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TEST STUDY ON ULTIMATE SOIL BEARING CAPACITY OF BURIED PIPELINE-SAND LATERAL INTERACTION

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Abstract

In order to predict the response and safety of the buried pipeline, equivalent soil spring was employed by many scholars. The key to obtain equivalent soil spring coefficient is to calculate ultimate soil bearing capacity of soil-pipe interaction. Many standards adopt bearing capacity coefficient to characterize the ultimate bearing capacity of the soil, which is depended on the internal friction angle of soil (φ) and the embedment depth/diameter ratios (*H/D*), but the embedment depth/diameter ratios in these standards are relatively small (about 10.0 or less), thus, the results from these standards will not be reasonable when the embedment depth/diameter ratios is larger than 10.0. So, there are some deficiency in these standards because the embedded depth of buried pipeline has been great larger than ever. In the view of the deficiency of acquiring bearing capacity coefficient, following the works of Trautmann and O'Rourke(1985), some studies have been done with ABAQUS software package to simulate the pipe-sand interaction by the authors, and a formula for calculating the soil bearing capacity coefficient was proposed, considering the effect of internal friction angle(φ), the embedment depth/diameter ratios (*H/D*) and diameter (*D*). In order to verify the reasonability of our previous simulation works, a series of model tests had been carried out. In this paper, these test works are presented and the influence factors are studied. Finally, some discipline are discovered, such as (1) The failure mode in deep embedded is different to that in shallow embedded; (2) The values in different test are different because of the difference in test conditions; (3) N_h will increase and then decrease with the increasing in *H/D*, the proposed formula in our previous work cannot simulate the test result very well when *H/D* is larger than 15.0, thus, a further research to study the ultimate soil bearing capacity of buried pipeline-sand interaction is needed.

Keywords: Equivalent soil spring; Bearing capacity coefficient; Model test; Pipeline-sand interaction

1. Introduction

Buried pipelines will be damaged when they subjected to some ground failures such as surface faulting, liquefaction induced soil movement, and landslide induced permanent ground deformation (PGD). In order to predict the response and safety of the buried pipeline, equivalent soil spring has been employed by many scholars (eg. Kennedy et al.[1], 1977; Wang and Yeh[2], 1985; Guo and Feng[3], 1999; Liang[4], 1995; Takada[5], 1998; Takada et al[6], 2001; Radan and Takada[7], 2003) in many analysis methods, including analytical methods and numerical methods. The key to obtain equivalent soil spring coefficient is to calculate ultimate soil bearing capacity of soil-pipe interaction. Some standards (American Lifelines Alliance(ALA)[8], 2005; China planning press[9], 2008) adopt bearing capacity coefficient ($N_{qh}=F_{max}/(\gamma HDL)$, where F_{max} is the ultimate soil bearing force, γ is the unit weight of soil, D is the diameter of buried pipeline, and L is the length of the buried pipeline.) to characterize the ultimate soil bearing capacity, which is related to the internal friction angle of soil (φ) and the embedment depth/diameter ratios of pipe(H/D), but the embedment depth/diameter ratios(H/D) in these standards is relative small (about 10 or less), the results from these standards will not be reasonable when the embedment depth/diameter ratios (H/D) is larger than 10.0. Thus, some works should be carried out for studying the ultimate soil bearing capacity of soil-pipe interaction because the embedded depth of buried pipeline has been great larger than ever[10].

In view of the deficiency of method to acquire bearing capacity coefficient, following the works of Trautmann and O'Rourke[11](1985), some works have been done with ABAQUS software package to simulate the pipe-sand interaction by the authors (Li and Li[12], 2016), and a formula for calculating the soil bearing capacity coefficient was proposed, considering the effect of internal friction angle(φ), the embedment depth/diameter ratios(H/D) and diameter(D). In order to verify the result of our previous simulation works, a series of model tests were carried out. These test works will be presented in this paper.

2. Previous Works

Some standards (American Lifelines Alliance(ALA)[8], 2005; China planning press[9], 2008) have proposed the method to obtain the bearing capacity coefficient N_{qh}. Fig. 1 is the value of N_{qh} for sand recommended by ALA[8], which can be used when the H/D is less than 10.0. China planning press (2008) published a formula (Eq. 1) to calculate the bearing capacity coefficient N_{qh} and the ultimate yield force P_u, where these parameters C_0, C_1, C_2, C_3, C_4 depend on the internal friction angle of soil[9]. Fig. 2 is the relationship between N_{qh} and H/D depending on Eq. 1 and these parameters proposed in literature [9], which indicates that the N_{qh} is not reasonable when H/D>17 and $\varphi \geq 40°$.

