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RECONNAISSANCE REPORT ON GEOTECHNICAL AND GEOLOGICAL ASPECTS OF THE 14-16 APRIL 2016 KUMAMOTO EARTHQUAKES, JAPAN

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ABSTRACT

On 16 April 2016, a moment magnitude (M_w) 7.0 earthquake struck the Island of Kyushu, Japan. Two major foreshocks (M_w 6.2 and M_w 6.0) contributed to devastation in Kumamoto City, Mashiki Town and in the mountainous areas of the Mount Aso volcanic caldera. This report summarises geotechnical and geological aspects of the earthquakes that were observed during a field investigation conducted by the NZSEE Team in collaboration with Japanese engineers and researchers. Many houses and other buildings, roads, riverbanks, and an earth dam, either on or adjacent to the surface fault rupture or projected fault trace, were severely damaged as a result of both the strong ground shaking and permanent ground displacement. In the Mount Aso volcanic caldera, traces of medium to large scale landslides and rock falls were frequently observed. A number of landslides impacted homes and infrastructure, and were reported to have killed at least 10 people out of the 69 confirmed deaths associated with the earthquake. In a few suburbs of Kumamoto City and in Mashiki Town, localised liquefaction took place, causing lateral spreading, differential settlements of the ground and riverbanks, sinking and tilting of buildings, foundation failures, cracks on roads, and disruption of water and sewage pipe networks. The overall effects from liquefaction related hazards appeared relatively minor compared to the damage caused by shaking, landslides and surface fault rupture. Based on the field survey, key findings are highlighted and recommendations to NZ engineering practice are made in the report.

INTRODUCTION

The Kyushu Region of Southern Japan was affected by a series of moment magnitude (M_w) 6 to 7 earthquakes during 14^{th}-16^{th} April 2016, followed by hundreds of aftershocks. These earthquakes, referred herein as the Kumamoto Earthquake Sequence, caused significant damage over a wide area, including Kumamoto City, Mashiki Town and the Mount Aso volcanic caldera, see Figure 1.

The New Zealand Society for Earthquake Engineering (NZSEE) has a strategy to use targeted missions to learn from relevant earthquakes that happen around the world, and bring back learnings that can be applied to enhance earthquake engineering practice in New Zealand. The aim is to increase New Zealand's resilience to earthquake hazards.

NZSEE decided that there were valuable lessons to be learnt from the Kumamoto Earthquake Sequence, particularly in relation to ground damage from the earthquakes, and selected a four-member team of experienced geotechnical professionals with expertise in geotechnical engineering, engineering geology and associated research. The team comprised Dr Gabriele Chiaro (Team Leader), Gavin Alexander, Pathmanathan Brabhaharan and Dr Christopher Massey, who were on the ground between 7 and 14 May 2016.

The NZSEE team members joined Japanese investigation teams comprising geotechnical engineers from the University of Tokyo and Osaka City University. This provided an invaluable learning experience, as it allowed rapid access to the sites of interest, enabled key geotechnical/geological information to be gathered (otherwise available only in Japanese), provided an opportunity for valuable technical discussions and permitted collection of soil samples for further geotechnical analyses.

The survey trip was planned in a way that most of the relatively large geographical area that was severely affected by the earthquakes was able to be covered on the ground. This allowed the NZSEE team to observe and record the type and spatial distribution of the main hazards triggered by the earthquakes. Figure 2 shows the daily investigation routes taken and the main places of interest that were visited during the reconnaissance survey. The observations were made only three to four weeks after the main earthquakes, when the government and local authorities were still in the emergency response phase, but after the critical and traumatic phase where the injured and dead had been evacuated. Thus numerous earthquake impacts were observed first-hand by the team, before major repair work that would obliterate the evidence of damage from the earthquake. During the visit, it was not possible to arrange meetings with the relevant Japanese government officials. The team therefore is not aware of the specific details relating to the response of the government and local authorities to the disaster.

This report provides a reconnaissance-level description of the types and extent of landslides and other ground damage

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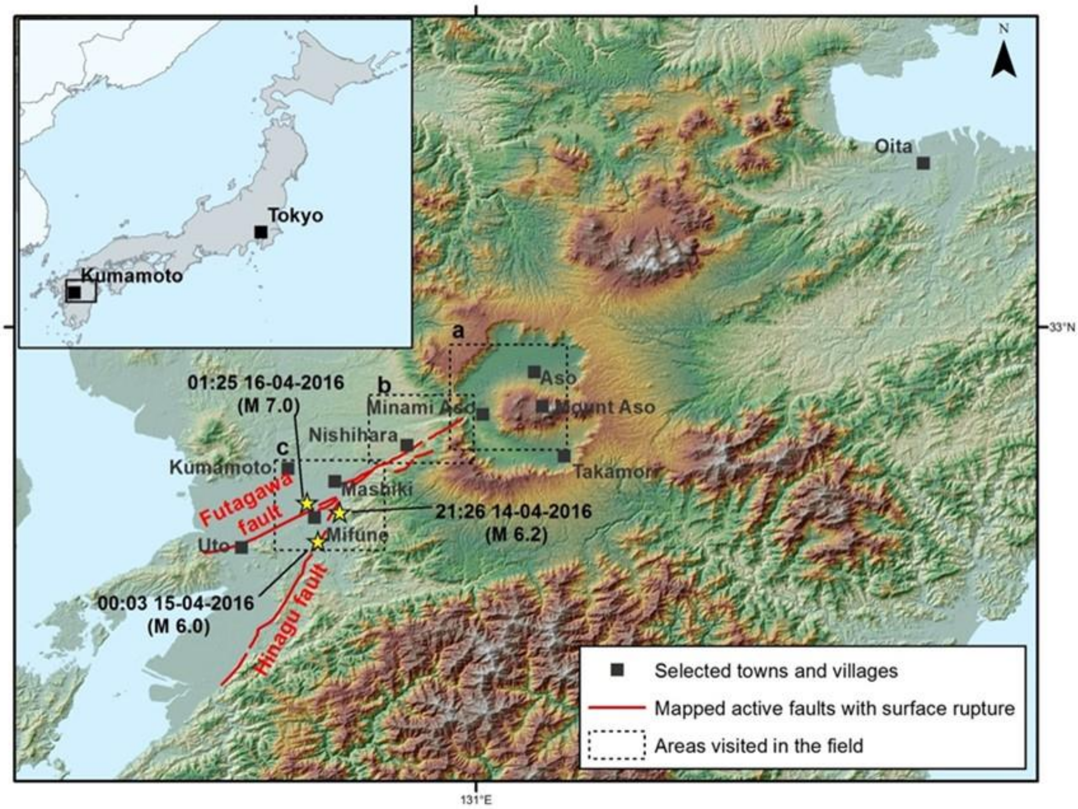

Figure 1: Location of the three main earthquakes along with the main areas visited on the ground by the NZSEE team. The background shade model is based on the ASTER 30 m DEM. The location of the two active faults (taken from the geology map of Japan, Figure 6) with associated surface rupture during this earthquake sequence are also shown.

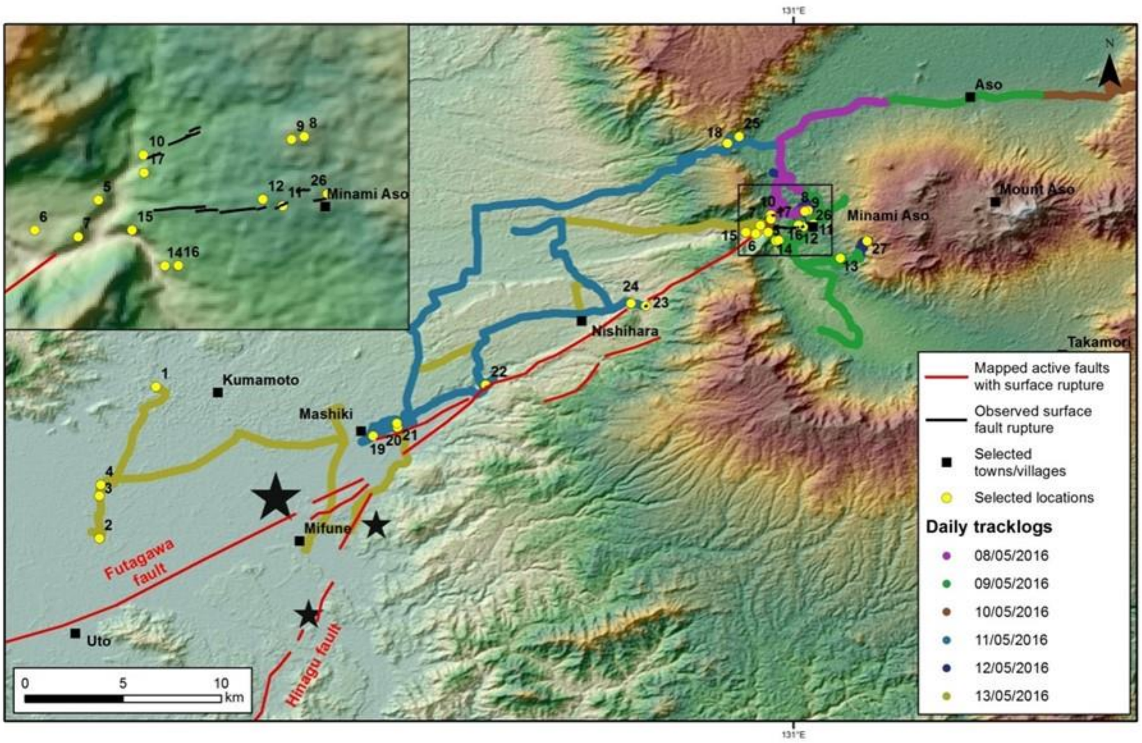

Figure 2: Selected locations and areas visited by the NZSEE team (track logs) on the ground. The inset map is a smaller-scale view of the Minami Aso area, where much of the landslide and surface fault rupture hazards associated with this earthquake sequence were observed.

triggered by the Kumamoto earthquakes of 14 to 16 April 2016, and the consequent damage to infrastructure and the built environment. Observations of the performance of the buildings and infrastructure in response to the strong ground shaking and associated ground damage also provided a unique opportunity to see how certain construction methods and materials performed. This report builds on the two previous "In-Country Reports" prepared by the team [1, 2] by describing in more detail the observations of earthquake ground damage made by the NZSEE team and discussing the relevance and implications of these observations to New Zealand. The report also provides some discussion about the significance of the observations in the context of the potential for earthquake-induced ground damage and consequent damage to the built environment in New Zealand. Such observations can therefore help identify where similar hazards and impacts could occur in New Zealand, as well as provide insights on how to mitigate against such hazards.

It should be noted that the observations and views expressed in this report are those of the NZSEE team. The team was helped greatly by Japanese colleagues to understand the background and context of the observed hazards and their impacts. However, the team's findings are based primarily on field observations, supplemented by other information taken from published data and reports, news articles (available at the time of writing) and from discussions with Japanese colleagues.

THE 2016 KUMAMOTO EARTHQUAKE SEQUENCE

The Earthquake Events

The primary earthquakes associated with the 2016 Kumamoto Earthquake Sequence in Kumamoto Prefecture, Kyushu, Japan, comprised (based on US Geological Survey data [3]):

- M_w 6.2 (M_{JMA} 6.5) fore-shock at about 11.4 km depth, at 21:26 (JST) on 14 April 2016, located on northern part of the Hinagu Fault zone;
- M_w 6.0 (M_{JMA} 6.4) fore-shock at about 6.7 km depth, at 00:03 (JST) on 15 April 2016, located on northern part of the strike-slip (right lateral) Hinagu Fault zone;
- M_w 7.0 (M_{JMA} 7.3) earthquake (the largest earthquake) at about 12.4 km depth, at 01:25 (JST) on 16 April 2016, located on the Futagawa Fault zone.

The local magnitudes M_{JMA} are based on the Japanese Metrological Agency observations [4]. The locations of these earthquakes and the aftershocks that followed (up to 24 May 2016) are shown on Figure 3.

There were a number of aftershocks after the main earthquake on 16 April 2016, and some of these have been large ($M_w > 5$). The magnitudes of the earthquakes that occurred during the field visit were smaller than M_w 5.

The focal mechanism associated with lateral strike-slip faulting and the relatively shallow depth of the hypocentres (7-12 km) played an important role on the severity and spatial distribution of damage in the affected areas.

Location of major historical earthquakes that occurred in Kumamoto Prefecture are also shown in Figure 3, for completeness. The 2016 Kumamoto Earthquake Sequence is the first series of damaging earthquakes to hit Kumamoto since 1889 when the M_w 6.3 Kinpozan Earthquake destroyed hundreds of houses and parts of Kumamoto Castle, and killed 20 people [5].

Strong Motion Earthquake Data

Data from the M_w 7.0 earthquake collected by the JMA from their K-NET and KiK-NET strong motion network shows that the maximum horizontal peak ground acceleration (single component) of 1.18 g was recorded at station KMMH016 near Mashiki (Figure 4), approximately 7 km NE of the epicentre. The maximum vertical peak ground acceleration of 0.89 g was also recorded at station KMMH016. The subsurface shear-wave velocity profile for this station [6] indicates that the topmost 15 m has a shear wave velocity less than 240 m/s suggesting the site would be the equivalent of a subsoil Class C site under Standards New Zealand NZS 1170.5 [7].

