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A study of damage to sandy soil due to liquefaction induced by earthquakes and of methods for predicting liquefaction

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ABSTRACT: We propose an analysis of the incidence of liquefaction using a combination of two simple methods employed to estimate liquefaction in Japan. The process of this analysis is as follows: the unit weigth of soil is assessed using the surveyed N-values corresponding to geologies and soil types; liquefaction potential corresponding to depth is estimated using horizontal oscillation values during earthquakes varying from 0.15 to 0.25 by 0.01 increments; the magnitude of horizontal oscillation which causes liquefaction is determined using the relationship between the liquefiable layer and non-liquefiable layer. To examine the adequacy of this analysis, detailed field investigations and borings were carried out to survey liquefaction damage to coastal sand dunes induced by the 1983 Nihonkai-chubu earthquake. The results of the surveyes and the analysis were 90% indentical. It is suggested that the proposed analysis can increase accuracy in forecasting the incidence of liquefaction in coastal sand dunes.

1 INTRODUCTION

Liquefaction induced by the Nihonkai-chubu earthquake (magnitude 7.7) on May 26, 1983 caused marked marked damage to soil on the east side of the sand dunes stretching along the Japan Sea coastline, a flat area in Aomori Prefecture and Akita Prefecture, resulting in damage to many houses. We carried out field investigations of damage due to liquefaction in this area for eight years commencing immediately after the earthquake. Especially, damage to houses, the sand volcano phenomenon, soil crackage, etc., were investigated in detail in areas which suffered remarkable damage, i.e., Hachiryu Town and Wakami Town in Akita Prefecture and Shariki Village in Aomori Prefecture, with about 100 borings being taken at and near sites where the sand volcano phenomenon occurred. Based on these investigations, estimative calculation was attempted using a combination of two simple methods for predicting liquefaction employed in Japan and a few new analytic techniques. Results were compared with the actual occurrence of liquefaction. We herein report the results of the field investigations, soil properties, and the adequacy of this analysis.

2 OUTLINE OF GEOLOGY AREAS WHICH SUFFERED LIQUEFACTION

Hachiryu Town and Wakami Town, located on the west edge of the Hachirogata reclaimed land, suffered liquefaction accompanied by marked damage during the Nihonkai-chubu earthquake. This area, consisting of high sand dunes, low sand dunes, lowland behind the sand dunes, and alluvial lowland, lies two kilometers from the coast of the Japan Sea, the source of sand for the sand dunes in this area. The incidence of liquefaction caused damage mainly at the border of the sand dunes and the lowland behind. In Shariki Village spreading over the Byobuyama sand dune area, adjacent to the west edge of the Tsugaru Plain, and the delta of the Iwaki River, east of the sand dune area, liquefaction occurred on the delta adjacent to the lowland between sand dunes, the alluvial terraces, and the sand dune area. Especially, alluvial terraces such as Tomiyachi, Ushigata, Shimoushiata, and Otappi suffered serious damage. Figure 1 shows the sites of liquefaction caused by the main shock of the Nihonkai-Chubu earthquake and isoseismal lines estimated by questionnaire survey of damage carried out by Goto et al.

3 LIQUEFACTION POTENTIAL OBTAINED BY ESTIMATIVE METHOD

There are various methods of estimating liquefaction potential, including those utilizing the relationship among liquefaction, the N-value of soil, grain size, and the oscillation of earthquakes (mainly maximum acceleration). Of these, we used the method described in the publication entitled Aseismic Design in the Specifications of Road Bridges in Japan and Explanation (Chapter V) and another method which utilizes residual pore water pressure data. For application of these methods, proper assessment of the unit weight of soil (ρt) and of the maximum acceleration at the ground surface (αmax) is important.

