GROUND DEFORMATION BUILT UP ALONG SEISMIC FAULT ACTIVATED IN THE 2016 KUMAMOTO EARTHQUAKE

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The Kumamoto Earthquake has caused extensive damage to a variety of fascilities alog ground ruptures that appeared along the known trace of Futagawa fault. Moreover close to 500 millimeters of rain fell on some parts along the quake-hit areas on June 20 and 21, causing further extensive damage, highlighting the difficulty to cope with earth-quake-flood multi hazards. This paper describes some unique features of ground deformations that appeared along the fault, and the effect of the heavy rain on some of these deformed grounds.

Key Words : *Kumamoto earthquake of 2016, ground deformation, torrential rain*

1. INTRODUCTION

Starting with a magnitude-6.5 foreshock on April 14, 2016, a series of major earthquakes including the magnitude-7.3 main shock on April 16 have hit the central Kumamoto area of Kyushu, Japan, causing deaths, injuries and widespread damage to various facilities. The activity of the fault, whose right-lateral offset appeared in the main shock along the previously known section of the Futagawa fault zone, caused extensive damage to roads, bridges, a tunnel and a dam. The observed features of the damage again showed that not only intense shakes but also ground deformations such as landslides, lateral spread of embankments and levees, soil liquefactions etc., which are found within a swath along the fault trace, can be equally or often more responsible for devastations. Moreover close to 500 millimeters of rain fell on some parts along the quake-hit areas on June 20 and 21, causing further extensive landslides and flooding, highlighting the difficulty to cope with earthquake-flood multi hazards. This paper describes some unique features of ground deformations that appeared along the fault.

2. BURIED TRACES OF GROUND DEFORMATION

LiDAR, Laser based altimetry, can penetrate through tree canopy, revealing detailed feature of bare earth left behind by past natural hazards, and the LiDAR image of the mountain slope along the outer rim of the Aso crater shows evidence of past landslides as well as the most recent one that has hit an important location for traffic, transmission lines and a waterway leading to a penstock (Fig. 1)[1)]. Moreover cracks are seen along the exposed scar indicating future risk. Ministry of Land, Infrastructure, Transport and Tourism, MLIT, thus, has a plan to remove a greater part of the unstable soil mass remaining behind the exposed scar[2)]. However this will be a long-lasting project, and MLIT is currently taking a 2 billion JPY urgent countermeasure stabilizing the uppermost slope face of 30,000 m^2 and constructing 7 m high and 300 m long retaining wall near the toe of the slope using un-manned construction machinery to protect reconstruction works for national route 57 and Hohi railway line[2)].

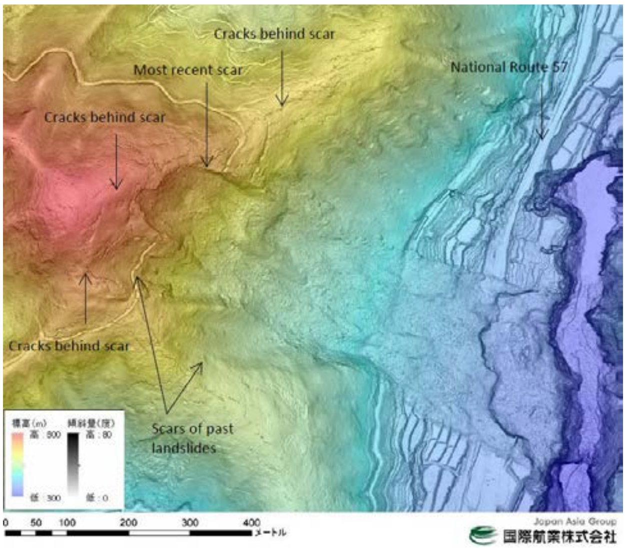

Fig. 1 Scars of past and most recent landslides and cracks appearing behind the scars indicating future risk (LiDAR image from Kokusai Kogyo Co. Ltd)[1)]

3. SWATH OF GROUND DEPRESSION IN ASO CALDERA BASIN

Soils are hystrisis materials exactly like a magnetic tape recording the past. As long as clear evidence for past large soil deformation was there in LiDAR images, landslides/active fault maps etc., we could bring potential hazard to light and take necessary actions (Fig. 1)[1)]. However these pieces of evidence can be often buried beneath surface soil deposits. One of the seldom-seen-before phenomena in the main shock was an about 10 km-long swath of ground depression that appeared in the northwestern part of the basin of Aso caldera.