Strong shaking was also recorded at stations between Mashiki and Mount Aso (Figure 4 and Table 1). The isoseismals of Modified Mercalli shaking Intensity (MMI) shown in Figure 4 are based on the strong motion data from the K-NET and KiK-NET stations and have been plotted by USGS Shake Map [3, 6]. These show two main areas where shaking was greater than MMI 9 (IX). The larger of the two areas extends northeast from the M_w 7.0 earthquake epicentre, along the Futagawa Fault

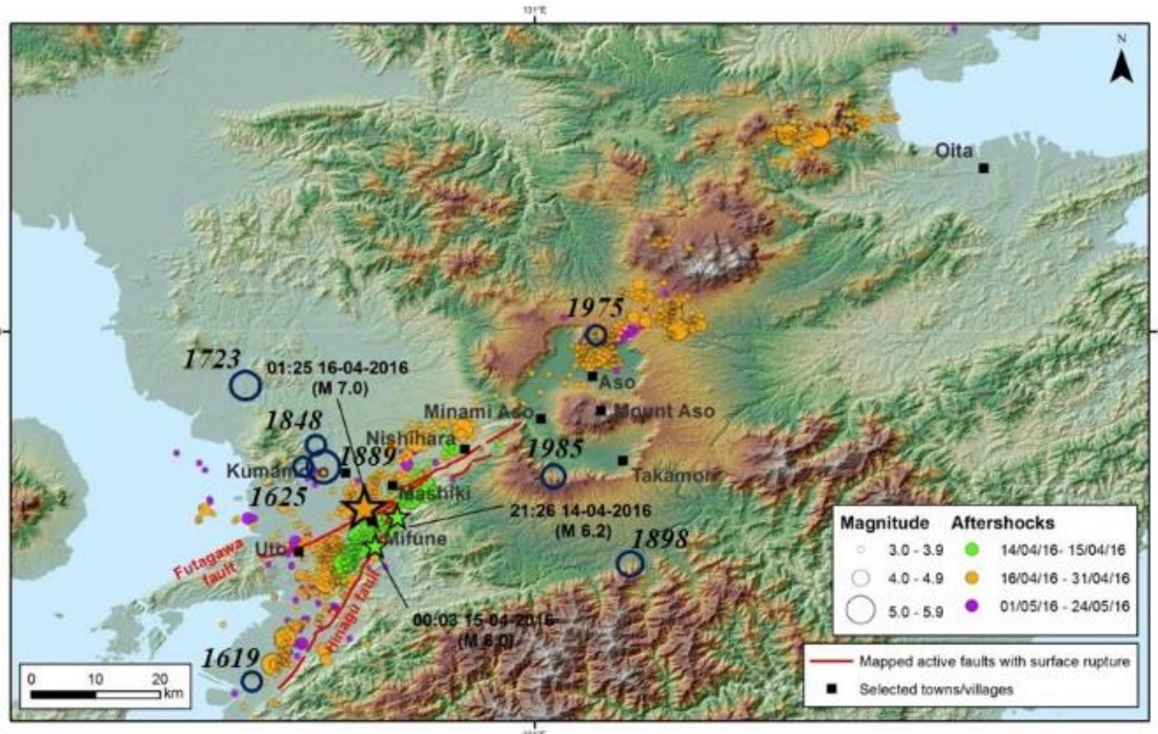

Figure 3: Location of the earthquakes, and their magnitude (M_w) taken from data published by the JMA [4]. Major historical earthquakes occurred in Kumamoto Prefecture (from Usami [8]) are also reported for completeness.

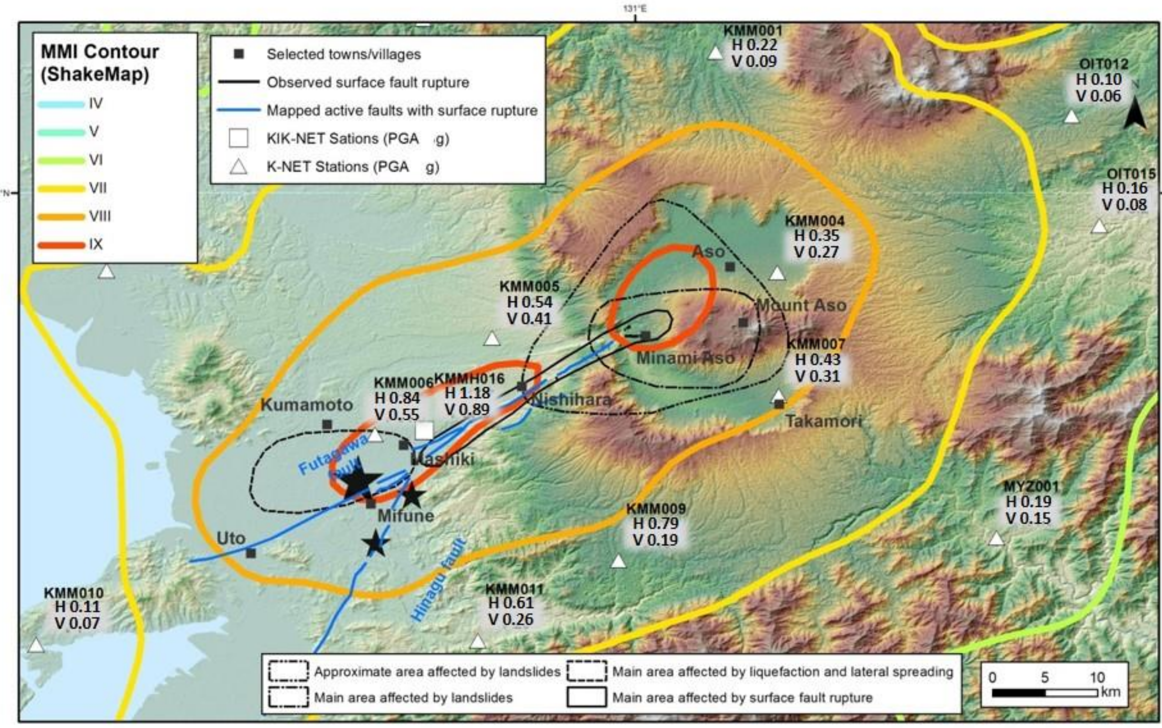

Figure 4: Main areas affected by landslides, liquefaction and lateral spreading, and surface fault rupture. The isoseismals (Modified Mercalli Intensity, MMI) are taken from the USGS Shake Map [3]. Strong motion stations locations are taken from KiK-NET and K-NET [6]. The peak horizontal (H; single component) and vertical (V) ground accelerations (units are in g) shown are for the main M_w 7.0 earthquake on the 16 April 2016. The values are taken from the KiK-NET and K-NET strong motion network data.

towards Nishihara, and the smaller area extends northeast from the northeast tip of the Futagawa Fault. The areas of strong shaking may suggest fault directivity effects, and the strong shaking around the inner base of the Mt. Aso caldera may suggest basin effects.

Most of the observed severe earthquake damage was confined within the MMI 9 isoseismal and along the Futagawa Fault, in the area where there was evidence of surface fault rupture, but where no strong motion stations were located.

The three-component ground accelerations measured by the KiK-NET and K-NET strong motion stations at Mashiki Town (KMMH016) and Kumamoto City (KMM006) are shown in Figure 5. High vertical and horizontal accelerations were recorded by most of the KiK-NET and K-NET strong motion stations located in proximity to the main active faults in the Kumamoto Prefecture (Figure 4).

Rainfall

Kumamoto Prefecture is located on the Island of Kyushu, which is at the southern end of the Japanese archipelago. The climate is monsoonal, with relatively mild weather year round comprising wet summers (June to August with mean monthly rainfall of >300 mm) and mild but dryer winters (December to February with mean monthly rainfall of < 100 mm).

The two main earthquakes were preceded by heavy rainfall a week before the events, and followed afterwards by heavy rainfall on 21st April 2016. These rainfall conditions are typical for this time of year, but may have contributed to the severity of the observed earthquake related land damage.

Table 1: Peak ground accelerations recorded at KiK-NET and K-NET strong motion stations in the epicentral region for the M_w 7.0 earthquake (16 April 2016) [6].

Station	Peak ground accelerations (g)		
	NS	EW	UD
KMMH016	0.67	1.18	0.89
KMM006	0.84	0.63	0.55
KMM009	0.79	0.65	0.19
KMM011	0.61	0.61	0.26
KMM005	0.54	0.49	0.41
KMM007	0.28	0.43	0.31
KMM004	0.27	0.35	0.27

GEOLOGY AND GEOMORPHOLOGY OF THE AFFECTED AREA

The geology of the area is shown in Figure 6, which is taken from the 1:200,000 scale geology map produced by the Geological Society of Japan [9]. The volcanic rocks in the area around Minami Aso Township mainly comprise late Pleistocene non-alkaline felsic and mafic volcanic rocks, (ignimbrite, volcanic breccia and some basalt lava flows). Inside the caldera, most of the slopes are covered by volcanic pyroclastic soils (airfall deposits), ranging from a few metres to tens of metres in thickness. These soils are known to be sensitive to pore-water pressure changes and earthquake loading, and there have been numerous past studies on landslides in these materials [10-12].

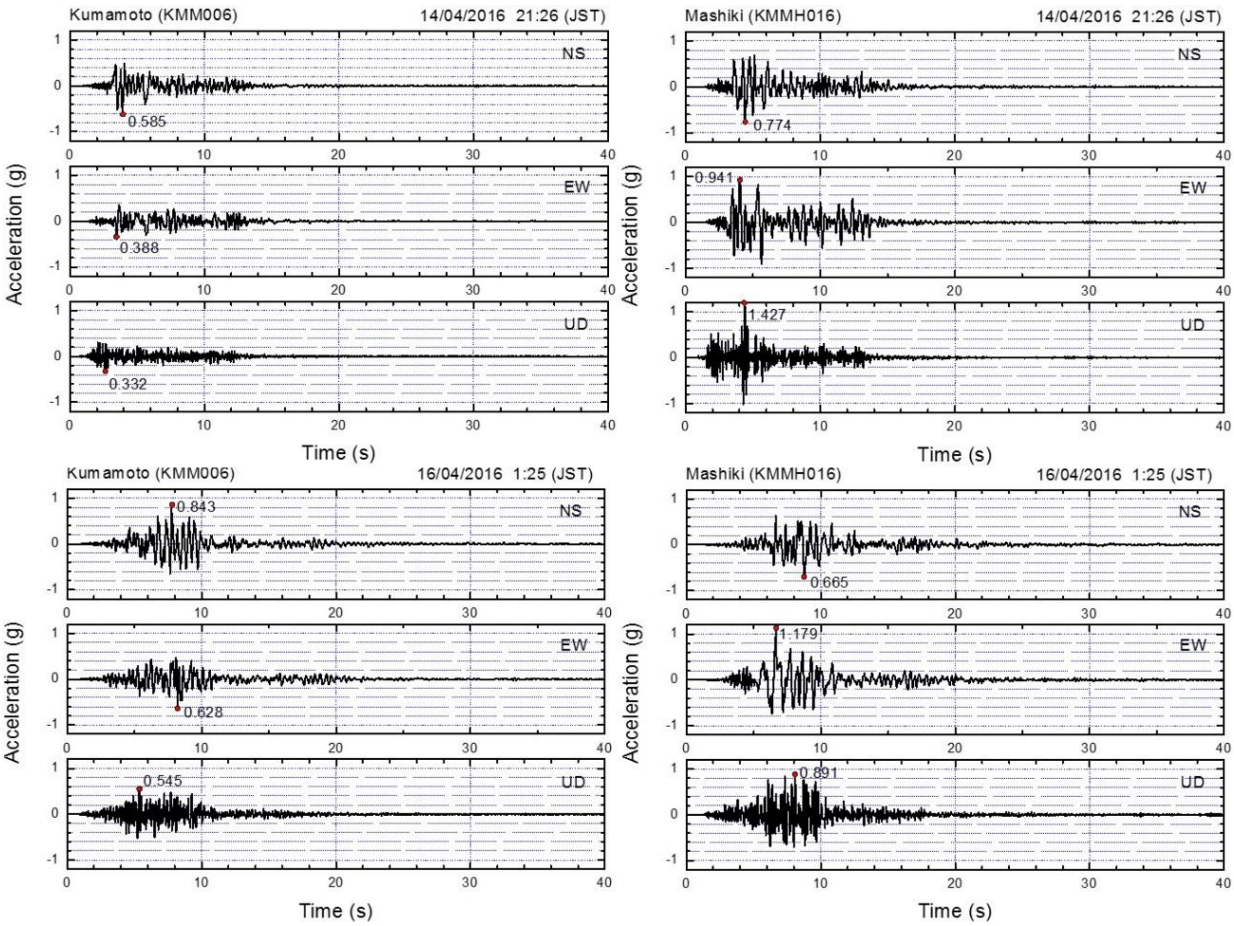

Figure 5: Three-component acceleration records measured at KMMH016 (Mashiki) and KMM006 (Kumamoto) strong motion stations during the two major events [6].

