Evaluation of Static and Dynamic Methods of Determining Pile Capacity in Georgia

Final Project Report

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I. Introduction

Driven pile design and construction at the Georgia Dept. of Transportation (GDOT) Geotechnical Laboratory has for many years relied upon simple but relatively crude techniques for estimating pile capacity and acceptance criteria. Procedures currently used for estimating static capacity are highly empirical and can require significant judgment and experience to use confidently. Additionally, the basis for the methods used have become obscure over the years and the reliability is uncertain. Dynamic capacity determinations (used for field control of pile driving) are based upon a variation of the old Engineering News Formula; this and other pile driving formulae are notoriously unreliable and have been replaced in many state DOT's by wave equation techniques.

Given the tools provided by improvements in technology and the pile load test data available over the last 20 years, there is an opportunity to improve the reliability of pile capacity estimates from both a static design standpoint and from a dynamic evaluation standpoint. The former is needed for preliminary estimates of pile lengths and performance as well as to provide input for equipment selection criteria. Dynamic analyses using the wave equation techniques can provide the means to evaluate a contractor's proposed equipment in advance of construction to verify that the proposed equipment is capable of driving piles without damage, select the optimum pile cross section for drivability, and establish a bearing graph of blows per foot vs estimated capacity for a specific pile type and length and pile driving system.

Although wave equation analyses provide much useful information for design and construction, there remains uncertainty with respect to the driving efficiency of the hammer and other parts of the driving system during the actual field installation. The Pile Driving Analyzer (PDA) equipment provides a measure of the energy imparted to the pile by the hammer and thus provides a means to remove some of the uncertainties associated with the wave equation analyses. When used with a pile hammer to restrike the pile at several days or more after initial driving, this type of dynamic measurement is thought to produce the most reliable estimate of actual static capacity short of conducting a time consuming and expensive static load test.

Objectives

The objectives of this study are to assemble the data available to evaluate static and dynamic methods of estimating pile capacity and perform analyses so that the most reliable methods can be identified and employed in design and construction. In addition, this exercise is intended to provide an evaluation of the accuracy and precision of the proposed static and dynamics methods so that design and construction of driven pile bridge foundations can be made more economical and reliable.

The focus of the study is on driven piling in Georgia and neighboring states with similar geologic conditions. The practice of the GDOT Geotechnical Laboratory utilizes primarily standard penetration testing (SPT) for soil borings for bridge foundation design; because of the investment in equipment and training with this technology, this practice is likely to remain dominant for years to come and thus the static pile capacity predictive methods should be compatible with this practice. The GDOT Geotechnical Laboratory has the equipment and training to perform wave equation analyses and to make PDA measurements in the field. However, it is recognized that the present staffing levels at the Laboratory are not sufficient to permit the routine use of PDA measurements (i.e., on a large percentage of bridge jobs or even of piling on a particular job). Most field inspection of pile installation is presently performed by GDOT Division inspectors with limited training in geotechnical engineering principles.

Overview of the Study and Format of the Report

This study has been conducted by assembling and analyzing data from bridge sites in Georgia and neighboring states where pile load test results and other significant data are available. These data have been placed into a computer data base utilizing a Lotus123 spreadsheet format so as to allow easy access and portability. Analyses have been performed of the performance of three proposed methods (and two additional modifications of these methods for a total of five) for computing static pile capacity using SPT soil boring data. For those sites for which dynamic measurement data are available, these data have been incorporated into an additional computer data base and the performance of the wave equation code and PDA analyses has been evaluated. Recommendations for the GDOT practice have been proposed.

The large amount of data obtained and generated during this study would make compilation of the entire effort into one report unwieldy and tedious. Therefore, this report is intended to provide a summary of the most important aspects of the analyses performed, the significant findings, and the recommendations for the practice of the GDOT. The hardcopy details which are included in the computer spreadsheet type data base are included in a formatted printout bound separately as Appendix A. The details of all of the analyses performed of the static methods of computing pile capacity are bound separately as Appendix B. The details of all of the analyses performed of the dynamic methods of computing pile capacity are bound separately as Appendix C. The Lotus123 (version 3.1) spreadsheet data are available on computer diskette. In addition, the input data files for the wave equation analyses (performed using GRLWEAP, 1994 version) and the PDA digitized time records from the dynamic load test sites are available on diskette.

The following chapters provide a summary of the data assembled, the static and dynamic analyses performed, the significant findings, and the recommendations for the practice of the GDOT. Interested readers are referred to Appendices A, B, and C for more details.

II. Load Test Data

A major portion of the effort involved in this study has been directed toward the development of a data base of relevant load test information to serve as a basis for comparison of various methods. The criteria used to select and categorize these data and the format used for this study are briefly described below.

Static Load Test Data

Static load test data from a total of 84 load tests were included within this study. These came from sites in Alabama, Georgia, South Carolina, the northern part of Florida, and one site along the coast in Mississippi. The criteria used for inclusion of load test data for this portion of the study were:

a) the test site should be within the general geographic and geologic area of interest,

b) there should be sufficient soils information comparable to a typical bridge foundation investigation in Georgia (typically including visual classifications, groundwater information and SPT data),

c) it should be possible to interpret the measured failure load using the Davisson criteria from the load vs settlement data,

d) pile types and installation techniques which are typical of driven piling used for highway bridge construction in Georgia (e.g., no timber piles, augercast piles, or other types not routinely used by GDOT), and

e) pile driving data should be available; although not directly used for the static capacity calculations, driving data provides correlation of the test pile with the expected stratigraphic profile and may be useful for future evaluations.

The load test data have been assembled into a database using Lotus123 (version 3.1) spreadsheets in which each load test comprises a single two dimensional spreadsheet and the total database can be thought of as a "stack" of individual spreadsheets. This format has been used by Prof. Townsend and his coworkers at the Univ. of Florida and has been adopted for this study. The spreadsheet format allows the user to access the data in an organized manner, with spreadsheet "macros" used to generate comparison plots, statistical parameters, and load settlement graphs. Figure 1 provides a printed illustration of the data contained within the database, illustrating the pile and pile driving information, the load settlement curve, the soils information, and the computed static capacity data.

·TOTAL FRICTIONAL CAP :	MOBILE COUNTY
DATE OF LOAD TEST:	3-10-92

ENGINEER / REFERENCE : ALABAMA HIGHWAY DEPT.

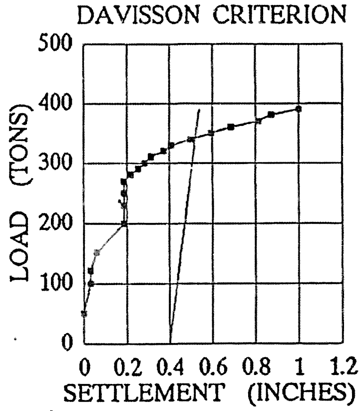
PILE DATA BENT NO. & LANE BENT 7 RAMP 0-2 PILE NO. 1

PILE TYPE :	PSC
PILE WIDTH / DIAMETER (IN) :	30.0
TOTAL PILE LENGTH (FT) :	76.0
EMBEDDED PILE LENGTH (FT) :	58.0
TOTAL WEIGHT OF PILE (TN) :	35.63
METHOD OF INSTALLATION :	DRIVEN PILE
TENSION OR COMPRESSION TEST :	C
TIP EMBEDMENT MATERIAL :	TAN SILTY SAND

PILE DRIVING DATA

HAMMER TYPE :	DELMAG D-62-22
WEIGHT OF HAMMER (LB) , W :	14600
ENERGY (FT-LB) , E :	63168
PRE-BORED DEPTH (FT) :	0
SET PER LAST BLOW (IN) , S :	0.207

LOAD-SETTLEMENT CURVE
DAVISSON CRITERION



GROUND SURFACE ELEVATION :	100 FEET
GROUNDWATER DEPTH :	12 FEET

SPT BORING : FB-4 STATION : 118+80

DEPTH (FT.)	SPT-N	SOIL CODE SPT91	SOIL DESCRIPTION
5.0	16	2	SILTY SAND
10.0	12	2	SILTY CLAY
15.0	18	2	SI SA CLAY
20.0	11	2	SAND W/CLAY
25.0	8	2	SANDY CLAY
30.0	13	2	TAN SILTY SAND
35.0	16	2	
40.0	18	2	
45.0	21	2	
50.0	22	2	
55.0	19	2	
60.0	27	2	
65.0	42	2	
70.0	30	2	
75.0	43	2	

SPILE2 CAP =	869 TONS	(601)
SPT91 CAP =	443 TONS	
GA DOT CAP =	714 TONS	(476)
DAVISSON CAP =	345 TONS	

PILE CONCRETE DATA

UNIT WEIGHT OF CONCRETE (PCF) :	150.0
CONCRETE UNCONFINED STRENGTH (PSI) :	5000
PILE ELASTIC MODULUS (PSI) :	5646052

Note
Pile type PSC signifies a prestressed concrete pile.
The capacities in parantheses are obtained from the respective modified methods.

Figure 1 Example of Static Load Test Data Base

load tests which are included in the database (out of a great many more than 84 which were considered) meet the acceptance criteria for this study set forth above and have been included in the Lotus123 format. Contributors of load test information include the Alabama, Georgia, and South Carolina DOT's, the Univ. of Florida, Eustis Engineering, Westinghouse Geotechnical Services, F & ME Consultants, and S & ME Consultants. The static load test data include the following charactaristics:

a) 71 prestressed concrete (PSC) piles
   9 steel pipe piles (commonly referred to as metal shell piles)
   4 steel H-piles
b) 50 of the piles were in predominantly sand soils
   27 of the piles were in predominantly clay soils
   7 of the piles were in mixed clay/sand strata
c) 43 of the PSC piles were driven without any predrilling or jetting
   28 of the PSC piles included some predrilling or jetting

The relatively large proportion of data comprised of PSC piles reflects the general tendency in the southeastern states to use this type of piles on major projects (where static load tests might more often be conducted) in coastal plains geology (where major projects with load test data are more common). Although steel H-piles are quite common in Georgia, the load test data available for this study were quite scarce, and this lack of H-pile data represents a significant limitation of the use of the results of this study for this pile type.

