Comparison of Methods for Estimating Pile Capacity

WA-RD 163.1

Final Report
August 1988

Washington State Department of Transportation
Planning, Research and Public Transportation

in cooperation with the
United States Department of Transportation
Federal Highway Administration

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COMPARISON OF METHODS FOR

ESTIMATING PILE CAPACITY

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Final Report

Research Project Y-3400
Task 9

Prepared For
Washington State Department of Transportation
and in cooperation with
U.S. Department of Transportation
Federal Highway Administration

August 1988

WASHINGTON STATE DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. WA-RD 163.1	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Comparison of Methods for Estimating Pile Capacity		5. REPORT DATE August 1988 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Fragaszy, Dr. Richard J.; Higgins, Dr. Jerry D; Argo, Mr. Douglas E.		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Washington State Transportation Center Department of Civil & Environmental Engineering Washington State University Pullman, WA 99164-2910		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. Y3400, Task 9
12. SPONSORING AGENCY NAME AND ADDRESS Washington State Department of Transportation Transportation Building, KF-01 Olympia, WA 98504		13. TYPE OF REPORT AN PERIOD COVERED Final Report 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

A comparative study of ten pile driving formulas is described. The formulas are the Danish, ENR, Modified ENR, Eytelwein, Gates, Hiley, Janbu, Navy-Mckay, PCUBC, and Weisbach. The ultimate load for each of sixty-three pile load tests was determined using the Q-D over 30 method to determine ultimate capacity.

The predicted pile capacity was divided by the measured capacity to obtain normalized values. Statistical analysis for coefficient of variation were performed on the logarithm of the normalized capacities to determine which formula provided the most consistent prediction of pile capacity. The Gates formula proved to be the best and the widely used ENR one of the worst with a coefficient of variation approximately 2-3 times higher than that for the Gates formula.

17. KEY WORDS Piles, pile formulas, pile capacity, ultimate capacity, factor of safety	18. DISTRIBUTION STATEMENT

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified	62	

DOT FORM 310-022 (11/86) -1216-

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ABSTRACT

A comparative study of ten pile driving formulas is described. The formulas compared are the Danish, ENR, Modified ENR, Eytelwein, Gates, Hiley, Janbu, Navy-McKay, PCUBC and Weisbach. The data from sixty-three pile load tests, conducted in the Puget Sound and lower Columbia River areas in Washington and Oregon, were obtained from the files of consulting firms and state Transportation Departments. The ultimate load for each pile load test was determined using three methods. As there was little difference among the three methods, the least subjective one, the Q-D over 30 method, was used to determine ultimate pile capacity.

The predicted pile capacity was divided by the measured capacity to obtain normalized values. Because these data are not normally distributed, it was necessary to use the logarithm of the normalized capacities (which are normally distributed) in statistical analyses. Calculations of coefficient of variation for each formula show that the Gates formula provides the most consistent prediction of pile capacity. The ENR formula is among the worst of the ten formulas with a coefficient of variation approximately 2-3 times higher than that for the Gates formula.

A second statistical method was used to determine the divisor required to adjust each formula so that a given measure of safety is obtained. When the same measure of safety is used, the range of actual safety factors obtained is much smaller using the Gates formula, again indicating that it is the best of the ten examined. An economic comparison shows that for the same measure of safety, replacement of the ENR formula with the Gates formula would result in higher average predicted pile capacities and, therefore, more economic pile foundations.

SUMMARY

In order to determine if the Washington State Department of Transportation should replace the Engineering News Formula with some other dynamic formula for estimation of pile capacity, a study has been conducted of the relative performance of ten different pile driving formulas. Data were collected from sixty-three pile load tests conducted in western Washington and northwest Oregon. Pile types in this data set include open and closed steel pipes, steel HP sections, timber, concrete, hollow concrete and Raymond step tapered piles. Three methods of calculating ultimate pile capacity based on the pile load tests results were used and the results compared. Relatively little difference was found among the three methods and the least subjective of the three (the Q-D over 30 method) was chosen to establish the capacities of the test piles.

The predicted capacity for each pile was calculated using the Danish, ENR, Modified ENR, Eytelwein, Hiley, Gates, Janbu, Navy-McKay, PCUBC and Weisbach formulas. Scatter graphs of the predicted capacity vs. 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. Histograms of these values for each formula showed that the data are not normally distributed. To allow statistical comparisons, the logarithm of the normalized capacities were used, as their distributions are normally distributed.

The coefficient of variation for each formula is an indication of how much scatter there is in the plot of predicted vs. measured capacity. Low values of the coefficient of variation indicate that the formula, if modified properly by a constant, predicts capacities close to the measured

values. The results of these analyses show that the Gates formula is the most accurate of the ten. It also shows that the ENR formula is among the worst of the ten formulas compared. The coefficient of variation for the ENR formula is approximately 2-3 times higher than for the Gates formula.

A second method of comparison was used which allows the calculation of a divisor required to produce a specific measure of safety for each formula. The measure of safety is determined by the percentage of piles for which the measured capacity is expected to be lower than the formula prediction. This method also provides the spread of actual safety factors which would result from the use of each formula for a given measure of safety. The larger this spread, the more piles there will be that are overdesigned. The Gates formula was again found to be the best, and the ENR formula ranked near the bottom.

An economic analysis was conducted which shows that for the same measure of safety, use of the Gates formula will result, on the average, in higher allowable capacities and, therefore, lower costs.

CONCLUSIONS

A comparative study of ten pile driving formulas has shown that the Gates formula consistantly provides the best estimate of pile capacity as measured by pile load tests. The Danish, Hiley, Janbu, PCUBC, and Weisbach formulas also provide reasonable estimates of pile capacity for most pile types and soil conditions. The ENR, Modified ENR, Eytelwein and Navy-McKay formulas are significantly worse predictors of pile capacity.

Using statistical techniques, each formula can be modified by a divisor to provide equal safety, as measured by the percentage of piles which would have an actual capacity less than the allowable capacity predicted by the formula. These same techniques provide a measure of the actual maximum safety factor which results when the divisor is applied. Although the magnitude of the divisor is not an indication of the quality of the formula prediction, the difference between the divisor and the actual maximum safety factor required for the given level of overall safety is such an indication. Use of the Gates formula results in the smallest range of actual safety factors, thus indicating that fewer pile capacities will be grossly underestimated if the Gates formula is used compared to any of the others.

This study has also shown that when the ENR formula is used by WSDOT (with a divisor of 6), it can be expected that more than 5% of the predicted capacities will exceed the actual pile capacity. However, if the Gates formula is used with a divisor such that only 5% of predicted capacities will be higher than actual capacity, a slight increase in average predicted capacity will result. The use of the Gates formula will, therefore, result in lower costs and increased safety.

RECOMMENDATIONS

This study clearly points out the benefits which would result if WSDOT abandons use of the Engineering News formula and replaces it with the Gates formula, using the divisor applicable to the desired level of safety. Both economic savings and increased safety would result. It is, therefore, the recommendation of the writers that this be done.

This study has also pointed out that adequate records of pile load tests are not always kept. Because of this, it was not possible to include in this study a comparison with wave equation methods. It is therefore strongly recommended that ,in any future pile load tests, complete driving records be kept, as well as sufficient details concerning the soil conditions so that wave equation analyses can be performed.

Although it was not possible to compare wave equation methods with formula predictions, wave equation methods have many uses beyond estimation of pile capacity. Pre-qualification of hammers and identification of potential pile damage are two examples. Because of these additional uses, and evidence in the literature generally showing the superiority of the wave equation over formulas, it is strongly recommended that WSDOT continue use wave equation analyses on all but very small jobs. The Gates formula (or any other) should be viewed as an additional indication of pile capacity, rather than the main or only method used.

INTRODUCTION

This report presents the results of the second phase of a three phase study designed to improve the methods used by the Washington State Department of Transportation (WSDOT) for construction control of pile driving and estimation of pile capacity. In the first phase, a review of literature and a survey of state highway departments were conducted. The results, reported in Fragaszy et al (1), showed that the Engineering News formula is still the method used by the majority of states to estimate pile capacity. Wave equation and pile analyzer methods are used by a small number of states, mainly in connection with their larger pile projects. The review of literature included descriptions of several studies in which comparisons were made between pile load capacity predictions using various dynamic formulas and actual pile load test results. These comparisons brought out two important points. The first is that the Engineering News formula generally provides a very poor estimation of pile capacity compared to several other formulas. The second is that there appears to be no formula clearly superior to all others. Although a few formulas were consistently among the best, none stood out as the obvious one to use in all situations. Local soil conditions and pile type generally have a great impact on the accuracy of each formula.

Because WSDOT uses the Engineering News formula, along with wave equation methods and pile analyzers, it was decided that a study should be conducted to compare formula predictions with the results of pile load tests conducted in the Pacific Northwest. The objective of this study is to recommend changes in WSDOT's methods of estimating pile capacity to improve safety and/or economy of pile supported structures. To achieve this objective, an extensive effort was made to collect data from as many pile load tests conducted in western Washington and northwest Oregon as possible. For those tests in which complete data were obtained, calculations of ultimate load were made based on pile load test data. Using the data from the pile load tests, the ultimate capacity of each pile was calculated using each of the ten formulas. Details of the pile load tests, the methods used to interpret the test data, and the formulas predictions are presented in the next section of this report.

Following the description of ultimate load calculations, the next section of the report describes the statistical analyses used to compare the formulas. The last section presents the results of the statistical analyses and a discussion of the results. Figures and tables illustrating the results are presented in this section; complete results can be found in the Appendices. Further details of the statistical techniques used can be found in Argo (2).

PILE LOAD TEST RESULTS

Collection of data

To compare the accuracy of several pile driving formulas, it is necessary to obtain the results of as many pile load tests as possible, conducted in the area of interest. A consistent method of determining the ultimate pile capacity from these pile load tests must be used and there must be sufficient data regarding the actual pile driving to allow the use of each formula.

Due to the expense of pile load tests, no tests were done specifically for this project. All of the 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. A total of 41 reports of pile load tests conducted in the Puget Sound and lower Columbia River areas were obtained. These reports contain 103 individual pile load tests. Of these, 38 load tests are not usable due to incomplete data. This lack of data prevented the proper use of some or all of the dynamic formulas, or it prevented an accurate determination of the ultimate capacity of the test pile. Two other load tests were rejected because the piles were damaged during driving. The remaining 63 usable tests include 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 are 41 piles driven in cohesionless soil and 11 in cohesive soil. The remaining piles were driven at sites with layers of both cohesive and cohesionless soil. A complete summary of the information for all piles that were used can be found in Appendix A.

Calculation of Ultimate Pile Capacity

There are many different methods of reducing the data from a pile load test to determine ultimate pile capacity. Each method will usually result in a different prediction of ultimate pile capacity. Several methods were used by the various firms and agencies which conducted the load tests used for this study. It was, therefore, not possible to use the reported ultimate loads to compare with formula predictions.

To calculate ultimate pile capacity for each pile load test, three methods, commonly used by WSDOT engineers, were chosen. The three methods are the Q-D over 30 (Q_{D30}) , the elastic tangent (Q_{ET}) and the double tangent (Q_{DT}) methods The procedure for each method is given in Appendix B. The ultimate pile capacity was calculated by each method and a comparison made to determine which method to use for the comparison with formula predictions. The results of these calculations, also presented in Appendix B, show little difference among the three methods. Therefore, the least subjective method, Q_{D30}, was chosen for the comparison.

The predicted ultimate capacity was calculated using each of the ten formulas. The specific form used for each formula is presented in Appendix C and the ultimate capacities which were obtained are shown in Appendix D.

METHODS OF COMPARISON

The most important quality of a dynamic equation is that it be consistent in its prediction of the pile capacity. A formula which is consistently high or low can easily be corrected by the application of a multiplying factor. However, if the equation is erratic, it is very difficult to adjust it to a usable form. Thus, the scatter in the predictions of each formula needs to be compared, not just the value of the average prediction.

Scatter graphs were plotted of the predicted vs. measured capacity of each formula. This was done to give a visual indication of the scatter. There were a few points which plotted outside the limits of these graphs (600 tons), but including these points would have compressed the graphs too much. A 45 degree line, indicating the points where the predicted and measured capacities are equal is also shown on each graph.

The predicted ultimate loads were divided by the measured capacity, and histograms were plotted of these ratios to determine if the data are normally distributed. Because the data were not normally distributed, the ratios were transformed by using the common logarith of each ratio. Histograms plotted from these transformed data are normally distributed; therefore, the transformed data were used for statistical analysis.

The first method used to quantify the scatter of each equation was the coefficient of variation of the transformed data. The coefficient of variation is defined as the standard deviation divided by the mean. If the data are normally distributed, the coefficient of variation provides a normalized value for each equation which can be directly compared with the coefficients of variation of the other equations. Since 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} will be used to refer to these values. The closer CV_{LOG} is to zero, the more consistent the formula is.

A more practical method of comparison is taken from Agerschou (3) and is based on limiting the percentage of unconservative formula predictions; i.e., the percentage of formula predictions which are higher than the actual pile capacities. For a given level of safety (e.g., 98%, which corresponds to limiting the percentage of unconservative predictions to 2%), a divisor is calculated which is applied to the ultimate capacity predicted by the formula. Although the divisor looks like a safety factor, and is called a "nominal safety factor" by Agerschou, it is not a safety factor in the usual sense of the word. It is a factor based on statistical analysis which allows the adjustment of the formula prediction to produce a given level of safety. A safety factor, on the other hand, is an arbitrary factor which hopefully makes up for lack of knowledge about the soil and/or pile and uncertainties in the design procedures. The two, therefore, should not be compared.

The upper limit of actual safety factors which would result is also computed by Agerschou's method. This value shows the extent of overdesign which must be accepted to assure a given level of safety. Use of a formula with a high upper limit will result in significant overdesign for many piles. In the following section the required divisors for two levels of safety, 98% and 95%, are presented along with the resulting upper limits to the actual safety factors which result.

RESULTS OF STATISTICAL ANALYSES

Examples of scatter graphs and histograms are shown in Figs. 1-2 for the ENR formula and Figs. 3-4 for the Gates formula. A qualitative feel for the data can be obtained by examination of these figures and the remaining scatter graphs and histograms shown in Appendices E and F, respectively. It should be clear from these figures that none of the formulas can be considered accurate predictors of pile capacity. It should also be clear that there are significant differences in accuracy among the ten formulas. A comparison of the histograms or scatter graphs for the ENR and Gates formulas, for example, should leave little doubt which is the better formula. The Gates scatter graph shows a reasonably close fit to a straight line relationship. The majority of the points fall slightly below the 45 degree line, indicating that the equation under predicts the measured capacity. The ENR formula, in contrast, significantly over-predicts pile capacity in the 160 - 260 ton capacity range. However, if a reduction or safety factor is applied to lower the predicted capacities in this range, the formula would significantly under-predict capacity of many of the piles.

