GEOTECHNICAL/ GEOLOGICAL PROBLEMS HIGHLIGHTED IN THE RECENT DESTRUCTIVE EARTHQUAKES IN JAPAN

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ABSTRACT

Remote sensing imagery with “very high” spatial resolution is becoming routinely available. Because soils are hysteresis materials exactly like a magnetic storage device recording the past, high-resolution remote sensing images often capture not only the real devastations but also marks of past disasters, suggesting that similar events may have happened over and over at the same location. Actual examples in recent earthquakes such as the 2011 Great East Japan Earthquake, the 2016 Kumamoto Earthquake and the 2018 Hokkaido Eastern Iburi Earthquake are given herein. These examples include liquefactions, landslides, etc. As long as clear evidence of past large soil deformations is there, we can bring potential hazard to light and take necessary actions. However, these pieces of evidence can often be draped with surface soil deposits particularly when we have volcanoes nearby. Moreover, porous nature of these volcanic matters can cause never-seen-before phenomena of large soil deformation, which phenomena are to be thoroughly studied and passed down to posterity.

Introduction

Earthquake hazard maps have been prepared by many municipalities in Japan as a mean to help people know earthquake-hazard-susceptible locations. The Japanese Ministry of Land, Infrastructure, Transport and Tourism made a web portal “Wagamachi” available in 2007 (MLIT, 2007) to bring hazard-map information from diverse municipalities. “Wagamachi” literally means “My town”. However, when we look up liquefaction hazard maps on this web portal, we realize that there yet remain many municipalities left completely blank, which include those affected by liquefactions in recent devastating earthquakes. The Japanese Ministry of Internal Affairs and Communications made its study result public in 2015 (MIC, 2015). The result says that 33% of municipalities in Japan never had regular full-time officers for disaster management. This percentage has been improved as compared with 45% in 2009. However, it still remains as a difficult task for many municipalities to prepare liquefaction hazard maps, which task requires a lot of time, efforts, costs and knowledge to not only read many borehole logs but also develop scenario earthquakes.

However, soils are hysteresis materials exactly like a magnetic storage device recording the past. Thus, high-resolution remote sensing images often capture not only the real devastations but also marks of past disasters, suggesting that similar events may have happened over and over at the same location. Actual examples in recent earthquakes such as the 2011 Great East Japan Earthquake, the 2016 Kumamoto Earthquake and the 2018 Hokkaido Eastern Iburi Earthquake are given herein. These examples can offer another perspective on what will likely happen in the future.

Liquefactions

Once soil liquefies in an earthquake, liquefied soil grains are going to re-establish slowly their fabric due to the effect of gravitational force, which process is very similar to the process that they were originally deposited in water. Thus, the liquefaction hardly improves the soil’s characteristics, and the granular fabric can remain as weak as before. Yokoyama et al. (2012) conducted a series of Swedish weight sounding (SWS) tests in Urayasu, Chiba, Japan, which liquefied in the Moment Magnitude ($M_w$) 9.0 Off the Pacific Coast of Tohoku Earthquake of March 11th, 2011, also known as the Great East Japan Earthquake. The team had conducted the tests at the same location over and over since before the earthquake, and they could see the chronological change of the liquefied soil in terms of its strength (equivalent N value) as shown in Figure 1. It is noted in this figure that it took about a month or two for the liquefied soil to regain its strength, and the regained soil strength was slightly above or below its original strength (broken line), indicating that it has again become vulnerable to liquefaction.

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The March 11th, 2011 Great East Japan Earthquake has shown that a long stretch of landfills along shorelines of the Tokyo Bay has very high susceptibility to liquefaction, causing concerns about re-liquefactions of the area in the scenario earthquake expected in the capital’s metropolitan area. An attempt was made by the author and his colleagues to detect liquefaction-induced soil subsidence from raster images converted from airborne LiDAR (Light Detection and Ranging) data before and after the earthquake (Konagai et al, 2013). To eliminate deep-seated tectonic displacements and systematic errors of LiDAR surveys, the template matching technique was used for clusters of pile-supported buildings and bridge piers chosen as templates in source images of the target areas. The obtained subsidence maps describe the spatial distribution of soil subsidence in great detail (Figure 2 for the northeastern half of the Tokyo Bayshore Area). Figure 2 shows changes in elevation measured after almost all sand ejecta were cleared up from streets. As the color shifts from yellow to blue, the ground subsidence becomes larger (see the legend). Taking the slow strength-recovery process of liquefied soil into account, the amount of ground elevation loss was considered not due to the soil densification but largely due to the removal of sand ejecta. Therefore, it is expected that there yet remain liquefaction-susceptible weak soils just beneath blue-colored sunken areas. Some recent studies including the one by Kiyota et al. (2017) are now paving the way to assess liquefaction potential in a quantitative manner with easy-to-reach information of in-situ shear wave velocities. These methods together with the ground-subsidence maps will help examine the liquefaction susceptibility over a wide area in a rational and practical way.
Landslides

