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Research Paper

Geotechnical damage due to the 2016 Kumamoto Earthquake and future challenges

H. Hazarika[1], T. Kokusho[2], R.E. Kayen[3], S. Dashti[4], H. Fukuoka[5], T. Ishizawa[6], Y. Kochi[7], D. Matsumoto[8], H. Furuichi[9], T. Hirose[10], T. Fujishiro[11], K. Okamoto[12], M. Tajiri[13] and M. Fukuda[14]

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A B S T R A C T

The 2016 Kumamoto earthquake with a moment magnitude of 7.0 (Japanese intensity = 7) that struck on April 16 brought devastation in many areas of Kumamoto Prefecture and partly in Oita Prefecture in Kyushu Region, Japan. The earthquake preceded a foreshock of magnitude 6.5 (Japanese intensity = 7) on April 14. This paper summarizes the damage brought to geotechnical structures by the two consecutive earthquakes within a span of twenty-eight hours. The paper highlighted some of the observed damage and identifies reasons for such damage. The geotechnical challenges towards mitigation of losses from such earthquakes are also suggested.

1. Introduction

The 2016 Kumamoto earthquakes are a series of earthquakes including a magnitude 7.0 main shock, which struck at 01:25 JST on April 16, 2016 beneath Kumamoto City, Kumamoto Prefecture on Kyushu, Japan, at an epicentral depth of about 10 kilometers and a foreshock earthquake with a magnitude 6.5 at 21:26 JST on April 14, 2016, at an epicentral depth of about 11 kilometers. Chain events of 6.5 magnitude foreshock and 7.0 Magnitude main shock that occurred within 28 hours, called The 2016 Kumamoto Earthquake, resulted in huge loss of lives and properties. This was the strongest earthquake ever recorded in Kyushu (since the JMA was established). A summary of the earthquake can be found on Table 1. The epicenter of the main shock and the distribution of aftershocks are shown in **Fig. 1.** More than 1,500 aftershocks have been recorded by the Meteorological

[1] Professor, Department of Civil Engineering, Kyushu University, Fukuoka 819-0395, Japan, hazarika@civil.kyushu-u.ac.jp
[2] Prof. Emeritus, Chuo University, Tokyo, Japan
[3] Professor, University of California, Los Angeles, USA
[4] Assistant Professor, University of Colorado, Boulder, USA
[5] Professor, Niigata University, Niigata, Japan
[6] Senior Researcher, National Research Institute for Earth Science and Disaster Resilience, Tsukuba, Japan
[7] President, K's Lab Inc., Yamaguchi, Japan
[8] Manager, Japan Foundation Engineering Co., Ltd., Fukuoka, Japan
[9] Manager, Giken Ltd., Tokyo, Japan
[10] Engineer, Giken Ltd., Tokyo, Japan
[11] Chief Engineer, Fukuyama Consultant Co. Ltd., Kitakyushu, Japan
[12] Deputy Manager, Fukuyama Consultant Co. Ltd., Kitakyushu, Japan
[13] President, Tajiri Engineering Office, Kumamoto, Japan
[14] General Manager, Taisei Geotech. Co., Ltd., Fukuoka, Japan
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Table 1. Earthquake exceeding JMA seismic intensity level 6 since 14 April, 2016

Date and Time	Hypocenter	Magnitude	JMA Seismic Intensity (Max)	
14 April 2016 21:26 JST	Kumamoto area of Kumamoto Prefecture	6.5	7	Foreshock
14 April 2016 22:07 JST	Kumamoto area of Kumamoto Prefecture	5.8	6 weak	
15 April 2016 00:03 JST	Kumamoto area of Kumamoto Prefecture	6.4	6 strong	
16 April 2016 01:25 JST	Kumamoto area of Kumamoto Prefecture	7.0	7	Main shock
16 April 2016 01:45 JST	Kumamoto area of Kumamoto Prefecture	5.9	6 weak	Aftershock
16 April 2016 03:55 JST	Aso area of Kumamoto Prefecture	5.8	6 strong	
16 April 2016 09:48 JST	Kumamoto area of Kumamoto Prefecture	5.4	6 weak	

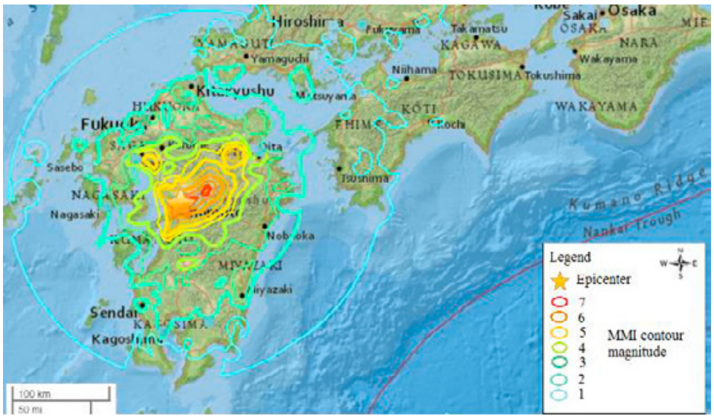

Fig. 1. Epicentre of the earthquake and distribution of aftershocks (Source: USGS).

