Comprehensive Design Example 2: Foundations for Bulk Storage Facility

Problem

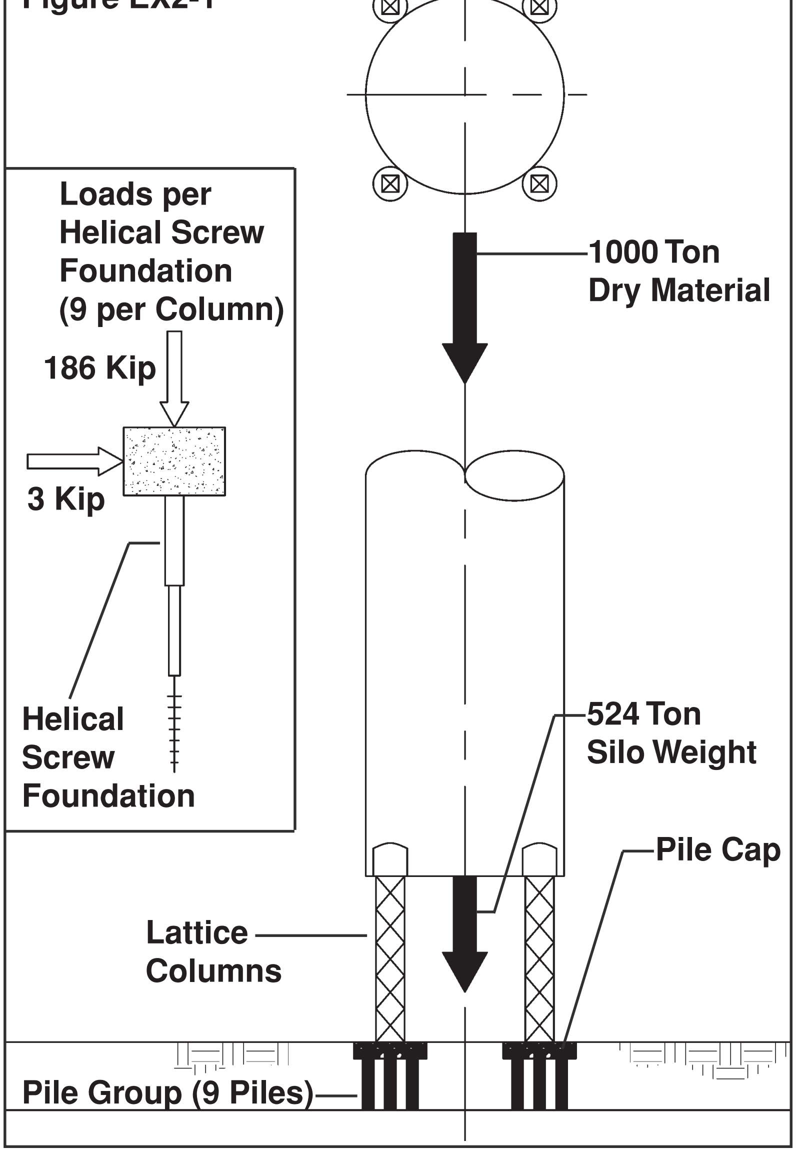
The project consists of building several dry product storage silos near an existing rail siding in an open field presently used for truck parking and loading. The new steel silos are to be 32'-0 in diameter, 75'-0 tall and store 1000 tons of dry material. The site is located in a zone 3 seismic area that has limited annual rainfall, but is irrigated.

Soil borings (boring B-2 included in this example) indicate zero to 3 feet of gravel fill covers the native surface soil, which is a sandy silt with an average blow count N = 8 blows/ft (bpf), to a depth of 11'-0 below the surface. This strata is in turn underlain by 8'-0 of loose clean fine sand having an average blow count, N = 8 bpf. From 19'-0 to 26'-0, the borings indicate very stiff clays with N = 22 bpf. From 26'-0 to 48'-0, the soil is a medium stiff to stiff clayey silt with an average blow count, N = 16 bpf. The strata from 48'-0 to the limit of the boring is very stiff clays and sandy silts with an average blow count, N = 23 bpf. The water table was measured to be 14'-0 below the surface, but is expected to fluctuate with irrigation. The nature of the soil profile and location of the water table indicated a low probability for liquefaction of the soil.

