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MEASURES DEVELOPED IN JAPAN AFTER THE 1964 NIIGATA EARTHQUAKE TO COUNTER THE LIQUEFACTION OF SOIL

S. Yasuda[1] and K. Harada[2]

ABSTRACT

In Japan, many remediation methods against liquefaction have been developed since the 1964 Niigata Earthquake, which caused severe damage to structures due to liquefaction. The methods are classified into two categories: ground treatments to prevent liquefaction, and measure that strengthen structures to prevent or minimize damage if the ground liquefies. The remediation methods have been applied to many kinds of structures, such as oil tanks, quay walls, bridges and buildings. The effectiveness of ground treatments to prevent liquefaction has been proved during past earthquakes. However, a new problem was raised during the 1995 Hyogoken-nambu (Kobe) Earthquake because recorded accelerations were far greater than the design acceleration. Then, studies on the adoption of performance-based design started. The 2011 Great East Japan (Tohoku) Earthquake demonstrated the need for a new concept of measures to prevent liquefaction in areas encompassing houses, roads and lifelines. One of these measures is lowering the ground water table. The applicability of this measure has been confirmed by in-situ tests and analyses, and lowering work started in several cities in 2013.

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In Japan, many remediation methods against liquefaction have been developed since the 1964 Niigata Earthquake, which caused severe damage to structures due to liquefaction. The methods are classified into two categories: ground treatments to prevent liquefaction, and measure that strengthen structures to prevent or minimize damage if the ground liquefies. The remediation methods have been applied to many kinds of structures, such as oil tanks, quay walls, bridges and buildings. The effectiveness of ground treatments to prevent liquefaction has been proved during past earthquakes. However, a new problem was raised during the 1995 Hyogoken-nambu (Kobe) Earthquake because recorded accelerations were far greater than the design acceleration. Then, studies on the adoption of performance-based design started. The 2011 Great East Japan (Tohoku) Earthquake demonstrated the need for a new concept of measures to prevent liquefaction in areas encompassing houses, roads and lifelines. One of these measures is lowering the ground water table. The applicability of this measure has been confirmed by in-situ tests and analyses, and lowering work started in several cities in 2013.

Introduction

Japan is a narrow country with a spine of high mountains. Many small rivers flow from the mountains with strong currents, forming small alluvial lowlands near their estuaries. Most big cities are located in the lowlands that comprise about 30% of Japan's land mass. Liquefiable reclaimed lands have been constructed by filling bays, oceans, old river channels, swamps, ponds and rivers in cities. Moreover, there are many liquefiable natural grounds, such as sand dunes, natural levees and deltas. Seismic activity is very intense and frequent in Japan. Therefore, sandy grounds have frequently liquefied, severely damaging structures. However, the need for countermeasures against liquefaction was not widely recognized until the 1964 Niigata Earthquake, which severely damaged many structures due to liquefaction in Niigata City. After this earthquake, many remediation methods were developed.

Outline of the Liquefaction-induced Damage during the 1964 Niigata Earthquake

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Niigata City is located on the estuaries of the Shinano and Agano rivers. Liquefaction occurred during the 1964 Niigata Earthquake in the lowland formed by these rivers, at the locations shown in Figure 1. Many buildings, houses, tanks, bridges, roads, railways, river dikes and buried pipes were damaged due to liquefaction. Figure 2 shows damaged apartment houses in Kawagishi Town. According to an inhabitant who was on the roof of a house, these houses settled and tilted gradually after the main shock. Ishihara and Koga (1981) conducted a detailed soil investigation near the houses and estimated that the sand layer at a depth of GL-3 m to GL-13 m liquefied. In Niigata City, the number of reinforced concrete buildings increased markedly after a large fire burned much of the city in 1955. By the time of the Niigata Earthquake, 1,530 such buildings

