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MODELING SOIL BEHAVIOR WITH SIMPLE SPRINGS, PART 1

Spring Placement and Properties

This is the first of a two-part article covering the use of simple springs to model soil behavior. Covered in this article are suggestions for spring placement and procedures for calculating spring stiffness and ultimate spring strength. Covered in the second part of this article (to be published in the June 2014 issue) are the use of springs in a plane-frame structural analysis and determination of the ultimate lateral capacity of a post or pier foundation. Part 2 also includes an overview of safety factors for allowable stress design and resistance factors for load and resistance factor design.

The interaction between an embedded post or pier foundation and the surrounding soil is a complex, three-dimensional problem that is simplified for structural analysis. When assessing this interaction, designers are interested in two different but related phenomena. First is the deformation of the soil as load is applied to the soil by the foundation system. Second is the ability of the soil to resist the applied load without failing. These two phenomena are herein referred to as *soil stiffness* and *soil strength*.

In assessing the effects of lateral forces applied to the soil by a shallow post or pier foundation, the latest version of ANSI/ASAE EP486.2 takes two different approaches. The first approach uses the set of equations published in the document. This approach is referred to as the *simplified method* because it does not require any special computer software, just a basic calculator. In many respects, this approach could be referred to as the traditional method because it mirrors past procedures.

The second approach relies on modeling soil with a series of simple springs. This approach requires structural analysis software and is referred to as the *universal method.*

Modeling soil behavior with simple springs is a *discrete* approach to analysis that has been used for well over a century. A summary of foundation-soil interaction models developed by researchers who have used this discrete approach has been provided by Maheshwari (2011). Within the post-frame building community, McGuire (1998) used a spring model to study the behavior of nonconstrained posts subjected to ground-line shear forces and ground-line bending moments applied such that they caused below-grade post rotation in opposite directions (see Load Case B in **Figure 1**). McGuire conducted his investigation to illustrate that when shear and bending moments are so applied, most equations used to calculate allowable embedment depth are not applicable.

When to Model with Soil Springs

The modifier *universal* used in ANSI/ASAE EP 486 was given to the soil spring method because the method can be used without restriction. Conversely, use of the simplified method assumes the following:

1. At-grade pier/post forces are not dependent on below-grade deformations.
2. The below-grade portion of the foundation has an infinite flexural rigidity (EI).
3. Soil is homogeneous for the entire embedment depth.
4. Soil stiffness either is constant for all depths below grade or linearly increases with depth below grade.
5. Width of the below-grade portion of the foundation is constant. This generally means that there are no attached collars or footings that are effective in resisting lateral soil forces.

