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Investigation on the damage to Kumamoto Castle stone wall related to the 2016 Kumamoto Earthquakes

T. Ohsumi

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ABSTRACT

A major earthquake with a magnitude (M_{JMA}) 6.5 foreshock and a M_{JMA} 7.3 main shock occurred at 1:25 on April 14 and 21:26 on April 16, 2016, respectively, in the Kumamoto region. According to the Kumamoto Castle research center, the reported damages to Kumamoto Castle included 23 important cultural properties, the 27 reconstructed structures and 523 stone wall deformations. Thirty percent of all of the stone walls were damaged. The stone wall foundation used two different construction techniques from the Kato age and Hosokawa age. The damage patterns with respect to the shapes of the stones in the walls were investigated and compared. The damaged stone walls which related to the main shock, were mainly constructed Hosokawa ages. In addition, the damage patterns in the reinforced concrete reconstructed Castle Keeps (Tensyu) / turrets (Yagura) and existing historical wooden structures were compared.

1. Introduction

In 2016, major earthquakes with a magnitude (M_{JMA}) 6.5 foreshock (NIED, 2016a) and an M_{JMA}7.3 main shock struck (NIED, 2016b) Kumamoto Prefecture and the surrounding region. According to the Kumamoto Castle Research Center, the reported damage to Kumamoto Castle included 23 important cultural properties, the 27 reconstructed structures and 523 stone wall deformations. Of all of the stone walls, 30% were damaged. Aftershocks continued to cause further damage in the weeks following the main shock. The stone wall foundation was constructed using two different techniques during the Kato age and Hosokawa age. Those method called as Sangi-tsumi construction method used in the late Kato age and early Hosokawa age, characterized by a steeply sloping stone wall. The present study investigated and compared the damage patterns with respect to the shapes of the stones in the walls. The stone walls damaged by the main shock were mainly constructed during the Hosokawa age.

2. Foreshock and main shock

According to the Kumamoto Castle research centre, damages of Kumamoto castle were noticed in Kumamoto city hall boards: At June 10, 2016. 10 important cultural properties, 7 restoration buildings and 6 castle stone walls were damaged related to the foreshock. However, 13 important cultural properties, 20 restoration buildings, 517 castle stone walls were damaged related to the main shock. Also, approximately 12,345 m^2 Ground condition were deformed. The damage of the stone wall in 30% of the whole related to main shock. The collapse of the stone wall in 10% of whole, which were correspond

Principal Research Fellow, National Research Institute for Earth Science and Disaster Resilience (NIED), 3-1 Tennoudai, Tsukuba, Ibaraki 305-0006, JAPAN, t_ohsumi@bosai.go.jp
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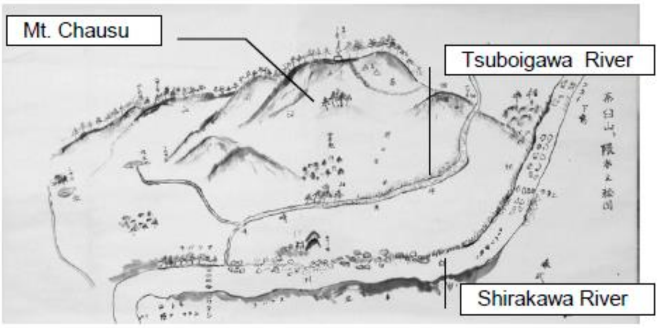

Fig. 1. Kumamoto old illustrated map (Kumamoto city museum possession).

Fig. 2. Photograph of the shallow slope of a stone wall at Hagi Castle, Yamaguchi Prefecture, Japan (photo by T. Ohsumi, taken in 1990).

Fig. 3. Photograph of the Niyo stone walls of the Kumamoto Castle. Kato family age (shallow slope: front part). Hosokawa family age (steep slope: inner part)(photo by T. Ohsumi, taken in 1989).

Fig. 4. Example of the Sanki-tsumi construction method at Nagoya Castle, Aichi Prefecture, (photo by T. Ohsumi, taken in 1990).

Fig. 5. Photograph of Uto Yagura, which is designated as an important cultural property. (photo by T. Ohsumi, taken August 11, 2016).

approximately 8,200 m^2. The damages has been ongoing.

