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The Amazing Mechanism of the Standing for 700years of the Tall Masonry Stone Tower of 32m in height on Manmade Sandy High Mound by Shallow Direct Foundation, Bayon Temple, Angkor, Cambodia

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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 32m in height from the base foundation mound consists of manmade fill of 14 m in thickness. The foundation was studied and found as a simple shallow direct foundation. This is just like a 10 story RC building standing upon thick manmade sand fill without such a deep foundation as piling. At present, such a structure based upon thick sandy fill shall lose the foundation stability in the dry season under the monsoon climate of South-eastern Asia. The amazing mechanism, standing for 700 years, has been identified as the unsaturated characteristics of well compacted silty sand.

1 Bayon Temple

The Bayon temple, the Cambodian Buddhist pyramid temple at the centre of the ancient city of Angkor Thom, is the symbolic centre of the Khmer empire. 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 trenched foundation. [1]

Fig.1 Bayon Temple

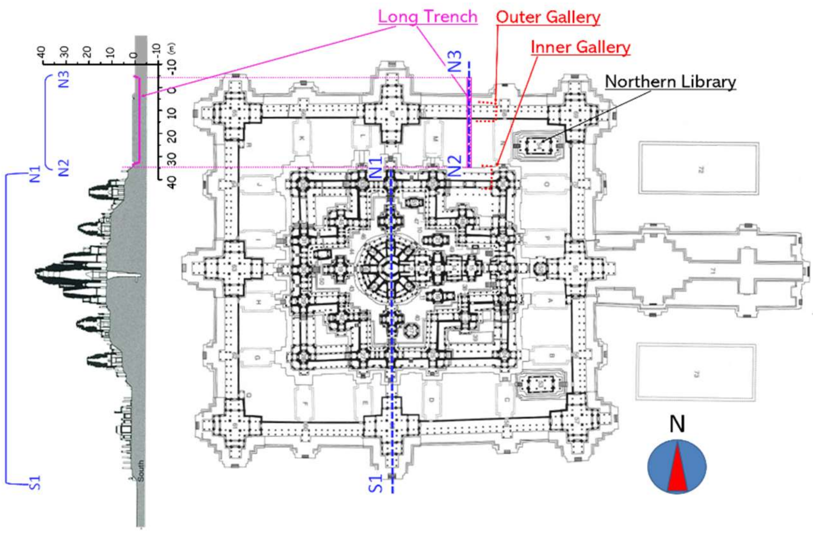

Fig.2 Plan and vertical section

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2 Foundation System

2.1 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 and has resulted in finding no supporting stones, but only very dense sandy fill beneath the base stone support as shown in Fig.3. [2]

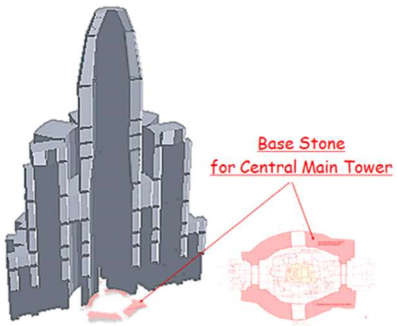

Fig.3 Direct shallow base stone Main Tower

2.2 Foundation mound with vertical shaft at the centre

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

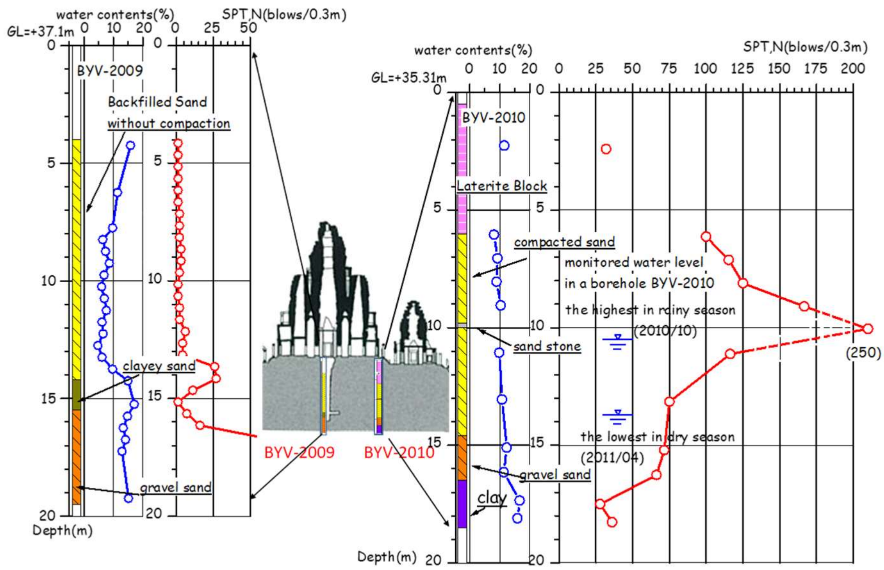

Fig.4 Borings at the vertical shaft and at top terrace

Geotechnical boring was performed at the backfilled vertical shaft and at the top terrace of the original manmade filled mound as shown in **Fig**. 4.

