Effects of Ageing on Liquefaction Resistance of Sand; Possible Fusion with Studies on History

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ABSTRACT: Liquefaction occurs dominantly in young sandy deposits but the meaning of “young” has not been studied elaborately. The current practice by SPT-N is not good enough because the experiences during the 2011 gigantic earthquake in Japan demonstrated that those practices underestimated the liquefaction resistance in the aged alluvium. Liquefaction scarcely occurred in more aged alluvia sand in spite of low SPT-N values. The present study addresses the seismic behavior of sand where liquefaction either did or did not occur during recent earthquakes and the age of subsoil is known by historical records. One of the sites whose age is written in historical documents but location has been lost was detected by analyzing bore hole database. Accordingly, the first author’s data on relationship between liquefaction probability and soil age was extended to a greater age. It was concluded that soils older than 400 years have substantially higher resistance against liquefaction.

1 INTRODUCTION

Subsoil liquefaction is one of the major threats to urban infrastructures because the induced large deformation of ground stops the operation of such facilities as lifelines and foundations. To mitigate this kind of natural disaster, one of the essential issues is the precise assessment of soil resistance.

The East-Japan earthquake of magnitude=9 in 2011 demonstrated that such inexpensive structures as houses and lifelines cannot afford the cost of available mitigation technologies. In this regard, it is important to properly evaluate the liquefaction vulnerability of subsoil and promote necessary soil improvement to people.

Fig. 1 illustrates the distribution of liquefaction in the Tokyo Bay area. Obviously liquefaction concentrated in recent manmade islands along the coast, while the alluvial and other older subsoils did not liquefy. It seems therefore that the age of soil affects the liquefaction resistance of soil. Because this age effect is not positively taken into account by existing design codes, the current liquefaction risk assessment probably underestimates the resistance. The objective of this paper is the quantitative evaluation of the age effect. Note that the underestimation of resistance is a conservatism that is certainly relevant for construction of safe structures. However, construction of less expensive structures needs more precise assessment in order to avoid unnecessarily costly construction.

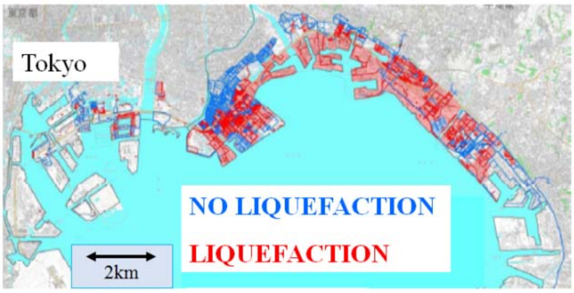

Fig. 1 Liquefaction sites in Tokyo Bay area in 2011

In practice, the factor of safety against liquefaction, F_L, is calculated by

$$F_L = R/L \qquad (1)$$

where the resistance (R) is determined by using SPT-N and other borehole data, while the seismic load (L) is determined by using the peak acceleration at the ground surface. If SPT-N increases with soil age to a full extent, no further study would be necessary on ageing of liquefaction resistance (R). Fig. 2 summarizes several studies on the increase of penetration resistance with soil age. It is suggested that the equivalent SPT-N increases for only one month or so after the total disturbance and redeposition of sand after liquefaction or compaction. This feature is not consistent with the age effect in Fig. 1 over a longer time period. Thus, more specific study is needed on temporal increase of liquefaction resistance of sand that is not accounted for by SPT-N.

