IPA News Letter Volume 5, Issue 1 March 2020

Special Contribution

Contribution of geotechnical engineering towards recovery from damage caused by the 2011 Tohoku earthquake - Summary of the 2019 Ishihara Lecture in Rome -

Ikuo Towhata

Visiting Professor
Kanto Gakuin University, Japan

ABSTRACT: The 2011 Tohoku earthquake with the moment magnitude of 9.0 caused unexpected and disastrous damage over the entire Tohoku and Kanto Regions of Japan. While tsunami damage has been widely known, liquefaction affected people's properties as well. The post-earthquake reconstruction of communities addressed many geotechnical issues, and the present paper attempts to introduce them to readers within the limited page allocation.

Keywords: 2011 Tohoku earthquake, damage, tsunami, liquefaction, reconstruction

INTRODUCTION

Mitigation of natural disasters is one of the major missions of civil engineering. This mission is becoming increasingly more important in the recent decades because people and public sectors have started to desire more safety for the welfare and continuity of their value. In other words, the value of the modern community after economic development substantially relies on the capability of individuals and the value of human resources is remarkably more important than that under lower level of development in less developed communities. In the latter, individuals are often considered to be replaceable labor. In this respect, the target of disaster mitigation used to be limited to important structures in pre-modern times whereas the current target is the general public.

Geotechnical hazards typically occur during earthquakes and heavy rains exemplified by slope failures and collapse of subsoil as shown by liquefaction. Therein, an entire district or area is uniformly affected and the geotechnical disaster mitigation has to address the general public. This nature of geotechnical disaster mitigation accounts for the reason why it used to attract minor public concern in the 20th Century when the value of people was lower, and why it has become more valuable among people only in the recent few decades.

The first two decades of the 21st Century experienced several natural disasters that affected the geotechnical bases of human community, resulting in the loss of safe living conditions and local industrial bases. Examples of such events were the seismically-induced slope failures in Pakistan in 2005 (Mw=7.6) and in China in 2008 (Mw=7.9) that directly destroyed human settlements and transportation networks while generating flood risks due to breaching of natural dams. Another example is subsoil liquefaction in residential districts underlain by young sandy deposits that occurred in New Zealand in 2010 and 2011 together with eastern Japan in 2011. The collapse of foundation ground under existing houses made complete loss in values of personal real estate, affecting the continuity of the damaged community.

Tsunami is another kind of natural disaster that profoundly affects the continuity of a human community. In case of extremeness, it affects entire nation as exemplified by the events in the Indian Ocean (2004) and Tohoku District of Japan (2011). It is possible herein for geotechnical engineering to mitigate the disaster by offering good and appropriate technology such as construction of sea walls and refugee embankment.

In 2019, the author was granted with an honorable opportunity to deliver the "Ishihara" Lecture during the 7th International Conference on Earthquake Geotechnical Engineering that took place in Rome (Towhata, 2019). The content of this lecture consisted of the achievements of geotechnical engineering, whether or not the author was involved, that attempted to help the community recover from the induced seismic damage. Mitigation of future disaster of a similar kind was another important aim. The present paper is intended to summarize the lecture, while adding some points that have been found valuable after the lecture. Note that the topics concerning rainfall-induced disaster are excluded from this paper due to page limitation although they are important as well for the continuity of human communities.

SEISMOLOGICAL ASPECTS OF THE 2011 TOHOKU EARTHQUAKE

The 2011 Tohoku earthquake registered the seismic magnitude of Mw=9.0 and caused damage over the Pacific Coast region of the Tohoku District (Fig. 1). The induced damage was due to strong and elongated ground shaking such as exemplified by slope instability, collapse of building structures together with their non-structural members, and subsoil liquefaction as well as those due to tsunami in the coastal region. Noteworthy was the nation-wide loss of logistics due to destroyed transportation routes and the economic aftermath such as energy shortage.

