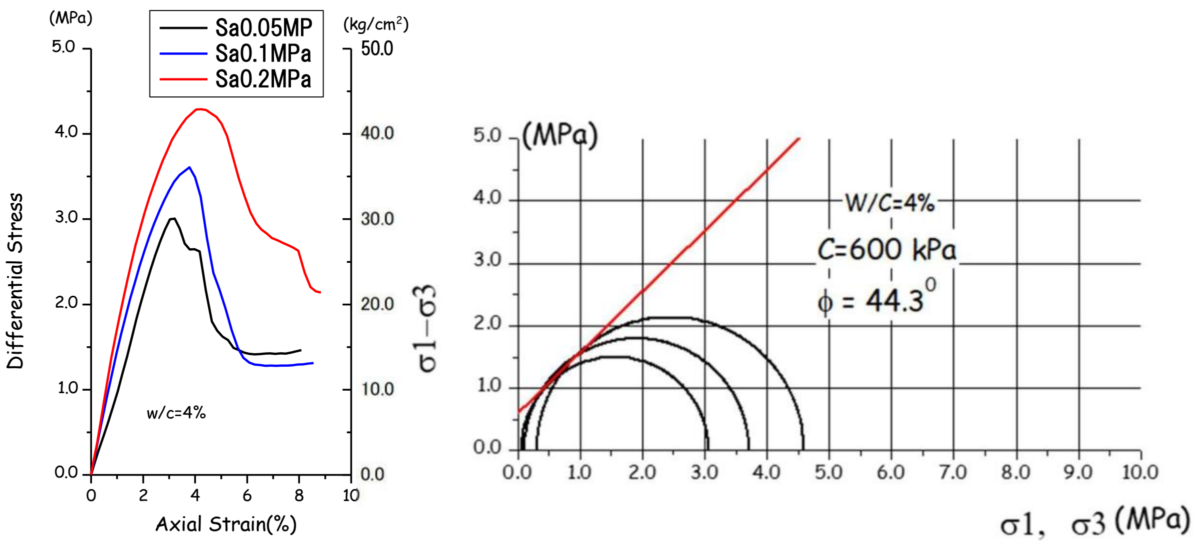


Figure. 14 **Undrained Triaxial Compression Test**

Safety of the Foundation of Bayon

The safety of the bearing capacity of the foundation of the Central Tower of Bayon for construction steps was carried out by 3D FEM Analysis by Plaxis as shown in Figure.15. The strength of the sand mound was assumed as f=30° of frictional angle and C= 150(kPa) as well as C=100(kPa). Figure.16.
When the cohesion decreases down to C=150kPa, plastic yielding will appear beneath the foundation mound. If the cohesion further decreases to C=100kPa, the plastic zone further develops near the foundation of the vertical shaft.

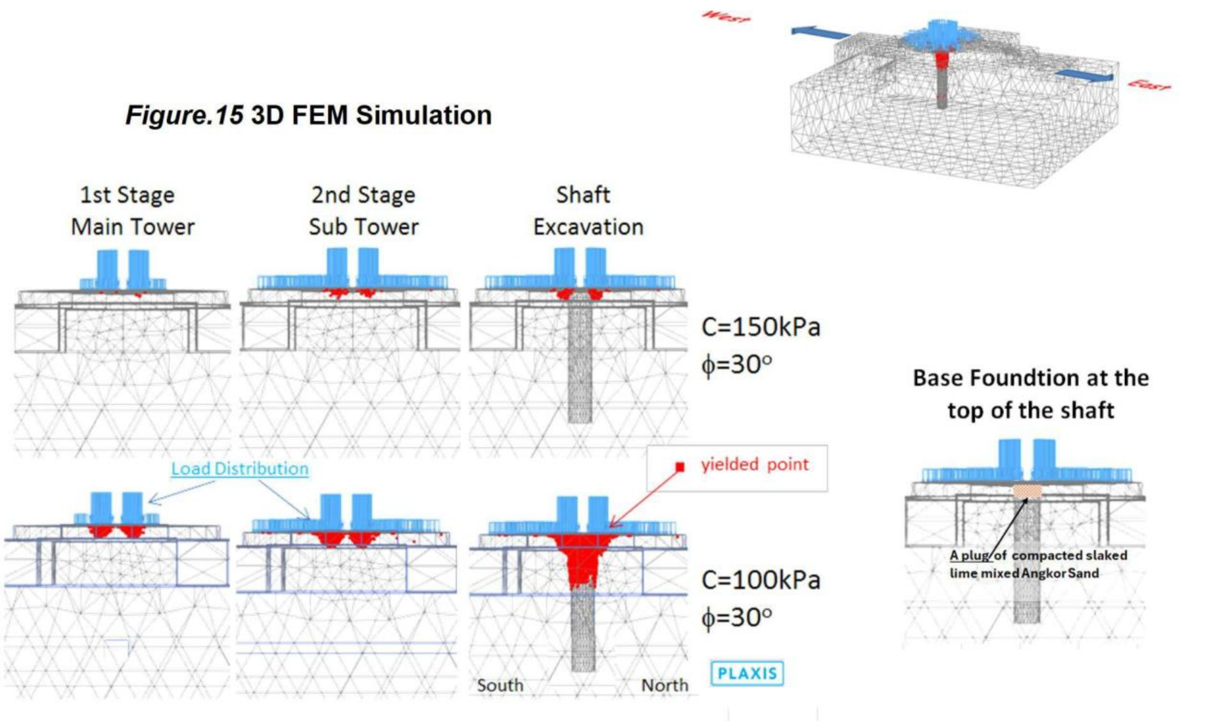


Figure.16 Plastic zones at foundation with construction steps **Figure.17** Plug at the top of the sha**ft**
Countermeasure against weakened foundation due to rainfall