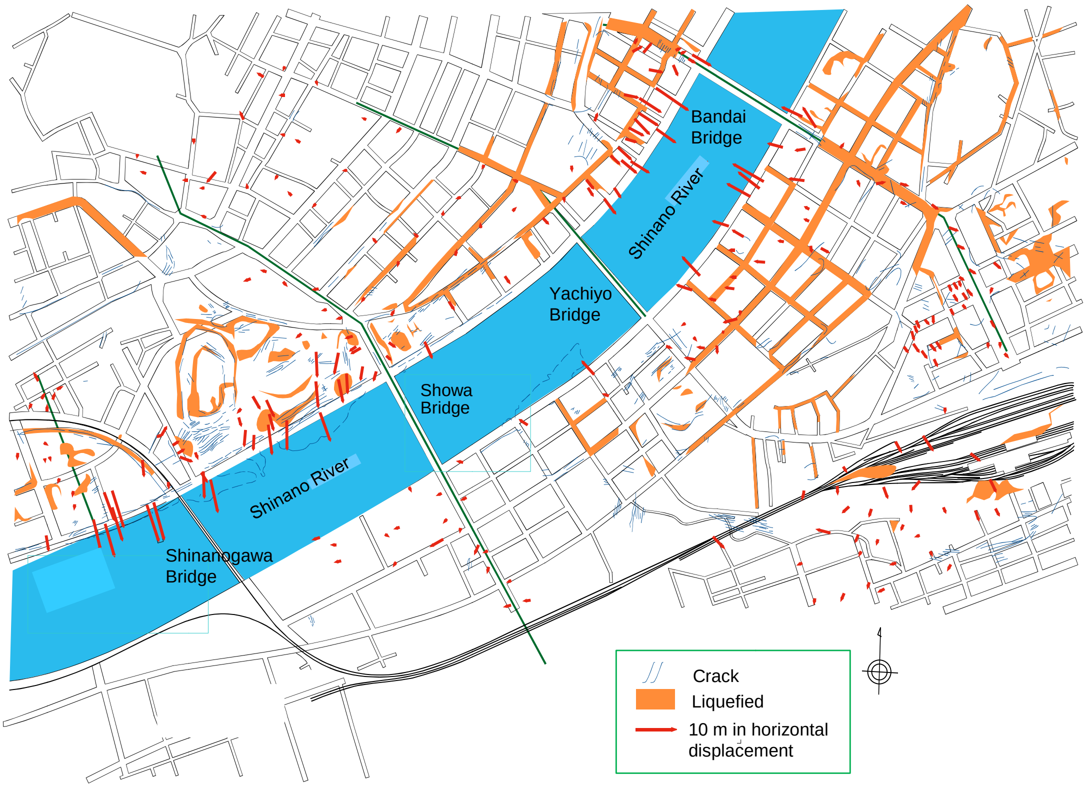

Figure 1. Sites of liquefaction and permanent horizontal ground displacements in Niigata City caused by the 1964 Niigata Earthquake (Hamada et al, 1986)

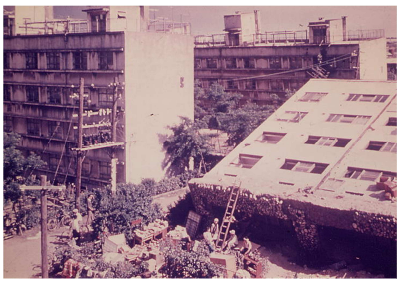

Figure 2. Settled apartments at Kawagishi Town (Photo by Watanabe)

Figure 3. Settled and tilted oil tanks (Photo by Watanabe)

Figure 4. Collapsed Showa Bridge (Photo by Watanabe)

Figure 5. Uplifted sewage tanks (Photo by Watanabe)

Figure 6. Tilted abutment of Yachiyo Bridge (Photo by Watanabe)

Figure 7. Tilted pier of Shinanogawa Bridge (Photo by Watanabe)

had been constructed. Among them, 340 reinforced concrete buildings were damaged by liquefaction during the 1964 earthquake. About half of the damaged buildings settled and tilted without cracks forming in their walls. Oil tanks settled and tilted, as shown in Figure 3. The Showa Bridge, which crosses the Shinano River, collapsed, as shown in Figure 4. According to several witnesses, the bridge girders started to fall about one minute after the main shock. Detailed soil investigations and the observation of a damaged pile were carried out after the earthquake and clarified that the liquefaction depth was about 10m and the pile was bent at almost the same depth as that of the liquefied soil. It was estimated that the piles deformed substantially in the horizontal direction during small shaking after the main shock because the bearing capacity of the surrounding ground had decreased drastically due to liquefaction (Yoshida et al., 2007). Buried pipes, a manhole and tanks were also damaged. An uplifted sewage tank is shown in Figure 5.

