Application of Geotechnical Experience for People – Activities after 2011 Tohoku Earthquake

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ABSTRACT
Construction technology has developed substantially in the past decades but its public image is not very high. One reason for this is that construction engineering, inclusive of geotechnical engineering, did not show up clearly in front of people by working on topics of people's direct concern. It is a pity that not only the ordinary people but also engineers in other fields have not been aware of the value of geotechnical engineering. The above situation exhibited unfortunate situations after the 2011 Tohoku earthquake of magnitude=9. One of them was the significant failure in house foundations that totally destroyed the value of the well-designed super structures. The failure occurred in low-quality fills in residential development in hilly areas as well as in liquefaction-prone man-made islands. The available design principles mostly addressed public sectors and big industries who were able to afford costs for soil investigation, advanced design and construction. People's poor knowledge of engineering made it difficult for them to talk with experts about the way of reconstruction. To solve this adverse situation, a simplified interpretation of soil investigation was developed and a qualification of geotechnical engineer for the people's sake was created under the initiative of the Japanese Geotechnical Society (JGS) in collaboration with several other institutions. Nowadays many geotechnical experts are engaged in soil improvement projects under existing houses that are prone to future liquefaction. Same situation is repeated after the 2016 Kumamoto earthquake. Another important situation is found in the Fukushima No.1 Nuclear Power Plant where heavy damage was caused by tsunami attack and nuclear fuels melted down. Initially, efforts were made solely by nuclear experts but gradually it became clear that the solution of this nationwide problem needs collaboration of many disciplines. JGS is thus trying to apply geotechnical approach to pave roads to the final solution.

1 INTRODUCTION

Construction technology has achieved a tremendous development since the middle of the 20th Century and geotechnical engineering is not an exception. This success was made possible by a scientific way of thinking on the nature of external action, material properties and construction procedure among many others. Consequently, many big structures have been constructed in harsh natural environments and many of them have survived natural conditions that are even more difficult than expected during design. It seems, however, that care has not been taken sufficiently of people and their properties because they cannot afford the cost required by modern construction technology. Hence, people are not aware of the value of geotechnical engineering and take everything for granted. As a consequence, they are easily affected by natural disasters. Another reason for their ignorance is that construction technology has not attempted to appeal to people because they are not the major customer. Not only the ordinary people but also other engineering fields have not been aware of the value of geotechnical engineering.

The above situation exhibited unfortunate situations after the 2011 Tohoku earthquake of magnitude = 9. One of them was the significant failure in house foundations that totally destroyed the value of the well-designed super structures (Fig. 1). The failure occurred in low-quality fills in residential development in hilly areas as well as in liquefaction-prone man-made islands. The available design principles mostly addressed public sectors and big industries who were able to afford costs for soil investigation, advanced design and construction. People's poor knowledge of engineering made it difficult for them to talk with experts about the way of restoration.

Facing this situation, the author and many experts of the Japanese Geotechnical Society started working on people's issue, proposing new guidelines to assess the quality of residential land's subsoil, designing liquefaction mitigation for private residential land, and even developing geotechnical methods to promote solution of a nuclear accident. The present paper addresses those activities with which the author is very familiar.

A situation that deserves attention occurred in the Fukushima No.1 Nuclear Power Plant where heavy damage was caused by tsunami attack and melt-down of nuclear fuels occurred. Initially, efforts were made solely by nuclear experts who tried to stop the leakage of radioactively contaminated ground water and to remove the molten fuels from the destroyed reactors. Although those tasks needed the use of advanced geotechnical engineering, the nuclear people did not pay attention to it. After realizing the difficulty of the problems, they started to understand the importance of collaboration with geotechnical engineering.

2 SPECIAL NATURE OF GEOTECHNICAL ENGINEERING

It is important to understand the difference of soil/geotechnical engineering and other engineering fields that are better known to people. First, the size of geotechnical engineering target is substantially bigger. Size of dams, tunnels, harbors and building foundation are often of the order of 100 meters or kilometers which is far greater than the sizes of semi-conductors, automobiles and even ocean-going vessels. Ideas that may work in a small scale may not work in a large scale. Second, the geotechnical materials which is namely 'subsoil' is not uniform because it was made by nature. Nature does not care the uniformity or quality control. Hence, material properties vary from place to place and possibly change with time (weathering or ageing). The material properties change further under the effect of water. Third, we cannot capture the types and properties of soils and rocks everywhere. We can somehow see them in samples and cores from bore holes. These difficulties made the basic principles of geotechnical engineering substantially different from those of other fields of engineering.

