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A NEW TYPE OF WAVE EQUATION ANALYSIS PROGRAM

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CONFERENCE ON THE APPLICATION OF STRESS-WAVE
THEORY TO PILES, OTTAWA, ONTARIO, 25-27 MAY 1988

THE WAVE EQUATION PAGE FOR PILING
[HTTP://WWW.VULCANHAMMER.COM/WAVE](http://www.vulcanhammer.com/wave)

A NEW TYPE OF WAVE EQUATION ANALYSIS PROGRAM

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ABSTRACT

This paper describes a new wave equation analysis program called ZWAVE, which is a program specifically for external combustion hammers. The program is described in detail, the discussion dealing with topics concerning the program such as 1) the numerical method the program uses to integrate the wave equation, which is different from most other wave equation programs; 2) the modelling process of both cushioned and cushionless hammers; 3) the automated generation of mass and spring values for both hammer and pile; 4) the method of dealing with plastic cushions; 5) the use of a recently developed model for computing shaft resistance during driving; 6) the computation and generation of values based on basic soil properties such as shear modulus, Poisson's Ratio and soil density; 7) the completely interactive method of feeding data to the program; 8) the method used to compute the anticipated rebound and the energy used to plastically deform the soil; and 9) the format of the interactive input of the program and the program's output. Sample problems for the program, along with comparison of the program results with data gathered in the field, are presented.

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INTRODUCTION

For nearly thirty years now the finite difference wave equation analysis, as pioneered by Smith (1964), has been the state of the art in the analysis of the penetration resistance and dynamic stresses of piling driven by impact hammers. Although finite element routines such as Smith and Chow (1984) describe are now beginning to be used, the finite difference programs remain by far the predominant method of pile driving analysis, both for the prediction of pile behaviour during impact and for analysis after driving. This is especially true in the wake of the development of microcomputers, for finite element analysis with these at present can be very consuming of both computer time and memory.

ZWAVE, developed at Vulcan Iron Works, is a new finite difference wave equation analysis program, designed to analyse the hammer/pile system behaviour of systems driven with external combustion hammers. By this, we mean hammers with combustion of the motive fuel separate from the workings of the hammer itself, as opposed to internal combustion units such as the diesel hammers. This would include not only the air/steam hammers manufactured for a century by Vulcan and others, but also include the hydraulic hammers manufactured by such makers as Menck, Hydroblok, IHC, Udcomb, etc..

The development of the source code for ZWAVE has begun by converting the TTI wave equation program as modified by Holloway (1975) to Microsoft Basic on an IBM PC-XT computer and compatibles; further details on the TTI program are given by Hirsch et. al. (1968, 1976). The development of the program then proceeded using the Microsoft Quick-Basic compiler, which both increased the speed of computation greatly and produced a stand-alone run file for ease of use and distribution. As a result of its origins and development, ZWAVE is similar in both basic theory and many details to existing wave equation programs. Thus, it would be redundant to describe here the basics of wave equation theory in this paper; in addition to the TTI material referenced above, the documentation of WEAP/WEAP86 by Goble et. al. (1976, 1986) is also relevant background for ZWAVE. In this paper, only the improvements made in the development of ZWAVE will be described here.

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FEATURES

Numerical Method

In order to integrate the wave equation, both the Smith and TTI wave equation routines used a modified, first-order Euler method. This was doubtless a necessity in view of the computing speed available when these programs were developed. Later routines use higher order methods; predictor-corrector methods (WEAP86--Goble et. al. (1986)), Crank-Nicholson techniques (Levacher (1986)), fourth-order Runge-Kutta integration (BATLAB--Bossard and Corte (1984)), to say nothing about the use of impedance methods (ADIG--Meunier (1984)). With a problem as non-linear in nature as this one, it would seem that, given the capabilities of current digital computers, at least a second order method be necessary for proper integration.

For ZWAVE, it was initially decided to use a Heun Method with a single corrector, as described in Chapra and Canale (1985); however, problems were experienced with excessive deflections and velocities, generally originating at the slack in the pile head. Problems like this are not unique to ZWAVE; other programs, such as WEAP86, deal with excessive deflections and stresses by introducing small amounts of dampening into the system. While any engineering material has some dampening in it, if possible this should not be used to correct problems with the numerical integration scheme.

