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Ground deformation and proposed mitigation during 2011 gigantic earthquake in Japan

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ABSTRACT: There are three types of important ground deformation caused by earthquakes. The first is the one by subsoil liquefaction. Although many countermeasures to stop liquefaction are available nowadays, they are not relevant for small structures. The 2011 earthquake severely damaged house foundations by liquefaction and now attempts are going on to reduce future risk by inexpensive soil improvement under “existing” houses. The second is slope instability. Fill parts of residential development in hilly areas were severely damaged. The Japanese Geotechnical Society established a system of qualified evaluator of subsoil so that people can easily know the potential risk of their land upon natural disasters. Moreover, recent experiences in Wenchuan earthquake in China and Kashmir earthquake in Pakistan indicate that slope failures may continue for years or more if they are located near a big causative fault. Local communities have to be prepared for this difficult situation. The third is fault. Although rare, fault action can cause fatal damage in structures. The current mitigation against fault is only avoiding. It is attempted to develop technologies that can reduce fault-induced damage of “existing” structures.

1 INTRODUCTION

Natural disaster is always a terrible phenomenon and our community unanimously wishes to avoid it. However, because the nature is beyond human control, it is impossible to stop the onset of natural disasters and we can only mitigate the negative aspects of natural phenomena. For this aim, human has developed many technologies and social systems. Natural disaster is an effective opportunity to validate those developments under real adverse situations. Hence, after disasters, we have to study what happened and try to learn lessons. The M=9 gigantic earthquake in Japan associated with tsunami was a terrible disaster but, at the same time, many lessons were learnt and opportunities for better safety in future were offered. The concerned topics range from tsunami mitigation, nuclear issues, ground shaking etc. to post-quake response and shortage of electricity and fuels. The present paper picks up three issues out of them and addresses details with a special emphasis on better future.

2 2011 EARTHQUAKE OF M=9 IN JAPAN

The bottom of the Pacific Ocean off the north-east part of Japan has been tectonically very active and many earthquakes of magnitude around 8 occurred in the past once every hundreds of years or so. Accordingly, the next one had been expected to occur as well with a seismic magnitude of around 8. What happened in 2011 was, however, substantially more devastating with its magnitude of 9 whose tectonic rupture extended over several hundreds of km associated with many aftershocks. Notably the height and range of tsunami were beyond the preparation.

Figure 1 Intact buildings in the center of Sendai City

A good news is that very few buildings were damaged during the earthquake (Figure 1) because of the development of structural dynamics and seismic design codes for buildings. Similarly, harbours, railway structures etc. that were designed against earthquakes by the latest design principles were able to survive the gigantic earthquake. What were significantly affected were such inexpensive structures as private house foundation, river levees, and lifelines that had not been prepared for earthquake effects because of financial limitations. Another problem happened in fuel supply and logistics. They are however out of scope of the author.

3 LIQUEFACTION IN HOUSE FOUNDATION AND FUTURE MITIGATION

3.1 Damage in personal residential ground

Many man-made islands have been constructed since 1970s along the shore of Tokyo Bay and some of them were designated as residential areas. Moreover, small lakes have been buried and converted to residential development in the recent decades. Liquefaction occurred in those young loose sandy water-saturated subsoil significantly in 2011. Figure 2 shows a typical liquefaction damage of a private house in which there is no structural damage but subsidence and tilting are substantial. Because of the subsidence, connection with lifelines were destroyed. Liquefied sand flowed into sewage pipelines from broken connections and stopped the sewage operation. Because of the tilting, daily life caused bad health problems; if tilting was more than 6/1000, residents felt dizziness and headache (Japan Structural Consultants Association, 2011). Heavy structures subsided while lighter underground structures floated. Figure 3 illustrates an underground parking that floated extensively due to liquefaction.

Figure 2 Liquefaction-induced subsidence

Figure 3 Floating of underground car parking

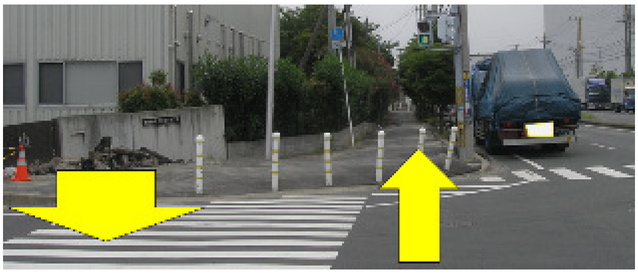

Figure 4 Subsidence of private building into liquefied subsoil induced distortion of public sidewalk

The current legal framework states that the restoration and possible soil improvement are responsibility of land owners who are seldom engineers. Although the owners complain that they did not know anything about liquefaction risk when they purchased the land, the legal principle does not change.

The author has been and still is engaged in the technical advisory for restoration of Urayasu City that is immediately to the east of Tokyo where liquefaction in man-made island affected more than 9000 houses. Because this number is substantial and similar bad situation happened in many other municipalities as well, the national government established a framework of public support for restoration of private houses. This program spends public fund to improve subsoil under both public streets and private houses together, because liquefaction in private land induces deformation in public land, affecting road traffics and operation of lifelines (Figure 4). This way of thinking was approved by the financial sector of the national government and the public money was allowed to be spent on improvement of private land against liquefaction. More accurately, 50% of soil improvement expenditure is paid by the governmental money while the remaining is shouldered by individuals and local municipalities.

