The Authenticity and Integrity of the Soil and the Foundation of the Heritage Structure of Bayon Temple, Angkor

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Abstract. Soils and foundation of Bayon temple of Angkor Thom has been studied since 1994 by Japanese Government Team for Safeguarding Angkor (JSA). The main tower of Bayon of 32 m in height from the base foundation mound which consists manmade fill of 14 m in thickness. The foundation was studied and found as a simple shallow direct foundation. This is just like a10 story RC building standing upon thick manmade sand fill without such a deep foundation with piling. At present, such a structure based upon thick sandy fill will lose the foundation stability in rainy season under monsoon climate of South-eastern Asia. The amazing mechanism attributed to the monument the standing for 700 years has been revealed as the unsaturated characteristics of well compacted silty sand.

Keywords: Bayon temple · foundation mound · direct foundation · Kaolin sand · Angkor

1 Bayon Temple, Angkor

The Bayon temple, the Cambodian Buddhist pyramid temple at the center of the heart of the ancient city of Angkor Thom, is the symbolic center of the Khmer empire of the late 12th early 13th century. The Bayon temple was constructed by King Jayavarman VII (1181–1220). In addition to the Central Tower, 54 towers with faces at each four sides are located on a man-made soil mound with three stepped terraces as a trenched foundation. [1] In 1994, Japanese Government Team for Safeguarding Angkor (JSA) started the study of Bayon temple in various field including geotechnical engineering (Fig. 1).

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Fig. 1. Bayon temple

2 Foundation System and Ground Conditions

2.1 Trenched Foundation and Ground Condition

Archaeological team of JSA studied the underground structure of the northern side of the first terrace extending to outside of the temple as shown a long trench of N2-N3 in Fig. 2. The result of the trench is shown in Fig. 3. The original ground surface was excavated 2–3 m not only the inside of the temple but also the outside ground of about 10 m from the outer gallery and backfilled with compacted sand. After the backfilling, further additional filling was made to construct the first terrace of the mound.

The section view of the Bayon temple is shown in Fig. 3, which show three stepped terraces with height of +2.5 m, +6.0 m, and 12.4 m. The main tower of Bayon stands upon the top of the mound of +13. 8m which is 42.2 in height.

JSA performed a geotechnical boring to about 100 m at northern yard outside of the temple. The ground consists of sandy soils down to around GL-35 m with several silty layers followed by weathered tuff layers as shown in Fig. 4. SPT, N-values increases with depth from N = 0 to 50.

Underground water levels show seasonal change from the top of the ground surface at the end of rainy season to the lowest level of GL-5.0 m at the end of the dry season. SPT-N-values increases during the dry season as shown in Fig. 4.

