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Study on Relationship between Elastic Wave Profile and Stones' Condition in Angkor Monument

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Abstract In this paper, we purpose to assess the crack and deterioration level of composed stones in Angkor Monument, Cambodia, by an elastic wave test. The degree of deterioration and crack is generally examined by supersonic wave test, electromagnetic wave test and hardness test. However, the above general methods are difficult to be applied to the stones in Angkor Monument, because there are some problems such as damages on the surface relief and an accuracy of the test results which highly depend on the surface deterioration level. Therefore, in this paper, we suggest the method of an elastic wave test by slightly knocking on the stones. Then, we analyze the elastic wave's profile, such as velocity, amplitude ratio and frequency etc. From the results, we examine about the relationship between the elastic wave profile and existence of crack or deterioration level of stone. The above examinations are applied to assess the structural safety of composed stones in Angkor Monument.

Keywords: Angkor Monument, masonry, elastic wave, deterioration

Introduction

Angkor Thom, one of Angkor Monument in Cambodia, was built in 12th century. Most of the monuments are composed of sandstone or laterite blocks and there is no bond such as mortar between stones.

Now, Angkor Monument faces the risk of collapse, and some stones used in monuments are deeply deteriorated. However, it is difficult to identify how the deterioration of stones causes a collapse of the monument and the level of severe deterioration. And, there is a risk to damage monuments by the general method to measure a strength or hardness of a concrete block.

In this paper, we suggest a method not to damage the monuments, which is named as an elastic wave test, and examine the relationship between the elastic wave characteristic and the stones' deterioration or crack.

We conducted an elastic wave test in two monuments which were Prasat Suor Prat tower and Bayon Southern Library in Angkor Thom. The former, Prasat Sour Prat, is composed of 12 towers. Prasat Sour Prat towers are mainly composed of laterite blocks and have 4 openings of sandstones at each side. Prasat Sour Prat tower N1 had been restored by JASA in 2005 because it was judged that there was a high risk of collapse. Then, we tested at the cracked sandstones of openings. The latter, Bayon Southern Library, has been restored since 2006. On September in 2009, we conducted some tests at compacted soil surface in a platform. Some parts of the platform are re-constructed through the restoration process and the others are kept as an original compacted soil. So, we tested and compared the characteristics at the re-constructed site and the original site.

Relationship between Wave's Characteristics and Material Properties

Now, ultrasonic non-destructive testing is used for safe evaluation of facilities and structures such as power plants and bridges as well as deterioration check of monuments. Fig.1 shows material properties and faults evaluated from characteristic of ultrasonic wave. We suppose that these relationships between ultrasonic characteristic and material property can be applied to elastic wave.

In material properties shown in Fig. 1, we consider that elastic modulus, anisotropy, tensile strength (which are evaluated from velocity), crack and micro-damages (which are evaluated from damping ratio) are important to assess the stability of monuments' structure. In this paper, wave's velocity and amplitude ratio are mainly examined. In following chapter, we study elastic wave's velocity of new sandstone in relation to anisotropy, time lag or amplitude ratio of used sandstone in relation to crack, and velocity of compacted soil in relation to stiffness.

