Geotechnical Damage Caused by the 2016 Kumamoto Earthquake, Japan

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ABSTRACT: *On the 16th of April 2016, the Kumamoto earthquake (M_w 7.0) hit the Central Kyushu Region, Japan, following a M_w 6.2 shock on the 14th of April. The earthquake sequences caused severe damage in Kumamoto Prefecture. This paper presents quick reconnaissance results focusing on geotechnical damage features, which were observed during field investigations immediately after, one, and two weeks after the main shock. The damage surveys were carried out in southern Kumamoto City, Mashiki Town, Aso Caldera area and their suburbs. In southern Kumamoto City, evidence of liquefaction was found at many locations, and some buildings and river levees suffered from significant settlement and deformation; damage to an embankment of Kyushu Highway also seemed to be the result of liquefaction. The majority of the damaged residential houses were found in Mashiki Town and its suburbs, which may be linked to intense earthquake motions associated with the seismic fault location. In Aso Caldera area, a number of moderate to large scale landslides and their significant impact to structures were observed. The greater part of landslide masses in Aso Caldera area was a mixture of volcanic ash, andsol, a highly porous dark-colored material comprising of volcanic ash mixed with organic matter, and pumice. These porous materials might have experienced significant strength reduction during the earthquake.*

KEYWORDS: 2016 Kumamoto earthquake, damage survey, liquefaction, embankment, landslide, volcanic soil

SITE LOCATION: IJGCH-database.kmz

INTRODUCTION

An intense earthquake of M_w 6.2 (USGS, 2016) occurred on the 14th of April 2016 (local time 9:26 p.m.) followed by the main shock of M_w 7.0 on the 16th of April (local time 1:25 a.m.) in Kumamoto Prefecture, Japan. The epicenter of the main shock was about 5 km west of the earthquake that occurred on the 14th of April. A series of these major earthquakes was the result of strike slip faulting along the recognized traces of Hinagu Fault and Futagawa Fault Belts. As far as we recognize, the damage due to the main shock on the 16th of April might have been worsened by the earthquake on April the 14th. The series of major earthquakes caused significant geotechnical and structural damage to various facilities along the fault ruptures that appeared in Kumamoto City, Mashiki Town, Aso City and their suburbs. As of the 14th of May 2016 these major earthquakes caused 49 deaths and 1625 injuries.

According to a rupture model for the main shock developed by NIED (2016), the rupture propagated north-east from the epicenter with its maximum slip of 4.6 m. The fault length and width are 56 and 24 km respectively, and its dip angle is 65 degrees. Figure 1 shows the survey route and the earthquake fault traces. The largest strong ground motion was observed at a seismological station in Mashiki Town (KMMH16, Fig. 1). The resultant peak horizontal ground accelerations (PGAs) of 0.923g and 1.313g were recorded at KMMH16 during the earthquakes of April 14th and 16th respectively. The vectorial sum

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of the two measured horizontal motions, the vertical motion and acceleration response spectra at KMMH16 are shown in Fig. 2. The acceleration response spectra suggest that the amplitudes for the main shock are generally greater than those for the earthquake of April 14th. For both earthquakes peak values of response spectra appear below 1.0 s, and the intense shaking in the short period range might have been responsible for severe structural damage to residential houses in Mashiki Town and its suburbs.

Following the 2016 Kumamoto earthquake, the Japan Society of Civil Engineers (JSCE) dispatched survey teams to the affected areas to piece together evidence of this tragic event. The team of the authors visited the damaged areas immediately after the main shock (the 16-17th of April), one, and two weeks later (the 22nd-24th of April and the 29th of April to the 1st of May). This paper briefly reports the preliminary damage observations of the geotechnical issues caused by the major earthquakes of Kumamoto. In addition, some emergency restorations completed within about a couple of weeks after the main shock are reported. The survey areas covered in this paper are shown in Fig. 1 as well as the epicenters of these major earthquakes.

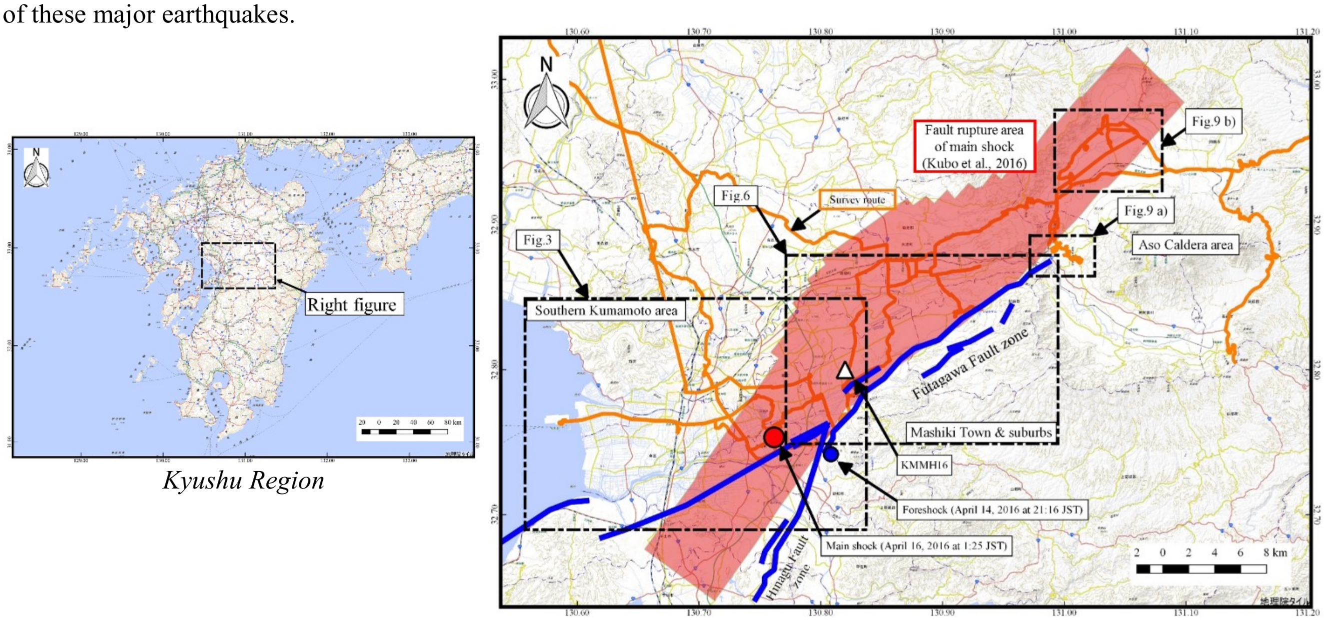


Figure 1. Location of the epicenters of earthquakes, earthquake faults and survey route.

