Procds. of the 16th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering,
October 14-18, 2019, Taipei, Taiwan

Analyses to elucidate the mechanism of the grabens that formed in Aso during the 2016 Kumamoto Earthquake in Japan

Susumu Yasuda[1], K. Ishikawa[2], K. Katsuyama[2]

[1] Resilient Smart City Research Center, Tokyo Denki University, Ishizaka, Hatoyama, Hiki-gun, Saitama 350-0394, Japan.
[2] Architectural, Civil and Environmental Engineering, Tokyo Denki University, ditto, Japan,

ABSTRACT

The 2016 Kumamoto earthquake caused many grabens, approximately 50 m wide, in the caldera of the Aso Volcano in Japan. The authors conducted detailed site investigations to determine the mechanism of the grabens. The measurement of the displacement by SAR from satellites showed horizontal displacements of about 2 to 3 m occurred. Deep borings, microtremor array observation and reflection survey showed that soft clay is deposited from GL-17 m to GL-51 m and the bottom of this soft clayey layer is inclined. The analysis by ALID showed that the soft clay flowed due to the earthquake, causing the horizontal displacement of the surface soil layer and the graben at the ground surface.

Keywords: Soil investigation, Earthquake, Graben, Caldera

1 INTRODUCTION

A special and strange belt-like subsidence, called “graben,” which has not occurred in past earthquakes, formed in various parts of the Aso Valley in the Aso caldera during the 2016 Kumamoto Earthquake in Japan. These grabens caused severe damage to approximately 100 houses, roads, water and sewage pipes, rice fields, and river dikes. The authors conducted detailed site investigations, etc. to determine the mechanism of the grabens and to propose an appropriate method to restore the affected ground to a usable state. Then, with the support of JSPS KAKEN, in May 2017 the authors scheduled a three-year plan. The followings are study items:

<Research on the mechanism of the graben and restoration method>

1) Estimation of surface deformation, 2) Investigation on damage, 3) Grasp of soil condition in Aso Valley, 4) Survey of shallow soil condition, 5) Survey of deep soil condition, 6) Analysis of seismic wave, 7) Detailed soil investigation, 8) Investigation of the depth of cracks, 9) Observation of soil samples, 10) Test on the physical and mechanical properties soil samples, 11) Analyses for the mechanism of the graben, 12) Model tests, and 13) Propose on the restoration method.

<Possibility of the occurrence of the graben in other area in Japan>

14) Study on the possibility of the occurrence of the graben in other area in Japan, and 15) Propose appropriate countermeasures. Presently, the authors have completed stages 1) through 11) of this plan. The results of 1) to 9) have been presented in the paper by Yasuda, Ishikawa, Ohbo, Nagase, and Murakami (2019). Therefore, the analysis results of 10) and 11) are presented in this paper by briefly referring to these results.

2 OUTLINES OF THE RESULTS OF 1) TO 10)

In the Aso Valley, grabens occurred in many districts such as Kario, Uchinomaki, Ozato, Matoishi and Yakuinbaru. The damage situation in Kario districts is depicted in Figure 1. A 1.3 m deep and 50 m wide graben appeared in this district. Two people in this district testified as follows:

i) houses settled without much feeling of shaking;
ii) a garden lantern and furniture did not topple over, and window glasses did not break; and
iii) approximately 50 cm wide cracks occurred on the ground, and a rod could be inserted down to a depth of approximately 6 m.

Figure 1. Damage due to the grabens at Kario district.

The distribution of the ground surface displacement was measured by laser scanning from satellites. Measured result showed that the ground has displaced to the north side by several tens of centimeters in the whole Aso Valley. However, there are districts where the amount of change seems to be particularly large, such as Kario and Uchinomaki districts. Based on the distribution of displacement, horizontal displacement, vertical displacement, and horizontal strain of the ground along typical lines in the five districts were analyzed. Figure 2 depicts the results along the ① to ①' line at Kario district. Positive horizontal displacements in the figure shows the displacement to the northwest direction. The horizontal and vertical displacements and the strain in the horizontal direction were compared with the location of the graben:

(1) Horizontal displacement and settlement sharply increased from 1800 m to 1700 m, and large tensile strain was generated. After the horizontal displacement reached a peak value of approximately 2.5 m (a value obtained by subtracting the displacement amount of the entire district), and the tensile strain reached a negative peak value of approximately 2.5%, the horizontal displacement decreased to approximately 1450 m.

