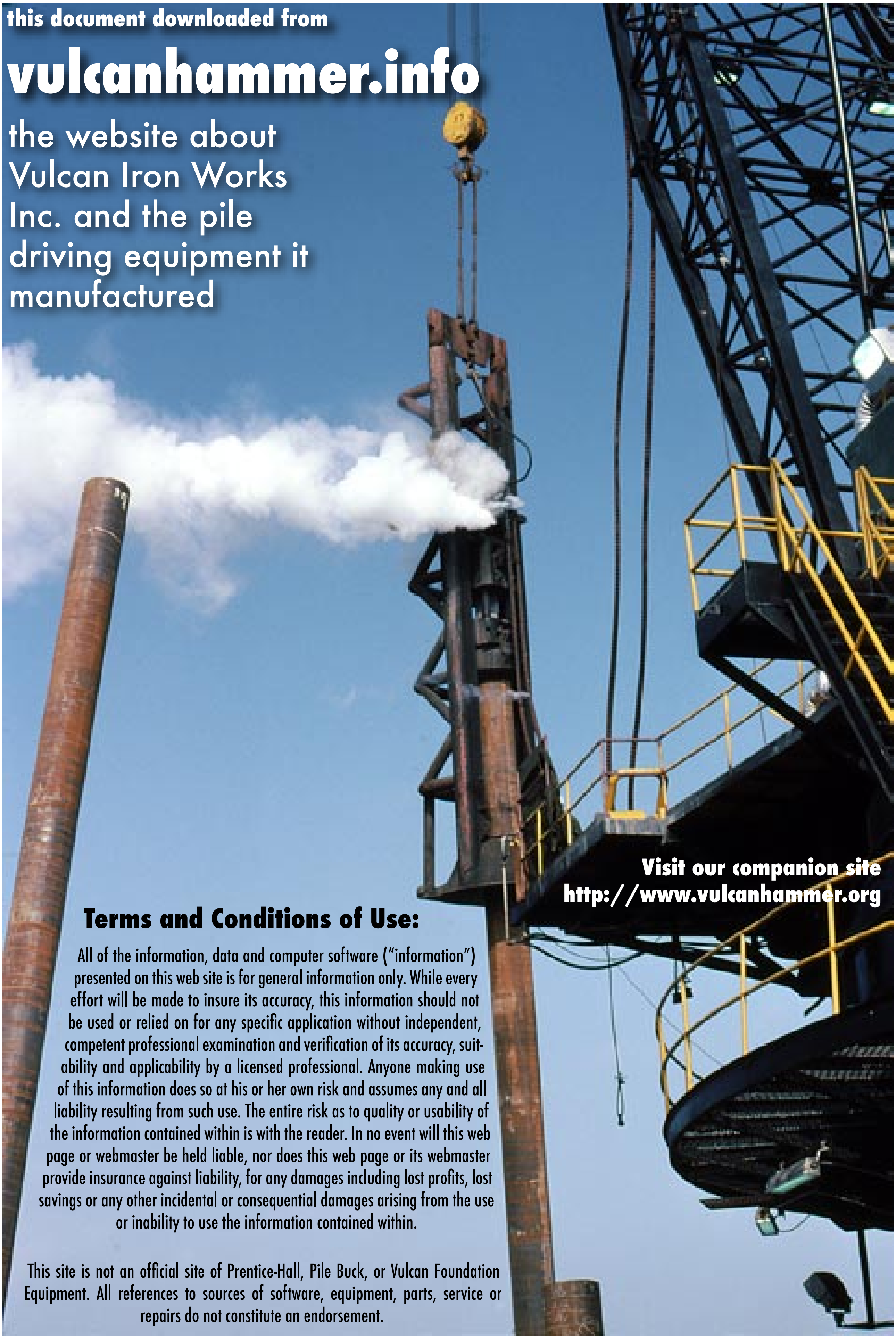

RECENT WEAP DEVELOPMENTS

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INTRODUCTION

During the past ten years, pile driving analysis by the wave equation has become a widely accepted method. The Federal Highway Administration of the United States Department of Transportation deserves special credit for its efforts in the dissemination of wave equation know-how by providing

- o program and documentation packages,
- o workshops and seminars, and
- o support for further research and development.

New programs and manuals have recently been released which greatly expands the versatility of the approach. The new release includes additional options, results from correlation studies, input and output programs and other enhancements. It also contains changes which may produce results which differ from those produced by other versions.

