WAVE EQUATION CORRELATION STUDIES

Gabriel Thendean[1], Frank Rausche[1], Garland Likins[1], Mark Svinkin[1]

Abstract

The end of driving and beginning of restrike correlation results of wave equation analyses with the static load test results are presented. Results from both standard analyses (using GRLWEAP recommendations) and hammer/ driving system performance adjusted analyses (based on dynamic testing results) are included. Based on these results, the dynamic soil model parameters, damping factors and quake, were back-calculated and their relationships with respect to soil types were investigated. For long term capacity predictions based on the end of driving standard GRLWEAP capacity, an apparent setup factor concept is introduced and a table of conservative setup factors for various soil types is presented.

Introduction

Pre-installation studies of impact driven pile foundations using the public domain wave equation analysis program or its proprietary successor, GRLWEAP, have routinely been required in the United States and worldwide. This method is explained in detail in the Federal Highway Administration (FHWA) Manual on the Design and Construction of Driven Pile Foundations (Hannigan et al., 1996). As part of a recent research project (Rausche et al., 1996), correlation studies were performed to compare wave equation predicted capacities with the static load test capacities.

The objectives of the correlation studies presented here include: first, the investigation of the statistical reliability of the wave equation capacity predictions for both end of driving (EOD) and beginning of restrike (BOR) conditions; second, the re-evaluation of the capacity predictions after adjustment of hammer/driving system performance based on the dynamic

[1]GRL and Associates, Inc., 4535 Emery Industrial Parkway, Cleveland, Ohio 44128, USA

testing results; third, both the back-calculation of damping factors and quake values and the investigation of relationships between these parameters with respect to soil types; and finally, calculation of apparent setup factors. A total of 99 cases were included in this for the correlation studies.

Description of Database

GRL maintains a database which currently contains more than 200 cases of static load test piles with dynamic tests also performed on the same pile. This database is regularly augmented with new cases submitted from all over the world meeting the following basic requirements:

- Static load test was carried to *failure* as defined by the Davisson's failure criterion which is then called the ***static load test capacity***. An exception is granted if failure was not reached but could be extrapolated within at most 110% of the maximum applied load. Pile description, tip elevation, date and time of test, and pile top load-set curve are the minimum required static load test data.

- A dynamic restrike test using a Pile Driving Analyzer (PDA) was performed after a waiting period, comparable to the time of static testing, following pile installation. Force and velocity records from BOR and preferably also EOD are available. The BOR blow count meets any one of the following three requirements.

  less than the equivalent of 1200 blows/m or 360 blows/ft, or

  less than 1600 blows/m or 480 blows/ft but only if the standard GRLWEAP analysis overpredicted the static load test capacity, or underpredicted the static load test capacity within 5%, or

  at absolute refusal only if both standard GRLWEAP and CAPWAP analyses overpredicted the static load test capacity, or underpredicted the static load test capacity within 5%.

- Soil information is available including soil description, soil strength such as SPT, and other relevant information. The soil boring should be in the vicinity of the load test pile and extend below the pile toe.

- Pile driving log (or at least the blow counts from EOD and BOR) must be available and include pile length, pile tip elevation at EOD and BOR, hammer and driving system information.

Correlation Considerations

It was assumed that both static load test results and blow count logs were accurate. In many soils, pile capacity and blow count continually change with time due to setup or relaxation. Therefore, differences in capacity and blow count should be expected, and these differences increase as time between tests elapses. Potential measurement errors in both static and dynamic tests, alternative failure definitions in static test evaluation, and differences in time of testing after installation are the most important reasons why exact agreement between static and dynamic test results is virtually impossible for all data sets. Further discussion has been given by Likins et al. (1996).

Obviously, the established database cannot be used for all types of investigation. A purely statistical use of the database may be hampered by the following shortcomings.

- Only well engineered cases are included, *i.e.*, those with instrumented restrike tests, complete site documentation, and a static load test.
- Instrumented restrike tests are normally preceded by the instrumented initial installation; if poor hammer performance was present during the installation, it had likely been corrected before the restrike.
- Sites with very high soil setup probably were excluded from the database, either because the static load test did not fail, or the BOR blow count exceeded the database requirement limit.
- On a significant number of sites, several piles were tested and their data were included in the database. Unless these test sites were for important or large projects, the large number of test piles may indicate unusual or difficult soil conditions at these sites.

These shortcomings are not a major drawback for the purpose of this paper. However, caution should be exercised when attempting to draw general conclusions from the results presented here.

Correlation Procedure

Wave equation analyses for these correlation studies were performed with GRLWEAP, Version 1.993-1, described by GRL (1995). Several correlation studies were performed using the 99 selected cases. An outline of the wave equation correlation study procedure is presented in Table 1.

The first correlation effort was to compare the wave equation capacity predictions based on field observed blow counts from (a) EOD and (b) BOR and bearing graphs from standard wave equation analyses. The capacities were identified as ***standard GRLWEAP capacities***. The standard wave equation analyses utilized the recommendations of the GRLWEAP manual for hammer and driving system, pile, and Smith soil model parameters as appropriate for the particular site conditions. Furthermore, for a realistic input of soil resistance distribution, a static analysis was performed following the recommendation of the FHWA manual.

Table 1: Outline of GRLWEAP Correlation Procedure
Standard Smith Soil Model used for all Analyses
1. Retrieve Data and Evaluate Static Load Test Results.
2. Perform Preliminary Static Analysis - FHWA Recommendations
3. Perform Standard Wave Equation Analysis Find Standard WEAP Capacities for EOD and BOR
4. Compare Measured EMX and FMX from Restrike with 3.
5. Perform (EMX, FMX) Adjusted Wave Equation Analysis Find (EMX, FMX) Adjusted WEAP Capacities for EOD and BOR
6. Back-Calculate Dynamic Soil Parameters Adjust J_s, J_t, or Q_t for Capacity and BOR Blow Count Correlation
7. With Back-Calculated Soil Parameters from 6, Find Correlated Capacities for EOD (Adjust EMX and FMX if EOD Data Available)
8. Find Apparent Setup Factor

The second correlation effort used the maxima of force (FMX) and transferred energy (EMX) measured by the PDA together with bearing graphs from wave equation which inputs were adjusted to match these measurements. The FMX and EMX adjustment was done by changing the hammer transfer efficiency and/or the hammer cushion properties for steel piles, or the pile cushion properties for concrete piles. The adjustment was considered sufficient when calculated and measured EMX and FMX values agreed within 10%. Standard soil parameters were again used and therefore the results were identified as ***standard adjusted GRLWEAP capacities***.

The third correlation effort used the predictions from the first and second efforts, but with site averaged to avoid bias to the statistical evaluation, by including more than one data set with the same soil condition. The site averaging reduced the number of observations from 99 to 45. And of these 45 sites, 20 had only one test pile and the remaining 25 sites had two or more test piles.

Discussion of Correlation Results

Figures 1 through 4 present the EOD and BOR correlations obtained with and without adjustment (correlation efforts 1 and 2). Each point in these figures represents a pile for which the capacity was calculated based on bearing graph and field observed blow count. The general tendency of the wave equation EOD results to underpredict the static capacities is obvious. This is particularly true for the adjusted method (lower mean value). On the other hand, BOR results tend to overpredict, even after adjustment for hammer/driving system performance.

For a better comparison of the prediction methods, the statistical evaluation method for predicted capacities adopted by Briaud and Tucker (1988) was followed. The predicted capacities were divided by the static load test capacities and the resulting capacity ratios were statistically investigated by computation of mean and coefficient of variance (C.O.V.) in Table 2. The C.O.V. is defined as the standard deviation divided by the mean. Table 2 (lines 1, 3, 5, and 7) summarizes the statistical results of Figures 1 through 4. The static pile capacity calculations (static analysis), based on SPT N-values and the FHWA Manual recommendations (Hannigan et al., 1996), are presented on line 11 of Table 2 for completeness.

From the mean and standard deviation, a log-normal probability density function was calculated and plotted for visual evaluation of capacity predictions. The log-normal function was chosen because it took into account the non-symmetrical effect of capacity ratio (underprediction=0 to 1, overprediction=1 to ∞). The higher and narrower the curve of a particular method, the better the precision of its prediction, corresponding to a lower C.O.V. Obviously, a capacity ratio of 1.0 is also desirable. The location of the curve's peak (or better the areas under the curve) indicate whether the method would tend to overpredict or underpredict. The log-normal curves bring out averages between predictions which are not necessarily apparent from the scattergrams of Figures 1 through 4. Further discussions of this method have been given by Briaud and Tucker (1988) and Likins et al. (1996).

