Objective seismic motion for liquefaction countermeasures in residential areas of Inashiki City Ibaraki, Japan

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ABSTRACT

Appropriate countermeasures against residential damage induced by liquefaction under great earthquakes in Inashiki City, Ibaraki were investigated because residences sustained severe damage from the 2011 off the Pacific coast of Tohoku Earthquake of March 11, 2011. Metrics to ascertain the magnitude of objective seismic motions and the effectiveness of countermeasures were established, along with their targeted levels for securing safety. This paper presents outlines of damage features in Inashiki under actually measured seismic motion (259 Gal acceleration, 5-weak seismic intensity, M9) of the 2011 off the Pacific coast of Tohoku Earthquake. Simultaneously, the paper reports results of numerical simulations of liquefaction that damaged residences conducted to validate the model. To assess earthquake-related liquefaction, the repeatability of damage features observed from the great earthquake was improved as explained below. i) Age effects corresponding to the sedimentary time period of sandy deposits are considered when evaluating liquefaction factor $F_L$. ii) Sandy deposits with plasticity index $I_p$ of less than 25 are assumed for liquefiable layers. iii) Ground surface displacement $D_{cy}$ corrected according to the magnitude of liquefaction factor $P_L$. Subsequently, results from numerical analysis of liquefaction severity for cases with and without countermeasures were compared under the actually measured seismic motion. Then numerical analyses were conducted for cases under the seismic motion (200 Gal and M9.0), which are guidelines by the Ministry of Land, Infrastructure and Transport in Japan. Based on results from the numerical analysis stated above, setting of a fundamental policy was proposed for determination of countermeasures against liquefaction under a great earthquake. Countermeasures should be sought that enable attainment of rank A ($H_1 > 5$ m, $H_1$ is thickness of a non-liquefaction layer which is continuous from the ground surface) and rank B1 ($H_1 > 3$ m and corrected $D_{cy} \leq 10$ cm) under seismic motion of type 2 (medium shock by great quake: 200 Gal, M9.0) in all regions, except for areas ranked locally as B2 ($H_1 > 3$ m and corrected $D_{cy} > 10$ cm).

Key word : Seismic motion, Liquefaction, Countermeasure, Residence, Numerical analysis, Inashiki

1. INTRODUCTION

In the 2011 off the Pacific coast of Tohoku Earthquake, liquefaction caused damage in many urban areas of the Tohoku region on the Pacific side and the Kanto region. The seismic motions measured in Inashiki, generated by the main shock of the earthquake, lasted for a long period of time. And an aftershock was generated.

A purpose of this study is to investigate damage of the liquefaction that occurred because of such the seismic motions. In addition, it is to examine liquefaction countermeasure by the method of the liquefaction assessment that can reproduce damage.

We carry out the liquefaction assessment by the method, based on the literature and considering findings in the literature. And we develop that method, based on new findings provided in this investigation.
This paper reports seismic motion measurements in four districts badly damaged by liquefaction in the East district of Inashiki city in Ibaraki prefecture, located in the north of the Kanto region (total area covered by the urban liquefaction countermeasure project: 54.8 ha) and assessment of urban liquefaction countermeasures.

2 SEISMIC MOTIONS IN INASHIKI CITY

Figure 1 shows the earthquake measurement locations in and around Inashiki city. Figure 2 and Table 1 shows the seismic motions measured in Kessa of Inashiki city (the east building of Inashiki City Hall) near the four districts in the East district covered by the urban liquefaction countermeasure project (Nishishiro, Kessa/Rokkaku, Yasuji-gawa/Sakaijima and Kamisuda).

The seismic motion in Kessa, Inashiki, generated by the main shock of the earthquake (M9.0) that occurred off the Sanriku coast at 14:46 on March 11, 2011 measured 259.4 Gal as the maximum acceleration at the surface level (NS component), and the motion lasted for a long period of time (50 Gal or above for more than 1 min). The seismic motion generated at the same location by the aftershock of the earthquake (M7.6) that occurred off the Ibaraki coast 30 minutes later at 15:15 on March 11, 2011 measured 181.3 Gal as the maximum acceleration at the surface level (NS component).

3 OVERVIEW OF DAMAGE IN INASHIKI

The 2011 off the Pacific coast of Tohoku Earthquake caused damage throughout Inashiki. Especially in the southeastern area (East district), large-scale liquefaction occurred and caused enormous damage to houses, farmlands, roads, water supply and sewer systems and other infrastructures.

The number of damaged houses in Inashiki exceeded 4,000, among which 286 houses were completely or partially destroyed on a large scale, and...
244 houses were damaged by liquefaction. (See Table 3.) The infrastructures suffered from compound damage such as road liquefaction and damage to the water supply pipes and sewers under the roads.