The second of the preceding simplify-

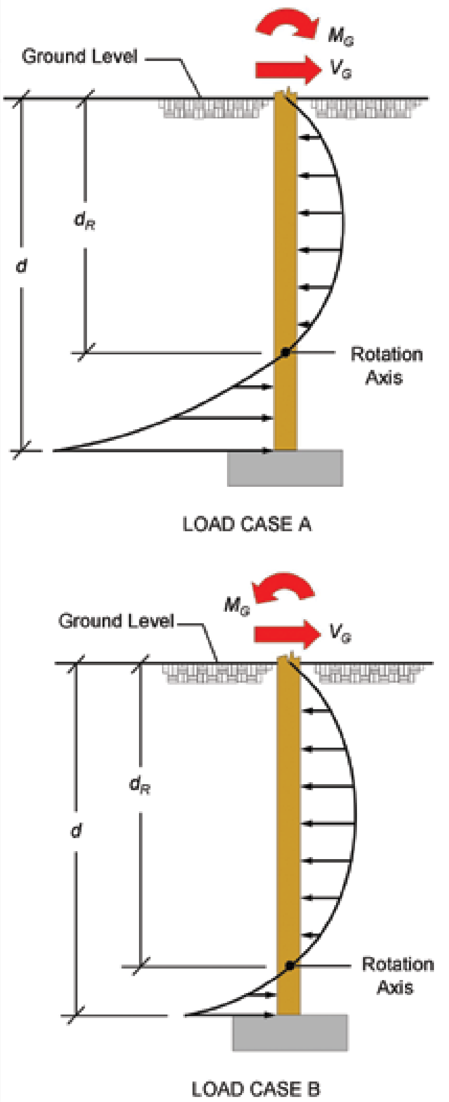

Figure 1. Free body diagrams of nonconstrained post foundations. Load Case A: both ground-line shear and bending moment cause clockwise rotation of embedded portion of post. Load Case B: ground-line shear and bending moment cause clockwise and counterclockwise rotation, respectively, of embedded portion of post.

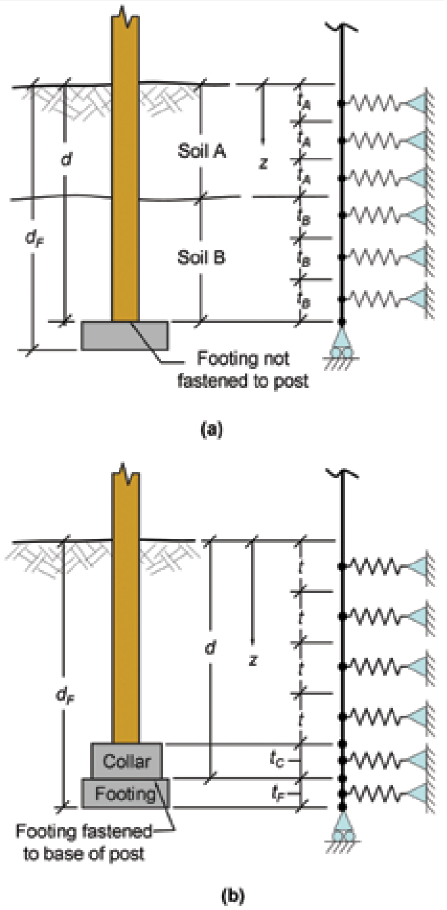

Figure 2. Modeling soil behavior with springs (a) in layered soils, and (b) with collar and footing attached to embedded post

ing assumptions—that the below-grade portion of the foundation is infinitely stiff—is assumed to hold where soil stiffness is assumed to increase linearly with depth and:

$$d < 2\{E\,I/(2A_E)\}^{0.20}$$

or where soil stiffness is assumed constant with depth and:

$$d < 2\{E\,I/(2E_S)\}^{0.25}$$

where d is depth of embedment; EI is flexural rigidity of the post/pier foundation; E_S is Young's modulus of the soil; and A_E is the linear increase in Young's modulus with depth below grade.

When a post/pier foundation does not comply with one of the five conditions associated with application of the simplified method, consideration should be given to using the universal method with its soil springs. In some cases, the results will be significantly different.

Placement of Soil Springs

Figure 2a illustrates the use of soil springs to model a nonconstrained post in a multilayered soil. **Figure 2b** shows the modeling of a nonconstrained post that has an attached footing and an attached collar. In this case individual springs are required for both the footing and the collar because each has different widths relative to the post.

Figure 3 shows an embedded post that abuts a slab-on-grade (i.e., a surface-constrained post). To model the restraint that the slab provides when the post moves toward the slab, the slab is modeled as a vertical roller support (**Figure 3a**). Because the slab abuts only the inside of the post and is not attached to the post, it does not apply a force to the post when the post moves away from the slab; thus it is modeled as a nonconstrained post (**Figure 3b**).

A closer spring spacing enables more accurate estimation of post/pier forces and soil pressures. ANSI/ASAE EP486.2 recommends that soil-spring spacing, t, not exceed $2w$ where w is the side width of a rectangular post/pier and diameter of a round post/pier. (Note: the side of a rectangular post or pier is the surface perpendicular to the loaded face.) Generally, at least five springs should be used.