At the most basic level, the problem is twofold. First, any time a continuous medium is divided up into finite segments, the fineness of the results will be adversely affected; this is demonstrated by Meirovitch (1975). Second, it is necessary at all times and all places in the system to maintain both conservation of momentum and of energy. In the integration from acceleration to velocity, conservation of momentum is preserved because the integration equations are essentially those of momentum conservation. However, when the second stage of integration is reached from velocity to displacement, in most methods the change in displacement is simply computed by multiplying the time by the velocity in some fashion. Thus in this step there is no guarantee that the conservation of energy by preserved. With higher, say fourth-order methods, the precision of the method will probably take care of this but for lower order methods this is not necessarily the case.

ZWAVE solves the second problem by modifying the Heun Method and directly integrating both the velocity and the displacement from the acceleration, thus both reducing numerical error and insuring conservation of energy. ZWAVE also works to reduce integra-

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tion error through double precision accumulation of sums and maintaining the time step as one half of the shortest spring-mass period found in the system.

Hammer Modelling

ZWAVE models pile hammers in one of two ways. For hammers with a hammer cushion but no anvil (not a pile accessory "anvil", but an anvil as is found on diesel hammers) are modelled with a rigid ram and a cushion spring. This will cover most air/steam hammers, such as the Vulcan hammers. For all other hammers, the user divides the ram into segments with masses and springs, as is done with piles.

Segment Generation

ZWAVE uses automatic segment property generation throughout the program. For pile and cushionless hammer segments, the user inputs the length, cross-sectional area, and material; the program computes the spring and mass values. A similar algorithm is used for hammer and pile cushions. Contrary to much current practice, ZWAVE concentrates the mass in the centre of the segment, as is done in the model of Van Weele and Kay (1984). Strictly speaking, this is the correct practice for any finite difference method. The only really serious side effect of this is to create a massless node at the pile toe; this is dealt with positional averaging techniques.

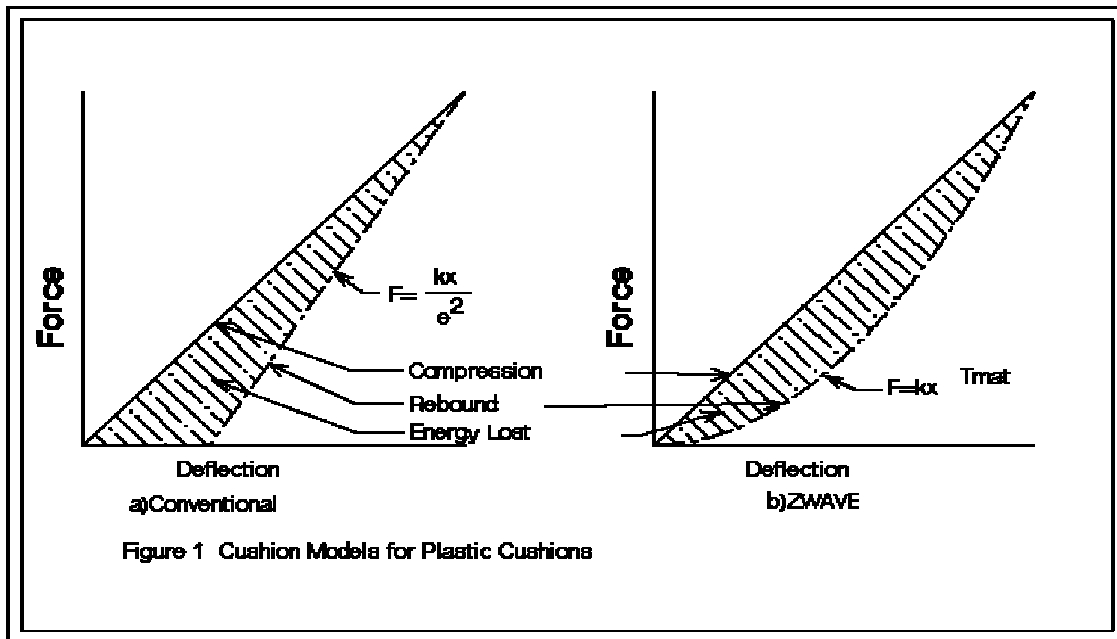
Plastic Cushions

Virtually all pile and hammer cushions are plastic to some degree. The amount of plasticity of a cushion is expressed by the coefficient of restitution, which is in fact the square of the ratio of the energy put into the cushion during compression to the energy gotten back from the cushion during relaxation.

Most wave equation analyses handle the compression and relaxation as shown in Figure 1a, using straight line compression and relaxation functions. The most serious problem with this is that the cushion completely unloads before the absolute compression of the cushion spring reaches zero, forcing some elaborate algorithms to deal with the resulting gap. While this gap exists with real cushions, it is a serious problem only while the cushion is being "run in" and not when it has been in use for a while.