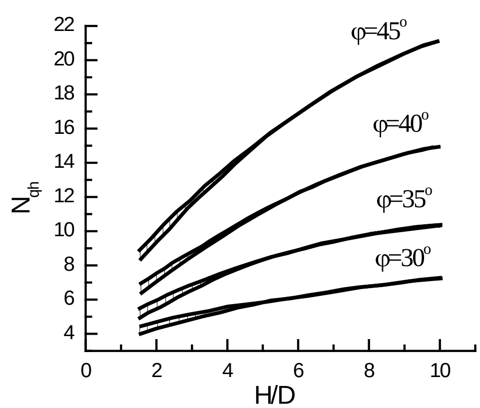


Fig.1 Values of N_{qh} for sand recommended by ALA

$$\left.\begin{aligned} P_u &= N_{qh}\rho_{sl} gHDD_L \\ N_{qh} &= C_0 + C_1(H/D) + C_2(H/D)^2 \\ &\quad + C_3(H/D)^3 + C_4(H/D)^4 \end{aligned}\right\} \tag{1}$$

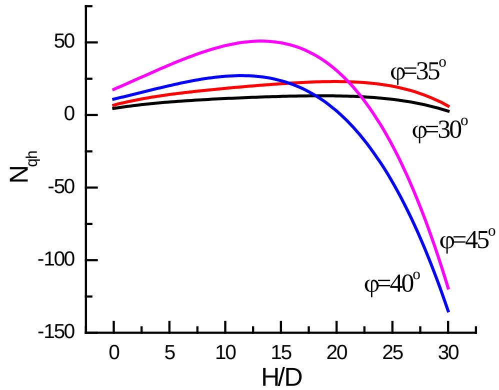


Fig.2 Values of N_{qh} for sand recommended by seismic technical code for oil and gas transmission

In our previous work[12], some numerical model, based on the test works of Trautmann and O'Rourke[11] (1985), were built with ABAQUS software package to simulate the pipeline-sand interaction, which were validated with their test results. Moreover, the effects of pipe diameter and embedded depth on the bearing capacity coefficient were analyzed and some conclusions were obtained, such as the lateral bearing capacity coefficient decreases with the increasing in diameter of pipeline when the embedment depth/diameter ratios is constant; and the relationship between the lateral bearing capacity coefficient and the embedment depth/diameter ratios submit to exponential curve, which was explained from the point of view of soil arch effect. Finally, a formula for calculating the bearing capacity coefficient for sand foundation was proposed, considering the effect of internal friction angle (φ), the embedment depth/diameter ratios (H/D) and pipe diameter (D). Eq. 2 is the formula proposed in our previous works, and Fig. 3 is the comparison of numerical results and the results proposed by ALA[8].

$$N_h = -18.5e^{-\frac{H}{0.3\varphi D}} + 0.44\varphi - 1.05D + 6.4 \tag{2}$$

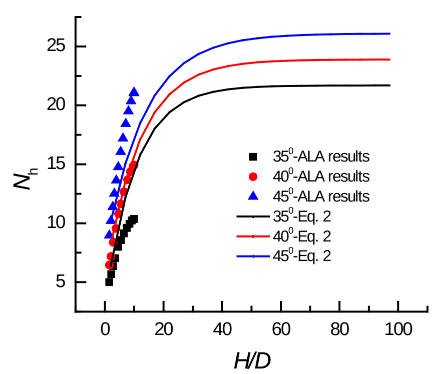


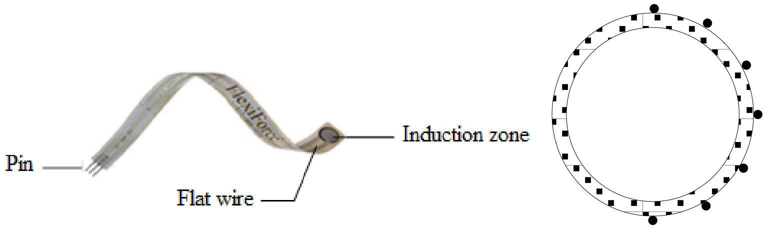
Fig.3 Proposed formula results Vs. ALA results

