PULL-UP RESISTANCE OF BURIED PIPES OF DIFFERENT CROSS SECTIONS

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Rigidly connected pipelines near a structure are typically broken due to deformation of the ground associated with post-liquefaction settlements after large earthquakes. For simplicity, model-scale pipe pulling-up, instead of pulling-down, tests are conducted to investigate the resistance associated with ground deformation in dry, unsaturated and saturated condition, with different buried depth. Also different cross sections of the model pipes of either round or angular shapes are investigated. For the angular pipe, aluminum bars with angular shape are attached on round pipe crown, i.e., angular roof, aiming at a possible mitigation measure. Pull-up resistance and ground deformation are compared through measured resistance-displacement curves and image analyses by PIV (Particle Image Velocimetry) technique. Equation of the maximum uplift resistance proposed by Trautmann (1985) is validated for shallowly buried pipes in dry sand. For deeply buried pipes in dry and unsaturated sand, inclined slip surface is observed by the image analysis. Then a new equation of the maximum uplift resistance is proposed, which takes into account the inclined slip surface. With the angular roof attached at the crown of the round pipe, pulling-up resistance was reduced about 20%.

Key Words : *uried pipe; Uplift resistance; Image analysis, Uplift mechanisms*

1. INTRODUCTION

Pipelines are usually buried in sandy soil in shallow depth by a trenching method. Consequently, it always leads to a loose condition in backfill which is liquefiable during large eathquakes. Given a small vibration to the pipelines, liquefaction might occur in backfill due to the reduction of the soil effective stress, which is manifest as reduction of uplift resistance. Ground deformation where underground structures are buried arising from seismic liquefaction can be significantly large due to the high compressibility of a matrix of saturated loose sands. This sort of vulnerability is generally resulted from uplift damage of the underground structures as the sand liquefies and the following settlements with the pore water pressure dissipation. Dynamic centrifuge model tests are regarded as an excellent way to give good predictions on the study of dynamic loading on soil-pipe interaction. A series of centrifuge model tests had been conducted in order to figure out the uplift behavior of pipe sections during liquefaction (Hoe et al 2003). A significant uplift behavior was reported in liquefiable sand layer compared with those in non-liquefiable layers. Thus, in the response of intense shaking induced by a major earthquake, uplift damage is known as the typical damage pattern to pipelines related to liquefaction, whereas break off is considered as the typical damage pattern to pipe-structure joint portion in post-liquefaction settlements.

In major earthquakes, damage patterns such as extractions and break offs, were occurred at the rigidly connected joint of pipe ends and the structures (Hamada et al. 1996). As for the damage to the urban pipelines which are rigidly connected to structures, forces due to settlement would result in a large bending moment at the pipe ends. As a result, citizens suffered from the water supply cut-off. Therefore, to have a more clear understanding of pipeline and soil interaction in liquefiable soil during the post-liquefaction process has become a pressing issue.

In general, if the downward forces could be reduced, the damage could be mitigated. However, to reproduce reconsolidation test in 1g field is difficult, therefore conversely, pulling-up test of buried pipes in loose sand is conducted to investigate the uplift resistance and associated ground deformation. Trautmann et al. (1985) summarized the conventional simplified evaluation of uplift resistance in dry sand under plane strain conditions for buried pipe by introducing a vertical slip surface theory, in which, sand failure is assumed to take place along vertical surfaces extending from the edges of the two sides to the ground surface, therefore the maximum uplift resistance $F_{u\_\max}$ is given by,

$$F_{u\_\max} = \gamma\left[HD - \frac{\pi D^2}{8} + KH^2 \tan\varphi_{ps}\right] \tag{1}$$