Moreover, extensive ground flow occurred, aggravating the damage. The distribution of ground displacement due to ground flow was measured 22 years after the earthquake from aerial photo surveys made before and after the earthquake (Hamada et al., 1986). This study confirmed that extremely large ground displacements, of up to 8 m, occurred along the Shinano River, as shown in Figure 1. The river's banks had been protected mainly by sheet piles. The ground behind the sheet piles flowed towards the river, pushing the piles towards the centre of the river. Many piles collapsed onto the river bottom. The maximum distance of ground flow from the river was about 300 m. Many structures, such as road bridges, a railway bridge, buried pipes and buildings, were severely damaged by the ground flow, as shown in Figures 6 and 7.

History of the Development of Countermeasures against Liquefaction after the Niigata Earthquake

During the 1964 Niigata Earthquake, many oil tanks settled due to liquefaction. However, some tanks had no damage because their foundation ground had been compacted by vibro-floatation (Watanabe, 1966). This was the first time that the effectiveness of compaction of the ground against liquefaction was recognized. Based on this experience, the ground under several tanks at a factory in Hachinohe City was improved. Shortly after the improvement work, the 1968 Tokachi-oki Earthquake hit the site and demonstrated the effectiveness of the compaction method again (Ohsaki, 1970). After these events, many kinds of remediation methods were developed in Japan. In 1993, the Japanese Geotechnical Society compiled a reference on remediation methods against liquefaction. Figure 8 summarizes the remediation methods recognized by the JGS in 1998 and 2004. These methods are classified into two categories: i) improve the liquefiable soil to prevent liquefaction, ii) strengthen structures to prevent their collapse if the ground should be liquefied. In the first category, six methods of soil improvement are cited: (1) compaction (densification); (2) solidification; (3); replacement; (4) groundwater lowering; (5) drainage (pore water dissipation); and (6) shear deformation control. The first three

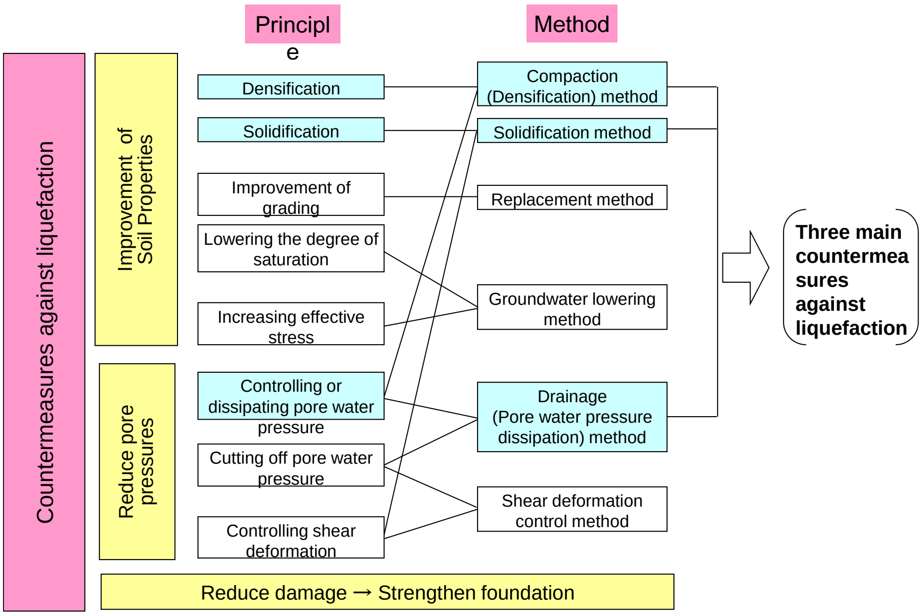

Figure 8. Principles and methods to counter liquefaction (JGS, 1998 , 2004)

Table 1. History of countermeasures against liquefaction (Harada et al., 2013)

