17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

EXCESS PORE WATER PRESSURE ACTING ON BURIED PIPES IN LIQUEFIED GROUND AND ITS FACTOR OF SAFETY AGAINST UPLIFT

N. Sento[(1)], Y. Miyazaki[(2)]

[(1)] *Professor, Department of Civil Engineering, College of Engineering, Nihon University, sentou.noriaki@nihon-u.ac.jp*
[(2)] *Engineer, Kinoshita Sustainability Solutions Ltd., yusyalv99@gmail.com*

Abstract

Uplift damage to buried pipes due to liquefaction has been observed after past earthquakes. In practical design, the uplift force acting on buried pipes is regarded as a buoyant force in a slurry with a specific gravity of almost 2. The uplift force should be evaluated considering the hydrostatic pressure and excess pore water pressure distribution acting on the buried pipe; however, only a few attempts have been made to measure the excess pore pressure surrounding the buried pipes.

In this study, the excess pore water pressure acting on buried pipes was measured, and the uplift force and factor of safety against uplift were evaluated by a gravitational shaking table test. The ground was prepared using silica sand with a relative density of 40%. An acrylic resin pipe with a diameter of 100 mm and specific gravity of 0.53 was buried 200 mm beneath the ground surface. The ground was saturated and the water level was set at the ground surface. The excess pore water pressures at the crown, side, and bottom of the pipe were measured using embedded pressure gauges. Sinusoidal waves with a frequency of 2 Hz and 20 s duration were applied with a maximum acceleration of 300 cm/s^2 in Case 1 and 400 cm/s^2 in Case 2. The uplift force (F_B) was evaluated using the excess pore pressures at the crown and bottom of the buried pipe. The factor of safety against uplift (F_U) was evaluated based on the weight of the pipe (F_T), effective overburden load (F_{WS}), and shear forces acting at both sides of the soil block above the pipe (F_{SP}).

The following conclusions were drawn from this study: (1) the maximum effective pore water pressure ratio was almost zero at the crown and almost 1 at the bottom of the pipe, (2) the F_B evaluated using the test results was almost twice the F_B estimated by the practical method, and (3) the buried pipe moved upward when the F_U was below 1. The minimum F_U during shaking was approximately thrice the F_U estimated by the practical method.

Keywords: Liquefaction, Buried pipe, Excess pore water pressure, Uplift, Factor of safety

1. Introduction

Uplift damage to buried pipes in a soft ground such as reclaimed ground due to liquefaction has been observed after past earthquakes.

In practical design, the uplift force acting on buried pipes is regarded as a buoyant force in a slurry with a specific gravity of almost 2 [1]. An uplift force should be evaluated considering the hydrostatic pressure and excess pore water pressure distribution acting on the buried pipe; however, only a few attempts have been made to measure the excess pore pressure surrounding the buried pipes [2].

In this study, the excess pore water pressure acting on buried pipes in saturated loose sand was measured to evaluate the uplift force by a gravitational shaking table test. The factor of safety against uplift was proposed and the estimated value was compared with that estimated by the current practical design.

2. Test method

Model ground was prepared in a rigid container with 600 mm width, 600 mm height, and 600 mm depth. A two-dimensional shaking table using actuators consisting of a permanent magnet system was used in this test. Silica sand No.6 with a ρ_s of 2.618 g/cm^3, e_{max} of 0.835, e_{min} of 0.512, and D_{50} of 0.265 mm was used to prepare a loose sand layer. The soil particle size distribution is shown in Fig.1, and a schematic diagram of the model is shown in Fig.2. A loose sand layer with a thickness of 450 mm and relative density of 40% was prepared by the pluviation method. The ground was saturated with CO_2 and de-aired water. The water level was set at the ground surface.

A schematic diagram of the buried pipe is shown in Fig.3. An acrylic resin pipe with an outer diameter of 100 mm, inner diameter of 80 mm, length of 500 mm, and mass of 2.064 kg was buried 200 mm beneath the ground surface. The specific gravity of the pipe was 0.53.