Dynamic Load Test Data

Dynamic load test data from a total of 14 piles were included within this study. These came from sites in Alabama, Georgia, South Carolina, and one site along the coast in Mississippi. The criteria used for inclusion of load test data for this portion of the study were:

a) the test site should be within the general geographic and geologic area of interest,
b) static load test data should be available,
c) restrike blows on the test pile should be available at a time near that of the static load test,
d) there should be PDA measurements available for both end of initial driving and beginning of restrike, and
e) there should be sufficient information on the driving system to allow WEAP analyses to be performed.

The dynamic pile load test data are contained within a spreadsheet format as described previously, although in a somewhat different format. An example of the data contained within the spreadsheet data base of dynamic pile data is presented on Figure 2. This figure illustrates the pile, hammer, driving system, and other installation details along with the soils information and a brief summary of the PDA measurement data. The actual PDA measurement data are contained within a separate file which can only be read and illustrated using the PDA software; the spreadsheet data base contains a summary of the capacity indicated by interpreting these measurements. Also illustrated on Figure 2 is the WEAP bearing graph, computed using the details on the hammer, pile, and driving system provided on the spreadsheet but not utilizing the PDA measurement. The objective in including the WEAP bearing graph data are to provide the kind of information which might be available on a project which did not have PDA measurements available.

The data available in the static and dynamic load test data bases described above provide the basis for the evaluations performed in the following chapters.

PILE SERIAL NO. :	SC1
EOD/BOR :	EOD
CLIENT :	SCDHPT
PROJECT :	New Battery Creek Bridge, SC
DATE OF TEST :	7-23-90
BENT/LANE :	NA
PILE NO. :	TEST PILE

PILE DETAILS

PILE TYPE/MATERIAL :	PS CONCRETE, OCT
PILE LENGTH (FT.) :	64 FT. (+2.5 FT. STINGER)
WALL THICKNESS (IN.) :	NA
SIZE/C.S. AREA (SQ.IN.) :	477 SQ. IN. (24 in.)
DESIGN CAPACITY (KIPS) :	
SPLICE DETAILS :	

ELEVATION DETAILS

TOTAL LENGTH (FT.) :	64 FT. (+2.5 FT. STINGER)
EMBEDDED LENGTH (FT.) :	61 FT.
GR. ELEVATION :	+8 MSL
TIP ELEVATION :	-53

HAMMER DETAILS

MAKE/MODEL :	VULCAN 320/520
RATED ENERGY (KIP-FT) :	60-[illegible]
WEIGHT (KIPS) :	20
HAMMER ACTION :	
AIR/DIESEL :	AIR
OPEN/CLOSED :	

SOIL INFORMATION

BRIEF SOIL :	Calcareous sand w/gravel sized
DESCRIPTION :	limestone particles

OTHER DETAILS

PREDRILLING :	Preaugured to 40' on 7/21
RESTRIKE :	RESTRUCK
WAIT PERIOD (DAYS) :	3 DAYS
JETTING :	

SERIAL NO. 1

WEAP INFORMATION

EOD	EOD BLCT. (BPF) :	72
	PREDICTED CAPACITY (KIPS) :	980
	PDA CAPACITY (KIPS) :	890
	HAMMER :	VULCAN 320/520
	HAMMER CUSHION :	PLYWOOD
	PILE CUSHION :	9" PLYWOOD
BOR	BOR BLCT (BPF) :	
	PREDICTED CAPACITY (KIPS) :	
	PDA CAPACITY (KIPS) :	
	DAVISSON LOAD (KIPS) :	
	HAMMER :	
	HAMMER CUSHION :	
	PILE CUSHION :	

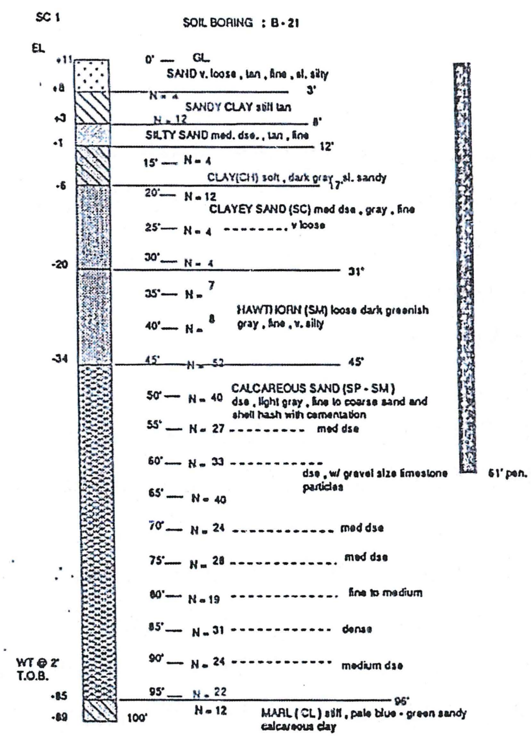
PDA INFORMATION

EOD	PDA CAPACITY (KIPS) :	890
	METHOD USED :	RAU
	SOIL DAMPING :	0.4
BOR	PDA CAPACITY (KIPS) :	
	METHOD USED :	
	SOIL DAMPING :	
	DAVISSON LOAD (KIPS) :	
	BACKCALC. J :	

SETUP INFORMATION

WAIT PERIOD :	3 DAYS
SETUP (%) :	4.2
SETUP (KIPS) :	50

Figure 2 Example of Dynamic Load Test Data Base



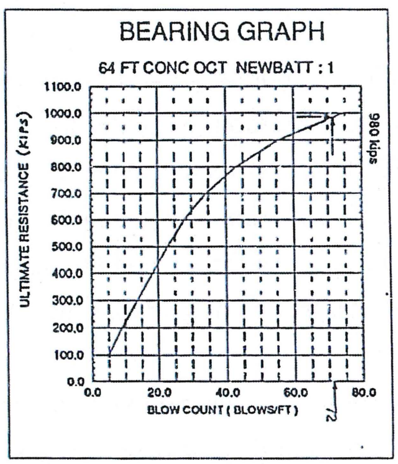


Figure 2 (cont) Example of Dynamic Load Test Data Base

III. Evaluation of Static Capacity Methods

Estimates of static pile capacity based solely on soil boring information are necessary in the design phase of the project to establish a basis for foundation design, estimate pile length requirements, and identify potential difficulties. In many instances, notably where scour effects must be taken into consideration, it may not be possible to rely solely upon driving resistance criteria for estimation of pile capacity. In order to provide the most reliable method possible based on currently available soil boring information, an evaluation of several methods of predicting static pile capacity has been performed and is described in this chapter.

Methods Examined

Several methods for computing static pile capacity from standard penetration test data have been examined in this study. The methods chosen for evaluation are available to the GDOT Geotechnical Laboratory and have been utilized by other state DOT's. These are:

- GDOT Method, currently used in practice in Georgia
- SPILE2, a computer code distributed by FHWA
- SPT91, a computer code developed and used by the Fla. DOT

In addition to these three, modifications of the GDOT and SPILE2 methods were suggested by the initial results of comparisons and these "modified" GDOT and SPILE2 methods have been included.

A very brief description of each of the methods follows. Note that many of the piles in the static load test data base were installed using predrilling and/or jetting techniques, and none of these methods include a direct provision for accounting for such installation effects. The technique used with each method to account for predrilling/jetting is briefly described below. Details on the specific implementation of each method are available in Appendix B.

GDOT Method. This method represents the current practice of the Georgia DOT Geotechnical Laboratory. Correlations between SPT blow count and allowable side friction capacity (tons per foot of pile) or pile end bearing capacity (tons) are presented in chart form for both clays and sands for piles of different types and sizes. The actual basis for these charts is not known, but is thought to be based upon Vesic's tests at Ga. Tech in the early 1960's. No corrections for overburden stress are made, the raw SPT values are entered into the chart to read off unit values of capacity directly. GDOT engineers report that these charts are intended to include a factor of safety of 3; therefore, the "computed capacity" using this method is taken as 3 times the allowable value computed using the design charts. In order to account for jetting and predrilling, the capacity in the jetted or predrilled zone was estimated by limiting the SPT N value to no more than 5 within the zone of jetting and/or predrilling. This approach was used for any type of jetting and for predrilling in which the predrilled hole was at least within 2 inches of the pile width or larger. Predrilled holes 4 inches or more smaller than the pile width were ignored and the raw SPT N values from the soil boring log were used.

Modified GDOT. Because of an observed tendency to overpredict capacity in many cases using the GDOT method, a "modified" GDOT estimated capacity has been computed in an attempt to improve the method. The modified GDOT is simply the chart values used as described above multiplied by a presumed factor of safety of 2 instead of 3.

SPILE2. This code has been developed and distributed by FHWA for use in state DOT's and is a very user friendly software implementation of the Nordlund procedure for piles in sand and the Tomlinson procedure for piles in clay. Both of these procedures have been used on a nationwide basis for years. The procedures include the use of empirical graphs which have been incorporated into the computer code. Most importantly, these procedures are based upon the use of the angle of internal friction (ϕ) for sands and the undrained shear strength (S_u) for clays; in order to use these methods for soils for which only SPT data are available it is necessary that a correlation between SPT data and ϕ or S_u be included within the code. The correlations include a correction of the SPT data for overburden pressure and thus require an estimate of soil unit weights (which have been estimated, but are not directly available from SPT sample data). The SPILE2 method employed in this study has been implemented using the code as is with the SPT data from the field boring logs. The effects of predrilling and jetting have been accounted for by limiting the SPT N values input within the predrilled/jetted zone as described for the GDOT method above. A more detailed description of the SPILE2 procedures is provided in Appendix B of this report and in the user manual for the code.

Modified SPILE2. As with the GDOT method, the SPILE2 code was noted to overpredict capacity in many cases (in sands) and an attempt was made to improve the correlation with the load test data base information by modifying the procedure (in sands only). As a convenient and simple way of modifying the correlation of ϕ with SPT N values, the modified SPILE2 calculation has been performed by first multiplying the SPT N value by 0.7 and then otherwise performing the computation in the same manner. This modification has the effect of "scaling" the correlation of ϕ with SPT N values.

