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Research Paper

Restoration of damaged stone walls of Kumamoto castle due to the 2016 Kumamoto Earthquake

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ARTICLE INFORMATION

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ABSTRACT

The 2017 Kumamoto earthquake caused damages to many stone walls of Kumamoto castle. Paper shows facing curves of deformed or collapsed stone walls can be interpreted comparing with the traditional guideline contributed to the stone piling technique. Reconstruction works are aimed to return the collapsed stone wall to the original features. The original curve of stone wall is possibly evaluated at the remained stone wall adding the existing measurement data. There were many deformed stone wall of Kumamoto castle before the 2016 Kumamoto earthquake. The stone wall is congenitally fragile to deform. Deformation level is evaluated comparing the deformed curve of stone wall and the traditional stone piling guidelinel. Stability analysis of stone wall should include deflected facings of stone wall. Paper shows the role of depth of stone wall on the base of thin skeleton model of stability analysis.

1. Introduction

Stone walls of Kumamoto castle have been damaged by the two strong earthquakes in1889 and 2016. Most of stone walls due to the 2016 Kumamoto earthquake were identified as the same wall faces damaged by the 1889 Kumamoto earthquake. However, restoration work has been continued from the 1889 Kumamoto earthquake to the 2016 Kumamoto earthquake. Many rebuild stone walls conducted from 1966 were collapsed.

Sustainable construction techniques were developed in every historical stage to pile up the shape of curved face and piling of stones. Tomita (2008) shows 7 historical stages of stone piling methods in Kumamoto castle. Kitagaki (2006) shows that the historical process of Kumamoto castle stone wall become the reference on the stone piling history of castles in Japan.

Measured data of curved stone walls show the historical curved in every period stage as well as the deformed curve of stone wall due to 1889 Kumamoto earthquake remained without restoration. Period and remained deformation due to 1889 Kumamoto earthquake are proved to be coexisted.

How to restore historical structures is required to follow authenticity that means to return to original position and using original materials. But restoration in strict to original condition is possible to be damaged when earthquake attacks in future. Therefor concept of minimum reinforcement authenticity should be established. Concerning specialists in many fields take seats together. It is important to reach consensus to guide principle of restoration against natural disaster. Level of minimal reinforcement changes to concerning the historical structure.

This paper includes the historical difference of curve of stone walls and how to the predict safety of sliding and rotating of every stone. Identification of construction period of stone wall and evaluation of stability is the basic concept of restoration work.

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Note: Discussion on this paper is open until September 2018.

2. Traditional curve of stone wall facing

There are two famous design guidelines in Japan to identify curve of the stone wall of the castle. The Guideline Gotoke Bunsho document is applied to Kanazawa castle and Document Isigaki Hidennosyo to Kumamoto castle. Both guidelines give same curve of the stone wall. However, corresponding equations are expressed in different form. These procedures are governed to the concept of roof of Japanese traditional gable. On the way of restoration, this survey should be started to identify the historical face of curved, which is specified the construction period. Even if the construction period was different, curve of the stone wall is interpreted along same design guideline. Hence, discrepancy from the reference curve introduced from the traditional stone piling guideline is possible to interpret the degree of change from the original curve. Two traditional stone piling guidelines, even if their representative equations are different in form, are may be unified to the curve derived from the traditional Japanese gable guideline. **Figure 1** shows the result obtained from three equations corresponding to the stone wall of Yonken yagura.

There are three conditions of change between actual curve in present and the approximated curve, which is original curve of stone wall. Deformation level 1 means suitable fitting, level 2 a little bit difference and level 3 corresponds to clear discrepancy. Figures of deformation amount level are shown in **Fig. 2** to **Fig. 4.**

There are two ways to approximate the actual curve of stone wall depending on the traditional stone piling method, Ishigaki Hidennosyo. Approximation A means curve drawn on focusing root and top portion. On the contrary, approximation B is to draw a curve, focusing on the lower part of stone wall. Considering the stability characteristic of stone wall, approximation B is more important.

Figure 5 shows the relationship between the angle of the root of approximation B and height. And circles

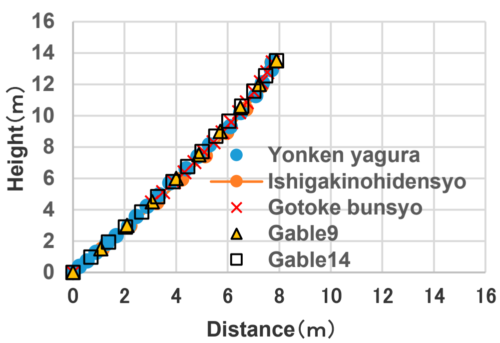

Fig. 1. Interpretation by the traditional guidelines for stone piling technique.