The excess pore water pressure was measured at the center and end of the pipe using pressure gauges embedded at the crown, side, and bottom of the pipe.

The residual ground displacement was measured using 34 colored glass beads embedded in the ground [3]. The uplift displacement was measured at the ends of the pipe using wire displacement transducers. In addition, the excess pore water pressure and acceleration of the ground were measured.

A sinusoidal wave with a frequency of 2 Hz and 20 s duration was applied perpendicular to the pipe axis. The maximum acceleration was 300 cm/s^2 in Case 1 and 400 cm/s^2 in Case 2. In this paper, the result of Case 1 is mainly discussed.

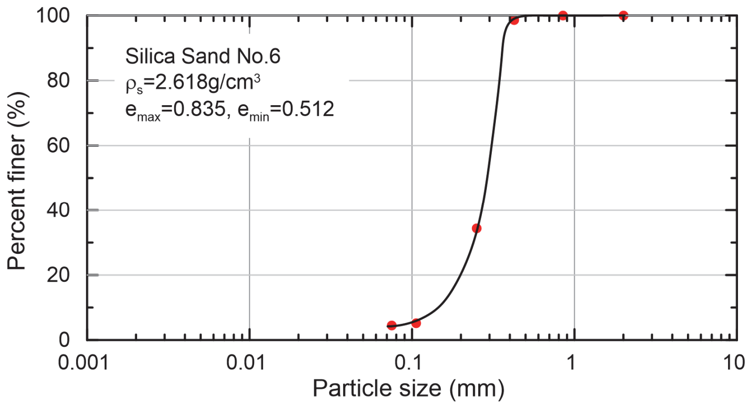

Fig. 1 – Soil particle size distribution

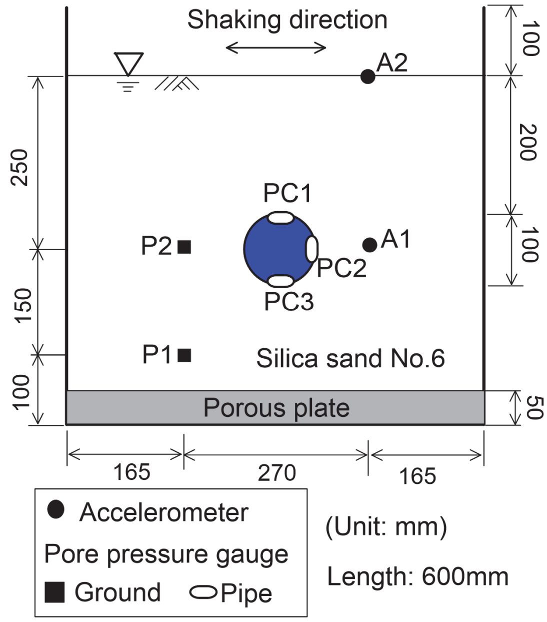

Fig. 2 – Schematic diagram of model

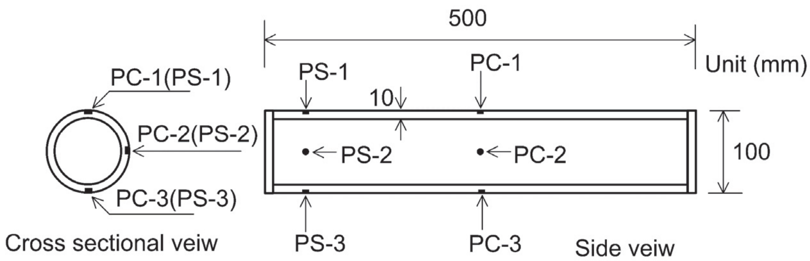

Fig. 3 – Schematic diagram of buried pipe

3. Test results

The time history of excess pore water pressure of the ground is shown in Fig.4. The excess pore water pressure (P2) at the center depth of the pipe reached a level corresponding to an excess pore water pressure ratio (r_u) of 1.0; therefore, the soil liquefied. On the other hand, the r_u fluctuated between 0 and 1 due to dilatancy.