SPT91. The SPT91 code is a very user friendly computer code developed and used by the Florida DOT. This procedure uses an empirical correlation between SPT N values and unit side friction and end bearing values which has been developed based upon load tests results of PSC piles in Florida in primarily sandy soils (but correlations are available for a variety of soil types). The method has been used for all of the piles in this data base, but such use represents an extrapolation of the method to piles for which it was not originally intended. One feature of this procedure is that soils with SPT N values of 5 or less are considered to have no contribution to capacity. In order to avoid completely neglecting soils within the predrilled and/or jetted zone, the soils within such zones have been taken to have a limiting SPT N value of 6 (instead of 5 as used previously). Predrilled holes 4 inches or more smaller than the pile width have not been subject to this limitation. More details on the SPT91 procedure and its implementation in this study are available in Appendix B and in the user manual for the code.

Methods of Comparison

For the comparisons of predicted vs measured capacity based on the methods described above and the static load test data base, it is important to define the terms which will be used and the methods in which these comparisons have been made. Some important concepts are described below.

Definition of Failure. There are literally dozens of different ways in which failure can be defined from the data of a static load test. Perhaps the most common, and the method used in this study, is the Davisson criteria in which failure is defined as the load at a displacement equal to an amount generally proportional to the pile width and stiffness. This method is no more theoretically satisfying than others, it is simply a convenient point of reference which provides a consistent definition that is widely used and recognized. This criterion is also considered suitable because it limits displacements at "failure". Loads beyond the Davisson failure load generally result in very large pile displacements, but not always; some piles (particularly large displacement piles in sand) will continue to support significant loads beyond the Davisson failure load although at increasing displacements. It is important to note that correlations of a particular method with a pile "ultimate capacity" is highly dependent upon how that "ultimate capacity" is defined! Note that only SPT91 makes a distinction between the "Davisson" failure load and other definitions of "ultimate" capacity; for SPT91, the Davisson load has been used as the "predicted" pile capacity. With the GDOT and SPILE2 methods the computed pile capacity has been compared with the Davisson failure load from the load test data.

Ratio of Q_p/Q_m and $LogQ_p/Q_m$. In order to directly compare predicted and measured pile capacities (with "failure" as defined above), most comparisons presented in this report use the ratio of the predicted (Q_p) to measured (Q_m) capacities. Perfect agreement would thus be a ratio of 1. Because this ratio can vary theoretically between 0 and infinity, the direct use of the Q_p/Q_m ratio would skew the statistical evaluations; for example, a greater weight would be given to a ratio of 2.0 than to a ratio of 0.5 although most engineers would generally consider that these two numbers are equally in error. Therefore, most statistical comparisons are made using the $\mathrm{Log}(Q_p/Q_m)$ which would vary more nearly symmetrically for underprediction and overprediction about an ideal mean of 0 (Log(1)=0).

Standard Deviation. The standard deviation has been computed for the $\mathrm{Log}(Q_p/Q_m)$ values to evaluate the variability of a particular method. A prediction method may *on average* be fairly accurate (have a mean of Q_p/Q_m near 1), but if a large standard deviation is observed, this would indicate that the method lacks precision. A prediction method which has good precision will be reflected by a low standard deviation, even though the mean may or may not be accurate. If the standard deviation is low (the method is precise), then the essential elements affecting the capacity are being captured with the predictive method and it may be that the accuracy can be improved by revising the correlations.

Reliability Index, RI. The reliability index, RI, is a calculated number which represents the sum of the absolute value of the mean of the $\mathrm{Log}(Q_p/Q_m)$ values and the standard deviation. Of itself, the RI has no meaning. However, when comparing different methods, this is a term which includes both the accuracy and the precision of a particular method and thus it provides a rational basis for comparing between methods. Since the ideal value of the mean of the $\mathrm{Log}(Q_p/Q_m)$ values should approach zero and the ideal standard deviation should approach zero, a relatively lower RI value would indicate a generally superior prediction method. This term was first introduced by Dr. Jean-Louis Briaud in a similar study and has been adopted to the current research as simply a rational basis for comparison between predictive methods.

Probability of Underdesign. Given a set of predicted vs measured pile capacity data which provide a statistical mean and standard deviation, it is possible to estimate the probability of a "failure" occurring for a design using a particular prediction method. For design, the predicted failure capacity of the pile is divided by a factor of safety to compute an allowable design load on the pile. The computed probability of underdesign would then represent the probability that the actual "failure load" for a given pile would be less than the design load. Of course, in this context "failure load" is as indicated by the Davisson criterion cited above. For an ideal case with a factor of safety of 1.0 and a mean of the Q_p/Q_m = 1.0, the probability of failure would be 50%. For a realistic case with a factor of safety on the order of 2 to 3, the probability of failure should be very low, on the order of a few percent or less; the most significant factor affecting the probability of failure at such levels (out on the "tail" of the normal distribution curve) is the standard deviation of the method. Of course, a method which has a low mean value ($Q_p/Q_m < 1$) would also result in a lower probability of failure but only because the method is systematically underpredicating capacity (i.e. the method is very conservative, on average). Such a case could represent a method which is wasteful in being overconservative. The best method would be one which provided a very low probability of failure at some factor of safety and also had a low RI number (compared to alternative methods).

Comparison of Methods with Static Load Test Data

This section provides a comparison of the methods described above with the static load test results from the 84 piles in the data base. In order to investigate the potential advantages and difficulties with these predictive methods, comparisons are provided on the basis of soil type as well as pile type and installation technique (whether predrilling/jetting was used). Details of all of the analytical comparisons made are provided in Appendix B, along with tables indicating the particular test piles used in each comparison and the actual computed and measured values. The section which follows provides a summary of the more interesting comparisons. Note that a number of additional analyses were also performed in an attempt to identify trends with respect to pile length, soil capacity, etc., which did not clearly distinguish any systematic bias which could be attributed to such factors.

PSC Piles in Sand, no Predrilling or Jetting. A total of 18 test cases are included in this group. These data are presented first because they represent a straightforward data set in similar soil conditions, all with the same type of pile, and without any complicating factors such as predrilling or jetting. Plots of predicted vs measured capacity for all 5 methods are provided in Appendix B, but are considered too numerous to present in this summary; a summary of the data within this catagory is presented on Table 1 below.

Method:	GDOT	GDOT(m)	SPILE2	SPILE2(m)	SPT91
Q_p/Q_m	1.78	1.20	1.60	1.18	0.98
Std. Dev.	0.18	0.18	0.24	0.19	0.22
R.I.	0.43	0.26	0.45	0.26	0.23
Prob. of Failure (%), F.S.=2.0	39.74	10.56	34.46	10.04	8.38
Prob.of Failure (%), F.S.=2.5	21.05	3.71	21.10	3.67	3.51
Prob. of Failure (%), F.S.=3.0	10.65	1.32	12.92	1.31	1.52
F.S. for Prob. of Failure = 1%	4.70	3.13	5.81	3.13	3.27

Table 1, Static Load Tests on PSC Piles in Sand w/o Predrilling/Jetting

The data presented in Table 1 indicate that the GDOT and SPILE2 methods are unconservative for this data set, although the modified versions of these methods greatly improve their accuracy. The RI for the SPT91 procedure is the lowest, but the modified GDOT and SPILE2 values are quite close. The data in this table suggest that a factor of safety of around 3 would be required to maintain a probability of failure of approximately 1%.

PSC Piles in Sand, with Predrilling or Jetting. A total of 25 test cases are included in this group. This represents a greater number than for the case without predrilling or jetting, a number which demonstrates the widespread use of these techniques with PSC piles in the southeast. Compared to the previous dataset, these provide a measure of the effect of predrilling and jetting on the ability to reliably predict capacity. Note that the zone of soil in which predrilling and/or jetting was used had modified SPT N values for purposes of pile capacity prediction as described earlier in this chapter. Presented below is the summary table of predicted vs measured pile capacity values in this category.

Method:	GDOT	GDOT(m)	SPILE2	SPILE2(m)	SPT91
[illegible]	1.72	1.15	1.93	1.38	0.76
[illegible]ev.	0.18	0.18	0.18	0.19	0.18
[illegible]	0.41	0.24	0.47	0.33	0.29
Prob. of Failure (%), F.S.=2.0	35.57	8.85	46.61	19.50	0.87
Prob.of Failure (%), F.S.=2.5	18.00	2.87	26.86	8.45	0.18
Prob. of Failure (%), F.S.=3.0	8.69	0.96	14.69	3.59	0.04
F.S. for Prob. of Failure = 1%	4.45	2.98	5.12	3.77	1.96

Table 2, Static Load Tests on PSC Piles in Sand with Predrilling/Jetting

The data illustrated on Table 2 suggest that the modified GDOT provides the best R.I. by virtue of having a predicted mean closest to the measured mean; the standard deviation of all of the methods are nearly equal. The SPT91 method provides the lowest probability of failure by far, undoubtedly because this method is quite conservative for this dataset. It could be that the method used to account for the predrilling/jetting effects is too severe for this method and thus the method is quite conservative where predrilling/jetting is used to install the piles. Based on these data, the use of a design factor of safety of 3.0 would yield a probability of failure of 1% or less for both the SPT91 method or the modified version of the GDOT method.

All Piles in Sands. There are 50 load test cases in predominantly sand soils, including piles which have been predrilled and/or jetted and steel pipe or H-piles. The majority of these cases are PSC piles as included in the two data sets described above. Presented on Table 3 below are the composite analyses of all data at sites composed of predominantly sand soils.

Method:	GDOT	GDOT(m)	SPILE2	SPILE2(m)	SPT91
Q_p/Q_m	1.69	1.09	1.67	1.18	0.81
Std. Dev.	0.20	0.20	0.23	0.22	0.21
R.I.	0.41	0.23	0.45	0.30	0.31
Prob. of Failure (%), F.S.=2.0	35.80	9.51	36.70	14.92	3.07
Prob.of Failure (%), F.S.=2.5	19.77	3.59	22.36	6.94	0.99
Prob. of Failure (%), F.S.=3.0	10.65	1.39	13.45	3.29	0.34
F.S. for Prob. of Failure = 1%	4.94	3.18	5.74	3.84	2.50

Table 3, Static Load Tests on Piles in Sand

The data presented above suggest that in sand, on the whole, the modification proposed to the GDOT method results in the most reliable of the methods considered for estimation of static pile capacity in sand. A factor of safety of approximately 3 is required to yield a probability of failure of less than 1% for an individual pile designed according to this procedure.

All Piles in Clay. A total of 27 load test cases are available in predominantly clay soils, 23 of which are PSC piles. Of these, only 2 cases included predrilling. Note that for piles in clay, the SPILE2 method uses a completely different procedure (the Tomlinson procedure) than for sands (the Nordlund procedure). The modification of the correlation between SPT N values and ϕ for sands is not used with SPILE2 in clay soils, so only 4 methods are included in this group as presented on Table 4 below.