The back filled 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]

3 Characteristics of sandy soil of the foundation mound

3.1 Grain size 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 Figure 5. 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 block and sandy fill mound. The ancient engineers in Khmer clearly identify these two types of clayey fill and sandy fill.

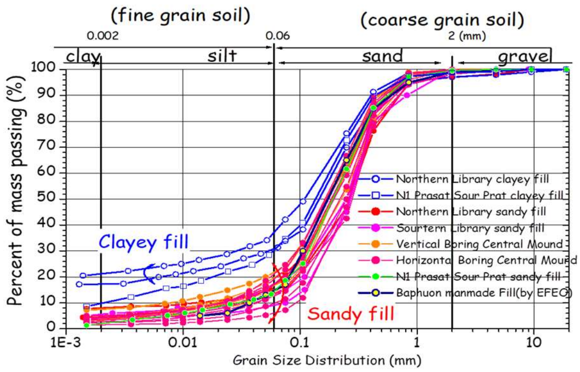

Fig.5 Grain size distribution of the soils of filled mound.

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 shown in **Fig**. 6. 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.

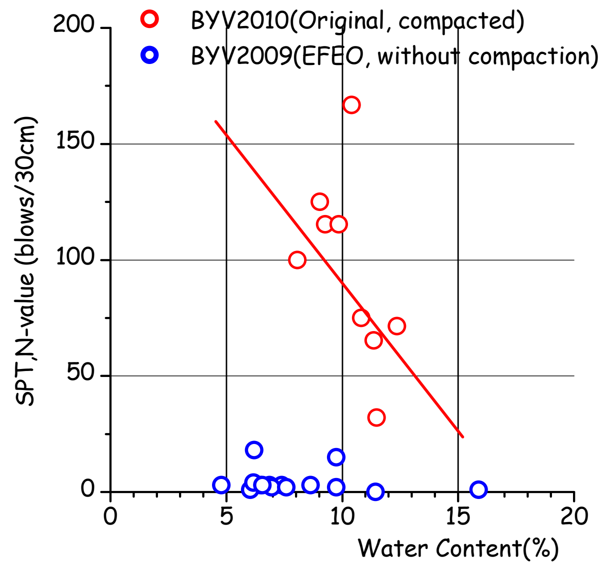

Fig.6 SPT-N-values vs. water contents

Sampled soil of very high SPT-N-value for boring BYV2010 looks like soft sandstone as shown at the upper leftist position of **Fig**. 7. When the sampled soil was put into water, it sucked water, and finally collapsed within 10 minutes as shown in **Fig**. 7.

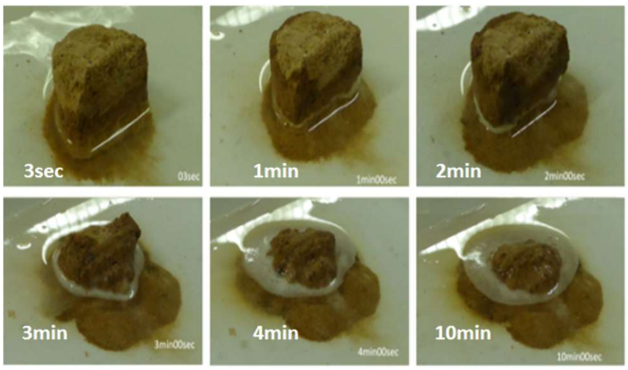

Fig.7 Collapse of the sampled sandy fill in water

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.

Fig.8 shows Yamanaka Cone Tester which is uniquely designed to measure cone bearing strength to cover a wide range strength around from 50 to 5,000 (kN/m2) by the changing diameter of the cone base.

Yamanaka cone penetration tester was used to evaluate the bearing strength of the soils as shown in **Fig**. 9. The results are shown in **Fig**. 10 and It shows clearly an increase of strength more than 50 times due to the decrease of the water content.

