CAPWAP CORRELATION STUDIES

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Abstract

The correlation results of CAPWAP and static load test are presented. The original, automatic, best match, and radiation damping CAPWAP results are compared with the static load test. The importance of using CAPWAP restrike result when comparing capacities is discussed. The guidelines for selecting shaft radiation damping parameters used in this correlation studies are also presented.

Introduction

Dynamic pile testing with a Pile Driving Analyzer is routinely required on many piling projects worldwide. The testing procedure is documented by many standard agencies such as the American Society for Testing and Materials (ASTM D 4945). The CAse Pile Wave Analysis Program, or "CAPWAP", is a rigorous signal matching computer program which uses dynamic pile testing data to compute pile static bearing capacity and its distribution along the shaft and at the toe, soil damping and stiffness, and a simulated pile static load-set graph.

CAPWAP combines a wave equation type soil model and a continuous pile model with the field recorded dynamic pile testing data, and iteratively determines the unknown soil parameters by signal matching. While wave equation analysis (WEAP) models the hammer and must assume its level of performance, CAPWAP replaces the hammer model with the measurements as a boundary condition. Furthermore, while wave equation

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analysis requires assumptions regarding soil parameters, CAPWAP computes these parameters in the signal matching process. Further description of the CAPWAP method is presented in the program manual (GRL 1995).

The objectives of the CAPWAP correlation study presented here include: first, to investigate the statistical reliability of CAPWAP capacity predictions; second, to critically re-evaluate CAPWAP procedures and results for future improvement; third, to study CAPWAP's soil radiation damping model and to provide guidelines for its proper use, and fourth, to investigate relationships between the dynamic parameters (damping and quake) with respect to soil types. A total of 82 piles selected from the GRL database were used in the correlation studies.

Description of Database

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

- Static load test was carried to "failure" as defined by the Davisson's failure criterion. An exception is granted if failure was not reached but could be extrapolated within at most 110% of the maximum applied load. Pile description and length, 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 was performed after a meaningful waiting time following pile installation (a comparable time to static load test time). The force and velocity records from the beginning of restrike (BOR) are available, and preferably also for end of driving (EOD). For a meaningful comparison with static load test, CAPWAP results of the dynamic restrike test were used in the correlation studies. Using dynamic restrike test data for pile capacity evaluation is a standard procedure; due to a disturbed soil, pile capacity at the end of driving often does not reflect the soil condition encountered during a static load test.

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

- Pile driving record (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 the static load test had been accurately performed. It is recognized, however, that force or displacement measurements of any static load test may contain errors. The "*static load test capacity*", evaluated by Davisson's criterion which is among the more conservative criteria, allows more static tests to reach "failure" rather than criteria with more liberal deflection limits. Thus, it permits more data to qualify for admission into the database. Of course, other failure criteria would result in a range of failure loads for the same test.

In many soils, pile capacity continually changes with time due to setup or relaxation, and thus many specifications require a wait period after installation before the static load test is performed. Since static and dynamic testing usually occurs after different waiting periods, further differences in capacity should be expected, and 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.

Correlation Procedure

For all 82 cases investigated, several CAPWAP results are presented. The *original* CAPWAP results were performed by different engineers on a variety of computers over a period of many years as the data was acquired and thus came from different versions of CAPWAP. Later in this paper, a comparison between the original CAPWAP results and the reanalyzed CAPWAP results from the 1.993.1 version will be presented.

For consistency of comparison, dynamic data were also reanalyzed with CAPWAP, Version 1.993-1. This version of CAPWAP program has a built in automatic search routine based on over 25 years experience to provide a solution with no user interaction. The "*automatic*" results thus obtained were independent of any engineer's interaction or skills. A responsible engineer will always check and modify the CAPWAP results and almost always include additional analysis. The automatic result, however, is presented to show that the completely automated solution gives reasonable results.

After CAPWAP automatic matching was complete, the soil model was manually iteratively improved to obtain a "*best match*" (with lower error differences) with a standard soil model. This standard practice involves, as a minimum, the review of resistance distribution and other dynamic parameters. After the best match was obtained, the data was analyzed with the "*radiation damping*" soil model. In summary, the CAPWAP reanalyzed results include the "*automatic*", "*best match*", and "*radiation damping*" solution results.

Discussion of Correlation Results

CAPWAP capacities calculated by automatic, best match, and radiation damping match were compared with static load test capacities in Figures 1(a), 2(a) and 3(a), respectively. Comparisons were made after finding the ratio of capacities by CAPWAP and static test for each data set, and the statistical mean, coefficient of variation, number of piles and the log-normal probability density function, similar to that used by Briaud and Tucker (1988), are presented in Figures 1(b), 2(b) and 3(b). Table 1 summarizes the mean and coefficient of variation for each of the three methods. Curves with lower coefficients of variation (C.O.V.) are generally higher and narrower, and reflect methods where good capacity correlation is more predictable. The curve's peak (or better the areas under the curve to the left and right of a perfect prediction with ratio of 1.0) indicates whether the method would tend to overpredict or underpredict. Overpredictions have greater prominence in the half-space to the right of the peak. Underpredictions are squeezed between 0 and the peak. While it is reasonable to treat overpredictions with greater care, this feature helps explain why underpredicting methods appear to have a somewhat greater precision than overpredicting ones.

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 dynamic capacities, is the *time of testing* of both static load test and dynamic restrike test (Goble et al. 1980; Likins et al. 1988; Skov and Denver 1988; Svinkin et al. 1994). 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 dynamic 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 dynamic restrike test was performed before the static load test and a ratio of 3.0, for example, means the dynamic restrike test was performed three times later than the static load test relative to EOD. Since many studies show setup increases linearly with the log of time, the time difference was considered acceptably small with a time ratio (T1/T2) between 0.33 and 1.25. Most of the investigated data had time ratios between 0.67-1.25. Only 11 cases had time ratios greater than 1.25, where the dynamic restrike test was performed significantly later than the static test.

Figures 1 to 3 demonstrate the importance of *time of testing* as in every case the coefficient of variation of the CAPWAP to static load test ratio is smallest when the time ratio is "close" (0.33 to 1.25). The figures also clearly show the largest variability of capacity prediction occurs when the static load test is performed significantly later than the dynamic restrike test such that the time ratio is less than 0.33. The study contained 30 such cases. In general practice, often the dynamic restrike test is performed within the first two days following pile installation as a matter of compromise or convenience to minimize costs and speed determination of driving criteria to facilitate production. However, the static load test often is made a week or more after the installation due to code requirements. For clean sands, the capacity is generally thought to not change significantly after driving. However, in the more usual case of piles installed into layered soils or in soils with fine grain content, additional setup occurs after the dynamic restrike test and before the static load test and therefore the early restrike capacity underpredicts the static load test capacity. Thus the capacity ratio is often less than one for time ratios less than 0.33.

It is apparent that capacity predictions from a dynamic test correlated better with static tests if the restrike test was performed at a time after installation that is comparable to the static load test. Recent trends in practice recognize this and many dynamic testing specifications now require longer wait times after pile installation before the restrike test. For a dynamic test with many blows performed shortly before the static test on a pile with sensitive soils, the capacity may decrease (temporarily) blow by blow, the soil strength will not have sufficient time to recover, and the a static test will have reduced failure load. Thus, restrike tests with many blows shortly before a static load tests are discouraged. In some cases, the *restrike* turns into a *redrive*, advancing the pile a significant distance and possibly into a new bearing layer; in such cases, the dynamic restrike test can no longer be directly compared with the static load test. Several data sets were excluded on this basis. For all these reasons it was concluded that the dynamic restrike test should ideally be performed as soon as possible ***after*** the static load test to obtain the best correlation between the two tests. Hopefully, though the static test does not affect the pile capacity either because of soil sensitivity (pile loses capacity during static test) or excessive static displacements (pile seats deeper into the bearing layer), or other reasons. As it is impossible to perform both tests simultaneously, some of the difference between the two results are attributed to this time factor difference.

