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Field investigation and model tests on differential settlement of houses due to liquefaction in the Niigata-ken Chuetsu-Oki earthquake of 2007

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Abstract

A massive earthquake struck the Niigata Chuetsu-Oki region of Japan on July 16th, 2007, claiming 11 lives and damaging about 6000 houses. The earthquake had a magnitude of 6.8, with data from an accelerograph managed by a nationwide strong-motion observation network known as Kyoshin Net (K-net) showing a maximum value of 668 gal (NS). In the Matsunami district of Kashiwazaki city (located on land filled and developed as a residential area from around 1970 onward) about 3 km northeast of Kashiwazaki Railway Station, many houses were damaged due to liquefaction. A field investigation, including a boring survey, surface wave exploration and measurement of differential settlement of houses knocked aslant by soil liquefaction, was conducted to determine the relationship between the extent of damage to houses and the area's geological structure. It was found that most houses severely damaged due to liquefaction were located around the boundary between sand dunes and the local river delta. Additionally, the relationships linking sloping geological structure, the thickness of the liquefaction layer and total/differential settlement of houses were clarified from the results of shaking table model tests conducted in this study. Test results showed that it is important to consider multidimensional influences caused by sloping geological structure in the estimation method of liquefaction potential in order to predict and assess degree of damage to houses due to liquefaction.

Keywords: Liquefaction; Differential settlement; Shaking table test; Triaxial test; Surface wave exploration

1. Introduction

The Niigata-ken Chuetsu-Oki Earthquake that hit Japan on July 16th, 2007, killed 11 people and damaged more than 6000 houses. The quake registered 6.8 on the magnitude scale of the Japan Meteorological Agency (2007) (JMA), and the K-net Kashiwazaki (NIG018) measured PGA (peak ground acceleration) of 668 gal (NS) (National Research Institute for Earth Science and Disaster Prevention, 2007). Many houses were damaged, and ground deformation types such as liquefaction were observed in Kashiwazaki City and Kariwa Village (Fig. 1). In the Hashiba district of Kashiwazaki City and in Kariwa Village, foundation damage to timber houses and ground deformation were extensively observed. In these areas, liquefaction-related damage to houses and ground failure similar to those seen in the Mid Niigata Prefecture Earthquake of 2004 (Japanese Geotechnical Society, 2007) also occurred (Japanese Geotechnical Society, 2009a; Onoue et al., 2011).

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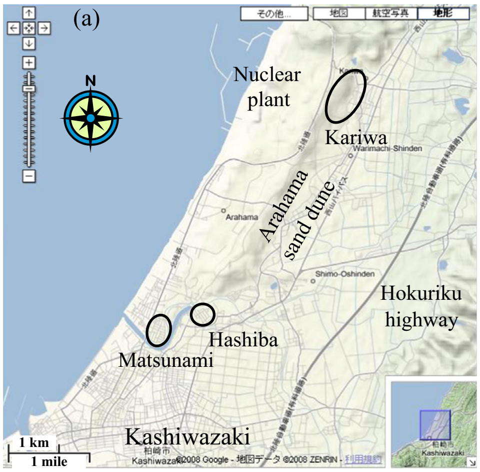

Fig. 1. Liquefaction site in Kashiwazaki and Kariwa in the Niigata-ken Chuetsu-Oki Earthquake of 2007 (map by Google map).

This was the second experience of severe earthquake damage in the region within a span of three years.