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

In an effort to determine which formulas are most accurate for different pile or soil types, the values of CV_{LOG} were calculated for several different groupings according to pile or soil type. The values for

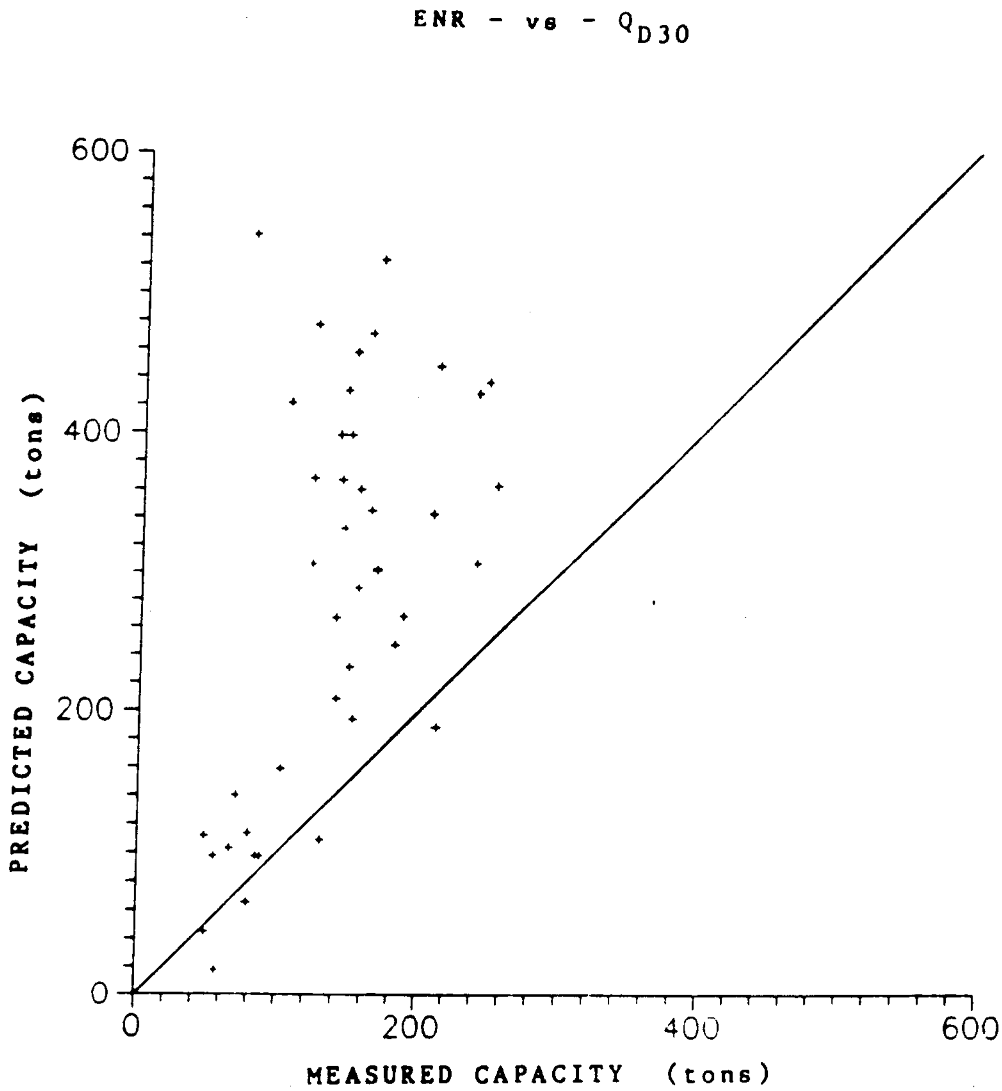


Figure 1. Plot of predicted - vs - measured capacity for the ENR formula.

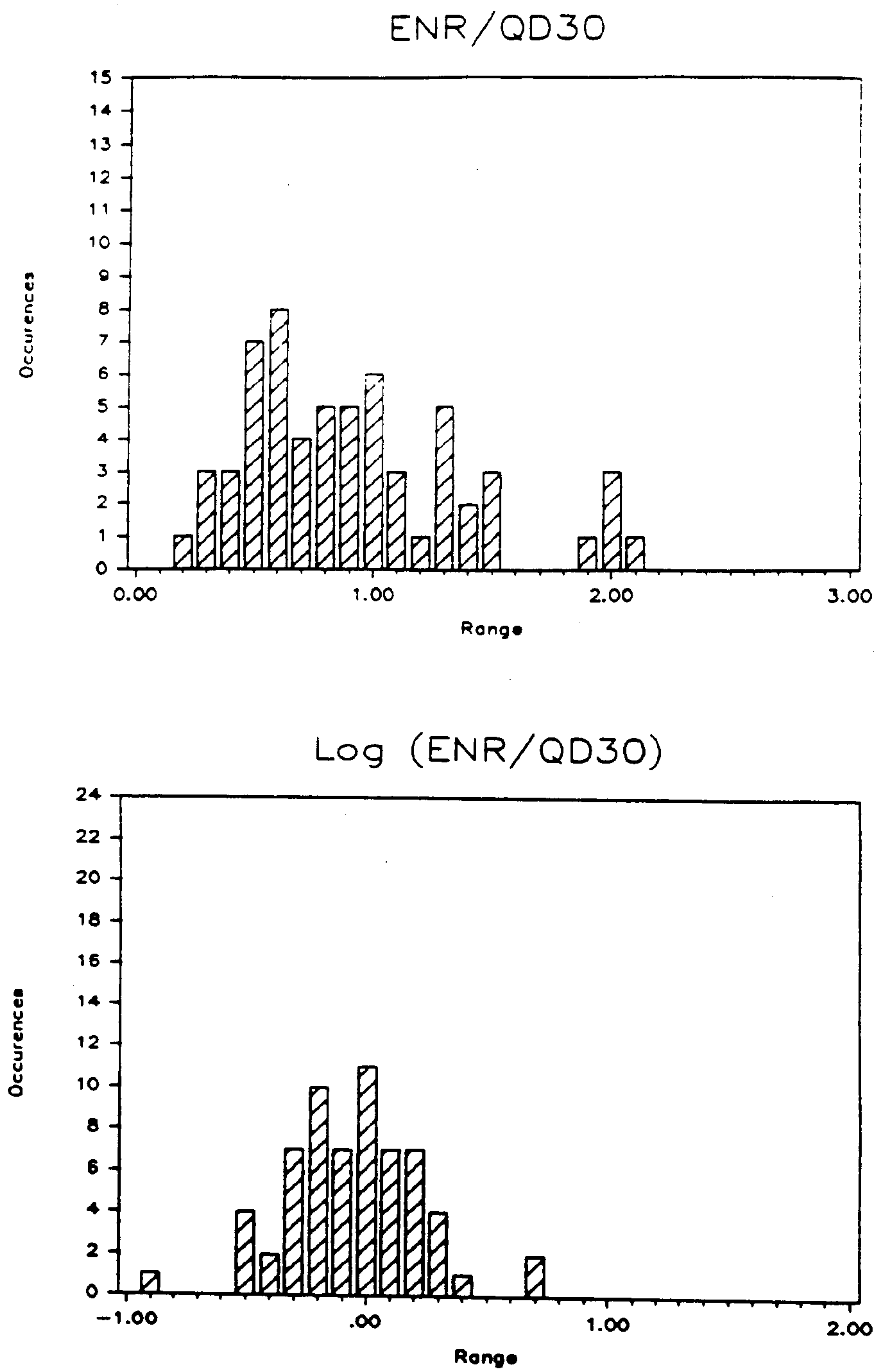


Figure 2. Histograms for raw and transformed data - ENR formula.

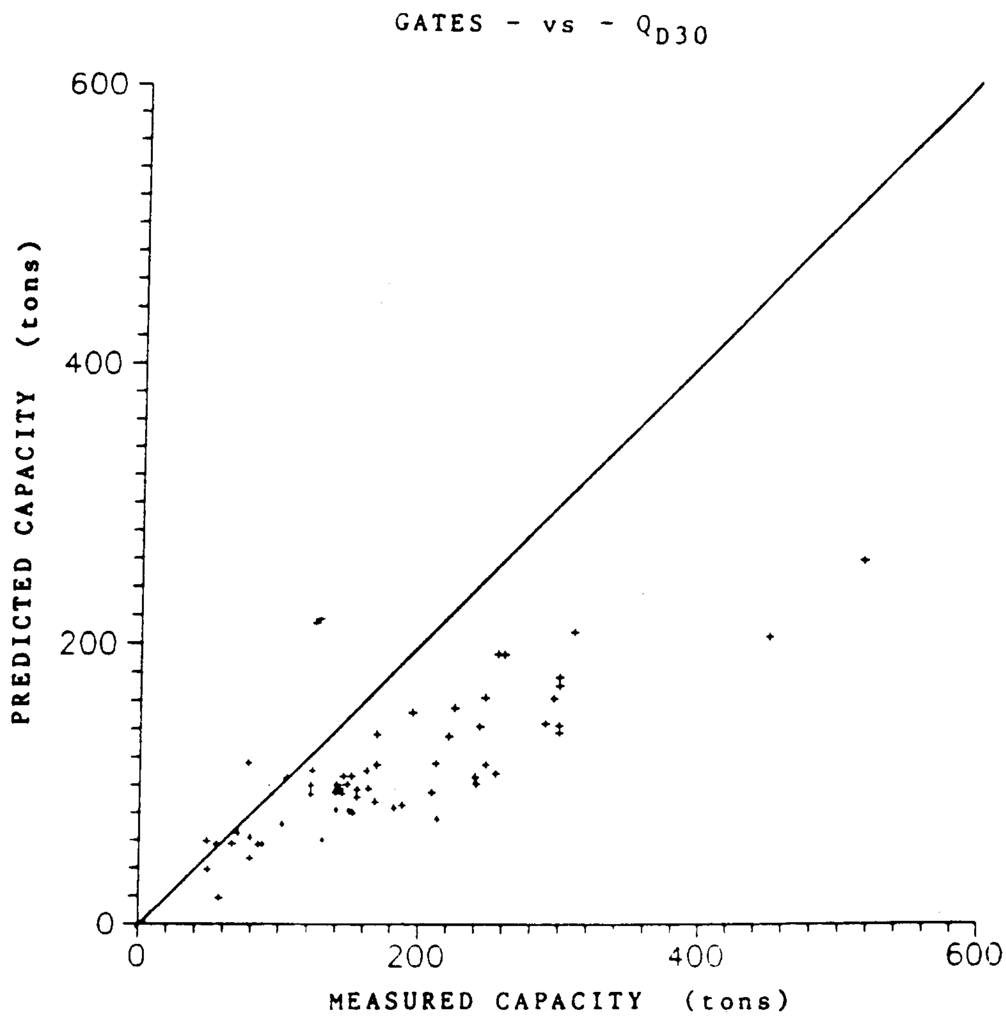
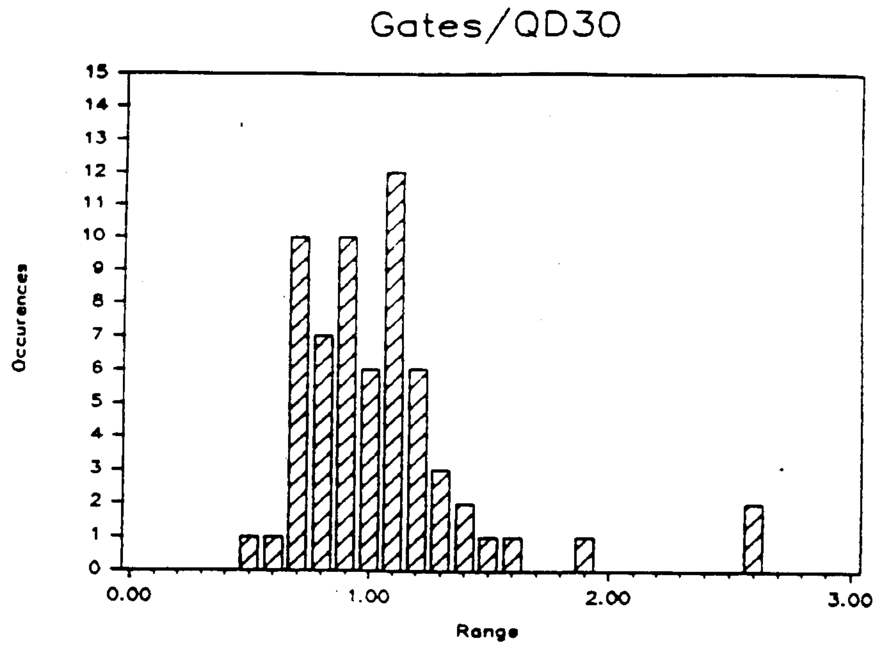


Figure 3. Plot of predicted - vs - measured capacity for the Gates formula.



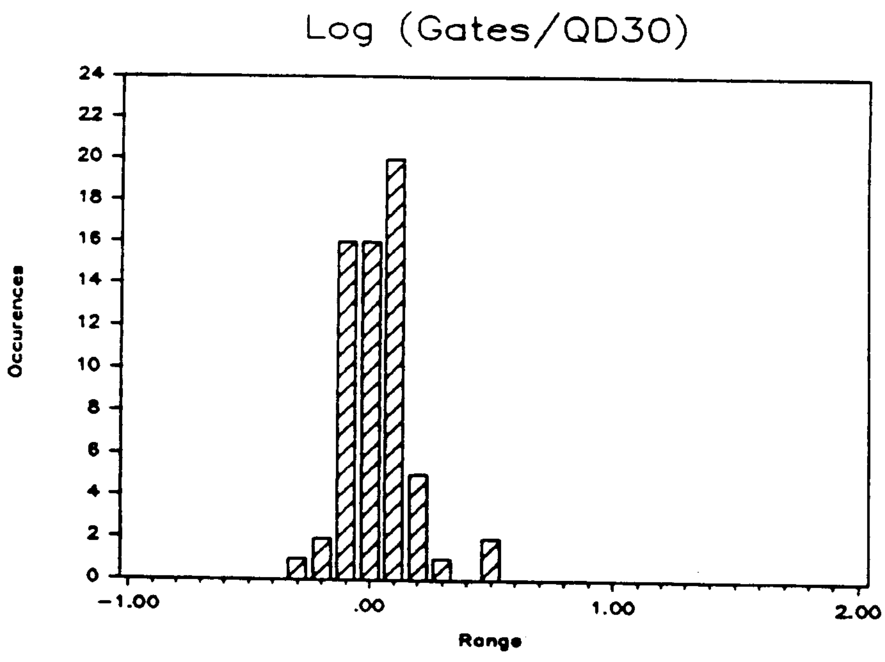


Figure 4. Histograms for raw and transformed data - Gates formula.

eight different groups are presented in Table 1, and the rest may be found in Appendix G. In all but one of the different groupings, the Gates equation is ranked first, and it is a very close second for the piles in cohesive soils. The PCUBC, Hiley, Weisbach, and Danish formulas group quite tightly together, but they have larger values of CV_{LOG} than does the Gates formula. The Janbu formula is in this same group with the exception of the piles in cohesionless soils. The ENR, Modified ENR, and Eytelwein formulas have consistently larger values of CV_{LOG} than the equations above, and the Navy - McKay formula is consistently last by a large margin.

