TECHNICAL ARTICLE

Ongoing Study on Protection of Personal Houses from Liquefaction Problems

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INTRODUCTION

Two years are going to pass after the M=9 gigantic earthquake in Japan that took place on March 11, 2011. Because the earthquake damage caused many new problems, attempts for reconstruction are still going on, and one of the very difficult problems concerns the liquefaction damage on personal properties. Because the authors had an opportunity to present their study during the 4th International Symposium on Forensic Geotechnical Engineering, Bangalore, India, in January, 2013, they re-write their paper for this issue of ISSMGE Bulletin. It is aimed to discuss what has been missing in the traditional kind of geotechnical earthquake engineering.

Traditional technology on mitigation of liquefaction problems started to develop in 1960s after two earthquake disasters in Alaska and Niigata. Many achievements have been made with rational or sophisticated approaches such as the use of SPT-N or CPT for subsoil investigations, collection of undisturbed soil samples for laboratory tests, and densification or grouting or installation of gravel drains for damage mitigation by using big construction machines. Consequently, the vulnerability of many structures have been drastically reduced in the recent times and the earthquake in 2011 caused few liquefaction problems in engineered important structures. It is, however, noteworthy that those measures are feasible only when sufficient financial resources are available.

During the earthquakes in 2010 and 2011, liquefaction affected such structures as river levees (Photo 1), embedded life lines (Photo 2), and personal houses (see the next chapter). Those structures are characterized by their limited budgets that are available for disaster mitigation. Levees and lifelines are too long for the overall reinforcement against subsoil liquefaction. Their construction cost per unit length does not allow the significant reinforcement either. Consequently, the disaster management philosophy in the past aimed to restore any seismic damage within a short period of time after a quake.

Photo 1. Liquefaction damage in Hinuma levee

Photo 2. Disconnection of sewage pipeline and deposit of sand after liquefaction (damage study in Tokyo Bay area, 2011)

Protection of Personal Houses from Liquefaction Problems (continued)

After the 2011 earthquake, the authors have been deeply involved in restoration works. This article attempts to address one part of their activities.

HOUSE DAMAGE CAUSED BY SUBSOIL LIQUEFACTION

There are many manmade lands along the shore of Tokyo Bay. Because of the proximity to the Tokyo downtown and convenience in commuting, those lands have been developed as residential areas. In 2011, liquefaction severely affected houses in the lands (Photo 3). The house damage consists not of structural breakage but of significant subsidence and tilting. Subsidence causes inconvenience in life, poor drainage of rain water, and disconnection of lifelines. Tilting is more serious; tilting more than 1% is fatal in daily life; causing headache and dizziness.

Photo 3. Tilting of house caused by liquefaction in a manmade island in the Tokyo Bay area

