LRFD Code Development for Foundation Structures in Korea-Reliability Analysis of Static Bearing Capacity Evaluation of Driven Steel Pipe Piles

Kiseok Kwak, Jaehyun Park, Juhyung Lee
Korea Institute of Construction Technology, Korea

Kyung Jun Kim
North Carolina Department of Transportation, USA

Jungwon Huh
Chonnam National University, Korea

ABSTRACT: Reliability analyses of the static bearing capacity analysis methods for driven steel pipe piles adopted in the Korean Standards for Foundation Structures have been performed as part of the efforts to develop the Load and Resistance Factor Design Code for foundation structures in Korea. Over 2,000 static load test data on driven steel pipe piles were collected from all around the country. After review of the load-displacement curves, subsurface investigation reports, and other related documents, only 43 load test data were found to be useful for the reliability analysis. These load test piles were sorted into two cases: pile tip on soil case and pile tip on rock case. Resistance bias factor statistics of each pile tip case were evaluated for the two static design methods. Reliability analysis was performed by two types of First Order Reliability Methods, Mean Value First Order Second (MVFOSM) method and Advanced First Order Second (AFOSM) method. AFOSM method resulted in a little larger reliability indices than MVFOSM method, but the difference was not significant.

1 INTRODUCTION

In recent, structural and geotechnical engineering design in a number of countries including United States, Canada, and European Union has shifted from Allowable Strength Design (ASD) to Load and Resistance Factor Design (LRFD). Goble (1999) surveyed LRFD practice of government agencies in the United States (US) and Canada. Some of the states in the US reported significant discrepancies between the conventional ASD practice and the design by the newly adopted LRFD code. In the Province of Ontario, Canada, the LRFD highway bridge design code (1983) resulted in overly conservative and expensive design. It is important to incorporate local ASD experience and practice accumulated over many decades in developing LRFD codes in order to make them acceptable to the local engineering and construction communities. This can be achieved by selecting the target reliability indices for calibration of load and resistance factors based on reliability analysis of the current ASD practice.

This paper presents the reliability analysis of static bearing capacity design methods commonly used in Korea for driven open-ended steel pipe piles. This is part of the research effort in Korea for LRFD implementation in geotechnical engineering. Over 2,000 static load test data on driven steel pipe piles were collected from all around the country and reviewed. To minimize the load test cost, most of the load tests were stopped when the design load was verified; thus the load-displacement curve did not provide a reliable failure load. Only 43 load test data showed a reliable failure load and were selected for this study. Based on these load test data, statistics of the resistance bias factors were evaluated, and the reliability of the current static bearing capacity analysis methods was evaluated by the First Order Reliability Method (FORM).

2 STATIC LOAD TEST DATA

Collection of reliable load test data is the most important and time-consuming task for reliability analysis and LRFD code development. Static load test reports on driven steel pipe piles were collected from all around Korea along with available records of design, construction, subsurface investigation, and laboratory testing. In addition, research papers and theses on this subject were also reviewed to increase the pool of useful database. Even though a total of 2,227 static load test data were collected and reviewed, it was found that most of the data did not have a failure load that could be used in this study. This was due to the fact that most of the tests were planned to verify the design bearing capacity of the pile, and the load test was terminated once it achieved a load equal to 1.5 to 2 times the design load. Additionally, some of the load tests with a failure load were discarded due to lack of other supporting documents such as site boring logs or pile installation records. Only 43 static load test data were found reliable and useful for this study. All of these test piles were driven into mixed soil layers of sand, gravel, silt, and clay. The tip of 31 test piles was on soil and 12 was on rock (weathered or weak rock). The data were sorted into two cases for reliability analysis: 1) pile tip on soil, and 2) pile tip on rock.

Table 1 Measured Bearing Capacity of Piles with Tip on Soil

Test Pile	Pile Dimension		N at Tip	Measured Capacity (kN)						
	Diameter (mm)	Length (m)		Davisson	Shape of Curve	DeBeer	D=25.4 ㎜	D=0.1B	ASCE 20-96	Average
T-2	508	34	27	1529	1666	1813	1530	1931	1480	1658
T-3-1	610	9.6	26	2254	2234	2176	2499	2744	2342	2375
T-3-2	508	7.4	26	1470	1578	1323	1764	2058	1597	1632
T-3-3	610	7.3	43	2087	2558	2450	2646	-	2215	2391
T-4	508	7.3	31	2352	2205	2146	-	-	2381	2271
T-6-1	610	22.9	10	1911	1823	1666	2019	2519	2078	2003
T-6-2	610	25.8	50	3332	3332	2793	2881	3900	3489	3288
T-7	508	7.3	32	2205	2136	2087	2666	-	2303	2280
T-8-1	508	41.3	N/A	-	3489	-	4116	-	-	3802
T-8-2	711	22.2	N/A	2646	2205	-	-	-	3058	2636
T-8-3	508	19.1	N/A	4998	5547	-	5782	-	5459	5446
T-9	610	7.7	37	1264	2058	2744	2156	3038	1539	2133
T-10	813	54.6	4	6086	-	-	5243	-	6625	5985
T-11	406	21.2	45	-	1568	-	-	-	-	1568
T-12	508	28	50	2528	2254	1695	2450	-	2568	2299
R-1	508	33	5	4018	3724	2940	3263	3920	4067	3655
R-2	508	24	11	6341	6439	6003	5243	6419	6488	6155
R-3-1	609	36.5	13	5145	5655	4018	3871	5998	5596	5047
R-5-1	610	42.4	27	7056	6723	6125	4116	7507	7869	6566
R-5-2	610	57.4	50	4802	6272	5934	3136	4998	6448	5265
R-6-1	610	24.5	46	6860	6135	6321	5135	8232	7291	6662
R-6-2	610	23.3	37	4929	4959	4900	4332	6938	5488	5258
R-7	508	31.4	25	1323	1240	1225	1352	1470	1343	1326
R-8	609	55	32	3538	3994	3984	2254	3812	3704	3548
R-9	508	17	5	4880	4969	4508	4508	-	4802	4733
R-10	508	9.5	44	2960	3018	2646	3283	-	2607	2903
R-11	406	9.5	47	3156	3185	2842	3234	-	3028	3089
J-2-1	508	39	50	4243	3920	-	3744	-	4371	4070
J-2-2	508	39	50	4900	4459	-	3949	-	4920	4557
J-2-3	508	38.5	50	-	3557	2597	3920	-	-	2519
J-3	406	9.5	33	2891	2254	-	-	-	-	2573