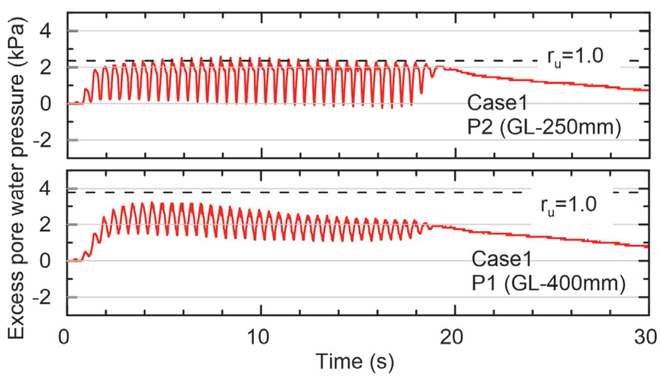

Fig. 4 – Time history of excess pore water pressure of the ground

The excess pore water pressure at the center of the pipe is shown in Fig.5. The excess pore water pressure at the bottom of the pipe (PC3) reached a level corresponding to an r_u of 1.0; therefore, the soil in the vicinity of the pipe liquefied. On the other hand, the excess pore water pressure at the crown (PC1) is approximately zero; therefore, the soil does not liquefy above the pipe and may behave as a solid. The excess pore water pressure at the side of the pipe generates an r_u of up to 0.7, and it fluctuates within wide limits.

The residual displacement of the pipe and ground after the test is shown in Fig.6. The surrounding soil below the pipe moves toward the center of the ground. Since the displacement of ground above the pipe is almost the same as the pipe displacement, a massive soil mass above the pipe moves upward and the pipe is subjected to an effective overburden pressure of this soil mass. The width of this soil mass is probably almost the same as the pipe diameter, as estimated from the displacement vectors of the ground.

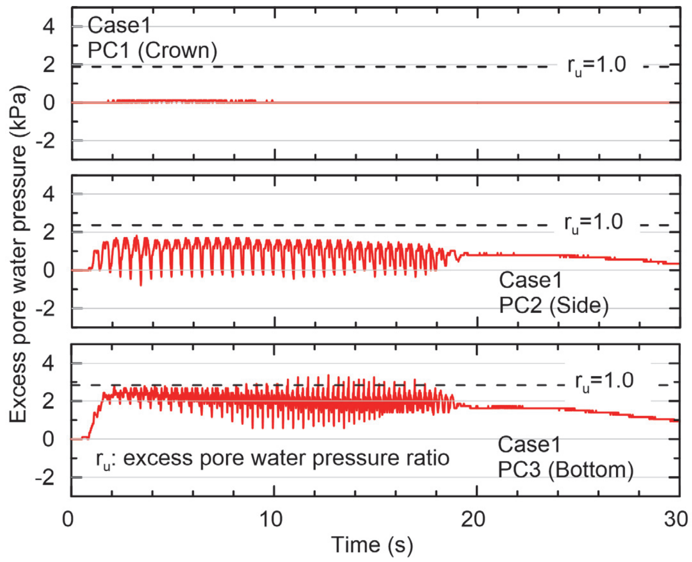

Fig. 5 – Time history of excess pore water pressure on buried pipe

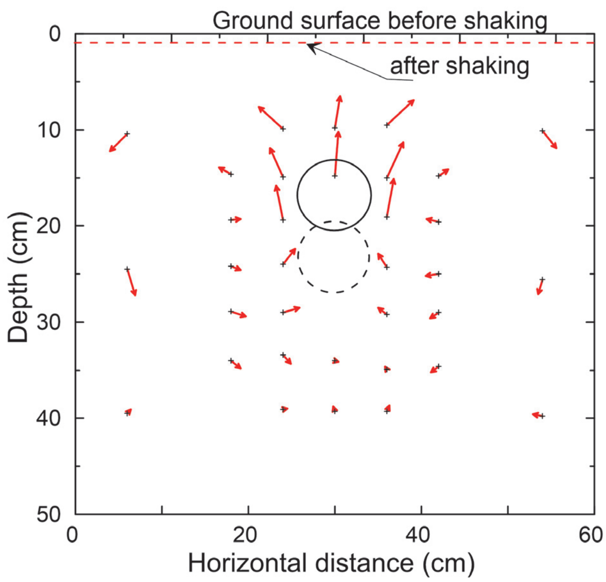

Fig. 6 – Residual displacement of ground and buried pipe after shaking (Case 2)

