Behavior of Laterally Loaded Cast-in-situ Concrete Piles Compared with Analytical Predictions
해석적 방법으로 비교한 횡방향 하중을 받는 현장타설말뚝의 거동

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개 요 : 2개의 현장에 대하여 4본의 직경 40cm 현장타설말뚝을 시공하였다. 횡방향 재하시험 결과를 Chang, Randolph 그리고 Reese의 방법으로 예측한 결과와 비교하였다. 그 비교 결과 Chang과 Randolph의 방법은 실무적으로 관심이 있는 변위까지에서는 횡방향 거동을 합리적으로 예측할 수 있었고, 이 방법들을 사용하는데 있어서 중요한 변수는 표준관입시험으로 구한 N치와 흙의 탄성계수(E_s)의 관계를 나타내는 경험상수이다. 한편, Reese의 p-y곡선을 이용하여 구한 하중-변위 곡선은 동일한 변위에 대하여 실제 실험결과에 비하여 1/2~1/3정도의 하중 값을 나타냈다. Broms방법은 말뚝이 시공된 지반의 종류에 따라 실제의 극한지지력에 비하여 극한 지지력을 너무 작게 제시할 수 있다고 판단된다.

Key words : lateral load test, subgrade reaction modulus, p-y curve, ultimate lateral resistance

1. Introduction

Piles are almost always designed to resist lateral loads and moments. In the design of such piles, two criteria must be satisfied; First, an adequate factor of safety against ultimate failure; and second, an acceptable deflection at working load. In many practical cases, however, the design of piles for lateral loading is dependent on satisfying a limiting lateral deflection requirement that may result in the specification of allowable lateral loads much less than the lateral capacity of piles. To this end, theoretical approaches for predicting lateral movements have been developed extensively. There are mainly the subgrade reaction approach and the elastic approach. Both can be formulated to care for nonlinearity, but in different manners.

In the use of aforementioned approaches, it is essential to evaluate the soil's Young's modulus which is most frequently obtained for cohesionless soils from empirical relations between the modulus and field test data, e.g., the N values of Standard Penetration Tests. There are several empirical constants suggested by colleagues, which differ by up to 600% each other.

Prototype lateral load tests are executed on 2 sets of 4-40cm cast-in-situ concrete piles at two different locations to verify the validity of some theoretical approaches predicting lateral displacements as well as the empirical relations between soil's elastic moduli and field test data.

The approaches adopted herein to compare with the test results are Chang (1937), Randolph (1981), and p-y curve (Reese, 1994) methods. At the end, ultimate lateral resistances of piles at two different sites are calculated by Brom's method (1964) and compared with the test results. Since it is not intended to load the piles to the ultimate failure, the comprehensive conclusions are not expected. Nevertheless, by inspection of the lateral displacements in the actual load-displacement curves at the ultimate lateral loads predicted by Brom's method, meaningful conclusions have been drawn in this study.

2. Test Sites

Two test sites are selected among those where construction works are being done under the supervision of Korea Highway Corporation. One is K-bridge site, and the other is S-bridge site, which are more than 100km apart each other.

Plan views of test sites are shown in Figs.1 and 3. As is shown in the figures, borings are executed at the centers of the test piles. The boring logs are briefly summarized in Figs.2 and 4. It may be noticed from the figures that the top soil of K-bridge site is a fill layer of mid size aggregates mixed with sands with the N values of 22, and that of S-bridge site is also a fill layer of silty sands with N values of 6 to 7.

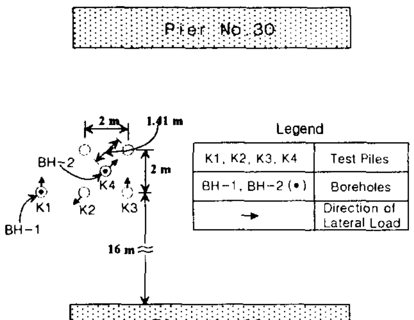

Figure. 1. Plan View of Test Piles Arrangement and Borehole Locations (K-Bridge Site)