Starting with a $M_w$6.5 foreshock on April 14, 2016, a series of major earthquakes including the $M_w$7.3 main shock on April 16 hit the central Kumamoto area of Kyushu, Japan, causing deaths, injuries and widespread damage to various facilities. The observed features of the damage again showed that not only intense shakes but also ground deformations such as landslides, etc., which were found within a swath along Futagawa fault that moved in this earthquake, can be equally or more often responsible for devastations. According to Japan Railway Kyushu (2017), 73% of about 750 compiled damage reports were of landslides, rock falls and debris flows, 20% were due to rail track deformations, and the remaining 7% were about damage to buildings. The “Ground zero” in terms of extensive damage to transportation systems was in and near a narrow valley cutting deep across the world largest caldera of Mt. Aso. This opening has formed as a consequence of an accumulation of continual extensional movements of the SW-NE trending Futagawa fault that diagonally crosses the caldera wall. Major landslides occurred along this narrow valley and along the wall of the caldera. These landslides included the largest one that has hit an important location for traffic, transmission lines and a waterway leading to a penstock (see Figure 3). LiDAR. Laser based altimetry, can penetrate through tree canopy, revealing detailed feature of bare earth left behind by past natural hazards, and the LiDAR image in Figure 3 shows evidence of past landslides as well as the most recent one. Moreover, cracks are seen along the exposed scar indicating potential future risk.

Soils are hysteresis materials exactly like a magnetic storage device recording the past. As long as clear evidence for past large soil deformation is there in LiDAR images, landslides/active fault maps etc., we can bring potential hazard to light and take necessary actions. However, these pieces of evidence can often be draped with surface soil deposits particularly when we have volcanoes nearby. Moreover, these volcanic matters are extremely porous and thus have crushable nature. Once these volcanic matters are completely water saturated, grain crushing, which can occur in an intense earthquake, can cause a sudden increase in excessive pore water pressure, and trigger landslides even on extremely gentle slopes. One of these large-scale runout slope failures, known as the Takanodai landslide on a 12 degrees gentle slope, destroyed at least 7 houses and killed 5 people (Chiaro et al., 2018).

The $M_w$6.7 September 6, 2018 Hokkaido Eastern Iburi Earthquake produced the largest area of multiple landslides, $A_{exposed} \cong 13.4 \, \text{km}^2$, in the past 100 years or more. The multiple landslides can largely be attributed to the geological features of the region. As shown in many reports of geological surveys, the region is draped thick with volcanic ash and crushable pumice from nearby volcano eruptions of Shikotsu (about 40,000 years ago), Eniwa (about 20,000 years ago) and Tarumae (about 9,000 years ago). Many of these landslides slid even on very gentle slopes. To examine the mobilized frictional coefficient, the movement of a single planar and coherent landslide mass that has slid along Line C3-C4 in Figure. 4 was discussed by Konagai et al. (2018). This planar landslide mass, after sliding on the very gentle slope with the average inclination of about 0.2 (Figure 4), hit the opposite wall of a shallow valley and stopped forming a transverse
bulge as illustrated in Figure 5. This bulge is assumed to have developed where two-dimensional wedges of passive soil failure formed one after another at the boundary between the toe part pressed against the opposite valley wall and the slowing tail part with the uniform thickness $H$ as illustrated in Figure 5. This tail part was gradually shortening until its final length of $L$ was reached. Equation (1) shows the final equilibrium condition immediately before the final length $L$ of the tail part is reached:

$$\gamma_t H L \sin \theta - \gamma_t H L \mu \cos \theta \geq \frac{1}{2} K_p \gamma_t H^2$$

(1)

where, an inequal sign is necessary because the bulge worked as a surcharge, $\gamma_t$ = unit weight of the wet landslide mass, and $K_p$ = coefficient of passive earth pressure, which is given by:

$$K_p = \tan^2 \left( \frac{\pi}{4} + \frac{\phi}{2} \right)$$

(2)

with $\phi$ = internal friction angle of the landslide mass, which ranges in the epicentral area from 42 to 48° under low effective confining pressures (Kitago et al., 1973). Assuming that $\phi \approx 45^\circ$, $H \approx 1.5$ m and $L \approx 30$ m for the Line C3-C4, $\cos \theta \approx 1$ and $\sin \theta \approx \theta$ given that $\theta \approx 0.2$, one obtains;

$$\mu \leq \theta - \frac{1}{2} K_p \frac{H}{L} = 0.2 - \frac{5.83 \times 1.5}{2 \times 30} \approx 0.054$$

(3)

There are still much to examine to be sure, but this value suggests that the sliding surface beneath the landslide mass must have been very slippery like a banana peel.