Tashuoka and Adachi outlined a method for assessment of ρt by soil types. We employed a formula based on quantitative theory to estimate density, referring to a method in which ρt is assessed using the surveyed N-values corresponding to geologies and soil types. The correlation coefficient of the values obtained by the formula, the N-values measured in Akita Prefecture

after the earthquake, and about 100 data of unit weight was 0.89. With applicablility supported by this value, we adopted this technique to estimate ρt.

Four types of data are generally used to calculate maximum acceleration: (1) surveyed acceleration, (2) intensity scacle, (3) magnitude and distance from epicenter, and (4) data on fallen gravestones. However, (1) and (2) were not obtained at liquefaction sites, and values of (3) and (4) were unreliable, making it impossible to determine maximim accelerations in the three towns. Therefore, horizontal oscillation, Ks, ($\alpha max/g$, g : the acceleration of gravity) needed for estimative calculation could not be obtained. Thus, Ks values were varied from 0.15 to 0.25 by 0.01 increments, and calculation was carried out corresponding to depth.

Figure 2 shows the estimated critical acceleration of liquefaction using the two above-mentioned methods, liquefaction potential, actual damage obtained by field investigations, and water levels in boring holes (measured in May and June) in Wakami Town. Figure 3 shows liquefaction potential estimated using the two methods and columns showing depth of boring spots in Wakami Town. Black portions indicate liquefiable layers. The same estimation was carried out for Hachiryu Town and Shariki Village. Results of this estimation at Ks 0.20 were 84.2% identical to actual liquefaction which occurred in Wakami Town, 98.8% indentical in the case of Hachiryu Town, and 89.4% indentical in the case of Shariki Village. Based on these consistent findings, Ks during the earthquake in the three towns is estimated to be about 0.20 (horizontal acceleration $\alpha max \fallingdotseq 200$ Gals).

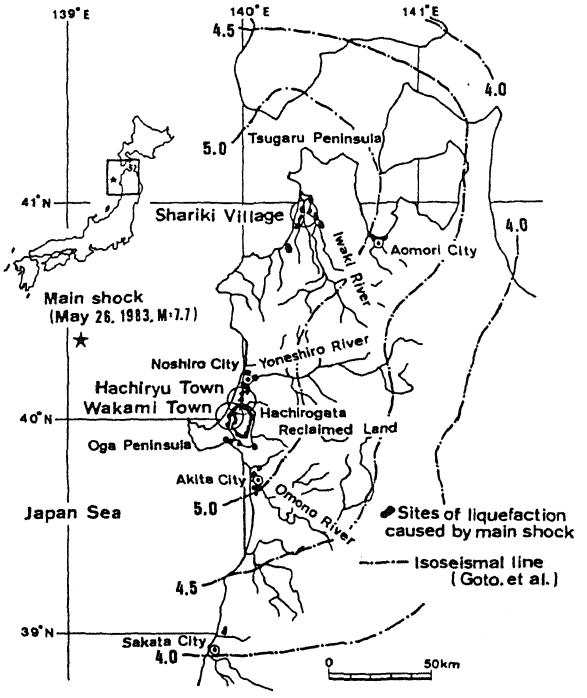


Figure 1. Distribution of sites of liquefaction and isoseismal lines caused by the Nihonkai-Chubu earthquake