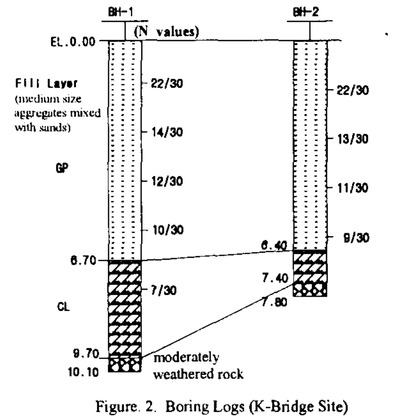

Figure. 2. Boring Logs (K-Bridge Site)

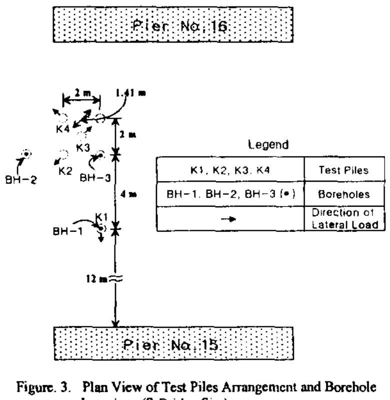

Figure. 3. Plan View of Test Piles Arrangement and Borehole Locations (S-Bridge Site)

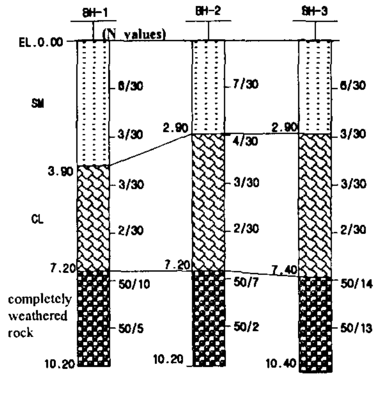

Figure. 4. Boring Logs (S-Bridge Site)

3. Test Pile Construction

Two sets of 4-40cm cast-in-situ concrete piles are constructed using the Reversed Circulation Drilling (RCD) method. Casings are inserted through the soil layers to prevent the cave-in failure of the surrounding soils. Test pile lengths are listed in Table 1. The piles are controlled to be embedded in a bedrock to a certain depth. Eight of 25mm re-bars are inserted in the concrete piles forming an inner concentric circle.

After the completion of the lateral load tests, test borings are executed at the center of the piles to examine the integrity of the piles, and uniaxial compression tests are done on cored samples. The test results are summarized in Table 2.

Table 1. Test Pile Lengths

	K - Bridge*				S - Bridge**			
Pile No.	K1	K2	K3	K4	S1	S2	S3	S4
Length(m)	9.4	8.3	8.3	8.0	10.4	10.5	11.2	11.9

* Each pile is embedded one diameter length in the moderately weathered rock

**Each pile is embedded 3m in the completely weathered rock

Table 2. Informations on Concrete Piles

		K - bridge	S - bridge
Concrete	Uniaxial compressive strength (kPa)	25,212	41,987
	Modulus of Elasticity (kPa)	1.64×10^7	2.25×10^7
Tensile strength of steel bar (kPa)		$2,75\times10^5$	3.92×10^5

4. Test Results

Lateral load tests are executed following ASTM D3966. Test results are shown in Figs. 5 and 6 for sites of K-bridge and S-bridge, respectively. In Fig. 5, the load-displacement curve of K4-pile is extended by extrapolation to compensate the loss of the resisting capacity caused by a local defect of concrete near the pile head. Lateral loads corresponding to the displacements of 6.4mm(1/4 inch) and 15mm for each pile of both sites are listed in Table 3.

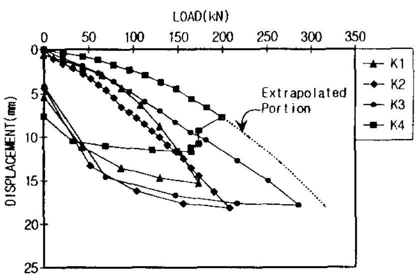

Figure. 5. Lateral Load-Displacement Curves from Field Tests (K-Bridge Site)

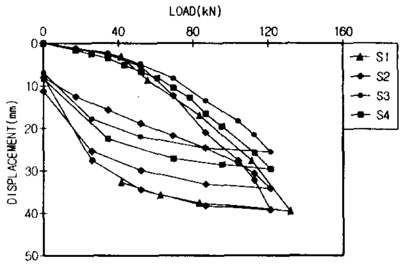

Figure. 6. Lateral Load-Displacement Curves from Field Tests (S-Bridge Site)

Table 3. Lateral Loads at the Displacements of 6.4mm(1/4inch) and 15mm

	K - bridge(kN)					S - bridge(kN)				
Pile No.	K1	K2	K3	K4	Ave.	S1	S2	S3	S4	Ave.
Lateral Loads at 6.4mm Displacement	105.9	81.4	119.7	174.6	120.4	50.0	54.9	58.9	49.1	53.2
Lateral Loads at 15mm Displacement	171.7	178.5	251.1	(286.5)*	222.0	77.5	74.6	92.2	83.4	81.9

* Extrapolated Value.