This paper reports on the results of earthquake damage investigation work conducted in the Matsunami district in the region. Liquefaction evidence such as sand boiling was observed and a lot of houses were damaged and destroyed due to liquefaction-induced differential settlement there. Health disorders, such as dizziness, due to liquefaction-induced differential settlement in the 2000 Tottoriken-seibu earthquake were reported by Yasuda et al. (2004) for the first time, in which it has been pointed out that liquefaction-induced differential settlements pose significant monetary problems for inhabitants: restoring tilted houses so that they become horizontal is extremely costly. Also, this same issue occurred in the following many severe earthquakes, such as the 1964 Niigata earthquake, the 1990 Philippine Luzon earthquake (Adachi et al., 1992), the 1999 Kocaeli Turkey earthquake (Bray and Sancio, 2009), Mid Niigata Prefecture Earthquake in 2004 (Japanese Geotechnical Society, 2007), the Niigata-ken Chuetsu-Oki Earthquake in 2007 (Japanese Geotechnical Society, 2009a) and the 2011 Great East Japan Earthquake (Yasuda et al., 2012; Tokimatsu et al., 2012; Mori et al., 2012). However, as pointed out by Bertalot et al. (2013), field data on the liquefaction-induced (differential) settlement of shallow foundations are still scarce because of the objective difficulty in estimating the extent of liquefied soil at damaged sites.

Liquefiability and extent of liquefaction are commonly estimated with the semi-empirical method proposed by Youd and Idriss (2001), and Idriss and Boulanger (2008). Estimation of the liquefaction-induced settlement of shallow foundations is done by the empirical design chart developed by Liu and Dobry (1997), based primarily on field data of building settlement observed by Yoshimi and Tokimatsu (1977) following the 1964 Niigata earthquake. Adachi et al. (1992) verified the validity of the proposed chart for the liquefaction-induced building settlements measured in the city of Dagupan after the 1990 Luzon earthquake. Acacio et al. (2001) also provide similar data about the Dagupan City case. Other than those above, there has been a large body of literature on liquefaction-induced settlement in soil deposits involving both case histories and physical model studies e.g. by Tokimatsu and Seed (1987), Nagase and Ishihara (1988), Ishihara and Yoshimine (1992), Sancio et al. (2004) and so on.

On the other hand, in Japan, the factor of safety against liquefaction F_L value based on the standard penetration test (SPT) blow-count (the Japan Road Association, 2002) and the probability of liquefaction P_L values, determined using the method set out by the Japan Road Association (2002), are widely used in order to assess the needs for liquefaction countermeasure. However, the above-mentioned estimation method on the liquefaction-induced settlement of shallow foundations is not implemented in the references (the Japan Road Association, 2002, Architectural Institute of Japan, 2001, 2008), let alone the liquefaction-induced differential settlement of shallow foundations. The liquefaction-induced inclination of houses may be greatly affected by several factors, such as soil condition, seismic condition, sand boiling, the dimension of houses, eccentric weights, and the distance between adjacent houses. It is still a very important issue to understand these mechanisms and estimate the liquefaction-induced differential settlement of shallow foundations.

In this paper, the relationship between ground conditions and the causes for damage houses at Matsunami district were investigated based on the outcomes of surface wave exploration, Swedish weight sounding (SWS) tests, boring investigation involving standard penetration tests (SPT) and measurement of liquefaction-induced differential settlement in damaged houses. Based on the above mentioned investigation results, the shaking table model tests were conducted in order to investigate the relationships linking sloping geological structure, the thickness of the liquefaction layer and total/differential settlement of houses. Test results showed that it is important to consider multidimensional influences caused by sloping geological structures in the estimation method of liquefaction potential in order to predict and assess degree of damage to houses due to liquefaction.

2. Field investigation

2.1. Overview of geographical conditions in Kashiwazaki city

The Matsunami district sits on land filled for the development of a residential area from around 40 years ago. It is located about 3 km northeast of Kashiwazaki Railway Station on the right bank of the Sabaishi River near its mouth and on the hinterland of the Arahama dunes. According to the terrain classification map for the district (Fig. 2), the northwestern part of Matsunami is classified as sand dunes, and the southeastern part is a natural levee area.

2.2. Overview of damage caused by the earthquake

Fig. 3 shows the distribution of damaged houses in Matsunami based on the emergency risk judgment table for