Method:	GDOT	GDOT(m)	SPILE2	SPT91
Q_p/Q_m	1.42	1.05	1.09	0.86
Std. Dev.	0.15	0.15	0.17	0.16
R.I.	0.30	0.17	0.21	0.22
Prob. of Failure (%), F.S.=2.0	16.11	3.10	6.06	1.10
Prob.of Failure (%), F.S.=2.5	5.05	0.60	1.70	0.19
Prob. of Failure (%), F.S.=3.0	1.52	0.12	0.48	0.03
F.S. for Prob. of Failure = 1%	3.18	2.35	2.71	2.02

Table 4, Static Load Tests on Piles in Clay

Note that again the modified GDOT method proved most reliable for piles in clay soils, although it can be said that all methods performed significantly better in clays than in sands. The probability data suggest that a lower factor of safety could be used in clays (2.5 or less) than in sands while maintaining a probability of failure of less than 1%.

All 84 Load Test Cases. Although the correlations for differing soil types tend to be obscured by lumping all of the data together, it is instructive to evaluate the overall reliability of the methods evaluated in this study. In addition to the 50 piles in sand and the 27 piles in clay, this data set includes an additional 7 load test cases that represent such a mixture of soil types that the capacity could not be reliably stated as predominantly sand or clay. The composite of all test cases are shown on Table 5 below. Note that the modified version of SPILE2 includes a modification only in sands; the correlations used between SPT N values and S_u in clays is the same for both versions of SPILE2.

Method:	GDOT	GDOT(m)	SPILE2	SPILE2(m)	SPT91
Q_p/Q_m	1.54	1.03	1.44	1.16	0.82
Std. Dev.	0.18	0.18	0.22	0.20	0.19
R.I.	0.38	0.20	0.38	0.26	0.28
Prob. of Failure (%), F.S.=2.0	26.90	5.71	26.11	11.90	2.12
Prob.of Failure (%), F.S.=2.5	12.71	1.74	14.01	4.80	0.56
Prob. of Failure (%), F.S.=3.0	5.82	0.55	7.56	1.97	0.16
F.S. for Prob. of Failure = 1%	4.13	2.75	4.74	3.40	2.28

Table 5, Static Load Tests on All 84 Piles, All Soil Types

The data on Table 5 summarize the work on evaluation of methods to predict static pile capacity using SPT N values. These results suggest that of the existing methods, only the SPT91 code could be considered reliable for use in design. This code is somewhat conservative, and has a standard deviation which is not significantly better than the GDOT and SPILE2 procedures. After the modifications described previously and used in this study, both the GDOT and SPILE2 correlations with measured capacity were improved, and the modified GDOT method was the most accurate procedure overall. The SPT91 method provides a lesser probability of failure for a given factor of safety because of the overall conservatism of the method, not because of improved accuracy.

Summary and Conclusions Regarding Static Load Test Analyses

Conclusions which can be derived from the data presented in this chapter are presented below. In general, these conclusions apply to the predominantly PSC piles in the database; the relatively few number of H-piles in the database are considered insufficient for generalizations regarding H-piles.

1. The modified GDOT method was the most accurate and reliable overall procedure used to estimate static capacity of the piles in the database from SPT N values.
2. The SPT91 method results in the lowest probability of "failure" as defined by the Davisson method for a given factor of safety. This procedure is no more accurate than others, but is somewhat conservative overall.
3. The reliability of computed capacities in sands are much lower than those in predominantly clay soils.
4. Predrilling and jetting have the effect of reducing overall capacity and introduce additional uncertainty into the predicted capacity.
5. A factor of safety on the order of 3 is required to reduce the probability of failure to around 1% or less for a given pile designed according to the modified GDOT method.
6. The existing GDOT method is unconservative overall, according to the Davisson failure criterion and the data available in this load test data base.
7. A spreadsheet type data base format has been generated with a substantial number of static load test cases, and this format has the potential to be used to improve predictive methods as additional test data and/or computational methods become available.
8. It is the opinion of the writer that there appear to be large inherent uncertainties with respect to predictions of static pile capacities based upon SPT N values and it is unlikely that any method can be developed which greatly improves the ability to predict capacity due to this uncertainty with SPT data.

Special Consideration for Scour Effects

Note that these load test data include all soils contributing to capacity; on many actual projects there would likely be some zone of soil which is discounted due to scour effects. The effect of removal of overburden due to scour on the subsequent pile capacity is not accounted for with the

SPT91 or GDOT methods which use SPT N values directly. The overburden which is present undoubtedly contributes to the SPT N values.

The inherent inability to directly account for changes in overburden pressure with the methods based on empirical direct use of SPT N values suggest that the more fundamental SPILE2 procedure has advantages in this regard. In order to use SPILE2 in an analysis involving scour and soil parameters derived from SPT values, the engineer would need to either:

1) manually estimate pile/soil friction angle values which are derived from the SPT N-values and then perform analyses for the condition including scour, or
2) perform two analyses, the first using soil conditions representative of the time of the soil boring (the code would compute pile/soil friction values using the input SPT N-values), and the second for the condition including scour with the user providing the pile/soil friction values from the first analysis as input for the second. Suggested modifications as outlined in this report might be included to improve reliability.

It is generally suggested that two analyses be performed (existing and "after scour" conditions) so as to provide an estimate of the ultimate capacity for the existing condition even if the scour condition controls. This estimate for the existing condition will be the capacity which must be overcome in order to drive piles to the required embedment for the scour condition.

For the methods utilizing SPT N values directly, a rational approach to analysis of "scoured" conditions might be to adjust the SPT N values to account for the expected change in overburden pressure. Many commonly used correlations of soil strength parameters with SPT N values are based upon adjustment factors related to the square root of the effective overburden stress, $(\sigma'_v)^{1/2}$. If SPT N values are related to $(\sigma'_v)^{1/2}$, then a change in σ'_v would theoretically produce a change in N such that:

$$N_f = N_i \sqrt{\frac{\sigma'_{vf}}{\sigma'_{vi}}}$$

where,

N_f = *SPT N value after scour*
N_i = *SPT N value at time of boring*
σ'_{vf} = *effective vertical stress after scour*
σ'_{vi} = *effective vertical stress at time of boring*

Thus two analyses might be performed using these methods to estimate pile capacity with the scour condition computation performed using the SPT N values adjusted as above for the reduction in overburden pressure due to scour, and with the ultimate capacity for construction (required to overcome driving resistance) computation performed using the SPT N values made during the initial field investigation

As an example of the use of the above modification of SPT N values, consider the following case. A standard penetration resistance of 26 b/f is measured at a depth of 50 feet in a sand with the groundwater level at a depth of 10 feet. The soil has a total unit weight of 120 pcf above the groundwater table and 125 pcf below; therefore, the effective vertical stress at the sampling depth is (10)(120) + (40)(125) - (40)(62.4) = 3704 psf. At this location, 20 feet of scour is anticipated, and thus the effective vertical stress at the same elevation after scour would be (30)(125) - (30)(62.4) = 1878 psf. The revised SPT N value for use after scour with either the GDOT or SPT91 methods would then be $(26)(1878/3704)^{1/2} = 19$ b/f.

It is likely that the above correction is somewhat conservative with respect to pile capacity, because the horizontal stress in the ground is not likely to feel the same stress relief from scour as is the vertical stress. However, the proposed adjustment is a rational approach for design.

IV. Evaluation of Dynamic Capacity Methods

Estimates of static pile capacity from dynamic measurements of driving resistance are important to verify that the design capacity is achieved on an individual pile basis and to serve as an acceptance criteria to determine when pile driving may cease. In addition, capacity determined by dynamic field measurements can serve as a low cost form of load testing which may reduce the need for static load tests. In order to evaluate the reliability of several different approaches to estimating capacity from dynamic measurements, the dynamic load test data assembled for this study have been analyzed as described in the sections which follow.

Methods Examined

Several methods for computing static pile capacity from driving resistance measurements have been examined in this study. The equipment and means for making such measurements and computations are currently available to the GDOT Geotechnical Laboratory and have been utilized by other state DOT's. These are:

- Wave Equation Analysis (WEAP) computed capacity based upon end of initial drive (EOID) blow count measurement,
- Pile Driving Analyzer (PDA) indicated capacity using the Case Method computation and based upon EOID measurement,
- WEAP computed capacity based upon a beginning of restrike (BOR) blow count measurement, and
- PDA indicated capacity using the Case Method computation and based upon BOR measurement.

A new Pile Driving Analyzer (PAK model) and the most current version of GRLWEAP has been purchased from Goble Rausche Likens and Assoc., Inc. as a part of this project and this equipment and software provided to the GDOT Geotechnical Laboratory. These tools have been used for all of the WEAP and PDA analyses performed. A brief description of each technique follows. A more complete description of the WEAP analysis and the Case Method computations used with the PDA along with details on the specific implementation of each method are available in Appendix C.

WEAP Analyses. The wave equation computations (either for EOID or for BOR) have been performed to generate a "bearing graph" relation between blow count and static capacity for a given hammer and driving system for each of the piles in the dynamic load test data base. The approach used for these analyses has been to make calculations as would be done by a geotechnical engineer in advance of construction on the basis of driving system information provided for approval by a pile driving contractor. Thus, no information would commonly be available on pile hammer or driving system efficiency other than the typical values provided as a part of the GRLWEAP hammer data base. The basic objective of this exercise is thus to evaluate the reliability of the bearing graphs produced using this procedure. These bearing graphs would typically be used during construction by field inspectors (in lieu of some driving formula). Both end of drive (EOID) and beginning of restrike (BOR) analyses are performed in the same manner. Note that accurate measurements of blow count (typically expressed in blows/foot) are important for such analyses; in many cases these were obtained by measuring the set for 10 blows. For diesel hammers, ideally one should obtain the stroke by observation of the ram travel. In the absence of such information, the diesel hammers were evaluated as if they were operating at maximum combustion chamber pressure for the given driving resistance.

Soil quake (displacement at which full soil resistance is mobilized) and damping resistance (resistance which is proportional to the velocity of penetration, and which is not counted as a part of static pile capacity) factors were generally taken in accordance with the recommendations of the GRLWEAP user's manual. In most cases the computed static resistance is not particularly sensitive to these coefficients within the range of values considered reasonable, although restrike resistance in clays is perhaps more significantly affected. Some attempts were made to back-calculate soil damping resistance values from the load test data.