Fig. 2 shows cracks that appeared on the ground surface. Aerial photo-interpretations of southwestern and northeastern segments of cracks were made by the Geospatial Information Authority of Japan[3)] and Kokusai Kogyo Co. Ltd.[1)], respectively. They include every visible cluster of cracks no matter what their causes are. Majority of cracks of the southwestern

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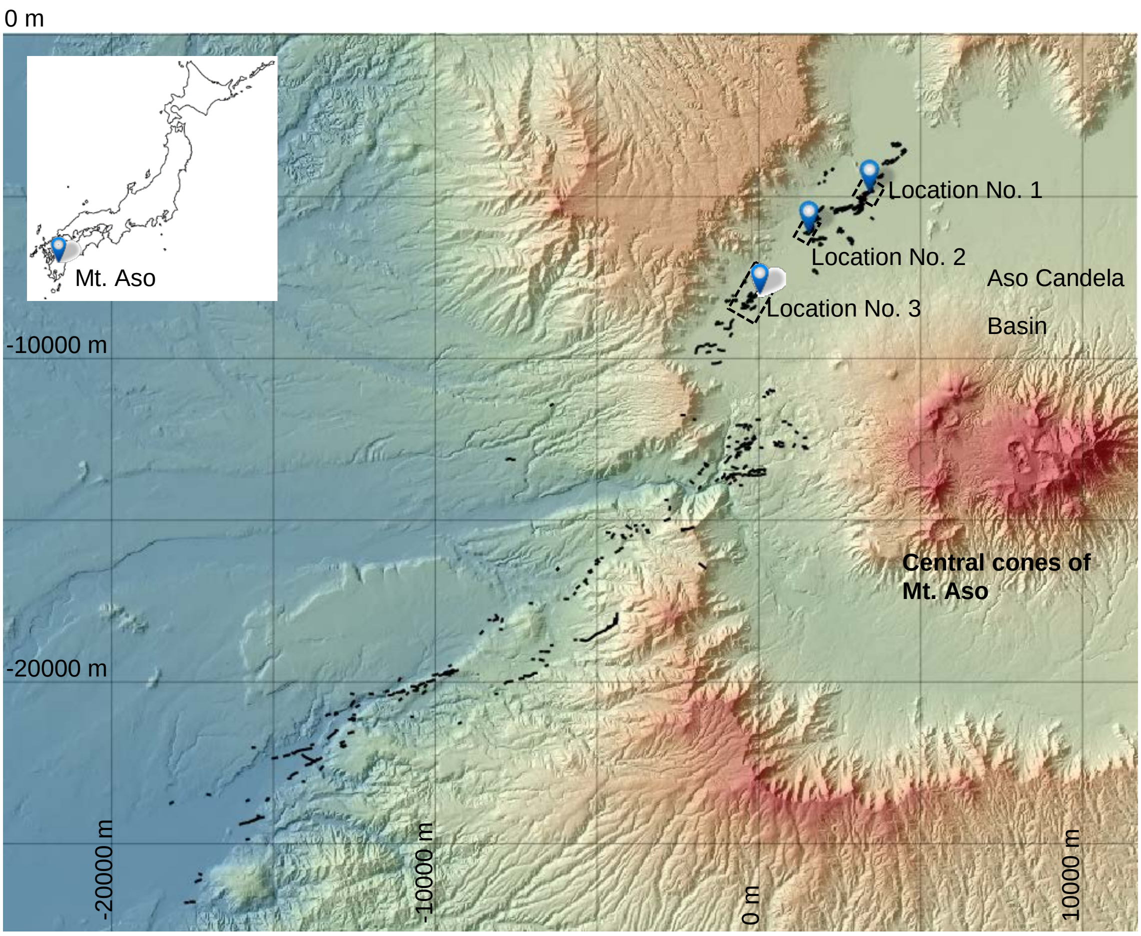