Importance of in-situ investigation is well understood by us. There is no need to mention the importance of elaborate and precise measurements in bore holes. The problem comes from the heterogeneity of subsoil. The information obtained at selected bore-hole places is not necessarily valid at other places. Hence, interpolation is often made by empirical judgement. Only geotechnical experts know that such an interpolation is a kind of imagination while people of other disciplines misunderstand that it is the reality. More subsoil investigations that are less expensive should be conducted between bore-hole sites and provide good interpolation. Our society has been seeking for mitigation of geo-disasters without knowing much about these features of geotechnical engineering.

3 HAZARDS IN RESIDENTIAL LAND IN HILLY TERRAIN

3.1 Seismic Instability of Residential Land

Figure 1 compares the post-earthquake situation of a residential land near Sendai City after the 2011 Tohoku earthquake. In spite of the distance of merely a few hundred meters, the damage extent was completely different between cut and fill parts.

Similarly, the 2016 Kumamoto earthquake sequence revealed the problem lying in artificial fills. Fig. 2 shows one of the most heavily damaged areas where the residential land is located upon a former small valley. Most probably the original subsoil is a soft valley deposit and the overlying artificial fill is not well compacted as is often the case in such a local community. Thus, most houses in this area was destroyed. Fig. 3 clearly demonstrates that good earthquake resistance of a superstructure is not good enough to avoid damage unless subsoil condition is good. This place is located upon a big residential fill and its slope surface deformed substantially.

Significant distortion in Fig. 4 occurred in the middle part of the same residential fill as in Fig. 3. As suggested by the distance from the slope shoulder being approximately 200 meters, this depression was induced by a deep-seated sliding that occurred in the fill, probably along the interface between the original slope and the man-made fill. The problem is that the residents cannot afford the cost of reconstruction of the entire fill. They could not assess such a risk before they purchased the land. Similar instability occurred at many residential areas in Kumamoto in 2016. In 2017 the national government will provide financial supports to restore the damage in such residential areas but noteworthy is that restoration of private properties (improvement of values) should not be 100% conducted by public fund. Individual residents will have to shoulder a substantial amount of needed expenditures although they are not responsible for the induced disaster.

(a) Filled part with significant damage

(b) Cut part with virtually no damage

Figure 1. Different damage extent in residential land in hilly area in Sendai

Figure 2. House damage in Mashiki Town in Kumamoto

Figure 3. Tilting of house that is located near unstable slope shoulder (Kumamoto)

Figure 4. Depression near the center of residential fill in Fig.3 (Kumamoto)

3.2 Vulnerability to Rainfall Disaster

Rainfall is another threat to residential lands. Although not being seismic, the problem of slope instability induced by heavy rainfall should not be overlooked when safety of

Figure 5. Residential land affected by debris flow during heavy rain (Hiroshima)

residential land is discussed. Morales et al. (2001) reported rainfall-induced failure of a slope under newly-developed residential land near Manila, the Philippines, where 60 residents were killed. Debris flow in Hiroshima, 2014, destroyed houses in recent residential land (Fig. 5) and claimed 74 lives. The problem is that the affected residential land was developed upon alluvial fans that were produced by ancient debris flows. Unfortunately people were not aware of the risk of living in such a vulnerable place and decided to live there based on good landscape, comfortable environment, and convenient living conditions as well as land price.

Further problem is that the heavy rainfall occurred in midnight and residents could not recognize the ongoing hazardous situation. Recent experiences (Wakayama with 11 casualties and 29 missing, 2011; Northern Kyushu Island with 30 deaths and 3 missing, 2012; Izu-Ohshima Island with 39 casualties, 2013; Hiroshima, 2014; Kanto-Tohoku with heavy flooding, 2015; Lionrock Typhoon in Iwate, 2016) indicate that heavy rain often occurs in midnight and early dawn when the humid air at high altitude is cooled down and rainfall is triggered. Note that evacuation is very difficult in darkness before sunrise.