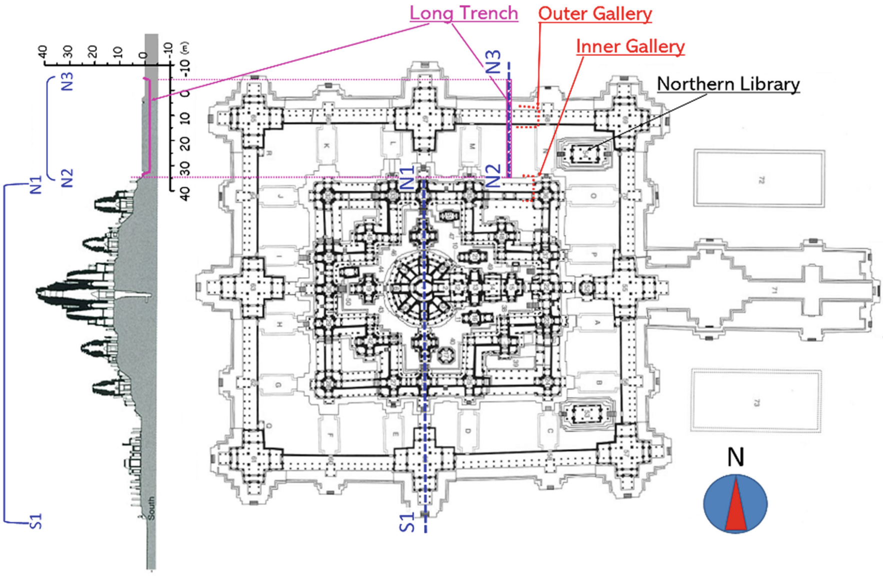

Fig. 2. Plan of Bayon temple with position of the long trench

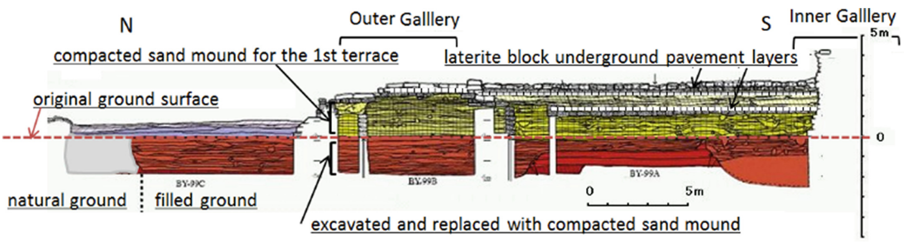

Fig. 3. Archaeological section of the long trench at the north side of Bayon temple

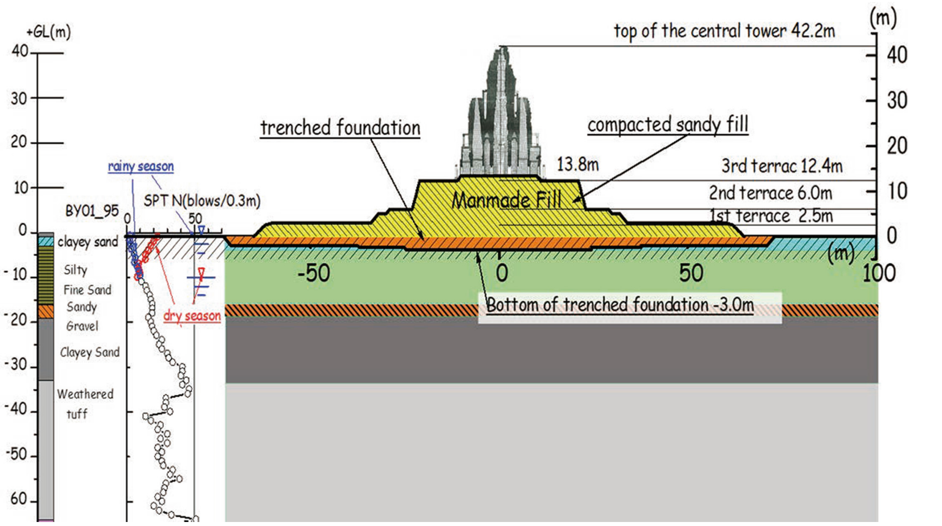

Fig. 4. .

2.2 Direct Shallow Foundation

JSA conducted 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 masonry structure.

Horizontal hand auger tests were carried out at 5 points as shown in Fig. 5 and has resulted in finding no supporting stones, but only very dense sandy fill beneath the base stone support. [2] The direct shallow foundation was confirmed as the foundation type of the main tower of the Bayon.