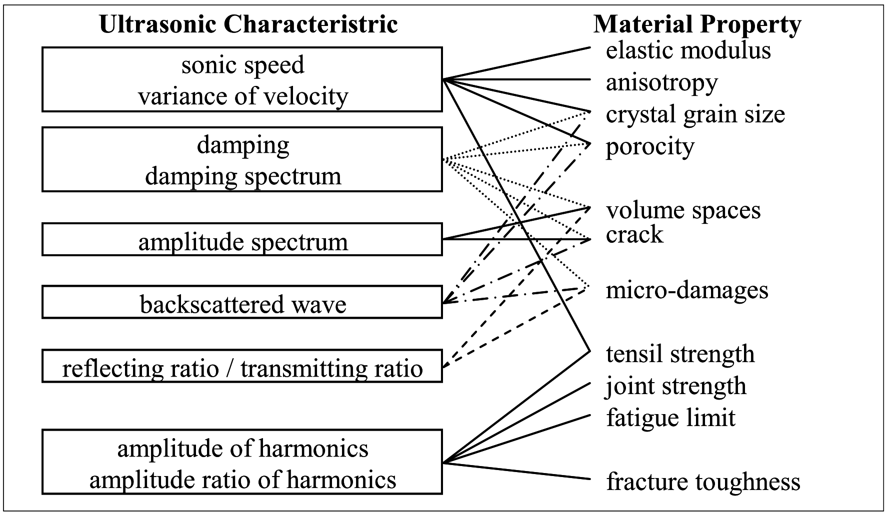

Figure 1: Relationship between ultrasonic characteristic and material property

Elastic Wave Test

Outline of Test On September 16-19, 2009, we examined elastic wave of sandstone, laterite and compacted soil used in Angkor Monument. Places where the test was practiced are shown in Tab.1. This examination was aimed at studying about a basic property of elastic wave in each material, and mainly at the effect of deterioration and crack.

In this examination, elastic wave was made by slightly knocking the test body and the time history was recorded by two terminals. And, a terminal at the impact point is called as first terminal and the other, which have an interval from the knocking point, is called as second tarminal. Then, we examined by two methods. In a method, we shifted the mesured points with keeping a regular interval of 3 patterns, 10, 20 or 30 cm, between terminals. In the other method, we gradually changed a span by moving the second terminal with fixing the first terminal.

Table 1: Places where test is practiced

test body	*place*	
new sandstone	---------------	
laterite block	Prasat Suor Prat tower N1	
sandstone	Prasat Suor Prat tower N1	northern opening
		western opening
concrete beam	Prasat Suor Prat tower N3	eastern opening
compacted soil	Bayon Southern Library	

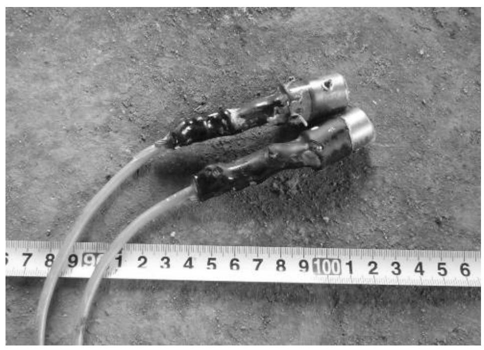

Figure 2: Two terminals used in the test

Definitions in analysis of Wave Profile We mention about three definitions in this examination as Fig. 3 and Fig. 4. First, we calculated velocity of elastic wave as the time from the span divided by the lag of first peak between the span. Secondly, amplitude ratio is calculated by the ratio of each terminal's first peak value. Finally, we conducted the normalization by setting the maximum amplitude of first terminal as the criterion.

$$\textit{Velocity of elastic wave} = \frac{\textit{Span between terminals}}{\textit{Time lag}} \tag{1}$$

$$\textit{Amplitude ratio} = \frac{\textit{Second terminal's maximum amplitude}}{\textit{First terminal's maximum amplitude}} \tag{2}$$