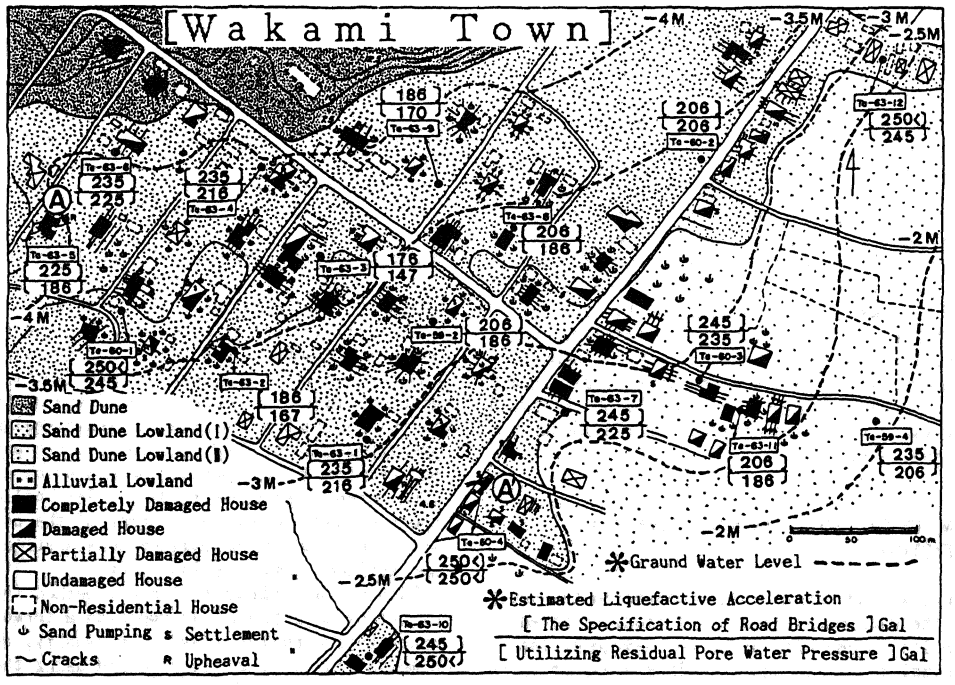


Figure 2. Estimated Liquefactive Acceleration and Ground Water Level in Wakami Town