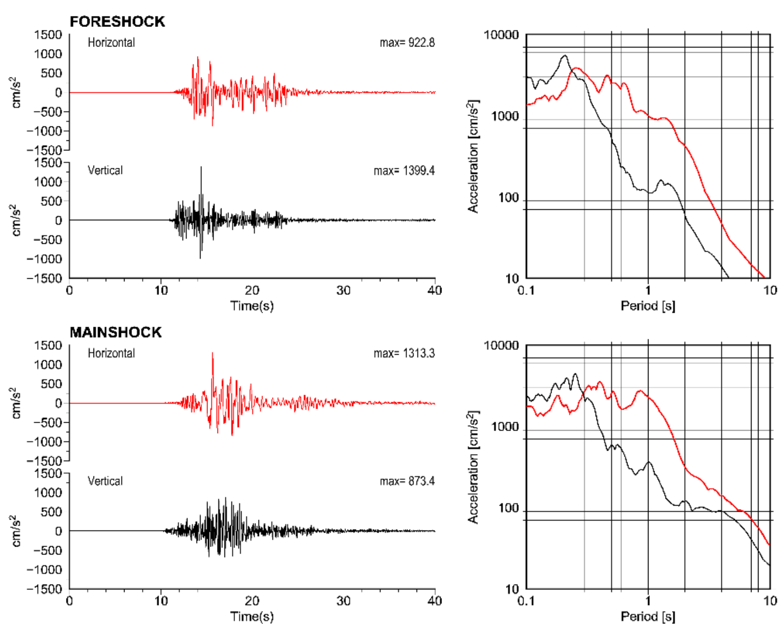


Figure 2. Recorded accelerograms and 5%-damped spectral accelerations at KMMH16 in Mashiki Town (NIED, 2016).

LIQUEFACTION IN SOUTHERN KUMAMOTO CITY

Figure 3 shows the survey route and the location of investigation sites in this section. Southern Kumamoto City was surveyed to understand the liquefaction-induced damage to residential houses and river levee. In addition the cause of damage to an embankment of Kyushu Highway, which caused serious disruption of emergency distribution in the affected area, was investigated.

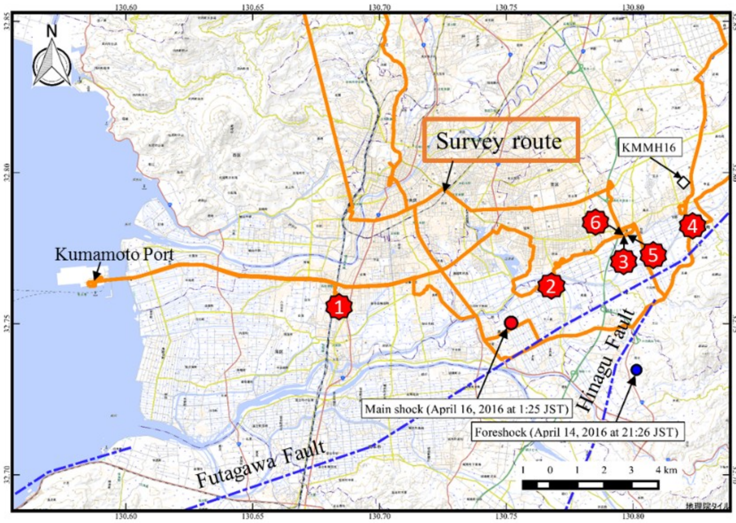


Figure 3. Survey route and locations of investigation sites in southern Kumamoto City (modified from Google map).

Liquefaction-induced Damage

Prior to the 2016 earthquake the local government of Kumamoto City (2014) had produced a liquefaction susceptibility map for every possible earthquake scenario in the Kumamoto Region based on the the physiographic division and borehole loggings, and southern Kumamoto City was indicated as being a moderate to significant liquefaction vulnerable zone. Following the 2016 earthquake, evidence of liquefaction was found over a wide area in the southern Kumamoto City, especially, downstream basin of Midorikawa-River and Shirakawa-River (Yasuda and Ishikawa, 2016). The authors also found boiled sand on the streets and in private properties in Karikusa district, Kumamoto Port, and reclaimed residential areas along the Akitsugawa-River, a branch of Midorikawa River (Fig. 3).

Figure 4 shows the liquefaction-induced damage to buildings in Karikusa district (site 1). The building suffered from significant settlement of about 50 cm. The adjacent building also suffered from a tilting of about four degrees. Similar damage to residential houses was observed in Majima district (Figure 5, site 2) which is a reclaimed land along the river. In addition, liquefaction as evidenced by sand boils present in Kumamoto Port, however, the liquefaction-induced damage to major facilities was not reported. As a whole impression of liquefaction during the Kumamoto earthquake, the number of damaged buildings and facilities was much fewer than in the Kanto region during the 2011 Off Pacific Coast of Tohoku Earthquake (Yasuda et al., 2012; Towhata et al., 2014).

Figure 6 shows the typical liquefaction-induced damage to a river levee (site 3). Large settlement and lateral deformation was found at the levee along Akitsukawa-River. According to a landform classification map for flood control, provided by Geospatial Information Authority of Japan (GSI) shown in Fig. 7, the damaged levee is located at the old river channel, which suggests that a shallow soft deposit liquefied, inducing lateral spreading toward the river. Kyushu Regional Development Bureau of MLIT (2016) reported damage of variable severity to the levees of the Midorikawa-River and Shirakawa-River. They identified a total of 171 sites, however, their emergency restoration was almost completed as of middle of May. The settlement of levees, for example, caused a large gap between the embankment and bridge girders leading to a transportation problem (Figure 8, site 4). As of the end of April, such problems have occurred at many locations, however, they have been temporally solved by the installation of a filled slope (Figure 9, site 5). Although the locations of liquefaction are widespread in Kumamoto City (Wakamatsu et al., 2016), there have been no official report of serious liquefaction-induced damage; there are neither collapse of buildings nor washout of levees due to liquefaction.

Figure 4. Liquefaction-induced damage to buildings in Karikusa district (Site 1 in Fig. 3) (32° 45'35.70"N, 130° 40'59.76"E).

Figure 5. Liquefaction-induced damage to residential houses in Majima district (Site 2 in Fig. 3) (32° 45'52.69"N, 130° 46'7.49"E).

Figure 6. Liquefaction-induced damage to levee along Akitsukawa-River (Site 3 in Figs. 3 and 7) (32° 46'43.56"N, 130° 47'40.27"E).

