Reconstitution of foundation platform of Prasat Suor Prat by compaction of original soil with slaked lime, Angkor Ruins, Cambodia

Reconstitution de la plate-forme de la fondation de Prasat Suor Prat par compactage du sol d'origine additionné de chaux éteinte, sur les ruines d'Angkor, au Cambodge

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ABSTRACT: Angkor ruins are situated at Siem Reap in Cambodia and are composed of many masonry structures of temples, moats and large earth embankment for a reservoir. They were constructed from the 9th to the 15th centuries. These cultural heritages in ancient Angkor have been in dangerous states that have resulted in collapse from various severe natural forces. The individual masonry towers of Prasat Suor Prat at Angkor Thom were studied and investigated. The N1 Tower was deemed as the most dangerous tower among them for restoration work. It has inclined 6.6 degrees towards a nearby pond with a northwest direction. The compacted sandy formation was found from -1.5m from the original ground surface and to +3.5m above the ground. The safety factor for the ground bearing capacity in rainy season was calculated with S.F=1.1. When its bearing strata were reconstituted, it was designed to have a sufficient safety factor value of S.F>1.5. To achieve this purpose, the original sandy soils were mixed with slaked lime and compacted by tamping with Geo-textile. The material soil used for the platform was a mixture of different soils of original sandy soil, clayey soil and lateritic soil at weight ratios of 70%, 15% and 15%. Slaked lime was added to the mixed soil 1 at a rate of 0.1.

RÉSUMÉ: Les ruines d'Angkor sont situées à Siem Reap au Cambodge et sont composées de nombreux temples à structure en maçonnerie, de fossés et d'une grande digue autour d'un réservoir. Ils ont été construits entre les 9e et 15e siècles. Ces héritages culturels de l'ancien Angkor sont dans un état dangereux résultant d'écroulements résultant de forces naturelles sévères. La maçonnerie particulière des tours de Prasat Suor Prat à Angkor Thom a été l'objet d'études et d'investigations. La Tour N1 a été jugée la plus dangereuse parmi celles-ci, justifiant un travail de restauration. Elle est inclinée de 6.6 degrés en direction d'un étang proche, vers le nord-ouest. Une formation sablonneuse compactée a été identifiée de -1.5m de la surface originelle jusqu'à 3.5m au-dessus. Le facteur de sécurité en terme de capacité portante en saison des pluies a été évalué à S.F =1.1. Quand les couches portantes ont été reconstituées, le facteur de sécurité a été amélioré jusqu'à la valeur S.F >1.5 considérée comme suffisante. Pour parvenir à ce but, les sols sablonneux originaux ont été mélangés avec de la chaux éteinte, compactés et renforcés avec du géo-textile. Le sol utilisé pour la plate-forme était un mélange de différents sols, constitué du sol sablonneux original, de sol argileux et lateritique selon des ratios en poids de 70%, 15% et 15%. La chaux éteinte a été ajoutée au mélange à raison de 0.1 pour 1.

KEYWORDS: Angkor ruins, cultural heritage, reconstitution, foundation, soil improvement, slaked lime,

1 INTRODUCTION

Angkor ruins are situated at Siem Reap in Cambodia and are composed of many masonry structures of temples, moats and large embankment for reservoir, that were constructed from the 9th to the 15th centuries. These ruins were registered as Cultural Heritages Sites by UNESCO in 1992. At the same time these were listed as Endanger World Heritages Site. Afterwards, in 2004 these were removed the list by many conservation activities around groups from the world. However they are still under dangerous states resulting in collapse by human activities and natural forces that sometimes may cause collapses, etc.

In 1993, Japanese Government team for Safeguarding Angkor was organized and has been working at on investigating and conserving them (Nakagawa 1996-2005).

This paper reports on a conservation project was carried out (Nakagawa 2005, Akazawa et al. 2009).

2OUTLINE OF OBJECTIVE STRUCTURE

Prasat Suor Prat in Angkor Thom is composed of 12 towers and terraces. The towers are masonry structures. They are constructed materials out of laterite blocks. They are designed to look like three stories. Each tower constructed differently and has different structure problems, for example, openings of wall joints and leaning of towers etc...