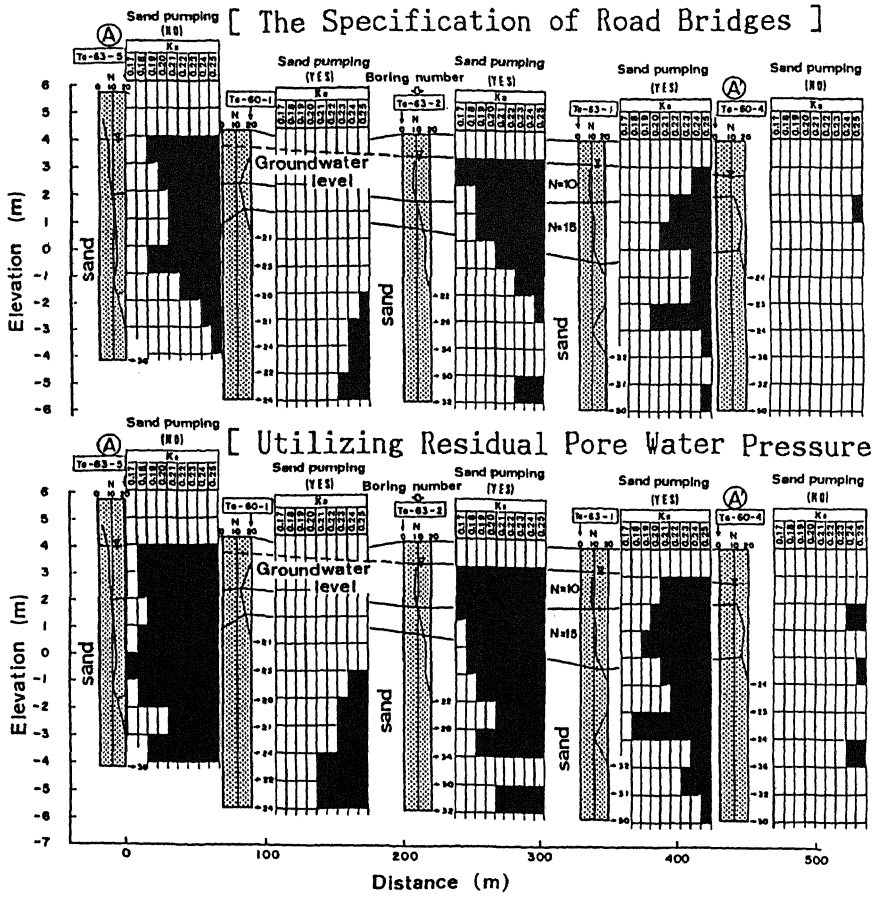


Figure 3. Incidence of Liquefaction

4 OUTLINE OF SOIL PROPERTIES

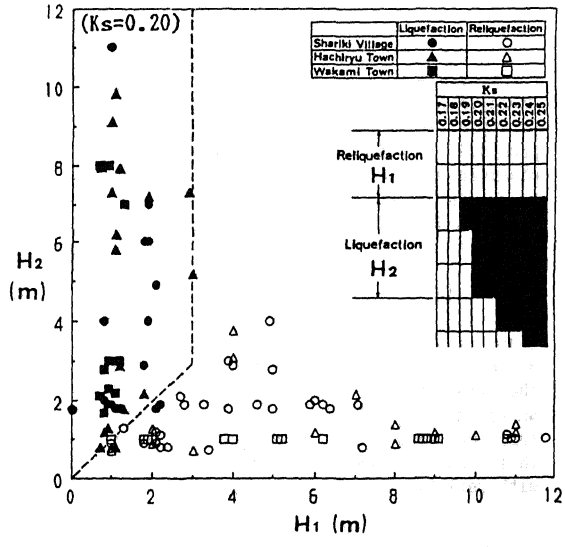
The soil properties of the three towns assuming a Ks value of 0.20 (αmax≒200 Gals) are as follows.

4.1 Liquefiable layers and non-liquefiable layers

Figure 4 shows the relationship between the thickness of the liquefiable layer and that of the non-liquefiable layer, based on the liquefaction potential of the boring sites estimated using the two methods previously mentioned and the incidence of liquefaction at those sites. This figure indicates that layers more than three meters thick did not suffer liquefaction.

4.2 N-value and mean grain size (D_{50})

The distribution of the N-values and that of the mean grain sizes (D_{50}) are respectively show in Figure 5 and Figure 6, based on the N-value at each boring site, the results of physical testing of



