Conservation practice

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Relation between sub-soil and masonry structure of Angkor monument

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ABSTRACT: This paper is composed of two parts. One is a survey at Bayon, Angkor Thom. The other is an application of a discontinuum structural analysis to dry masonry. Preceding a structural analysis of Bayon, we apply the discontinuum structural analysis to Prasat Suor Prat and verify the structural stability of the monument in order to verify the influence of the masonry construction as well as the character of sub-soil layer in wet condition. We purpose to evaluate a risk level of the structure and suggest the policy and procedure for the restoration of Bayon, using the information obtained through JSA restoration.

1 INTRODUCTION

Angkor Monument is not only a symbol of the traditional culture of Kingdom of Cambodia and that of the unity of the people, but also a cultural treasure of Asia. However, it is in great danger of the destruction now. So, several countries have been carrying out the restoration of Angkor Monument. In 1994, Japanese government organized JSA (Japanese Government Team for Safeguarding Angkor), led by Prof. Takeshi Nakagawa (Waseda University, Japan) and composed of specialists of various fields. From 2005, APSARA and JSA organized a joint team, JASA (JSA and APSARA Safeguarding Angkor). JSA selected Northern Library of Bayon, Prasat Suor prat, and the Northern Library inside the Outermost Enclosure of Angkor Wat as targets for the restoration, and conducted various studies and investigations about the structure of these monuments and completed re-building those two monuments. Now, JSA is planning the restoration for Bayon main tower. Our paper purposes to evaluate the risk level of the structure.

Preceding our research, the researches of the upper structure, foundation soil and ground were mainly conducted by GRI (Geo-Research Institute, Japan) and Prof. Toshiro Maeda(Waseda University, Japan). GRI researched the mechanical effects of various factors such as wind, water and temperature. Prof. Toshiro Maeda analyzed the structural characteristics of the tower structure connected with the substructure through the vibration behavior with use of the micro-tremor measurement.

On the collapse mechanism of Bayon, we consider the following five factors influential to the monuments during long time span 1. The degradation of the drainage system 2. Shrinkage and swelling effects of the ground caused by rainy and dry season 3. The ground to the structural behaviors 4. The strong wind against the masonry structure 5. The original masonry construction.

We are trying to solve non-linear relation between displacement and stress occurred by the above various factors of the collapse mechanism. In this paper, we propose and apply a discontinuum structural analysis method of dry masonry and verify the effectiveness of the method in comparison to the data observed during JSA restoration of Prasat Suor Prat. With this method, we will quantitate the serious level of Bayon by structural analysis in future. We totalized and estimated the effects of the above five factors to the collapse process of the monument with non-linear behavior of displacements and stresses within the monuments.

Figure 1. Bayon outside view © JSA.

2 REPORT OF INVESTIGATION AT BAYON

2.1 *Outline of Bayon*

Construction of Bayon, the central temple of Angkor Thom, was initiated by Jayavarman VII in the latter half of 12th century. Main tower of Bayon stands up 31 m high from the artificial terrace of the shape with two crossing rectanglar of 38 m long and 25 m width individually, and 42 m high from the ground. Four rectangular side embankments surround the Tower and make a cross shape. The main tower consists of the central tower and eight sub towers with front porch on the artificial terrace.

From GRI report, the present position of the center of the tower is found dislocated to 235 mm to the north and 275 mm to the west (in total, 361 mm to the northwest) from the center of the cross lines of entrance gates of the central tower at the upper terrace. If this dislocation is caused by inclination of the tower, the inclination is 12.4 mm/m or 0.71 degrees of the angle of the inclination.

2.2 *Report of present state at Bayon*

We surveyed the severe level of the damage to Bayon. By observing the state of the towers, many stones have cracks, lacks, gaps and outwards. Bayon is constructed of dry masonry, the drop of one critical stone will cause the collapse of upper structure. And the critical damaged area which should be reinforced urgently was founded at Tower 14 and 15, shown in Figure 2. Now, we are planning the urgent reinforcement at Tower 14 and 15.