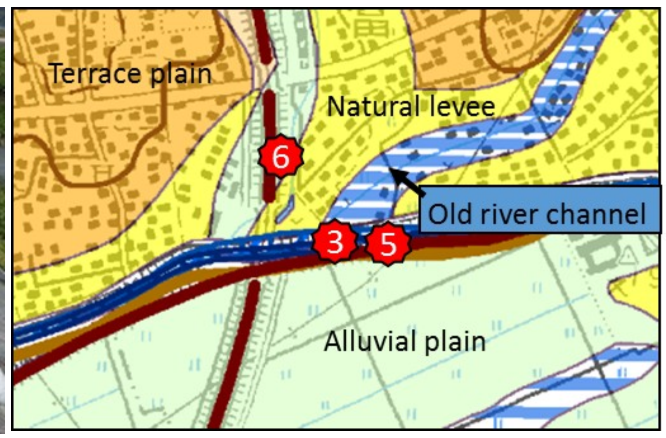


Figure 7. Landform classification map and location of the damaged sites (Modified from GSI's map).

Figure 8. A large gap at bridge girder due to settlement of embankment (Site 4 in Fig. 3) (32° 47'2.15"N, 130° 49'17.70"E).

Figure 9. Temporary restoration work (filled slope) for settlement of levee (Site 5 in Figs. 3 and 7) (32° 46'44.47"N, 130° 47'45.43"E).

Damage to Highway Embankment

At site 6 in Fig. 3, a 50 m-long embankment on one side of Kyushu Highway, which connects Fukuoka to Kagoshima, suffered from significant damage (Fig. 10). The damage was caused by the earthquake on the 14th of April, in the form of subsidence and lateral flow. The highway was closed to traffic until the end of April, which disrupted emergency distributions in the affected areas. According to the land classification map (Fig. 7) and old aerial photos taken before the construction of the highway provided by GSI (2016) (Fig. 11), the exact location of the damaged embankment use to be a small river channel, which suggest that the process of liquefaction of saturated loose filled soil was the potential cause of damage to the embankment. In fact, the residential house near the damaged embankment suffered from large tilting as shown in Figure 10, indicating a bearing capacity lowering of foundation ground due to liquefaction.

Since the other side of the embankment survived the earthquake, as an emergency response, the number of driving lanes at the damaged embankment was temporary reduced to one in each direction, and only the one-lane reopened from the 29th of April. Due to the critical importance of the Kyushu Highway, however, careful investigation shall be conducted to thoroughly understand the cause of the damage observed and to propose effective countermeasures for the conclusive restoration of the embankment.

Figure 10. Damage to Kyushu Highway embankment (Site 6 in Figs. 3 and 7) (32° 46'46.80"N, 130° 47'39.40"E).

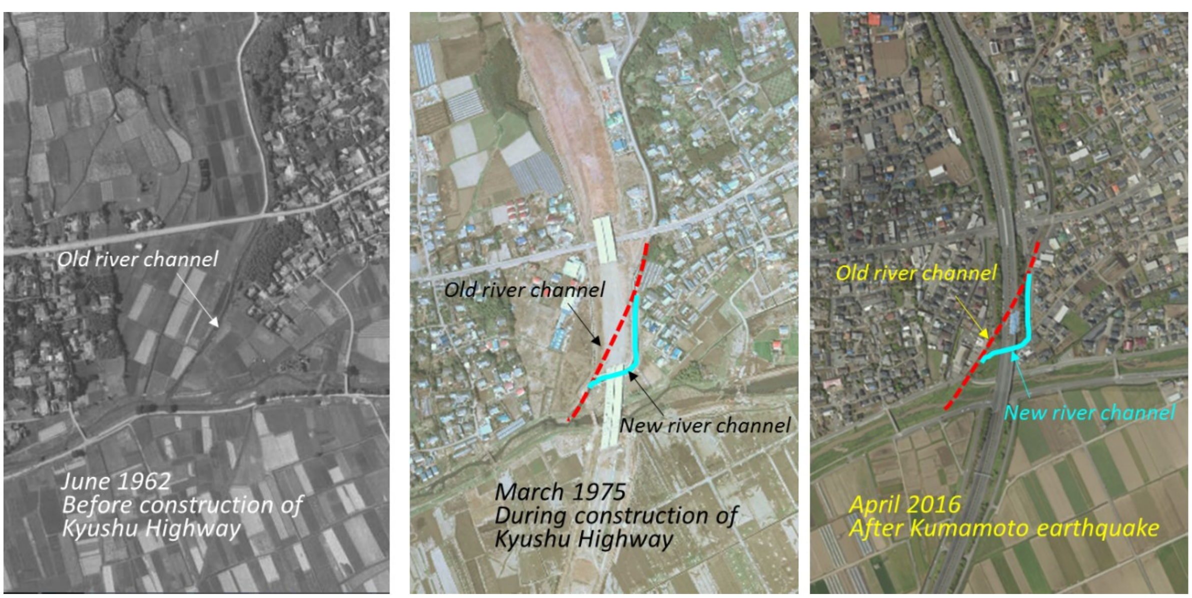


Figure 11. Aerial photo of damaged highway embankment before and after the 2016 Kumamoto earthquake (Modified from GSI aerial photo).

GEOTECHNICAL AND STRUCTURAL DAMAGE IN MASHIKI TOWN AND SUBURB AREA

Figure 12 shows the survey route and the location of investigation sites in this section. Many residential houses in Mashiki Town were devastated, especially the yellow-colored area in the figure, causing about 40% of total death due to the earthquake sequences. Along the Route 443 in Mashiki Town, a section of road (about 100 m in length) built upon embankments was damaged. In addition, a variety of geotechnical and structural damage was observed in some Mashiki suburbs.

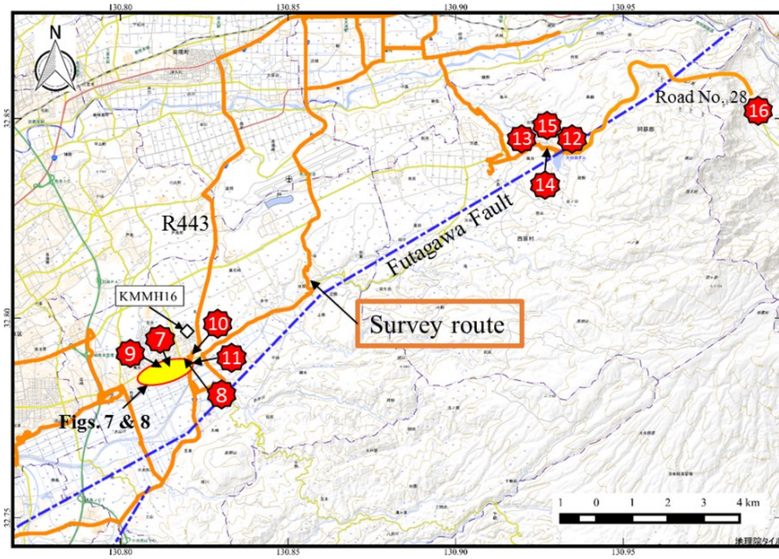


Figure 12. Survey route and locations of investigation sites in Mashiki Town and suburb area.

