# Unsolved engineering problems after 2011 gigantic earthquake in Japan

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**ABSTRACT:** The gigantic earthquake of magnitude=9 in 2011 in Japan caused many unexpected problems in the community. The significant number of problems over a vast area interacted with one another and made the situation much worse. Nuclear issues have developed to political problems and are difficult to solve in a short time. In addition, engineering is encountering such problems as mitigation of the risk caused by the next tsunami attack, protection of people's houses from subsoil liquefaction, and the preparedness for very rare seismic events in future. The balance between life safety and continuation of economic activities is the key issue but the decision is often affected by political and emotional issues. Because of the speakers majoring field, the talk will put emphasis on geotechnical issues. Note that this report is a minor modification of one of the author's recent papers that were published, first, during the Indian Geotechnical Conference (2011) and, second, in an electronic issue of the Indian Geotechnical Journal

**KEY WORDS:** Earthquake, Liquefaction, Embankment, River levee, Damage investigation, Ageing

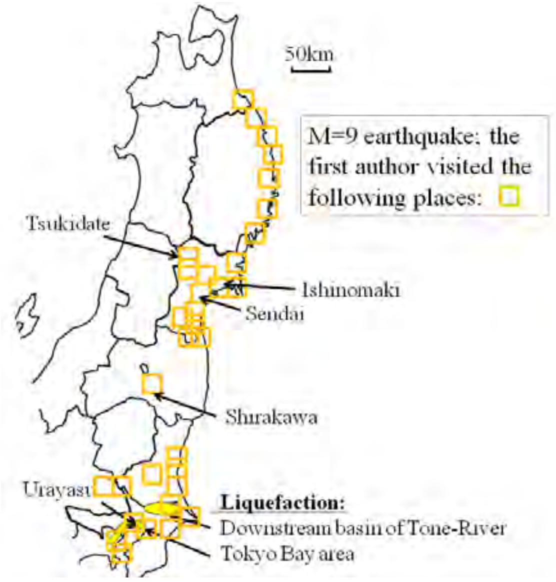


Fig. 1 Sites of first author’s damage study [1]

## INTRODUCTION

The gigantic earthquake of Mw=9 that hit the eastern part of Japan on March 11, 2011, produced a variety of damages that had not been well experienced by human community so far. On the other hand, good seismic performance was observed as well in some structures. The present paper, hence, is going to address those findings and indicate future problems to be tackled from now on. The content of this paper comes certainly from the authors’ own field studies at many places as shown in Fig. 1. This figure illustrates the distribution of damages as well and the fault rupture was located in the Pacific Ocean to the east, ranging almost all along the coast in this figure.

## ON SEISMIC MOTION

As the great seismic magnitude of 9 implies, the size of the earthquake rupture ranged hundreds of km. Fig. 2 shows the *NS* acceleration that was recorded at Ishinomaki *K-NET* station (Fig. 1). Noteworthy is the long duration of shaking, exceeding 100 seconds, and the existence of two strong phases. The former feature implies many number of cyclic loadings, affecting the occurrence of subsoil liquefaction at many places, while the latter feature comes from the superposition of more than one rupture zones. The strongest peak acceleration of 2,900 cm/s$^2$ was recorded in Tsukidate (Fig. 1). Although heavy damage may be supposed under this strong action, the reality was totally opposite (Fig. 3a). In a local town of Tsukidate to the north of Sendai City (see Fig. 1), no significant damage occurred in spite of the horizontal acceleration of nearly three times the gravitational acceleration (Fig. 3b). Therefore, the conventional pseudo-static design principle that suggests significant earthquake force under this strong acceleration is not a reality. No significant damage was reported for most buildings in Sendai City in the affected area, either.

## COSEISMIC SUBSIDENCE OF COASTAL REGION

The subduction mechanism between the Pacific Ocean plate and the Japanese Archipelago induced rebound of the ocean bed at the onset of the earthquake. This was the cause of the devastating tsunami along the coast line. In contrast to the 4.5-m uplift in the seabed, the coastal area subsided by 1.5 m at maximum (announcement by the Meteorological Agency). Consequently, drainage of tsunami water became difficult and the low ground level together with the disappearance of sea walls made the coastal area extremely vulnerable to high waves during typhoons. Fig. 4 shows the Ishinomaki City with ground surface covered by water. Similar coseismic subsidence occurred during the 1946 Nankai earthquake of Mw=8.1 or more in Japan and the 1960 Chile earthquake of Mw=9.5 together with some other gigantic quakes in the past. In contrast to those former events after which the ground level came back to the original level within several months or a few years, the present subsidence has not been recovered very much (as per the end of October, 2012).