3.2 Public project of soil improvement in private land

The planned soil improvement is carried out on a block of towns which consist of, for example, 100 houses and a unanimous agreement of all families is required. Another issue is that people do not want to demolish houses prior to soil improvement. Hence, subsoil has to be treated while keeping intact the fragile wooden houses at the surface. Also, the technologies to be employed have to be validated in advance because the soil improvement is carried out under public responsibility. As a consequence, ground water lowering and construction of underground grid walls were chosen as candidates.

Ground water lowering constructs underground impervious walls around a treated area and then installs electric pumps to remove underground water (Figure 5). When there is an impervious layer underneath, the liquefiable sandy layer can be maintained unsaturated and unlikely to liquefy. This method is inexpensive and was exercised in Amagasaki City near Osaka after the 1995 Kobe earthquake (Figure 6). Although a possible defect of water lowering is consolidation and subsidence, they did not happen significantly in the area of Figure 6. Most municipalities have chosen this option for soil improvement.

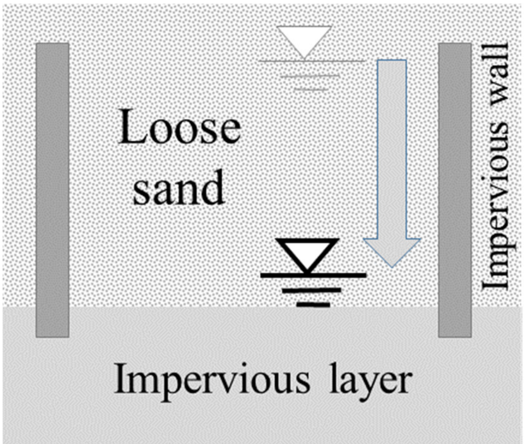

Figure 5 Principle of ground water lowering for liquefaction mitigation

Figure 6 Tsukiji area of Amagasaki City where ground water level was lowered

Urayasu city has approximately 9000 houses damaged by liquefaction. The problem here is that there is more than 40-meter thickness of soft clayey soil and this city experienced significant consolidation problems in 1980s and early 90s. Because of this, water lowering was not accepted and underground grid walls was selected. Figure 7 illustrates the idea of the grid wall; one square grid under one house. It restrains cyclic shear deformation of subsoil during earthquake shaking and reduces the development of excess pore water pressure. The surface unliquefiable soil further increases this mitigative effects. This technology became popular after the 1995 Kobe earthquake in which the grid wall foundation successfully prevented liquefaction in Kobe Harbour.

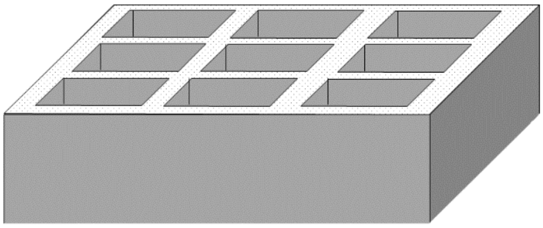

Figure 7 Schematic illustration of underground grid wall

The walls are going to be constructed by mixing soil and cement slurry. Because the walls have to be constructed under houses remaining at the ground surface, the construction machines have to be small enough to enter small spaces among

Figure 8 Small space among houses in Urayasu

houses (Figure 8). Hence a small machine such as in Figure 9 was newly developed. As per October 2015, residents are discussing whether or not they should accept this soil improvement and shoulder required expenditures. It is important that unanimous agreement of residents, which is typically 100 families, is necessary.

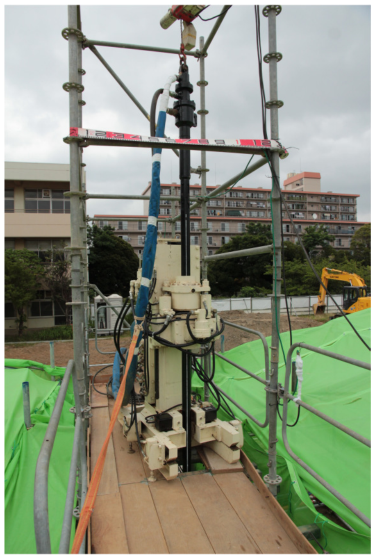

Figure 9 New small machine for construction of slurry wall

4 SLOPE INSTABILITY

4.1 Damage in residential land

The 2011 earthquake triggered few slope failures. Figure 10 is one of the failures. In contrast, residential areas constructed in hilly areas revealed many instabilities. Figure 11 shows a case in Sendai City in which hilly areas had been developed by cutting and filling. Although the cut part was stable, the filled part suffered significant deformation during the earthquake.

The problem is that the residents were not aware of the seismic vulnerability of their property. Being similar to the aforementioned liquefaction in house foundation, the problems in the hilly area are not the full responsibility of non-engineering people. It is important that the engineering community provides information on the seismic performance/safety of people's valuable real estates. In this regard, the Japanese Geotechnical Society, together with several other institutions, established a system of qualified subsoil evaluator so that people can easily know the potential risk.