The log-normal probability density functions for the correlations in Figures 1 through 4 are presented in Figure 5. Also superimposed on the plot is the

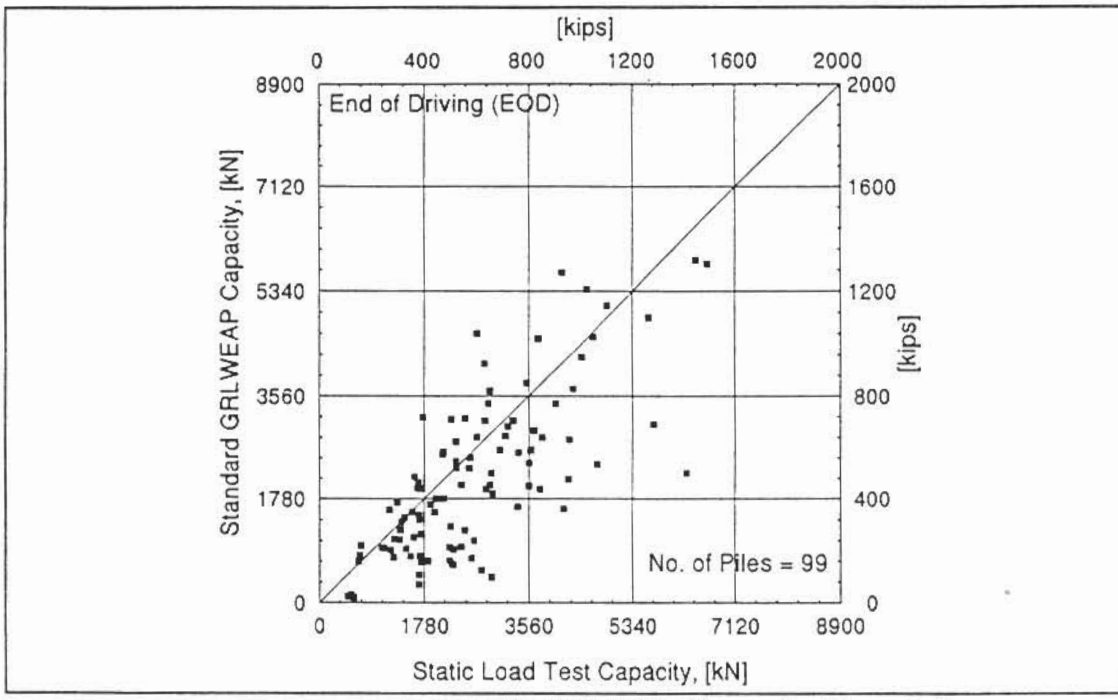

Figure 1: Standard GRLWEAP EOD Capacity Correlations

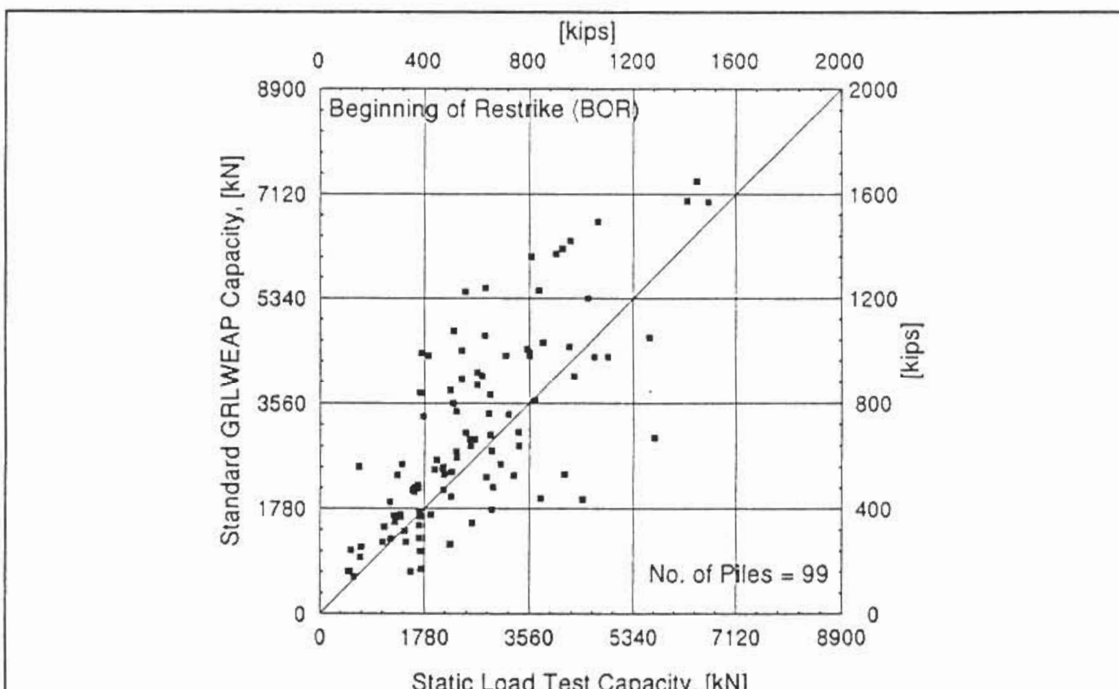

Figure 2: Standard GRLWEAP BOR Capacity Correlations

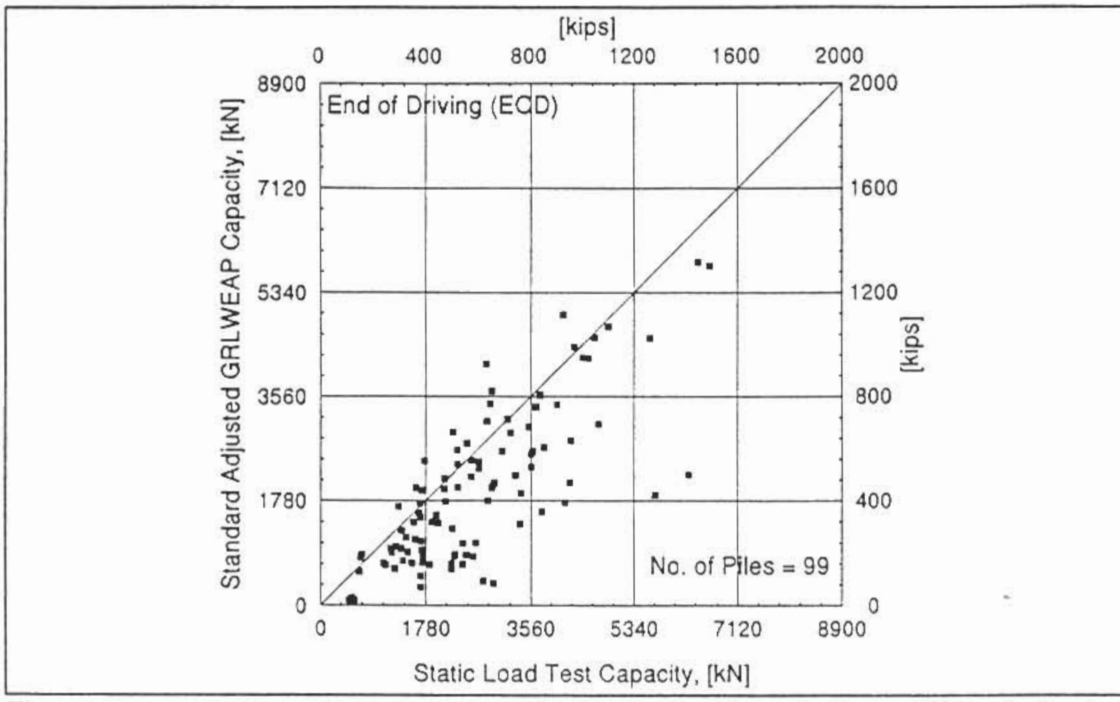

Figure 3: Standard GRLWEAP EOD Capacity Correlations With Adjusted Hammer/Driving System Performance