4.1 Lateral Displacements Predicted by Linear Methods

4.1.1Chang's Method(1937)

Chang's subgrade reaction method(1937) is widely used in East Asia, which is adopted in "Specificaions for Road Bridge Design" of Korea(1996) and Japan(1996). The lateral displacement of free headed pile can be calculated by the equation shown below.

$$\delta = \frac{(1+\beta h)^3 + 1/2}{3EI\beta^3} P \qquad (1)$$

,where δ : lateral displacement of pile

P : lateral load acted upon the pile head

h : distance to the load acting point from ground line

E : pile's modulus of elasticity

I : moment of inertia of pile

β : $\sqrt[4]{\frac{E_s}{4EI}} \left(= \sqrt[4]{\frac{k_h D}{4EI}} \right)$

k_h : the modulus of subgrade reaction

As seen in the above, Chang, in his original paper, equated $k_h D$ with E_s in the calculation of characteristic length, β. In the references (4) and (5), it is recommended to obtain the subgrade reaction, k_h from the empirical extrapolation relation with plate load test results, which is

$$k_h = \frac{E_s}{30}\left(\sqrt{\frac{D/\beta}{30}}\right)^{(-3/4)} \qquad (2)$$

To distinguish Chang's original β from the latter one, it will be named hereafter β_1 and β_2, respectively. In either case, E_s should be evaluated for the soils where the piles are embedded. Normally, in the cohesionless soils, it is obtained empirically from field test data, e.g., N values of SPT. Again, in the references (4) and (5), E_s =28N is recommended, while Schmertmann (1978) recommended variable relations depending upon soil types as summarized in Table 4. According to Table 4, it would be appropriate to use 12 for the E_s/N of K-bridge site, and 7 for that of S-bridge site. β_1 and β_2 are calculated for the sites different for different values of E_s/N and tabulated in Table 5. β_2 is always smaller than β_1 by about 10%. The lateral displacement predictions by Chang's method using β_1 as well as β_2 will be plotted and discussed later together with

Randolph's method.

Table 4. E_s/N for Different Types of Soils (Schmertmann, 1978)

Soil Type	E_s/N
Silt, Sandy silt	4
Fine sand, Medium sand	7
Coarse sand	10
Sandy gravel, Gravel	12 ~ 15

Table 5. β_1 and β_2 for Different Values of E_s/N

	K - bridge		S - bridge	
E_s/N \ β	$\beta_1(\times 10^{-3}cm^{-1})$	$\beta_2(\times 10^{-3}cm^{-1})$	$\beta_1(\times 10^{-3}cm^{-1})$	$\beta_2(\times 10^{-3}cm^{-1})$
28 (Specifications of Road Bridge Design, 1996)	8.66	7.96	5.96	5.22
12 (Schmertmann, 1978)	7.01	6.26	4.82	4.15
7 (Schmertmann, 1998)	6.12	5.40	4.21	3.57

4.2 Randolph's method (1981)

Randolph(1981) suggested simple algebraic expressions as a result of a parametric study using the finite element method and treating the soil as an elastic continuum. The expressions are as follows.

$$u = 0.25\frac{H}{G^{*}r_0}\left(\frac{E}{G^{*}}\right)^{-1/7} + 0.27\frac{M}{G^{*}r_0^2}\left(\frac{E}{G^{*}}\right)^{-3/7} \tag{3}$$

$$\theta = 0.27\frac{H}{G^{*}r_0^2}\left(\frac{E}{G^{*}}\right)^{-3/7} + 0.8\frac{M}{G^{*}r_0^3}\left(\frac{E}{G^{*}}\right)^{-5/7} \tag{4}$$

,where $G*$: Product of $G(1+3\nu/4)$

G : shear modulus of soil

u : lateral deflection of pile at ground level depth

θ : rotation of pile at ground level

H : lateral load on pile

M : moment applied to pile at ground level

E : Young's modulus

ν : Poisson's ratio

In Figs. 7 and 8, various prediction lines by Chang and Randolph methods for different empirical constants of E_s/N are plotted with the load-displacement curves obtained from the prototype lateral load tests. It is intended to compare the various predictions with the test results for a low displacement level (6.4 mm) as well as a relatively high displacement level (15mm) which is sometimes regarded as the maximum allowable displacement(Japanese Road Committee, 1966; Korea Road & Transportation Association,1996).