## PROBLEMS OF SEA WALLS

Sea walls have been conventionally designed to fully protect the local community from invasion of design tsunami. The height of the design tsunami has been determined on the basis of recent recorded experiences in the past 100 years or so. Because the quake in 2011 was the recurrence of a past big event in AD 869 (magnitude being more than 8.3), many sea walls were easily overtopped by tsunami this year.

Figure 5 demonstrates a damaged shape of a sea wall. The overtopping of tsunami water significantly eroded the ground behind the wall and this loss of soil there probably reduced the lateral resistance of the sea wall (passive earth pressure). Consequently, walls were translated toward the land, and, when the second and the following tsunamis came, there was no protection any more. Note that tsunami came 4 times.

In contrast, many river levees survived the attack of tsunami that propagated upstream through river channels (Fig. 6). This good performance is interpreted either as the tsunami propagated not normal but parallel to the levees or as the ground behind the levees had already been inundated by tsunami water that directly invaded from the coast line and protected ground from eroding impact of overtopping water. Conversely, Fig. 7 illustrates a damaged levee of Kitakami River to the east of Sendai where the channel bent and allowed tsunami to directly hit the levee.

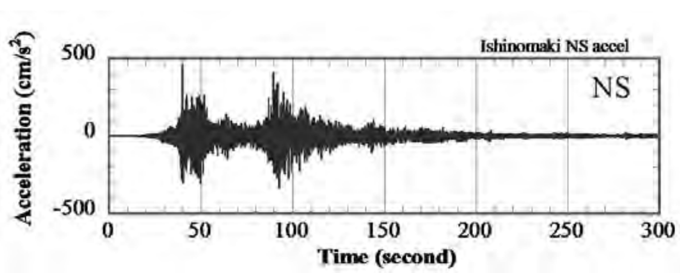


Fig. 2 Strong acceleration data (NS) at K-NET Ishinomaki Station

(a) Situation in Tsukidate Township 3 weeks after the quake


(b) Earthquake motion record in Tsukidate (after K-Net)

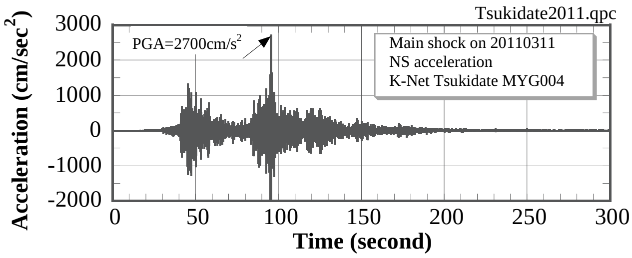


Fig. 3 Intact situation in Tsukidate Township


Fig. 4 Zero-level of water-covered ground surface in Ishinomaki City

Fig. 5 Destroyed shape of sea wall (near the mouth of Abukuma River to the south of Sendai City)


Fig. 6 River levee that survived tsunami in spite of overtopping (Natori River at Yuriage)

Fig. 7 Damage of Kitakami River levee that was directly hit by tsunami

**SLOPE INSTABILITY**

The slope instability problem was not very significant in spite of the size and magnitude of the earthquake. This is probably because, as Fig. 2 implies, most part of the motion had the amplitude of acceleration of more or less 200 $cm/s^2$ only, except a few high spikes. This is a significant difference of the present earthquake from the 2007 Kashmir and the 2008 Wenchuan events both of which caused tremendous number of slope failures and claimed lots of human lives. One of the few examples of big slope failures is shown in Fig. 8 where a weak volcanic deposit failed under the seismic action. This event buried houses and killed residents.

More damaging slope problems, although the size was smaller, occurred in artificial earth fills in hill areas. The residential development in Sendai City has traditionally been conducted in hilly areas where cut-and-fill construction has been the tradition. Fig. 9 reveals a damage example. This occurred in the fill part of the area, causing significant property loss to the residents. Furthermore, Fig. 10 shows the remaining sand at the surface. This sand was an ejecta from liquefaction, because this area was constructed by filling a small water stream. The fill was submerged in water and became vulnerable to liquefaction. In contrast, the cut part of the residential area was of minor damage (Fig. 11).