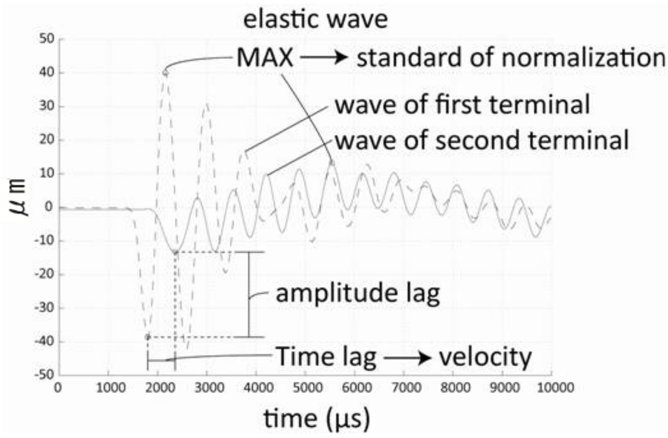

Figure 3: Definition of test result

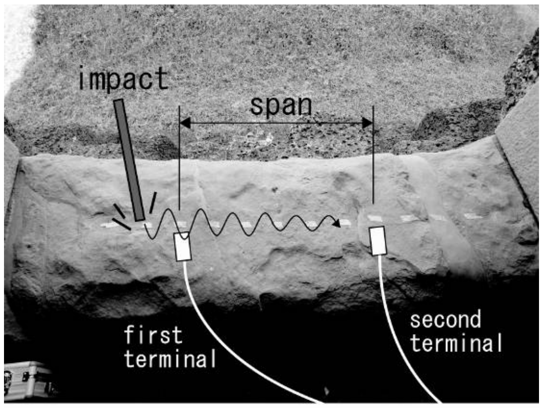

Figure 4: Outline of examination

Result of New Sand Stone To verify the relationship between the properties of elastic wave and bedding planes' direction, new sandstone was examined about three directions 1, 2 and 3 as Fig. 5. Then, Directions 1 and 2 are parallel to bedding plane while direction 3 is left surface of out of plane's direction in Fig. 5 and perpendicular to bedding plane.

Results of examination at each side are shown in Fig. 6-Fig. 8. These figures show the relationship between amplitude ratio (the horizontal axis) and velocity (the vertical line). In comparison of directions 1, 2 and 3, both characteristics have a scattering result in every span of 10, 20 and 30 cm. From this scattering result, but it is impossible to mention about the characteristics relied on the difference of bedding planes' direction in this examination.

