Characteristics of Lateral Rigidity of Offshore Piles in Incheon Marine Clay

Les caractéristiques de Rigidité Latérale de Tas Au large dans le Fusilier marin d'Incheon

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ABSTRACT

The load distribution and deformation of offshore piles in Incheon grand bridge are investigated, based on experimental tests and a numerical analysis. Special attention is given to the consideration of flexural rigidity in laterally loaded piles. Rigid- and flexible- pile analyses were conducted for comparison. A framework for determining the soil spring (p-y curves) is proposed from field and laboratory model tests. A numerical analysis that takes into account the proposed p-y curves was performed for major parameters on pile flexibility such as pile diameter, the length and the subgrade soil reaction. Based on the analysis, it is shown that there are significantly differences in bending moments and lateral displacements in flexible piles rather than rigid piles. Through the comparative studies, it is found that the p-y curves influences much more on the behavior of a flexible pile than of a rigid pile and thus the magnitude and distribution of the p-y curves highly influences on the pile behavior when the pile is designed as a flexible pile.

RÉSUMÉ

La distribution de charge et la deformation de tas au large dans le grand pont Incheon sont enquêtés, basés sur les épreuves expérimentales et une analyse numérique. On prête l'attention spéciale à la considération de rigidité flexural dans les tas latéralement chargés. Rigide –et flexible – les analyses de tas ont été accomoies pour la comparaison. Un cadre pour determiner le printemps de sol (p-y les courbes) est propose des épreuves modèles de terrain et de laboratoire. Une analyse numérique qui tient compte de p-y proposé se courbe a été execute pour les parameters importants sur la flexibilité de tas comme le diamètre de tas, la longeur et la réaction de sol de sous-qualité. Basé sur l'analyse, il est montré qu'il y a de façon significative des differences dans les moments de torsion et les déplacements latéraux dans les tas flexible plutôt que les tas rigides. Par les etudes comparatives, il est constaté que les courbes de p-y influencent beaucoup plus sur la conduit d'un tas flexible que d'un tas rigide et ainsi l'étendue et la distribution des courbes de p-y influencent hautement sur la conduite de tas quand le tas est conçu comme un tas flexible.

Keywords : Offshore pile, flexural rigidity, rigid- and flexible- pile, field and laboratory test, p-y curve, numerical analysis.

1 INTRODUCTION

In South Korea, a number of huge construction projects such as land reclamation for an international airport, high-speed railway, and harbor construction are in progress in urban and coastal areas. Offshore-drilled shafts are frequently used in those areas as required by the capacity demands.

Recently, large diameter piles were used as foundations for a long span bridge under both static and dynamic axial and lateral loads. Several empirical and numerical methods have been proposed for analyzing the load-deformation behavior of piles subjected to a lateral load. The load transfer curve (Matlock, 1970; Reese et al. 1975; O'Neill, 1984) is one of the most widely used method of laterally loaded piles. This approach is based on the concept that p-y curves are recommended for the analysis of piles. It consists of analyzing the pile as a structural beam on soil supports (springs). The spring (soil) modulus is generally not a constant but is a nonlinear function of depth, soil stiffness, and pile deflection. The traditional models are well known as semi-empirical approaches in which soil response is characterized as independent nonlinear springs at discrete locations. Therefore, these models do not account for the pile bending stiffness and the interaction of the pile-soil system. Moreover, most p-y curves used in practice are based on the results of lateral load test on relatively small diameter piles (e.g., Matlock: 0.33 m diameter steel-pipe piles; Reese et al.: 0.61 m diameter steel-piles; Reese and Welch: 0.90 m diameter drilled shaft) that may not consider the important concept of the pile flexural rigidity. A superior way to present the laterally large-diameter pile behavior in marine clay is to introduce the role of deflections in calculations such as a beam column analysis and a coupled set of load-displacement curves called p-y curves.

The objectives of this study are to propose p-y curves derived from experimental tests on instrumented piles in marine clay and to evaluate the effect of the relative flexural rigidity of the pile-soil system. The validity of the rigidity was analyzed through parametric studies.