Fig. 8 Failure of natural slope in Shirakawa City


Fig. 9 Damaged residential fill in Sendai


Fig. 10 Remains of liquefied sand at road surface in residential area where former water stream was filled with cut soil


Fig. 11 Relatively intact shape of residential development in cut part

The damage in the fill substantially affected overlying houses. This damage in the residential area is posing a serious problem about liability. First, the residents purchased their land from a developer. The residents did not have knowledge and information about seismic instability of land. Despite this, the current regulation states that the land owners, i.e., residents, cannot demand compensation. The current knowledge level of geotechnical engineering is considered insufficient to demonstrate lawfully the lack of care and responsibility of contractors and developers. Consequently, residents are forced to pay all the damage expenses. This situation is particularly bad when house mortgage is not yet returned 100%, while the house is destroyed. Similar situation will be mentioned later with regard to liquefaction.

Fig. 12 Liquefaction-induced lateral spread and subsidence of Naka River levee

## LIQUEFACTION PROBLEMS

Reports on the onset of subsoil liquefaction came mostly from the Tokyo Bay and surrounding areas. This, however, does not mean that no significant liquefaction occurred in the Sendai area that is closer to the fault rupture zone. Evidences of liquefaction in the coastal area of Sendai were washed away by tsunami. The known occurrence of liquefaction in the inland Sendai area and the entire Tokyo area is classified into two groups; i.e., liquefaction of river levees and liquefaction in manmade island.

### Liquefaction in River Levees

Many levees are situated on soft soil deposits. In particular, recent artificial change of river channels to a more straight shape resulted in new levees constructed on loose sandy deposits that are likely to liquefy. The number of damaged levees was nearly 2000, inclusive of major and minor damages. Fig. 12 illustrates a damaged shape of the Naka River levee in Mito City, about 100 km NE of Tokyo. The liquefiable sandy soil underlying this embankment caused lateral spreading and the consequent cracks in the longitudinal direction. At the same time, subsidence exceeded 1.5 m.

Conventionally, river levees have not been designed and constructed against earthquake effects, because the chance of simultaneous occurrence of flooding and strong seismic action has been considered sufficiently low. As an alternative, it has been required and practiced to restore any seismic damage within 14 days after the damage. This goal, however, was not achieved this time because of the huge total number of damage. In addition, the earthquake occurred on March 11 and the rainy season was supposed to start in late May or early June, lasting till the end of typhoon season in October. Thus, the damaged levees were not fully restored before the rainy season. In particular, the lack of construction fuels and equipments immediately after the quake made it difficult to commence the restoration works. Moreover, damage extents were increased by aftershocks. Consequently, most levees were temporarily filled back to the original elevation and possible weakening and softening inside their bodies were not repaired. During the rainy season, those levees were watched more carefully in order to avoid possible breaching.

It is widely known that liquefied sand is consolidated afterwards and its density increases. Because the risk of liquefaction decreases with increase in density, people imagine that previously liquefied sites are less likely to liquefy again during future earthquakes. Unfortunately, this idea is too optimistic. The liquefaction-induced densification of sand is not sufficient; relative density increasing only 10% or less, which is far less than what soil compaction works achieve. Fig. 13 illustrates one of the examples of repeated liquefaction that took place for the 4th time since 1978. Note in this photograph that the river channel is situated to the left of the levee in the front and the area to the right is an abandoned river channel where sand is loose and water-saturated. Similarly, liquefactions were repeated in Christchurch, New Zealand, 3 times in September 2010, February, and June in 2011 [2]. Hence, initiation of the re-construction delayed and was made very difficult.