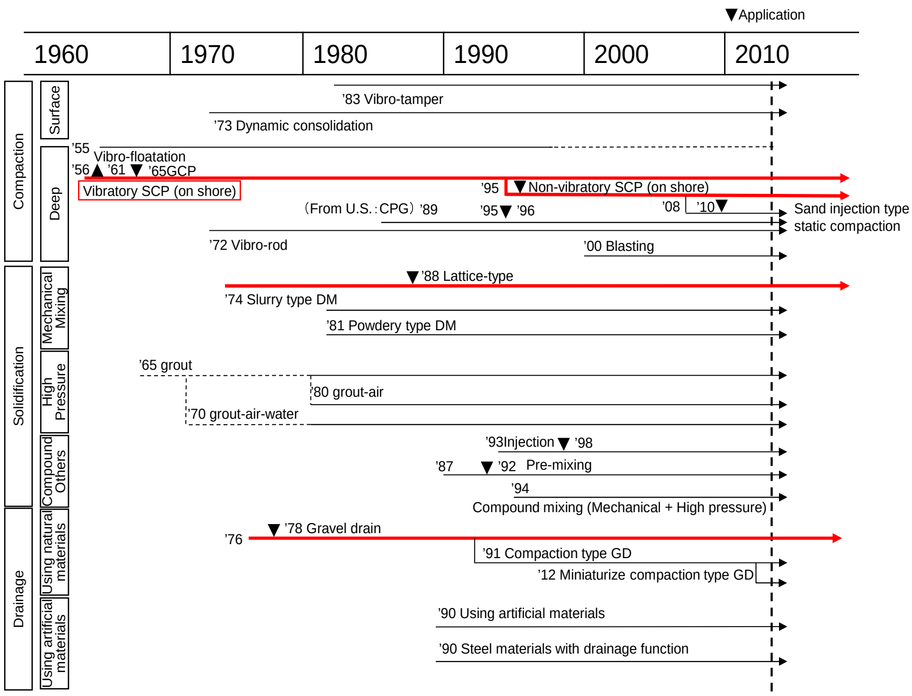

Table 2. Successful countermeasures against liquefaction observed in past earthquakes (Yasuda, 2005)

Earthquake	Treating method	Structure	Reference
1964 Niigata	Vibro floatation	Tank	Watanabe (1966)
1968 Tokachioki	Vibro floatation	Tank	Ohsakai (1970)
1978 Miyagike-oki	Sand compaction pile	Tank	Ishihara et al. (1980)
1983 Nihonkai-chube	Sand compaction plie	Tank	JSCE (1986)
1993 Kushiro-oki	Sand compaction pile and gravel drain	Quay wall	JGS (1994)

Table 3. Relationship between the density of the ground, the level of shaking and damage to structures and ground

		SPT N value		
		Less than about 10 (Loose)	About 10 to 25 (Medium dense)	More than about 25 (Dense)
Level 1 earthquake motion (As_{max} is about 150 to 200 Gals)	Liquefaction	Occurs	No occurrence	No occurrence
	Damage to structures	Severe	No occurrence	No occurrence
Level 2 earthquake motion (As_{max} is about 350 to 600 Gal)	Liquefaction	Occurs	Occurs	No occurrence
	Damage to structures	Severe	Occurs but not severe	No occurrence

methods, i.e., compaction, solidification and drainage, are the main countermeasures employed in Japan. Table 1 summarizes the history of applications of these three methods in Japan. The sand compaction pile (SCP) method, in which sand piles are installed to reinforce soft clayey ground, was the first to be developed. It was applied in the 1950s. In the 1960s, this method was applied as a liquefaction countermeasure. The lattice-type deep mixing (DM) technique of solidification and the gravel drain (GD) technique of drainage were developed as liquefaction countermeasures in 1970s and 1980s, respectively.

Before the 1995 Hyogoken-nambu (Kobe) Earthquake, remediation methods had been applied to many kinds of structures, such as oil tanks, quay walls, bridges, buildings, etc. The effectiveness of ground treatments against liquefaction has been reported during past earthquakes, as summarized in Table 2. The first and the second reports, by Watanabe and Ohsaki, were based on the Niigata and Tokachi-oki earthquakes. The effectiveness of sand compaction piles was observed during the 1978 Miyagiken-oki Earthquake (Ishihara et al., 1980) and the 1983 Nihonkai-chube Earthquake (JSCE, 1986). During the 1993 Kushiro-oki Earthquake, the effectiveness of sand compaction piles and gravel drains was observed at Kushiro Port. As shown by these examples, the effectiveness of the vibro floatation, sand compaction pile and gravel drain methods had been proved during earthquakes before the Kobe Earthquake (Yasuda, 2005).

