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The Use of Spreadsheets for the Seismic Design of Piles

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Keywords

deep foundations, seismic design, soil-structure interaction, spreadsheet, civil engineering education

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The Use of Spreadsheets for the Seismic Design of Piles

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Abstract

Understanding the response of pile foundations to seismic loads is a necessary prerequisite to properly analyze and/or design them. This objective presents the civil engineering student and teacher with a complex problem, which typically challenges and strains the traditional didactic educational approach. In teaching the topic, we had faced significant difficulties in meeting the challenge of leaving the students with a thorough appreciation and understanding of the material. This was reflected in course evaluation results and comments. As such, an attempt was initiated to improve and enhance the learning/teaching process by incorporating a spreadsheet-based set of analysis/design tools with associated graphical representations. The approach described herein proved to be an effective and accessible method, according to the feedback solicited from students. In this paper, the basic background and available methods for the design of laterally loaded piles are presented along with the developed spreadsheet tool. Two design methods were included; one is a commonly used solution for laterally loaded piles; the other is a hybrid method which we compiled during the course of our work. The programming techniques and the methodologies adopted are also included. The Excel spreadsheets which were developed are presented along with illustrative examples.

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1 Introduction

Understanding and mastering the seismic analysis and design of deep foundations is a challenging yet essential element of the advanced education of students in the field

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of civil engineering. Our past experience in the academic context of helping students achieve the desired outcomes had been a frustrating endeavor, given the time and effort invested. It is in part in response the need to provide a leaner and more efficient learning and teaching approach that the work described in this paper evolved.

In essence, the transfer of lateral loads from deep foundations to the subsurface strata is a complex soil-structure interaction problem. The movements and flexural stresses in the pile depend on the soil resistance, while the soil resistance is a function of the deformations of the pile itself. Furthermore, the ultimate resistance of a vertical pile to a lateral load and the deflection of the pile as the load builds up to its ultimate value are complex and involve the interaction between a semi-rigid structural element and soils which deforms partly elastically and partly plastically. Given the typically limited time and resources allocated to this topic in a three credit course, as other equally relevant applications are to be covered, imparting sufficient and fundamental understanding of this applied problem constitutes a real challenge that the spreadsheet approach presented herein attempted to meet.

In this paper, an Excel-based teaching and analysis tool is presented, which attempts to address some of the educational and applied challenges associated with the problem. The basic premise of the educational approach is anchored in the need and desire to empower the student to explore effects of the various parameters on the response of the piles in an environment designed to generate rigorous solutions with auto-generated and easy to interpret graphical representations. The paper also explores the benefits of coupling programming and spreadsheet calculations.

We have taken the spreadsheet developed through one cycle of testing in an actual classroom environment as part of a course on geotechnical earthquake engineering at the American University of Beirut in the Fall 2003 semester. The number of students registered for the course was 18 (10 graduate and 8 undergraduate students). The process and tool presented in this paper have significantly improved the educational experience from the teaching perspective, but also have generated more interest and response from the students than we had experienced in similar contexts using the traditional didactic approach. The use of the developed spreadsheets allowed us to adapt “what if?” scenarios to illustrate the effect and importance of certain parameters such as soil types, pile characteristics, levels and type of loading, etc. in the classroom in real-time.

2 Background—the engineering problem

Extensive work has been published on the resistance of piles to lateral loading. However, no simple design method has emerged, which can be universally applied to any soil and/or pile type. A number of interrelated factors influence the response of piles under seismic/lateral loading conditions. The pile stiffness is a critical factor given that it controls the deflection and determines whether the failure mechanism is one of rotation of a short rigid element, or flexure in bending of a long flexible member. The type of loading, whether sustained, alternating, or pulsating, influences the degree of yielding of the soil.

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Seismic loading is typically considered as an additional “pseudo-static” lateral load applied to the pile. Piles are then analyzed by separating the two cases of vertical and lateral loading and then superposing the results. However, such an approach is inaccurate in non-elastic, non-linear media such as soils. Nevertheless, superposition still yields acceptable results given the fact that vertical loading involves the deeper layers of soil while the horizontal loading tends to involve the near-surface layers.

Earthquake loads are usually accounted for by the following two methods: Equivalent static load or equivalent dynamic load (Poulos and Davis [11], and Nair [10]). The need for an equivalent load arises if the solution of the rigorous problem is time-consuming and difficult.

In this paper, the presented analyses and design methods are typically based on the “pseudo-static” approach. Two methods are currently in use to determine the magnitude of the equivalent static load to be applied at the top of the pile (Nair [10]):

- The load taken is a certain percentage of the vertical static load.
- The total lateral load applied is taken to be the base-shear utilized in the seismic analysis of the building resting on the piles.

To obtain the base shear of the building or the horizontal force applied at the top of the pile, the formula $F_h = F_v S_a / g$ is used.

From attenuation curves, and using deterministic or probabilistic seismic hazard analyses, a peak horizontal acceleration is obtained. It is then corrected, based on the type of *in-situ* soil. Normalized response spectra are then used to assign the appropriate spectral acceleration S_a for the design of the piles supporting the structure based on its natural period. F_v is the vertical force applied on the pile and g is the acceleration due to gravity.

3 The use of Excel spreadsheets

Despite the rational adoption of the simplified methodologies presented earlier, the analysis of the laterally loaded piles remains a difficult undertaking. The complexities are associated in part with the difficulty of calculating and visualizing the moments and deflections along the full length of the piles given certain loading conditions, as well as the understanding of the effects of the various inter-related parameters that influence the pile design (Figure 1). The “difficulty in visualizing behavior” was in fact the problem most identified by earlier student evaluation and feedback. As such, and in part in order to promote a more fundamental understanding of the problem, solutions and visualizations within an Excel spreadsheet environment were developed for use in the classroom. Whenever we needed to perform a task repeatedly, a Visual BASIC macro, which is basically a series of commands and functions that can be run on the fly, was embedded within the spreadsheet. This enabled us to automate some loops and repetitive procedures and solve for values using trial and error.

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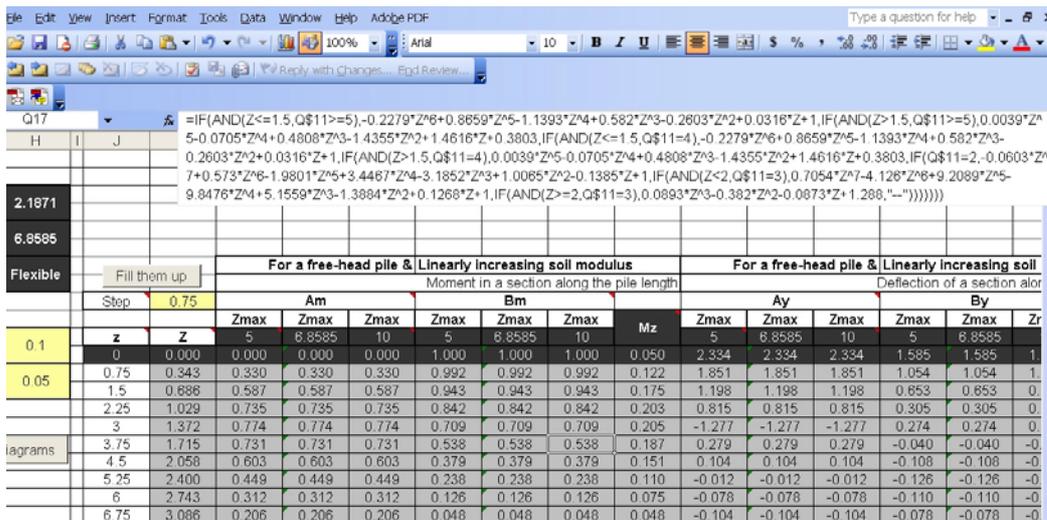


Figure 1: The level of complexity of the formulas used in the various spreadsheets

The seismic pile design methods which were incorporated in the spreadsheets were the “Characteristic Load Method” (Duncan *et al* [5]), and the “Hybrid Analytical Method” (based on Matlock and Reese [8] and Davisson and Gill [4]).

These design methods were adopted given that they are typically used in engineering practice today. Automating the various expressions and procedures involved in the analyses allowed us to develop a reliable and useful design tool. In this context, when using this tool for education in the classroom, students are being introduced to professional level practice while at the same time relying on the same approach to gain knowledge of the fundamentals. The exposure to academic teaching tools which can also serve the purpose of real-world design aids is an added benefit which enriches the educational experience of the student of applied engineering.