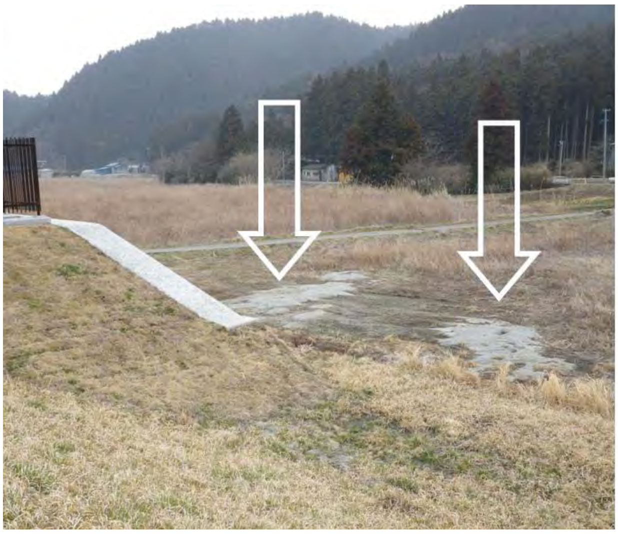

Fig. 13 Repeated liquefaction at Kita-Wabuchi site of Eai River to the north of Sendai; sand ejecta shown by arrows


Fig. 14 Damaged levee resting on unliquefiable clayey subsoil (levee of Naruse River, north of Sendai)

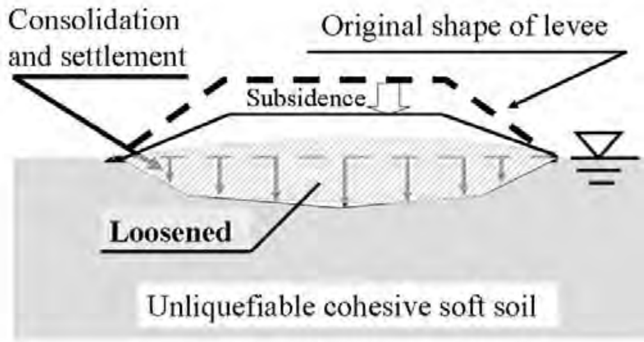


Fig. 15 Mechanism of liquefaction in originally compacted river levee after consolidation settlement in foundation

A more significant and new problem is attracting a serious concern. Fig. 14 shows the distortion of a levee that rests on unliquefiable clayey deposit. The sliding of the slope surface and lateral bulging as well as the subsidence of the crest had been considered unlikely in the engineering practice when the foundation is composed of unliquefiable material. The reality is more complicated.

Figure 15 illustrates the current understanding of the mechanism. First, during normal times, the compacted body of a levee sinks into soft clayey deposit that is subject to consolidation and settlement. Second, the subsided part of the levee is submerged in ground water. This water-saturation has been confirmed by excavation and restoration of damaged levees after the 1993 Kushiro-Oki earthquake [3] and the present earthquake. Third, the subsided part is made looser and liquefiable by an unknown procedure. some engineers suggest that river levees resting on very soft clay deposits are hardly compacted in practice. Since this part of the idea is not yet verified, more information is expected after the completion of ongoing detailed studies. In addition, the practitioners are now facing a problem how to identify this kind of liquefaction-prone sections out of thousands of kilometers of levees in alluvial planes.

There are many levees, in contrast, that were not affected by liquefaction. They proved that such mitigation measures as grouting, compaction, and drainage are effective. Detailed information is now being assembled and will be published in near future.

**Liquefaction in Residential Area Resting on Manmade Islands**

Since 1960s, residential development has been practiced intensely in Tokyo area by constructing artificial islands in the Tokyo Bay. The employed soil material mostly came from seabed dredging in harbours. The major feature of this soil is its fine grain size with low plasticity of fines.

Figure 16 illustrates a site of typical liquefaction in Urayasu City (Fig. 1) to the east of Tokyo. The subsidence of ground after liquefaction is estimated to be 50 cm. The grain size distribution of sand ejecta is shown in Fig. 17. Note that the fines content increases as distance from the ejection crater increases, suggesting that fine grains are more likely to be transported by flow of ejected water than coarser grains. Further note that the tested sand was non-plastic in spite of its substantial fines content.

Fig. 16 Liquefaction and sand ejecta in Urayasu City

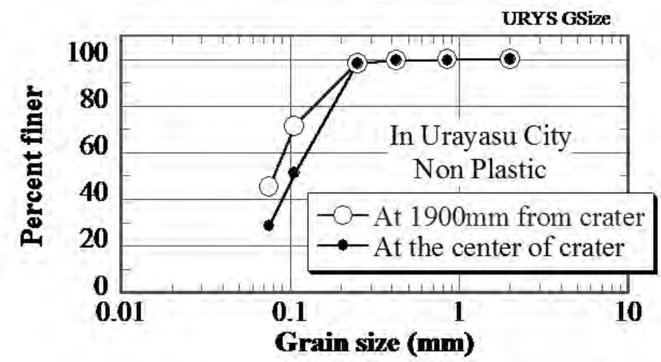


Fig. 17 Grain size distribution of ejected sand

Fig. 18 Differential settlement between surface of liquefied ground and pile-supported building