PDA Case Method Computation. The PDA equipment provides a potential improvement over the WEAP analysis in that the equipment provides a direct measurement of the energy delivered to the pile, as well as some indication of the pile response to the applied energy. All dynamic load test data within the dynamic data base include PDA measurements, and the raw measurements were evaluated using the PDA software installed on a computer in the Auburn University Geotechnical Laboratory. In some cases, the measurement data were available on diskette or were obtained using the Ga. DOT equipment purchased as a part of this research. In other cases where measurements had been made with older equipment, data were read from analog tape recordings and converted to digital form for analysis using the current PDA software. In all cases reported in this study, the actual computations of capacity were performed by the Auburn University research team using the field measurement data.

The Case Method computation of capacity used with the PDA data is made as a closed form solution to estimate capacity from the measurement of strain and acceleration at the pile head. Different forms of the Case Method computation are recommended based upon the shape of the measurement vs time, a measurement which suggests whether the pile appears to have predominantly end bearing resistance or large quake values, etc. In general, the recommendations of the PDA users manual have been followed with respect to the appropriate form of the Case Method computation as well as the soil damping factor used in the computation.

Note that the CAPWAP method of analyses for back calculation of static capacity using a PDA measurement has not been performed as a part of this study.

EOID vs BOR Measurement. Computations of static capacity have been made with both the WEAP analyses and PDA Case Method for both end of initial drive (EOID) and beginning of restrike (BOR) measurements for comparison with static load test results. Of course, the dynamic measurement of capacity gives an indication of the static resistance at the time the measurement is made and generally some time-dependent increase in capacity is observed after driving is ceased. In every case used in this study, the BOR measurement has been made within a few days of the time of the static load test, and the static load test measurement has been made days to weeks after EOID. Thus, one would naturally expect the BOR measurement to represent an improved estimate of static capacity over the EOID measurement. However, for routine pile installation, decisions must be made on when to stop driving based on the EOID performance and this comparison thus provides some measure of the reliability of those estimates of capacity. In addition, these comparisons provide the kind of information needed to develop engineering judgement regarding "set up", i.e. the amount of increase which might normally be expected over time after EOID.

The BOR measurement is typically based upon the first few blows of restriking the pile. It is observed with the PDA that it often takes a few blows for a hammer to "warm up", or to begin operating at the optimum efficiency. It is also possible that within a few blows after starting to restrike the pile the soil resistance will begin to drop as pore pressures in the soil build up and remolding of the soil around the pile occurs. Thus, the BOR measurements are subject to some uncertainty with respect to these factors. For the PDA capacity, the computed static capacity has been made using the earliest representative blow which gave a measured driving energy near the full capacity of the hammer. For the WEAP analyses, the blow count used is generally that estimated from the observed set of the pile after several (often 10) blows. A useful technique which can be used with the diesel hammers is to shut off the fuel supply to the hammer and have the contractor lift the ram and drop it from a known height like a drop hammer. This was generally not done on the measurements in the dynamic pile data base, but would be advisable for future measurements.

Methods of Comparison

As in the previous chapter with static capacity predictions from geotechnical data, a few terms must be defined for reference.

Definition of Failure. The Davisson criteria for failure has been used for the static load test measurement, as described in chapter 3. For WEAP and PDA Case Method predictions of capacity, the Davisson criteria has traditionally been used to develop correlations.

Ratio of Q_p/Q_m and $LogQ_p/Q_m$. As was used in chapter 3, comparisons between the static capacity predicted from the dynamic measurement (Q_p) and measured (Q_m) from the static load test are generally based on the ratio of Q_p/Q_m, with the $Log(Q_p/Q_m)$ used for statistical measurements.

Standard Deviation. The standard deviation has been computed based on the $Log(Q_p/Q_m)$ values to evaluate the variability of a particular method.

Reliability Index, RI. The reliability index, RI, is a calculated number which represents the sum of the absolute value of the mean of the $Log(Q_p/Q_m)$ values and the standard deviation, as defined in chapter 3.

Probability of Underdesign. Using the predicted failure capacity of the pile is divided by a factor of safety to compute an allowable design load on the pile, the probability of a "failure" occurring for a design using a particular prediction method is computed.

All of the above terms are consistent with the methods used for predictions of static capacity based on SPT data described in chapter 3, and thus it is possible to compare the reliability of dynamic capacity predictions with those made in advance of construction.

Comparison of Methods with Static Load Test Data

This section provides a comparison of the methods described above with the static load test results from the 14 piles in the dynamic pile data base. Because this number of piles is much more limited than for the conventional static load test data base, it is not feasible to separate the data by pile type and soil type to the extent possible in chapter 3. However, some trends with respect to soil type are noted as described in the following sections. Note that although there are 14 piles in the data base, some were restruck and load tested more than one time later so that there may appear to be more than 14 data points on several plots.

Figure 3 (figure 4-1A from Appendix D) presents a plot of static capacity (Davisson load) from static load tests vs dynamic indications of capacity using PDA Case Method capacity from restrike measurements. All of the BOR PDA values available in the data base are shown, along with lines representing ±20% of a perfect correlation. The most striking feature of this plot is the excellent agreement which is noted. Only 2 of the 18 points lie outside of this ±20% envelope.

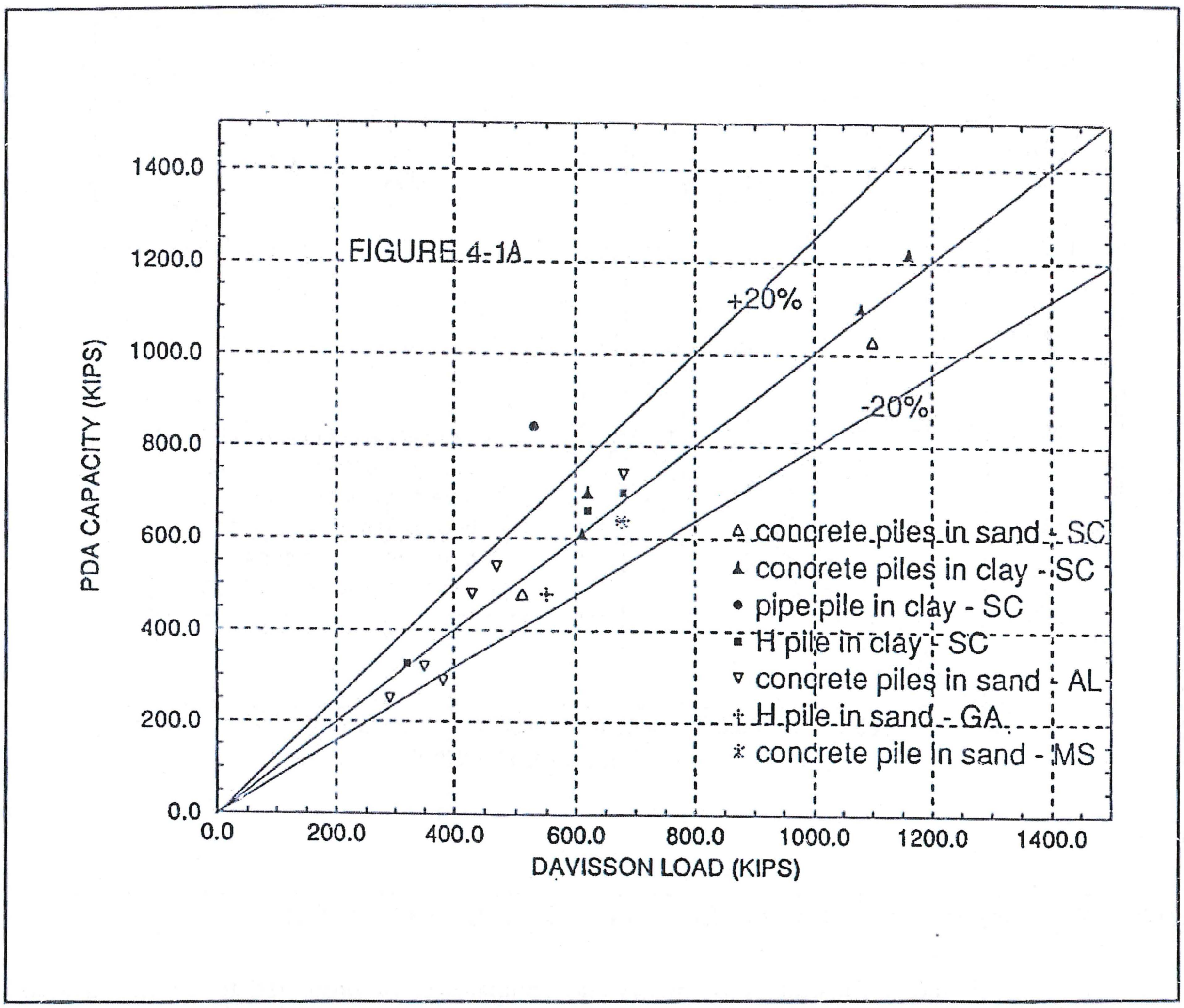


Figure 3 Comparison of Davisson Load and PDA Capacity (BOR)

Figure 4 provides a similar plot for the WEAP analysis of BOR data, with similar good general agreement between predicted and measured static capacity although with a bit more scatter than for the PDA BOR data. Three of the 18 data points lie outside the ±20% range.

