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Restoration of foundation of northern library of Bayon temple, Angkor

Restauration de la fondation de la bibliothèque nord du temple Bayon à Angkor

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ABSTRACT
Restoration work of northern library of Bayon in Angkor Thom, Cambodia, is described in terms of geotechnical aspects. The original foundationconsists of compacted sand of about 5m in height with 10m and 15m in width and length. Partial dismantling was perfomrmed and reconstructed by slacked lime mixed soil. The paper reports general aspect of the ground condition, dismantling process, and reconstruction of the foundation with mechanical properties of compacted slacked lime mixed soil.

RÉSUMÉ
Le travail de restauration de la bibliothèque nord du temple Bayon àAngkor Thom, Cambodge, est décrit d'un point de vue géotechnique. Lafondation originale consiste de sable compacté d'une épaisseur de 5m et d'une largeur et longueur de 10m et 15m. Une démolition partielle eutlieu et fut suivie d'une reconstruction avec du sol mélangé avec de la chaux. Le papier reporte l'aspect général des conditions du sol, le processus de démolition, et la reconstruction de la fondation avec des propriétés mécaniques du sol compacté et mélangé avec de la chaux.

1 INTRODUCTION

In October, 1993 an inter-governmental conference on safeguarding Angkor was organized by UNESCO in Tokyo to discuss international cooperation and decided to set an Internal Coordinating Committee:ICC) co-chaired by Ambassedors from Japan and France to discuss and adjust the safeguarding activities by various countries and organization .
Japanese Government Team for Safeguarding Angkor(JSA, Director General:Prof.T.Nakagawa, Waseda Univ.) started in 1994 funded by UNESCO/Japan Trust Fund for the Preservation of the World Cultural Heritage. The author has joined JSA to study geotechnical characteristics of the ground in Angkor and problems for conservation of the structures. This paper describes geotechnical aspects of a masonry structure founded upon filled foundation and its restoration by JSA(JSA, 2000).

2 LIBRARY AT BAYON TEMPLE IN ANGKOR THOM

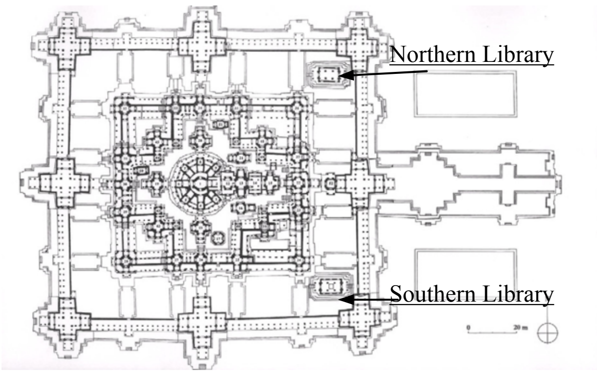

Figure 1. Plan of Bayon temple, Angkor Thom(from EFFEO)

Angkor Thom, which means "large town", of rectangular area of 3km x3km enclosed by wall of 9m high surrounded by moat. It locates 25km north from the great lake of Tonle Sap in Cambodia. Bayon temple that is shown in Fig.1 was constructed at the center in the Angkor Thom in the 13th century. There are two independent masony buidings in eastern side in the outer gallerly called northern and southern library. The library is meant a structure to store books, however, so called a library in Angkor consists of masonry structure with open windows and is difficut to use as "library" practically. The word was used to reffer the structure as sybolic measure. The northen library as shown in Fig.2 was found severely damaged at both of east and west ends and was decided to consolide by JSA.

