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Geotechnical Aspects of the N1 Tower, Prasat Sour Prat, Angkor Thom, Cambodia

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Abstract This paper presents a case study of foundation of an inclined independent masonry tower in Angkor. One of the Prasat Sour Prat towers had been dismantled before reconstruction for conservation. The foundation was inclined as the same as the upper structure of the tower and spreading outwards. The inclination was considered caused by foundation failure with some differential settlements of the ground. During dismantling, the soil layers exposed on the trenched section were found rather horizontal than the inclined state that had been expected. Laterite blocks of step slope stones was found to have slid down along the soil mound of the foundation. The mechanism might have been caused by weakening of soil strength by wetting ground. Without dismantling, the real mechanism of the inclination was never known as well as the corresponding counter measures.

Keywords: Angkor, Prasat Sour Prat, dismantling, inclination, masonry tower

Introduction

The Japanese Government Team for Safeguarding Angkor (JSA) was formed in 1994 and has been engaged in conservation work since then. One of heritage structures for conservation work was Prasat Sour Prat that stands in the eastern side of the Royal Plaza, Angkor Thom.

Photo 1: Prasat Sour Prat

N1 Tower, Prasat Sour Prat

Inclination of the Outer Wall of Prasat Sour Prat There are 12 towers called Prasat Sour Prat and shown in Photo 1. The angles of inclination of the outer surface of the towers were measured and

shown in Fig.2 except S6 that was failed down and impossible to measure. In general, the directions of inclinations are within a few degrees towards eastwards except two towers of N1 and S1. N1 has inclined towards northwards and S1 towards or both for pond nearby (JSA 1997). The Tower N1 showed the largest inclination of 4-6degrees and JSA began conservation work for the N1 Tower.

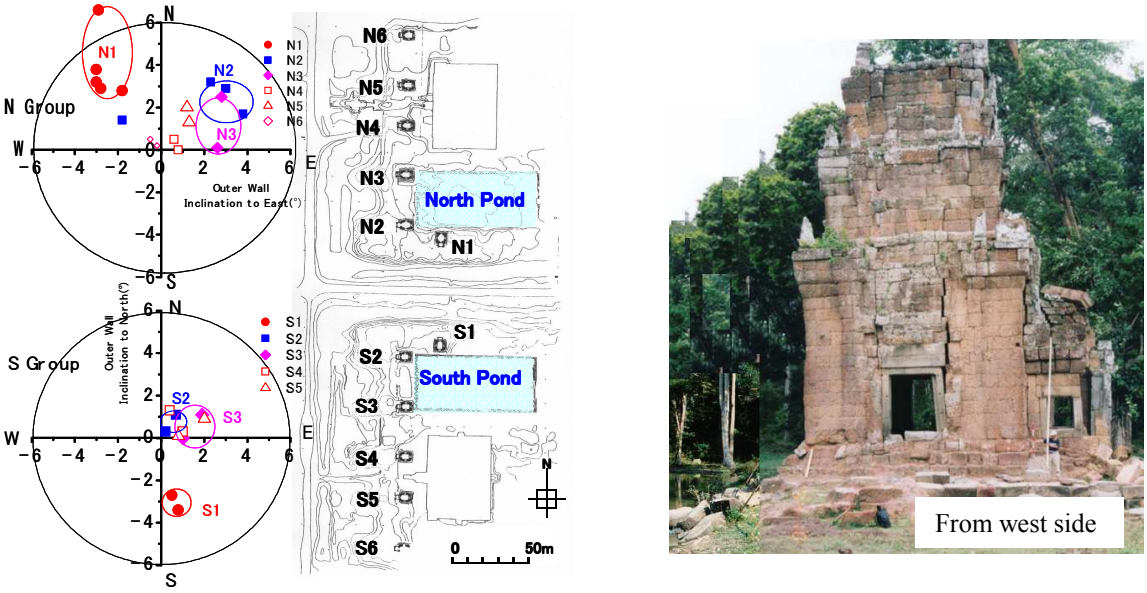


Figure1: Prasat Sour Prat, inclination of wall of the towers and N1 Towerof Prasat Sour Prat

Inclination of the Steps of the Foundation The height of the surface of steps blocks was measured (JSA 1995) and plotted in Fig.2. The average angles of the inclinations for east, north and west faces are calculated ranges from 15-50cm/10m.The maximum inclination was top step of the west face of 50cm/10m, which is about5.7 degrees northwards with the same order of that of the outer walls of the N1 tower.