2 LATERAL LOAD TESTS

Field tests were conducted at the Incheon bridge site in South Korea (Figure 1). Due to the complex pile-soil interaction, a comprehensive geotechnical investigation was carried out to accurately define the soil profile and properties at the test site. This investigation was performed on three boring holes (W107, W108, W117), with conventional sampling near the test piles. Field tests were standard penetration testing (SPT) and cone penetration testing (CPT). Conventional sampling includes split spoon SPT undisturbed (72mm diameter) and disturbed (55mm diameter) soil samples. Laboratory tests were performed to determine particle size distribution, Atterberg limits, soil classification, shear strength, and consolidation characteristics. Figure 2 shows an idealization of the subsurface profile with borehole and shaft embedment for test piles based on the results of field and laboratory tests. The properties of soils and pile geometries used in these tests are listed in Table 1.

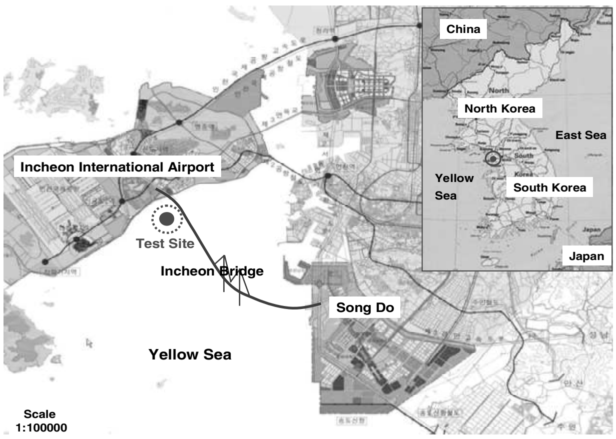

Figure 1. Location map of field test site

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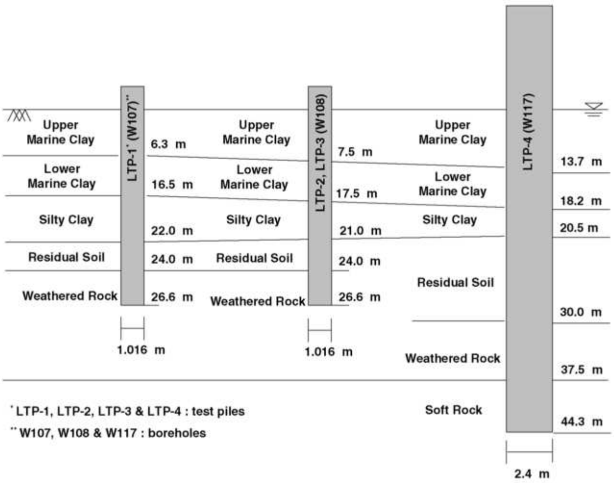


Figure 2. Composite soil profile with test results

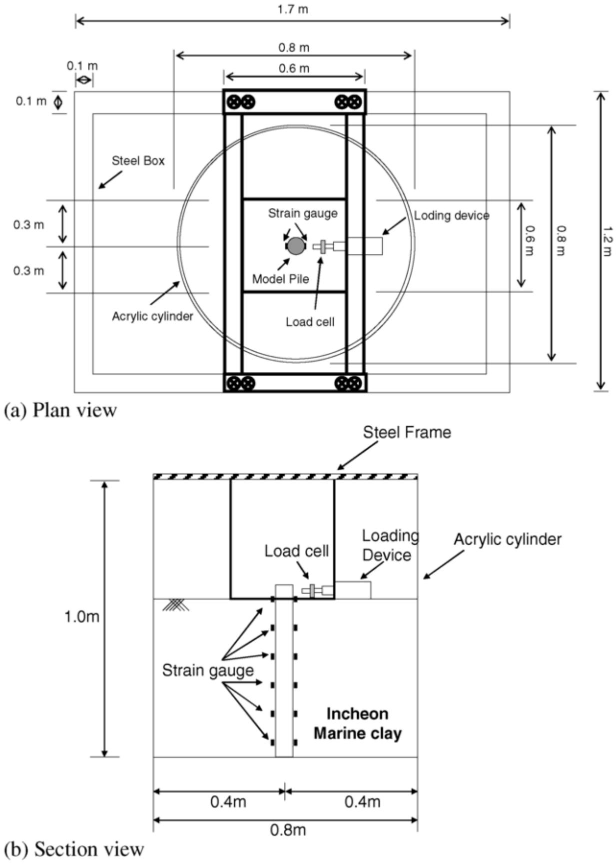
Table 1. Material properties and geometries. (field load test)