The divisors required for 98% and 95% assurance that the actual safety factor will be greater than or equal to 1.0 based on Agerschou's method are shown in Tables 2-4. Table 2 provides these quantities using data from all pile load tests. It shows, for example, that the ultimate capacity predicted by the ENR formula should be divided by 9.06 to obtain allowable capacity, if it is required that 98% of the time the actual capacity will be greater than the allowable capacity. If this divisor (9.06) is used, the resulting actual safety factors will range as high as 14.36! In contrast, the Gates formula prediction should be divided by 1.21, resulting in actual safety factors up to 3.6. Tables 3 and 4 present the same calculations, using data from only clay sites and cohesionless sites, respectively. As expected, the same general trends are evident from the analyses presented in Tables 2-4 and from the coefficient of variation analyses.

Discussion

The results of this study follow the trend of similar comparative studies which have been done elsewhere. The same formulas which have fared

Table 1 CV_{LOG} Values for Selected Pile Types and Soil Conditions

ALL PILES (N=63)

RANK	FORMULA	CV_{LOG}
1	Gates	0.14
2	Hiley	0.20
2	PCUBC	0.20
4	Danish	0.21
4	Weisbach	0.21
6	Janbu	0.29
7	Modified ENR	0.30
7	Eytelwein	0.30
9	ENR	0.32
10	Navy-McKay	0.91

ALL EXCEPT TIMBER (N=57)

RANK	FORMULA	CV_{LOG}
1	Gates	0.13
2	Danish	0.19
2	Hiley	0.19
2	Janbu	0.19
2	PCUBC	0.19
2	Weisbach	0.19
7	ENR	0.28
7	Eytelwein	0.28
9	Modified ENR	0.29
10	Navy-McKay	0.58

All PILES IN COHESIONLESS SOILS (N=41)

RANK	FORMULA	CV_{LOG}
1	Gates	0.11
2	Danish	0.21
2	Hiley	0.21
2	PCUBC	0.21
5	Weisbach	0.22
6	Modified ENR	0.27
7	Eytelwein	0.29
8	ENR	0.30
9	Janbu	0.33
10	Navy-McKay	0.92

ALL PILES IN COHESIVE SOILS (N=11*)

RANK	FORMULA	CV_{LOG}
1	PCUBC	0.18
2	Gates	0.19
3	Weisbach	0.20
4	Hiley	0.21
4	Janbu	0.21
6	Danish	0.22
7	Eytelwein	0.31
8	Modified ENR	0.35
9	ENR	0.38
10	Navy-McKay	0.65

*Sample size is too small to provide reliable results

Table 1 Continued

H-SECTION (N=5*)

RANK	FORMULA	CV_{LOG}
1	Gates	0.08
2	PCUBC	0.11
3	Danish	0.13
3	Weisbach	0.13
5	Janbu	0.14
6	Hiley	0.16
7	Modified ENR	0.20
8	Eytelwein	0.24
9	ENR	0.25
10	Navy-McKay	0.34

SQUARE AND OCTAGONAL CONCRETE (N=20)

RANK	FORMULA	CV_{LOG}
1	Gates	0.18
2	Weisbach	0.20
3	Danish	0.21
4	Janbu	0.22
4	PCUBC	0.22
6	Hiley	0.23
7	Eytelwein	0.31
8	Modified ENR	0.36
9	ENR	0.39
10	Navy-McKay	0.68

RAYMOND STEP TAPER (N=16)

RANK	FORMULA	CV_{LOG}
1	Gates	0.09
2	ENR	0.16
2	Hiley	0.16
4	Danish	0.17
5	Weisbach	0.18
6	Eytelwein	0.19
6	Janbu	0.19
8	Modified ENR	0.20
9	PCUBC	0.22
10	Navy-McKay	0.77

TIMBER (N=6*)

RANK	FORMULA	CV_{LOG}
1	Gates	0.18
2	PCUBC	0.23
3	Hiley	0.25
4	Danish	0.30
5	Weisbach	0.32
6	Modified ENR	0.37
7	Eytelwein	0.46
8	ENR	0.49
9	Navy-McKay	0.60
10	Janbu	0.90

*Sample size is too small to provide reliable results

FORMULA	Divisor for 98% safety	Upper limit of 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	Divisor for 95% safety	Upper limit of 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

Table 2. Divisor and Upper Limit Safety Factors for 98% and 95% Safety. Calculated for all piles (N = 63)

FORMULA	Divisor for 98% safety	Upper limit of safety factors
PCUBC	1.63	5.11
Gates	1.36	5.52
Weisbach	3.55	6.13
Hiley	2.30	6.31
Janbu	2.35	6.66
Danish	3.29	7.25
Eytelwein	7.70	13.57
Modified ENR	6.41	18.68
ENR	11.90	25.18
Navy-McKay	35.37	150.19

FORMULA	Divisor for 95% safety	Upper limit of safety factors
PCUBC	1.39	3.69
Gates	1.15	3.92
Weisbach	2.97	4.27
Hiley	1.92	4.37
Janbu	1.94	4.56
Danish	2.70	4.88
Eytelwein	5.94	8.07
Modified ENR	4.79	10.41
ENR	8.63	13.23
Navy-McKay	21.45	55.25

Table 3. Divisor and Upper Limit Safety Factors for 98% and 95% Safety. Calculated for Clayey Soils (N = 11)

FORMULA	Divisor for 98% safety	Upper limit of safety factors
Gates	1.01	2.73
Hiley	2.46	6.40
PCUBC	1.81	6.52
Danish	3.09	6.69
Weisbach	3.72	7.14
Modified ENR	3.86	8.51
Eytelwein	5.34	9.29
ENR	7.38	11.49
Janbu	3.43	17.42
Navy-McKay	23.90	187.59

FORMULA	Divisor for 95% safety	Upper limit of safety factors
Gates	0.92	2.24
Hiley	2.05	4.42
PCUBC	1.50	4.49
Danish	2.56	4.58
Weisbach	3.06	4.82
Modified ENR	3.12	5.55
Eytelwein	4.27	5.96
ENR	5.79	7.06
Janbu	2.58	9.85
Navy-McKay	14.18	66.02

Table 4. Divisor and Upper Limit Safety Factors for 98% and 95% Safety. Calculated for Cohesionless Soils (N = 41)

best in other comparisons (Danish, Gates, Hiley, Janbu, PCUBC, and Weisbach) also are ranked high in this study. Of these, the Gates formula clearly is the best, ranking first in all but one comparison (clayey soils) where it was a close second. The ENR, Modified ENR, Eytelwein, and Navy-McKay formulas can easily be seen to be very unreliable.

This study clearly points out two important aspects of the question of whether WSDOT should abandon use of the ENR formula. 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 current safety factor (divisor) used with the ENR formula may not provide the level of safety desired. Based on the data from all pile load tests, a divisor of 6.95 would be required to assure that the predicted capacity was greater than actual capacity 95% of the time, and a divisor of 9.06 would be necessary for 98% assurance. Although the data set for some of the subgroups, such as timber piles, is small, use of the data from all piles provides a large enough sample to have confidence in the validity of the results.

Based on this study it seems apparent that the ENR 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 and should be used in preference to any other. The Gates formula is not significantly more difficult to use than the ENR 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.

Economic Effects of Using the Gates Formula

To evaluate the economic effects of changing to the Gates formula, comparisons of allowable load using several different assumptions were made. The average allowable load for all piles (N=63) based on the Gates formula was calculated using the divisors for 98% and 95% assurance. This was also done using the ENR formula. In addition, the average allowable capacity for the ENR formula was calculated using a divisor of 6.0, the current WSDOT practice. In this way, a comparison can be made using the same measures of safety for both formulas and also using two specific measures of safety for the Gates formula and the current method used for ENR. The results of these four analyses are presented in Table 5.

When both formulas are used with 98% assurance that the allowable capacity will be higher than the actual capacity, the Gates formula gives an average allowable capacity of 95.4 tons vs. 69.2 tons using the ENR formula. This is an average increase of 38%, with no additional risk. The allowable capacity is higher using the Gates formula for 55 out of 63 piles. When 95% assurance is used, (a more realistic value) the Gates formula gives an average allowable capacity of 108.9 tons, vs. 90.2 tons using ENR, an increase of 21%.

Since WSDOT currently uses a factor of 6.0 with the ENR equation, the average allowable load using this value was calculated. The average allowable capacity in this case is 104.5 tons, approximately 4% less than that obtained with the Gates formula using 95% assurance.

The economic benefits of switching to the Gates formula clearly depend on the choices made in the selection of the divisor. If the comparison is made between the ENR formula as it is currently used, and the Gates formula with 95% confidence, the economic benefits are small, but positive If the comparison is made using the same level of safety, the economic benefit of switching to the Gates formula will be substantial.

Table 5 Comparison of Average Allowable Loads Based on Gates and ENR Formulas

	Divisor Used			Average Allowable Load (tons)		
	98%[1]	95%[1]	Current[2]	98%	95%	Current
ENR	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

1 divisor, based on data from all piles

2 divisor currently used for ENR formula, equivalent to 92.5%

APPENDIX A

PILE LOAD TEST INFORMATION

Abbreviation Key

HP - steel H pile
CP - closed steel pipe pile
OP - open steel pipe pile
FP - concrete filled steel pipe pile
SC - square prestressed concrete pile
OC - octagonal prestressed concrete pile
ST - Raymond step taper pile
T - timber pile

The definitions of the symbols used in this section may be found in Appendix H.

!	eh Hammer Efficiency	Eh [in-lb] Rated Energy	Wr [lb] Weight of Ram	Wp [lb] Weight of Pile	Lp [in] Length of Pile	Ap [in^2] Area of Pile	Ep [psi] Modulus of Elasticity	s [in/bl] Inverse of Blow-count
Pile HP-1:	Incomplete							
Pile HP-2:	Incomplete							
Pile HP-3:	0.85	234000.00	6500.00	3604.00	816.00	15.51	29000000.00	0.17
Pile HP-4:	0.80	180000.00	5000.00	957.60	360.00	16.80	29000000.00	1.00
Pile HP-5:	0.80	312000.00	8000.00	2898.00	720.00	12.40	29000000.00	0.31
Pile HP-6:	0.80	234000.00	6500.00	3570.00	1020.00	12.40	29000000.00	0.28
Pile HP-7:	0.85	230400.00	6500.00	3180.00	720.00	15.50	29000000.00	0.32
Pile CP-1:	0.80	1080000.00	30000.00	45120.00	1920.00	82.54	29000000.00	0.05
Pile CP-2:	0.80	1080000.00	30000.00	40890.00	1740.00	82.54	29000000.00	0.04
Pile CP-3:	Incomplete							
Pile CP-4:	1.00	447600.00	14000.00	4256.61	720.00	20.76	29000000.00	0.11
Pile CP-5:	Incomplete							
Pile CP-6:	0.80	312000.00	8000.00	1006.55	360.00	9.82	29000000.00	0.16
Pile OP-1:	Incomplete							
Pile OP-2:	Incomplete							
Pile OP-3:	1.00	447600.00	14000.00	4256.61	720.00	20.76	29000000.00	0.40
Pile OP-4:	0.90	651600.00	6600.00	5925.40	1560.00	13.40	29000000.00	0.23
Pile FP-1:	0.85	293400.00	8000.00	5546.68	624.00	31.22	29000000.00	0.19
Pile FP-2:	0.80	312000.00	8000.00	6283.19	600.00	113.10	5175361.50	1.00
Pile FP-3:	0.86	360000.00	5070.00	2237.73	495.60	15.86	29000000.00	0.10
Pile FP-4:	Incomplete							
Pile FP-5:	Incomplete							
Pile FP-6:	0.85	294000.00	8000.00	2243.20	960.00	8.25	29000000.00	0.24
Pile FP-7:	0.90	651600.00	6600.00	2720.90	1320.00	5.94	29000000.00	0.38
Pile FP-8:	0.90	651600.00	6600.00	2362.23	1404.00	5.94	29000000.00	0.09
Pile FP-9:	0.90	651600.00	6600.00	2180.52	1296.00	5.94	29000000.00	0.36
Pile SC-1:	Incomplete							
Pile SC-2:	Incomplete							
Pile SC-3:	0.80	312000.00	8000.00	4000.00	300.00	144.00	3000000.00	0.20
Pile SC-4:	0.80	312000.00	8000.00	11200.00	840.00	144.00	3000000.00	0.69
Pile SC-5:	0.80	390000.00	10000.00	10890.00	600.00	196.00	3000000.00	1.50
Pile SC-6:	0.80	390000.00	10000.00	11980.00	660.00	196.00	3000000.00	1.50
Pile SC-7:	Incomplete							

Parameters used in the dynamic formulas for this study.

	e Elastic loss ENR	K (PCUBC) .25-steel .10-others	C1 [in] Hiley	C2 [in] Hiley	C3[in] Hiley	Cd Janbu	Lambda Janbu	n Coefficient of Rest.
Pile HP-1	Incomplete							
Pile HP-2	Incomplete							
Pile HP-3	0.10	0.25	0.00	0.41	0.10	0.83	12.28	0.77
Pile HP-4	0.10	0.25	0.00	0.07	0.10	0.78	0.11	0.77
Pile HP-5	0.10	0.25	0.00	0.48	0.10	0.80	5.28	0.77
Pile HP-6	0.10	0.25	0.00	0.77	0.10	0.83	6.82	0.77
Pile HP-7	0.10	0.25	0.00	0.41	0.10	0.82	2.99	0.77
Pile CP-1	0.10	0.25	0.04	0.42	0.10	0.98	268.06	0.55
Pile CP-2	0.10	0.25	0.04	0.39	0.10	0.95	449.43	0.55
Pile CP-3	Incomplete							
Pile CP-4	0.10	0.25	0.00	0.72	0.10	0.80	44.97	0.77
Pile CP-5	Incomplete							
Pile CP-6	0.10	0.25	0.00	0.27	0.10	0.77	12.00	0.65
Pile OP-1	Incomplete							
Pile OP-2	Incomplete							
Pile OP-3	0.10	0.25	0.00	0.72	0.10	0.80	3.34	0.77
Pile OP-4	0.10	0.25	0.00	1.04	0.10	0.88	44.21	0.77
Pile FP-1	0.10	0.25	0.00	0.31	0.10	0.85	4.74	0.77
Pile FP-2	0.10	0.25	0.10	0.17	0.10	0.87	0.26	0.63
Pile FP-3	0.10	0.25	0.00	0.50	0.10	0.82	33.36	0.77
Pile FP-4	Incomplete							
Pile FP-5	Incomplete							
Pile FP-6	0.10	0.25	0.00	0.72	0.10	0.79	17.41	0.77
Pile FP-7	0.10	0.25	0.00	1.04	0.10	0.80	31.96	0.77
Pile FP-8	0.10	0.25	0.00	0.94	0.10	0.80	578.35	0.77
Pile FP-9	0.10	0.25	0.00	0.86	0.10	0.80	33.37	0.77
Pile SC-1	Incomplete							
Pile SC-2	Incomplete							
Pile SC-3	0.10	0.10	0.25	0.20	0.10	0.83	4.48	0.75
Pile SC-4	0.10	0.10	0.17	0.28	0.10	0.96	1.03	0.63
Pile SC-5	0.10	0.10	0.06	0.60	0.10	0.91	0.14	0.58
Pile SC-6	0.10	0.10	0.06	0.11	0.10	0.93	0.16	0.58
Pile SC-7	Incomplete							

Parameters used in the dynamic formulas for this study.