3.1 Building the spreadsheets

A large set of parameters, some of which are interrelated, is involved in the analysis. In order to facilitate the interaction between the student and the spreadsheets, which may seem intimidating at first glance, the cell values that require an input by the user are highlighted in light yellow and the ones that will be automatically generated are highlighted in dark grey. Furthermore, the student is guided through the design-analysis process by comments/hints which are linked to the individual cells. They include the definition of each term, the units that should be used, etc. (Figure 2).

Some of the calculations involve trial and error procedures and loops. In such instances, Visual BASIC macros were assigned to specifically created buttons for the purpose of running these loops and obtaining the required parameter value with minimal effort. The idea is to lessen time spent on performing tedious and repetitive tasks which

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encroach on the “quality-learning time” and reduce the tedium to a few mouse clicks while maintaining the advantages of spreadsheet interfaces (Figure 2). It is important to add here that the automated processes do not create “black boxes” invisible to the student, but merely perform those tasks that are fully understood and clearly explained.

After entering all the required parameters the response of the piles, expressed in terms of moments and deflections along the pile length, can be calculated at a depth increment assigned by the user. Charts are then auto-generated in separate worksheets to visualize the variation of these moments and deflections with depth. To do that, the usual charting procedure is used and recorded in a new macro, its code modified to fit regardless of the actual data limits. This specific macro is assigned to a button for future re-use. This ability of creating “instantaneous” graphed results as variables are modified or changed is at the core of the power of the spreadsheets in an educational context. Students were encouraged to explore the effect of changing the pile stiffness, material, soils, etc. on the predicted behavior. This was simply not possible prior to the introduction of this approach into the classroom.

Based on the feedback we received from the students who took part in the course evaluation, a majority noted the spreadsheets used in the seismic design of piles as key for their appreciation of the various elements involved and their contribution to the overall response. The spreadsheets enhanced the problem solving task extensively and allowed us to assign a greater number of different tasks and problems.

	A	B	C	D	E	F	G	H
1	Problem Variables							
2	in the Soil		Characteristic Load P_c		8.64684	Characteristic Moment M_c		62.1715
3	Sand or Clay	clay	Applied Load P_t		0.1	Applied Moment M_t		0.05
4	Brittle or Plastic	plastic	Ground line deflection due to the applied load y_{tp}		0.00887	Ground line deflection due to the applied moment y_{tm}		0.00054
5	λ for P_c	1	Load P_m equivalent to M_t		0.02147	Moment M_p equivalent to P_t		0.36404
6	λ for M_c	1	Ground line deflection y_{tpm} due to the P_t+P_m		0.01265	Ground line deflection y_{tmp} due to the moment M_t+M_p		0.01064
7	e_{50}	0.02						
8	α_p	0.202						
9	S_u	0.048						
10	--	25						
11	$C_p\phi$							
12	γ							
13	K_p							
14	in the Structure							
15	L							
16	B							
17	R_1	1.7						
18	E_p	27800						
19	Material check	concrete						
20	Pile type	free						
21	Reduction of I_p	50%						
22	I_p	0.010800						
23	Criterion for the use of CLM	check						
24								
25								

Figure 2: Light yellow cells, dark grey cells, comments, and VB buttons used in the various spreadsheets

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In the following sections the two analysis methods are illustrated through the example of a pile embedded in clay and supporting an earthquake load equivalent to a static horizontal load of 0.1 MN and a moment of 0.05 MJ. The response of the pile will be analyzed using the created Excel spreadsheets. Tables and figures are added to show the results of both methods allowing for some comparison.

The example considers a square concrete free-headed pile, 15 m long, 0.6 m wide. The concrete modulus is equal to 27800 MPa. The pile is embedded in a plastic, normally consolidated clay, with a linearly increasing soil modulus. The soil undrained shear strength is 48 kPa, the soil modulus is 36 MPa ($= 750 \times$ undrained shear strength), and the coefficient of modulus variation is approximately 6000 kPa m^{-1} depth.

4 Characteristic load method (CLM)

The characteristic load method can be used to determine:

1. Deflections due to lateral loads for free-head conditions, fixed-head conditions, and the “flag-pole” condition.
2. Deflections due to moments applied at the ground line.
3. Maximum moments for the free-head conditions, fixed-head conditions and the flag-pole condition.
4. The location of the maximum moment in the pile or drilled shaft.

Despite the number of simplifying assumptions the characteristic load method still involves many parameters. Tabulating these parameters was deemed necessary in order to ease the spreadsheet-based trial and error processes (Figure 3). All relevant parameters are explained in detail in the following paragraphs.

4.1 Non-dimensional relationships with characteristic load P_c and moment M_c

The characteristic load method formulation is based on non-dimensional relationships related to load and moment. Equations (1)–(3) describe load and moment.

$$P_C = \lambda_1 B^2 E R_1 \left(\frac{\sigma_p}{E R_1} \right)^{m_1} (\varepsilon_{50})^{n_1} \quad (1)$$

$$M_C = \lambda_2 B^3 E R_1 \left(\frac{\sigma_p}{E R_1} \right)^{m_2} (\varepsilon_{50})^{n_2} \quad (2)$$

$$R_1 = \frac{64I}{\pi B^4} \quad (3)$$

Note that the moment of inertia ratio, $R_1 = 1.00$ for solid circular cross-sections and 1.70 for solid square cross-sections. For plastic clay and sand, $\lambda_1 = \lambda_2 = 1.00$. For

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	A	B	C	D	E	F	G	H
1	Problem Variables							
2	in the Soil							
3			Characteristic Load P_c	8.64684		Characteristic Moment M_c	62.1715	
4	Sand or Clay	clay	Applied Load P_t	0.1		Applied Moment M_t	0.05	
5	Brittle or Plastic	plastic						
6	λ for P_c	1	Ground line deflection due to the applied load y_{tp}	0.00887		Ground line deflection due to the applied moment y_{tm}	0.00054	
7	λ for M_c	1						
8	ε_{50}	0.02	Load P_m equivalent to M_t	0.02147		Moment M_p equivalent to P_t	0.36404	
9	σ_p	0.202						
10	S_u	0.048	Ground line deflection y_{tpm} due to the P_t+P_m	0.01265		Ground line deflection y_{tmp} due to the moment M_t+M_p	0.01064	
11	--	25						
12	$C_{p\Phi}$	2.5						
13	γ	0.015	Estimated ground line deflection due to moment and load	0.01165				
14	K_p	2.4639						
15	in the Structure							
16	L	15						
17	B	0.6	For a free-head pile:			For a fixed-head pile:		
18	R_1	1.7						
19	E_p	27800						
20	Material check	concrete	Characteristic length estimate	2.319		--	0.19711	
21	Pile type	free	T	Check				
22	Reduction of I_p	50%						
23	I_p	0.010800	--	0.17083				
24	Criterion for the use of CLM	check	Z_{max}	6.46831				
25								

Figure 3: The Excel worksheet of the characteristic load method

Table 1: Typical ε_{50} values (Matlock [9])

Soil Type	ε_{50}
Disturbed, remolded, soft clay	0.020
Normally consolidated medium clay	0.010
Brittle, stiff, sensitive clay	0.005
Medium dense sand with little or no mica	0.002

brittle clay, $\lambda_1 = (0.14)^{n_1}$, and $\lambda_2 = (0.14)^{n_2}$. For clay, $\sigma_p = 4.2s_u$. For sand $\sigma_p = 2C_{p\Phi}\gamma B \tan^2(45^\circ + \Phi'/2)$.

P_c is the characteristic shear load, and M_c the characteristic moment load. λ_1 and λ_2 are dimensionless parameters that depend on the soil stress-strain behavior. B represents the diameter of the foundation, and E the modulus of elasticity of the foundation (200,000 MPa for steel; $4700\sqrt{f'_c}$ for concrete; 11,000 MPa for pine wood), where f'_c is the 28-day compressive strength of concrete (MPa). The representative passive pressure of soil is denoted by σ_p , and ε_{50} is the axial strain at which 50% of the soil strength is mobilized, obtained from triaxial compression tests or from Table 1. The exponents m_1, n_1, m_2, n_2 are those from Table 2. I is the moment of inertia of foundation, and s the undrained shear strength from the ground surface to a depth of $8B$. The effective friction angle (deg) from ground surface to a depth of $8B$ is represented by Φ' , while $C_{p\Phi} = \Phi'/10$ denotes the passive pressure factor. Finally, γ is the unit weight of soil from ground surface to a depth of 8-pile diameters. If the water table is within this zone, use a weighted average of γ and $\gamma_b = \gamma - \gamma_w$. All the above parameters were tabulated in Excel in the format shown in Figure 3. The soil properties are reduced to

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Table 2: Values of the exponents m and n (Evans and Duncan [6])

Soil Type	For Pc		For Mc	
	m_1	n_1	m_2	n_2
Clay	0.683	-0.22	0.46	-0.15
Sand	0.57	-0.22	0.4	-0.15

Table 3: Constants for Load-deflection equations $y_t/y_c = a_1 (P_t/P_c)^{b_1}$ (Brettmann & Duncan [2])

Constant	Clay		Sand	
	Free head	Fixed head	Free head	Fixed head
a_1	50	14	119	28.8
b_1	1.822	1.846	1.523	1.5

those of the upper 8-pile diameter depth.

