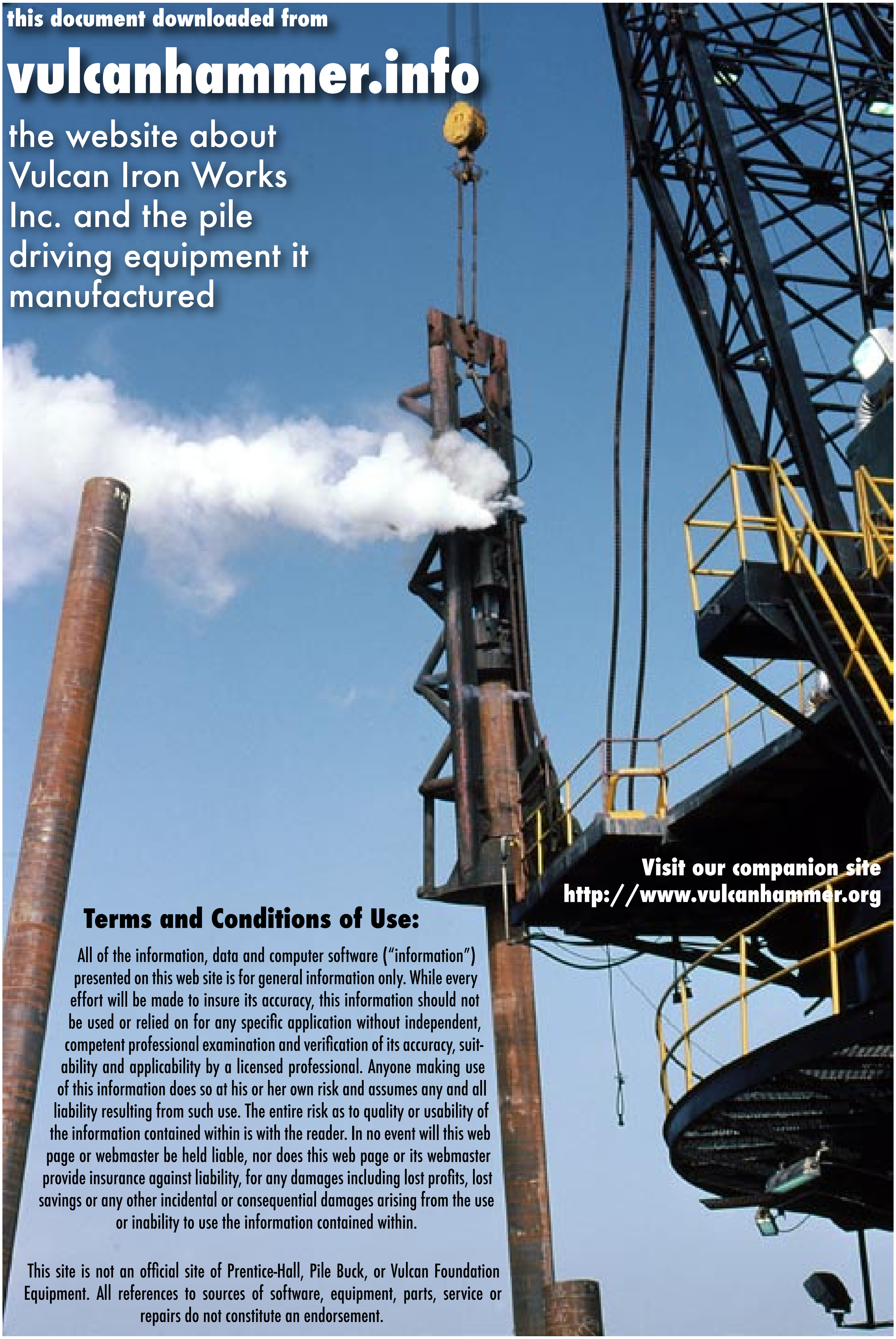

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A Pile Design Analyser for Academic Use

Don C. Warrington[1]

Abstract

A design analysis technique is presented for driven pile foundations. It is intended for an academic environment. Based on proven and publicly available code, a new set of routines was developed in PHP that enable the estimation of static pile capacity, the generation of axial load-deflection curves, the generation of p-y curves and their application using a finite-difference technique, the analysis of the response of a pile bent to both force and moment loads, and the driveability analysis of the piles using a wave equation program. An example of the use of the program is given along with proposals for future improvements.

Introduction

A large portion of driven pile foundations are for public works projects. It has been in the interest of public works authorities—national, state and local—to insure that these are designed and built in a manner that is economic, safe and performs the function required of the foundation. For this reason various agencies of the Federal and state governments have sponsored and disseminated a great deal of research, which is reflected in the design methods and codes in use today.

This activity extended to computer programs when computer aided design and analysis became viable for widespread use. Frequently the development of computer programs was either initiated or furthered by federal and/or state research sponsorship. And example of this is the finite difference wave equation analysis. This was originated in the private sector by Raymond Concrete Pile Company (Smith, 1960.) However, further development took place with the support of the government, both with the TTI (Lowery et. al., 1969; Hirsch et. al., 1976) and WEAP (Goble and Rausche, 1976) programs. Similarly the development of the p-y curve method for lateral pile analysis had extensive government involvement in addition to that of the oil companies, which used it in the design of offshore oil platforms (U.S. Army Corps of Engineers, 1996; the wave equation benefited from this as well.)

The result of government involvement was that, until the 1990's, most of the code for these programs was in the public domain. The nature of computers made the dissemination and use of the code the province of specialists, but advances in personal computers spread the use of these programs, useful if not always user-friendly. The advent of the internet made dissemination of these programs simple, both by federal (FHWA) and state (FL DOT) agencies and private websites (vulcanhammer.net).

In the meanwhile the nature of public works is the improvement of the productivity of an

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economic system, which adds value to the tools used in the design and construction of these projects. Thus organisations saw the commercial potential of taking publicly produced code, then enhancing and modernising it. Thus the wave equation WEAP was developed into GRLWEAP, the lateral pile analyser COM624 was developed into LPILE, and so forth. The commercial programs not only have been successful with designers and contractors, but their existence and examples of their use have been disseminated in government publications.

Although there is nothing inherently wrong with this process, certain classes of users found themselves at a disadvantage to invest in these commercial products. One of those were public works agencies and contractors outside of the developed countries where funding is not at the level of developed countries. Another group are those who only use the programs on an occasional basis, although many practitioners would argue that these organisations and individuals would be better off contracting a specialist for the kind of specialised design work these programs support.