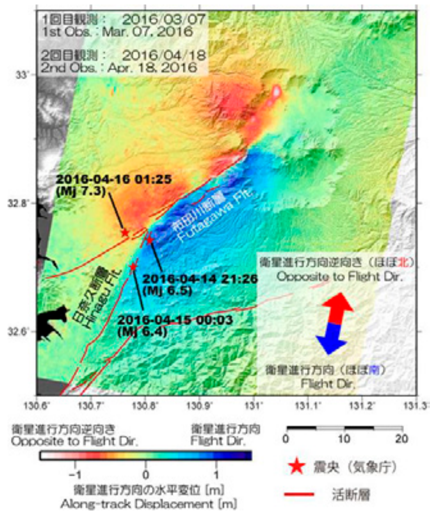

Fig. 2. Futagawa fault and Hinagu fault (Source: GSI).

Agency of Japan since April 14. The earthquake resulted in substantial damage to infrastructure including buildings, cultural heritage of Kumamoto castle, roads and highways, slopes and river embankment due to earthquake induced landslides and debris flows, and fault induced ground subsidence. At a surprisingly limited extent, liquefaction occurred only in a few districts of Kumamoto City and in the port areas.

The Fire and Disaster Management Agency of Japan (FDMA) has reported that 50 people were killed (49 direct, 1 missing), 350 persons suffered severe injuries, and 1,234 suffered slight injuries. Property damage amounted to 2,487 houses completely destroyed, 3,483 houses partially destroyed, and 22,855 houses damaged but habitable. Fire destroyed 16 houses. In addition, more than 3 billion USD has been estimated for the civil infrastructure losses. Reconstruction cost is estimated to be around 6-8 billion USD.

The earthquake also resulted in heavy damage to infrastructures and loss of lives due to large-scale landslides, slope failures and debris flows. In order to carry out the damage analysis and construct landslide hazard map of the Aso area, where damage was concentrated, a joint investigation team consisting of researchers from Japan and the USA was formed, under special funding scheme called J-RAPID by the Japan Science and Technology Agency (JST). The authors conducted four surveys in the devastated areas: the first one was immediately after the earthquake during April 16-17, the second one during May 11-14 and the third one during June 24-26 and the fourth one during August 22-24. This report summarizes the damage brought by the earthquake in and around Kumamoto city. The report also highlighted some of the possible reasons for such damage and geotechnical challenges towards the reconstructions of the devastated region.

2. Mechanism and seismicity of the earthquake

2.1 Earthquake mechanism

The 2016 Kumamoto earthquake on April 16, 2016 was the largest earthquake in Kyushu island in the last twenty years. Hinagu and Futagawa fault zones are the sources of the April 14 foreshock and April 16 main shock, respectively. As seen in **Fig. 2,** the main shock and its

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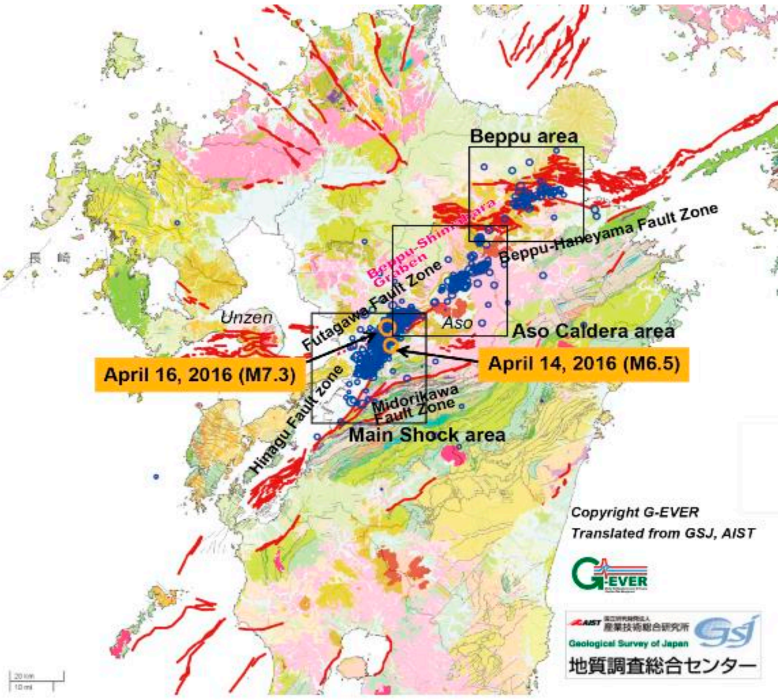

Fig. 3. Seismic activity and geological information in central Kyushu (Source: GSJ).