3. History of Kumamoto Castle

Fig. 1 is a reproduction of the old illustrated map which came in the Middle Ages. Mt. Chausu is the current Kumamoto Castle whole neighborhood. The topography before the construction of a castle is drawn into a hilly terrain form. Shirakawa river drifts to the south from the east side. River terrace is seen in the east side of the castle. Tsuboigawa river joins in Shirakawa river. Tsuboigawa river is consisted by a part of the of Kumamoto Castle moat. Construction of Kumamoto Castle began in 1601 and was completed in 1608, for Kiyomasa Kato. At that time, the castle area was about 5.3 km in circumference, encompassing a total area of 980,000 m^2, which included 49 turrets, 18 turret gates, and 29 castle gates.

3.1 Stone wall material and structural type

The stone material for the walls of Kumamoto Castle came mainly from Mt. Gion (1,322 m above sea level), and was transported to the site using the Horikawa river. The main constituents of the stone wall material are andesite and granite. The foundations are a sedimentary layer originating from the volcanic ash of Mount Aso, deposited ca. 90,000 years ago. There are few welded tuff components and the sedimentary layer containing pumice is about 40 m. The soft volcanic ash layer was extremely difficult to construct a stone wall on (Tomita, 2008).

Generally, if the ground is soft, shallow slope stone wall is used, such that the load pressure from above is

Fig. 6. Photograph of the stone wall of Iidamaru Yagura (2004 reconstruction), which was constructed using the Sangi-tsumi method. (courtesy of Prof. K. Meguro, taken Oct. 26, 2016)

Fig. 7. Photograph of the stone wall of Inui Yagura (2003 reconstruction), constructed using the Sangi-tsumi method. (photo by T. Ohsumi, taken Aug. 11, 2016)

Fig. 8. Photograph of the stone wall of Bagu Yagura (1966 reconstruction), constructed using the Sangi-tsumi method. (photo by T. Ohsumi, taken Aug. 11, 2016)

dispersed below the masonry with an arc-like gradient, similar to the stone walls of Hagi Castle in Yamaguchi prefecture (**Fig. 2**). The rock used in such walls is poor in strength and poor in water retention (Tomita, 2008). The stone wall of Kumamoto Castle has two types (**Fig. 3**). The inner part and the front part of the stone wall constructed in the Kato age have a shallow slope, whereas the other parts constructed in the Hosokawa age have a steep slope. The shallow shape of the Kato-age walls was selected based on the weak ground, whereas the steep gradient of the Hosokawa-age walls was selected based on the accumulation of trees. The question of which of these methods was more suitable is a matter for discussion in future investigations.

This construction method is a stack of stones of the same size in a corner stone. Sangi-tsumi is another construction method used in the late Kato age and early Hosokawa age. It involves alternately stacking the long side apsednd the short side of a rectangular stones, resulting in a stone wall with a steep gradient (Owada 2006). An example of the Sangi-tsumi method is shown in **Fig. 4**. On the rear of the stone wall, round cobble stones with excellent permeability are arranged. In the 2016 Kumamoto earthquakes, the stone wall of the Uto Yagura (**Fig. 5**) maintained non-collapsed. Even after in excess of 1000 aftershocks, except for enlargement of curvature, the height of technology of the Ano construction method was confirmed. In contrast, as for the Sangi-tsumi method, as seen in Iidamaru Yagura (**Fig. 6**), Inui Yagura (**Fig. 7**) and Bagu Yagura (**Fig. 8**), leaving the corn stone accumulation part, the middle of the stone wall collapsed. Depending on the investigation, it may be necessary to restore the keep and turrets using contemporary technology not approved by United Nations Educational, Scientific and Cultural Organization (UNESCO).

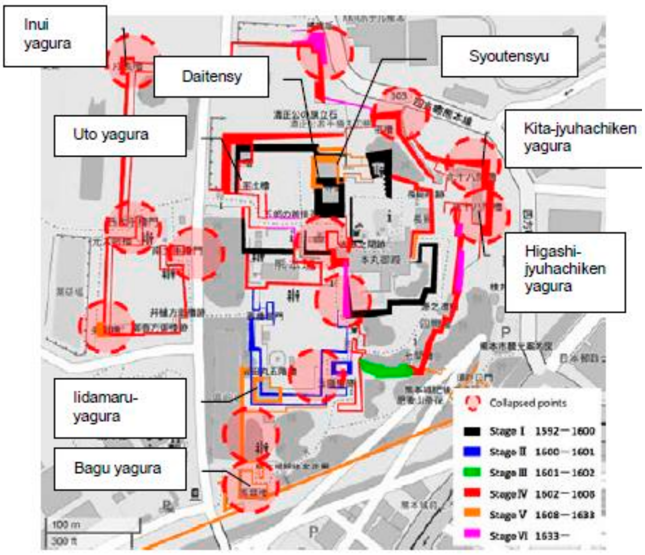

Fig. 9. Diagram showing the history of the stone walls (Tomita, K., (2008) edited by Ikuta, S).