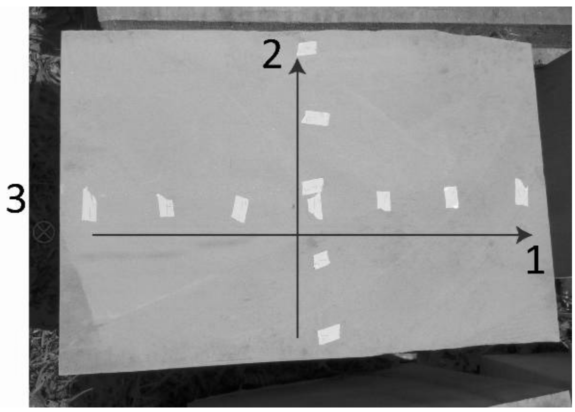

Figure 5: New sandstone

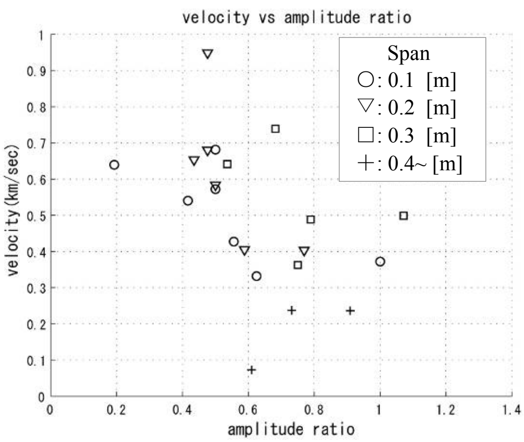

Figure 6: result of direction 1

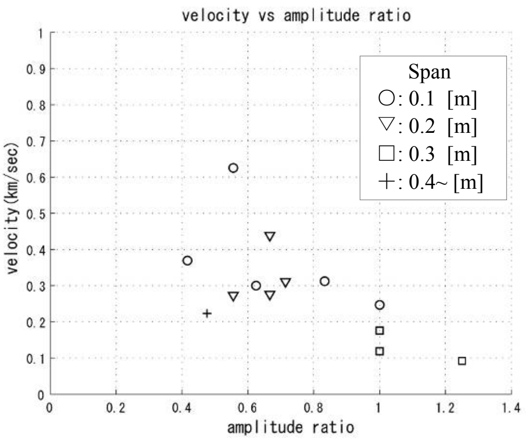

Figure 7: result of direction 2

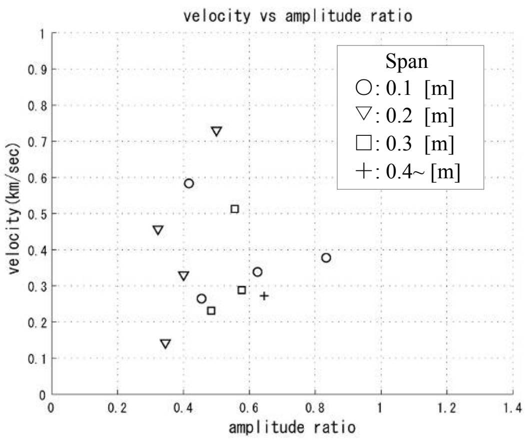

Figure 8: result of direction 3

Result of Sandstone Beam of Prasat Suor Prat Tower N1 Now, examination of a beam of western side of Prasat Sour Prat tower N1 is described. After the tower was restored, a crack was observed at the center of this beam (Fig. 11).

Normalized time history profile of elastic wave at each measured point is shown in Fig. 10, in which higher number of vertical line means the span between the first terminal and second terminal. In Fig. 11, the vertical axis shows the time lag between two terminals, and the horizontal axis means the position of two terminals. In comparison of solid lines (there is a crack) and dotted lines (there is no crack), it is resulted that the velocity of waves is lower and amplitude widely decays when there is a crack. This phenomenon was not occurred at a sound beam of northern opening where we conducted same examination. Fig. 12 also proves that velocity of wave with cracks is lower when span is same.

As shown in Figs. 12, 13 and 14, when there is a crack between terminals, the regression equations of span S, velocity V and amplitude ratio R are represented as Eq.(3), (4) and (5).

$$V = 0.248 \ln S + 0.662 \tag{3}$$

$$R = 0.614\, e^{-2.42\, V} \tag{4}$$

$$R = 0.441\, e^{-137\, S} \tag{5}$$

In Fig. 12, Eq.(3) shows that the velocity when there is a crack gradually converges to the average velocity when there is no crack as the span is longer. It means that the effect that the existence of crack decreases the velocity is reduced by the longer span. And, in Fig. 14, Eq.(5) shows the tendency of divergence decrease when there is a crack.

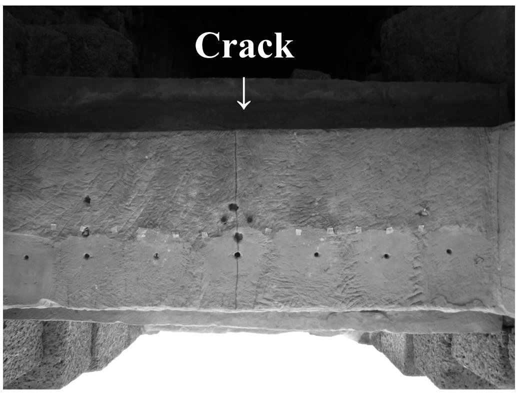

Figure 9: Beam of tower N1 western opening (upward view)

