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Technical Paper

Uplift mechanism of open-cut tunnel in liquefied ground and simplified method to evaluate the stability against uplifting

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Abstract

The liquefaction of sandy soil during earthquakes causes the uplift of relatively light structures such as open-cut railway tunnels. The potential for the uplift of underground structures is usually evaluated by the factor of safety against uplift (F_s), which only considers the force equilibrium of the structures in the vertical direction. However, design procedures which employ the factor of safety to evaluate uplift may be too conservative for assessing the uplift behavior of underground structures. It is necessary to establish a new method to directly predict the residual displacement or to predict whether or not the uplift behavior will have a negative influence on the serviceability of underground structures. In this study, therefore, a series of shaking table tests was performed using the open-cut tunnel model, and the relationship among the uplift behavior of the tunnel, the degree of liquefaction, the external forces acting on the tunnel and the deformation of the liquefied ground was investigated through precise measurements. The experiment revealed that critical uplift behavior does not occur when the level and the area of liquefaction are limited to a restricted range even if the factor of safety against uplift falls to less than 1.0. After the wide area around the tunnel reached complete liquefaction, the uplift behavior of the tunnel increased rapidly. Based on these test results, the detailed mechanism of the uplift behavior and the applicability of the factor of safety were examined. In addition, a new method was suggested to evaluate the stability level of open-cut tunnels against uplift.

Keywords: Liquefaction; Uplift behavior; Shaking table test; Seismic design standard

1. Introduction

The liquefaction of sandy soil during earthquakes causes the uplift of relatively light structures which are buried below the ground surface. Actually, sewer pipes and manholes suffered major uplift damage due to liquefaction during the 1993 Kushiro-Oki Earthquake (JGS, 1994; Koseki et al., 1997a) and the 2004 Niigataken-Chuetsu Earthquake (Yasuda and Kiku, 2006). After the Niigataken-Chuetsu Earthquake, a detailed soil investigation was conducted before the restoration work. It was concluded that the uplift of manholes and pipes occurred due to the liquefaction of the sand fill, and the cement mixing method was selected as the suitable restoration work (Yasuda and Kiku, 2006).

Underground structures in a liquefied ground, such as open-cut railway tunnels, can also suffer from similar uplift damage. For example, the open-cut railway tunnel for Sendai Airport

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Transit suffered from uplift damage during the 2011 off the Pacific Coast of Tohoku Earthquake (Osawa, 2011). In current earthquake design procedures, the potential for the uplift of underground structures is evaluated by the factor of safety, which only considers the force equilibrium of the structure in the vertical direction. However, it is difficult to predict the residual uplift displacement of underground structures in this way.

The uplift behavior of underground structures caused by liquefaction is often studied by shaking table model tests. Koseki et al. (1997b) performed a series of model tests to investigate the uplift mechanism of a variety of underground structures, such as a completely-buried box structure, semi-buried roads and sewer manholes and pipes, and summarized the behavior of the surrounding subsoil layer during and after shaking as well as the effect of the structure type. Ishida et al. (2002) conducted shaking table tests to investigate the effect of countermeasures in reducing the floating of light underground structures upon liquefaction of the soil. The test results showed that sheet pile walls with a drainage function reduced the uplift behavior effectively. In this study, the relationship between the uplift displacement and the factor of safety against uplifting was also investigated.

Sasaki and Tamura (2002) conducted a series of centrifuge model tests on an underground structure. The material and the density of the model ground, the shape of the model structure, the height of the overburden layer above the tunnel and the height of the groundwater level were varied in these tests. It was revealed that the width of the tunnel, the depth of the liquefied layer below the tunnel and the number of waves in the earthquake input motion had a large impact on the uplift displacement of the tunnel. On the other hand, the height of the overburden layer above the tunnel had less of an impact on the uplift displacement.

Otsubo et al. (2013, 2014) performed a series of shaking table model tests to validate several new mitigative measures that are applicable to both damaged lifelines and lifelines that are located in earthquake-prone regions. For example, the effectiveness of using recycled materials (crushed concrete, glass and tire-chips) and chemical grouting was verified. In addition, economical countermeasures, without the excavation of backfill, were developed. These countermeasures included drainage pipes and a horn-type structure that connects embedded pipelines and the road pavement.

Chian et al. (2014) and Chian and Madabhushi (2012) carried out numerical analyses and centrifuge experiments with shallow circular structures. The influence of the earthquake input acceleration and the effect of the buried depth of the structure on its uplift response were investigated. Both numerical and experimental analyses showed comparable results in acceleration, excess pore water pressure and uplift displacement. Both analyses also showed the necessary for high excess water pressure and large input acceleration for the development of uplift.

Many experimental studies have revealed that the factor of safety against uplift is one of the most useful parameters for predicting the potential for uplift; however, it is difficult to predict the uplift displacement. For example, Koseki et al. (1997b) calculated the factor of safety of underground model structures in their model tests and found that the uplift of the structures, which was accompanied by the lateral deformation of the surrounding subsoil, continued when the safety factor was almost equal to or less than unity. These results indicate that the safety factor can be used to evaluate the triggering of the uplift of underground structures.

Ishida et al. (2002) confirmed through shaking table tests that the uplift behavior started just after the factor of safety became almost equal to unity; however, the uplift displacement was small unless the factor of safety was less than 0.8. Sasaki and Tamura (2002) investigated the factor of safety of an actual underground structure which did not uplift during the 1995 Hyogoken-nanbu Earthquake. It was found that the factor of safety was largely smaller than unity even if the residual uplift displacement was limited.

These investigations indicate that even if it has been predicted that certain structures will be uplifted during a large earthquake, based on the vertical force equilibrium during the earthquake, the structures do not always suffer from critical vertical displacement which affects their serviceability. The design procedure which employs the factor of safety for the evaluation of uplift may sometimes be too conservative for assessing the uplift behavior of underground structures. Thus, it is necessary to establish a new method to directly predict the residual displacement or to predict whether or not the uplift behavior will have a negative influence on the serviceability of underground structures.

To the best of our knowledge, the detailed mechanism of the uplift behavior of underground structures, especially the relationship among the uplift behavior of a tunnel, the degree of liquefaction, the external forces acting on the tunnel and the deformation of the liquefied ground, has not been investigated sufficiently in past studies.

In this study, therefore, a series of shaking table tests using the open-cut tunnel model was performed, and the relationship among the uplift behavior, the degree of liquefaction, the external forces and the deformation of the liquefied ground was investigated through precise measurements. Based on these test results, the detailed mechanism of the uplift behavior and the applicability of the factor of safety were examined. In addition, a new method was suggested to evaluate the stability of open-cut tunnels against uplift.

2. Seismic design for underground structures against liquefaction

In the previous design standard for open-cut railway tunnels, the factor of safety was obtained from the vertical force equilibrium and was employed for evaluating the potential for uplift due to the liquefaction of the ground (Railway Technical Research Institute, 1999). This factor of safety, F_s, was obtained as follows:

$$F_s = \frac{W_B + W_S + 2Q_S + 2Q_B}{U_s + U_D} \geq 1.0 \quad (1)$$