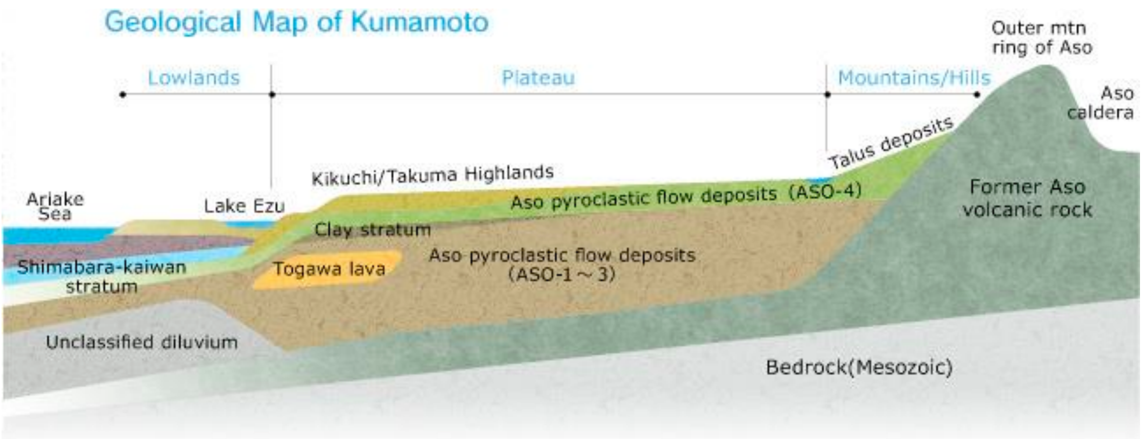

Fig. 4. Geological map of Kumamoto (Source: GeLK).

aftershocks are distributed along the Futagawa and Hinagu active faults (GSI). These two faults are among the 100 active faults designated by the Central Disaster Prevention Council of Japan, out of more than 2000 faults distributed throughout the Japanese archipelago. The earthquake occurred as the result of more than 2 m strike-slip faulting at shallow depth. Focal mechanisms for the earthquake indicate that slip occurred on a right-lateral fault striking northeast.

Geological Survey of Japan (GSJ) reported that the epicenters of the present earthquake sequence show wide distribution in the zone of Beppu-Shimabara Graben from the west to the east coast of the middle Kyushu with a distance of about 200 km and a width of a few tens of km. The earthquake sequence are presently very active at Hinagu Fault Zone and Futagawa Fault Zone in western Kyushu, Aso Volcano area in central Kyushu, and Beppu-Haneyama Fault Zone in eastern Kyushu **(Fig. 3).**

2.2 Geology of the Kumamoto Area

The geological map of the Kumamoto area is in **Fig. 4.** Kumamoto city and Mashiki town are located north of Kumamoto alluvial plain, which is composed of pyroclastic flow deposits. The Futagawa fault cuts the lava plateau and continues along the boundary between the Kumamoto plain and rocks. The Hinagu fault in south juxtaposes alluvial plain with bedrocks and runs north through bedrocks to merge with the Futagawa fault (Okumura, 2016).

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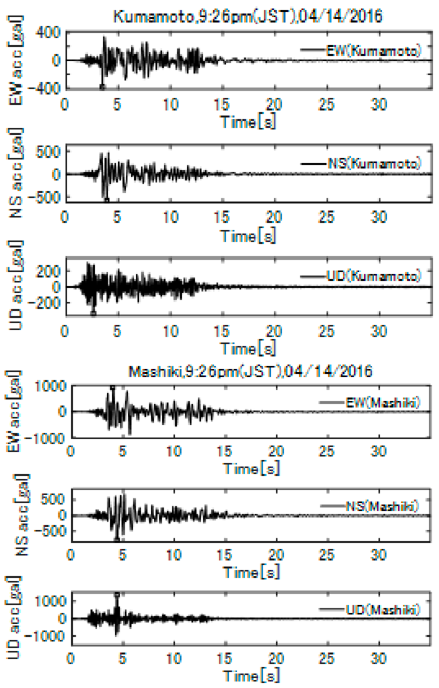

Fig. 5. Ground motion due to foreshock of April 14 (Source: KiK-net and JMA).