But the one group probably at the greatest disadvantage in this situation are students. The long-term future of driven piles as a widespread form of deep foundations depends in part on the ability to introduce students to the design of driven piles at the undergraduate level, a fact recognised by organisations such as the PDCA with their educational course for college professors. But without the availability of computer routines to handle the more complex aspects of driven pile design—such as pile dynamics with the wave equation—the student's exposure to driven pile design remains limited.

The public domain programs such as Microwave, WEAP87, SPILE, Driven and COM624P are still available for academic use without charge, a significant advantage in an academic situation. Because of changes in the operating environment, these programs are becoming more problematic to run, and are still not as user-friendly as one would like. However, although programs such as Geo-Slope exist in free academic versions for general geotechnical analysis (which actually promote the full version in a commercial setting,) commercial routines have not been implemented in a similar way for driven pile design and analysis in an academic setting.

Purpose of the Project

The purpose of this project was to develop a driven pile analyser with the following characteristics:

1. The routine would analyse all basic aspects of driven pile performance, including basic static capacity, axial load-deflection behaviour, lateral load-deflection behaviour, and hammer-pile-soil performance during driving.
2. The routine would be available to students and instructors alike on a free basis.

3. The routine would be independent of the operating system of the student’s computer, which would obviate having to distribute it in multiple versions.

The project was carried out during the period 2004-6 on the vulcanhammer.net website. It is currently active at http://www.vulcanhammer.net/soils/.

Operating Environment and Theoretical Basis of the Routines

It was determined at the start that the simplest way to implement any of these design analysis routines was to do so on a web-based system. In this environment, the routines would be coded in PHP and the calculations performed on an ordinary web server. The results would be presented in standard HTML in a web browser, which could be then printed out or transferred to a spreadsheet for further analysis and graphical presentation.

This left us with the question of what routines to use. Academic routines do not require the extensive features expected of commercially used software, and the use of standard HTML forms provides an interactive method of data input. Moreover, although web servers do have the capacity to perform mathematical calculations, the distributed nature of their computing power limits the possible complexity of the analysis.

With all of this in mind, we determined that the best way of implementing the analyser was to take older codes, use them to construct new routines, and adapt the new codes for use on a web server. The codes we chose to begin with are as follows:

1. PX4C3, an axial pile load-deflection analyser developed by Harry Coyle (Texas A&M University) and Lymon Reese (University of Texas) in the 1960's. The primary purpose of this routine was to enable the student to run a “virtual load test” on the pile in question, which in turn would enable the application of various failure criteria.
2. BENT1, a pile bent analyser primarily intended for lateral loading analysis of piles either individually or as a group. It was written by Dr. Frazier Parker, Jr. at the Waterways Experiment Station in Vicksburg, MS under the guidance of Lymon Reese and Hudson Matlock. BENT1 also included the subroutine COM62, the ancestor of all of the COM624 and LPILE programs in use today, and MAKE, which generates p-y curves based on soil and pile properties.
3. TAMFOR, a time-shared version of the TTI wave equation program. This routine was also used for the ZWAVE program (Warrington, 1988), although the changes in theory implemented in that program were not incorporated into this one.

The first two routines are described in Radhakrishnan and Parker (1975) and the third by Holloway (1975). The use of these routines will be explained shortly.

The one “missing link” in all of this was a routine to estimate the static capacity of the pile, a necessary prerequisite for both the "virtual load test" and certainly the wave equation analysis. This was constructed independently, as will be shown below.

Construction of PHP Code

All of the routines that were used to develop the current analyser were written in FORTRAN and run on computers using card input and line printed output (Cress et. al., 1968). In addition to the vast changes in I/O that have taken place with computers since these were written, most of the programming languages in use on the internet today—PHP, Java, JavaScript, CGI, Perl, etc.—are heavily inspired in their syntax by C. Both of these facts required extensive rewriting of the codes, which in many cases transformed the codes beyond recognition. Some of the issues in reconstructing these codes are as follows:

- All of the input and output routines had to be rewritten. The input is performed through standard HTML forms. Obviously input of later variables was dependent upon earlier ones. For example, property input of clay soils requires different parameters than that of sands, and so the dialogues for each of these is different.
- The various routines were constructed on different web pages. Data (either input or computed) transferred from one page to the next was done using the "GET" method, i.e., passed through the URL. This both made checking passed parameters simpler and enables a specific case to be performed at a later stage in the analysis without having to go through the earlier stages.
- Although PHP has the necessary mathematical functions needed for these analyses, the extensive use of "arithmetic if" statements in the FORTRAN routines (a statement with no counterpart in PHP) made rewriting the logic of the routines necessary, which in some cases made exact replication of the original results impossible. This was especially true with the BENT1 set of routines.

Construction of the Analyser

The final result of this code transformation is a system of routines which can be divided into four (4) parts.

1. Dennis and Olson Analyser
    a. This method is described in Dennis and Olson (1983a, 1983b) and summarised by Schroeder et. al. (2003).
    b. The soil is assumed to be homogeneous, and the pile top and soil surface are assumed to be the same. No "free" pile protrusion is allowed.
    c. The pile is assumed to have a uniform cross section all along its length, both for

    cross sectional area and perimeter. There is a separate input for pile toe area (as opposed to cross-sectional area,) which allows the analysis of piles such as closed ended pipe piles.

   d. The water table is located somewhere between the pile head and the pile toe. If it is input outside of these limits, the program will adjust the location of the water table.
   e. Assumptions (b), (c) and (d) apply to all aspects of the design analyser.
   f. At this time calculations are only available in U.S. Units. This limitation extends to all of the routines.

2. TAMAXIAL
   a. This program attempts to simulate the results of a load test of the pile analysed by the Dennis and Olson Method. Using the same information, it generates a pile head load-deflection curve. It does this by using a finite difference program and generated t-z curves along the pile. The program is based on the PX4C3 routine. The program uses the given load transfer vs. pile movement curves and computes the load settlement characteristics of an axially loaded pile. Load transfer vs. pile movement curve is designated as t-z curve. The program interpolates point bearing values corresponding to a given toe movement from a previously input point bearing vs. toe movement curve. The program then solves the pile head deflection using a finite difference technique.
   b. Since we do not have actual load-deflection results or experimentally determined t-z curves, we used an eclectic collection of t-z curves from research data. These can be found in Mosher and Dawkins (2000). From this document, we used the SSF4 and SF5 methods for pile shafts and toes (respectively) in sand and CSF1 and the method of Ashenbrener and Olson (1984) methods for pile shafts and toes in clay.
   c. Once these load-displacement curves are generated, methods such as Davisson's methods can be used to determine the pile capacity, which in turn can be compared with the results of the Dennis and Olson method.
3. TAMBENT
   a. This set of routines computes the horizontal and vertical deflection and rotation of a group of piles joined together by a pile cap. It also computes the lateral deflections and moments on piles in the group.
   b. TAMBENT calls a subroutine based on COM62 that uses a finite difference routine to analyse the effects of lateral loading of each pile in the group. The results are then applied to the entire structure. As this is a non-linear phenomenon, the analysis is iterative.