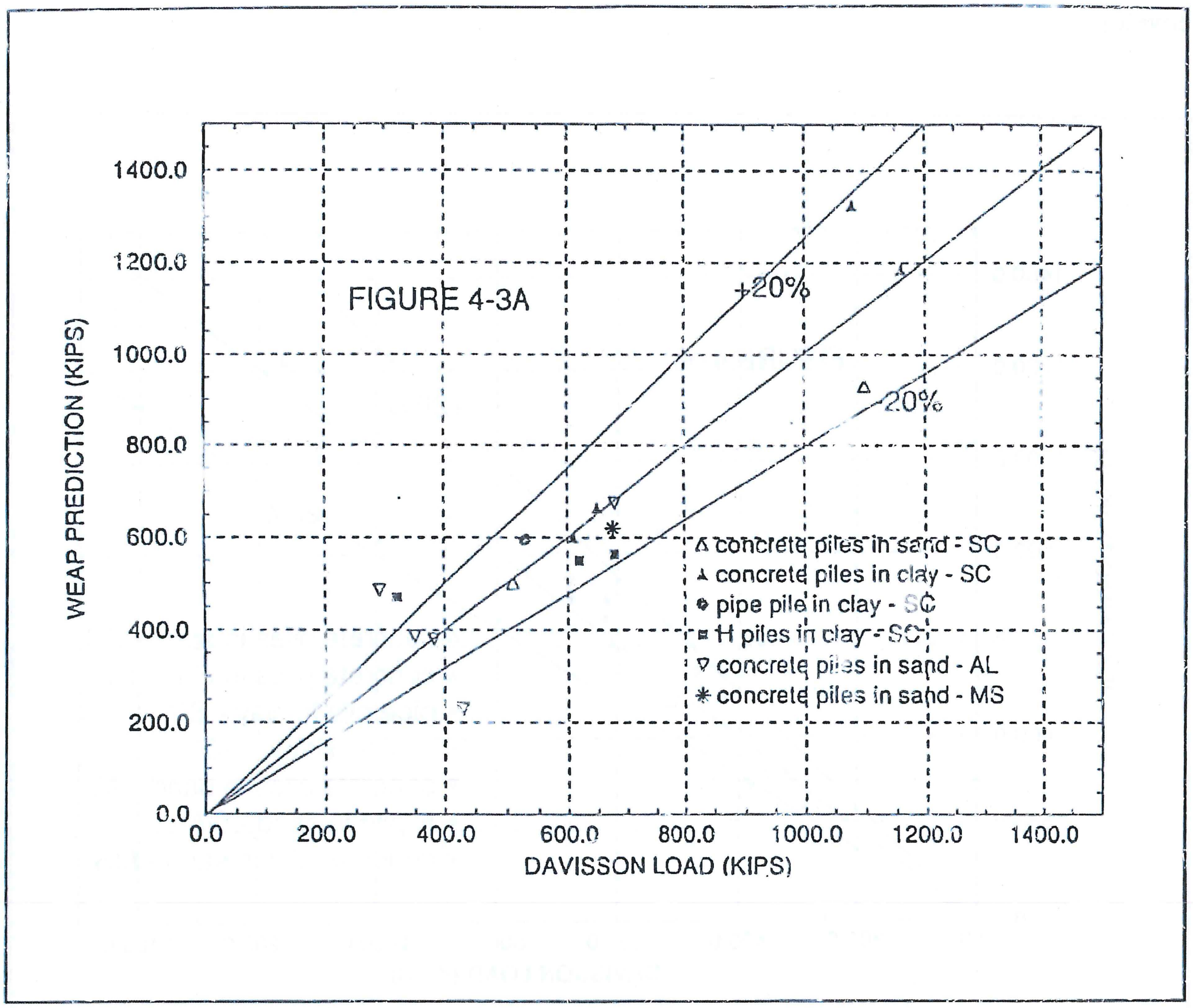


Figure 4 Comparison of Davisson Load and WEAP Capacity (BOR)

Figures 5 and 6 illustrate graphically the comparison of predicted to measured static capacity when comparing predicted capacity based on EOID measurements vs subsequent static (Davisson load) capacity for the PDA Case Method and the WEAP analyses, respectively. These data indicate relatively much poorer agreement; a large proportion of the predicted capacities plot well below the measured values, although some overpredictions of capacity are also noted. Because there is a general tendency for capacity to increase with time after driving, this result is perhaps to be expected. However, what is most notable is the fact that the "setup" observed with these data did not correlate well with soil type or other factors.

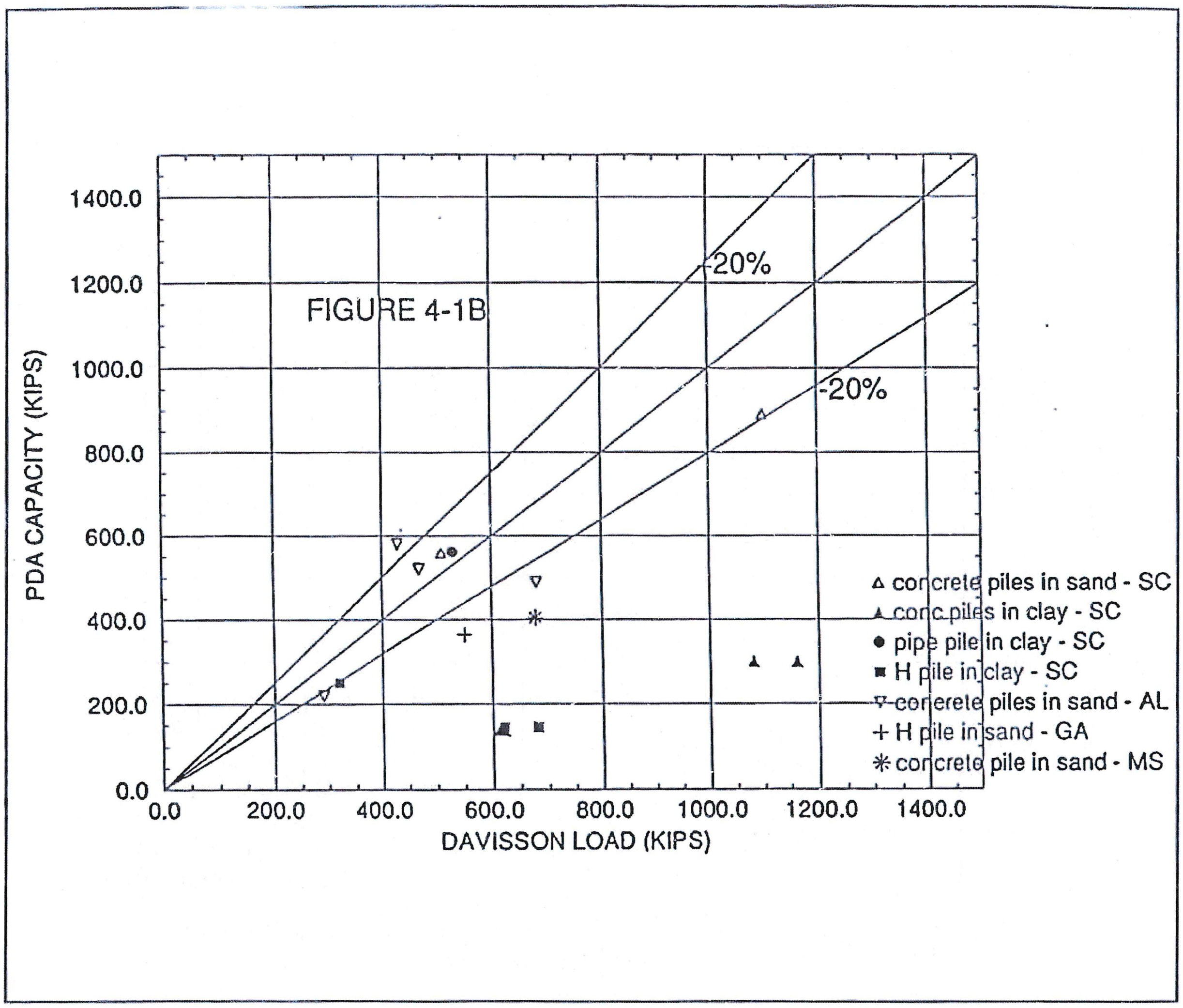


Figure 5 Comparison of Davisson Load and PDA Capacity (EOID)

All of the data presented on Figures 3 through 6 are summarized on Table 6, along with the statistical calculations as presented for static methods in the previous chapter. The Q_p/Q_m data shown on Table 6 confirm that both the PDA Case Method computations and the WEAP analyses were very accurate on average when restrike (BOR) measurements were made and quite conservative on average when based on end of drive (EOID) measurements. Between the two BOR measurements, the PDA Case Method was more precise as indicated by the lower standard deviation. The reliability index (RI) as defined earlier is quite low for both of the methods based on BOR. Note that the standard deviation and RI values for the BOR values are lower than for the static methods presented in the previous chapter by factors of 3 to 6! The EOID measurements are actually worse than the static predictions based on SPT borings.

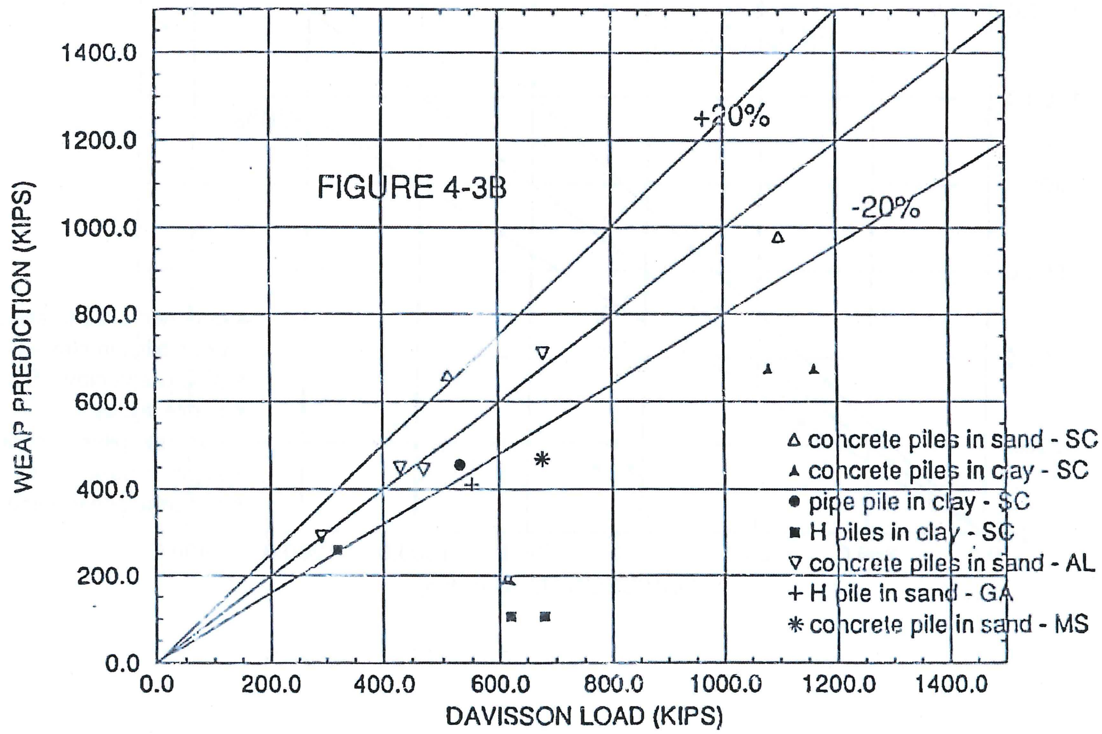


Figure 6 Comparison of Davisson Load and WEAP Capacity (EOID)

The probabilities of failure for the piles in the data base (as defined using the Davisson criteria) for an individual pile designed with a factor of safety of 1.5 to 2.5 are also shown on Table 6, along with the factor of safety which would be necessary to provide a risk of failure of 1%. Note that either method based on BOR measurements provides extremely low probabilities of failure for a factor of safety even as low as 2.0, and the factor of safety required to maintain a risk of failure of not more than 1% is well below 2 (below 1.5 for the PDA - BOR). Either method using EOID measurements includes a greater risk, owing to the much larger standard deviations with these measurements.