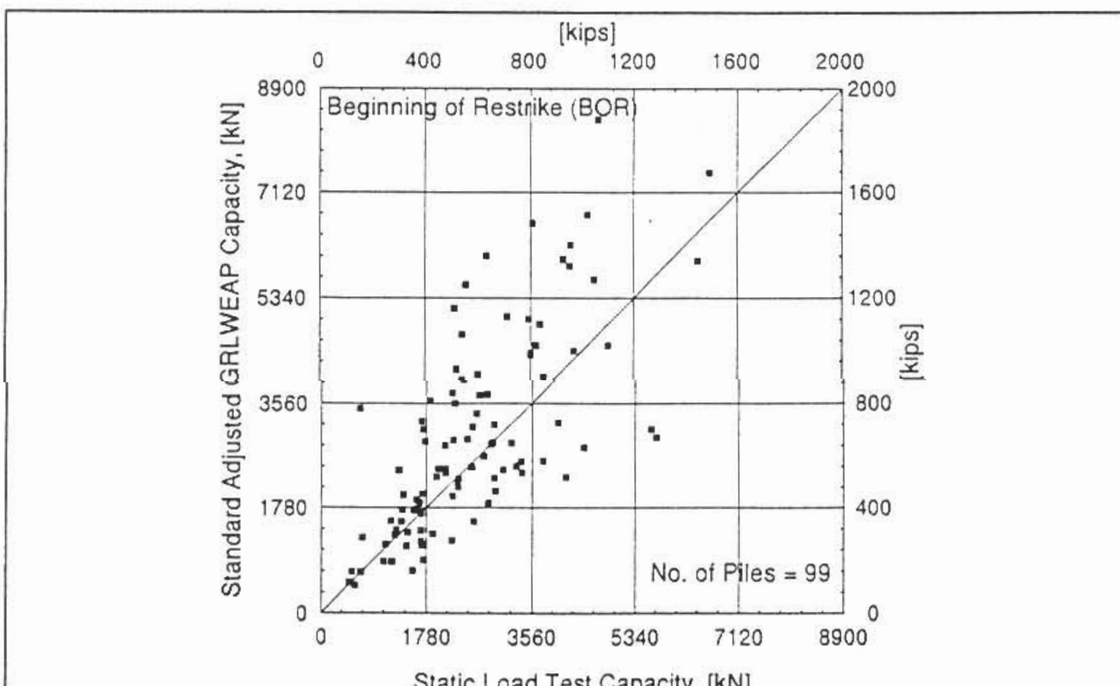

Figure 4: Standard GRLWEAP BOR Capacity Correlations With Adjusted Hammer/Driving System Performance

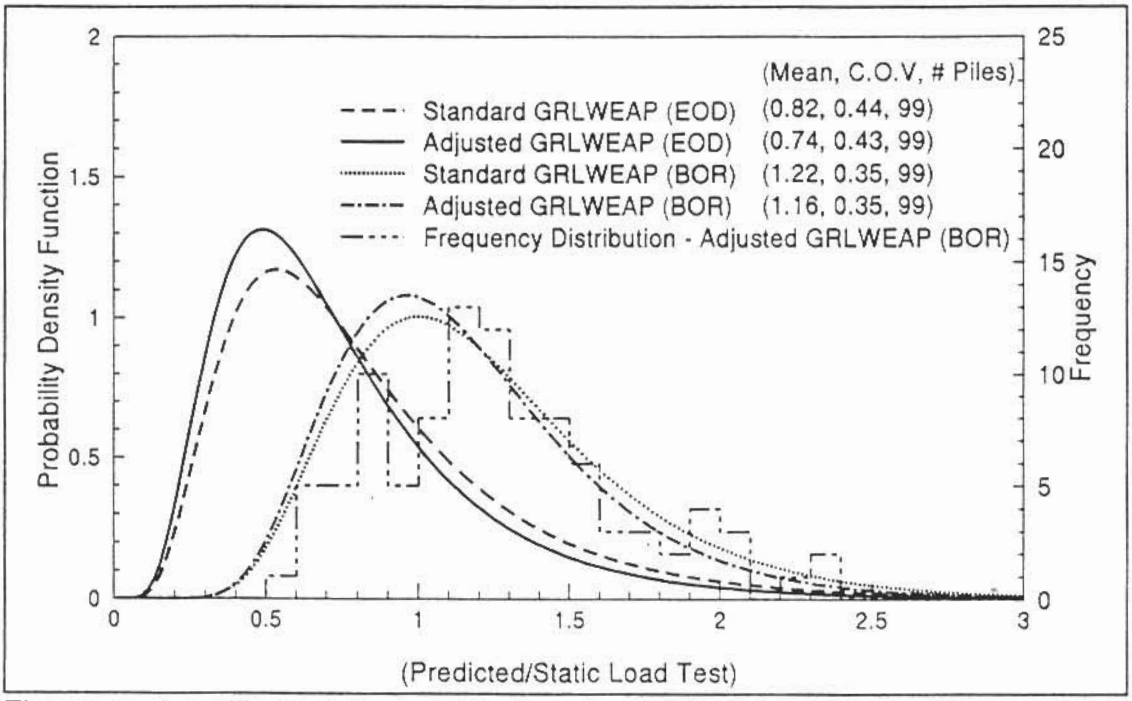

Figure 5: Log-Normal Probability Density for Standard GRLWEAP EOD and BOR Predictions, With and Without Adjustment; and Frequency Distribution for Standard GRLWEAP BOR Predictions

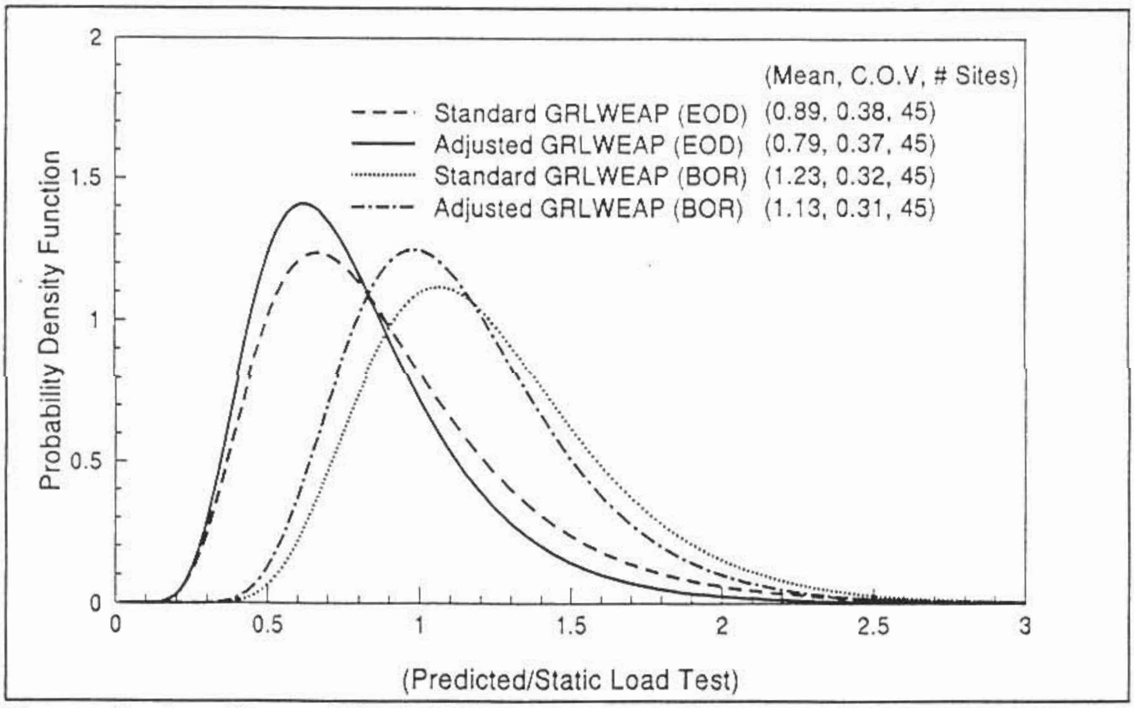

Figure 6: Log-Normal Probability Density for Standard GRLWEAP EOD and BOR Predictions, With and Without Adjustment (as in Figure 5 but Site Averaged)

actual frequency distribution of the adjusted BOR capacities (correlations from Figure 4). The frequency distribution is not smooth because of the limited sample size. The log-normal function of the adjusted BOR capacities matches the frequency distribution reasonably well and justified the use of this function for visual evaluation.