4. Pipe uplift estimation due to liquefaction

The schematic diagram of the forces acting on the buried pipe considering the above evidence and a previous study [2] is shown in Fig.7. Here, H is the distance from the ground surface to the center of the pipe, and D is the pipe diameter. The upward force is uplift force (F_B), and the downward forces are the weight of the pipe (F_T), effective overburden load (F_{WS}), and shear force acting at both sides of the soil block above the pipe (F_{SP}). These forces per meter of pipe length are presented below.

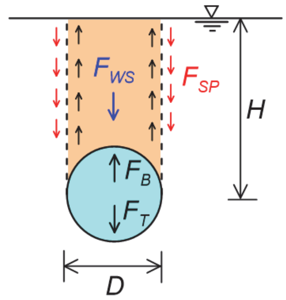

Fig. 7 – Schematic diagram of forces considering the uplifting of buried pipe

The F_B is calculated by Eq. (1) and consists of F_{BS} due to hydrostatic pressure and F_{BE} due to the excess pore pressure acting on the pipe.

$$F_B = F_{BS} + F_{BE} = \frac{\rho_w g \pi D^2}{4} + \frac{(P_3 - P_1)\pi D}{4} \tag{1}$$

where P_1 and P_3 are the excess pore water pressures at the top and bottom of the pipe, respectively. The time history of the F_B considering the experiment date is shown in Fig.8. The F_B evaluated using the test results was almost twice the F_B estimated by the practical method in which liquefied soil is regarded as a slurry with a specific gravity of almost 2. A nearly zero P_1 observed in the test causes this uplift force difference. The F_B also fluctuates due to the excess pore pressure fluctuation caused by dilatancy. The time histories of the F_B and pipe uplift displacement are shown in Fig.9. The pipe uplifts with fluctuation synchronized with the response of the F_B.

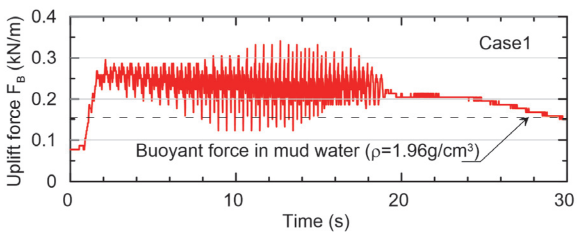

Fig. 8 – Time history of uplift force (F_B)

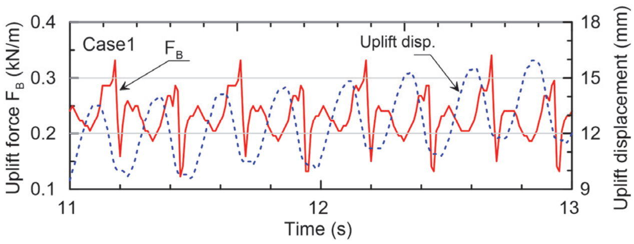

Fig. 9 – Time histories of uplift force and uplift displacement

The downward forces are shown below. The F_T is calculated by Eq. (2).

$$F_T = \frac{\rho_p g \pi D^2}{4} \tag{2}$$

where ρ_p is the density of the pipe. The F_{WS} is calculated by Eq. (3).

$$F_{WS} = \gamma'\left(HD - \frac{\pi D^2}{8}\right) \tag{3}$$

where γ' is the effective unit weight of soil (9.430 kN/m^3) used in this estimation. The F_{SP} is calculated by Eq. (4).