Figue 4. Relationship between non-liquefied layer and liquefied layer

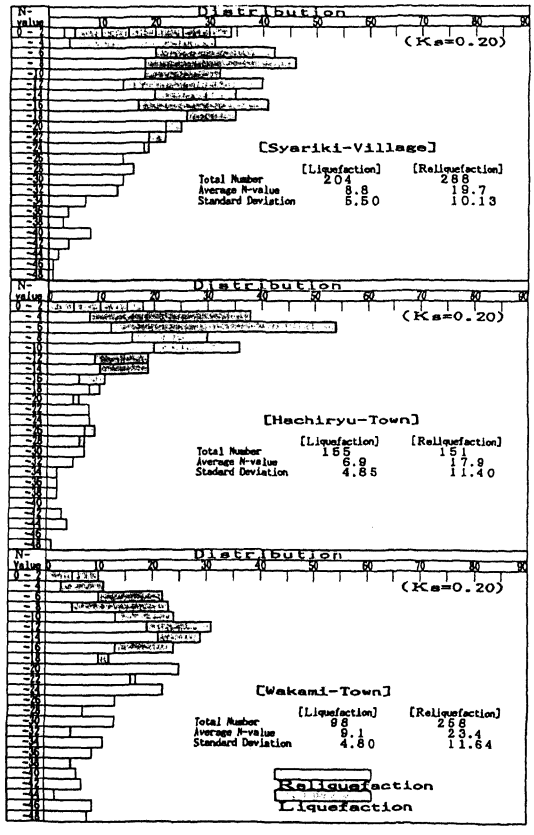


Figure 5. Distribution of N-values

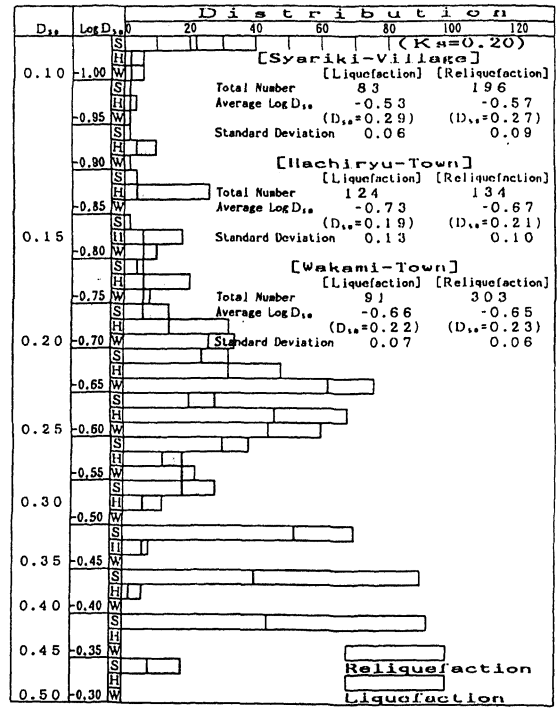


Figure 6. Distribution of Mean Particle Size

sample soils, and the relationship between thickness of the liquefiable layer and that of the non-liquefiable layer.

Frequent liquefaction was recognized when the N-value was under 15. The distribution of D_{50} had a wide range from 0.10 to 0.70 mm for Shariki Village. In particular, remarkable liquefaction was observed where D_{50} was from 0.30 to 0.45 mm. As for Hachiryu Town and Wakami Town, the distribution of D_{50} ranged from 0.10 to 0.40 mm, and remarkable liquefaction was observed where D_{50} was from 0.10 to 0.25 mm. This is thought to be due to the different conditions of the sand deposited in the sand dunes.

4.3 N-value and depth

Based on the N-values of the boring sites and estimation of the liquefiable and non-liquefiable layers, the relationship between the N-value and depth is shown in Figure 7. The critical N-value curves of three criteria proposed in Japan are also shown in this figure. These criteria are quite consistent with reality.

4.4 Fines content (PF) and clay content (PC)

Based on the results of grain size analysis of

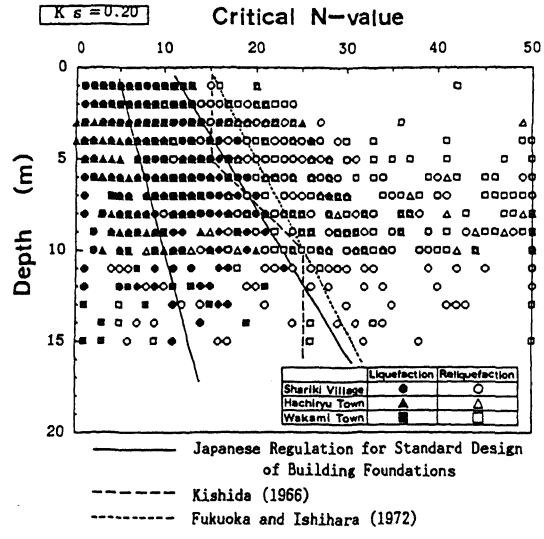


Figure 7. Depth and critical N-values

sample soils obtained at the boring sites and estimated liquefiable and non-liquefiable layers, the relationship between fines content (PF) and clay content (PC) is shown in Figure 8. This figure indicates that in the three towns liquefaction occurred in sandy soil with PC≦10% if sand and silt had high fines content.

4.5 Dynamic shear strength ratio ($\tau R/\sigma v$) and dynamic shear stress ratio ($\tau L/\sigma v$)

As to the dynamic properties of soil, the relationship among the N-value, dynamic shear strength ratio obtained by estimative calculation, and dynamic shear stress similarly obtained is shown in Figure 9. In all towns, liquefaction was frequently caused when the N-value was in a range from 0 to 15 and the dynamic shear strength ratio was from 0.15 to 0.40, increasing in primary proportion. The distribution of dynamic shear stress ratio was concentrated between 0.20 and 0.40 in the case of Shariki Village and between 0.30 and 0.40 in the case of Hachiryu Town and Wakami Town. As with the dynamic shear strength ratio, frequent liquefaction was caused when the N-value was under 15.