Table 2: Statistical Summary of Capacity Ratios (Predicted / Static Load Test)

Line	Prediction Method	Status	Number of Piles/Sites	Mean	Standard Deviation	Coefficient of Variation (C.O.V.)
1	Standard GRLWEAP	EOD	99	0.82	0.36	0.44
2		EOD-Avg	45	0.89	0.34	0.38
3		BOR	99	1.22	0.43	0.35
4		BOR-Avg	45	1.23	0.39	0.32
5	(EMX,FMX) Adjusted Standard GRLWEAP	EOD	99	0.74	0.32	0.43
6		EOD-Avg	45	0.79	0.29	0.37
7		BOR	99	1.16	0.41	0.35
8		BOR-Avg	45	1.13	0.35	0.31
9	CAPWAP (Original)	BOR	99	0.92	0.20	0.22
10		BOR-Avg	45	0.94	0.15	0.16
11	Static Analysis	All	89	1.30	0.88	0.68
12		Avg	43	1.34	0.97	0.72

Because of the potential for overemphasizing the peculiarities of a particular site with more than one load test pile, Figure 6 summarizes the prediction results for sites rather than piles (see also lines 2, 4, 6, and 8 of Table 2). The somewhat narrower and higher peak curves (compared to those of Figure 5) and slightly lower C.O.V.'s suggest that sites with several piles had unusually complex properties.

To provide a frame of reference, CAPWAP restrike predictions (line 10 of Table 2) and static formula results (from the first correlation effort and listed in line 12 of Table 2) were plotted in Figure 7, together with wave equation BOR predictions (same as BOR of Figure 6). It is apparent that static analysis results are significantly less reliable than wave equation results, and the CAPWAP results are much better than wave equation results. The legend *original* CAPWAP refers to the fact that this analysis had been

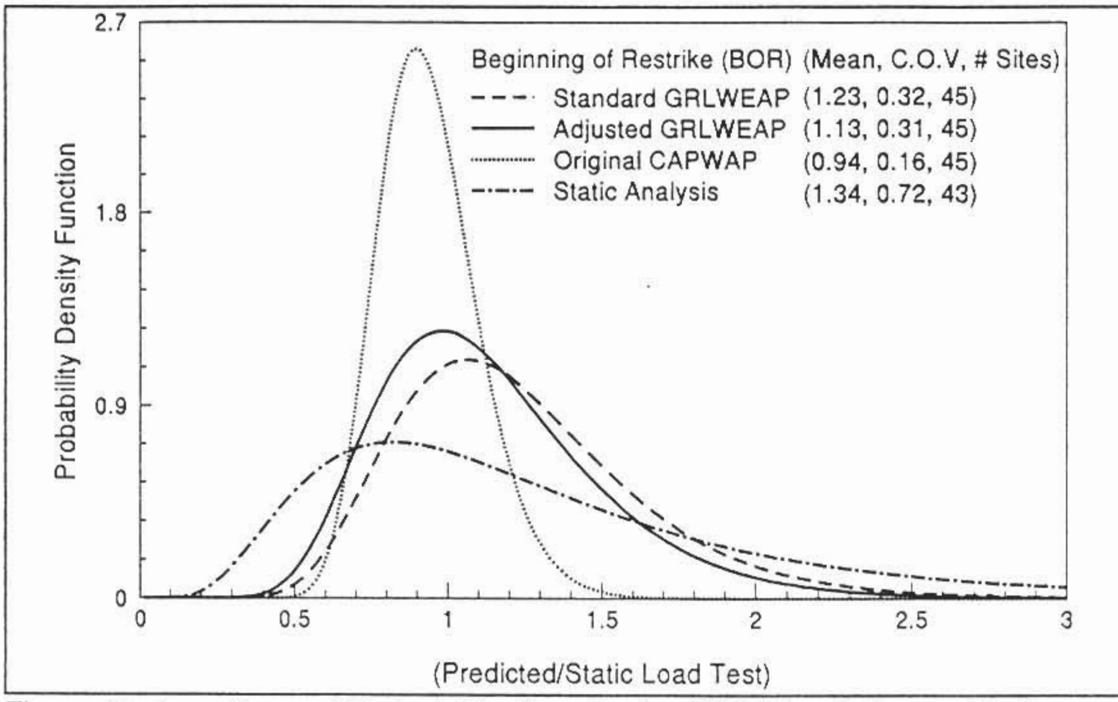

Figure 7: Log-Normal Probability Density for BOR Predictions with Several Methods (Site Averaged)

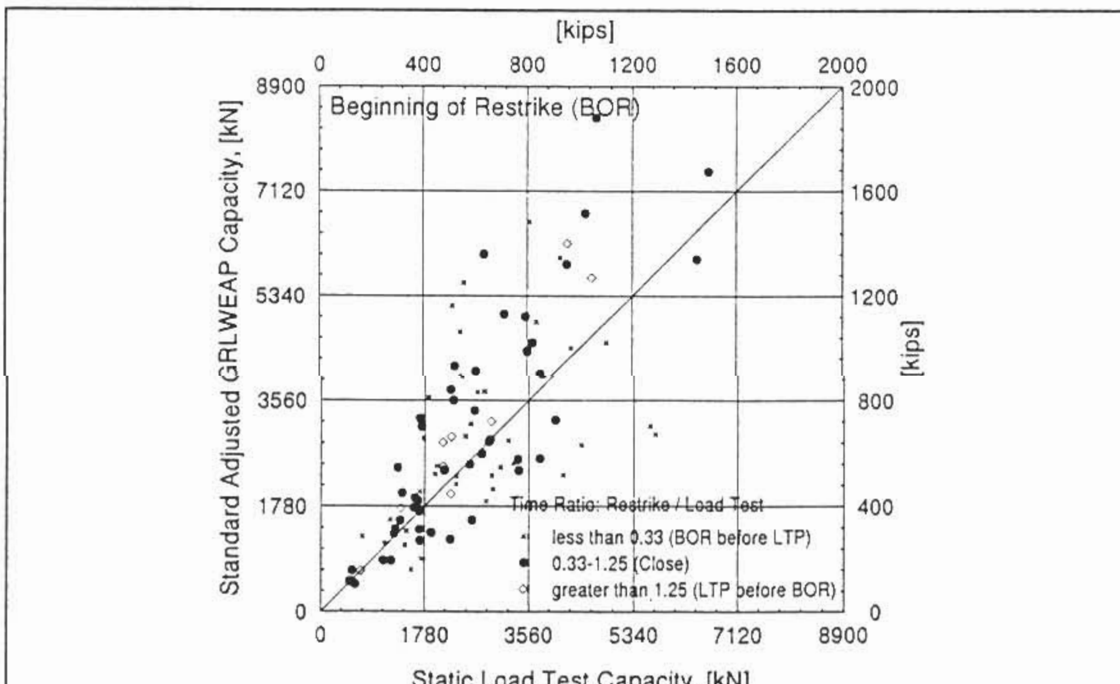

Figure 8: Standard Adjusted GRLWEAP BOR Capacity Correlations, and Categorized by Time Ratio

performed at the time of the actual test and not at the time of this correlation study. Further studies of the CAPWAP results are described in a companion paper (Likins et al., 1996).

Time Ratio

Pile capacity usually changes with time after installation due to soil setup or relaxation. Therefore a very important factor when comparing static and restrike capacities is the *time of testing* of both static and dynamic tests. In this study, the time difference was expressed as a ratio (T1/T2), where T1 is the number of days between end of driving (EOD) and restrike test, and T2 is the number of days between the end of driving (EOD) and static load test. Thus, a time ratio (T1/T2) less than one means the restrike test was performed before the static load test and a ratio greater than one means the restrike test was performed after the static load test.

Categorizing the capacities by three time ratios, the statistical evaluations for wave equation BOR capacities both with and without hammer/driving system performance adjustment are presented in Table 3. The wave equation BOR capacities with adjustment for three time ratios are also presented in Figure 8. Two log-normal functions are shown in Figure 9: time ratio "less than 0.33" and "greater than 0.33" (because there were only 10 cases from "greater than 1.25"). As already demonstrated for CAPWAP correlation by Likins et al. (1996), the capacity correlation is superior (lower C.O.V.) when the restrike test is performed close to or shortly after the static load test (time ratio greater than 0.33).