People's doubt on safety of nuclear power plants and the consequent closure of most reactors were of substantial economic influence. Although they are important as well, the present paper cannot touch upon them due to page limitation. The seismic aftermath was characterized by the long duration of aftershocks (Fig. 2). Because strong aftershocks continued for many months and there was a fear that another big "one" was coming soon, it was difficult to resume the recovery efforts immediately after the earthquake. Another difficulty came from the long duration time of strong shaking (Fig. 3) because of the huge seismic energy (Mw=9.0) and a need for revised design codes was felt. Another issue is the coseismic subsidence in the coastal area (Fig. 4). Because the subsidence exceeded 1 meter in the epicentral area, tsunami height relative to the ground level became higher by the same amount than the original expectation.

Fig. 1. Tohoku Region and location of Sendai City

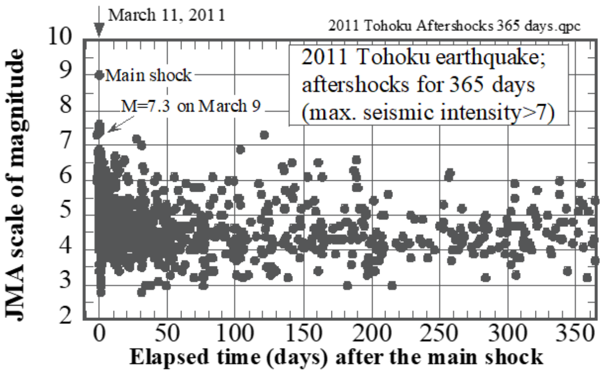

Fig. 2. Aftershocks in Tohoku Region (data by Japan Meteorological Agency; intensity>3)

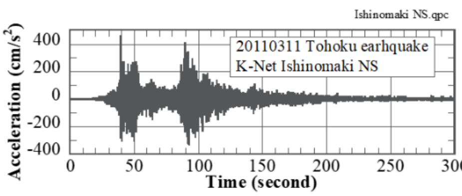

Fig. 3. K-Net acceleration record of Tohoku earthquake at Ishinomaki

Fig. 4. Lowered ground level due to coseismic subsidence in Bansekiura near Sendai City

GEOTECHNICAL DAMAGE

Tsunami is a phenomenon of water but mitigation of tsunami damage is closely related with geotechnical engineering. Fig. 5 demonstrates the shape of a sea wall destroyed by incoming tsunami. Sea water overtopped the wall and scoured the landside foot of the embankment. After the wall was lost during the first tsunami attack, the following tsunami attacks were able to flow into land without much resistance. This implies the need for scour-resistant design of sea walls. It is noteworthy, further, that the former tsunami disaster in Banda Aceh in Sumatra, Indonesia, in 2004 was characterized conversely by the effects of retreating water whose flow concentrated at the weakest points of sea barriers, as eyewitnesses told the author during his reconnaissance.

The disaster in 2011 showed a very difficult feature of tsunami disaster mitigation. The coast of Tohoku Region experienced big tsunami disasters in 1896, 1933 and 1960 prior to 2011 (Fig. 6). The memory of the gigantic event in AD 869 had been gone after many centuries. Following the 1933 disaster, many local communities decided to relocate their sites to higher places where the risk of tsunami was obviously negligible. Then the problem was the inconvenience of daily life because people were living mainly on fishing in the sea. Thereafter, the national government constructed high sea walls to protect many local communities. Fig. 7 shows one of them in the Tohni-Hongo Township. The height of this wall was designed by considering the tsunami height in 1896 that was the highest in the known history. Then, people felt safe and came back to the coastal area behind the new wall. It was unfortunate that the tsunami in 2011 was even higher than the wall and the community was destroyed (Fig. 8). If the community had remained in the high places, nobody would have been killed in 2011, although living on fishing would have been inconvenient. This tragedy shows that empiricism cannot always give us perfect safety and that we have to overcome a dilemma between safety during rare natural disasters and convenience in daily life.