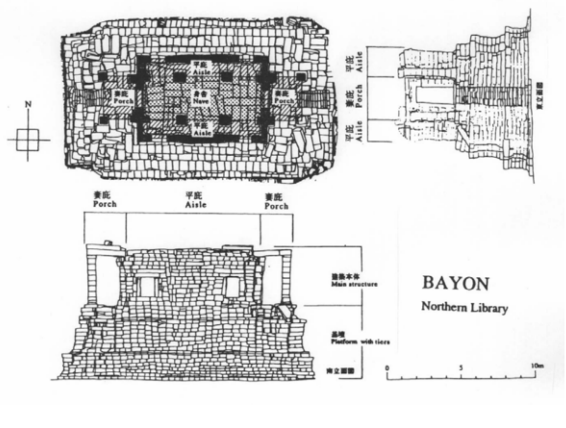

Figure 2. Northern Library, Bayon (H=9.5m, L=19m, W=11m)

3 ANASTYLOSIS AND RESTORATION FOR THE NORTHERN LIBRARY AT BAYON

Anastylosis is a restoration method that means literally "re-erection of columns," in Greek, "ana" means re-establishing and "stylos" means column. This methodology has been widely adopted as the international standard procedure to restore the historical monuments. French team had tried in 1930s to restore such monument as Banteai Srei in Angkor with great success. However, when they also applied the same technique to other structures in Angkor, it became clear that the application of simple anastylosis have resulted in settlements and structure failure. In 1950s, they started restoration work of Baphuon temple that consists of sand compacted fill of about 30m in height with steep slope of about 24deg. The compacted fill failed when the height reached at 5m. They tried again with the same result. They have realized the needs of structure stabilization in addition to the putting parts to the original positions. They have changed the basic design to support the sand fill by concrete retaining wall of 5m in height(Bruno,1989). Restoration of the fill made of silt and sandy with steep slope is one of the challenging field in geotechnical engineering in Angkor.

4 GROUND CONDITION AT BAYON TEMPLE

The ground condition of the nearby Bayon temple is shown in Fig.3. The foundation ground for northern library is about 2m higher level than the surrounding one outside of Bayon temple where the boring was performed. SPT(standard penetration test) value increases with depth down to 20m. The ground water level was monitored for several years and found at ground surface at the end of the rainy season and reaches at the lowest depth of 5 to 6meters. SPT value in dry season is larger than those in rainy season at the ground surface due to wet and dry effect on the surface soil.

Based upon archaeological excavation, we found a pavement layer of laterite blocks below the foundation and another one at 2m below the surface pavement. The foundation of the library was found well compacted sandy soil that shows cone penetration resistance of qc=2.0MPa. The estimated STP value is about N=20.

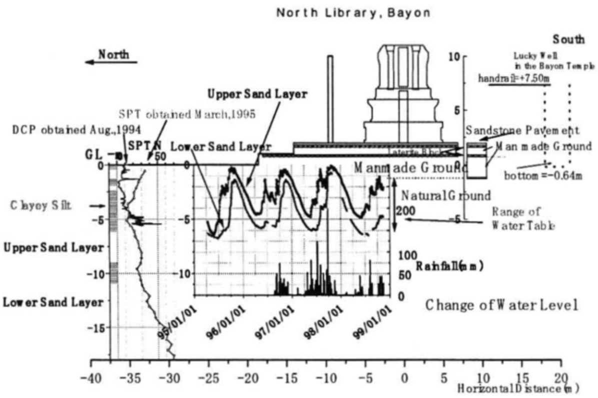

Figure.3 Ground Condition at Bayon, Angkor Thom

5 DISMANTLING AND INSIDE STRUCTURE AND RELATED GEOTECHNICAL CHARACTERISTICS

Dismantling was planned for two purposes. One was to take off damaged parts where structurally failed and another was to study the inside structure of the foundation.

Damaged parts are upper structure of stone masonry and east and west ends of the foundation. The dismantled part of the foundation is shown in Fig.4. During the dismantling process of foundation, the inside structure became to be exposed as shown in Fig.5.

