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Numerical Analysis of Peak Uplift Resistance for Pipelines Buried In Sand

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Abstract

A pipeline is one of the most important structures for the transportation of fluids such as oil, natural gas, and wastewater. The uplift behavior of pipelines caused by earthquakes and buoyancy is one of the reasons for the failure of pipelines. The objective of this study is to examine the peak uplift resistance using parametric studies with numerical modeling of PLAXIS 3D Tunnel. The effects of burial depth and pipe diameter on the uplift resistance of loose and dense sand were first examined. Subsequently, the effects of the length of geogrid layers and the number of geogrid layers were examined to prevent uplift behavior.

Keywords: Buried pipelines, Uplift resistance, Burial depth, Geogrid, Numerical modeling, Finite element method

1. Introduction

Marine pipelines are important subsea structures for transporting fluids such as crude oil, natural gas, and wastewater. These pipelines exhibit uplift behavior owing to natural phenomena such as buoyancy, earthquakes, and self-weight and such behavior is the main cause of pipeline failure. The major domestic and overseas studies on the uplift resistance of buried pipes are as follows. An overseas study reported that anchor-type structures (used for foundation construction involving uplift forces in ground structures) and pipes exhibit similar uplift behavior (Edward A. Dickin, 1994). The pipe burial depth and pipe diameter according to the geogrid reinforcement and the peak uplift resistance (PUR) of the pipelines buried in sand according to the geogrid length and layers were calculated using an indoor model experiment and numerical modeling (Danial Jahed Armaghani, 2015). In South Korea, an indoor model experiment was performed to assess the uplift behavior of pipe anchors buried in sand according to their burial depths and anchor diameters (Bang S.T., 2003). An indoor model experiment and numerical modeling were performed to assess PUR in clay according to the burial depth, water content, plate diameter, and uplift speed (Yoo D.M., 2013). The effects of the uplift speed, location of the front wall of the soil tank, width of the geogrid sample, and presence of passive resistance members on the soil and geogrid friction characteristics were assessed for weathered granite soil (Jo S.D., 1996).

In this study, the PUR of the pipes buried in loose and dense sand was calculated according to the burial depth, pipe diameter (D), geogrid length and layers, and presence of hydraulic pressure at constant height.

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Table 1 Properties of the material

Parameter	Unit	Loose sand	Dense sand	Pipe	Geogrid
Unit weight $[\gamma]$	kN/m^3	15	17	1	1
Friction angle $[\varphi]$	Degree	32	40	-	-
Cohesion $[c]$	kN/m^2	1	1	-	-
Poisson ratio $[v]$	-	0.3	0.3	0.2	0.3
Tensile strength $[T]$	kN/m	-	-	-	60
Modulus of elasticity $[E]$	kN/m^2	20,000	35,000	2.6E7	-
Apparent opening size	mm^2	-	-	-	21

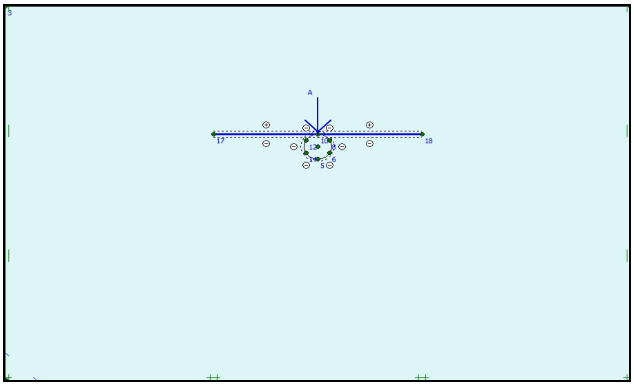

Fig 1 Modeling pipeline and geogrid in PLAXIS 3D Tunnel

PLAXIS 3D Tunnel (reference manual), which is a three-dimensional finite element analysis software program, was used for the analysis. In general, this software program is widely used for the deformation analysis of the ground around the entrance of the tunnel. In this study, a pipe without tunnel lining and with small unit weight was simulated. The geogrid was simulated as a plate element for the numerical modeling.

