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Numerical assessment of liquefaction mitigation effects on residential houses: Case histories of the 2007 Niigata Chuetsu-offshore earthquake

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ABSTRACT

In this study, the effectiveness of liquefaction countermeasures for residential houses was explored using a fully coupled dynamic effective-stress finite element procedure. Numerical analyses were conducted on two wooden houses that were damaged to different degrees due to dune liquefaction during the 2007 Niigata Chuetsu-offshore earthquake. House A, which was only improved by horizontal drainage pipes to lower the ground water level, was completely destroyed; however, house B, which was improved by a horizontal drainage system, soil–cement mixtures, and steel-pipe piles, was slightly deformed. Numerical results show that the effects of the sand dune slope on the damage to the two houses were somewhat different. For house B, it was found that the steel-pipe piles were more effective. Two countermeasures generally led to a greater degree of reduction in both lateral and vertical displacements of house B than only a single countermeasure employed. In addition, the combined implementation of steel-pipe piles and soil–cement mixtures was the most effective among the cases with two countermeasures.

1. Introduction

One of the most dramatic causes of damage to residential houses during earthquakes is the development of soil liquefaction beneath and around houses. The devastating effects of liquefaction that result in differential settlements, the lateral movement of foundations, the tilting of houses, and some bearing failures, have been observed in previous major seismic events, such as the 1964 Niigata earthquake [1], the 1990 Luzon earthquake [2], the 1995 Hyogoken-Nanbu earthquake [3], the 2004 Niigata Chuetsu earthquake [4], the 2007 Niigata Chuetsu-offshore earthquake [5], and the 2011 Christchurch earthquake [6]. In particular, the more recent Great East Japan earthquake on March 11, 2011 generated the widest liquefaction areas in the history of Japanese earthquakes, and produced many liquefaction events, causing the foundations of houses to fail [7]. Severe damage was inflicted on many houses in the alluvial plain area of the Tone River and the coastal area of Tokyo Bay due to sand boiling and ground deformation associated with liquefaction.

Such earthquake-induced liquefaction hazards necessitate the development of appropriate mitigation measures. Over the years, various mitigation measures have been proposed to reduce earthquake-induced liquefaction hazards, such as concrete piles, steel-pipe piles, sheet piles, cement grouting, foundation densification, gravel drains/stone columns, sand compaction piles, desaturation, etc. Most of these liquefaction countermeasures have been studied by centrifuge tests, shaking table tests and field tests. Numerical analyses have frequently been used to supplement these physical model tests [8–10]. Among these proposed countermeasures, concrete piles and cement grouting have been reported in the mitigation of building liquefaction [11–13]. Sheet piles have frequently been adopted to mitigate the liquefaction of quay walls [14,15], existing bridge foundations [16], soil structures such as river dikes [17], and highway or earth embankments [18–20]. Foundation densification has been applied to mitigate the destructive effects of liquefaction on earth embankments [19,21] and bridge sites [22]. Gravel drains or stone columns were usually employed as a liquefaction countermeasure for earth embankments [20], site improvement

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[23–25], and underground structures [9]. Sand compaction piles have often been used to mitigate the liquefaction of earth embankments [20] and for ground improvement [26]. Desaturation is a newly proposed method for liquefaction mitigation [27–29] and must be adequately studied for practical applications. However, limited research has been devoted to develop liquefaction countermeasure techniques for residential houses [30]. This lack of study is likely due to the fact that liquefaction countermeasures, such as cement grouting, sand compaction piles, sheet piles, etc., are too costly for most homeowners. Thus, it is necessary to study cost-effective design of liquefaction countermeasures for residential houses.

During the 2007 Niigata Chuetsu-offshore earthquake (M_w=6.8), most wooden houses were destroyed due to dune liquefaction [5]. Such houses had been rebuilt after they were damaged by the dune liquefaction induced by the 2004 Niigata Chuetsu Earthquake (M_w=6.8) [4], and various techniques were used to mitigate the potential effects of liquefaction on different houses. After the 2007 Niigata Chuetsu-offshore earthquake, two wooden houses were investigated in Kariwa Village, Kashiwazaki City, Niigata Prefecture. These two houses suffered different levels of damage: house A, where the ground was improved using only horizontal drainage pipes to lower the ground water level (GWL), was completely destroyed; house B, on the other hand, where the ground was improved using a horizontal drainage system to lower the GWL, soil–cement mixtures, and steel-pipe piles, was only slightly deformed.

In this study, numerical analyses were performed on these two houses to assess and improve the effectiveness of the liquefaction countermeasures for residential houses. The fully coupled dynamic effective stress analysis software program UWLC was employed for the numerical analyses of the two houses. A modified Pastor–Zienkiewicz III model [31] was used to describe the liquefaction behaviors of the younger sand dune layer. The parameters of the model were quantified by the laboratory tests on undisturbed samples and the Standard Penetration Test (SPT) data. The input motions for the numerical analyses were calculated by SHAKE91 [32] using the seismic motions recorded by the vertical array at the service hall of Kashiwazaki-Kariwa Nuclear Power Plant (KK-NPP). First, the lateral displacements of the ground surface calculated by UWLC were compared with those calculated by the method of Zhang et al. [33] to verify the reliability of the UWLC results. Second, the effects of the sand dune slope on the damage to two houses were investigated. Finally, the effectiveness of each countermeasure used for house B and the combinations of two countermeasures was studied.