Fig. 2 Aerial photointerpretation of cracks that appeared on the ground surface[4)]: Interpretations of southwestern and northeastern segments of cracks were made by the Geospatial Information Authority of Japan[3)] and Kokusai Kogyo Co. Ltd.[1)], respectively. Authors' survey was conducted within areas enclosed in boxes of dashed line . UAV was flown over Locations 1, 2 and 3 (Coordinate reference system: JGD2000 / Japan Plane Rectangular CS II)

Fig. 3 A pair of UAV photographs of ground depression with the center of each photograph located at around N32.9662º, E131.0364, Location No. 1 in Fig. 2 (Flight altitude: 75m) [4)]

segment appeared along the Hinagu and Futagawa fault system, whose presence had been recognized, while northeastern segment of cracks exhibits a complex, interwoven pattern of fractures diagonally across the basin sediment of Aso Caldera. The latter is the abovementioned swath of ground depression that extends fragmentally over about a 10 km distance.

Flying over at a particular point at around N32.9662º, E131.0364 for example, one notices that the swath of ground depression is about 40 to 50m wide and 1 to 1.5 m deep. A pair of UAV photographs of this location shown in Fig. 3 can be perceived as a single image in terms of depths. As can be perceived, southeastern ends of plastic greenhouses dropped down onto the depressed ground. Water is stopped along the southern vertical offset of the ground. No clear indication of either right-lateral of left-lateral offset can be seen.

Being located several 10m NNE off the UAV picture frame (Fig. 3), there is a house standing by the edge of northwestern offset of the ground at N32.9568º, E131.0368 (Fig. 4). The exposed soil wall shows a stratified structure of brownish volcanic ash, pumice and andosol, which is highly porous and dark-colored developed from volcanic ash mixed up with organic matters. The crack here was more than 1 m deep with no clear indication of sand ejecta. A lady, the owner of the house standing by the car on

Fig. 4 House hanging a little over the northwestern offset of the ground at N32.9568º, E131.0368 (near Location No. 2) [4)]

the right, witnessed that "her neighbor's house behind her dropped all at once, keeping its shape as it was, immediately when the intense shake of the main event of April 16th hit it. The drop of the ground was anything but slow".

A UAV-based 3D digital surface model (DSM) was prepared as shown in Fig. 4. To fully define the coordinate system for the extracted DSM, four points were chosen off the swath of ground depression. Exact absolute positioning of these points with an advanced system such as dual-frequency GPS is mandatory, but for a quick and preliminary

