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Effect of load test interpretation on the resistance factors of driven piles

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ABSTRACT: The effect of pile load test interpretation methods on the resistance factors (ϕ) of driven piles was investigated using a load test database of thirty-four square precast prestressed concrete (PPC) piles tested to failure. For each pile load test, the ultimate load carrying capacity was determined using nine different load test interpretation methods. In addition, the capacity of each pile was calculated from cone penetration test (CPT) soundings using three CPT methods and from borehole data using the static α-method. Analysis was conducted to evaluate the effect of the load test interpretation on the resistance factors needed for load and resistance factor design (LRFD) of single driven piles. Resistance factors for the investigated methods were determined using reliability-based analyses, while other design input parameters were determined based on the AASHTO LRFD design specifications for bridge substructure.

1 INTRODUCTION

This paper presents an evaluation of the effect of pile load test interpretation methods on the resistance factors of single driven piles. The evaluation was based on a pile load test database of thirty-four square precast prestressed concrete (PPC) piles tested to failure. Each tested pile in the database has cone penetration test (CPT) soundings and borehole data adjacent to its location. The ultimate load carrying capacity for each pile was determined using nine different load test interpretation methods. The load carrying capacity of each pile was also calculated from the CPT soundings using three CPT methods and from borehole data using the static α-method. Analysis was conducted to evaluate the effect of the load test interpretation methods on the resistance factors needed for load and resistance factor design of single driven piles using the CPT methods and the static α-method. Resistance factors for the investigated methods were determined using reliability-based analyses, while other design input parameters were determined based on the AASHTO LRFD design specifications (1998) for bridge substructure.

2 PILE LOAD TEST DATABASE

Titi and Abu-Farsakh (1999) developed a load test database of thirty-four square precast prestressed concrete (PPC) piles and the corresponding soil exploration data including CPT soundings in Louisiana soils. All piles included in the database were friction piles that showed a plunging failure during the load test. The same load test database was used in this paper to evaluate the effect of different load test interpretation methods on the resistance factors for pile design using CPT methods and static α-method.

Analysis was conducted on each pile load test (load-settlement curve) to estimate the ultimate capacity using nine different interpretation methods. The ultimate pile capacity estimated from the load test using the interpretation methods (i.e. measured pile capacity) is designated as R_m. For all test piles in the database, the coefficient of variation of R_m, estimated using all interpretation methods, ranges from 1.1 to 11.9%. This indicates that there is a variation in the measured pile capacity as determined by the different interpretation methods. Therefore, the resistance factors are influenced by the load test interpretation method used in the calibration.

3 CPT METHODS

In this research, three CPT methods were used to determine the load carrying capacity of each test pile in the database. These methods are: Schmertmann (1978), De Ruiter & Beringen (1979), and Bustamante & Gianeselli (1982). The pile load carrying capacity determined by CPT methods is referred to as R_n. Briaud & Tucker (1988) used the Log Normal distribution to evaluate the performance of the pile capacity prediction methods. The Log Normal distribution is acceptable to represent the ratio of R_n/R_m, however, it is not symmetric around the mean, which means that the Log Normal distribution does not give an equal weight of underprediction and overprediction of the method. Therefore, the Log Normal distribution was used to evaluate the different methods based on their prediction accuracy and precision. This was achieved by evaluating the mean and standard deviation of the predicted to measured capacity ratio (R_n/R_m). The use of CPT methods for the design of driven piles via LRFD requires the determination of resistance factors as well as other input parameters. Only the resistance factor for the Schmertmann (1978) method is given in the AASHTO LRFD Bridge Design Specifications.

4 LOAD AND RESISTANCE FACTOR DESIGN

The load and resistance factor design for highway bridge substructures is described in details by Withiam et al. (2001). The LRFD concept hinges on the principle that the material resistance must exceed the effect of loads, which can be expressed as:

$$\phi R_n \geq \Sigma \eta_i \gamma_i Q_i \tag{1}$$

where, R_n is the nominal resistance, ϕ is the resistance factor, Q_i is the load effect, γ_i is the load factor and η_i is the load modifier that accounts for the effects of ductility, redundancy, and operational importance.

In reliability-based analysis, the probability of failure is used to quantify the safety of piles. The probability of failure is expressed as:

$$p_f = P(R < Q) \tag{2}$$

The probability of failure can also be expressed using the reliability index β. The reliability index used in this paper is based on Level I probability theory (first order second moment reliability theory), which is considered accurate by Withiam et al. (2001) for most purposes.