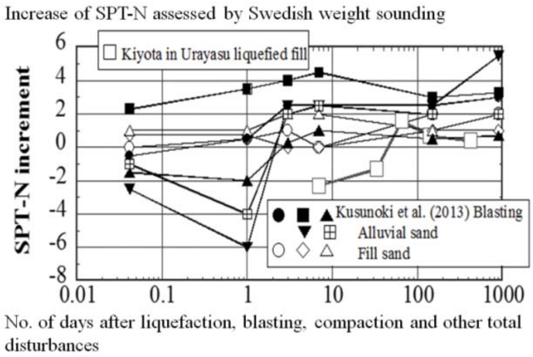

Fig. 2 Increase in equivalent SPT-N with time after soil disturbance

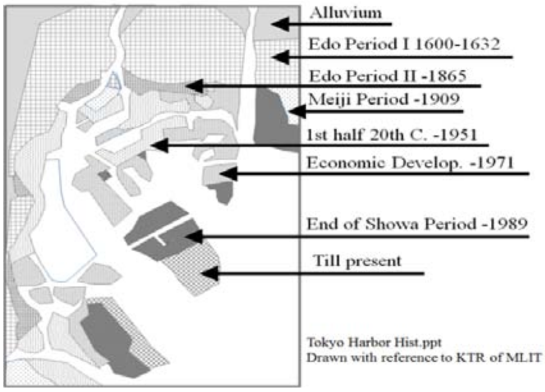

Fig. 3 Age of land reclamation in Tokyo's bay area.

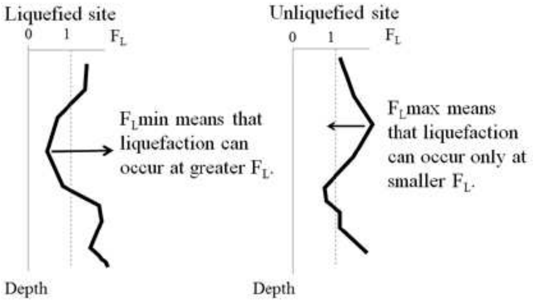

Fig. 4 Use of maximum and minimum values of F_L

2 LIQUEFACTION IN TOKYO BAY AREA

A case-history study on the age effect on liquefaction resistance of soil requires the following conditions to be satisfied:

1) It is known whether liquefaction occurred or not during an earthquake.
2) The intensity of earthquake shaking at the ground surface is known by nearby motion records.
3) Borehole data is needed in order to calculate the liquefaction resistance of subsoil by means of existing empirical formula.
4) Age of soil is known.

The experience during the 2011 gigantic earthquake satisfies those requirements. In addition to the liquefaction information as in Fig. 1, the age of land reclamation is reasonably recorded over the past 400 years (Fig. 3), while earthquake motion record is available by K-Net and many public institutions provide borehole database in the region. With these beneficial situations, the authors calculated the factor of safety against liquefaction, F_L, during the 2011 earthquake at many places with and without evidences of liquefaction.

The aim of the study was to determine the boundary value of calculated F_L between liquefaction and no liquefaction. Theoretically the boundary is 1.0 but, if it decreases with age, the increase of liquefaction resistance with age would be validated. Fig. 4 illustrates the employed methodology. First, Fig. 4 Left schematically illustrates a variation of F_L with depth over the entire artificial layer and alluvial deposits at a site of liquefaction. Although such an evidence as ejected sand is known at "liquefied" sites, it is not known which sublayer liquefied and the intended boundary value is still uncertain. It is reasonable, however, that the boundary value is greater than the minimum F_L (F_L,min); otherwise F_L is greater than the boundary value over the entire depth and no liquefaction would be possible, which is contradictory to the reality. At "unliquefied" sites, on the contrary, the boundary value should be less than the maximum F_L (F_L,max); otherwise, F_L is less than the boundary value over the entire depth and liquefaction would occur everywhere, which is against the reality again. Consequently,

$$F_L\text{,min} < \textit{Boundary}\ F_L < F_L\text{,max} \qquad (2)$$

In this paper, the method of liquefaction analysis by the Highway Bridge Design Code of JRA was employed for assessment of F_L.

3 AGE EFFECT AS DETECTED IN TOKYO BAY AREA

Fig. 5 plots the upper and lower bounds of the boundary F_L value in Eq. 2 against the era of land construction. The upward and downward arrows indicate that the boundary value lies between them, most likely in the shaded area. It is herein possible to state that the boundary value decreases with age, implying the temporal increase of liquefaction resistance as expected. However, the range of the boundary value is wide and further improvement is necessary.

Fig. 5 was improved by

(1) considering the effects of elongated shaking during the 2011 earthquake of magnitude=9 by which more cyclic loading was applied to soil and liquefaction resistance was reduced (resistance was multiplied by 0.8),

(2) considering the effects of NS and EW two-directional shaking (further multiplied by 0.9), and

(3) only at sites of liquefaction, the intensity of ground surface motion was amplified by soft thick subsoil (multiplied by 4/3). This correction was necessary because the employed K-NET records were obtained at unliquefied sites.