Method:	PDA - BOR	WEAP - BOR	PDA - EOID	WEAP - EOID
Q_p/Q_m	1.02	0.99	0.53	0.61
Std. Dev.	0.07	0.11	0.29	0.28
R.I.	0.07	0.11	0.56	0.49
Prob. of Failure (%), F.S.=1.5	0.5	4.8	5.8	7.9
Prob. of Failure (%), F.S.=2.0	<0.01	0.2	2.3	3.1
Prob. of Failure (%), F.S.=2.5	<0.01	0.01	1.0	1.3
F.S. for Prob. of Failure = 1%	1.45	1.77	2.47	2.67

Table 6, Pile Capacity Using Dynamic Measurements

Other Important Points Relating to Dynamic Methods

In addition to the results of the capacity computations presented above, several other items of importance were examined as a part of this study, as summarized below.

Backcalculated Soil Damping (J) Values Using PDA. In an attempt to provide feedback on the soil damping constant used in the PDA Case Method computations, the measured static soil resistance from the static load test was used to backcalculate the soil damping (J) value which would be required to yield perfect agreement between predicted and measured static capacity. Only BOR measurements were used for these backcalculations so as to avoid introducing another variable (time-dependency) which would confuse the issue. These computations indicated a range of J-values of 0 to 0.4 for piles driven to tip in sands with an average of 0.20. For the piles in clays, J-values ranged from 0.31 to 1.14 with an average of 0.74. Complete data on back calculated J-values are presented on Table 4-5 in Appendix C. No distinct trend relating to pile size or stiffness was evident from the limited number of cases available in this study. The variation in J-values relating to soil type was such that large variability in this parameter can be expected, especially with clay soils, even across a given site.

However, this variability did not lead to large errors in the computations of capacity (presented in the previous section) when restrike blows are available. The data generated in this study do not generally conflict with the general guidelines provided in the PDA manuals.

Observed "Setup". Based on the PDA computed capacity for end of drive (EOID) and restrike (BOR), these data provide some indication of the amount of soil "setup", or increase in capacity with time, which was observed during the few days to weeks between these events. For the time periods contained within the dynamic pile test data base, setup in the range of -17% to +58% (average of +18%) was observed at the sites which were primarily sands and setup in the range of +30% to +400% (average of +240%) was observed at the sites which were primarily clays. Complete data on setup is provided on Table 4-10 in Appendix C. The most notable feature of these observations is the extreme variability; this variability is reflected in the high standard deviation numbers in the comparison of predicted to measured static capacity for EOID measurements shown previously on Table 6. In general, setup in clays was substantially larger than for sands, but the variability is so great that generalities here can be dangerous.

"Relaxation", i.e. a reduction in capacity with time or a negative setup value, was observed in two instances in sands. Both of these cases were with driven PSC piles, one at a site in Alabama and the other at a site in South Carolina.

Real vs Apparent Relaxation. The data available in the dynamic pile test data base provide an opportunity to observe cases of both real and apparent relaxation. Real relaxation is an actual reduction in static capacity over time. In this discussion, the PDA capacity computed using the Case Method is taken as an indication of the actual static capacity, and thus real relaxation is defined in this context as a reduction in the PDA indicated capacity. In addition to the two cases of real relaxation mentioned above, there were three cases of "apparent" relaxation (two in South Carolina, one in Alabama). Apparent relaxation is defined as a case in which the observed blow count for a given hammer was observed to be reduced upon restriking the pile from that observed at end of initial driving, but the actual PDA indicated capacity increased or stayed the same. This apparent relaxation occurs when the hammer is observed to operate more efficiently on the restrike blows than on the end of initial driving blows. Such an increase in hammer (or system) driving energy would generally not be evident without the PDA measurement, although for open-ended diesel hammers it might be possible to observe an increased stroke.

Comparison of Measured and Computed Driving Energy. A major concern related to the use of the WEAP analysis which is addressed with the PDA equipment is that of the hammer efficiency and the actual energy transmitted to the pile. All of the WEAP analyses presented in this report have been performed using the default efficiency values contained within the

GRLWEAP hammer data base which is provided with the code. It is instructive to examine the data within the dynamic pile data base to see how much in error these default values might be. Note that the hammer efficiency is only one component of the difference between the rated hammer energy and the actual energy transferred to the pile. Energy losses also occur through the cushion(s) and impact between the hammer and pile. While hammer efficiency numbers are often taken in the range of 50% to 70%, the actual ratio of energy transferred to the pile to hammer rated energy (called the "transfer ratio") is quite a bit lower. Transfer ratios ranged from 15% to 65% in this study.

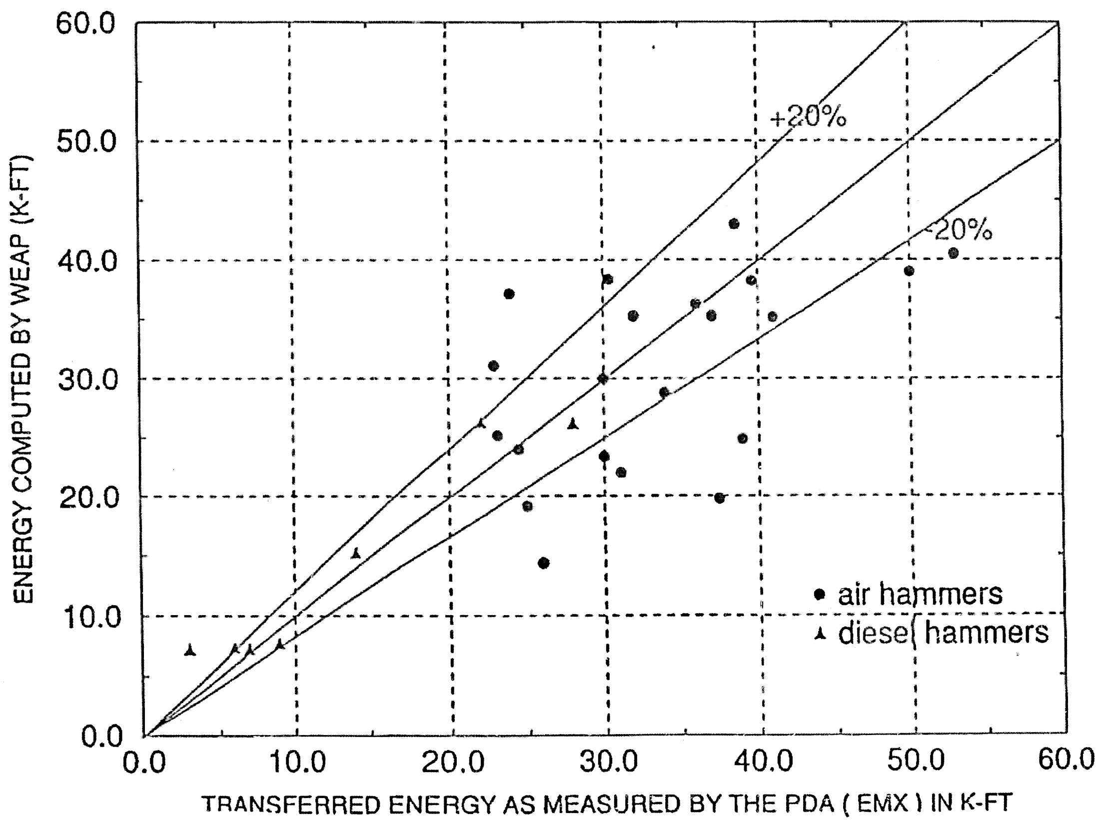


Figure 7 Comparison of WEAP vs PDA Energy Transferred to the Pile

Presented on Figure 7 is a plot of transferred energy computed using the WEAP code with default hammer and cushion efficiency values vs the transferred energy measured directly with the PDA equipment. These data reveal a significant variability, although on the average, the values computed using the WEAP default parameters appeared to be reasonable. An interesting point is that the air hammers appeared to be somewhat more variable than the diesel hammers. However, it must be noted that there is a greater tendency to use air hammers with the larger PSC piles which may have been disproportionately represented in the dynamic pile data base.

Summary and Conclusions Regarding Dynamic Analyses

Conclusions which can be derived from the data presented in this chapter are:

1. The dynamic estimates of capacity based on end of initial drive (EOID) measurements using either WEAP or the PDA are only marginally better than the static methods of computing capacity presented in the previous chapter of this report. A factor of safety on the order of 2.5 to 3 (for PDA and WEAP, respectively) is required to provide a probability of failure of 1% or less based on the dynamic pile test data base.
2. The dynamic estimates of static capacity based on the restrike measurements (BOR) are by far the most reliable indication of capacity of any considered in this study. The PDA measured capacity from the BOR measurement was significantly more reliable than the WEAP indicated capacity from a preconstruction bearing graph, but the most substantial improvement in reliability is represented by conducting a restrike measurement. A factor of safety on the order of 1.5 to 2 (for PDA and WEAP, respectively) is sufficient to provide a probability of failure of 1% or less based on the dynamic pile test data base.
3. Backcalculated soil damping values were observed to be quite variable, and generally higher for clays than for sands. The observations in this study were in broad general agreement with the recommendations suggested in the PDA manual.
4. Observed soil "setup" between EOID and BOR was extremely variable and considerably higher for clays than for sands. These observations underscore the need for restrike testing.
5. Two cases of real relaxation were observed and three cases of apparent relaxation. The apparent relaxation can be distinguished using the PDA equipment. The cases of real relaxation again emphasize the need for restrike testing.
6. The energy transferred to the piles during driving which is predicted using WEAP with the default values in the GRLWEAP hammer data base revealed some variabilities

compared with those values of transferred energy observed with the PDA equipment. However, systematic over- or under- estimation of energy was not observed.