Pile Type

Figures 4 through 6 distinguish pile types, material types, and shapes. Generally, the CAPWAP capacity predictions are equally good for all pile types.

Comparison Between Automatic, Best Match, Radiation Damping Results

For qualitative comparison of all cases with time ratios between 0.33 and 1.25, the log-normal probability distribution function for the three prediction methods is presented in Figure 7. The automatic and best match CAPWAP capacity prediction to static load test capacity have means of the ratio of slightly below unity and thus "conservative". The average radiation damping CAPWAP capacity prediction is slightly higher than the static load test capacity. However, the mean of the ratio is only 1.03; since in most cases the dynamic test followed the static load test, this might simply reflect additional setup. The radiation damping ratio results have a coefficient of variation of only nine percent meaning it is narrowly banded which can be observed visually. Statistically, with a mean capacity of 103 percent of the static value and a standard deviation of 9 percent, 95 percent of all predictions should be within two standard deviations of the mean, or in other words within 85 and 121 percent of the static load test value.

The comparisons of CAPWAP and static test results are based on Davisson's failure criterion evaluation which is generally conservative, relatively easily applied, and widely accepted. This assumes failure at a relatively small settlement of an equivalent end bearing pile. However, most piles investigated had significant shaft friction. Furthermore, the Davisson procedure uses the pile stiffness, which for concrete piles or concrete filled pipes, requires knowledge of the static elastic modulus of the concrete. Thus the Davisson evaluation procedure is not entirely without uncertainty. If the static test indicates abrupt plunging failure almost all load evaluation methods yield similar results. However, where the static test exhibits strain hardening, different evaluation methods indicate significantly differing failure loads. Such variability is not easily reflected in statistical comparison. If one visually inspects a static load test curve, a lowest possible failure load can be found. Similarly, the maximum applied load could be considered an upper bound capacity. In all cases, the lowest possible failure load for the static load test was below the CAPWAP result, while the maximum applied load was above the CAPWAP result. Admittedly, the determination of the proper static load capacity is difficult and allows for some difference of opinion. It must be concluded that the dispersion in probability density functions shown in Figure 7 is due to dispersion in both the dynamic and static test results and due to differences in waiting time between the two tests.

For comparison purposes, the CAPWAP radiation damping results for the time ratios between 0.33 and 1.25 are presented in Figure 8 together with the CAPWAP *original* results from the same piles. Note, the number of piles from the original is less than the radiation damping because some data sets do not have the original results. In Figure 9, the CAPWAP radiation damping results are compared with wave equation results and static analysis methods specified by the Federal Highway Administration (Hannigan et al., 1996) and clearly demonstrates the superiority of the CAPWAP analysis of the measurements over any other method which depends only upon assumptions (or empirical correlations) with theoretical calculations. The wave equation correlation results are further discussed by Thendean et al. (1996).

Dynamic Soil Parameters

Figures 10 to 13 present soil damping factors and quake values calculated by CAPWAP plotted against the *dominant soil type* along the shaft or at the pile toe. The dominant soil type at the pile shaft was determined based on the soil layer which provided most of the pile shaft resistance. The figures show the soil parameters determined from both best match CAPWAP and from the radiation damping CAPWAP models. For the toe soil parameters, the SPT N-value of the soil near the pile toe is also presented. For the dynamic soil parameters, no clear trend can be established. However, the average Smith damping constants slightly decrease for both skin and toe as the soil grain size increases. The average shaft quake is always about 0.1 inches. However, large toe quakes seem to occur in clay soils, and in silty, fine and coarse sands. Previous studies (Likins, 1983) have shown that large quakes can occur in any soil type if it is saturated. Not enough data exists to allow for conclusions on dynamic soil parameters for piles driven in predominately silt.

It should be noted that the results summarized in Figures 10 to 13 are from analyses of *restrike* data as it is customary for CAPWAP capacity predictions. It has been observed that the damping constants are generally higher for restrike than for the same pile in the same soil at the end of driving. Furthermore, frequently toe quakes are lower during restrike than during driving. Thus, the parameters presented here are not applicable for wave equation analysis predictions based on end of driving observations.

Guidelines for Using Radiation Damping

The CAPWAP correlation study presented here with the radiation damping model, utilized the following guidelines in the selection of the shaft radiation damping parameters mass, MS, and dashpot constant, SK. These parameters are described in the CAPWAP Manual (GRL, 1995). (Toe radiation damping was not used.)

Shaft support soil mass, m_s MS [kips] = NFac (.34 Ci) [ft] (1a)

or, MS [kN] = NFac (5.0 Ci) [m] (1b)

Shaft radiation damper, $SK = \{(A3)\ (NFac)(\Omega)\}/Z_1$ (2)

where A3 is the average of the three highest friction per unit length CAPWAP results for all soil segments (kips/ft or kN/m), NFac is the ratio of number of pile segments to soil segments in the embedded portion of the pile, Ω should be between 4 and 8, Ci is the circumference (in m or ft) and Z_1 is the impedance of the top pile segment (kip/ft/sec or kN/m/sec).

It is reasonable to assume that the mass of soil set in motion by the moving pile is related to the area of the pile soil interface and hence the circumference of the pile. The damping constant, SK, must be carefully selected. If the damper is too stiff then it will have little effect. Thus, selection of a high value will tend to produce solutions like those of the best match which did not use the radiation damping model. However, if the damping value is set too low, then the resulting solution may overpredict the capacity (the capacity generally increases as the SK value is reduced), providing a solution which may become non-conservative. The solution should further have a Smith shaft damping factor of less than 0.4 sec/ft (1.3 sec/m) and a shaft unloading quake not less than 0.3 times the loading quake.

It is suggested that for driving resistances of less than 24 blows/ft (80 blows/m), the radiation damping model should not be employed as it tends to increase the predicted capacity which may not be justified where high velocities and high penetrations cause a large viscous and Coulomb damping effects. The results obtained to date also suggest that radiation damping is more appropriate for the analysis of displacement piles than open profiles such as open ended pipes or H piles.

Conclusions

Statistical correlations of restrike CAPWAP results presented here clearly demonstrate this method's superiority over any other capacity prediction method. The importance of time after driving on the capacity determined is obvious and is the reason CAPWAP capacity predictions are best obtained from restrike tests conducted as long after pile installation as is reasonably allowable. The radiation damping model provides the best results but must be used within suggested guidelines.

Table 1: Summary CAPWAP Capacity Prediction at Different Time Ratio							
Time Ratio[1]	No. of Piles	Mean (CW/LTP)			Coefficient of Variation		
		Auto-matic	Best Match	Radiation Damping	Auto-matic	Best Match	Radiation Damping
less than 0.33	30	0.94	0.89	1.00	0.29	0.17	0.21
0.33 - 1.25	41	0.98	0.95	1.03	0.18	0.15	0.09
greater than 1.25	11	0.97	0.96	1.04	0.20	0.16	0.13

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.