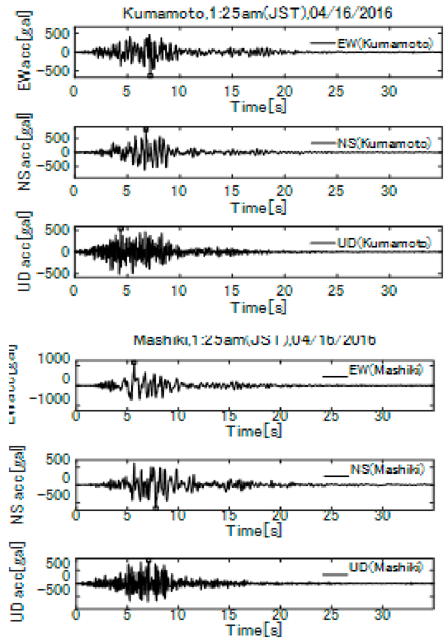

Fig. 6. Ground motion during the main shock (Source: KikNet and JMA).

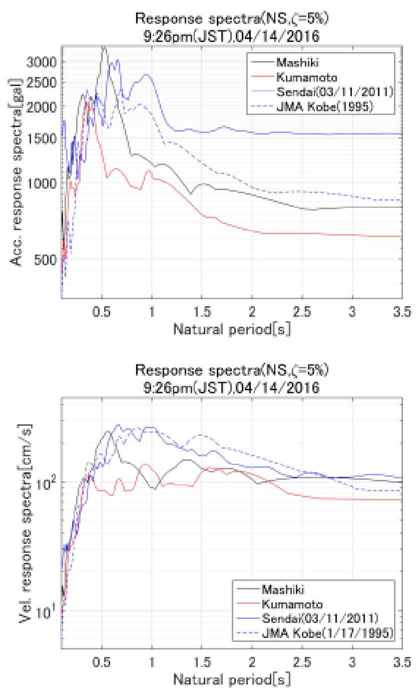

Fig. 7. Acceleration and velocity spectra of the foreshock (Source: KikNet and JMA).

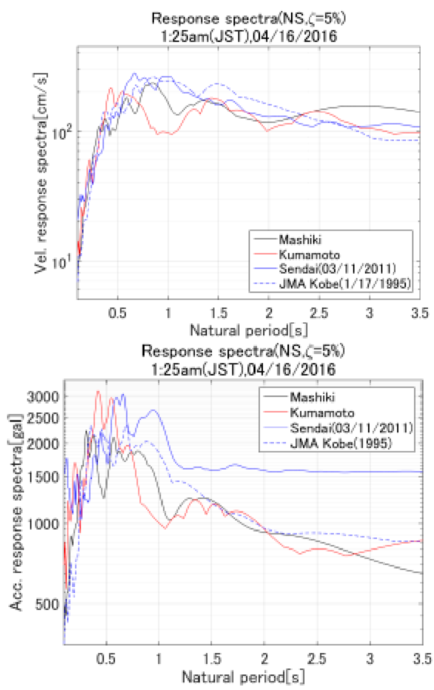

Fig. 8. Acceleration and velocity spectra of the main shock (Source: KikNet and JMA).

2.3 Seismicity of the Earthquake

During the M 6.5 foreshock, the largest recorded ground acceleration of 1580 Gal was measured at Mashiki town. The ground motions measured at two locations of Mashiki town (KiK-net Mashiki) and Kumamoto city (K-NET Kumamoto) during this foreshock are shown **Fig. 5.**

During the main shock of 7.0 magnitude, the peak ground accelerations again exceeded 1000 Gal at Mashiki town. The main-shock ground motions measured at Mashiki town and Kumamoto city during the main shock are shown **Fig. 6.**

The acceleration and velocity response spectra of the foreshock (NS component) are presented **Fig. 7,** while **Fig.**

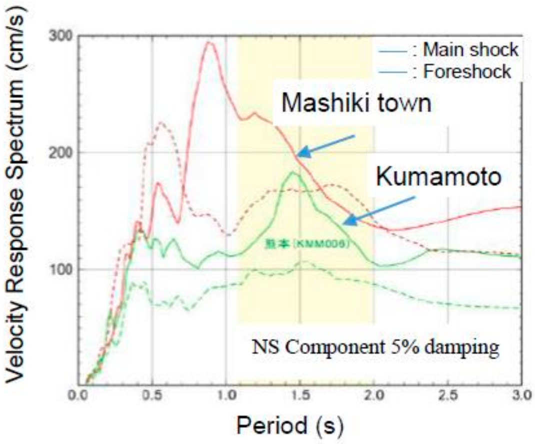

Fig. 9. Comparison of the velocity spectra of the two events (Source: ERI, University of Tokyo).

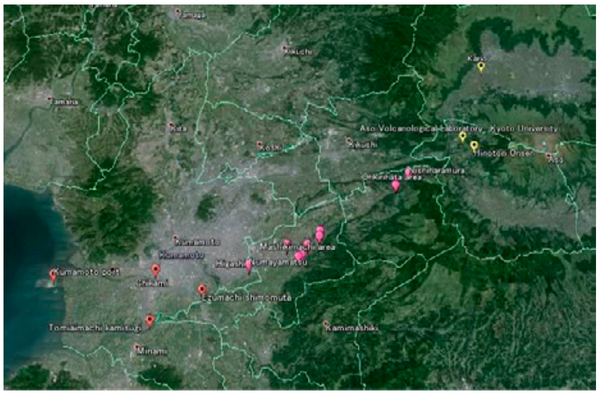

Fig. 10. Surveyed locations (Source: Google map).