Problems Pointed out by the 1995 Kobe Earthquake

Kobe City is built on a narrow alluvial plain facing Osaka Bay. Coastal areas of the city have been reclaimed for many years to enlarge the flat land areas. Liquefaction occurred in these reclaimed lands and at two large, man-made islands, Port and Rokko islands, during the 1995 Hyogoken-nambu (Kobe) Earthquake. Recorded accelerations were very strong, up to 600 to 800 Gals in the central zone of Kobe City. In general, surface acceleration decreases if the ground liquefies. Even so, about 400 Gals of maximum surface acceleration was recorded at a liquefied site on Port Island. Very strong shaking caused severe damage to structures in Kobe. Therefore, it was necessary to investigate new design concepts that could withstand very strong shaking. The Japan Society of Civil Engineering organized a technical committee to deal with these problems. The committee suggested basing earthquake-resistant design on two types of ground motion: Level 1 earthquake motion, which is likely to strike a structure once or twice while it is in service, and Level 2 earthquake motion, which is very unlikely to strike a structure during a

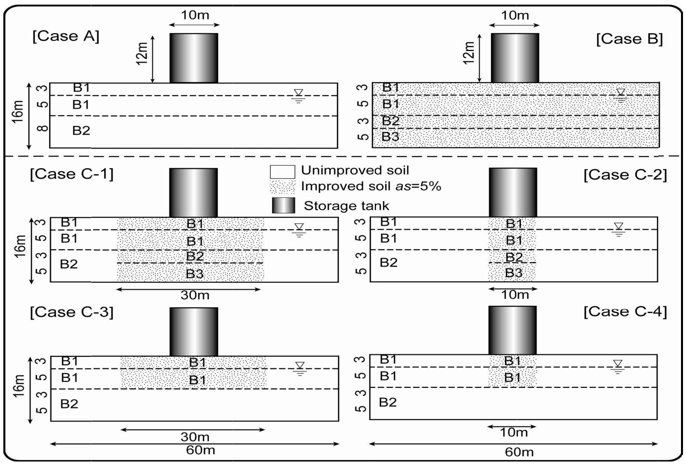

Figure 9. Model grounds for the joint analyses (Sento et al., 2004)

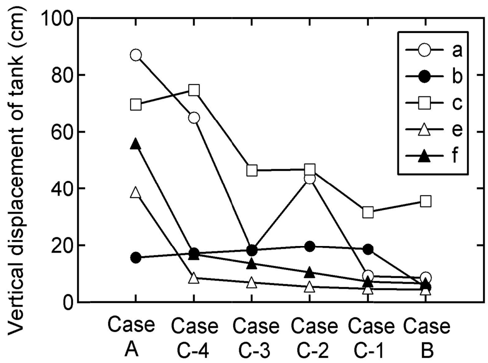

Figure 10. Effect of improved area on the settlement of a tank (Sento et al., 2004)

structure's life time, but when it does, it is extremely strong.

According to this concept, design accelerations for Level 1 and Level 2 earthquake motion have been introduced in several design codes. The design acceleration for Level 2 earthquake motion is about twice to three times the acceleration for Level 1 earthquake motion. In general, the critical soil density at which liquefaction occurs increases with an increase in earthquake motion. Liquefaction may occur in medium dense ground, as well as in loose ground. However, the damage to structures in or on medium dense ground should not be severe, as summarized in Table 3. Therefore, it is necessary to evaluate not only the occurrence of liquefaction but also the deformation of structures. The serviceability of a structure should be considered in the design of its foundation, based on its evaluated deformation. This is "performance-based design." The performance-based design of countermeasures against liquefaction was introduced after the Kobe Earthquake. This method is a rational way to decide the area to be improved. Joint analyses to determine the appropriate area of soil improvement to prevent the settlement of a raft foundation were carried out in 2003 (Sento et al., 2004). A hypothetical model of ground beneath a storage tank was used for the analyses. Six different cases with varying configurations in cross section were analyzed, as shown in Figure 9. Seven different liquefaction analysis codes were used for the analyses. Figure 10 compares the analyzed vertical displacement (settlement) of the model tank. In this figure, Case A and Case B are the unimproved case and fully improved case, respectively. Case C-1 to Case C-4 are partially improved cases. Though the settlements analyzed by the seven codes differ, settlement tends to decrease with an increase in the improved area. The appropriate improvement area can be judged based on the allowable settlement.