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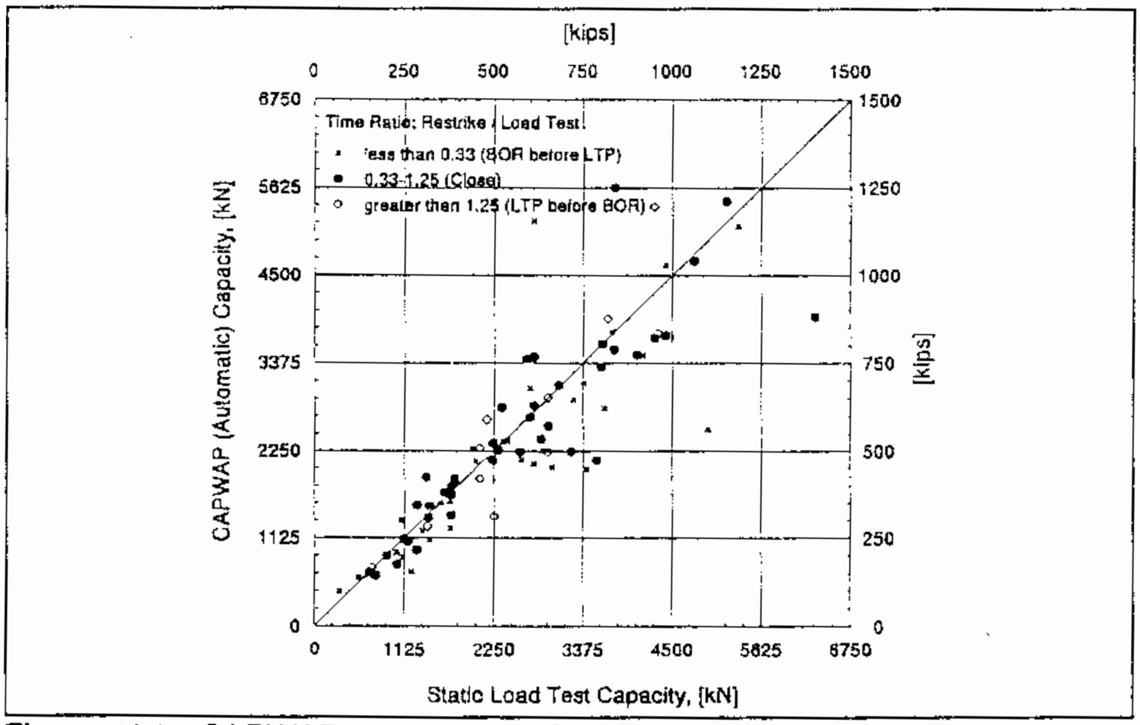

Figure 1(a): CAPWAP (Automatic) Capacity *vs* Static Load Test Capacity Showing Different Time Ratios

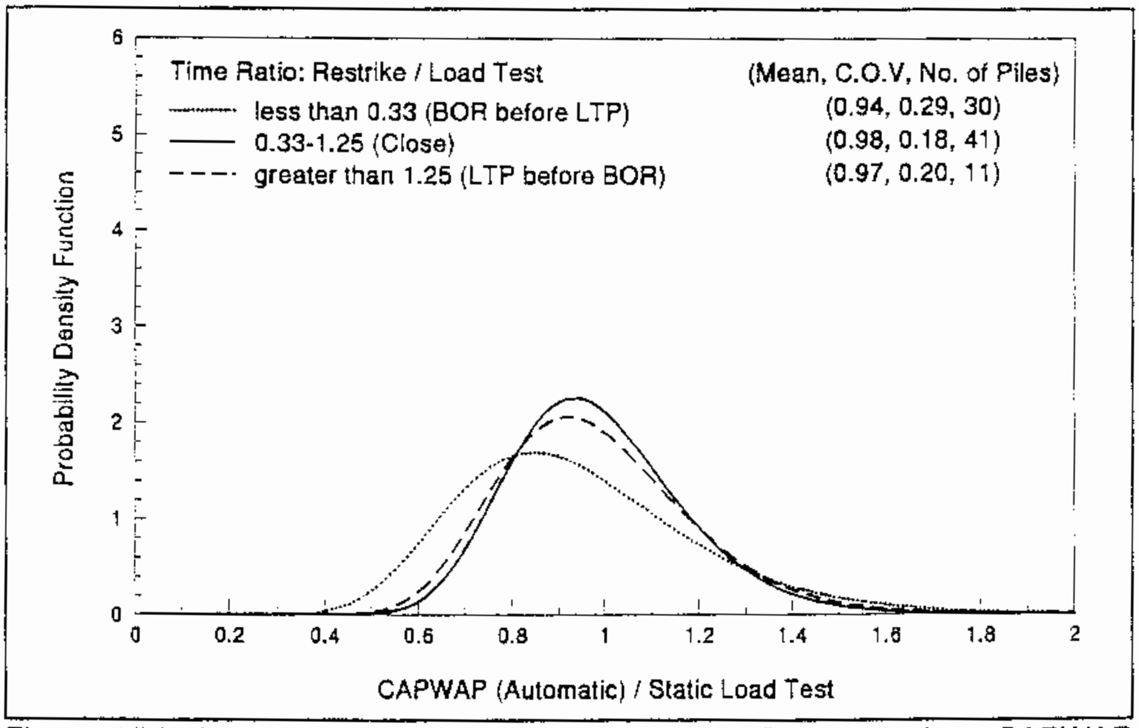

Figure 1(b): Log-Normal Probability Density Function for CAPWAP (Automatic) Capacity Prediction at Different Time Ratios

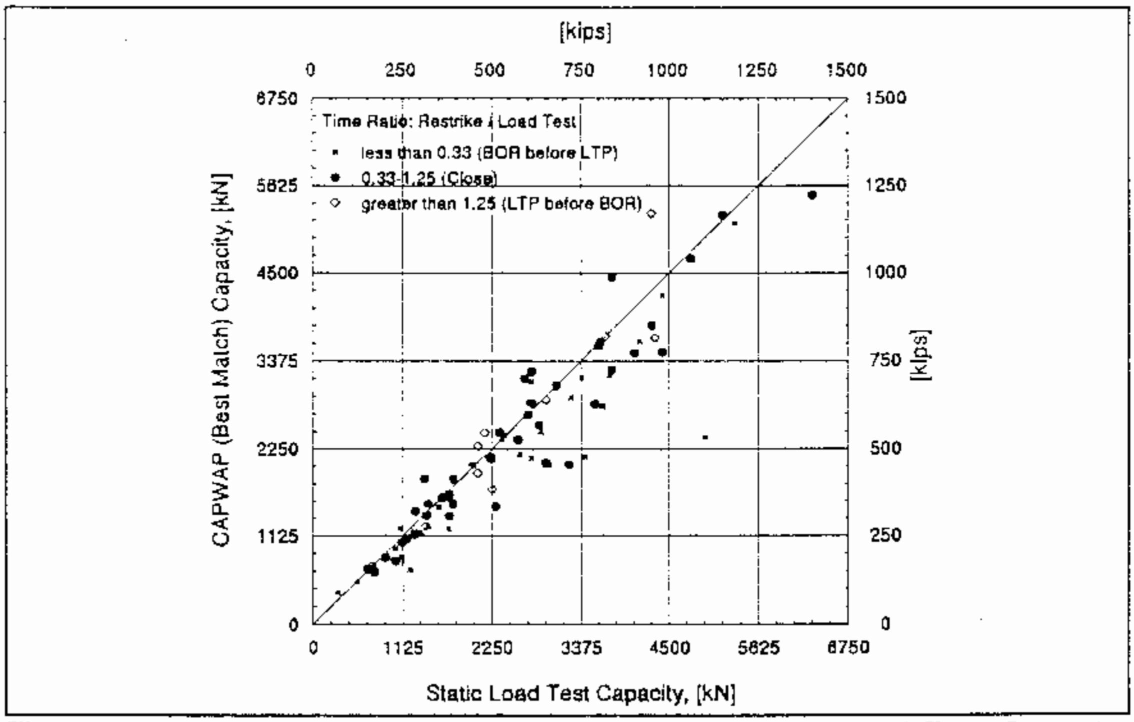

Figure 2(a): CAPWAP (Best Match) Capacity *vs* Static Load Test Capacity Showing Different Time Ratios