The selected test data represent all parts of Korea except Jejoo Province. The diameter of the test piles was in the range of 406mm to 812mm. Ten of them were 6m to 10m long, 17 were 10m to 30m long, and 16 were 30m to 58m long. The static load test was performed using one of the three types of loading procedures described in the American Society for Testing and Materials (ASTM) Designation 1143: standard loading, quick loading, and cyclic loading. It has been reported that the loading procedures do not affect the test results (i.e., pile capacity) significantly (Paikowsky et al., 1999), and this study did not differentiate the test data based on the loading procedures. A majority of the selected load test data showed only total bearing capacity without a separate value of shaft or tip resistance because no load transfer readings along the pile shaft were made during the test. Hence, reliability analysis was performed only for total pile capacity.

Table 2 Measured Bearing Capacity of Piles with Tip on Rock

Test Pile	Pile Dimension		N at Tip	Measured Capacity (kN)						
	Diameter (mm)	Length (m)		Davisson	Shape of Curve	DeBeer	D=25.4 mm	D=0.1B	ASCE 20-96	Average
T-1	508	15.5	41	5292	5125	4537	5292	-	-	5062
T-5	508	6.5	>50	960	960	882	1568	-	1058	1086
T-8-4	406	9.5	33	2597	-	-	-	-	2862	2729
T-10-2	508	33	>50	16092	16092	16092	15494	-	16092	15972
R-3-2	508	30	>50	-	3381	-	3038	3920	3410	3437
R-3-3	610	30	>50	6664	6292	-	4900	7281	6889	6405
R-4-1	609	13.1	>50	7311	7644	8095	7448	-	7840	7668
R-4-2	609	19.8	>50	7203	6997	6272	6566	-	7678	6943
R-4-3	609	30.3	>50	7399	7605	6047	5321	8291	7948	7102
J-1-1	508	12	>50	2323	2254	2156	2499	2862	2421	2419
J-1-2	508	12	>50	2038	1960	1744	2205	2614	2107	2111
J-1-3	508	12	>50	2185	2313	1852	2577	-	2450	2276

Table 3 Ksx for Six Failure Criteria

Pile Tip on Soil						Pile Tip on Rock					
Criterion	No. of Data	K_{sx} Mean	K_{sx} S. D.	K_{sx} Max.	K_{sx} Min.	Criterion	No. of Data	K_{sx} Mean	K_{sx} S. D.	K_{sx} Max.	K_{sx} Min.
Davisson	28	1.029	0.145	1.688	0.890	Davisson	11	1.017	0.052	1.131	0.956
Shape of Curve	30	1.024	0.171	1.361	0.867	Shape of Curve	11	1.019	0.052	1.131	0.934
DeBeer	23	1.089	0.316	1.382	0.778	DeBeer	9	1.125	0.082	1.231	0.947
D=25.4 mm	27	1.105	0.233	1.774	0.855	D=25.4 mm	11	1.032	0.173	1.335	0.693
D=0.1B	15	0.864	0.097	1.113	0.702	D=0.1B	5	0.853	0.026	0.880	0.808
ASCE 20-96	27	0.978	0.108	1.387	0.834	ASCE 20-96	11	0.965	0.043	1.026	0.894

There are several failure criteria available to estimate ultimate bearing capacity of a pile from the load-displacement curve. The measured bearing capacity can be quite different depending on the selection of the failure criterion. Six different failure criteria were employed in this study to estimate the pile's ultimate bearing capacity: Davisson, Shape of Curve, DeBeer, D=25.4mm, D=0.1B (where, D: pile top displacement and B: pile diameter or width), and ASCE 20-96 (1997). The load-displacement curves of the 43 test piles were evaluated by the six failure criteria, and the results are summarized in Table 1 for the piles with tip on soil, and in Table 2 for the piles with tip on rock.