Three main groups of non-dimensional relationships are used in the characteristic load method: Load-deflection, moment-deflection, and load-moment. Different relationships for each group are used for sands and clays. The load-deflection and load-moment relationships are further subdivided into free-head and fixed head conditions.

A single-term exponential equation in the form of $y = ax^b$ where a is a constant and b is an exponent, is used for the non-dimensional relationships. The coefficients a and b are obtained from a power regression analysis. The constants and exponents for each of the relationships are determined within the spreadsheet tool using an iterative, non-linear, least squares curve fitting technique.

$$y_t/y_c = a_1 (P_t/P_c)^{b_1} \quad \text{With } a \text{ and } b \text{ deduced from Table 3.} \tag{4}$$

$$y_t/B = a_2 (M_t/M_c)^{b_2} \quad \text{With } a \text{ and } b \text{ deduced from Table 4.} \tag{5}$$

$$P_t/P_c = a_3 (M_{\max}/M_c)^{b_3} \quad \text{With } a \text{ and } b \text{ deduced from Table 5.} \tag{6}$$

In these equations, y_t is the ground line deflection, B the pile or drilled shaft diameter or width, P_t the lateral load at top of pile or drilled shaft, M_t the moment at the top of pile or drilled shaft, and M_{\max} is the maximum moment.

The flexural stiffness, $E_p I_p$, of reinforced concrete piles and drilled shafts should be reduced when tensile stresses are large enough to cause cracking. The magnitude of the reduction of $E_p I_p$ depends on the ratio of the maximum moment computed to the ultimate moment capacity or cracking moment of the section. For cracked sections, the

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Table 4: Constants for Moment-deflection equations $y_t/B = a_2 (M_t/M_c)^{b_2}$ (Brettmann & Duncan [2])

Constant	Clay	Sand
a_2	21	36
b_2	1.412	1.308

Table 5: Constants for Load-moment equations $P_t/P_c = a_3 (M_{max}/M_c)^{b_3}$ (Brettmann & Duncan [2])

Constant	Clay		Sand	
	Free head	Fixed head	Free head	Fixed head
a_3	1.22	1.63	0.425	0.669
b_3	0.79	0.86	0.762	0.84

moment of inertia of concrete is reduced to 40% – 50% of the value for the full-uncracked concrete section. No reduction is made in the moment of inertia of the steel.

4.2 Deflection due to combined load and moment

Given that the response is non-linear, simply adding the deflections caused by the lateral load and the moment is not sufficient. Instead, the non-linear effects should be taken into account by using a non-linear superposition procedure accounted for in the spreadsheet solution developed.

The first step in the non-linear superposition is to calculate the deflections that would be caused by the load P_t or E4 acting alone y_{tp} and by the moment M_t or H4 acting alone y_{tm} using the equations listed in the previous section and written in Excel as follows:

y_{tp} or E6
=IF(AND(B4="sand",B21="free"),B17*119*((E4/E2)^1.523),
IF(AND(B4="sand",B21="fixed"),B17*28.8*((E4/E2)^1.5),
IF(AND(B4="clay",B21="free"),B17*50*((E4/E2)^1.822),
IF(AND(B4="clay",B21="fixed"),B17*14*((E4/E2)^1.846),"--"))))

y_{tm} or H6
=IF(AND(B4="sand",B21="free"),B17*36*((H4/H2)^1.308),
IF(AND(B4="sand",B21="fixed"),B17*36*((H4/H2)^1.308),
IF(AND(B4="clay",B21="free"),B17*21*((H4/H2)^1.412),
IF(AND(B4="clay",B21="fixed"),B17*21*((H4/H2)^1.412),"--"))))

The second step is to get the load P_m that can cause y_{tm} and the moment M_p that can cause y_{tp} as follows;

P_m or E8
=IF(AND(B4="sand",B21="free"),((H6/(B17*119))^(1/1.523))*E2,
IF(AND(B4="sand",B21="fixed"),((H6/(B17*28.8))^(1/1.5))*E2,

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IF(AND(B4="clay",B21="free"),((H6/(B17*50))^(1/1.822))*E2,
IF(AND(B4="clay",B21="fixed"),((H6/(B17*14))^(1/1.846))*E2,"--"))))

M_p or H8

=IF(AND(B4="sand",B21="free"),((E6/(B17*36))^(1/1.308))*H2,
IF(AND(B4="sand",B21="fixed"),((E6/(B17*36))^(1/1.308))*H2,
IF(AND(B4="clay",B21="free"),((E6/(B17*21))^(1/1.412))*H2,
IF(AND(B4="clay",B21="fixed"),((E6/(B17*21))^(1/1.412))*H2,"--"))))

The third step is computing the average of y_{tpm} caused by the load $P_t + P_m$ and y_{tmp} caused by $M_t + M_p$ using the equations of the previous section:

y_{tpm} or E10

=IF(AND(B4="sand",B21="free"),B17*119*(((E4+E8)/E2)^1.523),
IF(AND(B4="sand",B21="fixed"),B17*28.8*(((E4+E8)/E2)^1.5),
IF(AND(B4="clay",B21="free"),B17*50*(((E4+E8)/E2)^1.822),
IF(AND(B4="clay",B21="fixed"),B17*14*(((E4+E8)/E2)^1.846),"--"))))

y_{tmp} or H10

=IF(AND(B4="sand",B21="free"),B17*36*(((H4+H8)/H2)^1.308),
IF(AND(B4="sand",B21="fixed"),B17*36*(((H4+H8)/H2)^1.308),
IF(AND(B4="clay",B21="free"),B17*21*(((H4+H8)/H2)^1.412),
IF(AND(B4="clay",B21="fixed"),B17*21*(((H4+H8)/H2)^1.412),"--"))))

4.3 Maximum moments and their location

In fixed-head flexible piles or drilled shafts, the maximum moment occurs at the top, where the pile or shaft is embedded in the cap. In free-head flexible piles and drilled shafts, the maximum moment occurs at some depth below the ground. The magnitude and location of the maximum moment can be estimated using the theory, for soil modulus increasing linearly with depth: the characteristic length T , solution by trial and error of the following equation is first calculated.

$$y_{comb} = \frac{2.43P_t}{E_p I_p} T^3 + \frac{1.62M_t}{E_p I_p} T^2 \quad (7)$$

This is done by running a simple Visual BASIC macro assigned to a button named "Check". (Ref. Figure 3). This macro is as follows:

Sub trialanderror()

Cells(19, 5) = 0

Do

Cells(19, 5) = Cells(19, 5) + 0.001

Cells(21, 5) = Cells(20, 5)

Loop Until Cells(21, 5) = "check"

End Sub

The formula in Cells(20,5) or E20 is:

=IF(AND((((((2.43*E4)/(B23*B19))*E19^3)+((1.62*H4)/(B23*B19))*E19^2)/E13>0.99),((((((2.43*E4)/(B23*B19))*E19^3)+((1.62*H4)/(B23*B19))*E19^2)/E13<1.01)), "check", IF(OR(B21="Fixed",B21="fixed"),"check","retry"))

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The idea is to keep increasing the value of

$$\left(\frac{2.43P_t}{E_p I_p} T^3 + \frac{1.62M_t}{E_p I_p} T^2 \right) / y_{comb}$$

from zero until it reaches 1. At that point the macro stops and the correct value for the characteristic length is given in cell E19.