APPENDIX B - MEASURED ULTIMATE CAPACITY

There are many different ways to determine the ultimate capacity of a pile from the load verses deflection data that are obtained from a pile load test. In order to provide a uniform reference for comparison, the same method of determining ultimate capacity should be used for all piles. Therefore, all measured capacities for this study were determined using each of the following three methods which were suggested by the staff of the Washington State DOT.

The first method is called the Q-D over 30 or "Q_{D30}" method. This method has three main steps:

1) Calculate the elastic compression of the pile assuming that all of the load is transferred to the tip of the pile, and plot this line on the load-deflection graph.
2) Plot a line parallel to the elastic compression line which intersects the Y axis at a distance from the origin equal to the pile tip diameter divided by 30.
3) Locate the point where the line plotted in step 2 intersects the load-deflection curve. The load at this point is the ultimate capacity of the pile.

The second method is called the elastic-tangent or "Q_{ET}" method. This method has four steps:

1) Calculate the elastic compression of the pile assuming that all of the load is transferred to the tip of the pile. Plot this line on the load-deflection curve.
2) Draw a line which is parallel to the elastic compression line and tangent to the load-deflection curve.

3) Draw a line tangent to the plunging portion of the load-deflection curve with a slope of 0.05"/ton.

4) Locate the point where the two lines plotted in steps 2 and 3 intersect. The load at this point is the ultimate capacity of the pile.

The third method is called the double tangent or "Q_{DT}" method. This method has three steps:

1) Draw a line tangent to the initial portion of the load-deflection curve.

2) Draw a line tangent to the plunging portion of the load-deflection curve with a slope of 0.05"/ton.

3) Locate the intersection of the two lines drawn in steps 1 and 2. The load at this point is the ultimate capacity of the pile.

Examples 1, 2, and 3 in Figure B1 illustrate each of these methods.

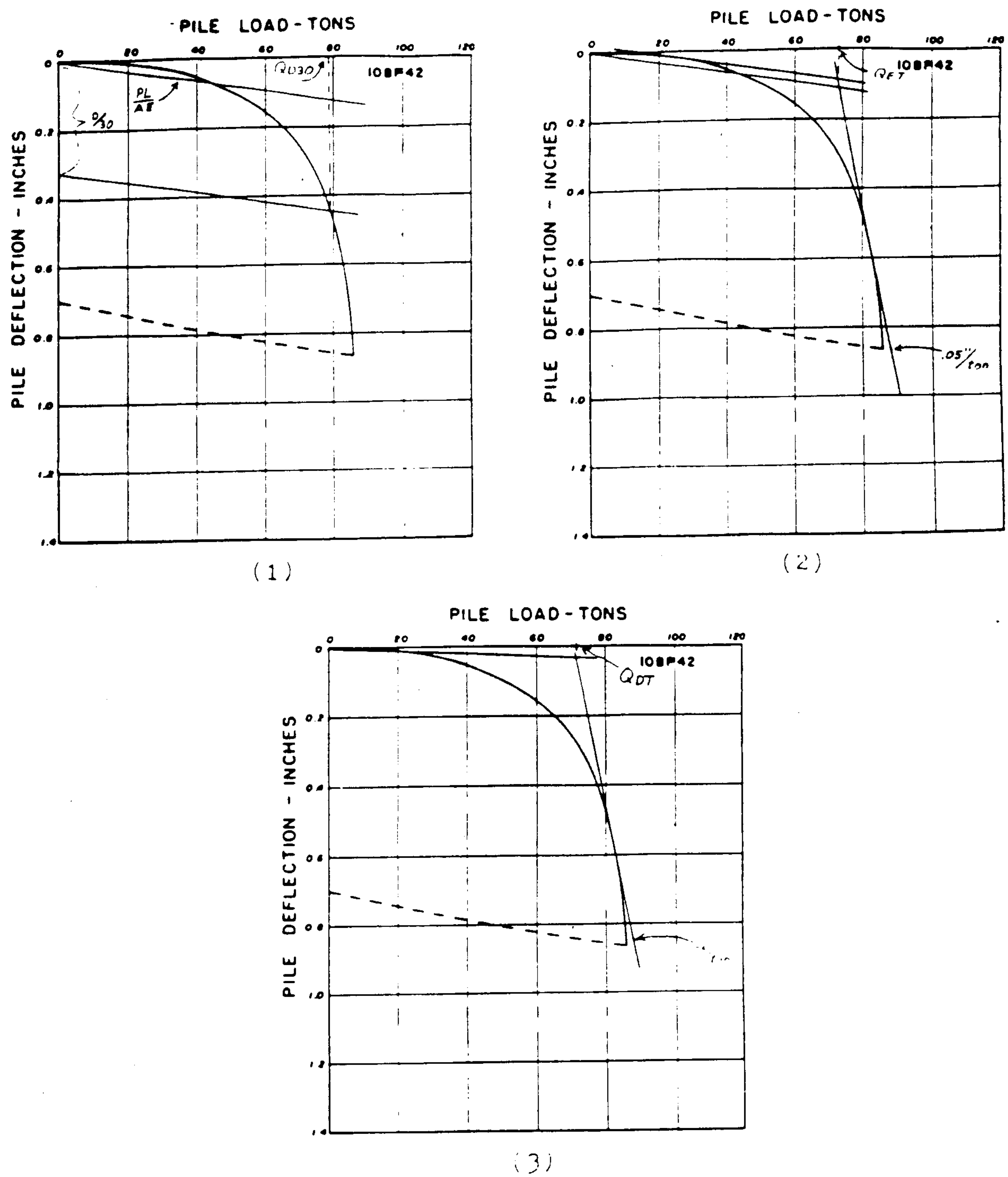


Figure B1. Examples of the methods used to determine the measured ultimate capacity.

MEASURED PILE CAPACITY FROM PILE LOAD TESTS

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				

APPENDIX C

FORMULAS USED IN THE STUDY

ENR $$Q_u = \frac{e_h E_h}{s + z}$$

Mod. ENR $$Q_u = \frac{e_h E_h}{s + z} \cdot \frac{W + n^2 w}{W + w}$$

Hiley $$Q_u = \frac{e_h E_h}{s+(C_1+C_2+C_3)/2} \cdot \frac{W + n^2 w}{W + w}$$

Gates $$Q_u = 27 \sqrt{e_h E_h}(1-\log s)$$

e_h = 0.75 for drop hammers
E_h = 0.85 for other hammers
Q_u (kips), s (in), E_h (ft-kips)

Janbu $$Q_u = \frac{e_h E_h}{K_u s}$$

$$K_u = C_d \left[1 + \sqrt{1 + \frac{\lambda}{C_d}} \right]$$

$$C_d = 0.75 + 0.15 \frac{w}{W}$$

$$\lambda = \frac{e_h E_h L}{AEs^2}$$

Danish

$$Q_u = \frac{e_h E_h}{s + \sqrt{\frac{e_h E_h L}{2AE}}}$$

PCUBC

$$Q_u = \frac{e_h E_h \cdot \frac{W + Kw}{W + w}}{S + \frac{Q_u L}{AE}}$$

K = 0.25 for steel piles
= 0.10 for all other piles

Eytelwein

$$Q_u = \frac{e_h E_h}{s \quad 1 + \frac{w}{W}} \quad \text{(drop hammers)}$$

$$Q_u = \frac{e_h E_h}{s + \left[0.1 \quad \frac{w}{W}\right]} \quad \text{(steam hammers)}$$

Weisbach

$$Q_u = \frac{-sAE}{L} + \sqrt{\frac{2e_h E_h AE}{L} + \left[\frac{sAE}{L}\right]^2}$$

Navy-McKay

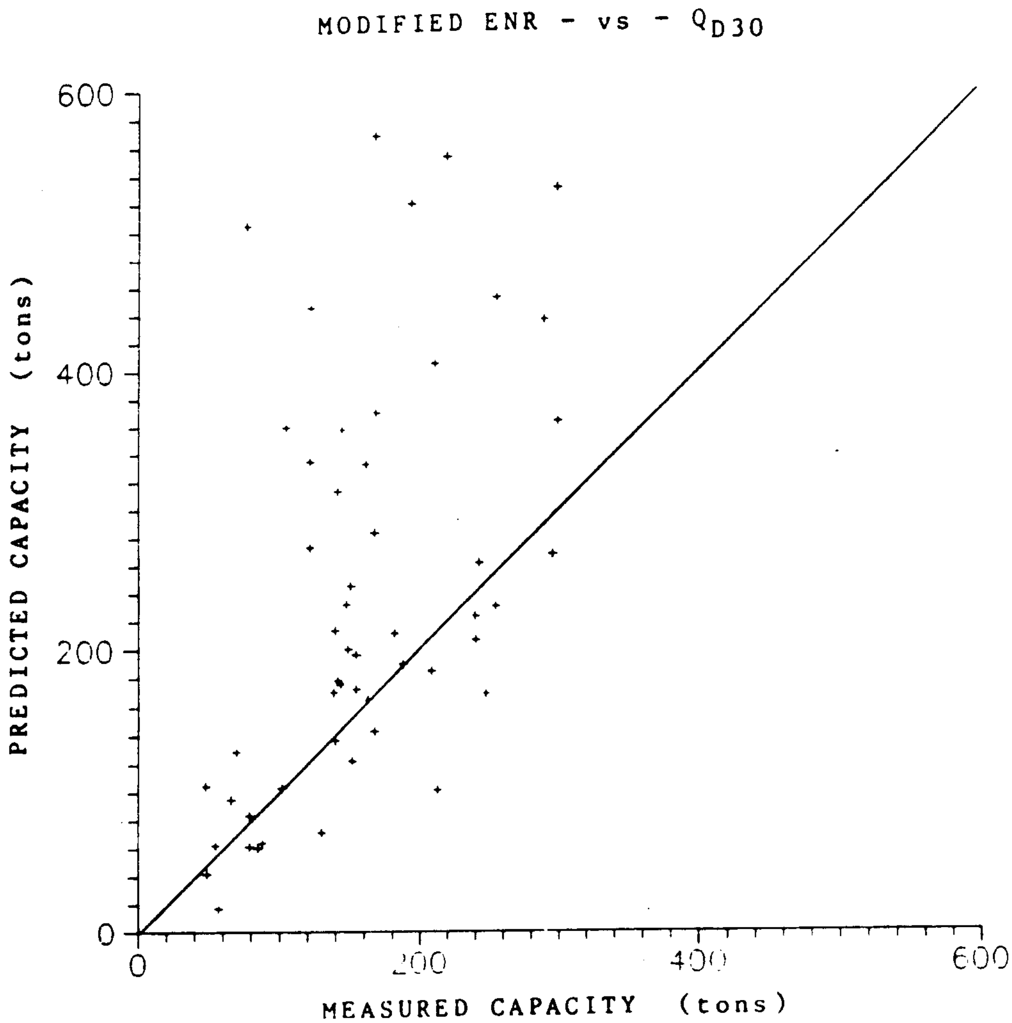
$$Q_u = \frac{e_h E_h}{s\left[1 + 0.3 \frac{w}{W}\right]}$$

APPENDIX D--FORMULA PREDICTIONS OF ULTIMATE LOAD

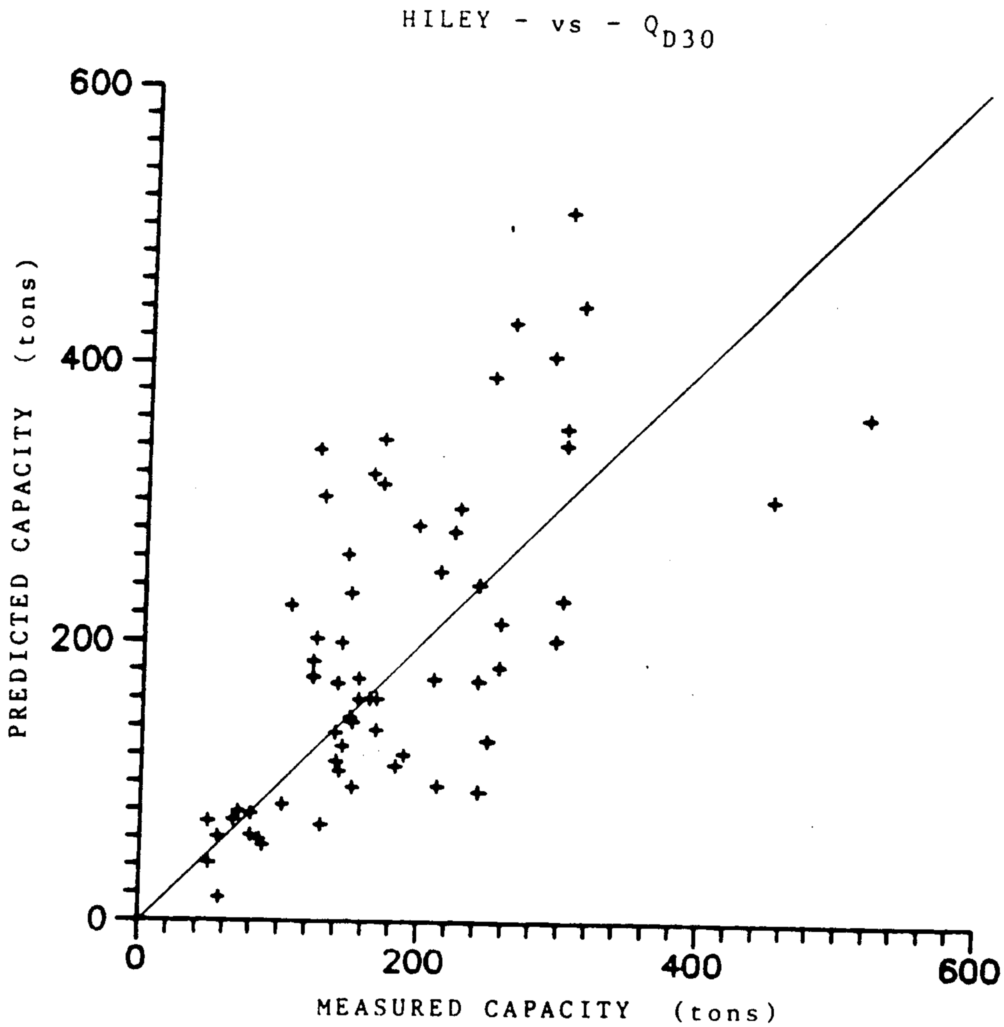
Pile Number	Q_{D30}	ENR	Mod. ENR	Hiley	Gates	Janbu	Danish	PCUBC	Eytel-wein	Weis-bach	Navy-McKay
HP-3	142	366	313	200	97	140	167	115	438	192	497
HP-4	79	65	61	62	47	45	59	57	71	69	68
HP-5	122	306	273	186	93	134	155	120	363	184	366
HP-6	182	247	211	112	83	100	118	84	280	139	288
HP-7	149	231	200	147	81	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