Soil	Upper Clay	Lower Clay	Silt	Residual soil	Weathered Rock	Soft Rock
γ_t (kN/m^3)	17.5	17.5	17.8	17.8	20.2	20.5
N value	1~3	4~7	12~19	44	50/15~	100
c_u (kPa)	18	42	-	-	-	-
ϕ (Deg)	-	-	24	34	32	33
PI (%)	25~30	30~35	35~40	-	-	-
μ_s	0.3	0.3	0.3	0.3	0.25	0.25
OCR	0~2	1~2	<2	-	-	-
ε_{50}	0.02	0.01	-	-	-	-
Pile	Steel pile			Drilled Shaft		
D (m)	1.02			2.4		
T (m)	0.016			-		
L (m)	26.6			44.3		
γ (kN/m^3)	72			25		
E_p (kNm^2)	2.0x10^8			2.6x10^7		
I_p (m^4)	0.0063			1.629		
Pile No.	LTP-1, LTP-2, LTP-3			LTP-4		

The testing procedure followed ASTM D-3966 reaction pile method, applying small, approximately equal increments of the load at equal short time intervals. The lateral load tests were conducted on the two types of piles, which are the steel piles and the drilled shaft. The steel piles LTP-1, LTP-2 and LTP-3 had a 1.016 m outer diameter and 16 mm wall thickness. Each pile was driven (using oil pressure hammer) such that 1.0 m of pile remained above the ground surface. The final depth of driven piles was recorded as 25.6 m. The drilled shaft (LTP-4) had a 2.4 m diameter, 45 m embedment length, and was 9.1 m above the ground surface.

Lateral loads were imposed on the piles using the loading devices reacting against a reaction pile. The one- or two-way cyclic loads were applied to the test piles. To obtain the ultimate resistance of the test piles (LTP-1, LTP-2, and LTP-3), the applied lateral load was increased substantially to 900 kN, which corresponds to its maximum value. The drilled shaft (LTP-4) utilized a smaller target lateral load (850 kN) than the ultimate load because the drilled shaft would be used as the foundation of the real bridge.

In this study, a series of laboratory load tests also performed that complement the limitation of field load test. The laboratory test setup is briefly described below. As shown in Figure 3, a sample box was made of a transparent acrylic cylinder having an 800 mm diameter and 1000 mm height. The size of cylinder was designed large enough to minimize the influence of the boundary effect.



					β	E_pI_p (kNm^2)
MP-1	Short pile	18	32	400	1.1	4.36
MP-2	Short pile	42	32	400	1.6	4.36
MP-3	Long pile	18	32	650	2.4	4.36
MP-4	Long pile	42	32	650	3.0	4.36

Note : βL is the dimensionless length ($=\sqrt[4]{K/4E_pI_p}\times L$),
where K =modulus of subgrade reaction

The test soil was marine clay from the field load test. Laboratory vane tests were conducted to determine the undrained shear strength (c_u) of the test soil at several positions with depth. Based on this data, the test soil with two different undrained shear strengths (18 kPa and 42 kPa) was prepared by controlling water content. The summary of the model tests is presented in Table 2.

3 TEST RESULTS AND DISCUSSION

3.1 *Proposed p-y curves from load tests*

The characteristic p-y curves are experimentally constructed via load tests. The soil resistance per unit length (p) is calculated by double differentiating the pile bending moment (M) distribution (Hetenyi, 1946).

$$p = \frac{d^2M}{dz^2} \tag{1}$$

where z denotes the depth. The method of fitting smooth curves through the bending moment profile data used fifth-order polynomial functions. The lateral pile displacement (y) used the test value directly.