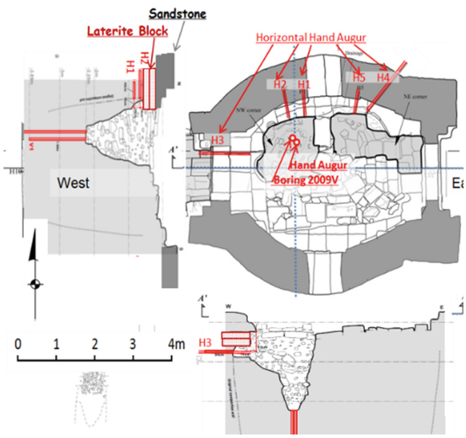

Fig. 5. Archaeological excavation of the base foundation

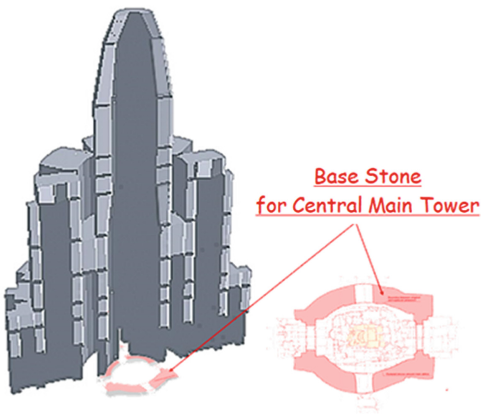

Fig. 6. Direct Shallow foundation

2.3 Foundation Mound with Vertical Shaft at the Center

EFEO, a France sponsored organization, in 1933 dug out the center of the base of the main central tower below the pavement and found a fragmented Buddha statue. It was recorded that the vertical shaft had been backfilled.

Geotechnical boring was performed at the backfilled vertical shaft and at the top terrace of the original manmade filled mound as shown in Fig. 7.

The backfilled soil for BY09 was found in a very loose state of SPT, N-values N $<$ 4 of BYV2009. Another boring of BYV2010 at the top terrace shows the sandy fill lower than GL-6m of N = 100–150, which is a very large value compared to the expected values of 20–40 for common filled sandy soil [3, 4].

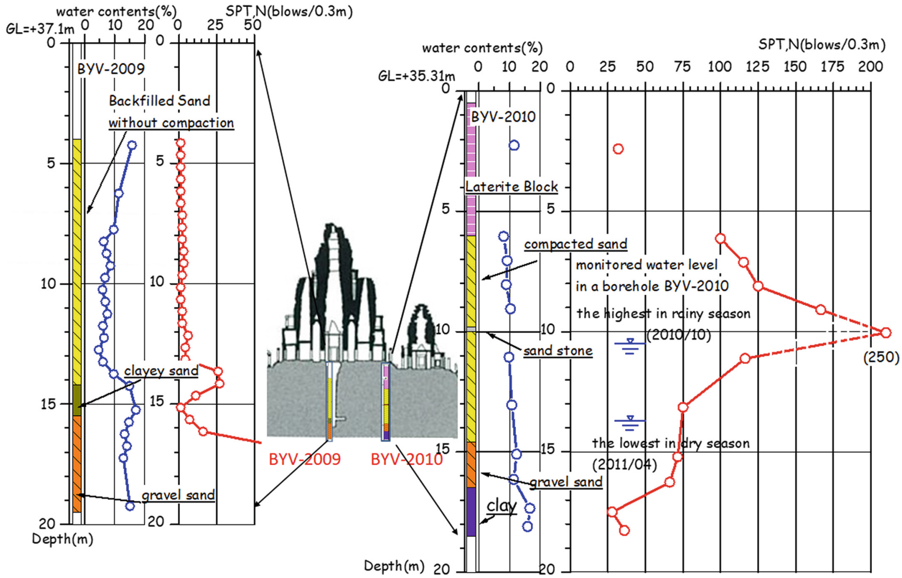

Fig. 7. Borings at the vertical shaft and at top terrace

3 Characteristics of Sandy Soil of the Foundation Mound

3.1 Grainsize Distribution of the Filled Soil

The grain size distributions of the sampled soil by the boring of BYV2010 and BYH2010-30 as well as other sites are shown in red and blue colour for sand and clay soils respectively in Fig. 8. The sandy soil is filled soil and the entire samples of the filled soil show the same distribution, which implies very uniform fill material. The silty/clayey fill was found at the boundary of such zone to prevent seepage as laterite blocks retain the sandy fill mound. The ancient Khmer engineers in clearly identify these two types of clayey fill and sandy fill.

3.2 Weakening Strength with Water Contents

The obtained SPT, N-values are plotted against water contents of the sampled soils for both borings and is shown in Fig. 9 No relationship is found for BV09 of the backfilled soil; however, the decrease of water is found to result in the increase of the SPT, N-values for boring BV10.Sampled soil of very high SPT-N-value for boring BYV2010 looks like soft sandstone as shown at the upper left position of Fig. 10. When the sampled soil was put into water, it sucked water, and finally collapsed within 10 min as shown in Fig. 10.

