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The over-prediction of liquefaction in alluvially deposited volcanic sediments

D. Anderson & K.W. Franke
Brigham Young University, Provo, UT, USA

S. Dashti & M. Badanagki
University of Colorado Boulder, Boulder, CO, USA

R. Kayen
University of California Berkley, Berkley, CA, USA

ABSTRACT: In the 2016 M7.0 earthquake in Kumamoto, Japan, soil liquefaction occurred both less frequently and less severely than expected given the young geologic environment, high ground motions, and numerous layers of loose volcanic sand deposits. This paper summarizes findings from our field, laboratory, and analytical studies to assess the lower occurrence of liquefaction. Measured in-situ SPT and CPT resistance values were evaluated with current liquefaction triggering procedures. Undisturbed samples were subjected to cyclic triaxial testing. Furthermore, an extensive literature review on Kumamoto volcanic soils was performed. Our findings suggest that current liquefaction triggering procedures over-predict liquefaction frequency and effects in alluvially deposited volcanic soils. Volcanic soils were found to possess properties of soil crushability, high fines content, moderate plasticity, andunanticipated organic constituents. Cyclic triaxial tests confirm the high liquefaction resistance of these soils. Moving forward, geotechnical engineers should holistically consider a soil and geology before relying on standard liquefaction triggering procedures.

1 INTRODUCTION

The 2016 Kumamoto earthquake sequence is comprised of a series of earthquakes that began with a moment magnitude 6.2 event on the Hinagu Fault on April 14, 2016 (epicentral depth of about 11 kilometers), followed by another foreshock of moment magnitude 6.0 on the Hinagu Fault at on April 15, 2016, and a larger moment magnitude 7.0 event on the Futagawa Fault on April 16, 2016 beneath Kumamoto City, Kumamoto Prefecture on Kyushu, Japan (epicentral depth of about 10 kilometers). These events are the strongest earthquakes recorded in Kyushu during the modern instrumental era. The earthquakes resulted in substantial damage to infrastructure including buildings, cultural heritage sites (e.g., Kumamoto Castle), roads and highways, slopes, and river embankments due to earthquake-induced landsliding and debris flows. Surface fault rupture (Figure 1) produced offset and damage to roads, buildings, river levees, and an agricultural dam. Surprisingly, given the extremely intense earthquake motions, surface evidence of liquefaction was observed in only in a few districts of Kumamoto City and in the port areas, suggesting that the geotechnical properties volcanic soils were less susceptible to liquefying than expected given the intensity of earthquake shaking. Little to no lateral spread displacement was observed in the levees along the many riverbanks throughout the region as well.

2 GEOTECHNICAL EXTREME EVENT RECONNAISSANCE ASSOCIATION (GEER) IN KUMAMOTO, 2016

Immediately following the KES, the Geotechnical Extreme Event Reconnaissance (GEER) Association coordinated with the Japanese research colleagues to organize a post-event engineering reconnaissance effort to document engineering and scientific effects of significance for the purpose of advancinggeotechnical research and practice in this type of environment. The GEER Kumamoto field team's main goals were to (1) quantify the spatial extent and characteristics of the surface fault rupture, and (2) to document geotechnical failures and non-failures (e.g., damage from the Kumamoto and Aso San Caldera area due to soil-foundation-structural failures, ground failures, soil liquefaction, landslides, and damage to bridges, piers, ports and harbors, lifeline systems, earth dams, levees, and other critical facilities). It was deemed important to document not only poor ground performance, but also surprisingly good ground performance in the Kumamoto region with regard to expected liquefaction effects that were not encountered.

Due to the necessary follow-on recovery and reconstruction activities, much of the critically important observable damage was perishable. As such, the GEER team was on the ground in the damage zone within three weeks after the event, immediately after the initial humanitarian response phase had ended. In accordance with the main team goals stated above, the primary daily duties of the Kumamoto GEER reconnaissance team were to (1) identify critical case histories, and (2) report its findings rapidly on the GEER website through the preparation of a publicly available technical report (Kayen, Dashti, et al. 2016). The basic fault layout and earthquake sequence is shown in Figure 1.