Only 18 out of the 43 load-displacement curves provided an ultimate capacity for all six criteria, and D=0.1B criterion was applicable to only 20 test data. For each test data, the average of the estimated ultimate capacities by all the applicable failure criteria was computed, and the ratio of the average capacity over each failure criterion capacity (K_{sx}) was also computed. The statistics of K_{sx} for each failure criterion were evaluated and summarized in Table 3.

Davisson, Shape of Curve, and ASCE 20-96 criteria appeared to perform equally well (i.e., mean K_{sx} close to one with smaller standard deviation) among the six. However, Shape of Curve criterion is generally more subjective than ASCE 20-96 and Davisson criteria, and ASCE 20-96 is not yet widely accepted in Korea. Davisson criterion was proven to perform the best in other research project (Paikowsky, 2004). Therefore, Davisson criterion was chosen to determine the ultimate capacity from the load test, which is called 'measured capacity'.

3 STATIC BEARING CAPACITY EVALUATION

The Korean Design Standards for Foundation Structures (2003) adopts two static bearing capacity analysis methods. These two methods were used to estimate the static ultimate capacity (Q_u) of the 43 test piles. The first method is expressed in the following formula.

$$Q_u = (\sigma_v' N_q + c N_c) A_p + \Sigma f_s A_s \tag{1}$$

where, σ_v' : effective overburden pressure at pile tip with the depth limit to 20B (B: pile diameter)
N_q : bearing capacity factor as a function of soil's friction angle (ϕ)
c : cohesion of soil
N_c : bearing capacity factor for cohesion, $N_c = 9$ for soils with $\phi = 0$
A_p : cross section area of pile assuming 100% plugging
f_s : unit frictional resistance along the shaft
$= K_s \overline{\sigma_v'} \tan\delta$ for cohesionless soils
where, $K_s = 1.4 (1 - \sin\phi)$ and $\delta = 20$ degrees
$\overline{\sigma_v'}$: average effective overburden pressure along the shaft
$= \alpha c_u$ for cohesive soils
where, α : adhesion factor, and c_u : undrained shear strength of soil
A_s : pile shaft surface area

It has been a general practice in Korea that open-ended steel pipe piles are assumed to be plugged completely during pile driving, and the whole cross sectional area of the pile tip is used in static bearing capacity evaluation. When the shear strength values of soil were not available, the friction and cohesion values were estimated from standard penetration test (SPT) blow counts (uncorrected N values) using the formulae proposed by Hara, et al. (1971), which are adopted in the Korean Design Standards for Foundation Structures. The second method is the empirical formula proposed by Meyerhof (1976) as presented below.

$$Q_u = m N_p A_p + n N_s A_s \tag{2}$$

where, $m = 3 L_b/B \leq 30$ (L_b: pile embedment depth)
N_p : average SPT N value in the vicinity of pile tip
n = 0.2
N_s : average SPT N value along pile shaft
$m N_p \leq 1500$ metric tons/m^2, $n N_s \leq 10$ metric tons/m^2

Static bearing capacity of the 43 test piles was calculated by these two methods for the same pile size and length as used in the load test, and for the subsurface conditions of the test site. The computed static bearing capacities are called 'predicted capacity' and summarized in Tables 4 and 5 along with soil properties, ground water depths, and measured bearing capacities by the Davisson criterion. Equation (2) was not applicable to four test piles (T-8-1, T-8-2, T-8-3, and T-8-4) because no SPT data was available for either pile tip or shaft. Also, the load-displacement curves from test piles T-8-1, T-11, R-3-2, and J-2-3 did not provide a failure load by the Davisson criterion. Accordingly, these test data could not be used for resistance bias factor calculation and reliability analysis. As shown in Fig.1, there is no good correlation between the measured capacity and the predicted capacity by either static analysis method. In general, Equation (2) provides more conservative prediction of pile bearing capacity than Equation (1).

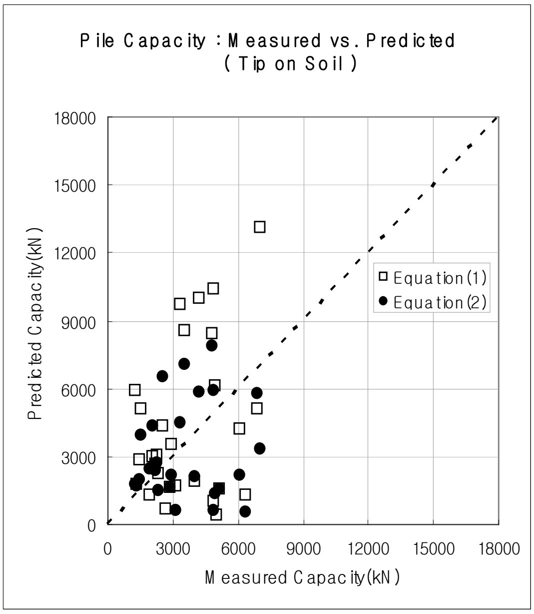
Table 4 Predicted Bearing Capacity of Piles with Tip on Soil