2. Numerical Modeling Conditions

2.1 Hydraulic Pressure Condition Inactivation

The model used for the numerical modeling had a width of 600 mm, height of 400 mm, and depth of 200 mm. The pipes were 150 mm long with three diameters: 26, 36, and 46 mm. The geogrid was 200 mm wide with three lengths: 200, 300, and 400 mm. The geogrid was used in a single layer or two layers. When it was used in two layers, the gap was 50 mm. The boundary conditions were $U_x = U_y = 0$ in the horizontal direction and $U\_x = 0$ in the vertical direction. The Mohr-Coulomb constitutive equation was used to analyze the behavior of loose and dense sand. The study by Hamed Niroumand (2012) was consulted for the physical properties of soil, and the study by Danial Jahed Armaghani (2015) was consulted for the physical properties of the pipe and geogrid. Based on the study by Babu (2009), the geogrid was replaced with a plate type material. The parameters used in this numerical modeling are listed in Table 1. The pipe was designed by tunnel section without lining in PLAXIS 3D TUNNEL., and a concentrated load was applied on top of the pipe to achieve maximum load (Fig. 1). The mesh was generated using a medium mesh as a whole, and dense grids were added to the pipe and geogrid. The earth pressure coefficient (K) was $K_0 = 1 - \sin\varphi$, *Where* φ represents the internal friction angle of the soil. As the earth displacement value according to the self-weight must be calculated first in the initial stress setting after mesh generation, the physical properties of the soil were applied to the tunnel section and the geogrid was set to an inactive state. The calculation was performed in two steps except for the initial stress. In the first step, the geogrid was implemented in slices 1 and 3, and both the geogrid and pipe were implemented in slice 2. In the second step, the concentrated load was implemented.

2.2 Hydraulic Pressure Condition Activation

Conditions such as the structure size and pipe diameter were the same, but different water pressure depths were employed according to the burial depth. The water pressure depth was 3H.

3. Numerical Modeling Results

The PUR of the pipes buried in loose and dense sand was calculated while the influence factors, such as the pipe diameter, burial depth, layers and length of geogrids, and presence of hydraulic pressure, were varied. Forty-two calculations were performed for loose and dense sand separately in the absence of hydraulic pressure and 24 calculations were performed for loose and dense sand separately in the present of hydraulic pressure. Therefore, a total of 132 calculations were performed.

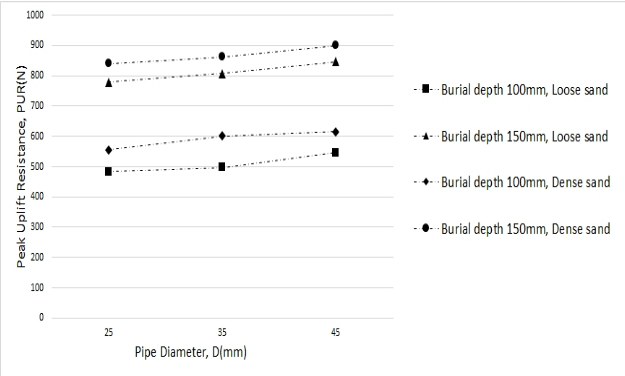

Fig 2 Effect of pipe diameter and burial depth in loose and dense sand with no hydraulic pressure

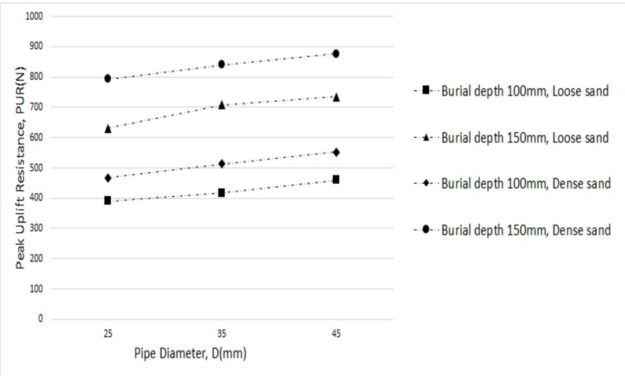

Fig 3 Effect of pipe diameter and burial depth in loose and dense sand with hydraulic pressure