For the low displacement level, Chang with β_1 and E_s/N of 12 predicts the best, and for the large displacement level, Chang with β_1 and E_s/N of 7 or with β_2 and E_s/N of 12 or Randolph with E_s/N of 7 predicts alike and the best. For both displacement levels, Chang with β_1 and E_s/N of 7 or Chang with β_2 and E_s/N of 12 predicts the best, still standing in a conservative side, and Randolph with E_s/N of 7 predicts the next.

It is observed in these comparisons that using β_2 for Chang's method gives more conservative results than using β_1, but by lowering the ratio of E_s/N, the amount can be compensated. Therefore, it is thought to be the best to use Chang's method with β_1 and E_s/N of 7 regardless of soil conditions and the displacement levels, for it gives good results and is the simplest to use.

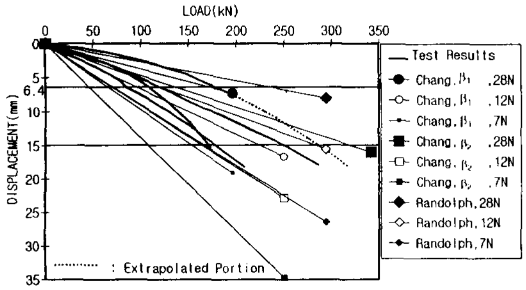

Figure. 7. Comparison of Test Results with Predictions of Linear Methods (K-Bridge Site)

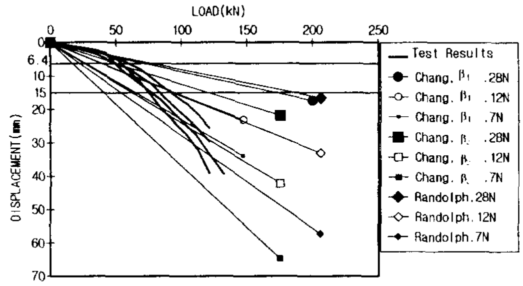

Figure. 8. Comparison of Test Results with Predictions of Linear Methods (S-Bridge Site)

4.3 Comparison of Test Results with p-y Curves (Reese & Wang, 1994)

As is observed from the load-displacement curves of load tests, the relationship between load and displacement is nonlinear. The most widely-employed approach dealing with non-linearity is the so called "p-y" method developed by Reese and co-workers.

Commercially available package program, LPILE, which is developed by Reese and Wang (1994) is utilized to construct p-y curves for the test piles in two different sites. Input data for LPILE are listed in Table 6. The resulting p-y curves obtained from the LPILE are plotted in Figs. 9 and 10 with lateral load-displacement curves of field tests.

In Table 7, average values of test results are compared numerically for different levels of displacements with the predictions of p-y curves obtained by Reese method as well as API method which is a slightly modified version of Reese, both of which are from the output of LPILE.

In the case of the K-bridge site whose top soil is stiffer than the S-bridge site, p-y curves predict about one third of actual loads for both displacement levels, while, in the case of the S-bridge site, p-y curves predict about one half of the actual loads for both displacement levels.

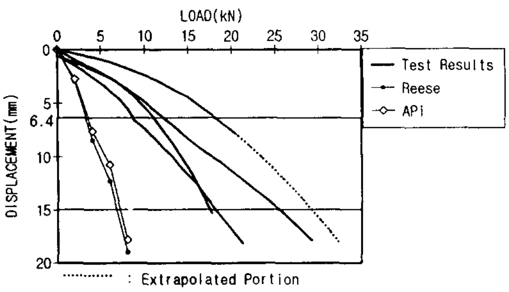

Figure. 9. Comparison of Test Results with p-y curves of Reese(1974) and API(1987) (K-Bridge Site)