Fig. 6 illustrates the improved results. The ageing effect is now more obvious than in Fig. 5.

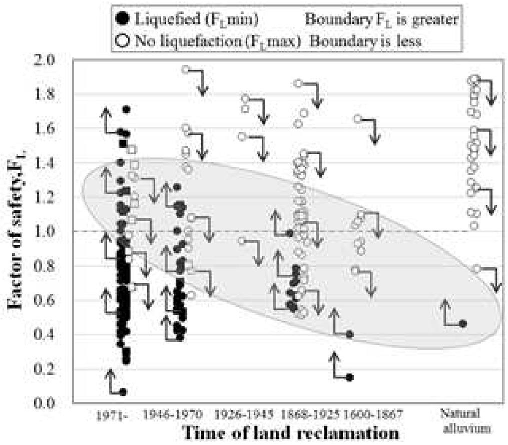

Fig. 5 First product on relationship between soil age and liquefaction potential assessed by the Highway Bridge Design Code.

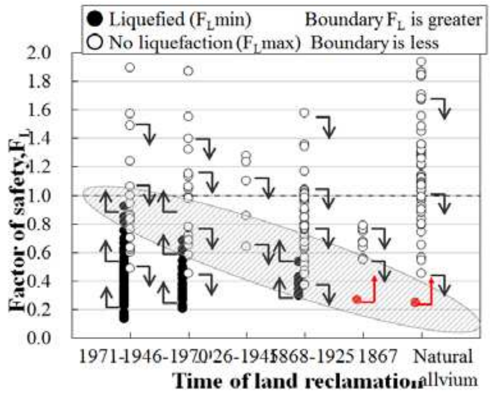

Fig. 6 Improved correlation between soil age and liquefaction potential (Highway Bridge Design Code).

4 STUDY ON OLDER SUBSOIL

The data from Tokyo is limited to the age of 400 years or less because of the short history of Tokyo area (Fig. 3). To extend the range of study to even older soils, two sites near Kobe were studied on subsoil behavior during the 1995 Kobe earthquake.

The first site is Tsukiji in Amagasaki City to the west of Osaka where a manmade island was constructed in AD1610s. Liquefaction occurred significantly in 1995 at the soil age of 380 years approximately. A plenty of borehole data was available here together with the earthquake motion data at a nearby Amagasaki Harbor.

The second site was Kyoga-shima Island in present Kobe that was constructed in late AD 12th Century. This study was difficult because this island is now buried under modern land reclamation and its exact location was unknown.

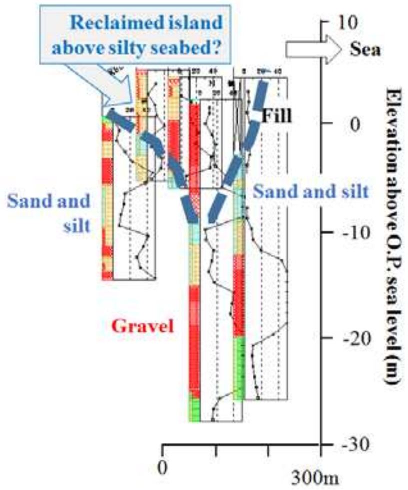

Fig. 7 EW subsurface cross section in Hyogo area of Kobe City.

The available knowledge about the Kyoga-shima Island was as what follows;

(1) It was constructed in the sea to the south east of the ancient Kobe Harbor as a break water.

(2) Until the middle of 19th Century, Kobe harbor was located in Hyogo area.

(3) The locally available material for land reclamation is weathered granite that includes big gravels and cobbles.

(4) In Hyogo area there are many historical places that are related with 12th Century. Thus, very approximate location of the Kyoga-shima is known but more precise site has been unknown. The present study made use of borehole database in order to detect the body of the ancient island. Fig. 7 shows one of the EW cross sections in which a gravelly mass rests on a curved layer of sandy-silty soil. This curvature was probably produced by the consolidation settlement due to the island's weight. Fig. 8 shows a horizontal cross section of the area at a depth of 4 m below the present sea level. It is interesting that the detected gravelly deposit has a limited size and that, to its south, there is a deposit of silty-sandy soil. Most probably this silty-sandy deposit indicates the location of a water channel or the entrance to the an-

cient harbor. From these considerations, the location of the ancient Kyoga-shima Island was decided where the soil age was around 800 years at the time of the Kobe earthquake. No liquefaction occurred at the time of the 1995 Kobe earthquake in this area.