The area affected by the earthquake sequence can be broadly split into three zones based on their contrasting geomorphology (Figure 1):

a Inner caldera – comprising a series of active volcanic vents. The slopes in this area range from gentle angles (<10 degrees) on the lower slopes, to very steep (>60 degrees) upslope towards the vents. The gentler lower slopes are mantled in volcanic soils (including pumice), which can be many metres thick and underlain by pyroclastic deposits (ignimbrites) and lava flows. The upper slopes are typically formed in rock (lavas and ignimbrites) with a shallow (up to 10 metres thick) mantle of volcanic soil.

b Shirakawa river valley – comprising a narrow break in the surrounding caldera outer wall on the south-western side, through which the Shirakawa River flows. The Futagawa Fault passes through this valley. The river has incised through the volcanic rocks forming a steep-sided gorge (up to 70 m in height) where it flows out from the caldera wall. The slopes on the southern side of the river are typically steep (>30 degrees to vertical) and formed in rock with a thin mantle of volcanic soil. The northern slopes comprise relatively gentle (5 to 20 degrees) alluvial terraces, slightly steeper fans (fluvial/debris flow) and steeper rock slopes (typically > 30 degrees slope).

c Outer caldera and alluvial plains – the caldera rim comprises a series of steep (> 30 degrees) "scarp slopes" formed of rock with a thin mantle of volcanic soil, on the eastern side. The "dip" slopes on the western side of the rim are much gentler (< 30 degrees) formed mainly in deep volcanic soils. Further west towards Mashiki Township and Kumamoto City, the slopes become relatively flat, and are formed mainly in alluvium.

GENERAL OBSERVATIONS OF THE EARTHQUAKE EFEFCTS

At the time of writing this report, the total number of reported deaths is 69, although some people are still missing. Based on newspaper reports, at least 10 of these deaths can be related to four landslides that are thought to have been triggered by the main earthquake on 16 April 2016 [13].

Damage to residential houses ranged from no damage in areas of low shaking or where houses had been recently constructed, to complete collapse, especially of the older traditional one-storey or two-storey timber houses, in the areas of strong shaking and surface fault rupture. Houses were also severely damaged or had been destroyed by a number of major landslides in the Mt. Aso volcanic caldera and on the slopes forming the caldera outer walls. Away from the areas close to the fault rupture, the heavy tiled roofs of houses appear to have been damaged by shaking, and were observed to have been protected with blue plastic sheets. In total several thousand residential houses were reported to have either been partially damaged or collapsed [14]. Mashiki Town appeared to be the worst-affected area.

The earthquake-induced shaking and landslides also caused considerable damage to roads, highways, rail transportation, linear infrastructure (pipes and cables) and high voltage transmission lines. Several bridges, including the critical Aso Ohashi Bridge, were completely destroyed or were significantly damaged by landslides.

Rupture along the main fault was mapped at the surface over several kilometres, from Mashiki Town (to the West) to Minami Aso Village (to the East), as shown in Figure 4.

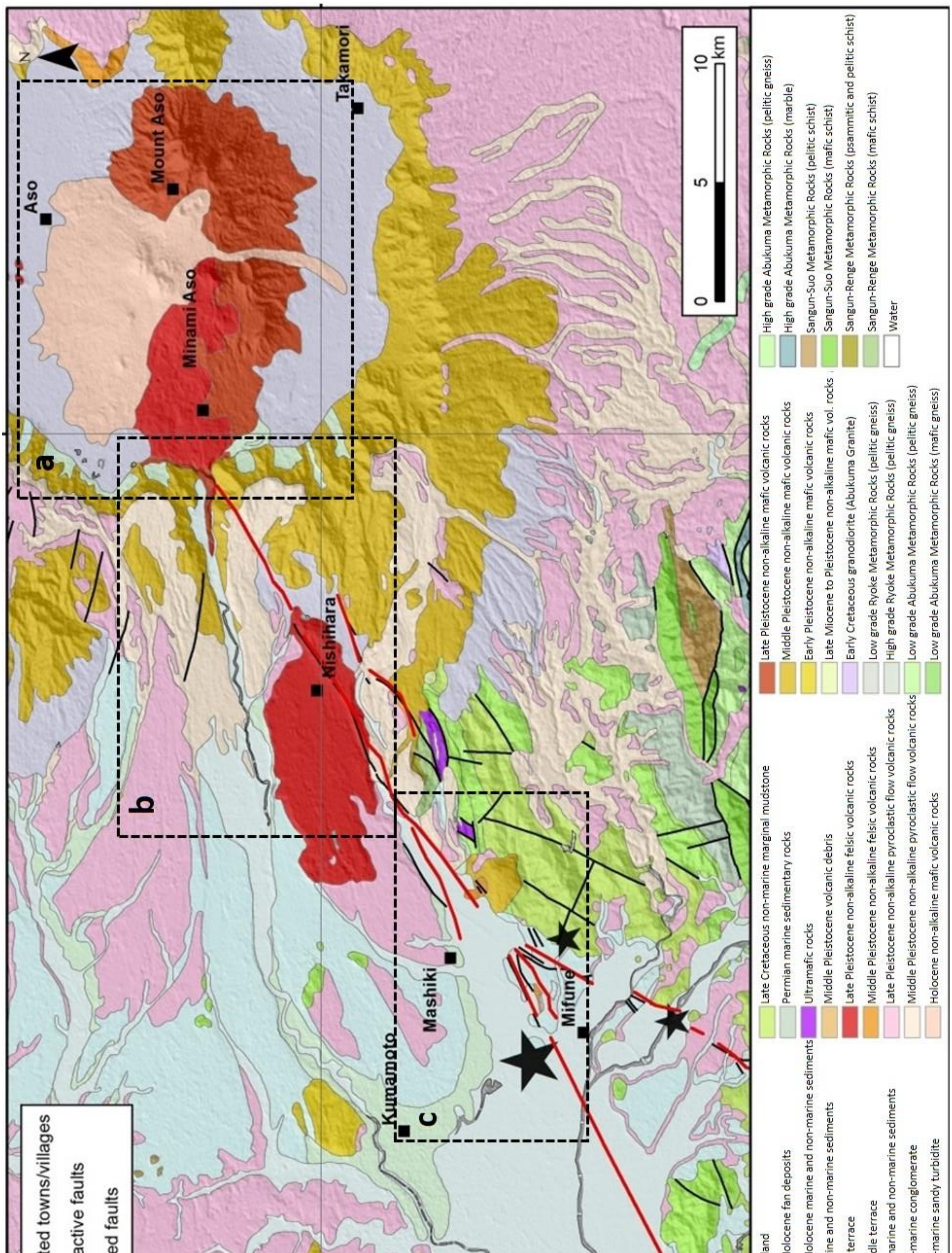

Figure 6: 1:200,000 scale seamless geology map of Kumamoto [9].

Many residents of Nishihara Village were evacuated over fears that the nearby Ookirihata earth-dam, damaged by fault rupture, could breach.

In a few suburbs of Kumamoto City and in Mashiki Town, localised liquefaction took place, causing lateral spreading, differential settlements of the ground and riverbanks, sinking and tilting of buildings, foundation failures, cracks on roads, and disruption of water and sewage pipe networks. The overall effects from liquefaction related hazards appeared relatively minor compared to the damage caused by shaking, landslides and surface fault rupture. The report prepared by GEER [15] considers the liquefaction effects in some detail and concludes: "*Surprisingly, given the intense ground motions, liquefaction occurred only in a few districts of Kumamoto City and in the port areas, indicating that the volcanic soils were less susceptible to liquefaction than expected given the intensity of earthquake shaking, a significant finding from this event that needs to be evaluated in future research*."

The type of observed earthquake hazard typically varies between the areas, although there are some similarities between the areas with regards to damage to buildings and retaining wall collapse.

In areas ***a*** and ***b***, the main types of hazard were landslides and surface fault rupture. These landslides mainly comprised earth flows and slides, debris flows and avalanches, earth/debris slides and slumps. Landslides in area ***a*** are reported to have killed at least 10 people out of the 69 confirmed deaths associated with the earthquake. In area ***c***, the dominant ground-damage hazards were liquefaction, settlement and lateral spreading. Effects from the surface fault rupture (severe permanent ground displacement and strong shaking) were evident in all three areas, in a narrow corridor each side of the surface rupture.

The following sections provide more detailed descriptions of the types of ground failures that were observed during the reconnaissance mission.

GROUND SHAKING AND BUILDING DAMAGE

It was apparent that severe ground shaking caused significant damage to buildings in the epicentral area and along the fault rupture corridor. Many houses and other buildings either on or adjacent to the surface fault rupture or projected fault trace were severely damaged as a result of both the strong ground shaking and permanent ground displacement.

The most common form of damage was to the tiled roofs of residential houses and buildings. Such damage extended further out from the immediate epicentral area. In many locations, blue plastic sheets had been used to cover damaged roofs, and were a common sight across the area, see Photo 1.

Most of the buildings appeared to have collapsed due to the strong ground shaking caused by the action of the inertia forces on the heavy roofs (Photo 2). Collapsed buildings were mostly old wooden one- and two-storey houses. The roofs of these houses were typically formed from "*kawara*" tiles, which were intentionally made to be heavy, in order to prevent them from "flying away" during typhoons. The Kumamoto district is one of worst typhoon disaster areas in Japan. It is also possible that deterioration of the structural members could have occurred as a result of insect damage.

Observations indicate that the lack of adequate bracing had contributed to this damage, as the houses appeared to have collapsed from rocking of the building during strong ground shaking. More modern houses appear to have been damaged and collapsed due to the presence of soft storeys, with garages in the lower storey.

Detailed inspection of this damage was not the focus of this team, however, the combination of heavy (tiled) roofs, lack of bracing and soft storeys appeared to have contributed to the damage and collapse of a number of these houses in the epicentral region.

Approximately 49 people were killed by collapse of houses [13]; most of these deaths were in private houses rather than concentrated in any particular building, although there were two cases where multiple deaths occurred in the same building.

FAULT RUPTURE

Fault rupture was observed in many locations by the team. Evidence of surface rupture (cracking) was able to be traced over a distance of many kilometres, from Mashiki Town, around and through Kurokawa Village and all the way to Aso City (Figure 4). The GEER report [15] contains extensive commentary on fault rupture.

Photo 1: Typical blue sheets covering damaged roofs in close proximity to the surface fault rupture (Location 22 in Figure 2: N 32.80487; E 131.8593).

Photo 2: Low damage to a new residential house (without tiled roof) and severe damage to two-storey timber house (with heavy tiled roof) observed in Mashiki Town (N 32.7876; E 130.8185).

Where fault related cracks pass through hard surfaces such as roads, lateral displacements (on individual cracks) were observed in the order of up to 0.1 m, with cumulative displacements of up to 1.5 m. Fault rupture of up to 2 m lateral displacements was observed in rice fields in area ***c***, on the outer caldera slopes (Photo 3). Major fault rupture hazard types observed during the reconnaissance are described henceforth.

Photo 3: Fault rupture of 1.8 m lateral displacements observed in rice fields in Mashiki Town (location 22 in Figure 2: N 32.80487; E 130.8593).

Photo 4: Surface fault rupture at the Ookirihata earth dam in Nishihara Village (Location 23 in Figure 2: N 32.8415; E 130.9321).

In Nishihara Village severe damage to the left hand side wall of the spillway of the Ookirihata earth dam and adjacent highway over dam crest were observed (Photo 4). No other damage was apparent to the team on the earth dam, but the dam has been drawn down following the earthquake. The GEER team [15] investigated this dam in detail and identified additional fault related damage.

In Minami Aso severe damage and collapse of houses adjacent to the fault trace was observed (Photo 5). Fault displacement of less than 0.5 m was noticed in the rice fields adjacent to housing area.

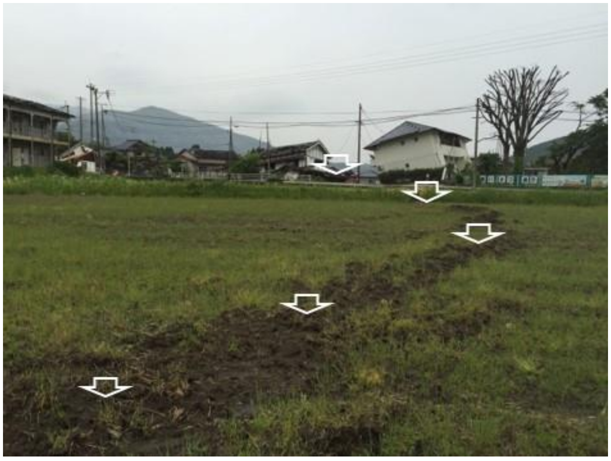

Photo 5: Collapsed apartment block located on the fault rupture in Kurokawa, Minami Aso Village (Location 17 in Figure 2: N 32.8852; E 130.9943).

LANDSLIDES

Distribution of Landslides

According to local residents, nearly all the landslides in areas ***a*** and ***b*** were triggered by the M_w 7.0 earthquake on 16 April 2016. This occurred at 01:25 am, when most people would have been asleep. The main area affected by landslides measures about 110 km^2. Figure 7 shows a plot of those areas affected by landslides triggered in similar magnitude earthquakes in New Zealand. Such relationships are only indicative, however, as the areas affected by landslides (triggered by strong ground shaking) can often be limited by the lack of steep topography on which landslides could occur.

The preliminary landslide mapping carried out by the PASCO Geospatial Group [16] has identified more than 280 landslides within the main area affected by landslides shown in Figure 4. This gives a landslide density of about 2.5 landslides per km^2 inside this area, which corresponds to the MMI ≥ 9 zone (Figure 4), and a landslide density of about 1 landslide per km^2 in the total area affected by landslides at MMI < 9. This number is thought to be a lower estimate of the total number of landslides generate by the earthquakes, as the mapping does not cover the entire area affected and only the larger landslides – those visible from satellite imagery – have been identified.

A total of 125 landslides have been documented by the Japanese authorities [17] as impacting homes and infrastructure. Nearly all of these are inside the main area affected by landslides shown in Figure 4.

Types of Landslides

Many landslides and associated cracks were observed in natural soil and fill material overlying bedrock, and many were also in rock, where only limited soil cover was apparent.