A series of laboratory tests were performed to see how much strength changes due to the decrease of the moisture contents. More than 25 samples in containers were prepared with water content of 15%, which almost creates a 100% saturated condition. The samples were placed outside of the test room and the water evaporated from the sample and the water content decreased day by day. Yamanaka cone penetration tester was used to evaluate the bearing strength of the soils as shown in Fig. 11. The results are shown in Fig. 12 and It shows clearly an increase of strength more than 50 times due to the decrease of the water content.

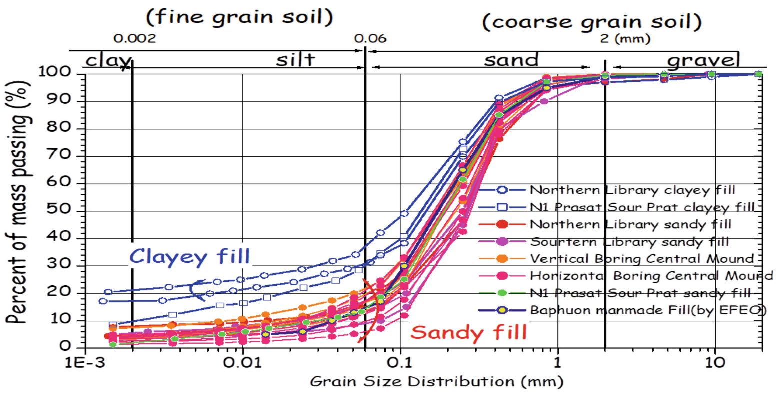

Fig. 8. Grainsize distribution.

3.3 Mineral Components of the Filled Sand

Micrograph of the section of the sample is shown in Fig. 13, where the round shape of sand is seen filled with clay material. X-ray diffraction analysis was applied to the fine particle of the foundation sand is shown in Fig. 14. In addition to quartz, halloysite (Kaolinite group) was detected as the clay component. Compared to other clay minerals, the power to absorb water is very small and does not swell and the volumetric change is very small and stable compared to montmorillonite.