Photo. 1. N1 tower (Before reconstitution)

N1 tower was selected as the most dangerous tower among them for restoration work (Photo. 1). This tower had inclined 6.6 degrees towards a nearby pond in a northwest direction. The dimensions of the tower are 21m in height and 9.2m×10.5m in width and length at base level.

3RESULTS OF INVESTIGATION

To advance the design of N1 tower's restoration, case histories were collected of restoration of similar building. The existing states of N1 tower structure and investigations of ground under it were carried out (Iwasaki et al. 2013).

Based on these results, principals, guidelines and methods for the N1 tower's restoration project were decided.

3.1 Case history

N3 tower (one of Prasat Suor Prat) was restored by École française d'Extrême-Orient in 1950, and its superstructure was dismantled and rebuilt.

50 years after its restoration, it inclined once again and structure materials for its openings were broken. It has been recognized that N3 tower is at risk of collapse. This leaning of N3 tower is supposed to have occurred during restoration work or just after it. It was thought to be caused by fact that superstructure was treated, and its platform and its base ground were not treated.

3.2 Survey of existing state

The change in N1 tower's inclination with progressing time has been monitored by plumbing, however there was no significant change. During the rainy season in October in 1997, when there was wind velocity of over 10m/s blew for a few days, 0.5mm/m of the lateral displacement was measured. Figure 1 shows this monitoring data with inclinations, wind velocity, rainfall and temperature for N1 tower. This fact shows that the tower's displacement was increased by the external force acting against the tower (in this case, gust wind during rainy season), and this displacements will be accumulated.

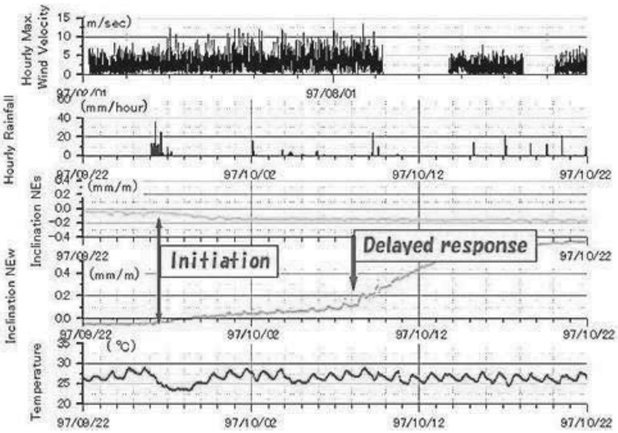

Figure 1. The measuring results of the amount of inclinations, the wind velocity, precipitation, and temperature of N1 tower.

Based on these facts, it is recognized that the foundation platform and the ground under it should be investigated in detail. First, a soil survey by hand auger was carried out, but results of it were insufficient to clarify the soil strata under the platform. It was concluded that the investigation of the tower state should be done by dismantling them, including excavating the base ground. Moreover, it is decided that these results will be used for designing of other ruins' restoration projects in future.

Photo. 2 and Figure 2 show soil strata under the platform of N1 tower. The compacted sandy formation was found from -1.5m from the original ground surface and to +3.5m above the ground, which the average thickness of one stratum was measured about 20cm. Figure 3 shows the grain size distribution curve of them. Figure 4 shows N-value distribution (by using standard penetration test) with depth. In figure white dots show the values in the dry season and the polygonal line shows them in the rainy season.

Photo. 2. Soil strata under the platform of N1 tower

Figure 2. North-South Section of N1 tower (Before restoration)

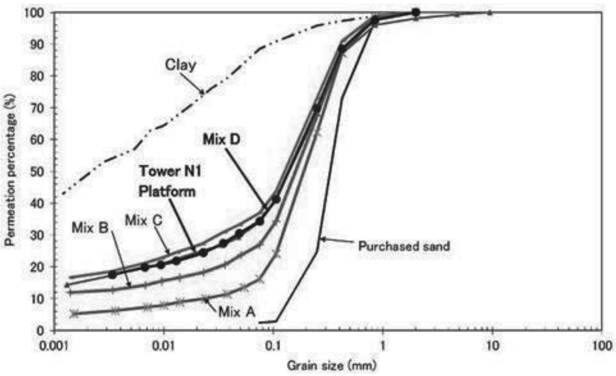

Figure 3. Grain size distribution curve of each soil

The average in-situ dry density of the compacted strata was measured at 1.69g/cm^3 at center of it and 1.73g/cm^3 directly under laterite blocks. Because the maximum dry density by Proctor's compaction test was measured at 1.88g/cm^3, these compacting layers were assumed to have been tamped with about 90% on degree of compaction.

