THE STRUCTURAL DESIGN OF PILE FOUNDATIONS BASED ON LRFD FOR JAPANESE HIGHWAYS

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Abstract

One of the motivations for applying reliability-based design to geotechnical engineering is to confirm that more reasonable and cost-effective design results will be obtained when owners and designers invest in more detailed geotechnical investigations. In this paper, we propose load and resistance factor design for the structural design of piles in pile foundations for Level 1 earthquake situation. The proposed load factors in the study are a function of the chosen soil investigation/testing and piling method, which is applied to the bending moment in piles. Therefore, better choices of soil investigation/testing and high quality piling method will result in more reasonable design results.

Introduction

Reliability-based design approaches, such as load and resistance factor design (LRFD) and partial factor design have been widely accepted in structural design. These design methods are also applied to several foundation design codes. One of the motivations for applying reliability-based design in geotechnical engineering is to confirm that more detailed geotechnical investigations will result in more reasonable and cost-effective design. For example, the standard penetration test (SPT) is conducted for every project and almost all design parameters can be derived using empirical transformation equations based on SPT-N values, though other soil investigations are carried out less frequently. However, the uncertainty in the Young's modulus of soil depends on the adopted geotechnical measurement, testing method and soil types.

As shown in Fig. 1, the peak bending moments at the pile top and underground govern the structural design of piles. For example, when the surrounding soil is relatively soft or when the number of pile rows is relatively large, a sway deformation mode prevails and the pile-top bending moment should be the (absolute) maximum bending moment. On the other hand, when the surrounding soil is relatively hard or when the number of pile

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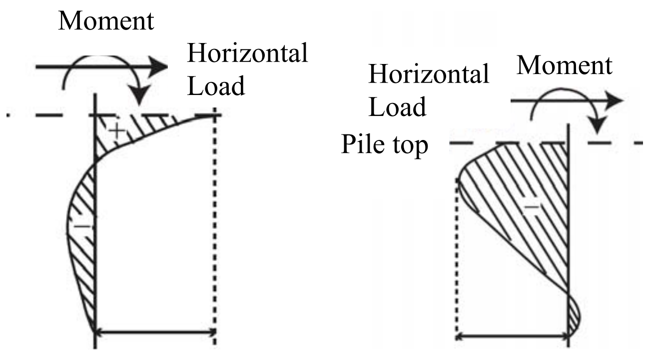
rows is relatively small, a rotation or inclination deformation mode prevails, and the underground peak bending moment should be the maximum bending moment. This indicates that the variation in stiffness of surrounding soil or axial resistance of piles is a major source of uncertainty in the calculated bending moment in piles.

However, load and resistance factors for the structural design of foundation structural members are usually the same as those used in typical structural design and they have no relationship with geotechnical aspects.

This study proposes a structural LRFD concept for piles of foundation considering the difference in reliability of geotechnical testing/investigation methods and piling methods so that design codes can support the effort to achieve more reasonable soil investigations and piling methods.



Case A Case B

Figure 1 Bending moment distribution in a pile

Variation in the Coefficient of Horizontal Subgrade Reaction

A horizontal load test database of piles is available in PWRI with boring log data. The observed coefficient of subgrade reaction at a displacement level of 1% of the pile diameter can be estimated using the beam-on-Winkler foundation theory, assuming a uniform coefficient of horizontal subgrade reaction, where 1% of the pile diameter is defined as the reference displacement level to estimate the coefficient of subgrade reaction in the Japanese Specifications for Highway Bridges. The average coefficient of horizontal subgrade reaction for the subsoil layers can also be calculated using typical empirical equations shown in the Japanese Highway Bridges Design Specifications. The coefficient of horizontal subgrade reaction is a function of Young's modulus of soil. Whereas the Japanese Highway Bridges Design Specifications shows that the Young's modulus of soil, E, is based on the secant modulus of an unloading-reloading cycle obtained by a plate loading test, an alternative empirical equation to derive the Young's modulus of soil from an SPT-N value is also provided as E = 2,800N (kN/m^2), because soil testing other than SPT is not often conducted. Accordingly, the model error in estimating the coefficient of the subgrade reaction can be derived by comparing the observed and calculated values for the case in which SPT-N values are used to estimate the Young's modulus of soil.