3.3 Qualified Evaluator of Geo-disaster Proneness of Residential Land

As stated above, many residential lands are prone to such natural disasters as earthquakes and heavy rains. The severity of those disasters are closely related with the quality of man-made fills, topographic environments and local surface geology. People are not aware of those problems and like to live there until fatal disasters occur. Recognizing such problems and need for experts' advice for people's safety, the Japanese Geotechnical Society (JGS) in conjunction with several institutions established "Qualified evaluator of residential land" who are geotechnical experts to evaluate the disaster proneness of residential land and provide relevant advices so that people can make decision not to purchase a particular residential land or to conduct necessary soil improvement (Towhata and Nakamura, 2015). It is believed therein that safety deserves spending money. The major features of the evaluator is as what follows;

- Evaluator is not a volunteer but a professional job who receives reasonable payment for service.
- Evaluators have sound knowledge and experience in such geotechnical engineering practice as fill construction, soil improvement, retaining wall design, house foundation and related codes/regulations. They get qualified through examination.
- However, evaluator is not necessarily an expert of slope disaster or soil liquefaction specifically.

To assist the activities of and maintain the quality of evaluators, JGS organizes continued education periodically.

Performance-based design is not yet applied to the residential land. The design still relies on conventional limit equilibrium (pseudo-static) seismic design that relies on assessed shear strength of soils. The main reason for this is that performance-based design, which aims assessing the seismically-induced deformation of geotechnical structures, requires more detailed subsoil investigations and more advanced design calculation. Although soil investigation and performance calculation are essentially important, people are reluctant to pay costs for them. Unfortunately people do not yet understand the value of professional advices very much and think that disaster is somebody else's problem until it happens to them. It is noteworthy on the other hand that knowledge of local disaster history and past land construction (filling valleys, land reclamation, etc.) over the past centuries is essentially important for successful land evaluation; such knowledge is possibly more important than capability of numerical analysis. Qualified evaluators are expected to carry out many activities to change this situation together with the geotechnical and geological institutions that conduct public education on disaster management.

3.4 Achievement of Geotechnical Engineering

Figure 6. Successful stabilization of slope (Shiroishi)

It is relevant to address several successes of geotechnical engineering during the 2011 earthquake. Fig. 6 shows a slope in Shiroishi near Sendai where an entire sloping residential area collapsed during the 1978 Miyagi-ken-Oki earthquake. Afterwards the slope was repaired, had drainage facilities installed and had been an open area (no house) until 2011. As shown in Fig. 6, this slope remained intact in 2011 in contrast to the adjacent areas where minor slope failure happened (Fig. 7). Thus, ground water lowering in a vulnerable slope is an effective measure for seismic stabilization.

Figure 7. Slope instability near the slope in Fig. 6

Because so many residential fills were affected by the 2011 Tohoku earthquake, it was decided to provide public financial supports to reconstruction of damaged fills. According to the policy of the Sendai City Government, the following points are important;

- Because the reconstruction improves the value of private properties (residential land), the residents should pay a part of the cost.
- The public support will be available if
  - the area of fill is greater than 3000 m^2 and more than 10 houses are situated on it, or
  - the original ground inclination was more than 20 degrees, the thickness of fill is more than 5 m and the number of houses is 5 or more.
  - It is also required that the possible failure of the fill is likely to affect such public infrastructures as road, river channel, railway, designated disaster shelter or evacuation roots, and 10 or more houses outside the fill.

Important roles are played herein by geotechnical engineers and qualified evaluators.

4 LIQUEFACTION PROBLEMS IN RESIDENTIAL LAND

4.1 Vulnerable Situation

The 2011 Tohoku earthquake caused significant liquefaction problems in recent residential areas. Fig. 8 illustrates subsidence and tilting of a house in Itako City. This area used to be a lake and, in the middle of 20th Century, the lake water was drained and farming land was created. Later, additional soil was filled on the farming land and a residential land was developed. Because the new fill was sandy (good bearing capacity for houses), not compacted as practiced at many places (for reducing cost and offering low land price), young in age and water-saturated (located in former lake), liquefaction occurred widely and substantially in this area. Liquefaction also affected lifelines embedded in sandy ground. Fig. 9 illustrates the inside of a sewage pipeline in Urayasu City. The pipeline was separated at the connection and liquefied subsoil came in and stopped the flow of waste water.

Note that liquefaction damage in 2011 occurred substantially in such less expensive structures as private house foundations, lifelines and river levees that cannot afford the cost needed for liquefaction mitigation. The affected people were not aware of the liquefaction hazard until the disaster happened and felt that some public support should be provided for reconstruction. For fairness, it should be mentioned here that many municipalities had prepared hazard maps before 2011 and let people know the earthquake risk, including liquefaction problems, although those maps overestimated liquefaction risk in some areas. Unfortunately, those maps did not attract much public concern.