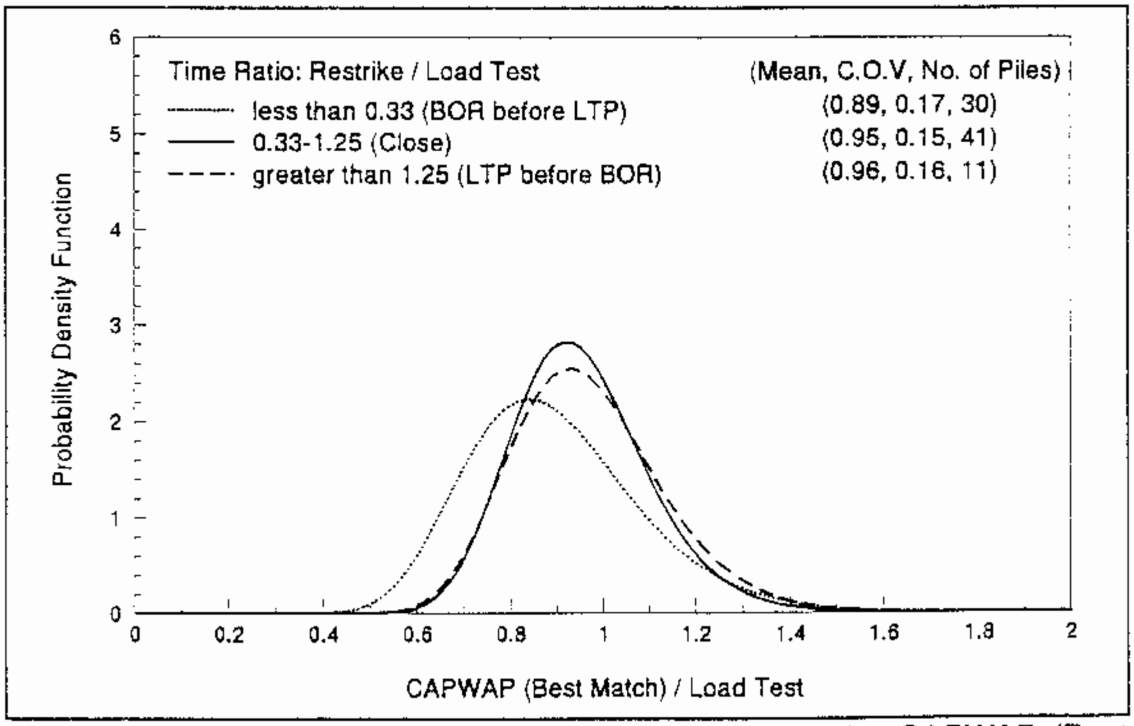

Figure 2(b): Log-Normal Probability Density Function for CAPWAP (Best Match) Capacity Prediction at Different Time Ratios

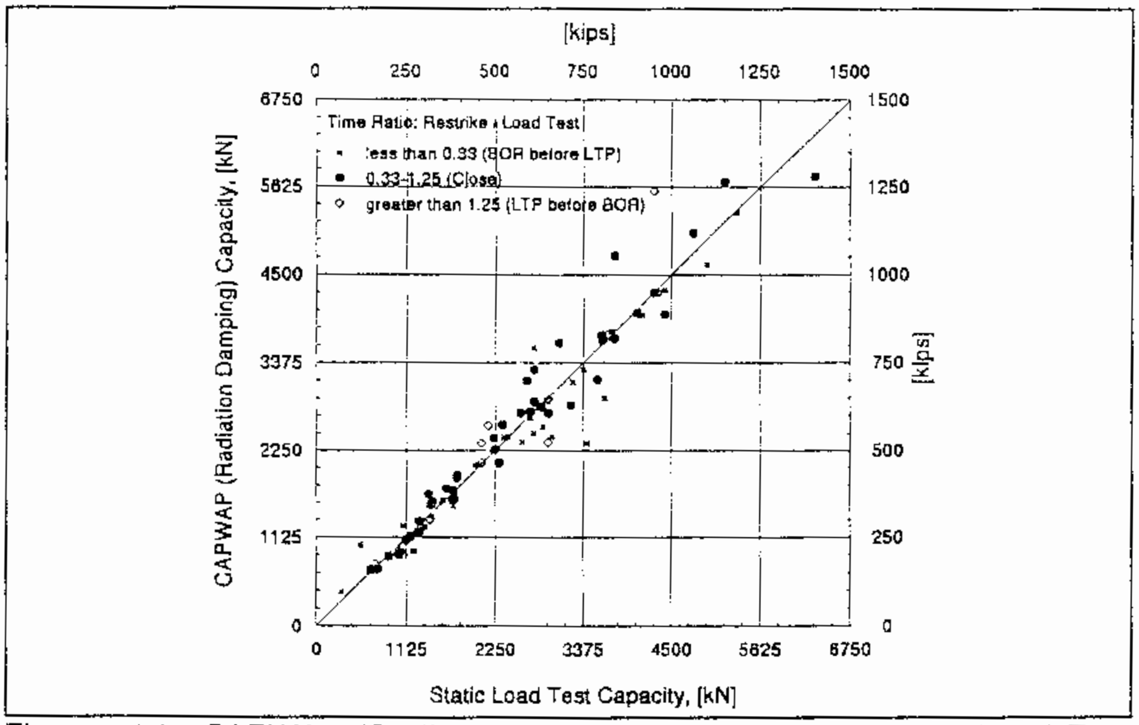

Figure 3(a): CAPWAP (Radiation Damping) Capacity *vs* Static Load Test Capacity Showing Different Time Ratios