Soil Spring Stiffness

All springs are assumed to exhibit linear-elastic behavior until a point of soil failure is reached, at which point the force in the soil spring stays constant as the spring undergoes additional deformation. A graphical depiction of this behavior is shown in **Figure 4**.

The initial stiffness, K_H, of an individual soil spring located at depth z is given as

$$K_H = 2.0\ t\ E_S \qquad (1)$$

where

t = thickness of the soil layer represented by the spring, in.

E_S = Young's modulus for soil at depth z, lbf/in²

ANSI/ASAE EP486.2 contains equations for calculating E_S from laboratory test results, prebored pressuremeter test (PMT) results, cone penetration test (CPT) results, standard penetration test (SPT) results, and undrained soil shear

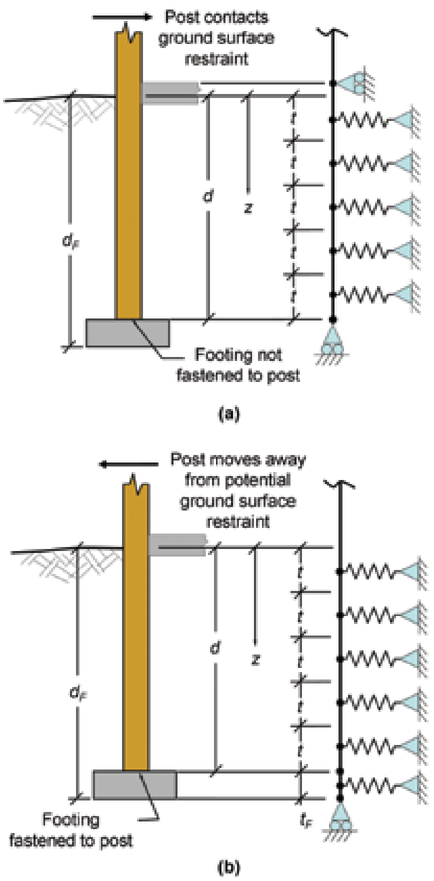

Figure 3. Modeling of an embedded post abutting a slab-on-grade when the post moves (a) toward the slab, and (b) away from the slab.

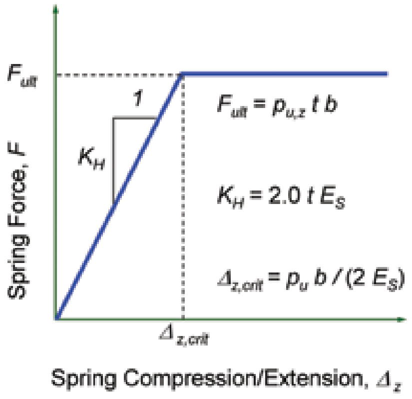

Figure 4. Load-displacement relationship for a soil spring.

Table 1. Presumptive Properties for Silt and Clay (Cohesive) Soils

Soil Type	Unified Soil Classification	Consistency	Moist unit weight, γ	Undrained soil shear strength[(a)], S_U	Young's modulus for soil, E_S[(b)(c)]
			lbf/ft³	lbf/in²	lbf/in²
Homogeneous inorganic clay, sandy or silty clay	CL	Soft	125	3.5	3920
		Medium to Stiff	130	7	6160
		Very Stiff to Hard	135	14	8400
Homogeneous inorganic clay of high plasticity	CH	Soft	110	3.5	1680
		Medium to Stiff	115	7	2800
		Very Stiff to Hard	120	14	4480
Inorganic silt, sandy or clayey silt, varved silt-clay-fine sand of low plasticity	ML	Soft	120	3.5	3920
		Medium to Stiff		7	6160
		Very Stiff to Hard		14	8400
Inorganic silt, sandy or clayey silt, varved silt-clay-fine sand of high plasticity	MH	Soft	105	3.5	1680
		Medium to Stiff		7	2800
		Very Stiff to Hard		14	4480

(a) Loading assumed slow enough that sandy soils behave in a drained manner.
(b) Estimate of stiffness at rotation of 1° for use in approximating structural load distribution. For evaluation of serviceability limit state, use values that are 1/3 of tabulated value.
(c) Constant values of stiffness used for calculation of clay response. Stiffness increasing with depth from a value of zero used for calculation of sand response.