Cracking, indicative of incipient landsliding, was observed on the relatively flat slopes (terraces) behind the sharp convex breaks in slope that form the edges of the steeply incised rivers and streams. In many areas ground cracks was observed in locations where the topography was locally steeper.

The slopes around the Aso Volcanology Laboratory of Kyoto University were extensively cracked, with the cracks extending many hundreds of metres across the ridge top. Vertical and horizontal permanent ground displacements (indicating back tilting and rotational movements) were measured across these cracks, suggesting that they were indicative of incipient landslides (and ridge-renting). On the steeper slopes at the edges of the area of cracking, the amount of permanent ground displacement increased, and in some areas the mass had broken down to form earth flows.

In addition to the earth flows, several debris flows also occurred on the steep flanks of the volcano. The source areas of these debris flows appeared to comprise failures in the volcanic soils overlying rock, with the toe of the failure surfaces being consistent with rock head. Much of the ground above and around these source areas was cracked, with evidence of permanent down-slope displacement indicative of incipient landslides. The steep debris trails below these source areas suggest that flow/avalanche movement mechanisms were dominant. Debris avalanches in predominantly weathered rock and shallow soil were also observed on the near the crest of the steep slopes of the inner caldera.

The main earthquake-induced landslides observed during the reconnaissance were classified into different types (according to Hungr et al. [18]), as listed below, and illustrated through examples henceforward:

- Earth flow/slide
- Debris flow
- Planar (translational) slide/slump
- Incipient landslide (cracking)
- Large debris (rock/soil avalanche)
- Small to moderate size debris avalanche
- Rock falls

Earth Flow/Slide

In Minami Aso Village (Location 9 in Figure 2), a mobile earth slide (100 m wide by 600 m long; estimated volume between 60,000 and 100,000 m^3) developed into a flow on low angle (around 10-15º) slopes, with a travel angle from landslide crown to debris toe (Fahrboeschung) of 6–7º (Figure 8b). Relatively large intact blocks of soil, grass and trees travelled towards the toe of the slope (Photos 6 and 7). Landslides travelled in three separate directions from a common source (Figure 8a) and destroyed at least 7 houses and killed 5 people at the Takanodai Housing complex, threatened many other houses, and blocked several roads.

Tension cracks and scarps (indicative of incipient landsliding) above the head scarp adjacent to the Aso Volcanological Laboratory were also observed indicating the potential for head scarp retrogression.

As shown in Photo 8, the slide surface was identified and traces of orange-coloured pumice soil were clearly noted on it. Two small trial pits (Figure 8) were excavated across the assumed slide surface and soil profile details are provided henceforward.

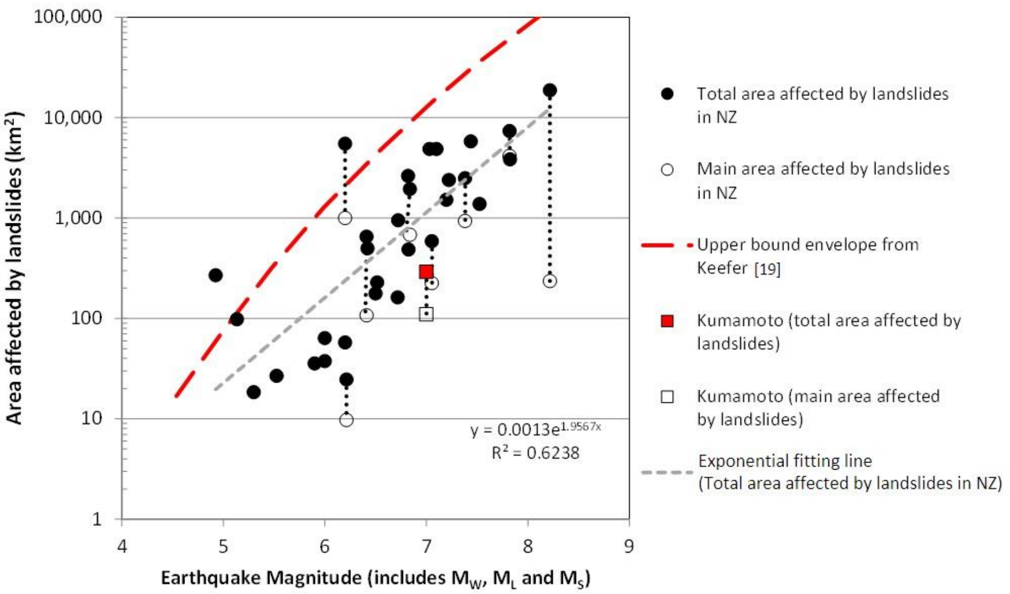

Figure 7: Relationship of the area affected by landslides during historical earthquakes of different magnitudes in New Zealand and worldwide. The squares represent the total and main area affected by landslides triggered by the M_w 7.0 Kumamoto earthquake on 16 April 2016 (modified from Hancox et al. [20]).

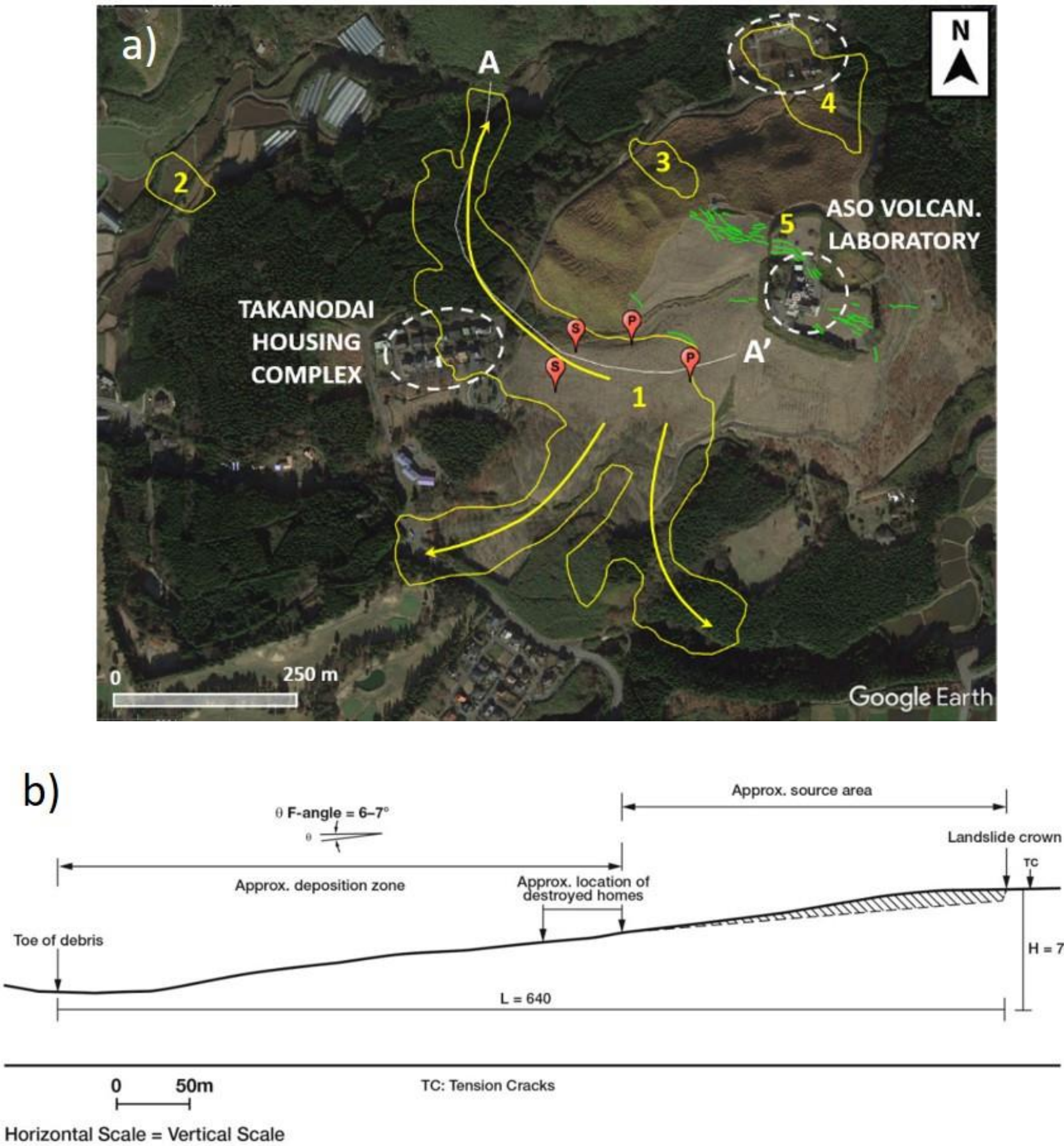

Figure 8: Location 9 in Figure 2 (No.1: main landslide; No.2-4 minor earth slides; No. 5 cracks; A-A' cross-section; s: soil sampling; p: trial pits); and b) cross-section through the Takanodai earth flow/slide.

Photo 6: Source of earth flow/slide in Minami Aso Village (looking downhill), with damaged houses and the large debris avalanche at Aso Ohashi Bridge visible in the distance (Location 9 in Figure 2: N 32.8851; E 131.0049).

Photo 7: View of the main landslide (looking uphill), with the Aso Volcanological Laboratory visible in the distance (Location 9 in Figure 2: N 32.8951; E 131.0135).

Photo 8. Traces of pumice soil on the slide surface.

Debris Flow

In Nagano, Minami Aso Village (Locations 13 and 27 in Figure 2), about four houses were hit and partially flooded by debris. More houses are now potentially at risk from subsequent debris flows along the channel initiated during rain events. A Sabo-dam (debris control structure) was damaged by the debris flow (Photo 9), one local road bridge was destroyed and another inundated by debris. There is likely to be an on-going long term impact following further storm events.

The channelised flow (2.8 km runout distance, impacting on 300 m by 120 m area in the main debris deposition zone) occurred along a steep drainage line, fed by multiple source areas on the steeper upper flanks of the volcanic cone high above the deeply incised valleys. Typically planar slides and rotational slumps developed into flows with debris feeding into the main channel (Photo 10 and Figure 9). Cracking, indicative of incipient landsliding, was prevalent in the upper reaches of catchment above the source areas. Source material was mostly volcanic soil. However, several large boulders were apparent in the debris, indicating that rock slopes failures in the valleys may have contributed to the debris. At the time of the survey, much of the debris was still located upslope of the main deposition zone, within the main drainage line. The estimated Fahrboeschung was about 10–11º (Figure 10).

Photo 9: Debris-flow deposits being cleared up (Location 13 in Figure 2: N 32.8643; E 131.0216).

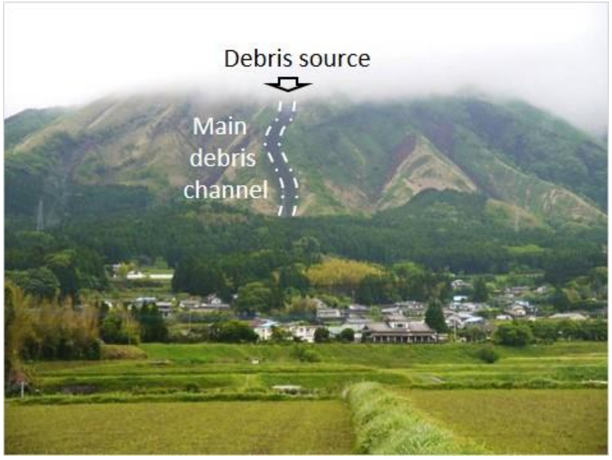

Photo 10: Debris flows sourced from the steep volcanic slopes above Kawayo, Minami Aso Village.

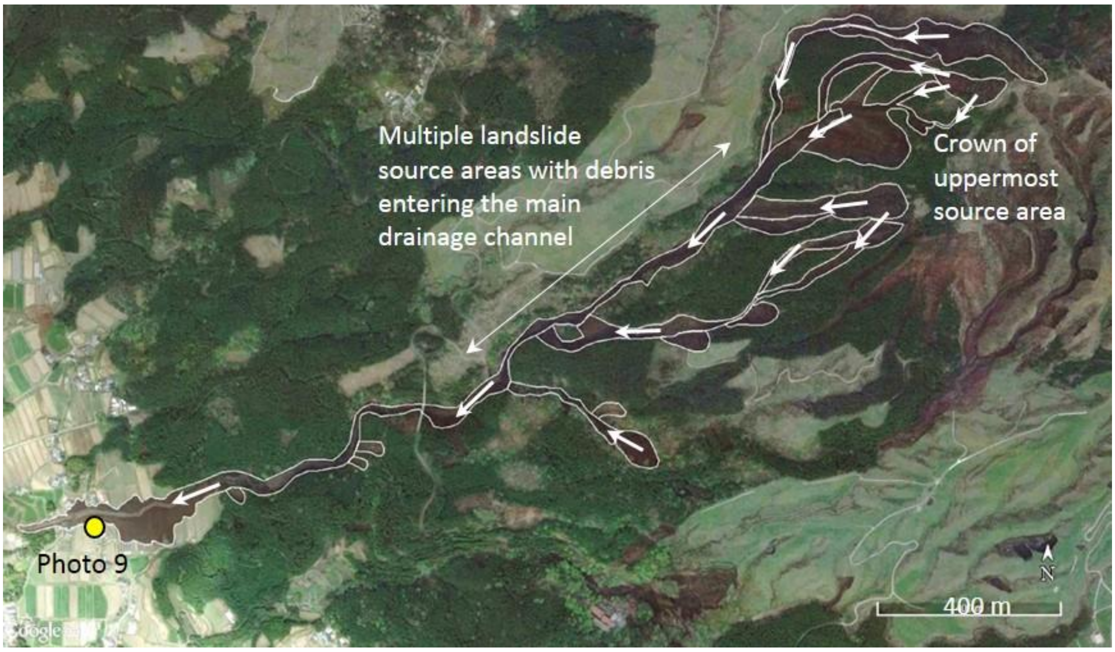

Figure 9: Google Earth image of the channelised debris flow near Nagano Village (Location 13 on Figure 2).