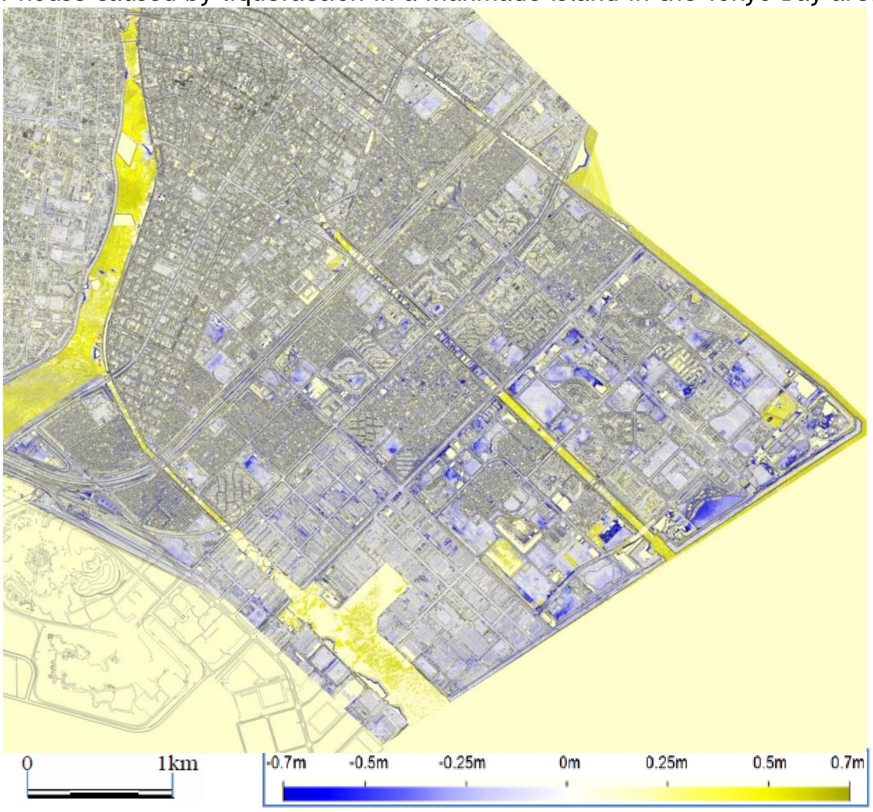

Figure 1. Soil subsidence map of Urayasu city (Konagai et al., 2011)

Protection of Personal Houses from Liquefaction Problems (continued)

In order to measure liquefied soil subsidence, two sets of Digital Surface Models (DSMs) obtained by airborne LiDAR (Light Detection and Ranging) surveys before and after the earthquake were compared with pile-supported RC buildings and bridge piers as templates for aligning the two sets. Figure 1 shows the obtained soil-subsidence map of Urayasu city. Although the subsidence can be seen over the entire stretch of the reclaimed land, the severity of liquefaction within this area was not uniform. In particular, remarkable subsidence is seen in the area reclaimed during the second half of the 20th Century, and it overlaps approximately with the spatial distribution of observed boiled sands in Photo 4.

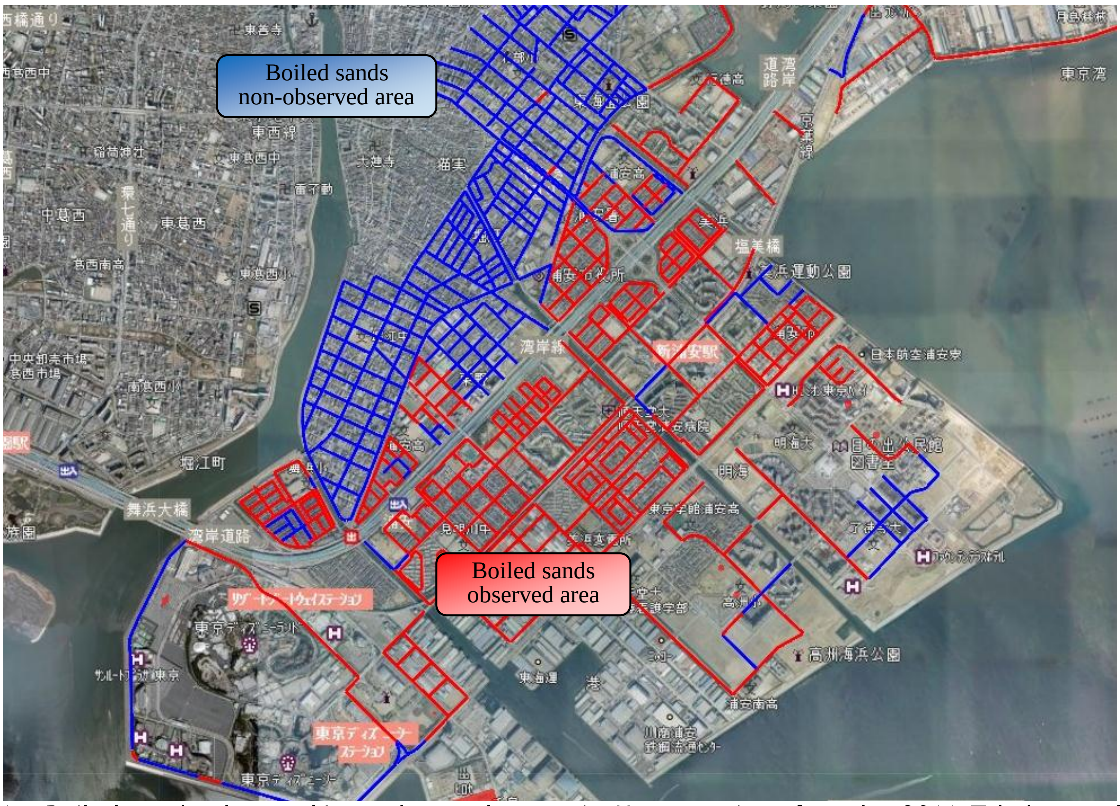

Photo 4. Boiled sands observed/non-observed areas in Urayasu city after the 2011 Tohoku earthquake (after joint research by Japan Geotechnical Society and Kanto Regional Development Bureau of the Ministry of Land, Infrastructure, Transport and Tourism)

