Comparison of Formula Predictions with Pile Load Tests

RICHARD J. FRAGASZY, DOUGLAS ARGO, AND JERRY D. HIGGINS

To determine whether the Washington State Department of Transportation should replace the *Engineering News* (EN) formula with another dynamic formula for estimating pile capacity, the relative performance of 10 pile-driving formulas was studied. Data were collected from 63 pile load tests conducted in western Washington and northwest Oregon. The predicted capacity of each pile was calculated using several formulas: Danish, EN, modified EN, Eytelwein, Hiley, Gates, Janbu, Navy-McKay, Pacific Coast Uniform Building Code, and Weisbach. The Gates formula provided the most consistent prediction of pile capacity for each pile type and soil condition analyzed. The average predicted pile capacity was compared using the Gates and the EN formulas for different levels of safety. For each level of safety chosen, the Gates formula produced a higher average pile capacity. As the level of required safety increased, so did the difference between the two formula predictions.

Despite the development of wave equation techniques and pile analyzers, the use of pile-driving formulas continues. Earlier publications (*1,2*) reported that the *Engineering News* (EN) formula was the preferred method of the majority of state highway departments for estimating pile capacity. A growing number of states use wave equation and pile analyzer methods to evaluate pile foundation installations for relatively large projects. The literature included in those early publications describes several studies that compared pile load test results and formula predictions.

These comparisons brought out three important points. First, the EN formula generally is a poor estimator of pile capacity when compared with other formulas. The second point is that, although a few formulas were consistently among the best, no one formula stood out as the formula of choice for every situation. Last, local soil conditions and pile type affect the accuracy of each formula greatly.

Because the Washington State Department of Transportation (WSDOT) uses the EN formula along with wave equation and pile analyzer methods, WSDOT and the Federal Highway Administration (FHWA) funded a study to compare formula predictions with the results of pile load tests performed in the Pacific Northwest. The objective of this study was to recommend changes in WSDOT's methods of estimating pile capacity to improve the safety and economy of pile-supported structures.

R. J. Fragaszy, Department of Civil and Environmental Engineering, Washington State University, Pullman, Wash. 99162-2910. D. Argo, GeoEngineers, Inc., Bellevue, Wash. 98005. J. D. Higgins, Department of Geological Engineering, Colorado School of Mines, Golden, Colo. 80401.

To achieve this objective, data were collected from pile load tests conducted in western Washington and northwest Oregon. For those tests in which complete data were obtained, capacity was calculated on the basis of pile load tests. The capacity of each pile was also calculated using 10 common pile-driving formulas. These predictions were then compared with the pile load test results to determine the accuracy of each formula. This paper presents the results of the study.

PILE LOAD TESTS

Data Collection

Data for this research were gathered from the records of various consulting firms in the Seattle-Portland area and from the Oregon and Washington state departments of transportation. Forty-one reports, describing 103 pile load tests performed in the Puget Sound and lower Columbia River areas, were obtained. Of the 103 tests, 38 were not usable because of incomplete data. Two other load tests were rejected because the piles were damaged during driving.

The remaining 63 usable tests included 6 timber, 20 prestressed concrete, 5 H-section, 4 pipe (open and closed), 7 concrete-filled pipe, 5 hollow concrete, and 16 Raymond step taper piles. Included in these tests were 41 piles driven in cohesionless soil, 11 in cohesive soil, and 11 where the subsurface conditions consisted of layers of both cohesive and cohesionless soil. Further details of the pile load tests are given by Argo (*3*).

Sufficient documentation to allow wave equation analysis was available for only four of the pile load tests. Rather than assume values for missing data, only dynamic formulas were studied.

Calculation of Pile Capacity

To determine pile capacity for each pile load test, WSDOT engineers chose the following three methods: D-over-30, elastic tangent, and double tangent. In the D-over-30 method, the elastic compression line for the pile is plotted on the load-settlement graph, assuming that all the load is transferred to the tip. A second line parallel to the elastic compression line, with a *y*-axis (settlement axis) intercept equal to the pile diameter divided by 30, is also drawn on the load-settlement graph. The interception of this line with the load-settlement curve gives the predicted pile capacity (Q_{D30}).

In the elastic tangent method, a line is drawn parallel to the elastic compression line and tangent to the load-settlement curve. A second line with a slope of 0.05 in./ton is drawn tangent to the plunging portion of the load-settlement curve. The point where these two lines meet is the predicted pile capacity (Q_{ET}).

In the double tangent method, two lines are drawn—one parallel to the initial portion and one parallel to the plunging portion of the load-settlement curve. The intersection of these two lines is the predicted pile capacity (Q_{DT}).

Pile capacity was calculated for every pile by each method and the results are presented in Table 1. The methods were compared to determine which method to use to evaluate formula predictions. Only small differences were found in the average pile capacity—the mean pile capacities were 188.1, 182.2, and 178.3 tons for the D-over-30, elastic tangent, and double tangent methods, respectively. The average maximum difference among the three methods was 13.2 tons—only 7.2 percent of the average capacity.

