Study on the restoration methods for the houses damaged by the liquefaction during the 2011 Great East Japan Earthquake

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ABSTRACT

About 27,000 wooden houses were damaged due to liquefaction during the 2011 Great East Japan Earthquake. There are four possible patterns to reconstruct damaged houses and/or areas. The author and his colleagues developed a new method by enclosing individual house by sheet piles. Effectiveness of the method was demonstrated by shaking table tests. On the contrary, if all or many settled and tilted houses are temporary repaired by uplifting, the ground in the whole area must be treated by special measures to prevent re-liquefaction. The MLIT established a new project, the “Urban liquefaction countermeasure project”. In this project, a wide existing residential area is treated by an appropriate countermeasure and its costs are shared by government and inhabitants. One of the available countermeasures is lowering the ground water table by drain pipes. The applicability of this method has been studied by in-situ tests, centrifuge tests and analyses. The construction of the drain pipes has started in three cities.

Keywords: liquefaction, wooden house, countermeasure

1. INTRODUCTION

The 2011 Great East Japan Earthquake caused liquefaction in many parts of the Tohoku and Kanto regions. In residential areas where liquefaction occurred, houses, roads, water pipes, sewage pipes and gas pipes were damaged, interrupting daily life (Yasuda et al., 2012). According to the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), about 27,000 wooden houses in Japan were damaged due to liquefaction as shown in Fig.1. In the design of 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., 2013). Many houses have been restored by lifting them, repairing their footings, and replacing them on their footings, and lifelines have been repaired in the four years since the earthquake.

2. CHARACTERISTIC OF DAMAGE TO HOUSES DUE TO LIQUEFACTION

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 1. 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.

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Fig.1. Number of houses damaged by liquefaction
Fig. 2 shows the author’s idea of the mechanism of the settlement of houses due to liquefaction. The settlement of a house probably occurs for two reasons: i) lateral flow due to a decrease of the shear modulus of the liquefied layer as shown in Fig. 2 (1), and ii) the densification of the liquefied layer due to the dissipation of excess pore water pressure as shown in Fig. 2 (2). When a liquefied layer is of uniform thickness and the upper non-liquefied layer is thin, houses penetrate into the ground, often at an angle, due to the lateral flow of the liquefied layer. In addition, uniform subsidence occurs due to the densification of the liquefied layer. However, if the non-liquefied layer is thick, penetration settlement is limited, though uniform subsidence due to the densification of the liquefied layer occurs.

The tilting of houses derives from non-uniform settlement. According to the authors’ previous study on the non-uniform settlement of houses, several factors affect non-uniform settlement (Yasuda and Ariyama, 2008). Among them, the effect of adjacent houses was dominant. If two houses are close to each other, they tilt inward toward each other as shown in Fig. 2 (1), and if four houses are close, they tilt toward their common center.

### 3 PATTERNS TO RECONSTRUCT DAMAGED HOUSES AND/OR AREAS

Many kinds of remediation methods for liquefaction have been developed in Japan since the 1964 Niigata Earthquake, which caused severe liquefaction-induced damage to many structures (Yasuda, 2005). Current countermeasures against liquefaction are classified into two categories (JGS, 1998a): i) methods to improve the liquefiable soil to prevent liquefaction, ii) methods to strengthen structures to prevent their collapse if the ground should be liquefied. In the first category, liquefaction strength is increased by establishing the following ground conditions: a) high density, b) stable skeleton, c) unliquefiable grain size or d) low saturation. Other methods to prevent liquefaction are: e) immediate dissipation of increased excess pore pressure, f) reduction of shear stress by increasing confining pressure, g) reduction of shear stress by building an underground wall.

There are four possible patterns to reconstruct damaged houses and/or areas by using current remediation methods, as shown in Fig. 3 and explained below:

1. **Pattern 1**: If many damaged houses in a residential area are demolished, the best option is to improve the ground in the entire area to prevent re-liquefaction and rebuild houses. Soil in a wide area can be improved easily by current techniques, such as sand compaction piles and deep mixing.

2. **Pattern 2**: If a damaged house is demolished, appropriate countermeasures to liquefaction must be applied before reconstruction. Many old houses in the Kanto Region have been replaced according to this.
pattern since the 2011 Great East Japan Earthquake.

(3) **Pattern 3**: 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.

(4) **Pattern 4**: If a settled and tilted house is repaired by uplifting, the ground beneath it must be treated by some advanced method to prevent re-liquefaction. A few houses have been restored using such a method since the earthquake.

### 4 REMEDIATION MEASURES FOR INDIVIDUAL HOUSES

One month after the 2011 Great East Japan Earthquake, a technical committee chaired by the author was organized in the Kanto Branch of the Japanese Geotechnical Society (JGS) to study the mechanism of the liquefaction-induced damage to houses and discuss appropriate countermeasures. Several possible countermeasures for new and existing houses, including several ideas which have not been confirmed quantitatively, have been proposed, as shown in Fig. 4 and Fig. 5, respectively. (Kanto Branch of the Japanese Geotechnical Society, 2013).