**Never-seen-before Phenomena**

The 2016 Kumamoto Earthquake was followed by torrential rain of June 20 and 21, 2016, and a low-lying
valley south of Mashiki town cutting shallow into the outer foothill of Aso Caldera was flooded (Konagai et al., 2017). When digital terrain models of this area before and after the earthquake are compared, this area is found sunken by more than a meter (Figure 6). The swelling water of Kiyama River that flows through the low-lying area overtopped the left river bank at the location of the red place mark shown in Figure 6. This ground subsidence is considered to be largely due to tectonic deformation. However, a never-before phenomenon observed in the west part of the inundated area was that many RC housings for pumping facilities for water wells were found tilting as illustrated in Figure 6. Kumamoto city depend 100% on groundwater from nearly 100 water wells, and the main shock was the most damaging, resulting in nearly 460,000 customers’ outages. One of the primary reasons for the outages was rather artificial due to regulatory requirements for clean water quality. Kumamoto city has set a standard on the allowable turbidity in drinking water. When the turbidity 5 on the Japanese Turbidity Standards (JIS K0101) is reached in any well, its pump stops automatically. If all pumps in the tilting housings have stopped due to the increase of turbidity, it may suggest that the soil grain crushing may have occurred in their common aquifer underneath the flood plain due to large strain build-up.

Angles and directions of tilt of these well-pump housings were measured using a total station (Figure 6). Tilt angles ranged from 1 to 2 degrees, and there was no clear directional regularity observed for these housings. However, it is noted that the steel shaft of each well embedded about 170 to 200 m deep in the thick deposit of volcanic matters goes straight up to its housing and is clamped to the floor off its exact center such that the steel shaft is much closer to one of four corner columns of the housing. Meanwhile four corner columns of the housing are supported by PC piles, 2 piles for each column, and thus total 8 piles, which are all about 20 m long embedded in the uppermost organic clay layer. Now that each housing is found tilting towards the farthest corner from its steel shaft, it is considered that the uppermost organic soil layer has sunken as a whole in the earthquake dragging down all PC piles, while the steel shaft of each well worked as a strut. Though negative skin frictional forces could have been exerted equally upon all PC piles, the largest distance from the strutting steel shaft made the moment from the farthest pile be the largest, and thus caused the housing to tilt in that particular direction.
The tilts of housings thus suggest that some layer(s) somewhere between -20m and -200m depths may have been sheared and compressed. This phenomenon and its cause are to be thoroughly studied because any deformation of the ground surrounding underground facilities can be responsible for damage to them.

Conclusions

Not only intense shakes but also large ground deformations in an earthquake can be equally or more often responsible for serious devastations. These ground deformations can occur over and over at the same locations. Even soils that liquefied in an earthquake, which often leave marks of serious ground depression, can remain as weak as before. That is why advanced remote sensing technology helps estimate susceptibility of ground deformations. Sometimes, these marks of large ground deformation can be draped with newly deposited soils such as pumice and volcanic ash. These porous volcanic matters can exhibit extremely slippery nature when they are wet and crumbled and cause multiple landslides even on gentle slopes. A never-seen-before phenomenon, which may be attributed to the crushable nature of volcanic matters, was observed in the 2016 Kumamoto Earthquake. Many RC water-well pump housings were found tilting near the western foothill of Aso volcano. Each housing has four legs on 20 m long pile foundations, while its steel shaft, embedded about 170 to 200 m deep in the thick deposit of volcanic matters, goes straight up to the housing and is clamped to the floor off its exact center. Since every housing was found tilting towards the farthest corner from its steel shaft, the shaft seems to have worked as a strut suggesting that some layer(s) above -200m depth may have been compressed in the earthquake. Even after the wound from a big earthquake heals, ground depressions remain forever causing long lasting problems such as flooding. For better post-quake rehabilitations and to be prepared for the next big event, landform changes are to be recorded in a quantitative manner, and their causes are to be thoroughly studied.

References