According to the Geologic Survey of Japan (GSJ), Kumamoto is located on a complex structure of Paleozoic, Mesozoic, Cenozoic, and Neogene rocks. Above this geologically old structure is a plain composed of Paleogene and Holocene pyroclastic flows and alluvial

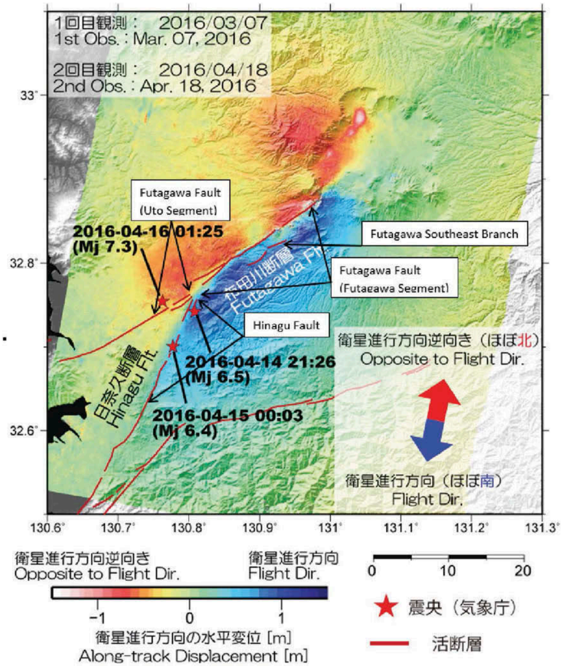


Figure 1. Multiple Aperture Interferometry (MAI) processed from ALOS-2 provided by the Geospatial Information Authority of Japan (GSI, 2016). The red lines are previously mapped active fault traces prior to this earthquake sequence.

sedimentation. The plain is composed of volcanically derived material intercalated with many layers of volcanic ash, deposited from the massive Aso caldera to the east.

The urban area of greatest damage, Mashiki-Mura is located on the south-facing slope above the alluvial plain and below the Pleistocene fluvial terrace deposits and pyroclastic flows. A manifestation of the volcanic origin of the sediments underlying Kumamoto City was seen in sand as surface ejecta resulting from the earthquake shaking of April 14 and April 16. With the exception to fill deposits, all of the observed sand boils were dark, seemingly mafic granular material. Inspection of this material found that it was composed of pumice and coherent granular volcanically derived material. The volcanic origin and dark coloration was in stark contrast to typical liquefaction surficial materials derived from the weathering of sedimentary, metamorphic, or plutonic rocks. It was hypothesized at the time of the reconnaissance that lack of abundant liquefaction manifestation or damage was likely due to the presence of high plastic fines content associated with hydrous clays that are products of weathering volcanic terrain. Volcanic soil is also highly angular compared with spherical quartz grains. This angularity may be associated with denser packing materials and lower liquefaction susceptibility.

3 PROCEDURE

A variety of testing methods were used to determine why liquefaction was sparse in the area. Four testing sites were chosen for test holes, SPT, and CPT analysis. The exact locations are listed in Table 1. Site 1 was chosen because of its proximity to liquefied farm fields. This neighborhood experienced no liquefaction and was located on a natural levee. Site 2-1 was chosen because it experienced the most severe liquefaction in Kumamoto city. Site 2-2 was located nearby to site 2-1, and suffered no liquefaction damage. Figure 2 shows that most samples were not susceptible to liquefaction according to the Bray and Sancio (2006) criteria. Site 4 was located close to the epicenter and was chosen because of perceived lateral spread

Table 1. Test sites for analysis of liquefaction triggering

Test Hole	Latitude	Longitude	Description
Site 1	32° 44’ 17.44”	130° 42’ 2.47”	Un-liquefied village, farm land liquefied
Site 2-1	32° 46’ 11.73”	130° 41’ 33.90”	Severe liquefaction, downtown
Site 2-2	32° 46’ 11.88”	130° 41’ 29.39”	No liquefaction. downtown
Site 4	32° 46’ 24.65”	130° 46’ 24.65”	Minor liquefaction, potential lateral spread