Besides the above, there are many locations repaired by EFEO (Ecole française d'Extrême-Orient) in 1930s. EFEO conducted conservation and restoration activities at Bayon from the early part of 20th century. However, after the repair by EFEO, other new cracks and gaps have proceeded. And, the repairs are severely damaged and should be conducted second repairing.

In our survey of Bayon central tower, we measured the inclination of the entrance pillars based on the 4 concentric circles shown in Figure 2, using the plump bob method. The characteristics of the inclinations are as follows. (1) There is a general inclination toward the outer direction. (2) There is a similarity in inclination tendency between concentric circles "1" and "2." (3) The inclination of pillars between towers is comparatively sharp. (4) The maximum inclination to the outer direction is 3.3 degrees at Tower 6 on concentric circle "4." The sharp inclination at the core of the tower cannot be neglected.

There are many open gaps in the wall of Bayon central tower. The gaps have also been observed and measured by the geotechnical engineering team. In this year's survey, we measured the gaps at the top and bottom of the wall. At present, the gaps will not immediately cause the collapse of the tower, but they should be observed continuously. The characteristics of the open gaps are as follows. (1) Generally, the gaps toward the top are wider than the gaps toward the bottom of the wall. (2) On "Wall 2–3," the gap between towers is comparatively wide. (3) There is no similarity in the tendency of the locations of the wide gaps between "Wall 1–2" and "Wall 2–3."

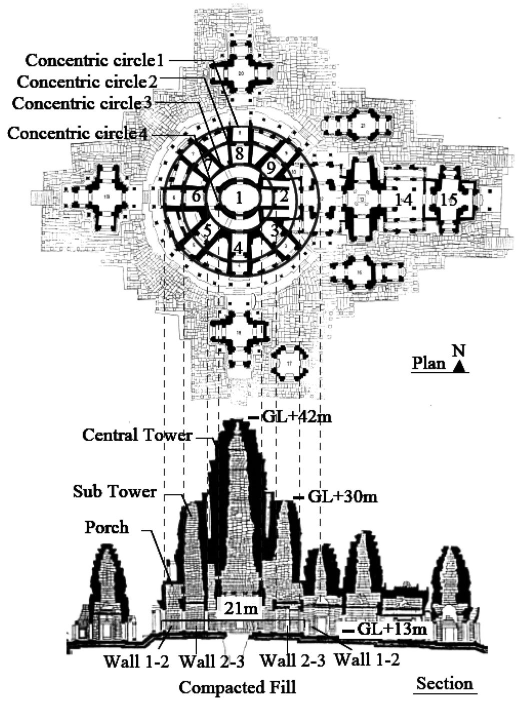

Figure 2. Plan and section of Bayon © JSA.

In the survey at the top of Bayon central tower, the condition of the damage is not so much caused by structural instability, but by the natural deterioration of stones over the years. The weakened strength by the deterioration can be the critical cause of the collapse at the top of Bayon central tower.

The behavior of Bayon central tower is influenced by several factors. At present, JSA is monitoring inclination, gap of stones, micro-tremor, weather, and subsoil. On the basis of monitoring data, we are trying to define the critical factors to the behavior of the tower.

3 STRUCTURAL ANALYSIS OF PRASAT SUOR PRAT

3.1 *Outline of Prasat Suor Prat*

Prasat Suor Prat is located at Royal Plaza of Angkor Thom. It is an architectural compound composed of

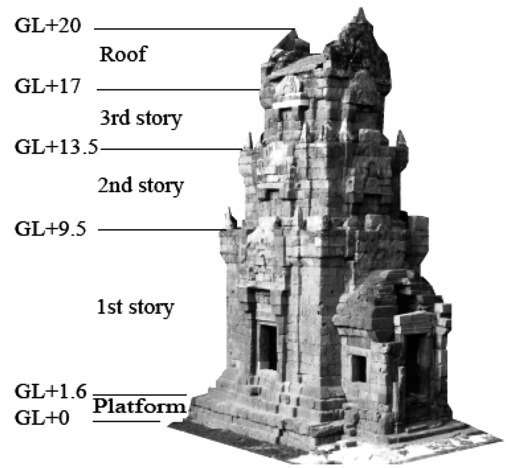

Figure 3. Prasat Suor Prat Tower N1 (after restoration) © JSA.