Possible weakening of the foundation is anticipated by continuous long precipitation thus by rainwater infiltrating deep into the ground near the foundation as shown in Figure.16. To prevent the failure, the top of the shaft was strengthened by compacted slaked lime mixed with Angkor Sand forming a plug with 1.0 m in thickness as shown in Figure.17.
When the strength decreases to C=150kNPa and f=300, no plastic yielding was analysed

Safety of Sand Mound in Heavy Rain Squall

Moisture sensors were installed at several depths of GL-0.1m, -0.5m, and -0.9m beneath the paved stone in the top terrace as shown in Figure 12. When it rains, the moisture increases at every depth with the smaller changes and much delay time for the deeper points.
This type of squall brings very heavy rain but, with rather short duration. Most of the rainwater runs out along the surface of the mound and a rather small amount of the rain infiltrates into the mound. When the rain stops, the moisture quickly decreases at every depth.

Under the present climate of squall, rainwater is not likely to infiltrate deep enough to decrease the bearing capacity of sand mound that supports the Central Tower. However, it may change the situation in a potential global warming climate, when the rain changes from squall to rather long and continuous precipitation as shown in Figure 18.

CONCLUSIONS

The foundation of the Bayon Temple was found to stand upon a thick sandy mound by direct shallow foundation. Angkor Sand shows the special character of bearing strength as a function of water contents as an increase in strength with the decrease of the water contents. However, the strength drops dramatically when the sand in submerged in water.

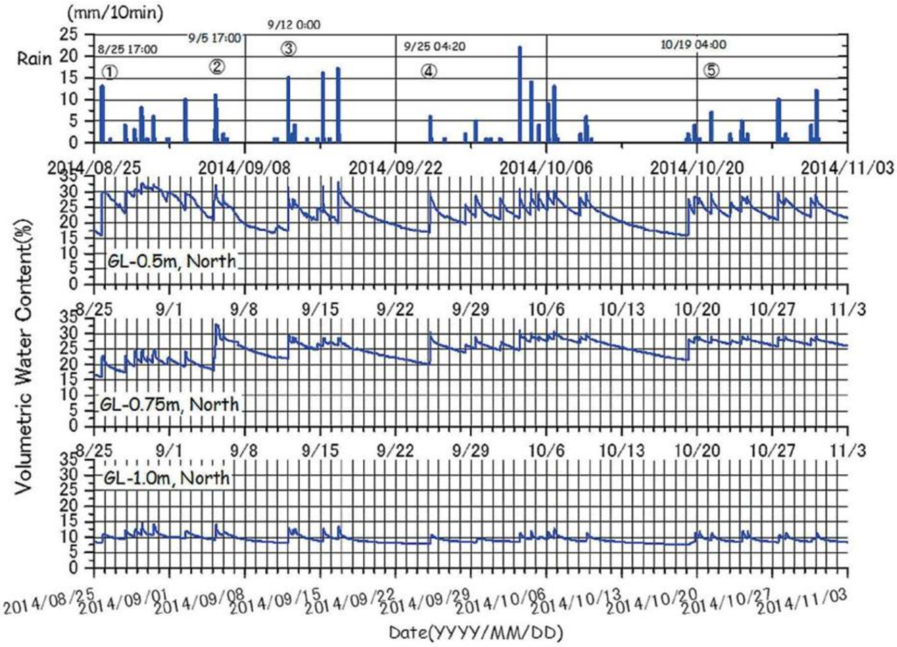
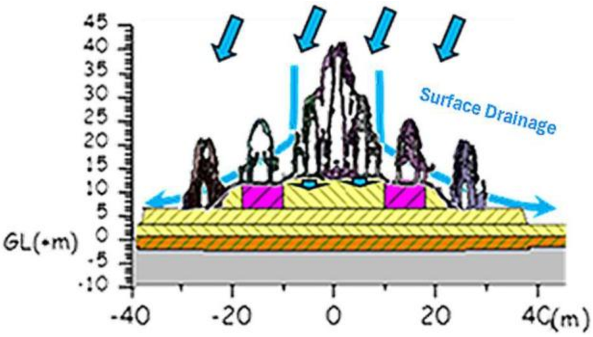


Figure 17 Monitored moisture change in rainy season (JSA, 2014-2015)



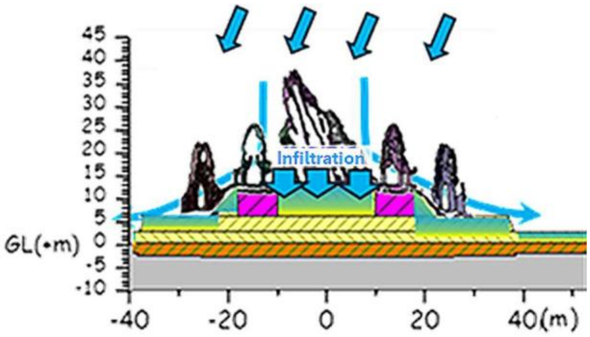


Figure 18 Squall type rain (short time rain) at present ***Figure 19*** Warm climate type (long time rain)

With the present climate of squall conditions, the sand mound keeps an unsaturated condition, however, the anticipation of continuous rain conditions will result in saturation of Angkor Sand resulting in the degradation and collapse of the sand mound of Ankor monuments in the future. Some countermeasures are being prepared to protect the Central Tower. Applicability to other Angkor monuments is under consideration.

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