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TECHNICAL AND SOCIETAL PROBLEMS TO BE SOLVED IN GEOTECHNICAL ISSUES

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ABSTRACT: The authors were impressed by their damage investigations after the quake that many problems were caused by insufficient development and dissemination of geotechnical engineering despite that actually more advantage is available from this field of engineering. For improvement of this situation, there has to be new philosophies in application of geotechnical engineering because many application fields are not financially well-supported. Budget saving may lead to catastrophic damage if unexpectedly severe natural disaster occurs. Finally, the importance of wider scope is discussed in future scope of re-construction and retrofitting of existing facilities. In addition, data interpretation on ageing effect on liquefaction potential is addressed.

Key Words: Great East Japan earthquake, geotechnical engineering, sea wall, liquefaction, performance-based design, policy for disaster mitigation

INTRODUCTION

After the occurrence of the earthquake on March 11th, 2011, the authors have been substantially engaged in damage investigations in many affected areas, ranging from the Tokyo Metropolitan Area to the Miyagi and Iwate Prefectures where tsunami and liquefaction damages were significant. It was surprising during the investigation trips that the damage extents were so severe in spite of the development of disaster mitigation technologies and social systems in the past several decades. For example, many sea walls were destroyed by overtopping of tsunami water and then allowed further attacks of tsunami on the local community. Slope failure and subsoil liquefaction in residential areas caused profoundly negative impacts on houses and other private properties. A question arose on the significance of many efforts that have been so far done for mitigation of natural disasters.

Another impression comes from the future scope of disaster mitigation. It seems still uncertain what aim is sought for in discussion of future. Immediately after the earthquake, the majority of public opinions were talking about the importance of human lives that have to be protected from natural disasters. After 10 months have passed, media reports difficulties in reconstruction of life and local communities that survived people encounter. However, the new scope has to be established as soon as possible because another gigantic earthquake is expected in the western Pacific coast of Japan within a few decades. In this regard, the present paper intends to discuss the desirable aim of reconstruction of the earthquake-hit community. Because the present symposium is addressed to people from a variety of fields of professions, the authors attempt to touch upon more societal topics than geotechnical issues.

DAMAGE CAUSED BY TSUNAMI

The importance and severity of tsunami-induced damage is already well-known. It is attempted here to describe additional remarks on the tsunami damage. Fig. 1 is a post-earthquake shape of a sea wall near the mouth of the Abukuma River to the south of Sendai. Evidently the soil behind the wall was lost because of scouring and this loss of passive earth pressure behind the wall allowed the wall to be removed easily under the tsunami pressure. Thus, the community that was supposed to be protected by the wall was severely destroyed.

Fig. 1 Destroyed shape of sea wall near the mouth of Abukuma River


Fig. 2 Destroyed industrial area in the water-front area of Kesen-numa City

One of the limitations of a sea wall as a tsunami protection measure was that the disaster was very significant once tsunami overtopped the wall. Hence, after the earthquake, discussion has been made on the goal to be achieved by the future tsunami-protection program undergoing such an extremely strong tsunami as experienced in 2011. Because of the financial difficulty in constructing very high walls (more than 10 m) along the entire tsunami-prone coast, the majority of public opinions has preferred to implement tsunami education for people and emergency evacuation programs. It is certainly true that high sea walls alone cannot solve all the problems, in particular people's lives, but such "soft" measures as education and evacuation cannot solve all the problems either. In the areas where there is no high ground for evacuation, a safety shelter such as high embankment or building has to be constructed. It is therefore pointed out that both conventional and new "soft" approaches should be combined to achieve the best goal.