One of the countermeasures against liquefaction effects on buildings is the use of a pile foundation. Fig. 18 illustrates a successful example of pile foundation. However, note the differential settlement at the ground surface, which destroyed the connection of embedded lifelines with the building. Lifeline damage is typically shown by floating of manholes of sewage pipes (Figs. 19 and 20). Connections of sewage pipelines were destroyed by liquefaction of backfill sand.

Fig. 19 2-meter floating of manhole

Fig. 20 Floating of a series of manholes

Figure 21 shows a tilted residential building. Due to lack of pile foundation in such a small structure, the subsurface liquefaction resulted in significant tilting and subsidence. Note, however, that there is no structural failure. Thus, the residual deformation and displacement are the essence of liquefaction-induced damage. Liability in such damage to private properties is now attracting concerns. It may appear that those who constructed the liquefaction-prone land are responsible. However, the current regulation understands that the level of geotechnical engineering is not so precise to assess to the order of cm the liquefaction-induced deformation of foundation under any future earthquakes. Many design charts and formulae exhibits a certain extent of data scattering and uncertainty. No need to mention the non-uniform subsurface structure of soils that cannot be fully identified by the current practice of soil investigation, in both technological and economical senses.. Thus, the owners, who are not engineers, have to pay for the damage, although local governments may offer some financial supports.


Fig. 21 Subsidence and floating of residential building

Fig. 22 Satisfactory performance of major road in Urayasu

Fig. 23 Liquefaction-induced distortion of sidewalk

The major roads in Urayasu City were able to maintain their function after the earthquake. Although some distortion occurred (Fig. 22), emergency vehicles were still able to travel at reasonable velocities. This good performance was achieved by special precautions during the road construction which decided to make pavement thicker than code requirements. It is noteworthy that subsurface liquefaction and the consequent volume contraction of sand under the pavement produced cavities underneath, and that the asphalt pavement started to collapse into the cavity at some places in summer when the temperature rose and the asphalt lost its mechanical strength.

Another problem in the road is the heaving of sidewalk (Fig. 23). It is therefore likely that lifeline underneath, if any, is subjected to large distortion. The causative mechanism of this problem is yet to be known but the authors suppose that the subsidence of embankment and other heavy structures behind pushed the subsoil laterally and then upwards towards the sidewalk pavement that was not as rigid as that in the main road (Fig. 22). The contribution of elongated shaking together with a strong aftershock (30 min. after the main shock) requires further investigation.

Figure 24 illustrates the distribution map of liquefaction in which streets along which liquefaction was observed are coloured by red, while those without liquefaction by blue. Obviously the south-eastern part of the city was affected by significant liquefaction, while the north-western part was free of liquefaction (Fig. 25). The latter part consists of the original alluvial ground that is as old as 100 years or more. Although the composing sand in this area is basically identical with the seabed sand that was dredged in the recent times and used for reclamation, the consequence of liquefaction was entirely different. This difference, in spite of similar SPT-N values is called the ageing effect at this moment, but its detailed mechanism is still unknown.

