Behavior of Joints and Crack of Masonry Stones Based upon In-situ Monitoring at the Central Tower, Bayon, Angkor Thom, Cambodia

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SUMMARY

This is to report the mechanical characteristics of stone joints and crack of the masonry structure of the Central Tower at Bayon Temple, Angkor Thom, Cambodia, which belongs to the Angkor Remains that were inscribed as a World Heritage by UNESCO in 1992.The Central Tower with about 31m in height and 23m in base diameter was constructed as a complex masonry structure with hollow space in the center. Stones of the outer surface have been fallen out and the present shape lacks axial symmetry that the original tower might have been designed and constructed. The mechanical process of fallout of stones has identified as progressive failure of a masonry column triggered by some existing crack in a single stone. To study mechanical characteristics of the stone masonry, movements of stone joints were monitored with temperature, rainfall, as well as wind velocities in 1997. Recent advancement of sensor technology, a continuous monitoring of change of moisture in the stone became available. We have installed gap sensors at joints between stones and at crack at stone surface and monitored for three months in rainy season as well as temperature and rainfall. Based upon monitored results and statistical analysis, we found that water contents and temperatures are major factors to affect the joints and cracks in addition to strong winds. The effects of relative importance of temperature or water are also found to depend upon the position of the joints and cracks in terms of exposure to sunlight and rainfall.

key words: Masonry structure, Angkor remains, Observation monitoring

1. Introduction

Bayon temple of Cambodia Angkor Tom is the existing which a sudden falling rock happens now, and the risk of the partial collapse of the tower has pointed out. The monitoring using the opening meter has been carried out at the gallery level of Bayon main central tower around the chosen point where it was impotant for observation of the progress of the crack opening from 1997. It has been suggested that the change of temperature and the rainfall had a high effect on the opening and closing of the crack in comparison with environmental parameter by observed chronological order data. We placed a displacement meter, moisture content, surface temperature near some cracks that the gallery level of Bayon central tower were dotted with and analyzed it. For those observed crack opening, we analyzed the crack opening by building the linear model. Those factors of the model are temperature and the rain. Using the environmental parameter data which we acquired, we expanded the linear model by indicating temperature and surface temperature, the rain and relations of surface moisture content clearly and examined the influence degree of the environmental parameter.

2. Monitoring with the observation equipment

We did update of monitoring machine parts and monitoring for the purpose of the chronological order data collection of temperature and rain in the Bayon main central tower newly.

We used soil water DECAGON EC-5 for monitoring surface moisture of stones and observe in particular it. This machine has been used for measuring moisture of the soil as an original but we used it for the stone's surface moisture in this

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observation. We fixed EC-5 in the monitoring point between sandstone and sandstone and think to perform long-term monitoring. EC-5 was the machine which measured moisture by using sensor both sides, but examined whether it was measurable of using only sensor one side by sand(Fig.1). As a result, we were able to confirm that we could measure stable numerical value even in the case of one side setting.

Fig. 1 EC-5 one side measurement experiment

We used Kett HI-520 about the revision of gathered chronological order data. We calibrated HI-520. Stone samples which we cuted and brought down to size of 50mm×60mm×20mm from new materials to be dotted with near Bayon remains in Cambodia was used . The using machine of measuring moisture was HI-520, and used 'D.mode' number in measuring. After having measured the mass in absolute dry condition, using dry kiln, we put it into water. We measured it by changing moisture of each sample, putting it on stones. The following lists were provided from here. Uchida and others measuring in 1999 and use the correspondence list that we analyzed (blue line) that it-type was near.

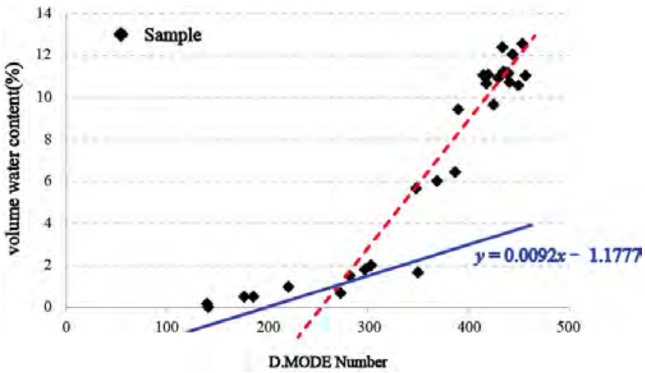

Fig.2 HI−520 list

We obtained the following expressions from here.

$$y = 0.0092x - 1.1777 \qquad (2.1)$$

x : HI-520 D.MODE number y : volume water content

With these, we measured it about moisture of the sandstone. We showed the setting situation of those monitoring apparatuses in Fig.3. We chose five places from the crack that Bayon central tower gallery level was dotted with, established opening meter, surface thermometer, moisture.