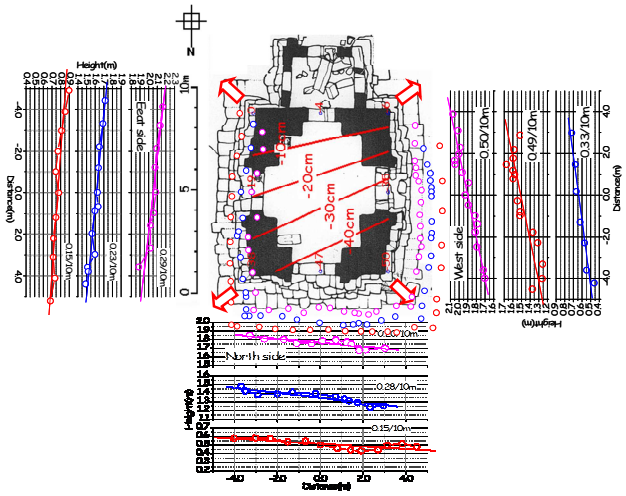


Figure 2: Inclination of blocks of step of the foundation of N1 Tower

Widening of the Bottom Space Distance of the Window There is a window for each wall of the tower. The horizontal space distance at the bottom between the frames was found wider than those at the top as shown in Photo 3. The measured distances are listed in Table 1 and the widened ratio was 6-8%.

Lateral Spreading of the Block of Stepped Wall Foundation Gaps were noticed between the blocks of step slope of the foundation. Typical example of step blocks of east face is shown in Fig.3. The gaps of northern side are marked with four different widths as legend in Fig.3.The widths of the most gaps are less than 3-5cm. The gaps are distributed more or less in random manner.

Photo: 3 Window frame (west side)

Table 1 Horizontal distance between vertical frames

	Distance between frames		Difference	Widened Ratio
Wall position	Top Lt	Bottom Lb	ΔL Lb−Lt	ΔL/Lt (%)
east	170.3	182.0	11.7	6.9%
west	171.3	185.0	13.7	8.0%
north	168.0	178.0	10.0	6.0%
south	124.0	131.7	7.7	6.2%

Table 2 Sum of gaps for each layer

step	Σd (cm)
1st step	26
2nd step	34
3rd step	16
4th step	25
average	25

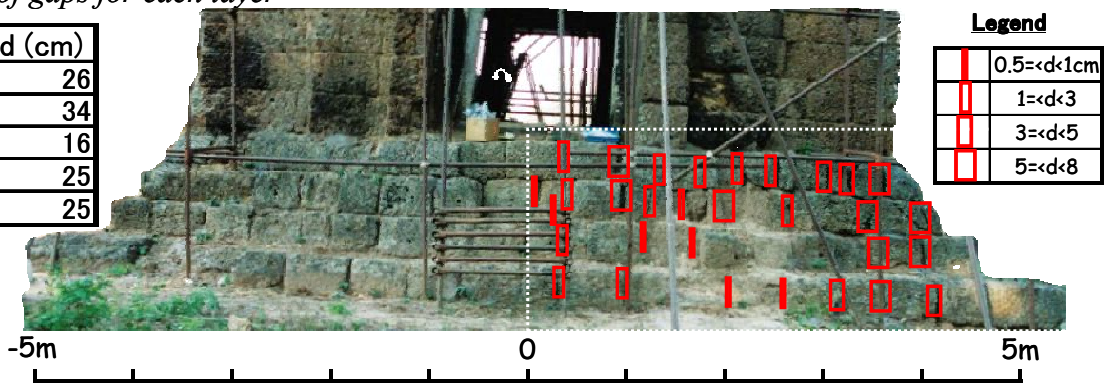
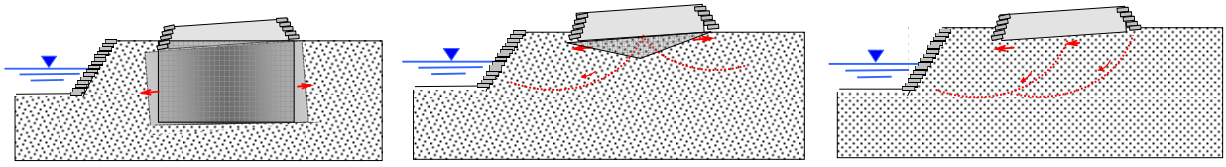