This paper describes the latest WEAP developments, discusses the impact of software changes and highlights some of the new options. It is hoped that this information will aid the engineer in making the best use of the available data and software, that it will contribute to accurate predictions and that it will help to avoid misinterpretations.

BACKGROUND

The wave equation approach was originally developed by Smith (1960) who presented a complete numerical analysis model for hammer, driving system, pile and soil. Smith also recommended parameters for various system components including the soil based on his experience with the Raymond Company.

Several researchers further investigated the ideas of Smith and further extended the concept. At the Texas Transportation Institute, the TTI program was developed and included in the FHWA software package, (Hirsch, Carr, and Lowery Jr., 1976). The WEAP program (Goble and Rausche, 1976), was developed starting in 1974 after it became evident that the basic Smith and TTI approach were inadequate for the analysis of diesel hammers. A large amount of field data (Goble, et al., 1975) was available to the authors of WEAP and the program was thoroughly tested by comparison with field results. WEAP not only provided the user with an improved hammer model but also with a simplified data input. For example, data for most common hammers was stored in a file and could be recalled by simply specifying the hammer identifying number. The numerical spring/mass pile model was automatically prepared from the area and modulus versus length data. Even the soil resistance distribution could be entered in a very basic form and several common distributions were stored for quick recall, thereby eliminating the need for calculations by the user and reducing the possibility of errors.

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Despite the proven accuracy of Smith's pile model, the realism of WEAP's diesel analysis, and the accumulated experience with the wave equation's soil parameters, the need for further work was evident. Thus, in 1981 a first WEAP update was made which included an expanded Users Manual.

Developments in microcomputer technology, new hammer types, new measurement results, research at the University of Colorado in Boulder (Hery, 1983) and a study on hammer performance (Rausche et al., 1985) suggested further updating of WEAP. This new program was presented together with a new set of manuals (Goble and Rausche, 1986). Differences between WEAP and WEAP86 were described by Rausche, et al., (1986).

After a one year trial period, user experiences were included in a slightly revised 1987 version of WEAP86. The revised manual also contained results from an extensive study on the calculated and actual performance of diesel hammers.

During this time period, additional features were incorporated into the program in a version called GRLWEAP. Preprocessing and postprocessing programs were implemented or improved for the PC version. With these features, easy access to the wave equation was provided to virtually any interested person and working with the program has been greatly simplified. However, it is still important that the user of the analysis results is thoroughly familiar with pile driving practice, with soil mechanics, and with the mechanics of the wave equation approach.

WEAP86 - 1987 VERSION

WEAP86 was also compared with the earlier WEAP program (Rausche, et al., 1986). Important new features were

- o Atomized Fuel Injection Model
- o Residual Stress Analysis Model
- o Additional Hammer Data
- o Improved Slack/Splice Model
- o PC Application Including Graphics
- o Driving System Data Collection

In 1987, the following main features were added.

- o Diesel Hammer Performance Study
- o Increased Speed for Diesel Analyses
- o Efficiency Reduction for Battered Pile Driving
- o Bearing Graph Program for Screen or Plotter

The 1987 release also includes editorial changes in both code and documentation, some hammer data sets were corrected or inconsistencies were removed. An alternative hammer data file was also prepared containing parameters used in the diesel hammer performance study.

GRLWEAP

In this program version, the WEAP authors now provide the user with a choice of either SI or English units and with further flexibility for often encountered situations which do not require the standard bearing graph output. Important new features are

- o Automatically varied stroke for constant capacity
- o Automatic analysis at various pile toe penetrations with computation of driving time
- o English (kip-ft-inch-ksi) or SI (kN-m-mm-MPa) units within the same program.
- o Maximum number of pile segments at 299 rather than 99 allowing analysis of piles up to 550 m (1800 ft) rather than 180 m (600 ft) long.

These additional features caused the program to exceed the FHWA specified 256 kByte memory. For this reason, the new program was developed on a proprietary basis. Brief descriptions of the new options follow.

The Varied Stroke - Constant Capacity Option

For diesel hammers, the driving criterion is often linked to stroke for verification of hammer performance. Typically, however, wave equation analyses are made for a series of increasing bearing capacity values with either fixed or varying strokes and a bearing graph is made which only includes one useful point: blow count for the desired capacity at one particular stroke.

To demonstrate both conventional and new approaches, Example 1 contained in the WEAP86 manual was reanalyzed. This case represented a Delmag D 12 hammer driving a 40-foot (12.2 m) 12 x 53 H-pile into granular soil for a 45-ton (408 kN) design load. Three analyses were performed to demonstrate the approaches of past and present.