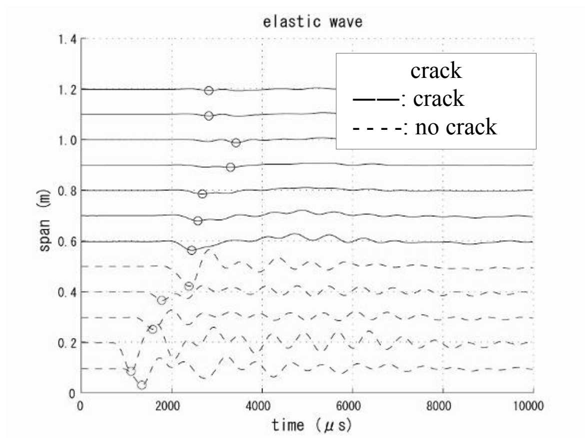

Figure 10: Normalized wave shape

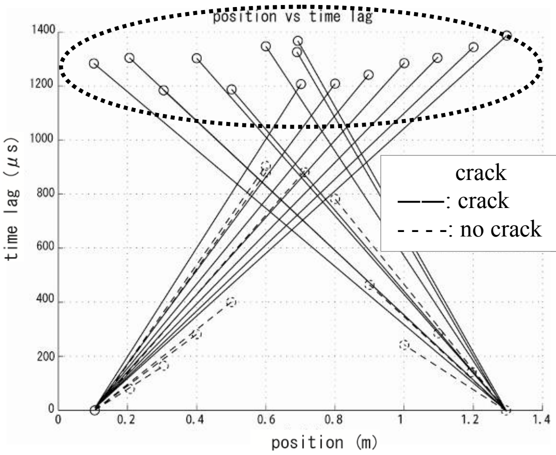

Figure 11: Position vs time lag

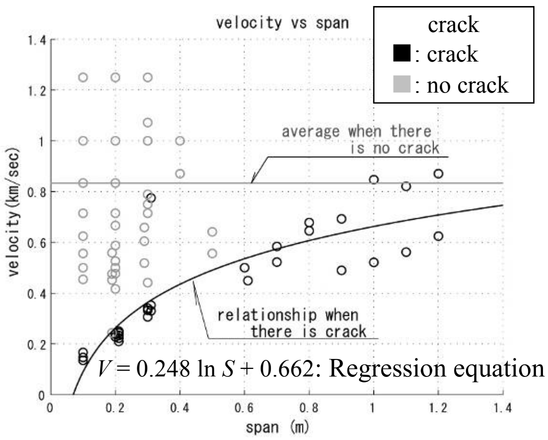

Figure 12: Span vs velocity

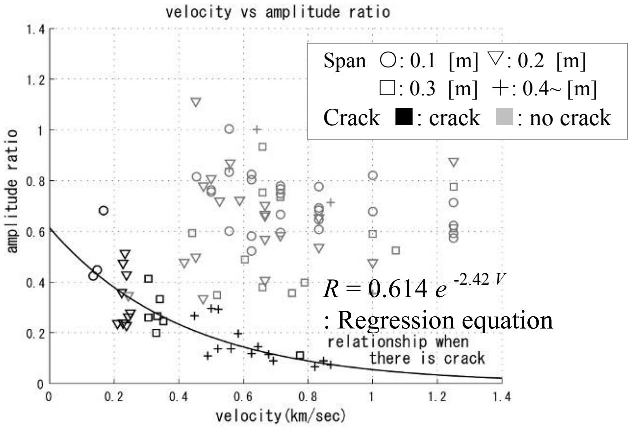

Figure 13: Velocity vs Amplitude ratio

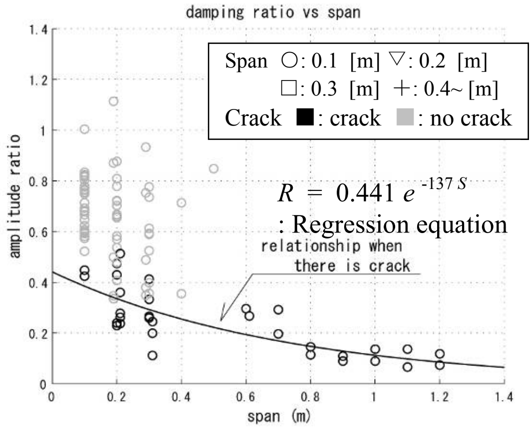

Figure 14: Span vs Amplitude ratio

Result of Compacted Soil of Bayon Southern Library Another elastic wave test as the above was conducted about compacted soil in platform of Southern Library of Bayon. We discussed by comparing between original compacted soil before improvement and compacted soil after improvement. Fig. 15 and Fig. 16 show the varieties of velocity and amplitude ratio respectively in each span subjected to original compacted soil and compacted soil after improvement. In the same way as above section, regression equations span S - amplitude ratio R is represented as Eq.6.1 and Eq.6.2, and span S - velocity V is also represented as Eq.7.

$$R = 0.749\, e^{-2.73\, V} \qquad \text{(original compacted soil)} \tag{6.1}$$

$$R = 0.319\, e^{-2.12\, V} \qquad \text{(improved compacted soil)} \tag{6.2}$$

$$V = 0.0564 \ln S + 0.475 \qquad \text{(improved compacted soil)} \tag{7}$$