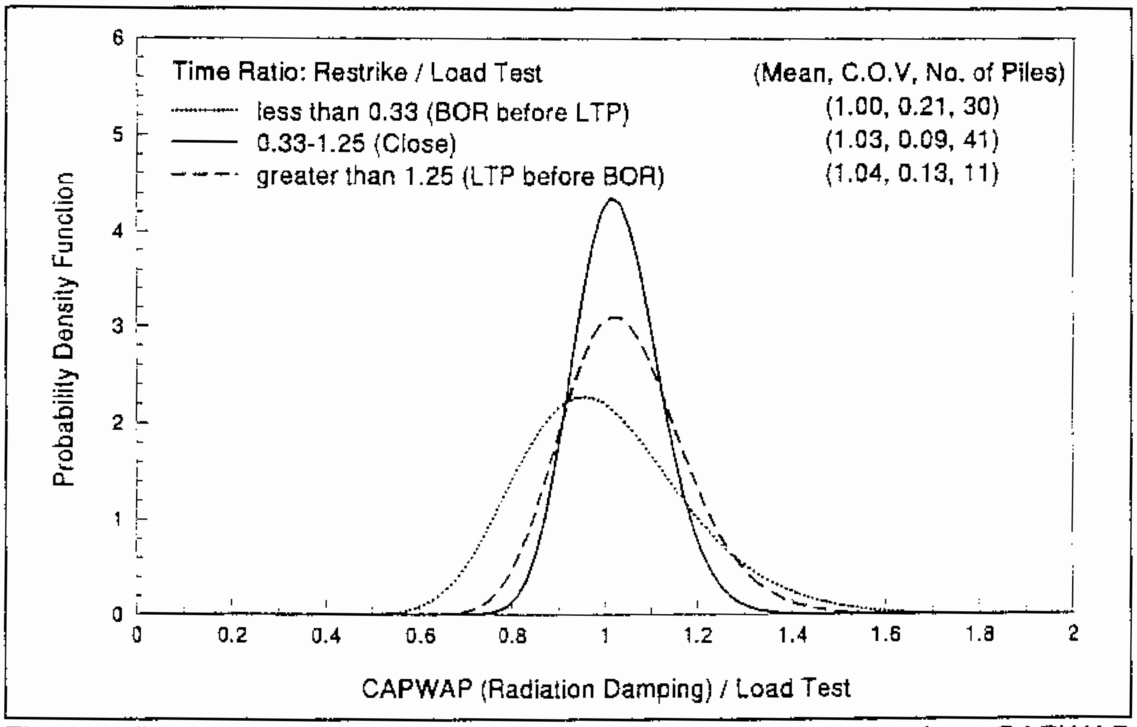

Figure 3(b): Log-Normal Probability Density Function for CAPWAP (Radiation Damping) Capacity Prediction at Different Time Ratios

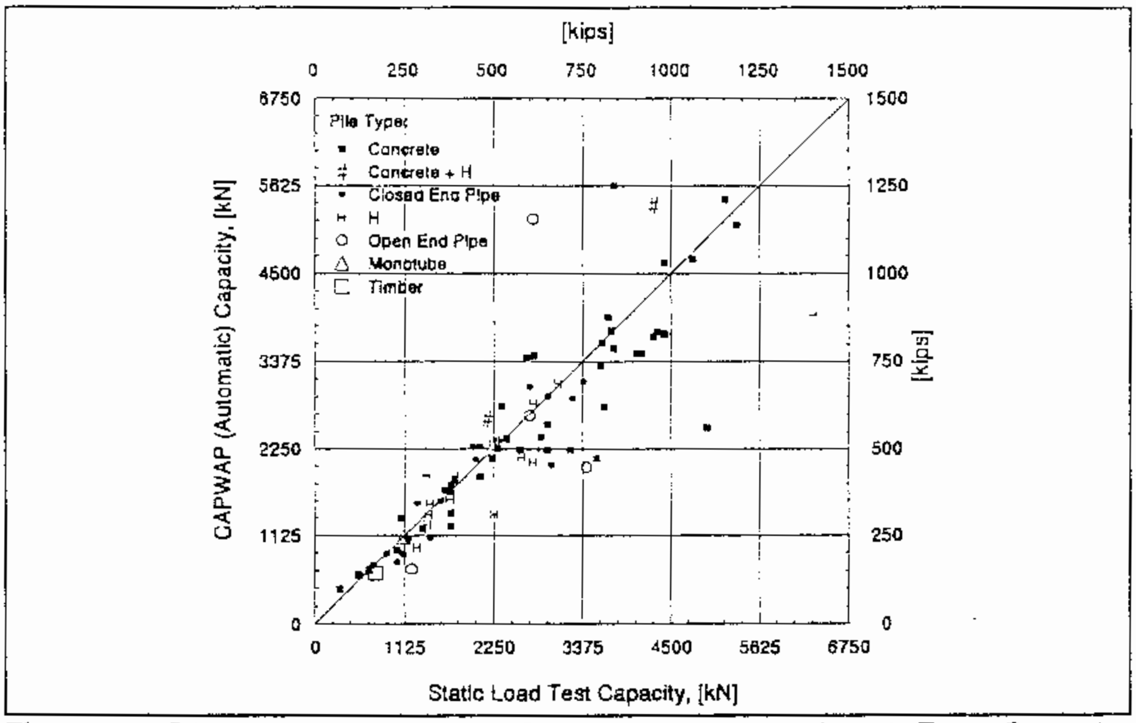

Figure 4: CAPWAP (Automatic) Capacity *vs* Static Load Test Capacity Showing Different Pile Types

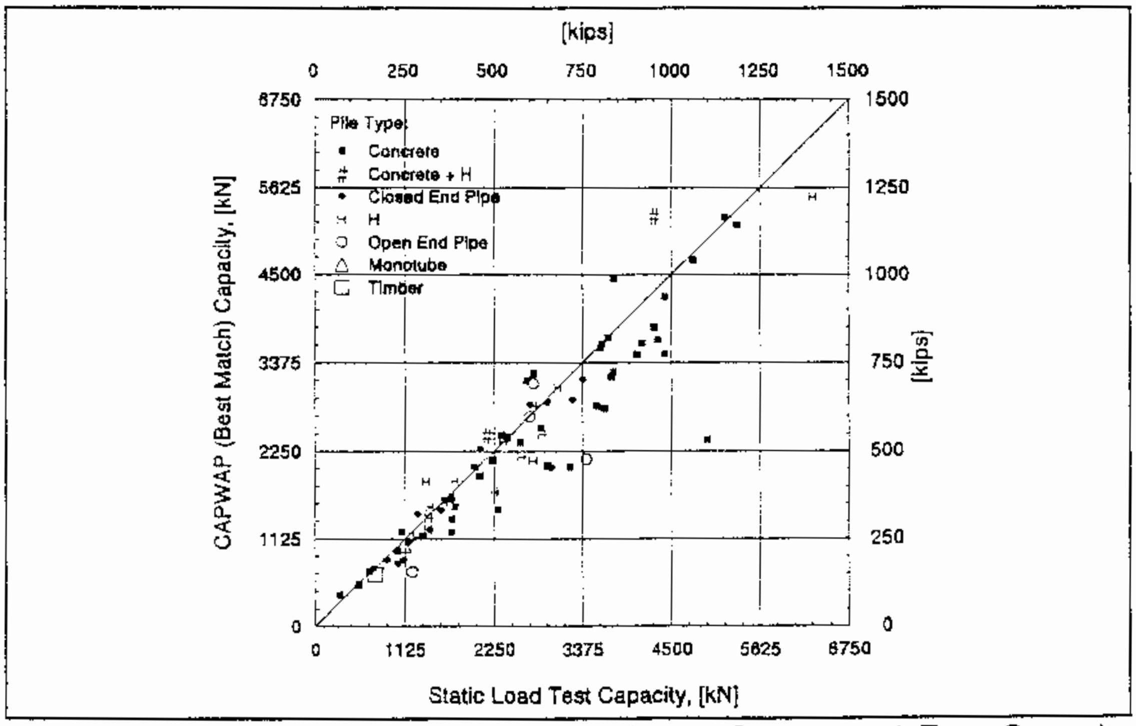

Figure 5: CAPWAP (Best Match) Capacity *vs* Static Load Test Capacity Showing Different Pile Types