Personal houses have not been well prepared for liquefaction in the foundation. People have not been aware of this kind of hazard in spite of public education. In a typical example, the person knew a liquefaction hazard map that was prepared by the local government but still did not take it seriously. This may imply that some safety measure should be set in force by regulation. On the other hand, there is an opinion that liquefaction does not kill people and that costly countermeasure against liquefaction is a matter of personal decision. It should be pointed out here that liquefaction in a personal house lot leads to breaching of peronal sewage pipes from which lots of liquefied sand flow into the sewage pipe networks and finally destroys the function of trunk lines (Photo 2). Thus, public involvement in liquefaction of personal land has a good reason to be practiced.

The problem lying in the liquefaction problem of houses is the limited personal budget that is available to prevent or mitigate the damage. Accordingly, compaction or drainage measures that are often employed in public or industrial projects are not commonly practiced in residential developments. It is also the case that people did not pay much attention to the liquefaction problem before the recent earthquake disasters, even though liquefaction hazard maps had been published by local authorities. Consequently, soil improvement for mitigation of liquefaction problems was not a common practice.

Protection of Personal Houses from Liquefaction Problems (continued)

After the 2011 earthquake, the Japanese residents of liquefaction-affected areas wished to restore their houses. However, the following problems made their restoration difficult.

1. Aftershocks continued for a long time and people were afraid that restored houses might be affected again by repeated liquefaction.
2. Most mitigation technologies were too expensive for personal efforts for future safety.
3. In Japan, the earthquake insurance was not enough for soil improvement to mitigate future liquefaction. The insurance concerned structural damage above the ground surface. Hence, subsidence and tilting induced by subsoil liquefaction were out of scope (Photo 3). This problem was later solved to a certain extent by considering the significant tilting of houses as a kind of structural damage.
4. People did not wish to demolish their houses because the damage was limited to subsidence and tilting, without structural failure. Soil improvement under existing structures is substantially more expensive than that in an open space.

SUBSOIL CONDITION IN MANMADE ISLAND

The urban expansion in the 20th Century converted such liquefaction-prone geomorphology as abandoned river channels and swampy area to residential areas. Construction of manmade islands took place as well for the same purposes. Accordingly, the constructed lands obtained such a liquefaction-prone subsoil as cohesionless fine loose materials with water saturation and young age. As a consequence, recent earthquakes in Dagupan of the Philippines and Kobe as well as the ones in New Zealand and Japan caused significant liquefaction and damage to houses.

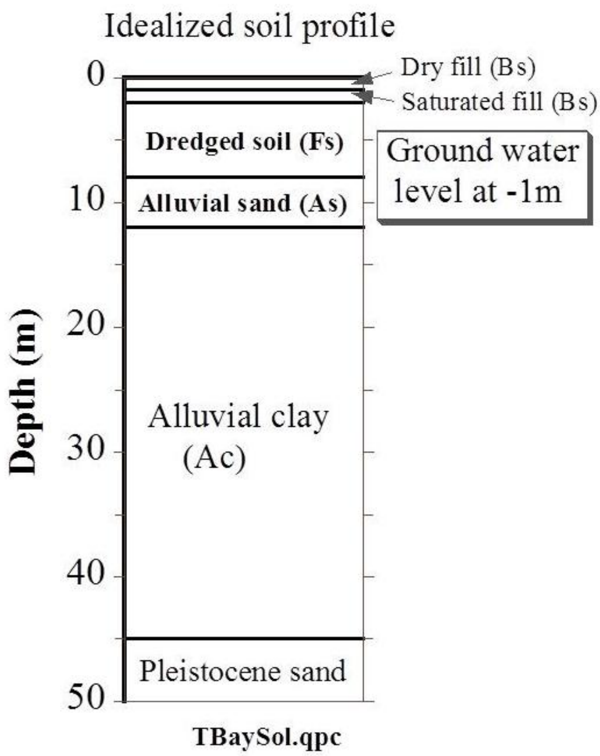

Figure 2. Idealized illustration of subsoil conditions in manmade islands in the Tokyo Bay area