Fig. 5. Damaged seawall near the Abukuma River mouth

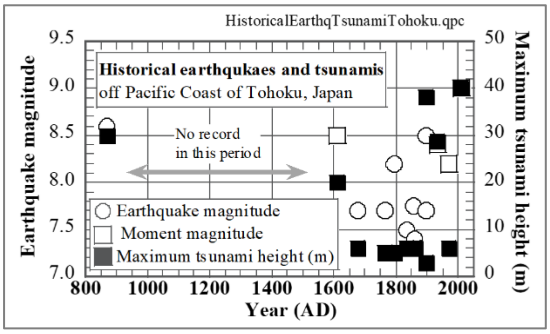

Fig. 6. History of devastating tsunami in east coast of Tohoku Region

Fig. 7. Sea wall in Tohni-Hongo that was constructed prior the disaster in 2011

Fig. 8. Destroyed community behind seawall (Tohni-Hongo Township)

Subsoil liquefaction was a significant problem in the residential areas and river levees. It happened in young cohesionless loose and water-saturated subsoil that underwent strong seismic shaking. Such liquefaction-prone soil was distributed in man-made islands in Tokyo Bay as well as along rivers where abandoned channels and former lakes had been filled with sandy soil for agricultural and residential developments. The significant extent of those damage was in clear contrast with the reasonably good performance of engineered foundation of important structures. This means that the lack of soil improvement budget was the cause of liquefaction disaster.

Figure 9 indicates a house that tilted due to subsoil liquefaction and extreme softening. Affected houses were located on recent reclaimed land and, generally, the responsibility for the poor quality of the land belongs to the owner of the land (owner of the house) or the architect as the representative of the owner. In other words, the legal liability is not with the contractor or developer. Due to this, the owners who were hardly experts of construction business and soil mechanics claimed the product liability of developers and contractors to whom, nowadays, more liability is assumed. It is still difficult, however, to assume 100% liability to them because the man-made island can be affected by the behavior of the underlying natural ground whose deficit is not necessarily the responsibility of the developers/contractors. Another possible problem in this regard is that ground improvement would have raised the land price upon purchase. The dilemma between safety and price of residential land is yet to be overcome.

Fig. 10 is a typical damage of embedded lifeline that was affected by liquefaction. Noteworthy is that liquefaction damage of lifeline is possible to occur not only in such liquefaction-prone ground as man-made islands but also in terrace geomorphology which hardly liquefies. Therein, the problem is the quality of backfill soil where compaction is desired but difficult in practice. See liquefaction in backfill in Fig. 11.

Considering the significant liquefaction effect, two actions were taken by engineering communities. The first one was development of a practical method to assess the liquefaction vulnerability of residential land and it consisted of the establishment of qualified evaluator of residential land (Towhata and Nakamura, 2015) as well as a new method of hazard assessment (Towhata et al., 2016a). The second action was through the governmental support to reconstruct liquefaction-resistant residential areas. In spite of the principle that recovery from natural disaster damage in personal properties is a responsibility of the owners and that public fund should not be spent on value increase of personal properties, the national government decided to provide supports because of the vast extent of damage on reliability of the urban environment which is public. The requirement was that public space (streets and avenues with lifelines) should be worked on together with the private space. The idea of "together" comes from the fact that liquefaction occurred equally in both public and private subsoils and future safety is achieved only through the overall ground improvement. Land owners were requested to shoulder 50% of the cost that was needed to improve their own land. Moreover, to improve both public and private lands at the same time, residents of the target area were required to unanimously agree on the project and payment. This requirement was not easy and many affected areas could not achieve it. As far as the author experienced, the major difficulties were as what follows;

- Very senior people are not interested in spending money on safety during future natural disaster. They prefer to keep their money for their descendants.
- Some people have retired and are living on a limited amount of pension money. They cannot afford the project.
- Others have already improved their home land by paying a substantial cost for such technology as compaction grouting and formation of micro piles under houses. Naturally, they do not wish to spend further money on repetition of ground improvement.

