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Seismic simulation of liquefaction-induced uplift behavior of a hollow cylinder structure buried in shallow ground

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ABSTRACT

When designing buried structures using a performance-based framework, it is important to estimate their uplift displacement. A simplified method is proposed for predicting the uplift displacement of a hollow cylinder structure buried in shallow backfill based on the equilibrium of vertical forces acting on the structure during earthquakes. However, this method only provides the maximum value, which frequently is overestimated in practical applications. To offset this limitation, first, the uplift behavior of buried hollow cylinder structures subjected to strong earthquake motions was simulated. Then, two-dimensional effective stress analyses based on the multiple shear mechanism for soil were conducted, and the results were compared with the centrifuge test data. The soil parameters were evaluated based on laboratory test results. The seismic response data from 20 g centrifuge tests were analyzed, and the results were generally consistent with the results of centrifuge model tests. In particular, the effective stress model showed a reasonable ability to reproduce the varying degrees of uplift displacement depending on the geotechnical conditions of trench soils adjacent to the hollow cylinder structures buried in shallow ground.

1. Introduction

When the ground is subjected to strong shaking during an earthquake, liquefaction and subsequent ground settlement and/or flow failures, which involve extremely large movements of soil masses, may cause serious damage to civil/geotechnical infrastructures. Among those infrastructures, lifeline systems buried underground, such as common utility conduits and sewage systems, are vulnerable to medium to large ground movement. The geotechnical structures buried near the surface have a wide range of applications, from small-scale pipelines for gas transmission, telecommunications, water supply, and sewerage pipelines, to large-scale structures, including tunnels for various transportation systems. Among these structures, sewerage manholes, which are hollow cylinder structures buried in shallow ground, can be damaged easily by uplift movements because they are relatively light-weight considering the buoyancy force resulting from the liquefaction of the adjacent subsoil caused by earthquakes [1,2].

The uplift phenomenon of buried structures has been reported after past earthquakes. For example, during the 2004 earthquake in Niigata-ken Chuetsu, Japan, more than 1400 sewage manholes were uplifted [3], causing serious liquefaction-related lifeline problems. In the 2010 earthquake in Maule, Chile, the uplifting of the sewage facility (manholes and sewage tank) was reported, and the sewage tank in San Pedro del Valle was uplifted by approximately 1.2 m, as shown in Fig. 1. Studies on the uplifting of buried structures began with field investigations [3–6]. More recently, experimental studies have been conducted that focus on the cause of damage and the mechanism of the uplift behavior of buried structures due to earthquake-induced liquefaction [1,7–12]. Many model tests have been employed to investigate the uplift resistance and the corresponding failure mechanisms [13–16].

In a previous study, the safety factor approach for uplifting was developed [4] and recommended for use during the design phase [17]. This safety factor is defined based on the equilibrium of vertical forces acting on an underground structure, which can be used to evaluate whether uplift will be triggered or not. The safety factor cannot estimate the degree of uplift, however. The uplift displacement may be an important factor to consider in the performance-based design of underground structures [18]. Honda et al. [19] noted the importance of determining the allowable extent of sewerage manhole uplift; they designed a questionnaire asking firefighters the degree to which sewerage manholes could lift while still allowing them to drive their emergency vehicles. Tobita et al. [20] proposed a simplified method to predict the

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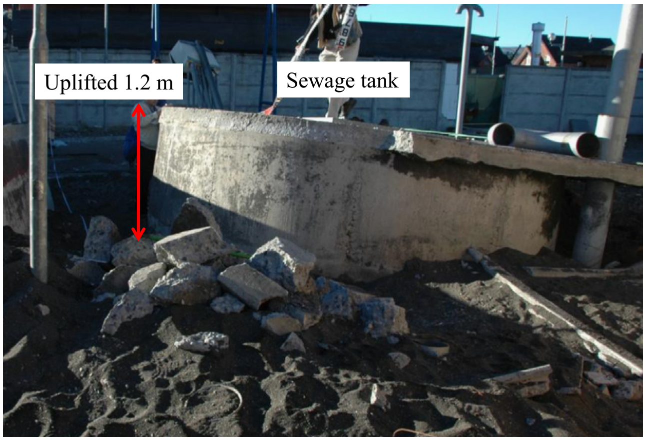

Fig. 1. Uplifted sewage tank after the 2010 Maule, Chile, earthquake.

maximum uplift displacement of buried structures in liquefied ground. However, their method tends to overestimate the uplift displacement when that displacement does not reach the maximum amount.