Table 2. Presumptive Properties for Sand and Gravel (Cohesionless) Soils

Soil Type	Unified Soil Classification	Consistency	Moist unit weight, γ	Drained soil friction angle, ϕ[(a)]	Increase in Young's modulus per unit depth below grade[(b)(c)(d)], A_E	
			lbf/ft³	Deg	lbf/in²/ft	lbf/in²/in
Silty or clayey fine to coarse sand	SM, SC, SP-SM, SP-SC, SW-SM SW-SC	Loose	105	30	440	37
		Medium to Dense	110	35	660	55
		Very Dense	115	40	880	73
Clean sand with little gravel	SW, SP	Loose	115	30	880	73
		Medium to Dense	120	35	1320	110
		Very Dense	125	40	1760	147
Gravel, gravel-sand mixture, boulder-gravel mixtures	GW, GP	Loose	135	35	2640	220
		Medium to Dense		40	3520	293
		Very Dense		45	4400	367
Well-graded mixture of fine- and coarse-grained soil: glacial till, hardpan, boulder clay	GW-GC GC, SC	Loose	120	35	1320	110
		Medium to Dense	125	40	1760	147
		Very Dense	130	45	2200	183

(a) Rapid undrained loading will typically be the critical design scenario in these soils. Laboratory testing is recommended to assess clay friction angle for drained loading analysis.
(b) Estimate of stiffness at rotation of 1° for use in approximating structural load distribution. For evaluation of serviceability limit state, use values that are 1/3 of tabulated value.
(c) Constant values of stiffness used for calculation of clay response. Stiffness increasing with depth from a value of zero used for calculation of sand response.
(d) Assumes soil is located below the water table. Double the tabulated A_E value for soils located above the water table.

strength. In the absence of such test data, ANSI/ASAE EP486.2 allows use of the presumptive values in **Table 1** for silts and clays and those in **Table 2** for sands and gravels. It is important to note that E_S is assumed to be constant with depth for silts and clays and to increase linearly with depth for sands and gravels. To calculate E_S at a particular depth in sands and gravels, multiply the A_E value in the far right column of Table 2 by depth, z. In equation form:

$$E_{S,z} = A_E\, z \qquad (2)$$

where

$E_{S,z} = E_S$ that is equal to zero at grade and increases linearly with depth z below grade
A_E = increase in Young's modulus per unit increase in depth z below grade, lbf/in³ (kN/m³)
z = depth below grade, in (m)

For a post that is driven into the ground or a helical pier that is turned into the ground, the material surrounding the post/pier at a given depth will have fairly uniform properties within several feet of the post/pier. This often is not the case for a post/pier that is placed in an augered hole that is backfilled with a different soil.

When soil backfill has properties different from those of the surrounding soil, Young's modulus E_S for soil at depth z can be calculated as

$$E_S = \frac{1}{I_S / E_{S,B} + (1-I_S)/ E_{S,U}} \quad \text{for } 0 < J < 3b \qquad (3a)$$

$$E_S = E_{S,B} \quad \text{for } J > 3b \qquad (3b)$$

$$E_S = E_{S,U} \quad \text{for } J = 0 \qquad (3c)$$

where

$E_{S,B}$ = Young's modulus for backfill at depth z
$E_{S,U}$ = Young's modulus for the unexcavated soil surrounding the backfill at depth z
I_S = strain influence factor, I_S, dimensionless = $[\ln(1 + J/b)]/1.386$ for $0 < J < 3b$
J = distance (measured in the direction of lateral foundation movement) between the edge of the backfill and the face of the foundation component at depth z (see **Figure 5**)
b = width of the post/pier, collar, or footing that is surrounded by the backfill at depth z

The strain influence factor is the fraction of total lateral displacement that is due to soil straining within a distance J of the face of the foundation.