in which, γ is the soil unit weight, H the depth to pipe center line, D the pipe diameter, φ_{ps} the friction angle of soil in plane strain, and K the coefficient of lateral earth pressure. In Eq. (1), the resistance consists of overlying soil weight and friction along two slip surfaces, soil weight is computed by eliminating the upper half of the pipe from the rectangular formed by H and D, while friction resistance is mainly depends on K value, which is a complex function of many factors, and usually determined by laboratory test results. Cheuk et al. (2008) investigated the uplift deformation mechanisms mainly based on the effect of particle size and soil density, they found 4 different stages can be distinguished through the whole uplift process by image analysis. Tobita et al. (2011) stated that the primary cause of uplift is the reduction of the effective confining stress around the bottom of an underground structure, this would trigger the flow of liquefied soil toward to the bottom caused by the anisotropic stress state, and then the uplift movement is initiated. Besides the excess pore water pressure, it is also suggested that the shear deformation of the ground around a trench might also be a major cause of uplift. Byren et al. (2012) carried out the uplift resistance tests for saturated sand with a particular focus on the effect of uplift rate. Their test results indicated a faster uplift rate have a great influence on the initial uplift resistance owing to positive excess pore water pressures generated around pipe. The magnitude of these pressures was sufficient enough to cause initial liquefaction of the backfill.

2. PULLING-UP TEST OF A BURIED PIPE

(1) Model steup

In total, sixteen casesof pulling-up tests were carried out in this study (**Table 1**). In the tests, varied parameters are the saturation degree (*Sr*: approximately equals to 0, 30%, 60%, 100%), buried depth (embedment ratio expressed as H/D equals 1 and 2). In Table 1, the capital letter R stands for the round pipe while A the angular pipe. Numbers prior to the underline stand for saturation degree and numbers following the underline represent the burial ratio H/D.

Pulling-up tests were carried out by using the equipment shown in **Fig. 1**. The electrical jack actuator (GSGLUK.RS44319) was placed on the 310 mm x 160 mm x 200 mm transparent sand box. It allowed a model pipe to be pulled upwards at a consistent rate.

The model ground was constructed with silica sand No.7 by the air-pluviation method to ensure a uniform density by dropping the sand from calibrated height (71cm) and bore diameter (2mm) of a plastic container. By this, relative density of about 40% (varied from 38% to 42%) was obtained. The densities were 13.0 kN/m^3,14.3 kN/m^3, 15.6 kN/m^3 and 18.0 kN/m^3 , respectively, for dry (Sr=0%), unsaturated (30%), unsaturated (60%), and saturated sand (100%). Colored sand with the same grain size is sprinkled in the model construction process to create a laminated sand layers which provide better contrast and clearer views of sand deformation near the pipe. Saturated model ground is constructed by injecting the de-aired water into dry ground models. Vacuum replacement method is used for measuring saturation degree.

Pipe models (**Fig. 2**) were made from stainless steel (SUS304) (Longitudinal length = 100mm, external diameter = 50mm, inner diameter = 46mm, thickness of pipe=2mm) with 2 steel woven wires attached on the crown to transmit the pulling-up force from the jack. By attaching polyester sheets, low-friction ends of the model pipe were realized to minimize the friction between the pipe ends and side walls of the box. The condition ensured the plane strain condition in which sand movement observed at the transparent side wall of sand box was identical to the other sections. The friction exerted between the pipe ends and the wall of the box was measured by pulling-up the pipe alone without sand deposits, and it, approximately 3N, is subtracted from the test results.

To see the effect of varied cross sections, an angular aluminum bar (63S) (Length = 40mm, thickness = 2mm) is attached on pipe crown (**Fig. 2**). It was fabricated by injecting silicon bond in the void to glue them tightly. The effect of angular pipe is considered as a possible mitigation measure against liquefaction.

It has to be mentioned that, in what follows, weight of pipe is excluded from the plotted resistance force. The weight due to the angular bar is offset by adding the same fraction of weight of the angular bar to the round pipe.