Accordingly, in Urayasu City, which the author was working for as a technical advisor, only 3 districts with approximately 470 families in total were able to achieve the unanimous agreement.

Fig. 9. Tilting of house situated on liquefied subsoil in Kashima City

Fig. 10. Floating damage of water pipeline in Itako City

Fig. 11. Backfill liquefaction effects on embedded pipeline; note that no liquefaction happened in the farm land (Naganuma City in Fukushima)

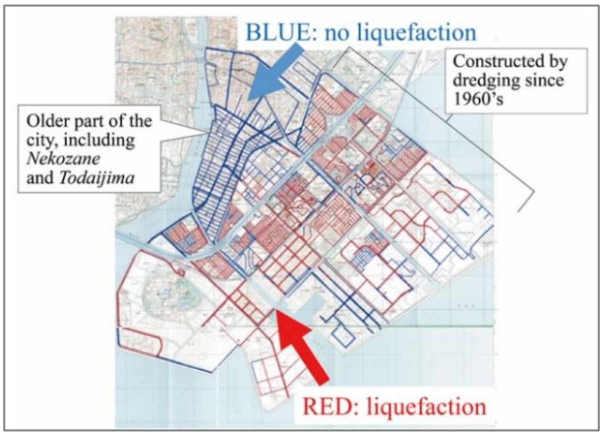

Fig. 12. Effects of soil age on liquefaction susceptibility of subsoil; example in Urayasu City

One of the important novel findings after the liquefaction reconnaissance was that the age of sandy soil significantly affected the proneness to liquefaction. Fig. 12 illustrates the distribution of liquefaction in Urayasu City. This city started its history as a small fishermen's village that was situated on a small sandbar (peninsula) at a river mouth. Shown by blue color in Fig. 12, this part of the city already existed in the 13th Century, according to local legends, and the subsoil here is probably as old as 1000 years or more. No liquefaction damage is known in this part of the city. In contrast, the remaining parts of the city are resting on very young man-made islands that were constructed after late 1960s. Significant liquefaction happened there unless soil improvement had been locally practiced; see red part in Fig. 12.

Seeing such age effect at many places, the author and his group worked on many case histories during the earthquake in 2011. The factor of safety against liquefaction was calculated at many places by using available bore hole data and nearby seismic records. It was found that the border of the factor of safety between liquefied and unliquefied sites, which is equal to 1.0 in principle, decreases with increasing soil age (Fig. 13), suggesting that aged soil has additional liquefaction resistance that is not accounted for in existing design codes. As a consequence, aged soil was less prone to liquefaction in spite of the factor of safety less than unity. Fig. 14 illustrates the increase in liquefaction resistance with soil age. While data from many other literatures are plotted together, the authors' output is illustrated by shaded rectangles and practice can increase the liquefaction resistance by 40% if age is 400 years or more (for details, refer to Towhata et al., 2016b).