The condition of $J = 0$ (and thus $E_S = E_{S,U}$) would apply to a driven pier/post for which the foundation is entirely surrounded by unexcavated soil. When a pier/post is entirely backfilled with concrete or controlled low-strength material (CLSM), E_S is simply equated to the Young's modulus for the soil surrounding the concrete or CLSM.

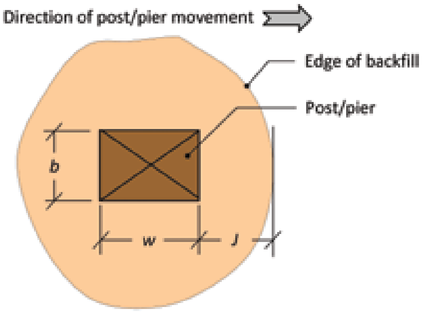

Figure 5. Top view of foundation showing distance *J* between the post/pier/footing/collar and the edge of the backfill

Soil Spring Strength

The ultimate load that an individual spring can sustain is given as

$$F_{ult} = p_{U,z}\, t\, b \qquad (4)$$

where

F_{ult} = ultimate load that an individual spring at depth z can sustain, lbf

$p_{U,z}$ = ultimate lateral soil resistance for unexcavated soil at depth z, lbf/ft²

b = width of the face of the post/pier, footing or collar that applies load to the soil when the foundation moves laterally, ft

t = thickness of a soil layer that is represented with a soil spring with stiffness K_H, ft

z = distance of spring below grade, ft

ANSI/ASAE EP486.2 contains equations for calculating $p_{U,z}$ from prebored PMT results and CPT results. Alternatively, $p_{U,z}$ can be calculated for cohesionless soils (sands and gravels) as

$$p_{U,z} = 3\,\sigma'_{v,z}\,K_P = 3\,(y\,z - u_z)\,K_P \qquad (5)$$

and for cohesive soils (silts and clays) as

$$p_{U,z} = 3\,S_U\,(1 + z/(2b)) \quad \text{for } 0 < z < 4b \qquad (6)$$

$$p_{U,z} = 9\,S_U \quad \text{for } z > 4b \qquad (7)$$

where

K_P = coefficient of passive earth pressure, dimensionless
$= (1 + \sin \text{Ø})/(1 - \sin \text{Ø})$

Ø = soil friction angle, degrees

$\sigma'_{v,z}$ = effective vertical stress at depth z, lbf/ft²
$= \sigma'_{v,z} - u_z = yz - u_z$

$\sigma'_{v,z}$ = total vertical stress at depth z, lbf/ft2
$= yz$

y = moist unit weight of soil, lbf/ft³

u_z = pore water pressure at depth z, lbf/ft²
= (vertical distance between depth z and water table) × 62.4 lbf/ft³

S_U = undrained shear strength at depth z, lbf/ft², numerically equal to cohesion, c, for a saturated clay soil

Different field and laboratory tests are available for determining soil friction angle and undrained shear strength. In the absence of any such tests, presumptive values from Tables 1 and 2 can be used.

It is important to note that although backfill properties may influence spring stiffness, they are not factored into calculations of ultimate spring strength. This is because the soil failure planes associated with the ultimate lateral capacity of the foundation are almost entirely located in the unexcavated soil surrounding the backfill.

Properties

When doing foundation design involving soil springs, one of the first steps is to construct a table of spring properties. For each spring this should include depth z, soil layer thickness t, foundation width b, Young's modulus E_S (or the increase in Young's modulus with depth A_E), spring stiffness K_H, undrained soil shear strength S_U for clay soils, effective stress $\sigma'_{v,z}$ and soil friction angle Ø for sands and gravels, ultimate lateral soil resistance $p_{U,z}$ and ultimate spring strength F_{ult}.