One year after the quake, re-construction of the tsunami-hit area is focused on. In this stage, one of the most important issues is the unemployment of survived people. Without regular income, people cannot start activities for re-construction of their community. The main reason for unemployment seems to be the fact that the local main industries, which is fishery and marine products industry in the tsunami-affected area, were totally devastated by tsunami (Fig. 2). The authors believe that efforts have to be made to protect, at least to some extent, industrial infrastructures from the tsunami effect. Obviously fish industries have to be located near the sea where tsunami risk is high. Because those infrastructures cannot evacuate upon the attack of tsunami, good sea walls and/or high tsunami-resistant buildings are meaningful.

In case that financial limitation does not allow construction of long and sufficiently high sea walls, an attempt has to be made to reduce scouring and erosion caused by overtopping of tsunami. It should be intended therein to maintain the shape of walls as much as possible after overtopping and to reduce the kinetic energy of tsunami water so that inundation and damage to structures may be minimized. Fig. 3 illustrates an idea to install geo-tubes behind and probably in front of a sea wall so that the tube may prevent erosion of geo-materials undergoing tsunami water flow. Geo-tube is a kind of soil reinforcement by which soil is placed in a long and large tube and soil is separated from contact with water flow.

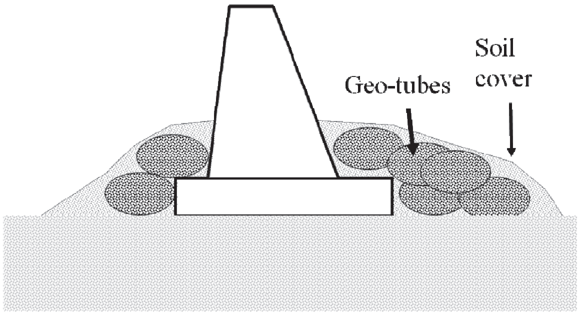


Fig. 3 Schematic illustration of prevention of scouring and erosion behind sea wall by geo-tubes

COSEISMIC SUBSIDENCE

Tectonic actions upon rupture of fault mechanism are often associated with vertical displacement at the earth surface that is either upwards or downwards. In 2011, the coseismic subsidence occurred upon rebound of the hanging-wall side of the reverse fault rupture; at some distance from the fault. In contrast, the sea bed near the fault got uplifted. Coseismic subsidence is important because the ground level along the coastal line sank at maximum 1.2m (Geospatial Information Authority, 2011) and a huge area was inundated (Fig. 4). Hence, reconstruction of local community has been postponed until filling of soil and lifting up of the ground surface. Until their completion, the inundated area is vulnerable to high tide and poor drainage during storms and heavy rains.

(a) Ishinomaki City

(b) Onagawa Harbor

Fig. 4 Inundation and low ground level caused by coseismic subsidence (in Miyagi Prefecture)

Although much cannot be discussed about coseismic subsidence in this text, it is noted that similar phenomena occurred during past gigantic earthquakes: Kohchi in 1946 during the Nankai earthquake, Japan, Valdivia City in 1960 in Chile, and Andaman as well as Nicobar Islands during the 2004 Sumatra earthquake. It is peculiar that the inundated areas in Kohchi and Chile came up again after the quakes (Towhata, 2008), while the subsided areas in 2011 do not come up or are coming up at an extremely low rate: 10 cm or less per year after 40-50 cm of subsidence (GIA, 2011). Thus, artificial restoration of the ground surface is needed.

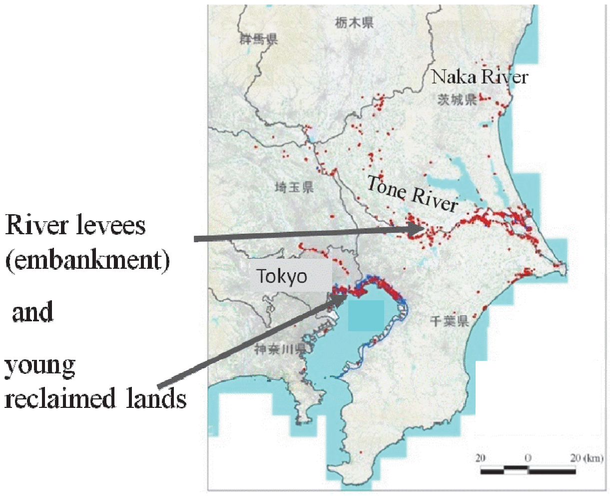


Fig. 5 Distribution of sites of liquefaction (MLIT and JGS, 2011)