Then the moment M_Z , at a depth equal to z , is calculated from equations derived from the values in Table 6 and from equation (8).

$$M_Z = A_m P_t T + B_m M_t \quad (8)$$

To use Excel, a formula needed to be created for A_m and B_m . To do that, poly-fitting in MATLAB was used. Then, linear interpolation is used to get the correct A_m or B_m for a particular Z_{max} . Two typical Excel formulas for A_m and B_m can be written as follows:

A_m or L12

```
=IF(AND(Z<=1.5,L$11>=5),-0.0552*Z^6+0.2175*Z^5-0.2136*Z^4
-0.1507*Z^3-0.0856*Z^2+1.0145*Z+0,IF(AND(Z>1.5,L$11>=5),
0.0198*Z^5-0.3261*Z^4+2.0962*Z^3-6.4768*Z^2+9.1767*Z
-4.0034,IF(AND(Z<=1.5,L$11=4),-0.0552*Z^6+0.2175*Z^5-0.2136
*Z^4-0.1507*Z^3-0.0856*Z^2+1.0145*Z+0,IF(AND(Z>1.5,
L$11=4),-0.0376*Z^4+0.4664*Z^3-2.0326*Z^2+3.3284*Z-1.041
,IF(L$11=2,-2.3599*Z^7+13.8516*Z^6-31.3601*Z^5+35.1888*Z^4
-20.9114*Z^3+5.6052*Z^2+0.4698*Z,IF(L$11=3,-0.4268*Z^9
+4.7435*Z^8-21.4445*Z^7+50.9252*Z^6-68.5924*Z^5+
53.0533*Z^4-23.0229*Z^3+4.8467*Z^2 +0.6119*Z,"--"))))))
```

B_m or O12

```
=IF(AND(Z<=1.5,O$11>=5),-0.2279*Z^6+0.8659*Z^5-1.1393*Z^4
+0.582*Z^3-0.2603*Z^2+0.0316*Z+1,IF(AND(Z>1.5,O$11>=5),
0.0039*Z^5-0.0705*Z^4+0.4808*Z^3-1.4355*Z^2+1.4616*Z
+0.3803,IF(AND(Z<=1.5,O$11=4),-0.2279*Z^6+0.8659*Z^5
-1.1393*Z^4+0.582*Z^3-0.2603*Z^2+0.0316*Z+1,IF(AND(Z>1.5
,O$11=4),0.0039*Z^5-0.0705*Z^4+0.4808*Z^3-1.4355*Z^2
+1.4616*Z+0.3803,IF(O$11=2,-0.0603*Z^7+0.573*Z^6-1.9801*Z^5
+3.4467*Z^4-3.1852*Z^3+1.0065*Z^2-0.1385*Z+1,IF(AND(Z<2,
O$11=3),0.7054*Z^7-4.126*Z^6+9.2089*Z^5-9.8476*Z^4
+5.1559*Z^3-1.3884*Z^2+0.1268*Z+1,IF(AND(Z>=2,O$11=3),
0.0893*Z^3-0.382* Z^2-0.0873*Z+1.288,"--"))))))
```

The relatively high level of complexity of the above formulas should be noted. These formulas are automatically filled in the Excel sheet by a simple automated copy/paste process during the run of the "Fill them up" button or macro. Figure 4 shows the moment values as they appear in the Excel worksheet after the macro is run.

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Table 6: Moment coefficients A_m and B_m (Matlock and Reese [7], Das [3])

$Z = z/T$	$Z_{max} = L/T \geq 5$		$Z_{max} = L/T = 4$		$Z_{max} = L/T = 3$		$Z_{max} = L/T = 2$	
	A_m	B_m	A_m	B_m	A_m	B_m	A_m	B_m
0	0	1	0	1	0	1	0	1
0.2	0.198	0.999	0.198	0.999	0.198	0.998	0.198	0.992
0.4	0.379	0.987	0.379	0.987	0.379	0.985	0.379	0.972
0.6	0.532	0.96	0.532	0.96	0.532	0.957	0.485	0.909
0.8	0.649	0.914	0.649	0.914	0.649	0.903	0.53	0.803
1	0.727	0.852	0.727	0.852	0.694	0.835	0.484	0.662
1.5	0.763	0.638	0.762	0.638	0.663	0.599	0.2	0.215
2	0.628	0.404	0.615	0.404	0.455	0.3	0	0
2.5	0.405	0.2	0.395	0.2	0.132	0.078		
3	0.225	0.06	0.198	0.073	-0.01	0		
4	0	-0.042	-0.025	0.03				
5	-0.033	-0.026						

Another Visual BASIC macro and button named "Draw Moment diagram" is then used to draw the moment diagram along the pile length. This macro also works by re-running previously recorded actions including the insertion of a new chart and its formatting. The generated plot of the moments with respect to depth is shown in Figure 5.

To illustrate how the spreadsheet was used in class and/or assignments, the question would be posed as to likely effect of having say a "stubbier" or thicker pile, say 1m in diameter. The results generated instantaneously, and shown in Figure 6, demonstrate that increasing the stiffness of the pile, increased the distributed moments in it.

5 Hybrid analytical method (HAM)

In an effort to expose students to additional available methods for the analysis of piles under seismic loading, a hybrid approach was formulated which combines the solutions provided by Matlock and Reese [8], and Davisson and Gill [4]. The methods were investigated and their respective strengths and limitations identified. The hybrid approach allows the solution of more complex problems than the LCM such those involving layered soils. It consists primarily of combining analytical analysis procedures which focus on various elements of the problem at hand. As such, the process presented narrows the margins of error and provides the essential data for calculating bending moments, shearing forces and deflections along the pile at the working loads. The fact remains that some factors, such as the non-homogeneity of most of the natural soil deposits and the disturbance to the soil caused by installing piles cannot be reproduced.

The educational benefit sought from this approach is to present the student with a

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	J	K	L	M	N	O	P	Q	R
6									
7	Fill them up		For a free-head pile:			Draw moment Diagram			
9	Step	0.75	Am			Bm			
10			Zmax	Zmax	Zmax	Zmax	Zmax	Zmax	Mz
11	z	Z	5	6.46831	10	5	6.46831	10	
12	0	0.000	0.000	0.000	0.000	1.000	1.000	1.000	0.050
13	0.75	0.323	0.312	0.312	0.312	0.993	0.993	0.993	0.122
14	1.5	0.647	0.563	0.563	0.563	0.951	0.951	0.951	0.178
15	2.25	0.970	0.718	0.718	0.718	0.862	0.862	0.862	0.210
16	3	1.294	0.774	0.774	0.774	0.744	0.744	0.744	0.217
17	3.75	1.617	0.753	0.753	0.753	0.584	0.584	0.584	0.204
18	4.5	1.940	0.653	0.653	0.653	0.432	0.432	0.432	0.173
19	5.25	2.264	0.510	0.510	0.510	0.291	0.291	0.291	0.133
20	6	2.587	0.371	0.371	0.371	0.173	0.173	0.173	0.095
21	6.75	2.911	0.257	0.257	0.257	0.084	0.084	0.084	0.064
22	7.5	3.234	0.169	0.169	0.169	0.024	0.024	0.024	0.040
23	8.25	3.558	0.102	0.102	0.102	-0.010	-0.010	-0.010	0.023
24	9	3.881	0.044	0.044	0.044	-0.024	-0.024	-0.024	0.009
25	9.75	4.204	-0.005	-0.005	-0.005	-0.022	-0.022	-0.022	-0.002
26	10.5	4.528	-0.033	-0.033	-0.033	-0.010	-0.010	-0.010	-0.008
27	11.25	4.851	-0.003	-0.003	-0.003	0.012	0.012	0.012	0.000
28	12	5.175		0.000	0.153		0.000	0.047	0.000
29	12.75	5.498		0.000	0.546		0.000	0.104	0.000
30	13.5	5.821		0.000	1.332		0.000	0.202	0.000
31	14.25	6.145		0.000	2.727		0.000	0.368	0.000
32	15	6.468		0.000	5.013		0.000	0.641	0.000