To be qualified, engineers must first obtain other established titles such as registered engineer, construction site manager etc. and then take an examination about detailed knowledge of residential land construction and related rules and regulations. The qualification is effective for five years, after which extension is approved if the person has been enrolled in continued education such as taking short courses and publishing their products. The author is making significant efforts to promote this qualification as the representative of the system.

Figure 10 Seismic failure of natural slope at Konoha-daira in Shirakawa City

Figure 11 Earthquake damage in a filled part of residential development in hilly area (Oritate of Sendai City)

4.2 Long-term instability of slopes after big earthquakes

This section addresses experiences in different earthquakes. Figure 12 shows a situation in a mountain area of Sichuan Province of China where debris flow started to occur frequently after the 2008 Wenchuan earthquake. The valley bottom in this figure is filled with debris and the mountain slope in the back side is totally unstable. Figure 13 indicates a similar post-earthquake slope instability behind

Muzaffarabad of north Pakistan which was severely damaged in 2005. Similar post-quake slope disasters occurred after the 1999 Chi Chi earthquake in Taiwan. All these sites are situated near big causative faults.

There are several causes of post-earthquake slope disasters as what follows;

(1) Soil falls down from mountain slopes during earthquake shaking, deposits at a valley bottom and is washed out during heavy rain,
(2) Cracks develop in a mountain slope and rain water flows into them,
(3) Soil and rock in a mountain body is mechanically disturbed (development of plastic deformation) during earthquakes and lose shear strength (Figure 14).

Figure 12 Frequent debris flow in Sichuan Province of China

Figure 13 Post-earthquake slope instability behind Muzaffarabad, Pakistan

5 ENGINEERING PERSPECTIVE ON FAULT

Fault has long been a target of scientific study and has not been studied in an engineering sense because it did not manifest very much in alluvial planes where human activities are high. This situation is changing nowadays and many structures are constructed in hilly and mountain areas. Consequently, engineering concern with fault is increasing.

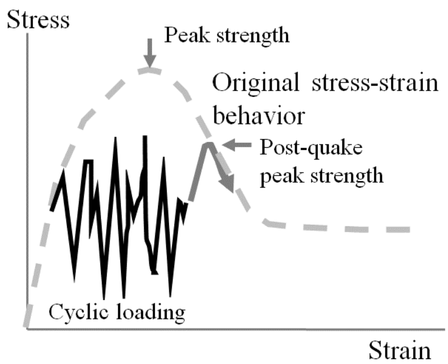

Figure 14 Loss of peak strength after seismic cyclic loading

Generally the only safety measure for fault problem is "avoiding" in which the land use upon potentially active faults is controlled or prevented (Fig. 15). In case of strike-slip faults in which horizontal displacement plays a major role, some measures have been taken; for example, a block structure in a concrete dam in New Zealand (Amos and Gillon, 2007) and a sliding foundation of Alaska Pipeline. More difficult situation occurs when vertical displacement is predominant. Figure 16 is an example of mitigation in which a station resting on a reverse fault is separated into three parts and will avoid collapse in case of fault displacement. The existing problem is that we cannot assess the fault displacement to occur and its probability in an engineering sense. Note that one of the reasons why all the nuclear power plants in Japan had to stop operation after the 2011 earthquake is the possible risk of fault action underneath. Discussion focused only on whether or not an underlying material discontinuity was fault and did not address the magnitude of displacement during future earthquakes. Our engineering is not developed enough to deal with such a rare event as occurs once every thousands of years.

Figure 15 Open space without building upon active fault (Kita-take fault, Yokosuka, Japan)

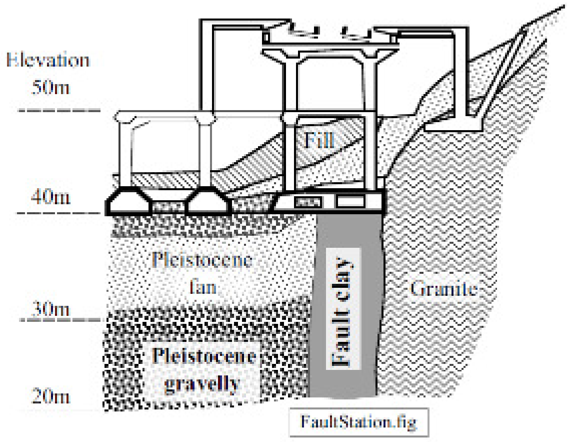

Figure 16 Separated structure of New Kobe railway station resting on reverse fault

6 CONCLUSIONS

The present paper summarizes the engineering experiences during recent major earthquakes and, in particular, geotechnical lessons learnt from the 2011 gigantic earthquake in Japan were addressed. The most important point that the current engineering does not care the seismic safety of inexpensive structures and that private properties were severely damaged. Efforts are now going on to restore liquefaction damages and a qualification system is being established for residential land safety. Slope instability may continue in fault regions for many years after big earthquakes. It is finally necessary to develop fault engineering in addition to the scientific study of faults.

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