Test Pile	N at Tip	Unit Weight of Soil (kN/m^3)		Friction Angle at Tip (degree)	C_u along Shaft (kN/m^2)	Ground Water (m)	Measured Capacity (kN)	Predicted Capacity (kN)	
		Shaft	Tip					Equation (1)	Equation (2)
T-2	27	18.1	18.1	38	N/A	-1.5	1529	5093	3929
T-3-1	26	18.1	18.1	38	N/A	-1.5	2254	3039	2691
T-3-2	26	18.1 - 20.1	18.1	38	N/A	-6.4	1470	2875	1991
T-3-3	43	18.1	18.1	40	N/A	-1.5	2087	2998	4314
T-4	31	18.1 - 20.1	20.1	39	N/A	-2.2	2352	2231	1471
T-6-1	10	18.1 - 20.1	19.6	N/A	147	-1.5	1911	1259	2417
T-6-2	50	18.1 - 21.1	20.1	44	163	-1.5	3332	9691	4471
T-7	22	21.1	22.1	40	N/A	-1.5	2205	2665	2390
T-8-1	N/A	18.1	18.1	N/A	49	-1.5	N/A	N/A	N/A
T-8-2	N/A	18.1	18.1	N/A	16	-1.5	2646	695	N/A
T-8-3	N/A	18.1	18.1	N/A	18	-1.5	4998	430	N/A
T-9	37	20.1 - 21.1	20.1	41	260	-3.4	1264	5927	1789
T-10-1	4	16.7 - 17.6	17.6	N/A	79 - 92	-1.5	6086	4210	2181
T-11	45	18.1 - 20.1	20.1	43	N/A	-1.5	N/A	N/A	N/A
T-12	50	22.1	22.1	44	N/A	-1.5	2528	4333	6541
R-1	5	18.1 - 20.1	18.1	N/A	92	-3.2	4018	1876	2107
R-2	11	18.1 - 18.6	18.1	31	29	-1.5	6341	1283	510
R-3-1	13	18.1 - 20.1	20.1	N/A	29 - 184	-3	5145	1557	1575
R-5-1	27	18.1 - 19.6	18.1	38	48 - 79	-1.7	7056	13087	3302
R-5-2	50	18.1 - 22.1	22.1	44	64	-1.7	4802	8425	7893
R-6-1	46	18.1 - 22.5	20.1	43	N/A	-1.5	6860	5077	5797
R-6-2	37	18.1 - 20.1	20.1	41	64	-1.5	4929	6135	1364
R-7	25	18.1 - 21.1	20.1	N/A	141 - 294	-1.5	1323	1790	1702
R-8	32	17.6 - 22.1	20.1	40	29	-4.0	3538	8586	7092
R-9	5	18.1 - 20.1	20.1	N/A	88	-4.5	4880	1043	612
R-10	44	20.1	20.1	43	N/A	-1.9	2960	3558	2151
R-11	47	17.2 - 20.1	20.1	44	108	-1.5	3156	1716	635

J-2-1	50	18.6 - 20.1	20.1	44	141 -485	-1.5	4243	10008	5872
J-2-2	50	18.6 - 20.1	20.1	44	141 -485	-1.5	4900	10416	5920
J-2-3	50	18.6 - 20.1	20.1	44	141 -485	-1.5	N/A	N/A	N/A
J-3	33	20.1	20.1	40	N/A	-1.5	2891	1657	1641

Table 5 Predicted Bearing Capacity of Piles with Tip on Rock

Test Pile	N at Tip	Unit Weight of Soil (kN/m^3)		Friction Angle at Tip (degree)	C_u along Shaft (kN/m^2)	Ground Water (m)	Measured Capacity (kN)	Predicted Capacity (kN)	
		Shaft	Tip					Equation (1)	Equation (2)
T-1	41	18.1 - 20.1	24.5	42	N/A	-1.5	5292	3433	1480
T-5	50	18.1	24.5	44	N/A	-1.5	960	1773	608
T-8-4	33	18.1	18.1	40	16	-1.5	2597	167	N/A
T-10-2	50	15.7 - 24.5	24.5	44	N/A	-1.5	16092	10277	5078
R-3-2	50	17.6 - 24.5	24.5	44	79	-1.5	N/A	N/A	N/A
R-3-3	50	18.1 - 22.1	24.5	44	79	-1.5	6664	6106	2362
R-4-1	50	17.6 - 24.5	24.5	44	29	-1.5	7311	5390	1598
R-4-2	50	17.6 - 24.5	24.5	44	N/A	-1.7	7203	6057	6545
R-4-3	50	17.6 - 19.6	24.5	44	105	-1.5	7399	6752	2057
J-1-1	50	18.1 - 24.5	24.5	44	N/A	-1.5	2323	3479	3791
J-1-2	50	19.6 - 24.5	24.5	44	N/A	-3.2	2038	4567	3688
J-1-3	50	20.1 - 24.5	24.5	44	N/A	-4.5	2185	6852	4481