ON MITIGATION OF LIQUEFACTION DAMAGE

The authors have been engaged in damage survey and official investigation on mitigation and future design principles in the context of subsurface liquefaction. These activities have been conducted both individually and as national as well as local governmental programs. The major issue to be discussed therein has been the cost-performance of liquefaction mitigation in relatively inexpensive structures for which financial limitations do not allow expensive existing technologies.

Since 1960s when liquefaction was first recognized as a hazard to the human society, as exemplified by the Alaskan and Niigata earthquakes in 1964, much effort has been made to develop technologies that can reduce or prevent liquefaction-induced damage. Methodologies have been developing for the past 40 years or more so that a variety of mitigation measures may be available; ranging from total prevention to reduction of induced damage together with post-liquefaction emergency actions. In spite of those, the earthquake in 2011 still induced significant liquefaction problems at many places. The back ground for this adverse situation is going to be discussed.

Figure 5 illustrates the locations of liquefaction in the Kanto Region around Tokyo Metropolitan area. It is therein found that the locations are classified into two groups; those along major rivers such as the Tone River in the middle of the Kanto Plain and those in the Tokyo Bay area.

First, liquefaction along rivers occurred because of local geological conditions. Throughout the history, those rivers have been changing their channels, both naturally and artificially, leaving hence former river channels everywhere where liquefaction-prone loose sandy deposits exist. Moreover, lakes and swamps in the lower reach of the Tone River have been reclaimed and filled with loose sand for residential development, and liquefaction-vulnerable soil condition has been produced. The present discussion focuses on the problems of dikes resting on former river channels in the present section and the problem of residential development will be discussed later on together with liquefaction in the Tokyo Bay area.

Liquefaction in levees

Figure 6 illustrates the distorted shape of the Tone River levee in Sawara City that is situated upon a former river channel. Because the foundation soil liquefied easily, the overlying body of embankment distorted. Levee is an inexpensive structure for which limited budget is allocated for construction and retrofitting. Therefore, quick restoration after a quake has been practiced traditionally in place of constructing highly resistant levees. Only in the recent decades, the public concern has focused on possible breaching and flooding that may occur immediately after seismic damage. In 2011, there were less than two months of time between the earthquake (March 11) and the beginning of the rainy season (early June). During this short time, it was not possible to perfectly restore all the damaged levees, and those damaged significantly were tentatively restored to the original height. The fundamental restoration had to be postponed until the post-rainy-season. During the rainy season and high water, the levels of patrol and alert were raised in order to avoid possible breaching. Fortunately the worst situation did not occur because no heavy rain or strong typhoon came to the Kanto Region in the rainy season of 2011. Noteworthy is that a river levee is a linear structure in which one breaching out of tens of (hundreds of) km of length can be fatal. More efforts are needed to identify potentially liquefiable sections of levees, evaluate the induced damage level, and retrofit the levee and the foundation to an "appropriate" extent. The appropriate retrofitting means that minor distortion is allowed to liquefied levees unless the risk of flooding during the possible high water level is negligible. Thus, the design philosophy is probabilistic and performance-based.

Figure 7 shows the subsidence and lateral displacement a levee of Hinuma that is one of the tributaries of the Naka River in north Kanto Region. Noteworthy is that the subsoil (Fig. 8) is totally clayey (Ac: alluvial clay) and not liquefiable. It is hence supposed that the body of the levee liquefied and developed significant distortion. To support this idea, the factor of safety against liquefaction (F_L) in the lower part of the levee was calculated by using the method of the Highway Bridge Design Code (2002 version). The input parameters were the intensity of acceleration at the surface $k=0.546G$ by referring to the nearby K-Net record, the depth = 4.3m, and $SPT\text{-}N = 6$, and F_L =0.588 was obtained. Fig. 9 illustrates another example of liquefaction in the body of a levee.