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

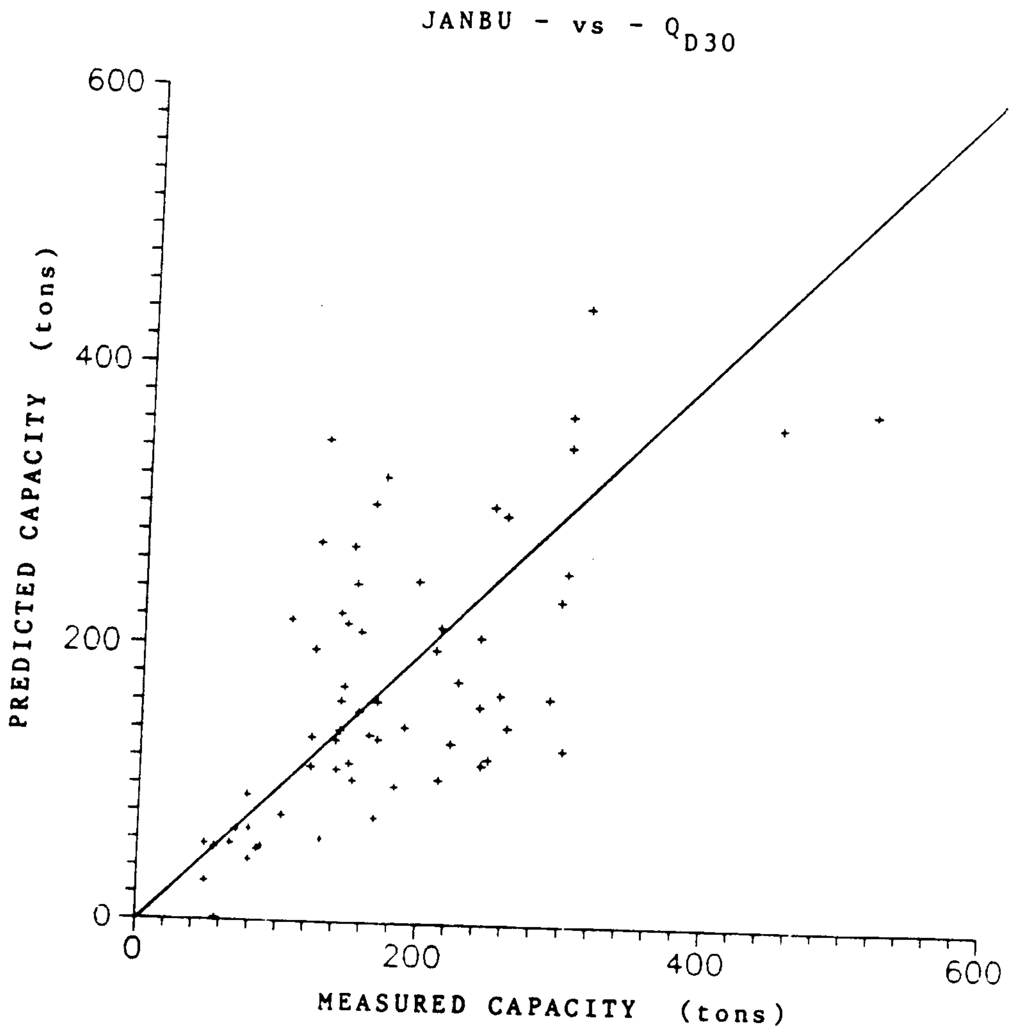
APPENDIX E - SCATTER GRAPHS



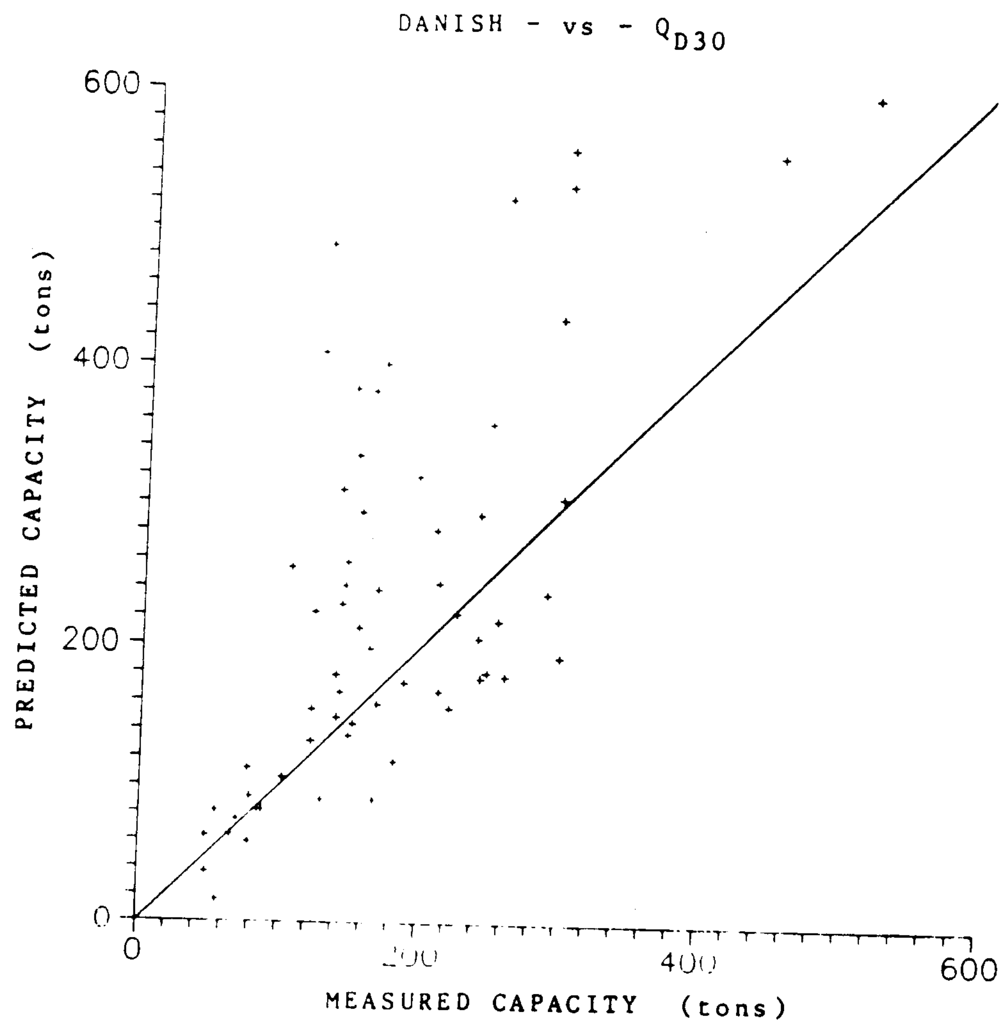
Scatter graph for predicted versus measured capacity for the Modified ENR formula.



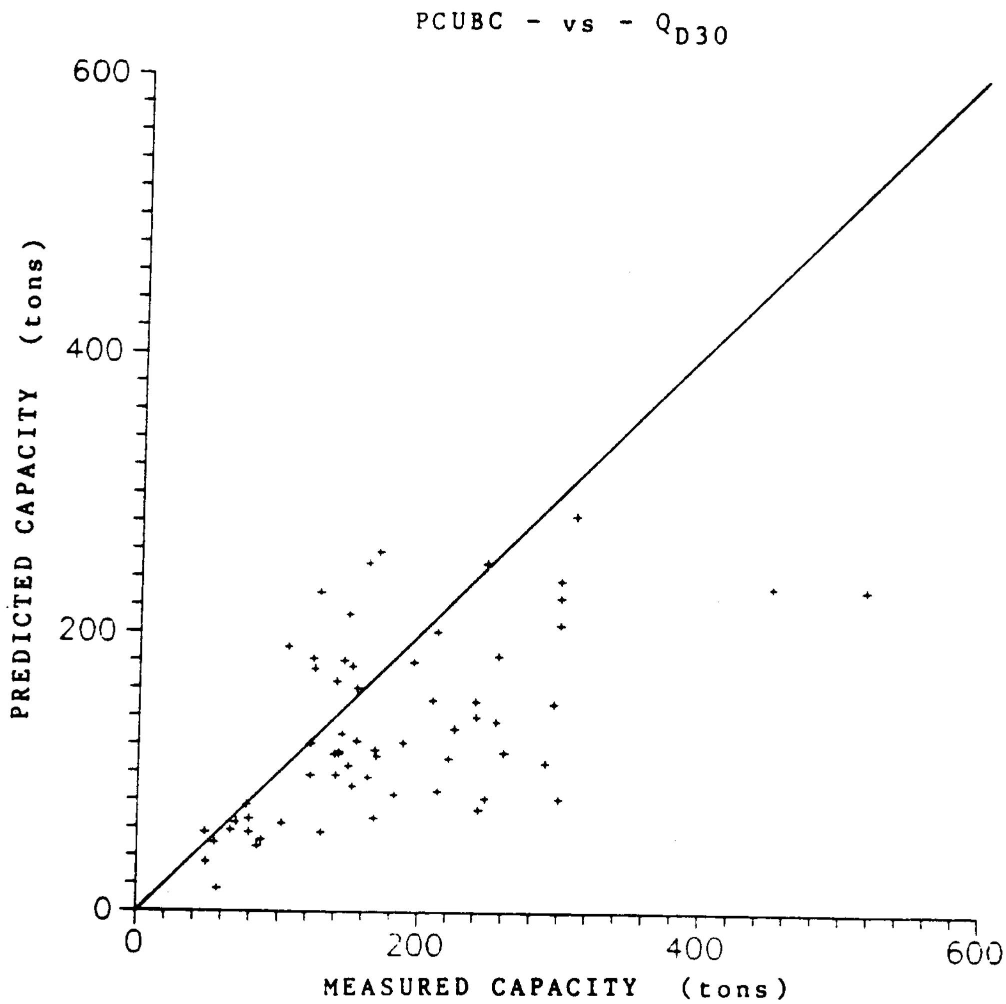
Scatter graph for predicted versus measured capacity for the Hiley formula.



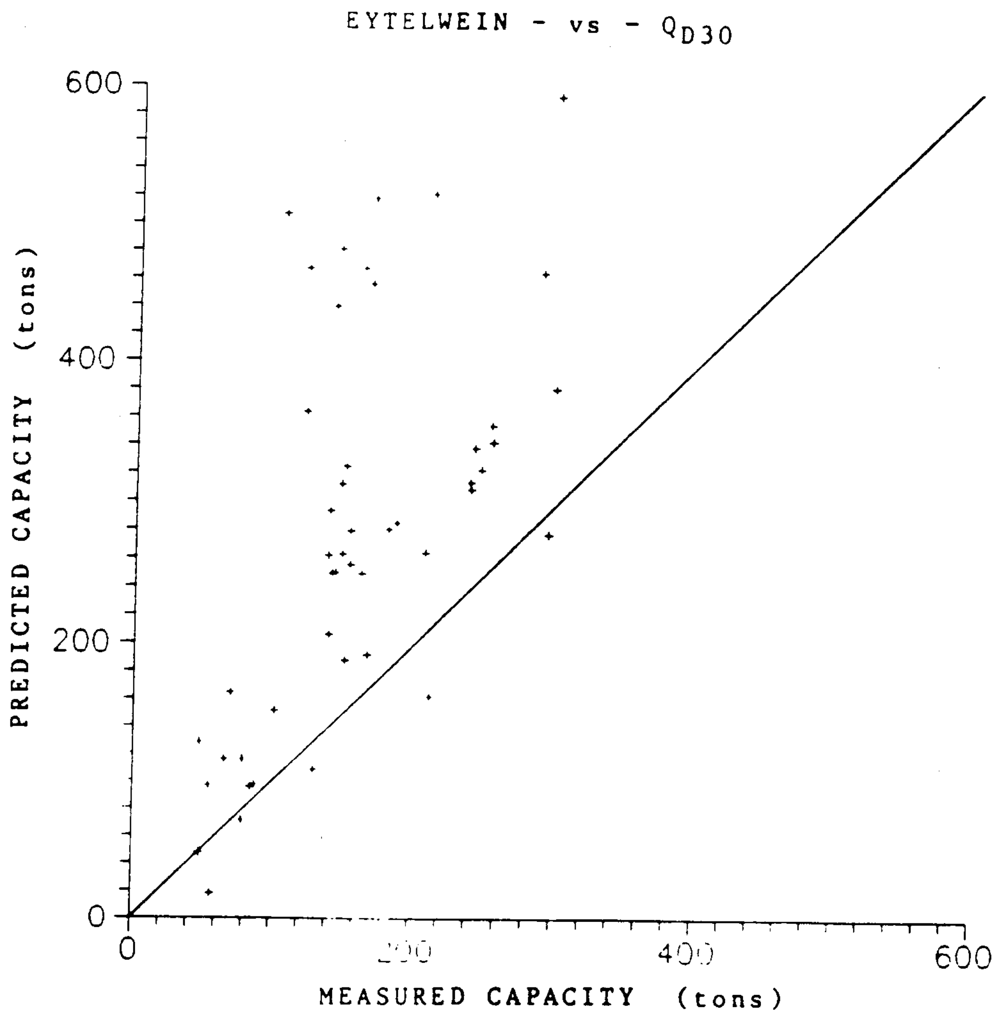
Scatter graph for predicted versus measured capacity for the Janbu formula.