To simplify matters, ZWAVE retains the linear compression function, but uses an exponential relaxation function, as shown in Figure 1b, which results in zero force at zero absolute compression for both compression and relaxation and some cushion force for any given

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cushion compression. The exponent is called T_{mat} ; it is computed directly from the coefficient of restitution by

$$T_{mat} = \frac{2}{e^2 - 1}, 0 < e \leq 1 \quad (1)$$

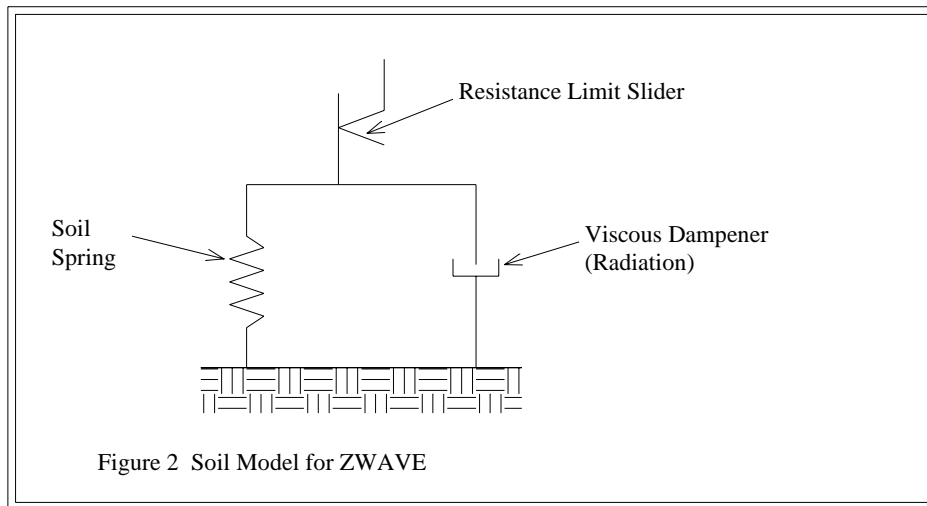
and is computed so that the energy loss ratio in the cushion from compression and relaxation is identical to both that used previously in wave equation analyses and taken experimentally in cushion tests such as that described in the standard of the Deep Foundations Institute (1986).

Shaft Resistance

The shaft resistance model in ZWAVE is somewhat different in two respects from many previous wave equation analysis programs.

First, as is the case with WEAP86, a truly viscous soil model is used for the dampening component. To arrive at this dampening coefficient, when conventional Smith values are used, the Smith dampening J_s is multiplied by the local resistance. (This is also the case with the toe.)

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Second, the soil model is as diagrammed in Figure 2. This is taken primarily from the work of Corte and Lepert (1986), and additionally from Randolph and Simons (1986). The major practical result of this is that at no time in the analysis of a pile does the dynamic exceed the static resistance; this tends to give the shaft friction effect like that of a rigid-plastic soil model. In view of this, ZWAVE follows the recommendation of Corte and Lepert (1986) that traditionally used dampening values be multiplied by 7.5

Advanced Soil Model

The same research used in the development of ZWAVE's shaft resistance model sets forth the procedure for the computation of soil properties such as soil spring constant and soil dampening from basic soil properties. ZWAVE makes provision for the user to take advantage of this recent work and, for single cases where the shaft and toe resistance per unit area of pile surface is known, to compute the soil spring constant, quake, and dampening. If we define the quantities of first soil shear wave velocity

$$c = \frac{G}{\rho} \quad (2)$$

and of soil relative impedance

$$I_0 = \rho c \quad (3)$$

we can compute the shaft spring constant for an element by the equation

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$$K_{sh} = 3.1416GL \quad (4)$$

and the toe spring constant as

$$K_t = \frac{2DG}{1-\mu} \quad (5)$$

while the shaft dampening (or more accurately the shaft soil impedance) is

$$C_{sh} = 3.1416DLI_0 \quad (6)$$

and the toe soil impedance/dampening is

$$C_t = \frac{1.08AI_0}{1-\mu} \quad (7)$$

To utilise these equations, in addition to the resistance values, the user need only input the soil shear modulus of elasticity, soil density, and soil Poisson's ratio. Two especially important items should be noted: first, the soil "dampening" is in reality a recognition that the soil is a continuum (more or less) of distributed mass and elasticity, and second, that the true "viscous dampening" of the soil is neglected.