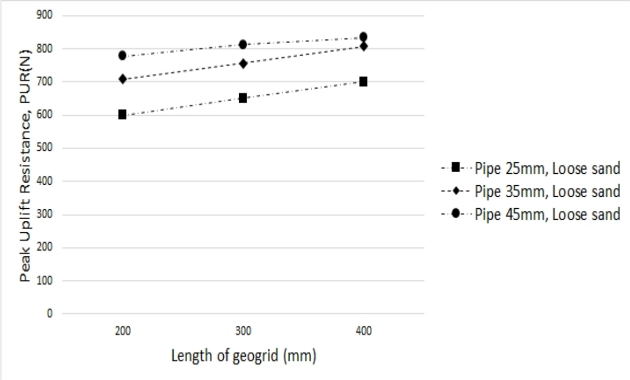

Fig 4 Effect of geogrid length in loose sand with no hydraulic pressure

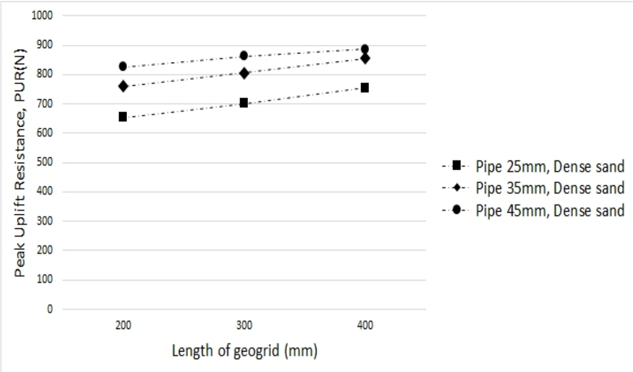

Fig 5 Effect of geogrid length in dense sand with no hydraulic pressure

3.1 Peak Uplift Resistance According to the Pipe Diameter and Depth

Fig. 2 shows the PUR of a pipe buried in loose and dense sand without hydraulic pressure according to the pipe diameter and burial depth. Fig. 3 shows the PUR of a pipe buried in loose and dense sand with hydraulic pressure according to the pipe diameter and burial depth. In the absence of hydraulic pressure, the PUR according to the burial depth was approximately 10 times higher than that according to the pipe diameter. The pipe buried in loose sand exhibited approximately 20% lower PUR than the pipe buried in dense sand. The uplift resistance was approximately 100–110 N lower in the presence of hydraulic pressure than in the absence of hydraulic pressure.

3.2 Peak Uplift Resistance According to the Geogrid Length

Figs. 4 and 5 show the PUR of a pipe buried at a depth of 100 mm in loose and dense sand without hydraulic pressure according to the geogrid length. Figs. 6 and 7 show the PUR of a pipe buried at a depth of 100 mm in loose and dense sand with hydraulic pressure according to the geogrid length. The uplift resistance according to the geogrid length tended to increase by approximately 50 N in the absence of hydraulic pressure and by approximately 25–32 N in the presence of hydraulic pressure.

3.3 Peak Uplift Resistance According to the Presence of the Geogrid

Fig. 8 shows the PUR of a pipe buried at a depth of 100 mm in loose and dense sand without hydraulic pressure according to the presence of a single-layer geogrid, and Fig. 9 shows the PUR of a pipe buried at a depth of 100 mm in loose and dense sand with hydraulic pressure according to the presence of a single-layer geogrid. Fig. 10 shows the PUR of a pipe buried at a depth of 100 mm in loose and dense sand without hydraulic pressure according to the presence of a double-layer geogrid, and Fig. 11 shows the PUR of a pipe buried at a depth of 100 mm in loose and dense sand with hydraulic pressure according to the presence of a double-layer geogrid. In the absence of hydraulic pressure, the uplift resistance after reinforcement was approximately 1.3 times higher than that before reinforcement. The uplift resistance with double-layer reinforcement was approximately 1.5 times higher than that with single-layer reinforcement. In the presence of hydraulic pressure, the uplift resistance increased by approximately 100 N with single-layer reinforcement and by 200 N with double-layer reinforcement. Fig. 12 shows the deformed mesh of double-layer geogrid in loose sand.