Protection of Personal Houses from Liquefaction Problems (continued)

Figure 2 illustrates an idea of the subsurface stratification in a manmade island in the Tokyo Bay area. There is a thick layer of alluvial clay in the lower elevation. This layer was formed when the sea water level rose during the post-glacier period. Being normally consolidated, this soil caused significant consolidation settlement during the construction of a manmade island at the surface. Above clay, there is an alluvial sandy layer that was formed when the sea level dropped a few meters during the more recent time.

In 1960s and 70s, many manmade islands were constructed mostly by means of dredging of the seabed sand. Although intended to be sandy, this sand often includes non-plastic silts whose liquefaction potential is not fully understood yet. After liquefaction, the boiled sand exhibited high content of fines, accordingly. Note that the fine grain size of dredged sand leads to a slow rate of sedimentation during land construction and, consequently, loose packing of grains, increasing the liquefaction potential of sand. The weight of the dredged layer caused significant consolidation settlement in the underlying alluvial clay for a long time. After the consolidation was completed, human community started.

Above the ground water level, the surface soil is made of sand that was obtained from borrow pits in hilly regions. Because it is not saturated with water, liquefaction is not a problem in this soil.

As stated above, the liquefaction risk was considered high in the dredged sandy layer. Hence, many industrial or public land users (owners) conducted available mitigation measures. In contrast, residential development projects adopted different policies. One was that the vulnerable sand had to be compacted for safety. This policy automatically increased the price of land sales. The other policy was that the lower land price without soil improvement met the people's (market's) demand. It was unfortunate that the real estate market accepted the second policy.

People in the liquefaction-affected area are of concern whether or not future earthquakes will cause a similar problem. This fear is reasonable because there are examples where liquefaction occurred repeatedly; for example, Christchurch in New Zealand in 2010 and 2011. Geotechnical engineering is able to answer this question.

In order to investigate the subsurface soil conditions after the 2011 earthquakes, Swedish weight sounding (SWS) tests were carried out at intervals of two or several months at the same location in Urayasu City, east of Tokyo, where severe liquefaction occurred during the earthquake. Herein, the estimated N_{spt} value was obtained from the observed SWS data according to the JIS A 1221.

Figure 3 compares the temporal variation of the estimated N_{spt} values. The test result before the earthquake which were obtained in 2002 are also plotted in this figure. From the result before the earthquake, soft soil deposits with estimated N_{spt} values of 5-10 could be found for a thickness about 9 m, and it clearly indicates likelihood of liquefaction in this soft layer. Fig. 4 shows the temporal variation of the average N_{spt} values in the estimated liquefied sand layer after the earthquake. Significant reduction in N_{spt} value can be observed about 7 days after the earthquake, while the estimated N_{spt} values increased with time later and returned to the original values or more about 2 months after the earthquake. Afterwards, there has been no noticeable increment in N_{spt} values. Consequently, the change in N_{spt} values between before and after the earthquake was almost negligible, which indicates that the investigated area is still of high risk of earthquake-induced liquefaction in future.

Protection of Personal Houses from Liquefaction Problems (continued)