Although this type of soil modelling has a great deal of promise, both in improving the accuracy of the analysis and in estimating soil dynamic properties from simple soil physical constants, much more work needs to be done in the practical integration of the wave equation with these properties.

Input Format

Most of the currently used wave equation analyses started out (and are still used in many installations) as batch FORTRAN programs on a mainframe or minicomputer with card input of data. Some have been converted for use on microcomputers, but the legacy of card input is still strong in the way the input is done.

ZWAVE was designed from the start for microcomputers, and specifically the IBM PC-XT and its compatibles; thus, an entirely new input format, independent of card input considerations, was chosen. Having loaded the program and commenced execution, the computer asks the user a series of questions about the hammer/pile system he or she wants to analyse. In the course of the input, the program makes decisions as to the type and number of questions it will need to ask in order to allow complete input of the data. Also,

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to speed input, default values for certain variables are offered, and many variables (such as the spring and mass variables) are automatically computed.

Details of this input system are given with the sample problem.

Rebound and Plastic Soil Deformation

ZWAVE, in common with other wave equation programs, computes the pile set by subtracting from the maximum deflection of the tip the total soil quake, which is a weighted average of the different soil quakes around the pile, computed in the same way as Goble et al. (1986). In addition to this, to provide additional data on soil deformation, ZWAVE computes the amount of energy the system expends in plastically deforming the soil. This energy is computed as the sum of the products of the individual element soil plastic deflections and the element resistances. Theoretically, at least, one could compute the set of the pile as

$$s = \frac{W_{fp}}{R} \quad (8)$$

as shown by Kummel (1984) and Warrington (1987). This result does not always agree with the conventionally computed figure; this is probably the result of several factors such as the lack of residual stress analysis (RSA) capability with ZWAVE or deficient soil properties.

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EXAMPLE PROBLEM AND COMPARISON WITH ACTUAL DRIVING

To demonstrate both the workings of ZWAVE and at the same time a comparison of ZWAVE's output with the actual results, we will consider the case of a test pile programme commissioned by the Jacksonville Electric Authority at the site of their Blount Island coil loading terminal on the St. John's River in Jacksonville, FL. The piles were a mixture of 14" and 20" square concrete piles and 16" and 24" diameter, 1/2" wall thickness steel pipe piles. These were driven during April and May of 1987 into a variety of fine sands. The piles were first driven, then restruck later. During the restriking, data concerning the piles' behaviour were taken using a Pile Driving Analyser; subsequently, the data were analysed with the CAPWAPC computer program. Static loading tests were also performed on the piling, following ASTM D-1143 for the compressive tests and ASTM D-3689 for the tension tests. The pile driving contractor was S. K. Whitty and Co., Inc. of New Orleans, LA, who used a Vulcan 510 for most of the driving and all of the restrikes. It is interesting to note that, in addition to this being the first job where ZWAVE was used for data comparison, it was also the first job for a Vulcan 510 to be used for pile driving. Geotechnical supervision was provided by Law Engineering. Further details of this jobsite and the testing results are described by Kett and McDaniel (1987).

Data from ten piles were made available; unfortunately, loading tests to failure following the Davisson criterion were valid for only five of the piles. Despite this, ZWAVE was run to compare with the actual results for all the piles, using the following procedure to develop the comparison:

- 1) Using manufacturer's data for the hammer and standard data for the cushion properties, the 510 hammer was modelled. To show this, and to show ZWAVE's input format, a sample of the hammer data input screen is shown in Figure 3.
- 2) Pile data was developed both from the driving log data and the CAPWAPC results, especially with the element division of the piles, which was made to be as close to the ones generated by CAPWAPC as possible.
- 3) Soil data was taken from the CAPWAPC, which included the soil resistance distribution, CAPWAPC's own estimate of the pile capacity, and soil quake and dampening properties.
- 4) Since no direct measurement of the hammer's mechanical efficiency was made, for each pile ZWAVE was run with the data from Steps (1-3) in increments of 5% until the closest

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match was made between CAPWAPC's and ZWAVE's maximum pile head enthr. Using this method, efficiency estimates ranged from 35-55%, which is probably explained by the fact that the number of blows during the restrrike were relatively few, not affording the hammer's operator the chance to bring the ram up to full stroke before measurements were taken.