(a) Sand boils in front of the levee (b) Distorted levee

Fig. 6 Damaged levee of Tone River in Sawara

Fig. 7 Damaged levee of Hinuma in Ibaraki

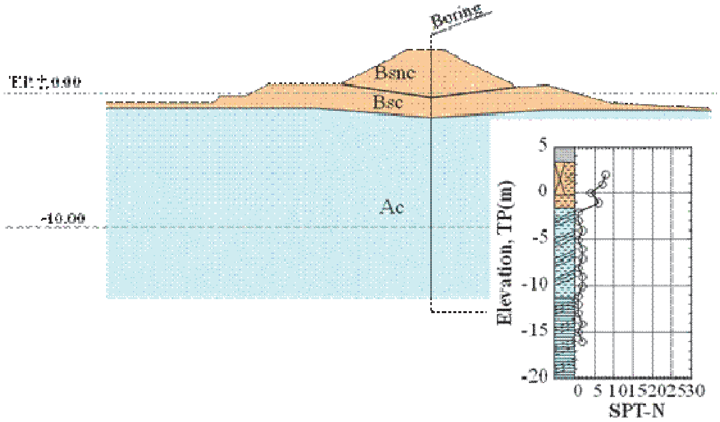


Fig. 8 Cross section of Hinuma Levee and subsoil condition (Sasaki et al., 2012)

The idea of liquefaction inside a levee was proposed after the 1993 Kushiro-oki earthquake in which levees of the Tokachi and the Kushiro Rivers resting on unliquefiable peaty soils developed significant distortion (Sasaki et al., 1994, and Kaneko et al., 1996). Initially, the surface of clayey soft deposit is level and a river levee is constructed upon it (Fig. 10). As long as this initial geometry lasts, the levee is situated above the ground water level, and its water content is not very high. Hence the risk of liquefaction is low. In reality, however, the weight of the levee induces consolidation and settlement. The base of the levee comes into subsoil, and the ground water comes into this part of the levee. The ground water level in the levee rises further because of the infiltration of rain water. Moreover, the soil density of this part of the levee might get looser upon subsidence and lateral extension. It is therefore supposed that, in 2011, liquefaction occurred in many levees resting on clayey subsoil. Further in-situ verification of this idea is being planned now.

Concerning the liquefaction inside a levee, the following technical problems have to be discussed. First, how can we identify the location of potentially liquefiable levee? Out of hundreds of km of length of a levee that is situated on soft clayey subsoil, sections of significant subsidence have to be identified at low cost probably without subsurface sounding. Also, the density and type (sandy or clayey) of soils in the levee have to be identified. Possibly a geophysical survey could play some role therein. Second, the level of ground water has to be determined for assessment of damage extent. However, the ground level is highly variable with seasons, and the highest water level in design consideration leads to high cost of retrofitting. Third, it is desired to lower the water table in the levee. In case the water table is higher than the ground surface, several types of drains are useful, although care has to be taken not to induce unacceptable rate of seepage flow during flooding. Thus, matching between safety during flooding and earthquake safety is always important. Drainage from the base of the levee that is lower than the ground surface is not easy. Although a trench excavation at the toe is promising, cost of the regional drainage system (operation of electric water pumping for example) is noteworthy. Here is again the conflict between safety and reasonable cost.

