The effect of fracture zones on a failed reinforced soil wall induced by severe ground motions during the 2016 Kumamoto Earthquake

Kunitomo Sahara[1], D. Suetsugu[2], N. Fukuda[3], T. Yoshimura[4]
H. Sato[5] and F. Hirae[6]

[1] Hirose Hokyodo & Co.,Ltd., 4-1-13 Toyo, Koto-ku, Tokyo 135-0016 Japan.
[2] Department of Civil Engineering and Architecture, Saga University, 1 Honjo-machi, Saga City, 840-8502, Japan.
[3] Shin-Nihon Consulting Engineers, Co., Ltd., 8-24-21 Tagami, Kagoshima City, 890-0034, Japan.
[4] Meidaikogyou Ltd., 3-43 Funakoji-cho, Beppu City, 874-0922, Japan.
[5] Heisei Chiken Co., Ltd., 1-7-25 Morooka, Hakata-ku, Fukuoka City, 812-0894, Japan.
[6] Nihonchiken, Co., Ltd., 5-25-25 Morooka, Hakata-ku, Fukuoka City, 812-0894, Japan.

ABSTRACT

Many infrastructures centered on Kumamoto were damaged following two seismic intensity 7 earthquakes, which occurred in April 2016. When the earthquake damage investigation group of the Japanese Geotechnical Society (JGS) investigated the structure of the roads, it found that the reinforced soil wall in the southern Aso mountains district had totally failed, while the adjacent wall remained despite being subjected to the same ground motion. During the slope excavation works for the reconstruction of the reinforced soil wall, two fracture zones appeared on the slope surface that were inactive faults. From these results, it was deduced that the collapse was due to abnormal variations in the reinforced soil wall immediately above the fracture zones.

Keywords: 2016 Kumamoto Earthquake; reinforced soil wall; gamma-ray survey; failure mechanism

1 INTRODUCTION

Many infrastructures centered on Kumamoto were damaged as a result of two seismic intensity 7 earthquakes, which occurred in April 2016. Following this, the earthquake damage investigation group of JGS investigated road structures such as embankments, retaining walls, bridge foundations and slope protection works (Mukunoki et al. 2016).

The characteristics of the damages revealed that severe ground fluctuations constructed on active faults and the related fractured zones were responsible for the damages rather than the ground motion arising from the earthquakes. The reinforced soil wall in southern Aso mountains district had totally failed while the adjacent wall remained intact despite being subjected to the same ground motion as shown in Photo. 1.

This paper focuses on the impact of the ground motion arising from the earthquake on fault or fracture zones, to understand the failure conditions. By applying the gamma-ray survey method and the observation of slope excavation works for reconstruction of the reinforced soil wall, two fracture zones were confirmed on the slope surface and the conjugate fracture zone. Following these results, this paper will argue that the collapse was due to abnormal variations in the reinforced soil wall immediately above the fracture zones.

Photo. 1. Adjacent failed and remaining reinforced soil wall

2 EARTHQUAKE DAMAGE OF STRUCTURES

Fig. 1 shows the relationship between the damaged structures and seismic intensity distribution in Kumamoto Prefecture after the main shock of 2016 Kumamoto Earthquake. It is not clear from the damages whether they are due to a pre-quake or a main shock, because the disaster survey was conducted after the main shock. The yellow areas in Fig. 1 illustrate severely damaged structures. The failed reinforced soil wall studied in this paper was situated between the lower 5 and 7 seismic intensity zones. However, undamaged structures were also found in the same zones. Most damaged structures were found along the