Fig. 11. Seismic subsidence in Uchinomaki area.

Fig. 12. Road damage and building damage due to subsidence.

Fig. 13. Subsidence on the opposite side.

Fig. 14. Abutment failure and retaining wall damage.

8 shows the same for the main shock. For comparison, two past large earthquakes in Japan (The 2011 Tohoku earthquake (Sendai) and The 1995 Kobe earthquake (JMA Kobe)) are also shown in the same figures.

Fig. 9 illustrates the comparison of the velocity spectra for the two events. Comparisons of the velocity response spectra of the two observational points (KiK-net Mashiki in red and K-NET Kumamoto in green) show that the motion was stronger on April 16 main shock on both the locations. In Mashiki town, the increase of predominant period from 0.6s to 0.9s may be attributed to the amplification of motion due to non-linear response (or liquefaction) of the ground (ERI, University of Tokyo).

3. Damage investigation and results

The authors conducted investigation covering major locations where damage was concentrated. **Fig. 10** shows the map of the locations in which the authors conducted the survey. In the following subsections, the results of the preliminary investigation are summarized.

3.1 Seismic subsidence, landslides, debris flow, and slope failures in Aso area

In Aso area, damage due to seismic subsidence and strong motion led to landslides, slope failures and debris

Fig. 15. Huge landslide and collapse of the Aso bridge (Photo Courtesy: American Geophysical Union).

Fig. 16. State of the landslide on May 12.

Fig. 17. Surficial failure in Aso.

Fig. 18. Swept away houses.

Fig. 19. Andisols and pumice layer in the slope.

Fig. 20. Cracks in the slope.

flow, which killed many people, and jeopardized the transportation network in that area.

In Uchinomaki area of Aso city, a co-seismic subsidence (Graben phenomenon) covering an area of about 2 km long and 1 km wide was found **(Fig. 11). Fig. 12** shows the condition of the road passing through the area depression zone and the state of the house across the road. Another house next to this house had no detrimental effect. According to the local resident (owner of the unaffected house), the shaking was mostly vertical and the subsidence was simultaneous to the earthquake as they could hear a huge sound while shaking was still continuing. At the greatest offset, the subsidence was more than 2 m **(Fig. 13).** The geotechnical bore hole data within 1 km of that area suggests that the area has more than 70 m of thick clay containing water content within the range of 150 to 280 % and void ratio ranging from 5 to 8. The N value of the soil layer between 20 to 40 m depth is almost equal to zero. Thus, it can be inferred that the surface soil in that area was sitting on the top of a soft soil layer, which may have caused such subsidence. In another location around the area, more than 1.5 m wide cracks were observed leading to the damage of a bridge abutment and failure of the retaining wall **(Fig. 14).**

In the Aso Caldera area, the damage was mostly related to earthquake-triggered shallow landslides and slope failures of the volcanic soils. These have led to bridge and road failures in that area. **Fig. 15** shows one of

Fig. 21. Hinotori hot spring disaster.

Fig. 22. Soils in that area (Haido).

Fig. 23. Concrete check dam collapse.

Fig. 24. Collapsed part of the dam.

the biggest landslides in the Minamiaso village area, the west side of Mt. Aso. The landslide covering a length of about 700 m, and width of about 200 m caused damage to the roads and bridges blocking the entire transportation network in that area. Route 57 and Japan Railway Hohi line were buried under the debris. The bridge abutment failed during the main shock, causing the Aso bridge to collapse. **Fig. 16** shows the state of the slope when the authors visited the area. It is clear that the flow of deposits is still continuing, and the debris may cause subsequent debris flows during the rainy season.There was a series of surficial landslides **(Fig. 17)** close to the Aso volcanological laboratory of Kyoto university along route 299 prefectural road. Many houses were swept away by the landslide **(Fig. 18).**

The authors observed that the soils in that area were composed of typical Andisols **(Fig. 19).** They are highly porous, dark-colored soils developed from parent material of volcanic origin and have excellent water holding capacity. Orange colored pumice layer was found sandwiched between those layers. According to geologist Prof. Kazunori Watanabe, Prof. Emeritus of Kumamoto University, who accompanied the authors during the survey, the orange colored pumice may have been formed about more than 30,000 years ago due to catastrophic volcanic eruption in and around Kusasenrigahama crater (Matsuda et al., 2003; Miyabuchi et al., 2004). Many cracks still remain in the slopes **(Fig. 20).** In some places, cracks as deep as 3 m were found. During rainy season starting soon, rain water may infiltrate through this crack, causing those slopes with cracks vulnerable to secondary disaster. More than 90 such vulnerable slopes exist.