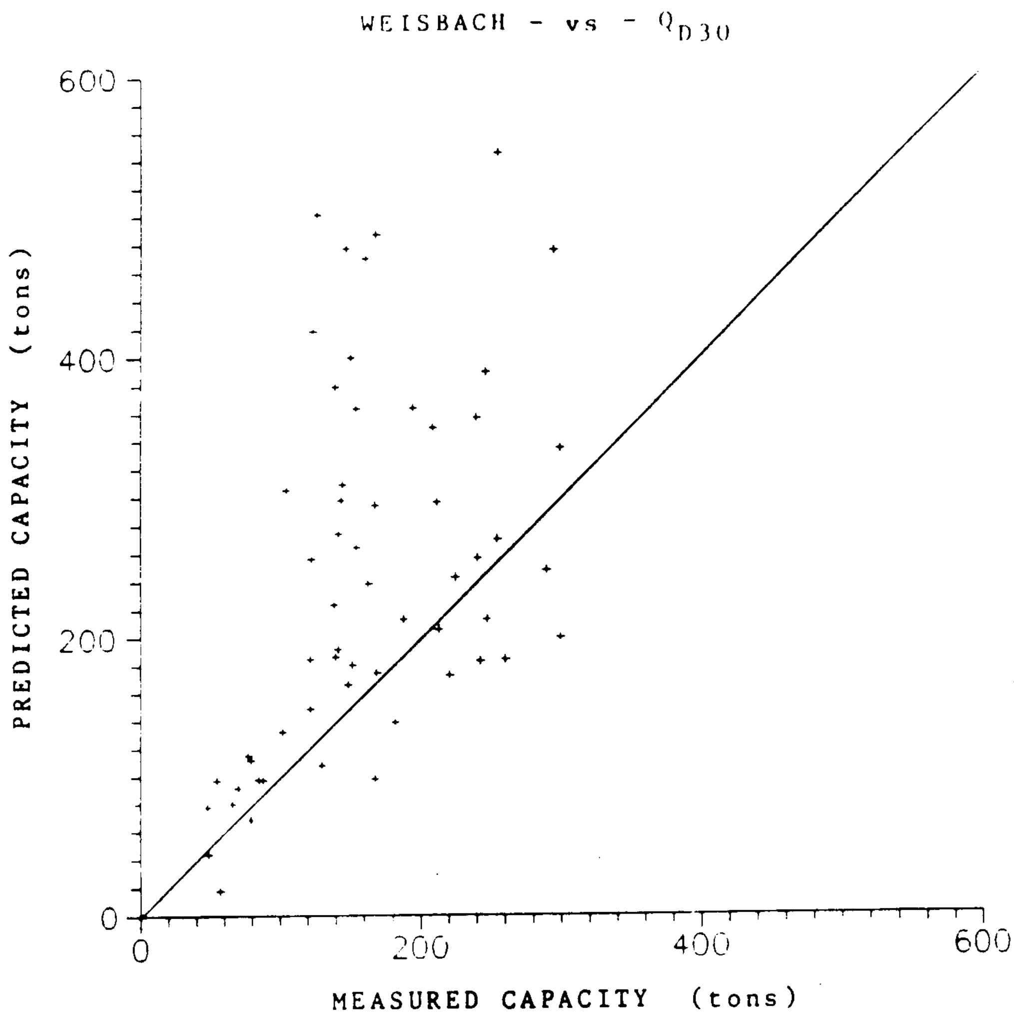
Scatter graph for predicted versus measured capacity for the Danish formula.



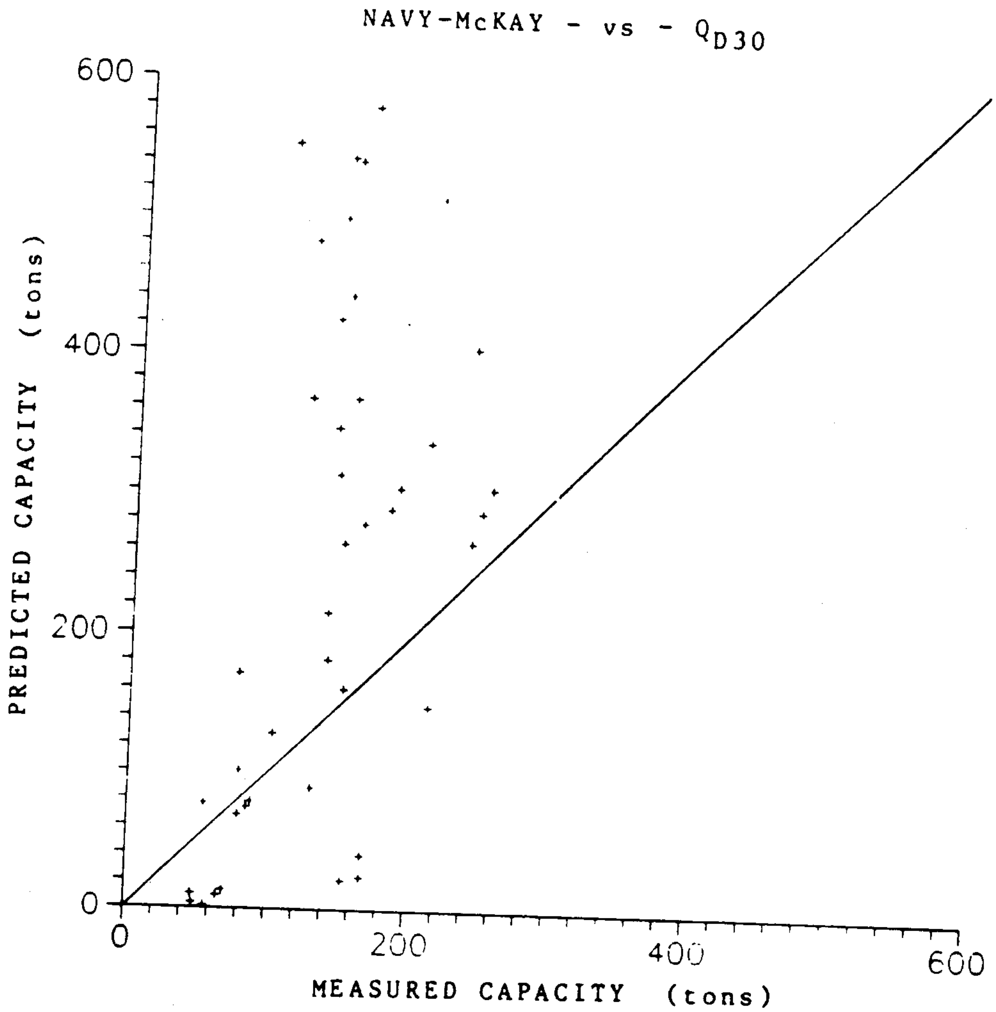
Scatter graph for predicted versus measured capacity for the PCUBC formula.



Scatter graph for predicted versus measured capacity for the Eytelwein formula.

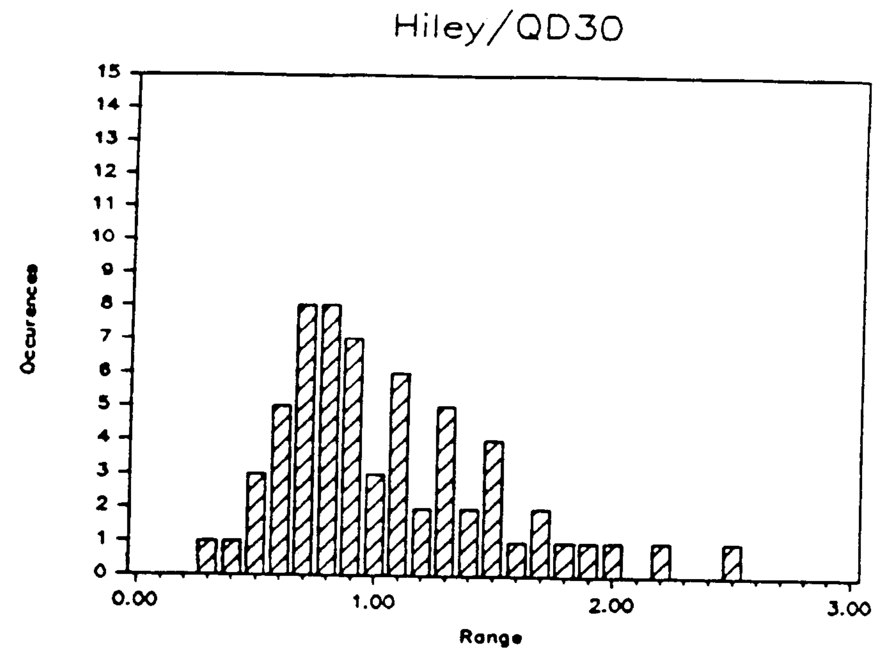


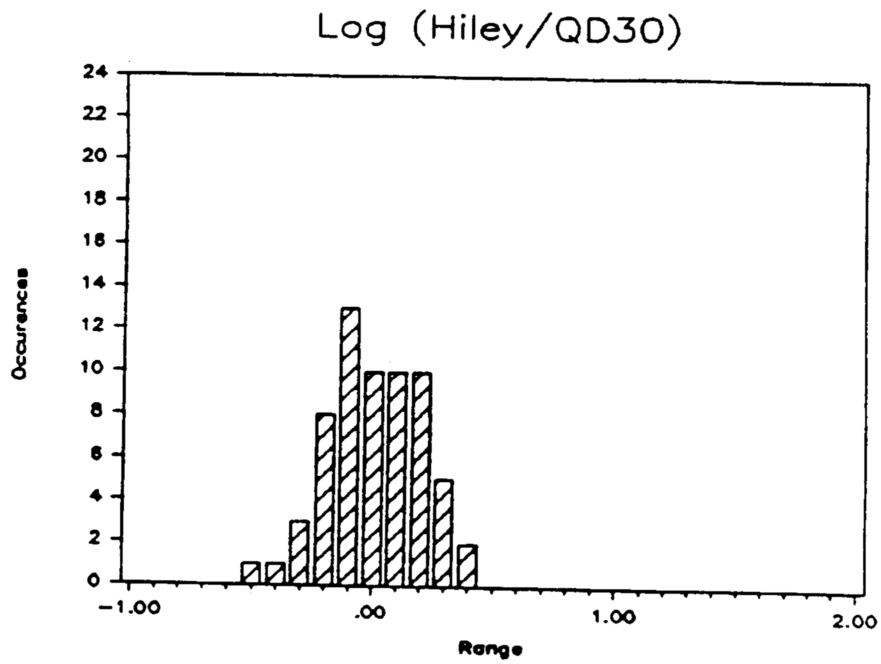
Scatter graph for predicted versus measured capacity for the Weisbach formula.



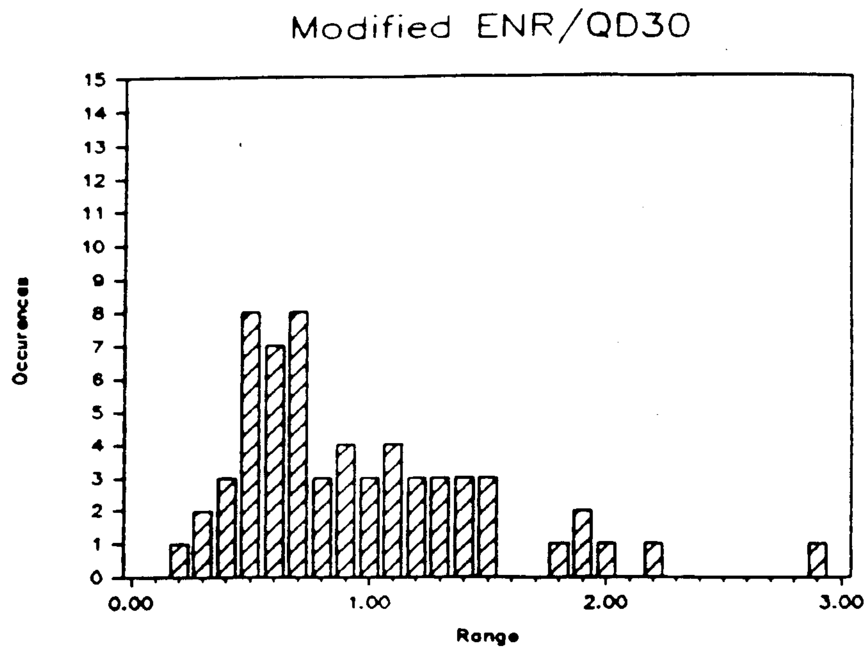
Scatter graph for predicted versus measured capacity for the Navy-McKay formula.