In Inashiki, agriculture is the key industry, and liquefaction also affected the agricultural infrastructures. Especially in the southeast area, rice paddies, pumping facilities and pipelines were severely damaged by liquefaction on the largest scale in the prefecture. Liquefaction occurred mostly on lowlands along the Tone River in the southeast part of the city (East district).

4 EXAMINATION OF LIQUEFIED GROUND THAT CAUSED DAMAGE

After the earthquake, we conducted boring surveys (hereinafter referred to as BOR) at 13 sites and sounding surveys by the Piezo Drive Cone test (PDC) at 55 sites to assess the liquefaction.

Figure 3 shows an estimated geological section of the Nishishiro district, one of the areas covered by the project. Figure 4 shows the altitudes of the ground levels of the BOR and PDC sites and the altitudes of the groundwater levels at the time of the survey. The altitudes of the ground levels range from -0.12 m to +2.33 m and those of the groundwater levels range from -0.93 m to +0.75 m.

Fig. 3. Estimated geological section (Nishishiro district)

Fig. 4. Relationship between ground height and groundwater level of research site

Fig. 5. Altitude distribution of N values
Figure 5 shows altitude distribution of N values at the BOR sites. Figure 6 shows altitude distribution of fine fraction content rate \( F_c \). The ground in the Nishishiro district and the Kamisuda district is mainly sandy soil, however, there are soft cohesive soil layers at or above a depth of 6 m. In the Kessa/Rokkaku district, the ground is also mainly sandy soil. There are soft cohesive layers around a depth of 5 m at the KB-1 site and 3 m at the KB-3 site. At the KB-2, cohesive soil exists in alternate layers. At the KB-4, there is little cohesive soil. The Yasujigawa/Sakaijima district has thicker cohesive layers than those of the other districts, and the soft cohesive layers exist at depths between 4 m and 11 m.

We developed the method of liquefaction assessment, based on the literature\(^3\) and considering findings in the literature\(^4,5\). We also explored ways of reproducing the extent of the damage by the 2011 off the Pacific coast of Tohoku Earthquake in the assessment. Differences between the assessment method we used and that in the literature\(^3\) are as follows.

(1) Consideration of the age effectiveness of ground formation

In calculating the safety factor against liquefaction, \( F_L \), we used the literature\(^4\) and considered the age effectiveness of ground formation for the sandy soil in and below the No. 2 sandy soil layer among the alluvial soil layers (the upper limit for correction factor by ground formation age, \( C_h \) is set as \( C_h = 1.4 \)).

\[
F_L = C_h \cdot \left( \frac{\tau_1}{\sigma_v'} \right) / \left( \frac{\tau_3}{\sigma_v'} \right)
\]

(1)

In the equation above, \( F_L \) is the safety factor against liquefaction, \( C_h \) is the correction factor by ground formation age, \( \tau_1 \) is the liquefaction resistance, \( \tau_3 \) is the equivalent cyclic shear stress, \( \sigma_v' \) is the vertical effective stress, of each depth of the examination spot.

(2) Target depth of liquefaction assessment

As the weights of houses are quite light, we set the
target depth of liquefaction assessment at 10 m to calculate the liquefaction index $P_L$: 5)

$$P_L = \sum F \cdot w(z) \cdot \Delta z$$  (2)

In the equation above, $F = 0.0$ (when $F_L > 1.0$), $F = 1 - F_L$ (when $F_L \leq 1.0$), $w(z) = 20 - 2z$ and $z =$ depth (m).

(3) Target layer of liquefaction assessment

Figure 7 shows the relationship between plasticity index $I_P$ and fine fraction content rate $F_c$ of the BOR sites, and Figure 8, the relationship between plasticity index $I_P$ and clay fraction content rate $CF$.

In this study, based on the comparison between the extent of damage in the area by the 2011 off the Pacific coast of Tohoku Earthquake and the result of liquefaction assessment, we used the soil layer with $I_P \leq 25$ as the target of assessment. At the PDC sites, however, no estimates of $I_P$ were available and we used the layer with $F_c \leq 35\%$ instead. Figure 9 shows the relationship between $P_L$ obtained by the assessment and the extents of damage. The $P_L$ values of the areas where damage by liquefaction was not identified were smaller than 15. There is a tendency that the greater the damage is, the larger the $P_L$ is.

(4)Calculation method of ground surface displacement $D_{cy}$

Figure 10 shows a chart of comparison between the observation result of vertical displacement of the ground before and after the 2011 off the Pacific coast of Tohoku Earthquake and the calculated ground surface displacement $D_{cy}$ of BOR sites comparable with the observation result. The $D_{cy}$ values on the chart are the settlement calculated using the literature3) and replacing cyclic shear strain $\gamma_{cy}$ by bulk strain $\varepsilon$.