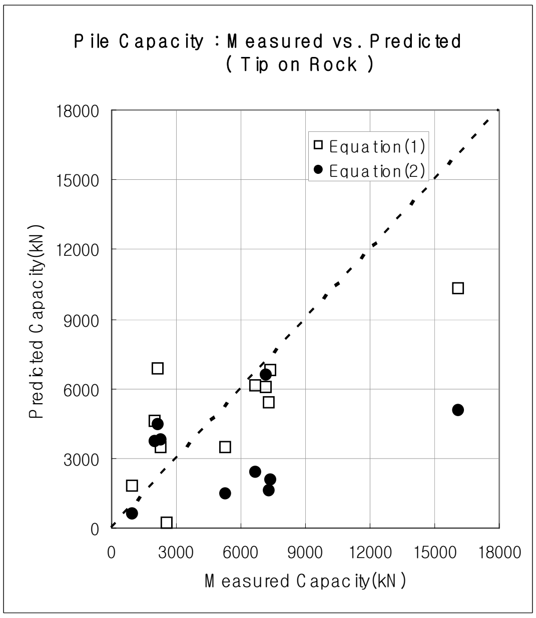


Fig.1 Correlation between Measured and Predicted Capacities

4 RESISTANCE BIAS FACTOR

Resistance bias factor is defined as the ratio of the measured ultimate bearing capacity from a load test over the predicted ultimate bearing capacity by a static bearing capacity formula. Resistance bias factors for the selected test piles were computed for the two static bearing capacity analysis methods described above. Table 6 is a summary of the resistance bias factors for piles with the tip on soil, and Table 7 is for piles with the tip on rock. For pile tip on soil case, Equation (1) appears to predict the bearing capacity more closely to the measured capacity than Equation (2), though both of them show a considerably high degree of variation in the bias factors. Even though both equations significantly underestimate, on the average, the static bearing capacity in both pile tip cases, the conservatism in the static analysis cannot be assured due to the large variation in the bias factors.

The resistance bias factor accounts for all of the uncertainties from various sources of errors such as model uncertainty, SPT blow count error, spatial variability of the soil parameters, load test error, soil sampling and testing error, and so on. The bias factor statistics are influenced by the size of the data set and the variation in the bias factors. Extremely outlying data points may not be representative of the resistance due to the large error in either the measured capacity or the predicted capacity. Therefore, it is reasonable to remove the far-outlying data points from the bias factor statistics. The bias factor values outside the boundaries defined by the mean plus or minus two times the standard deviation in Tables 6 and 7 were discarded. The statistics of the filtered resistance bias factors were computed to be used for reliability analysis and presented in Table 8. Distribution of these resistance bias factors was also examined as shown in Figures 2 and 3, and lognormal distribution was found to better represent the bias factor distribution.

Table 6 Resistance Bias Factors for Piles with Tip on Soil

Test Pile	Measured Capacity (kN)	Predicted Capacity (kN)		Resistance Bias Factor	
		Equation (1)	Equation (2)	Equation (1)	Equation (2)
T-2	1529	5093	3929	0.30	0.39
T-3-1	2254	3039	2691	0.74	0.84
T-3-2	1470	2875	1991	0.51	0.74
T-3-2	2087	2998	4314	0.70	0.48
T-4	2352	2231	1471	1.05	1.60
T-6-1	1911	1259	2417	1.52	0.79
T-6-2	3332	9691	4471	0.34	0.75
T-7	2205	2665	2390	0.83	0.92

T-8-1	N/A	2325	N/A	N/A	N/A
T-8-2	2646	695	N/A	3.81	N/A
T-8-3	4998	430	N/A	11.64*	N/A
T-9	1264	5927	1789	0.21	0.71
T-10	6086	4210	2181	1.45	2.79
T-11	N/A	1707	1486	N/A	N/A
T-12	2528	4333	6541	0.58	0.39
R-1	4018	1876	2107	2.14	1.91
R-2	6341	1283	510	4.94	12.43*
R-3-1	5145	1557	1575	3.30	3.27
R-5-1	7056	13087	3302	0.54	2.14
R-5-2	4802	8425	7893	0.57	0.61
R-6-1	6860	5077	5797	1.35	1.18
R-6-2	4929	6135	1364	0.80	3.62
R-7	1323	1790	1702	0.74	0.78
R-8	3538	8586	7092	0.41	0.50
R-9	4880	1043	612	4.68	7.97*
R-10	2960	3558	2151	0.83	1.38
R-11	3156	1716	635	1.84	4.97
J-2-1	4243	10008	5872	0.42	0.72
J-2-2	4900	10416	5920	0.47	0.83
J-2-3	N/A	1008	5794	N/A	N/A
J-3	2891	1657	1641	1.74	1.76
			Mean	1.73	2.10
			Std Deviation	2.34	2.71
			COV	1.35	1.30

* values outside the boundary of the mean plus or minus two times the standard deviation

Table 7 Resistance Bias Factors for Piles with Tip on Rock

Test Pile	Measured Capacity (kN)	Predicted Capacity (kN)		Resistance Bias Factor	
		Equation (1)	Equation (2)	Equation (1)	Equation (2)
T-1	5292	3433	1480	1.54	3.57
T-5	960	1773	608	0.54	1.58
T-8-4	2597	167	N/A	15.6*	N/A
T-10	16092	10227	5078	1.57	3.17
R-3-2	N/A	4479	4472	N/A	N/A
R-3-3	6664	6106	2362	1.09	2.82
R-4-1	7311	5390	1598	1.36	4.57
R-4-2	7203	6057	6545	1.19	1.10
R-4-3	7399	6752	2057	1.10	3.60
J-1-1	2323	3479	3791	0.67	0.61
J-1-2	2038	4567	3688	0.45	0.55
J-1-3	2185	6852	4481	0.32	0.49
			Mean	2.31	2.21
			Std Deviation	4.43	1.51
			COV	1.92	0.68