The reliability index for the CPT methods and the α-static method can be estimated from the load test database and the factor of safety associated with these methods, from the following expression:

$$\beta = \frac{\ln\left(\frac{\lambda_R FS\left(\frac{Q_D}{Q_L}+1\right)}{\lambda_{QD}\frac{Q_D}{Q_L}+\lambda_{QL}}\sqrt{\frac{1+COV_{QD}^2+COV_{QL}^2}{1+COV_R^2}}\right)}{\sqrt{\ln\left[\left(1+COV_R^2\right)\left(1+COV_{QD}^2+COV_{QL}^2\right)\right]}} \tag{3}$$

where COV_{QD}, COV_{QL}, and COV_R are the coefficient of variation values for the dead load, live load, and resistance, respectively; λ_{QD}, λ_{QL} and λ_R are the bias factors for the dead load, live load, and resistance, respectively; Q_D/Q_L is the dead load to live load ratio; and FS is the factor of safety used in these methods. The bias factor for the resistance is the ratio of the measured resistance (R_m) to the nominal value (R_n):

$$\lambda_R = \frac{R_m}{R_n} \tag{4}$$

The ratio of dead load to live load varies depending on the span length (Hansell, & Viest 1971). The AASHTO LRFD specifications provided values for Q_D/Q_L for different span lengths. These values along with the values presented by Withiam et al. (2001) are shown in Table 1.

As an example of the relationship between reliability index and probability of failure, a reliability index of $\beta = 2.5$ corresponds to a probability of failure $p_f = 0.62\%$ for normal distribution and $p_f = 1\ \%$ for Log Normal distribution. Reliability index values for common methods (e.g. α-method) used to predict the capacity of driven piles were reported in the range of $\beta = 1.5$ to 3.0 (Barker et al. 1991).

The reliability index was calculated using the load test database for the CPT methods and the static α-method. The reliability index for these methods ranges from $\beta = 1.28$ to 2.19. For Q_D/Q_L of 1.58 (corresponds to span length of 27.0 m), the static α-method reliability index is $\beta = 1.66$. These values are consistent with the range of β reported by Barker et al. (1991).

In order to determine the resistance factors for the three CPT methods and the static α-method using the load test database, a target reliability index has to be identified. Withiam et al. (2001) indicated that a target reliability index range $\beta_T = 2.0$ to

2.5 (p_f = 2.5 to 0.62%) for single driven piles is reasonable. Therefore, the analysis in this paper was conducted using reliability index values of β = 2.0 and 2.5, which will result in probability of failure values p_f = 2.5 and 0.62%, respectively.

Table 1: Variation of dead load to live load ratio (Q_D/Q_L) with span length

Span length (m)	Q_D/Q_L	
	AASHTO LRFD	Withiam et al. (2001)
9	0.52	0.52
18	1.06	1.04
27	1.58	1.56
36	2.12	2.07
45	2.64	2.59
50	3.00	2.88
60	3.53	3.46

The resistance factor (ϕ) is determined using the Log Normal distribution of resistance with considerations of dead and live loads from the following equation:

$$\phi = \frac{\lambda_R\left(\gamma_D \dfrac{Q_D}{Q_L} + \gamma_L\right)\sqrt{\dfrac{1+COV_{QD}^2+COV_{QL}^2}{1+COV_R^2}}}{\left(\lambda_{QD}\dfrac{Q_D}{Q_L}+\lambda_{QL}\right)\exp\left(\beta_T\sqrt{\ln\left[\left(1+COV_R^2\right)\left(1+COV_{QD}^2+COV_{QL}^2\right)\right]}\right)} \qquad (5)$$

where γ_D and γ_L are the load factors for dead load and live load, respectively.

The resistance factors for design of single driven piles using the CPT methods were evaluated based on load test database. The resistance bias factor λ_R and the coefficient of variation COV_R for each method were determined from the load test database. Values for other variables in Equation 5 were obtained from the 1994 AASHTO LRFD Bridge Design Specifications. These values are λ_{QD} = 1.08, λ_{QL} = 1.15, γ_D = 1.25, γ_L = 1.75, COV_{QD} = 0.13 and COV_{QL} = 0.18.