Though many remediation techniques against liquefaction had been developed before the Kobe Earthquake, as shown in Figure 8, many existing important structures were built without considering liquefaction. It is more difficult to apply compaction and solidification methods to improve liquefiable soil beneath existing structures than it is to apply these methods to improve liquefiable soil before a structure is built on it. However, special techniques which can be applied

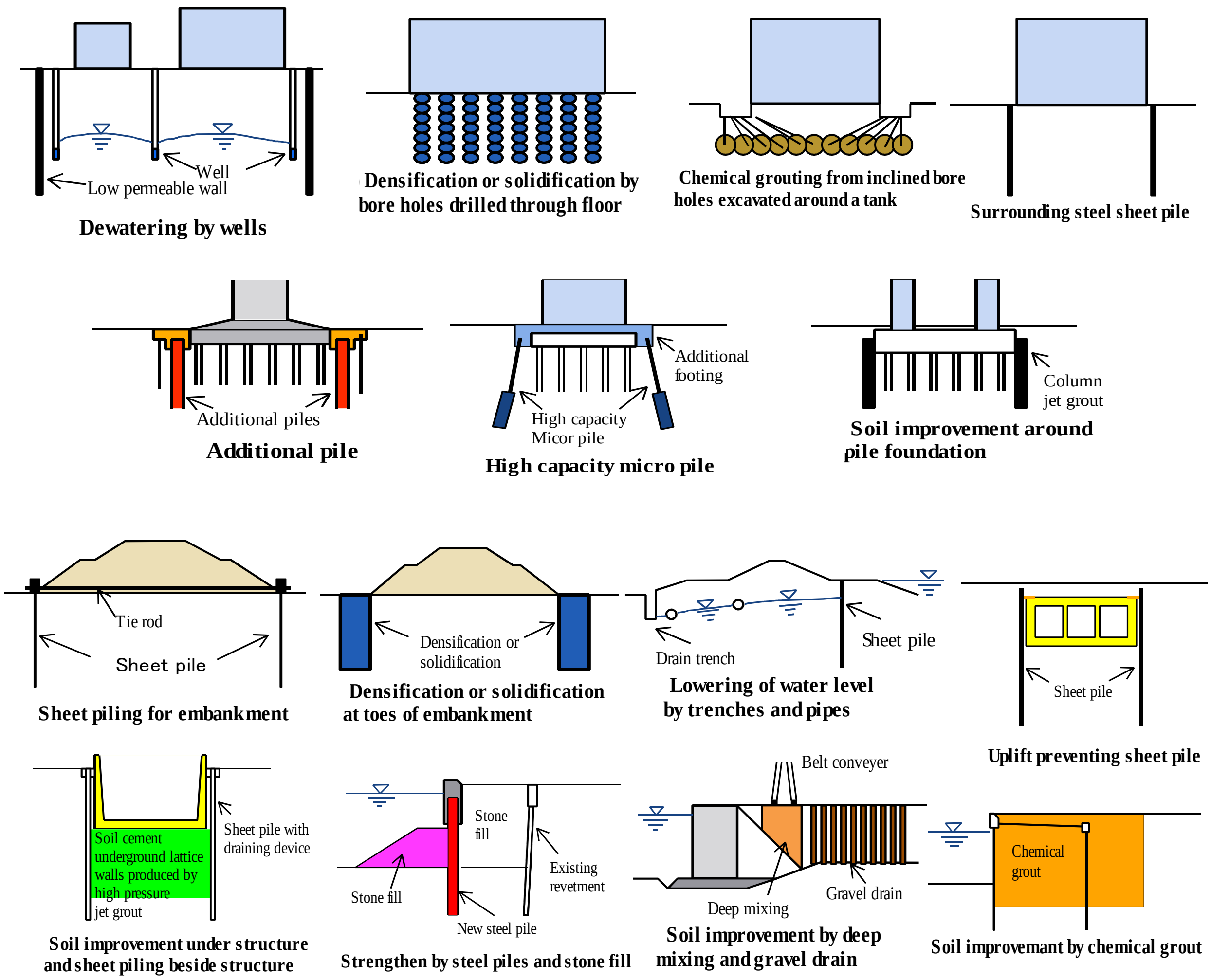

Figure 11. Remediation methods applied to existing structures(Yasuda, 2007)