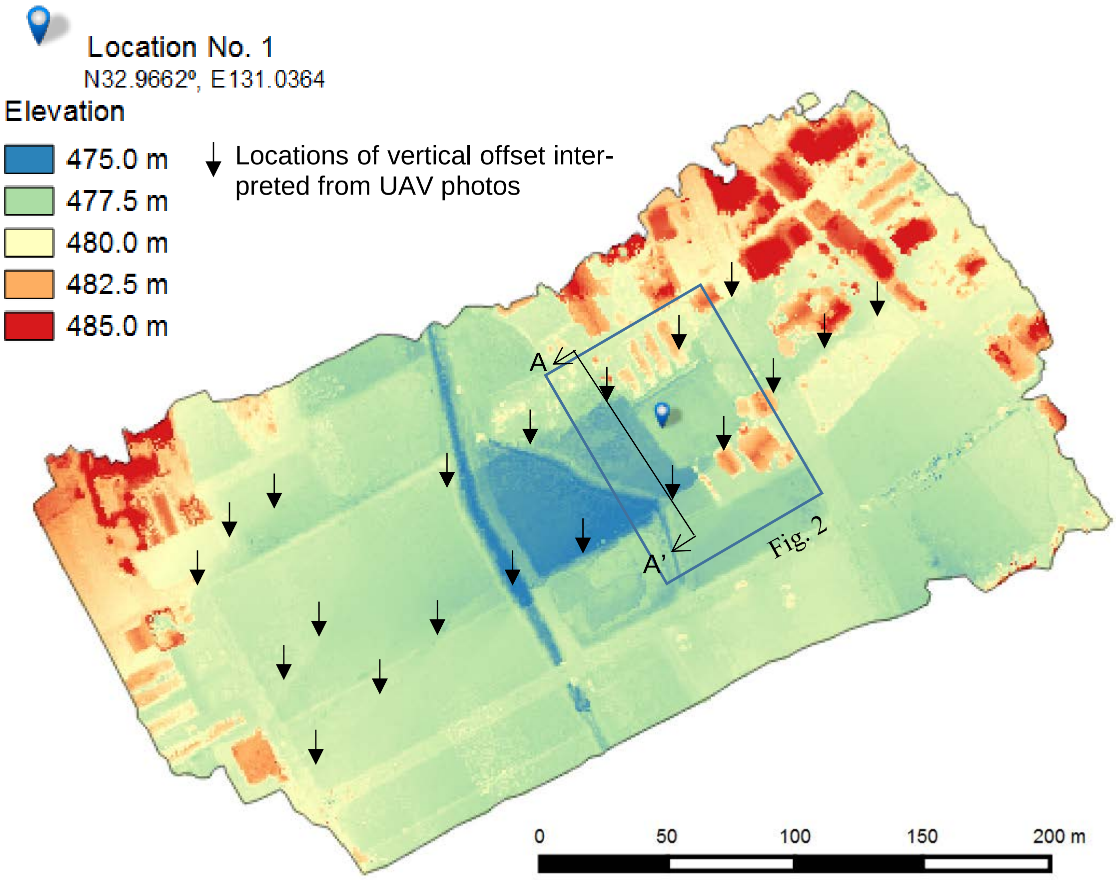

Fig. 5 Digital surface model of one part of swath of ground depression (Location 1, at N32.9662º, E131.0364º) [4)]

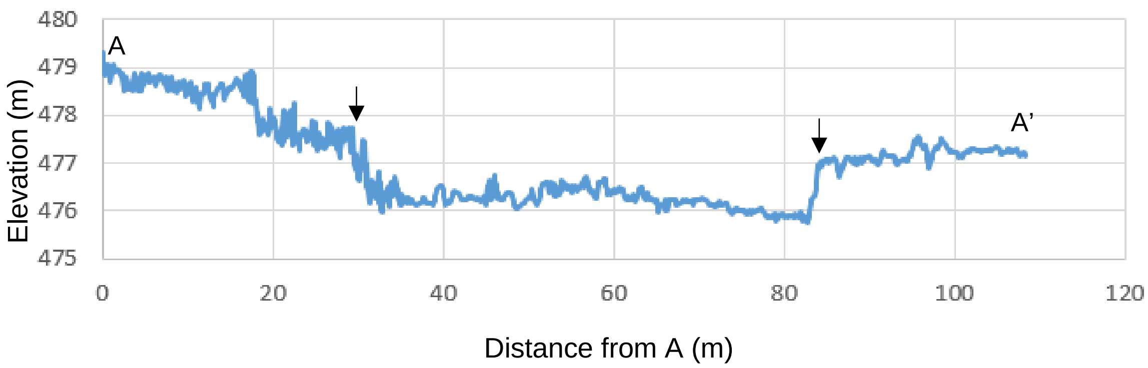

Fig. 6 Cross-section A-A' in Fig. 4[4)]

discussion, the coordinate values for these points were taken from "CyberJapan"[5)], a digital Japan tile map layer provided by Geospatial Information Authority of Japan. The obtained DEM can be thus subject to change in later publications.

Though the cloud of points extracted from DSM shows not only the bare ground surface but also vegetation and artificial objects, the swath of ground can be clearly seen particularly in the middle of the covered area where the swath is narrowest and deepest enough to stop water. A cross-section was taken along Line AA' in Fig. 5 (Fig. 6). A pair of two clear ground offsets shows that the swath has fallen by about 1m here. The swath of ground depression becomes gradually shallower and wider towards west end of the UAV-covered area.

One more location of UAV flight No. 3 (on July 2, 2016) is shown in Fig. 2, and an extracted 3D image is shown in Fig. 7. There is a clear swath of ground depression, No. 1, which extents along an electric power transmission line. One of its tower tilted with its southeastern foundations embedded in the depressed ground. One more swath of wet soil (No. 2 in Fig. 7) is seen on this image, which was considered to have emerged after the torrential rain of June 20 and 21.