Table 1 Test cases

Sr (%)	0		30		60		100	
H/D	1	2	1	2	1	2	1	2
R	R0_1	R0_2	R30_1	R30_2	R60_1	R60_2	R100_1	R100_2
A	A0_1	R0_2	A30_1	A30_2	A60_1	A60_2	A100_1	A100_2

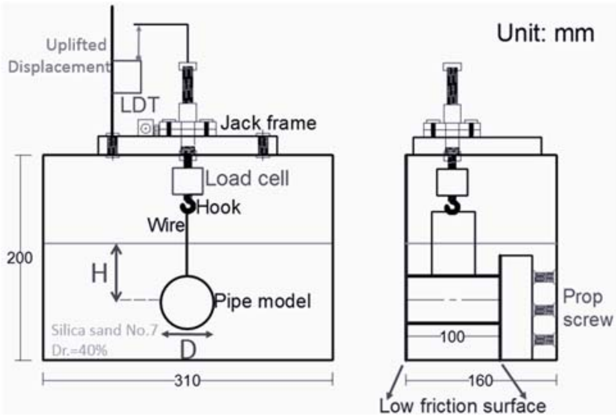


Figure 1 Test equipment

Measurements of the tests consist of two components, force and displacement. Uplift forces were measured with a load cell connected with a transfer metal plate which provided two steel woven wires to suspend the model pipe. By a predetermined uplift distance of 35 mm for all the test cases, 700 s was needed for the whole uplift process. The pull up speed was controlled by the loading system by setting a consistent uplift rate of 0.05mm/s with the controlling voltage of 5V with MotCtrl software (Ver.3.0). A laser displacement transducer (LDT) (IL-100, KEYENCE) was attached to measure the uplifted displacement of the pipe. The precision of load cell and LDT is 0.01N and 0.01mm, respectively. The data acquisition system is a dynamic strain logger (DC-104R, TML) with sampling frequency 1.0 Hz. In addition to these measurements, the whole process is recorded by a 12.0 mega pixel high-resolution camera (HDR-CX520V, SONY Corporation) for image analyses.

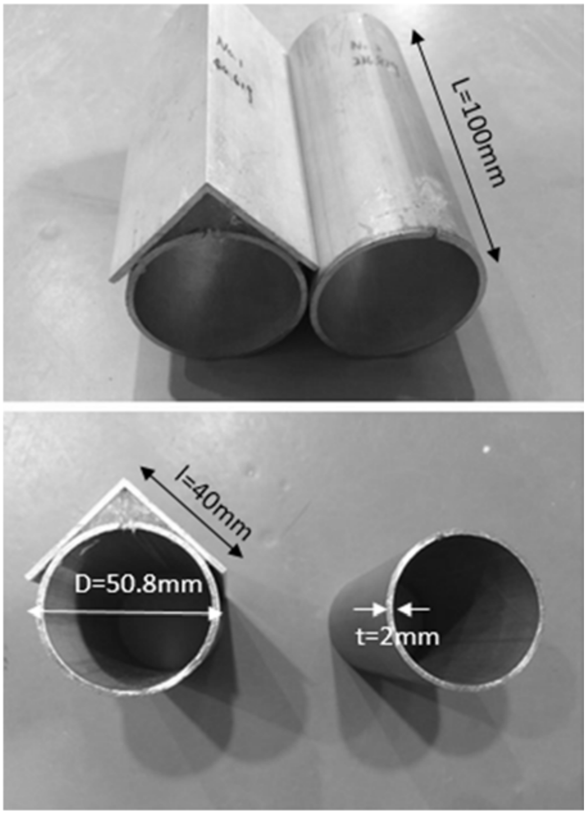


Figure 2 Round (right) and angular (left) pipe models

(2) Test results

The pulling-up process in terms of recorded images of Case R0_1 and Case A0_1 are, respectively, shown in **Fig. 3** and **Fig. 4**. As shown in **Fig. 3** and **4**, when the up-lift is small, i.e. 5mm or less, the affected area of the Case A0_1 (**Fig. 4**) seems to be smaller compared the one shown in **Fig. 3** at displacement of 5 mm. At 10 to 15 mm of the uplift displacement, sand located on the pipes flows into the void formed at the bottom of the pipe. However, as shown in **Fig. 4** at 10 to 15 mm, the amount of flow may be smaller due to the skirt of the angular bar. In larger uplift displacement, both show a similar deformation pattern.