to liquefiable soil beneath existing structures, such as the compaction grouting method and seepage grouting method, have been developed recently. On the contrary, the soil beneath an existing structure can easily be strengthened to prevent the collapse of the structure if the foundation ground should liquefy. Several new techniques have been developed and applied recently. In the design of methods to strengthen the foundation soil of structures, the allowable deformation of the structures must be defined because the strengthening effect must be judged based on the deformation of the structures. Therefore, performance-based design has been introduced. Examples of treatments of existing structures in Japan are schematically shown in Figure 11 (Yasuda, 2007).

New Remediation Concept established after the 2011 Great East Japan Earthquake

The 2011 Great East Japan Earthquake caused liquefaction in many places in the Tohoku and Kanto regions. According to the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), about 27,000 wooden houses in Japan were damaged due to liquefaction. In the design of

Table 4. New evaluation standard announced by the Japanese Cabinet

Grade of damage		Totally collapsed	Large-scale half collapsed	Half collapsed	Partially damaged
Evaluation method	Inclination	> 50/1000 	16.7/1000 to 50/1000 	10/1000 to 16.7/1000 	<10/1000
	Settlement	1m upper than floor	Up to floor	25cm to the top of footing	

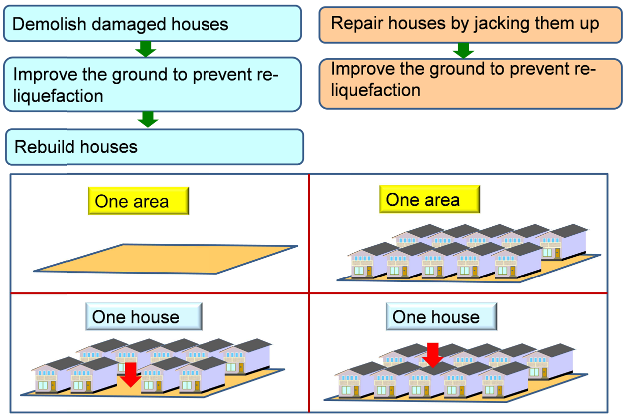

Figure 12. Four patterns to reconstruct damaged houses and/or areas

wooden houses, liquefaction had not been considered. This is the main reason such a large number of houses were damaged. The design code for buildings other than houses has considered liquefaction since 1974. Therefore, many buildings, bridges, elevated bridges, tanks, quay walls and other important structures were not damaged (Yasuda et al., 2013a). Many wooden houses settled and tilted, though they suffered no damage to walls and windows. In greatly tilted houses, inhabitants felt giddy, sick and nauseous, and found it difficult to live in their houses after the earthquake. In May 2011, the Japanese Cabinet announced a new standard for the evaluation of damage to houses based on two factors, settlement and inclination, as shown in Table 4. A new class of "large-scale half collapsed house" was also introduced, and houses tilted at angles of more than 50/1,000, of 50/1,000 to 16.7/1,000, and of 16.7/1,000 to 10/1,000 were judged to be totally collapsed, large-scale half collapsed and half collapsed houses, respectively, under the new standard.

In residential areas where liquefaction occurred, houses, roads, water pipes, sewage pipes and gas pipes were damaged, interrupting daily life (Yasuda et al., 2012). Many houses have been restored by lifting them, repairing their footings, and replacing them on their footings, and lifelines have been repaired in the three years since the earthquake. However, many inhabitants face the serious problem of how to prevent re-liquefaction during future earthquakes. There are four possible patterns to reconstruct damaged houses and/or areas, as shown in Figure 12. If all or many settled and tilted houses are repaired by uplifting, the ground in the whole area, including lifelines and roads, must be treated by special measures to prevent re-liquefaction. The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) established a new project eight months after the earthquake, the "Urban liquefaction countermeasure project". In this project, a wide existing residential area of more than 3,000 m^2, including roads, buried pipes and more than 10 houses, is treated by an appropriate countermeasure and its costs are shared by government and inhabitants, as schematically shown in Figure 13. The project aims to select effective countermeasures and determine how to share their cost with inhabitants. Available countermeasures have been compared in 12 damaged cities, and two methods, lowering the ground water table, as shown in Figure 14, and surrounding the foundation ground with lattice-type underground walls, have been selected as the most promising.