Influence of Ground Deformation On Structural Damage

There were numerous building collapses in Mashiki Town. Fig. 13 shows the typical damage to the residential houses in the yellow-colored area in Fig. 12 (site 7). The residents in the affected area reported that a number of houses suffered from moderate to significant structural damage due to the earthquake on the 14th of April and then totally destroyed by the main shock on the 16th. It is also reported that the number of deaths in this area was fewer than expected from the damage shown in Fig. 13 because many affected residents had already fled their damaged house after the earthquake of the 14th (Fukuwa, 2016).

Figure 13. Damage to residential houses in Mashiki Town (Site 7 in Fig. 12)
(32° 47'16.38"N, 130° 48'58.47"E).

According to the landform classification map in Fig. 14, the significantly damaged area (yellow-colored in Fig. 12) consists of terrace plain (late Pleistocene), talus deposit and alluvial soil. The area is also gently sloping to the south, thus different site amplification effects due to the different soil conditions and residual deformation of sloped ground may be expected. There were some reported cases following recent earthquakes in Japan where residential houses in a developed area of sloping ground suffered from significant damage due to ground deformation associated with a large scale landslide (Mori et al., 2012). A walk-through survey was therefore conducted to understand the effects of ground deformation on the damage to houses in this area.

Figure 15 shows the result of the authors' quick survey. The spatial distribution of the collapsed houses was concentrated in the sloped area which consists of terrace and talus deposits, whereas ground deformation observed on the roads near the damaged houses was limited, therefore a large scale landslide might not have occurred. The cause of significant damage to the houses in this area was likely due to earthquake motion and the residual displacement of the entire sloped ground had an insignificant effect on the damaged houses. Although some houses were found to be damaged by ground deformation, as shown in Fig. 16 and 17 (sites 8 and 9), they were likely caused by localized failure of filled soil. On the other hand, the damage to the houses in the alluvial deposit area was limited whereas evidence of liquefaction was found frequently as shown in Fig. 15. It is inferred that the liquefied soil incidentally behaved like a seismic isolation system for the residential houses in this area.

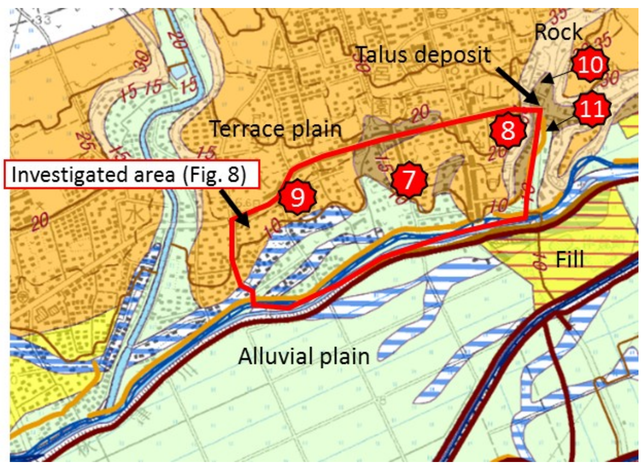


Figure 14. Landform classification map around the survey area in Mashiki Town (Modified from GSI's map, c.f. Fig. 12).

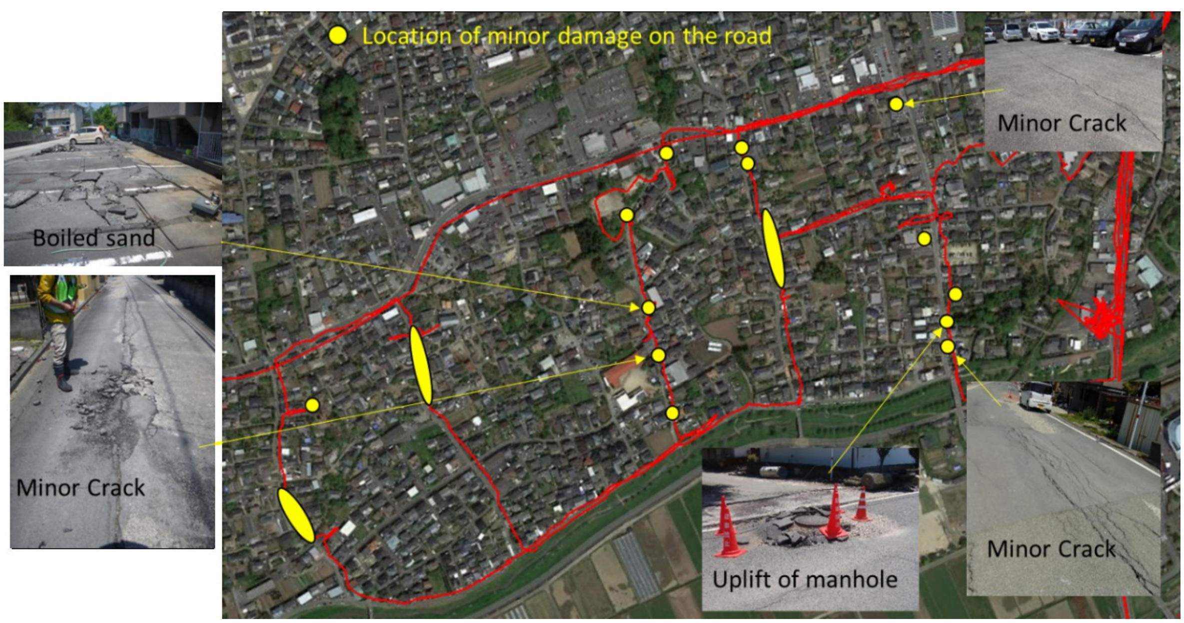


Figure 15. Result of survey on ground deformation of sloped residential area in Mashiki Town (c.f. Figs. 12 and 14).

Figure 16. Ground displacement-induced damage to a residential house (Site 8 in Fig. 12) (32° 47'24.96"N, 130° 49'12.75"E).

Figure 17. Ground displacement-induced damage to a residential house (Site 9 in Fig. 12) (32° 47'14.48"N, 130° 48'41.06"E).