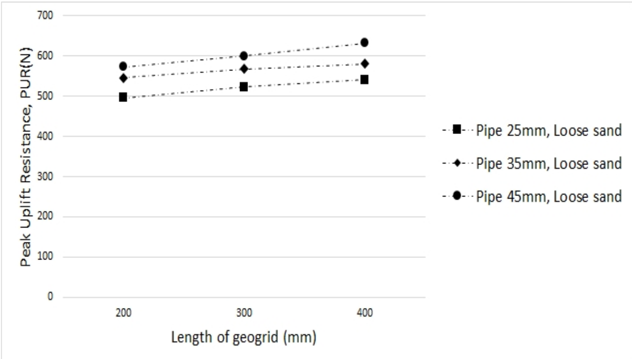

Fig 6 Effect of geogrid length in loose sand with hydraulic pressure

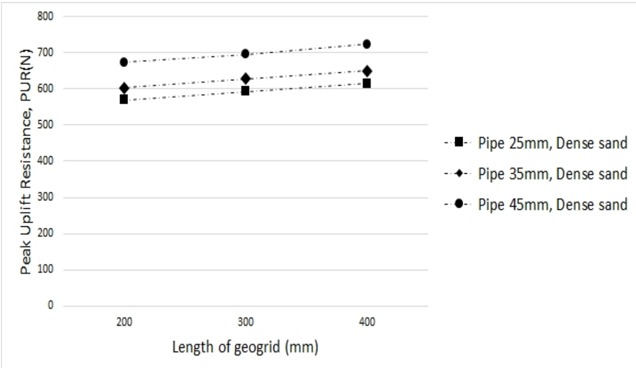

Fig 7 Effect of geogrid length in dense sand with hydraulic pressure

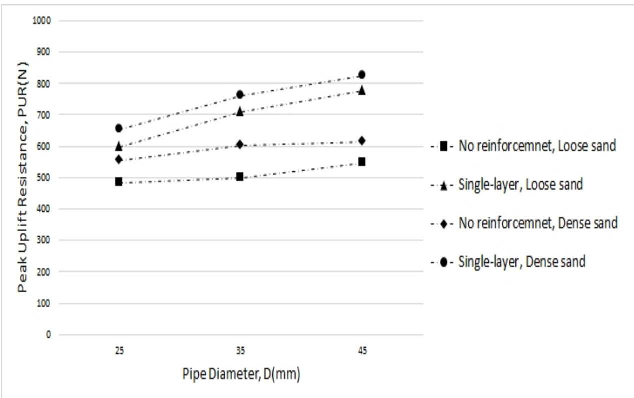

Fig 8 Effect of single-layer geogrid in loose and dense sand with no hydraulic pressure

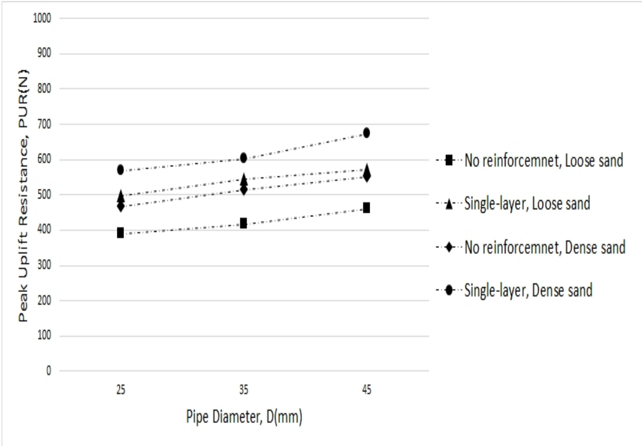

Fig 9 Effect of single-layer geogrid in loose and dense sand with hydraulic pressure