The D-over-30 method predicted the highest capacity 88 percent of the time and resulted in an average of 3.2 percent and 5.5 percent higher capacities than the elastic tangent and double tangent methods, respectively. The D-over-30 method was the most objective of the three, and the relatively small differences in capacity were not considered significant. Therefore, the D-over-30 method was used to compare formula predictions.

TABLE 1 MEASURED ULTIMATE PILE CAPACITIES

Pile Number	Q_{D30} (tons)	Q_{ET} (tons)	Q_{DT} (tons)	Pile Number	Q_{D30} (tons)	Q_{ET} (tons)	Q_{DT} (tons)
HP-3	142	140	137	OC-10	127	124	124
HP-4	79	73	71	OC-11	124	119	121
HP-5	122	119	118	OC-14	152	144	144
HP-6	182	178	172	OC-16	85	73	73
HP-7	149	153	148	HC-1	256	234	236
CP-4	247	237	236	HC-2	296	292	288
CP-6	123	116	116	HC-4	300	265	220
OP-3	212	201	200	HC-5	300	285	240
OP-4	225	219	209	HC-6	310	274	255
FP-1	145	135	130	ST-1	151	147	146
FP-2	79	80	79	ST-2	148	143	143
FP-3	300	313	318	ST-3	155	153	152
FP-6	122	113	110	ST-4	142	138	135
FP-7	221	204	198	ST-5	140	133	132
FP-8	261	252	243	ST-6	144	142	140
FP-9	169	154	148	ST-7	240	231	227
SC-3	105	98	100	ST-8	163	161	163
SC-4	102	99	100	ST-9	300	290	288
SC-5	88	80	78	ST-10	290	279	269
SC-6	55	49	51	ST-11	213	208	208
SC-8	140	128	126	ST-12	209	203	201
SC-10	130	122	120	ST-15	169	204	209
SC-13	188	180	180	ST-17	162	179	179
SC-14	241	231	229	ST-22	155	153	152
SC-15	255	246	245	ST-23	168	182	181
SC-16	85	73	73	T-1	168	163	160
SC-17	195	200	203	T-6	70	66	63
OC-1	518	512	473	T-7	66	62	58
OC-2	450	440	440	T-8	49	42	40
OC-3	620	610	610	T-10	48	47	46
OC-6	243	237	233	T-11	57	51	51
OC-9	248	241	237				

FORMULA PREDICTIONS

On the basis of the recommendations contained in an earlier study (*1*), the following formulas were selected for comparison: EN, modified EN, Hiley, Gates, Janbu, Danish, Pacific Coast Uniform Building Code (PCUBC), Eytelwein, Weisbach, and Navy-McKay. All inherent safety factors were removed, so the ultimate load is assumed to be predicted by each equation. The specific form of each equation used is given in Table 2. Using these formulas, the predicted capacities presented in Table 3 were calculated along with the capacities based on the D-over-30 method.

To illustrate the range of predicted-versus-measured capacity for each formula, scatter graphs were plotted. Two examples are presented in Figures 1 and 2, which show the predicted capacity based on the EN and Gates formulas, respectively, versus the measured capacity as determined by the D-over-30 method. A 45° line, representing the points at which the predicted and measured ultimate capacities are equal, is also shown on each graph.

In the example shown in Figure 1, it can be seen that the EN formula, without including any safety factor, significantly overpredicts pile capacity in most cases. More importantly, the data clearly are quite scattered; and it would be difficult, if not impractical, to adjust the formula to make the data fit near the 45° line. In contrast, it can be seen in Figure 2 that the predicted capacity, based on the Gates formula, is generally lower than the measured capacity and the data fall much more closely to a straight line. Applying a multiplying factor to the predicted capacity could bring the data more closely in line with the 45° line.

To allow statistical evaluations, the predicted capacities from each formula were divided by the measured capacities. Histograms of these ratios were plotted to determine whether the data are normally distributed, a necessary requirement for the statistical methods employed. The histograms, shown in Figures 3a and 4a for the EN and Gates formulas, respectively, reveal that the data are skewed. In order to perform statistical tests, the ratios were transformed by calculating the common logarithm of each. Histograms were again plotted, as shown in Figures 3b and 4b, and the transformed data were found to be normally distributed by a chi-square goodness-of-fit test. The transformed data set was then used as the basis for statistical comparisons.