3. Model test for pipe-sand interaction

3.1 Test apparatus

In order to study the interaction between buried pipeline and soil, an apparatus (Shown in Fig. 4) was designed by the authors, which consist of a soil basin, vertical hydraulic jack and its reaction frame, horizontal actuator and its reaction frame, lateral force baffle and steel strand. This apparatus has the following three features: (1) there is a window on the front of the soil basin to monitor the soil deformation during test. (2) It is easy to simulate the deep embedded depth by using the vertical hydraulic jack. (3) It is easy to be assembled. The size of the soil basin is 1.0m×1.1m×0.5m, and that of the monitor window on the front of the soil basin is 50mm×70mm. There are two rectangle holes on the right side of the soil basin, where the steel strand can pass through. The test pipeline and the horizontal actuator are connected with the steel strand where the horizontal actuator provide the pulling force, thus, the test pipeline can be pulled during test. At the same time, earth pressure gauges were used in the test, which were arranged on the surface of pipeline. Fig. 5 shows the earth pressure gauge and their positions.

Fig.4 Test apparatus



(a) Earth pressure gauge (b) Gauge layout on pipe

Fig.5 Earth pressure gauge and its positions

3.2 Overview of the experiments

In the tests, medium sand was used, which was sampled from Beijing city. Fig. 6 is the particle size distribution of the test sand. Layered filling method was employed in the test, where the weight of test sand was calculated with the formula $\gamma_d = \gamma/(1+\omega)$ and then placed in 5.0 cm lifts and each lift was compacted with a plate compactor during backfilling in test. The dry unit weight of soil was selected as the control standards for our test, and the three dry unit weight were 14.5kN/m^3, 16.0kN/m^3, and 17.0kN/m^3 respectively. Fig. 7 shows the relationship between dry unit weight of test sand γ_d and internal friction angle φ. Table 1 shows the test cases.

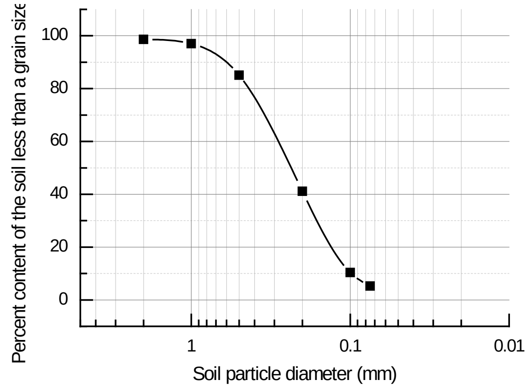


Fig. 6 Particle size distribution of test sand

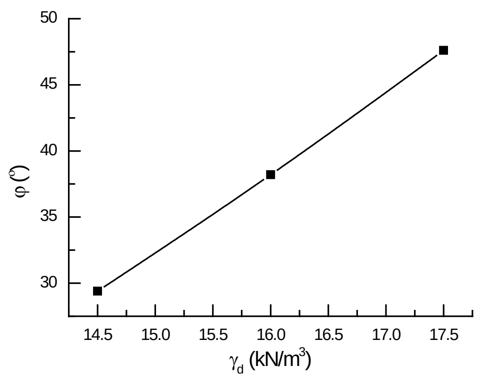


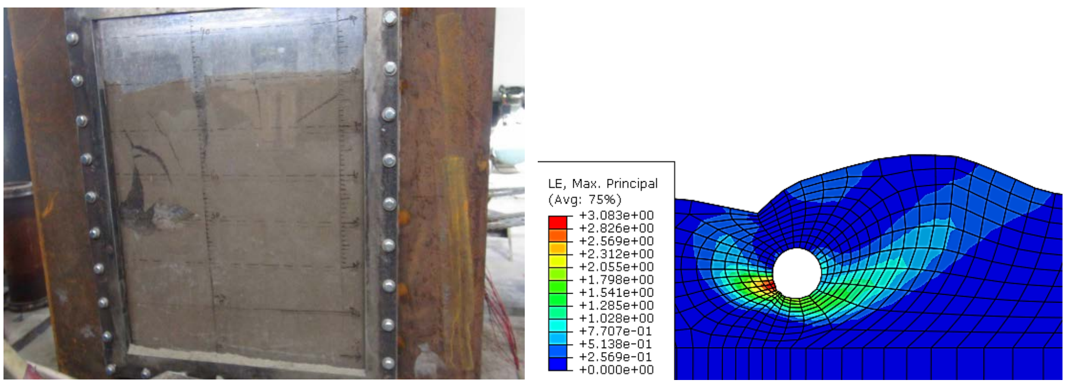
Fig.7 Internal friction angle Vs. dry unit weight of test sand