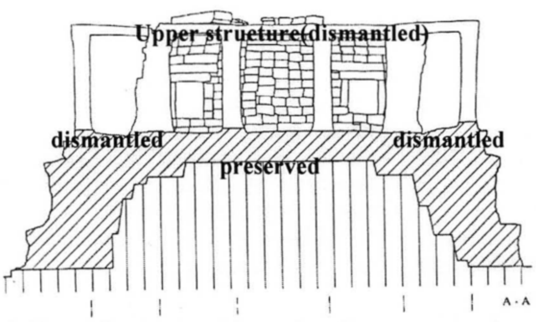

Figure 4. Dismantling portion of the northern library

From the base to top of the foundation, Surface of the retaining wall of the foundation consists of sandstone blocks. Inside the sand stone, we found laterite blocks that protects compacted fill of about 5m in height. The fill consists basically find sand and clayey layers of sandwiched structure as shown in Fig.5.

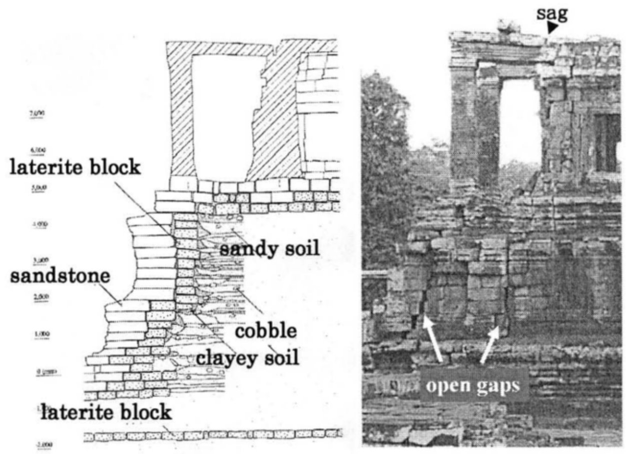

Figure 5. Inside and side look of west end of foundation

As shown in Fig.5, open gaps were recognized between sandstones blocks continuously. However, no clear slide surface was identified inside the fill, it was estimated that horizontal outward displacement of the foundation fill without any specified slide surface m

ay be major reason for the open gaps. Sag at the roof may be due to local settlement at the top surface of the foundation fill. Plate loading test was performed on the dismantled surface of the manmade fill foundation with a circular plate with a diameter of 10cm as shown in Fig.6. The Young's modulus of the compacted fill was estimated as E=15.1MPa assuming ν=0.3.

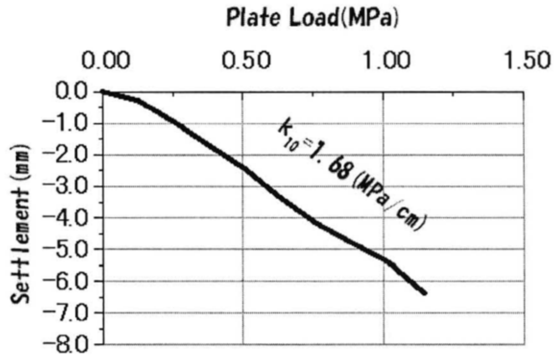

Figure 6. Result of plate loading test

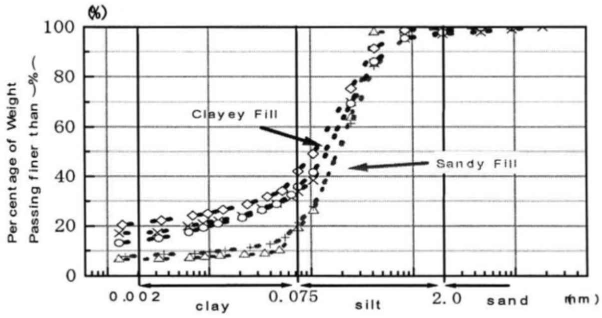

Figure 7. Grain size distribution of dismantled fil

Fig.7 shows grain size distribution of the fill material. The fill was mainly sandy soil with clayey soil was found mainly at the boundary between fill and laterite blocks. Fig.8 shows compaction characteristics by Proctor's standard method. The dry density measured at the site was ρ_d=1.797 that is about 95% of the maximum dry density and evaluated as highly compacted state.