* values outside the boundary of the mean plus or minus two times the standard deviation

Table 8 Statistics of Resistance Bias Factors for Reliability Analysis

	Pile Tip on Soil		Pile Tip on Rock	
	Equation (1)	Equation (2)	Equation (1)	Equation (2)
Mean	1.363	1.420	0.983	2.206
Standard Deviation	1.323	1.177	0.457	1.511
Coefficient of Variation	0.970	0.829	0.465	0.685

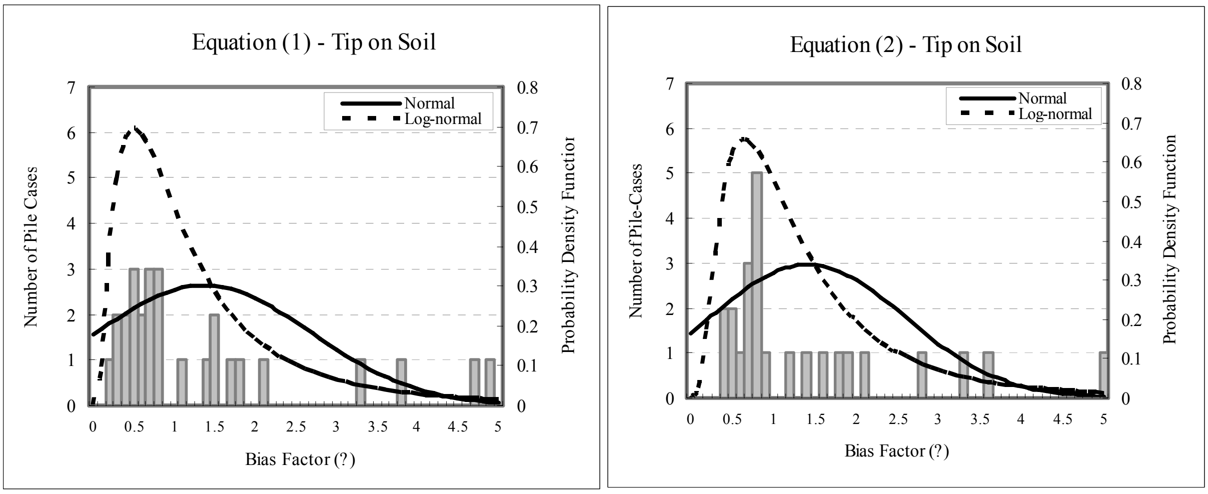


Fig.2 Distribution of Resistance Bias Factors for Piles with Tip on Soil

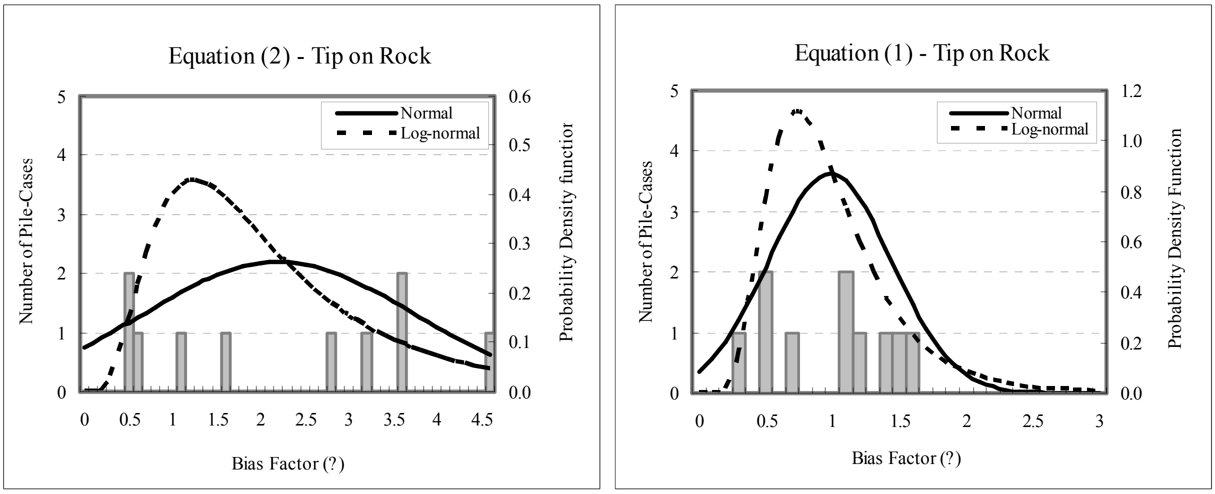


Fig.3 Distribution of Resistance Bias Factors for Piles with Tip on Rock

5 RELIABILITY ANALYSIS

Reliability of pile foundation design can be expressed in terms of probability of failure or reliability index. Assume that there are two basic random variables, the load (Q) and the resistance (R). The limit state function can be defined as g(R, Q) = 0, which can be a linear or nonlinear function of R and Q. The probability of failure, P_f, can be expressed by the following equation.