Figure 4: The calculation of the moment M_z at a depth equal to z

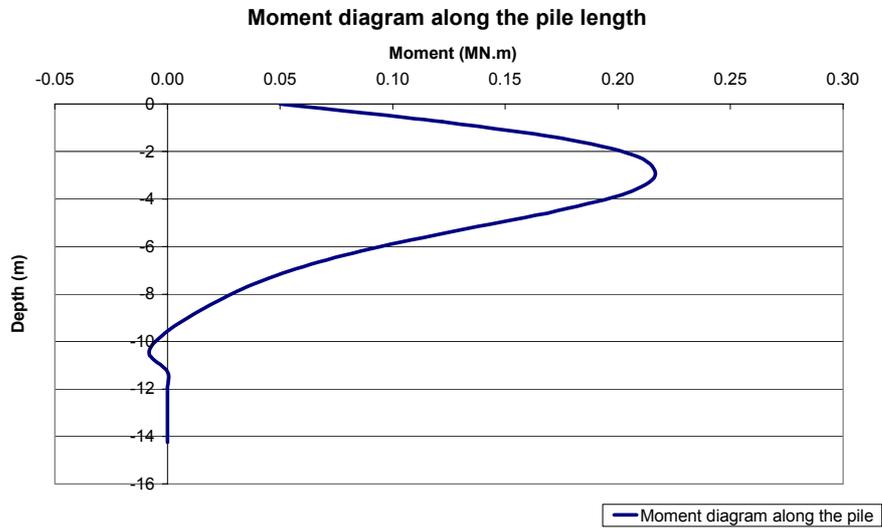


Figure 5: An Excel chart showing the moment diagram in a pile along its length

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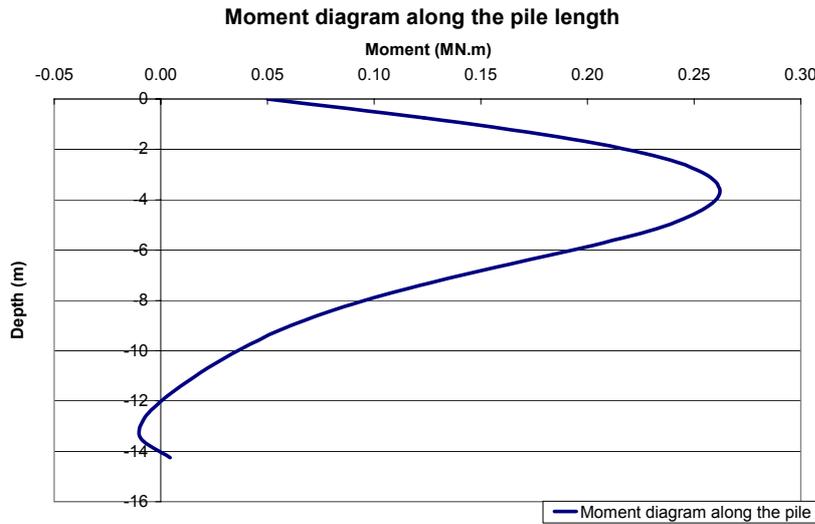


Figure 6: An Excel chart showing the moment diagram in a pile of different diameter ($D = 1m$ instead of $0.6m$)

number additional analysis methods in a clear and unifying context, rather than piecemeal.

The format of the Excel worksheet for the “hybrid analytical method” is shown below. The definition of each parameter is provided in the following paragraphs.

5.1 Stiffness factors and pile behavior

The first step in the process is to determine whether the pile will behave as a “short rigid unit” or as an “infinitely long flexible member”. This is done by calculating the stiffness factor for the particular combination of pile and soil. The stiffness factors are governed by the stiffness (EI value) of the pile and the compressibility of the soil. The latter is expressed in terms of a “soil modulus”, which is not constant for any soil type but depends on the width of the pile B and the depth of the particular soil being considered.

In the case of stiff over-consolidated clays, the soil modulus is generally assumed to be constant with depth. The stiffness factor, R , in units of length, is given by eq (9).

$$\text{stiffness factor, } R = \sqrt[4]{\frac{EI}{k}} \tag{9}$$

Vesic proposed in 1961 eq (10) to estimate the value of k a measure of the relative soil/pile stiffness (Das [3], Poulos and Davis [11]).

$$k = 0.65 \sqrt[12]{\frac{E_s D^4}{E_p I_p} \frac{E_s}{1 - \mu_s^2}} \tag{10}$$

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	A	B	C	D	E	F	G	H
1	Problem Variables							
2								
3	in the Soil							
4	Sand or Clay	clay		Estimate n_h			Stiffness factor T	2.1871
5	Stiff or Normal	normal	Depth	nh	nh*z		Zmax	6.3585
6	--	0.300	0	0	0			
7	nh	6000	1	5200	5200		Pile behavior	Flexible
8	--	36	2	5950	11900			
9	--	18.2	3	5450	16350			
10	in the Structure							
11	L	15	4	5850	23400			
12	D	0.6	5	4200	21000		Applied Load H0	0.1
13	Section Type	square	6	6000	36000		Applied Moment M0	0.05
14	Ep	27800	7	5750	40250			
15	lp	0.010800	8	6000	48000			
16	--	0.012000	9	6600	59400			
17	Pile type	free	10	5840	58400			
18			11	6750	74250		Draw moment and deflection diagrams	
			12	5600	67200			

Figure 7: The Excel worksheet of the hybrid analytical method

Table 7: Representative Values of n_h (Das [3])

Soil Type	n_h (kN/m^3)	
Dry or moist sand	Loose	1800 – 2200
	Medium	5500 – 7000
	Dense	15000 – 18000
Submerged sand	Loose	1000 – 1400
	Medium	3500 – 4500
	Dense	9000 – 12000

In eq (10), E_s is the Young's modulus of soil, which is 1500 to 2000 S_u for heavily over-consolidated clays, and 750 to 1200 S_u for lightly over-consolidated clay (Bowles [1]). S_u denotes the undrained shear strength of soil, D the pile width (or diameter), while μ_s represents Poisson's ratio of the soil, which vary between 0.3 and 0.5. For most normally consolidated clays and granular soils, the soil modulus is assumed to increase linearly with depth. The stiffness factor is in this case symbolized by the letter T and calculated as follows:

$$\text{stiffness factor, } T = \sqrt[5]{\frac{EI}{n_h}} \quad (11)$$

In the Excel worksheet, the student only has to enter the soil type and the correct formula is identified and used to calculate the appropriate stiffness factor (R or T).

Typical values of the coefficient of modulus variation n_h are shown in Table 7. For soft normally consolidated clays, $n_h = 3500$ to 14000 $kN m^{-3}$. For soft organic silt, $n_h = 1500$ $kN m^{-3}$.

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If the soil is layered and we have different values of n_h at different depths, the constant value of n_h that must be used is the result of a linear regression between $n_h \cdot z$ and z . For this purpose, a new macro was created within the proposed spreadsheet tool and assigned to a button named “estimate n_h ” (Figure 7). This macro is as follows:

```
Sub linearregressiontogetnh()
Dim t As Integer
t = 0
Do
If Application.WorksheetFunction.IsNumber(Cells(t + 6, 4).Value) Then
t = t + 1
Cells(t + 6, 6) = Cells(t + 6, 5) * Cells(t + 6, 4)
Cells(t + 6, 6).Interior.ColorIndex = 56
End If
Loop Until Cells(t + 7, 4) = 0
Cells(7, 2) = Application.WorksheetFunction.LinEst(Range(Cells(6, 6),
Cells(t + 6, 6)), Range(Cells(6, 4), Cells(t + 6, 4)), False, False)
End Sub
```

The idea is that, when the user enters the values of n_h at the different depths (e.g.: cells D7:E18), and runs the macro, a worksheet function available to Visual BASIC called “LinEst” is used to get the straight line that best fits the data. The method used to get this line is the “least squares” method. An array that describes the line is then returned (value of cell B7 in our case).

Having calculated the stiffness factor (R or T), the criteria for behavior as a short rigid pile or as a long elastic pile can then be related to the embedded length L as follows:

$$L \leq 2 \times \text{stiffness factor} \implies \text{Rigid}$$

$$L \geq 4 \times \text{stiffness factor} \implies \text{Elastic}$$

5.2 Elastic analysis of laterally loaded vertical piles

Matlock and Reese [8] established a series of curves for normally consolidated clay and cohesionless soils for which the elastic modulus of the soil E_s is assumed to increase from zero at the ground surface in direct proportion to the depth. These curves represent the deformed shape of the pile and the corresponding bending moments, (shearing forces and soil reactions) using special coefficients. These coefficients are related to a depth coefficient Z for various values of Z_{\max} , where Z is equal to the depth z at any point divided by T and $Z_{\max} = L/T$.

For a linearly increasing soil modulus and a free pile head (subject to lateral load and moment), the deflections and moments in the piles are respectively obtained from equations (12) and (13).

$$y_A + y_B = \frac{A_y H T^3}{E_p I_p} + \frac{B_y M_t T^2}{E_p I_p} \quad (12)$$

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Table 8: Equations for the calculation of bending moments and deflection in free head piles carrying lateral load or moment at their heads in soils of constant modulus

Load on pile head		For free-headed pile	
Moment	M	Bending Moment	MM_h
Moment	M	Deflection	$My_m R^2 / (EI)$
Horizontal load	H	Bending Moment	$HM_h R$
Horizontal load	H	Deflection	$H y_h R^3 / (EI)$

$$M_A + M_B = A_m HT + B_m M_t \quad (13)$$

The A and B coefficients are obtained from Figures 8 and 9.

For a linearly increasing soil modulus and a fixed pile head (subject to lateral load), eqs (14) and (15) are respectively used for calculating the deflections and bending moments.

$$y_F = \frac{F_y HT^3}{E_p I_p} \quad (14)$$

$$M_F = F_m HT \quad (15)$$

The F coefficients are obtained from Figure 10.