The ordinate indicates the ratio of the observed value to the calculated value of the coefficient of horizontal subgrade reaction. The abscissa indicates the average SPT-N value, N_{ave}, for the subsoil layers over the characteristic pile length, η,

$$\eta = [(kB) / (4E_pI_p)]^{1/4} \qquad (1)$$

where k is the coefficient of subgrade reaction, B is the foundation width (i.e., pile diameter), and E_pI_p is the bending rigidity of the pile. The governing soil classification for the subsoil layers within the characteristic pile length is indicated by different symbols. For subsoil layers having an SPT-N value smaller than 5, even the bias, λ_k, ranges from 1 to 4. For subsoil layers having an SPT-N value not smaller than 5, the bias, λ_k, is approximately 1.0 and the coefficient of variation, COV_k, is 0.60 for sandy soils and 0.70 for cohesive soils.

The model error in the estimation of the coefficient of subgrade reaction, k, is comprised of the model error in the estimation of the Young's modulus of soil, E, and the transformation error from the Young's modulus of soil, E, to the coefficient of subgrade reaction, k. The bias λ_k and the coefficient of variation COV_k of the subgrade reaction, k, are given as follows:

$$\lambda_k = \lambda_E \times \lambda_T \qquad (2)$$

$$COV_k^2 = COV_E^2 + COV_T^2 \qquad (3)$$

where λ_E and COV_E are the bias and COV of the Young's modulus of soil, E, and λ_T and COV_T are the bias and COV of the transformation error from E to k. Accordingly, the uncertainty in k is a function of the uncertainty in E that depends on the choice of soil investigation and testing method as well as soil classification.

The PWRI database indicates that the empirical equation of $E = 2800N$ (kN/m^2) has a bias, λ_E, and coefficient of variation, COV_E, of approximately 1.0 and 0.55 for sandy soils, where the data for cohesive soils is not available. Finally, based on Eq. (3), we can approximate the COV of the transformation error from E to k, COV_T as 0.25. This value is considered independent of the soil investigation method.

Based on a study by Phoon and Kulhawy, the uncertainty in estimating the Young's modulus of soil, λ_E and COV_E, is modeled as shown in Table 1 for several soil investigation and testing methods. Finally, using Eq. (3), the values of λ_E and COV_E shown in Table 1 and the transformation error from E to k, $\lambda_E = 1.0$ and $COV_E = 0.25$, the uncertainty in the coefficient of subgrade reaction can be set as listed in Table 2 as a function of soil investigation methods and soil classification.

Table 1 Uncertainty in the Young's modulus of soil

Soil investigation / testing	Uncertainty in E_{PMT} or E_{Lab}	
	λ_E	COV_E
Pressure meter test (PMT, Direct)	1.0	0.30
Laboratory test (Lab, Direct)	1.0	0.30
SPT-N (Transformation)	1.0	0.55

Table 2 Uncertainty in the coefficient of subgrade reaction

Soil investigation / testing	Prevailing soil condition	Uncertainty in k	
		Bias	COV
Pile load test	—	1.0	0.25
Pressure meter test or laboratory test	—	1.0	0.45
Only SPT	Sandy	1.0	0.60
	Cohesive	1.0	0.70
	$N_{ave} < 5$	1.0	1.00

Variation in the Axial Pile Spring Constant

In the current Japanese design specification, axial pile spring constant which installed at the pile top is modeled as function dependent on the rigidity of pile and pile length. However, the estimation accuracy is low especially the case of short pile or high rigidity pile.

In order to improve estimation accuracy of Kv, estimation equation is newly proposed. Displacement at pile top depends on not only the rigidity of pile but also the deformation of the tip of the pile. Therefore, displacement at the top of the pile can be expressed by the sum of pile deformation and displacement at the tip of pile shown this equation, and Kv is expressed as Eq(4).

$$K_V = \frac{1}{\frac{L}{2EA}\left(1+\gamma_y-\zeta\right)+\xi\frac{4\gamma_y}{\pi D_p{}^2 k_v}} \qquad (4)$$

Where,

γ_y : Estimated tip transmitting ratio which the pile is yield at the top of pile ($0 \leqq g_y \leqq 1$) . It is assumed as $\gamma_y = X\gamma_{10d}$

γ_{10d} : Estimated tip transmitting ratio which the displacement of the top of pile is reached at 10% of pile diameter. It is assumed as $\gamma_{10d} = R_p / R_{Nu}$

R_p : Ultimate bearing at the tip of pile estimated by using bearing estimation equation $(=q_d \cdot A)$

R_{Nu} : Ultimate Bearing estimated by using bearing estimation equation

X : Modification coefficient to estimate tip transmitting ratio which the pile is yield at the top of pile shown in Table 3

ζ : Modification coefficient to estimate deformation of pile shown in Table 3

ξ : Modification coefficient to estimate displacement of the tip of pile shown in Table 3