The first method used to quantify the scatter of each equa-

TABLE 2 DYNAMIC FORMULAS

ENR	$Q_u = \dfrac{e_h E_h}{s + z}$
Mod. ENR	$Q_u = \dfrac{e_h E_h}{s + z} \cdot \dfrac{W + n^2 w}{W + w}$
Hiley	$Q_u = \dfrac{e_h E_h}{s+(C_1+C_2+C_3)/2} \cdot \dfrac{W + n^2 w}{W + w}$
Gates	$Q_u = 27 \sqrt{e_h E_h}(1\text{-log } s)$ e_h = 0.75 for drop hammers E_h = 0.85 for other hammers Q_u (kips), s (in), E_h (ft-kips)
Janbu	$Q_u = \dfrac{e_h E_h}{K_u s}$ $K_u = C_d \left[1 + \sqrt{1 + \dfrac{\lambda}{C_d}} \right]$ $C_d = 0.75 + 0.15 \dfrac{w}{W}$ $\lambda = \dfrac{e_h E_h}{AEs^2}$
Danish	$Q_u = \dfrac{e_h E_h}{s + \sqrt{\dfrac{e_h E_h L}{2AE}}}$
PCUBC	$Q_u = \dfrac{e_h E_h \cdot \dfrac{W + Kw}{W + w}}{S + \dfrac{Q_u L}{AE}}$ K = 0.25 for steel piles = 0.10 for all other piles

TABLE 2 (*continued on next page*)

TABLE 2 (*continued*)

Eytelwein	$$Q_u = \frac{e_h E_h}{s\left(1 + \frac{w}{W}\right)} \quad \text{(drop hammers)}$$
	$$Q_u = \frac{e_h E_h}{s + \left[0.1 \frac{w}{W}\right]} \quad \text{(steam hammers)}$$
Weisbach	$$Q_u = \frac{-sAE}{L} + \sqrt{\frac{2e_h E_h AE}{L} + \frac{sAE}{L}}$$
Navy-McKay	$$Q_u = \frac{e_h E_h}{s\left[1 + 0.3 \frac{w}{W}\right]}$$

tion was the coefficient of variation (standard deviation divided by the mean) of the transformed data. Because the data for this study are log-normally distributed, the coefficients of variation were computed for the logarithms of the data; thus, the term $CV_{\log}$ is used to refer to these values. The closer $CV_{\log}$ is to zero, the more consistent the formula prediction.

The second method of comparison was taken from Agerschou (*4*), in which a divisor is calculated for each formula. This divisor is based on a statistical analysis of the ratio between formula predictions and load test results, such that its application to the formula results in a specific percentage (usually 98 percent) of all formula predictions having actual safety factors above 1.0 (i.e., a predicted capacity less than the measured capacity). The use of this divisor results in a wide range of actual safety factors. The upper limit of actual safety factors that would result is also computed. This value shows the extent of overdesign that must be accepted to ensure 98 percent safety. Use of a formula with a high upper limit would result in significant overdesign for many piles.

Although the divisor might appear to be a safety factor (it replaces the safety factor in the formula), it is not. A safety factor is an (almost) arbitrary factor used to account for variation in the parameters used in the calculation. The divisor is a statistically derived factor that allows the restriction of failure to a small, specified level.

Agerschou chose a 98-percent confidence level in his work (*4*). This, perhaps, represents the strictest tolerance that might be required for situations in which extreme safety is required. A more reasonable level for bridge foundations and similar transportation structures where excessive loading of a single pile does not have catastrophic consequences might be 95 percent. The divisors for both these confidence levels were used in this research.

RESULTS OF STATISTICAL ANALYSES

A qualitative feel for the data can be obtained by examining the scatter graphs and histograms of the data shown in Figures 1 through 4. On the basis of these figures and those for the other eight formulas presented by Argo (*3*), it is clear that none of the formulas can be considered accurate predictors of pile capacity, although some are significantly better than others. A comparison of the Gates and EN formulas should leave little doubt as to which is the better formula.

The Gates scatter graph shows a reasonably good fit to a straight line relationship, with a tendency to slightly underpredict the measured capacity. The EN formula, in contrast, significantly overpredicts pile capacity in the 160- to 260-ton-capacity range. However, if a reduction of safety factor is applied to lower the predicted capacities in this range, the formula would significantly underpredict the capacity of many piles.

Several equations show a trend of curving upward farther away from the 45° line for piles with increasing measured capacity. These formulas are EN, modified EN, Danish, and Weisbach. The Janbu, PCUBC, and Eytelwein formulas appear to plot near the 45° line on the average, but the graphs indicate significant scatter (*3*).