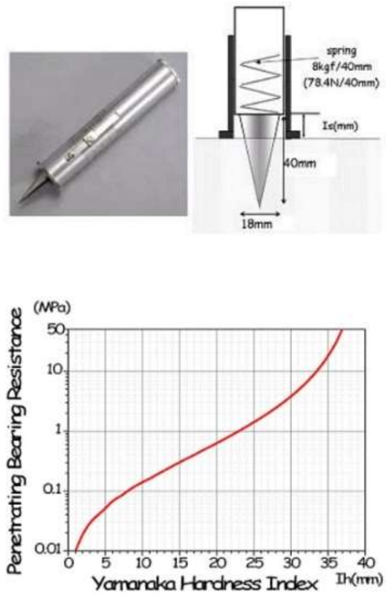

Fig.8 Yamanaka Cone Tester

Fig.9 Yamanaka test for filled sand with samples of different water content by drying step

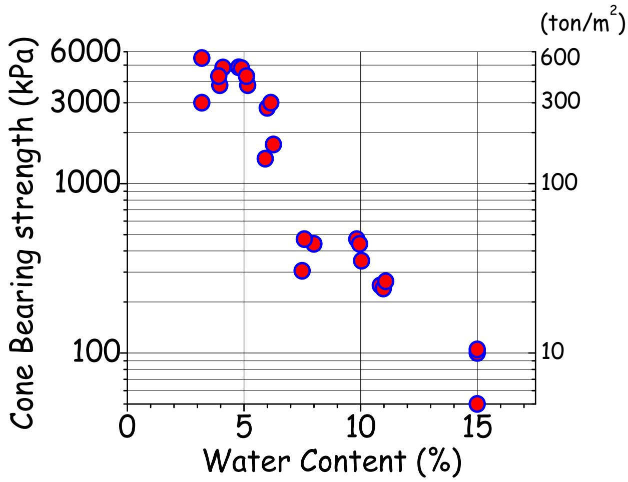

Fig.10 Cone bearing strength vs. water content.

3.3 Mineral component of the foundation sand

Micrograph of the section of the sample is shown in **Fig**. 11, where the round shape of sand is seen filled with clay material. X-ray diffraction analysis was applied to the fine particle of the f foundation sand is shown in **Fig**. 12. In addition to quartz of sand, 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.

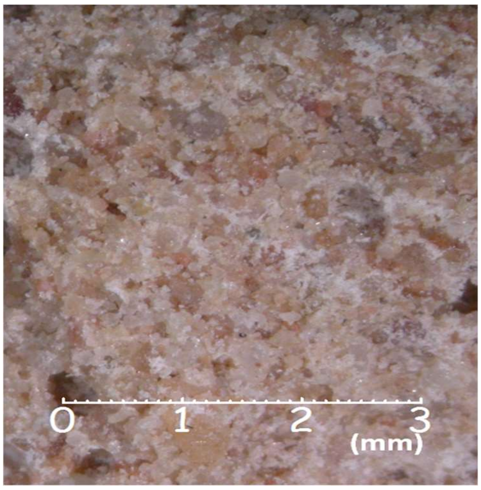

Fig.11 Base stones of Main Tower

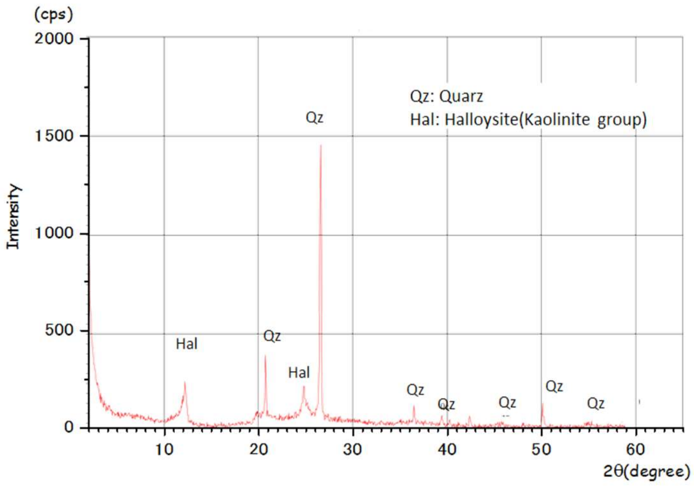

Fig.12 X-ray Refraction analysis for the filled soil

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 meniscus of the water film created between nearby particles to make bridging the particles as shown in **Fig**.13.

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**. 4. 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**. 7 is possible under free boundary conditions. In the field, the densely compacted soil with some confinements keeps its stability with the large frictional angle.