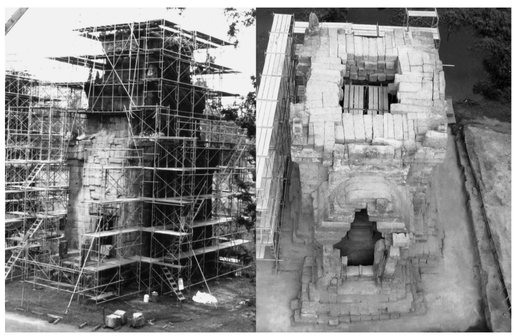

Figure 4. Restoration view of Prasat Suor Prat Tower N1 © JSA.

long terraces extending in the north-south direction and twelve towers. It is believed that it was constructed at the end of 12th century or beginning of 13th century. Prasat Suor Prat is a Khmer expression meaning "Towers of the tight-rope Dancers", but the real function is not unclear. Each of towers has a three-story tower structure with a rectangular plan and antechamber attached to the front facade. JSA divides the towers into the northern and southern groups. Tower N1 is at the south end of northern group and fronts to North Pond.

JSA selected Tower N1 as the most dangerous tower. Then, JSA began the repair and dismantling of Prasat Suor Prat Tower N1 from 2002 and have finished the restoration in 2005. The restoration work was conducted by complete dismantling the structural elements, restoring the damaged elements, platform and foundation, and reassembling them to be the original appearance of the tower.

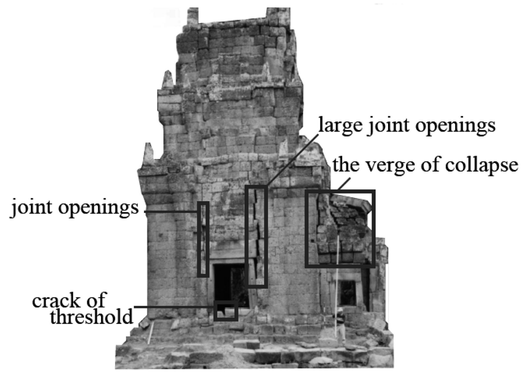

Figure 5. Damage situation of Prasat Suor Prat Tower N1 (before restoration).

From the restoration of Tower N1 by JSA, a spot of joint openings tends to be appeared as follows. (1) Large joint openings are appeared in only 1st story. (2) Joint openings are appeared between a jumb and adjoining wall. (3) Joint openings are appeared from the head corner of windows and doors to upper direction.

3.2 *Characteristics of masonry construction and structural analysis model*

This section describes about characteristics of a masonry construction of Tower N1. A structural characteristics derived of the masonry construction at Tower N1 is as follows. (1) The four corners of the upper structure are alternately layered three stones and behave independently. (2) The masonry over the head of windows and doors has the structural weakness. (3) Vertical arrangement of laterite blocks occurs the vertical joint openings. (4) Vertical and horizontal arrangement of laterite blocks effect on the behavior of upper structure.

The above characteristics are effective to the structural characteristics of Tower N1. In section 3.4, considering the characteristics of the masonry construction, we made a structural analysis model of Tower N1. From the drawings measured during the restoration work of JSA, the model is simplified from the real masonry and shown in Figure 6.

3.3 *Outline of discontinuum structural analysis*

The structural characteristics of Angkor monument constructed of dry masonry, the construction can't be analyzed by usual analysis method based on continuum mechanics. Displacement of dry masonry has been accumulated with slips and gaps between stones. And, we propose a discontinuum structural analysis considering a friction between stones. In this paper,

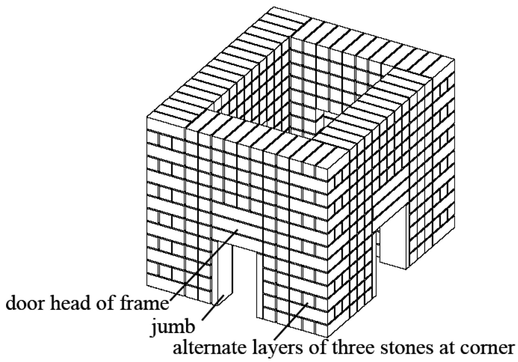

Figure 6. Masonry characteristics of 1st story, Prasat Suor Prat Tower N1.