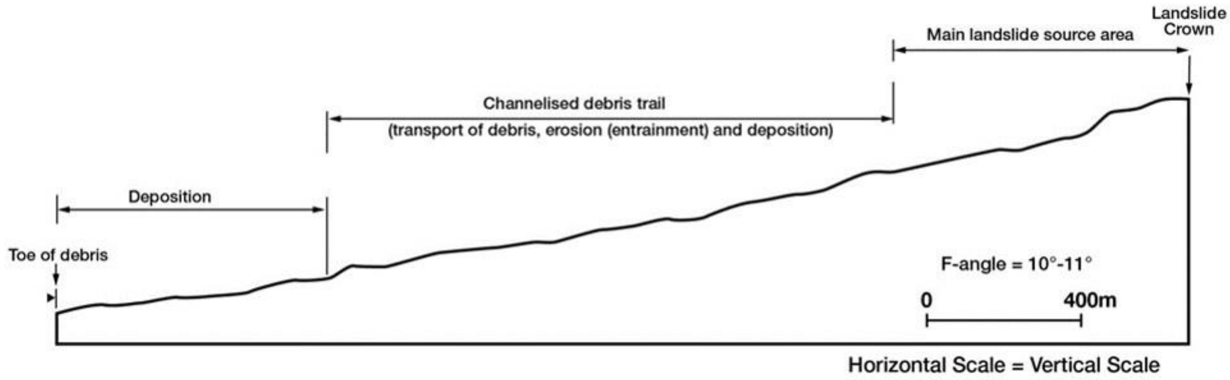

Figure 10: Cross-section along the channelised debris flow near Nagano Village (Location 13 on Figure 2).

Planar (Translational) Slide/Slump

In Tokyu Country Town, Minami Aso Village (Location 12 in Figure 2), a planar slide affected approximately 40 houses (Figure 11) and severely damaged access roads and services. The slide had an extension of 400 m by 120 m and an estimated volume of 400,000 to 600,000 m^3 (assuming a depth of between 8 and 12 m).

Intact displaced rafts of debris on a low angle slope (about 3º) appeared to be translating along rock head. A graben had developed at the head scarp, with slumping (rotation) and toppling of the debris rafts adjacent to the steeper slopes of the stream, near the toe of movement (Figure 12). Cumulative lateral displacements were greater than 2.5 m horizontally, localised vertical displacement of up to 1 m were recorded across some cracks. There is a possibility of on-going displacement due to water ingress through cracks and broken services. Volcanic soil and subdivision fill overlay the rock.

Typical damage to houses and land observed in Tokyu Country Town during the survey are shown in Photos 11 and 12.

Figure 11: Google Earth image of the earth slide/slump at Tokyu Country Town (Location 12 in Figure 2). This landslide damaged about 40 homes.

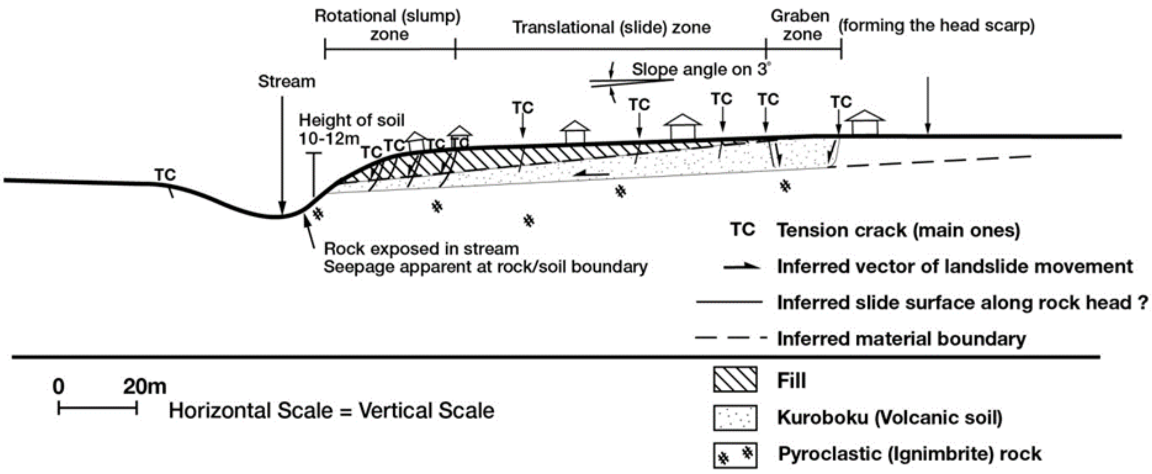

Figure 12: Cross-section through the earth slide/slump at Tokyu Country Town.

Photo 11: Translational slide / slump at Tokyu Country Town, Aso. About 40 houses were affected by landslide movement (N 32.8796; E 131.0030).

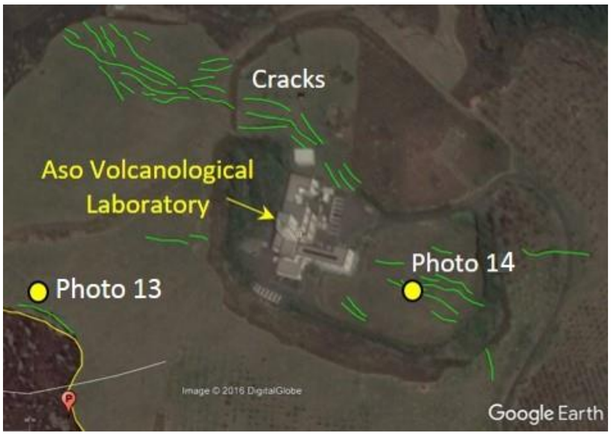

Figure 13: Google Earth image of the incipient landsliding at the Aso Volcanological Laboratory. Location 8 in Figure 2.

Photo 12: Toe area of the translational slide/slump at Tokyu Country Town showing the transition from sliding to slumping towards stream (N 32.8805; E 131.0025).

Photo 13: Extensive cracking located upslope near the Aso Volcanological Laboratory (N 32.8857; E 131.0069).

Incipient Landslide (Cracking)

As indicated in Figure 13, multiple cracks extending many 100's of metres across the ridge crest were observed at the Aso Volcanological Laboratory (Location 8 in Figure 2). Crack widths varied from a few cm to over 1 m with vertical and horizontal displacements apparent. Movement vectors across cracks suggested rotation (slumping) towards the north, indicative of incipient landslides (ridge-renting). On the steeper slopes at the edges of the area of cracking the amount of permanent ground displacement increased, and in some areas the mass had broken down to form more mobile earth flows/slides (Photo 13).

The Aso Volcanological Laboratory appeared to be damaged and had been red placarded. Services and other infrastructure crossing the cracks are likely to be severely disrupted. There is potential for future landslides to occur from water ingress, which could impact on homes below not already damaged.

As shown by Photo 14, cracking was located also above the head scarp of the translational flow/slide adjacent to the Aso Volcanological Laboratory, indicating the potential for head scarp retrogression.

Photo 14: A typical cracking located near the scarp of the translational slide/slump below the Aso Volcanological Laboratory (N 32.8851; E 131.0050)

Large Debris (Rock/Soil Avalanche)

Photo 15 and Figure 14 show the largest avalanche of rock and volcanic soil (820 m long by 200 m wide; estimated volume of 900,000 to 1,000,000 m^3, including source area and entrainment) caused by the Kumamoto earthquakes.

The debris overwhelmed and removed the main highway and destroyed the Aso Ohashi Bridge across the Shirakawa River (Photo 16), including any services on the bridge. One person in a car on the bridge at the time of the failure is assumed to have been killed although the car and person have not been retrieved. This bridge was a lifeline as it provided access for residents of Minami Aso and surrounding area to the local hospital and Kumamoto City. Loss of the bridge caused major disruption to transportation, as transport is limited to a narrow, windy road over the caldera rim.

The source area is located in what appears to be weathered rock (regolith) near the crest of a steep and high slope. The debris from the source area seems to have entrained colluvium and terrace gravels (soil) located below the source. As shown in Figure 15, the Fahrboeschung was estimated to be 23º (±2º). The debris travelled into the main Shirakawa River, destroying the main road bridge, and temporarily blocking the river. The debris dam was apparently breached soon after its formation.

Photo 15: Debris avalanche at Aso Ohashi Bridge (Location 10 in Figure 2: N 32.8834; E 130.9896).

Photo 16: Toe of the debris avalanche at Aso Ohashi Bridge. Note the bridge has been destroyed by the landslide (Location 10 in Figure 2: N 32.8834; E 130.9896).

Small to Moderately Sized Debris Avalanches and Cracking

Landslides and cracking extended intermittently for several kilometres along the crest of the steep slopes adjacent to the Shirakawa River near Toshita Kawayō (Figure 16a). A typical cross section is reported in Figure 16b.

Some failures are joint controlled (columnar jointing) and some are confined to the regolith. Cracks with vertical and horizontal displacement indicating movement towards the cliff edge (indicative of incipient landsliding) were located upslope above the debris avalanche head scarps. In some locations the cracks had not fully developed into debris avalanches.

Roads, power lines and other services were severely damaged by lateral displacements in the areas of cracking. A bridge deck (an alternative route across the Shirakawa River) was completely destroyed by one debris avalanche (Photo 17). Moreover, the western abutment of another bridge across the river (which was still intact) dropped by about 1.5 m vertically, making the bridge deck inaccessible to vehicles (Photo 18). The damage to these bridges and the Aso Ohashi Bridge mean that the main access route to Kumamoto City is now via an alternative route that winds up the slopes of the caldera, adding approximately two hours of journey time to Kumamoto City.

Figure 14: Google Earth image of the debris avalanche that destroyed the main road bridge across the Shirakawa River (Location 10 in Figure 2).

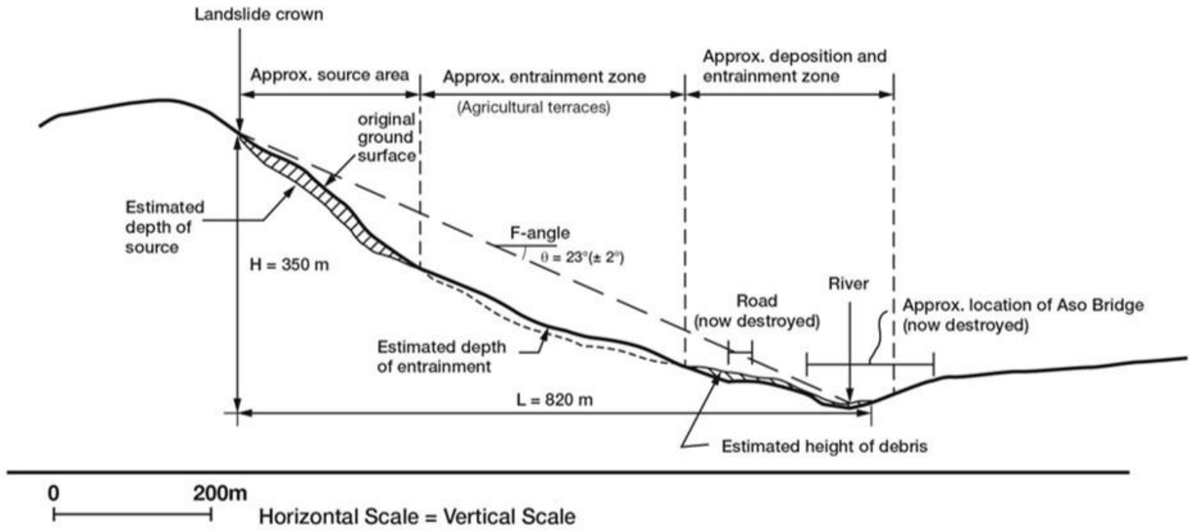

Figure 15: Cross-section through the debris avalanche that destroyed the Aso Ohashi Bridge.