(a) Traditional Wave Equation Analysis with fixed stroke
(b) Conventional WEAP Analysis with variable stroke
(c) GRLWEAP Analysis with fixed ultimate capacity

a) Traditionally, the hammer stroke is fixed at the rated stroke and a series of bearing capacity values is analyzed. The capacity is then plotted as a function of the computed blow count. (Fig. 1a). For a 90-ton capacity, the required blow count would be 21 blows per foot (21 blows/0.3 m).

(b) The typical WEAP analysis was illustrated as the first example in the manual and allows the stroke to vary with resistance. Both stroke and capacity are plotted as a function of the computed blow count. In this current example, the required blow count would be 42 BPF (138 BPM) and it would be stipulated that the hammer stroke should be at least 5.4 ft (1.7 m) (Fig. 1b).

(c) The GRLWEAP analysis with the varied stroke option produces blow counts for 10 different stroke values for the same capacity. GRLWEAP automatically

•Traditional Wave Equtn: Ru varies, max h

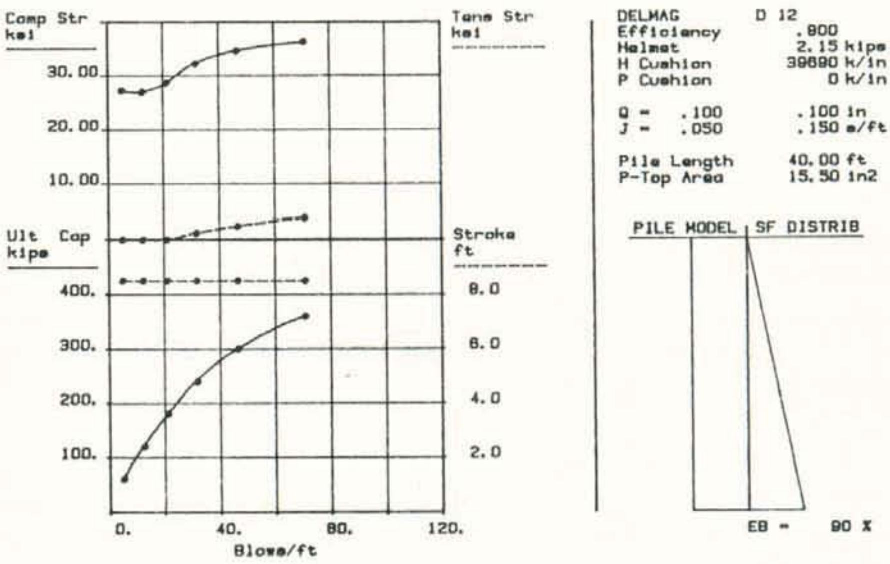

Figure 1a: Bearing Graph From Traditional Wave Equation; Constant Maximum Stroke, Variable Capacity.

•Conventional WEAP: Ru and h vary.

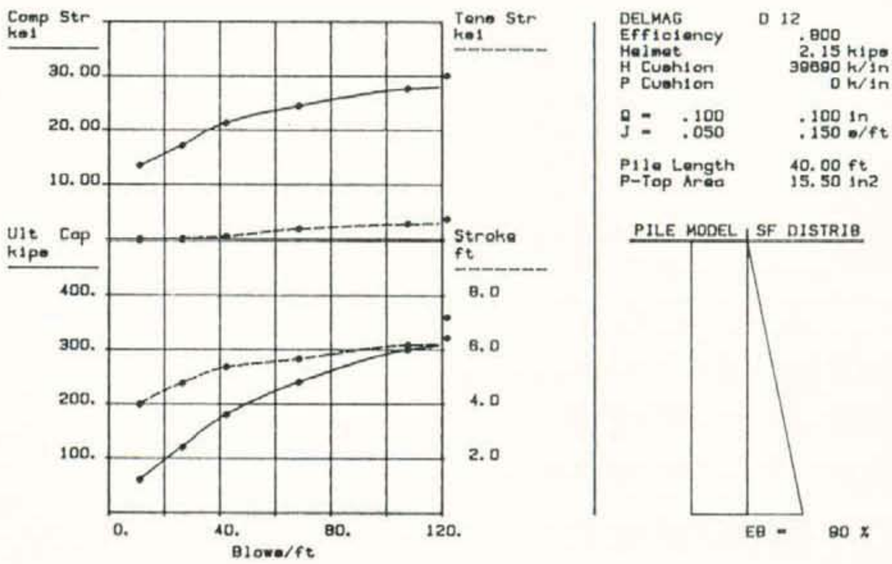

Figure 1b: Bearing Graph from Conventional WEAP Analysis; Variable Capacity with Variable Computed Stroke.

adjusts the fuel pressures such that downward and upward strokes match. In the field, the inspector would observe the hammer stroke e.g., by means of a Saximeter, and would then determine the minimum required blow count from the stroke vs. blow count plot (Fig. 1c).