The cause of the ground depression is not clear yet. No clear indication of sand ejecta was found, which

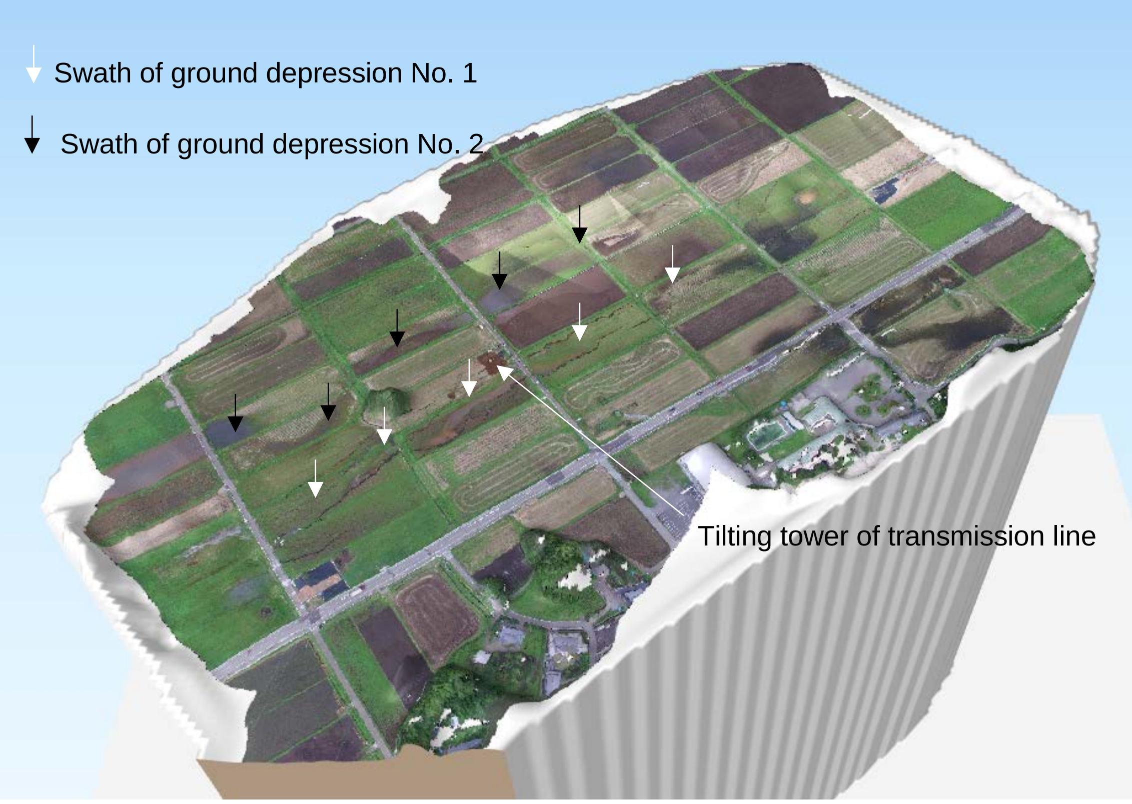

Fig. 7 3D terrain image extracted from UAV photos (Location 3 in Fig. 2)