(2) From 1400 m to 1050 m, the horizontal displacement gradually decreased, and the vertical displacement increased.

Borings, SPT, sampling, and PS logging were conducted at four sites in order to thoroughly investigate the condition of deep soil layers at Kario district. Figure 3 is an estimated soil cross section under and around the graben. A sandy or clayey layer with a thickness of approximately 17 m deposited from an altitude of 478 m to 461 m. In the north zone from the graben, clayey and sandy layers deposited alternately. The SPT *N* values of the clayey and sandy layers are approximately 5 or less, and 10 to 30, respectively. In the south zone, a dense sandy layer with SPT *N* values of 15 to 40 was deposited. On the other hand, the soil sediment in the old lake ranges from clayey silt to silty clay with SPT *N* values of 1 to 3. Moreover, it was found that a sandy layer interposed in the lake deposit at approximately 430 m to 440 m altitude. The upper surface of the lake deposit is almost flat. On the contrary, the bottom of the lake deposit is inclined with a gradient of approximately 3% toward north. The interposed sandy layer is also inclined with almost the same gradient.

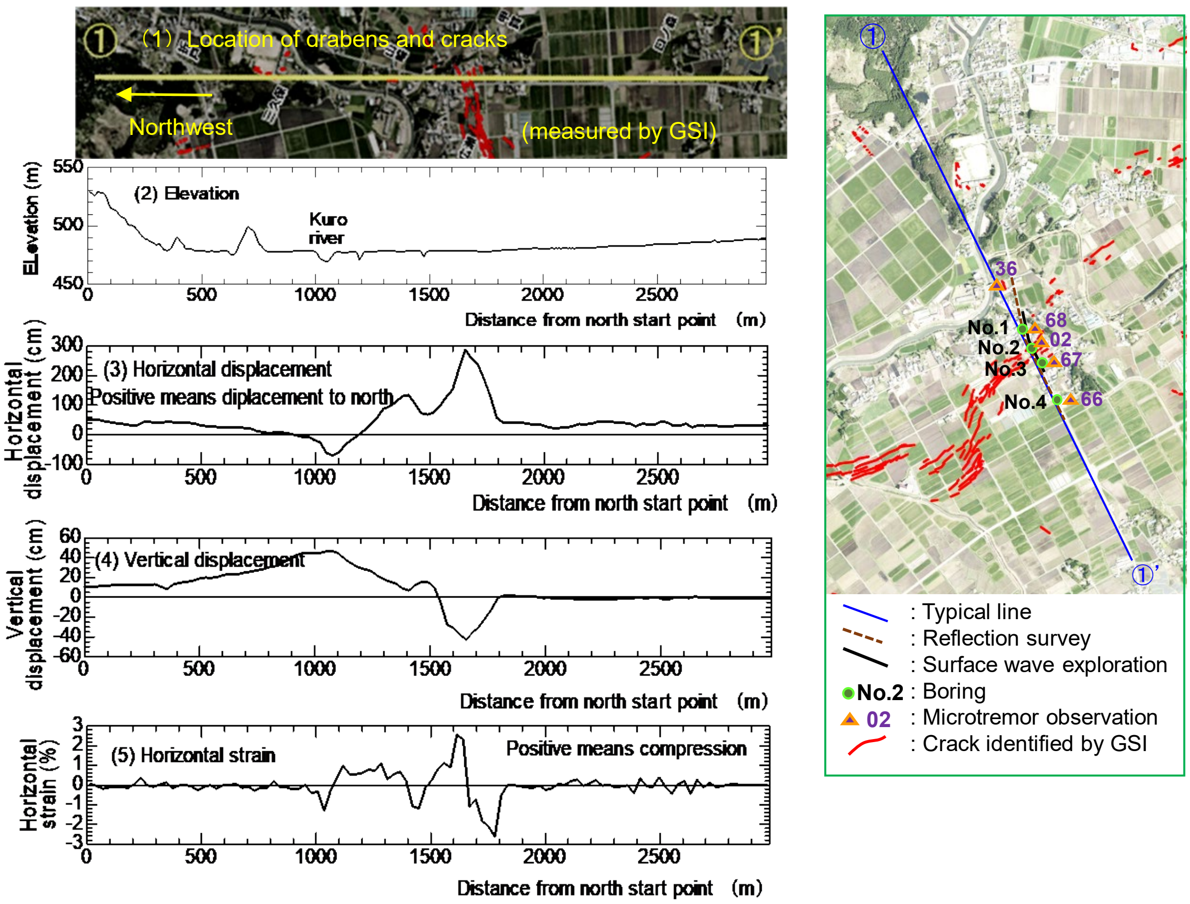

Figure 2. Distribution of displacement and strain along a line in Kario district.

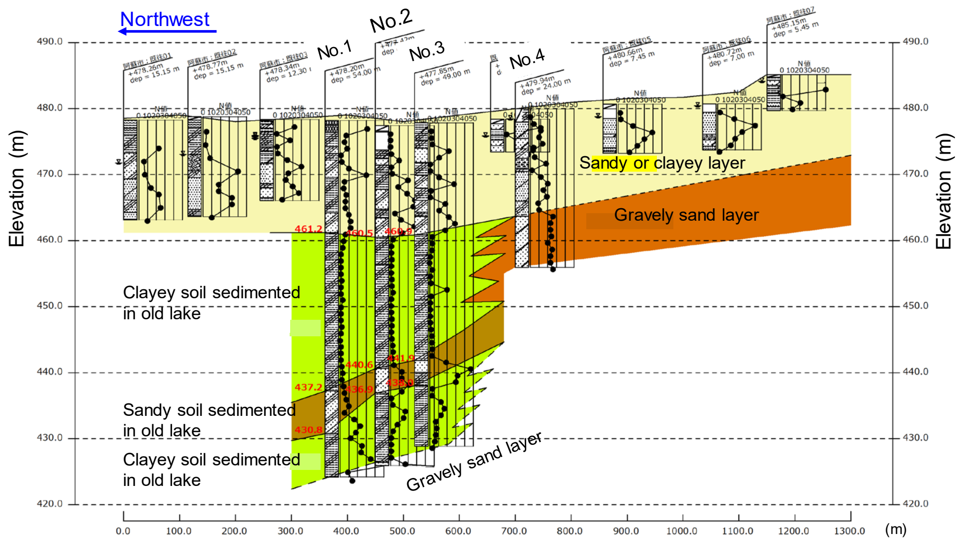

Figure 3. Soil cross section at Kario district.

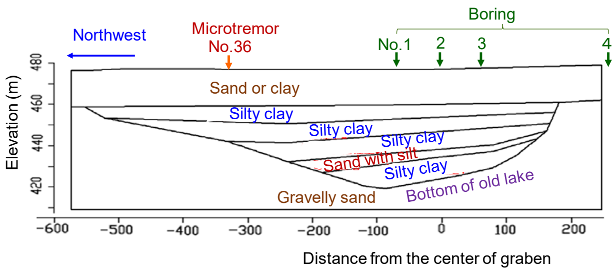

Figure 4. Estimated cross section of soil layers at Kario.

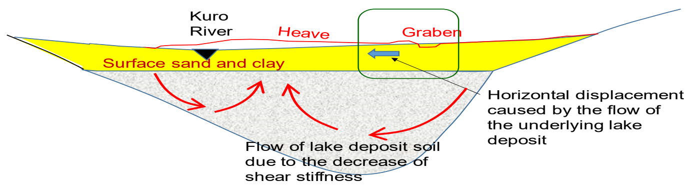

Figure 5. Diagram of the mechanism of graben formation.

