Chapter 9: Pile Design Using DCALC*

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9.1 Introduction:

Although driven piles have had a long history of use in construction, the practice of designing pile remains something of an art, due to uncertainties about the mechanics of pile behavior. How do we analyze the behavior of a pile supported in a material like soil? Soil isn't like other elastic engineering materials, such as steel and concrete. It's a "viscous solid": Particles and grains, flowing and crushing on top of each other – with the additional complication of water pressure caused by the pile ramming process.

In 1948, Karl Terzaghi wrote about the complexities presented in understanding pile behavior:

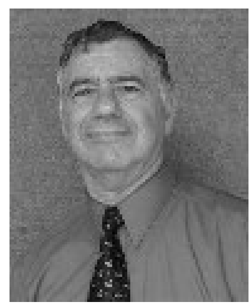
> "Because of the wide variety of soil conditions encountered in practice, any attempts to establish rules for the design of pile foundations necessarily involves radical simplifications, and the rules themselves are useful only as guides to judgment. For the same reason, theoretical refinements…are completely out of place and can be safely ignored." (Ref. 1, p. 526)

Karl Terzaghi
(1883-1963)

Not very encouraging words coming from the father of soil mechanics!

Now, contrast the above statement with another opinion by Harry Poulos, an acknowledged expert in this field:

> "Despite this pessimistic evaluation, the past *three decades* have seen a gradual change in pile design procedures, from essentially empirical methods towards methods with a sounder theoretical basis." (Ref. 2)



Harry Poulos
Univ. of Sydney

So, what has changed since Terzaghi's time?

Numerical methods, developed since the 1960's by Poulos and his contemporaries, can provide a fuller understanding of pile behavior compared to past methods.

This paper intends to discuss elementary pile design topics in one short chapter, for practicing structural engineers. We will divide this task into broad subtopics:

- Current methods for determining the ultimate pile load resistance for LRFD design based on the Illinois Department of Transportation's methods
- Numerical methods for determining the pile settlement and downdrag forces, based on Poulos' extensive research

(* DesignCalcs, Inc. http://www.designcalcs.com)

The secondary objective of this paper is to describe DCALC's pile design applications. Several example problems will be presented, comparing results to published results for verification purposes.

As a practicing structural engineer, I have always relied on geotechnical engineers for foundation recommendations. At this stage in my career, I decided to develop a pile design application, mainly out of curiosity. Starting with a blank slate, I began this venture not quite sure of what the pile design application would look like, except that it should be easy to use by structural engineers like myself.

I've listed several resources that I've read while researching this topic at the end of this paper. Probably the most highly referenced and practical text on this subject is "Pile Design and Construction Practice", by M. J. Tomlinson (Ref. 3). On the other end of the difficulty spectrum is, "Pile Foundation Analysis and Design", by Poulos and Davis (Ref. 4). This latter text, published in 1980 (pre-dawn to the personal computer revolution) provides a rational approach to pile design, well suited for the purpose of writing pile design applications. In my opinion, Poulos and Davis were well ahead of their time.

The task of taking Poulos' methodologies and writing a useful DCALC application was quite difficult, requiring almost a year's worth of learning curve on my part. Eventually the pile settlement application, "PILESETL", produced results that are consistent with published results.

In keeping with the writing style of other DCALC chapters, I have included short history lessons on the development of theories, including photographs of important engineers of the past. It is my belief that, as engineers, we need to keep a historical perspective about the development of theories in order to better understand these topics.

9.2 DCALC's Pile Design Applications:

DCALC has the following pile design applications:

- BORING: This program is used to collect soil boring data. It is also used by other DCALC geotechnical applications and is described in Chapter 8, "Settlement Calculations Using DCALC" (http://dcalc.us/Tutorials/Chapter8.pdf)

- PILE: This program designs driven piles for ASD and LRFD loads, using the methods that have been adopted by the Illinois Department of Transportation and the AASHTO LRFD Specification.

- PILESETL: This program computes the settlement of a single pile or a pile group, based on numerical methods developed by Poulos and his contemporaries.

After describing the essential theory used, the use of the above applications will be described. Examples used for verification purposes are listed, which the user can also try to become familiar with the application usage.

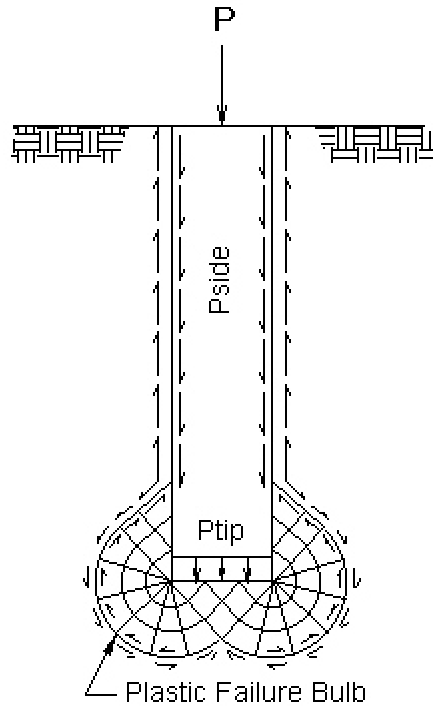
9.3 Designing Piles for Ultimate Loads:

The traditional method used for designing piles is to evaluate the ultimate failure mechanism of the pile, and then applying a generous safety factor to account for uncertainties. A pile resists loads by a combination of side friction and tip resistance.

Side Friction:
Friction will exist between the soil and the surface of the pile. The friction is composed of two potential parts:

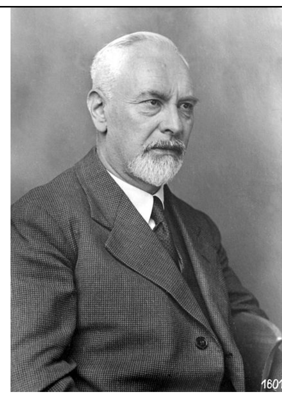
Pside = Soil Force (action normal to pile) * tan(ϕ)
+ Adhesion (for clay)

Traditionally, values of side friction have been determined based on test data for various soil types.



Tip Resistance:
The resistance at the pile tip is determined by an analysis of the plastic failure state. Karl Terzaghi developed equations for the plastic strength, borrowing from work on the Theory of Plasticity by Ludwig Prandtl.

In 1951, G. Meyerhof extended Terzaghi's equations into the format that is commonly used today.



Ludwig Prandtl
(1875-1953)

Of the above two sources of resistance, "side friction" is the least certain. Traditionally, values of side friction based on test data have been compiled in graphical form. Tomlinson's reference on this subject has been used as a standard reference for side friction values.