Example 1

Foundation Description

A nominal 6- by 6-inch post is embedded 4 feet. It rests on a concrete footing but is not attached to the footing. Two nominal 2- by 6-inch wood blocks, 12 inches in length, are bolted to each side of the base of the post to increase the uplift resistance and lateral strength capacity of the foundation. The top 2.5 feet of soil are classified as medium to stiff ML silts. The next several feet of soil below this clay layer are classified as medium to dense SW sands. The water table is located 7 to 8 feet below grade. For this first example, backfill is assumed to identically match the surrounding soil. A depiction of this foundation is shown in **Figure 6**.

Spring Placement

Three depths are associated with an abrupt change in soil and/or post design properties that will affect spring placement. The obvious two are the change in soil type at a depth of 30 inches and the change in foundation width from 5.5 inches to 12 inches at a depth of 42.5 inches. The less obvious change is that associated with the ultimate strength of clay soil. In accordance with equations 6 and 7, the ultimate strength F_{ult} of cohesive soils switches from increasing linearly with depth to remaining constant with depth at a distance 4*b*, which is equal to 22 inches because post width *b* is 5.5 inches. The selected placement is shown in Figure 6.

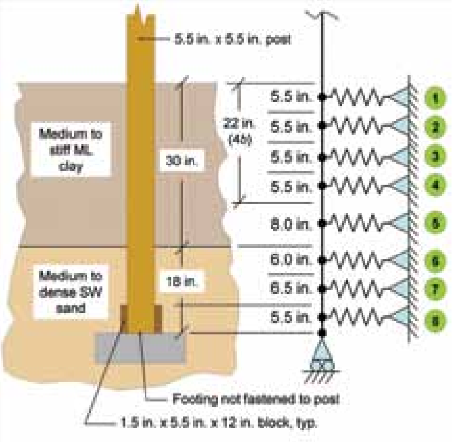

Figure 6. Spring positioning for examples

Presumptive Properties

From Table 1, the medium to stiff ML silt has a moist unit weight y of 120 lbf/ft³, an undrained soil shear strength S_U of 7 lbf/in² and a Young's modulus of 6160 lbf/in². From Table 2, the medium to dense SW sand has a moist unit weight y of 120 lbf/ft³, a drained soil friction angle Ø' of 35 degrees and an increase in the Young's modulus with depth A_E of 220 (lbf/in²)/in. With respect to the latter, the table value of 110 (lbf/in²)/inch is doubled in accordance with footnote (d) because the soil represented by the springs is all located above the water table.

Tabulated Values

Soil-spring stiffness and ultimate strength values are compiled in **Table 3**. To keep everything in consistent units, the moist unit weight of 120 lbf/ft³ is listed in Table 3 as 0.06944 lbf/in³. Depth z for each spring was automatically calculated in the spreadsheet as $z_i = z_{(i-1)} + (t_i + t_{(i-1)})/2$, where i is the spring number. Because the water table was located

Table 3. Soil Spring Properties for Example 1

Spring Number	Soil Type	Consistency	Face width of foundation at spring location, b	Thickness of soil layer represented by spring, t	Distance from surface, z
			inches	inches	inches
1	ML (Inorganic silt, sandy or clayey silt)	Medium to Stiff	5.5	5.5	2.75
2	ML (Inorganic silt, sandy or clayey silt)	Medium to Stiff	5.5	5.5	8.25
3	ML (Inorganic silt, sandy or clayey silt)	Medium to Stiff	5.5	5.5	13.75
4	ML (Inorganic silt, sandy or clayey silt)	Medium to Stiff	5.5	5.5	19.25
5	ML (Inorganic silt, sandy or clayey silt)	Medium to Stiff	5.5	8	26
6	SW (Clean sand with little gravel)	Medium to Dense	5.5	6	33
7	SW (Clean sand with little gravel)	Medium to Dense	5.5	6.5	39.25
8	SW (Clean sand with little gravel)	Medium to Dense	12	5.5	45.25