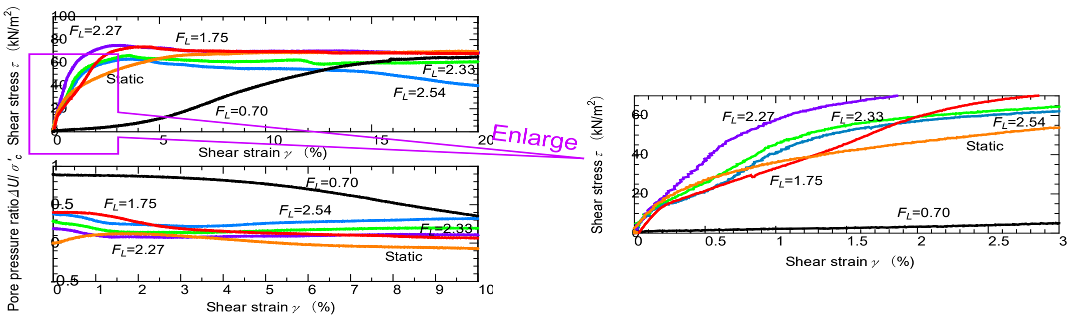

Figure 6. Stress strain curves after cyclic loading in different F_L.

3 CYCLIC TORSIONAL TESTS TO OBTAIN SOIL PAREMETERS FOR RESIDUAL DEFORMATION ANALYSIS

Based on the studies by microtremor array and reflection survey, the authors confirmed that the bottom of the old lake is V-shaped as shown in Figure 4 and assumed that the lake deposited soil flowed due to the earthquake as schematically shown in Figure 5. The authors also believe that the flow of the lake soil may be simulated by the “ALID,” residual deformation analysis (Yasuda et al., 2017), same as the simulation conducted for liquefaction-induced flow.

Thus, the authors conducted cyclic torsional shear tests to obtain soil parameters for the ALID analysis using undisturbed samples taken at the No.2 site in the Kario district. In the tests, cyclic shear stress was applied under undrained condition identical to the cyclic shear stress applied in conventional liquefaction tests at pre-determined cycles. Finally, a monotonic load was applied to the undrained specimen. The stress-strain behavior at this stage was considered post-liquefaction (post-failure) behavior. Figure 6 shows stress strain curves after cyclic loading for the lake deposited clay at the depth of about 25 m. F_L value in the figure is the ratio of shear stress amplitude to the shear stress amplitude just failure. Namely, if F_L<1.0 the sample failed. If the shear stiffness of the soil is defined as the ratio of shear stress by shear strain at 1%, the stiffness of the sample F_L=0.7 is about 1/100 of the stiffness of the samples at F_L>1. Therefore, the authors estimate that the stiffness of the lake deposit soil decreased due to the shaking of the Kumamoto Earthquake, resulting in large deformation and the grabens. Figure 7 shows the relationships between F_L and $G_1/G_{0,i}$ for three samples, where G_1 is the stiffness of the samples of after cyclic loading and $G_{0,i}$ is the stiffness of the samples without cyclic loading.

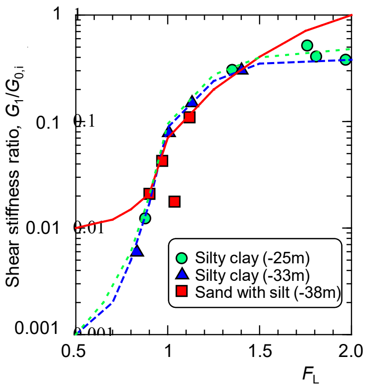

Figure 7. Relationships between F_L and $G_1/G_{0,i}$ for three samples.

4 SEISMIC RESPOSE ANALYSIS AND RESIDUAL DEFORMATION ANALYSIS

In the analysis by ALID, the static finite element method is applied in the following steps:

(1) Step 1: The static stress distribution and deformation of the ground before an earthquake were evaluated by static FEM based on the stress-strain relationships of intact soils.

(2) Step 2: Two-dimensional seismic response analysis was conduct by FLUSH. Then, the distribution of the safety factor against liquefaction, F_L, was evaluated.

(3) Step 3: The deformation of the ground due to softening was evaluated by static FEM using the relationships shown in Figure 7.