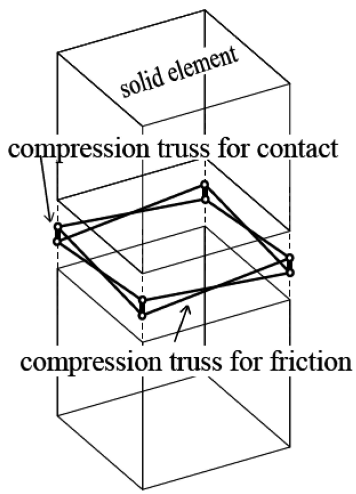

Figure 7. Concept model of discontinuum structural analysis.

we applied the modified non-linear FEM analysis of push over method. The procedure of our proposed method is as follows. Between adjacent stones, the contacted stones affect compression each other and the separated stones don't affect. The mechanism of the contact between stones is modified to a compression truss (Fig. 7). And, the friction between stones is modified to a compression truss whose material characteristic is bilinear (Fig. 8). Maximum load of a static friction is replaced with an allowable stress of the compression truss for the friction, and a kinematic friction is replaced with the axial stiffness. Considering the mechanism of the friction as the bilinear characteristic, we conducted the discontinuum structural analysis of push over method.

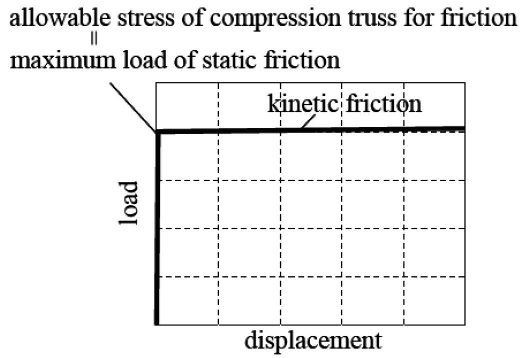

Figure 8. Bilinear model of friction.

3.4 *Discontinuum structural analysis of Tower N1*

By applying the discontinuum structural analysis to Tower N1, we assessed the effects of the masonry construction to the structural behaviors of Tower N1. In modeling, only 1st story is assumed as a discontinuum model, but the other parts are assumed as continuum models. The masonry construction referred in Figure 6 is considered in modeling. Because of the characteristics such as the large joint openings observed only at 1st story (Fig. 5), we assumed the modeling appropriate. According to the vertical force of each layer and location, each maximum load of the static friction between vertical stones is calculated and replaced with the allowable stress of the compression truss for the friction. But, maximum load of static friction between horizontal stones is uniformly set as an approximate low value. Coefficient of static friction is set as 0.5. Push over analysis is controlled by dead load.

The result is as follows. (1) Different behavior between a part over the window and adjoining wall is observed. (2) Tendency of outward-swinging is observed. (3) Concentration of stress at the jumb is observed.

The above result generally agrees with the observed state of Prasat Suor Prat, shown in Figure 5.

3.5 *Effect of sub-soil mechanism to Tower N1*

Before the restoration, Tower N1 inclined 4.96% to Northwest. Uneven subsidence below the platform is considered as the biggest potential cause of the inclination. Uneven subsidence relates to the structure of platform, which is constructed of a sandy foundation surrounded by laterite blocks. Rainwater eroded the sandy foundation inside the platform away and uneven subsidence is occurred at the platform. In addition, the strength of the surface layers of the ground greatly differs between dry season and rainy season, so remarkable decline of the stiffness

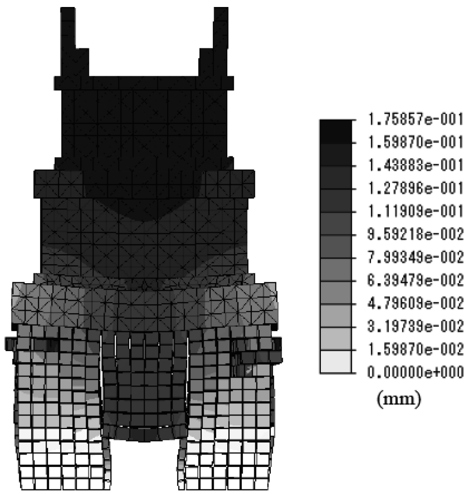

Figure 9. Deformation image.