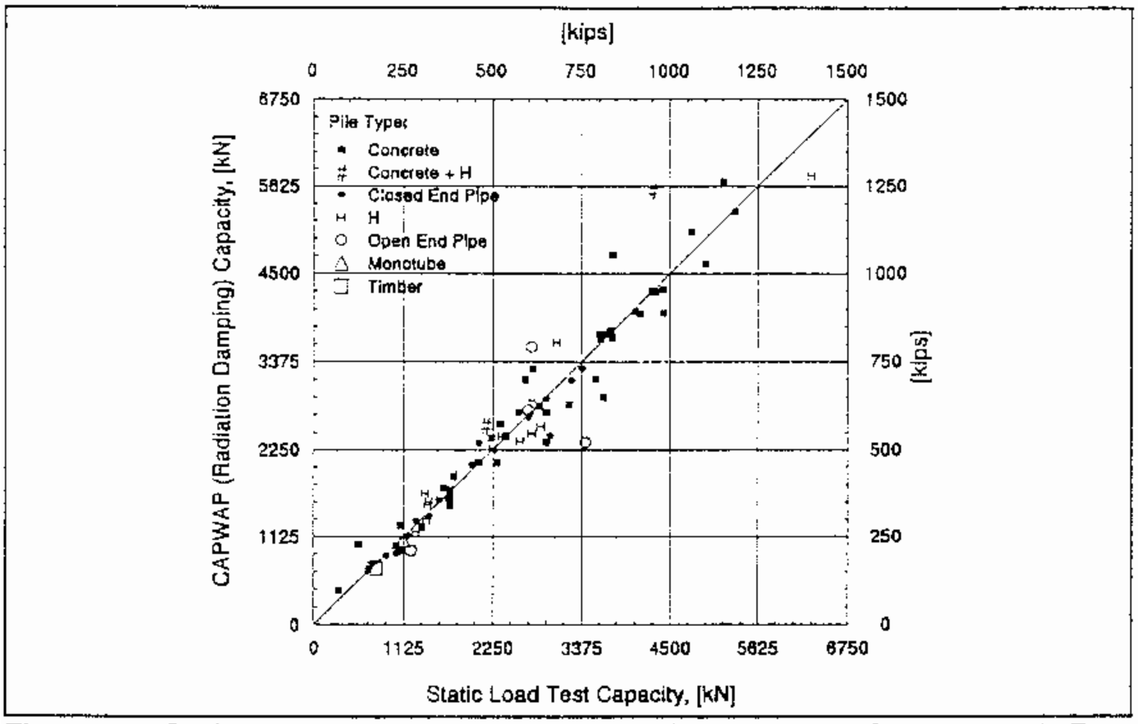

Figure 6: CAPWAP (Radiation Damping) Capacity *vs* Static Load Test Capacity Showing Different Pile Types

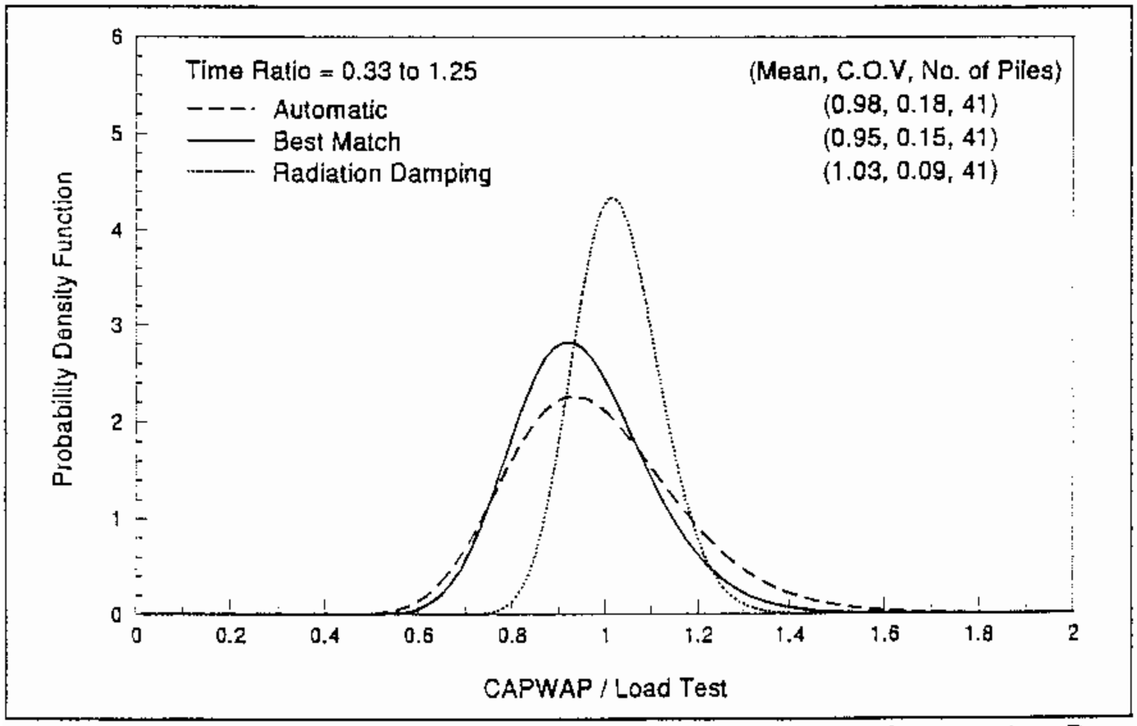

Figure 7: Log-Normal Probability Density Function for Automatic, Best Match, and Radiation Damping CAPWAP Capacity Prediction

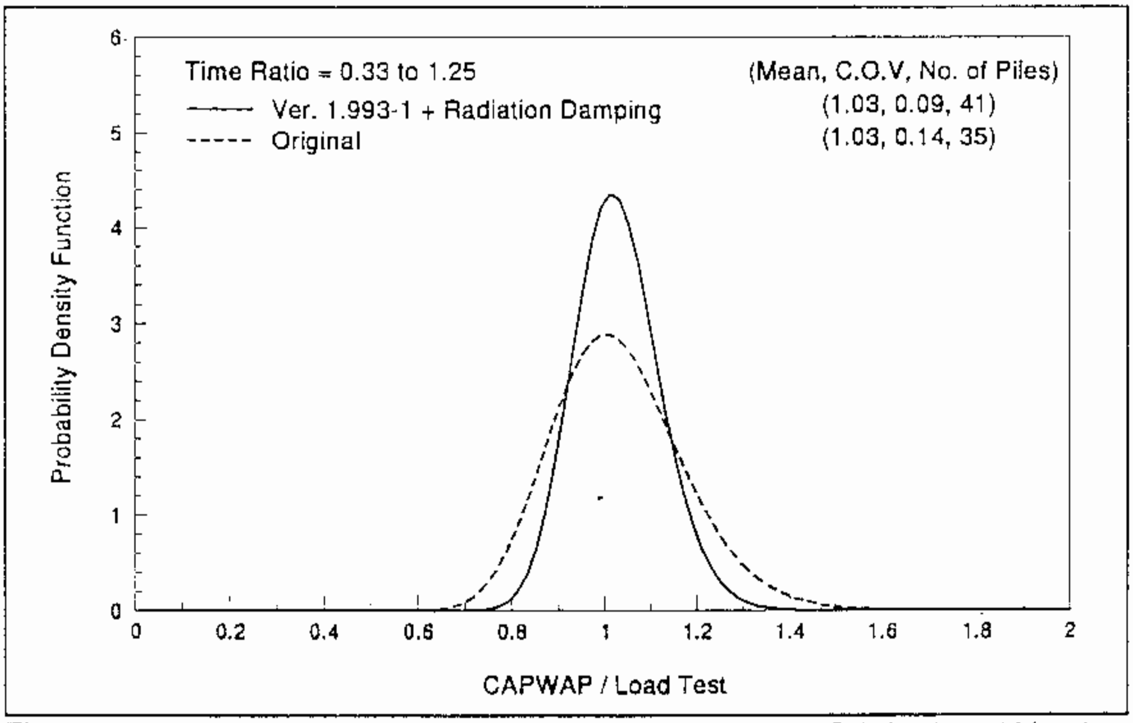

Figure 8: Log-Normal Probability Density Function for Original and Version 1.993-1+ Radiation Damping CAPWAP Capacity Prediction