Figure 8 shows the results of estimating the input seismic wave in the Kario district based on the observation records obtained in the Aso Valley during the Kumamoto Earthquake. Figures 9 and 10 show the distribution of peak acceleration and F_L, respectively. Figure 11 shows analyzed deformation. Based on these figures, it can be concluded that lake deposited soil has flowed due to the decrease in shear stiffness, resulting in horizontal displacement of the ground surface and graben as assumed in Figure 5.

CONCLUSIONS

Detailed soil investigation and analyses were conducted to elucidate the mechanism of the grabens that formed in Aso during the 2016 Kumamoto Earthquake in Japan. The main conclusions drawn to date are listed below:

(1) Horizontal displacements of approximately 2 m to 3 m occurred, causing horizontal tensile strain at, and around, the grabens.

(2) A thick clayey layer sediment deposited in an old lake under a graben. The bottom of the soil layer is V-shaped.

(3) The analysis by ALID showed that the soft clay flowed due to the earthquake, causing the horizontal displacement of the surface soil layer and the graben at the ground surface.

ACKNOWLEDGEMENT

This work was supported by JSPS KAKENHI Grant Number JP 17H03306. The research is going with 11 researchers. The authors would like to express sincere thanks to them.

REFERENCES

Yasuda, S., Yoshida, N., Adachi, K., Kiku, H. and Ishikawa, K. (2017): Simplified evaluation method of liquefaction-induced residual displacement, *Journal of Japan Association for Earthquake Engineering*, Vol.17, No.6, pp.1-20.

Yasuda, S., Ishikawa, K., Ohbo, N., Nagase, H. and Murakami, S. (2019): Investigation on mechanism of the grabens that formed in Aso during the 2016 Kumamoto Earthquake in Japan, *Proc. of the 7th International Conference on Earthquake Geotechnical Engineering*, (in printing).

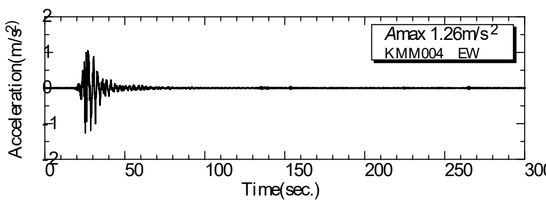

Figure 8. Input seismic wave.

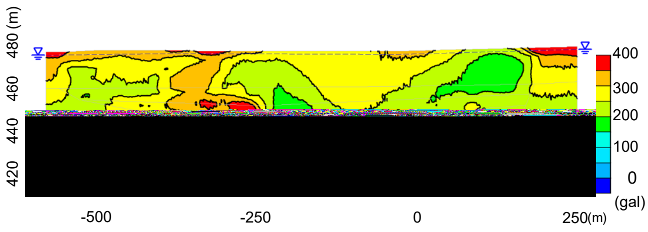

Figure 9. Distribution of peak acceleration.

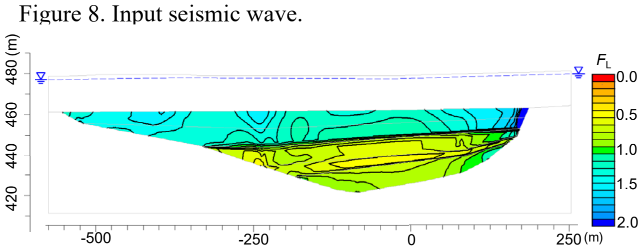

Figure 10. Distribution of F_L.

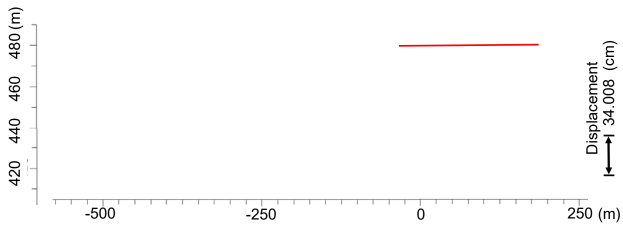

Figure 11. Analyzed deformation.