Lately, research done by Dr. James Long of the University of Illinois in association with the Illinois Department of Transportation (IDOT) has taken a fresh approach to formulizing values for side friction. In lieu of presenting side friction values in the form of graphs, equations have been developed based on the extensive records of pile loading tests. The IDOT document presenting these equations can be downloaded from the IDOT website at http://www.dot.il.gov/bridges/Design%20Guides/Design_Guides_Web.pdf as a "Design Guide", titled "Geotechnical Pile Design Procedure – AGMU Memo 10.2". In addition, IDOT provides pile design spreadsheets that can be downloaded from their website.

The pile design criteria in the AASHTO LRFD Specification is a fairly involved process. To provide specific guidance for designers on new LRFD pile design methods, some state DOT's, have prepared pile design policies. The above referenced IDOT document is particularly useful for designers.

Essentially the task of designing a pile for LRFD is twofold:

- To compute a pile type that has a **nominal strength** that is adequate to support factored loads. This is called the "**Factored Resistance Available**". <u>This is the pile strength that we use to design our structure using LRFD loads</u>. The pile strength must take into account various factors that may occur during the life of the structure, such as:
  - Downdrag
  - Scour
  - Liquefaction
- Next, we must compute the **pile resistance** that the field can monitor during driving. This is called the "**Nominal Required Bearing**". When a pile is installed, there is initially no downdrag, scour or liquefaction – therefore, we must take those factors "off the table" in this calculation. Contractors monitor a pile's resistance by measuring the number of blows per inch to drive a pile into the ground, using a formula called the "Gate's Formula". Gate's Formula uses the Nominal Required Bearing to determine the objective blows per inch.

The DCALC application, "PILE", is based on IDOT's methodology. IDOT also has a freely available spreadsheet that can be downloaded from their website.

If you are designing a bridge in Illinois, IDOT's pile design spreadsheet is ***the way*** to determine the necessary pile length and size. After becoming familiar with the spreadsheet and understanding the theory behind it, the spreadsheet is the most effective (and required) tool that you can use. The spreadsheet is particularly helpful for comparing pile alternatives.

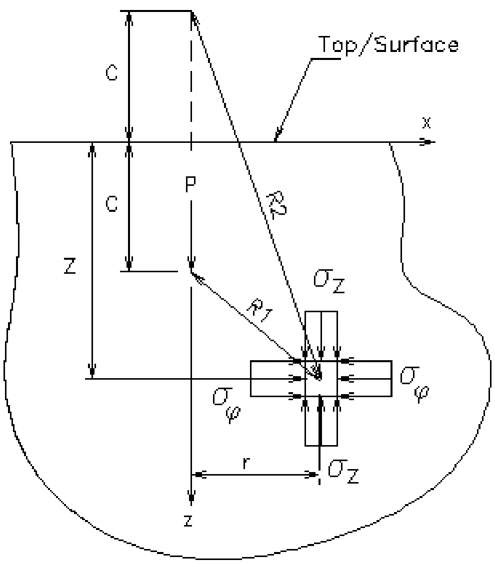
Having said that, DCALC has its own pile design application, "PILE". Designing a pile using PILE is a very quick process, automating the entire process. The PILE application produces explicit calculations, similar to hand calculations, that can be checked.

A designer may want to use PILE to check the spreadsheet's results, or to better understand the spreadsheet results. Also, it will be necessary to run PILE if you need to run PILESETL, which computes settlement.

9.4 Mindlin's Solution to a Point Load in A Semi-Infinite Solid:

The most interesting mathematical problems addressed by the Theory of Elasticity were largely solved during the 19th and early 20th century. A particularly influential mathematician was Boussinesq, who derived the solution of a point load on the surface of a semi-infinite solid. Boussinesq's solution has found great use in the field of geotechnical engineering as a method for determining settlement of spread footings. Another interesting solution (yet limited in practical importance) is Kelvin's solution to a point acting inside an *infinite* mass.

In 1936, Raymond Mindlin learned of H.M. Westergaard's interpretation of Kelvin's solution based on a series of lectures at the University of Michigan. Westergaard reinterpreted Kelvin's solution into a form of vector notation developed by Galerkin in 1930. Based on insights from these lectures, Mindlin was able to solve the problem of a point load inside a semi-infinite mass by superimposing a combination of Galerkin strain fields.



Point Load Inside a Semi-Infinite Solid

Raymond Mindlin
(1906-1987)

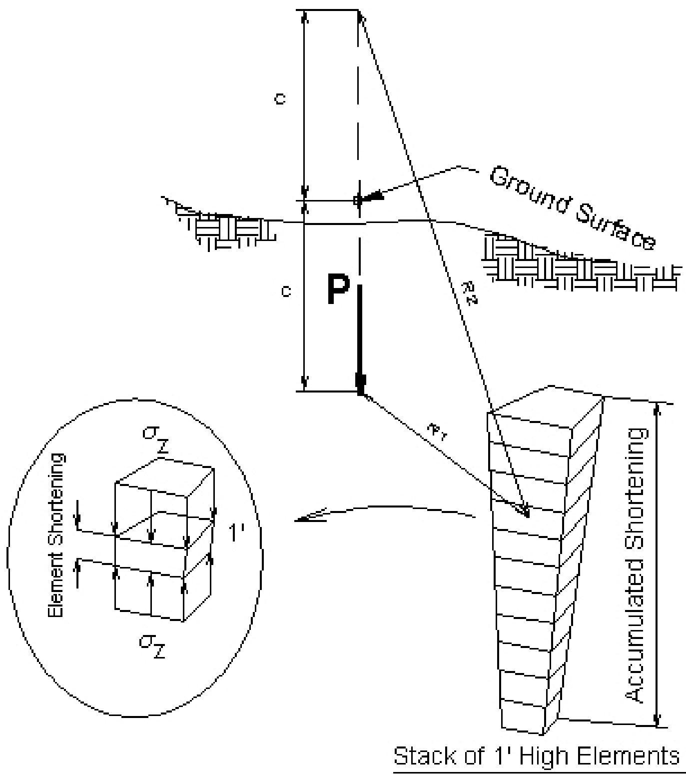
Solution to the problem (sign convention: tension = "+", compression="-"), from Ref. 6:

$$\sigma_r = \frac{P}{8\pi(1-\mu)}\left[\frac{(1-2\mu)(z-c)}{R_1^3} - \frac{(1-2\mu)(z+7c)}{R_2^3} + \frac{4(1-\mu)(1-2\mu)}{R_2(R_2+z+c)} - \frac{3r^2(z-c)}{R_1^5} + \frac{6c(1-2\mu)(z+c)^2 - 6c^2(z+c) - 3(3-4\mu)r^2(z-c)}{R_2^5} - \frac{30cr^2z(z+c)}{R_2^7}\right],$$

$$\sigma_\theta = \frac{P(1-2\mu)}{8\pi(1-\mu)}\left[\frac{(z-c)}{R_1^3} + \frac{(3-4\mu)(z+c)-6c}{R_2^3} - \frac{4(1-\mu)}{R_2(R_2+z+c)} + \frac{6c(z+c)^2}{R_2^5} - \frac{6c^2(z+c)}{(1-2\mu)R_2^5}\right],$$

$$\sigma_z = \frac{P}{8\pi(1-\mu)}\left[-\frac{(1-2\mu)(z-c)}{R_1^3} + \frac{(1-2\mu)(z-c)}{R_2^3} - \frac{3(z-c)^3}{R_1^5} - \frac{3(3-4\mu)z(z+c)^2 - 3c(z+c)(5z-c)}{R_2^5} - \frac{30cz(z+c)^3}{R_2^7}\right],$$

9.4.1 A Numerical Approach To Settlement Using Mindlin's Solution:
DCALC uses the following numerical approach for computing settlement due to a point load by considering a stack of 1 foot high elements:



In the above figure, a point load is shown inside a semi-infinite mass. In this case, the "semi-infinite mass" is the earth. We can conveniently evaluate the shortening in individual stacked elements that are each one foot high as follows:

- The stresses, σz, σx, and σy are calculated for each element using Mindlin's solution
- The vertical strain of each one foot high element is,

  $\varepsilon z = \sigma z\ (1 - \upsilon(\sigma x + \sigma y))$, where "υ" = poisson's coefficient of soil
- The vertical shortening of each one foot high element "i" is,

  $S_i = \varepsilon z / E_s * 1$ foot, where "E_s" = modulus of elasticity of the soil
- The shortening of the stacked column is the accumulated shortening of all the one foot high elements:

  Accumulated shortening = $\Sigma\ S_i$

We can compute the settlement of the stacked column due to the load, P, by starting the numerical integration from the "bottom up" to the point in question. If the "bottom" is sufficiently lower than the load P, (such as the bottom of soil boring log) the stresses and strains will be virtually zero. This approach has the additional advantage of being easily adapted to any type of layered soil condition, by using the "E_s" appropriate to the layer in question.

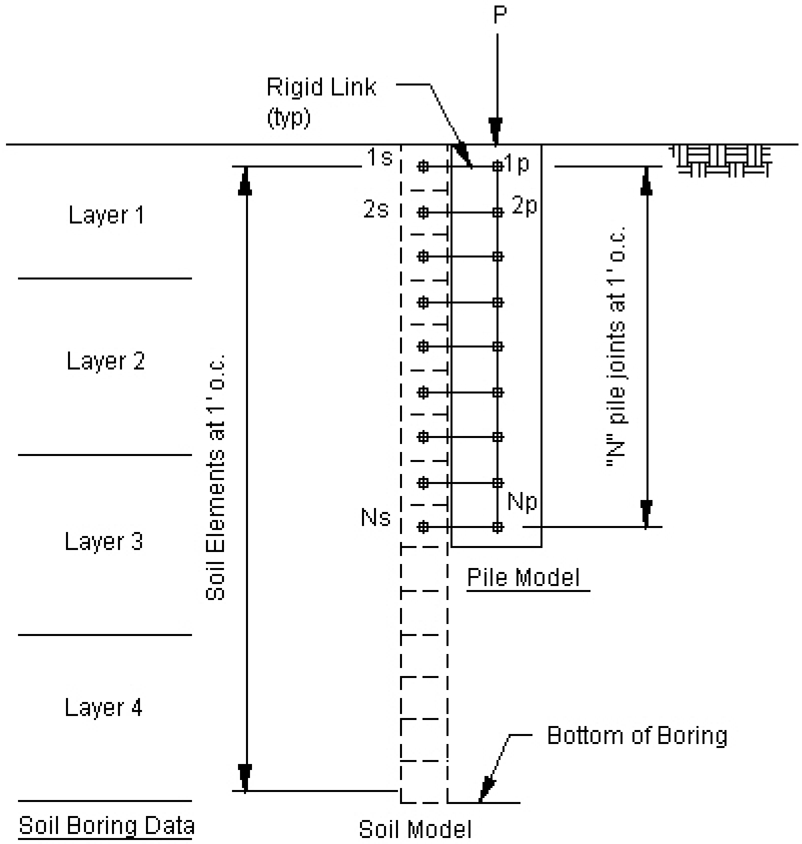
9.5 Poulos' Method Used to Compute Pile Settlement (Single Pile)

The following approach has been adapted from Chapter 5 of "Pile Foundation Analysis and Design" by Poulos and Davis, 1980

Note: Some of the methodologies used by DCALC differ in approach from those used by the reference, but the intent is the same. For example, the referenced text utilizes closed form integral forms to compute settlement; whereas, DCALC uses a numerical approach (see preceding section). Also, the terminology used here differs from this reference, although not in meaning, for consistency with finite element terminology used by DCALC (For example: "matrix of soil displacement influence" is termed "soil flexibility matrix" in this paper.)