Table 3. Soil Spring Properties for Example 1 ***(continued)***

Spring number	Increase in Young's modulus with depth, A_E	Young's modulus, E_S	Horizontal spring stiffness, K_H	Moist unit weight, γ	Undrained soil shear strength, S_U	Coefficient of passive earth pressure, K_P	Effective vertical soil stress at spring location	Ultimate lateral soil resistance at spring location, p_U	Maximum force allowed in spring F_{ult}
	(lbf/in^2)/in	lbf/in^2	lbf/in	lbf/in^3	lbf/in^2		lbf/in^2	lbf/in^2	lbf
1	-	6160	67800	0.0694	7			26.3	794
2	-	6160	67800	0.0694	7			36.8	1110
3	-	6160	67800	0.0694	7			47.3	1430
4	-	6160	67800	0.0694	7			57.8	1750
5	-	6160	98600	0.0694	7			63.0	2770
6	220	7260	87100	0.0694		3.69	2.29	25.4	837
7	220	8635	112300	0.0694		3.69	2.73	30.2	1080
8	220	9955	109500	0.0694		3.69	3.14	34.8	2300

below all the springs, the effective vertical stress for all soil springs was numerically equal to the total vertical stress.

Comments

The stiffness of an individual spring is not a function of the width of the foundation element that the spring is acting upon. Consequently, a spring that will be pushing on an 18-inch-wide footing is assigned the same stiffness as one at the same depth in the same soil that is pushing on a 6-inch-wide post. Conversely, ultimate spring strength is a function of the width of the foundation element upon which the spring acts. The significant impact that this dependence can have on ultimate spring strength is evident when comparing F_{ult} for springs 7 and 8 in Table 3.

Example 2

Foundation Description

This is the same foundation described in example 1 with the exception that the backfill is a mixture of the ML silt and SW sand removed by the 18-inch-diameter auger used to form the post hole. The mixture is compacted by hand in 6-inch lifts.

Spring Placement

The abrupt change in soil and/or post design properties that affect spring placement are the same as for example 1; thus the same spring placement is used.

Presumptive Properties

Properties for the unexcavated soil remain as compiled in Table 3. The mixture of approximately 2.5 feet of ML silt with approximately 2 feet of SW sand is likely to produce a soil that would grade out as a silty sand (SM). Determination of the exact designation would require knowledge of the particle size distributions of the ML and SW soils prior to mixing. Hand compaction of this backfill in 6-inch lifts should provide a medium to dense consistency. From Table 2, a medium to dense SM soil has a moist unit weight γ of 110 lbf/ft^3, a drained soil friction angle Ø' of 35 degrees, and an increase in the Young's modulus with depth A_E of 110 (lbf/in^2)/in. With respect to the latter, the table value of 55 (lbf/in^2)/inch is doubled in accordance with footnote (d) because the backfill is entirely located above the water table.

Tabulated Values

Soil spring stiffness values are compiled in **Table 4**. The A_E values for unexcavated soil and $E_{S,U}$ values in Table 4 are identical to the A_E and E_S values in Table 3. Equation 3a was used to calculate an effective Young's modulus for the soil, E_S, from Young's modulus for the unexcavated soil, $E_{S,U}$, and Young's modulus for the backfill, $E_{S,B}$. Values for ultimate spring strength F_{ult} have not been included in Table 4 because they are identical to those in Table 3. As previ-