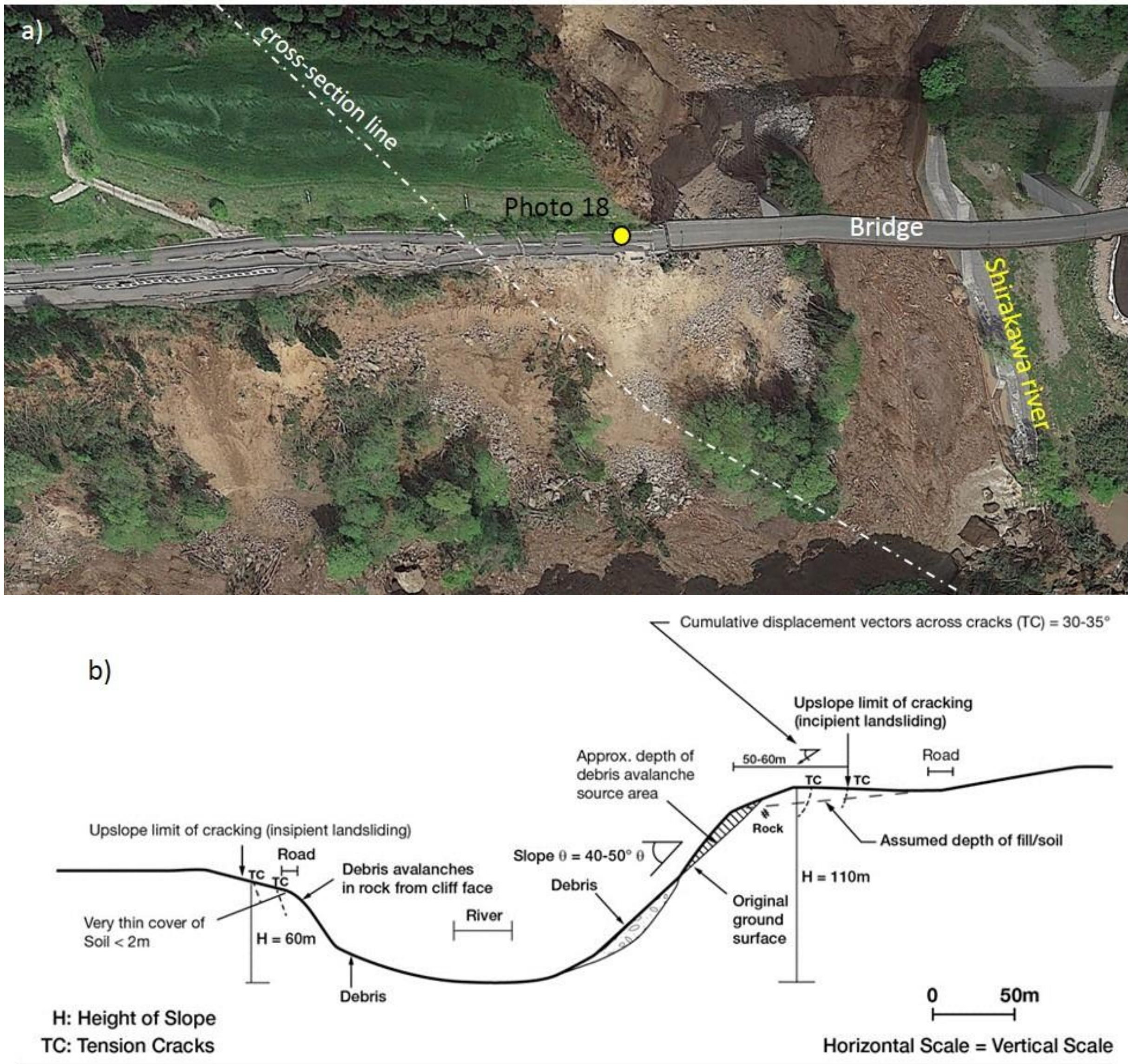

Figure 16: a) Google Earth image of the slope adjacent to the Shirakawa River (Location 5 in Figure 2); and b) cross-section through the slope.

Photo 17: Bridge deck destroyed by a relatively small debris avalanche (N 32.8752; E 131.9886).

Photo 18: Displacement of the road bridge abutment. The displacement resulted from loosening and toppling of the of the jointed rock mass supporting the abutment foundation (N 32.8764; E 131.9827).

Rock Falls

Near Tochinokibaru hot spring (Locations 14 and 15 in Figure 2), many rock falls blocked the main road (Photo 19). The estimated volume of rock falls was from a few m^3 to many hundreds of m^3. Source material was welded tuff, ignimbrite, basaltic lava and lava breccia.

The rock falls sourced from the steep rock slopes above the Shirakawa River and main road. The runout was approximately 70 m, with a Fahrboeschung of about 32º. Many of these slopes had been modified by the construction of rock fall mitigation measures, comprising shotcrete, mesh and dowels apparent. In many locations the shotcrete, concrete grids and mesh had been damaged due to rock mass dilation induced by the earthquakes. Photo 20 shows the impact of one of the largest rock fall encountered during the survey, where a single block crushed two cars on the local road below the main road.

Topographical Amplification of Shaking

Cracking (incipient landsliding) and small to moderately sized debris avalanches were observed adjacent to the sharp convex breaks in slope along the steeply incised Shirakawa River valley. Larger debris avalanches, debris flows and associated cracking also occurred near the crests of the steeper inner crater slopes and the steep upper slopes on Mount Aso volcano. In addition, many of the earth flow and slides appeared to have developed in the thick volcanic soils overlying rock. In some locations their rupture surface appeared to be consistent with rock head.

Many of the landslides in the steep hillsides appear to be located near the top of the ridge or terrace, with the debris from these failures flowing further down the slope.

These patterns of ground cracking, the morphology and topographic position of the landslide source areas and the materials exposed in them, suggest amplification of shaking caused by:

- Localised variations in topography; and
- Material velocity contrasts, i.e. differences between the shear wave velocities of the soils and rock, coupled with the rock/soil mass strength.

These observations suggest that topographical amplification effects, exacerbated by the presence of weak soils and weathered rock may have been an important factor in the triggering of the landslides.

Photo 19: Typical rock fall on the road near the Tochinokibaru hot spring (N 32.8746; E 131.9884).

Photo 20: Cars crushed by rock fall near the Tochinokibaru hot spring (N 32.8711; E 131.9982).

Sensitive Volcanic Soils

Many of the earthquake-induced earth flow/slides occurred on gentle slopes and were highly mobile. Observations of the materials forming the identified slide surface of the earth flow/slide at the Aso Volcanological Laboratory suggest that failure may have occurred in weathered soils derived from pyroclastic fall deposits. Two small trial pits were excavated across the recognised slide surface by Kyoto University and the NZSEE team.

Soil exposed in the trial pit and a borehole describing a typical soil profile up to the depth of 14 m is reported in Figure 17. The soil consists of (1) Kuroboku volcanic ash with organic contents (black colour); (2) volcanic ash Akaboku (red/brown colour); (3) pumice soil; and (4) soft/weathered rock. Significantly, water seepage was clearly observed within the pumice soil layer, indicating that the Akaboku ash soil (clay-like soil) is much less permeable than the pumice soil.

It is not known which material initiated the failure, but it is possible that the slide surface may have been: i) in a wet thin (>10 cm) halloysite pumice layer; ii) in an underlying thin (about 10 cm) very wet clay layer; or iii) at the boundary between the two. The NZSEE team took block samples of these materials for laboratory testing.

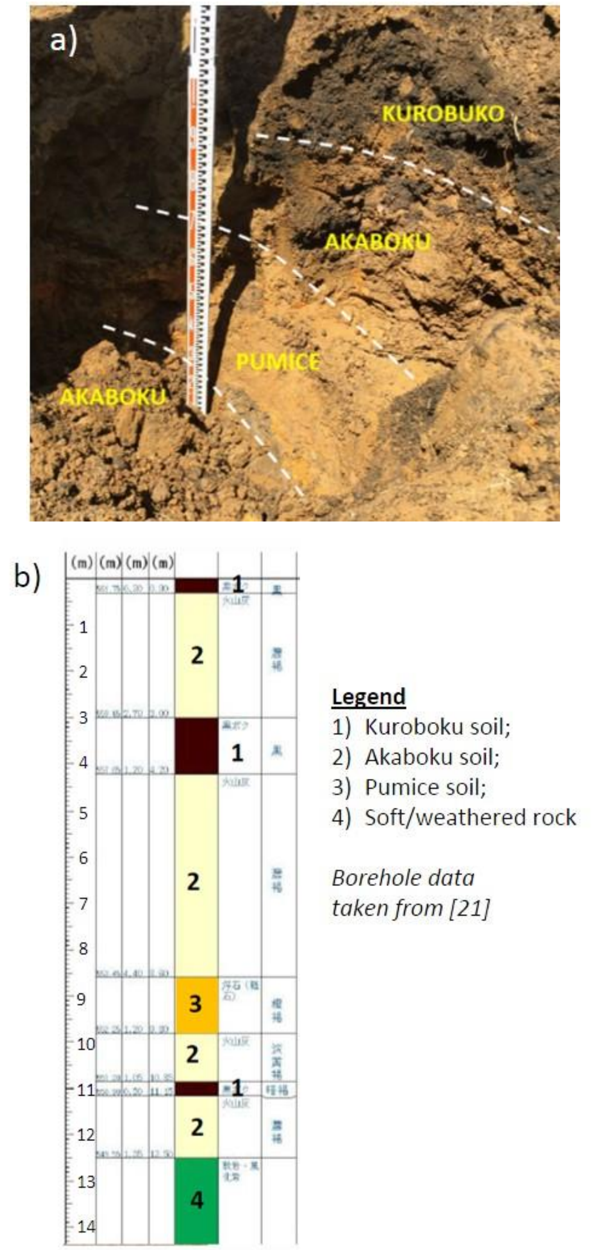

Figure 17: a) Soils exposed in wall of a trial pit excavated in the northern flank of the landslide; and b) typical borehole data around Aso Volcanological Laboratory [taken from 21].

Landslide Runout

The relationship between landslide volume and landslide height (H) to length (L) ratio measured from the source crest to debris toe (Fahrboeschung) for the Aso Ohashi Bridge debris avalanche, Nagano channelised debris flow and the Aso Volcanological Laboratory earth slide/flow, have been plotted on Figure 18 with similar types of landslides compiled by GNS Science from published data sources from around the world. The debris avalanche fits with the other debris avalanches contained in the data set. The channelised flow also fits with the other channelised flows contained in the data set.

The earth flow/slide at the Aso Volcanological Laboratory plots between the 63% and 95% confidence lines fitted to all of the plotted data, and is similar to the data from the "strongly retrogressive flow slides in sensitive clays" data set.

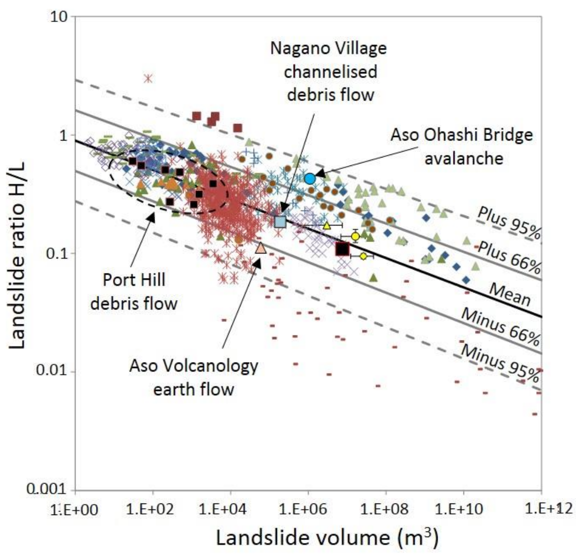

Figure 18: Relationship between landslide volume and Fahrboeschung (Landslide height to length ratio, measured from the source crest to debris toe).

Landslide Slope Height and Inclination

The relationship between slope height and slope inclination for the main types of landslide triggered by the M_w 7.0 16 April 2016 earthquake and discussed in the previous sections, have been plotted in Figure 19 against:

- similar landslides that were triggered during the 2010/11 Canterbury earthquake sequence;
- landslides triggered by the 2008 Wenchuan earthquake; and
- landslides plotted by Keefer [19].

The data for the large Aso Ohashi Bridge debris avalanche (two data points representing the range in the data), plot with the similar data from the larger debris avalanches triggered by the Wenchuan earthquake. The small to moderate sized debris avalanches along Shirakawa River plot at the lower slope angle end of the data from debris avalanches triggered by the 2010/11 Canterbury earthquake sequence, suggesting that the rock mass strength is possibly lower than that related to the volcanic rocks of the Port Hills. The debris avalanche data from the Kumamoto earthquake does show that as slope height increases the volume of the debris avalanches produced also increases, which is

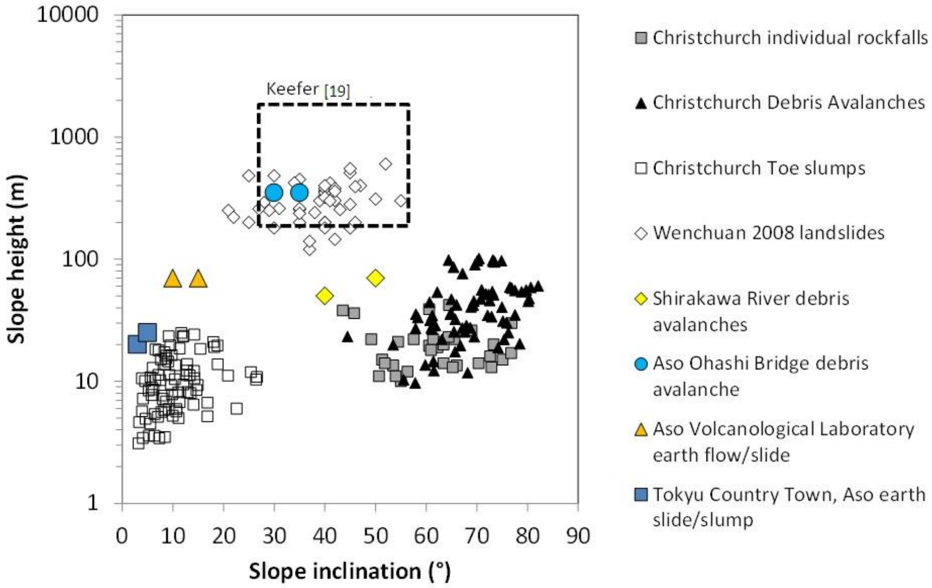

Figure 19: Relationship between slope height and slope inclination for the main types of landslide triggered by the M_w 7.0 16th April 2016 earthquake, plotted against the relevant landslides that were triggered during the 2010/11 Canterbury earthquake sequence, the 2008 Wenchuan earthquake and those plotted by Keefer [19].

consistent with the Canterbury and Wenchuan data sets. This is possibly due to the larger sizes of landslides mobilised in the high slopes, i.e. bigger slopes can produce bigger landslides.