3.2 History of the stone walls

Tomita (2008) classified the transition of stone wall of Kumamoto Castle from Stage I to V (**Fig. 9**). Stage I, constructed in 1599, features stone walls with a shallow slope. Stage II, ca. 1600, has stone walls with a steeper slope than Stage I. Stage III, in the first half of 1601, is typified by a mix of the Ano and Sangi-tsumi methods of construction. Uto Yagura, Continuous corner tower,

Fig. 10. Photograph of Daitensyu (right: 1960 reconstruction), Uto Yagura (centre) and Shotenshu (left: 1960 reconstruction) from Nino-maru park. (photo by T. Ohsumi, taken Aug. 11, 2016)

Fig. 11. Photograph of Daitensyu (left) and Shotenshu (right) from Hon-maru side. (courtesy of Prof. K. Meguro, taken Oct. 26, 2016).

Fig. 12. Photograph of Shotenshu-dai from Hon-maru side. (courtesy of Prof. K. Meguro, taken Oct. 26, 2016).

Fig. 13. Close-up photograph of Shotenshu-dai (courtesy of Prof. K. Meguro, taken Oct. 26, 2016).

Higashi Juhachiken Yagura, Kita Juhachiken Yagura, Akazu-no-mon, Hirakira Yagura, Tago Yagura, and Nishi-demaru-nishimen Ishigaki are representative structures of Stage IV. For Stage V, beginning in 1607, the lower stone wall of Iidamaru Yagura, Naga-kabe, and Shotenshu are representative. Stage VI began in the Hosokawa family age in 1633. In 1820, the foundation of Hazekata Sangai Yagura, typical of Stage VI, was renovated owing to enlargement of the curvature of the upper turret stone walls.

4. Castle Keeps (Tensyu) and Uto Yagura

Fig. 10 shows a full view of the greater keep (Daitenshu) and Uto Yagura. Only Uto Yagura is the collapse of the tile did not course.

4.1 Castle Keeps (Daitenshu / Shotenshu)

Daitenshu is 32 m tall, with three floors and six stories. The height of the stone wall foundation is 16 m. The lesser keep (Shotenshu) is 19 m tall, with two floors and four stories. The stone wall is the same height as Daitenshu. The keeps have connecting structures at the side of the entrance. The stone wall of Daitenshu has a shallow slope with a gentle curve, whereas that of Shotenshu is a steep slope. Daitenshu was attached to Shotenshu (Owada 2006). It is said that the lord Kato Tadahiro age (ranking 1611–1632) was built. Tiles were fallen from the roof of Daitenshu and Shotenshu following the earthquakes. **Fig. 11**, taken from Hon-maru side, shows that the stone wall foundation of Shotenshu subsided after the earthquakes, and part of the foundation, which is the Sangi-tsumi method, collapsed. **Fig. 12** and **Fig. 13** shows damage caused by subsidence of the foundation of Shotenshu (Shotenshu-dai). **Fig. 13** shows close-up photograph of Shotenshu-dai, which can see basement damage.

4.2 Uto Yagura

Uto Yagura is an important national cultural property built between 1601 and 1607. The stone wall has a

Fig. 14. Photograph of Tsuzuki Yagura taken from Kato Shrine. Unlike Uto Yagura, this turret was not reinforced to be earthquake resistant, and collapsed after the earthquakes (photo by T. Ohsumi, taken August 11, 2016).

Fig. 15. Photograph of Tsuzuki Yagura and Uto Yagura before the earthquakes (photo by T. Ohsumi, taken in 1989).