Figure 8. Liquefaction damage of house in Itako

Figure 9. Liquefaction damage of sewage pipe (Urayasu City Government)

4.2 Simple assessment of liquefaction proneness in residential areas

Because the liquefaction damage was severe in recent reclaimed land and man-made islands, a need was felt by the public sectors to develop a measure by which the liquefaction proneness of urban and residential lands is demonstrated in a simple manner. The target users of this measure was the local administrators and engineers as well as people who are not necessarily experts of geotechnical engineering. They do not clearly understand the meaning of factor of safety against liquefaction (F_L) and related parameters.

One of the earliest and well-known measures to simply demonstrate the liquefaction proneness is the H_1-H_2 diagram (Ishihara, 1985) in which H_1 stands for the thickness of surface stable soil crust while H_2 is the thickness of liquefaction-prone subsoil (Fig. 10). It is obvious that the greater thickness of H_1 provides more bearing capacity for houses and stability of embedded pipelines, thus reducing the liquefaction damage. It is also expected that the thinner H_2 reduces the damage possibly because vertical settlement and lateral spreading in the liquefied layer are reduced even if punching failure happens in the H_1 layer and house foundation comes into the H_2 layer.

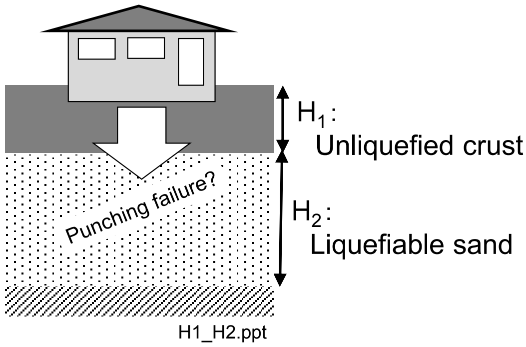

Figure 10. H_1-H_2 diagram

The good point of the H_1-H_2 diagram is the clear meaning of the importance of the H_1 layer, which is the bearing capacity for a house foundation. A shortcoming is the sensitivity of H_1 to a minor change of the factor of safety, F_L. If F_L changes from 0.99 to 1.01 near the surface, the H_1 value increases suddenly and the subsoil is considered significantly safer. On the other hand, H_2 is less sensitive to a minor change of F_L; increase of F_L from 0.5 to 0.95 does not change H_2 at all. Considering these issues, a different recommendation diagram was developed (Towhata et al., 2016) and has been set in force by the government.

In Fig. 11, the seismic (liquefaction) performance of subsoil is classified into 3 groups (A, B and C) and the ideas of these three performances are demonstrated in Fig. 12. If subsoil is classified into C group, soil improvement is recommended. The Dcy parameter in Fig. 11 is employed in the Recommendations for Design of Building Foundations (Architectural Institute of Japan, 2001) and is the integration of shear strain amplitude in subsoil;

$$D_{cy} \equiv \int \text{Shear strain amplitude(assessed by using } F_L\text{)}dz \qquad (1)$$

Hence, it is supposed to be equivalent with the horizontal displacement at the ground surface. The data points in Fig. 11 indicate the observed severity of liquefaction (sand ejecta) in 2011 near the analyzed sites of SPT-*N*. There is a good consistency between observed subsoil behaviour and the classified groups.

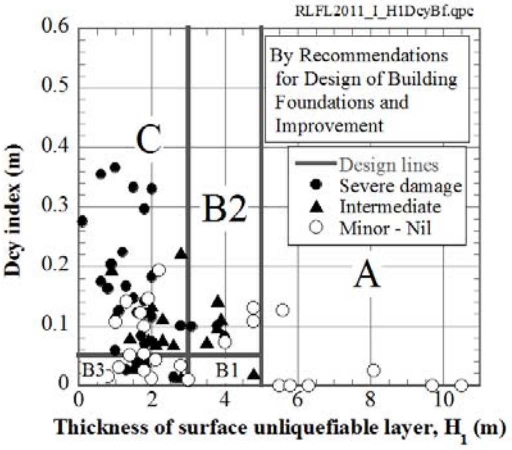

Figure 11. H_1-*D*cy diagram for quality evaluation of urban subsoil from liquefaction viewpoint

4.3 Ground Improvement Projects with Public-Private Collaboration

Because the liquefaction damage in residential area was so vast, a public-private collaboration framework was initiated for restoration. Noteworthy is that public fund is introduced into soil improvement in private land with the share of 50% each from respective sides. In principle, the public fund should not be spent on improvement of the value of private properties but in the case of vast liquefaction in urban areas, liquefaction in private land caused subsoil deformation under public streets and avenues where many lifelines are installed. Thus, private land can be improved for the safety of public properties with partial support of public fund.