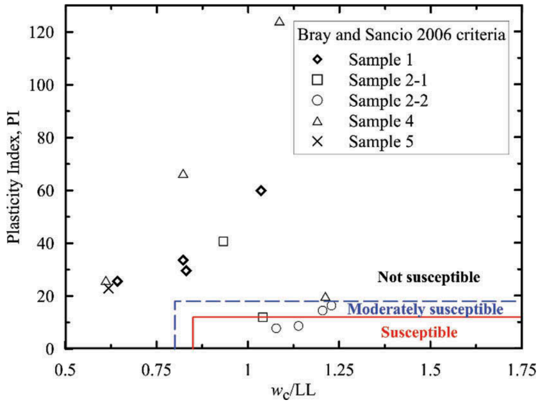


Figure 2. Liquefaction susceptibility based on Bray & Sancio (2006)

that had occurred. Each of these sites had laboratory, SPT, and CPT testing as well as undisturbed sample collection done by the Tokyo Soils and Research Co. Triaxial testing was done at the University of Colorado Boulder. An extensive literature review was conducted to better understand volcanic soils and their unique engineering properties.

SPT based liquefaction triggering procedures were performed using the Boulanger and Idriss (2014) method. This method is commonly used in the United States and is a well-researched method based on silica sands. The method is routinely updated with new case histories.

CPT based liquefaction triggering procedures were performed using the Boulanger and Idriss (2015) and Robertson and Wride (1998) methods. These methods are commonly used in the United States and give similar results that tend to be within 15% of each other. CPT-based liquefaction primarily defines a soil's susceptibility to liquefaction by comparing the Soil Behavior Type Index, I_c. An I_c value of 2.7 was considered not susceptible to liquefaction (Robertson, 2009).

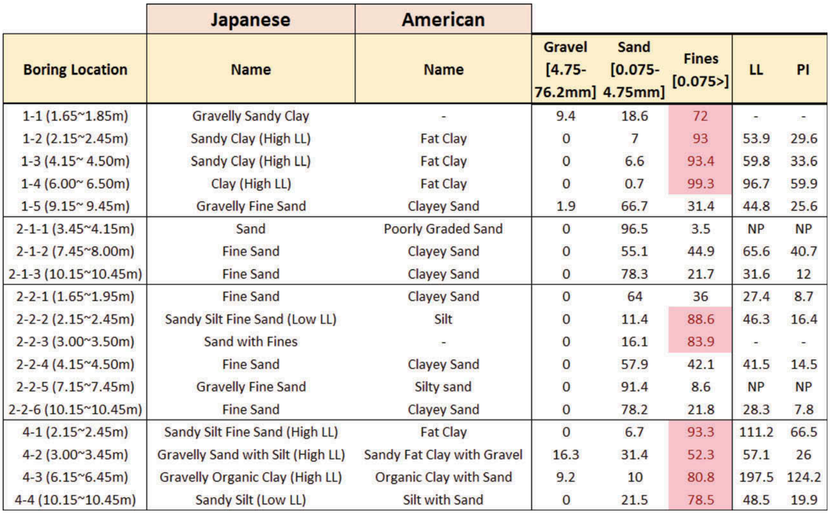
Isotopically consolidated, undrained, strain-controlled cyclic triaxial tests were conducted on a number of relatively undisturbed samples obtained from Kumamoto, Japan to evaluate their stiffness degradation and generation of excess pore pressures under cyclic loading with a range of strain amplitudes ($\varepsilon_a = 0.22 - 1.38\%$). The sinusoidal cyclic loading in the cyclic triaxial tests was applied with a frequency of 1 Hz.

4 RESULTS AND DISCUSSION

The SPT blow counts were unpredictably low for all the sites. Sites 1 and 4 had extremely low blow counts and several meters of hammer self-drop material. The lower 2 meters of these sites had blow counts of about 10-20. This is in standing with the pyroclastic sand layer that should be deposited at that depth throughout the plain. Sites 2-1 and 2-2 showed mostly low density sand. The sands were overlain by a layer of volcanic ash fall. Close inspection of Table 2 shows some discrepancies between Japanese and US soil classifications. It is likely that some translation errors on the side of the Japanese resulted in misclassification. In general, the soil summary shows a high fines content for all test holes. Even the dominate sand profiles of sites 2-1 and 2-1 show sands with significant plasticity and fines.