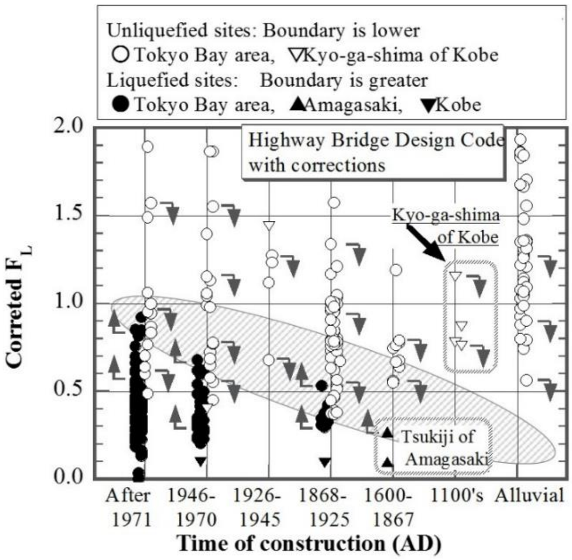

Fig. 13. Variation of assessed factor of safety with age of soil

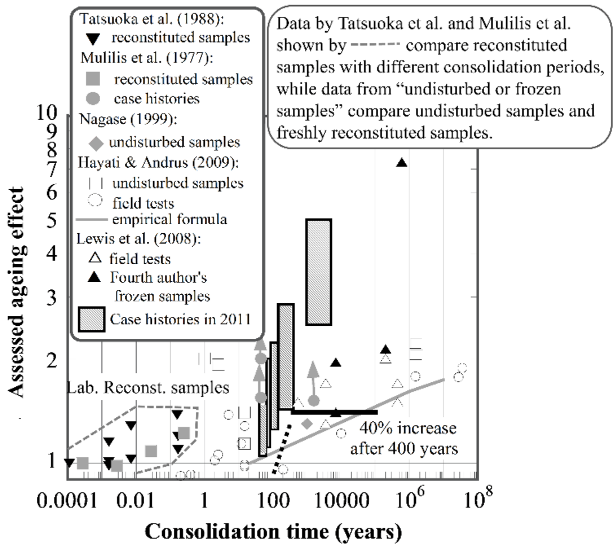

Fig. 14. Effect of soil age on increase in liquefaction resistance of sand; note that the quantitative trend in this figure is valid to Japan only (Towhata, 2018)

GROUND IMPROVEMENT TO MITIAGTE LIQUEFACTION RISK IN EXISTING RESIDENATIAL AREAS

To cope with the vast extent of liquefaction damage in residential areas, the national government set up a public support package by which the cost for ground improvement is supported to individuals. This was an exceptional action but is sometimes carried out in the recent times after "big" natural disasters. What is special herein is that public support is provided to improve the quality (value) of private lands, which is not allowed under normal conditions. From liquefaction viewpoints, the liquefaction in public space (streets in urban areas) and private land cannot be discriminated; both types of subsoil liquefy together and affect urban environment. From this perspective, two kinds of subsoil were improved together with 100% public fund in the public space and 50%-50% sharing between the public and land owners in private land.

The ground improvement projects were carried out under the responsibility of local governments, while cost was partially paid by local citizens in the target areas. Payment by citizens meant that citizens who were not necessarily civil engineers trusted the local governments and provided money. Thus, citizens were clients. Due to this, the projects had the following special features;

- No technical challenge because clients wished 100% success and were not interested in technological research and development
- Reliability of technology that has been verified through practice
- Ground improvement under existing houses
- No substantial damage in or disturbance to daily life of residents
- Reasonable financial burden to people

- Unanimous agreement of local communities on the project; public money should not be spent on ground improvement under single house.

Accordingly, there were only two possible methods of ground improvement; lowering of ground water level (Suwa et al., 2014; Yasuda, 2016) and construction of underground walls of grid shape (Suzuki et al., 1995). The latter method reduces the cyclic deformation of subsoil during earthquake shaking and thus reduces the possibility of liquefaction; see Fig. 15. Obviously, the first option is substantially less costly than the second one. About ten municipalities started to achieve unanimous agreement of residents in target areas. Some of them failed because residents did not wish to spend their money on future safety. Several municipalities achieved agreement and chose ground water lowering that was less expensive and did not even need personal expenditures (Fig. 16). Urayasu City unfortunately could not take this option because the city rests on 40-meter thick soft alluvial clay that caused significant consolidation problem from 1970s to 1990s and even nowadays. It was feared that additional consolidation settlement might be triggered by drainage and ground water lowering. Challenge had to be avoided in the framework of the people's project. Therefore, to carry out the second option of underground wall (soil-cement mixing) in a very narrow space between houses (Fig. 17), a small and light-weighted jet-grouting machine was developed (Fig. 18).