The data for the large earth flow/slide at the Aso Volcanological Laboratory plots above the slope heights of other slides/slumps and the toe slumps triggered during the 2010/11 Canterbury earthquakes. Although a different type of landslide to the Canterbury toe slumps and the Tokyu earth slide/slump, these data do show that earthquake-induced landslides can develop on relatively gentle slopes, as observed during both the Canterbury and Kumamoto earthquakes.

Future Landslides in the Area

Given the nature of the cracked slopes in the main area of shaking and the timing of the earthquakes shortly before the rainy season, there is a high potential for post-seismic landslides to occur. On 20 June 2016, heavy rainfall occurred across the prefecture, which triggered extensive landslides and flooding. The AGU Landslide Blog reports three deaths and two people missing [22]: i) in Kamiamakusa a 92-year-old man was killed in his house by a landslide; ii) in Uto two houses were buried, leaving one man dead and a woman missing; and iii) in Kumamoto city two people were trapped by a landslide in their home, one has been confirmed dead and the other is missing.

Regulatory Environment

As reported by Dang et al. [23], the Kumamoto prefectural government had created “landslide hazard maps” based on national standards for landslide prevention using the following criteria: 1) steep areas at least 5 m high with a slope of 30^o or more, 2) areas below a rapid mountain stream that has formed as alluvial fan, and 3) areas where landslides have occurred or are at risk of occurring.

This law limits where people can build e.g., new houses are not allowed to be constructed within a given distance from the toe of a dangerous slope. However, if slope angle and height only are used to distinguish such slopes, much of the Japanese countryside would be incorporated into the hazard maps. By including a material type class in the assessment (e.g., volcanic soils and other areas where sensitive materials are located), the amount of land included could be reduced.

LIQUEFACTION AND LATERAL SPREADING

Liquefaction and lateral spreading was observed in two areas visited by the NZSEE Team:

- Kumamoto City centre: in the relatively narrow corridor between Highway No. 3 and the Kyushu Shinkansen line railway; and
- Mashiki Town.

A summary of liquefaction characteristics and impact is provided henceforward.

Liquefaction in Kumamoto City

In Kumamoto City (Locations 2-4 in Figure 2), discrete areas of sand boils with ejection of sand indicative of liquefaction at shallow depth were observed. They were mostly adjacent to power poles (Photo 21) and foundations where the crust has been weakened. Localised lateral spreading also took place.

The impact of liquefaction mainly consisted of differential settlement, tilting and damage of residential houses (Photo 22). In some cases, depression of buildings into the ground suggested the occurrence of foundation failure.

Photo 21: Traces of sand ejection adjacent to power pole in Kumamoto City (N 32.7583; E 130.6823).

Photo 22: Liquefaction-induced tilting of two residential buildings in Kumamoto City (N 32.7600; E 130.6829).

Liquefaction in Mashiki Town

In Mashiki Town (Locations 19-21 in Figure 2), extensive subsidence and localised lateral displacement of the ground indicated the occurrence of liquefaction. Differential settlement, tilting and severe damage to residential houses as well as cracking of roads, kerbs and land were also common. However, liquefaction surface expression were limited perhaps due to the depth of the liquefiable layer being overlain by a crust of liquefaction resistant soils.

Few sand boils were also seen; however, these appeared to be limited to only some areas affected by liquefaction. The limited ejecta were observed to consist of coarse sand. The area appeared to have been developed from a previous paddy (rice) farming field, and with extensive drainage measures in place.

The subsidence has led to the potential for flooding, and the banks of the drainage channels along the residential areas had been raised using soil filled polyester bags wrapped with polythene as a temporary flood protection measure (Photo 23).

Photo 23: Temporary flood protection measure to mitigate the impact of liquefaction-induced subsidence of river bank in Mashiki Town (N 32.7832; E 130.8084).

Temporary repair to roads were typically observed in the areas affected by cracking, lateral displacement (near adjacent waterways or gentle slopes) and settlement of roads (Photo 24), and protrusion of manholes. Ramps up to bridges were built to remediate differential movement between apparently piled bridges and unsupported embankments. Besides, provisional portaloos and sewage pumping trucks were used to overcome damage to drainage and sewerage systems.

Photo 24: Cracking, lateral displacement and tilting of power lines induced by lateral spreading in Mashiki Town (N 32.7860; E 130.8177).

PERFORMANCE OF BUILT INFRASTRUCTURE

Observations of Damage

The observations of the team were dominated by buildings and infrastructure damage caused by:

- Permanent ground displacement in response to surface fault rupture in a narrow strip of ground either side of where the fault ruptured at the surface;
- Strong ground shaking confined to an area either side of the surface fault rupture;
- Landslides and slope cracking (incipient landslides), triggered by the earthquakes;
- Retaining wall failures (local and global) and their performance;
- Bridge and road collapses (triggered by landslides);
- Liquefaction and lateral spreading leading to localized damage in areas of alluvium around Mashiki and Kumamoto City (area ***c***).

Residential Housing

The earthquakes are understood to have caused the following impact on residential houses in the Kumamoto Prefecture [14], which had about 315,000 houses (as of 20 May 2016):

- Total 96,421 houses were affected (damaged);
- Fully collapsed – 7,994;
- Partially collapsed – 17,818;
- Slightly damaged – 70,609;
- The remainder with minor damage.

The damage was caused by a combination of:

a) Strong ground shaking in the epicentral area,

b) Liquefaction and associated subsidence, lateral spreading and foundation failure, and

c) Landslides.

Lifelines

The main observed impacts were on:

- *Transportation routes*, as bridges were destroyed and damaged by landslides and ground shaking, and in some locations road carriageways had been removed and/or severely cracked by landslides;
- *Hospital* – where access was severely limited due to the collapse of a bridge impacted by a landslide and destruction of the adjoining roads; also, threatened by debris flow;
- *Power lines* – temporary high voltage (66kV) pylons and repairs were observed; and
- *Drainage and water services* – severely impacted in a narrow strip of ground either side of where the fault ruptured at the surface and in the areas affected by liquefaction and lateral spreading.

As illustrated by Figure 20, a lot of critical infrastructure (major roads and bridges, railway line, hospital, high voltage transmission lines and a dam site) was concentrated along the main Shirakawa River valley at the natural break in the slopes forming the outer crater (locations 5, 6, 7, 10, 15 and 17 in Figure 2). Multiple hazards occurred in this area as a result of the earthquakes, mainly active faulting and landslides, and as a result the main bridges and power lines across the river were destroyed. The Asotateno Hospital may have to close as it is now too far for people to travel to from inside the crater. The hospital was the main one for people living in Aso.

Retaining Walls

Retaining walls are extensively used to support roads, slopes above roads and housing platforms in the epicentral area subject to damage.

The types of retaining walls observed were:

- Reinforced concrete walls,
- Unreinforced (typically) concrete facing of slopes,
- Reinforced earth walls,
- Tied-back retaining wall with expanded polystyrene (EPS) lightweight backfill (two locations), and
- Gravity boulder walls.

Types of damage observed in retaining walls are described henceforward.

1: Debris flow threatening Asotateno Hospital
2: Debris avalanche destroyed highway and the Aso Ohashi Bridge (c.f. Photos 15 and 16)
3: Fault rupture severely damaged buildings (c.f. Photo 5)
4: Debris avalanche undercut highway making it impassable
5: Debris avalanche and cliff top recession and cracking destroyed the high voltage transmission line
6: Incipient landsliding severely impacts bridge making it impassable
7: Erath flow/slide destroyed railway line
8: Access to dam construction site destroyed
9: Incipient landsliding in rock and debris avalanches caused road bridge to settle (c.f. Photo 18)
10: Debris avalanche destroyed road bridge (c.f. Photo 17)

Figure 20: Location of critical infrastructure concentrated along the main Shirakawa River valley at the natural break in the slopes forming the outer crater. Multiple hazards occurred in this area as a result of the earthquakes, active faulting and landslides, and as a result the main bridges were destroyed and power transmission lines across the river required interim replacement.

Unreinforced (typically) Concrete Facing Walls

Collapse of numerous unreinforced concrete walls was observed (Photos 25 and 26). Most of the damaged walls had a height between 2 m and 4 m. Their failure induced cracking and displacement of ground supported, sometimes leading to undermining and tilting of houses.

Photo 25: Collapse of a typical unreinforced wall in Nishihara Village (N 32.8056; E 130.8583).

Photo 26: Fault rupture-induced collapse of a concrete facing unreinforced wall near the Ookirihata earth dam in Nishihara Village (N 32.8413; E 130.9317).

Reinforced and Unreinforced Concrete Walls

Complete collapse of reinforced and unreinforced concrete walls (1 m to 4 m high) was common in the area affected by fault rupture and strong ground shaking (Photo 27). Some of the failures led to undermining and tilting of houses or caused the partial or full closure of roads due to collapse of one or sometimes both lanes of road.

Displacement of the wall was also common, causing cracking of the ground behind. Photo 28 shows the displacement of the upper part of the wall along a construction joint.

Photo 27: Complete collapse of a typical unreinforced concrete wall in Minami Aso Village (N 32.8844; E 130.9918).

Photo 28: Displacement of the upper part of a wall along construction joint (N 32.8843; E 130.9916).

Reinforced Earth Wall

The total collapse of a reinforced earth wall (6 m to 10 m high) along part of its length (Photo 29) was observed near Tokyu Country Town. Pulled out reinforcement strips were visible, and possibly the global failure extended beyond reinforced blocks. The wall was supporting a road that lost at least one lane (Photo 30), leading to realignment of the road uphill.

Photo 29: Total collapse of a reinforced earth wall near Tokyu Country Town (N 32.8805; E 131.0039).

Photo 30: Effects of the collapse of the reinforced earth wall (shown in Figure 29) on the supported road (N 32.8804; E 131.0040).

Tied-back Retaining Walls with EPS Backfill

A tied-back wall (8 m high) with steel soldiers and a single row of small diameter anchors, apparently with expanded polystyrene (EPS) backfill, appeared to have performed well despite numerous boulders had landed on the road supported by it (Photos 31 and 32).

Photo 31: Good performance of a tied-back retaining wall with EPS backfill (N 32.8711; E 130.9916).

Photo 32: Road above the tied-back retaining wall (shown in Photo 31) closed by rock fall (N 32.8714; E 130.9924).

Retaining Wall with EPS Block Backfill

Photo 33 shows a concrete facing wall with EPS block backfill (3m to 5m high) that was built to form a road embankment near the Asotateno Hospital. The wall appeared to have overall performed well with some cracking along the road, and cracking and failure of some wall panels. However, as illustrated by Photo 34, the road was closed by a landslide further along the road and by fault rupture displacements (see Figure 20).

Photo 33: Good performance of a retaining wall with EPS block backfill (N 32.8792; E 130.9833).

Photo 34: Some cracking appeared on the road supported by the walls shown in Photo 33 (N 32.8792; E 130.9833).

Bridges and Approaches

Types of damage observed by the NZSEE team for bridges and approaches in liquefaction areas and mountainous areas are described hereafter.

Short Span Concrete Bridges in Mashiki Town

In Mashiki Town, settlement of approaches of short span concrete bridges were often observed (Photo 35), leading to temporary ramps being formed to provide access (Photo 36). Such bad approach performance can be associated with liquefaction-induced settlement of the riverbank showed in Photo 23.

In the same area, a two span bridge was observed to have jumped 300 mm laterally off its bearings (Photos 37 and 38). In such a case it is believed that this was the effect of combined strong vertical and horizontal accelerations recorded in Mashiki Town.

Photo 35: Typical settlement of short span concrete bridge approaches observed in Mashiki Town (N 32.7830; E 130.8085).

Photo 36: Temporary ramp being formed to provide access due to settlement of short span concrete bridge approaches (N 32.7830; E 130.8085).

Photo 37: A two span bridge jumped 300 mm laterally off its bearings (view from the road) (N 32.7864; E 130.8186).

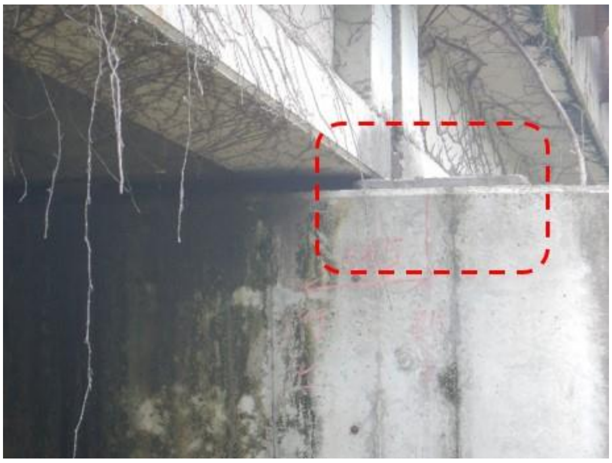

Photo 38: A two span bridge jumped 300 mm laterally off its bearings (view of the bearing) (N 32.7864; E 130.8186).

Long Span Steel Girder Bridge in Mashiki Town

In the liquefied area of Mashiki Town, ground settlement around bridge piers was observed (Photo 39), but this did not affect the performance of long span steel girder bridges. The bridge, however, appeared to have jumped off its bearings. This led to local buckling of the bottom web of the girders. The girders were re-levelled temporarily with steel plates either side of original bearings (Photo 40). Moreover, punching of the ends of the I-shape girders into the abutment wall caused shearing of back wall (Photo 41).