Davisson and Gill [4] have analyzed the case of elastic piles in an elastic soil with constant modulus. The bending moments and deflections are related to the stiffness coefficient R using the equations of Table 8.

Note that the effect of fixity at the pile head can be allowed for by plotting the deflected shape of the pile from the algebraic sum of the deflections and then applying a moment to the head which results in zero slope for complete fixity, or the required angle of slope for a given degree of fixity.

The dimensionless depth coefficient Z used in the curves is equal to z/R and $Z_{\max} = L/R$. These curves are obtained for free-head piles carrying a moment at the pile head and zero lateral loads or, with zero moment at the pile head and carrying a lateral load. The length L must be greater than $2R$. The needed coefficients are obtained from Figures 11 and 12.

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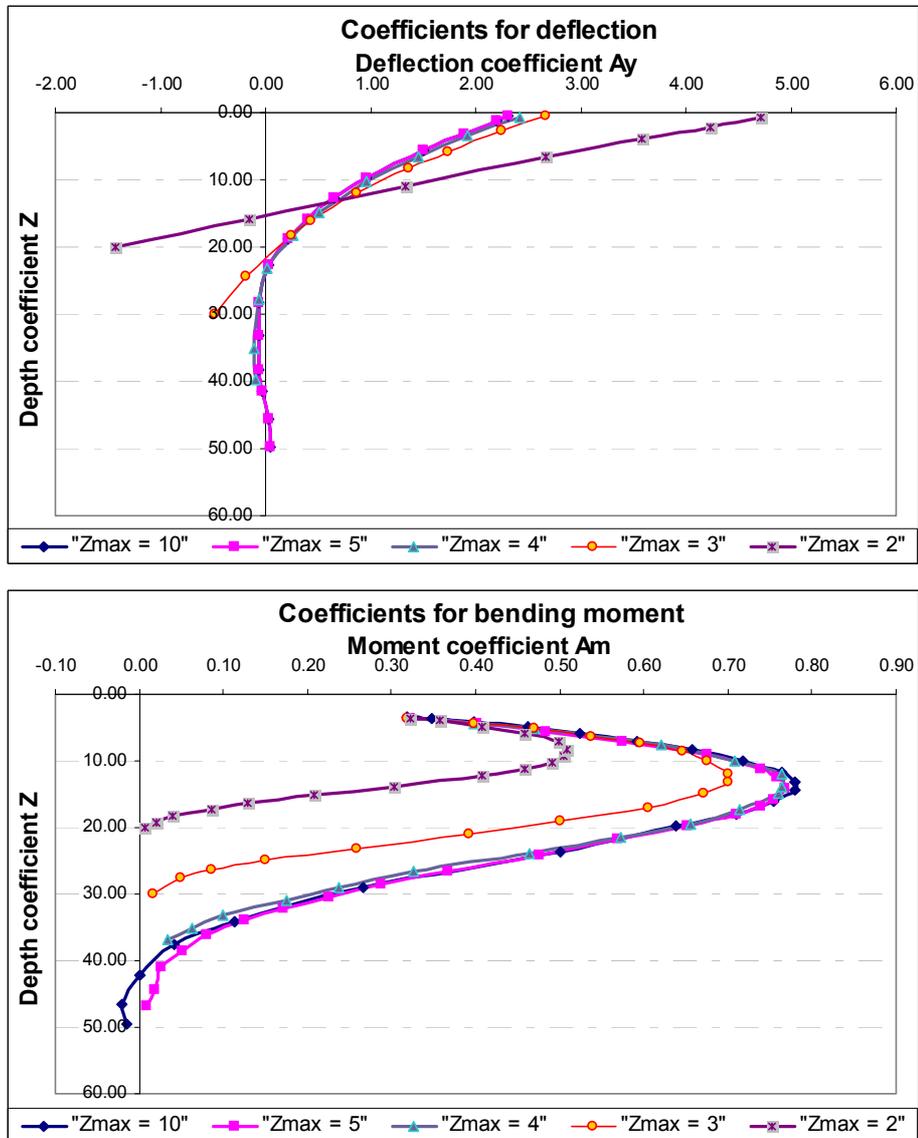


Figure 8: Coefficients for laterally loaded free-headed piles in soil with linearly increasing modulus (after Matlock and Reese [8]): and A_y and A_m

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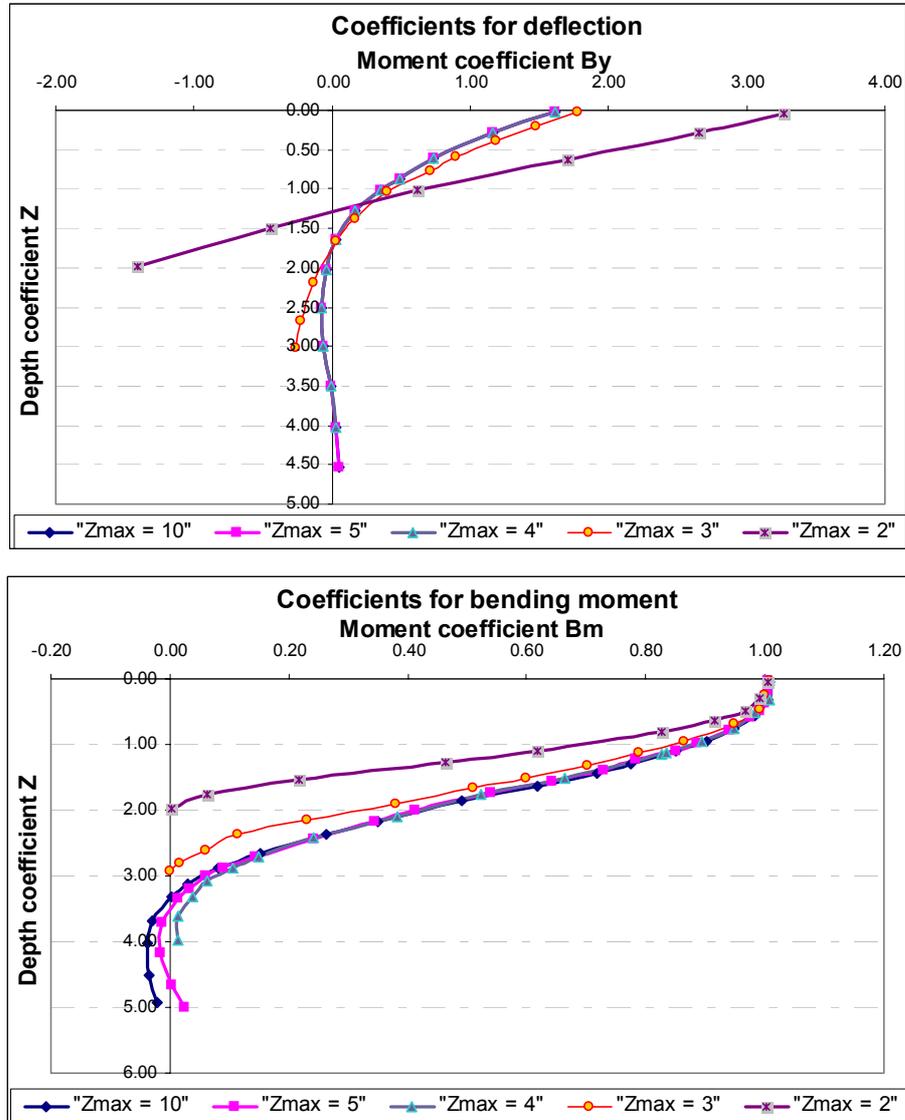


Figure 9: Coefficients for piles with moment at free head in soil with linearly increasing modulus (after Matlock and Reese [8]): B_y and B_m