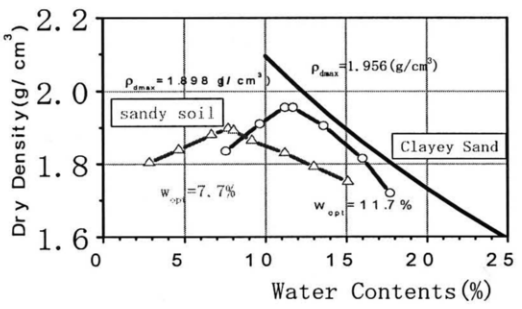

Figure 8. Compaction characteristics of sandy and clayey soil

6 UPHEAVAL CAUSED BY DISMANTLING

Differential heave during dismantling was measured by horizontal inclinometers (Fig.9). A reference level point was damaged and the absolute settlement was not known. The results were shown in Fig.10. Relatively larger heave was measured at southeast side compared to northwest side. The differential heave was about d=2mm. The unload due to dismantle was estimated as 370kN. Assuming the Young's modulus of 15.1MPa, the heave may be estimated as the following equation.

$$\delta = \frac{(1-\nu^2)}{2aE}\Delta F$$

where δ : heave, ν : Poisson's ratio, a: equivalent radious =8m, and ΔF: unload=0.37MPa

The estimated heave is δ=1.4mm, which is less than the measured differential heave. Since one sided heave was caused by more or less even unloading, the base ground beneath the foundation may not be uniform. The southeast side is weaker than the northwest side. However, there is no specialized heave near at both ends where the upper structure had deformed. Also the difference in heave is considered small and does not affect upon the reconstruction of the monument.

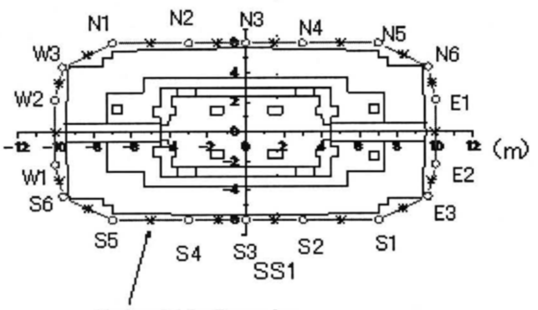

Figure 9. Setting horizontal inclinometer surrounding Library

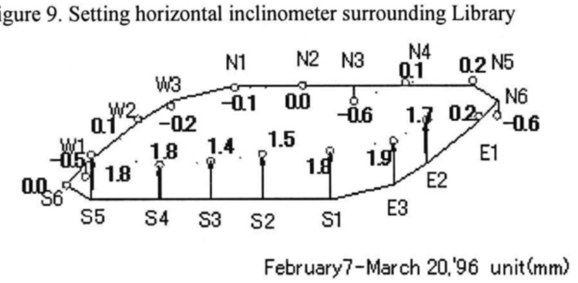

Figure 10. Differential heave caused by dismantling

7 MECHANISM OF FAILURE OF STURCUTURE

The roof of the library is fallen down, which might have been caused by large displacement of wall and columns. Level measurement of the top of the foundation shows some settlement at the both ends of the foundation. Increased gaps of the stones of the north and south sides at the both ends were recognized as to show instability of the ends of the foundation. The main reasons are considered as weathering of laterite block inside the sandstones and flow out of the compacted fill that have resulted settlement of the filled foundation.

8 MECHANICAL CHARACTERISTICS OF FOUNDATION FILL

In the design stage, we compared several possible types of fill such as sandy soil as original, cement mixed soil, and slacked lime mixed soil. We have performed laboratory tests to find best suitable material to be used. The major mechanical characteristics required for the fill foundation are bearing capacity and settlement.