These $D_{cy}$ values tended to be underestimated more significantly at the sites with larger vertical displacement observed. In this study, using the equation 3, we corrected $D_{cy}$ according to $P_L$ (hereinafter referred to as corrected $D_{cy}$: Shown in Figure 10).

$$\text{Corrected } D_{cy} = a \cdot D_{cy}$$  (3)

In the equation above, $a = 1.0$ ($P_L < 5$), $a = 2.0$ ($5 \leq P_L < 15$) and $a = 4.0$ ($15 \leq P_L$).

Figure 11 shows the relationship between corrected $D_{cy}$ and the extent of damage. The corrected $D_{cy}$ is mostly larger than 10 at sites where the extent of damage is large. The corrected $D_{cy}$ is smaller than 10 where the extent of damage is small.

5 MAGNITUDE OF SEISMIC MOTION TARGETED FOR LIQUEFACTION COUNTERMEASURE AND TARGET EFFECT OF LIQUEFACTION COUNTERMEASURE

There are three types of basic magnitudes of seismic motions; Type 1 (medium shock by medium quake: 200 Gal, M7.5), Type 2 (medium shock by great quake: 200 Gal, M9.0) and Type 3 (large shock by epicentral quake: 350 Gal, M7.5)5). In this study, after primary selection of techniques as liquefaction countermeasure, we examined the effects of the groundwater level lowering technique and the grid-pattern soil improvement technique on the three basic types of seismic motions and the motion observed in Inashiki (259.4 Gal, M9.0). As a result, we have selected the former as our recommended technique.

Figure 12 shows the examination result of the liquefaction countermeasure on the seismic motion observed in Inashiki and Type 2 motion. The chart shows the relationship between corrected $D_{cy}$ and non-liquefiable layer thickness $H_1$ with and without the groundwater level lowering technique (the groundwater level is lowered to an altitude of T.P.-3.0 m).

Without the countermeasure, $H_1$ values are smaller than 3.0 m at most sites. The corrected $D_{cy}$ values are smaller than 10 in any seismic motion where the extent of damage is small. With the countermeasure, $H_1$ values are larger than 3.0 m at all the sites and the corrected $D_{cy}$ values are small. However, the corrected $D_{cy}$ values are larger than 10 even with the countermeasure at 20 sites in (1) of Figure 12 and eight sites in (2).

In similar examination of the groundwater level lowering on Type 1 seismic motion, although we don’t
go into detail in this paper, \( H_1 \) values are larger than 3.0 m and the corrected \( D_{cy} \) values are smaller than 10 at all the sites except two sites.

We have sought techniques that achieve ranks other than C (very likely to cause significant liquefaction) on any magnitude of seismic motion using an assessment diagram with the thresholds for B1 to B2 and B3 to C set as corrected \( D_{cy} \) \( \leq 10 \), based on the above examination results and an \( H_1 \) to \( D_{cy} \) assessment diagram (ranking as A, B1, B2, B3 or C) in the literature\(^5\). Considering subsidence or other effects of a fall in groundwater level, we have selected as the basic countermeasure the technique that achieves the rank A or B1 for Type 2 seismic motion in all the areas covered by the project except for those to be ranked as B2 locally.

6 CONCLUSION

We have studied the damage in Inashiki city caused by the 2011 off the Pacific coast of Tohoku Earthquake and examined liquefaction resulting in damage. And we have carried out the numerical simulations of liquefaction that damaged residences. As a result, it is found that, to assess earthquake-related liquefaction, the repeatability of damage features observed from the great earthquake was improved as explained below.

i) Deposits with plasticity index \( I_p \) of less than 25 are assumed for liquefiable layers

ii) Ground surface displacement \( D_{cy} \) corrected according to the magnitude of liquefaction factor \( P_L \).

In addition, we have also assessed liquefaction countermeasures using liquefaction assessment with improved reproducibility of the damage and determined the technique, its target effects and target magnitude of seismic motion. Based on the results of numerical analyses which was conducted for the cases under the seismic motion (200 Gal, M9.0), which are guidelines by the Ministry of Land, Infrastructure, Transport in Japan, the followings were pointed out.

iii) Setting of a fundamental policy was proposed for determination of countermeasures against liquefaction under a great earthquake.

iv) Countermeasures should be sought that enable attainment of rank A and Rank B1 under seismic motion of type 2 (200 Gal, M9.0) in all regions, except for areas ranked locally as B2.

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