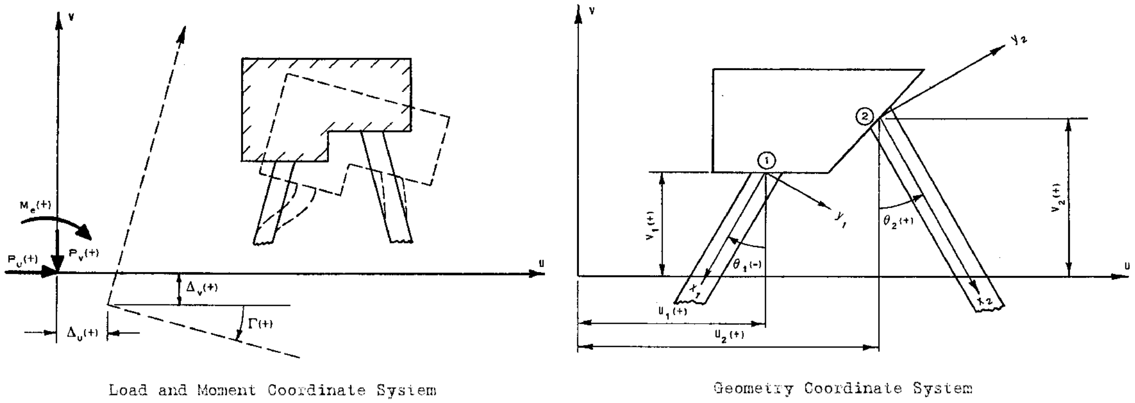
c. In addition to analysing the lateral load-deflection behaviour of the structure, TAMBENT also includes the axial load-deflection curves in its analysis. The axial load-settlement curves for the piles are generated using the TAMAXIAL program described above.

d. In addition to the data entered for the single piles, it is necessary to enter the information for each pile location. TAMBENT is a two-dimensional analyser, but multiple piles at a given location are permitted. Figure 1 shows the geometry used for the tabular entry at the bottom of the page.

e. The p-y curves in this program are always generated, based on the theory described in Radhakrishnan and Parker (1975). Work since then has vastly advanced our understanding of the actual profile of p-y curves from what is shown in this program. The program always generates six p-y curves for each pile, one at the head, one at the toe, and the other four evenly spaced in between. p-y curves for segments between these points are found through linear interpolation. This routine is *strictly* for teaching purposes; for anything beyond very basic instruction and certainly for analysis of real piles, one should use a program such as COM624 or LPILE.

f. No lateral or axial group effects are included in this analysis. No seismic or cyclical loading can be analysed by this routine.

Figure 1 Pile Group Coordinate Systems (after Parker and Radhakrishnan, 1975)



Load and Moment Coordinate System

Geometry Coordinate System

4. TAMWAVE

a. Ultimate pile capacity data is taken from the results of the Dennis and Olson method analysis.

b. A triangular distribution is assumed for cohesionless soils. A uniform distribution is assumed for cohesive soils.

c. Wave equation properties for Vulcan and Raymond hammers are included in the hammer list. The values listed are nominal and may not match what actually exists in the field (this is especially true with the cap weights.) Only external combustion hammers with hammer cushions can be analysed with TAMWAVE. This excludes diesel hammers, cushionless hammers such as the IHC, and non-impact hammers.

d. Hammers are analysed only at full energy. If the tensile stresses at lower resistances exceed allowable stresses (especially with concrete piles,) this indicates that the hammer energy needs to be reduced at lower resistances (such as those encountered in the early stages of driving.) This is normal practice; more developed wave equation programs can analyse this problem directly.

e. Pile cushions are assumed to be plywood.

f. Hammer cushion data can be obtained from Goble and Rausche (1986). In the absence of this, the following properties can be used:

   i. Micarta and Aluminium: E=350,000 psi, e=0.8

   ii. Hamortex: E=125,000 psi, e=0.77

g. The model is limited to 21 pile elements. For 5' maximum segment lengths, this limits the pile length to 105' and for 10' segments 210'. Beyond this the segment lengths are excessive by any accepted criteria.

h. The program does not take into consideration any increase or decrease in pile capacity after driving. More information on this can be found in Hannigan et. al. (1997).

i. There are no graphical capabilities associated with this program. Force-time curves are not available. The program will always output a "bearing graph" list of pile resistances vs. blow counts and these can be plotted with a spreadsheet. If only the bearing graph appears, this indicates that the hammer selected will not induce any set in pile at all at the resistance calculated by the Dennis and Olson method.

These routines are in turn incorporated into four web pages of data input and analysis; these are as follows:

1. The first page accepts basic input for the Dennis and Olson method estimation of pile capacity. The program asks for basic pile parameters (size, material, length, etc.) and the basic soil type. The routine at this stage also asks for input of the number of piles to be analysed in a group; up to ten different pile locations in a bent is allowed, and the locations can have multiple piles. Entry of zero allows the user to skip pile bent (and lateral pile) analysis.

2. The second page is a continuation of the first in that it asks for detailed soil properties

based on the type of soil selected earlier. It also asks for the pile top arrangement for multiple-pile bent analysis if that was allowed earlier, requiring both the location of the pile top from a selected origin and the batter angle of the piles. Single pile lateral analysis can also be performed if desired.

3. The third page performs several steps:
    a. It reports the results of the Dennis and Olson method for basic pile capacity.
    b. It processes the data for axial and lateral analysis.
    c. It generates the axial load-settlement curve by calling the TAMAXIAL routine. These curves are output in tabular form. We did not generate graphical data as we felt that this was best left to the student.
    d. If requested earlier, it analyses the lateral load-deflection behaviour of the piles (individual or group) by calling the TAMBENT routine, which in turn calls the routines for p-y curve generation and the finite-difference analysis of the piles in lateral loading.
4. The last page is for the TAMWAVE wave equation analyser. It asks for some additional data. TAMWAVE has its own small hammer database. Data is output in tabular form.