Step 1: Define the geometry and joint configuration of the pile-soil model

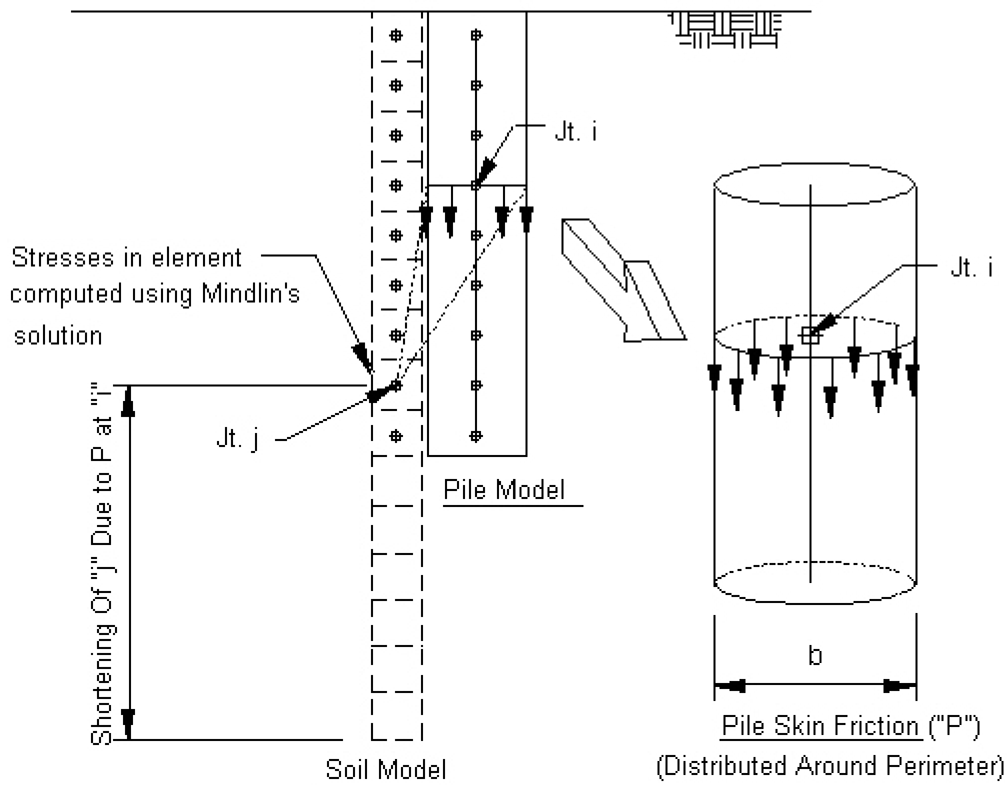
A finite element model of the pile is first developed by considering the soil and the pile as two separate finite element models that are rigidly linked ("no slip" condition):



The pile model is divided into 1 foot tall segments. The soil model is located on the side of the pile, consisting of 1 foot stacked soil elements that extend down to the bottom of the boring.

DCALC utilizes soil boring data which the user must input into the BORING application. A soil boring must be sufficiently deeper than the bottom of the pile, because we will be assuming that stresses and settlement at the bottom of boring are negligible.

Step 2: Determine the stiffness properties of the soil structure



For each soil joint that is adjacent to a pile joint, we need to compute the settlement at soil joint "j" due to a unit load, P=1 k, at joint "i". The pile load is further subdivided around the perimeter of the pile (Poulos and Davis recommend subdividing the load into 50 fractional parts.)

As described in the previous section, the stresses, σz, σx, and σy are calculated for each element using Mindlin's solution. Then the shortening of soil element "j" is computed, based on the soil properties. Then the settlement of the soil stack from the bottom of the boring is computed.

The result of the process is a deflection coefficient, "α_{ij}" – the settlement at "j" due to P=1 k at "i".

This process is repeated for all soil elements below joint "i". (It is not necessary to compute the settlement of soil elements above "i", as will be explained.)

We then assemble the <u>lower triangle</u> of the **soil flexibility matrix**, as follows:

$$[f_{soil}] = \begin{vmatrix} \alpha_{11} & \text{(Don't compute upper triangle!)} & & \\ \alpha_{21} & \alpha_{22} & & \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & \\ . & . & . & \\ \alpha_{N1} & \alpha_{N2} & \alpha_{N3} \ldots\ldots & \alpha_{NN} \end{vmatrix}$$

Based on Maxwell's reciprocal law, the coefficients of the upper triangle must equal the coefficients of the lower triangle:

$$[f_{soil}] = \begin{vmatrix} \alpha_{11} & \alpha_{21} & \alpha_{31} & & \alpha_{N1} \\ \alpha_{21} & \alpha_{22} & \alpha_{32} & \ldots\ldots\ldots & \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & \ldots\ldots & \\ . & . & . & & \\ \alpha_{N1} & \alpha_{N2} & \alpha_{N3} & \ldots\ldots & \alpha_{N4} \end{vmatrix}$$

← Upper triangle reflects the lower triangle

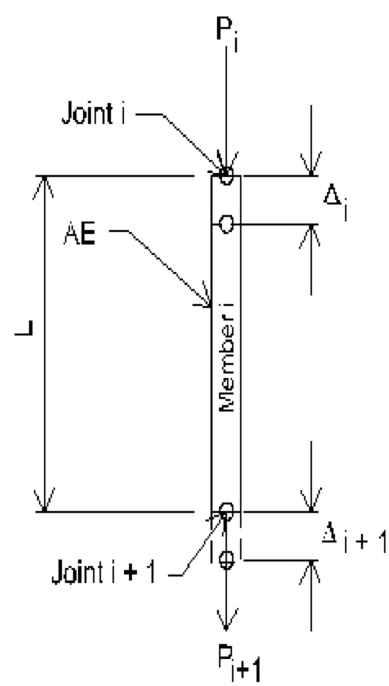
←Joint N

The **soil stiffness matrix** is then computed as the inverse of the soil flexibility matrix:

$$[K_{soil}] = [f_{soil}]^{-1}$$

<u>Step 3: Compute stiffness properties of a typical pile element</u>

Depicted on the right is a simple finite element bar representing the pile member "i".



The relative shortening of the bar due to "P_i" is,

$\Delta_i - \Delta_{i+1} = P_i*L/AE$

$\Rightarrow P_i = AE/L*(1 \;\; -1)*\{ \Delta_i \;\; \Delta_{i+1}\}$

Force equilibrium requires that

$P_i+P_{i+1}=0$

$\Rightarrow P_{i+1} = -P_i = -\, AE/L*(1 \;\; -1) \; * \{ \Delta_I \;\; \Delta_{i+1}\}$

$= \;\; AE/L*(-1 \;\; 1)* \{ \Delta_i \;\; \Delta_{i+1}\}$

Therefore,

$$\begin{vmatrix} P_i \\ P_{i+1} \end{vmatrix} = \frac{AE}{L} * \begin{vmatrix} 1 & -1 \\ -1 & 1 \end{vmatrix} \begin{vmatrix} \Delta_i \\ \Delta_{i+1} \end{vmatrix}$$

The element stiffness matrix for this simple bar is,

$$[K_i] = \frac{AE}{L} * \begin{vmatrix} 1 & -1 \\ -1 & 1 \end{vmatrix}$$

<u>Step 4: Assemble the pile stiffness matrix:</u>

The overall pile stiffness matrix is constructed by summing the element stiffness matrices:

$$[K_{pile}] = \frac{AE}{L} * \begin{vmatrix} 1 & -1 & 0 & 0\ldots & & 0 \\ -1 & 2 & -1 & & & 0 \\ 0 & -1 & 2 & -1\,.. & & 0 \\ & & -1 & 2\ldots & & -1 \\ 0 & 0 & 0 & \ldots. & & 2 \end{vmatrix}$$