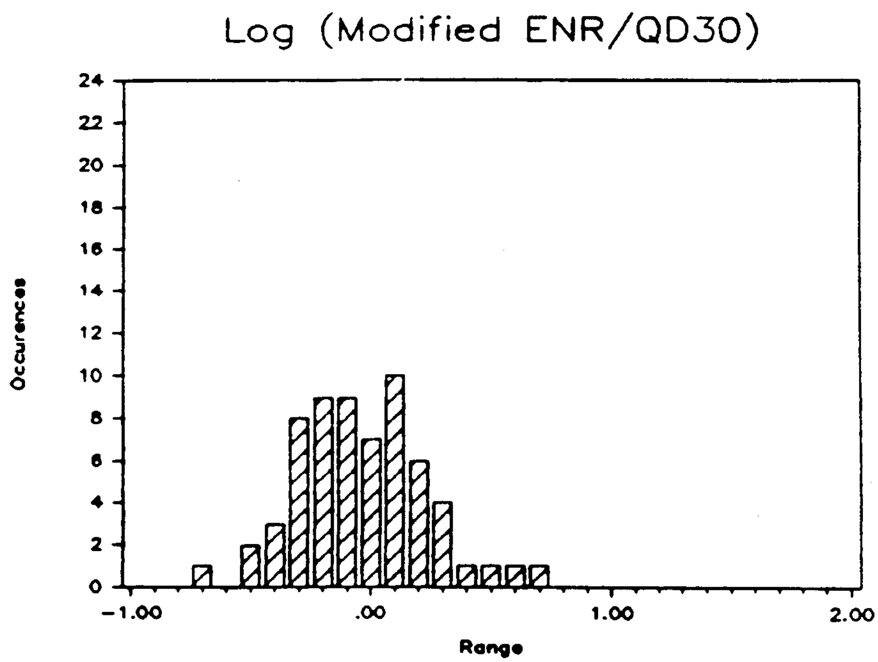
APPENDIX F - HISTOGRAMS



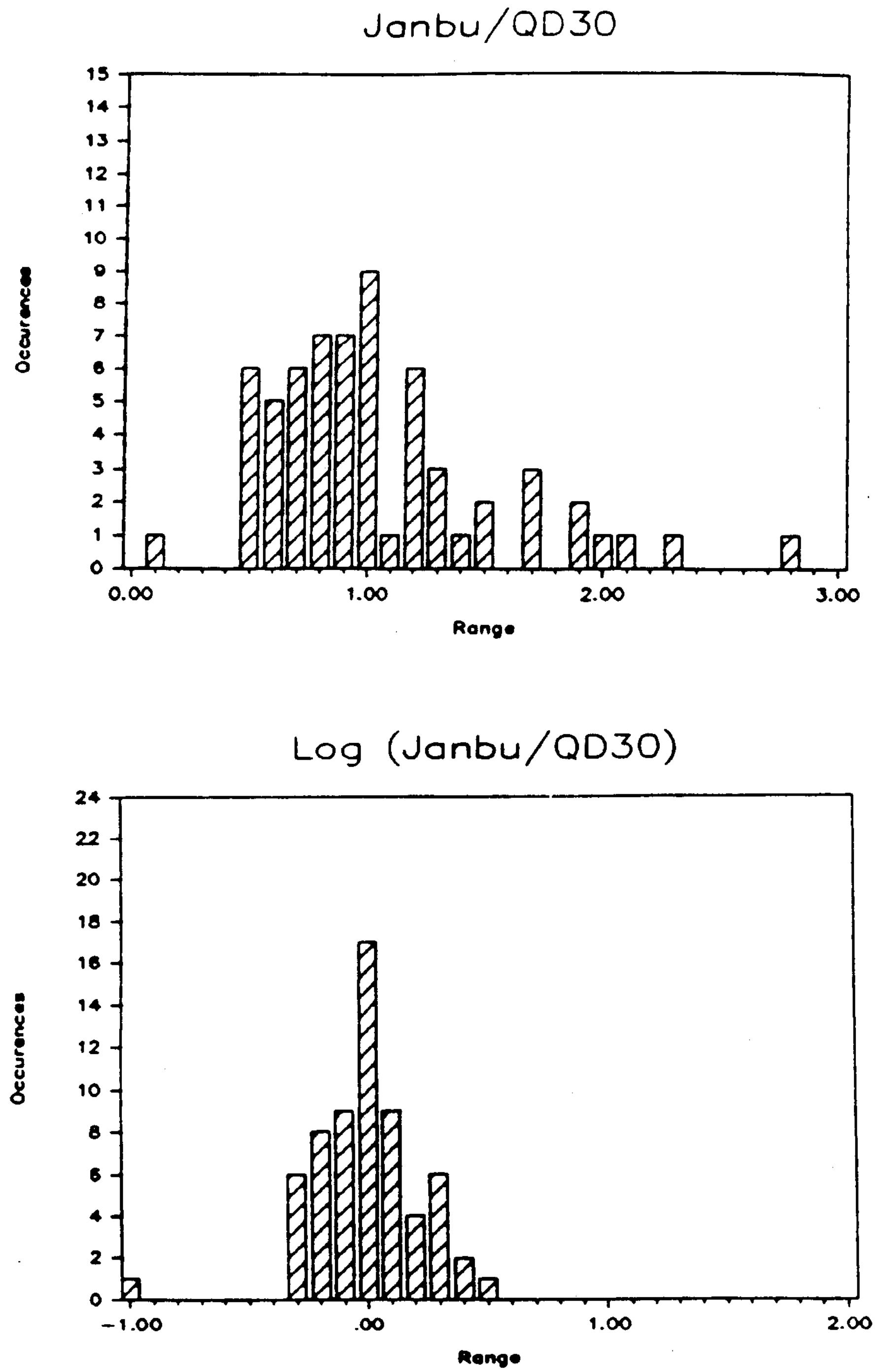


Comparison of histograms for raw and logarithm transformed data respectively for the Hiley formula.

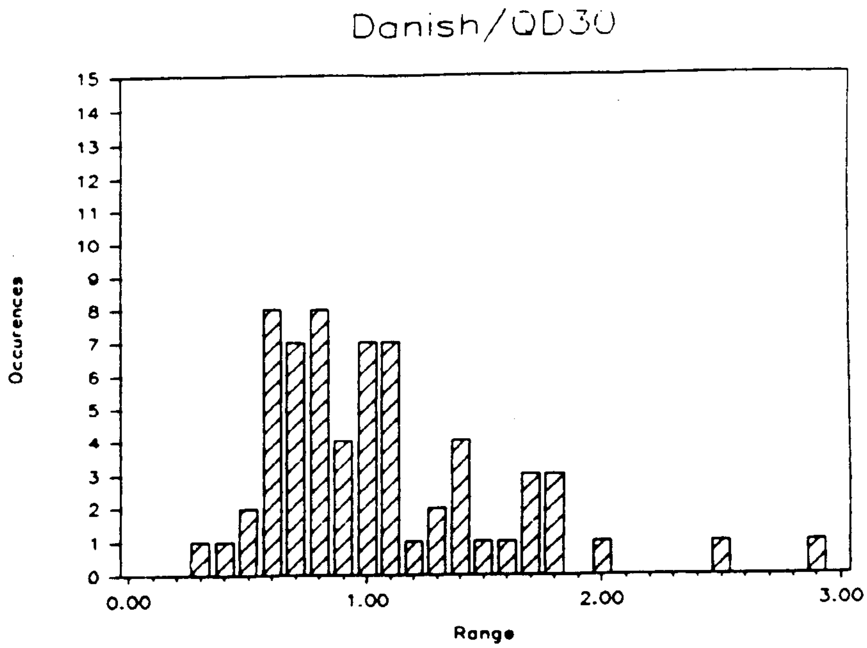


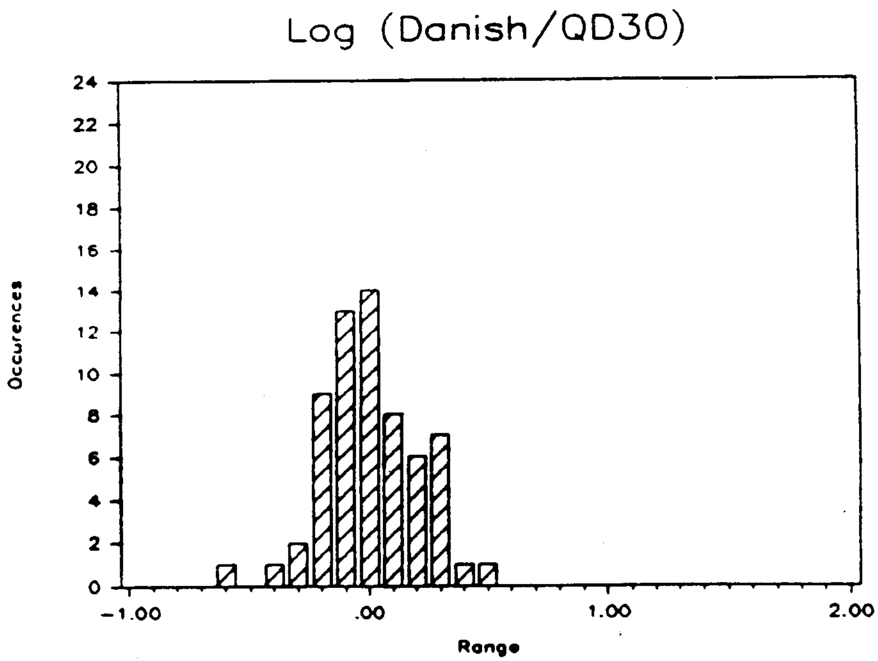


Comparison of histograms for raw and logarithm transformed data respectively for the Modified ENR formula.

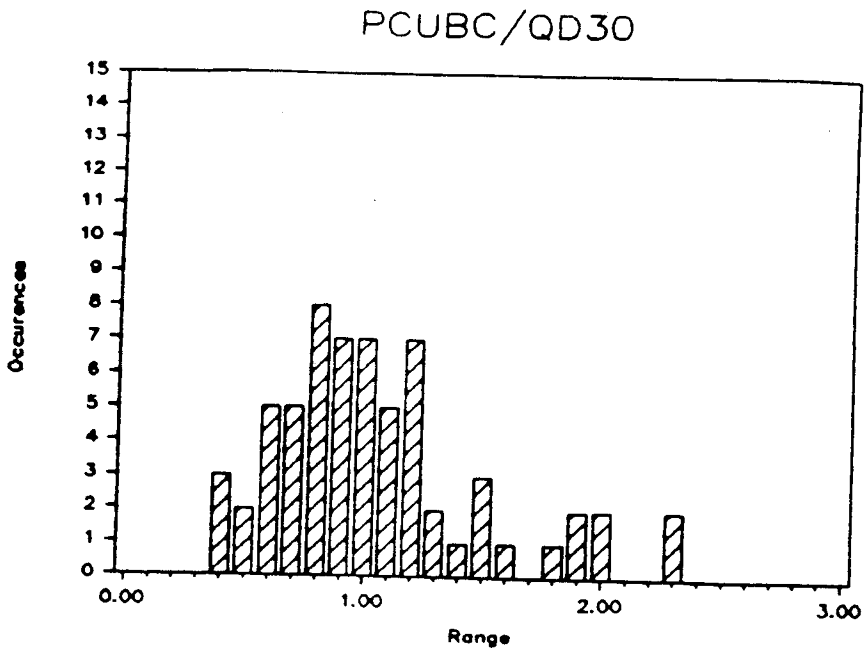


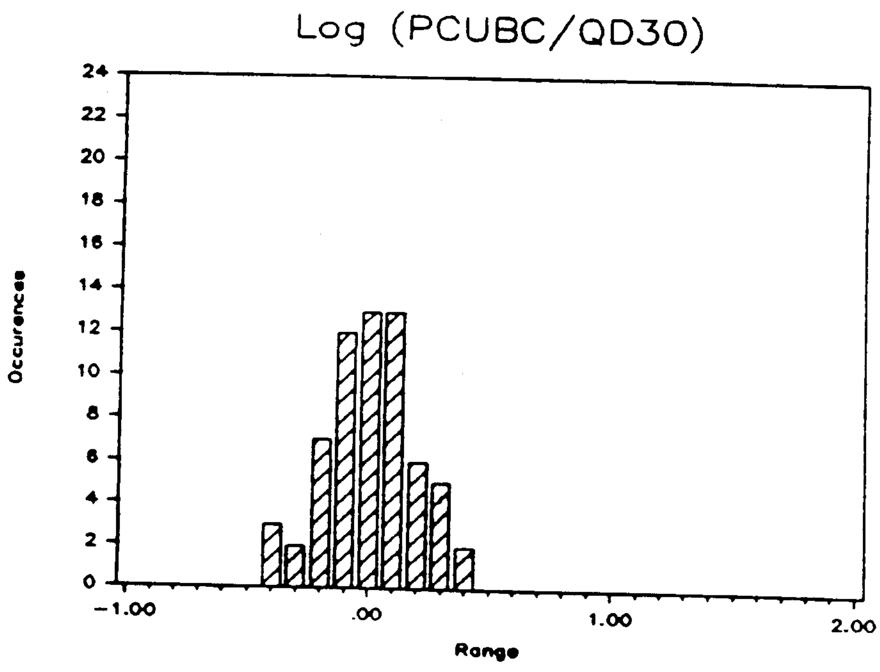
Comparison of histograms for raw and logarithm transformed data respectively for the Janbu formula.



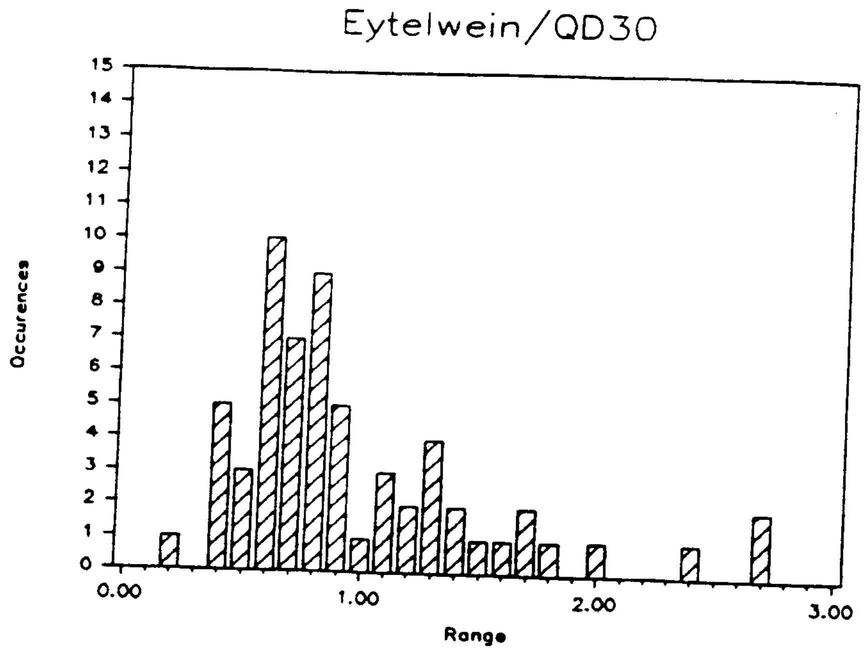


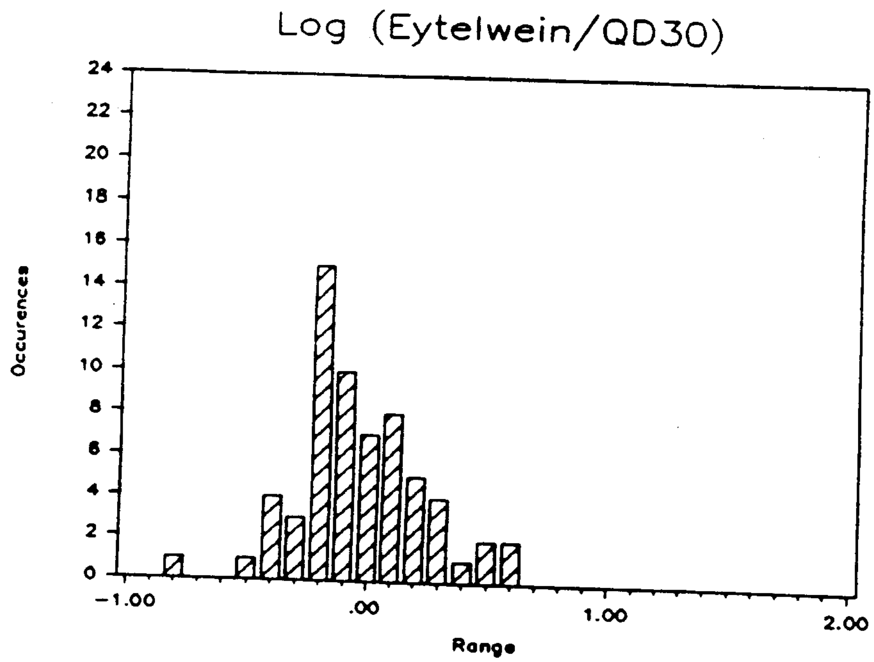
Comparison of histograms for raw and logarithm transformed data respectively for the Danish formula.