Damage to Route 443

A section of Route 443 at site 10 in Fig. 12 was damaged by the earthquake on the 14th of April. The road on the left side in Fig. 18 failed and subsided by a maximum of about 2.0-2.5 m. The photo also shows the significantly tilted trees at the middle portion of the sliding mass. At the time of the survey on the 16th of April, two days after the occurrence of failure, large soil bags were placed on the exposed failure surface to prevent further damage. According to the landform classification map shown in Fig. 14, the failure was likely to have occurred in the talus deposit and the perimeter of the failure is likely to be the boundary between talus deposit and late Pleistocene volcanic rock.

Approximately 150 m south of the above damaged site a differential settlement was observed (Photo 12b, site 11). According to the landform classification map in Fig. 14, it is indicated that the damaged site was recently constructed on the alluvial soil deposit. The damage, therefore, is attributed to strength reduction of foundation ground due to a process of liquefaction and/or that of the embankment, if the compaction work was inadequate. Immediately after the earthquake, emergency restoration work was rapidly conducted in the affected areas. As shown in Fig. 19, the restoration work for the damaged sites along Route 443 was completed a few days after the main shock.

Figure 18. Damage to Route 443 in Mashiki Town (Site 10 in Figs. 12 and 14) (32° 47'29.71"N, 130° 49'17.58"E).

Figure 19. Damages to Route 443 and their restoration for (a) site 10 and (b) site 11 (c.f. Figs. 12 and 14) (Site 10: 32° 47'29.71"N, 130° 49'17.58"E, Site 11: 32°47'24.33"N, 130°49'15.82"E).

Other Damage in Mashiki Town and Suburb Area

Mashiki and the surrounding areas were close to the seismic fault and suffered from a variety of geotechnical and structural damage due to the earthquakes. Damage to gravity-type and cantilever-type retaining walls (2-3 m high) was found at several locations due to surface manifestation of fault rupture. The retaining wall and dam spillway retaining wall at site 12 in Fig. 12 were structurally damaged as a result of the fault movement (Fig. 20).

Along the prefectural road No. 28 a section built upon an embankment suffered from major cracks, settlement and outward deformation as shown in Fig. 21 (site 13). The deformation of the embankment caused damage to a water pipeline followed by a water leak which resulted in significant erosion of the embankment. A large slope failure was observed at site 14; the length of the slope failure was about 130 m. The surface of the slope has been protected by a shotcrete with a thickness of 5-10 cm. The fallen boulders and debris which consist of late Pleistocene volcanic rocks (rhyolite and dacite) blocked the road completely (Fig. 22).

Figure 20. Damage to retaining wall and spillway retaining wall (site 12 in Fig. 12) (32°50'29.22"N, 130°55'55.83"E).

Figure 21. Damage to road embankment along prefectural road No. 28 (site 13 in Fig. 12) (32°50'36.63"N, 130°55'24.48"E).

Before the failure (Google Earth)

Figure 22. Slope failure along prefectural road No. 28 (site 14 in Fig. 12) (32°50'32.96"N, 130°55'40.65"E).

A number of residential houses along road No. 28 suffered from significant damage. As shown in Fig. 23, high collapse ratio of houses can be seen in the small village (site 15). In addition, modern bridges and a tunnel along road No. 28 suffered from serious damage. The girder of Ohkirihata Bridge moved about 1-1.5m and fell off its rubber bearings (Fig. 24, site 14). About 4 km north-east of Ohkirihata Bridge, Tawarayama tunnel suffered from a compressive axial failure and falling of lining concrete about 250 m from the tunnel portal (Fig. 25, site 16). The cause of compression of the tunnel was thought to be a surface fault movement in right lateral component, which was confirmed at the damaged location (Shirahama et al., 2016; Yoshimi, 2016). More information about the structural damages along road No. 28 due to the earthquake is reported in a separate report (Ikeda, et al., 2016).

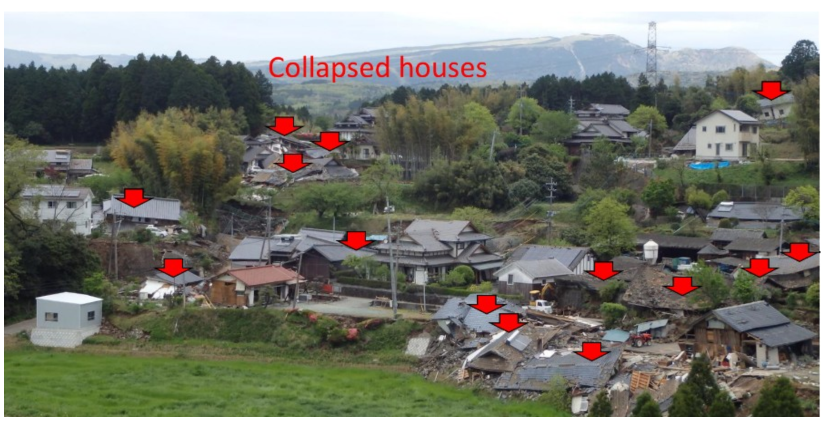


Figure 23. Damage to residential houses in Ohkirihata area (site 15 in Fig. 12) (32°50'36.91"N, 130°55'43.16"E).

Figure 24. The girder of Ohkirihata Bridge moved about 1-1.5m (Site 14 in Fig. 12) (32° 50'32.63"N, 130° 55'43.10"E).

Figure 25. Tawarayama tunnel suffered from axial compression failure (Site 16 in Fig. 12) (32° 51'35.68"N, 130° 58'6.86"E).

GEOTECHNICAL DAMAGE IN ASO CALDERA AREA

Natural slope failure and distortion of road embankment occurred at many locations in Aso Caldera area. Specifically, artificial earthfills for housing estate suffered from significant earthquake damage. In addition, a trough-like depression that extends fragmentally over several kilometers was observed in the basin of Aso Caldera. Fig. 26 is a map of Aso Caldera area showing locations of geotechnical damage that were investigated during the survey.