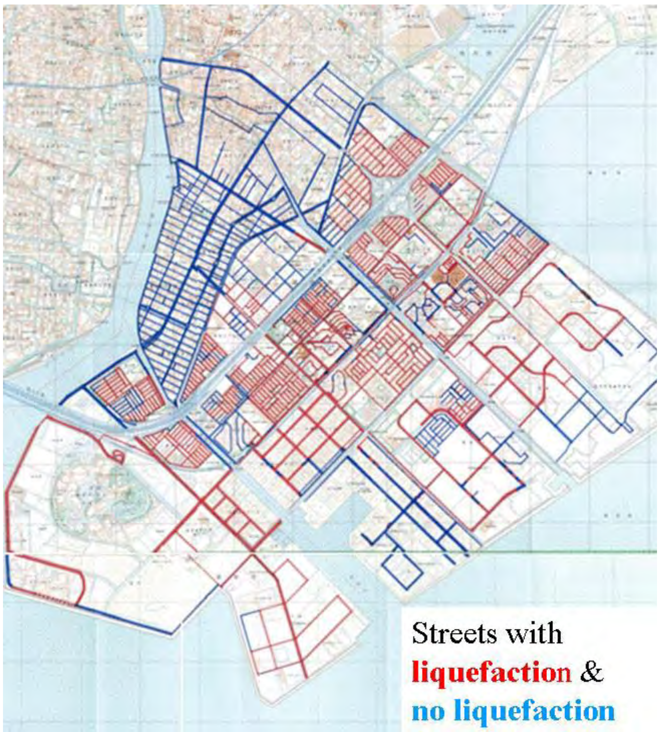

Fig. 24 Distribution of liquefaction in Urayasu City


Fig. 25 Lack of liquefaction in north-western part of Urayasu City

Fig. 26 Successful soil improvement by gravel drains against liquefaction

The lack of liquefaction in the young reclamation area in Fig. 24 was attained by a variety of soil improvement technologies. Although there are still some restrictions to publish those information, it is possible to demonstrate Fig. 26 where a block of residential area had been improved by sand compaction piles and gravel drains prior to building houses. Compaction was executed in the major part of this area, while gravel drains were installed near the border with adjacent residential areas in order to avoid noise and vibration. What is important is that soil improvement before house construction is easy and inexpensive, while improvement under existing houses is more than 5 times more expensive and is now causing problems in the local community. Although some people are accusing of land developers for ignoring the risk of subsoil liquefaction prior to sales, a local real estate businessman said that people had preferred to spent their money not on disaster mitigation but indoor decoration and convenience in life (dish washers etc.). It seems that a trade-off between safety and convenience is going to be a big issue of discussion. It is at least reasonable to say today that safety is not free of charge.

**Liquefaction in Other Areas**

Tone River (Fig. 1) is one of the biggest rivers in Japan and there are many swamps and meandering channels along its main stream. Some of those water areas were filled with soil and formed liquefiable subsoil conditions. Fig. 27 is a liquefied site where flooding in 19th Century created a pond (Fig. 28) that was later filled with sand. The problem was that the liquefaction risk in this area was not indicated in a local hazard map probably because the lack of bore-hole investigation.

Liability problems occurred in the area of Fig. 29. This area used to be swampy with thick clayey deposit. In 1950s, the local government filled sandy soil above the surface, and this thin sandy layer was naturally saturated with water. Although the liquefaction layer was thus thin, minor tilting in houses (1% or less) has caused residents severe headache and dizziness. The point of argument is whether or not the risk of liquefaction was foreseen in 1950s prior to the 1964 Niigata earthquake and whether or not the recent caution by the local government about liquefaction risk has been sufficient.

## ON AGEING EFFECT

The liquefaction hazard map that was prepared before the quake specified that the entire Urayasu City is prone to liquefaction. Reality was in contrast (Fig. 24), implying that the existing technology underestimates the liquefaction resistance of aged (not as young as manmade islands) sand. To shed light on this, the seismic stress ratio, *L*, was calculated at many places and plotted against the corrected $SPT\text{-}N_1$ value (Fig. 30). Black and open symbols in this figure correspond to the occurrence and lack of liquefaction, respectively. Different symbols correspond to different times of land construction (different ages). Further, the curve indicates the liquefaction resistance of sand assessed by JRA method (Highway Bridge Design Code by Road Association of Japan). Because of the non-plastic nature of dredged sand for reclamation, which is not accounted for in existing codes, the fines content in this calculation was set equal to zero except for the natural alluvium. It may be therein seen that there are many open symbols above the curve, suggesting that more aged soil is less likely to liquefy.

Fig. 27 Liquefaction in filled pond (Abiko City)

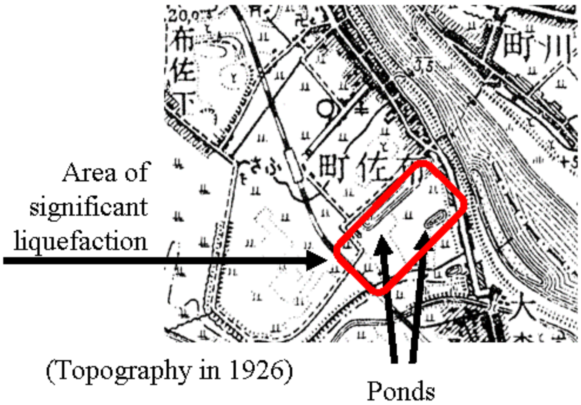

Fig. 28 Former topographical map in 1926 of the area in Fig. 26

Fig. 29 Liquefaction-induced tilting (Kazo City)