Table 3: Statistical Summary of BOR Capacity and Time Ratios

Prediction Method	Time Ratio[1]	Number of Piles	Mean	Standard Deviation	Coefficient of Variation (C.O.V.)
Standard GRLWEAP	less than 0.33	40	1.19	0.50	0.42
	greater than 0.33	59	1.25	0.38	0.30
(EMX,FMX) Adjusted Standard GRLWEAP	less than 0.33	40	1.14	0.49	0.43
	greater than 0.33	59	1.18	0.35	0.30

Note: 1 - "Time Ratio" is ratio of "time after driving until restrike" divided by "time after driving until static test"
Time ratio greater than 1.0 implies restrike after load test
Time ratio less than 1.0 implies restrike before load test.

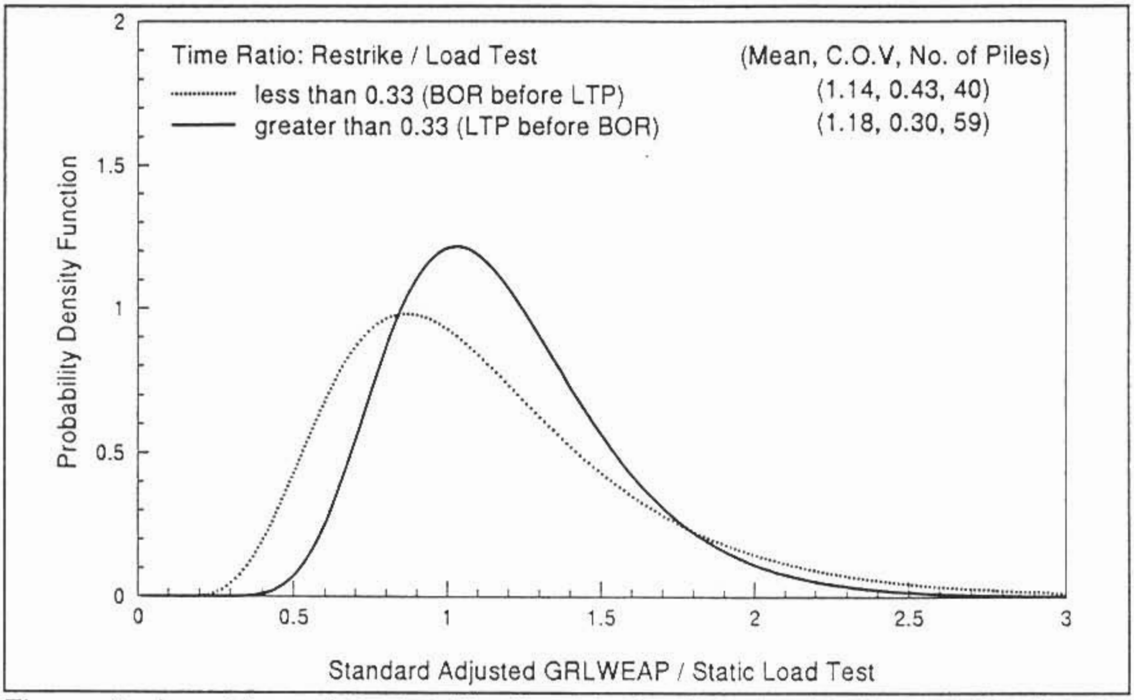

Figure 9: Log-Normal Probability Density for Standard Adjusted GRLWEAP BOR Predictions for Two Time Ratios

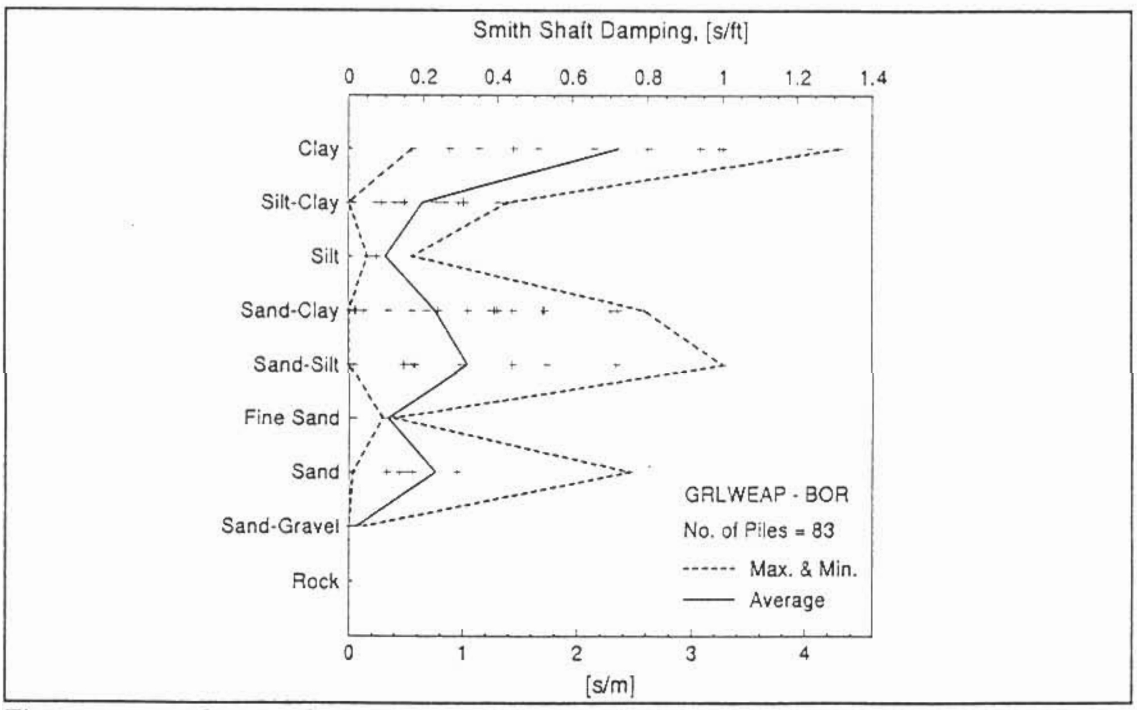

Figure 10: Smith Shaft Damping Factors Back-Calculated for Piles with More Than 30% Shaft Resistance

Dynamic Soil Parameters

The procedure for back-calculating the Smith shaft and toe damping factors (J_s and J_t) was based on the percentage of shaft or toe resistance calculated by static analysis, the static load test capacity, and the BOR observed blow counts (item 6 of Table 1). For pile shaft resistance more than 70%, J_s only was changed to meet the correlation, and for pile toe resistance more than 70%, J_t only was changed. For intermediate 30 to 70% pile shaft resistance, both J_s and J_t were changed by the same percentage. The shaft quake was 2.5 mm (0.1 inches) and the toe quake was set to pile diameter (D) divided by 120, unless CAPWAP's toe quake exceeded D/120 by more than a factor of 2.0, then the CAPWAP toe quake was input.

This procedure attempted to overcome the problem of non-uniqueness: a higher shaft damping factor could be compensated for by a lower toe damping factor or increases in quakes could be compensated for by decreases in damping factor. Results are presented in Figures 10 and 11 for shaft and toe damping factors versus the corresponding *dominant soil type*, respectively. For the shaft damping factors, the dominant soil is based on the soil layer which provide most of the pile shaft resistance. For the toe, the SPT N-value of the soil near the pile toe is also presented.

Back-calculated results vary strongly within the same soil types and, surprisingly, even the averages show very little correlation with soil type. The average damping factors are also high when compared with the GRLWEAP manual recommendations. The variability is in part attributed to the uncertainty of observed BOR blow count which is hard to measure accurately for one restrike hammer blow. In addition, pile set varies during consecutive restrike blows causing difficulty in blow count determination. The higher damping factors in comparison to the manual recommendations may perhaps be explained by the energy level during restrike and possibly by a change of shaft damping factor with setup time (Svinkin and Teferra, 1994). Furthermore, with BOR and EOD energy levels similar and with a high soil strength, BOR pile velocities will be lower than at EOD. A reduced pile velocity may require a higher damping factor (Coyle and Gibson, 1970), even though this effect could not be confirmed by Rausche et al. (1996).