Fig. 16. Photograph of Uto Yagura (right) and Tsuduki Yagura (left) (courtesy of Prof. K. Meguro, taken Oct. 26, 2016)

Fig. 17. Photograph of Uto Yagura inside of Hohoate-gomon (courtesy of Prof. K. Meguro, taken Oct. 26, 2016)

height of 20.5 m. The turret has three floors and five stories below the foundation floor is a squirrel that continues from the north side to the west side and a renovation was performed in 1989. It has a corridor on the top floor. A 25-m-long section of Tsuzuki Yagura on the west side collapsed after the earthquakes. Uto Yagura was reinforced by a steel brace installed at the opening. This seismic reinforcement improves strength and stability. However, since it was not similarly reinforced, Tsuzuki Yagura collapsed (**Figs. 14, 15, 16**). **Fig. 17** shows Uto Yagura from Hohoate-gomon, which stone walls were heavily damage.

Traditional construction methods followed the wisdom that roof tiles should be allowed to fall during an earthquake, to lighten the structure and prevent the building from collapsing. Although Daitenshu and Shotenshu, which are reinforced concrete (RC) structures, were damaged by the earthquakes, the roof of Uto Yagura and the dolphins adorning it were not damaged.

Uto Yagura has two layers of gables (Kara Mon) in straight lines. These gables characteristically protrude from the turret and are not continuous with the flat side (Kato 2011). Uto Yagura suffered little cosmetic damage other than the dislodged roof tiles. The differences are summarized below.

1) Roof direction

Although the number of researchers who stated the bearing was large owing to the slope collapse at the time of the earthquake, the horizontal behavior of the earthquake ground motion is circular and the direction is often unclear. The influence of azimuth is small considering that the roof tail gradually collapsed with more than 1,000 aftershocks.

2) Comparison of RC and wooden structures

Daitenshu and Shotenshu are modern reinforced concrete (RC) structures that retain their historical appearance in 1960, whereas Uto Yagura is an original wooden structure. Such wooden structures are flexible, whereas the rigid RC structure allowed high-frequency vibrations to propagate to the top of the roof. Also, in wooden construction, large beams are arranged to support the structural parts and wall stones on the foundation. This arrangement disperses the load of the structure (Kato 2011). In RC structure, it is doubtful whether this function will be demonstrated. In addition,

Fig. 18. Photograph of Inui Yagura (right: 2003 reconstruction), a wooden two-floor three-story turret that was rebuilt in 2003. Inui Yagura foundation was partial collapse in the middle of the stone wall. (photo by T. Ohsumi, taken July 20, 2016)

Fig. 19. Photograph of the stone wall of Kato Shrine (photo by T. Ohsumi, taken August 11, 2016)

Fig. 20. Photograph showing a stone from a collapsed wall. On the inner-facing side the Kannon Bodhisattva and an arrow hole were discovered (photo by T. Ohsumi, taken August 11, 2016)

Fig. 21. Photograph of Akazu-no-mon, which was designated as an important cultural property, was heavily damaged by the earthquakes (courtesy of Prof. K. Meguro, taken Oct. 26, 2016).

castles often use nailless joints such as Tsugite (straight) joints and Shiguchi (angle) joints used in shrine and temple construction (Kato 2011). These can absorb deformations, reducing earthquake-related damage. This method is used not only in Japan, and was demonstrated to be effective in the 2015 Gorkha, Nepal, Earthquake.

5. Storehouses (Yagura-gun), Yagura Foundation (Yagura-dai) and Gate Walls (Monpi Ishigaki)

5.1 Inui Yagura

Inui Yagura is a wooden turret, reconstructed in 2003, with two floors and three stories. This turret was constructed at the northern end of the site to defend the north-northwest. **Fig. 18** shows the foundation of Inui Yagura, which partially collapsed on the north side.

The foundation of Inui Yagura was constructed using the above-mentioned Sangi-tsumi method. Even in this earthquake, the corner stones kept their shape for all stone walls. In contrast, the middle parts of some walls partially collapsed, like in a landslide. It is a tower of restoration, and the foundation part of the collapsed turret is seen a steep structure. It is conceivable that the structure forming this impermeable layer induced the collapse of the stone wall in the middle part.