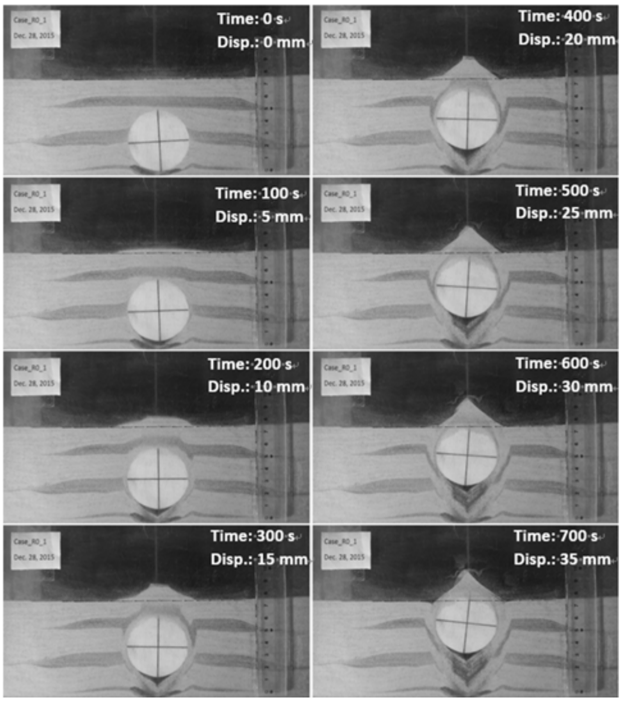


Figure 3 Pulling-up sequence of Case R0_1

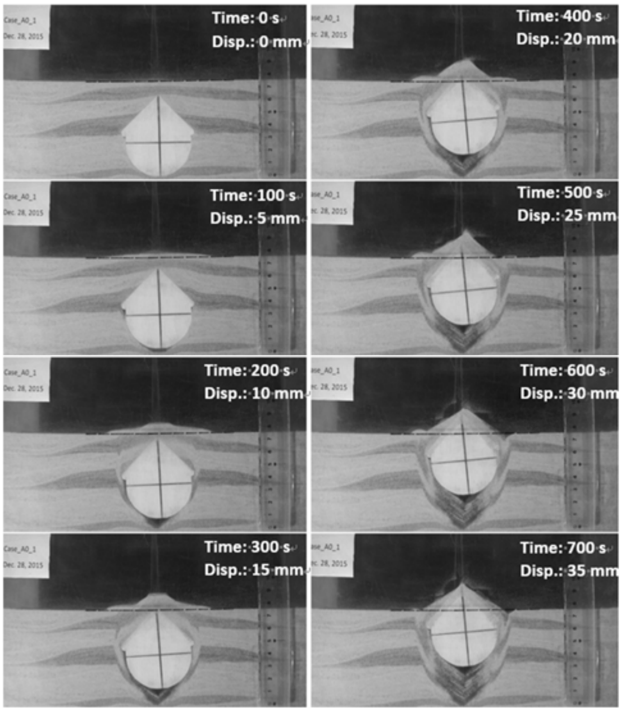


Figure 4 Pulling-up sequence of Case A0_1

Resistance-displacement curves of Case R0_1/2 and Case A0_1/2 are compared in **Fig. 5**. For Case A0_1, the peak uplift resistance of 3.3 N occurs when uplift displacement is 2.1 mm, whereas for round pipe (Case R0_1), the peak is 4.3 N at 2.5 mm. The peak resistance of angular pipe is smaller than that of the round pipe. The uplift resistances of both cases decrease rapidly after the peak. For the deeply buried cases, a peak resistance is 10.6 N for Case A0_2 at 12.5mm, which is smaller than that of 12.3 N of the Case R0_2 at about 14.0mm. This is similar to Case R0_1 and A0_1. Thus, for the dry sand case, it is shown that angular pipe can lower the pulling-up resistance about 14 to 21%, which in turn shows the exerted load due to settlements may be smaller in the angular pipe. However, high resistance level even after the peak is kept in the case of H/D=2 due to larger overburden stress. Further discussion with image analyses is presented in next section.