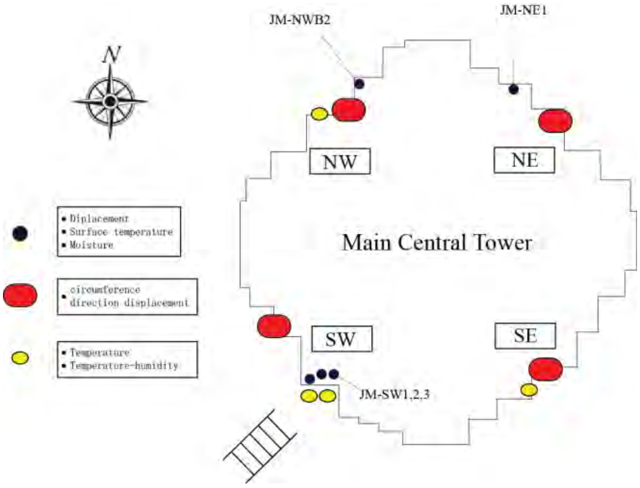

Fig.3 Sensor position in Bayon

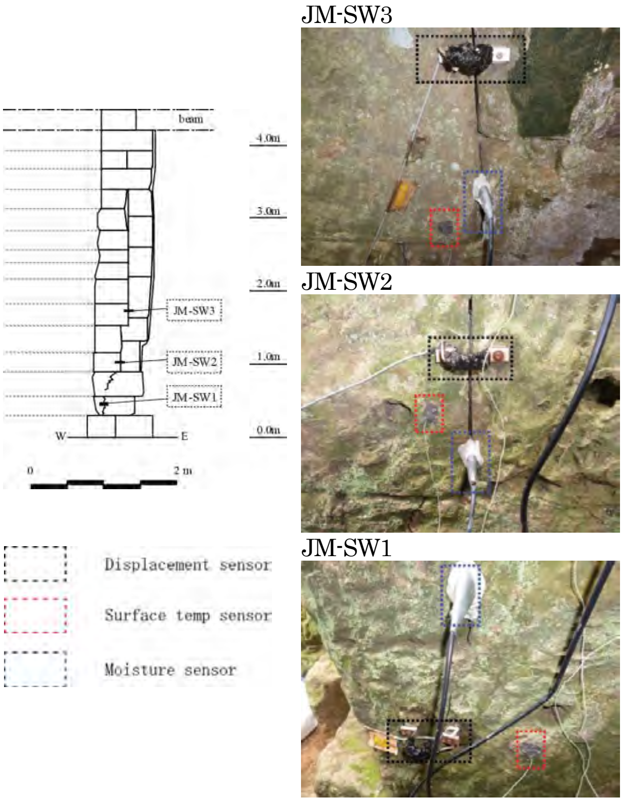

Fig.4 Sensor position SW1,2,3

In gallery level, the thing which plotted the rainfall for a change of surface moisture which we corrected was Fig..5 using DECAGONEC-5, HI-520. The change of moisture could be confirmed to move within 0~6% on the average, but the change at SW1 namely the crack neighborhood could be bigger than other measurement spots. Because we got the data of moisture changing of within 0~3% in a period without the rain, the soundness confirmation of the system was possible, and we could monitor it in future.

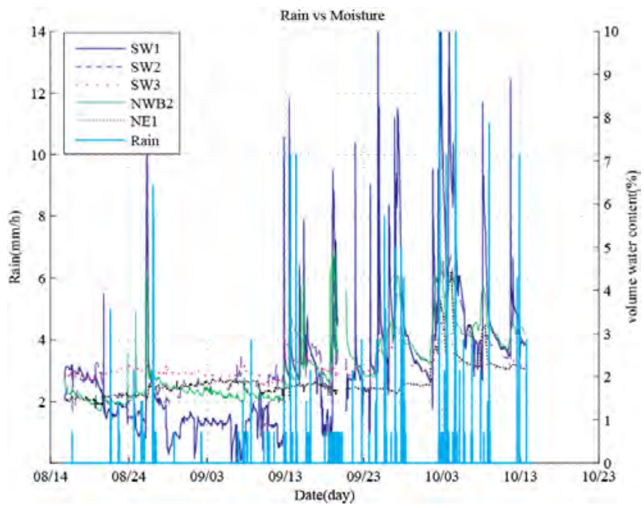

Fig.5 Rain vs volume water content(2013 year)