Based on these experimental p-y curves, curve characteristics are in general agreement with the hyperbolic functions of Goh et al (1997). Therefore, the following p-y curve is introduced:

$$p = \frac{y}{\dfrac{1}{K} + \dfrac{y}{p_u}} \qquad \text{[kN/m]} \tag{2}$$

where K is the modulus of subgrade reaction, p_u is the ultimate soil resistance and y is the horizontal deflection of pile.

In general, the soil resistance, p (kN/m) is a direct function of the lateral displacement y (m), modulus of subgrade reaction K (kN/m^2), and the ultimate soil resistance p_u (kN/m). In most of the previous models (Kim, 2009), the modulus of subgrade reaction of the p-y curve K is taken to be proportional to the soil modulus of elasticity (E_s) and pile diameter (D), and is inversely proportional to the Poisson's ratio of soil (μ) and flexural rigidity of the pile (E_pI_p). The result is a generalized function for K expressed as Equation 3.

$$K = \alpha \frac{E_S}{(1-\mu_S{}^2)} \sqrt{\frac{D}{D_{ref}}} \left[\frac{E_S D^4}{E_P I_P} \right]^{\beta} \qquad \text{[kN/m}^2\text{]} \tag{3}$$

where, μ_S is Poisson's ratio of soil; D is pile diameter (m); D_{ref} is 1.0 m; $E_P I_P$ is flexural rigidity of pile (kN-m^2); E_S is the soil modulus of elasticity (kN/m^2) which was represented by $K_C \times c_u$ (USACE, 1990); c_u is undrained shear strength; K_c is correlation factor that depends on the overconsolidation ratio and plasticity index; α, β are fitting parameters. Linear regression analysis was used to obtain the best-fit values of the parameter α and β.

The problem of the ultimate soil resistance p_u, has been studied by different researchers over the years. To date a rigorous closed-form solution does not exist because the soil resistance around laterally loaded piles is a very complex three-dimensional problem of the ultimate state of nonlinear elastoplasic mediums. To simplify this, the ultimate soil resistance (p_u) was obtained from p-y curves at each depth by fitting the experimentally obtained data points with a hyperbolic function of the form of Equation 2. The ultimate soil resistance was fitted by the following function.

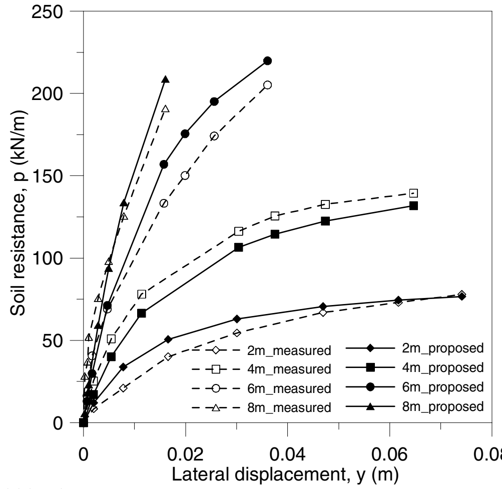
$$p_u = \kappa c_u D \left(\frac{z}{z_{ref}} \right)^{\lambda} \qquad \text{[kN/m]} \tag{4}$$

where c_u is the undrained shear strength (kN/m^2); z is the depth below soil surface (m); z_{ref} is 1.0 m; κ and λ are fitting parameters.

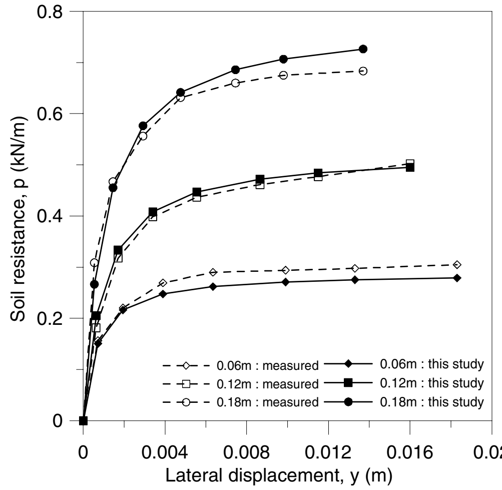
To evaluate the parameters κ and λ in Equation 4, the same procedure used to calculate the modulus of subgrade reaction K is used. Table 3 shows the values for the empirical parameter for marine clay based on the linear regression analysis. Finally, a single-modified hyperbolic p-y function for large diameter piles in marine clay can be obtained by substituting K and p_u into Equation 2. Figure 4 shows the proposed and observed p-y characteristics of field and laboratory test piles. The proposed p-y curves closely approach the measured values at most points.