Table 3 Modification coefficients

Pilling Method	X	ζ	ξ	
			Sandy, Gravel	Cohesive
Driven pile method	0.89	0.08	0.22	0.42
Vibro-hammer method	0.98	0.23	0.46	-
Cast-in-place RC pile Method	0.62	0.19	0.63	0.47
Bored pile method	0.76	0.09	0.30	-
Steel pipe soil cement pile method	0.72	0.38	0.31	-
Screwed steel pile method	0.78	0.28	0.40	-
Pre bored pile method	0.69	0.02	0.20	-

This equation includes three modification coefficients, X, ζ and ξ. These coefficients were adjusted to estimate the Kv values obtained by vertical pile loading test results. Fig.2 shows the comparison of estimated and measured Kv in case of cast-in-place RC pile. It is found that the improved Kv estimates the measured one well in comparison with the conventional one.

Table 4 shows the statistic of uncertainty of model error of the Kv. The characteristic point is that the each bias of proposed Kv is approx.1.0. This means that the proposed Kv is estimated the average of Kv well.

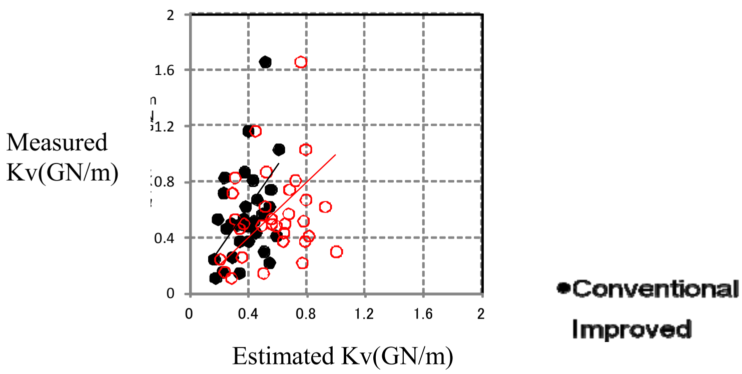


Figure 2 Estimated and Measured Kv relationships (Cast-in-place RC pile)

Table 4 Uncertainty of model error of axial pile spring Constant K_v

	Conventional			Proposed		
Piling Method	Bias	COV	Data	Bias	COV	Data
Driven pile method	1.29	0.39	90	0.99	0.37	29
Vibro-hammer method	1.11	0.14	4	0.97	0.33	4
Cast-in-place RC pile Method	1.40	0.64	59	1.14	0.60	33
Bored pile method	1.12	0.36	87	0.97	0.37	33
Steel pipe soil cement pile method	1.12	0.27	24	1.00	0.26	12
Screwed steel pile method	1.38	0.38	20	1.03	0.34	20
Pre bored pile method	0.78	0.29	39	0.98	0.30	13

Design Equation

In allowable stress design, both the tensile stress in reinforcement and the compressive stress in concrete are checked. Accordingly, the present study proposes the following LRFD equations for the pile bending moment:

$$\Psi \ M_{cal} \le \Phi_Y M_Y \qquad (5)$$

$$\Psi \ M_{cal} \le \Phi_U M_U \qquad (6)$$

where Ψ is the load factor or modifier that considers the uncertainty in the calculated pile bending moment in the pile, Φ_Y and Φ_U are the resistance factors for yield and maximum bending moment strengths, respectively, M_{cal} is the calculated pile bending moment in the pile, and M_Y and M_U are the yield and maximum bending moment strengths of the pile, respectively. The yield bending moment strength, M_Y, agrees with the bending moment at which a reinforcement bar becomes plastic and the maximum bending moment strength, M_U, agrees with the bending moment at which the bending strain in concrete reaches the compressive collapse strain. Based on above considerations, it is expected that the load factor, Ψ, that is applied to the calculated bending moment in piles becomes a function of the soil investigation/testing method and soil classification, because the distribution of the pile bending moment in the depth direction varies with the uncertainty in the coefficient of subgrade reaction, as stated above.

Code Calibration

1) Prototype foundations

A code calibration will be conducted for two prototype highway bridge foundation of piers for each piling methods using FOSM. The prototype highway bridge substructures are designed by Japanese Highway Bridges Design Specifications and are checked for allowable stresses for concrete and reinforcement with factors of safety. In this study, we deal with seismic design of pile foundations for the Level 1 (or frequent scale) Earthquake

Design situation. The combination of all dead loads and seismic inertial force from the superstructure is considered, and these loads are also considered as given conditions with no uncertainty. The design calculation is conducted using a typical beam-on-Winkler-foundation model. A schematic diagram is shown in Fig. 3. The axial resistance of a pile subjected to vertical loads is expressed using a spring arranged at the pile top.