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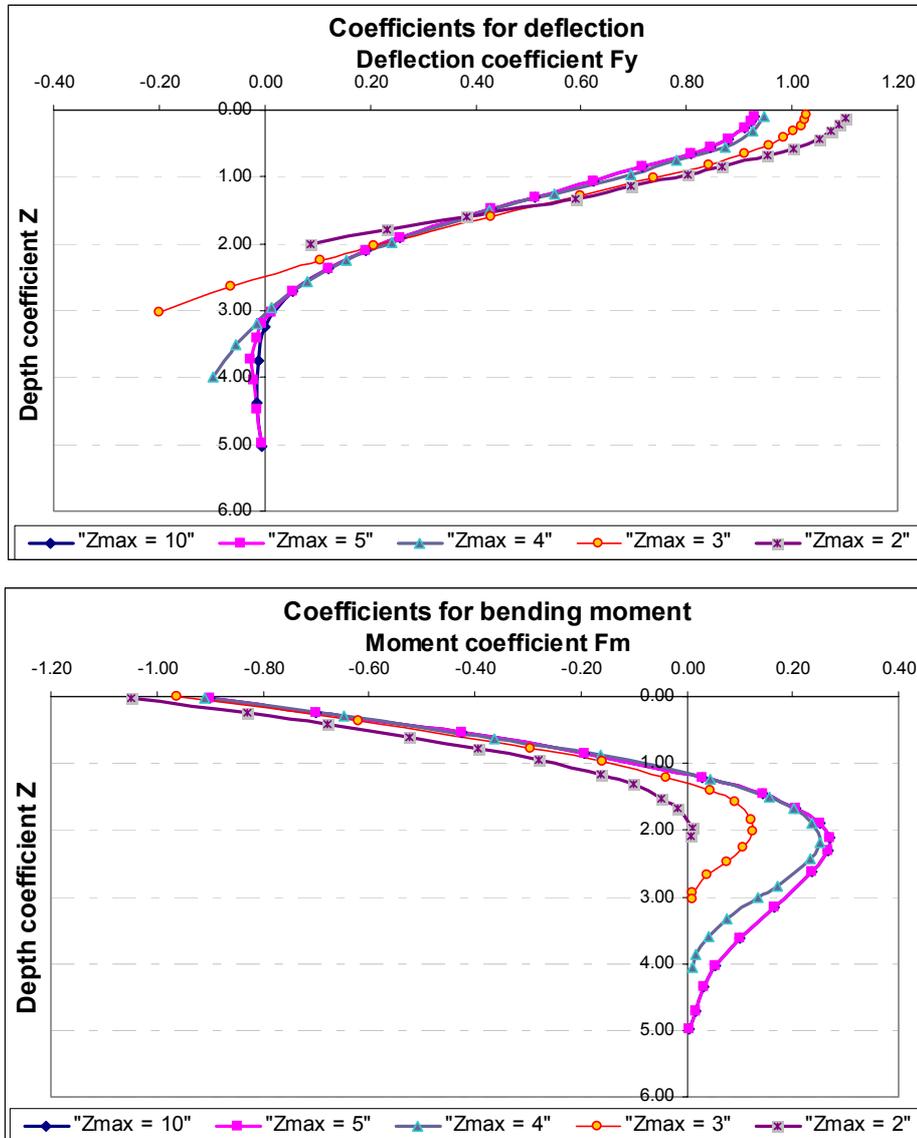


Figure 10: Coefficients for fixed headed piles with lateral load in soil with linearly increasing modulus (after Matlock and Reese, 1961 [8]): F_y and F_m

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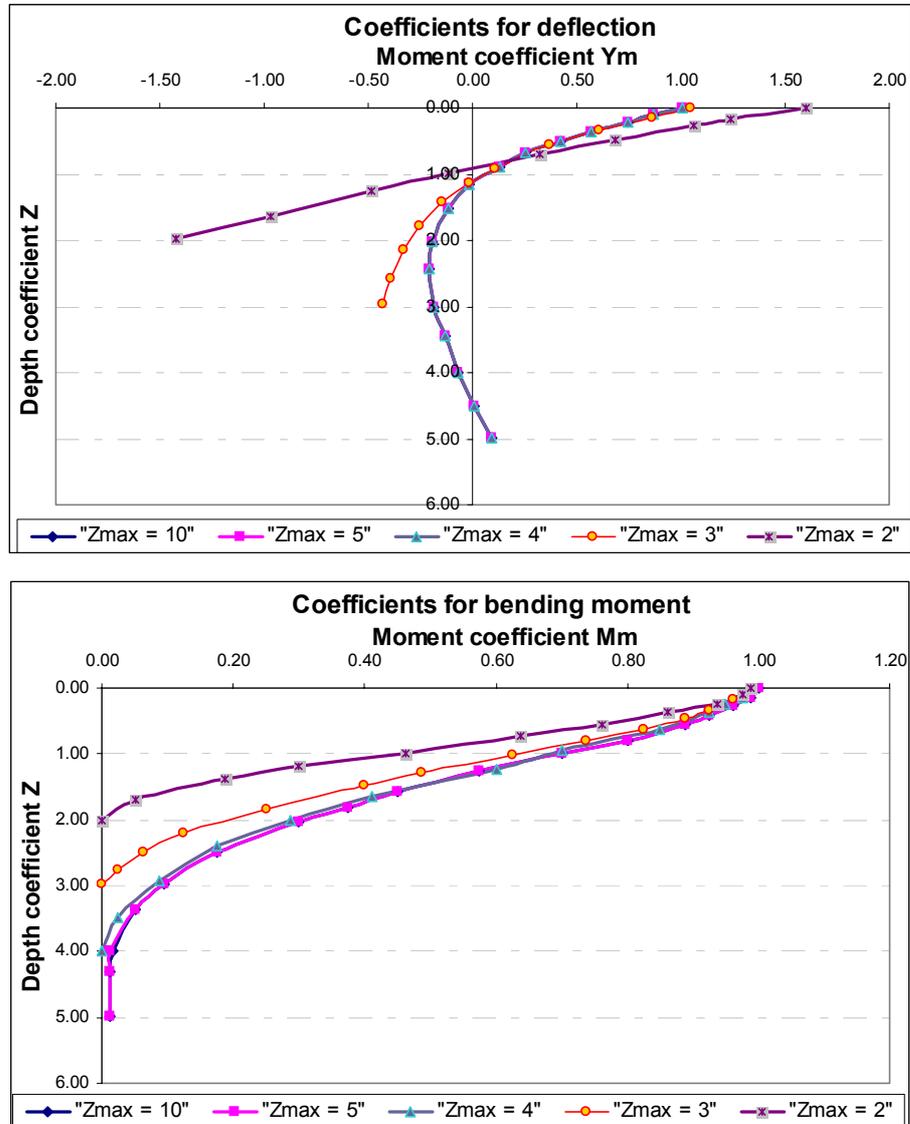


Figure 11: Coefficients for free headed piles carrying a moment at pile head in soil of constant modulus (after Davisson and Gill, 1963 [4]): Y_m and M_m

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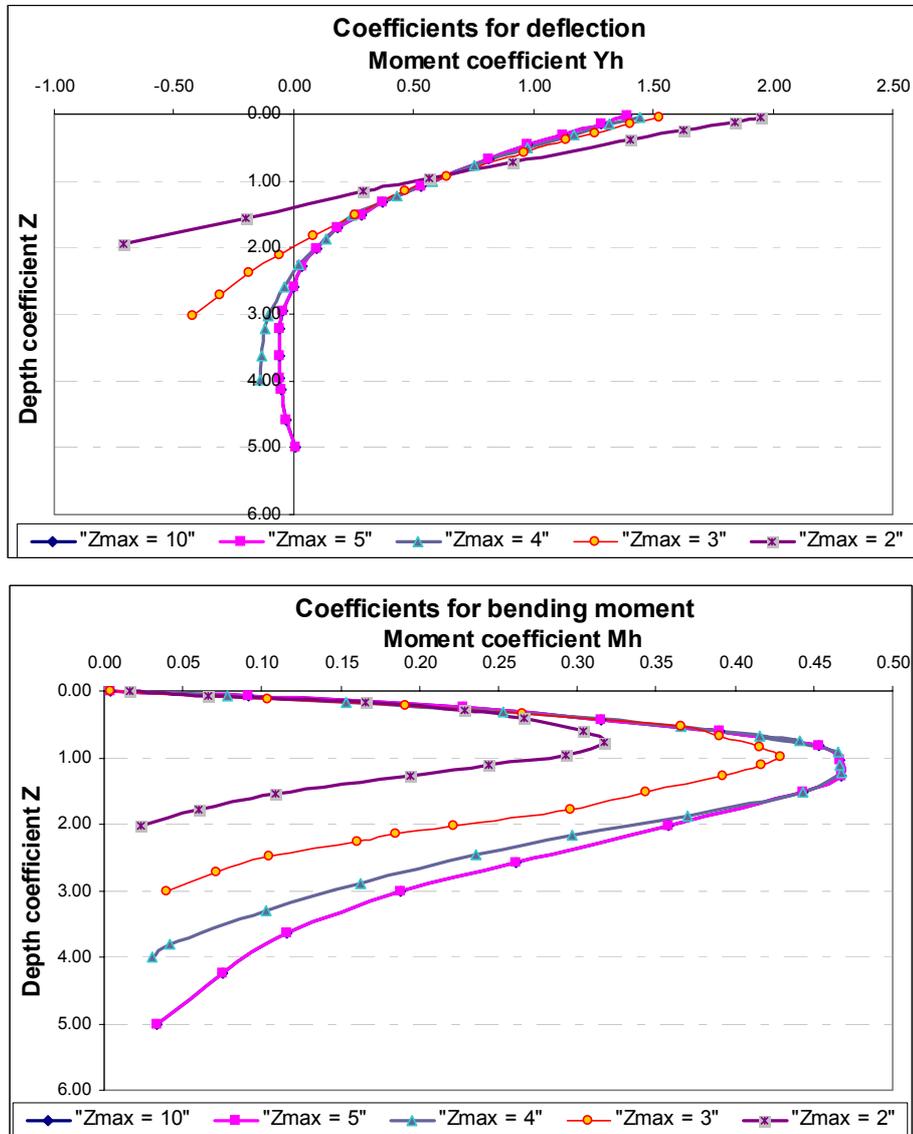