The surprisingly large average toe damping value of rock, nearly 0.66 s/m (0.2 s/ft), are from piles driven into soft weathered rock or shale where relaxation often occurs. Cases of piles driven into hard rock generally yield excessive blow counts and/or non-failing static load tests and therefore are absent from the data base. In addition, cases summarized in this study pertain to restrike situations with sometimes very low pile toe velocities (near refusal); this situation causes small capacity adjustments to produce rather large toe damping factor variations.

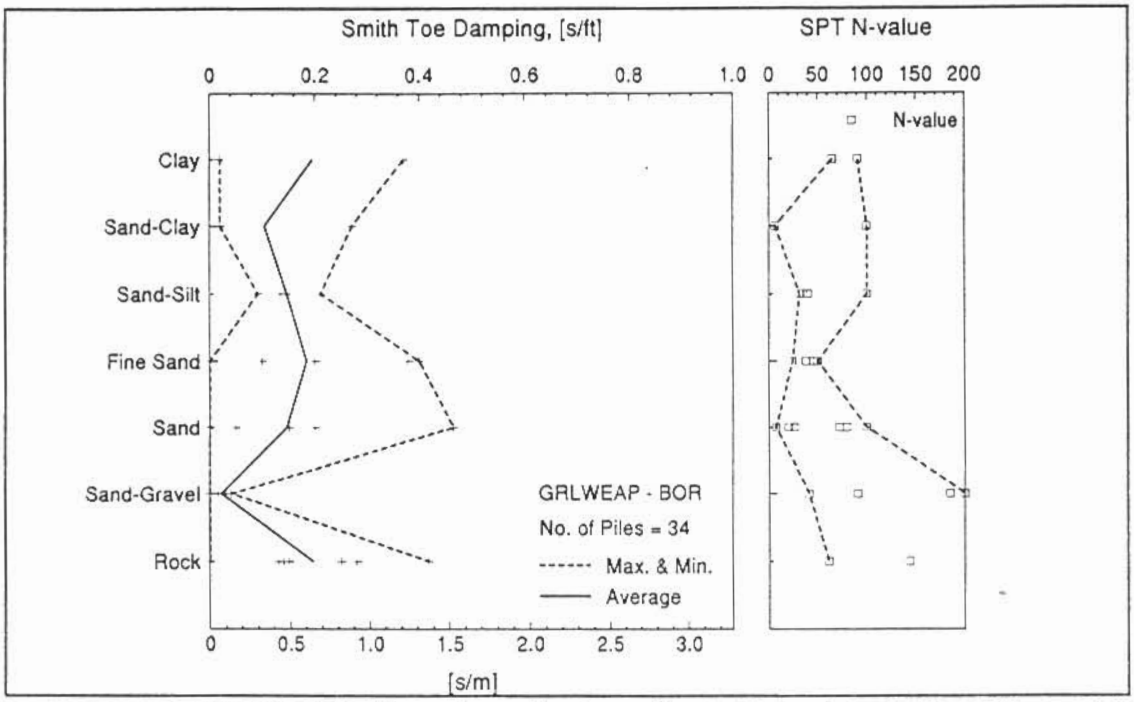

Figure 11: Smith Toe Damping Factors Back-Calculated For Piles with Less Than 70% Shaft Resistance

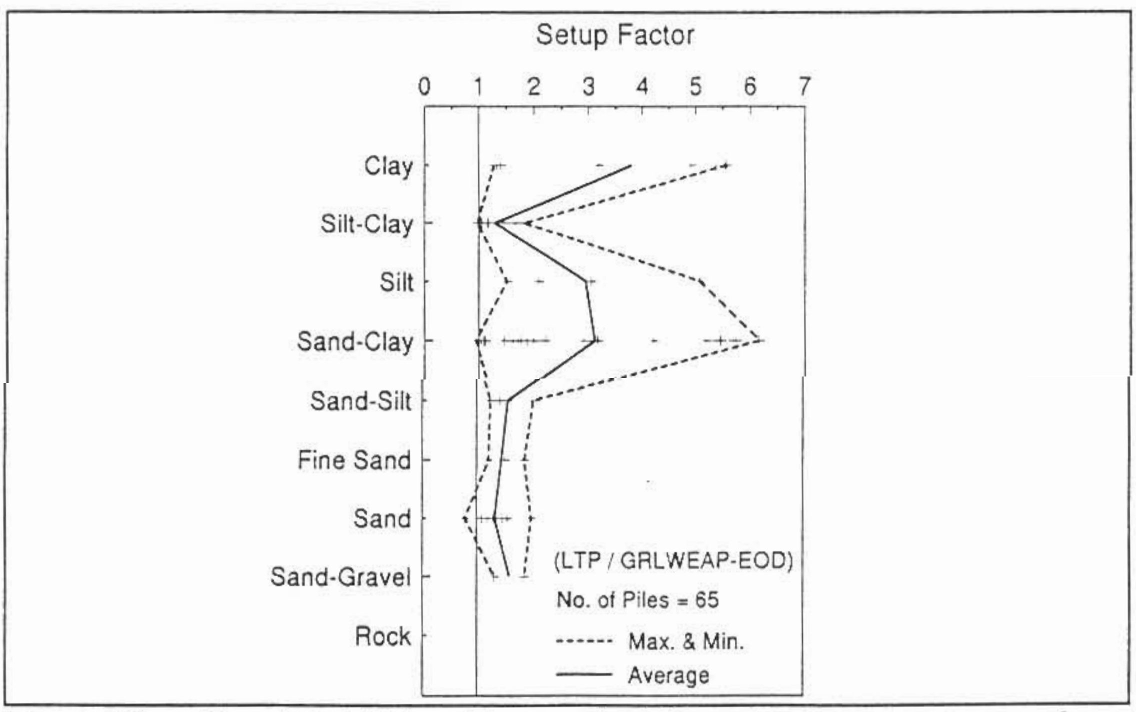

Figure 12: Correlated Setup Factors for Piles with More Than 50% Shaft Resistance

No differentiation has been made between pile types (*e.g.*, displacement and non-displacement), time of testing relative to the load test, geology, and soil conditions such as soft, hard, saturated, non-saturated, normally or over-consolidated materials among other important conditions. For example, it is possible that the low shaft damping values in clay occur primarily in hard clays. At this time, the database is not sufficiently large to allow for a statistically meaningful evaluation of such effects.

Apparent Setup Factors

The long term (static load test) pile capacity can be calculated from the product of EOD capacity and setup factor. To determine the setup factor from load test piles, it is necessary to determine the EOD capacity. Three different GRLWEAP EOD capacities were calculated: the ***standard capacity*** with and without hammer/driving system performance adjustment (items 3 and 5 of Table 1), and the ***correlated capacity*** (item 7 of Table 1). Three different apparent (*i.e.*, not based on an exact EOD capacity) setup factors: the ***standard setup factor,*** the ***adjusted setup factor***, and the ***correlated setup factor*** were calculated from the static load test capacity divided by the associated EOD capacity. The standard setup factor lends itself to a generally applicable method for situations without static or dynamic test.

Figure 12 shows the correlated setup factors versus the dominant shaft soil type, calculated from piles with more than 50% shaft resistance. Obviously, the setup factors for clay, silt, and sand-clay are highly variable.

Figure 13 shows the standard setup factor (on the left) and the adjusted setup factor (on the right) both also plotted versus the dominant soil type along the shaft. These setup factors have been averaged for individual sites with several piles. Interestingly, clay setup factors appear to be much less variable (and lower) than those shown in Figure 12. Sand-clay and sand-silt mixtures still indicate a high variability. Several points from the standard setup factor fell below the unity line which means that relaxation was indicated, (assuming the EOD analysis was correct). With the hammer/ driving system performance adjustments, the apparent relaxation was reduced (fewer point fell below the unity line).

For a more accurate estimate of the EOD capacity, CAPWAP EOD predictions were used with the static load test capacities to calculate a ***CAPWAP setup factor***. The average versus the dominant soil type along the shaft is presented in Figure 14 together with the average adjusted setup factor from Figure 13. These setup factors generally show good agreement except for clay. It should be pointed out that the high CAPWAP setup factor for clay was highly biased, based on five piles on one site and, therefore, not statistically representative.