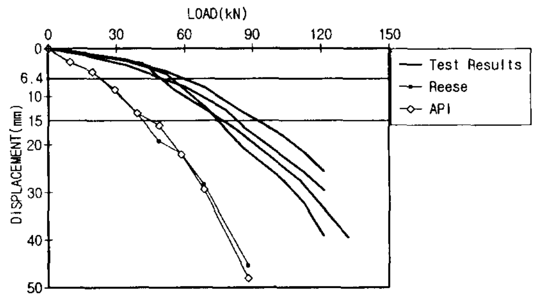

Figure. 10. Comparison of Test Results with p-y curves of Reese(1974) and API(1987) (S-Bridge Site)

Table 6. LPILE* Input Data

	Depth (m)	Unified Soil Classification	Unit wts. (kN/m^3)	Strength parameters (C=kPa)	k_h (kN/m^3)
K - bridge (GWL : -2.42m)	0~2.42	GP	17.1	C=0, Φ=35°	24,440
	2.42~6.55	GP	9.8	C=0, Φ=33°	16,294
	6.55~8.0	CL	5.9	C=24, Φ=0°	5,431
	8.0~8.27	M.W.**ROCK	15.7	C=100, Φ=0°	244,404
S - bridge (GWL : -1.57m)	0~1.57	SM	15.7	C=0, Φ=25.5°	6,789
	1.57~3.23	SM	7.8	C=0, Φ=25.5°	5,431
	3.23~7.27	CL	5.9	C=15, Φ=0°	2,715
	7.27~10.3	C.W.***ROCK	12.8	C=50, Φ=0°	122,202

* Package Program developed by Reese and Wang (1994), version 4.0.
** Moderately Weathered
*** Completely Weathered

Table 7. Lateral Loads from p-y curves (LPILE)

	Displacement	Ave. of Test Results (kN)	Reese (kN) (Reese/Ave.T.R.)	API (kN) (Reese/Ave.T.R.)
K - bridge	6.4mm	120.4	34.3 (0.28)	35.3 (0.29)
	15mm	222.0	65.7 (0.30)	70.6 (0.32)
S - bridge	6.4mm	53.2	23.5 (0.44)	23.5 (0.44)
	15mm	81.9	43.2 (0.53)	45.1 (0.55)

4.4 Ultimate Lateral Resistances

Ultimate lateral resistances are evaluated for the free head flexible piles in the two test sites by Brom's method(1964) using the equation shown below.

$$P = \frac{M_{yield}}{e + 0.54\left(\frac{P}{\gamma D K_p}\right)^{0.5}} \qquad (5)$$

,where P : applied lateral load

M_{yield} : yield moment of pile section

e : eccentricity of applied load from the ground surface

γ : unit weight of soil

D : diameter of pile

K_p : coefficient of passive lateral earth pressure

Ultimate lateral resistances are calculated by Eq. 5 for the K-bridge site and the S-bridge site. The results are 106.8kN and 124.5kN, respectively.

Since it is not intended to load test piles to ultimate failure, direct comparisons of ultimate failure loads with calculated values cannot be made. Instead, lateral displacements at the ultimate lateral loads are calculated for each piles of the two sites and tabulated in Table 7. From the table, the average of corresponding displacements to the ultimate resistance is found to be 33.7mm for the S-bridge site of top soil, which may be regarded as reasonable results. On the other hand, the average of corresponding displacements to the ultimate resistance is only 5.7mm, which is too small value as an ultimate failure displacement.

5. Conclusions

Prototype lateral load tests are executed, and the load-displacement curves from the tests are compared with analytical predictions. The first finding is that the linear subgrade reaction method, such as Chang's, assuming the modulus of the subgrade reaction to be constant along the depth even in sandy layers and merely equating k_hD to E_s can predict the lateral displacement reasonably well to the magnitude of practical interest. Randolph's method of simple algebraic expressions can also predict the lateral displacements almost as good as the Chang's method. The proper ratio of E_s/N to be input in the subgrade reaction approach or the elastic approach is presumed to be lying between 7 and 12 depending upon the method utilized to evaluate k_h.

Lateral load-displacement curves constructed by the p-y method of Reese predict one half to one third of actual loads for identical displacements.

For the prediction of ultimate lateral resistances of piles, it is found that Brom's method could give too small values compared to the actual ultimate resistances depending upon the types of soils where the piles are embedded.

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