Table 1– Test case

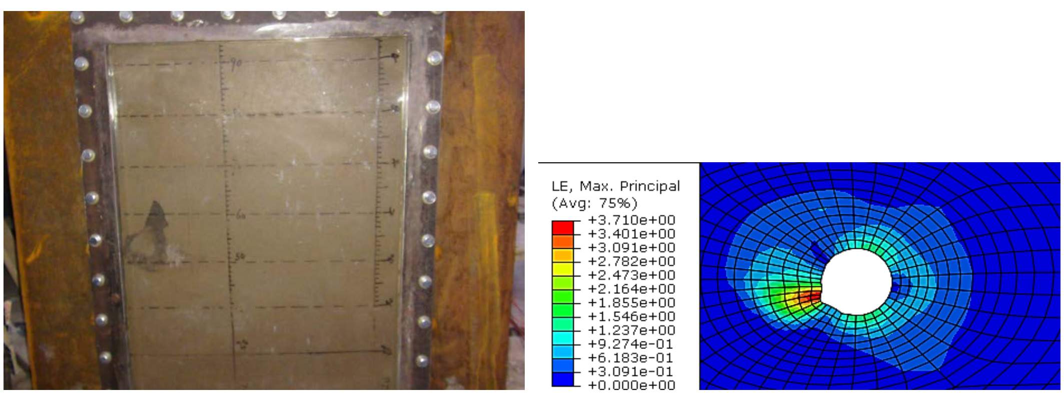
Dry unit weight (kN/m^3)	**Internal friction angle** (^{o})	**Material of pipe**	**Diameter** (mm)	**Embedment depth/diameter ratios** H/D	**Loading mode**	**Maxmum loading** (mm)	**Loading speed** (mm/s)
14.5	29.4	Steel pipe	60	1、3、5、8、10、15、20、30、50、80	Horizontal displacement loading	150	0.5
16	38.2			1、3、5、8、10、15、20、30、50、80			
17	44.5			1、3、5、8、10、15、20、30、50、80			
17	44.5		30	3			
			102				
			140				
			180				

3.3 Test results analysis

Fig. 8 shows the soil mass damage in shallow embedded and deep embedded conditions of our tests. Fig. 8a presents the failure in shallow embedded conditions, which is similar to Audibert's test[13], and indicates that the failure plane can be described with a logistic curve and divided into active zone, passive zone, and gravity equilibrium zone. The pipe pushs the soil mass of the passive zone to move, the above soil mass in front of the pipe will slide and failure under gravity due to the slide space was shaped behind the pipe. But the failure mode in deep embedded conditions is different to that in shallow embedded conditions, Fig. 8b shows that there is not an obvious failure plane in the above soil mass when the pipe move in the soil mass, there only leave a hole in backward sand behind the moving pipe, which means that the pipe movement only squeeze and compact the forward soil, but the shear destroy can not emerge in above soil mass.



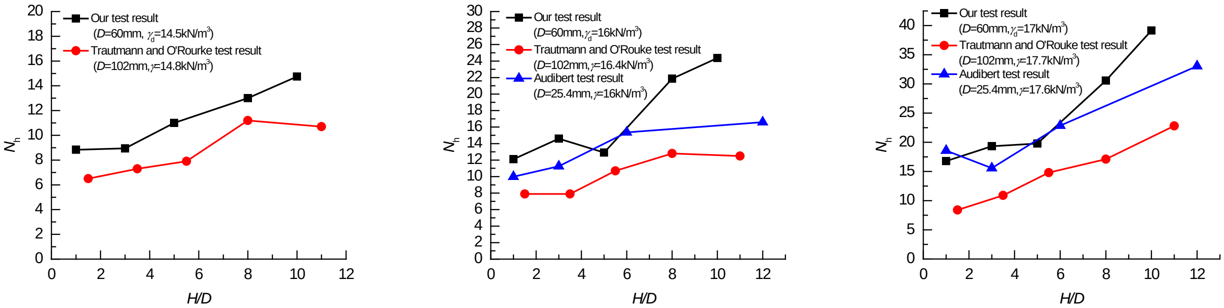
(a)shallow embedded



(b)deep embedded

Fig.8 soil damage photo in test and simulation result in our previous work

Fig. 9 are the comparison between our test results and the works of Trautmann and O'Rourke[11] and that of Audibert[13], which indicate that our test is similar to that of Trautmann and O'Rourke, and that of Audibert. But, the values are different because these test conditions are different, where the value of our test is largest and that of Trautmann and O'Rourke is smallest. So, the influence of the test condition on the response of sand-pipe interaction should be studied in the future.