To determine which formulas are most accurate for different piles and soil types, the values of $CV_{\log}$ were calculated for several groupings according to these parameters. The values for eight groups are presented in Table 4. In all but one of the groupings, the Gates formula is ranked first and is a close second for piles in cohesive soils. The PCUBC, Hiley, Weisbach, and Danish formulas group closely together, but they have larger values of $CV_{\log}$ than does the Gates formula. The Janbu formula is also in this group, except for piles in

TABLE 3 PILE CAPACITIES PREDICTED BY DYNAMIC FORMULAS (tons)

Pile Number	Q_{D30}	ENR	Mod. ENR	Hiley	Gates	Janbu	Danish	PCUBC	Eytel-wein	Weis-bach	Navy-McKay
HP-3	142	366	313	200	97	140	167	115	438	192	497
HP-4	79	65	61	62	47	45	59	57	71	69	68
HP-5	122	306	273	186	93	134	155	120	363	184	366
HP-6	182	247	211	112	83	100	118	84	280	139	288
HP-7	149	231	200	147	81	116	136	105	263	166	264
CP-4	247	1070	969	390	162	300	357	250	1604	389	1880
CP-6	123	476	445	336	110	197	223	181	714	257	742
OP-3	212	448	405	250	115	214	244	201	520	297	513
OP-4	225	886	716	295	154	176	223	131	915	243	1001
FP-1	145	429	358	262	106	215	258	180	480	309	542
FP-2	79	113	83	77	62	67	92	66	116	112	101
FP-3	300	774	678	341	137	254	304	206	1074	335	1367
FP-6	122	368	335	175	100	113	132	98	466	149	480
FP-7	221	617	554	278	135	132	156	110	718	173	710
FP-8	261	1536	1371	430	193	144	179	114	2314	184	2913
FP-9	169	632	568	312	136	134	159	112	739	175	734
SC-3	105	421	359	226	105	218	254	190	506	305	552
SC-4	102	159	103	84	72	78	106	64	151	132	128
SC-5	88	98	64	54	57	55	82	52	97	98	78
SC-6	55	98	62	61	57	54	81	49	96	97	76
SC-8	140	208	136	115	82	112	149	98	206	186	181
SC-10	130	109	71	70	60	61	90	57	108	108	88
SC-13	188	267	189	120	85	143	174	121	285	213	303
SC-14	241	306	206	173	101	158	205	140	307	257	265
SC-15	255	362	230	183	108	167	218	136	353	270	303
SC-16	139	267	170	136	94	133	179	113	262	224	215
SC-17	195	838	520	282	151	246	319	179	765	364	838
OC-1	518	2790	985	362	259	371	664	258	1004	695	3453
OC-2	450	1633	611	303	205	361	606	256	880	680	1302
OC-3	620	3730	1619	522	313	560	915	404	1822	935	12648
OC-6	243	812	262	94	142	117	178	74	337	183	1636
OC-9	248	436	169	131	115	121	182	82	321	213	286

TABLE 3 (*continued on next page*)

TABLE 3 (*continued*)

Pile Number	Q_{D30}	ENR	Mod. ENR	Hiley	Gates	Janbu	Danish	PCUBC	Eytel-wein	Weis-bach	Navy-McKay
OC-10	1271	1855	957	302	217	346	487	229	1128	500	5641
OC-11	124	1821	770	202	214	273	408	174	809	418	4487
OC-14	152	194	122	97	79	104	145	90	188	180	161
OC-16	85	98	60	59	57	53	83	47	95	98	74
HC-1	256	1499	452	214	193	294	521	183	341	545	2188
HC-2	296	1086	268	202	162	234	434	149	277	476	803
HC-4	300	1280	600	509	176	366	558	238	611	621	1309
HC-5	300	1152	532	353	171	344	531	225	591	608	954
HC-6	310	1800	788	442	208	444	671	284	800	719	2526
ST-1	151	457	245	143	106	243	333	176	324	400	539
ST-2	148	398	232	235	100	270	381	213	312	476	440
ST-3	155	360	196	160	96	210	293	160	279	364	366
ST-4	142	366	178	108	97	161	229	113	249	274	345
ST-5	140	398	213	170	100	223	309	165	293	379	423
ST-6	144	332	175	126	93	171	242	127	250	298	312
ST-7	240	428	224	241	106	208	292	151	313	357	403
ST-8	163	344	165	160	97	137	198	96	249	239	278
ST-9	300	840	364	231	142	128	193	82	379	200	1408
ST-10	290	855	437	406	144	165	238	107	463	248	1638
ST-11	213	188	101	98	75	106	168	87	162	206	149
ST-12	209	342	184	174	95	198	281	151	264	350	335
ST-15	169	522	370	344	114	320	400	258	517	487	689
ST-17	162	470	333	319	110	301	380	250	466	470	578
ST-22	155	288	172	175	91	153	212	122	255	265	21
ST-23	168	301	143	138	87	161	239	116	192	294	24
T-1	168	302	284	160	88	77	90	67	455	98	40
T-6	70	140	128	79	65	67	75	64	165	91	14
T-7	66	103	95	73	57	57	64	58	116	80	9
T-8	49	45	42	42	39	29	36	35	47	44	4
T-10	48	112	105	72	59	56	63	57	128	78	10
T-11	57	18	17	17	19	1	16	16	18	18	1