Figure 3: Gap distribution of step blocks at north of east face of N1 Tower of Prasat Sour Prat

Table 1 shows the summation of the widths for each step level. The averaged summation for four steps was 25cm. Since the half width of the foundation is about 4-5m, the horizontal expansion ratio was about 5-6% in average. Gaps in other sides were also recognized.

Mode of Deformation of the Foundation of N1 Two kinds of the deformations that characterize the foundation of Prasat Sour Prat were noticed. One is differential settlements that resulted in inclination of the Tower. Another is the horizontal spreading of the soil mound and widened width of the bottom of the window that might have been caused by the expansion of the ground beneath the window. Fig.4 shows three different geotechnical models that will results the two characteristic deformation of inclination and deformation. In any model, the soil layer under the foundation must tilt towards pond.



a. deformation without shear slide b. bi-directional slide c. uni-directional slide

Figure 4: Speculated deformation modes that associate with inclination and spreading of the foundation

Trenching During Dismantling

Streak Lines The vertical section of the soil mound beneath the foundation was exposed during the dismantling of the N1 Tower as shown in Photo 4. Many streak lines were recognized as in Photo 5.

The streak lines are whitish in color and softer than the surrounding soil with width of about 5mm. These streak lines were analyzed to obtain the distributions of the direction angles from the vertical.

Fig.7 shows the copies of the streaks on a trenched section and the distribution of the angle. The predominant angles was θ=±30 degrees. It is very likely that these streak lines were shear failure lines that were caused by vertical compression stress from the tower structure. The internal friction angle of the sandy soils with the natural water contents was obtained as ϕ=30 degrees that satisfies the relationship between the angle of failure line from the major principle direction and the angle of the internal fiction of the ground.