5.2 Kato Shrine (besides North Gate)

Kato Shrine enshrines Kato Kiyomasa. This shrine is located in the north side of Heizaemonmaru, Daitenshu, Shotenshu, and Uto Yagura. In the stone wall about 3 m in height built over 400 years in the shrine, a part adjacent collapsed to the north gate related to the earthquake (**Fig. 19**). The stone wall of corner stone has not collapsed, but the Middle part has collapsed. In this stone wall on the behind of the stone wall was arranged a back stated round cobble stone with excellent permeability. The stone walls collapsed with ruin of the North Ote Gate were collapsed, and the stones were scattered in the grounds. Inside of the collapsed stone wall was discovered the Kannon Bodhisattva of about 40 cm (**Fig. 20**). The Kannon Bodhisattva of this stone was

Fig. 22. Photograph of Akazu-no-mon before the earthquakes (photo y T. Ohsumi, taken in 1989)

Fig. 23. Photograph of Kita Juhachiken Yagura before the earthquakes (photo by T. Ohsumi, taken in 1989)

Fig. 24. Photograph of Kita Juhachiken Yagura . Located between Kato Shrine and Kumamoto Daijingu shrine, this turret completely collapsed (photo by T. Ohsumi, taken August 11, 2016)

Fig. 25. Photograph of Kita Juhachiken Yagura foundation, behind which a large V-shaped gully erosion was discovered that apparently worsened the collapse (photo by T. Ohsumi, taken August 11, 2016)

not appearing in the stone wall of the surface. It is said to be a stone monument carved and brought a statue of Buddha to the prayers of the 400 years ago, standing in the lotus position (Rengeza), and on the left with an image with something like lotus bud, intentionally Arrow hole (Ya-ana), and it seems that it is possible to do the work which draws the reference line which Slate wants to divide, allocates on the reference line and puts a decision and cracks the rock. Sometimes it was used as a diversion stone of Mounded tomb stone and tombstones (Gorin Tower, Houkyoin Tower, etc.) (Owada 2006). Inside the castle area, stone tablet (Ita-hi), which was draw the Statue of the Amida Nyorai, was discovered from the foundation stone of Jizo Yagura-mon (Kato 2011).

5.3 Hira Yagura and Akazu-no-mon

Hira Yagura, which stands to the right of the slope leading up to Akazu-no-mon was not cosmetically damaged by the earthquakes. Akazu-no-mon, which was designated as an important cultural property, was heavily damaged by the earthquakes (**Figs. 21, 22**).

5.4 Kita Juhachiken Yagura

Fig. 23 shows before the earthquakes. Kita Juhachiken Yagura, which is located between Kato Shrine and Kumamoto Daijingu shrine, completely collapsed. Behind Kita Juhachiken Yagura, there was a large V-shaped gully erosion at the top of the foundation, which worsened the collapse (**Figs. 24, 25**).

5.5 Kumamoto Daijingu and Higashi Juhachiken Yagura

Higashi Juhachiken Yagura foundation collapsed after the main shock. The collapsed storehouse and slope fell onto Kumamoto Daijingu, breaking through the roof and crushing the shrine. After the foreshock, although tiles