$$F_{SP} = 2\tau_{ave} H(1-r_u) \tag{4}$$

where τ_{ave} is the average shear stress at both sides of the soil mass. H is corrected considering the pipe uplift displacement. The r_u is evaluated using the ground excess pore pressure P2. The τ_{ave} is calculated by Eq. (5).

$$\tau_{ave} = \frac{\gamma' H}{2} K_0 \tan\phi' \tag{5}$$

where K_0 is the coefficient of earth pressure at rest, and ϕ' is the internal friction angle of soil. In this estimation, K_0=0.5 and ϕ'=30° are adopted. The time histories of the forces acting on the pipe are shown in Fig.10. The F_{SP} fluctuates similar to F_B and becomes zero when the soil liquefies.

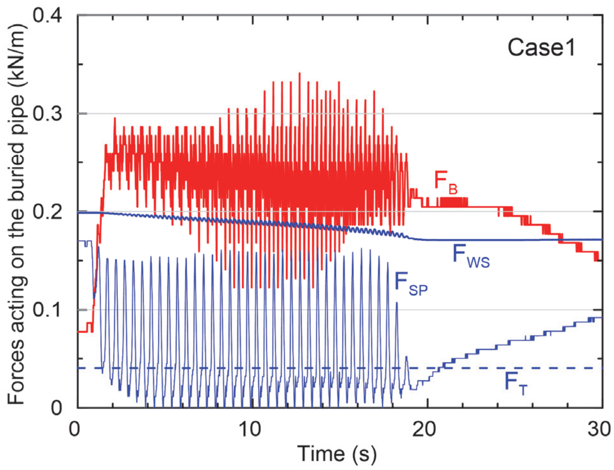

Fig. 10 – Time histories of forces acting on the buried pipe

Finally, the factor of safety against uplift (F_U) was evaluated using the above forces by Eq. (6).

$$F_U = \frac{F_T + F_{WS} + F_{SP}}{F_B} \tag{6}$$

The time histories of the F_U and uplift displacement of the pipe are shown in Fig.11. The pipe started to uplift as the F_U started to decrease below 1. The pipe continued to uplift as long as the F_U was below 1. The minimum F_U during shaking was approximately thrice the F_U estimated by the practical method [1].

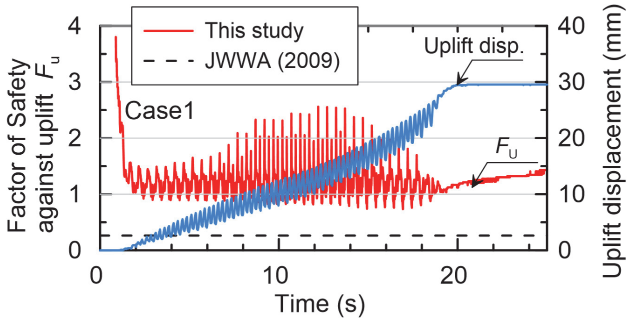

Fig. 11 – Time histories of safety factor against uplift and uplift displacement

5. Conclusions

The following conclusions are drawn from this study.

(1) The maximum effective pore water pressure ratio was almost zero at the crown and almost 1 at the bottom of the pipe.

(2) The F_B evaluated using the excess pore water pressure acting on the pipe was almost twice the F_B estimated by the practical method.

(3) The buried pipe moved upward when the F_U was below 1. The minimum F_U during shaking was approximately thrice the F_U estimated by the practical method.

6. References

[1] Japan Water Works Association (2009): Design codes of aseismic method for water work facilities and its interpretation, Part I General remarks, pp.78. (in Japanese)

[2] Chian SC, Madabhushi SPG (2012): Excess pore pressures around underground structures following earthquake induced liquefaction, *International Journal of Geotechnical Earthquake Engineering*, **3**(2), pp.25–41.

[3] Sento N, Saito K, Hirayama T (2018): Shaking model tests focused on the mechanism of the pipe uplift buried in the liquefied ground, *Division C: Geotechnics, Journal of JSCE,* **74**(3), pp.332–341. (in Japanese)