The results of analysis conducted to determine the resistance factors for the CPT methods and the static α-method using a target reliability index β_T = 2.5 are summarized in Table 2. Inspection of Table 2 indicates that the resistance factor (ϕ) for each prediction method (i.e. α and CPT methods), with respect to any load test interpretation method used, decreases with the increase of the span length (i.e. the dead load to live load ratio Q_D/Q_L). As an example, the ϕ value for α-method with respect to Butler-Hoy interpretation method decreases from 0.55 for span length of 9.0 m to 0.49 for span length of 60 m. This is due to the fact that the dead load has lower uncertainty and COV compared to the live load. Among the investigated load test interpretation methods, using De Beer & Wallays method resulted in the lowest resistance values for the static α-method and the CPT methods. The highest resistance values

Table 2. Variation of resistance factor with prediction and load test interpretation methods for different span lengths.

Load Test Interpretation Method	Span Length (m)	Resistance Factor (ϕ)			
		α-method	Schmertmann	De Ruiter & Beringen	LCPC
Butler-Hoy	9	0.55	0.50	0.68	0.65
Fuller-Hoy		0.58	0.49	0.69	0.64
Davisson		0.57	0.50	0.69	0.66
De Beer & Wallays		0.52	0.46	0.63	0.62
Hansen-80%		0.57	0.51	0.72	0.64
Hansen-90%		0.57	0.51	0.70	0.66
Chin		0.62	0.50	0.69	0.64
Mazurkiewicz		0.57	0.52	0.71	0.67
Vander Veen		0.62	0.53	0.71	0.69
Butler-Hoy	27	0.51	0.46	0.63	0.60
Fuller-Hoy		0.54	0.46	0.64	0.60
Davisson		0.53	0.47	0.64	0.61
De Beer & Wallays		0.49	0.43	0.59	0.57
Hansen-80%		0.53	0.47	0.67	0.59
Hansen-90%		0.53	0.47	0.66	0.61
Chin		0.57	0.47	0.64	0.60
Mazurkiewicz		0.53	0.48	0.66	0.62
Vander Veen		0.58	0.49	0.66	0.64
Butler-Hoy	36	0.50	0.45	0.62	0.59
Fuller-Hoy		0.53	0.45	0.63	0.58
Davisson		0.52	0.46	0.63	0.60
De Beer & Wallays		0.48	0.42	0.57	0.56
Hansen-80%		0.52	0.47	0.66	0.58
Hansen-90%		0.52	0.46	0.64	0.60
Chin		0.56	0.46	0.63	0.58
Mazurkiewicz		0.52	0.47	0.65	0.61
Vander Veen		0.57	0.48	0.65	0.63
Butler-Hoy	60	0.49	0.44	0.60	0.57
Fuller-Hoy		0.51	0.44	0.61	0.57
Davisson		0.50	0.45	0.61	0.58
De Beer & Wallays		0.46	0.41	0.56	0.55
Hansen-80%		0.51	0.45	0.64	0.56
Hansen-90%		0.50	0.45	0.62	0.58
Chin		0.55	0.45	0.61	0.57
Mazurkiewicz		0.50	0.46	0.63	0.60
Vander Veen		0.55	0.47	0.63	0.61

were obtained when Vander Veen method was used to determine the measured capacity from the pile load test.

Figure 1 shows a bar chart of the resistance values for span length of 9.0 m and reliability index 2.5. Examination of the figure indicates that on the prediction methods side, the De Ruiter & Beringen (1979) method showed the highest ϕ values while the Schmertmann (1978) method showed the lowest ϕ values when considering each individual load test interpretation method.

The Davisson (1972) method is one of the most commonly used method by practicing engineers. The US Army Corps of Engineers Manual on Design of Deep Foundations (1998) listed the following methods for estimating the ultimate capacity from pile load tests: Davisson method, Butler-Hoy, Hansen-80% and Hansen-90% method. Inspection of Table 2 shows that the ϕ value determined for α-method based on Davisson method, Hansen-80% and Hansen-90% method varies between 0.5 and 0.57, depending on the span length. The resistance factor ranges from 0.49 to 0.55 in case of using Butler-Hoy method. Among the four load test interpretation methods, the Davisson (1972) method reflects the average and therefore regarded in this paper as a suitable method for calibrating the resistance factors.

The results of the reliability-based analyses to determine the resistance factors for the α-method and the three CPT methods with target reliability index values of $\beta_T = 2.0$ and 2.5, for different span lengths, are summarized in Table 3. The analysis is based on the four methods of estimating the ultimate capacity from the pile load test, which are Davisson method, Butler-Hoy, Hansen-80% and Hansen-90% method. Among the four methods, using Butler-Hoy method resulted in the lowest resistance values of ϕ for $\beta_T = 2.0$ and 2.5 ($p_f = 2.5$ and 0.62%). For example, the ϕ value for span length = 9 m (i.e. Q_D/Q_L=0.52) ranges from 0.67 to 0.80 for $\beta_T = 2.0$ ($p_f = 2.5\%$), and from 0.55 to 0.68 for $\beta_T = 2.5$ ($p_f = 0.62\%$).