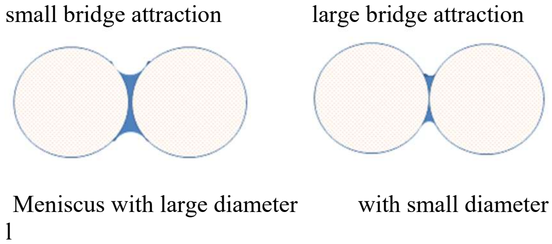

Fig.13 Vacuum suction of water within meniscus

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 **(Figs** 14, 15) had been installed at several depths at GL-0.5, -0.75, and -1.0m and the monitored results are shown in **Fig**. 15 with rain fall results. As expected, the volumetric water contents increases when the rain falls.

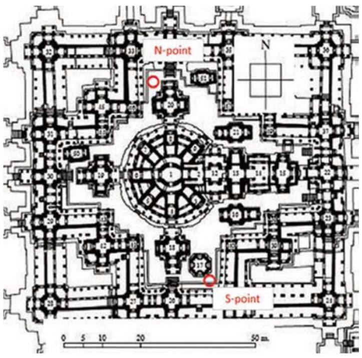

Fig.14 Monitoring points **Fig.15** Moisture sensor

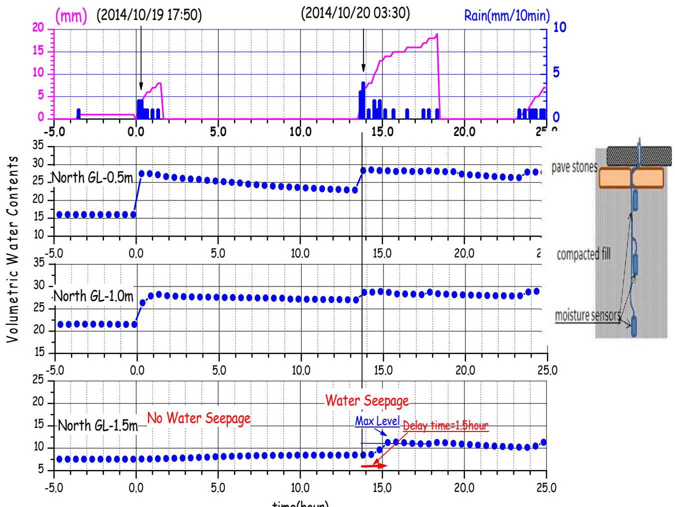

Fig.16 Monitoring of water content in the filled mound

In **Fig**. 16, 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,

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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 hours compared to the top sensor at the GL-0.5 m. The infiltration rate is about 1.0 m/1.5hours.

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.

3.6 Failure of Baphuon temple in 1943

Heavy rains have caused damages and failures of the temples and other structures in Angkor. Recent records of these failures are as follows,

1943 Baphuon Temple: northern east slope
1952 West Causeway, Angkor Wat: retaining wall
1997 Moat of Angkor Wat: failure of embankment.

Baphuon temple was constructed in about AD1060 and is located near Bayon in Angkor Thom shown in Fig. 18 from east front and the vertical section in Fig. 19.

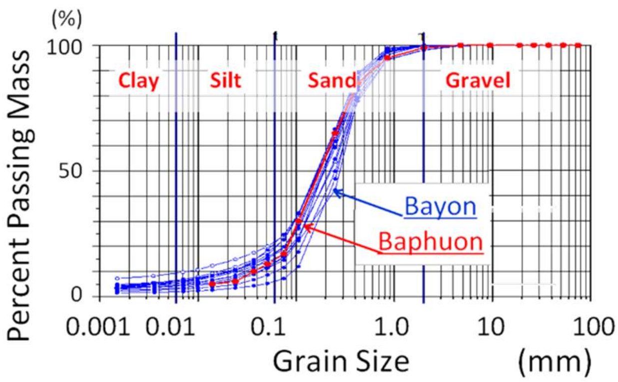

Fig.17 Response of moisture sensor by rain fall

The temple mound was constructed by sandy fill, which was found having the same characteristics of grain size distribution as shown in **Fig**. 17.

It is estimated to have the same strong strength under dry condition but weaken under wet condition as Bayon.

The mound was very high at 30 m from the ground with very steep slopes of 45 to 60 degrees.