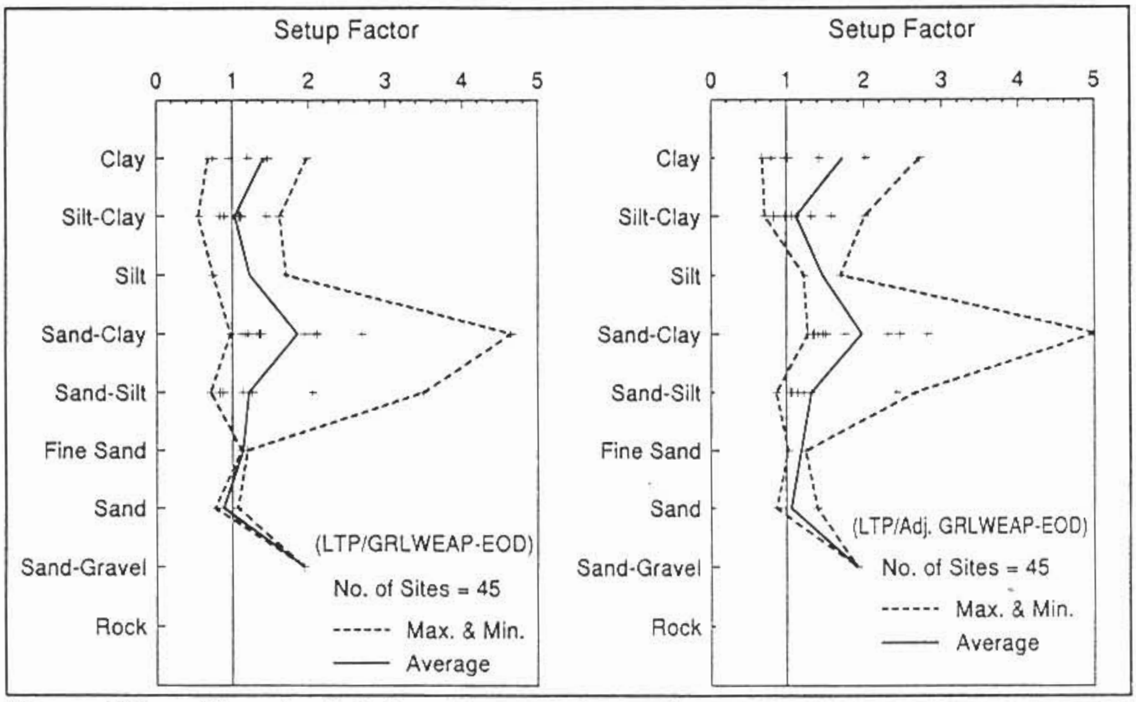

Figure 13: Standard Setup Factors from Standard GRLWEAP EOD With and Without Adjusted Hammer/Driving System Performance

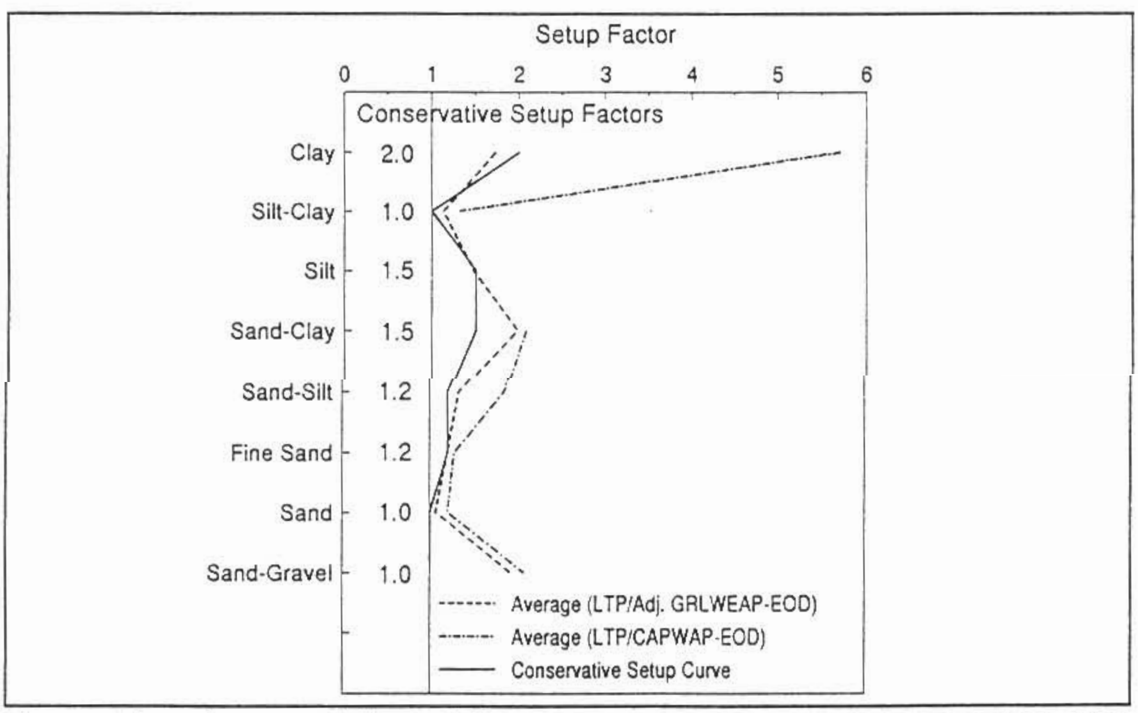

Figure 14: Average Adjusted Setup Factors, CAPWAP Setup Factors, and Conservative Setup Factors

Based on the setup curves in Figure 14, *conservative setup factors* were calculated. These values are both graphically and numerically depicted in Figure 14. To complete the study, conservative setup factors were applied to standard GRLWEAP EOD capacities with adjusted hammer/driving system performance and compared with the static load test capacities using capacity ratios. Results are presented in the form of log-normal functions in Figure 15. Obviously, on average, the standard GRLWEAP EOD capacities multiplied by the setup factors better agree with the static load test capacities than the unfactored EOD predictions. However, the variability of these predictions is greater than that of the BOR results.

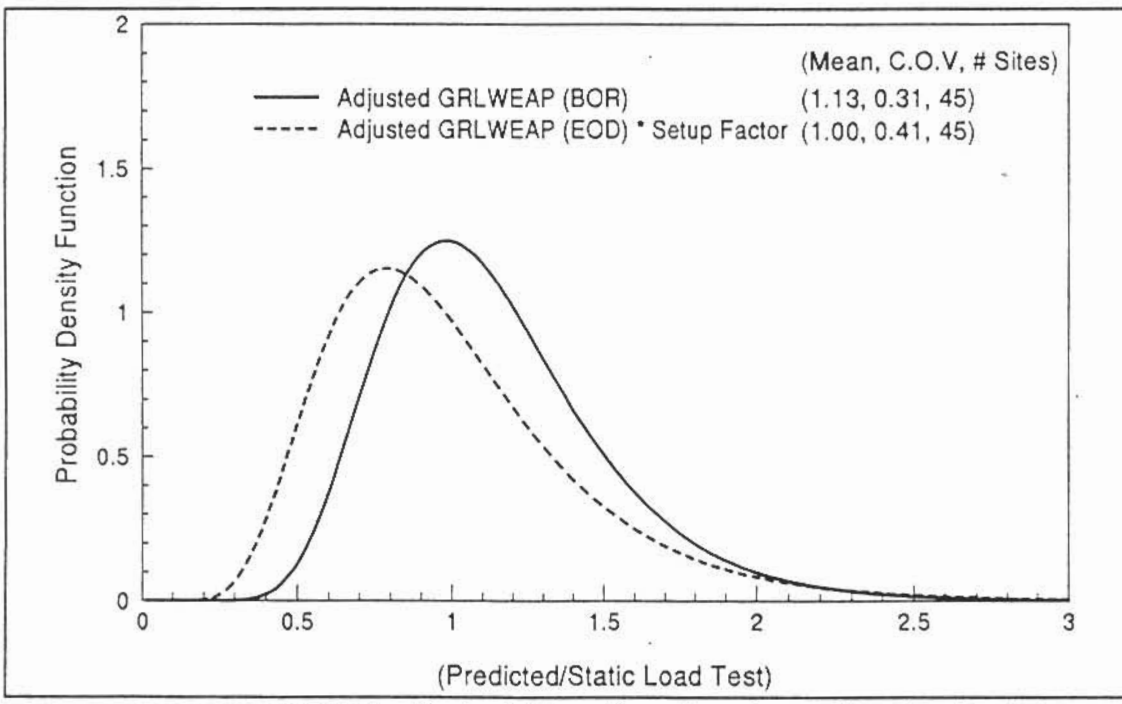

Figure 15: Log-Normal Probability Density for Standard Adjusted GRLWEAP BOR Predictions, and Standard Adjusted GRLWEAP EOD Predictions Factored with Conservative Setup Factors

Conclusions

Various correlations of wave equation predictions with static load test results have been presented. The results showed an improve capacity predictions when the dynamic testing results from PDA were used to adjust the hammer/driving system performance. The tendency of the EOD GRLWEAP to underpredict, and the BOR GRLWEAP to overpredict the load test capacities was demonstrated. Comparing different capacity prediction methods, wave equation analysis showed better results than the static analysis, and CAPWAP results were the best of the methods compared. The BOR GRLWEAP capacities also demonstrated that for a meaningful capacity correlation, the restrike test should be performed close to or shortly after the static load test.