The main features of this collaborative soil improvement project are summarized in what follows;

- People's houses on the ground surface remain unchanged and only underlying soil has to be improved.
- Public sector is solely responsible for the successful mitigation of liquefaction hazard and people (private sector) rely on recommended technology because people are not geotechnical experts.
- The responsibility of the public sector is high because people trust the public sector and pay their dues.
- Employed soil improvement technology needs to have been validated in the past so that people can trust it; no challenge.
- Soil improvement is conducted on a district basis (with tens of or over hundred families) and residents' unanimous agreement on the project is required.

The candidate technologies for soil improvement under existing houses were only ground water lowering and installation of grid underground wall. The former turns the liquefiable subsoil to unsaturated sand while the latter constrains the cyclic shear deformation of subsoil; both reduces the liquefaction probability under existing houses.

A: Nil – Minor

B: Intermediate

C: Poor

Figure 12. Illustration of three liquefaction performances in residential areas

(a) Ground water lowering

This measure is relatively inexpensive as compared with the installation of underground grid wall. The target area may be surrounded by impervious slurry wall, while here should be an impervious soil layer at the bottom, thus water-inflow is reduced. Then ground water is removed by pumping and/or installed drainage pipes. This technology was practiced in an oil refinery in Kawasaki City near Tokyo where subsoil was drained while maintaining the operation of refinery factory (Fig. 13). Moreover, Tsukiji district of Amagasaki City near Osaka adopted this technology. Therein, liquefaction destroyed houses during the 1995 Kobe earthquake. Afterwards, the damaged houses were removed, new fill was placed at the surface and drainage pipes were installed. Ground water flows under gravity through the pipes into tanks from which water is pumped up and drained into rivers. Because the thick clayey subsoil in Amagasaki City is overconsolidated, minor soil filling and water lowering have not caused consolidation problem (Fig. 14).

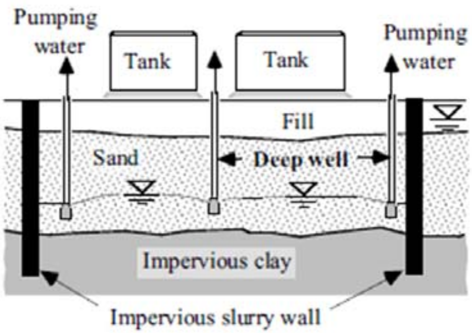

Figure 13. Ground water lowering under existing oil refinery in Kawasaki City near Tokyo


Figure 14. Intact situation in Tsukiji of Amagasaki City after ground water lowering


Figure 15 Hinode area of Itako City where ground water lowering was installed (picture taken on April 5, 2017)

Kuki and Itako Cities adopted this measure (Fig. 15). In these cities, the clayey subsoil is thin and consolidation settlement is negligible, or the liquefaction-prone sand is thin and the extent of water lowering is small. The area in Fig. 15 does not show consolidation problem induced by ground water lowering. It was a pity, however, that several cities declined the project because residents did not agree to burden the due costs.

(b) On constraint of cyclic shear of subsoil by grid underground walls

Urayasu City decided to employ this measure. The underground grid wall are installed from spaces between houses (Fig, 16) and constrain the cyclic shear deformation of sand during earthquakes. Ishii et al. (2017) in this conference provides more detailed information on its soil improvement project. This technology was first validated during the 1995 Kobe earthquake when a hotel building with a grid wall reinforcement remained intact in contrast to substantial liquefaction in the surrounding areas. This technology is more costly than ground water lowering but does not cause consolidation problem in the underlying normally consolidated clay. Because the details are described in Ishii (2017), the present paper addresses additional points only.