Fig.18 Baphuon Temple in Angkor Thom

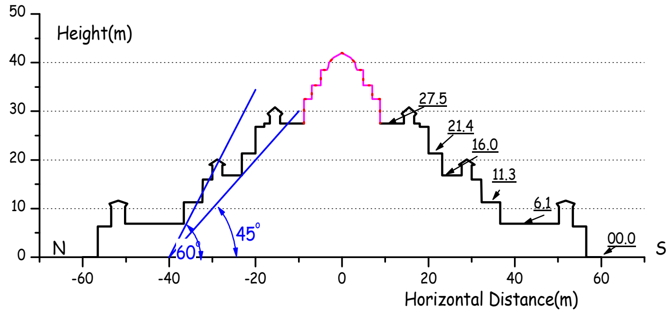

Fig.19 Vertical section of Baphuon Temple

Fig.20 Failure of north-eastern side in 1943 [6]

It is amazing fact such steep and high mound of manmade fill of natural sandy soil had been standing for 900 years, but failed in 1943 (**Fig.**20) [6].

4 Proactive countermeasures against the risk inherent with global warming

4.1 Anticipated risk to the heritage structure

Under the anticipated warm climate in the future, the rain type may change from squall to long and heavy rain. The strength of the filled sandy soil shall be weakened. Assuming the decrease of the strength of the foundation from ϕ=40°, C=1000kN/m2 to ϕ=40°, C=100kN/m2, a simulation result is 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 the foundation failure and deformation of the outer edge of the mound.

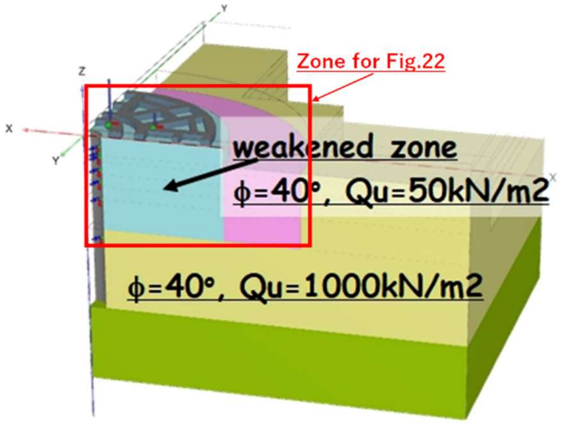

Fig.21 Weakened zone beneath the foundation.

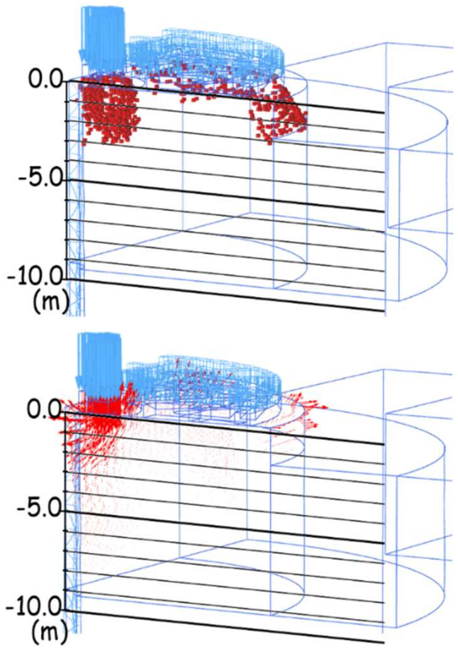

Fig.22 Plastic failure (upper) and displacement vector (lower) by the weakened soil.

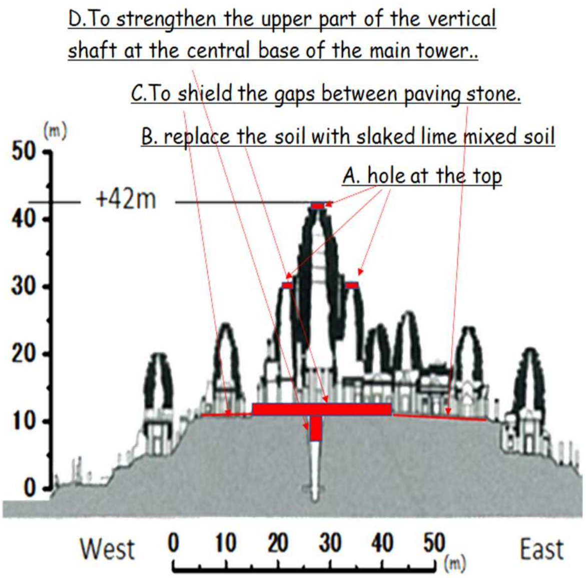

Fig.23 Proactive counter measures against global warming

4.2 Proactive counter measures against the risk of global warming caused events to Bayon

Among available methods to prevent the failure of the foundation and the displacements at the mound edge, a method to prevent rainwater from penetrating into the foundation was selected based upon the basic principle of the minimum countermeasure for preservation of heritage as shown in Fig.23 as follows,

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.

5 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 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 long 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 protect the Bayon tower.

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