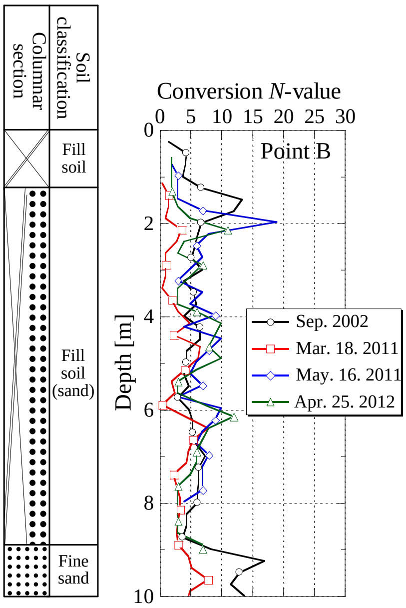

Figure 3. SWS test results measured in Urayasu city

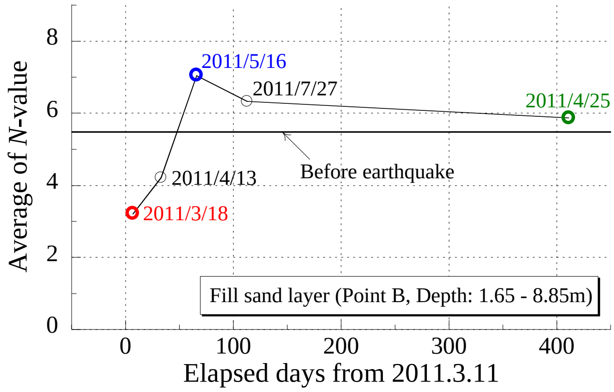

Figure 4. Variation with time of average N_{spt} values after the 2011 Tohoku earthquake

ONGONG ATTEMPTS FOR RECONSTRUCTION

There may be such an opinion that liquefaction-prone manmade islands are not relevant for human settlement. However, the place to live should be decided on the basis of such other issues as environments, distance of commuting and living convenience in addition to safety from natural disasters. The role of engineering is to improve the safety by developing new technologies.

The biggest problem for safety improvement was the limited financial ability of people. This was significant because the earthquake insurance was not enough and public support was not available for improvement of personal properties. The second point is important in a country prone to natural disasters where typhoons, heavy rains and landslides affect so many houses every year and public supports would be a heavy burden to the public budget.

(a) Overall view (b) Detail of uplifted sidewalk

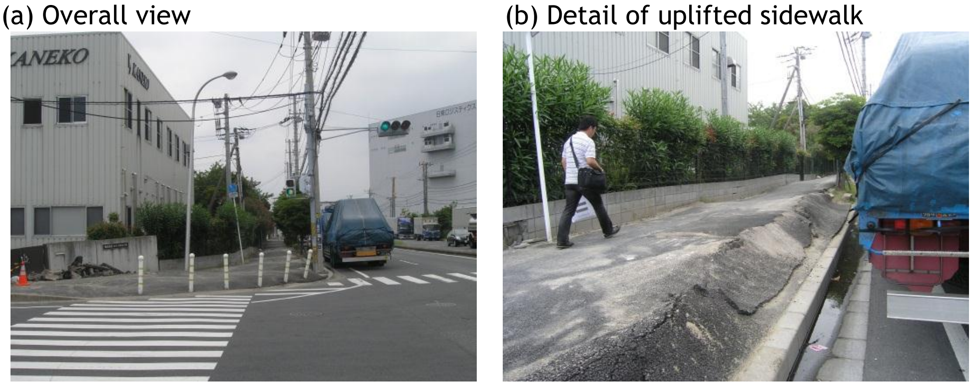

Photo 5. Distortion of sidewalk probably caused by subsidence of building behind

Protection of Personal Houses from Liquefaction Problems (continued)

What is going on is the combination of public and personal funds for reconstruction of communities. Basically, the public parts such as streets and lifelines are reconstructed and improved by the public fund. However, the execution of liquefaction-mitigation only under streets is not enough and, to fully protect the public facilities, the private land (house lots) should not develop liquefaction. This is because the ground deformation due to liquefaction in the private land easily affects the streets (Photo 5) and underlying lifelines. Moreover, the breakage of family sewage pipes introduced a huge amount of liquefied sand into the entire sewage lifeline networks and caused sand clogging in trunk pipes. Thus, it is considered reasonable to spend some amount of public funds to mitigate liquefaction in personal lands as well. Certainly, residents should pay due amount of money as well for fairness.

It deserves attention that people do not want to demolish and reconstruct their houses in spite of liquefaction risk under the foundation. Because soil improvement such as compaction and installation of drainage measures under existing houses is extremely difficult and costly, special technology has to be attempted.

The first idea for the mitigation of liquefaction risk is the installation of underground walls that constrain cyclic shear deformation of dredged sand and avoid liquefaction (Fig. 5). Installed under a pile-supported building with a wall spacing of 4-7 m at maximum, this technology successfully prevented liquefaction problem udder a building in Kobe in 1995.