$$P_f = \iint_{g<0} f_{R,Q}(r,q)\,dr\,dq \qquad (3)$$

in which, $f_{R,Q}(r,q)$ is the joint probability density function for the basic random variables R and Q. Since this integration is practically very difficult or impossible, analytical approximation or numerical simulation techniques are employed to compute the probability of failure. In this study, two types of First Order Reliability Methods (FORM), Mean Value First Order Second Moment (MVFOSM) method and Advanced First Order Second Moment (AFOSM) method were used to evaluate the reliability of the static bearing capacity design methods.

There are two sets of information that are required for reliability analysis of pile foundation design: load information in terms of statistics of load bias factors and resistance information in terms of statistics of resistance bias factors. The statistics of resistance bias factors used in this study are shown in Table 8. The load bias factor is defined as the ratio of the observed actual load over the nominal load. This study employed the statistics of load bias factors used for the American Association of State Highway and Transportation Officials (AASHTO) LRFD Bridge Design Code (NowaK, 1999). It was based on the assumption that the load statistics in Korea are not significantly different from those in the United States. This assumption is subject to verification in the future research. AASHTO LRFD Specification Strength I Case is considered as the critical loading case for pile bearing capacity, and the following load statistics were used in the reliability analysis: dead load bias factor mean(λ_{QD}) = 1.05, dead load bias factor coefficient of variation (COV_{QD}) = 0.10, live load bias factor mean(λ_{QL}) = 1.15, and live load bias factor coefficient of variation (COV_{QL}) = 0.20. Distribution of both dead and live load bias factors was assumed to be lognormal. Hansell and Viest (1971) reported that the ratio of dead load over live load (QD/QL) could be expressed by the empirical formula QD/QL = (1 + I)(0.0132L), where I is the dynamic load impact factor (= 0.33 for LRFD loads) and L is bridge span length in feet. From a survey of bridge span lengths in Korea, it was found that the span lengths in the range of 30 m ± (or 98 feet ±) were most common. Thus, QD/QL of 1.72 was chosen for reliability analysis.

Reliability Analysis by First Order Reliability Method (FORM)

Two random variables, the load (Q) and the resistance (R), are considered and they are assumed to be mutually independent and lognormally distributed. The limit state function in this case is defined as: g (R, Q) = ln (R) – ln (Q) = ln (R/Q). By definition, the reliability index (β) is the ratio of the mean value of the limit state function ($\bar{g}$) over its standard deviation (ζ_g), and it can be expressed in the following equation.

$$\beta = \frac{\ln\left[(\bar{R}/\bar{Q})\sqrt{(1+COV_Q^{\;2})/(1+COV_R^{\;2})}\right]}{\sqrt{\ln[(1+COV_R^{\;2})(1+COV_Q^{\;2})]}} \tag{4}$$

where, $\bar{R}$, $\bar{Q}$: mean values of R and Q, and COV_R, COV_Q : coefficients of variation of R and Q. For AASHTO Strength I Case, Q = QD + QL and $COV_Q^2 = COV_{QD}^2 + COV_{QL}^2$. By introducing factor of safety (FS) such that $\bar{R}$ = (FS) $\bar{Q}$ and the bias factors of both load and resistance (λ_{QD}, λ_{QL}, λ_R), β can be rewritten in the following form.

$$\beta = \frac{\ln\left[\frac{\lambda_R * FS * (QD/QL+1)}{\lambda_{QD} * (QD/QL) + \lambda_{QL}}\sqrt{(1+COV_{QD}^{\;2}+COV_{QL}^{\;2})/(1+COV_R^{\;2})}\right]}{\sqrt{\ln[(1+COV_R^{\;2})(1+COV_{QD}^{\;2}+COV_{QL}^{\;2})]}} \tag{5}$$

This is the formula used to calculate the reliability indices by the MVFOSM method. As shown in this equation, reliability index is a function of safety factor (FS), dead load over live load ratio (QD/QL), load statistics (λ_{QD}, λ_{QL}, COV_{QD}, COV_{QL}), and resistance statistics (λ_R, COV_R). The Korean Design Standards for Foundation Structures requires a minimum safety factor of 3.0 for pile bearing capacity design, and a safety factor larger than 3.0 has been used frequently in the Korean practice. Accordingly, reliability analysis was performed for safety factors of 3.0, 3.5, 4.0, 4.5, and 5.0. The computed reliability indices of the two static design methods for the two pile tip cases are summarized in Table 9.