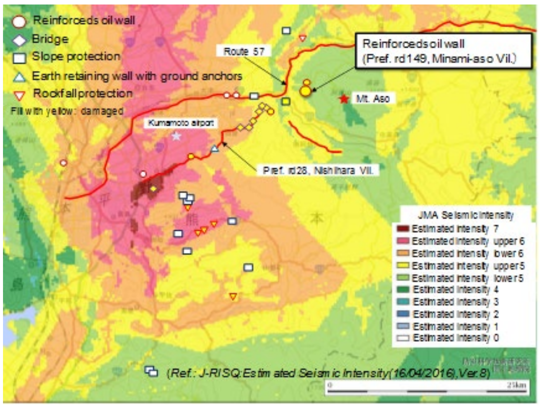

Fig. 1. Relationship between damaged structures and seismic intensity distribution after 2016 Kumamoto Earthquake

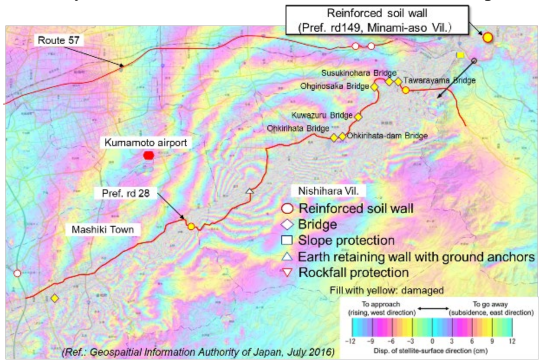

Fig. 2. Relationship between the crustal deformation map analyzed by interference SAR (GSI) and damaged structures

Prefectural road 28 despite the magnitude of the seismic intensity being different. Fig.2 shows the relationship between the crustal deformation map analyzed by interference SAR (GSI) and the damaged structures. As shown on the map, the failed reinforced soil wall in the southern Aso district was situated just in the large crustal deformation area.

3 DAMAGE OF REINFORCED SOIL WALL

The failed reinforced soil wall is located on Minamiaso, as shown in Fig. 1, and constructed along the Nigori-river of prefectural road No.149. The area was affected by the earthquake induced from the Futagawa fault. Many distinctive cracks, differential settlements, and displacements of the surrounding ground adjacent to the wall were observed, as shown in Fig. 3. In residential areas of right side of Nigori-river, horizontal crack displacement of 60cm on the the pavement at point (a) in Photo. 2 and the differential settlement at point (b) was observed as shown in Fig. 3. The failed reinforced soil wall is located on the line extending in the NW-SE direction connecting these points. On the other hand, in residential areas on the left side of Nigori-river, many cracks and differential settlements with right lateral displacement in the WSW-ENE directions are observed. These directions coincide with the Futagawa Fault, and are conjugate of the NW-SE direction. Fig.4 shows a plan view of the damaged reinforced soil wall. The reinforced soil wall had failed zones and the remaining

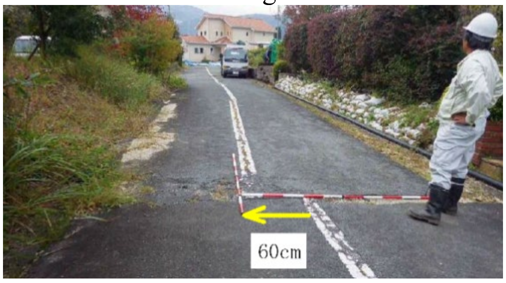

Photo. 2. Horizontal crack displacemment, 60cm at point (a)

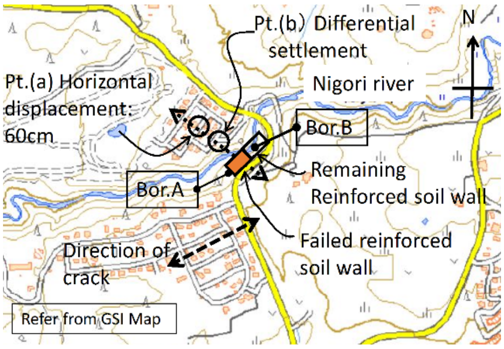

Fig. 3. Ground damages around failed reinforced soil wall

zones on the same wall surface. The features of the reinforced soil wall are as follows: 1) there is a river in front of the wall, and gravity type concrete wall was used for the foundation, 2) in the planar face, the zone where the wall curves to the front side failed, 3) the cross section of the failed zone had a two-step upper embankment; the remaining zone had one step, 4) in the failed zone, a free-standing facing condition was observed with direct sliding movement as shown in Photo. 3.