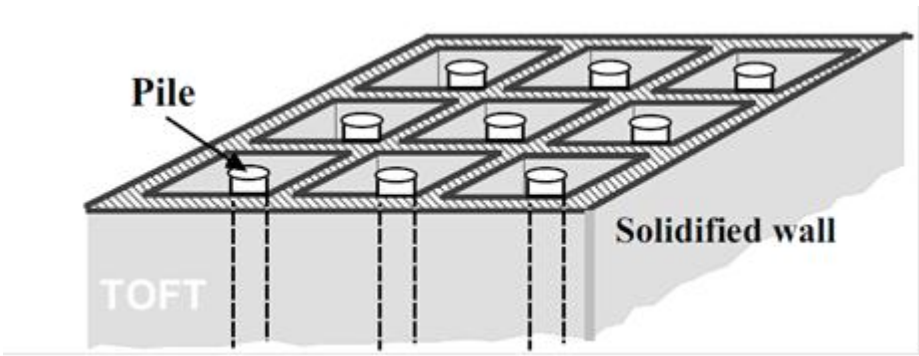

Figure 5. Square grid of underground rigid wall to prevent cyclic shear deformation of liquefaction-prone sand (piles in this illustration have nothing to do with liquefaction mitigation)

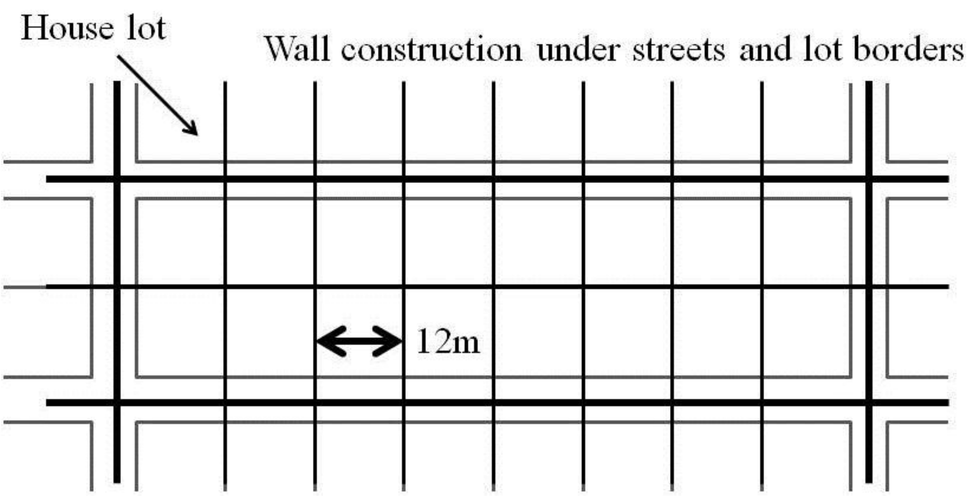

Figure 6. Installation plan of underground walls along both streets and housing lot boundaries

Protection of Personal Houses from Liquefaction Problems (continued)

In the case of a residential area, it is very possible to first install such walls under streets so that an entire residential block may be surrounded by an underground wall. However, this is not enough because the spacing between walls is of the order of 100 m (size of a block) and cyclic shear deformation of soil cannot be constrained. Thus, more walls have to be installed under borders of individual house lots (Fig. 6). This measure makes the wall spacing about 12 m. Currently, discussion is still going on about effectiveness of walls with this spacing. Because the depth of ground water is only 1m or 1.5m, the constraint effects of walls may or may not be enough in soils immediately below the ground water table. Note that further wall construction under existing houses is extremely difficult or costly.

The second idea is to lower the ground water table so that unliquefiable surface crust is formed. There is an empirical knowledge that a reasonably thick crust of soil reduces the effect of liquefaction in the lower part of the ground (Ishihara, 1985). To achieve this goal, a reasonably large area of residential community is surrounded by underground impervious walls and the ground water inside the wall is pumped up. Fig. 7 illustrates the first successful example of this measure that was constructed in an oil refinery near Tokyo.