In the MVFOSM analysis, the limit state function (g) is linearized at the mean values of the random variables rather than at a point on the failure surface. When g is non-linear, as in the case of g = ln (R/Q), a significant error may be introduced by neglecting higher order terms in the Taylor series approximation of the limit state function. Also, the reliability index may not be constant for different but mechanically equivalent formulations of the same limit state function. To overcome these deficiencies of the MVFOSM approach, the AFOSM analysis was also carried out in this study. In the AFOSM analysis, the limit state function is linearized at a point on the failure surface. The limit state function g (R, Q) can be expressed in the following format.

$$g = \ln\left(\frac{FS * \lambda_R * (QD / QL + 1)}{\lambda_{QD} * (QD / QL) + \lambda_{QL}}\right) \tag{6}$$

A computer program was coded following the iteration algorithm of the Rackwitz and Fiessler's FORM (1978) to facilitate the computing processes of the reliability indices. The flowchart of the computer program is shown in Fig.4. The computed reliability indices by the AFOSM method are also shown in Table 9.

Table 9 Summary of Reliability Analysis Using MVFOSM and AFOSM

Case / Factor of Safety	for Pile Tip on Soil Case				for Pile Tip on Rock Case			
	Equation (1)		Equation (2)		Equation (1)		Equation (2)	
	MVFOSM	AFOSM	MVFOSM	AFOSM	MVFOSM	AFOSM	MVFOSM	AFOSM
3.0	1.21	1.22	1.49	1.53	1.87	2.01	2.49	2.59
3.5	1.39	1.41	1.70	1.74	2.18	2.35	2.72	2.83
4.0	1.55	1.58	1.87	1.92	2.45	2.64	2.93	3.05
4.5	1.69	1.72	2.03	2.08	2.69	2.90	3.11	3.23
5.0	1.81	1.85	2.17	2.23	2.90	3.13	3.27	3.40

The AFOSM method resulted in a little larger reliability indices than the MVFOSM method, but the difference was not significant (1% to 3% for pile tip on soil case, and 4% to 8% for pile tip on rock case). It is noted that the reliability indices for pile tip on soil case are relatively small. This is due to the large variation in the resistance bias factors as shown in Table 8, which implies that the two static design methods used in Korea are not very reliable.

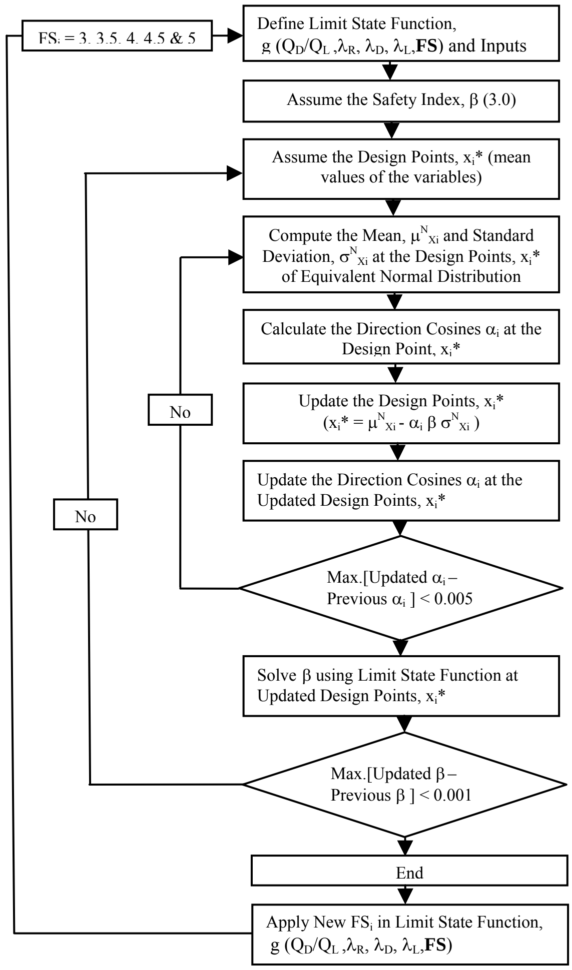


Fig.4 Flowchart for AFOSM Method

6 FINDINGS AND CONCLUSIONS

This study presents the following findings and conclusions.

1. Reliability of the static bearing capacity analysis methods for pile tip on soil case appears to be relatively low for safety factors in the range of 3 to 5. This implies that larger safety factors may have been used in the Korean pile design practice. Also, the variation in the resistance bias factors for both methods is quite large. It may be necessary to investigate better design methods for static bearing capacity of driven steel pipe piles.
2. Reliability of the static bearing capacity analysis methods for pile tip on rock case is not conclusive. The computed reliability indices appear to be within a reasonable range; however, the large variation in the resistance bias factors undermines the reliability of the static methods. Also, the size of the database is not large enough to draw a reasonable conclusion.
3. AFOSM method resulted in a little larger reliability indices than MVFOSM method, but the difference was not significant. It was expected since the same statistics of random variables for the two mechanically equivalent limit state functions were used in both reliability analysis methods.
4. Davisson's failure criterion appears to perform the best among the 6 criteria to measure ultimate bearing capacity of driven steel pipe piles.
5. More load test data need to be collected and reliability of the static bearing capacity analysis methods needs to be reevaluated to select the target reliability indices for LRFD code development.

ACKNOWLEDGMENT

This study was conducted under a research contract between the Korea Institute of Construction Technology (KICT) and the Ministry of Construction and Transportation (MOCT), Republic of Korea.

The writers would like to acknowledge the support and guidance of officers at MOCT, especially Mr. In-Hee Nam, Assistant Minister for Infrastructure.

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