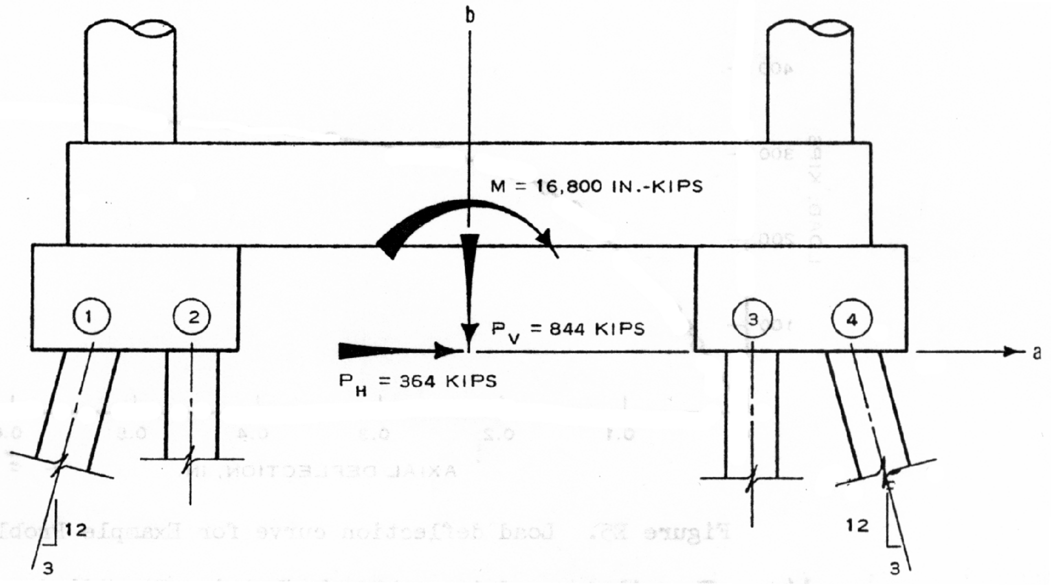
As mentioned earlier, the routines were encoded and tested over a three year period. The Dennis and Olson pile capacity calculator and the TAMWAVE wave equation were done and put on vulcanhammer.net in 2004. The following year saw the addition of the TAMAXIAL routine and 2006 saw the addition of TAMBENT.

Example Problem

The best way to show the operation and capabilities of the analyser is through an example. This example is adapted from Parker and Radhakrishnan (1975).

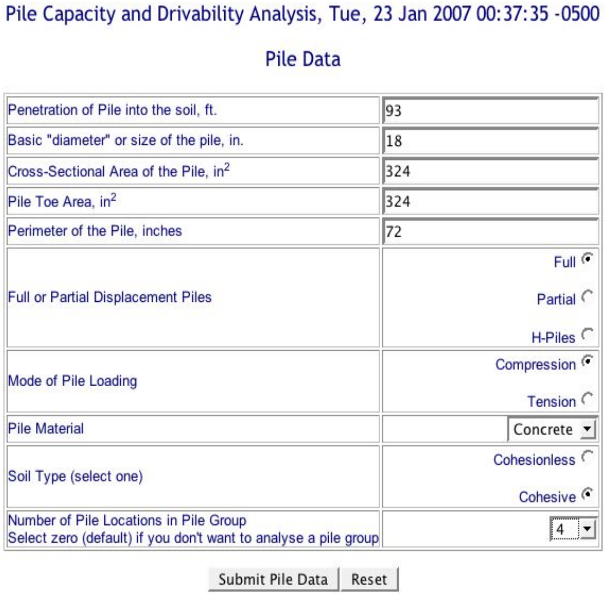
In this case, it is proposed to drive 93' long 18" prestressed concrete piles through a very soft clay (γ = 92 pcf, c = 500 psf.) The water table is at the soil surface. The piles are arranged in a six-pile bent with four pile locations as shown in Figure 2 with the outer piles 10.5' from the origin and the inner piles 7.5' from the origin. All of the pile heads are located on the x-axis. The outer piles are also at a 3:12 (14°) batter as shown. The figure also shows the force and moment loading on the bent. It should be noted that the capacity computed by the Dennis and Olson method is independent of these values.

Figure 2 Layout of Pile Bent (after Parker and Radhakrishnan, 1975)



The first thing to do is to enter the basic values of the pile and bent configuration, as is shown in the screen shot of the opening web form (Figure 3.)

Figure 3 First Page Web Form



Pile Capacity and Drivability Analysis, Tue, 23 Jan 2007 00:37:35 -0500

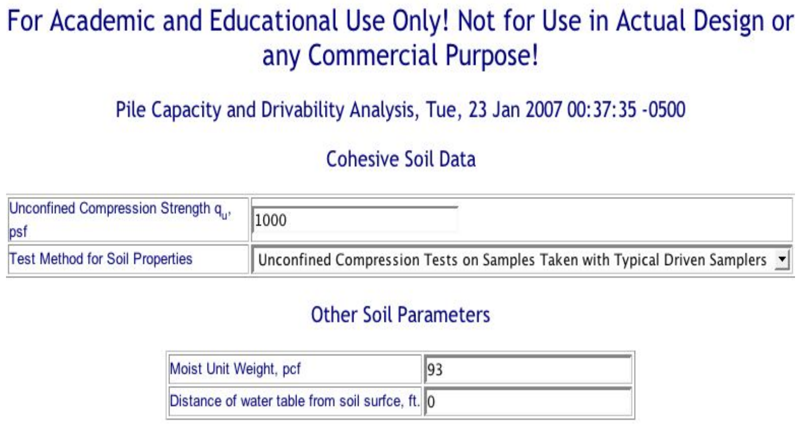
Pile Data

Penetration of Pile into the soil, ft.	93
Basic "diameter" or size of the pile, in.	18
Cross-Sectional Area of the Pile, in^2	324
Pile Toe Area, in^2	324
Perimeter of the Pile, inches	72
Full or Partial Displacement Piles	Full ● Partial ○ H-Piles ○
Mode of Pile Loading	Compression ● Tension ○
Pile Material	Concrete
Soil Type (select one)	Cohesionless ○ Cohesive ●
Number of Pile Locations in Pile Group Select zero (default) if you don't want to analyse a pile group	4

The pile loading mode is for the benefit of the Dennis and Olson analysis; choosing tension simply excludes the toe resistance from the pile capacity.