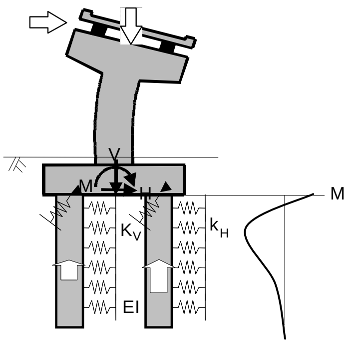
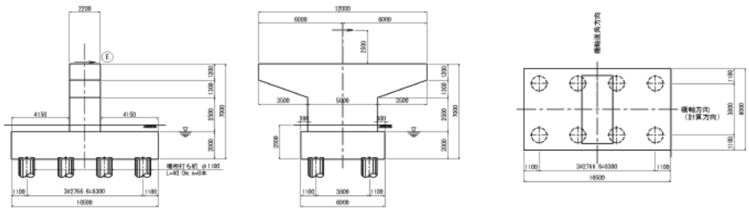
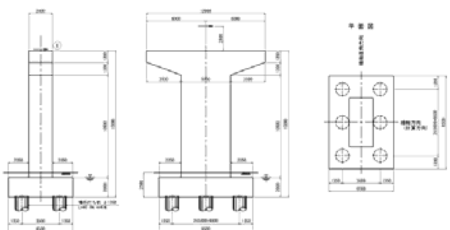


Figure 3 Design calculation model

In this paper, we basically introduce the cast-in-place RC piles (Drilled shaft) cases. The prototype highway bridge substructures are shown in Fig. 4. Because of simplicity, in consideration of the variation in the Young's modulus of soil, a uniform subsoil layer overlaying the bearing layer is assumed for both cases. The Case A foundation is designed so that the maximum bending moment in the piles will appear at the top of pile. The Case B foundation is designed so that the maximum pile bending moment will appear deep underground.



Case A (E_{PMT} = 1,400 kN/m^2, K_V, = 580,000 kN/m, Pile diameter, B, = 1,100 mm)



Case B (E_{PMT} = 8,400 kN/m^2, K_V, = 687,000 kN/m, Pile diameter, B, = 1,350 mm)

Figure 4 Prototype highway bridge substructures (cast-in-place RC piles)

2) Monte Carlo simulation for estimating the uncertainty in the calculated pile bending moment

The Monte Carlo simulation is conducted to estimate the variation in the calculated pile bending moment. The model uncertainties considered in the Monte Carlo simulation are listed in Tables 2, 4, and 5. All of the parameters are assumed to follow a lognormal distribution. The model uncertainty in the bending rigidity of the pile is estimated separately using a Monte Carlo simulation for the designed cross-sections considering the model uncertainty in the material property such as the Young's modulus of reinforcement and the unconfined strength of concrete that is cast underwater.

Monte Carlo simulation was conducted for different prototype design cases and different soil investigation or testing cases or piling methods. The calculation error is estimated by dividing the (absolute) maximum bending moment calculated in the Monte Carlo simulation by the (absolute) maximum bending moment obtained in the prototype design calculation.

Table 5 Model uncertainty in the material property of drilled shafts

Items	Nominal value	Bias	COV
Concrete strength, f_{ck}	24 N/mm^2	1.40	0.18
Young's modulus of concrete	Given as a function of f_{ck} in the Japanese Specifications for Highway Bridges and modeled to be deterministic in this study		
Yield strength of reinforcement (SD345)	345 N/mm^2	1.14	0.04
Young's modulus of reinforcement	2.00×10^5 N/mm^2	(constant)	(constant)

3) Monte Carlo simulation for estimating the uncertainty in the bending strength of the pile

A separate Monte Carlo simulation is conducted for the bending strength of a pile for the cross section of prototype structures. The material uncertainties in concrete and reinforcement are as listed in Table 5. The bending strength of a pile changes with the axial force on the pile with increasing seismic force. In other words, the increment in the axial force during an earthquake has an uncertainty because of the model error of the typical design calculation model, such as the coefficient of horizontal subgrade reaction and the axial spring of the pile. The variation in the axial force of the tensile pile can be estimated from the numerical results obtained in the previous Monte Carlo simulation for the uncertainty in the calculated bending moment, in which the structural design of the pile is governed by the design of the tensile piles. As a result, the uncertainty in the increment of the axial force during an earthquake is estimated to have a bias of 1.0 and a COV of 0.10.

The uncertainty in the yield bending moment strength, M_Y, and the ultimate bending moment strength, M_U, considered in this study is used based on the Monte Carlo simulation's result shown in Table 6.