In another location, Hinotori hot spring facilities were swept away by a landslide **(Fig. 21)** that occurred during the main shock. A honeymoon couple from Kagawa prefecture was killed due to that debris flow. The soils in that area were found to be of volcanic origin with very low plasticity. The water content was also found to be very high. This kind of soil loses strength easily during cyclic loading. Such soil characteristics in that area may have caused slope failure triggered by the earthquake loading. Since the slope failed during the main shock, the cyclic loading effect of the foreshock is another factor, which needs attention in the damage analysis of such slopes.

A check dam was found to be collapsed in Nagano area of the Aso village **(Fig. 23).** The right side of the check dam was swept away by about 100 m, and completely overturned **(Fig. 24).** Also, many debris were found near the overturned block **(Fig. 25).** Due to the collapse of the dam, the Tarutama river is eroded at many locations as

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Fig. 25. Debris around the dam.

Fig. 26. Erosion of the river channel.

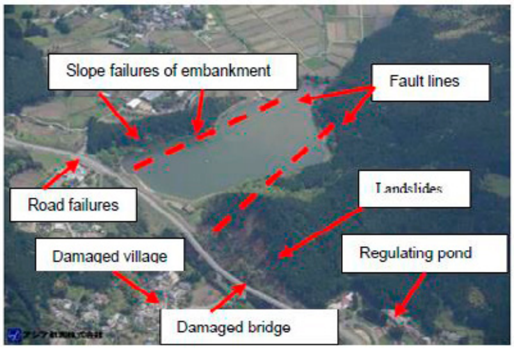

Fig. 27. A complete view of the reservoir before the earthquake and the related damage.

Fig. 28. Damage to control room.

Fig. 29. Damage to roads and retaining wall.

Fig. 30. Overflow of the regulating pond.

seen in **Fig. 26.** The exact reason of the failure is still unknown. However, continuous water flow close to the dam even before the earthquake can be one potential cause of such catastrophic failure.

3.2 Fault-induced damage in Nishihara village

Nishihara village towards the south of Aso area (Refer to **Fig. 10**) is located along the Futago fault. In this area, damage to an irrigation dam, many landslides and slope failures, road damage, retaining wall failures and bridge damage were observed.

The Ohkirihata dam is located in the Nishihara village of Kumamoto prefecture. It is an earth fill dam with a height of 23 m for irrigational purpose. Our first survey team arrived in that area around 10 A.M. on April 16 (the day of the main shock) and conducted surveys on the dam, control room, regulating pond, slopes and the roads along the dam. This section describes the state of damage of the reservoir, spillway, drainpipes, regulating pond, etc. **Fig. 27** shows a picture of the entire reservoir and the associated damage due to the earthquake.

Due to damage inflicted on the control room **(Fig. 28),** as an urgent measure, the water level in the reservoir was lowered by about 2 m. **Fig. 29** shows some of the damage in the upstream of the dam including the road, slopes, and the retaining wall.

Fig. 31. Overflowed water crossing the road.

Fig. 32. Scouring of the road embankment adjacent to spillway.

Fig. 33. Wall damage on the embankment.

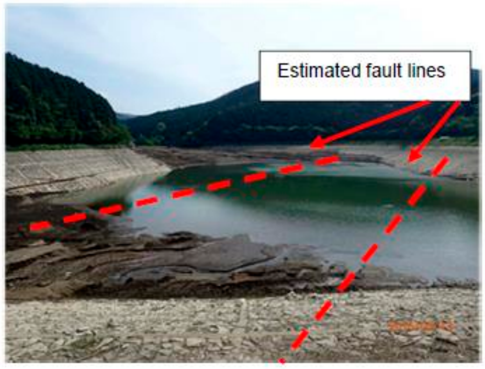

Fig. 34. Emptied reservoir and exposed fault lines.

Fig. 35. Slope failures along the embankment.

Fig. 36. Regulating pond (no overflow).

Due to strong motion of the earthquake and proximity of the fault zone, the control room tilted, and as a result, spindles were lifted off, rendering the switch gears non-functional and leading to loss of the water storage function. This ultimately led to the overflow in the regulating pond of the dam **(Fig. 30)**. The overflowed water crossed the road and created an artificial fall **(Fig. 31)**, which caused tremendous scouring of the road embankment. The scouring also could be observed in the road embankment, which is vulnerable to collapse at any time **(Fig. 32)**.

The spillway did not suffer damage, however retaining walls on the both sides of the embankment were displaced (especially the right side was displaced by more than 50 cm) as seen in the **Fig. 33.** During the second visit of the authors, it was observed that deformation of the sides of the spillway and the subsidence of the road increased further. The succession of many aftershocks may have exacerbated the situation. A detailed report on the damaged dam can be found in the paper by Hazarika et al. (2016) and Oettle et al. (2017).