- 5) Using all the data above except CAPWAPC's total bearing capacity data, a survey run was made for each pile. The actual restrrike blow-count from the driving logs was taken and corresponding pile capacity estimates from ZWAVE were then interpolated.

```
Hammer Data for Problem 1
Rated Striking Energy of Hammer, ft-kips? 50
Hammer Mechanical Efficiency, Percent? 45
Hammer Anvil y/n? n
Cushion Material y/n? y
Ram Weight, kips? 10
Cushion Pot Diameter, in.? 13.75
Cushion Pot Length, in.? 7.5
Cushion Pot Tangent Modulus of Elasticity, ksi? 125
Cushion Pot Coefficient of Restitution? .77
Drive Cap Weight, kips? 2.2
Pile Cushion Thickness (Enter Zero if None), in.? 6
Pile Cushion Tangent Modulus of Elasticity, ksi? 30
Pile Cushion Coefficient of Restitution? .5
Accept This Screen y/n?
```

Figure 3 Sample Hammer Input Data Screen for ZWAVE

The results of this procedure are summarised in Table 1. Piles A-B have the load test data, while Piles F-J do not. All piles returned a comparison for maximum tension and compression stresses. In general, the compressive stress correlation came out well, just slightly low in general, while the tension stress correlation was not as satisfactory, but in general was high. As for the bearing capacity/blow-count comparison, in general when CAPWAPC's capacity estimate was used, ZWAVE's blow-count came back lower than that of the driving logs, but when the survey interpolation was performed, ZWAVE's estimate improved for four of the five piles with a refusal load test, and on these four piles (A, B, C, and D) the capacity estimates are at least on par with and sometimes better than that of CAPWAPC.

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One additional item of note concerns the shaft friction. As Table 1 shows, the percentage of shaft friction varied widely. There is no apparent effect of the proportion of shaft friction to total friction in the comparisons. Whether the new shaft soil model produces superior results in and of itself is hard to tell with this data, and the advanced soil model was not invoked in this study; however, there is no evident degradation of the results with this model.

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TABLE 1
RESULTS OF DATA COMPARISON

Data ®	Pile Type	Maximum Stress, ksi				Pile Bearing Capacity, kips			Blow Count, BPF		Percent Capacity Shaft Friction
		<u>C</u>	<u>Z</u>	<u>C</u>	<u>Z</u>	<u>C</u>	<u>Z</u>	<u>LT</u>	<u>DL</u>	<u>Z</u>	<u>C</u>
A	2	2.08	1.67	-0.21	-0.25	361	456- 320	360	84- 41	50	61
B	2	2.47	1.87	-0.37	-0.22	474	608- 542	576	156- 107	72	64
C	1	2.83	2.96	-0.36	-0.44	477	442	344	160	235	92
D	2	1.56	1.62	-0.24	-0.07	457	530	600	432	204	83
E	2	2.41	2.07	-0.3	-0.48	436	650	280	120	54	82
F	1	3.15	3.3	-0.75	-0.51	521	560- 477	-	180- 96	126	14
G	4	18.68	16.34	-2.08	-6.6	303	528- 387	-	72- 36	24	96
H	4	19.6	18.78	-2.26	-1.12	878	997	-	592	176	72
I	4	20.19	18.56	-1.16	-4.5	910	909	-	576	540	44
J	3	21.92	22.36	-1.24	-1.26	491	575	-	∞	259	70

NOTES:

- 1) Pile Type: 1 = 14" Sq. Concrete, 2 = 20" Sq. Concrete, 3 = 16" Dia. Steel Pipe, 4 = 24" Dia. Steel Pipe
- 2) Data Sources: C = CAPWAPC, Z = ZWAVE, LT = Load Tests, Davisson Criteria, DL = Driving Logs
- 3) ZWAVE Pile Capacities interpolate from survey runs and driving log blow-counts.
- 4) When two values for ZWAVE Load Capacity/Driving Log blow counts are encountered, this results from blow-count variations during restrrike.

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SUMMARY

In its present form, the ZWAVE wave equation program provides an easy to use tool to analyse the penetration characteristics of hammer-pile-soil systems driven by external combustion hammers. It contains many features not found in other wave equation programs; some are ergonomic (the interactive input), some relate to the basic integration scheme, some to the soil modelling (the advanced soil input and the limiting of shaft resistance during pile movement). The comparison runs show that its algorithm is basically sound and the new features have the potential to improve the ability of the foundation designer to analyse pile dynamics. This potential, and any future improvement, will not be fully realised without further use and correlation of ZWAVE with actual pile driving.