An SPT analysis using Boulanger and Idriss (2014) liquefaction triggering procedures showed slightly conservative results but were generally consistent with observed field

Table 2. Soil summary data with differences between Japanese and American soil classification.



	Japanese	American					
Boring Location	Name	Name	Gravel [4.75-76.2mm]	Sand [0.075-4.75mm]	Fines [0.075>]	LL	PI
1-1 (1.65~1.85m)	Gravelly Sandy Clay	-	9.4	18.6	72	-	-
1-2 (2.15~2.45m)	Sandy Clay (High LL)	Fat Clay	0	7	93	53.9	29.6
1-3 (4.15~ 4.50m)	Sandy Clay (High LL)	Fat Clay	0	6.6	93.4	59.8	33.6
1-4 (6.00~ 6.50m)	Clay (High LL)	Fat Clay	0	0.7	99.3	96.7	59.9
1-5 (9.15~ 9.45m)	Gravelly Fine Sand	Clayey Sand	1.9	66.7	31.4	44.8	25.6
2-1-1 (3.45~4.15m)	Sand	Poorly Graded Sand	0	96.5	3.5	NP	NP
2-1-2 (7.45~8.00m)	Fine Sand	Clayey Sand	0	55.1	44.9	65.6	40.7
2-1-3 (10.15~10.45m)	Fine Sand	Clayey Sand	0	78.3	21.7	31.6	12
2-2-1 (1.65~1.95m)	Fine Sand	Clayey Sand	0	64	36	27.4	8.7
2-2-2 (2.15~2.45m)	Sandy Silt Fine Sand (Low LL)	Silt	0	11.4	88.6	46.3	16.4
2-2-3 (3.00~3.50m)	Sand with Fines	-	0	16.1	83.9	-	-
2-2-4 (4.15~4.50m)	Fine Sand	Clayey Sand	0	57.9	42.1	41.5	14.5
2-2-5 (7.15~7.45m)	Gravelly Fine Sand	Silty sand	0	91.4	8.6	NP	NP
2-2-6 (10.15~10.45m)	Fine Sand	Clayey Sand	0	78.2	21.8	28.3	7.8
4-1 (2.15~2.45m)	Sandy Silt Fine Sand (High LL)	Fat Clay	0	6.7	93.3	111.2	66.5
4-2 (3.00~3.45m)	Gravelly Sand with Silt (High LL)	Sandy Fat Clay with Gravel	16.3	31.4	52.3	57.1	26
4-3 (6.15~6.45m)	Gravelly Organic Clay (High LL)	Organic Clay with Sand	9.2	10	80.8	197.5	124.2
4-4 (10.15~10.45m)	Sandy Silt (Low LL)	Silt with Sand	0	21.5	78.5	48.5	19.9

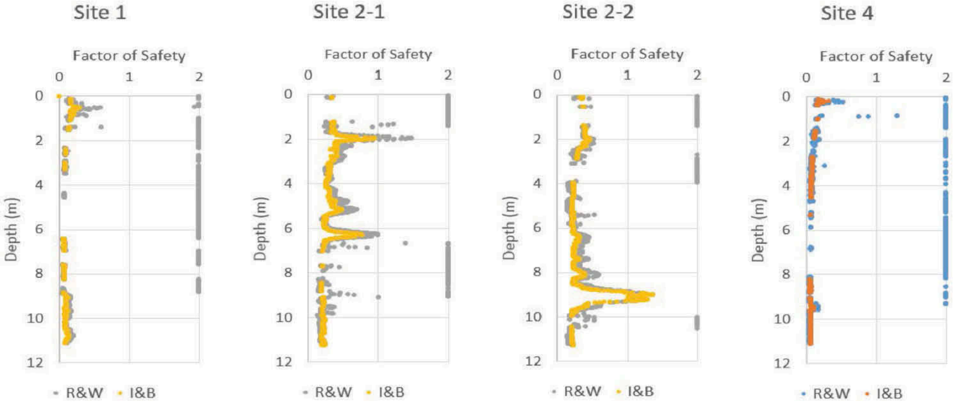


Figure 3. CPT liquefaction triggering using Boulanger and Idriss (2014) and Robertson and Wride (1998).

observations. Both sites 2-1 and 2-2 showed around 3 meters of liquefied material at depths less than 10 meters. This is consistent with site field observations of site 2-1 but inconsistent with field observations of 2-2, which confirmed no liquefaction induced settlement. Sites 1 and 4 were consistent with field observations. The lack of surficial liquefaction at site 2-2 may be partially due to a liquefaction resilient layer on the surface. A non-susceptible silty ash material was commonly found overlaying soils of the plains.