In order to overcome the limitations of these methods for estimating the uplift displacement of buried structures, two-dimensional effective stress analyses based on the multiple shear mechanism for soil were performed, and the results were compared with the centrifuge test data. The numerical approach based on the mechanics of the continuum body makes it possible to evaluate both failure modes and the extent of the displacement/stress/ductility/strain to which the complex soil-structure interaction is subjected. Furthermore, the effective stress analysis can estimate the transient behaviors of the uplift, as well as the maximum uplift displacement during shaking. In this study, such analysis was conducted for cases in which the uplift displacement does not reach its maximum, such as under a small amplitude of input acceleration, small number of load cycles, and compacted ground. To investigate its applicability, the numerical analysis also was performed for cases in which the uplift displacement reaches its maximum, such as in saturated soil below the ground surface and under a large amplitude of input acceleration as an input wave.

2. Centrifuge modeling tests

The geotechnical centrifuge facility at the Disaster Prevention Research Institute, Kyoto University, was employed. Model tests were conducted under 20 g with a hollow cylinder structure the size of a sewerage manhole scaled down to 1/20. According to the scaling rules for n in centrifuge modeling, the g centrifugal field, gravity, frequency, and acceleration were increased by n, while the length and time were decreased by n. The stress, strain, velocity, and fluid pressure in the prototype soil mass were preserved [21]. Table 1 specifies the material parameters of the model ground and the prototype of a structure. For comparison, a model with no mitigation method was shaken simultaneously with a model having some mitigation method. However, in this study, only the results from the model with no mitigation were used. Details of the model tests, including the effects of mitigation methods on uplift displacement reduction, can be found in [22] (Table 2).

2.1. Model preparation

Silica sand was used to form the model ground [12], which, as native ground, first was prepared in a rigid box ($45 \times 15 \times 30$ cm^3) by compacting moist silica sand up to 260 mm in lift (model scale) with a relative density (*Dr*) of approximately 85%. To install the model structure, which was made of an aluminum cylinder, a trench with a volume of $11.5 \times 11.5 \times 16$ cm^3 (model scale) was excavated. The model structure was placed on gravel at the bottom of the trench, as shown in Fig. 2. After excavation, a 10-mm-thick

Table 1
Parameters for soil and model structure.

Soil (silica sand)	Maximum void ratio	e_{max}	1.19	
	Minimum void ratio	e_{min}	0.71	
	Specific gravity	G_s	2.66	
	Wet sand	γ_t	14.8	kN/m^3
	Saturated sand	γ_{sat}	18.1	kN/m^3
	Friction angle b/w structure and soil	δ	10.0	deg
Model structure	Unit weight	γ_m	9.57	kN/m^3
	Diameter	d	1.10	m
	Length	h	3.00	m

Table 2
Summary of centrifuge model experiments and numerical simulation.

Test no.	Input acceleration m/s^2	Number of cycles	GWL m	Uplift displacement	
				Centrifuge model tests m	Numerical simulation m
CS1	6.78	30	0	1.100	0.522
CS2	2.05	30	1	0.000	0.051
CS3	4.64	30	1	0.181	0.189
CS4	7.15	30	1	0.952	0.263
CS5	6.91	15	1	0.234	0.206
CS6	6.47	30	1	0.000	0.035

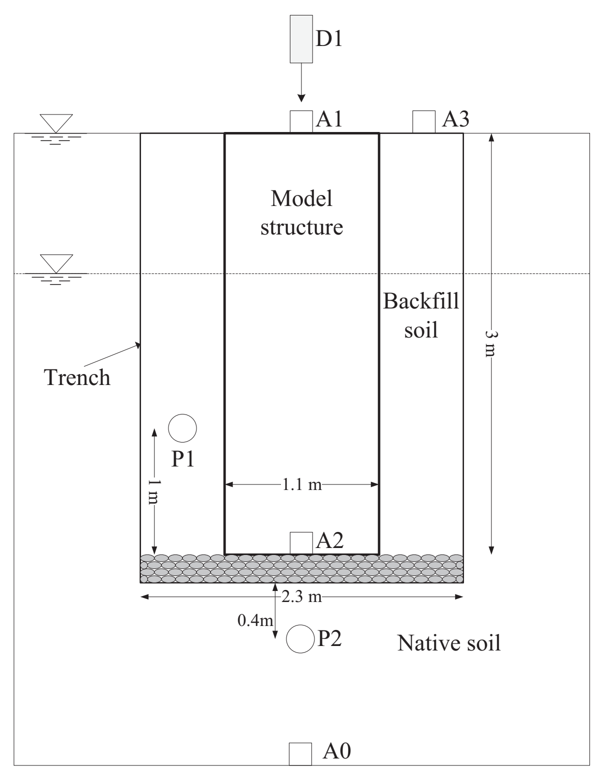

Fig. 2. Schematic of centrifuge model set-up (prototype scale).