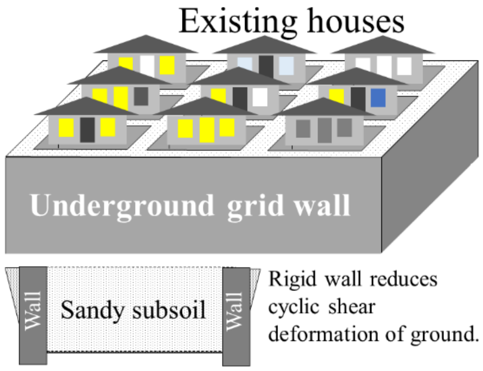

Fig. 15. Mitigation of liquefaction risk by installed underground walls of grid shape in narrow space among houses

Fig. 16. Ongoing drainage and lowering of ground water level in Kuki City (photograph by Prof. Koseki)

Fig. 17. Narrow space between houses in Urayasu City

Fig. 18. Newly-developed small and light-weighted jet-grouting machine

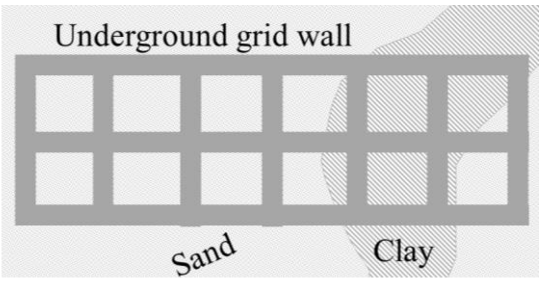

Fig. 19. Conceptual plan of installed grid wall in residential block

Fig. 20. Hindrance of jet grouting by unforeseen buried plastic drain

Figure 19 shows the idea of grid wall in a residential area. It was thought important that all the families in a target block of town unanimously agree on the project so that a complete set of grid wall might be installed. If any one family declines, the grid will be incomplete and its integrity during strong ground shaking will be of question. Noteworthy is that completeness of grid requires jet grouting even in clayey subsoil that may be encountered in a part of the target area.

When preliminary work started in early 2017, clay mass was encountered. As mentioned earlier, the area of Urayasu City is situated in a river mouth where different kinds of soil deposited in waterways at different geological times, leading to mottled pattern of soil-type distribution. This situation was made more complicated during the land reclamation works which put different types of soil at different places at different times. Although construction of liquefaction mitigation measure in clay did not make sense, the overall stability of grid wall required it. Then two problems occurred;

- Clay deposit did not allow uniform jet grouting; grout flowed away only through favorable channels or came out of the ground surface directly,
- Unforeseen plastic drains, that had been installed during land construction in 1970s or earlier in order to promote consolidation, twined around the grouting device and stopped the operation (Fig. 20).

Due to these two problems, the project was forced to stop for half a year and countermeasures were investigated. After trials and errors in the field, it was decided to take the following options;

- Higher jet pressure is applied to remove clay and drain from the device,
- Jet grouting is repeated two times to further ensure the successful work,
- The device is carefully inspected during jet grouting in order to detect possible twining of plastic drain,
- If drain twines, it is removed from the device and jet grouting is executed once more.

Fig. 21. Collected specimen of solidified clayey soil after modified working procedure

The improved procedure was adopted and drilled cores collected from the site were inspected to demonstrate 100% satisfaction (Fig. 21). Only one problem was the elongated construction period. Residents did not like it and voting showed that only one community with 33 families still agreed unanimously on the project. Thus, the ground improvement was finally executed in a very small scale in spite of the original idea (Fig. 22).

Fig. 22. Ongoing ground improvement by small jet grouting device in a very narrow space among houses

This chapter takes example of Rikuzen-Takata City in Iwate Prefecture that was inundated by tsunami up to the elevation of 10 to 17 meters. Considering this extent of inundation, the reconstruction project decided to construct a new sea wall of 12.5-meter height associated with elevating the ground surface level to 7-12 meters by earth filling as well. The volume of filled soil and the area of thus elevated ground are 114.2 million cubic meters and 3.03 square km, respectively (Figs. 23 and 24). One fear is that nine years have passed after the disaster and some people have moved out of the city, while others have got new houses at the top of hills (Fig. 25). Those people may not come to live in the newly elevated land. Because the population has decreased, it is not clear whether or not the newly elevated city will be fully occupied by residents in near future. Last and not least, it should be borne in mind that the ground level is likely to settle down by more than 1 meter during the fault rupturing (Fig. 26). Hence, the tsunami, which comes later, becomes higher than the expectation by this amount relative to the sunken ground.