3.1. Examination of the crack model based on past long-term observation data and the analysis technique

The cause of the crack opening examines each influence ingredient of temperature and the rainfall as a factor of the crack opening based on the past analysis. At first we think about analyzing the phenomenon by suggesting crack opening change model (expression (3.1)) that assumed temperature, rainfall chronological order data that was measured at Bayon temple in a year of the past (2002). We assumed a simple linear equation about the model and decided a parameter using a multiple regression analysis. We evaluated the validity of the model by a decision coefficient (expression (3.2)). We assumed a model such as Fig.6 about the rainfall model. This model the rainfall, was like a tank model.

$$y_{(i)} = a_1 T_{(i)} + a_2 R_{(i)} + a_3 \quad (3.1)$$

$y_{(i)}$: crack opening $T_{(i)}$: temperature $R_{(i)}$: rain

a_1, a_2 : partial regression coefficient a_3 : constant term

$$r = \frac{\sum (y_i - y)(\hat{y}_i - y)}{\sqrt{\sum (y_i - y)^2 \sum (\hat{y}_i - y)^2}} \quad (3.2)$$

$$R = r^2 \quad (3.3)$$

y_i: Target chronological order data y: model data

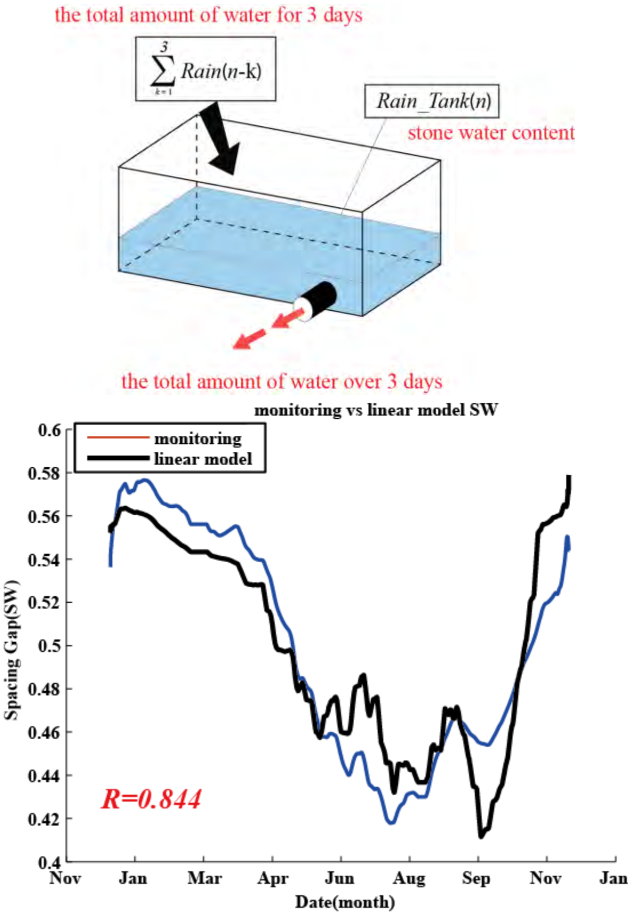

Fig.6 (upper) Rainfall savings model summary

(lower) monitoring data and model data (2002)

The decision coefficient was beyond 0.9 with a high thing by a point. As for this analysis technique, it might be said that it was effective means for the crack at Bayon central tower about Fig.6. In particular NE wave pattern was near to a rainfall tank model. The contribution ratio which was high could be confirmed, and it was thought that the consistency of a model and observation data was high.

3.2 Model to express the change of the crack from temperature, the rainfall

We made a model from past temperature, rainfall chronological order data in the foregoing paragraph. Therefore we inspected expansion of the analytical model, the precision using the environmental parameter data which we acquired newly by using the relations of temperature and surface temperature, the rain and moisture clearly. If measurement spot numbers for surface temperature and moisture of stones increase, cost and trouble would produce. Therefore we aimed at the possibility of the opening and shutting model of the crack to be made only in the environmental parameter that we measured easily of temperature and the rainfall by stating this expression of relations clearly. At first it was confirmed that modeling was possible and showed it in Fig.7 like an expression (3.4) about temperature and the surface temperature. And the value of the chronological order data of a calculation result and the observation result were very near.