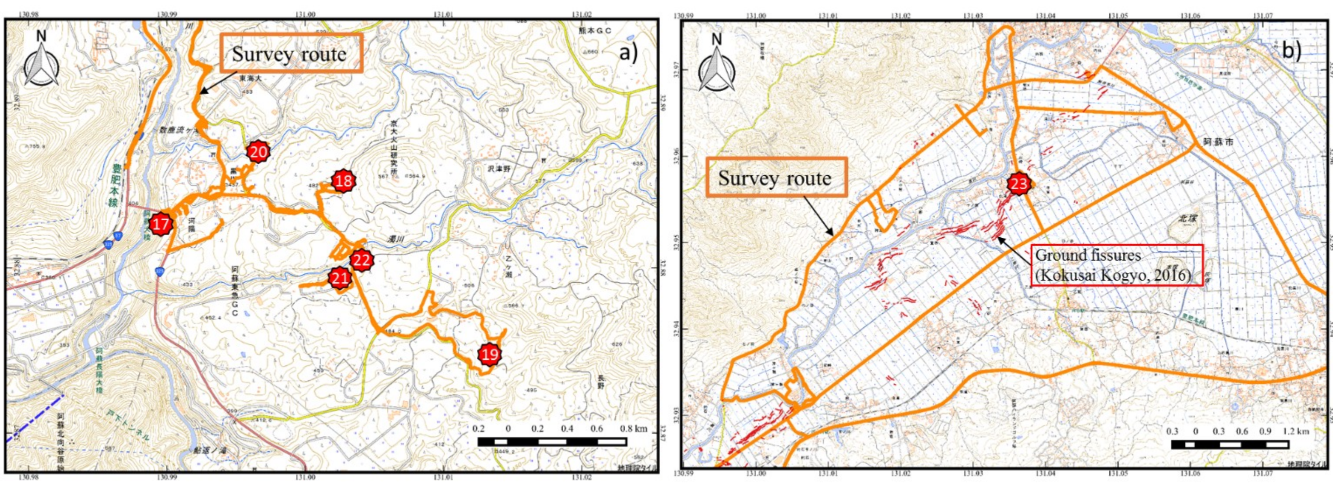


Figure 26. Survey route and locations of investigation sites in Aso Caldera area.

Landslides

A large number of natural slopes and road embankments failed in Aso Caldera area. Figure 27 shows the positional relationship between earthquake fault and landslides caused by the Kumamoto earthquake. The landslides in the figure were mapped by GSI (2016), and the data is available on their website. Aerial photos taken before and after the earthquake were used to generate this map. A spatial distribution of earthquake-induced landslides is affected by the fault mechanism (Hasi et al., 2011). The map shows that the landslides are on both sides of the seismic fault. This may be because a strike-slip component was the dominant fault movement of the earthquake.

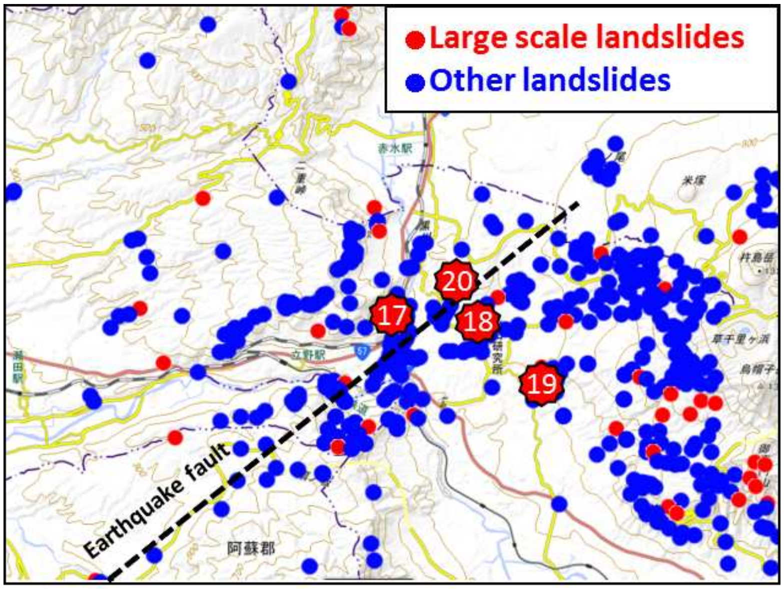


Figure 27. Positional relationship between fault and landslides in and around Aso Caldera area (Modified from landslide map of GSI, 2016).

Figure 28 shows a shallow landslide near Aso Ohashi Bridge caused by the main shock on the 16th of April (site 17). The landslide had a height of about 300 m (measured from the road level to the scrap) with an inclination angle of about 50 degrees at the top and about 25 degrees at the middle and bottom of the slope. The debris was a mixture of middle Pleistocene volcanic soils and boulders (tuff breccia); Route 57 and JR Hohi Main Line (railway) was also covered by it. The debris travelled a distance exceeding 800 m and fell into the Kurokawa-River along with Aso Ohashi Bridge. Evidence of mud debris was found on the opposite side of the river which is thought to have travelled along the bridge before its collapse. For this reason, the cause of bridge failure is considered to be the impact force and/or weight of debris that flowed down from the landslide source. Moreover, in Figure 28, taken one day after the event, water seeped out from the failed surface, which may explain the reduction of shear strength of the slope ground due to increase in excess pore water pressure during the intense earthquake.

Before the failure (Google Earth)