Fig. 9 Sand boils in the berm at the middle height of the Naruse River levee north of Sendai City

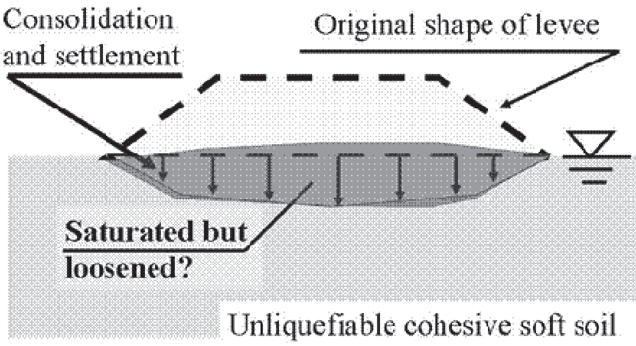


Fig. 10 Schematic illustration on mechanism of liquefaction in levee

(a) Tilting (b) Subsidence

Fig. 11 Damage of private houses caused by liquefaction

Liquefaction in residential development

The aforementioned problem of conflict between cost and safety is encountered in a more serious manner in mitigation of liquefaction problems in residential areas. Fig. 11 indicates damage of houses that are classified into two types; tilting in Fig. 11(a) and subsidence (penetration into foundation soil) in Fig. 11(b). Damage investigation revealed that most liquefaction occurred in young (construction in the second half of the 20th Century) and loose sandy deposits with high levels of ground water (Towhata, 2011). Noteworthy is that, within heavily liquefied municipalities, there are areas where soil had been improved by densification or installation of gravel drains, and liquefaction damage was avoided (Fig. 12a). In contrast, there were heavily liquefied areas as well within a short distance from successful areas (Fig. 12b). Although the areas in Fig. 12 were constructed and sold to people by the same organization, the earthquake performance was completely different. This situation can be attributed most probably to different economic policies; the present paper never intends to justify any of them:

1) As a business by the public sector, the seismic safety should be secured although the price may rise.
2) Residential land sold to people by the public sector should be of low price for the benefit of the people.

Both philosophies are reasonable. When the land was sold decades ago when people were not yet serious about the earthquake risk, the second idea was appealing to people more widely than the first one, although people's idea is opposite after the disaster. Thus, it is still uncertain which idea is reasonable in residential development projects, although the first one appears more acceptable today.

(a) No liquefaction (b) Liquefaction and boiled sand

Fig. 12 Contrast of liquefaction in manmade island of Urayasu City

After the quake, the first author received many inquiries from residents whose houses were affected by liquefaction. It is important to note that, although many houses were not structurally damaged, tilting of less than 10/1000 (Keino et al., 2011) causes dizziness and headache to residents. Obviously, subsidence destroyed connection between the house and buried lifelines.

Then the following issues had to be considered:

1) The risk of a big aftershock or other major earthquake in the near future was of concern. Therefore, people could not decide when they should repair their damaged houses.
2) People were seeking for relatively inexpensive measures that could restore the tilting and subsidence, and, at the same time, mitigate the problem of future liquefaction.
3) The restoration of private houses was not eligible to a public financial support, although a limited amount of public donation was supplied. Hence, people needed an inexpensive restoration measure that still did not sacrifice the safety.

The authors tried to find a mitigation that would satisfy people, but no good one was found. The major problem was the existing house at the ground surface that hindered any soil improvement effort or, at least, increased the cost drastically. One promising idea was the construction of underground walls in the streets that would restrain shear strain of soil from occurring during strong earthquakes and consequently would reduce excess pore water pressure. This idea was once considered promising by people because any reconstruction works under public roads were supposed to be paid by the public sector, thus reducing the private expenditures. Unfortunately, the idea of underground walls was considered less promising because the spacing between walls was too large to prevent liquefaction.

The next promising idea is lowering of ground water table, thereby increasing the thickness of unliquefiable soil layer near the surface and achieving more safety for surface structures (Ishihara, 1985). If lowering is practiced in a big scale (involving 100 houses or more), the cost becomes reasonable. The authors suppose there are several problems to be overcome in lowering of the ground water table;

1) In case the surface liquefiable soil is underlain by soft cohesive materials, consolidation and subsidence may be serious.