As for the saturated and unsaturated cases, although the uplift mechanisms are quite different from that in dry sand cases, angular pipe always leads to smaller uplift resistance.

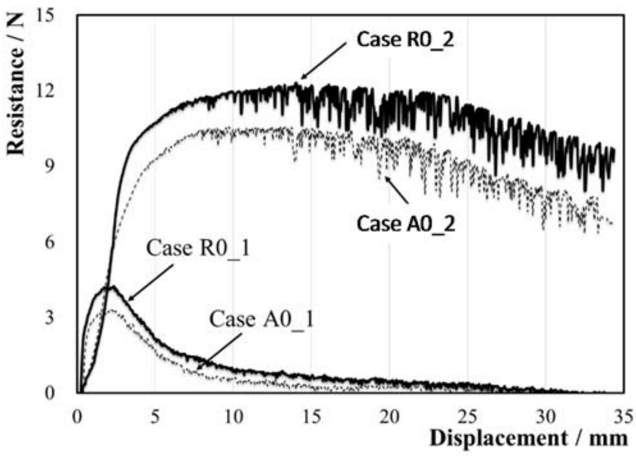


Figure 5 Measured pulling-up resistance in dry sand

3 MAXIMUM PULLING-UP RESISTANCE

In this study, the whole uplift process (700 seconds) was recorded with a video camera with a bit rate of 256 kbps, then 70 discrete images are exacted from the original recording for image analyses, namely the interval of the analyses is 10 seconds. The size of images is 1920 x 1080 pixels with resolution of 96 dpi in both horizontal and vertical directions. Those images are used for the PIV analyses.

As shown in **Fig. 6**, Eq. (1) predicts the maximum resistance for Case R0_1 quite well. However, it under estimates the deppely buried case, Case R0_2 (**Fig. 7**). Since Eq. (1) is derived by assuming the vertical slip surface of a round pipe in dry condition (**Fig. 8(a)**), it is reasonable to have good agreements. Howevr, there is a limitation if the slip surface is not vertical such as the case of a deeply buried pipe which may exhibit slip surfaces with an inclination (**Fig. 7**).

In order to overcome the inapplicability of the vertical slip surface theory for deeply buried case (Case R0_2) in dry sand condition, an inclined slip surface is incorporated to derive the new equation is given by Eq. (2).

$$F_{u\_max} = \gamma \begin{bmatrix} HD - \dfrac{\pi D^2}{8} + H^2 \tan\theta + \\ H^2 \left(1 + \tan^2\theta\right)\left(K \cos\theta + \sin\theta\right) \tan\varphi_{ps} \end{bmatrix} \quad (2)$$

Eq. (2) consists of two components, the first component represents the trapezoidal wedge instead of rectangular sand block implemented in Eq. (1) without a semicircular area occupied by pipe's cross section. The second component is the friction resistance induced along the assumed inclined surfaces.

As shown in **Fig. 9**, Eq. (2) predicts the maximum pulling-up resistance 12.2 N at the observed inclination angle of θ=8.8° in the Case R0_2. Contrary, with the measured resistance of 12.3 N, the inclined angle is back calculated as θ=9.1°. From **Fig. 9**, at θ=0°, which is the case of the vertical surface, the resistance is underestimated as 8.98 N. In **Fig. 9**, wight of wedge and friction force are separately shown as dotted lines.