There is no large difference between both compacted soils' amplitude ratio (Fig.15). The velocity of improved soil is higher than one of original soil, which reveals that improved soil is more compacted than original soil. In addition, the place where we examined was recently re-constructed, and soil with calcium hydroxide, which was used for improvement of compacted soil, takes a long time to get strength enough. Therefore, we consider that the difference of velocity will be clearer if we test in an area taking an enough long time after improvement.

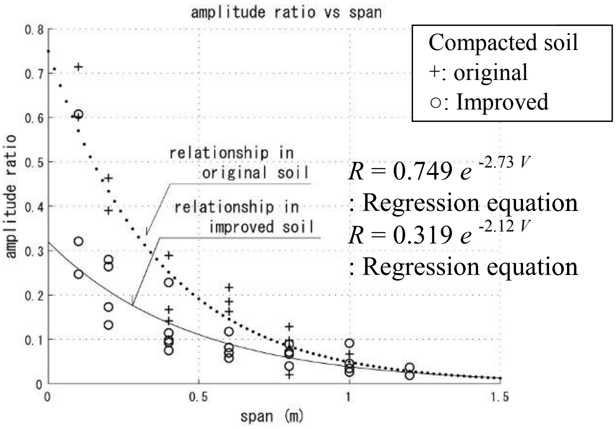

Figure 15: Span vs velocity

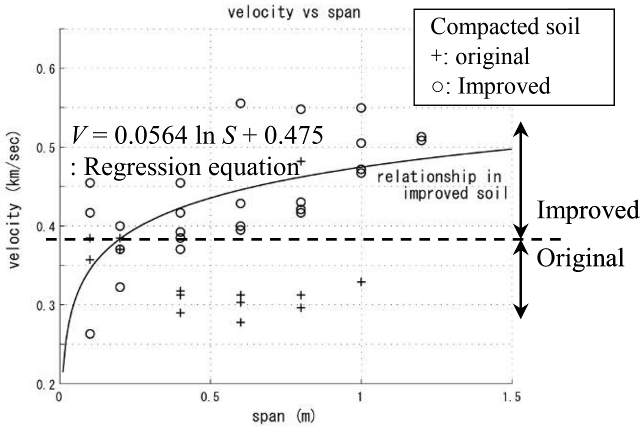

Figure 16: Span vs Amplitude ratio

Conclusions

The elastic wave test revealed follows.

- There is no certain difference of characteristics such as velocity and amplitude ratio relied on the difference of bedding planes' direction.
- The velocity of waves is lower and amplitude widely decays when there is a crack between two terminals.
- About compacted soil, the velocity at improved compacted soil is higher than the velocity at original compacted soil; therefore it is considered that improved compacted soil is more compacted than original compacted soil.

In this study, we suggested an elastic wave test as a method to examine about stones' condition without monument's damage. And, we showed basic properties of wave profile and stones' deterioration.

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