- The target area was constructed recently by dredged marine sand with high non-plastic fines content.
- The thickness of underlying soft alluvial clay is typically 40 meters. Consolidation settlement due to weight of new residential islands is more than 100 cm at the maximum and is still going on, but at a reduced rate, in some places.
- Design of underground grid wall needed to capture soil conditions that vary from house lot to house lot.
- The heterogeneous subsoil condition was investigated in detail by combining conventional SPT, undisturbed sand sampling (for liquefaction tests), and dynamic cone penetration for quick interpolation.
- Walls were constructed by cement mixing. Fig. 17 illustrates a trial construction of two oval segments of underground walls. Such segments were connected with each other to form a continuous wall.
- Seismic performance is assessed by using the input earthquake motion that occurred in 2011. Quasi-three-dimensional dynamic total stress analysis calculated the stress conditions in soil and the factor of safety against liquefaction was evaluated. It was aimed to achieve either $F_L>1$ in all liquefaction-prone sand or $D_{cy} \leqq 5$ cm and $H_1 \geqq 5$ m which means Class A in Fig. 11.

Consolidation settlement was of a big concern in 1980s in this city. Although the rate of settlement is reduced nowadays, it is not yet completed. To seek for the possibility of less expensive ground water lowering in this city, a water pumping test was started in 2013 (Fig. 18). Within several weeks, people of the city made a protest against pumping for fear of possible triggering of additional consolidation settlement and the city government stopped the test. Since then, only grid wall has been the target technology although it is more expensive. It was a great pity that ground water lowering was not studied in details. The lesson learnt was that technically and financially good measure may not be accepted by people. This situation can be called political difficulty.

Figure 16. Conceptual sketch of underground grid wall

Figure 17. Oval shape of soil improvement

Figure 18. Ongoing water pumping test in Urayasu

The public-private project of soil improvement under existing houses requires residents to pay due costs because, in principle, the public fund should not be spent on increasing the value of private properties. Use of the public fund was allowed because liquefaction occurs equally in both private and public lands and liquefaction in private land can cause distortion of public infrastructures such as roads and important lifelines. More than two years were needed for the financial sector of the government to accept this philosophy.

The project has to be conducted on a district basis with unanimous agreement of residents. In many districts the agreement was not achieved because of financial issues. We cannot accuse those who declined the project. Many reasons of their negative attitudes are understandable. For example,

- Some families had spent a huge amount of personal money on restoration of a damaged house prior to the governmental decision on financial support. So those families do not wish to spend additional money on ground improvement.
- Some municipal governments which chose ground water lowering requested residents to pay for operation of maintenance of water pumps for the coming decades but residents did not like this idea.
- There are residents who cannot afford the cost. Some aged residents do not want to spend money either. This is particularly a problem because recently pension for senior citizen is not very reliable.
- The author supposes that some senior citizens do not spend money on the project but prefer to give the money to their children.

5 RESPONSE TO THE NUCLEAR ACCIDENT AT FUKUSHIMA NO.1 POWER PLANT IN 2011

This chapter addresses a geotechnical efforts to challenge a new topic that can be handled by geotechnical engineering. It is aimed to show the public how important and useful the geotechnical engineering is. Because the activity still remains in its early stage, detailed performance discussion cannot be made here.

As is well known, this nuclear power plant was seriously damaged by the unexpectedly high tsunami waves. External power supply was lost, internal power generators were destroyed by water inundation and emergency batteries ran out. Hence there was no more energy to continue cooling the reactors. Fuels melted and damaged the reactor vessels and radioactive leakage occurred. After this accident, both public and private sectors carried out detailed investigations on its cause. The present paper, however, does not touch upon the cause and pays attention to the future issues how to solve the problem.

After fuels were cooled by water injection, three issues became important;

- Reducing contamination of ground water due to leakage from the reactors (cooling water is contaminated in the reactors and then leaks outwards),
- Removal of molten fuels from the damaged rectors,
- Final decommission (disassembling and disposal) of the power plant.

These important and difficult tasks were resumed under the leadership of top nuclear engineers. However, it was soon understood that the nature of the problem was extremely complicated and collaboration among different disciplines became indispensable. In 2014 the importance of geotechnical engineering for solving the problem was understood by the nuclear community and a task force of the Japanese Geotechnical Society was allowed to join the national team for solving the problem. Through this activity so far, the author became aware of the following differences in way of thinking between the nuclear community, public and geotechnical experts;

- Subsoil profiles which were drawn based upon a limited number of bore hole information are

considered absolutely correct by nuclear people,
- Because of many uncertainties under ground, any measure may not work perfectly as expected. In such a situation, geotechnical engineers try an additional choice (compensation grouting etc.) but public starts to accuse the original measure taken.
- An advanced scientific technology may work well in a small-scale laboratory environment but its practice in the real ground may be impossible (quantity effect and cost problem).