$$ST_{(i)} = b_1 T_{(i)} + b_2 \qquad (3.4)$$

$T_{(i)}$: temperature、$ST_{(i)}$: surface temperature

b_1 : partial regression coefficient、b_2 : constant term

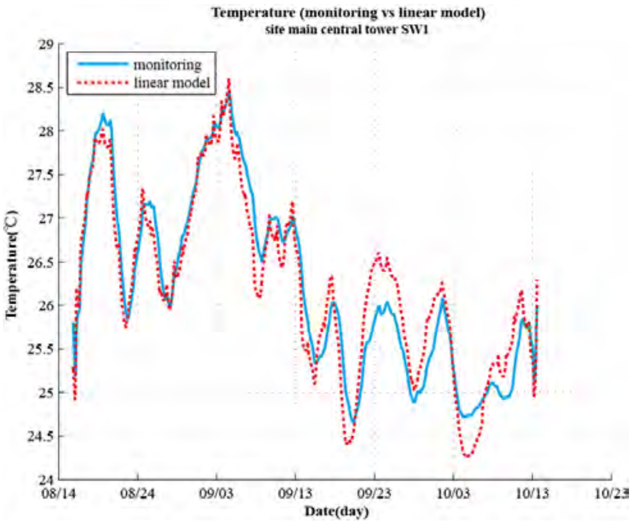

Fig.7 Comparison between calculation result and observation of the surface temperature in the chronological order

We made model about the relations of moisture and rainfall like an expression (3.5) successively. We applied a model type based on an expression (3.1) and lead an expansion model (3.6). In addition, we examine each contribution ratio of temperature, the rain in an expression (3.7). Each contribution ratio of temperature and the rain expressed an influence degree of each influence ingredient at the measurement spot. We showed the comparison result of temperature and rain influence degree in each measurement spot in Fig.8. Spot SW1 was the strong point of influence of the rain and, in each measurement spot, Fig.8 showed that an influence degree of each influence ingredient was different.

$$W_{(i)} = c_1 RT_{(i)} + c_2 \qquad (3.5)$$

$$y_{(i)} = d_1 T_{(i)} + d_2 \sum_{k=1}^{1} Rain_{(i-k)} + d_3 \qquad (3.6)$$

$W_{(i)}$:surface moisture 、$RT_{(i)}$: Rainfall savings model

c_1 : partial regression coefficient、c_2 : constant term

d_1, d_2 : partial regression coefficient、d_3 : constant term

$$t_i = \frac{a_i}{\sqrt{\frac{\sigma}{N(N-1)}}} \qquad (3.7)$$

$$\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{(N-1)}} \qquad (3.8)$$

t_i : t number、a_i : estimated coefficient、σ : standard deviation、N : sample number

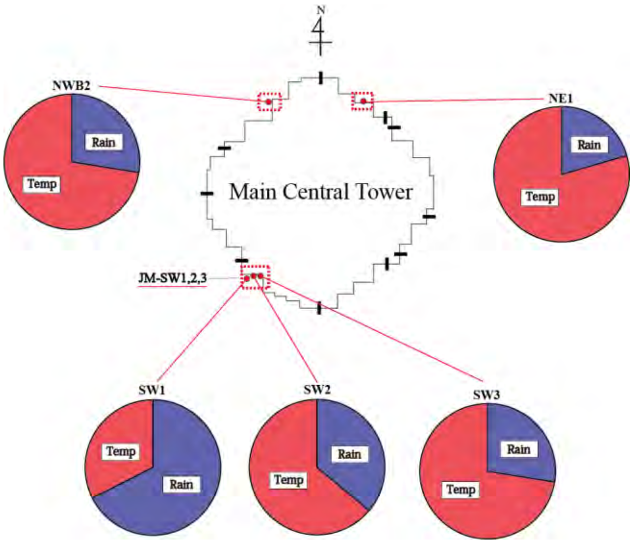

Fig.8 Temperature in each measurement spot, comparison of the rain influence degree

Influence of the rain was strong in the analysis in (8/14 - 10/14) in SW1 and SW2 follows. The aspect of the south side should be strong in influence of the sunlight, but influence of the rain was strong from analysis. It might be said that it was necessary to analyze the sunlight taken spot for the sandstone, a penetration course of the rain in future. Because the opening of the crack was bigger than other cracks, it might be possibility to reduce crack opening by taking measures for the rain in SW1. The decision coefficient was high in SW1, but a low result was provided in SW2. The factor (wind) except the parameter of temperature, rain might have an influence as a reason. We would make the improvement of the further measurement system and analysis-style expansion (parameter increase) and aim at showing an influence degree at the observation point more definitely in future.

4.2 Result

1) In Bayon main central tower gallery part, we suggested analytical model to assume temperature, the rain an ingredient. This parameter was monitoring data in environmental monitoring system.

2) By continuing an observation monitoring system, and performing it, we would be able to analyze a crack opening in a year, and the improvement of the crack change analysis would be possible in future by making a model to consider influence such as the wind except temperature, rain.

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