Photo 39: Ground settlement around piers of a long span steel girder bridge observed in Mashiki town (N 32.7787; E 130.79.39).

Bridges in Mountainous Areas (Geotechnical Effects)

In many cases, landslides caused the collapse of a number of bridge decks (Photos 42 and 43). Some of the bridges were reinforced concrete and others were steel arch bridges.

Abutment foundation failure (Photo 44) and severe disruption to approach embankment of one bridge (Photo 45) were caused by the collapse of underlain columnar jointed bedrock in an incised gorge.

Photo 40: Local buckling of girder bottom. The girders were re-levelled temporarily with steel plates either side of original bearings (N 32.7790; E 130.7939).

Photo 41: Punching of I-shape girder ends into the abutment wall caused shearing of back wall (N 32.7789; E 130.7943).

Photo 42: Landslides caused the collapse of a number of bridges in the mountainous areas of Mt. Aso volcanic caldera (N 32.8834; E 130.9896).

Photo 43: Landslides caused also the collapse of bridge decks in the mountainous areas of Mt. Aso volcanic caldera (N 32.8752; E 131.9886). See also Photo 17.

Photo 44: Abutment foundation failure due to the collapse of underlain columnar jointed bedrock (N 32.8770; E 130.9840). See also Photo 18.

Photo 45: Severe disruption to approach embankment due to the collapse of underlain columnar jointed bedrock (N 32.8744; E 130.9827). See also Photo 18.

Bridges in Mountainous Areas (Structural Performance)

In the mountainous areas of Mt. Aso volcanic caldera near the fault rupture corridor, large vertical and horizontal accelerations also had adverse effects of bridge performance.

For example, the connection of the retrofitted damper of steel arch bridge failed at one abutment, and damper buckled at other abutment (Photo 46).

A curved steel arch bridge jumped laterally off bearings – up to 1.0 to 1.5 m. (Photo 47). Fortunately the pier heads were wide and strong enough to accommodate the translation of the deck of the 260 m long bridge.

Photo 46: Connection of a retrofitted damper of steel arch bridge failed at one abutment (N 32.8779; E 130.9094).

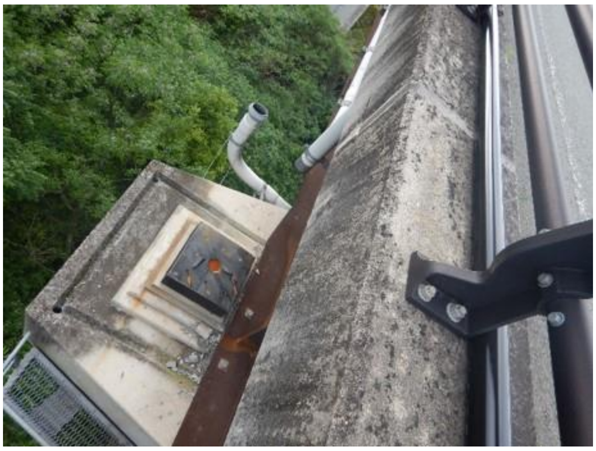

Photo 47: A curved steel arch bridge jumped laterally off bearings (N 32.8426; E 130.9272).

Expressway Embankment and Retaining Walls

In Mashiki Town, a retaining wall supporting an expressway embankment failed along a major drainage channel, removing two lanes of the expressway, and closing the adjacent bridge. The wall was being reconstructed at the time of the site visit using gravel filled polyester bags (Photos 48).

Expressway on embankment over low lying area suffered differential settlement which was particularly evident where the road passed over underpasses. Less settlement occurred at the structures than at the adjoining fill (Photo 49).

Photo 48: Collapse of a retaining wall supporting an expressway embankment. Gravel filled polyester bags were used to quickly rebuild the wall and reopen the expressway (N 32.7792; E 130.7943).

Photo 49: Settlement of expressway on embankment (N 32.7789, 130.7939.

Dam Sites

Ookirihata Earth Dam in Nishihara Village

In Nishihara Village, fault rupture damaged the spillway of the Ookirihata earth dam. The earth dam appeared to be relatively undamaged (Photos 50 and 51)

The reservoir was drawn down as a precaution and the village was evacuated immediately after the earthquake given the threat of dam break and flooding.

Photo 50: Fault rupture damaged the spillway of the Ookirihata earth dam (N 32.8414; E 130.9317). See also Photo 4.

Photo 51: Close up of the damaged spillway of the Ookirihata earth dam (N 32.8414; E 130.9317).

New Dam Construction Across the Shirakawa River Valley

In the Shirakawa River valley, the collapse of right abutment area destroyed the site access of a new dam and inundated construction equipment and infrastructure. Such damage is due possibly to fault rupture (Photo 52). At the time of the survey, remotely-controlled machines were used to clear up the site and rescue buried construction equipment in safety (Photos 53).

Photo 52: New dam construction site destroyed by fault rupture (N 32.8776; E 130.9764). See also Figure 20.

Photo 53: Remotely-controlled machines used to rescue buried construction equipment (N 32.8776; E 130.9764).

SOCIAL IMPACT

Sixty-nine people are reported to have been killed by the Kumamoto earthquakes [13]. Nine people died in the earthquakes on 14 April 2016 and the rest in the main earthquake on 16 April 2016. The nine deaths on 14 April 2016 are reported to have been caused by building collapses. A total of 1,679 people are reported to have been injured and one is missing. Of the 69 people killed, 49 deaths were caused “directly” by the earthquakes; 20 deaths following the earthquakes, due to injuries sustained during the earthquakes and from post-traumatic stress.

According to a preliminary report by the Ministry of Land, Infrastructure, Transport and Tourism of Japan [17], of the 49 deaths caused “directly” by the earthquakes, nine deaths were caused by landslides and their deaths are recorded as being from “asphyxiation” as they were buried alive. The missing person is also thought to have died due to a landslide as she was travelling on the Aso Ohashi Bridge, when it was hit by the debris avalanche, which caused it to collapse. The other 40 deaths were as a result of being crushed due to collapse of the buildings they were in.

Of the 20 people that died following the earthquakes, it has been reported that some of these deaths were due to deep-vein thrombosis, affecting people in the evacuation shelters. This is reported to have been a result of the limited physical space in these shelters. The Japanese Government is currently assessing each individual death to establish the causes.

KEY FINDINGS

Key findings from the NZSEE "Learning from Earthquakes" Mission to Kumamoto are as follows:

1. Engineering designed structures generally performed very well under moderately severe shaking, when not subjected to ground damage effects.
2. Severe building damage was concentrated relatively close to where the fault ruptured at the surface or along the projected fault plane.
3. Compared to liquefaction, which was a major feature of the Canterbury Earthquakes, the Kumamoto Earthquakes illustrated additional dominant hazards, such as landslides, ground shaking and fault rupture.
4. Landslides on steep slopes have failed in the upper parts of slopes, and this may be due to contribution from topographical amplification effects and the presence of weak soil / rock, leading to enhanced ground shaking.
5. Relatively gentle slopes can fail in earthquakes when underlain by weak and potentially sensitive soil (volcanic ash and pumice).
6. The hilltop cracking observed at the Aso Volcanological Laboratory may have been triggered by local site effects leading to amplification of shaking, possibly due to material contrast (shear wave velocity) and topography.
7. Rock slopes that perform well statically can fail in earthquakes, and lead to loss of support for structures founded on them. Dynamic performance of the rock slopes should be assessed considering the combined effects of ground shaking and the presence of rock defects and the rock mass characteristics.
8. Even small landslides / rock fall can lead to significant effects of the infrastructure, for example where the viaduct had its abutment undermined by slope failures, taking out the whole route.
9. Rainfall and wet conditions can lead to an exacerbation of the potential effects of landslides, both directly during an earthquake, and for a considerable period afterwards. There have already been three reported deaths and two people missing as a result of landslides triggered by rain in the region following the earthquake sequence.
10. Extreme load cases can cause failure of otherwise well-built structures. Examples include landslides on bridges causing catastrophic collapse, and landsliding undermining or engulfing well designed residential development.
11. Large vertical accelerations can have an adverse effect of structures which rely on gravity to restrain structures – bridges "jumping" off bearings. Fortunately the pier heads were wide and strong enough to accommodate the translation of the deck of a 260 m long curved steel girder bridge.
12. Unreinforced concrete facings on cut soil slopes performed well, except where the ground behind or beneath them was unstable and failed. Once the facing starts to move differently from the soil behind, loose drainage gravel behind it can drop down, wedging or jacking the facing out of alignment.
13. Site selection for urban development and route selection for critical infrastructure requires the identification of all potential geo-hazards, well beyond the immediate vicinity – for example Aso Ohashi Bridge, new dam construction site.
14. A lot of critical infrastructure (major roads and bridges, railway line, hospital, high voltage transmission lines and a dam site) was concentrated along the main river valley at the natural break in the slopes forming the outer crater. Multiple hazards occurred in this area as a result of the earthquakes, which effectively "cut off" people in the towns of Minami Aso and Aso from Kumamoto City. Access is now via local (minor) roads.
15. Benched cut slopes performed well compared to the surrounding slopes in a quarry.
16. Emergency flood protection can be achieved using soil filled bags wrapped in polyester, where liquefaction had led to subsidence.
17. Use of soil or gravel filled bags allows rapid and effective emergency slope repairs.
18. Underground utilities damaged by the earthquake were not being restored at the time of the visit one month after the earthquakes, because there was uncertainty about the future of some areas.
19. Liquefaction did not have significant surface expression in Mashiki Town, but the consequent subsidence and displacements led to significant damage. This is potentially due to the presence of a liquefaction resistant layer at the surface, but also, possibly due to increased liquefaction resistance of volcanically sourced alluvial deposits.

RELEVANCE FOR NEW ZEALAND

The observations made by the NZSEE team and their relevance to NZ are discussed below:

1. In general, the older houses with poor bracing performed worse than the newer ones.
2. Heavy tiled roofs led to poor performance, and while these are not common in some parts of New Zealand, they are still widely used in some areas.
3. Soft storeys performed poorly and this lesson from previous earthquakes was reinforced by observations in this earthquake.
4. About 10% of the total population were temporarily evacuated from those areas most affected by strong shaking, surface fault rupture and landslides. How would NZ cope with such an impact in e.g. Wellington?
5. There did not appear to be an obvious link between geohazard assessments being used to inform the locating of critical infrastructure (lifelines).
6. Land use planning should consider the potential effects of all natural hazards including earthquake effects.
7. Building on alluvial fans potentially introduces a risk to development from debris flow hazards in earthquakes, not only from extraordinary storm events.
8. A large proportion of those killed (at least 10) were from landslides. Many of the slopes are now cracked and there is an increase in the susceptibility of these cracked slopes to future failure in rain and/or earthquakes, and has led to further deaths. How would NZ deal with this?
9. At least two of the catastrophic landslides were on slopes that had not been identified as hazardous. It is important to consider the potential for landsliding even in gentle slopes, where such slopes are underlain by sensitive materials. For example, earthflows triggered by the 16th April 2016, earthquake were on slopes with angles of about 10-15º.
10. The volcanic soils in the earthquake performed poorly and led to failure of gentle slopes. A better understanding is required to consider the performance of New Zealand's volcanic soils in earthquakes – say in Tauranga and the

wider Volcanic Plateau and Taranaki which have sensitive ash deposits.

11. Unlike Japan, NZ does not currently carry out systematic hazard mapping to identify areas of potential landsliding.
12. Planning for post-liquefaction subsidence must consider effects on increased potential for flooding and the response to it. We have seen this effect in Christchurch.
13. Vertically unrestrained bridge structures can be dramatically affected by extreme vertical accelerations. It may be appropriate to review current guidance on dealing with this load case.
14. Earthquakes cause many hazards, and while liquefaction was a dominant hazard in Christchurch, it is not necessarily the case in all areas.

RECOMMENDATIONS FOR NEW ZEALAND ENGINEERING PRACTICE

The team suggests the following areas where further research or development of formal guidance is warranted:

- Encourage early involvement of appropriately experienced geo-professionals, as part of a multi-disciplinary team, in field visits and the selection of sites and routes for development of engineering projects.
- Review current guidance on site selection for development and major projects (e.g. Ministry for the Environment, Planning for development of land on or close to faults [24]) and develop expanded guidance to cover other hazards.
- Consider applying higher ground motion parameters for design close to active faults (need to consider what zone is appropriate based on the ground conditions and tectonics).
- Develop guidance for taking into consideration vertical ground acceleration in design and detailing.
- Research into the earthquake behaviour of sensitive/ unusual soils, including the liquefaction susceptibility of volcanically derived soils.
- Research into topographic amplification effects and guidance for design.

We are aware that some of these areas are already being investigated. Our observations from Kumamoto have confirmed the relevance and urgency of this work.

CONCLUDING REMARKS

Successful siting and design of resilient infrastructure requires the integrated effort of multi-disciplinary teams from an early stage, and should include geotechnical professionals, so that the hazards are identified to influence the design decisions.

Hazards originating well beyond a particular site can exceed design loadings or completely overwhelm buildings and infrastructure. The project team therefore, should look beyond the boundaries of the site.

A holistic approach from an early stage is essential to achieve resilient infrastructure, making sensible choices that take into consideration the wider environment and the uncertainty in the magnitude of hazards. As the design load cases could be exceeded, it is important to consider how the design can be tailored to ensure that the structure still performs in an acceptable manner to achieve resilience.

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