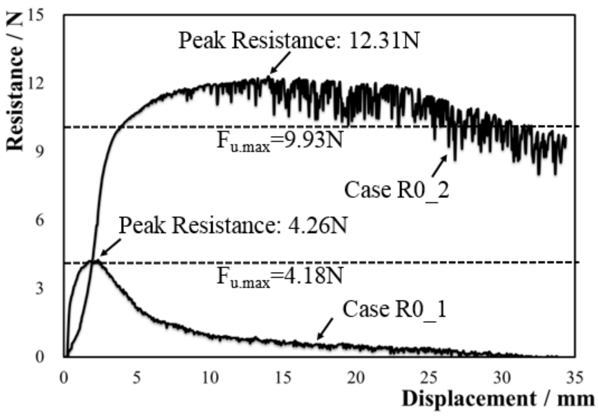


Figure 6 Measured pulling-up resistance for Case R0_1 and Case R0_2 and predicted pipe uplift resistance with Eq. (1).

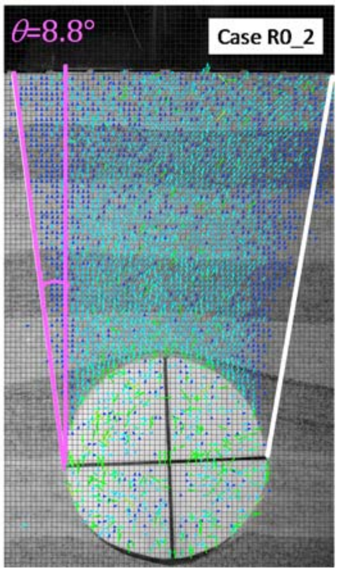
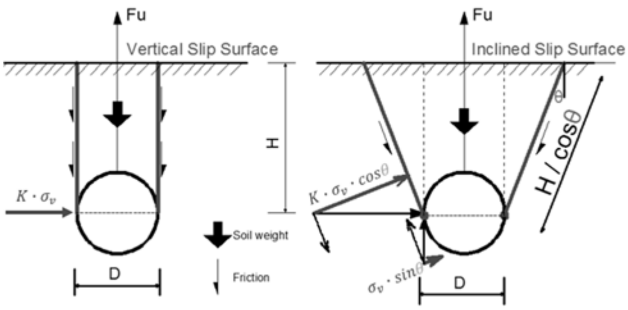


Figure 7 Deformation of the ground and inclined slip surface of Case R0_2. Vectors indicate velocity of sands associated with the pulling-up of pipe.



(a) (b)

Figure 8 Schematics of vertical and inclined slip surfaces.

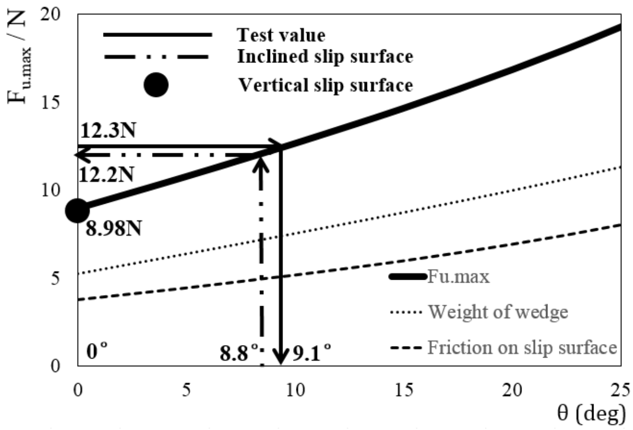


Figure 9 Variation of F_{u_max} with inclined angle (Case R0_2)

4. CONCLUSIONS

To investigate the uplift resistance and associated ground deformation of buried pipes, pulling-up test of model pipes are conducted under 1G subjected to different buried depth, saturation degree, and different cross sectional shape of a model pile. In this study, a part of pipe ends rigidly connected to a certain structure is regarded as the research target. Pulling-up resistance and displacements were measured in a series of the tests. The image analysis with the PIV is also utilized to visulally observe the deformation patterns.

Equation to estimate the maximum pulling-up resistance force of a round pipe by Trautmann (1985) was validated for shallowly buried pipe in dry sand. However, for deeply buried pipes in dry and unsaturated sand, inclined slip surface was observed by the image analysis and a new equation is proposed.

With the angular roof attached at the crown of the round pipe, pulling-up resistance was reduced about 20%.

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(Received September 2, 2016)