The vertical reinforced soil wall was constructed using integrated band steel-strips and high frictional angle embankment soil. Reinforcements and facings were put in place twenty years after construction, and no degradation was observed in the reinforcements and facings of the wall. Fig. 5 shows the estimated stratum cross section in the failed zone of the reinforced soil wall. The andesite rocks in the base layer is inclined towards the river. The volcanic cohesive soil layer and the collapsed soil layer are deposited on the base layer.

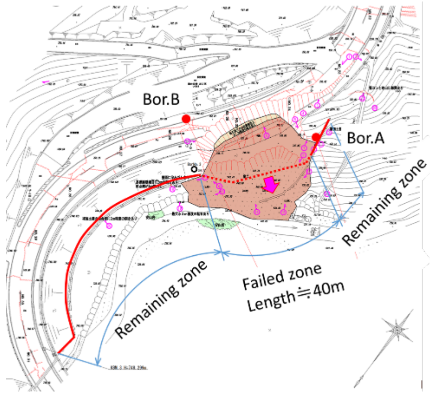

Fig. 4. Plan view of failed and non-failed reinforced soil wall

Photo.3. Self-standing facing of failed reinforced soil wall

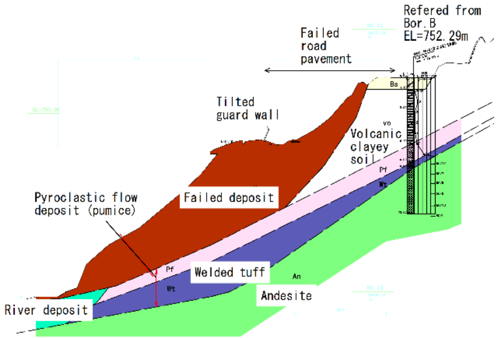

Fig. 5. Stratum cross section at failed reinforced soil wall

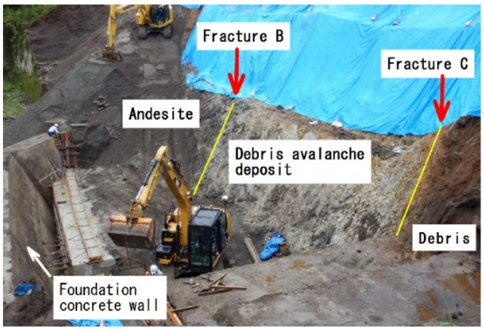

Photo. 4. Appearance of fracture B and C during excavation work

Photo. 5. Residual horizontaal displacement toword mountain side induced by intense ground motion

The inclination of the base layer cannot be assumed to affect the failure of the wall. During excavation works for the reconstruction of the reinforced soil wall, two fractures were observed as shown in Photo. 4. These were fracture B between the andesite and the debris avalanche deposit, and fracture C between the debris avalanche deposit and the old debris talus deposit. In the failed zone, a residual horizontal movement of 3cm toward the mountain side was confirmed at the construction joint of the foundation gravity wall as shown in Photo. 5. This demonstrates the intense ground motion that occurred under the reinforced soil wall induced from the soil stratum and fracture condition.