(a)Loose sand (b) Medium dense sand (c) Dense sand

Fig.9 Comparison between our test and other test

Fig. 10 shows the relationship between N_h and *H/D* derived from our test, which means that N_h will be increasing and then decreasing with the increasing in *H/D*. From Fig. 10, N_h will reach the peak value when *H/D* is about 15.0, and the value of N_h at dense sand is larger than that at loose sand. But, comparing the Fig. 10 to Fig. 3, we find that the calculate result with Eq.2 does not coincide well with the test result when *H/D* is larger than 15.0. We think one reason is that the Mohr-Coulomb model used in the Finite Element analyses can not discribe the dilation angle of sand tends to vary with the mean effective stress and mobilized friction angle during shearing process, and can not simulate strain-softening at large displacements. So, a better constitutive model of sands should be employed in future research. At the same time, the size of the test model maybe is another reason, so, the influence of the size of the test model will be an important content in our future works.

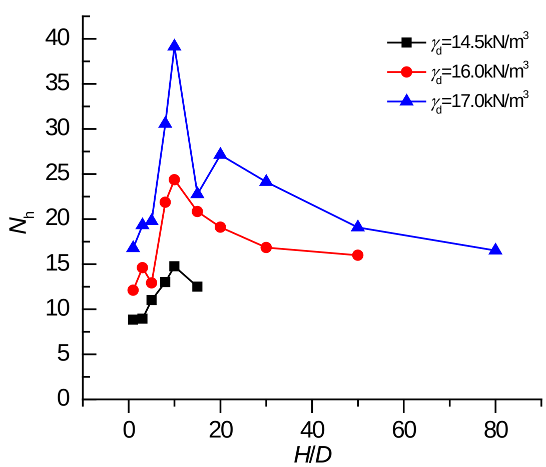
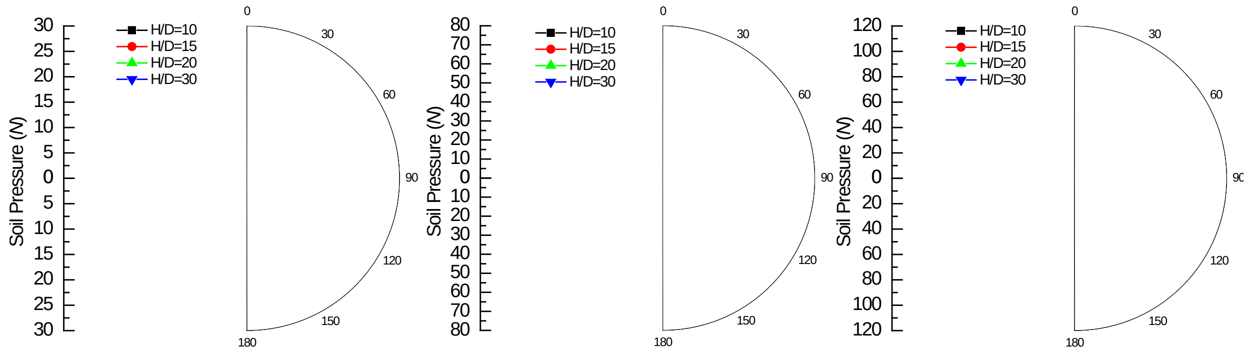


Fig. 10 Relationship between N_h and H / D

In the test, the earth pressure on pipe was also measured. Fig. 11 presents the earth pressure distribution on pipe in different cases, which indicates that the earth pressures at 60°, 90°, and 120° are larger and that at 0° and 180° are smallest. At the same time, the earth pressure on the upper of pipe is larger than that on the underpart of pipe.



(a)γ_d=14.5kN/m^3 (b)γ_d=16.0kN/m^3 (c) γ_d=17.0kN/m^3

Fig.11 Soil pressure on pipe

4. Summary and Conclusions

In order to verify the result of our simulation works, a series of model tests were carried out. In the paper, the previous works was described firstly, and the tests were introduced and the test results were analyzed, including the failure mode, the bearing capacity coefficient, and earth pressure distribution on pipe. Some conclusions were obtained, including (1) The failure mode in deep embedded is different to that in shallow embedded; (2) The values in different test are different because the test conditions are different; (3) N_h will increase and then decrease with the increasing in *H/D*, and a further research to study the ultimate soil bearing capacity of buried pipeline-sand interaction is needed; (4) The earth pressures at 60°, 90°, and 120° are larger and that at 0° and 180° are smallest, the earth pressure on the upper of pipe is larger than that on the underpart of pipe.

5. Acknowledgements

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