Both CPT liquefaction triggering procedures gave similar results as shown in Figure 3. Severe liquefaction was predicted at each site, with factors of safety varying by about 15%. Both procedures consistently predicted significant liquefaction for all sites on the scale of about 5-8 meters of liquefied material for each site. The CPT results do not reflect observed field observations. The source of error in the procedure seems to be in calculating the I_c of the material. The iterative procedure to acquire I_c does not seem to adequately account for some properties of volcanically derived soils such as soil crushability. Care should be taken when determining I_c for volcanic soils. Some of the complexities regarding the calculation of I_c is mentioned by Robertson especially with regards to high fines content soils (2009).

The cyclic triaxial tests indicated a generally high degree of resistance to liquefaction triggering at these sites. The approximate value of CSR and equivalent number of cycles observed during the strongest event in Kumamoto (2016) shown as the red star in Figure 4 plotted just below the CRR curve obtained from the triaxial tests, indicating these soils barely approached liquefaction only during the strongest and longest duration event. The results from different stages of analysis and testing are consistent and confirm why widespread liquefaction and its consequences were not observed in Kumamoto following such strong events.

The reasons the SPT was over conservative and the CPT was inaccurate for analysis is described by a simple observation observed by the GEER team when they visited Kumamoto directly after the 2016 earthquake. The members of the reconnaissance noted that much of the sand boils were composed of black, sticky, and pumiceous materials. All sand boils, with the exception of fill materials were dark, mafic granular material with cohesive pumice and volcanically derived material (Kayen et al, 2016). Three key components to Kumamoto volcanic soils that makes them more resilient to liquefaction than traditional quartz sands are 1) organic constituents, 2) high soil plasticity, and 3) soil crushability.

Dark soil is indicative of organic constituents in a soil. The Tokyo Soils and Research Co. noted organic components in many of the test holes. Many of the test holes contained minor bit of organic materials which is likely due to Holocene ash fall. Regular ash fall in the area damages and buries crops which were likely mixed into the deeper soil layers. The soils of Aso, which are the primary soils of which the Kumamoto plain is composed of, has clay rich

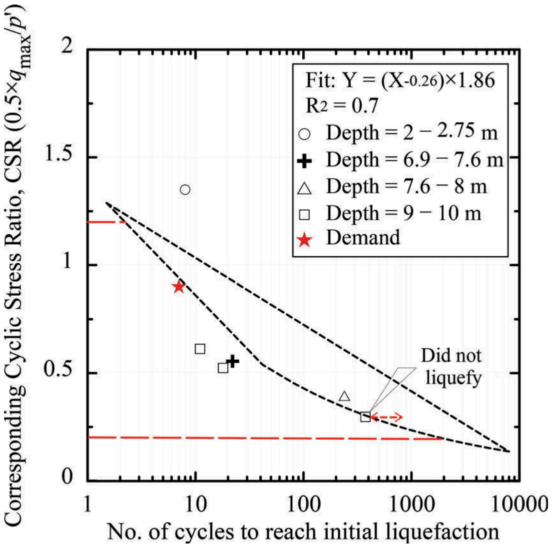


Figure 4. CSR vs. Number of cycles obtained experimentally on Kumamoto samples.

soils. These soils are allophanic and halloysite soils which are washed down into the Kumamoto plain. Because the Aso caldera is still active and regularly deposits fresh volcanic sediments, there is a continual supply of fresh volcanic components. Allophanic soils eventually weather into halloysite and eventually become kaolinite soils (Gieseking et al, 2012). The rate of organic accumulation in these soils is directly linear to the degree of clay material in the soil. Thus, for high clay component volcanic soils, it should be expected that there is some organic accumulation in the soil (Shoji et al, 1993). Organic components in a soil rapidly speed up the weathering process of volcanic ash soils and lead to fines generation. In addition, organics in a soil increase the soil's resistance to liquefaction.