Table 6 Uncertainty in M_Y and M_U (Cast-in-place RC pile)

Bias	1.15
COV	0.10

4) Load and resistance factors obtained by FOSM

FOSM is used to obtain the load and resistance factors. First, the reliability indexes of the prototype foundations are estimated. Table 7 shows the example of reliability indexes of Cast-in-place RC pile designed by current Japanese highway design specification for L1 Earthquake. It is found that β for positive side is more sensitive than for negative side by the difference of soil investigation methods. Additionally, beta value evaluated by SPT test which N value is less than 5 is smaller than the other cases. These results indicated that reliability of piles depend on the soil investigation methods, especially maximum bending moment appears at the head of pile.

Target Reliability index β_T is set based on evaluated reliability indexes of the typical types pile foundation designed by current design specification. Soil investigation method is assumed as SPT on sandy soil. Typical types pile foundations are assumed as following 3 types of pile foundations; Cast-in-place RC pile, Steel pipe pile by driven pile construction method and by embedding method by an inner excavation construction. Accordingly, we finally use the target reliability indexes of β_T = 1.8 and 3.1 for the yield and ultimate bending moment strengths, M_Y and M_U, respectively.

Table 7 Reliability indexes of Cast-in-place RC pile designed by current design specification for L1 Earthquake

		Yield Bending moment M_Y		Maximum bending moment M_U	
Soil investigation / testing		Positive	Negative	Positive	Negative
Pile load test		1.84	1.50	4.08	2.59
Pressuremeter test or laboratory test		1.54	1.50	3.54	2.59
Only SPT	Sandy soil	1.31	1.50	3.07	2.59
	Cohesive soil	1.20	1.50	2.85	2.59
	$N_{ave} < 5$ (bias =1.0)	0.86	1.50	2.27	2.59

Basically, load factor and resistance factor are set separately. However, we found that resistance factor was not sensitive, so resistance factor puts together in loading factor like Eq.(7) in this study. Moreover, new loading factor divides into two factors shown in Eq(8).

One is a loading factor considering the difference of pile types and piling methods. The other is a loading factor considering the difference of soil investigation or load tests. By this modification, we are able to clarify a merit to introduce the LRFD more clearly. These factors divided though trial and error method.

$$\Psi' = \Psi / \Phi \qquad (7)$$

$$M_d = \boldsymbol{\Psi_1} \cdot \boldsymbol{\Psi_2} \cdot \boldsymbol{M} \qquad (8)$$

Where,

M_d : Design bending moment of piles

M : Calculated Bending moment of pile

Ψ_1 : Load factor considering the difference of pile types and piling methods

Ψ_2 : Load factor considering the difference of soil investigation / load tests

Finally, the load factors are obtained as summarized in Table 9 and Table 10. As for the load factor considering the difference of pile type and piling methods Ψ_1, the load factor of cast-in-place RC pile tends to be larger than the others. It is assumed because the COV of Kv of this pile type is larger than the others. As for the load factor considering the difference of soil investigation and load testsΨ_2, it is found that it is to enable reasonable design by detailed soil investigation or load test.

Table 9 Load factor considering the difference of pipe type and piling method Ψ_1

Pile type and Piling Method	Yield Bending Moment M_Y		Maximum bending moment M_U	
	Positive	Negative	Positive	Negative
Cast-in Place RC Pile	1.80	2.05	1.90	3.75
Steel Pipe Pile(Drilled pile)	1.40	1.50	1.70	2.40
Prestressed High strength Concrete Pile(Drilled pile)	1.60	1.75	1.85	2.70
Steel Pipe Pile (embedding method by an inner excavation construction)	1.50	1.50	1.55	2.40
Prestressed High strength Concrete Pile(embedding method by an inner excavation construction)	1.75	1.70	2.00	2.90
Steel Pipe Soil Cement Composite Pile	1.30	1.25	1.55	1.70
Steel Pipe Pile (Screwed Steel Pile Method)	1.45	1.45	1.55	2.10
Preboring Pile Driving Method	1.65	1.60	1.95	2.60

Table 10 Load factor considering the difference of soil investigation and load testsΨ_2

Soil investigation / testing		Positive	Negative
Pile load test		0.90	1.00
Pressuremeter test or laboratory test		0.95	1.00
Only SPT	Sandy soil	1.00	1.00
	Cohesive soil	1.05	1.00
	$N_{ave} < 5$	1.15	1.00

Concluding Remarks

We proposed the load factors to verify the bending moment of pile of pile foundation for Level 1 earthquake based on LRFD design concept. However, the number of test calculations is not enough to finalize these load factors. We confirm validity of proposed load factors from these results and are going to revise them as needed.

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