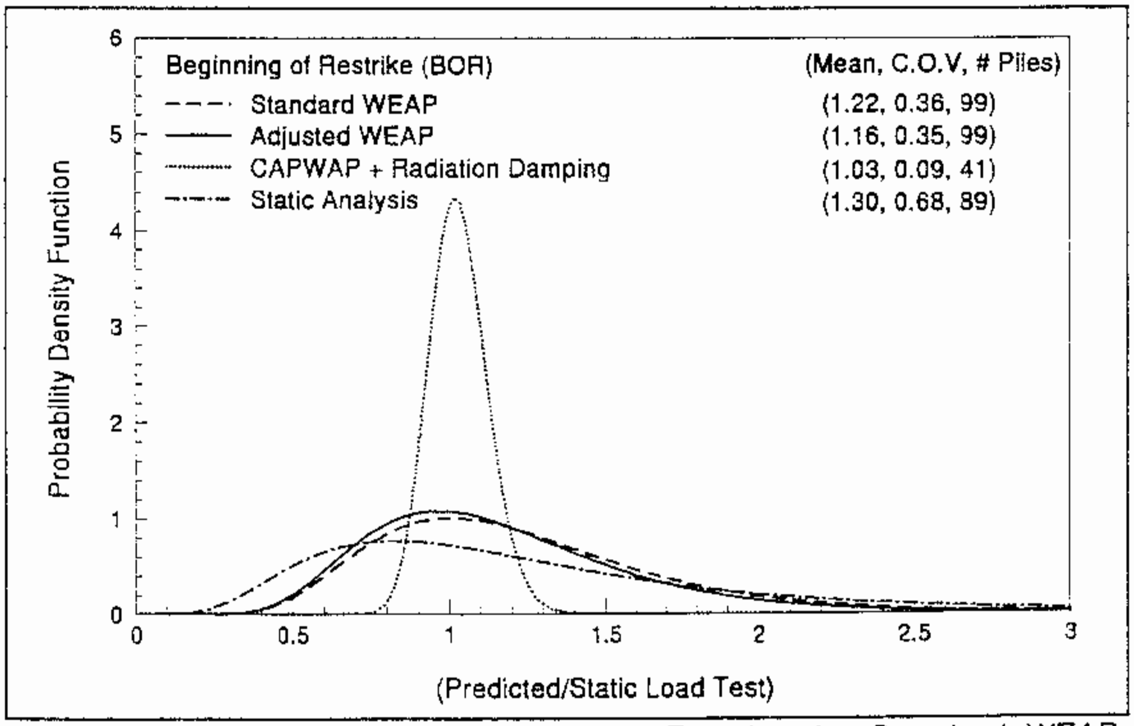

Figure 9: Log-Normal Probability Density Function for Standard WEAP, Adjusted WEAP, CAPWAP + Radiation Damping, and Static Analysis Capacity Prediction

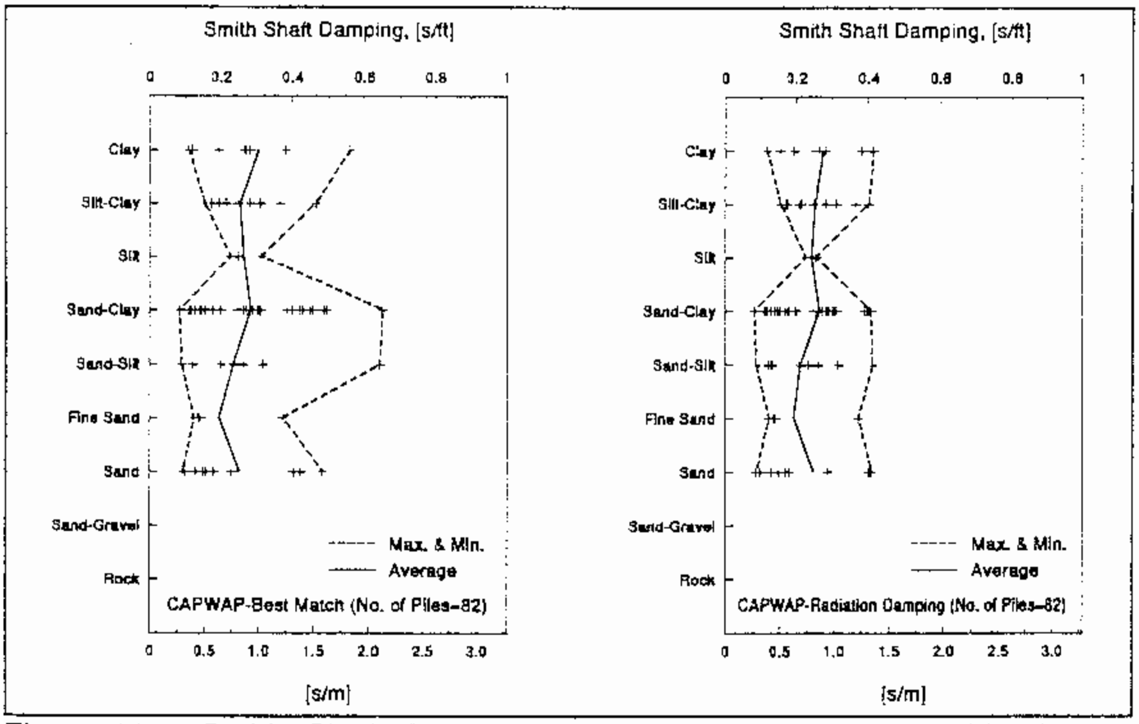

Figure 10: Smith Shaft Damping *vs* Soil Types from Best Match and Radiation Damping CAPWAP