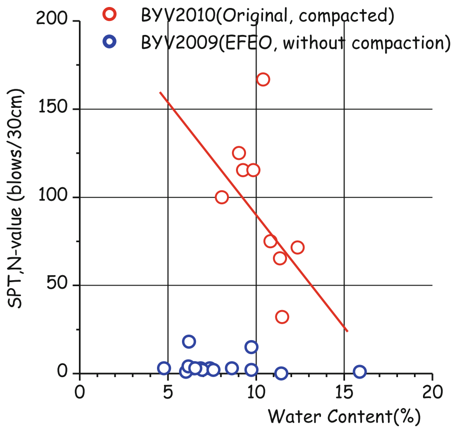

Fig. 9. SPT-N values vs. water contents

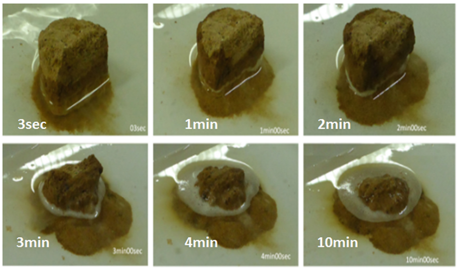

Fig. 10. Collapse of stiff filled sand in water condition

Fig. 11. Yamanaka Cone test

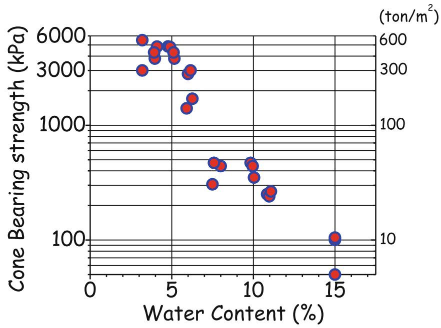

Fig. 12. Strength increase with decrease of water

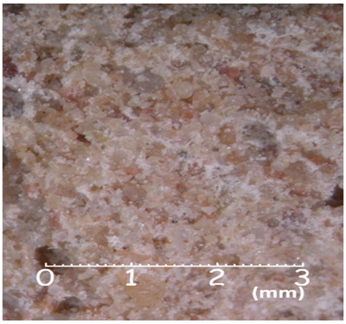

Fig. 13. Micrograph of sampled soil

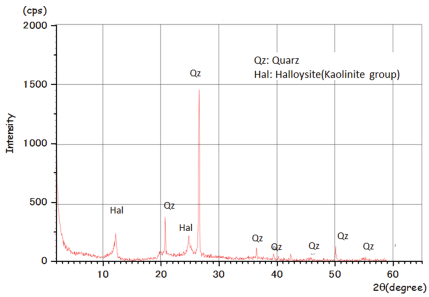

Fig. 14. X-ray diffraction analysis for the filled soil

3.4 Expected Mechanism of Dramatic Change of the Strength and Water Contents

A possible mechanism of the increase of the strength with the decrease of the water is the effects of the meniscus of the water film created between nearby particles to make bridging the particles as shown in Fig. 12.

The vacuum suction pressure of the water inside the meniscus is increased with the decrease of the radius of the meniscus. The increased vacuum suction pressure attracts soil particles that creates the very large strength as shown the extra-large SPT, N-values of N = 100–200 as shown in Fig. 3. However, when the soil is submerged in water, the water meniscus disappears, and the suction pressure diminishes resulting in the minimum level of the cohesion strength by kaolin clay. The sudden decrease of the strength with collapse as shown in Fig. 6 is possible under free boundary conditions. In the field, the densely compacted soil with some confinements keeps its stability with the large frictional angle.

(a) Meniscus with large diameter (b) Meniscus with small diameter

Fig. 15. Vacuum suction of water within meniscus (a) small attraction (b) large attraction

3.5 Field Monitoring of Water Contents by Rain

When rain falls and infiltrates into the mound, the water content within the mound will be increased. Monitoring the change of the moisture in the soil mound was performed in the platform mound at Bayon temple [5]. Moisture sensors (Fig. 16) had been installed at several depths at GL-0.5, -0.75, and -1.0 m and the monitored results are shown in Fig. 17 with rain fall results. As expected, the volumetric water contents increases when the rain falls.

In Fig. 17, the monitored results at S-point of two cases of rain events are shown. The earlier case shows the increase of the volume water content are found at the upper two depth points. The deepest point at GL-1.5 m, the volume water content keeps the constant value, which means the infiltrated rainwater reached to the upper two sensors but did not reach the bottom one. The amount of the rain was too small to provide enough rainwater in the earlier case. In the latter case, the sensor at the bottom of GL-1.5 m increases with a time delay of about 1.5 h compared to the top sensor at the GL-0.5 m. The infiltration rate is about 1.0 m/1.5h.

When the heavy rain stops the volume water content begins to decrease due to evaporation, and to some extent drainage. The present rain style is “Squall” which begins suddenly and continues for a few hours in heavy intensity and stops. In the squall type rain, rainwater penetrates from the surface to only a few meters, and did not cause fatal failure.