←Joint 1

←Joint N

Step 5: Compute stiffness properties of the composite soil-pile model:

A composite stiffness matrix is constructed, the form of which depends on if slip occurs between the soil and the pile. We will need to iterate the solution, checking whether or not slip occurs, and then assemble the **composite stiffness matrix** based on the following rules:

Rule 1: Composite stiffness at joint rows where slip does not occur ($\Delta_{soil} = \Delta_{pile}$)
At joint locations where slip does not occur, the row corresponding to the joint is assembled by adding the corresponding rows of the pile stiffness matrix and the pile stiffness matrix:

The row of $[K_{composite}]$ = The row of $[K_{pile}]$ + the row of $[K_{soil}]$

Rule 2: Composite stiffness at joint rows where slip occurs ($\Delta_{soil} <> \Delta_{pile}$)
At joint locations where slip will occur, the rows will consist of the corresponding row of the pile stiffness matrix:

The row of $[K_{composite}]$ = The row of $[K_{pile\ 1}]$

The definition of "slip" is the maximum side friction resistance of the pile, "Pside max, i"

Step 6: Compute applied force vector

The form of the applied force vector also depends on if slip occurs between the soil and the pile. The **applied force vector** is assembled based on the following example of the rules:

Rule 1: Applied force vector at joint rows where slip does not occur ($\Delta_{soil} = \Delta_{pile}$)

[F] =	Ptop	←Joint 1
	0	
	0	
	0	
	0	←Joint N

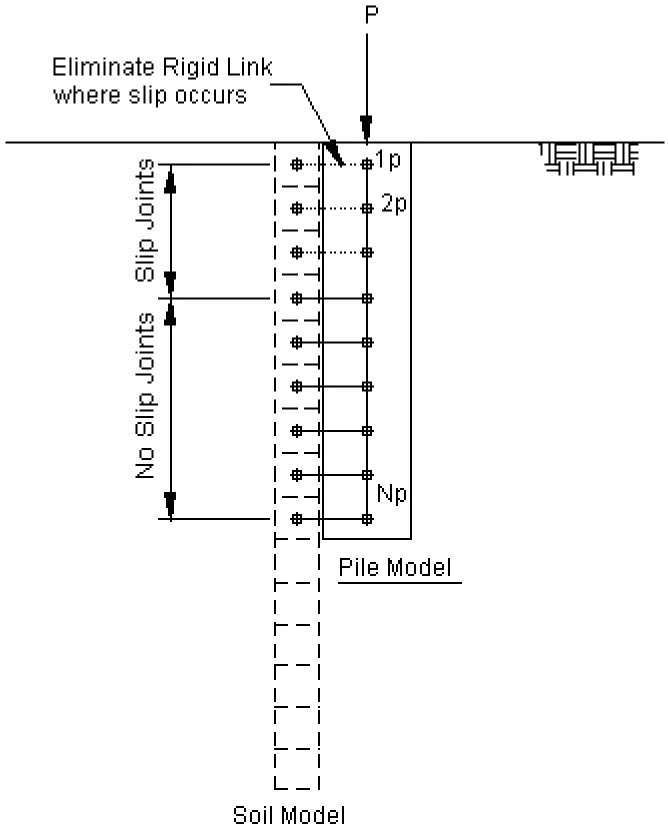
Rule 2: Applied force vector at joint locations where slip occurs ($\Delta_{soil} <> \Delta_{pile}$)

[F] =	Ptop – Pside 1	(slip occurring at joint 1)
	-Pside2	(slip occurring at joint 2)
	0	(no slip below…)
	0	
	0	←Joint N

In the above, "Ptop" is the load applied to the top of the pile.

Step 7: Put it all together:

The below detail shows a pile where slip has occurred in the top three joints:



The corresponding finite element formulation to this problem is,

$$\begin{vmatrix} 1 & -1 & 0 & 0 & 0 & 0 \\ -1 & 2 & -1 & 0 & 0 & 0 \\ 0 & -1 & 2 & -1 & 0 & 0 \\ 0 & 0 & -1 & \multicolumn{3}{c}{K_{soil}+Kpile} \\ \cdots & & & & & \\ 0 & . & . & & & \end{vmatrix} * \begin{vmatrix} \Delta_1 \\ \Delta_2 \\ \Delta_3 \\ \Delta_4 \\ \\ \Delta_N \end{vmatrix} = \begin{vmatrix} P_1 - P_{slip1} \\ -P_{slip2} \\ -P_{slip3} \\ 0 \\ \\ 0 \end{vmatrix}$$

which, written in matrix notation, is,

$$[K_{composite}] \quad * [\Delta] \quad = \quad [F]$$

Step 8: Invert the composite stiffness matrix, then solve for settlements:

$$[\Delta] = [K_{composite}]^{-1} * [F]$$

Step 9: Compute forces transferred to the soil:

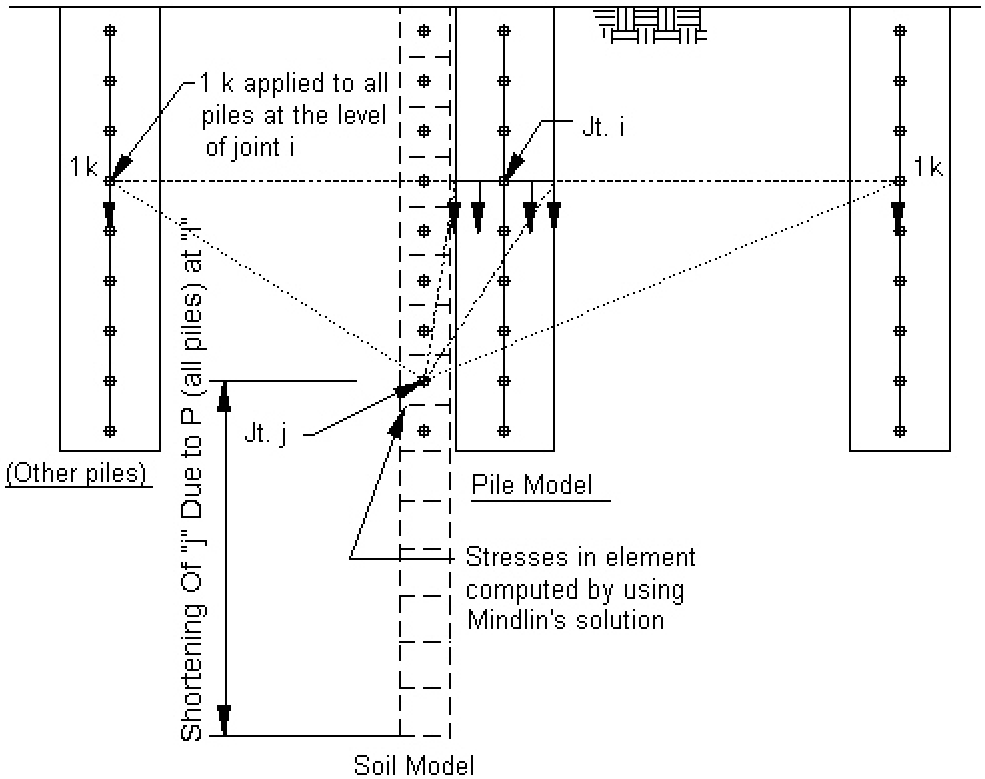
$$[P_{soil}] = [K_{pile}] * [\Delta]$$

Final Step 10: If $P_{soil} > P_{soil,\ max}$, then slip has occurred.

=>Go back to Step 5 and make necessary adjustments, iterating the solution.

9.5.2 Method Used to Compute Pile Settlements of Pile Group

The settlement of a pile group is determined by essentially same the method used to compute the settlement of a single pile, except the soil flexibility matrix requires adjustment in Step 2:



The stress in the soil element due to the pile adjacent to the soil model is computed by the same process as described in Step 2 (Explicitly: The unit load, P=1 k, is subdivided around the perimeter of the pile).

The “other” piles also contribute to the stress in the soil model. The contribution of stress is computed based on a unit load, P=1 k, applied at the centerline of the pile, at the same level at joint “i”.

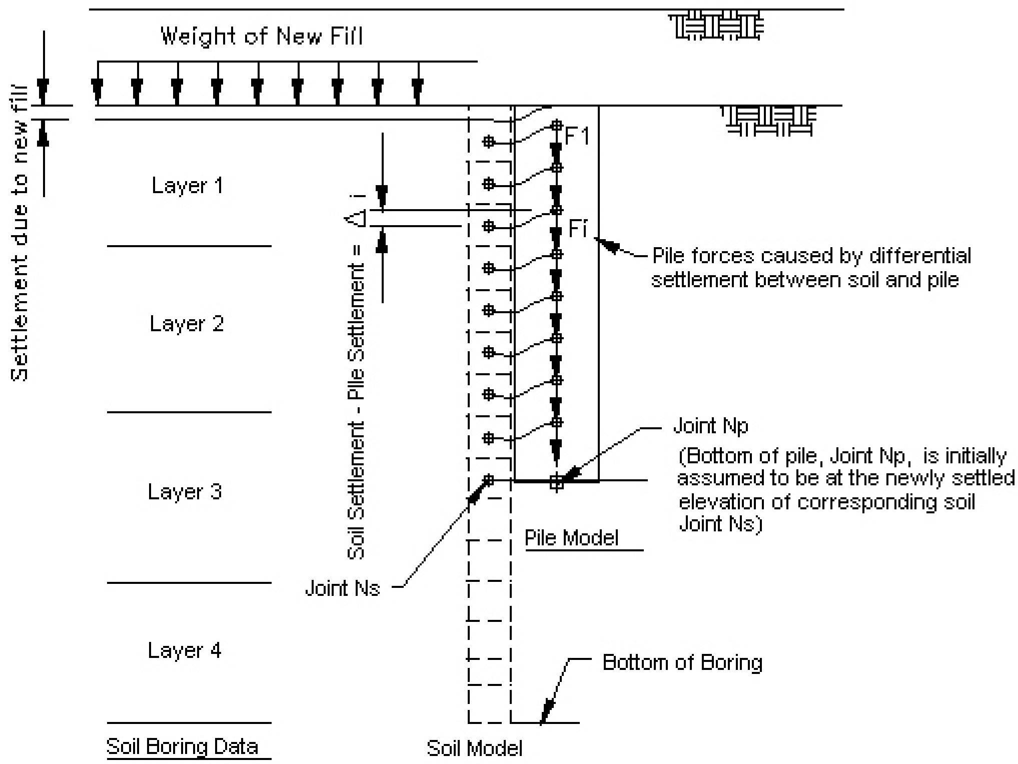
After computing the stresses in each element using Mindlin’s solution, as described before under Step 2, then the shortening of each element is computed and then the settlement of the soil stack is computed based on the accumulated shortening.

The soil flexibility matrix, [f_{soil}], is assembled using the above computed settlement coefficients.

After this adjustment to Step 2, the remaining steps are the same as described previously.

9.5.3 Method Used to Compute Pile Settlements Due to Downdrag (*)

Pile "downdrag" forces are typically caused by the settlement of soil due to the weight of new fill. Downdrag forces can also be caused if the water table is lowered, causing settlement of the surrounding the soil. In other words, rather than the problem of "force causes settlement", the problem is reversed and becomes "settlement causes force".



If new fill is present, we continuing from previous steps as follows:

Step 11: Compute the settlement of the soil due to the weight of the new fill, using conventional soil settlement methods (see http://dcalc.us/Tutorials/Chapter8.pdf)

Step 12: Assume that the pile "floats" downward with the settled soil. The bottom of the pile is initially assumed to be at the same elevation as the newly settled soil elevation. Based on rigid body movements, compute elevations of pile joints.

Step 13: Compute forces transferred to the pile:

$$[F_{DD}] = [K_{pile}] * [\Delta_{differential}]$$

Step 14:Compute additional settlement of composite pile-soil system:

$$[\Delta_{additional\ at\ pile}] = [K_{composite}]^{-1} * [F_{DD}]$$

Step 15: Revise elevations of pile joints, based on additional settlements. Re-compute $\Delta_{differential}$ between soil and pile.

Final Step 16: Iterate the solution (DCALC uses 10 iterations)

(*) The above methodology differs slightly from the approach presented by Poulos and Davis in their 1972 paper (Ref. 8)

9.6 Soil Properties to Be Used for Pile Settlement Calculations

In the previous chapter, "Settlement Calculations Using DCALC", the soil properties that are used for conventional settlement calculations for such things as spread footings were discussed (see http://dcalc.us/Tutorials/Chapter8.pdf). The same recommendations for elastic properties, Es, can be applied to for pile settlement calculations.

However, there is a major difference in methodology for how to compute long term pile settlement compared to conventional footings. Whereas for conventional settlement calculations a logarithmic function is used to compute long term settlement, this method does not apply for computing long term settlement of piles.