Once this data is submitted, the program passes to the second page, where additional soil data is requested, as shown in Figure 4.

Figure 4 Second Page Soil Data Form



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Pile Capacity and Drivability Analysis, Tue, 23 Jan 2007 00:37:35 -0500

Cohesive Soil Data

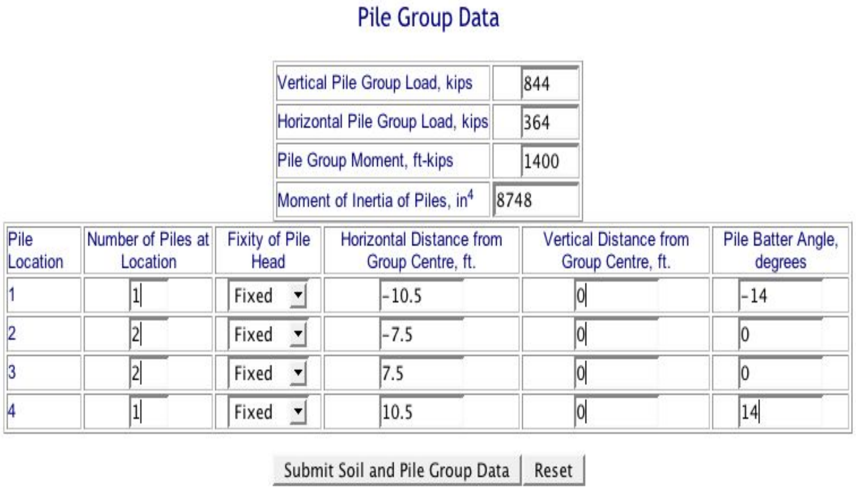
Unconfined Compression Strength q_u, psf	1000
Test Method for Soil Properties	Unconfined Compression Tests on Samples Taken with Typical Driven Samplers

Other Soil Parameters

Moist Unit Weight, pcf	93
Distance of water table from soil surfce, ft.	0

Since we opted for a pile bent, the second page also gives us the opportunity to enter the basic pile bent geometry, as shown in Figure 5.

Figure 5 Pile Bent Geometry Data Form



Pile Group Data

Vertical Pile Group Load, kips	844
Horizontal Pile Group Load, kips	364
Pile Group Moment, ft-kips	1400
Moment of Inertia of Piles, in^4	8748

Pile Location	Number of Piles at Location	Fixity of Pile Head	Horizontal Distance from Group Centre, ft.	Vertical Distance from Group Centre, ft.	Pile Batter Angle, degrees
1	1	Fixed	-10.5	0	-14
2	2	Fixed	-7.5	0	0
3	2	Fixed	7.5	0	0
4	1	Fixed	10.5	0	14

Once this data is submitted, the third page appears with the results from the Dennis and Olson method, TAMAXIAL and TAMBENT. The Dennis and Olson results are shown in Table 1.

Table 1 Pile Ultimate Capacity Analysis Results

	Penetration of Pile into the Soil, ft.	93	
	Basic "diameter" or size of the pile, ft.	1.5	
	Cross-sectional Area of the Pile, ft^2	2.250	
	Pile Toe Area, ft^2	2.250	
	Perimeter of the Pile, ft.	6.000	
	Pile Material	Concrete	
	Cohesion c, ksf	0.50	
	Strength Correction Factor F_c, psf	1.800	
	Pile Length Factor F_L	1.000	
	Adhesion Factor alpha	0.753	
	Unit Shaft Friction, ksf	0.68	
	Total Shaft Area, ft^2	558.000	
	Total Shaft Friction Q_s, kips	378.16	
	Unit Toe Resistance q_p, ksf	8.10	
	Total Toe Resistance Q_p, kips	18.23	
	Ultimate Resistance of Pile, kips	396.38	

The program then reports the p-y curves it has generated. Since the pile and soil conditions are identical for all piles and bent locations, there is only one set, as shown in Table 2.

Table 2 p-y Curve Set for Piles

Curve Number 1 and depth to curve is 0 inches

Wedge Failure Governs

Soil Reaction, pounds	Lateral Deflection, inches
0.0	0.000
125.0	0.043
125.0	180.000

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Curve Number 2 and depth to curve is 223.2 inches

Flow Failure Governs

Soil Reaction, pounds	Lateral Deflection, inches
0.0	0.000
217.4	0.144
307.5	0.288
376.6	0.432
434.8	0.576
486.1	0.720
532.5	0.864
575.2	1.008
614.9	1.152
652.2	1.296
687.5	1.440
687.5	180.000

Curve Number 3 and depth to curve is 446.4 inches

Flow Failure Governs

Soil Reaction, pounds	Lateral Deflection, inches
0.0	0.000
217.4	0.144
307.5	0.288
376.6	0.432
434.8	0.576
486.1	0.720
532.5	0.864
575.2	1.008
614.9	1.152
652.2	1.296
687.5	1.440
687.5	180.000

A Pile Design Analyser for Academic Use

Curve Number 4 and depth to curve is 669.6 inches

Flow Failure Governs

Soil Reaction, pounds	Lateral Deflection, inches
0.0	0.000
217.4	0.144
307.5	0.288
376.6	0.432
434.8	0.576
486.1	0.720
532.5	0.864
575.2	1.008
614.9	1.152
652.2	1.296
687.5	1.440
687.5	180.000

Curve Number 5 and depth to curve is 892.8 inches

Flow Failure Governs

Soil Reaction, pounds	Lateral Deflection, inches
0.0	0.000
217.4	0.144
307.5	0.288
376.6	0.432
434.8	0.576
486.1	0.720
532.5	0.864
575.2	1.008
614.9	1.152
652.2	1.296
687.5	1.440
687.5	180.000

Curve Number 6 and depth to curve is 1116 inches

Flow Failure Governs

Soil Reaction, pounds	Lateral Deflection, inches
0.0	0.000
217.4	0.144
307.5	0.288
376.6	0.432
434.8	0.576
486.1	0.720
532.5	0.864
575.2	1.008
614.9	1.152
652.2	1.296
687.5	1.440
687.5	180.000

The axial load-deflection curve is also generated, both in tension and compression, as different piles in the bent will be put in different loading modes. This is identical for all of the piles and is shown in Table 3.