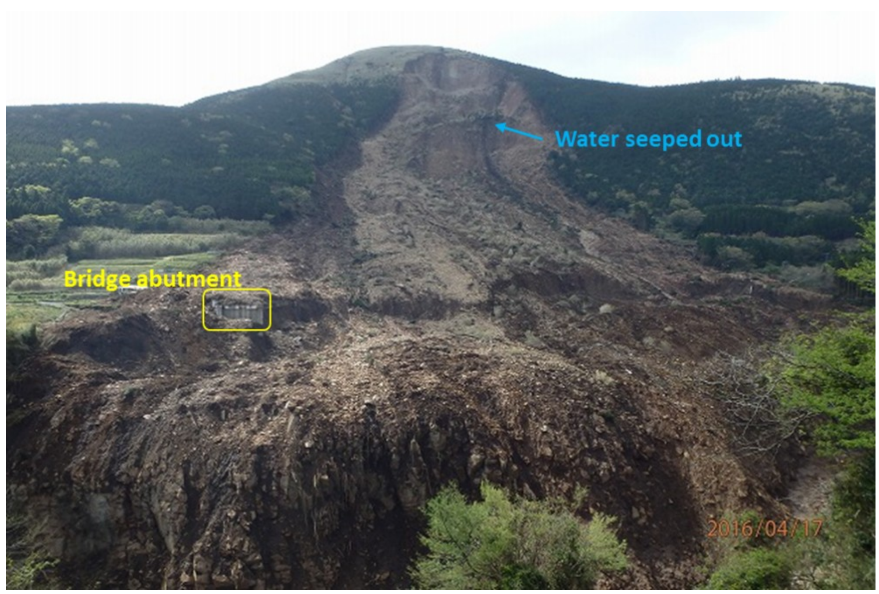


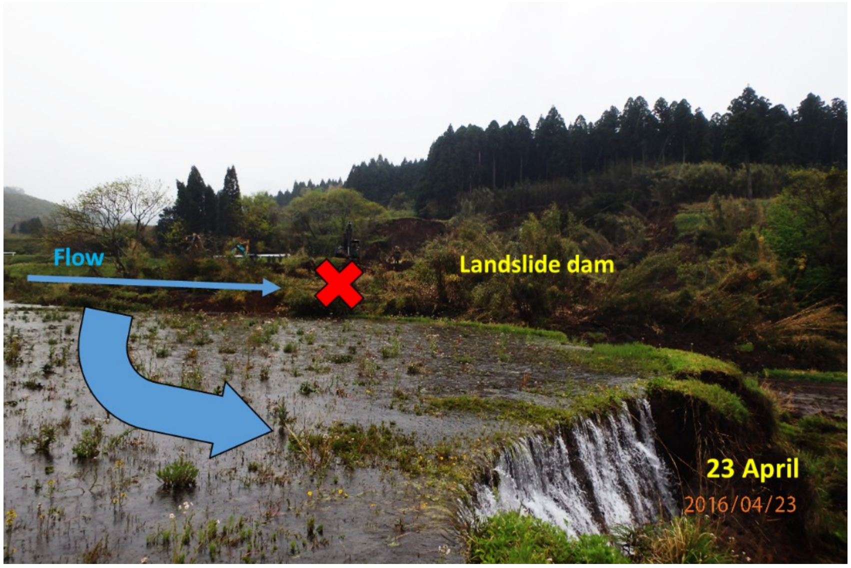
Figure 28. Landslide near Aso Ohashi Bridge (site 17 in Fig. 26). (32° 53'0.02"N, 130° 59'22.80"E).

At site 18 in Fig. 26, a large scale landslide occurred at a volcanic hill (late Pleistocene) with a height in excess of 80 m from its base. The failure occurred on a relatively gentle slope with an angle of less than 10 degrees. The sliding of the slope towards the toe, however, was remarkable as shown in Figure 29. This failure killed five people who were in the house at the middle of the slope. A few hundred meters south of the above landslide another landslide occurred and caused severe damage to the residential houses as shown in Figure 30 (site 19). The length of the landslide was 70 m with an inclination angle of about 10 degrees. As the Kumamoto earthquake is an inland earthquake which caused severe damage in the mountain area, it is often compared with the 2004 Chetsu earthquake (M_w 6.6) which hit Niigata Prefecture, Japan, and caused a number of landslides (Toyota et al., 2006). Slope failures triggered by the Chuetsu earthquake occurred at a sedimentary rock interface, and the slope angle before the failure was about 20 degrees on average (Yamasaki, 2008), which is much steeper than the cases in the Aso mountain area in the Kumamoto earthquake. The debris of the landslides in Aso Caldera area was a mixture of volcanic ash, andsol, a highly porous dark-colored material comprising of volcanic ash mixed with organic matter, and pumice. As shown in Figure 30, alternating layers were seen at the surface of the scrap. The cause of failure and long-distance flow at the gentle slope is not identified yet, however, since the natural deposited pumice is known to have high crushability, the soil may have experienced significant strength reduction associated with particle breakage during the earthquake.

A slope failure was observed at site 20 in Fig. 26; the length of the failure was about 100 m. The debris blocked the road and a tributary of the Kurokawa River completely; the blocked tributary overflowed with water spreading into the surrounding paddy field (Figure 31). To avoid the potential risk of flooding to the downstream villages following the landslide dam breaching, the relevant authority had excavated a spillway to secure the safety of the dam. The excavation was likely finished within two weeks of the event.

Figure 29. Large scale landslide in Aso Caldera area (site 18 in Fig. 26) (32° 53'5.47"N, 131° 00'10.56"E).

Figure 30. Landslide at gentle slope and its scrap (site 19 in Fig. 26) (32° 52'29.42"N, 131° 00'49.36"E).



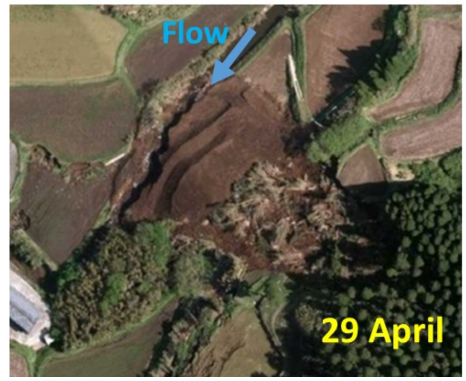


Figure 31. Landslide dam formed by the earthquake and excavation work completed (site 20 in Fig. 26) (32° 53'14.06"N, 130° 59'48.90"E).

Damage to Developed Residential Land

Figure 32 and 33 show damage of the road and house at site 21. Although this area reportedly survived the earthquake on the 14th of April, significant distortion of subsurface ground occurred during the main shock on the 16th of April. The spatial distribution of damage was severe at the northern part of the residential area. Figure 34 shows a comparison of aerial photos taken in 1975 and in 2016 (GSI, 2016), indicating that the damaged area use to be a paddy field but had subsequently been infilled during the construction of the housing estate. The filled soil in the damaged area is a local volcanic ash soil. Tanoue et al. (2005) reported that it is usually hard to construct a stable embankment from the ash deposited in the Central Kyushu area. It seems from Fig. 34 that the ground level of the northern part of the residential area was comparatively low in 1975, the filled soil might have been thicker for the northern side than the southern side. This might be why the earthquake-induced damage to the land was found to be severe in the northern side, however, structural damage to the residential houses in this area was negligible despite large ground deformation.

Figure 32. Damage to the road in residential area developed by filling (Site 21 in Fig. 26) (32° 52'43.89"N, 130° 59'58.89"E).

Figure 33. Damage to the house in residential area developed by filling (Site 21 in Fig. 26) (32° 52'45.06"N, 131° 00'1.44"E).