The wave equation user should exercise caution and check the pile stress levels in all three examples. Of course, in analysis type (a) a reanalysis with a lower stroke would be necessary if stresses are excessive; in (b) the hammer pressure may be reduced if stresses are too high at the specified capacity. In (c) strokes with high stresses are simply disallowed and the hammer must be run at a lower fuel setting to obtain correspondingly lower strokes and higher blow counts.

Blow Count vs. Depth

In a conventional drivablity analysis, the soil strength is usually calculated for a pile penetration of particular interest. The shaft resistance percentage, shaft resistance distribution, and soil parameters such as damping and quake are set to the values appropriate for the depth considered. After analyzing a series of capacities, a bearing graph is constructed and blow counts are selected not only for the investigated depth but also for others in the neighborhood or over the whole extent of pile penetration.

For pile drivablity analysis, this simple process is not satisfactory because it lacks accuracy and many bearing graphs should be produced to properly cover the total range of pile penetration. GRLWEAP now allows the program user to input the following quantities for up to twenty different elevations.

- o Shaft Resistance per Unit Depth
- o Toe Bearing
- o Shaft and Toe Quakes
- o Shaft and Toe Damping

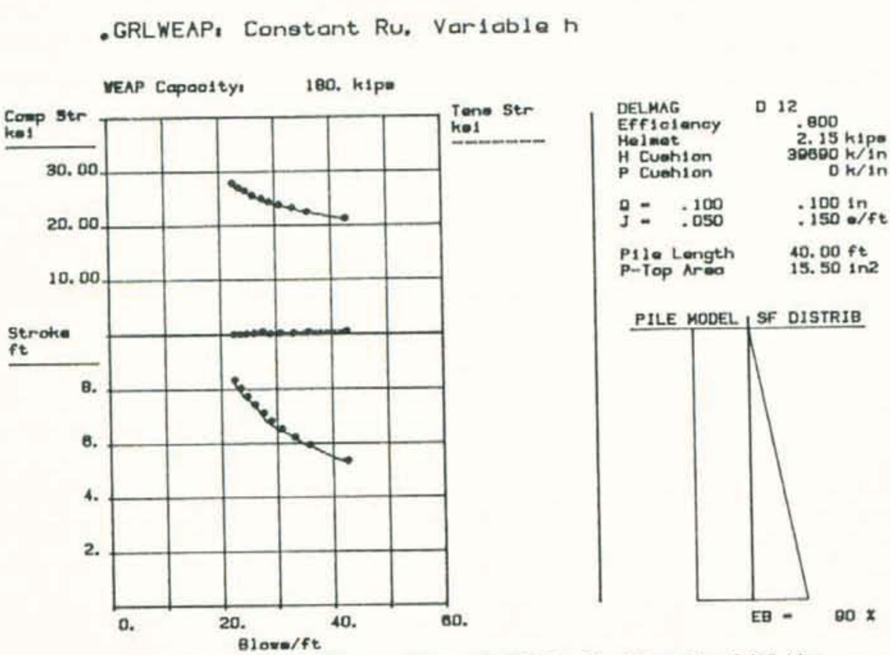

Figure 1c: Stroke vs. Blow Count From GRLWEAP for Fixed Capacity of 180 kips.

Instead of specifying a sequence of capacity values, the user enters up to ten depth penetration for which an analysis is to be performed together with up to six so-called shaft resistance modifications factors. For the first depth, the program uses the soil input data to determine toe bearing, toe quake and toe damping all by interpolation, shaft resistance by summation and shaft quake and damping by weighted averaging. The first shaft resistance modification factor is applied to the total shaft resistance. The static weights, preloading the pile before impact, are subtracted in a proportional manner from shaft and toe bearing. These subtracted weights include the hammer assembly, cap, and the pile above grade.