Fig. 23. Ongoing reconstruction of Rikuzen-Takata City

Fig. 24. Vast size of elevated ground in Rikuzen-Takata City

Fig. 25. New residential area at hill top

Fig. 26. Tectonic subsidence in Onagawa Harbor near Sendai where ground level is lower than the previous level by more than one meter

CONCLUSION

This paper attempts to summarize the author's "Ishihara Lecture" that was delivered in Rome in June 2019 during the 7th International Conference on Earthquake Geotechnical Engineering under the auspices of ISSMGE Technical Committee 203 on earthquake problems. While the lecture covered many topics such as tsunami disaster, subsoil liquefaction, coseismic subsidence of earth crust, model tests on improvement of seismic resistance of infrastructures and the nuclear accident of the Fukushima No.1 Power Plant in addition to the contents of this paper, the author limits his scope herein to geotechnical issues. It may be understood in this paper that substantial damage occurred to people's lives and properties and responses to the disaster required new geotechnical efforts.

REFERENCES

Suwa, S. and Fukuda, M. (2014) Case Study on Countermeasure to Liquefaction by Dewatering Method, Journal of the Society of Materials Science, 63(1): 21-27 (in Japanese).

Suzuki, Y., Saito, S., Kimura, T., Kibayashi, M. and Hosomi, H. (1995) Seismic performance of building foundation improved by grouting in square grid shape, Foundation Engineering & Equipment Monthly, 23(10): 54-58 (in Japanese).

Towhata, I. and Nakamura, H. (2015) Qualified evaluator of subsoil quality for safety of residential land, International Conference on Soft Ground Engineering (ICSGE2015), Singapore, Paper No. 180.

Towhata, I., Yasuda, S., Yoshida, K., Motohashi, A., Sato, S. and Arai, M. (2016a) Qualification of residential land from the viewpoint of liquefaction vulnerability, Soil Dynamics and Earthquake Engineering Journal, 91: 260-271.

Towhata, I., Taguchi, Y., Hayashida, T., Goto, S., Shintaku, Y., Hamada, Y. & Aoyama, S. 2016b. Liquefaction perspective of soil ageing, Geotechnique, 67(6): 467-478.

Towhata, I. (2018) Progress of Liquefaction Ageing in Seismically Active Japan, Geotechnical Earthquake Engineering and Soil Dynamics V, Texas Austin, GSP 290, 473-483.

Towhata, I. (2019) Summarizing geotechnical activities after the 2011 Tohoku earthquake of Japan, 7th Int. Conf. Earthquake Geotechnical Engineering, Ishihara Lecture, Rome.

Yasuda, S. (2016) Liquefaction mitigation in urban developed areas, Bulletin of JAEE, 28: 18-23 (in Japanese).

◆ A brief CV of Prof. Ikuo Towhata

Ikuo Towhata obtained his doctoral degree from the Civil Engineering Department of the University of Tokyo in 1982. Currently, he is a professor emeritus of that school and is a visiting professor at Kanto Gakuin University in Yokohama. He has been majoring mitigation of geotechnical disasters caused by earthquakes and slope failures through laboratory tests, shaking model test, mathematical/numerical analyses and field investigation. He is also interested in microscopic observation of soil mechanics phenomena such as development of shear band and ageing. In addition to academia, he is working for an architectural office and a geotechnical consultant firm. He is the author of an "encyclopedia" book entitled Geotechnical Earthquake Engineering published by Springer in 2008.