Table 3 Axial Load-Deflection Data for the Pile Head

Point Number	Pile Settlement, inches	Pile Load, kips
1	-18.000	-325.82
2	-1.117	-325.82
3	-1.097	-325.82
4	-1.077	-325.82
5	-1.057	-325.82
6	-1.037	-325.82
7	-1.017	-325.82
8	-0.997	-325.82
9	-0.977	-325.82
10	-0.957	-325.82
11	-0.937	-325.82
12	-0.917	-325.82
13	-0.897	-325.82
14	-0.877	-325.82
15	-0.857	-325.82

16	-0.837	-325.82
17	-0.817	-325.82
18	-0.797	-325.82
19	-0.777	-325.82
20	-0.757	-325.82
21	-0.737	-325.82
22	-0.717	-325.82
23	-0.697	-325.82
24	-0.677	-325.82
25	-0.657	-325.82
26	-0.637	-325.82
27	-0.617	-325.82
28	-0.597	-325.82
29	-0.577	-325.82
30	-0.557	-325.82
31	-0.537	-325.82
32	-0.517	-325.82
33	-0.497	-325.82
34	-0.477	-325.82
35	-0.457	-325.82
36	-0.437	-325.82
37	-0.417	-325.82
38	-0.397	-325.82
39	-0.377	-325.82
40	-0.357	-325.97
41	-0.337	-326.58
42	-0.318	-327.46
43	-0.298	-328.53
44	-0.278	-329.61
45	-0.259	-330.91
46	-0.241	-333.18
47	-0.222	-335.39
48	-0.203	-335.80
49	-0.183	-334.28
50	-0.153	-313.13
51	-0.087	-203.33

52	0.000	0.00
53	0.090	209.19
54	0.156	318.86
55	0.187	340.76
56	0.208	344.03
57	0.229	345.60
58	0.249	345.26
59	0.269	344.96
60	0.290	345.61
61	0.310	346.49
62	0.330	345.50
63	0.350	344.70
64	0.369	344.16
65	0.389	344.05
66	0.409	344.05
67	0.429	344.05
68	0.449	344.05
69	0.469	344.05
70	0.489	344.05
71	0.509	344.05
72	0.529	344.05
73	0.549	344.05
74	0.569	344.05
75	0.589	344.05
76	0.609	344.05
77	0.629	344.05
78	0.649	344.05
79	0.669	344.05
80	0.689	344.05
81	0.709	344.05
82	0.729	344.05
83	0.749	344.05
84	0.769	344.05
85	0.789	344.05
86	0.809	344.05
87	0.829	344.05

88	0.849	344.05
89	0.869	344.05
90	0.889	344.05
91	0.909	344.05
92	0.929	344.05
93	0.949	344.05
94	0.969	344.05
95	0.989	344.05
96	1.009	344.05
97	1.029	344.05
98	1.049	344.05
99	1.069	344.05
100	1.089	344.05
101	1.109	344.05
102	1.129	344.05
103	18.000	344.05

The results of the iteration are then reported in Table 4. As we noted earlier, the non-linear nature of the problem requires some kind of iterative solution. The iteration data shows the course of the convergence of the solution.

Table 4 Iteration Data for the Problem

Iteration Number	Vertical Deflection, inches	Horizontal Deflection, inches	Pile Head Rotation, degrees
1	0.412	0.258	0.078
2	0.195	0.311	0.051
3	0.107	0.276	0.022
4	0.072	0.249	0.006
5	0.063	0.232	0.002
6	0.063	0.228	0.002
7	0.063	0.228	0.002

The iteration data also shows the final vertical and horizontal deflection of the bent, along with its rotation.

The routine then proceeds to output the results for each pile group in the bent. Since the output is extensive, we will show the results for only one group, #1.

The first output is some general data about the pile group.

Table 5 General Information about Pile Group 1

Horizontal Coordinate of Pile Head, feet	10.50
Vertical Coordinate of Pile Head, feet	0.00
Pile Batter Angle, degrees	14.000
Axial Load on Pile at Pile Head, kips	259.45
Axial Deflection of Pile at Pile Head, Inches	0.120
Lateral Load on Pile at Pile Head, kips	46.12
Moment on Pile at Pile Head, ft-kips	-173.55
Lateral Deflection of Pile at Pile Head, inches	0.205
End Fixity of Pile Head	Fixed
Pile Head Size, inches	18
Length of Pile Increments, feet	1.00
Number of Increments	93
Set of p-y curves being used	1
Axial settlement curve being used	4
Pile Length, feet	93.00
Depth to Soil, feet	0.00
Iteration Tolerance, inches	0.001
Rotational Restraint Value	0.000
Boundary Condition 2	-0.00003

From here the shear, moment, deflection and lateral soil force are tabulated as a function of depth.

Table 6 Shear, Moment, Deflection and Lateral Soil Force as a Function of Depth for Pile Group 1

Depth, feet	Lateral Deflection y, inches	Moment, foot-kips	Lateral Soil Modulus, ksi	p, lb/ft
0.000	0.205	-173.569	2.89	-7,127.59
1.000	0.201	-129.372	2.82	-6,815.55
2.000	0.193	-91.880	2.74	-6,341.96
3.000	0.180	-60.651	2.67	-5,767.98
4.000	0.165	-35.138	2.60	-5,141.76
5.000	0.149	-14.738	2.52	-4,500.22
6.000	0.132	1.176	2.45	-3,870.75
7.000	0.115	13.217	2.37	-3,272.80
8.000	0.099	21.974	2.30	-2,719.36
9.000	0.083	27.993	2.22	-2,218.28