Photo 4: Excavated foundation soil mound

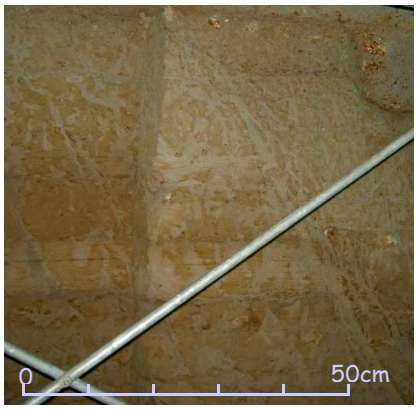


Photo 5: Streak lines on the trench section

Figure 6: (left) (rectangle in blue) Streak lines on the trenched section

Figure 7: (middle) Distribution of streak angle to vertical line

Figure 8: (right) Angle of shear line : θ to the principle axis

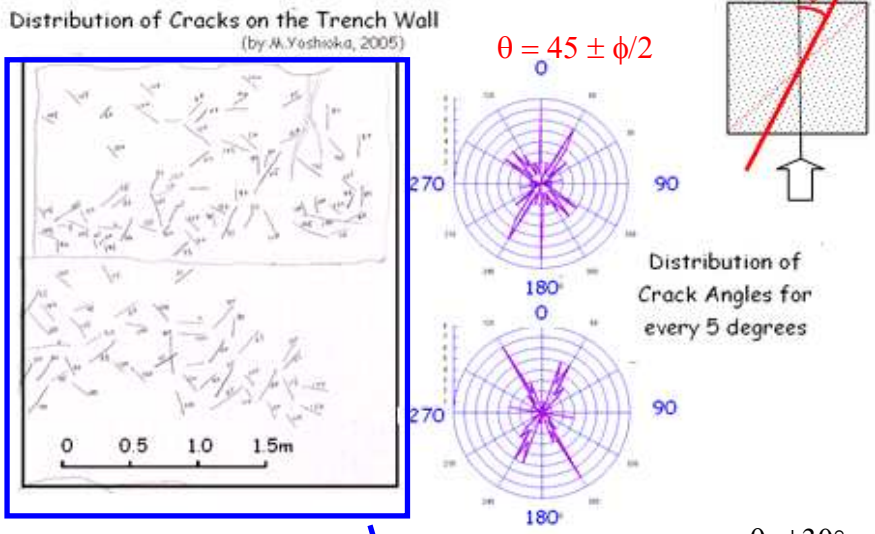


Figure 9: Trenched section

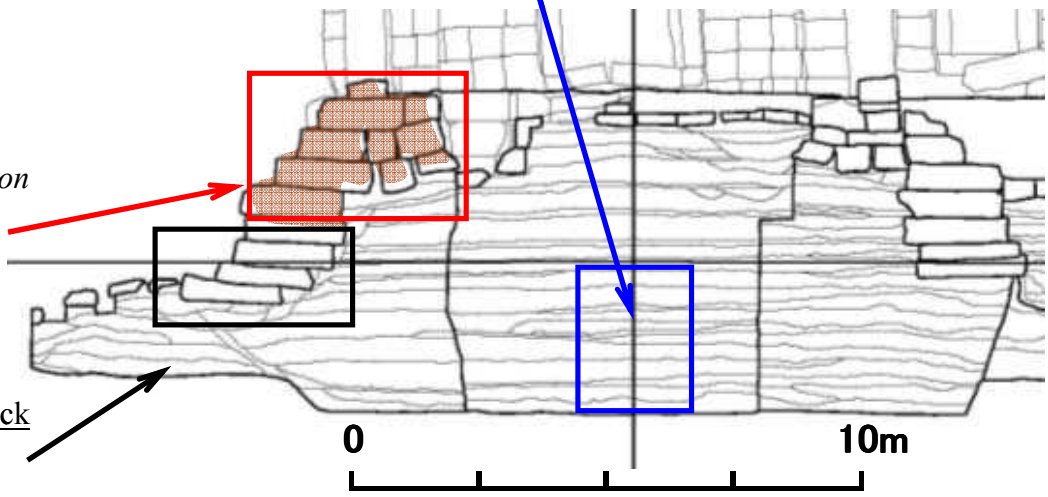


Figure 10： Laterite blocks of step slope

Deformation of Step Slope Fig.10 shows the vertical section of the soil mound beneath the foundation(Fukuda 2005). The compacted soil layer was found rather horizontal than inclined state that was expected by the deformations of the tower structure and the foundations. We realized that we had fallen in a pitfall of the difference between the speculation before dismantling and the exposed real section after trench. The speculation was based upon the experiences and the theory of geotechnical engineering. The pit fall was rather deep and not easy to be filled up. At the northend of the foundation mound, a step slope was found under a peculiar deformation as shown in Fig.10.

In Fig.10, it is clearly understood that the upper three laterite blocks at the outermost position were situated at lower height than the corresponding inner blocks. The compacted fill behind the laterite blocks was inclined outwards direction as shown in Fig.9 as well as Fig.10. Another deformation should be noted at the lowest part (rectangle in black, Fig.9) of the laterite block where the large downwards deformation of the ground was caused by probable bearing failure.