5 CONCLUSION

In this study, we estimated the unit weight of soil (ρt) corresponding to the surveyed N-values and soil types using a formula to assess density based on quantitative theory. Furthermore, estimative calculation was carried out for each boring site, with horizontal oscillation (Ks) ranging from 0.15 to 0.25 by 0.01 increments. The results of this calculation were checked with actual liquefaction, and were about 90% consistent in the case of all towns. It is inferred that marked liquefaction was caused where Ks was 0.20 during the earthquake (horizontal acceleration $\alpha max \fallingdotseq 200$ Gals).

Based on the isoseismal lines (the intensity scale of each town $I \fallingdotseq 5.3$) obtained by a questionnaire survey carried out directly after the earthquake by Goto et al., and by Kawasumi's formula, $\alpha max = 0.45 \times 10^{I/2}$, the horizontal acceleration in this area was found to be about 200 Gals, consistent with the results of this study.

It is thus considered that liquefaction in coastal sand dunes can be accurately estimated by this method.

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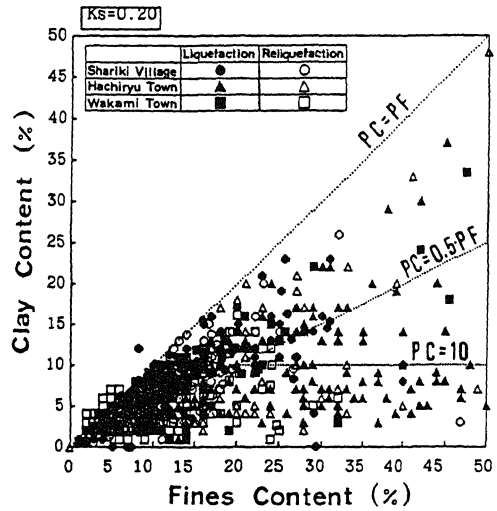

Figure 8. Relationship between fines content and clay content

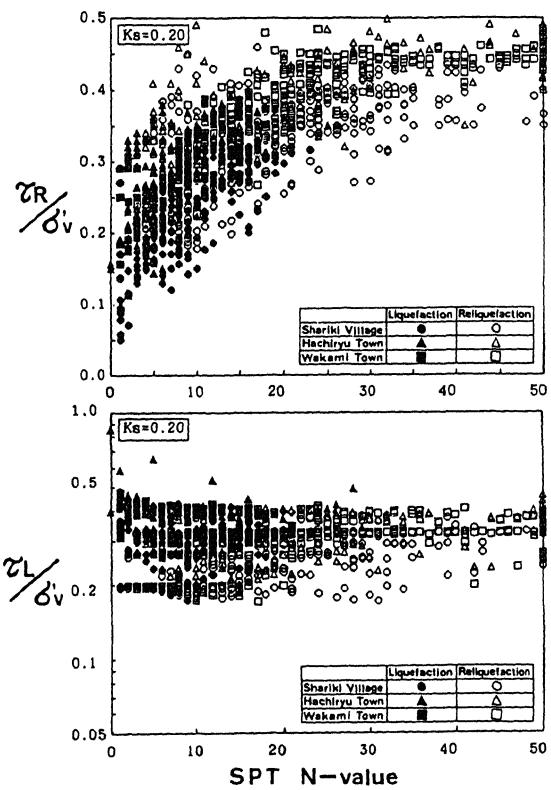

Figure 9. Relationship of N-value to dynamic shear strength ratio ($\tau R/\sigma v$) and dynamic shear stress ratio ($\tau L/\sigma v$)