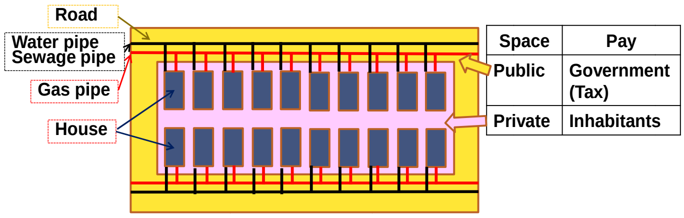

Figure 13. Plan of urban liquefaction countermeasure project

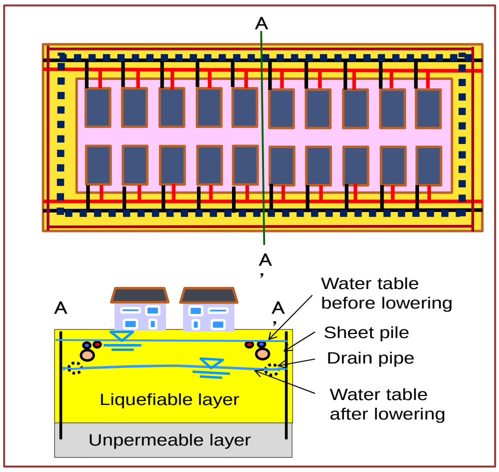

Figure 14. Lowering of ground water table

Figure 15. In-situ test to demonstrate the effect of drain pipes in Kamisu City

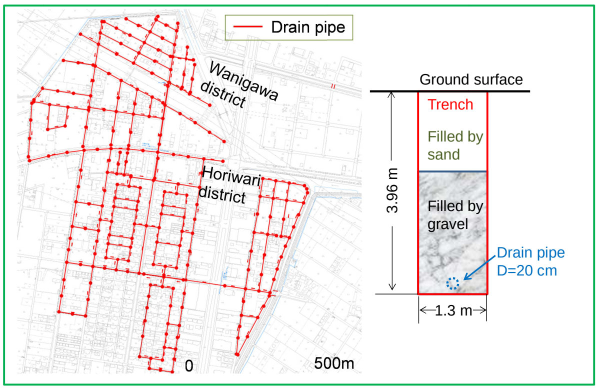

Figure 16. Layout and cross section of drain pipes in Kamisu City

The applicability of these methods is being studied by in-situ tests, centrifuge tests and analyses. Figure 15 shows in-situ test conducted in 2013 in Kamisu City for lowering the ground water table to about GL-3m by placing drain pipes. Two rows of drain pipes with a distance of 46 m were placed at a depth of GL-3.5 m in the excavated and filled trenches. Test results showed that the ground water table could be lowered to the depth of about GL-3 m in the area surrounded by the drain pipes. And the ground settlement due to the consolidation of alluvial clay layer was very small, less than 1 cm. It was decided by Kamisu City Government to treat an area of about 1 km by 1 km in the Horiwari and Wanigawa districts by this method. Figure 16 shows the layout and cross section of drain pipes. The construction of the drain pipes will start in June 2014. In Tokai Village, the construction of drain pipes to lower the water level was started in 2013. Similar constructions will start soon in several other cities.

Concluding Remarks

The history, classification and recent studies on countermeasures against liquefaction in Japan are introduced. Many kinds of remediation methods have been developed and applied to the foundation soil of important structures since the 1964 Niigata Earthquake. However, the foundation soils of many small structures, such as wooden houses, water and sewage pipes and roads, remain untreated. The foundation soils of these small structures must be treated as soon as possible. Another approach is to improve the liquefiable soil of an entire area by lowering the ground water table or by another method, as is being applied to cities damaged by the 2011 Great East Japan Earthquake. The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) published a guide to apply this new remediation concept to many cities based on the experience gained from the restoration of these damaged cities. It is hoped that, in the near future, the liquefiable areas in many cities will be treated by lowering the ground water table or by other methods to prevent liquefaction.

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