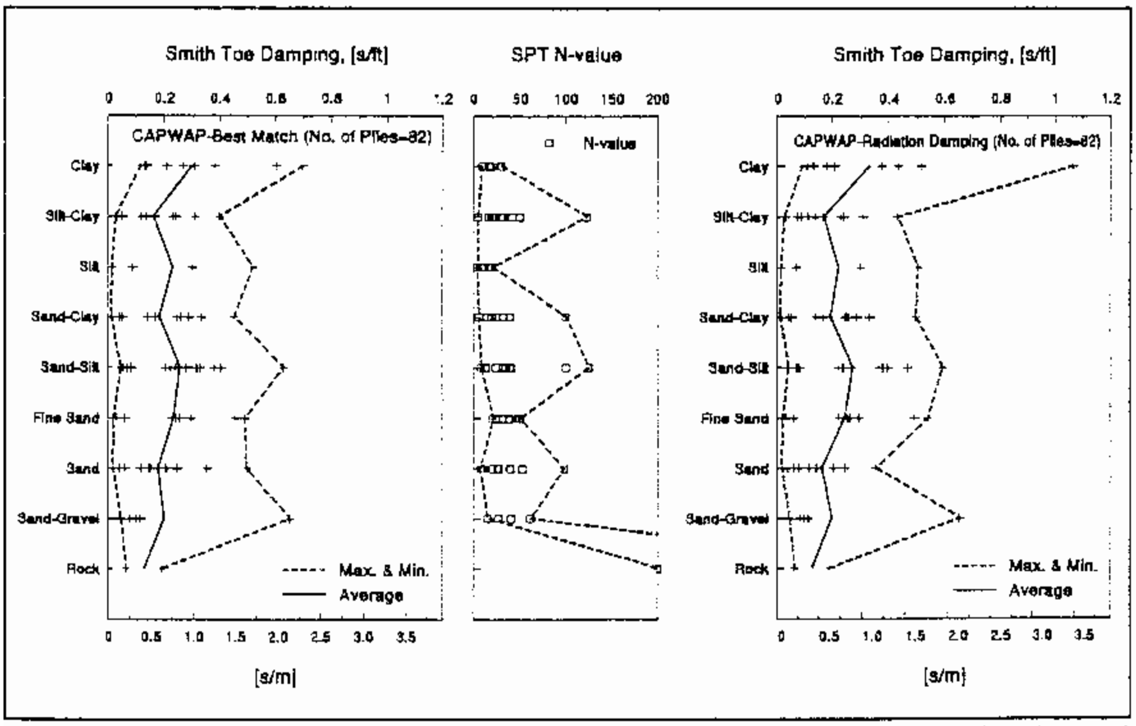

Figure 11: Smith Toe Damping *vs* Soil Types from Best Match and Radiation Damping CAPWAP

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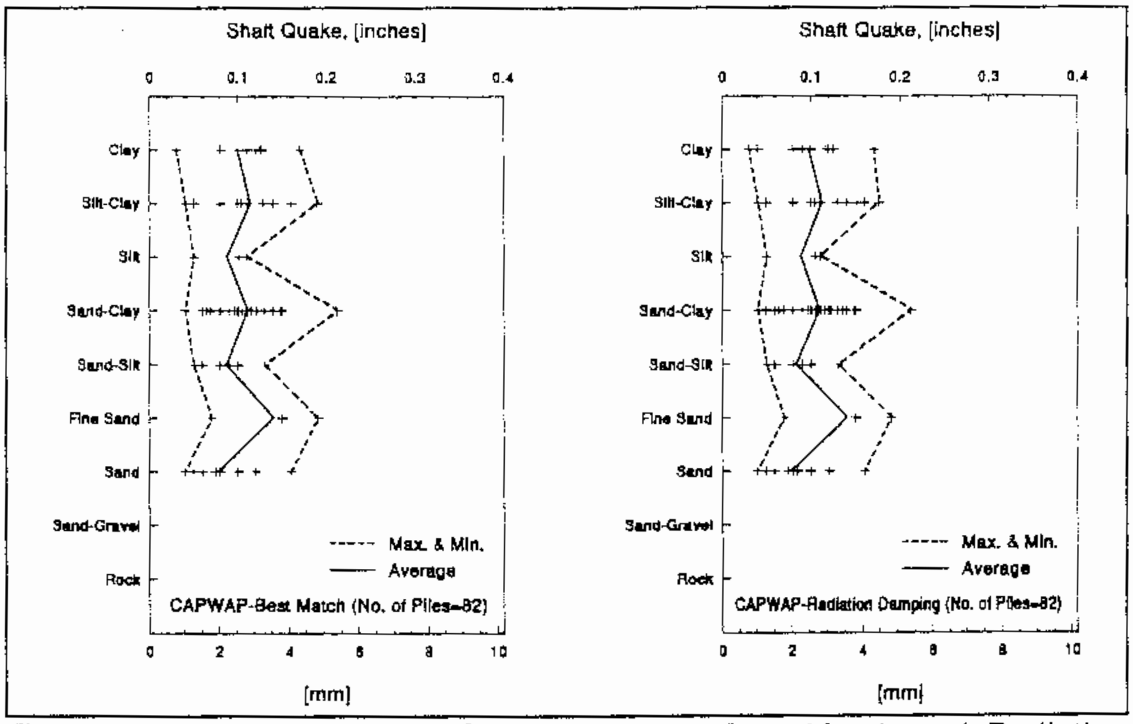

Figure 12: Shaft Quake *vs* Soil Types from Best Match and Radiation Damping CAPWAP

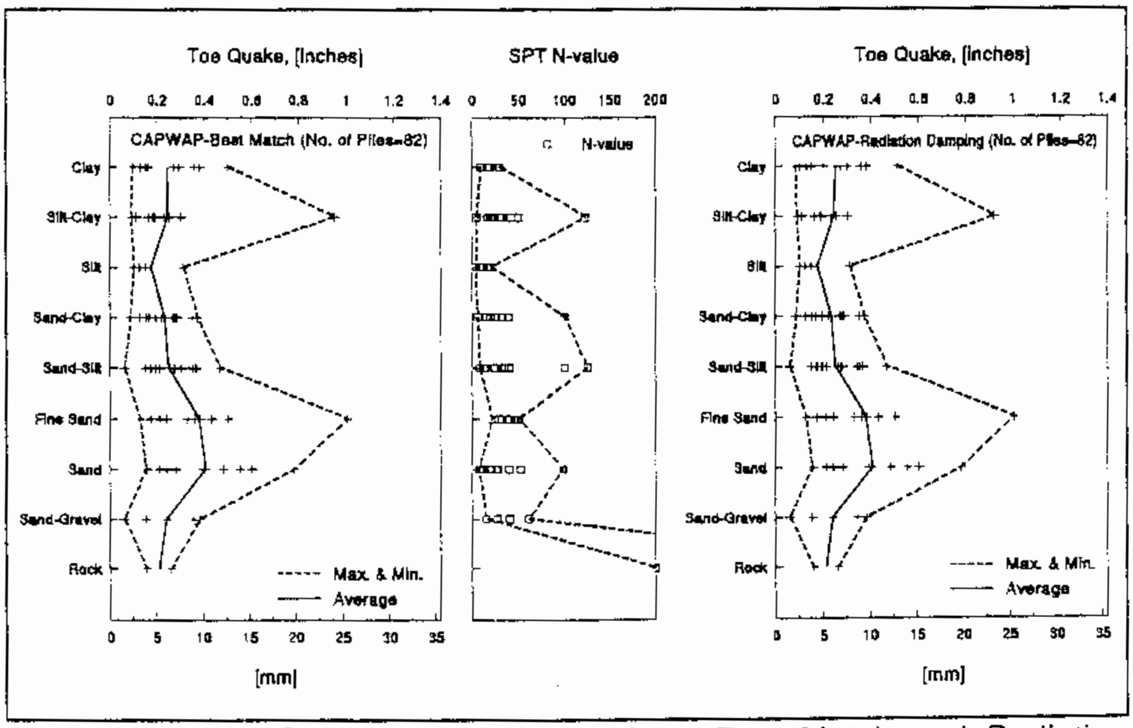

Figure 13: Toe Quake *vs* Soil Types from Best Match and Radiation Damping CAPWAP