The first wave equation analysis is now performed and the blow count obtained. Then, the second shaft resistance modification factor is applied, an analysis is again performed and repeated until all modification factors for the first pile depth have been analyzed. A summary, for a first standard bearing graph relating blow count to capacities with constant toe bearing and available skin friction, is then printed. The program then continues to analyze the second and other depth values in a similar manner. A final summary is included for each modification factor. This summary gives toe bearing, blow count, stress maxima, blow rate (blows per minute; variable for diesels) and total driving time for each shaft resistance modification factor.

UTILITY PROGRAMS

Preprocessors

For PC applications, a file must be generated which the wave equation program reads and analyzes. The original WEAP86 package included W86IN which guided the user through all necessary input phases. Later, MENU was written which included an extensive tutorial; this program is recommended for the novice to wave equation analysis. Finally, TEMPLATE was developed which includes all data tables of the manual in its "Help-Files". This latter program makes hammer data file searches and maintenance particularly convenient.

Postprocessors

Presentation of plotted wave equation results is much more informative than a listing of numerical values. A program was therefore prepared for either screen or plotter graphics. The individual plots that this program produces are

- o Force and Velocity at pile head as a function of time.
- o Three selected variables like Forces, Displacements, Accelerations, and Velocities in hammer or pile as a function of time.
- o Pile Variables vs. Time and Length (3-dimensional).
- o Bearing Graph
- o Stroke vs. Blow Count for a particular capacity.
- o Capacities, Stresses, Blow Count vs. Depth.

GRLWEAP also includes screen graphics of bearing graph and user selectable variables as they are being computed.

DIESEL HAMMER STUDY

The 1987 version of the WEAP86 manual contains the results of a comprehensive study of computed and measured diesel hammer performance. For 57 field tested situations, the maximum transferred energy, maximum force at pile head and hammer stroke were computed and compared with measured values. The correlation graphs shown in Figs. 2a, 2b and 2c indicate that good force correlations may be expected and that transferred energy predictions are fair and slightly nonconservative. Stroke values are approximately 20% low in the ranges near the rated hammer performance.

An attempt was made to model the hammers with a decreased Gas Law expansion coefficient for higher combustion pressures in the cylinder and therefore higher strokes. However, significantly higher computed force and energy values resulted and - to maintain a good force and energy correlation - a hammer efficiency reduction from 0.80 to 0.72 had to be applied. It was found that this alternative set of hammer data would produce better stroke correlations in the upper ranges; however, for easy driving with lower strokes, the correlation would be worse.

It was also concluded that any given hammer may perform rather differently depending on its state of maintenance. It would be a mistake to provide hammer data which corresponds to the best possible state of hammer performance. For this reason, the original WEAP86 hammer data file is acceptable. However, the results should be used in the following manner:

- To assure sufficient bearing capacity, the diesel hammer stroke should be at least as high as the computed one.
- To assure that computed driving stresses are not limited, the diesel hammer stroke should not exceed 1.2 times the computed value.

These are simple rules and it is recommended that hammer, driving system, and pile and soil performance should be confirmed by field measurements. For average hammer performance, WEAP86 produces satisfactory correlations.

OTHER DEVELOPMENTS

Hydraulic Hammers with Internal Monitoring

During the past year, analyses of hydraulic hammers frequently were requested. Several of these new hammers use a hammer-internal sensor which measures the ram's impact velocity. Furthermore, these hammers are frequently used without a hammer cushion. A limited amount of measured data were available which suggested that such hammers may be analyzed with a 95 percent efficiency even though they are of the external combustion-double acting type. If the impact velocity is not measured and the analysis is for hammer ratings, the efficiency should be 50 percent.

Hammer Data File Maintenance

Review of the WEAP86 hammer data file indicated the following problems.

- Double acting air/steam hammers had been entered with actual rather than equivalent strokes. This produced extremely low stresses and high blow counts.
- ICE hammer data included inconsistent efficiency values.