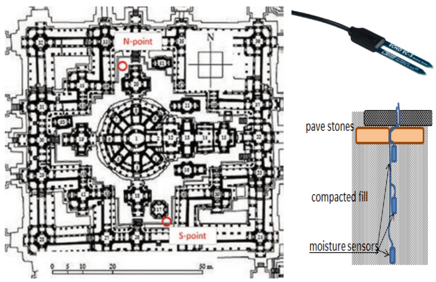

Fig. 16. Monitoring points and sensor

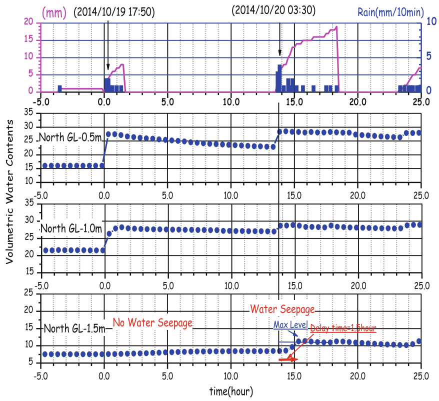

Fig. 17. Monitored results of water in the filled mound

4 The Authenticity of the Foundation of Main Tower of Bayon

As discussed in the previous sections, the shallow direct foundation of Bayon has been standing for about 700 years because of the special character of sandy filled mound. Figures 18 and 19 compares the stability of foundation in common sand fill and that of Bayon temple. In common sand fill, RC10 story building as well as the main tower of Bayon with shallow direct foundation will collapse. Pile foundation is the common design procedure at present.

Sand filled mound of Bayon temple shows extraordinarily large strength in dry, but weakened in wet and saturated conditions. Main tower of Bayon has been supported safely with direct foundation in the sand filled mound of Bayon temple in monsoon climate with “squall type rain.”

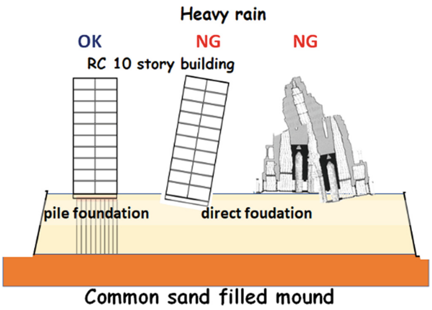

Fig. 18. Common sand filled mound

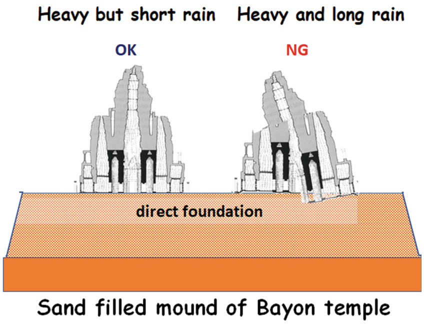

Fig. 19. Sand filled mound of Bayon temple

The character defining elements of the foundation system of Bayon temple consist of several factors as follows:

1. Trenched foundation extending to outside of the temple
2. Three stepped mound is constructed by compacted uniform sandy soil
3. Uniform grain-size distribution of sand with 10–20% of fine grain contents
4. Very large strength of the sandy fill in dry but weakened under water
5. Thick laterite block surrounding the base of the foundation of main tower from the 2^{nd} step

5 Proactive Countermeasures Against the Risk Inherent with Global Warming

5.1 Anticipated Risk to the Heritage Structure with Global Warming

In the coming climate warming period, the rain type of "squall" at present is anticipated to change to "long and heavy" rain. This change of climate could result in the deeper penetration of rainwater into the sandy filled mound and weaken the foundation mound. As noted in Fig. 7, the vertical shaft with backfilled soil in very loose state could cause inwards displacement and finally failure of the shaft resulting the collapse of the main tower of Bayon.

Based upon a serious of borings at the mound, the basic structure of the foundation is found as the shallow direct foundation on sandy soil which is surrounded by a thick laterite blocks of 6 m in thickness as shown in Fig. 20.

The mechanical strength of soil is generally expressed frictional resistance angle and cohesion. The very dense compacted sand is assumed to have a constant value of the shear resistance internal frictional angle as $\phi = 40°$. The cohesion may be assumed as the highest uniaxial compression strength value of $Qu = 1000$ (kN/m^2) in dry state and the lower one of $Qu = 5$ (kN/m^2).

A 3D FEM model of the foundation was created to simulate the mechanical behavior by weakened sandy filled mound as shown in Figs. 21 and 22. Plastic failure points are concentrated into just beneath the Central Tower and the outer edge of the surrounding foundation step. zones. Direction of the displacements beneath the foundation is not only downwards but also inwards which is caused by the very loose state of the sand. Direction of the displacement at the outer edge of the foundation mound is a horizontal outwards direction.