Remediation measures for individual houses must be applicable to a narrow space and economical. If penetrated to the depth of the non-liquefiable layer, steel or soil-cement mixed piles satisfy both these conditions for newly constructed houses. Many houses in Japan have been constructed using these methods. Though these methods prevented the settlement of houses during the 2011 Great East Earthquake, sewage pipes around houses were damaged due to the liquefaction-induced subsidence of the surrounding ground. Therefore, steel or soil-cement mixed piles do not prevent all liquefaction-induced damage in a residential area. Normal soil improvement methods, such as sand compaction pile and deep mixing, are economical but not easy to apply in a narrow area. To make them applicable in a narrow area would require the development of small, quiet construction machines. On the contrary, compaction grouting and seepage methods are applicable in a narrow area but are not economical. Their cost must be reduced to make them practical.

Soon after the 2011 Great East Japan Earthquake, efforts to modify current liquefaction countermeasures for individual new or existing houses started.

One modification is the “gravel drain with compaction” method, in which a compact machine is used, instead of a normal, large machine, as shown in Fig. 6 (Harada et al., 2013). This method was applied in 2012 to the ground beneath the site of a house in Urayasu City that was demolished by the Great East Japan Earthquake before a new house was constructed. The area of the site was only 106.8 m² and the site was surrounded by adjacent houses. Through compaction, the diameter of each gravel layer expanded from 400

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**Fig. 4.** Possible countermeasures for constructing new houses (JGS Kanto, 2013)

**Fig. 5.** Possible countermeasures for existing houses (JGS Kanto, 2013)

Other ideas for new houses:  
i) top shaped foundation, ii) fill,  
iii) lattice type wall
mm to about 500 mm. However, the SPT N-value of the soil increased by only 5 to 7 after this method had been applied because the ground was very fine silty sand with 42% silt and clay content. The effect of the gravel drain only, neglecting the effect of densification, was considered in the design of gravel piles arranged in square configuration 1.55 m apart to resist liquefaction under a peak acceleration of 200 cm/s². Moreover, the penetrating settlement of the newly constructed house during very intense Level 2 shaking of 343 cm/s² was estimated using the ALID/Win computer program (Yasuda et al., 1999) at only 3 cm.

The compaction grouting method could be applied to existing houses by digging holes through floors and applied at several sites soon after the 2011 Great East Japan Earthquake. However, it was necessary to cut holes through floor slabs and dig bore holes through these holes in the floor. A more simple technique, in which bore holes are dug from outside a house using an inclined bore-hole machine, was developed as shown in Fig. 7. This new technique can be applied to existing houses at moderate cost.

The impact of enclosing the foundation soil of a house with sheet piles, as schematically shown in Fig.8, on the mitigation of settlement of the house if the foundation ground is liquefied had been studied by small shaking table tests on model houses by the author and his colleagues before the 2011 Great East Japan Earthquake. Immediately after the earthquake, its applicability to actual houses was discussed and additional small-scale and large-scale shaking table tests were conducted. Settlement of the model houses of ¼ scale with sheet piles and without sheet piles were measured in the large-scale shaking table tests as shown in Fig.9. Penetration settlement of the model house without sheet piles, with half-length sheet piles and with full-length of sheet piles were 14.1 cm, 3.5 cm and -4.1 cm (model house did not settle but surrounding ground settled 4.1 cm), respectively. Subsequently, this method was applied to a newly constructed house, and to an existing warehouse.

5 REMEDIATION MEASURES FOR A WIDE EXISTING RESIDENTIAL AREA

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 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 m², 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 Fig. 10. 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 a special method, lowering the ground water table, as schematically shown in Fig. 11 has been selected as the most promising in several cities. The level of lowering is designed as about 3 m below ground surface by comparing damaged and non-damaged houses during the 2011 Great East Japan Earthquake and past earthquakes. Fig. 12 shows the author’s idea why about 3 m is enough to prevent penetration settlement of a house though the ground below the water table liquefies.

The applicability of these methods is being studied by in-situ tests, centrifuge tests and analyses. Fig. 13 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. Fig. 14 shows the layout and cross section of drain pipes. The construction of the drain pipes started in June 2014. In Tokai Village and Itako City, the construction of drain pipes to lower the water level was also started.

6 CONCLUSIONS

There are four possible patterns to reconstruct damaged houses and/or areas, i) reconstruct houses in a wide area of demolished houses by improving the ground, ii) reconstruct a house in a narrow space with appropriate countermeasure, iii) treat a wide existing residential area by lowering water table, and iv) take appropriate countermeasure for an existing house. Several new techniques have been developed after the 2011 Great East Japan Earthquake. A remarkable approach to improve the liquefiable soil of an entire area by lowering the ground water table is being applied to several cities damaged by the earthquake.

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Fig. 13. In-situ test to demonstrate the effect of drain pipes in Kamisu City

Fig. 14. Layout and cross section of drain pipes in Kamisu City