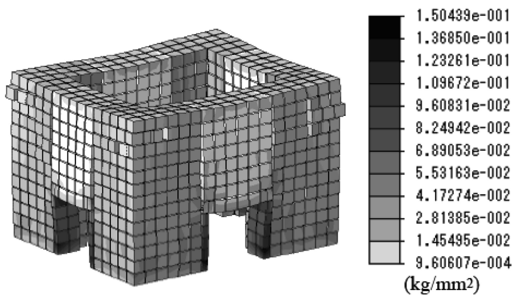

Figure 10. Von-Mises stress image of 1st story.

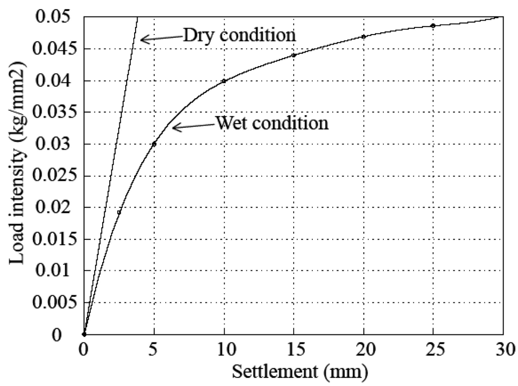

Figure 11. Load-displacement curve of surface ground.

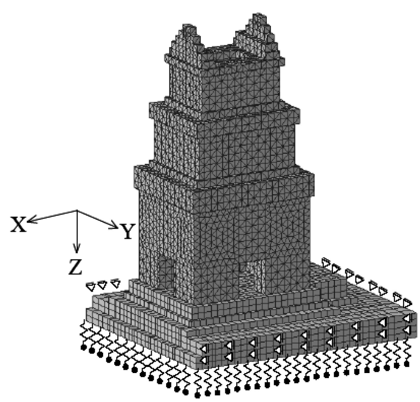

Figure 12. Structural analysis model.

in wet condition causes uneven subsidence. GRI conducted a plate load test on surface layers in dry and wet condition (T.Nakagawa et ar. 2005). Based on their researches, we determined a polynomial of load displacement curve in wet condition by least square method (Fig. 11).

Then, we replaced the stiffness of surface layers, which shows the non-linear characteristics in wet condition and linear characteristics in dry condition (Fig. 11), to the stiffness at the base of FEM model (Fig. 12). To consider the non-linear stiffness in FEM analysis, we adopted an equivalent linearization method. Thus, we studied about effects of the decline of the stiffness in wet condition to the inclination.

The process of the equivalent linearization is as follows. Firstly, a vertical displacement is calculated from load displacement curve to comply with a vertical reaction of every node on the boundary surface. Secondly, a secant stiffness determined from the above displacement and reaction is applied to the spring stiffness at every node on the boundary surface and FEM analysis reflected the new stiffness is conducted again. Then, the above process is repeated until the residual error between the displacements derived of FEM analysis and load displacement curve converges sufficiently.

Table 1. Material characteristics of FEM model.

	E kg/m^2	ν	γ kg/m^3
Laterite	2.0×10^9	0.25	2.33×10^3
Compacted fill	2.8×10^6	0.3	1.75×10^3

In FEM model, material characteristics are shown in Table 1, and loading condition is only dead load. As a horizontal boundary condition, a horizontal displacement of 3 lateral faces shown in Figure 12 is bounded.

The result is shown Figure 13 and Table 2. From this result, maximum displacement to X direction which means a direction of Northern Pond increased by 85% in wet condition.