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NOMENCLATURE

c	Speed of Sound in a continuous medium, ft/sec
C_{sh}	Shaft Dampening, slug/sec
C_t	Toe Dampening, slug/sec
D	Diameter of Pile, ft.
e	Coefficient of Restitution, dimensionless
F	Cushion Force, lb
G	Shear Modulus of Elasticity, lbf/ft ²
I_0	Relative Impedance of Material, slug/sec-ft ²
k	Cushion Spring Constant, lb/ft
K_{sh}	Shaft Soil Spring Constant, lb/ft
K_t	Toe Soil Spring Constant, lb/ft
L	Pile Element Length, ft.
ρ	Density, slug/ft ³
R	Ultimate Resistance of soil, lb.
s	Set of pile, ft.
T_{mat}	Exponent of Cushion Rebound, dimensionless
W_{fp}	Energy Lost in Plastic Deformation of Soil, ft-lb
x	Deformation of Cushion, ft.
μ	Poisson's Ratio

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ACKNOWLEDGEMENTS

Thanks must go to Kevin F. Kett of Law Engineering, Inc., Jacksonville, FL, for furnishing all the information on the Blount Island job; Mr. Richard Nelson of Pile Equipment, Inc., Jacksonville, FL, for his tireless assistance in information procurement; and Dr. David Rempe for his use of preliminary versions of ZWAVE. Finally, this work was produced to the greater glory of God, with whom all of this was possible, and without whom no foundation can be laid.

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NOTES AND ADDENDA

Notes on the Internet Edition

In preparing this paper for electronic publication, every effort was made to insure fidelity with the original; however, a few changes were necessary, which are as follows:

- 1) The text was of course reformatted in a word processor, in this case Star Office 5.2. The formulae were formatted with a proper equation editor.
- 2) There were a couple of corrections from the original; also, the spelling was harmonised, as the instructions for the original conference demanded but was not carried out in the published paper.
- 3) Figures 1 and 2 were originally drawn in DesignCad for DOS 3.0. They were cut and paste into the text via DesignCad for Windows 7.0 and this resulted in some changes in the fonts. Figure 3 is now an actual screen shot and not the text dump of the original.
- 4) The disclaimer was added after the abstract.

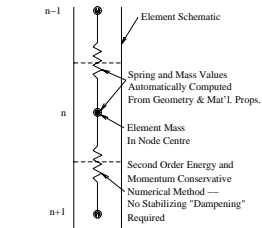
Addendum – Poster Session Presentations

The original conference encouraged presenters to present summaries of their material on posters so that the participants could view them in a Poster Session. Following this page are the posters for this paper. They give additional graphical views of the theory presented in the paper along with a graphical representation of the test case. As was the case in 1988, they enhance the understanding of the paper itself.

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ZWAVE Wave Equation Analyzer: Features



Computational and Numerical Features of ZWAVE

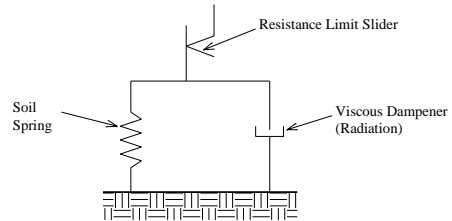


Figure 2 Soil Model for ZWAVE

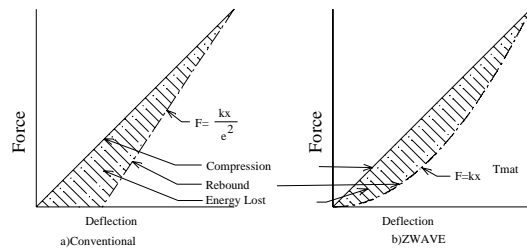


Figure 1 Cushion Models for Plastic Cushions

Other Features:

Advanced Soil Model -- computes soil radiation dampening, spring constant and quake from basic soil properties

Completely interactive input format

Energy Balance of System Computed

A NEW TYPE OF WAVE EQUATION ANALYSIS PROGRAM

Don C. Warrington, P.E., Vulcan Iron Works Inc.

ZWAVE Wave Equation Analyzer: Comparison

JOB SITE DESCRIPTION

Location: Blount Island, Jacksonville, FL
 Owner: Jacksonville Electric Authority
 Project: Test Pile Programme
 Contractor: S.K. Whitty and Co.

Pile Hammer: Vulcan 510, 50 ft-kip energy
 Piles: 14" and 20" Square Concrete
 16" and 24" Steel Pipe
 Soil: Fine Sands

Capacity Determination: ASTM D-1143/D-3689 Load Tests, CAPWAPC