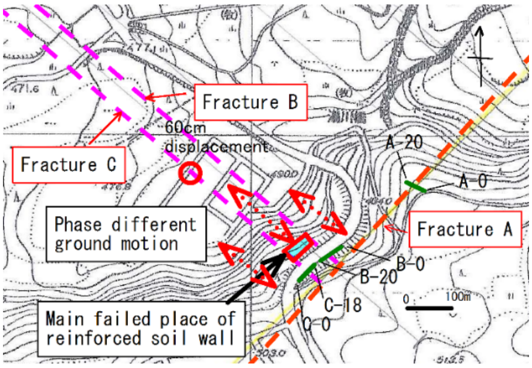

Fig. 6. Fractures distribution confirmed by gamma-ray survey

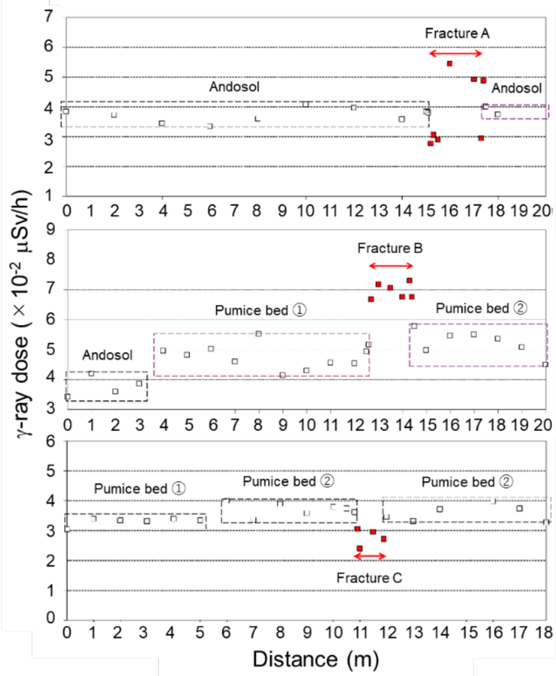

Fig.7. Relationship between gamma-ray intensity and distance

4 GAMMA-RAY SURVEY

Yoshimura et al (2012, 2013) proposed the gamma-ray survey method for finding geological weak fractures such as faults, rock joints, and splits, for the design of infrastructures. From topographic analysis, three lineament structures were estimated around the area. Gamma-ray surveys were conducted in directions traversing those lineament structures. Weak gamma-ray radiation of natural origin is emitted from rocks on earth. In original grounds and/or rocks that have undergone fracture phenomenon due to crustal deformation, the magnetism of the substance changes, resulting in an abnormal gamma-ray intensity. Gamma-ray intensity can be measured by using a scintillation survey meter. Fig. 6 shows the locations of three fracture zones (A, B, C) from a gamma-ray survey during reconstruction works. Fig. 7 shows the relationship between gamma-ray inensity and the measured distance in fractures A, B and C. From the measured results, the width of fracture A was 2.2m (N 40° E), fracture B was 1.5m (N 50° W), and fracture C was 0.8m (N 50 ° W). Since the reinforced soil

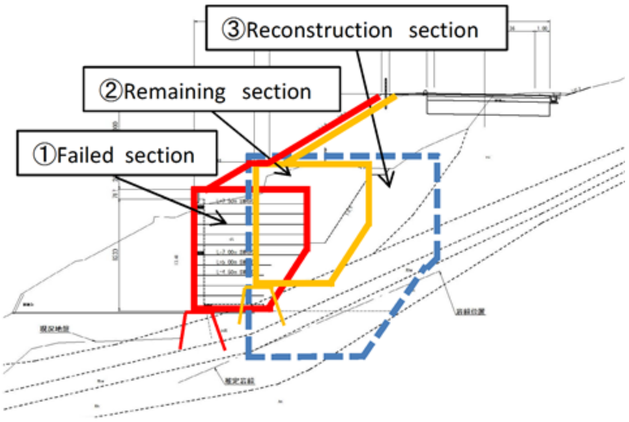

Fig. 8. Cross sections of failed, remaining and reconstruction of reinforced soil wall

wall was located directly above the area surrounded by three fractures (fracture A, B, C in Fig. 6), the failure was influenced by complex ground fluctuations at the time of the earthquake. In the vicinity of Minami-Aso village, a passive earthquake fault, inactive fault induced by the earthquake motion of the Kumamoto earthquake, was observed. It is inferred that the three fractures confirmed by the gamma-ray survey are also inactive faults.