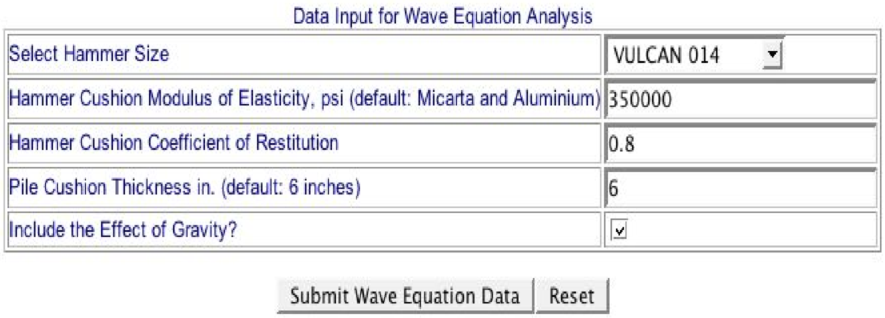
10.000	0.069	31.770	2.15	-1,773.36
11.000	0.056	33.747	2.08	-1,385.36
12.000	0.044	34.309	2.00	-1,052.78
13.000	0.033	33.789	1.93	-772.58
14.000	0.024	32.468	1.85	-540.66
15.000	0.017	30.578	1.78	-352.34
16.000	0.010	28.310	1.70	-202.65
17.000	0.004	25.815	1.63	-86.61
18.000	-0.000	23.212	1.55	0.61
19.000	-0.004	20.589	1.51	64.85
20.000	-0.006	18.013	1.51	114.38
21.000	-0.008	15.537	1.51	151.01
22.000	-0.010	13.198	1.51	176.53
23.000	-0.011	11.025	1.51	192.59
24.000	-0.011	9.034	1.51	200.77
25.000	-0.011	7.237	1.51	202.47
26.000	-0.011	5.636	1.51	199.00
27.000	-0.011	4.229	1.51	191.50
28.000	-0.010	3.010	1.51	180.97
29.000	-0.009	1.970	1.51	168.28
30.000	-0.009	1.096	1.51	154.18
31.000	-0.008	0.375	1.51	139.30
32.000	-0.007	-0.207	1.51	124.16
33.000	-0.006	-0.664	1.51	109.15
34.000	-0.005	-1.012	1.51	94.63
35.000	-0.004	-1.264	1.51	80.83
36.000	-0.004	-1.434	1.51	67.93
37.000	-0.003	-1.535	1.51	56.06
38.000	-0.003	-1.579	1.51	45.29
39.000	-0.002	-1.576	1.51	35.65
40.000	-0.001	-1.536	1.51	27.14
41.000	-0.001	-1.468	1.51	19.73
42.000	-0.001	-1.379	1.51	13.37
43.000	-0.000	-1.275	1.51	7.99
44.000	-0.000	-1.162	1.51	3.53
45.000	0.000	-1.044	1.51	-0.10

46.000	0.000	-0.926	1.51	-2.98
47.000	0.000	-0.810	1.51	-5.20
48.000	0.000	-0.698	1.51	-6.84
49.000	0.000	-0.593	1.51	-7.98
50.000	0.000	-0.495	1.51	-8.70
51.000	0.001	-0.406	1.51	-9.06
52.000	0.001	-0.325	1.51	-9.13
53.000	0.000	-0.253	1.51	-8.97
54.000	0.000	-0.189	1.51	-8.63
55.000	0.000	-0.135	1.51	-8.15
56.000	0.000	-0.088	1.51	-7.58
57.000	0.000	-0.049	1.51	-6.94
58.000	0.000	-0.016	1.51	-6.27
59.000	0.000	0.010	1.51	-5.58
60.000	0.000	0.030	1.51	-4.91
61.000	0.000	0.046	1.51	-4.25
62.000	0.000	0.057	1.51	-3.63
63.000	0.000	0.065	1.51	-3.05
64.000	0.000	0.069	1.51	-2.51
65.000	0.000	0.071	1.51	-2.03
66.000	0.000	0.071	1.51	-1.59
67.000	0.000	0.069	1.51	-1.21
68.000	0.000	0.066	1.51	-0.88
69.000	0.000	0.062	1.51	-0.59
70.000	0.000	0.057	1.51	-0.35
71.000	0.000	0.052	1.51	-0.14
72.000	-0.000	0.047	1.51	0.02
73.000	-0.000	0.042	1.51	0.15
74.000	-0.000	0.037	1.51	0.25
75.000	-0.000	0.032	1.51	0.33
76.000	-0.000	0.027	1.51	0.38
77.000	-0.000	0.023	1.51	0.41
78.000	-0.000	0.019	1.51	0.43
79.000	-0.000	0.015	1.51	0.43
80.000	-0.000	0.012	1.51	0.42
81.000	-0.000	0.010	1.51	0.41

82.000	-0.000	0.007	1.51	0.38
83.000	-0.000	0.005	1.51	0.35
84.000	-0.000	0.004	1.51	0.32
85.000	-0.000	0.003	1.51	0.29
86.000	-0.000	0.002	1.51	0.25
87.000	-0.000	0.001	1.51	0.21
88.000	-0.000	0.001	1.51	0.17
89.000	-0.000	0.000	1.51	0.13
90.000	-0.000	0.000	1.51	0.09
91.000	-0.000	0.000	1.51	0.05
92.000	-0.000	0.000	1.51	0.01
93.000	0.000	-0.102	1.51	-0.03

After this the wave equation analysis is performed. The input data is shown in Figure 6.

Figure 6 Input Data Screen Shot for the Wave Equation Analysis



Data Input for Wave Equation Analysis

Select Hammer Size	VULCAN 014
Hammer Cushion Modulus of Elasticity, psi (default: Micarta and Aluminium)	350000
Hammer Cushion Coefficient of Restitution	0.8
Pile Cushion Thickness in. (default: 6 inches)	6
Include the Effect of Gravity?	☑

The TAMWAVE routine allows for a “trial and error” procedure to determine the appropriate hammer to drive the piles. Thus several hammers can be tried without having to re-analyse the entire system.

Once TAMWAVE is run, the results are presented, as shown in Tables 6 through 9.

Table 6 Basic Parameters of the Wave Equation Analysis

Time Step, sec	0.00020
L/c, sec	0.00748
Pile Toe Element Number	21
Length of Pile Segments, ft.	4.8947368421053
Shaft Friction Distribution	Uniform
Gravity Included?	Yes
Hammer Manufacturer and Size	VULCAN 014
Hammer Rated Striking Energy, ft-lbs	42000
Hammer Efficiency, percent	67
Length of Hammer Cushion Stack, in.	16.500
Total Resistance *for detailed results only*, kips	396.4
Percent at Toe	4.60
Toe Quake, in.	0.150
Shaft Quake, in.	0.100
Toe Damping, sec/ft	0.15
Shaft Damping, sec/ft	0.20