The largest vertical load at the base of a column which includes the missing roof weight is 0.3-0.4MN with a base area of 0.6mx0.6m, which results in vertical stress about 1MPa.The allowable settlement is estimated as 0.5cm, which leads the minimum subgrade reaction coefficient as k=0.6-0.8MPa/cm. The corresponding Young's modulus is 32-43MPa.

9 SELECTION OF FILL MATERIAL

It is decided to adapt either cement or slacked lime mixed soil rather than simple mixture of sand and clay because of shortage of uniaxial strength. Cement mixed soil develops much higher strength with shorter time compared to slacked lime mixed soil. However, the slacked lime is much more chemically stable than cement for longer range of period. We have selected the slacked lime mixed soil as the basic fill material considering the stability of the material for more than a few centuries.

Local material of sand and clay are mixed to obtain the similar distribution of sandy and clayey soils used in the original ground. These soils are called as Fill Type I and Type II. Their grain size distributions are shown in Fig. 11.

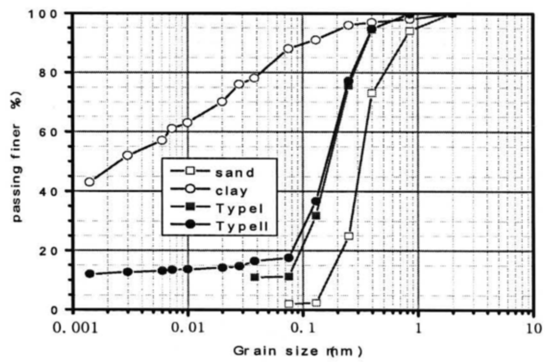

Figure 11. Grain size distribution of soil material used for fill.

Fill type I and II consist of sand, clay, and slacked lime. The mass ratios of each component are shown in Table-1.

Table 1: Mass ratio and W/C for Fill Type I, II

Type	Mass ratio			Water contents	
	sand	clay	slacked lime	mix-ing	compac-tion
I	1.0	0.1	0.1	8.2%	7.0-7.2%
II	1.0	0.2	0.1	8.5%	7.2-7.5%

The slacked lime mixed soil increases its strength gradually with time because of the slow chemical process of carbonation. The fill material was mixed with water contents for mixing in Tab-1. After mixing, the fill material was left over for curing. The cured fill material is spread over with about 10cm. The elephant foot is used to compact the fill with 5 to 10times of tamping until no more compaction is realized.

Type I fill is used for general platform of the foundation. Type II fill material is used as sealing material such place as boundary between laterite block and fill and the top of the foundation where seepage infiltration is to be avoided.