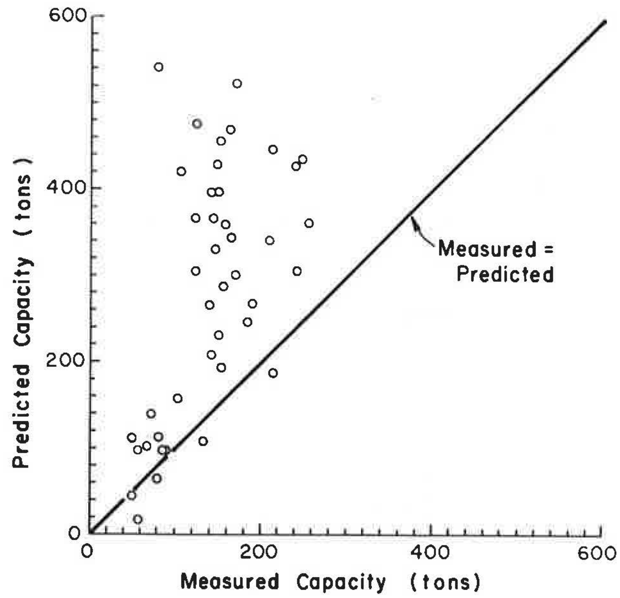

FIGURE 1 Predicted versus measured pile capacity for the EN formula.

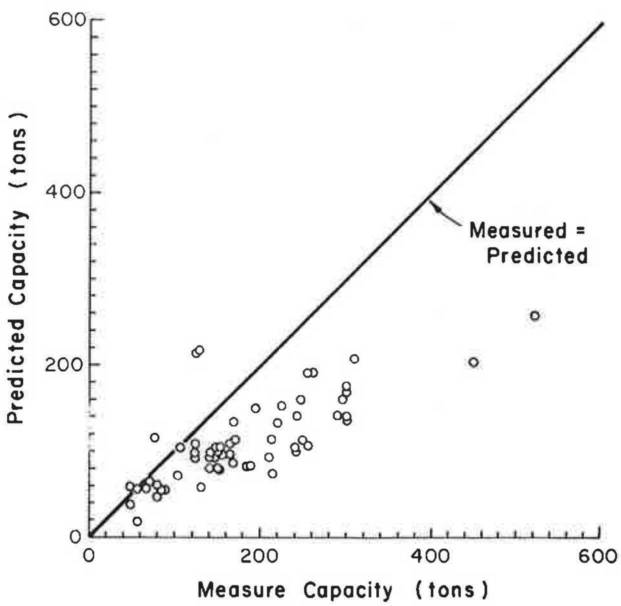

FIGURE 2 Predicted versus measured pile capacity for the Gates formula.

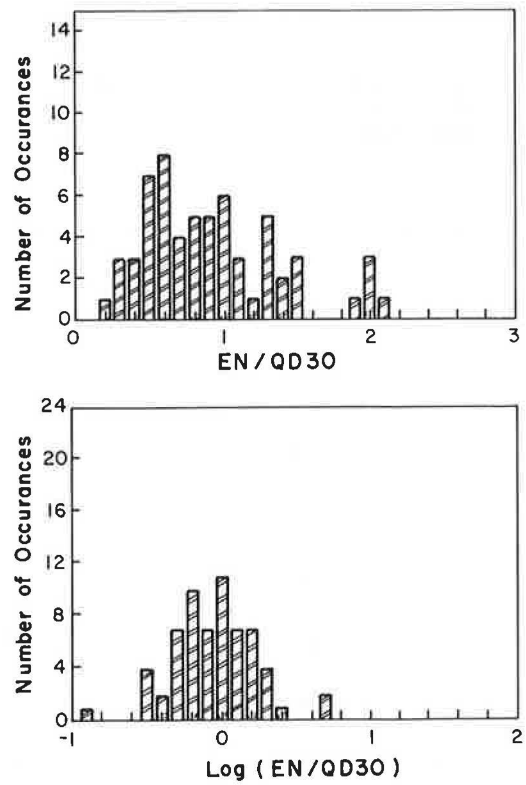

FIGURE 3 Histograms for raw and logarithm-transformed data for the EN formula.