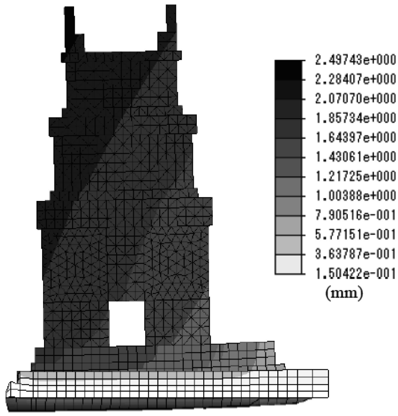

Figure 13. Deformation image.

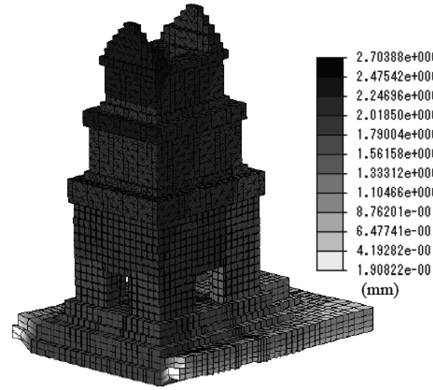

Figure 14. Deformation image including platform.

Table 2. Result of structural analysis.

	Dry condition	Wet condition	Increment percentage
Linearity	Linear	Non-linear	
Maximum displacement of X direction	0.686 mm	1.27 mm	85%
Maximum displacement of Y direction	0.0351 mm	0.0338 mm	−3.37%
Maximum displacement of Z direction	1.43 mm	2.03 mm	42%

3.6 *Relation between sub-soil mechanism and masonry structure at Tower N1*

Applying the discontinuum structural analysis, we inspected the effects of the ground to the upper structure in Tower N1. In the modeling, the discontinuum model of the upper structure is same as the model of section 3.4 and the continuum model under the platform, concluding the spring stiffness in wet condition, is also same as the model of section 3.5.

The result is as follows. (1) On the inclination of the upper structure, there is no so difference between the discontinuum model and continuum model. (2) The parts of corners, walls and stones over the window behave independently while mutually affecting the others.

As Figures 15 and 16 show, the behavior of 4 corners is inspected by the discontinuum structural analysis that we propose. From the result, we confirmed that the masonry construction of 4 corners was effective to the structural stability of the upper structure.

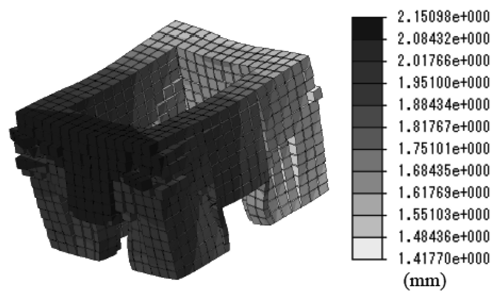

Figure 15. Deformation image of 1st story.

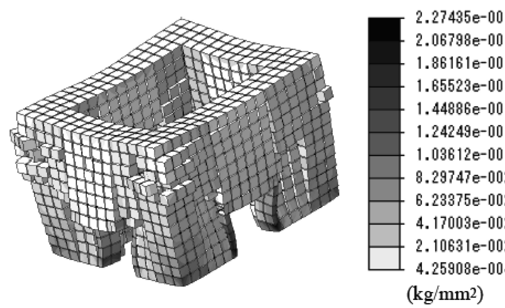

Figure 16. Von-Mises stress image of 1st story.

4 CONCLUDING REMARKS

In our paper, we proposed the structural analysis technique to assess the structural behavior of dry masonry in Angkor monument. From the result of the proposed techniques applied to Prasat Suor Prat, we verified the effectiveness of the technique by reflecting the structural characteristics of the masonry construction. The result of the structural analysis concluded that the masonry at four corners behaved as a continuum and

was effective to secure the structural stability of the upper structure.

We will improve the discontinuum structural analysis to reflect the mechanism of the sub-soil and platform. By further developing the techniques, we will quantitate the damage level of Bayon at present and the future.

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