Fig. 6 included data obtained from two historical sites as well. It is reasonable now to state that the boundary value of F_L decreases over the age range of 800 years. The inverse value of the boundary F_L stands for the increase of liquefaction resistance with age. Considering the range of remaining uncertainty, Fig. 9 was drawn. There is a good consistency with preceding studies on ageing. Note, however, that the ageing in the present study concerns the increase in liquefaction resistance exceeding what ageing of SPT-N implies, while other previous studies simply addressed the increase of liquefaction resistance with time. For practice, the present study proposes that liquefaction resistance of soils older than 400 years has liquefaction resistance 40%, with reasonable safety margin, greater than what existing design codes suggest.

The present paper does not discuss about the cause of ageing. The authors (Shintaku and Towhata, 2013) counted the number of grain dislocation under sustained stress and suppose that the fabric structure such as void distribution and grain-to-grain contacts is improved with time, leading to increase of mechanical properties of sand.

5 CONCLUSIONS

A study was made of the liquefaction events during past earthquakes such as the 1995 Kobe earthquake and the 2011 great earthquake in east Japan. By interpreting the assessed factor of safety at liquefied and unliquefied sites, it was found that the boundary factor of safety between liquefied and unliquefied sites decreased with the age of subsoil. This implies that the liquefaction resistance of soil increases with age and that the liquefaction hazard assessment should take this fact into account. For a temporary use, the authors propose to increase the liquefaction resistance by 40% if the soil age exceed 400 years. Note that the authors do not intend to criticize existing design codes because they provide reasonable conservatism to seismic design of important structures by not considering the age-induced increase of liquefaction resistance. The authors intend to apply their findings to less expensive structures that do not afford costly soil improvement and need more precise assessment of liquefaction risk. Furthermore, this study interpreted borehole data base to find the location of a historical man-made island which history researchers had been searching for many years. This achievement is a good example of fusion of engineering and historical studies.

ACKNOWLEDGEMENT

The authors express their sincere gratitude to Dr. S. Suwa for kind advices about interpretation of seismic performances. The employed bore hole data was provided by many data bases in Tokyo and Chiba areas of Japan as well as the Kansai Geo-informatics Network. The financial support was provided by Tokyo Gas Company as well. Those supports are deeply appreciated by the authors.

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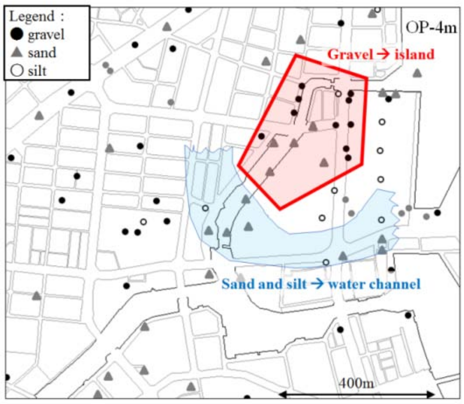

Fig. 8 Horizontal cross section of Hyogo area in Kobe City at 4m depth below sea level

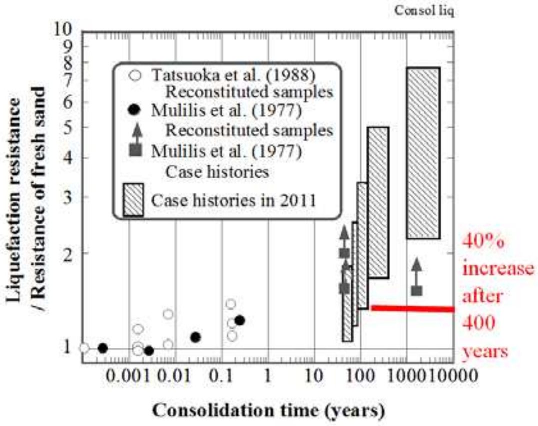

Fig. 9 Obtained ageing effect on liquefaction resistance increasing with time