For secondary pile settlement an adjusted modulus of elasticity of clay layers is used, as follows:

$$E(drained) = E(undrained) * 2*(1+\upsilon)/3$$

9.7 Comparison of DCALC's PILESETL Program to Published Results

In the following examples, a comparison to results produced by PILESETL to published results is illustrated.

As this software is an integrated process, the user will go through the following steps:

1. Enter soil boring data into the BORING application
2. Run the PILE application, to either design or analyze a pile
3. Run PILESETL

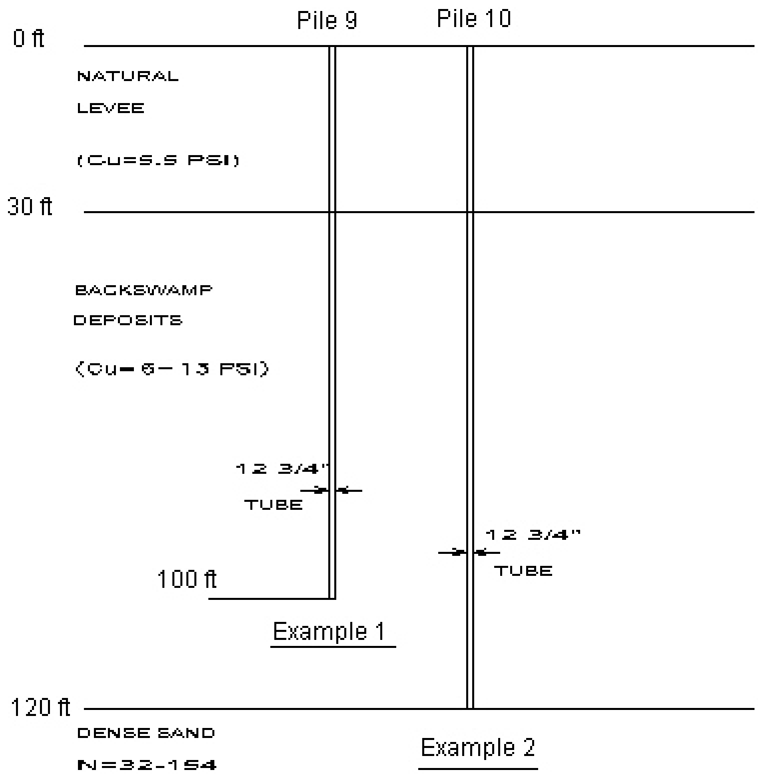
PILESETL is designed to apply the previous design theory as one automated process. The user should verify the soil properties - in particular "Es" - as this will effect the computed settlements.

DCALC input and output files for these examples can be downloaded from http://dcalc.us/Downloads/PILESETTEMENT.zip

- If you are a licensed DCALC user, you will need to create a new directory, then unzip the files into the new directory.
- If you are not a licensed DCALC user and you are trying out the DCALC demo, you will need to unzip the files into the C:\DCALC\DEMO directory (however, this will render all other DEMO calculations useless).

9.7.1 Examples 1 and 2:

These examples are described in Poulos and Davis' text (Ref 4). In 1969, pile tests at site on the banks of the Mississippi River were made by researchers Darragh and Bell. Mattes also made an analytical prediction of settlement, which is included in Poulos and Davis' text.



These examples have also been analyzed using DCALC's PILESETL program, with the following results:

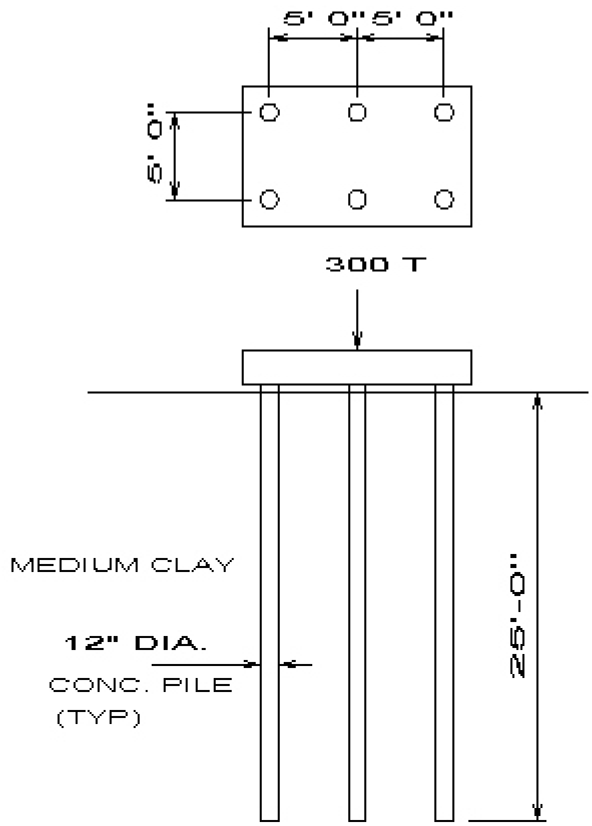
Example 1 Comparison of Results:

	Measured	Predicted by Mattes	DCALC Result
Top Settlement	0.10 in	0.09 in	0.101 in
Base Settlement	0.015 in	0.01 in	0.01 in

Example 2 Comparison of Results:

	Measured	Predicted by Mattes	DCALC Result
Top Settlement	0.17 in	0.16 in	0.20 in
Base Settlement	0.02 in	0.016 in	0.01 in

9.7.3 Examples 3:
This example is used to verify the settlement of a pile group. In Poulos' and Davis' text (Ref. 4), an Illustrative Example on p. 119 is presented, illustrating the methodology used in the text.