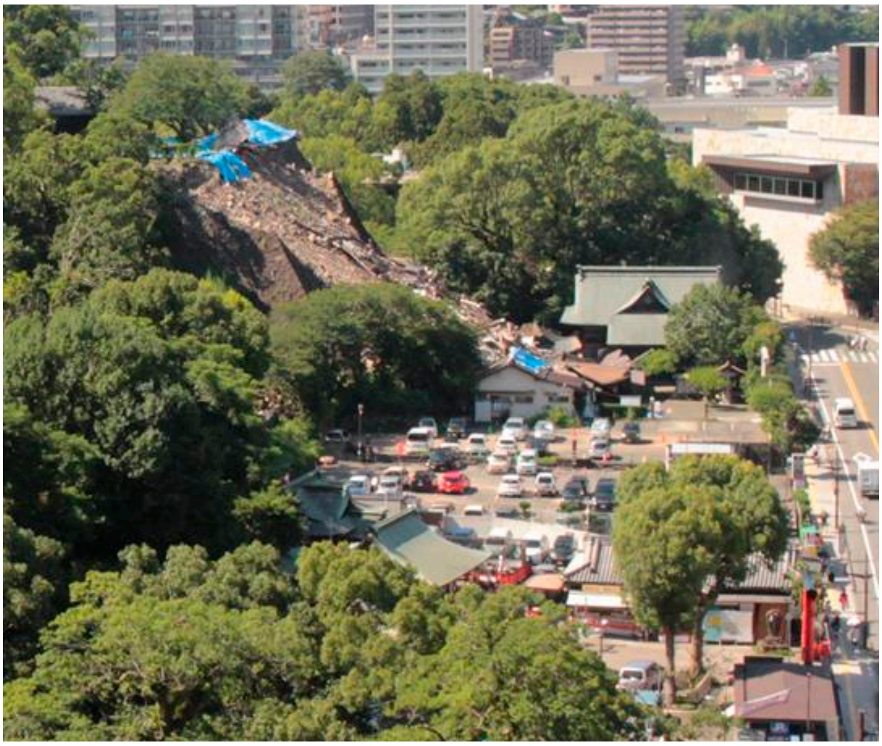

Fig. 26. Photograph of Kumamoto Daijingu and HIgashi Juhachiken yagura (photo by T. Ohsumi, taken July 20, 2016)

Fig. 27. Photograph of the longest wall in the castle, Naga-kabe, along Tsuboigawa river. An 80-m-long section of this wall collapsed after the earthquakes (photo by T. Ohsumi, taken July 20, 2016)

Fig. 28. Photograph of Naga-kabe and Bagu Yagura-dai (1966 reconstruction) (photo by T. Ohsumi, taken August 11, 2016)

were reported to have fallen, there was no obvious damage to the stone walls (**Fig. 26**).

5.6 Hira Yagura and Naga-kabe

Naga-kabe, the longest castle wall, at 242 m, was connected to Hira Yagura from the eastern end of Takeno Maru to the westernmost Bagu Yagura-dai. This long wall (**Fig. 27**) on the south side was built as protection from the Satsuma clan. An 80-m section of Naga-kabe collapsed after the earthquake.

The junction of Long wall was off and the Long wall part was collapsed. Hira Yagura is in the southern corner of Kumamoto Castle. It is a RC restoration, completed in 1966, and it escaped serious damage despite a large load being applied to the joint at the time of the earthquake.

5.7 Bagu Yagura

Bagu Yagura, a storehouse for armor during peacetime, was dismount because this place was the castle owner's entrance gate crossing the Geba Bridge. This place was

Fig. 29. Photograph of Bagu Yagura-dai before (left; photo by T. Ohsumi, taken in 1989) and after the earthquakes (right; photo by T. Ohsumi, taken August 11, 2016)

Fig. 30. Photograph showing enlargement of foundation settlement cased the white wall at Bagu Yagura (photo by T. Ohsumi, taken July 20, 2016)

Fig. 31. Photograph showing stone monument rotated by the main shock (photo by T. Ohsumi, taken July 20, 2016)

get ride off a horse to attend the main building of the castle. Bagu Yagura was restored in 1966 but became deteriorated. It was again dismantled and restored in 2008, and reopened to the public in September 2014.

6. Findings

1) The stone wall foundation used two different construction techniques from the Kato age and Hosokawa age. The damage patterns with respect to the shapes of the stones in the walls were investigated and compared.
2) Kato-age stone walls with shallow slopes were constructed on soft ground. Their characteristic shape and that of the “musha-gaeshi”, which repelling warriors, at the top are attractions for tourists visiting Kumamoto Castle.
3) Sangi-tsumi is another construction method used in the late Kato era and early Hosokawa age, characterized by a steeply sloping stone wall. Iidamaru Yagura and Inui Yagura are typical examples of this construction. The middle part of the stone wall foundations under these turrets partially collapsed.
4) Roof tiles fell from restored RC structures Daitenshu and Shotenshu, and the dolphins adorning the roof were damaged. In contrast, the original wooden structure Uto Yagura did not suffer such damage to the roof tiles or dolphins. Traditional wooden buildings have better vibration absorption.
5) Uto Yagura is reinforced against seismic activity by a steel brace installed at the opening, which a renovation was performed in 1989. Unfortunately, Tsuzuki Yagura lacked such reinforcement and collapsed after the earthquake.
6) Behind the Kita Juhachiken Yagura foundation, there was a large V-shaped gully erosion at the top of the slope, which seems to have worsened the collapse of this structure.
7) The settlement enlargement of foundation cased the white wall at turret related to the earthquakes. Also, since it seems to be an enlargement of curvature of stone walls prompt action is desired.

Acknowledgements

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