Figure 11:Displaced blocks

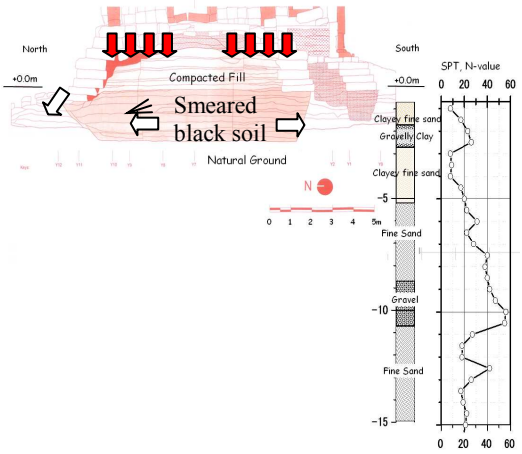


Figure 12: Foundation of N1 Tower and geotechnical condition

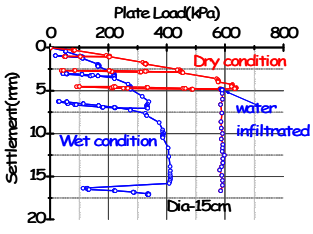


Figure 13: Plate load test

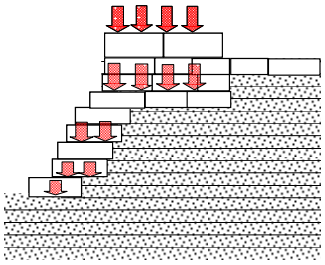


Figure 14: At completion of construction

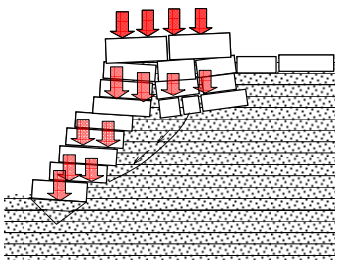


Figure 15: Stress redistribution

Speciality of Geomechnism of the N1 Tower

The estimated mode of the deformation of the outer surface of step slope was different from what was found at the inside soil mound underneath the foundation.

The streak lines indicate that the soil mound had yielded and vertical compression strain might have been larger than the horizontal expansion of 5%. Smeared soil in balck color was found in the sheared zone beneath the sliding blocks of step stones as shown in Fig.12. The geotechnical conditions at 50m apart from N1 tower is also shown in Fig.12.

The soil underneath the compacted soil is clayey fine sand of SPT N=10. The soil was capable to support the load from the tower and may be classified as stiff clay or medium dense sandy soil.

Probable Scenario of the Deformation of the Foundation of the N1 Tower, Prasat Sour Prat

The expected modes of deformation shown in Fig.4 were considered by basic geotechnical concept but did not agree with the field facts. One of the possible scenarios to explain the deformation characteristics of the foundation identified by the excavation may be considered as follows,

1. Results of plate load tests are shown in Fig.13 for two cases of the dry compacted mound with wetting step and the wet mound. It was shown that the bearing capacity for the dry ground was larger than 600kPa but the settlement increased as water was infiltrated into the ground. That of the wet ground was about 400kPa that was significantly lower than dry case.
2. The load of the upper load to the foundation increased to about 400kPa during the construction of the upper tower, the compacted fill was enough bearing capacity under dry condition. Load was transmitted to the lower step stones and to the ground by sliding shear along the slope as well as bearing resistance at the bottom of the step block as shown in Fig.14.
3. Rain water infiltrated into the soil mound from the surface, which increased moisture contents of soil and weaken the soil stiffness, the bearing capacity, and the shear resistance.
4. When the shear resistance was fully mobilized and the soil became weaken, the acceptable load by the soil decreased. The extra load that could not be supported by the ground was to redistribute to the adjacent step blocks. Load to the adjacent block was increased and transferred downwards.
5. The gradual redistribution of the load from the upper to the lower blocks caused to increase the load upon the bottom block finally resulted in bearing failure of the ground.
6. Thus, the process of wetting soil mound might have resulted in the plastic deformation of the soil mound and caused horizontal spreading as well as slip down of the step blocks along the mound slope to the northwards with no confinement of displacement. These stress redistribution and associated deformation is shown in Fig. 15.

Conclusions

The inclination of the N1 Tower in Prasat Sour Prat was considered to be caused by the deformation of foundation that associated with tilted soil layers. During the dismantling the tower structure, the trenching revealed that the soil layer was not tilted but horizontal as the original states with streak lines of yielding pattern. The inclination of the tower as well as spreading of the foundation might have been caused by stress redistribution associated by softening soil due to wetting. It provides an important case study to show that the dismantling is the only way to arrive the true mechanism of the deformation of heritage structure.

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