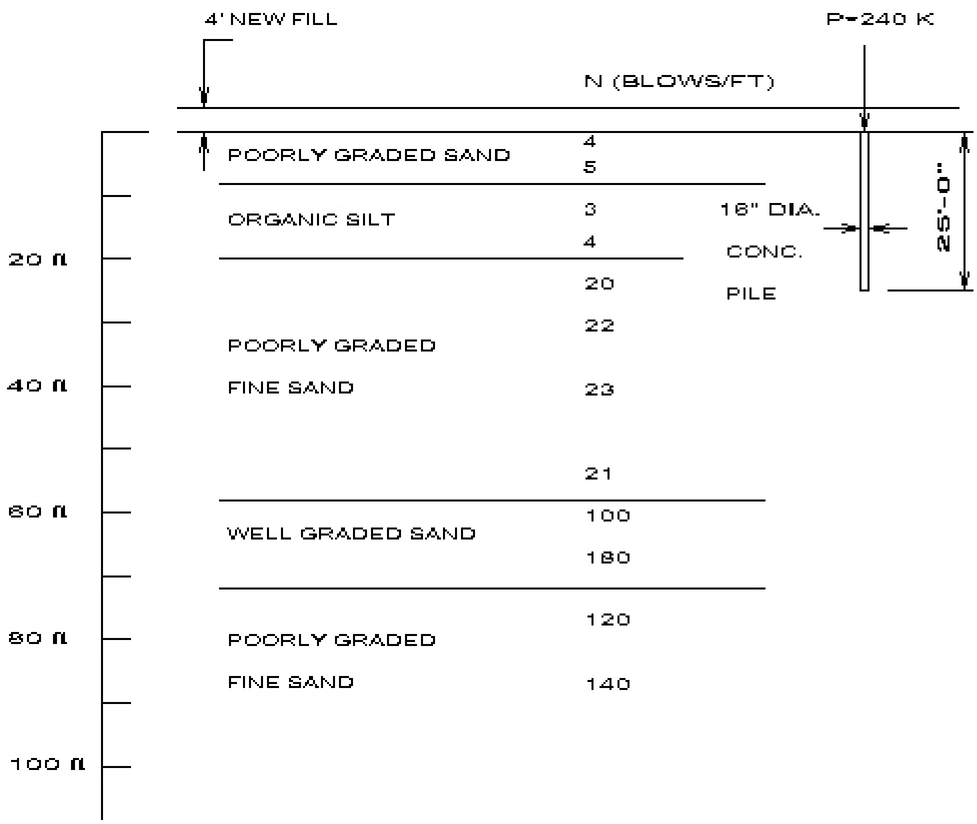


This example have also been analyzed using DCALC's PILESETL program, with the following results:

	Published Reference	DCALC Result
Predicted top settlement	1.62 in	2.014 in

The difference in results is most likely due assumptions that needed to be made about soil parameters for the DCALC run.

9.7.4 Examples 4:
This example appears as Example 18-4, in J.E. Bowles book, "Foundation Analysis and Design" (Ref. 9). In 1974, pile settlements for a building under construction were reported by Koerner and Partos.

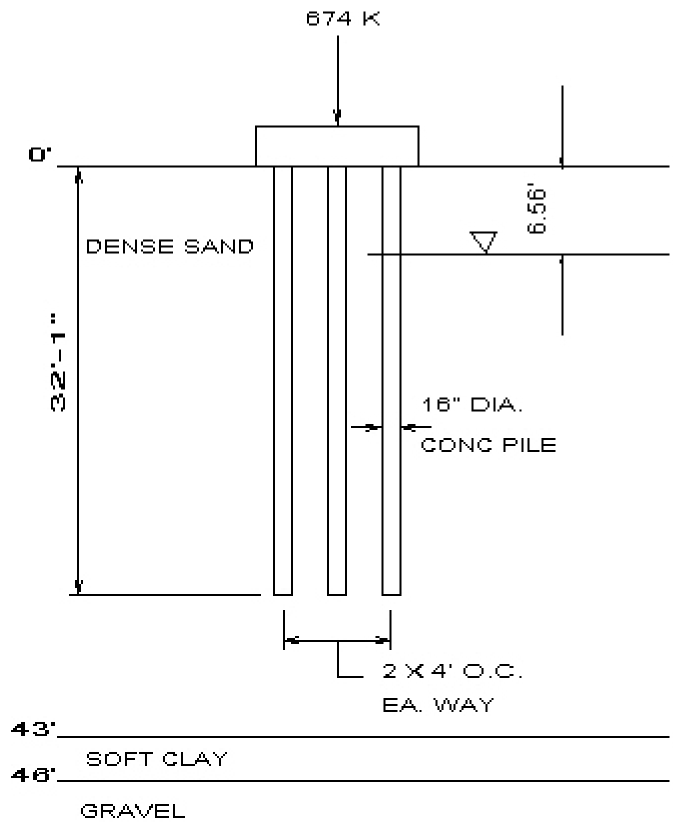


Bowles uses several approaches for predicting the pile settlement, with ambiguous results.

This example have also been analyzed using DCALC's PILESETL program, with the following results:

	Published Reference	DCALC Result
Predicted top settlement	1.5 in to 3.3 in with and average of ΔH = 3.2 in	3.049 in

9.7.5 Examples 6:
This example appears as Example 8-8, in "Foundations and Earth Retaining Structures" by Muni Budhu (Ref. 10).



This example have also been analyzed using DCALC's PILESETL program, with the following results:

	Published Reference	DCALC Result
Predicted top settlement	27 mm = 1.06 in	0.742 in

The difference in results is most likely due assumptions that needed to be made about soil parameters for the DCALC run. Also, the difference in methodology used by the reference may account for the slight difference in settlement.

List of References:

Reference 1: "Soil Mechanics in Engineering Practice", by Karl Terzaghi and Ralph Peck, published by John Wiley and Sons, 1948

Reference 2: "Pile behaviour – theory and application", by H.G. Poulos, published in Geotechnique, 1989

Reference 3: "Pile Design and Construction Practice", by M. J. Tomlinson, published by Viewpoint Publications, 1977

Reference 4: "Pile Foundation Analysis and Design", by Poulos and Davis, published by John Wiley and Sons, 1980

Reference 5: AASHTO LRFD Bridge Design Specifications, Customary U.S. Units, 4th Edition, 2007

Reference 6: "Forces at a Point in the Interior of a Semi-Infinite Solid", by Raymond D. Mindlin, published in *Physics*, May 1936

Reference 7: "The Behavior of Axially Loaded End-Bearing Piles", by H.G. Poulos and N.S. Mattes, published in *Geotechnique*, 1969

Reference 8: "The Development of Negative Friction with Time in End –Bearing Piles", by H.G. Poulos and N.S. Mattes, published in *Geotechnique*, 1972

Reference 9: "Foundation Analysis and Design", by Joseph E. Bowles, 4th Edition, published by McGraw-Hill Publishing Company, 1988

Reference 10: "Foundations and Earth Retaining Structures", by Muni Budhu, published by John Wiley and Sons, 2007

Other Selected Readings:

"Negative Skin Friction and Settlement of Piles", byt Bengt Fellenius, University of Ottawa, Canada, 1984

"Elasticity and Geomechanics", by R. O. Davis and A. P. S. Selvadurai, published by Cambridge University Press, 1996

Website Credits:

Illinois Department of Transportation Website:
http://www.dot.state.il.gov/bridge/brdocuments.html
(For pile design information, see "Bridge Manual Design Guides and Detail Examples")

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Photograph of Poulos is from the University of Sydney website.