V. Conclusions and Recommendations

The observations and analyses reported in this summary of the study suggest a number of conclusions and recommendations which the GDOT Geotechnical Laboratory may wish to consider for future practice with respect to driven piling in Georgia.

1. Estimates of Static Capacity based on SPT Data Should be Considered as Preliminary Only and Should be Verified by Field Measurements.

Reliability of all of the methods of computing static capacity based on SPT data were relatively poor compared to field measurements during construction. The standard penetration test is a relatively crude index of soil properties and cannot replicate the complicated changes in soil stresses, material properties, and pile/soil interface charactaristics which occur during and after pile installation. In addition to the variability measured within the database described in this study, there is potential for additional variability related to changes in soil charactaristics across a bridge site. Given the much higher reliability available on an individual pile basis using only a site and project specific WEAP bearing graph along with observations of pile driving resistance, it is clear that the greatest potential improvements in economy and reliability are available from attention to field performance. Of course, static capacity estimates during the design stage are important to establish conceptual design and to include an evaluation of the resistance contribution of soil materials which are subject to scour.

2. Modify the GDOT Method of Computing Static Capacity for Design Based on SPT Data.

On the basis of soil boring information with only SPT N values for design of pile foundations for axial load, the most reliable method for the predominantly PSC pile load test data base generated for this study was the modified form of the GDOT charts. The best prediction of failure load according to the Davisson criterion is obtained by multiplying these allowable chart values by a factor of 2 to obtain the failure load.

In order to maintain a probability of around 1% that the design load will not exceed the failure load, a factor of safety of at least 3 is required with this method. Therefore, the allowable loads used for design (according to this criterion) should be 2/3 of the present chart values (multiply by 2 to obtain failure load, divide by 3 for F.S.). It should be noted that this and all other methods were less reliable in sands and in sands where predrilling and/or jetting has been performed. Where capacity is primarily from clay soils, a factor of safety for design of 2.5 might be justified as having an equal reliability.

Given the relatively large standard deviation with all of the methods examined and the general uncertainties relating to SPT testing and correlations with static soil properties, it is considered unlikely that any method based solely on SPT data can greatly improve reliability of static pile capacity estimates.

3. Use Dynamic Field Measurements from Restrike Blows on Selected Piles.

The most significant potential improvement in estimation of pile capacity is provided by field measurement of driving resistance, particularly with restrike blows. The PDA capacity computed using the appropriate Case Method provided exceptional reliability when used with a restrike measurement. Estimated capacity from a WEAP bearing graph and a restrike blow count proved somewhat less reliable, but still far superior to any other means.

Estimated capacity from an end of initial driving measurement was not substantially more reliable than static methods based on SPT N values due to uncertainty related to soil setup (or relaxation in rare instances).

A suggested practice which could greatly enhance reliability would be to drive indicator piles across the site and perform restrike testing on those piling. These restrike measurements would provide a fairly reliable indication of capacity, especially if combined with one or more static load tests on selected piles, and would provide some indication of the setup observed so that a routine driving criteria can be set on the project for installation of production piles. On large or costly projects, PDA measurements should be made. On routine projects for which field measurements with the PDA are less critical, these measurements should be based on the WEAP analysis bearing graph performed for the specific site and driving equipment.

On projects where dynamic measurements will be made based on restrike blows, a factor of safety of 2 could be used and even still result in an improvement in reliability over design based on static analyses alone.

4. Require Contractor Submittal of Proposed Pile Driving System for Approval and Establish a WEAP Bearing Graph on Each Project.

This submission is already required by many southeastern states (so contractors should be used to it), and is essential so that the WEAP analyses can be performed in advance of construction. In addition to providing a bearing graph for use by field inspectors, this analysis provides a verification that the driving system proposed is capable of installing the piles to the required capacity without overstressing the pile or resulting in excessive blow counts. The Ga. DOT could consider allowing the contractor to perform their own WEAP analyses for submission, but this approach includes a risk of manipulation of the parameters used in the analyses. There are always uncertainties in using WEAP with respect to the driving system parameters (hammer efficiency, in particular), but the GRLWEAP hammer data base proved to be reasonably accurate for the data examined in this study. Of course, suspiciously performing driving systems or unusual field observations should be considered cause to utilize the PDA equipment on a particular project. The Ga. DOT specifications should include a provision for field PDA measurements at the engineers' discretion to verify equipment performance and the suitability of the bearing graph used on the job.

It is suggested that the use of ENR and other simplistic driving formulae be discontinued. Although not specifically evaluated in this research, there is a substantial body of research which indicates that such techniques are so unreliable as to be of little use at best, and misleading at worst.

5. Conduct Static Load Tests Including Dynamic Measurements on Future Projects in Georgia.

The data used in this study are primarily from southeastern states other than Georgia; the test data available from Ga. DOT projects are very limited. It is important that additional test data be generated on DOT projects in Georgia which include good quality geotechnical data, PDA measurements for both end of driving and restrike at the time of static load testing. Such data would:

- allow for improvements in the data base, particularly for steel piles for which data are very limited, and in soils within the Georgia coastal plains region,
- provide opportunities for Ga. DOT engineers to obtain first hand information on performance (including soil setup), which is critical to develop judgment and identify important considerations during field installation which can affect results,
- provide for a demonstration of the effort to improve pile foundation design and construction practice in the field, and involve field inspectors in the effort, and
- provide the information necessary to facilitate future improvements in practice. For example, a future evaluation of the "CAPWAP" code which is used to perform a more sophisticated and detailed evaluation of capacity from a PDA measurement might be performed if the data are available.

6. Include an Evaluation of the Effects of Scour on Both Design and Dynamic Measured Capacity.

Scour has become a design concern which has major impact on foundation design on almost every bridge which crosses water. It is important to note that the dynamic estimates of capacity provided with either WEAP or the PDA is based on observed driving resistance inherently includes all of the soil which is contributing to the driving resistance. In the event that some of the soil must be discounted due to scour, then it would be necessary to compute separately the amount of additional capacity this soil would add to the observed capacity during driving so that the pile is driven to a sufficient resistance that the post-scour capacity is adequate for the design. Thus, where deep scour is anticipated at a site, it is necessary to make two separate computations of capacity; one for the design condition where scour has occurred and the capacity of the pile is at a minimum, and a second for the "construction" condition where soil that is to be neglected for design must be included in the capacity required for acceptance. There will always be some uncertainty as to how much this soil might be contributing to the measured dynamic resistance during driving, and also as to how much effect the overburden pressure of this soil has on the capacity of the underlying strata.

In order to include the effects of scour in analyses of static capacity from soil borings and SPT data, the use of a more fundamental design method such as is implemented in the code SPILE2 has particular advantages. Estimated pile/soil friction from the soil boring data can be used directly in the revised analyses including scour. The direct empirical correlations used in the GDOT and SPT91 methods do not provide means of directly dealing with changes in soil conditions relative to those present at the time of the soil boring. A rational method of adjusting the SPT N values for use with these methods has been presented in "Section III - Special Consideration for Scour Effects".

With regard to field measurements, the computer code "CAPWAP" can provide a rational means of estimating the distribution of capacity along the pile from a PDA restrike blow measurement, and should be considered as a future subject of research and possible implementation in design. It is recommended that the Ga. DOT consider the purchase of this code and the evaluation of the code in conjunction with future instrumented static load tests which would provide some indication of the distribution of load capacity along the pile. It might also be possible to conduct several load tests in two phases in which the first might be through an existing soil formation at grade and a second test performed after removal of overburden soil around the pile to simulate scour.

7. Other Considerations for Future Research in Bridge Foundations.

In addition to the important concerns and research needs related to scour mentioned above, several additional suggestions for consideration as future research topics in bridge foundation engineering are presented below.

- Research into the design and performance of drilled shaft foundations. Because of concerns related to scour, pile foundations are being forced to achieve greater and greater penetrations. Under such conditions, drilled shaft foundations often prove to be competitive alternatives in terms of both cost and performance. A maturing drilled shaft construction industry and an improved ability to test these types of foundations for both concrete integrity and axial and lateral load carrying capacity has allowed drilled shafts to be considered on a more widespread basis for highway projects. The Ga. DOT has limited experience with drilled shaft foundations and little performance testing information on which to base designs. Additional research is needed to allow well engineered designs of drilled shaft alternates for bridge foundations.

- Evaluation of in-situ testing of soil properties for improved foundation design. Although standard penetration testing (SPT) has been the basis for design for many years, there may be opportunities to improve on this technique. The use of automatic hammers (which fall freely without the added resistance of the cathead rope attached) may provide more reliable and/or reproduceable measurements. These hammers are also quite likely to provide quite different measurements than the older techniques which comprise much of the database described in this report. Some research has been initiated by GRL, Inc. into the use of the PDA equipment on the SPT anvil and/or drill string to determine soil damping, quake, and resistance parameters for pile foundation design. This approach may offer an opportunity to improve capabilities using existing equipment and should be considered for future research in Georgia (or possibly joint participation with the ongoing GRL effort). Alternative in-situ testing devices to SPT could also be considered as potential improvements to foundation design practice.

- Evaluation of lateral capacity of deep foundations and development of p-y curves at sites in Georgia. Deeper scour depths, ship impact loads, longer spans, have all contributed to an increased tendency for lateral load considerations to control or significantly affect foundation design. The recommended approach using the "p-y method" as implemented in the code COM624 includes empirical p-y curves which are used to represent soil resistance. These soil resistance curves are derived from load test experience primarily by the Texas DOT, and additional research in the form of load testing and evaluation of results is very much needed in the southeast. This is particularly true where drilled shafts socketed into rock are used, or pile group foundations are designed for large lateral loads from vessel impact. It might be possible to incorporate some significant testing and research into upcoming construction projects where these considerations are important.

- Use of CAPWAP to evaluate dynamic measurements. This subject was discussed under item 5 above, and is listed here for completeness.