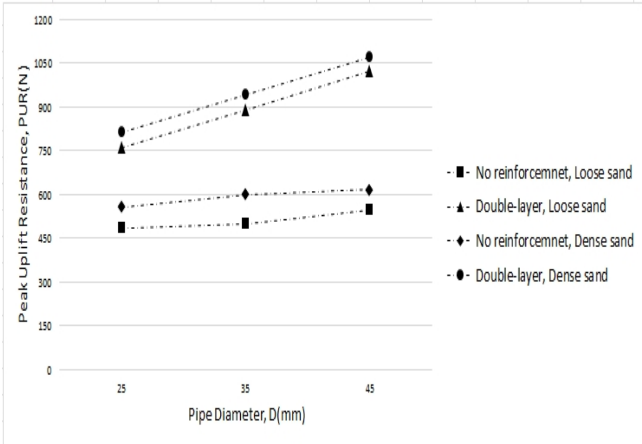

Fig 10 Effect of double-layer geogrid in loose and dense sand with no hydraulic pressure

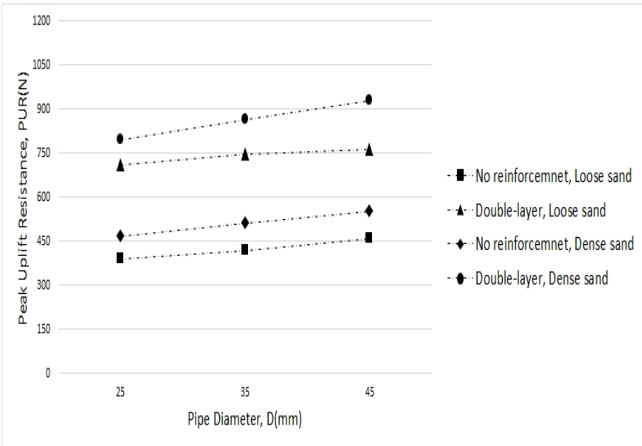

Fig 11 Effect of double-layer geogrid in loose and dense sand with hydraulic pressure

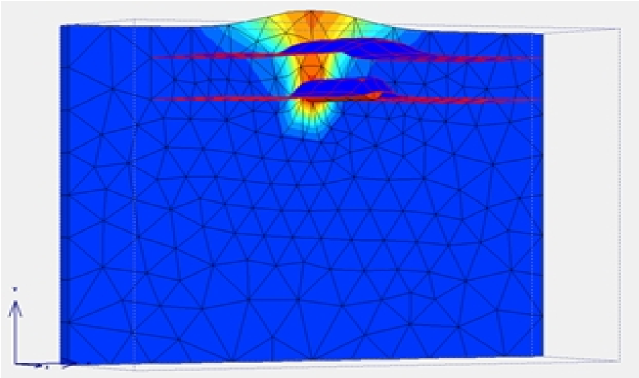

Fig 12 Deformed mesh of double-layer geogrid in loose sand

5. Conclusion

In this paper, the PUR of the pipes buried in loose and dense sand was calculated while the influence factors, such as the pipe diameter, burial depth, quantity and length of geogrids, and presence of hydraulic pressure, were varied. The following are the conclusions drawn.

(1) As the pipe diameter increased, the PUR increased regardless of the presence of hydraulic pressure, but the rate of increase was lower than that according to the burial depth. The PUR also increased as the geogrid for ground reinforcement became longer regardless of the presence of hydraulic pressure, but the rate of increase was lower than that according to the increase in the number of geogrids.

(2) The uplift resistances consistently increased regardless of the presence of hydraulic pressure, but the PUR in the absence of hydraulic pressure was approximately 100 N higher than that in the presence of hydraulic pressure for all the analysis conditions. This study calculated the uplift resistance of the pipes buried in sand using only numerical modeling prior to an indoor model experiment. It is necessary to perform an indoor model experiment in the future and compare its results with the results of this study.

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