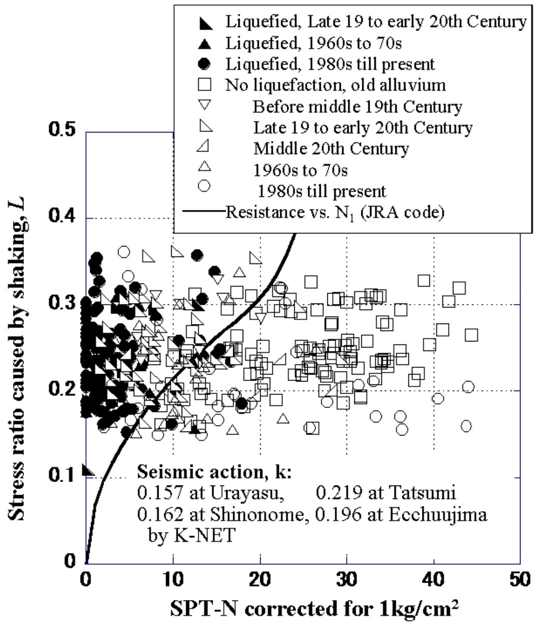

Fig. 30 Relationship between induced stress ratio, $L$, and SPT-N

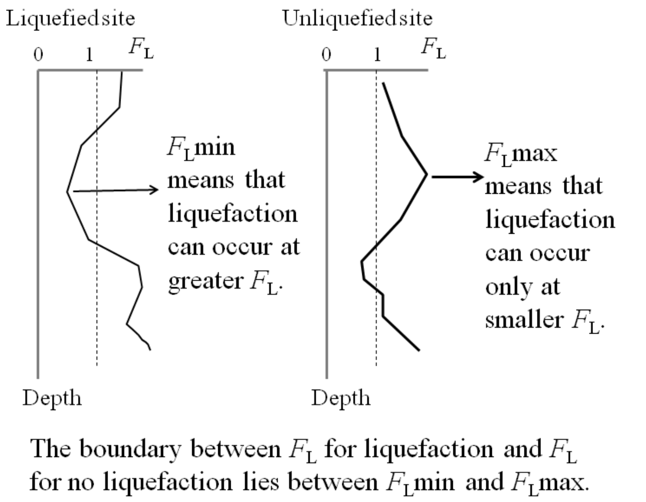


Fig. 31 Meanings of minimum and maximum values of $F_L$ at liquefied and unliquefied sites

The existing codes do not explicitly consider the age of soil except possible increase of SPT-N with age. It was therefore attempted to assess the factor of safety against liquefaction ($F_L$) by using the 2002 Highway Bridge Design Code of Japan and compare it against the real soil behavior during the earthquake. The aim is to find out the border between $F_L$ values corresponding to liquefaction and $F_L$ values corresponding to no occurrence of liquefaction. The border value may be different from the conventional practice of 1.0 because of the ageing effects. Hence, profiles of $F_L$ values in recent subsoil at many studied sites in Tokyo Bay area were examined. As Fig. 31 illustrates, the border value of $F_L$ is greater than the $F_{Lmin}$ at liquefied sites, but less than $F_{Lmax}$ at unliquefied sites. By plotting these maximum and minimum values against the age of sites, Fig. 32 was obtained to show that the possible border values of $F_L$ are located in the shadowed area, decreasing with the increase in age, implying that the more aged soils are unlikely to liquefy even though the calculated $F_L$ is smaller.

It was further supposed that the surface acceleration at the ground surface of liquefied site should be increased from the values in Fig. 29 because those acceleration was recorded at unliquefied sites where soil condition was relatively better. Considering the extent of liquefaction in Urayasu City [4], the acceleration was increased by 33% only at liquefied sites. In addition, the assessed liquefaction resistance at all the sites was reduced twice by first 20%, considering the long duration of shaking (many number of cyclic shear stress), and second 10%, because of the two-directional shaking effects [5]. Consequently, Fig. 33 was obtained to make the border range narrower. The border value of $F_L$ decreases with age, implying that liquefaction becomes unlikely in more aged soil in spite of lower $F_L$ values. Thus, the liquefaction resistance increases with age.