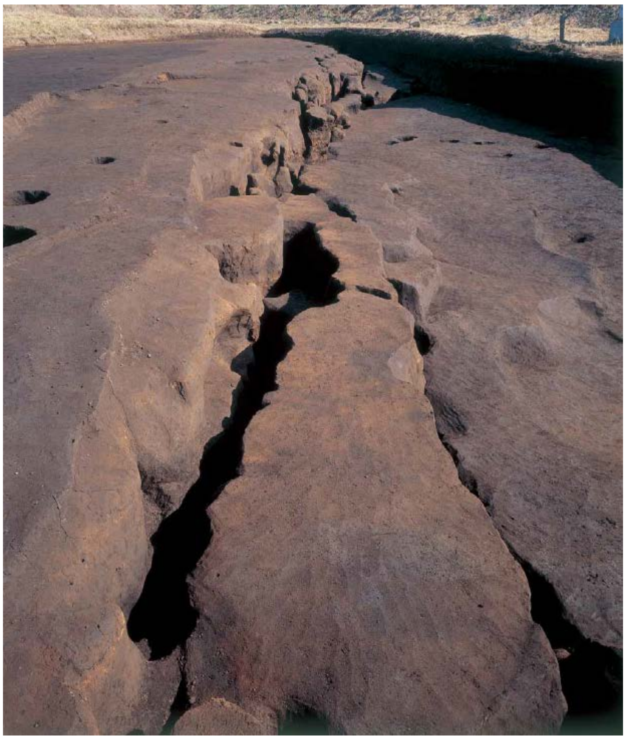

Fig. 8 Fault trace excavated at Onobaru Ruin near Location No. 2 in Fig. 2 (Kumamoto Prefecture)[6)]

ejecta may have canceled the soil volume that have subsided. This depression may be due to a reflection of deep-seated tectonic movements which exhibits some tensile components in the transverse direction of the swath of ground depression. By way of trial, the cracks were laid over the along-track displacements pattern analyzed by the Geospatial Information Authority of Japan using MAI (Multiple Aperture Interferometry) method[4)]. The cracks seemingly appear where large tensile strain built up.

There was no clear early indication of presence of the hidden swath of ground depression. However the educational board of Kumamoto Prefecture reported in 2015 that a normal fault trace was found in Onobaru Ruin of Yayoi Period (c. 300 bce–c. 250 ce) of Japanese Iron Age at N32.95056º, E131.0261º (Fig. 8)[6)].

Whatever the cause was, the swath of ground depression as well as other quake and rain-induced landform changes is to be recorded in a quantitative manner, because large ground deformations can be repeated in any extreme natural events as can be seen in the past major earthquakes.

4. TILTING HOUSING OF PUMPS FOR CLEAN WATER WELL

Except for ground ruptures that appeared along the known trace of Futagawa fault, no clear sign of large ground deformations was seen on the flood plain of Akitsu and Kiyama rivers. However some RC housings for pumping facilities were found tilting near Akita clean water distribution field (Fig. 9). Kumamoto city depend 100% on groundwater from

Fig. 9 RC housing of pump for clean water well near Akita clean water distribution field (Location: N 32.767028º, E 130.778574º)

Fig. 10 Inundated flood plain near Akita clean water distribution field (Photo: Asahi Shinbun Digital, http://www.asahi.com/articles/ASJ6P4VM7J6PTIPE01Y .html)[8)]

nearly 200 wells, and the main shock was the most damaging, resulting in nearly 460,000 customers outages[7)]. One of the primary reasons for the outages was rather artificial due to regulatory requirements for clean water quality. Kumamoto city has set a standard on the allowable turbidity in drinking water. When the turbidity of 5 is reached in any well, its pump stops automatically[7)]. If pumps in the tilting housings have stopped due to the increase of turbidity, it may suggest that the soil grain crushing may have occurred in their common aquifer beneath the flood plain due to large strain build-up. These tilting RC well-pump housings, which are supported by about 22 m long piles reaching isolated lenses sandwiched in the soft deposit, can be a sign of residual deformation of the soil deposit.

The area spreading east of Akita clean water distribution field was flooded in the torrential rain of June 20 and 21 as shown in Fig. 10. It was reportedly due to a burst in the left bank of Kiyama river. However it will be necessary to study the inundated area during the flooding in the light of ground deformation buildup.

5. SUMMARY

One of the most spectacular aspects of the 2016 Kumamoto earthquake was that large ground displacements buidups were seen along the activated Futagawa fault system. These deformations included an about 10 km-long continual swath of ground depression that appeared together with complex, interwoven pattern of fractures across the northwestern basin of Aso caldera. Even the deformations were not clearly visible, tilting of RC housings of pumps for clean water wells may have been a reflection of ground deformation buildups. In the torrential rain of June 20 and 21, water may have stopped in some of low lying little depressed lands. Even after the wound from a big earthquake heals, ground depressions remain as they are causing long lasting problems. For better post-quake rehabilitations, landform changes are to be recorded in a quantitative manner.

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