It is shown that the effects of the weakened filled soil by the long and heavy rain will cause plastic zones in the foundation and deformation of the inwards and outwards directions at the inside of the shaft and at the outer edge of the mound, respectively (Table 1).

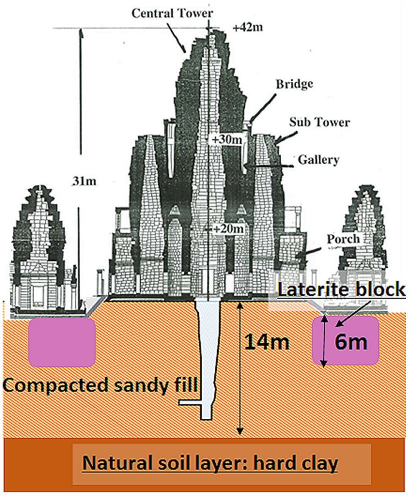

Fig. 20. Foundation of main tower of Bayon

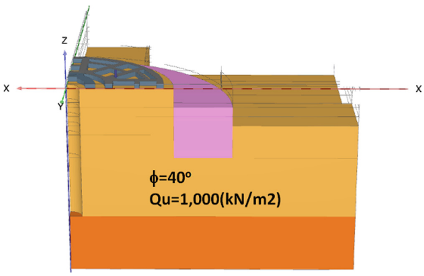

Fig. 21. Strength of sandy fill at present

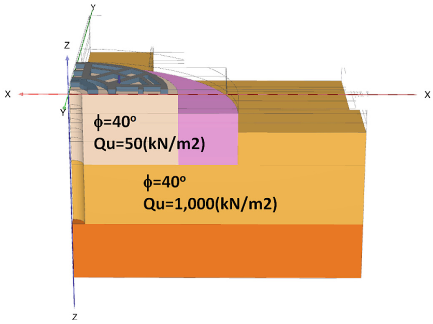

Fig. 22. Weakened sandy fill beneath the main tower

5.2 Proactive Counter Measures Against the Risk of Global Warning to Central Tower of Bayon

The plastic zone near the vertical shaft is found to concentrate just beneath the base stone of the central tower within about three meters. Inwards horizontal displacements

Table 1. Load to direct foundation

	unit	Central Tower	A sub-tower
Unit mass	kN/m^3	23	23
Vol	m^3	967	156
mass	kN	22,240	3,588
area	m^2	15	7.64
load	kPa	1,482	470

Central tower section is colored in red and sub-tower in blue in the Fig. 23 below.

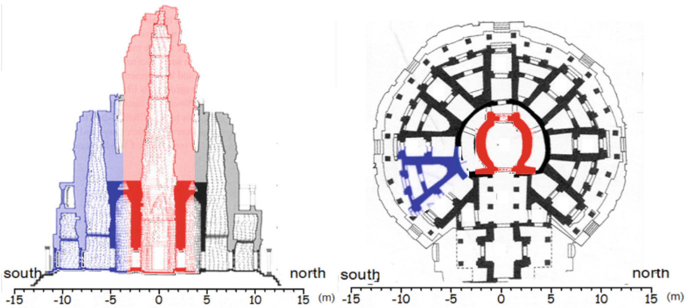

Fig. 23. Sections of the main tower and a sub-tower

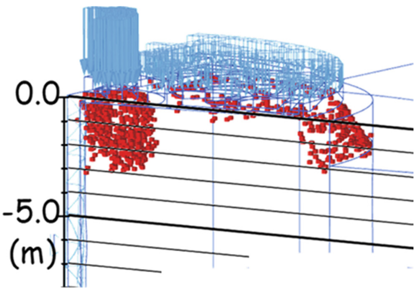

Fig. 24. Plastic yield zone

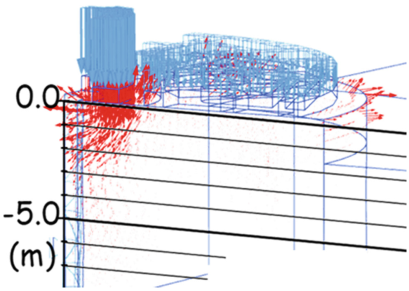

Fig. 25. Displacement vector

also appear associated with the plastic zone beneath the base stone within three meters. Another plastic zone is recognized around the edge of the foundation mound with outwards displacements. The simplest measure to keep the integrity of the characteristics of the sandy fill in Bayon temple is to provide impervious layers beneath the surface stones.