Table 3. Empirical parameters for proposed p-y curves

Type	Factors		Proposed
Modulus of subgrade reaction (K)	α 17.4	β 0.66	$K = 17.4 \dfrac{E_s}{(1-\mu_s^2)} \sqrt{\dfrac{E}{D_{ref}}} \left[\dfrac{E_s D^4}{E_p I_p} \right]^{0.66}$
Ultimate soil resistance (p_u)	κ 3.25	λ 0.59	$p_u = 3.25\ c_u\ D \left[\dfrac{z}{z_{ref}} \right]^{0.59}$



(a) Field load test



(b) Laboratory load test

Figure 4. Test results and proposed p-y curves for Incheon marine clay

3.2 *Comparison with Existing p-y curves*

As shown in Figure 5, the proposed p-y curves for Incheon marine clay are tested by comparing the two well known p-y curves by Matlock (1970) and O'Neill and Gazioglu (1984). The typical p-y characteristics of a test pile based on pile load tests and predictions using the Matlock (1970) and O'Neill and Gazioglu (1984) functions are plotted on the same graph.

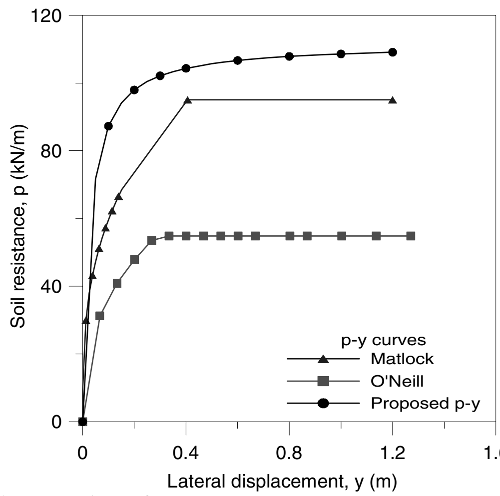
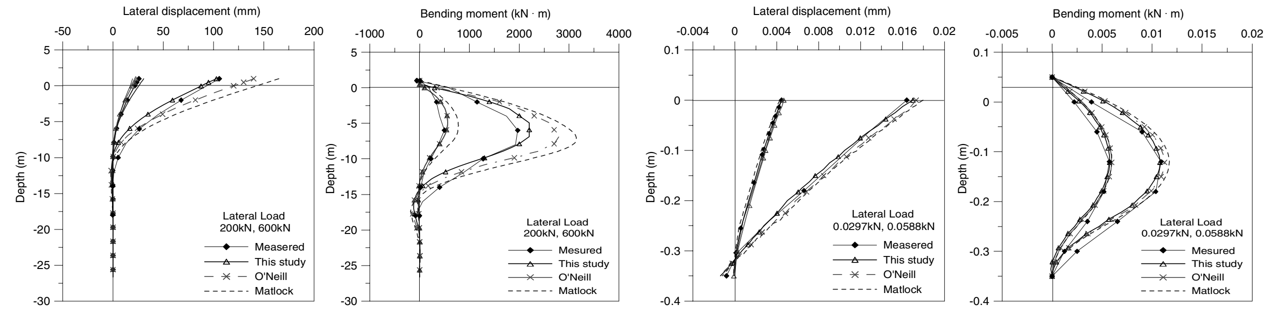


Figure 5. Comparison of p-y curves

The results by O'Neill and Matlock models show significant differences in the shapes and magnitudes of the ultimate soil



(a) Lateral displacement (LTP-1) (b) Bending moment (c) Lateral displacement (MP-1) (d) Bending moment

Figure 6. Comparison of predicted results (LTP-1 : flexible pile; MP-1 : rigid pile)

resistance (p_u) compared to the proposed p-y curves estimated from load tests. The existing models (O'Neill clay model and Matlock soft clay model) show that different values of initial stiffness are followed by perfectly plastic behavior. The proposed p-y curve exhibits the highest ultimate soil resistance, despite having an initial slope (modulus of subgrade reaction) smaller than the Matlock model.