Plate bearing in-situ test of plate loading on original compacted sandy ground showed the yield load of 290 - 340 kN/m^2 under wet condition. Since the contact pressure in the ground beneath the foundation of the tower was estimated at 270kN/m^2, the safety factor against the ground bearing capacity in rainy season was calculated at SF=1.1, which was considered as small and not safe. When the external force acts on the tower in the rainy season, the inclination, the subsidence and the differential settlement of them will increase.

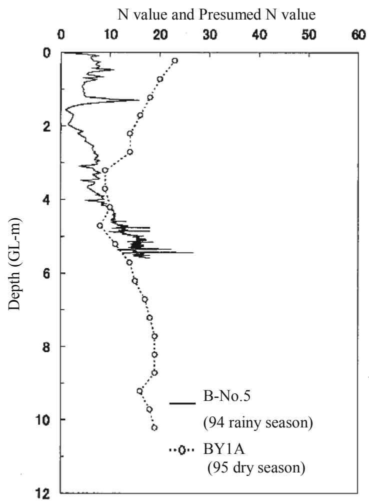

Figure 4. N-value distribution

4CONSTRUCTION METHOD

The principle for this reconstitution is to adopt the original tamping method for excavated original soils. However, if the bearing layers are reconstituted by the original tamping method with original soils, their bearing capacities will be same as original states and capacity reduction in rainy season will not be avoided. When constructed with the original excavated soil, it is concluded that it should be improved with some stabilizing materials for soils.

In the case of surface soil stabilization in place, Portland cement or hydrated lime is used as a hardening agent. Hydrated lime should be accepted for this case, because it is easy to buy it near the jobsite and to handle it for working. Moreover it is used for long time.

5MIXING TEST OF SLAKED LIME-SOIL AND RESULTS

Table 1 shows the proportions of material soils to be prepared and slaked lime to be mixed for them. In Table 1, item "sand" means excavated sandy soil which was used at the tower's erection. Each mixed soil is mixed this "sand", clayey soil and lateritic soil with weight ratio in Table 1. Slaked lime, which is a stabilizing material, is added to the mixed soil 1 at rates of Table 1. The mixing purpose of clayey soil is expected the stabilized effect with chemical reaction of clay minerals and slaked lime. Also, on lateritic soil mixing, it is intended that the ferromagnetic ion and aluminum ion in it will promote chemical hardening reactions. Grain size accumulation curves of mixed soils are shown in Fig.3. Results of the test were evaluated by comparison of unconfined compression strengths on treated specimens.

Table 1. Proportion of mixed soil

items	sand (excavated sandy soil)	clayey soil	lateritic soil	slaked lime mixture rate (%)
mixture A	100	0	0	5, 10, 15
mixture B	85	15	0	5, 10, 15
mixture C	70	30	0	5, 10, 15
mixture D	70	15	15	5, 10, 15

1) Unconfined compression strengths of treated specimens were increased as the mixing rates of slaked lime were increased.

2) The unconfined compression strengths and the deformation moduli of tested specimens increased with their curing times, and proportional relation between them was recognized. Relation between the curing time and the unconfined compression strength on mixed soil D is shown in Figure 5.

3) The changes of their dry densities by curing time were not recognized.

Figure 5. Relation of unconfined compression strength and curing time

Based on above-mentioned results, the material soil used for the foundation platform and its base ground was a mixture of three different soils of the original sandy soil, clayey soil and lateritic soil at weight ratios of 70%, 15% and 15%(mixing soil D proportion). Slaked lime, which was a stabilized material, was added to the mixed soil 1 at a rate of 0.1.

6CONSTRUCTION PROCEDURE AND UTILIZATION OF GEO-TEXTILE

It is decided that mixed soil D proportion should be used for material soil and slaked lime should be used for a stabilized material at adding to the mixed soil 1 at a rate of 0.1. The construction method will be applied by tamping method.

The construction procedure on jobsite is as follows.