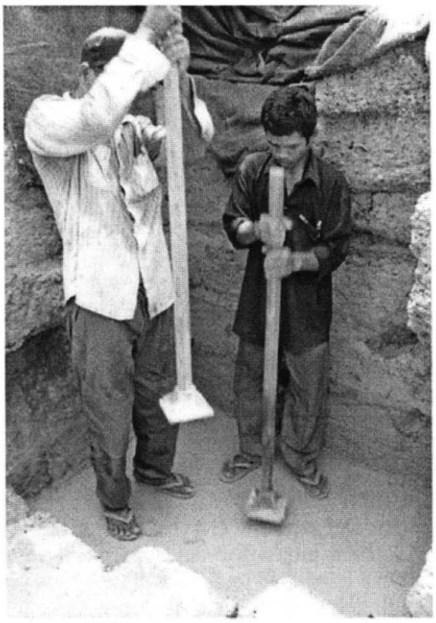

Photo 1 Elephant foot for ground compaction

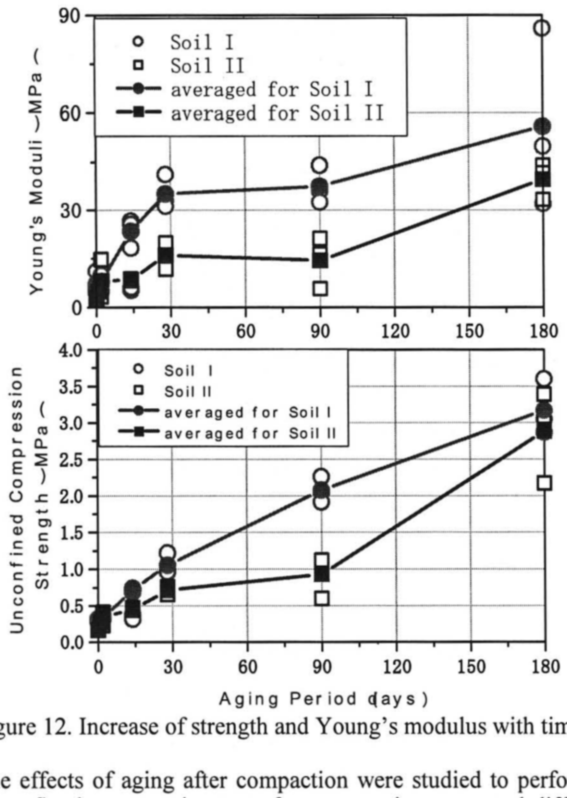

Figure 12. Increase of strength and Young's modulus with time

The effects of aging after compaction were studied to perform unconfined compression test after compaction at several different period of aging up to 180days as shown in Fig.12 It was found that the strength is only 0.3MPa just after compaction but increases linearly with time and reach the required strength of 1MPa after 30days for Soil type I. After six months, the strength reached about 3MPa that gives safety factor of S.F.=3.

The Young's modulus also increases to about 40MPa after six months that we have set for the quality of the foundation fill.

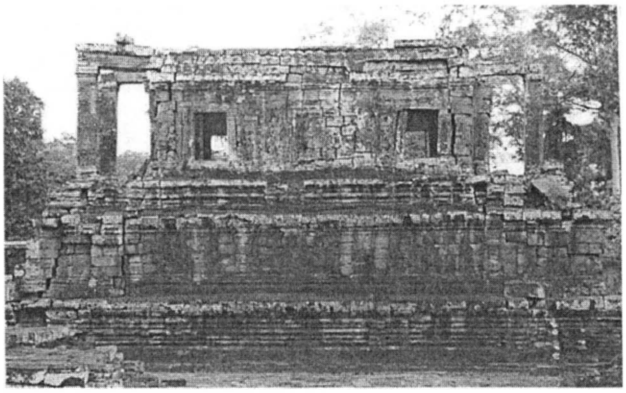

Photo 2 Northern Library, Bayon Temple-before restoration

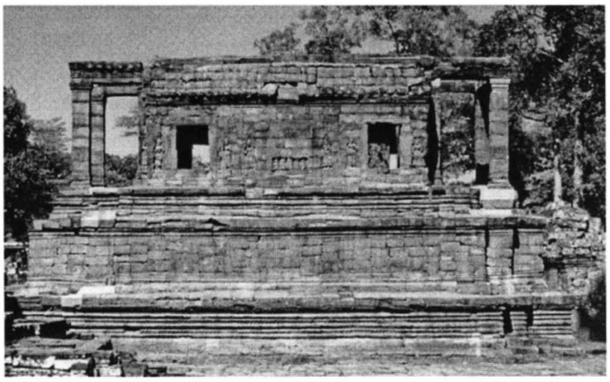

Photo 3 Northern Library, Bayon Temple-after restoration

10 CONCLUSION

It was first time in Angkor to apply the modern geotechnical engineering to construct high foundation by soil compaction. The geotechnical principle was useful to determine the necessary mechanical quality of the fill ground and to select appropriate soil material and methods to construct the foundation of the structure. The material used and the methods developed are not the same as ancient Khmer engineer used. We used almost the same soil and added slacked lime to cover the shortage of the original method. In this sense, the developed method might be called modified anastylosis for high foundation mound made by soil in Cambodia.

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