2) In particular, differential settlement of foundation of houses would cause fatal effects on houses.
3) Lowering of ground water often needs continuous operation of pumps that require substantial cost of operation and maintenance.
4) Safety and reliability of ground water lowering is not very clear during unexpectedly strong earthquakes.

It is supposed therefore that lowering of the ground water table should be practiced if and only if 100 % of the concerned people agree. Otherwise, lowering should not be done because compensation for possible house damage during consolidation settlement costs profoundly. Thus, there seems to be no good mitigation technology that is sufficiently effective but inexpensive. People should accept lowering of ground water or, in place of any public support for safety of houses, individual house owners should do efforts. When existing houses are demolished after, probably, 30 years, more efficient and less expensive mitigation measures for liquefaction problem can be conducted.

EFFECT OF AGEING OF SAND ON LIQUEFACTION RESISTANCE

Figure 13 demonstrates the distribution of liquefied areas (shown by red color) and unliquefied areas in Urayasu City. It is shown here that liquefaction occurred in younger manmade lands that were constructed after 1960s while no liquefaction occurred in more aged subsoil. It seems therefore important for assessment of liquefaction risk to take into account the ageing effects so that the reliability of the assessment may be improved. Note, however, that the study of ageing is meaningful if SPT-N and other sounding data do not account for the ageing. The study is useful practically if the risk of liquefaction decreases with the increase of age although SPT-N and other sounding data do not increase with age correspondingly.

Studies on ageing effect on liquefaction resistance of sand were conducted by Mulilis et al. (1977) and Tatsuoka et al. (1988). Both conducted laboratory tests by changing the time of consolidation and suggested an increase of liquefaction resistance with time. However, the consolidation time in the laboratory was limited to 100 days because of many technical limitations. In this regard, Mulilis et al. (1977) studied case histories to extend the consolidation time to nearly one million days. The present study attempts to study case histories of liquefaction as well.

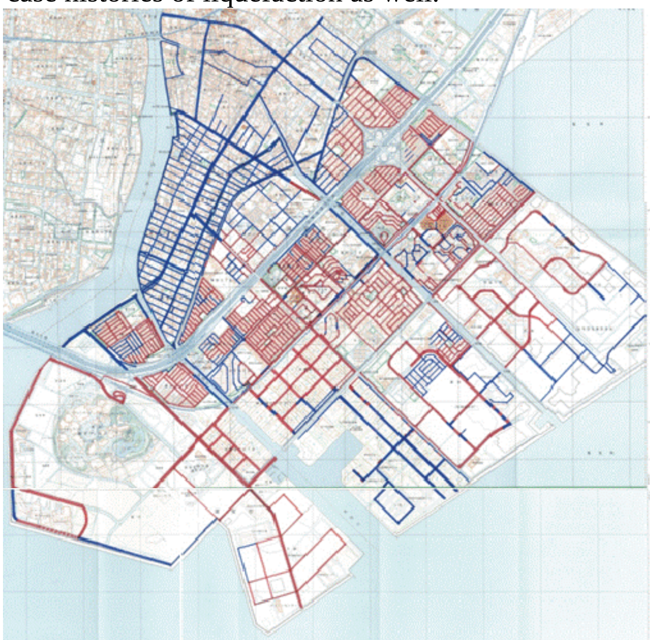


Fig. 13 Distribution of liquefaction in Urayasu City of Chiba

Cases with and without liquefaction were collected from the eastern part of Tokyo and Urayasu City of Chiba where the age of land reclamation is clearly known. The information on soil profile was collected from database that was developed by JGS. Fig. 14 indicates the relationship between the normalized N_1 of standard penetration tests and the seismically induced stress ratio, *L*. This *L* value was calculated by using the maximum horizontal accelerations that were recorded at nearby K-Net stations. As expected, data from liquefied and unliquefied sites are separated to some extent by the curve suggested by the Highway Bridge Design Code (2002 version). The study on ageing concerns whether or not this border curve changes with the age of soil. In other words, the boundary of the factor of safety against liquefaction, F_L, between liquefaction and no-liquefaction may change with age, although the current practice assumes that this boundary is F_L=1. The F_L value was calculated by using the Highway Bridge Design Code.