Back-calculation of dynamic soil parameters (such as setup of damping factor and/or quake) generally indicated great scatter. Several setup factors were calculated using different GRLWEAP EOD capacities. Based on the setup factors calculated from the static load test capacities and the EOD GRLWEAP with hammer/driving system performance adjustment capacities, and the static load test and EOD CAPWAP capacities, conservative setup factors for various soil types were established.

Acknowledgement

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References

Briaud, J. L. and Tucker, L. M., "Measured and Predicted Response of 98 Piles," ASCE, Journal of Geotechnical Engineering, Vol. 114, No.9, 1988.

Coyle, H. M. and Gibson, G. C., "Empirical Damping Constants for Sand and Clay," ASCE Journal of the Soil Mechanics and Foundations Division, Paper No. 7296, SM3, 1970.

GRL and Associates, Inc., "GRLWEAP Manual," 4535 Emery Industrial Parkway, Cleveland, Ohio 44128, USA, 1995.

Hannigan, P. J., Goble, G. G., Thendean, G., Likins, G. E., and Rausche, F., "Design and Construction of Driven Pile Foundations," Working Draft, U.S. Department of Transportation, FHWA Contract No. DTFH61-93-C-00115., 1996.

Likins, G. E., Rausche, F., Thendean, G., and Svinkin M., "CAPWAP Correlation Studies," Fifth International Conference on the Application of Stress-Wave Theory to Piles, Orlando, FL, 1996.

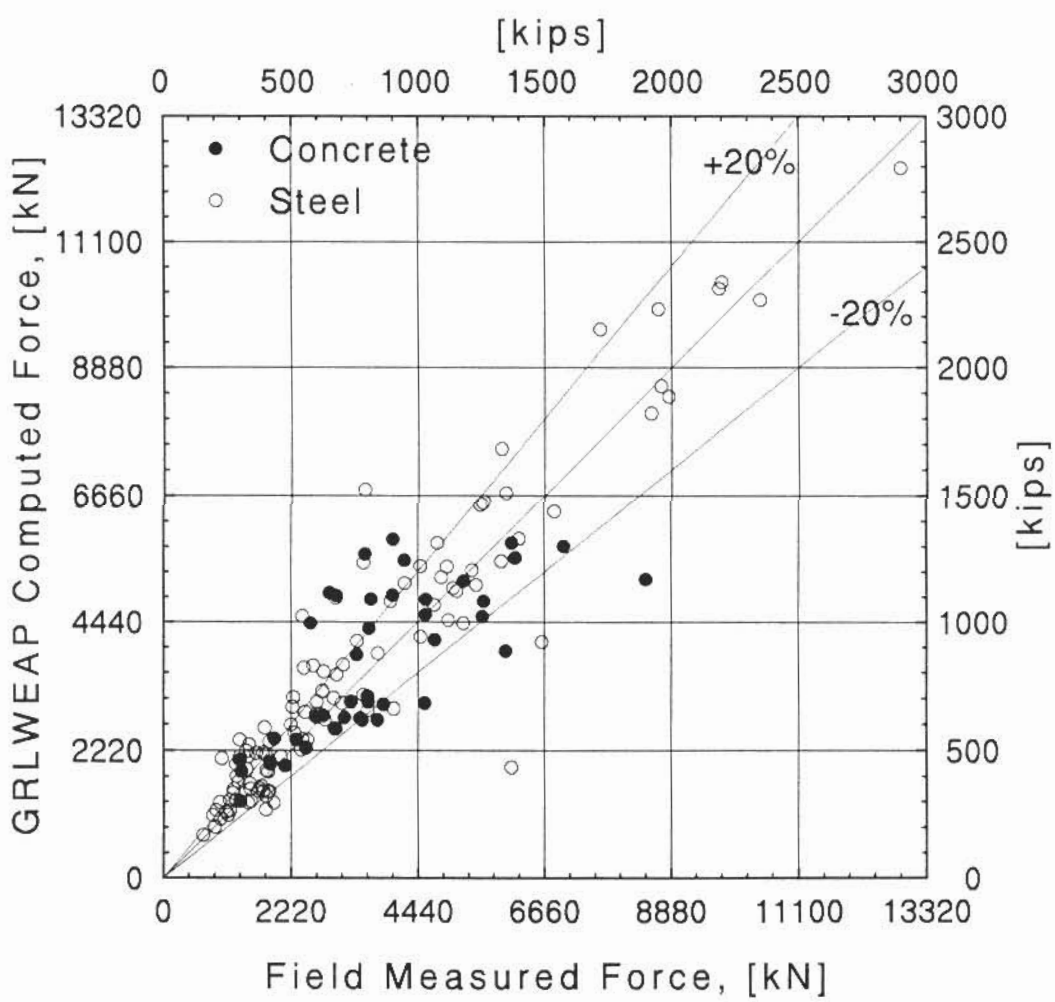
Rausche, F., Thendean, G., Abou-matar, H., Likins, G. E., and Goble, G. G., "Determination of Pile Driveability and Capacity from Penetration Tests," Final Report, U.S. Department of Transportation, FHWA Contract No. DTFH61-91-C-00047, 1996.

Svinkin, M. and Teferra, W., "Some Aspects of Determination of Pile Capacity by the Wave Equation," ASCE Structures Congress XII, Atlanta, GA, 1994.

Correlation of GRLWEAP Computed *vs* Field Measured Forces and Energies

Force Correlation

The following figure presents the GRLWEAP computed forces versus the field measured forces. There are 103 piles (42 concrete and 61 steel piles) for the correlation. These data were obtained from the GRL Driven Pile Database. The forces were measured in the field with the Pile Driving Analyzer (PDA). In the figure, a different type of marker was used to identify the concrete and steel piles. The purpose is to demonstrate whether the pile cushion used during concrete pile driving has any significant effects on the GRLWEAP force prediction. Without any statistical analysis, it does appear that GRLWEAP predicts equally well for both steel and concrete piles. Based on a simple statistical analysis of the force ratio which is defined as the GRLWEAP computed force divided by the field measured force, the mean force ratio was 1.05 and 1.13 for concrete and steel piles, respectively. The corresponding Coefficients of Variation (C.O.V.) were 0.28 and 0.24, respectively. Also shown in the figure are the 1:1 ratio line and the ±20% spread lines.



Energy Correlation

The following figure presents the GRLWEAP computed transferred energies versus the field measured transferred energies using the same data as the above force correlation. The transferred energies were measured in the field with the Pile Driving Analyzer (PDA). Also in this figure, a different type of marker was used to identify the concrete and steel piles. The purpose is to demonstrate whether the pile cushion used during concrete pile driving has any significant effects on the GRLWEAP transferred energy prediction. Based on a simple statistical analysis of the transferred energy ratio which is defined as the GRLWEAP computed transferred energy divided by the field measured transferred energy, the mean transferred energy ratio was 1.13 and 1.19 for concrete and steel piles, respectively. The corresponding Coefficients of Variation (C.O.V.) were 0.44 and 0.30, respectively. Also shown in the figure are the 1:1 ratio line and the ±20% spread lines. The correlation shows that the energy prediction has a higher variation (higher C.O.V.) for both concrete and steel piles due to the various hammer performance in the field. It should be noted that our database contains jobs of higher quality engineering. Therefore, the performance of the hammers in our database may be better than normal since hammer performance problems noted during the dynamic testing are likely to have been fixed.