Figure 12: Coefficients for free headed piles carrying a lateral load at pile head in soil of constant modulus (after Davisson and Gill [4]): Y_h and M_h

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	J	K	M	P	R	T	W	Y
7			For a free-head pile &	Linearly increasing soil modulus		For a free-head pile &	Linearly increasing soil modulus	
8	Fill them up		Moment in a section along the pile length			Deflection of a section along the pile length		
9	Step	0.75	Am	Bm		Ay	By	
10			Zmax	Zmax	Mz	Zmax	Zmax	
11	z	Z	6.8585	6.8585		6.8585	6.8585	yz
12	0	0.000	0.000	1.000	0.050	2.334	1.585	0.00939
13	0.75	0.343	0.330	0.992	0.122	1.851	1.054	0.00729
14	1.5	0.686	0.587	0.943	0.175	1.198	0.653	0.00469
15	2.25	1.029	0.735	0.842	0.203	0.815	0.305	0.00308
16	3	1.372	0.774	0.709	0.205	-1.277	0.274	-0.00423
17	3.75	1.715	0.731	0.538	0.187	0.279	-0.040	0.00094
18	4.5	2.058	0.603	0.379	0.151	0.104	-0.108	0.00028
19	5.25	2.400	0.449	0.238	0.110	-0.012	-0.126	-0.00014
20	6	2.743	0.312	0.126	0.075	-0.078	-0.110	-0.00036
21	6.75	3.086	0.206	0.048	0.048	-0.104	-0.078	-0.00043
22	7.5	3.429	0.127	0.001	0.028	-0.098	-0.043	-0.00038
23	8.25	3.772	0.063	-0.021	0.013	-0.069	-0.015	-0.00025
24	9	4.115	0.008	-0.024	0.000	-0.028	0.000	-0.00010
25	9.75	4.458	-0.030	-0.013	-0.007	0.008	0.003	0.00003
26	10.5	4.801	-0.014	0.008	-0.003	0.018	0.000	0.00006
27	11.25	5.144	0.000	0.000	0.000	0.000	0.000	0.00000
28	12	5.487	0.000	0.000	0.000	0.000	0.000	0.00000
29	12.75	5.830	0.000	0.000	0.000	0.000	0.000	0.00000
30	13.5	6.173	0.000	0.000	0.000	0.000	0.000	0.00000
31	14.25	6.516	0.000	0.000	0.000	0.000	0.000	0.00000
32	15	6.859	0.000	0.000	0.000	0.000	0.000	0.00000

Figure 13: Typical output of the calculation of the deflection (yz) and the moment (M_Z) at a depth equal to (z) for a free head pile and a linearly increasing soil modulus

In order to produce a “useful” form of the Hybrid Method which facilitates the process of teaching the method and learning it, *all the above curves* had to be translated into equations to be used in Excel. Particular points on the curves were therefore chosen and then poly-fitted using MATLAB. The generated equations were then inserted in the Excel worksheets to obtain the moment distribution and the deflection at each section along the pile length.

Figure 13 presents the results of the moment and deflection values for the example problem as they appear in the Excel worksheet after running the “Fill them up” button or macro. Another Visual BASIC macro and button named "Draw Moment and deflection diagrams" automate the drawing of the moment and deflection diagrams along the pile length. The plot of the moment diagram with respect to the pile length is Figure 14. The results obtained using the CLM for the same example are also presented in the same figure for comparison. The two methods appear to yield significantly close values for the moments along the pile length. In essence this validates the developed tool.

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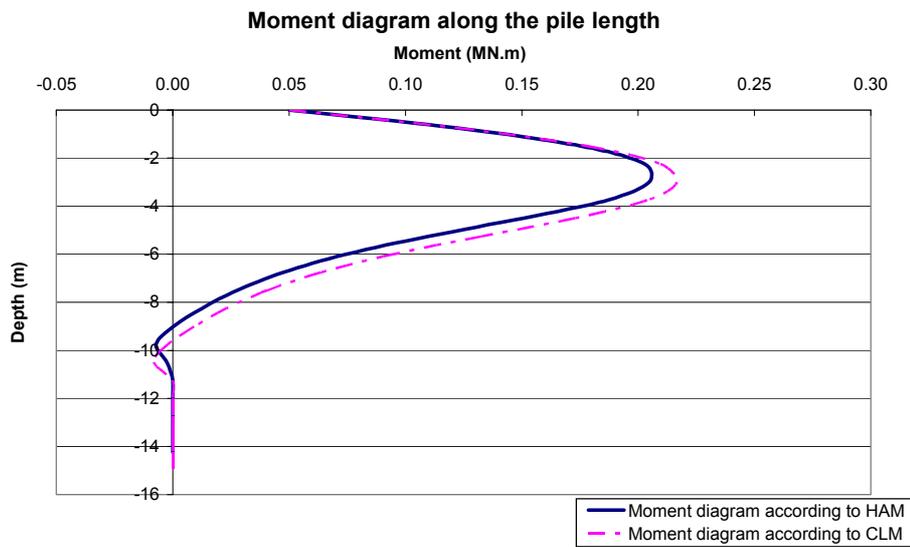


Figure 14: An Excel chart showing the moment diagram in a pile along its length

6 Summary and conclusions: academic use and value

In applied engineering, and particularly in the area of geotechnical engineering the teacher and students are presented with a number of problems where the response and behavior of the element of interest is complex and very difficult to visualize and explain. In essence, most problems involving responses conditioned by soil-structure interaction, fall under that category. Traditionally, the educational process and learning outcomes associated with these problems have left a lot to be desired. In our experience teaching deep foundations and the response of piles, the task of tackling the response of piles to lateral loads and moments has been the most challenging and frustrating. The available methods, the number of parameters involved and the empiricism embedded in many of the approaches compounded the difficulties. In response to the above, a new approach was sought, relying primarily on incorporating the power and functionality of spreadsheets. The basic idea was to facilitate the teaching process by providing the teacher with a method based on real-time demonstration of concepts and which also empowered students to explore the effect of various parameters and variables on the response and behavior of the piles.

In this paper, the process of development and use of a spreadsheet-based tool for the analysis of piles under seismic/lateral loading was documented. The significance of the work presented lies in the reduction of the presentation, comprehension and teaching of highly complex soil-structure interaction problem to an Excel environment where various aspects of the analysis can be easily explored, and their importance and effects on overall pile behavior immediately assessed and plotted. The problem of the seismic design of

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deep foundations is only one of a number of soil-structure interaction problems where the application of the analytical and graphing power of Excel could result in an easy-to-use-and-demonstrate product which enhances the process of learning and teaching.

We have already introduced the approach described in this paper to a class on geotechnical earthquake engineering at the American University of Beirut in the Fall 2003 semester. The number of students registered for the course was 18 (10 graduate and 8 undergraduate students). The response to the use of the spreadsheets approach was very positive, in the form of interested and interesting questions and feedback, students taking the spreadsheets to generate parametric studies and proposing improvements to the spreadsheets in form and content. This was from the teaching perspective a marked difference to the response we had prior to the introduction of this approach in the course in question in previous semesters when a traditional didactic approach was the norm.

We believe that the most clearly identifiable improvement allowed by the spreadsheet approach was the adoption of “what if?” scenarios to illustrate the effect and importance of certain parameters such as soil types, pile characteristics, levels and type of loading, etc. in real-class-time. The end of semester evaluation comments from some students, both graduate and undergraduate, included that same point.

In summary, to date our experience with using the spreadsheet tool in teaching the fundamentals of pile-soil interaction under seismic loading to classes of seniors and graduate students in civil engineering has been rewarding. The student response to the exercise presented in this paper has prompted us to explore the adoption of similar approaches for other civil engineering/geotechnical/structural applications.

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