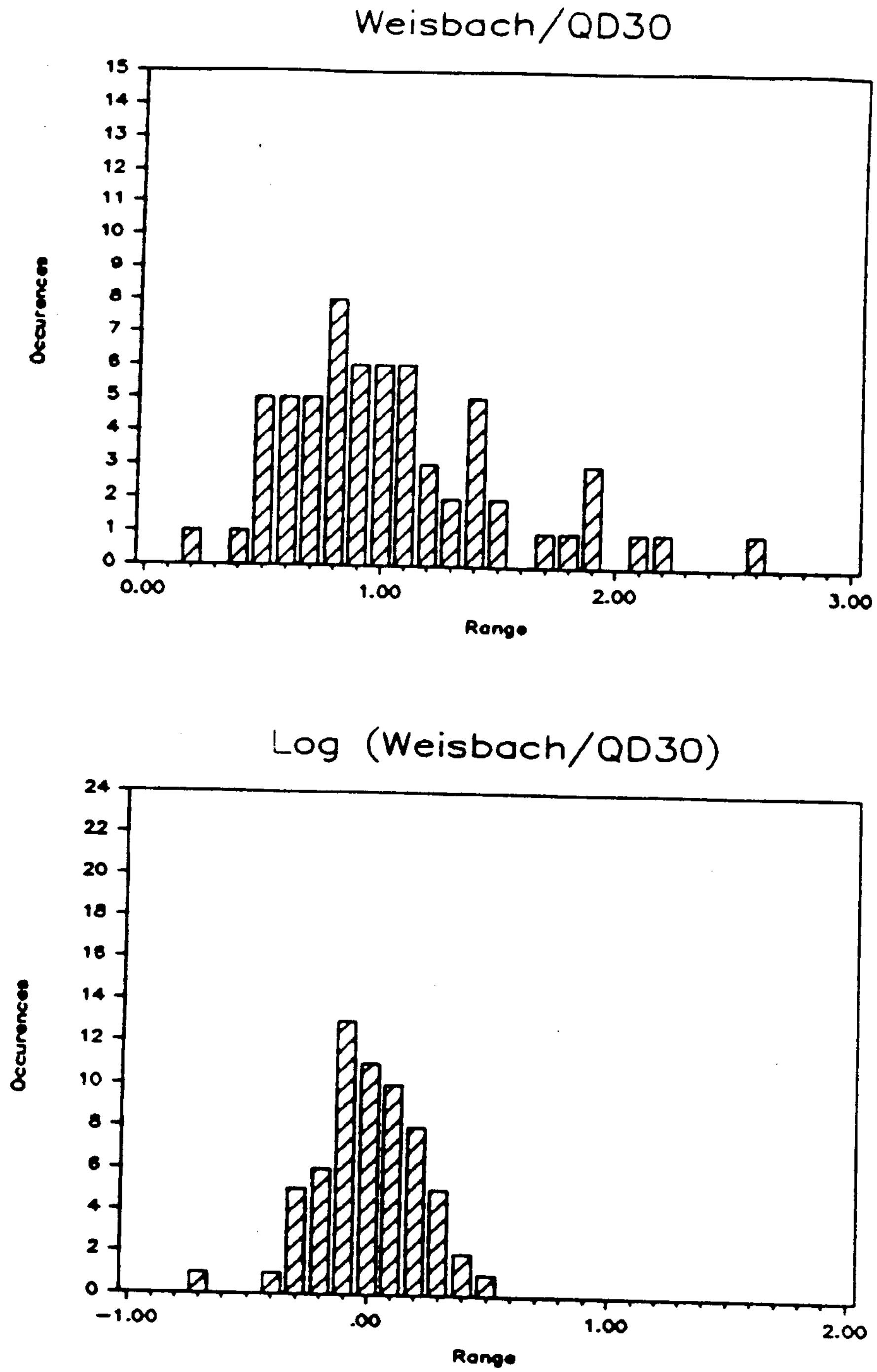


Comparison of histograms for raw and logarithm transformed data respectively for the PCUBC formula.

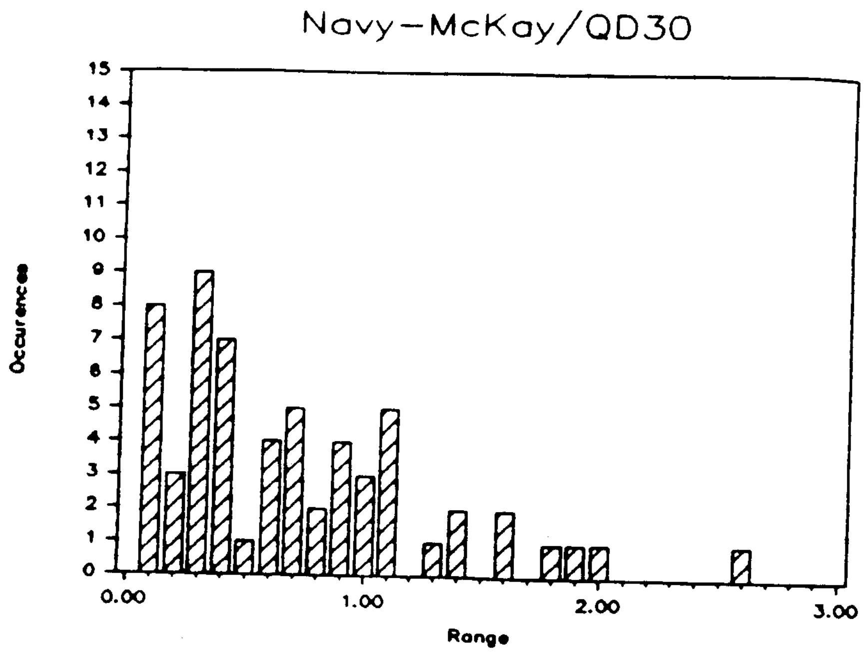


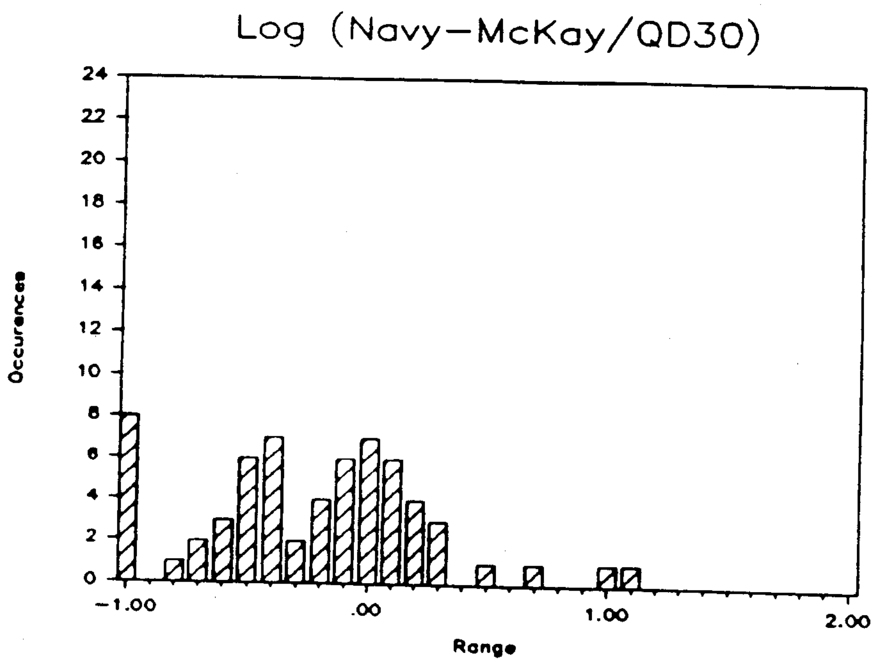


Comparison of histograms for raw and logarithm transformed data respectively for the Eytelwein formula.



Comparison of histograms for raw and logarithm transformed data respectively for the Weisbach formula.





Comparison of histograms for raw and logarithm transformed data respectively for the Navy-McKay formula.

APPENDIX G - VALUES OF CVLOG FOR ALL PILE SUBGROUPS

H-SECTION N = 5*

RANK	FORMULA	CV_{LOG}
1	Gates	0.08
2	PCUBC	0.11
3	Danish	0.13
3	Weisbach	0.13
5	Janbu	0.14
6	Hiley	0.16
7	Modified ENR	0.20
8	Eytelwein	0.24
9	ENR	0.25
10	Navy-McKay	0.34

CLOSED PIPE N = 2*

RANK	FORMULA	CV_{LOG}
1	Modified ENR	0.01
2	ENR	0.02
2	Eytelwein	0.02
4	Navy-McKay	0.04
5	Danish	0.05
5	Janbu	0.05
7	Gates	0.06
7	Weisbach	0.06
9	PCUBC	0.07
10	Hiley	0.09

OPEN PIPE N = 2*

RANK	FORMULA	CV_{LOG}
1	Hiley	0.02
2	Danish	0.04
3	Gates	0.05
4	Janbu	0.06
4	Weisbach	0.06
6	Eytelwein	0.10
6	Modified ENR	0.10
8	PCUBC	0.11
9	ENR	0.14
10	Navy-McKay	0.15

CONCRETE FILLED PIPE N = 7*

RANK	FORMULA	CV_{LOG}
1	Gates	0.08
2	Hiley	0.09
3	Janbu	0.14
4	Danish	0.15
4	PCUBC	0.15
6	ENR	0.17
6	Modified ENR	0.17
6	Weisbach	0.17
9	Eytelwein	0.19
10	Navy-McKay	0.27

SQUARE CONCRETE N = 11

RANK	FORMULA	CV_{LOG}
1	Gates	0.14
2	Weisbach	0.15
3	Danish	0.16
3	PCUBC	0.16
5	Janbu	0.18
6	Hiley	0.19
7	Eytelwein	0.27
8	ENR	0.28
9	Modified ENR	0.29
10	Navy-McKay	0.47

OCTAGONAL CONCRETE N = 9

RANK	FORMULA	CV_{LOG}
1	Gates	0.22
2	Weisbach	0.24
3	Danish	0.25
4	Hiley	0.27
4	Janbu	0.27
6	PCUBC	0.28
7	Eytelwein	0.33
8	ENR	0.35
9	Modified ENR	0.39
10	Navy-McKay	0.57

CV_{LOG} values for selected pile types.

* Sample size is too small to provide reliable results.

HOLLOW CONCRETE N = 5*

RANK	FORMULA	CV_{LOG}
1	Danish	0.05
1	Gates	0.05
1	Weisbach	0.05
4	ENR	0.07
5	Janbu	0.08
6	PCUBC	0.09
7	Hiley	0.15
8	Modified ENR	0.16
9	Eytelwein	0.20
9	Navy-McKay	0.20

RAYMOND STEP TAPER N = 16

RANK	FORMULA	CV_{LOG}
1	Gates	0.09
2	ENR	0.16
2	Hiley	0.16
4	Danish	0.17
5	Weisbach	0.18
6	Eytelwein	0.19
6	Janbu	0.19
8	Modified ENR	0.20
9	PCUBC	0.22
10	Navy-McKay	0.77

TIMBER N = 6*

RANK	FORMULA	CV_{LOG}
1	Gates	0.18
2	PCUBC	0.23
3	Hiley	0.25
4	Danish	0.30
5	Weisbach	0.32
6	Modified ENR	0.37
7	Eytelwein	0.46
8	ENR	0.49
9	Navy-McKay	0.60
10	Janbu	0.90

CV_{LOG} values for selected pile types.

* Sample size is too small to provide reliable results.

ALL PILES N = 63

RANK	FORMULA	CV_{LOG}
1	Gates	0.14
2	Hiley	0.20
2	PCUBC	0.20
4	Danish	0.21
4	Weisbach	0.21
6	Janbu	0.29
7	Modified ENR	0.30
7	Eytelwein	0.30
9	ENR	0.32
10	Navy-McKay	0.91

ALL EXCEPT TIMBER N = 57

RANK	FORMULA	CV_{LOG}
1	Gates	0.13
2	Danish	0.19
2	Hiley	0.19
2	Janbu	0.19
2	PCUBC	0.19
2	Weisbach	0.19
7	ENR	0.28
7	Eytelwein	0.28
9	Modified ENR	0.29
10	Navy-McKay	0.58

H-SECTION AND ALL PIPE N = 16

RANK	FORMULA	CV_{LOG}
1	Gates	0.09
2	Hiley	0.14
2	PCUBC	0.14
4	Danish	0.15
4	Janbu	0.15
6	Weisbach	0.16
7	Modified ENR	0.20
8	ENR	0.23
9	Eytelwein	0.24
10	Navy-McKay	0.32

H-SECTION, AND OPEN AND CLOSED PIPE N = 9

RANK	FORMULA	CV_{LOG}
1	Gates	0.08
2	PCUBC	0.14
2	Weisbach	0.14
4	Danish	0.15
4	Hiley	0.15
4	Janbu	0.15
7	Modified ENR	0.22
8	ENR	0.26
8	Eytelwein	0.26
10	Navy-McKay	0.35

SQUARE AND OCTAGONAL CONCRETE N = 20

RANK	FORMULA	CV_{LOG}
1	Gates	0.18
2	Weisbach	0.20
3	Danish	0.21
4	Janbu	0.22
4	PCUBC	0.22
6	Hiley	0.23
7	Eytelwein	0.31
8	Modified ENR	0.36
9	ENR	0.39
10	Navy-McKay	0.68

ALL CONCRETE N = 25

RANK	FORMULA	CV_{LOG}
1	Gates	0.16
2	Weisbach	0.18
3	Danish	0.20
3	Janbu	0.20
3	PCUBC	0.20
6	Hiley	0.22
7	Eytelwein	0.30
8	Modified ENR	0.33
9	ENR	0.35
10	Navy-McKay	0.59

CV_{LOG} values for selected pile categories.

* Sample size is too small to provide reliable results.

ALL PILES IN COHESIONLESS SOILS N = 41

RANK	FORMULA	CV_{LOG}
1	Gates	0.11
2	Danish	0.21
2	Hiley	0.21
2	PCUBC	0.21
5	Weisbach	0.22
6	Modified ENR	0.27
7	Eytelwein	0.29
8	ENR	0.30
9	Janbu	0.33
10	Navy-McKay	0.92

ALL PILES IN COHESIVE SOILS N = 11*

RANK	FORMULA	CV_{LOG}
1	PCUBC	0.18
2	Gates	0.19
3	Weisbach	0.20
4	Hiley	0.21
4	Janbu	0.21
6	Danish	0.22
7	Eytelwein	0.31
8	Modified ENR	0.35
9	ENR	0.38
10	Navy-McKay	0.65

CV_{LOG} values for selected pile categories.

* Sample size is too small to provide reliable results.

APPENDIX H - NOTATION

A = cross-sectional area of pile

A' = cross-sectional area of cushion block

B = static supplement factor in Rabe's formula (14)

C = temporary compression loss in the cap, pile, and soil in Rabe's formula (14)

C1,C2,C3 = coefficients for Hiley formula (12)

e_h = efficiency of striking hammer (<1.0)

E = Young's modulus of elasticity for pile

E' = Young's modulus of elasticity of the cushion block

E_h = manufacturer's hammer energy rating

h = height of free fall of hammer

K = a coefficient to account for elastic compression plus other losses in Redtenbacher's classical formula

L = length of pile

L' = axial length of cushion block

M = hammer efficiency factor (13)

m = range of the mean

N = sample size less one

n = coefficient of restitution for hammer cushion

Q_u = ultimate bearing capacity of pile in soil

S = standard deviation of the sample

s = pile penetration for last blow (pile set)

t = value of the student's t distribution

w = weight of pile

W = weight of hammer

X = mean of the sample

z = 0.1 for steam hammers; 1.0 for drop hammers

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