The soils in the Kumamoto area have high levels of plasticity. Even the sandy soils had levels of plasticity typically considered too high for liquefaction susceptibility. This must be due to the weathering of volcanic ash soils and pyroclastic material. Man-made fill had little to no plasticity and was susceptible to liquefaction, as seen in the neighborhood to the north of site 4. However, for the most part, other soils were too plastic to liquefy. The Japanese publicly available boring logs typically did not display this amount of soil plasticity, unless there was accompanying soil test data available. Some farm lands which had sand and gravelly upper soil layers experienced liquefaction. It seems that ash falls from the surrounding Aso caldera have deposited a meter thick layer of silty volcanic ash, which may have limited surficial manifestations of liquefaction. In addition, this silty ash layer would have easily weathered into clay. The less plastic material would have been the native pyroclastic flows which were at least 10 meters or deeper. These layers are composed of pumice and other crushable grains and would have weathered into clayey material, quite like the surface of the Kumamoto plain. High fines content is further explained by the geomorphology of the plain. The Kumamoto plain is home to several large rivers that often overflow and deposit flood sediments. Much of the plain is classified as a floodplain and natural levee. Many of the finer grained suspended loads in the rivers, would have been able to deposit onto the plain, which would greatly increase the plasticity of the soil. Because of the regular frequency of flooding which occurs even with manmade levees and flood protection, there is a large clay content in the soil.

Pumice grains in the soil gave artificially low values for both SPT and CPT penetration readings. These materials are crushable and tend me break easily when testing with dynamic testing equipment like the SPT hammer or CPT cone. The Kumamoto plain is made of volcanic sediments, mainly weathered welded tuff and volcanic top soil from the Aso caldera.

Crushable soils tend to have a high shear resistance, be angular, and have greater resistance to liquefaction (Liu et al, 2015). Soil crushability of pumice mainly applied to coarse-grained soils such as sands and gravel. Crushable soils have less correlation of relative density on cyclic resistance due to particle crushing. Thus, standard liquefaction triggering procedures, which heavily utilize relative density to determine liquefaction triggering are not appropriate for these soils. Dense pumiceous sands are similar to dense quartz sands but loose pumiceous sands have been reported to have twice the cyclic resistance of loose quartz sands (Orense et al, 2014). The soils in the Kumamoto plain were not directly tested for their crushability. However, reconnaissance and other reports confirmed the presence of pumice in the city and welded tuff, which is partially composed of pumice, lapilli, volcanic ash, and lithic fragment certainly has some degree of crushability. Standard triggering procedures for liquefaction tend to under predict a soil's resistance to liquefaction (Orense et al, 2012). SPT testing is a dynamic test in which large strains are exerted upon the soil, crushing soil with the impact and giving lower SPT values than reality. Likewise, CPT testing was found to underestimate the cone penetration value required for a specific CRR. Non-destructive methods such as shear wave testing is the best way to test crushable soils.

Lastly, publicly available boring logs retained the driller's visual classification on the soil log, rather than updating the log after soil testing. Only examining soil testing results can one confirm the accuracy of the boring log. This was confirmed by inspecting public tests logs and the boring logs from the Tokyo Soils and Research Co. The given boring logs retained field classifications and did not update to laboratory classifications.

5 CONCLUSION

This paper discusses why substantial liquefaction was predicted for the 2016 Kumamoto earthquake. The main reasons liquefaction did not occur were due completely to the soil conditions in the plain. Engineers should holistically consider the geology and any unique aspects of a soil before continuing on with traditional analysis methods. In the case of Kumamoto, the special properties of the volcanic soils were key to understanding the paucity of liquefaction. The following were conclusion obtained after this research.

1. Volcanic soils, depending on the region and depositional type, may contain properties of soil crushability. Additional laboratory testing should be performed to better understand the soil before correlations are applied.
2. Volcanic soils can quickly weather into fine clay material with high plasticity.
3. Volcanic soils may contain higher levels of organic components than traditional soils.
4. Care should be taken to understand classification schemes and practices for foreign nations. This will greatly assign in misinterpreting data.

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