To obtain detailed information on the behavior of test piles a numerical analysis was performed by a finite difference method (beam-column method). The material properties have accordingly been chosen by the field and laboratory tests (Table 1 and Table 2).

Figure 6 shows the predicted and measured lateral displacement and bending moment profiles in LTP-1 and MP-1. The proposed p-y curves closely predict the general trend of the measured displacement and bending moment compared with the existing p-y analyses. A reasonably good agreement between the proposed and the existing p-y curves is obtained for the initial loading step. Beyond the initial loading step, the existing p-y curve analyses have a larger displacement and bending moment than the proposed p-y curves. This demonstrates that for the p-y curves there exist different shapes, which result from different soil-pile rigidities as a function of the magnitude of ultimate soil resistance (p_u) and the modulus of subgrade reaction (K), so that these curve shapes have an influence on the set of prediction results. In order to verify the effect of lateral pile-soil rigidity, rigidity criterion (Broms, 1964; Randolph, 1981) has been introduced and applied to the test piles in clay. Here the value of pile characteristic (β) can be estimated by Equation 5,

$$\beta = \sqrt[4]{\frac{K_{ave.}}{4E_p I_p}} \tag{5}$$

where K_{ave} is the average value of K , and $E_p I_p$ is the flexural rigidity of the pile. This equation gives the value of the pile characteristic β as 0.148 m^{-1} and dimensionless length βL as 3.95 in LTP-1. Based on this, it was found that LTP-1, LTP-2, LTP-3, MP-3, and MP-4 are in the flexible piles category ($\beta L > 2.3$), and LPT-4, MP-1, and MP-2 pile are considered to be in the rigid pile category ($\beta L < 2.3$) . As shown in Figure 6, p-y curves have a greater influence on the behavior of a flexible pile (LTP-1) than for a rigid pile (MP-1).

From this comparative study, it is important to define the characteristic length (βL). It can be explained by noting that flexible piles presents that the influence of characteristic of p-y curves is more significant than in the rigid pile.

4 SUMMARY AND CONCLUSIONS

The main objective of this study was to investigate the non-linear behavior of the laterally loaded pile embedded in marine clay soil using experimental tests and analytical studies. A series of field and laboratory load tests were conducted on Incheon marine clay to determine pile behavior. The piles examined were steel piles (LTP-1, LTP-2 and LTP-3), the drilled shaft (LTP-4), and the laboratory model piles (MP-1, MP-2, MP-3, MP-4), which were subjected to cyclic lateral loading to develop empirical p-y curves.

A limited parametric study was performed to examine the effect of pile-soil rigidity for different soil and pile conditions. Through comparative study, it was clearly demonstrated that the rigid pile is not influenced by the characteristics of various p-y curves. From the findings of this study, the following conclusions are drawn;

1. By taking into account the rigidity difference effect, the proposed p-y function appropriately and realistically represents pile-soil interactions for large diameter piles in marine clay.
2. The two existing p-y curves (O'Neill and Matlock) were compared with the proposed p-y curves at the same depth. It was shown that the three soft clay models have different shapes that are represented by the magnitude of ultimate soil resistance (p_u) and initial slope (K), and that these curve shapes impact pile behavior.
3. The characteristic length is a direct function of the values of the pile characteristic (β) and the pile depth (L). A major parameter influencing β is the pile diameter (D), bending stiffness ($E_p I_p$), and modulus of subgrade reaction (K). Comparative case studies show that the p-y curves have a greater impact on the behavior of a flexible pile ($\beta L > 2.3$) than of a rigid pile ($\beta L < 2.3$); thus the magnitude and distribution of the p-y curves highly influence the pile behavior when the pile is designed to be a flexible pile.

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