The highest resistance values were obtained when Hansen-80% method was used to estimate the ultimate capacity from the pile load test. For example, theϕ value for span length = 9 m ranges from 0.70 to 0.84 for βT = 2.0, and from 0.57 to 0.72 for βT = 2.5.

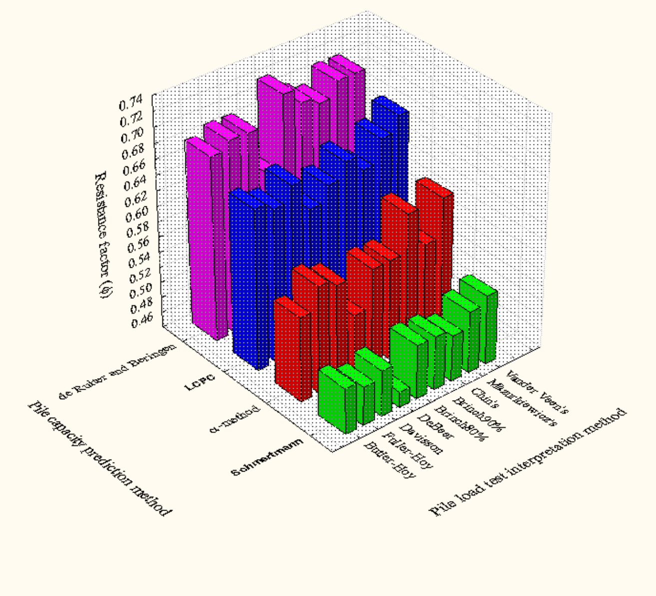

Figure 1. Variation of resistance factor for the CPT methods and the static α-method with respect to different load test interpretation methods for span length of 9.0 m.

Table 3. Summary of the analysis of resistance factors

Load Test Interpretation Method	Pile Capacity Prediction Method	Span Length (m)							
		9		27		36		60	
		β =2.0	β =2.5	β =2.0	β =2.5	β =2.0	β =2.5	β =2.0	β =2.5
Davisson	α-Method	0.68	0.57	0.64	0.53	0.62	0.52	0.61	0.50
	LCPC	0.77	0.66	0.71	0.61	0.70	0.60	0.68	0.58
	Schmertmann	0.61	0.50	0.56	0.47	0.55	0.46	0.54	0.45
	De Ruiter	0.81	0.69	0.75	0.64	0.74	0.63	0.72	0.61
Butler-Hoy	α-Method	0.67	0.55	0.62	0.51	0.61	0.50	0.59	0.49
	LCPC	0.76	0.65	0.70	0.60	0.69	0.59	0.67	0.57
	Schmertmann	0.60	0.50	0.56	0.46	0.55	0.45	0.53	0.44
	De Ruiter	0.80	0.68	0.75	0.63	0.73	0.62	0.71	0.60
Hansen80%	α-Method	0.70	0.57	0.65	0.53	0.64	0.52	0.62	0.51
	LCPC	0.75	0.64	0.70	0.59	0.68	0.58	0.66	0.56
	Schmertmann	0.62	0.51	0.57	0.47	0.56	0.47	0.55	0.45
	De Ruiter	0.84	0.72	0.78	0.67	0.77	0.66	0.75	0.64
Hansen 90%	α-Method	0.69	0.57	0.64	0.53	0.63	0.52	0.61	0.50
	LCPC	0.77	0.66	0.71	0.61	0.70	0.60	0.68	0.58
	Schmertmann	0.61	0.51	0.57	0.47	0.56	0.46	0.54	0.45
	De Ruiter	0.82	0.70	0.77	0.66	0.75	0.64	0.73	0.62

5 CONCLUSIONS

This paper presented an evaluation of the effect of pile load test interpretation methods on the resistance factors (ϕ) of single driven friction piles. A pile load test database of thirty-four square precast prestressed concrete piles tested to failure was used to calibrate the resistance factors. For each pile load test, the ultimate load carrying capacity was determined using nine different load test interpretation methods. In addition, the load carrying capacity of each pile was calculated using three CPT methods and the static α-method.