To fill the gap between geotechnical engineering and other parts of the community, geotechnical engineers have to demonstrate their capabilities through the activities in the task force. From the geotechnical viewpoint, attention has been paid to the following issues;

(1) Construction of many underground walls in the site in order to control and prevent the radioactive contamination of ground water environment (the most important walls were constructed by soil freezing),
(2) Capturing the location and properties of molten fuels in the damaged reactors,
(3) Decision on how to remove the molten fuels,
(4) Final repository of radioactive wastes.

To date, issues (1) and (2) are going on while (3) and (4) have not reached conclusions.

Heavy discussion was made against the construction of underground frozen walls around the reactor buildings because soil freezing (Fig. 19) has not been used for a long-term (7 years) operation and continuity of the wall was questioned. As per March 2017, soil freezing is said to be completed with possible discontinuity being filled with grouting.

The situation of molten debris in the reactors is not clearly known yet although methodologies for removal of debris have to be decided within a few years from now on. As far as the author knows, the ongoing studies on the situation inside the reactors concern the location of molten debris and their chemical/radioactive natures. Because removal is a mechanical work, more attention should be paid on shear strength, brittleness and grain size of the debris. Unfortunately these geotechnical issues are out of concern of top nuclear experts.

Figure 19. Coolant pipes for construction of frozen soil wall under ground

Removal of molten fuel, issue (3), requires the working environment to be safe. It means that local radioactivity has to be reasonably low around the reactor vessels. To achieve this goal, cooling water in the vessels should not leak outwards. To stop this leakage, repairing work has to be conducted for vessels under less radioactive environment. Then, how can we reduce the radioactivity? This is a dilemma. The Japanese Geotechnical Society, as a member of Special Task Force, has proposed the use of heavy mud water for which a special kind of clay with *G*s>3 is mixed with water and placed inside the damaged reactors.

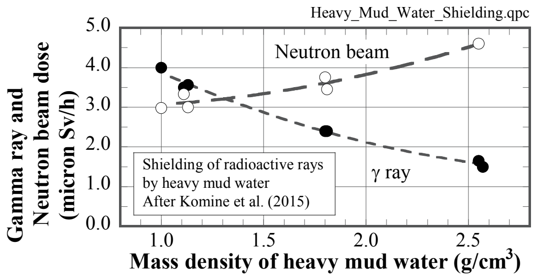

Figure 20. Radioactive shielding effect of heavy mud water (drawn after Komine et al., 2015)

This mud water can fill the complicated space in the reactor vessels and drastically reduce the leakage of contaminated water (because of its low permeability). Further, its high mass density can shield the γ ray while its high water content can reduce the propagation of neutron beam. Fig. 20 illustrates typical results of laboratory tests on the shielding in this mud water. Because the shielding of the two kinds of radioactivity are contradictory to each other (increasing for one beam and decreasing for the other with the change of density), it will be aimed in near future to determine the optimum density of the heavy mud water by assessing the long-term change of the source radioactivity in terms of both γ ray and Neutron beam during the next 40 years in which the decommission work of the abandoned power plant will be carried out. The desired performance here is that the radioactive environment around the damaged reactors are maintained safe so that decommission works may be carried out.

6 CONCLUSION

The present paper addresses the author's experiences in the damage restoration efforts after the gigantic 2011 Tohoku earthquake in Japan. Because the performance-based design is the main theme of the conference, it was attempted to introduce performance aspects of the works. The major conclusions herein are listed in what follows.

- To improve the public image of geotechnical engineering, efforts were made to challenge problems that are closely related with or attracting concerns of people.
- People's ignorance of geotechnical engineering causes geo-disasters during harsh natural conditions as exemplified by slope disasters during heavy rain and failure of house foundations during earthquakes.
- After the 2011 Tohoku earthquake many efforts have

been made to develop safer community during earthquakes.

- The Japanese Geotechnical Society established a professional title of qualified evaluator of residential land so that people can receive expert advices.
- Several residential lands affected by subsoil liquefaction have been reconstructed by public-private joint activities of soil improvement.
- It was a pity that there were communities that did not join the reconstruction activities due to financial reasons.
- Efforts are being made by geotechnical engineering to settle down the nuclear accident of the Fukushima No. 1 Power Plant.

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