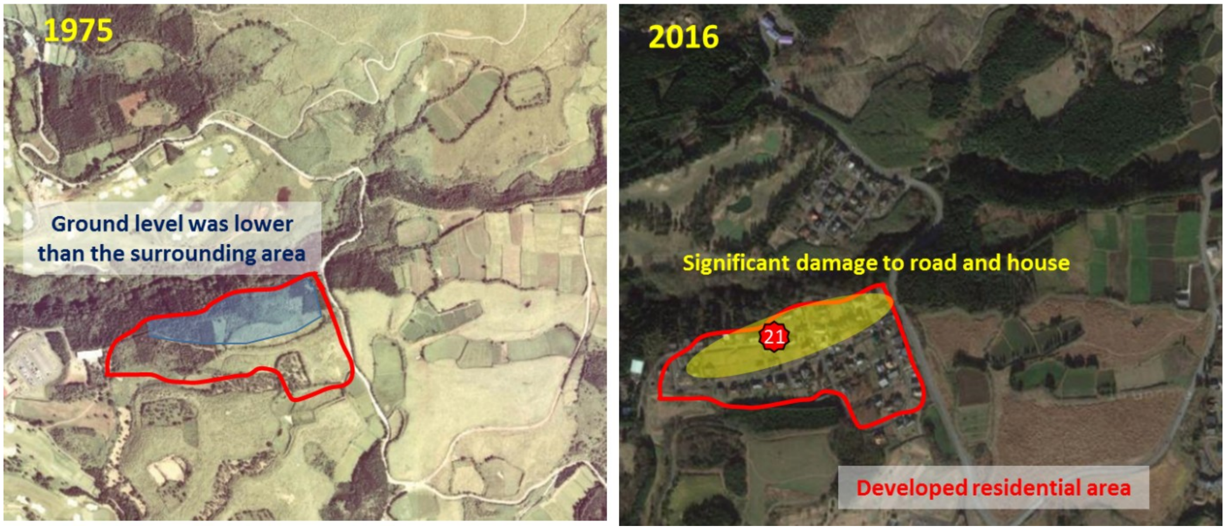


Figure 34. Aerial photo of damaged residential area in 1975 and after the 2016 Kumamoto earthquake (Modified from aerial photo of GSI, 2016).

Other Geotechnical Damage in Aso Caldera Area

A 50 m-long embankment on prefectural road No. 149 (site 22 in Fig. 26) suffered from damage in the form of slope failure. Ground fissures and road pavement damage were also found there. This embankment (about 10-15 m high) was constructed along the small river by using a reinforced soil retaining wall technique (Terre-Armee), the wall was also damaged significantly as shown in Figure 35. Steel strip materials pulled out from the backfill soil were found on the failed slope surface. The reason for the failure of the reinforced soil retaining wall is not yet identified.

A trough-like depression was found at several locations in the basin of Aso Caldera. According to both the authors' site investigation and aerial photointerpretation of cracks on ground surface provided by the GSI (2016) and Kokusai Kogyo co. ltd (2016), the trough-like depression, with a maximum depth of about 1-1.5 m, was found to stretch several kilometers in length, the width of the depression was several tens of meters. At site 23, the ground depression caused damage to a residential house (Fig. 36). The damage due to the depression has also been harmful to agriculture in this area (Figure 37). The mechanism of the depression, however, is not yet identified. The residents in the affected area reported that the depression occurred immediately when the main shock occurred on the 16th of April. The fact indicates that the cause of the depression was probably not liquefaction. Refer to a separate report by Konagai et al. (2016) for further information about this feature.

Figure 35. Damage to road embankment and reinforced retaining wall (Terre-Armee) (site 22 in Fig. 26) (32° 52'52.01"N, 131° 00'14.84"E).

Figure 36. Ground depression-induced damage to the residential house (Site 23 in Fig. 26) (32° 57'23.84"N, 131° 2'12.31"E).

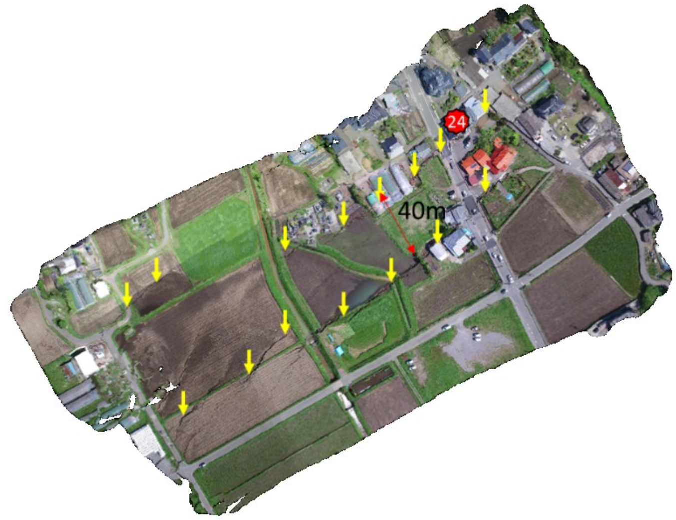


Figure 37. Digital image obtained by UAV around the trough-like depression area (c.f. Fig. 26).

CONCLUSION

The Kumamoto earthquake sequence, M_w 6.2 shock on the 14th of April and M_w 7.0 main shock on the 16th of April 2016, caused significant geotechnical and structural damage to various facilities in Kumamoto City and its suburbs in the Central Kyushu Region, Japan. Meanwhile, restoration works have been progressing more quickly than expected. Authors conducted preliminary damage survey immediately after the main shock (the 16-17th of April), one, and two weeks later (the 22nd-24th of April and the 29th of April to 1st of May). The results from the damage survey are summarized as follows:

Evidence of liquefaction was found over a wide range in the southern Kumamoto City. Liquefaction caused large settlement and a number of cracks at the levee along Akitsukawa River. In addition, some residential houses and buildings suffered from large settlement and/or tilting. According to the landform classification map, the locations of liquefaction-induced damage are indicated as alluvial plain or fill, which may be linked to the loose soil condition. Significant damage to Kyushu Highway, which might be caused by liquefaction, was observed at the site where an old river channel was filled before the construction of the highway.

A variety of geotechnical and structural damage was observed in Mashiki Town and its suburbs. High collapse ratio of residential houses was observed in Mashiki Town. The main cause of the damage to houses was likely due to earthquake motion, whereas some houses were found to be damaged by the ground displacement. A section of Route 443 suffered from significant damage in the form of ground failure and subsidence, however, the restoration work for such damage was completed within a few days of the main shock. In addition, damage to retaining walls and road embankments were found at many locations in and around Mashiki Town. Further damage to infrastructure including significant damage to large bridges and a tunnel could be found along the prefecture road No. 28.

A number of moderate to large scale landslides occurred in Aso Caldera area. A huge quantity of debris from a landslide at the west end of the caldera travelled a long distance and fell into Kurokawa River together with the Aso Ohashi Bridge. In addition, many landslides occurred at relatively gentle slope during this earthquake. The debris of the landslides in Aso Caldera area was a mixture of volcanic ash, andsol, a highly porous dark-colored material comprising of volcanic ash mixed with organic matter, and pumice, which might have experienced significant strength reduction during the earthquake. Hidden cracks in the slopes effected by earthquake will potentially increase the risk of further slope failure during the upcoming rainy and typhoon season from June to October. Meanwhile, damage to the residential land and a reinforced soil retaining wall was also observed in Aso Caldera area. A trough-like depression found in the basin of Aso Caldera caused damage to residential houses and agriculture, however, the mechanism of the depression is not yet identified.

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