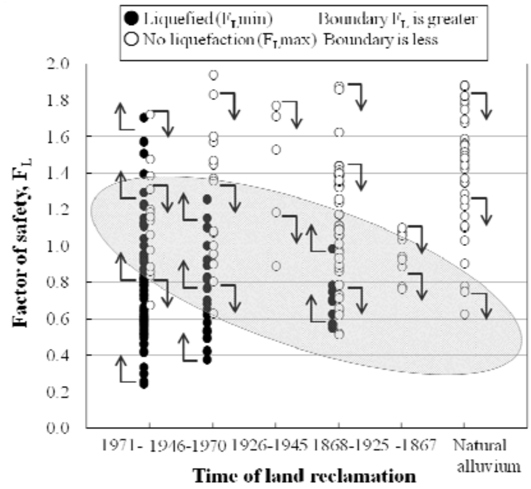


Fig. 32 Possible ageing effect on the border value of $F_L$ between liquefied and unliquefied sites

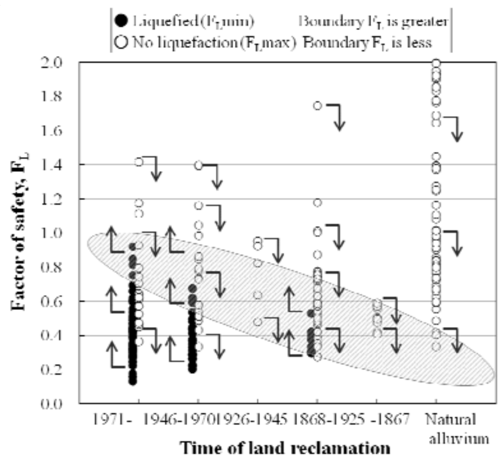


Fig. 33 Revised insights on ageing effect on the border value of $F_L$ between liquefied and unliquefied sites

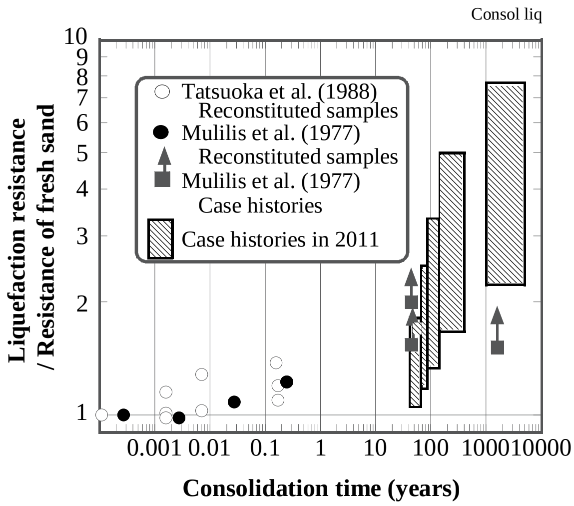


Fig. 34 Assessed effect of ageing on liquefaction resistance of sand obtained from the cases in 2011

The shadowed range in Fig. 33 was reinterpreted as the relationship between the age of soil and the increase of liquefaction resistance that is inverse to border $F_L$ values. Fig. 34 depicts the results, considering the uncertainties in soil age and border $F_L$ values. It is noteworthy that the present study is consistent with two former studies and, if the lower bound is taken, the liquefaction resistance of natural alluvium is approximately two times greater than that of very recent sand. Note that the present discussion mainly concerns ageing in the past hundreds years and is in clear contrast with those discussion during the longer Pleistocene period of time.

## CONCLUSIONS

The present paper addressed many geotechnical problems that were caused by the gigantic earthquake in March, 2011, Japan. The major points made herein are summarized in what follows.

1) The seismic force was not very strong but the elongated shaking and aftershocks probably increased the extent of damage.
2) Importance of liquefaction inside river levee embankments was recognized.
3) Liquefaction of dredged sand with non-plastic fines is important in man-made islands.
4) Liability to liquefaction damage in privately-owned land is a new topic to be solved.
5) Soil improvement under existing houses is needed.
6) There is a need to improve the liquefaction-hazard map by introducing more reasonable method for assessing liquefaction resistance of soils.
7) Effect of age on liquefaction resistance of sand deserves more attention.


## ACKNOWLEDGMENT

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