5 DISCUSSION OF THE FAILURE

At the beginning, it was assumed that the retaining wall founded under the reinforced soil wall collapsed by a horizontal inertial force due to the earthquake. The foundation wall remained stable without damages as shown in Photos. 4 and 5. In addition, the groundwater and seepage flow were not observed on this site. The grain size distribution test, which was carried out to check the performance of the banking material quickly, showed results that contained fine fracture and the friction angle of the soil satisfied the standard (F_c=8% < 25%, φ=41°>30°) respectively.

Fig.8 shows estimated cross section of the failed wall (①), remaining wall (②) and reconstruction wall (③). ② signifies a perspective of an adjacent wall to the failed wall. And ③ represents a cross section of the wall reconstructed after the earthquake. Safety factors against sliding of the reinforced zone had calculated as 1.20, 1.24 and 1.45 for large scale earthquake in cases ①, ② and ③ sections respectively. This means that the safety conditions were sufficient under the limit equilibrium calculations. As mentioned above, the failed reinforced soil wall was surrounded by three fractures. It is, however, believed that not only were the seismic inertia forces in the reinforced zone, backfill and the overburdened embankment zones responsible for the collapse, but also the phase difference in the ground motion induced from non-active fractures affected to the collapse as shown in Fig. 9. Intense ground motion produced forces that pushed the reinforced soil wall forward, and finally

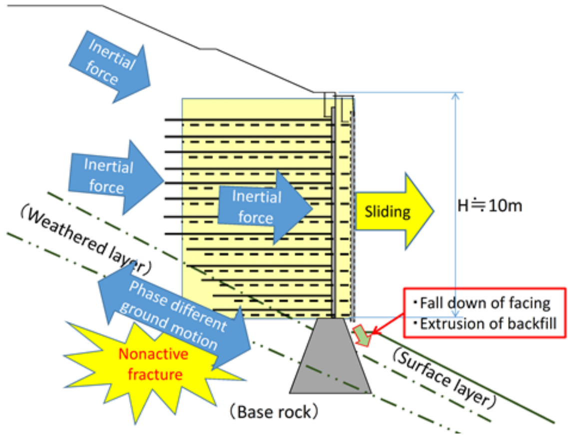

Fig. 9. Three seismic acting forces affection the failed wall

resulted in its fall from the gravity foundation wall.

6 CONCLUSION

The following may be concluded from the survey:

(1) Failed reinforced soil walls were located in an area with a large crustal movement area around the Futagawa fault zone. The damage to the structures was affected by the magnitude of the ground's displacement rather than its vibration.

(2) Three fractures, which were defined as inactive faults, were detected from the gamma-ray survey at the back of the reinforced soil wall.

(3) From results of field investigations, the reinforced soil wall failed due to the following two inertial forces and the ground displacements: 1) the inertial forces of the reinforced soil wall including the backfill, 2) the inertial force of top fill on the reinforced soil wall, and 3) the phase difference in the ground motion caused by fractures existing under the reinforced soil wall, and the extrusion of the back ground surrounded by three fracture zones.

ACKNOWLEDGEMENTS

The authors would like to express sincere appreciation for the cooperation of Minamiaso Village for this investigation.

REFERENCES

Mukunoki, T. et al (2016), Reconnaissance report on geotechnical damage caused by an earthquake with JMA seismic intensity 7 twice in 28h, Kumamoto, Japan, Soils and Foundations, Vol.56, No.6, 947-964.

Yoshimura, T., Fukuda, N. (2012): Newly developed method of predicting slope collapse places triggered by faults combined with γ-ray and magnetic susceptibility survey, Proc. Int. Symp. Earthquake-induced landslides, IS Kiryu 2012 Japan, 857-862.

Yoshimura, T., Fukuda, N., Hodo, M., and Baimakhan, A. R. (2013): Importance to evaluate of fault fracture zones for construction of infrastructures in mountain area by γ-ray survey, Proc. 7th Int. Join Symp. Problematic Soils and Environment in Asia, JS Okinawa 2013, 167-172.