The data of N_1 and L in Fig. 14 changes in the vertical direction in a single borehole data. The particular plotted data correspond to

1) the minimum factor of safety against liquefaction, $F_L$min, at sites of liquefaction because this $F_L$min indicates that the abovementioned boundary value is greater than $F_L$min, (see Fig. 15) and
2) the maximum $F_L$max at sites without liquefaction because this $F_L$max suggest that the boundary value is less than $F_L$max.

Figure 16 plots $F_L$max and $F_L$min thus defined against age of soils. Note that the boundary F_L lies between the upward and downward arrows. It seems reasonable to state that this boundary value decreases as the age increases, implying that aged soil is unlikely to liquefy even when F_L value is less than unity. In other words, SPT-N values that are employed in calculation of F_L does not account for the increase of liquefaction resistance with age.

For further discussion, the plotted data was modified or improved by considering the amplification of ground motion at liquefied soft ground. The dynamic analysis at liquefied sites of Urayasu showed that the surface motion was approximately 30% greater than the nearby K-Net record which was obtained on unliquefied soil (report to the city government, unpublished yet). In this regard, all the F_L values at liquefied sites in Fig. 16 was reduced to 75% (= 100%/130%) of the original values.

The results are presented in Fig. 17. It is more clearly shown that the boundary value of F_L decreases with increase of age and that liquefaction resistance of soil increases with age. This increase rate is equivalent to the inverse of the boundary F_L. Fig. 18 demonstrates this increase in which the range of uncertainty in both the boundary F_L and the soil age (construction period is longer than one year) are accounted for. The newly obtained data is consistent with those from previous studies.

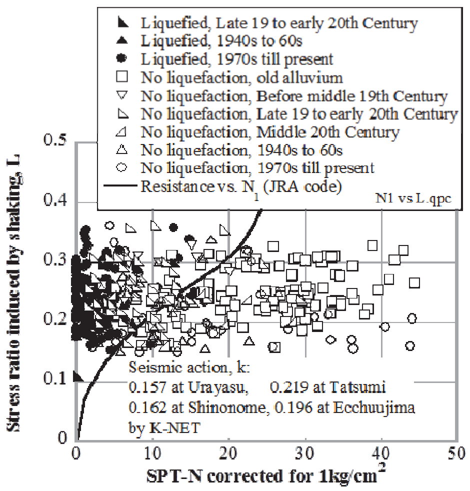
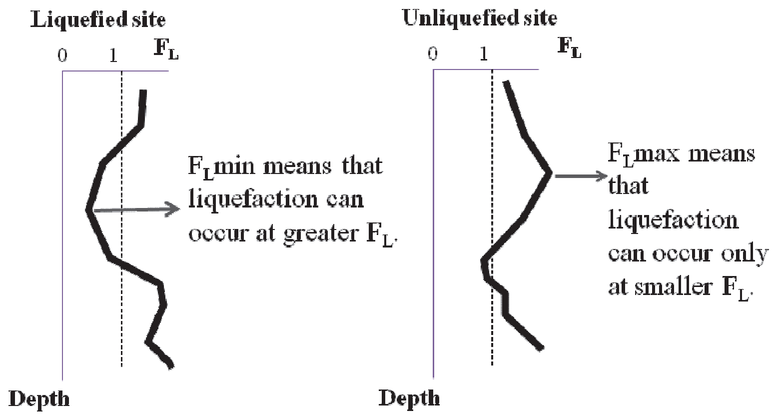


Fig. 14 Relationship between cyclic shear stress ratio, L, and the normalized SPT-N at sites with and without liquefaction.



The boundary between F_L for liquefaction and F_L for no liquefaction lies between $F_L$min and $F_L$max.