2. Case histories

Inaba District in Kariwa Village is located at the eastern foot of a dune (see the yellow region in Fig. 1(a) [34]), which separates the Sea of Japan and Kariwa Plain. Most wooden houses, from house A to house B in Fig. 1(b), built at the eastern foot of the dune were severely damaged because of the liquefaction of the dune. Two cross sections investigated, A–A′ and B–B′ (see Fig. 1(b)), are depicted in Fig. 2, which shows the ground surface before and after the earthquake and a schematic distribution of the water table line, the steel-pipe piles, the horizontal drainage pipes or system, and the borehole logs. As shown in Fig. 3, house A was displaced horizontally by 130 cm and vertically by 120 cm upward and was inclined forward by approximately 9°; however, house B settled by about 12 cm, and its lateral displacement slightly narrowed the side ditch near the house [35] (Fig. 4(b)), but unfortunately its value was not reported in references. In addition, no tension cracks were observed in house B. Details regarding such house damage have been reported by Isobe et al. [35], Inotsume et al. [36], and Yamada et al. [37].

The details of the liquefaction countermeasures implemented for the two houses are as follows. There were four horizontal drainage pipes measuring 150 mm in diameter with a bottom depth of 0–2 m in the yard of house A, as shown in Fig. 4(a). For house B, the drainage system featured a sand filter and a standard cross section measuring 50 cm wide and 40 cm high; the system was constructed by wrapping gravel around drainage pipes with a mat. A porous concrete pipe measuring 100 mm in

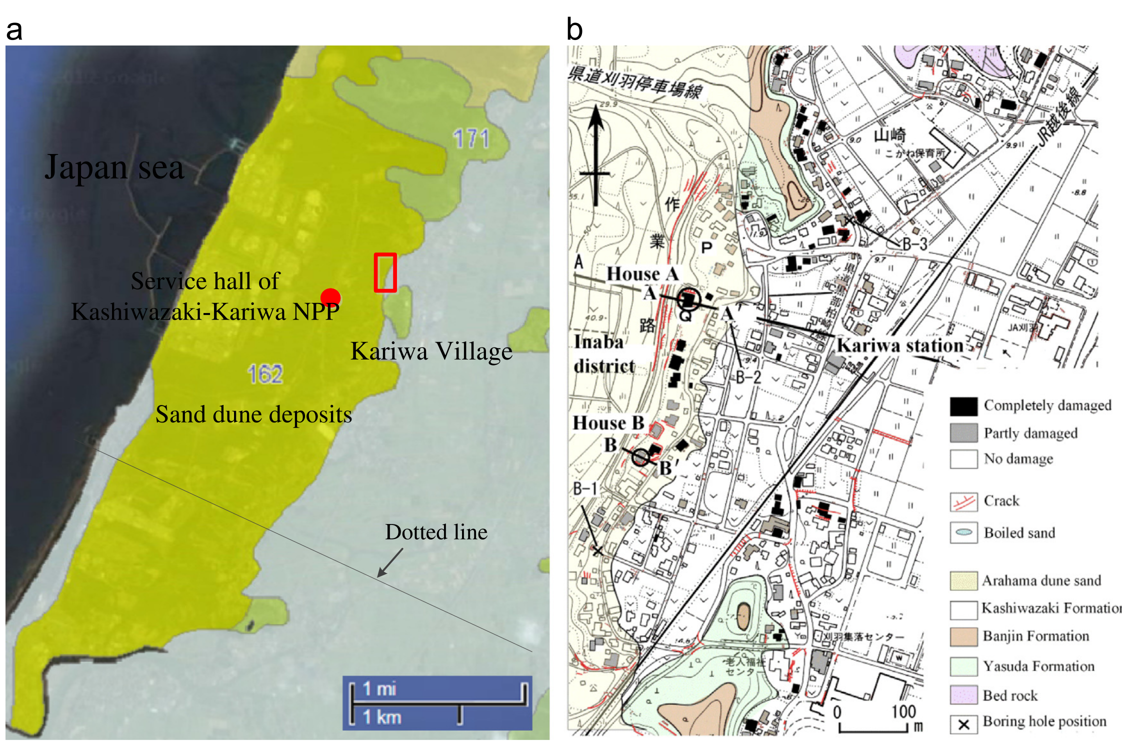

Fig. 1. (a) Geological map of Inaba district in Kariwa village, Kashiwazaki City, Niigata Prefecture [34] and (b) schematic map of Inaba district [5] (see the rectangle in Fig. 1(a)).