1) The material soil treated by slaked lime should be spread at 15 cm of its thickness, after then it should be compacted to a thickness of about 7.5cm. By the repeat of this work, the base ground should be developed to the designated level.

2) Compacting work is decided by the field trial work to be composed of 3 steps. Primary compaction should be conducted using a wooden rod (dia.3cm) with man power's tamping, and followed by secondary compaction using a flat steel plate (15cm×15cm×1cm) as the same manner. Finally, surface compaction should be conducted by using of a tamping rammer.

3) The designated base ground for the tower will be made of laminated structure with 7cm thickness tamping layers. Since there is a smooth surface among each layer, its existence may make a week point on the mechanical standpoint. In order to secure the bond of each layer, roughening work for each compacted surface should be done before tamping of the next layer. The surface roughening work should be performed by using of steel rakes with manpower.

When allowable bearing capacity is 1.2MN/m^2, it is assumed that the compressive strength in-place should be about 60 percent of the strength obtained in the laboratory test. This means that the target value should be 2 MN/ m^2. In the case of mixed soil D, it would be take a curing time of more than 90 days to achieve a value of 2MN/m^2. However, since the reconstitution work for the superstructure will be needed to be executed without waiting 90days, some measure to reinforce the improved soil should be needed until the onset of its strength. As above-mentioned consideration, it is decided that Geo-textile should be applied for temporally reinforcement of improved soils until the onset of its strength.

The designing study was preceded on a section of base ground in Figure 6 which spread and inserted 3 layers of Geotextile. Table 2 shows the specification of Geotextile which was utilized. One of the effects of Geo-textile is to work as reinforced materials of shear resistance for soil mass. When using this effect for the designing base ground, it is expected that it increases safety factor to the sliding failure by about 20 percent.

Figure 6. Section of spreading Geo-textile

Table 2. The specification of Geotextile

items	contents
type	KJV-6000
base texture	high-strength vinylon
width	2,000mm
weight	320g/m^2
tensile strength	59.0kN/m
reduction coefficient	0.6

On the other hand, when the curing time of treated soil is short, it is considered that the strength of base ground is insufficient for the bearing capacity. The base ground, which is composed of tamping layers and Geo-textile, may not have uniformly mechanical behaviors. It is supposed that only Geo-textile resists the overturning moment, which generates from the tower's load. As a result, it is simulated that Geo-textile will be able to share 26 percent of the total overturning moment. When converting this value to the settlement, it is estimated 40cm.

Based on above-mentioned result, Figure 7 shows a decided section for reconstitution of the foundation platform.

7CONCLUSION

This project has been achieved in May, 2005. After that, monitoring for these structures is being done. Until present after the reconstitution, there is no trouble on them.

A consensus, which cultural heritages should be conserved and saved from various collapsing factors, is changing in recent. If modern materials and modern methods will be applied for restoration works of heritages, the historic value on it may be spoiled. Therefore it is demanded that materials and methods for restoration works will not spoil the historic values of heritages. From these viewpoints, a concept about "authenticity and heritage" is discussing now, especially on consideration of designing and working for heritage geo-technology. The authors desire for this paper to become a reference for the same purpose.

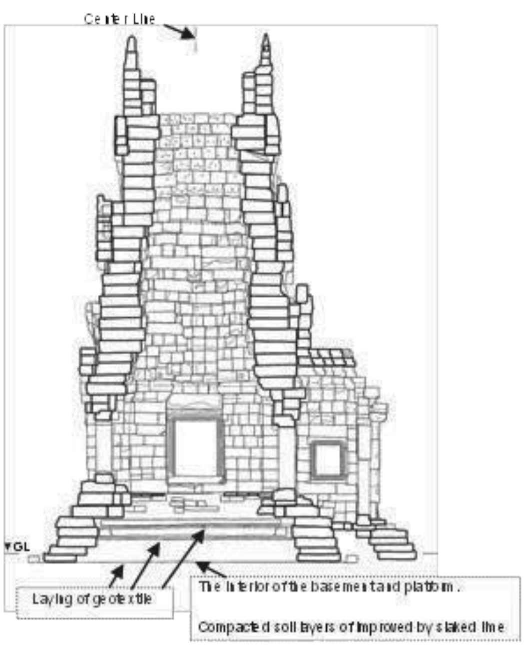

Figure 7. Decided section for reconstitution of the foundation platform

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