Table 4. Soil Spring Properties for Example 2

Spring number	Face width of foundation at spring location, b	Thickness of soil layer represented, t	Distance from surface, z	Increase in Young's modulus with depth, A_E		Young's modulus for un-excavated soil, $E_{S,U}$	Young's modulus for backfill, $E_{S,B}$	Backfill thickness, J	Strain influence factor, I_S	Young's modulus, E_S	Horizontal spring stiffness, K_H
				Un-excavated soil	backfill						
	inches	inches	inches	(lbf/in^2)/in	(lbf/in^2)/in	lbf/in^2	lbf/in^2	inches	-	lbf/in^2	lbf/in
1	5.5	5.5	2.75	-	110	6160	303	6.25	0.548	530	5840
2	5.5	5.5	8.25	-	110	6160	908	6.25	0.548	1480	16250
3	5.5	5.5	13.75	-	110	6160	1513	6.25	0.548	2300	25260
4	5.5	5.5	19.25	-	110	6160	2118	6.25	0.548	3010	33130
5	5.5	8	26	-	110	6160	2860	6.25	0.548	3780	60390
6	5.5	6	33	220	110	7260	3630	6.25	0.548	4690	56290
7	5.5	6.5	39.25	220	110	8635	4318	6.25	0.548	5580	72530
8	12	5.5	45.25	220	110	9955	4978	4.75	0.449	6870	75570

ously noted, this is because backfill does not factor into calculations of F_{ult}.

Summary

The latest version of ANSI/ASAE EP486 incorporates the ability to use soil springs to model the behavior and predict the ultimate strength of shallow post/pier foundations for conditions not previously possible. This includes situations where soil properties vary with depth and the thickness of the foundation is not constant.

This article summarized and demonstrated methods for calculating the stiffness and strength of these soil springs. In Part 2 of this article, methods for incorporating the use of springs in plane-frame structural analyses will be presented, along with special techniques used to determine the ultimate lateral capacity of a post/pier foundation.

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EXPO UPDATE

RON SUTTON RECEIVES PERKINS AWARD AT EXPO

At the 2014 Frame Building Expo in Nashville, NFBA presented the distinguished Bernon G. Perkins Award to Ron Sutton of Morton Buildings. The award, given annually to an outstanding industry professional, was named after the man who furthered the pole building's evolution from a temporary structure into a long-lasting one. The award is among NFBA's highest honors.

Sutton, licensed as a professional engineer in 42 states, is co-chair of the NFBA Technical and Research Committee, sharing responsibility for overseeing the general work assigned to the committee. This work includes identifying technical issues facing the post-frame industry, establishing the technical research agenda, and recommending standards for the post-frame industry.

On the T&R Committee, Sutton coordinated the testing of NFBA's 1-hour-rated fire-wall assembly and served on the task force that worked on the 3-hour fire-wall assembly. He currently chairs the committee's task force on insurance industry guidelines. Besides serving on NFBA's Editorial Review Committee for *Frame Building News* since the magazine's beginning, he has contributed to a number of NFBA's publications, including its *Post-Frame Building Design Manual*. In 2003 he received the *Rural Builder* Hall of Fame Award.

"I would like to personally congratulate Ron on achieving the Perkins Award," said NFBA board chair Rick Hess. "Ron has given his time and expertise to the post-frame industry for many years. As co-chair of the T&R Committee, he helps lead that group in promoting the industry. He has earned this prestigious award through all of his efforts. Thanks, Ron!"

Andy Williams, NFBA's technical director, said of Sutton: "Ron's passion about post-frame construction is apparent each time we discuss one of the T&R Committee projects. He is constantly ensuring that all aspects of a problem are evaluated and that the final project results show post-frame construction in the best possible light."

"Ron is able to convey a clear and concise plan of action for the broad range of projects that are handled by the committee," Williams continued. "From seismic design to the field use of engineering and construction details, Ron has a wealth of experience that he draws on to make sure a project is correctly executed. I find his knowledge level—and understanding of how post-frame construction interfaces with the 'real world'—to be of tremendous help in identifying which areas of the post-frame market deserve emphasis."

NFBA congratulates Ron Sutton and thanks him for his dedication to the advancement and integrity of the post-frame industry. **FBN**