Resistance factors for the investigated methods were determined using reliability-based analyses, while other design input parameters were determined based on the AASHTO LRFD design specifications for bridge substructure. Results of the analysis showed that the resistance factor values depend on the pile load test interpretation method. The highest and the lowest resistance factor values were obtained when Vander Veen and De Beer & Wallays methods were used to determine the ultimate capacity of the pile, respectively. The analyses also indicated that using Davisson method resulted in ϕ values that are close to the average value of all investigated methods.

6 REFERENCES

AASHTO. 1994. LRFD Highway Bridge Design Specifications. 1st Edition, American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO. 1998. LRFD Bridge Design Specifications. 2nd Edition, American Association of State Highway and Transportation Officials, Washington, DC.

Barker, R. M., Duncan, J. M., Rojiani, K. B., Ooi, P. S. K., Tan, C. K., & Kim, S. G. 1991. Manuals for Design of Bridge Foundations. NCHRP Report No. 343, *Transportation Research Board*, NCR, Washington, D.C.

Briaud, J-L & Tucker, L.M. 1988. Measured and Predicted Axial Response of 98 Piles, *Journal of Geotechnical Engineering*, ASCE, Vol. 114, No. 8, pp. 984-1001.

Bustamante, M & Gianeselli L. 1982. Pile Bearing Capacity Predictions by Means of Static Penetrometer CPT. *Proceedings of the 2nd European Symposium on Penetration Testing*, ESOPT-II, Amsterdam, Vol. 2, pp. 493-500.

Butler, H. D. & Hoy, H. E. 1977. The Texas Quick-Load Method for Foundation Load Testing-User's Manual. Report No. FHWA-IP-77-8.

Chin, F. K. 1970. Estimation of the Ultimate Load of Piles not Carried to Failure. *Proceedings 2nd Southeast Asian Soil Conference in Soil Engineering*, Singapore, pp.80-90.

Davisson, M. T. 1972. High Capacity Piles. *Proceedings of Lecture Series on Innovation in Foundation Construction*, ASCE, Illinois Section, Chicago, pp. 81-112.

De Beer, E. E. & Wallays, M. 1972. Franki Piles with Overexpanded Bases. La Technique des Travaux, No. 333, pp. 48.

De Ruiter, J. & Beringen F.L. 1979. Pile Foundations for Large North Sea Structures. *Marine Geotechnology*, Vol. 3, No. 3, pp. 267-314.

Fuller, F. M. & Hoy, H. E. 1970. Pile Load Tests Including Quick-load Test Method Conventional Methods and Interpretations. HRB 333, pp. 78-86.

Goble, G. 1999. Geotechnical Related Development and Implementation of Load and Resistance Factor Design (LRFD) Methods. Transportation Research Board, NCHRP Synthesis 279, Washington D.C.

Hansell, W. C. & Viest, I. M. 1971. Load Factor Design for Steel Highway Bridges. *AISC Engineering Journal*, Vol .8, No. 4, pp. 113-123.

Hansen B., J. 1963. Discussion: Hyperbolic Stress-Strain Response. Cohesive Soils. *J. Soil Mech. Found Div*. ASCE, Vol. 89, No. SM4, pp. 241-242.

Mazurkiewicz, B. K. 1972. Test Loading of Piles According to Polish Regulations. Royal Swedish Academy of Engineering Sciences Commission on Pile Research. Report No. 35, Stockholm, 20 pp.

Vander Veen, C. 1953. The Bearing Capacity of a Pile. *Proceedings, 3rd International Conference on Soil Mechanics and Foundations Engineering*, Vol. 2, Zurich, pp. 84-90.

Schmertmann, J.H. 1978. Guidelines for Cone Penetration Test, Performance and Design. U.S. Department of Transportation, Report No. FHWA-TS-78-209, Washington, D.C., p. 145.

Titi, H. H. & Abu-Farsakh, M. Y. 1999. Evaluation of Bearing Capacity of Piles from Cone Penetration Test Data. Report No. FHWA/LA.99/334, Louisiana Transportation Research Center, Baton Rouge, Louisiana.

U.S. Army Corps of Engineers. 1998. Design of Deep Foundations. Department of the Army Engineering Instructions, Engineering Instructions No. 02C097,.

Withiam, J. L., Voytko, E. P., Barker, R. M., Duncan, J. M., Kelly, B. C., Musser, S. C., & Elias, V. 2001. Load and Resistance Factor Design (LRFD) for Highway Bridge Substructures. Publication No FHWA HI-98-032, NHI Course No. 13068, Federal Highway Administration, Washington D.C.