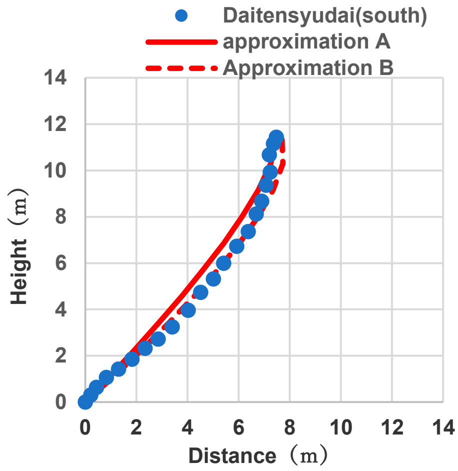

Fig. 2. Evaluation of deformation level 1.

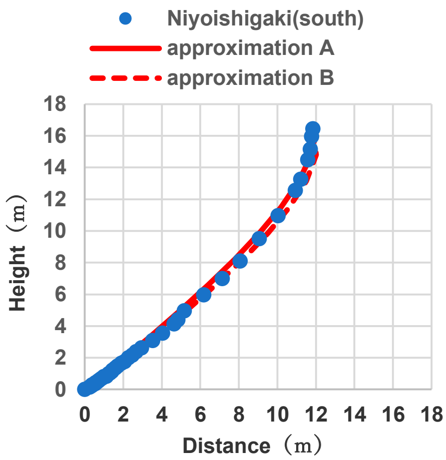

Fig. 3. Evaluation of deformation level 2.

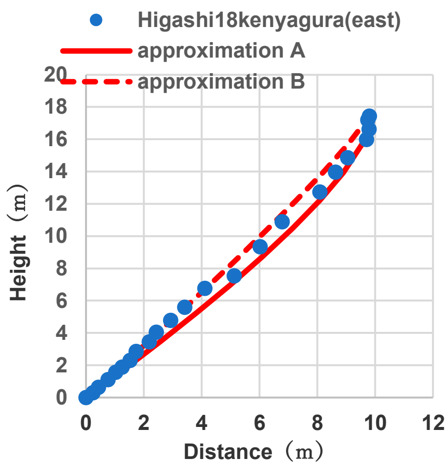

Fig. 4. Evaluation of deformation level 3.

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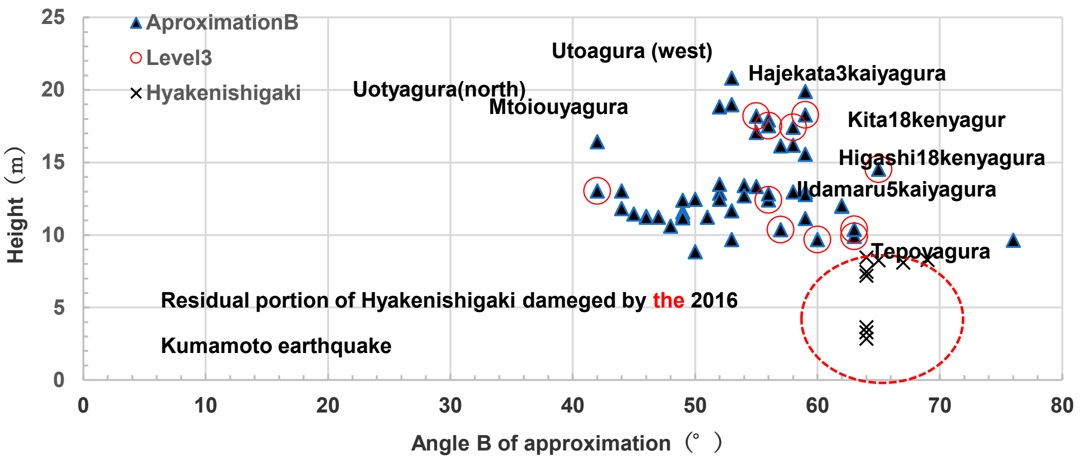

Fig. 5. Change of stone wall facing and damaged stone wall.

correspond to level 3 of discrepancy. Many points of higher degree of angle of approximation B correspond to group of level 3. Instead of measured data at Hyaken ishigaki, there are measured data of 51, of which 39 are divided to level 1, 2 data are grouped into level 2, and 10 data to level 3. 8 of group of level 3 are collapsed due to the 2016 Kumamoto earthquake. 2 of group of level 1 are collapsed. On the other hand, data of group 2 are kept stable.

3. Stability evaluation methods of static and dynamic

Thin film skeleton model of the surface of the stone wall was developed to predict the static and dynamic safety factor for shearing and rotation. The analysis model is composed of homogeneous trapezoid blocks. Height of the element of trapezoid stone strongly affects to the safety factor. Vertical length of the element is used of about 45cm, and its depth is 1.5 times of vertical length. Magnification of 1.5 is chosen based on the survey record of Kumamoto castle. The presented model uses the trapezoidal brocks of same shape. The basic theory is applied for static safety. And dynamic model contains spring force acting at the centre of gravity of trapezoidal blocks. Dynamic deformation is predicted through harmonic oscillation function.

Figure 6 shows the vertical distribution of safety factor of shearing and rotation, and the representative gain displacement. **Fig. 7** shows the relationship between the shearing and rotation. These calculation results are affected by the depth of stones pilled.