Among several methods of interventions available, three basic principles of conservation of cultural heritage, ie.1. minimum level intervention, 2. incremental approach, and 3. Removable/reversible measures are to be considered.

The proposed method at present consists of the following four methods to prevent the rainfall penetration into foundation mound and strengthening the upper portion of the vertical shaft from the top to about 5 m in depth as shown in Fig. 26.

A. To close openings at the top of main and sub-towers to prevent rainwater infiltration.
B. To replace soils under stepped stone with lime mixed sand to stop infiltration of rainwater.
C. To shield the gaps between paving stone.
D. To strengthen the upper part of the vertical shaft at the central base of the main tower.

In addition to the above-mentioned prevention of rainwater penetration into the foundation mound, the present surface drainage system should be studied. If the capacity of drainage is smaller than the anticipated rainfall under the warm climate, necessary modification should be arranged.

5.3 Monitoring the Moisture Change During Rain

Monitoring system of rainfall at the Bayon and moisture contents in the filled mound should be established. There are two methods available to monitor the change of the water contents of the filled mound. The direct method is to install moisture sensors at several depths as shown in Fig. 16. Another method utilizing a geophysical method such as electric survey, which utilizes the change of electric resistance of the ground with water contents However, this method does not give precise changes of moisture at points, but rather evaluates the moisture condition by the change of electric resistivity at different time of surveys. The combination of these methods is expected to provide overall better understanding of the field situation and are recommended to be adapted.

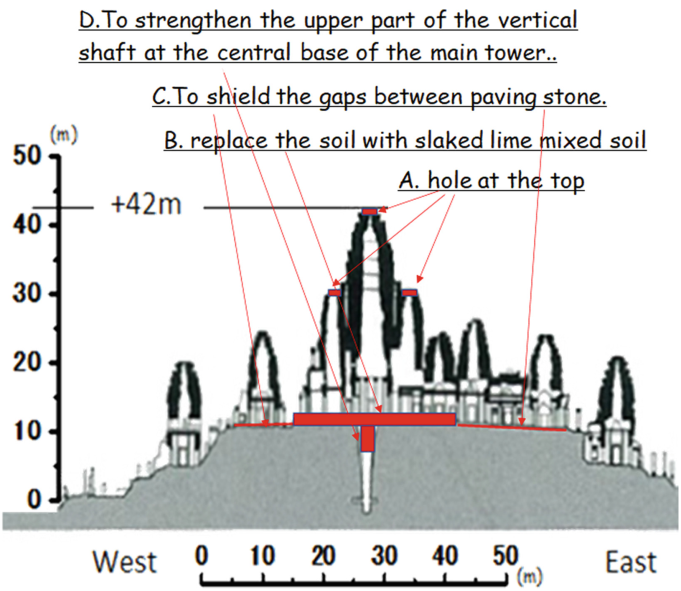

Fig. 26. Countermeasures against water penetration to the foundation mound

6 Conclusions

The filled sandy soil of the foundation mound for Bayon temple was identified as kaolin sand very stiff in unsaturated dry condition, but easily collapsed under submerged conditions. In the past and present, the rain type has been "squall type" of very heavy rain fall but rather in short duration and resulted in a cyclic process of infiltration of rainwater and evaporation with no damage within the foundation mound. However, in the coming warm climate, the rain is anticipated to be not only heavy, but also continuous in duration which may bring deep infiltration of water into the foundation mound resulting in the collapse of the main tower. Against the anticipated failure caused by global warming events, a proactive method is proposed as the minimum counter measure to keep the integrity of the character defining elements of the authenticity and protect the Bayon tower.

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