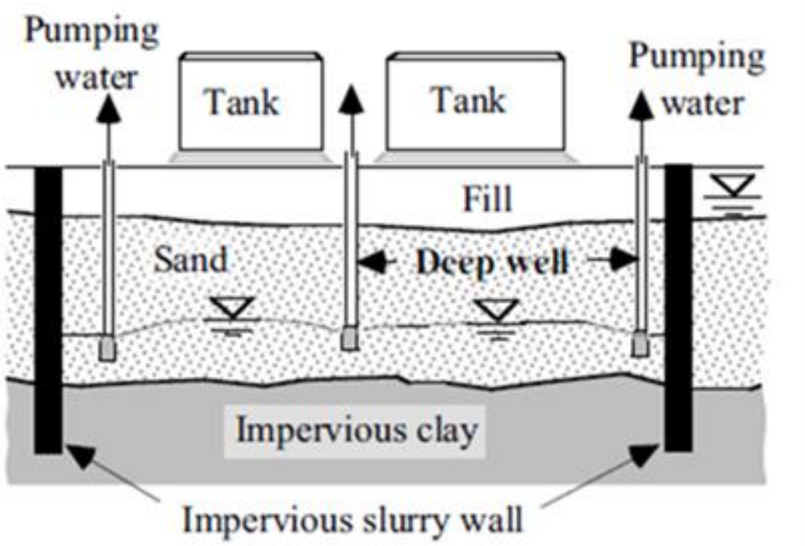

Figure 7. Example of lowering ground water level for mitigation of liquefaction in an oil refinery

Photo 6 shows another example in which ground water level was lowered for mitigation of liquefaction. Most houses in this area were destroyed by subsoil liquefaction during the 1995 Kobe earthquake. Also, the ground level in this area had been lower than the surrounding sea level because of ground water pumping and consolidation of soft clay, and inundation had been a problem. To solve these two problems at the same time, all the damaged houses were demolished, drainage pipes were installed to lower the ground water level by 1.5 to 2 m, and new soil of 1.5 m in thickness was filled at the surface, thus creating an unliquefiable layer of 3 to 3.5 m in thickness. To date, the weight of the new fill has not caused a problem of consolidation settlement. Most probably, the pumping of ground water was prohibited in 1960s, the water level rose since then, the effective stress in the clayey subsoil decreased, the clay became over-consolidated, and hence the settlement has been kept small even after the placement of the new fill at the surface. In contrast, the soft clay in the Tokyo Bay area is normally consolidated and a care must be taken of significant settlement in case of pumping ground water.

Protection of Personal Houses from Liquefaction Problems (continued)

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

Installation of liquefaction mitigation measures will help re-establish the value of the affected towns as good residential areas. Although the proposed lowering of ground water and installation of underground walls have many good points, they have shortcomings as well. Moreover, the execution of these measures requires general agreement of residents, which may not be very easy. Further, there seems to be the following issues to be solved:

1. Some people have already installed liquefaction measures under their houses. They do not like further expenditures for the proposed measures.
2. People with low income may not want to pay money for future liquefaction mitigation.
3. Lowering of ground water may cause ground subsidence and differential subsidence of houses to some extent. People in general have to understand this risk or decline the installation of water lowering.
4. The proposed measures are designed against what is called the Level-1 design earthquake that may happen once during the life period of structures; the return period being approximately 50 years or so. House protection from a possibly stronger earthquake is the business of individual residents.

CONCLUSION

- After the 2011 gigantic earthquake of M=9, one of the major issues is the damage to personal properties for which the disaster mitigation cannot expect sufficient funding and the conventional mitigation measures are not very useful. Moreover, people wish to maintain their houses untouched, in spite of the liquefaction-induced tilting and subsidence.
- In this regard, two possible mitigation measures have been considered and addressed here, which are construction of underground walls for constraint of cyclic shear strain in the subsoil and lowering of ground water table. Both of them are of some deficiencies, and residents have to do additional efforts for the safety of their personal real estates.
- To install those measures, general agreement of people is necessary.

Protection of Personal Houses from Liquefaction Problems (continued)

ACKNOWLEDGMENT

The present paper addresses a small part of more comprehensive activities of damage reconnaissance and damage mitigation after significant liquefaction during the M=9 gigantic earthquake in Japan. The activities in this paper were carried out in collaboration with the Japanese Geotechnical Society, the Japan Society of Civil Engineers, and Urayasu Municipal government. The authors express their sincere gratitude to those assistances.

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