Fig. 15 Significance of minimum and maximum factor of safety against liquefaction in a single borehole data.

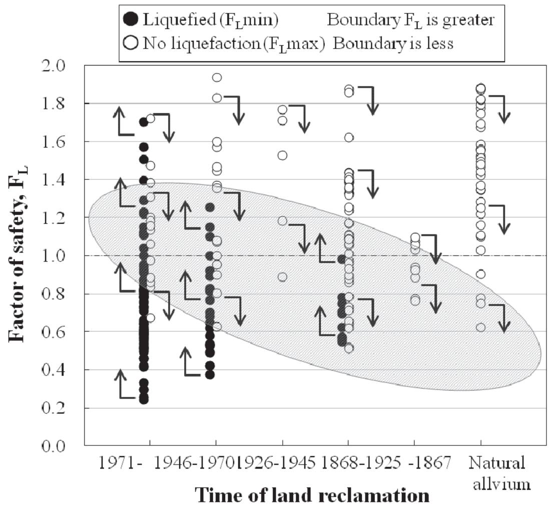


Fig. 16 Possible ageing effect on the border value of F_L between liquefied and unliquefied sites.

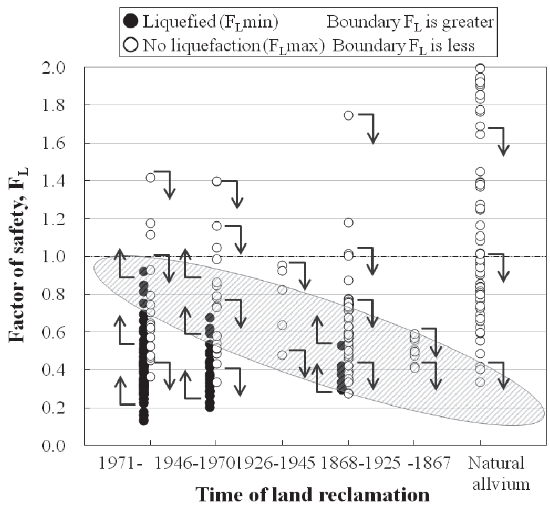


Fig. 17 Revised insights on ageing effect on the border value of F_L between liquefied and unliquefied sites

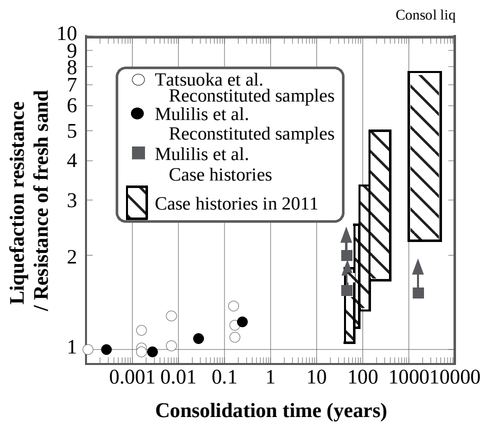


Fig. 18 Assessed effect of ageing on liquefaction resistance of sand obtained from the cases in 2011 (arrows on symbols by Mulilis et al. implies that the true ageing effect is greater than the plotted value.)

CONCLUSIONS

Geotechnical damage and liquefaction events caused by the gigantic earthquake in 2011 were reviewed and discussed. The major conclusions drawn from this study are as what follows.

1) The role to be played by the geotechnical engineering is more than conventional perception. Typical example is the mitigation of scouring behind a sea wall undergoing tsunami overtopping.
2) Liquefaction inside a river levee is now suspected to be one of the major causes of damage. Mitigation of this problem needs lots of efforts from now on.
3) Liquefaction damage in house foundation was serious. There seems to be no good mitigation for this problem that can be practiced at low cost with good performance.
4) The ageing effect on liquefaction resistance of sand was demonstrated by using borehole database and information on onset of liquefaction.

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