Table 7 Element Data for Wave Equation Analysis

Element	Element Weight, lbs.	Element Stiffness, kips/in	Element Cross-Sectional Area, in^2	Element Soil Resistance, kips	Element Slack, inches	Element Coefficient of Restitution	Element Initial Velocity, ft/sec	Element Soil Shaft Stiffness, kips/in
1	14,000.0	4,957.5	233.71	0.0	1,000.000	0.80	11.38	0.0
2	3,800.0	1,530.1	324.00	0.0	1,000.000	0.54	0.00	0.0
3	1,652.0	27,580.6	324.00	19.9	0.000	1.00	0.00	199.0
4	1,652.0	27,580.6	324.00	19.9	0.000	1.00	0.00	199.0
5	1,652.0	27,580.6	324.00	19.9	0.000	1.00	0.00	199.0
6	1,652.0	27,580.6	324.00	19.9	0.000	1.00	0.00	199.0
7	1,652.0	27,580.6	324.00	19.9	0.000	1.00	0.00	199.0
8	1,652.0	27,580.6	324.00	19.9	0.000	1.00	0.00	199.0
9	1,652.0	27,580.6	324.00	19.9	0.000	1.00	0.00	199.0
10	1,652.0	27,580.6	324.00	19.9	0.000	1.00	0.00	199.0
11	1,652.0	27,580.6	324.00	19.9	0.000	1.00	0.00	199.0
12	1,652.0	27,580.6	324.00	19.9	0.000	1.00	0.00	199.0
13	1,652.0	27,580.6	324.00	19.9	0.000	1.00	0.00	199.0
14	1,652.0	27,580.6	324.00	19.9	0.000	1.00	0.00	199.0
15	1,652.0	27,580.6	324.00	19.9	0.000	1.00	0.00	199.0
16	1,652.0	27,580.6	324.00	19.9	0.000	1.00	0.00	199.0
17	1,652.0	27,580.6	324.00	19.9	0.000	1.00	0.00	199.0
18	1,652.0	27,580.6	324.00	19.9	0.000	1.00	0.00	199.0
19	1,652.0	27,580.6	324.00	19.9	0.000	1.00	0.00	199.0
20	1,652.0	27,580.6	324.00	19.9	0.000	1.00	0.00	199.0
21	1,652.0	121.5	324.00	19.9	1,000.000	1.00	0.00	199.0
22	0.0	0.0	0.00	18.2	0.000	0.00	0.00	0.0

Table 8 Detailed Results for Wave Equation Analysis at Dennis and Olson Computed Capacity

Element	Time Step for Maximum Compressive Stress	Maximum Compressive Stress, ksi	Time Step for Maximum Tensile Stress	Maximum Tensile Stress, ksi	Maximum Deflection, in.	Final Deflection, in.	Final Velocity, ft/sec
1	10	3.69	289	0.00	0.880	-4.637	-11.38
2	29	1.93	289	0.00	0.777	0.065	-0.90
3	30	1.88	120	0.13	0.324	0.224	-0.41
4	32	1.82	122	0.25	0.315	0.223	-0.46
5	34	1.77	123	0.36	0.314	0.222	-0.45
6	36	1.71	124	0.42	0.314	0.221	-0.42
7	38	1.66	156	0.41	0.313	0.219	-0.37
8	40	1.60	85	0.44	0.308	0.217	-0.32
9	43	1.55	86	0.48	0.302	0.216	-0.28
10	45	1.50	88	0.47	0.298	0.216	-0.24
11	47	1.44	89	0.47	0.300	0.216	-0.22
12	49	1.39	89	0.37	0.305	0.217	-0.22
13	51	1.34	140	0.33	0.310	0.218	-0.26
14	53	1.28	140	0.40	0.311	0.219	-0.30
15	50	1.22	101	0.43	0.310	0.220	-0.30
16	51	1.17	102	0.57	0.308	0.221	-0.27
17	51	1.08	102	0.66	0.308	0.222	-0.28
18	51	0.91	102	0.65	0.313	0.223	-0.34
19	52	0.67	103	0.54	0.320	0.223	-0.43
20	52	0.37	103	0.29	0.326	0.223	-0.53
21	63	0.09	190	0.00	0.329	0.224	-0.58

Table 9 Bearing Graph and Summary Results of Wave Equation Analysis

Permanent Set of Pile Toe, inches	Blows per Foot of Penetration	Soil Resistance, kips	Maximum Compressive Stress, ksi	Element of Maximum Compressive Stress	Maximum Tensile Stress, ksi	Element of Maximum Tensile Stress	Number of Iterations
1.198	10.0	99.1	1.89	3	1.34	10	350
0.483	24.9	198.2	1.89	3	1.00	10	314
0.284	42.2	297.3	1.88	3	0.79	17	299
0.179	66.9	396.4	1.88	3	0.66	17	289
0.092	130.8	495.5	1.87	3	0.53	18	283
0.019	638.6	594.6	1.86	3	0.40	18	278
0.000	0.0	693.7	1.86	3	0.35	18	275

All of the results can be copied and pasted into a spreadsheet for further analysis and graphical presentation. Once the analysis is complete, the entire process can be started once again.

A Pile Design Analyser for Academic Use

Discussion

- The primary objective of the analyser is to provide reasonable results for the input data. This has been achieved. The analyser enables the student to perform complex computations on basic systems, irrespective of the computer and operating system that he or she has.
- One serious objection to the code upon which the analyser is based is that it is very old. There are two ways to respond to this.
  - The first is that it was necessary to limit the web server resources the PHP code required for analysis. The simplest way to do this was to use routines designed for very old computers with limited power. It is a testament to the expansion of computer power that routines that once required a very large and expensive computer to run now can be performed on a web server with its “shared” resources.
  - The second is that the basic theory behind many of the analytical techniques used for deep foundations today has not advanced as much as one would like to think. The wave equation, for example, is still a one-dimensional, finite-difference analysis, even though it has been enhanced with the addition of diesel hammers, residual stress analysis, and the like. The p-y curve method likewise requires a one-dimensional finite-difference technique. Both of these techniques have had long roads to general acceptance from their original formulation and dissemination in the 1970’s. For example, the general method of dealing with lateral loads on driven pile foundations has been to use batter piles, thus transforming a lateral problem into an axial one. It took almost twenty years from the origination of the p-y method to “general acceptance” as a method for designing laterally loaded pile foundations. The wave equation’s own “road” has only been a little shorter than this. The “antiquity” of the code used here is a reminder that the incorporation of new techniques into foundation design is not as rapid of a process as one would like.
- One thing that was necessary with this code was to “feature limit” it so as to actively discourage it from commercial use. The “academic use only” disclaimer is prominently displayed on every page of the analysis. This is done with other software (Geo-Slope) as well. However, there are some features which probably need to be added in future updates to the routine, such as allowing pile protrusion above the soil surface. Some enhancements to the output may also be in order.

Conclusion

The design analyser shown here is a viable instruction tool for both the static design of pile foundations and bents (both axial and lateral) and the wave equation analysis of the installation. Its use of an open source server language (PHP) and the ability to interact with a web browser make it ideal for wide use. It is not only subject to future improvement, but also hopefully will inspire other efforts along the same lines so as to help further the education of civil engineers in the design and installation of driven piles.

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