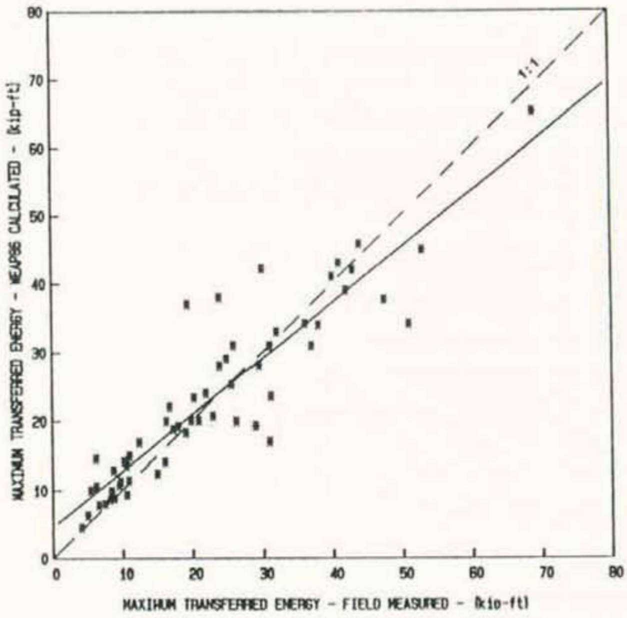

Figure 2a: WEAP86 Computed and Field Measured Transferred Energies.

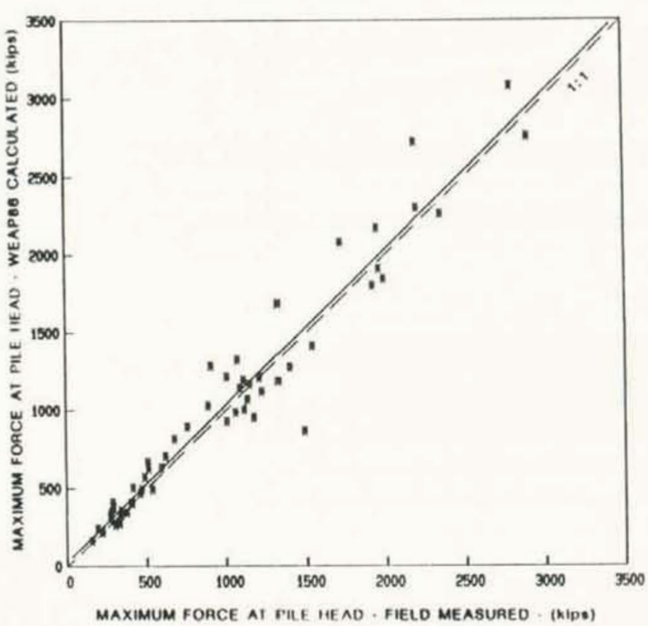

Figure 2b: WEAP86 Computed and Field Measured Maximum at Pile Head.

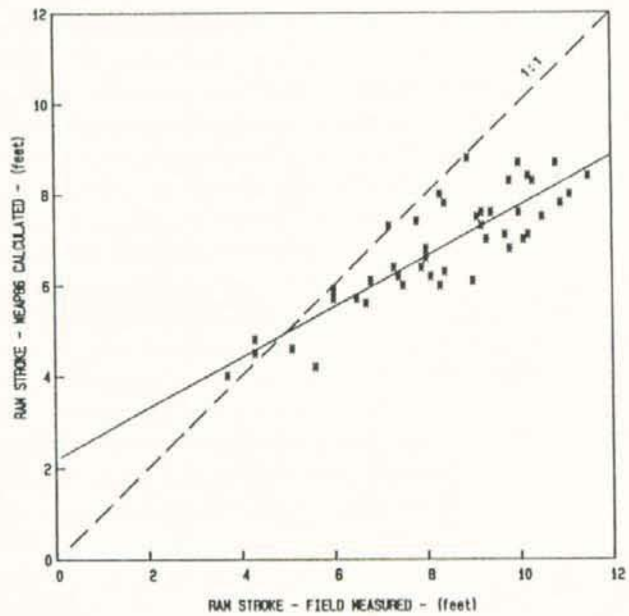

Figure 2c: WEAP86 Computed and Field Observed Diesel Hammer Strokes.

A few other incorrect entries were also found. All reported problems, errors or inconsistencies were corrected in the WEAP87 data file.

SUMMARY AND CONCLUSIONS

The addition of new analysis options, convenient input routines and elegant output programs have made the use of the wave equation a more pleasurable and less time consuming task than in the past. In addition, the following conclusions are drawn:

- o Blowcount vs. stroke for diesel hammers may be a valuable construction control tool.
- o Blowcount vs. depth analyses will improve both speed and accuracy of complicated drivability analyses.
- o Measurement results suggest that good correlations of stresses and transferred energies can be obtained using WEAP86 even though the stroke of diesel hammers may be underpredicted by up to 20 percent. It was found that hammer data adjustments for better stroke correlations do not necessarily yield improved agreements.

ACKNOWLEDGEMENTS

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