The continuous overflow almost emptied the reservoir, which the authors observed in their second survey within four weeks **(Fig. 34)**. We could visually observe the faults that passes through the dam. Therefore, it could be concluded that the major damage was due to these faults. We could also see slope failures at two locations of the dam embankment **(Fig. 35)**. Regulating pond has come to the normal state **(Fig. 36)**, however, the scouring caused

Fig. 37. Scouring of the road embankment.

Fig. 38. Landslide blocking the access road.

Fig. 39. Slope failure on the main road.

Fig. 40. Retaining wall (about 5 m high) failure.

Fig. 41. Liquefaction in Akitsu river dike.

Fig. 42. Lateral displacement of quay wall.

Fig. 43. Lateral spreading in the embankment road.

to the road embankment was severe, and it is vulnerable to collapse at any time **(Fig. 37)**.

There were also a lot of landslides and slope failures and road damage **(Fig. 38)** around the road including a bridge within 1 km of both sides of the faults. The main road suffered landslides as well as subsidence **(Fig. 39).** About the 90% of the houses down the road completely collapsed including an engineered retaining wall **(Fig. 40)**. A preliminary survey results of the dam damage are described in Hara et al (2016).

3.3 Damage in Mashiki town due to strong motion and liquefaction

Mashiki town is the area where major building damage was observed due to the strong motion. There were a lot of geotechnical damage mostly related to liquefaction and associated lateral spreading. **Fig. 41** and **Fig. 42** respectively show the Akitsu river embankment with sand boils and displacement of the quay wall due to lateral spreading. **Fig. 43** shows the lateral displacement-induced failure of the embankment road. About 30 cm subsidence of the river bank and more than 20 cm of lateral displacement of road were measured. The dark colored sand boils **(Fig. 41)** indicate the existence of volcanic soils in the area. In a parking lot belonging to JA (Japan Agricultural Cooperatives Group) office of Mashiki town, which is close to the Akitsu river, a large amount of sand boils were observed **(Fig. 44).** The color of the sand boils (appears to be clean sand), however, was different from the one found in the bank of Akitsu river. In few national and prefectural roads too liquefaction induced settlement

Fig. 44. Sand boils in JA parking lot.

Fig. 45. Subsidence of the road.

Fig. 46. Uplifting of manhole.

Fig. 47. Sand boils in a school ground.

Fig. 48. Settlement of the ground around a pile supported building.

Fig. 49. Subsidence and voids beneath the foundation.

Fig. 50. Differential settlement and tilting of another building supported on spread footing.

Fig. 51. Building damaged due to differential settlement.

(Fig. 45) and upliftment of manhole **(Fig. 46)** were observed. Many traditional Japanese style houses were damaged due to the strong motion in that area.

3.4 Liquefaction induced damage in minami ward of Kumamoto

Southern part of Kumamoto city (Minami ward) experienced liquefaction in limited areas causing damage to residential houses including a hospital building due to differential settlement.

Most of the liquefaction related damage were concentrated in the area, which are old river channel or floodplain. Sand boils observed in a school ground, which is the designated disaster evacuation place in that residential area, is shown in **Fig. 47. Fig. 48** shows a residential building, where sub-meter settlements of the ground around the building were observed. The building itself did not undergo any differential settlement, as according to the owner of the building, pile foundations were used in the building. However, subsidence induced voids beneath the foundation is a concern of the owner **(Fig. 49)**. Another building adjacent to the above building **(Fig. 50)** was found to suffer from differential settlement and tilted by more than 1 degree making it unsuitable to live. Apparently, this building was founded on spread footing. The geomorphology of this area indicates that it was developed by reclamation of an old river channel.

In Hirata district of Minami ward, several buildings were damaged due to ground subsidence. Differential

Fig. 52. Dark colored sand boils around the building.

Fig. 53. Subsidence around a new private hospital building.

Fig. 54. Subsidence at the backside of the hospital building.

Fig. 55. Liquefaction induced road damage (Uplifted manhole).

Fig. 56. Liquefaction in port complex.

Fig. 57. Sand boils (max. dia. > 1.5m).

Fig. 58. Lateral spreading and sinking of road .

Fig. 59. Quay wall of the port (no damage).

settlements of the buildings were common features. Some boundary walls were partially or fully collapsed. Sand boils and liquefaction induced settlement of the buildings **(Fig. 51)** were observed. The sand boils were found to be black in color **(Fig.52)** indicating that the soils is of volcanic origin. One of the most affected buildings in that area was a new private hospital. A subsidence of as much as 40 cm was observed around the building. Ground subsidence can

Fig. 60. Differential settlement of the ferry terminal.

Fig. 61. Subsidence around the terminal building.

Fig. 62. Damage to over-bridge due to differential settlement.

Fig. 63. Bridge with scaffolding (May 11).