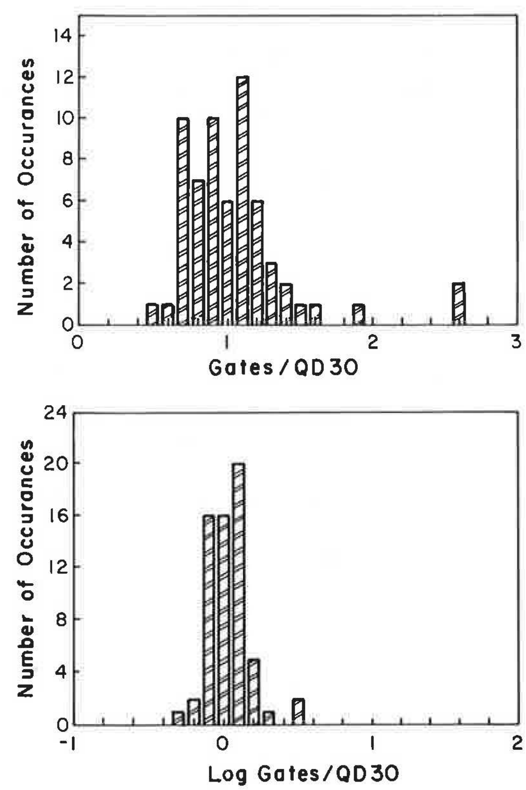

FIGURE 4 Histograms for raw and logarithm-transformed data for the Gates formula.

cohesionless soils. The EN, modified EN, and Eytelwein formulas have consistently larger values of $CV_{\log}$ than the above formulas. The Navy-McKay formula is consistently last by a large margin.

The divisors required for 98 percent and 95 percent assurance that the actual safety factor will be greater than or equal to 1.0 are shown in Table 5. For example, if it is required that 98 percent of the time the actual capacity will be greater than the allowable capacity, then the pile capacity predicted by the EN formula should be divided by 9.06 to obtain allowable capacity. If this divisor (9.06) is used, the resulting actual safety factors will range as high as 14.36. In contrast, the

TABLE 4 CV_{LOG} VALUES FOR SELECTED PILE TYPES AND SOIL CONDITIONS

ALL PILES (N=63)			ALL EXCEPT TIMBER (N=57)		
RANK	FORMULA	CV_{LOG}	RANK	FORMULA	CV_{LOG}
1	Gates	0.14	1	Gates	0.13
2	Hiley	0.20	2	Danish	0.19
2	PCUBC	0.20	2	Hiley	0.19
4	Danish	0.21	2	Janbu	0.19
4	Weisbach	0.21	2	PCUBC	0.19
6	Janbu	0.29	2	Weisbach	0.19
7	Modified ENR	0.30	7	ENR	0.28
7	Eytelwein	0.30	7	Eytelwein	0.28
9	ENR	0.32	9	Modified ENR	0.29
10	Navy-McKay	0.91	10	Navy-McKay	0.58

All PILES IN COHESIONLESS SOILS (N=41)			ALL PILES IN COHESIVE SOILS (N=11*)		
RANK	FORMULA	CV_{LOG}	RANK	FORMULA	CV_{LOG}
1	Gates	0.11	1	PCUBC	0.18
2	Danish	0.21	2	Gates	0.19
2	Hiley	0.21	3	Weisbach	0.20
2	PCUBC	0.21	4	Hiley	0.21
5	Weisbach	0.22	4	Janbu	0.21
6	Modified ENR	0.27	6	Danish	0.22
7	Eytelwein	0.29	7	Eytelwein	0.31
8	ENR	0.30	8	Modified ENR	0.35
9	Janbu	0.33	9	ENR	0.38
10	Navy-McKay	0.92	10	Navy-McKay	0.65

TABLE 4 (*continued on next page*)

TABLE 4 (*continued*)

H-SECTION (N=5*)			SQUARE AND OCTAGONAL CONCRETE (N=20)		
RANK	FORMULA	CV_{LOG}	RANK	FORMULA	CV_{LOG}
1	Gates	0.08	1	Gates	0.18
2	PCUBC	0.11	2	Weisbach	0.20
3	Danish	0.13	3	Danish	0.21
3	Weisbach	0.13	4	Janbu	0.22
5	Janbu	0.14	4	PCUBC	0.22
6	Hiley	0.16	6	Hiley	0.23
7	Modified ENR	0.20	7	Eytelwein	0.31
8	Eytelwein	0.24	8	Modified ENR	0.36
9	ENR	0.25	9	ENR	0.39
10	Navy-McKay	0.34	10	Navy-McKay	0.68

RAYMOND STEP TAPER (N=16)			TIMBER (N=6*)		
RANK	FORMULA	CV_{LOG}	RANK	FORMULA	CV_{LOG}
1	Gates	0.09	1	Gates	0.18
2	ENR	0.16	2	PCUBC	0.23
2	Hiley	0.16	3	Hiley	0.25
4	Danish	0.17	4	Danish	0.30
5	Weisbach	0.18	5	Weisbach	0.32
6	Eytelwein	0.19	6	Modified ENR	0.37
6	Janbu	0.19	7	Eytelwein	0.46
8	Modified ENR	0.20	8	ENR	0.49
9	PCUBC	0.22	9	Navy-McKay	0.60
10	Navy-McKay	0.77	10	Janbu	0.90