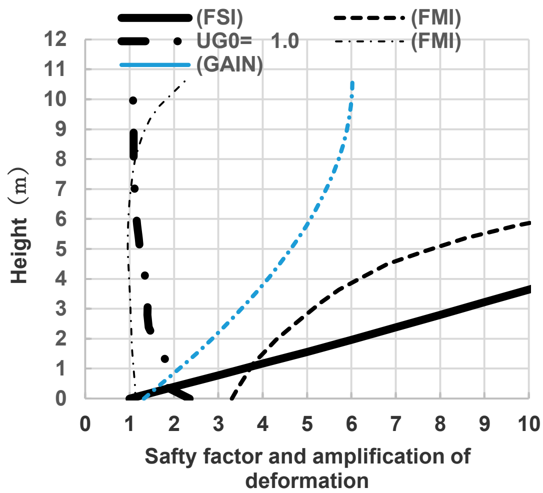

Fig. 6. Vertical change of safety factor.

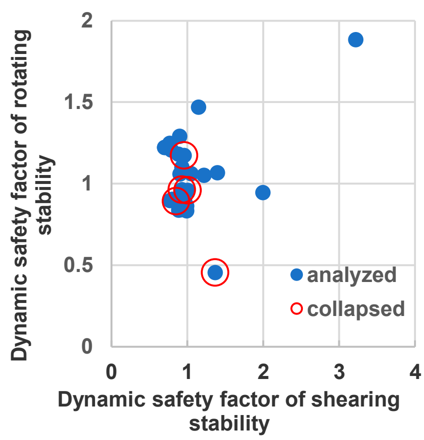

Fig. 7. Safety factor of stone walls.

4. Location of collapsed stone walls of Kumamoto castle

Modern executed reconstruction work started from 1959 by Kumamoto city. However, most of the stone walls rebuild of Kumamoto city are collapsed by 2016 Kumamoto earthquake. Signs(○) in **Fig. 8** are stone walls where have been reconstructed from 1959, signs(×) in **Fig. 8** are where collapsed due to the 2016 Kumamoto earthquake. As considering the mechanical structure of the low height stone wall collapsed, the main course is predicted to use shorter depth of stone than the stable required condition through analyzing using the thin film skeleton model. Higher height and steeper slope aren't unique cause.

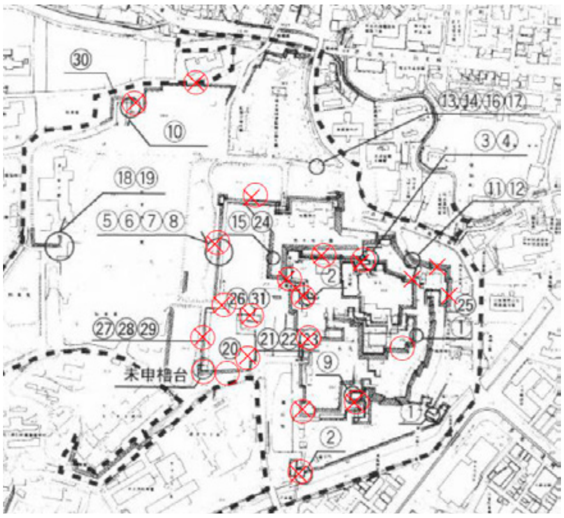

Fig. 8. Collapsed walls and reconstruction wall.

5. Case history of restoration of Sendai castle with minimum reinforcement authenticity

Restoration of Sendai Castle was completed on the concept of minimum reinforcement authenticity (2006). It includes (1) using Geotextile, (2) improvement of grading of backfill, (3) using deeper stone at a suitable position.

Typical section of restoration of stone wall shown in **Fig. 9** is attained to agree by the specialist of many fields. This section was derived through stability analysis. This face skeleton model can give the same result with the leaning wall design method.

6. Conclusions

Northern stone wall of Sendai castle was restored by Sendai city through many research meeting sit in company with many fields and actualizing minimal reinforcement authenticity. It was completed in 2008 and it remained without damage by the 2011 Tohoku great earthquake.

Process of restoration of Kumamoto castle should be followed in the same process executed by Sendai city. There are three engineering points focused on minimum reinforcement authenticity. They are identified using longer of stone, reinforce by Geotextile at the top portion of stone wall and use better grading of back fill.

Furthermore, the historical construction period of stone wall as identified by Tomita (2008) and Kitagaki (2009) should be followed as well as keeping landscape of Kumamoto castle.

This paper shows the important role of the traditional guidelines on evaluating the original curvature figure of stone wall, and refers the necessity of reinforcement of back fills of cobble.

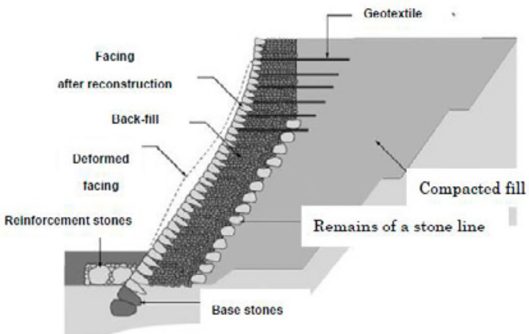

Fig. 9. Reinforcement wall of Sendai castle.

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