Fig. 64. Repaired rive dike (Kase river).

Fig. 65. Repaired rive dike (Midori river).

also be seen near stairs (backside) of the building **(Fig. 54).** The hospital building itself was safe with no differential settlement due to use of pile foundation. Liquefied soil can be seen around a residential building located at backside of the hospital building. About 15 cm differential settlement, and about 2 degree tilting were observed in that building. Boundary wall of the building was found to be tilted containing many cracks, indicating the effect of liquefaction.

Many roads were damaged in the affected area near the hospital. **Fig. 55** shows one of the damaged roads with uplifted manhole. About 18 cm lateral spreading of that road was observed. Drainage system was also damaged at several locations along the road.

3.5 Liquefaction induced damage in Kumamoto port

Although some infrastructural facilities within the Kumamoto port complex, such as roads and building entrance, were damaged due to liquefaction, the main port itself did not suffer much loss. The first author arrived in the port area in the morning of April 17. A lot of sand boils were observed in the port complex **(Fig. 56),** which resulted in the settlement of the entrance of the ferry terminal and road damage. **Fig. 57** shows some sand boils with maximum diameter of 1.5 m in the port complex

Fig. 66. Sand boils, subsidence and lateral spreading in Midori river dike.

Fig. 67. Highway damage in Kyushu highway (Source: AGU and AAS).

Fig. 68. Highway damage in Oita expressway (Source: AGU and AAS).

Fig. 69. Highway abutment damage in Kyushu expressway (Photo courtesy: Dr. Y. Sagawa, Kyushu.

resulting in the maximum settlement of about 30 cm. Liquefaction induced lateral spreading and sinking of the road was also observed **(Fig. 58)**. The liquefaction in the areas also led to some minor laterals spreading as seen. No significant damage to the quay wall **(Fig. 59)**, however, was observed. The entrance of the ferry terminal was affected by differential settlement **(Fig. 60)** that led to the closer of the terminal for few weeks.

Maximum settlement around the building was observed to be more than 80 cm **(Fig. 61).** The over bridge connecting the port terminal also suffered damage due to differential settlement **(Fig. 62).** In the second visit to the area by the authors on May 11, a temporary retrofitting of the bridge **(Fig. 63)** was seen to prevent any further damage by the aftershocks. Interestingly, the soils in the port area are different from those found in the other liquefied areas discussed before. According to some information gathered by the authors, sand mats that were used to consolidate the thick clay layer in the port areas may have liquefied. The liquefied sands were found to be clean sand as opposed to the volcanic soils found in most of the other liquefied areas.

3.6 Liquefaction induced damage in some river dikes of Kumamoto city

River dikes of Kase river, Midori river and Shira river were damaged due to liquefaction and lateral spreading. Fearing the danger of further erosion due to forthcoming rainy season, the local government was very quick to do the immediate repairment work. **Fig. 64** shows the temporary repairment work in the Kase river dike using recycled concrete. **Fig. 65** shows the immediate repairment work in the dike of Midori river. Some traces of sand boils and liquefaction induced subsidence were still found in that area **(Fig. 66).**

3.7 Damage to highways

The authors do not have any direct information on the damage to highways, as the admission were restricted to those sites, when the authors arrived there. Based on the collected information from various sources, few damages of the Kyushu Highway are summarized in this subsection. **Fig. 67** shows the damage to Kyushu highway in Kumamoto prefecture. **Fig. 68** shows the blocking of the highway due to landslides in Oita expressway, Oita prefecture. **Fig. 69** shows the highway embankment damage and retaining wall failure in Kyushu highway near Mashiki town. A part of the highway was closed for about two weeks. The immediate repairment work of the highway is underway as seen in the figure.

4. Conclusions

Some of the important conclusions derived based on this reconnaissance survey are as following.

1. The damage was localized in areas lying above or close to the faults.
2. The reason for damage are combination of many factors including the fault location, succession of high intensity foreshock, main shock and aftershocks, soil characteristics and liquefiable areas without liquefaction prevention methods.
3. Landslides and slope failures were due to special characteristics of volcanic soils in the Aso caldera area.
4. Liquefaction was mostly found in the river embankments and in areas developed by reclaiming the old the river estuaries.
5. Landslides with fissures that are still remaining make them vulnerable to the secondary sliding during heavy rain.
6. Most of the damaged structures were not seismically designed for a Level 2 event.
7. The nature of soils from the river banks to Aso caldera areas differs in their nature and characteristics. The mechanism of such widespread damage can only be ascertained through proper testing and evaluate of those soils.
8. Improvement of the existing earthquake hazard maps in mountainous areas is needed.
9. Repeated loading due to high intensity foreshock and main-shock motions resulted in an elevated levels of damage. The effect of successive foreshocks, main-shock, and aftershocks, may have to be considered in the future design in areas where such fault induced earthquakes are expected.

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