*Sample size is too small to provide reliable results

TABLE 5 DIVISOR FOR 98% AND 95% LEVELS OF SAFETY CALCULATED USING ALL DATA

FORMULA	98% Assurance Divisor	Upper Limit of Actual Safety Factors
Gates	1.21	3.61
PCUBC	1.78	5.99
Hiley	2.53	6.17
Danish	3.16	6.76
Weisbach	3.72	6.93
Eytelwein	7.03	12.19
Modified ENR	5.29	12.37
Janbu	3.11	12.86
ENR	9.06	14.36
Navy-McKay	33.08	278.54

FORMULA	95% Assurance Divisor	Upper Limit of Actual Safety Factors
Gates	1.06	2.80
PCUBC	1.49	4.19
Hiley	2.11	4.29
Danish	2.61	4.62
Weisbach	3.07	4.71
Eytelwein	5.48	7.40
Modified ENR	4.12	7.49
Janbu	2.41	7.73
ENR	6.95	8.44
Navy-McKay	18.87	90.59

Gates formula prediction should be divided by 1.21, resulting in actual safety factors up to 3.61.

To evaluate the economic effects of changing to the Gates formula, comparisons were made of allowable load using several different assumptions. The average allowable load for all piles ($N = 63$) based on the Gates formula was calculated using the divisor for 98 percent and 95 percent assurance (1.21 and 1.06, respectively). This was also done using the EN formula (9.06 and 6.95, respectively). The average allowable load based on the EN formula was also calculated using the customary safety factor of 6.0, as well as the allowable load for the Gates formula using the same level of safety, 92.7 percent. In this

TABLE 6 COMPARISON OF AVERAGE ALLOWABLE LOADS BASED ON GATES AND EN FORMULAS

	Divisor Used			Average Allowable Load (tons)		
	98%	95%	Current[a]	98%	95%	Current
EN	9.06	6.95	6.0	69.2	90.2	104.5
Gates	1.21	1.06	1.01	95.4	108.9	113.9

[a]Typical safety factor used for EN formula, equivalent to 92.5 percent.

way, a comparison can be made using the same measures of safety for both formulas. The results of these analyses are presented in Table 6.

When both formulas are used with a 98 percent assurance that the allowable load will be lower than the actual capacity, the Gates formula gives an average allowable capacity of 95.4 tons versus 69.2 tons using the EN formula. This is an average increase of 38 percent, with no additional risk. The allowable capacity is higher using the Gates formula for 55 out of 63 piles. Using the known pile capacities based on the pile load tests, an average actual safety factor can be calculated. For the Gates formula, that safety factor is 1.97 and for EN it is 2.72. When 95 percent assurance is used (a more realistic value), the Gates formula gives an average allowable capacity of 108.9 tons versus 90.2 tons using EN—an increase of 21 percent. These average capacities reflect average actual safety factors of 1.73 and 2.09.

Using the current safety factor of 6.0 for EN, the average allowable load is 104.5 tons, approximately 4 percent less than that obtained with the Gates formula using 95 percent assurance. Using the same level of safety (92.7 percent), the Gates formula predicts an average capacity of 113.9 tons, 9 percent higher than EN. The average actual safety factor using the EN formula in this case is 1.8 compared with 1.65 for the Gates formula.

The economic benefits of switching to the Gates formula clearly depend on the choices made in selecting the desired assurance level (safety factor). If the comparison is made between the EN formula (as it is currently used) and the Gates formula with the same level of safety, the economic benefits are small, but positive. If the comparison is made using higher levels of safety, the economic benefit of switching to the Gates formula will be substantial.

DISCUSSION OF RESULTS

The results of this study follow the trend of similar comparative studies reported elsewhere. Those formulas that fared well in other comparisons (Danish, Gates, Hiley, Janbu, PCUBC, and Weisbach) also ranked high in this study. Of these, the Gates formula clearly is the best—ranking first in all but one comparison (cohesive soils), where it was a close second. The EN, modified EN, Eytelwein, and Navy-McKay formulas are clearly unreliable.

Using the EN Formula

This study points out two important aspects of the question of whether the EN formula should be used in western Washington and northwest Oregon. The first is that other formulas clearly do a better job of predicting pile capacity, in particular the Gates formula. The second is that the typical safety factor (6.0) used with the EN formula may not provide the level of safety desired. On the basis of the data obtained from all pile load tests, the EN calculation of pile capacity should be divided by 6.95 to ensure that the allowable load is less than the actual capacity 95 percent of the time, and a divisor of 9.06 is necessary for 98 percent assurance. Although the data set for some of the subgroups, such as timber piles, is small, the authors believe that use of the data from all piles provides a large enough sample to produce confidence in the validity of the results.

From this study, it seems apparent that the EN formula should not be used in western Washington and northwest Oregon. If use of a formula is desirable, the Gates formula provides the most consistent estimation of pile capacity of those investigated and should be preferred over all others. The Gates formula is not significantly more difficult to use than the EN formula and requires only a calculator with common logarithm and square root functions. The data required are the same: the set in inches and the energy of the hammer in foot-pounds. It should be emphasized, however, that the Gates formula will not always result in higher pile capacities. It is possible that, for a given project, the Gates formula may require more or deeper piles, or both.

Implementation

The implementation of the recommendations from this paper raises some interesting questions. The first question involves the use of a divisor of 1.06 or 1.21 with the Gates formula, depending on the level of safety required. This is much lower than the safety factor recommended in standard references (*5*). Bowles recommends the use of 3.0, and safety factors of 2 to 3 are commonly used by engineers in the United States.

Understandably, individuals who design pile foundations may be hesitant to make what might appear to be a significant change in safety factor. However, it should be emphasized that a different approach to the question of safety is suggested based on statistical analyses of real test data from a specific area of the country. The divisor recommended is not a safety factor but rather an adjustment factor based on a group of pile load tests and the level of safety desired. The resulting average actual safety factors for the piles analyzed in this study range from 1.65 to 1.97, depending on the degree of safety required. These are quite reasonable values for design.

A major purpose of a study such as this is to allow safe but less conservative design. When sufficient statistical data are available, such a design is possible as long as the results are applied *only in the region of the country and for the types of piles covered by the study*. In other locations, the divisor used should be based on similar statistical analyses. If none are available, the use of a safety factor in the 2 to 3 range, rather than a divisor, is sensible.

A second question concerns the relationship between allowable load calculations based on pile load tests and formula predictions. Current WSDOT practice when pile load tests are conducted is to specify an allowable load equal to one-half the ultimate load determined by the pile load test. To be consistent with this practice, it can be argued that the formula prediction, either EN or Gates, should also be divided by 2 to obtain the allowable load. Such a practice would result in much lower allowable loads than are currently used. However, the current use of a safety factor of 6.0 to obtain an allowable load with EN has not resulted in serious failures.

How can one justify reducing the allowable loads by an additional factor of 2? The authors believe that two points should be made. First, the use of a safety factor of 2 when pile load tests are conducted appears overly conservative in most cases, unless the consequence of small settlement is severe. For the pile load tests used in this study, the average settlement at ultimate load (based on the D-over-30 method) is 4.8 percent of the pile diameter (less than ¾ in., on average). The magnitude of settlement at one-half the ultimate load is 1.2 percent of pile diameter (less than ⅙ in., on average). This results in almost negligible settlement. In situations where soil conditions are reasonably uniform throughout a site and settlement tolerances are not extreme, a lower safety factor on pile load test results for this study area can be justified, perhaps in the range of 1.5 to 1.75.

Second, the Gates and EN formulas with the appropriate divisor yield an allowable load, not the ultimate load as do the pile load tests. The actual ultimate capacity for the vast majority of piles is greater than the predicted capacity; hence, the actual safety factor is greater than 1.0, averaging between 1.65 and 2, depending on the safety level desired. The actual safety factor for a given pile cannot be known unless the pile is tested. Even in those cases where the loading is near the ultimate, it appears unlikely that settlement would be excessive. There is no real way to make the two methods comparable because one is based on an actual test result on a similar, nearby pile, and the other is based on a formula prediction of allowable load.

SUMMARY

To determine whether WSDOT should replace the EN formula with some other dynamic formula for estimating pile capacity, the relative performance of 10 pile-driving formulas was studied. Data were collected from 63 pile load tests conducted in western Washington and northwest Oregon. Included in this data set are open and closed steel pipes, steel HP sections, timber, concrete, hollow concrete, and Raymond step tapered piles. Three methods of calculating pile capacity based on pile load test results were used and the results compared. Relatively little difference was found and the most objective of the three (the D-over-30 method) was chosen to establish the capacities of the test piles.

The predicted capacity of each pile was calculated using the Danish, EN, modified EN, Eytelwein, Hiley, Gates, Janbu, Navy-McKay, PCUBC, and Weisbach formulas. Scatter graphs of the predicted versus the measured capacity were plotted for each formula. To perform statistical analyses of the data, the predicted capacity was normalized by dividing it by the measured capacity. Because these data are not normally distributed the logarithms of the normalized capacities, which are normally distributed, were used.

Analyses of the coefficient of variation for each formula show that the Gates formula is the most accurate of the 10 formulas compared and that the EN formula is among the worst. The coefficient of variation for the EN formula is approximately 2 to 3 times higher than that for the Gates formula.

In addition, a second method of comparison was used in which the measure of safety was determined by the percentage of piles for which the measured capacity was expected to be lower than the formula prediction. This method also provided the spread of actual safety factors resulting from the use of each formula for a given measure of safety. The Gates formula was again found to be the best, and the EN formula again ranked near the bottom.

Subsequent economic analyses showed that for the same level of safety, the Gates formula resulted, on average, in higher allowable capacities and therefore lower costs.

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