Possible solution

The silos are to be supported on four lattice columns, which are in turn supported on pile caps at the ground surface. Relatively soft/loose surface soils require deep foundations, such as driven piles, drilled shafts, or alternate solutions like helical screw foundations. The pile caps will tie multiple pile foundations together. Required factors of safety are 2.0 against compression, 2.0 against tension, and 1.5 against lateral. Figure EX2-1 illustrates the problem.

Figure EX2-1



Step 1: Feasibility

• **Site Access –** the site is road and railroad accessible, no overhead or underground obstructions. The owner wishes to keep the truck parking area operational during installation of the foundations, so relatively small installation and supply equipment is needed.

• **Working Loads –** The silos will be supported on multiple, generally vertical pile foundations terminated in pile caps at the four lattice columns. Due to capacity constraints, it will not be possible to support the dead weight of the silo and 1000 ton dry material with a single helical screw foundation per lattice column – note that working (design) compression loads for helical foundations is typically less than 100 kip. Multiple helical piles are required.

• **Soils –** Boulders, large cobbles, or other major obstructions are not present. The stiff clays do not appear to be too hard to penetrate with Type SS material, but may be too hard for Type HS material. See Table 8.3 for help determining which helical screw foundation product family to use.

• **Qualified Installers –** Local A.B. Chance Co. certified dealer is available. This dealer is also trained and certified to install HELICAL PULLDOWN™ Micropiles. Other certified dealers are within 100-mile distance.

• **Codes –** Local building codes allow for both shallow and deep foundations. Deep foundations require special inspection by the structural engineer, or the owner's representative. Cost-bid must be competitive with other systems. Owner may pay small premium for fast installation time and low construction impact to working site.

Step 2: Soil Mechanics

See statement of problem above.

Step 3: Loads

See statement of problem above. The dead load is 524 ton for the silo and 1000 ton for the dry material. Total dead load is 524 + 1000 = 1524 ton, or 1524/4 = 381 ton per column. Three load cases apply:

- CASE I: Vertical gravity loads; Compression = 381 ton, Shear = 0, Uplift = 0
- CASE II: Earthquake loads; Compression = 417.5 ton, Shear = 9.3 ton, Uplift = 0
- CASE III: Wind w/ Silo Empty; Shear = 7 ton, Uplift = 13.5 ton

The required ultimate compression capacity per column is 417.5 x 2 = 835 ton. The required ultimate shear capacity per column is 9.3 x 1.5 = 14 ton. The required ultimate uplift capacity per column is 13.5 x 2 = 27 ton. In this example, the limiting factor for helical pile design is the compression and shear load requirements. The compression load requires a pile group whose individual pile capacities equal or exceed the 835 ton per column. The lateral load requirement necessitates enlarging the shaft of the helical screw foundation a length sufficient to provide the required resistance.

Step 4: Bearing capacity

By inspection, the bearing soils are the stiff clays and silts below the 20'-0 depth. Find the ultimate bearing capacity in the stiff clays and silts by using the general bearing capacity equation as detailed in Step 4.

Helix Capacity: $Q_h = A_h(cN_c + q'N_q + 0.5\gamma'BN_\gamma)$ Eq. 4.1

Total Capacity: $Q_{ult} = \Sigma Q_h$ Eq. 4.2

To simplify the calculations, use HeliCAP® Engineering Software to determine bearing capacity with the soil profile as shown in soil boring B-2. Table EX2-1 is a HeliCAP® summary report showing the results of a six-helix configuration (8"-10"-12"-14"-14"-14") with an overall length of 49'-0. The predicted bearing capacity is 155 kip compression and 150 kip uplift. This bearing capacity requires the

Type SS200 product family, which can provide the necessary torque to install the helical foundation (See Table 8.2).

Table EX2-1

HeliCAP SUMMARY REPORT

Job Name: Graymont Western Lime Silos

Job Number: Example 2

Boring No: B-2

Anchor Use: Compression

C:\Documents and Settings\glseider\My Document
6/23/2003 9:49:08 AM
Water Table Depth: 8 ft

Capacity Summary

Anchor Number	Anchor Family	Helix Depth (ft)	Helix Capacity (kips)	Total Anchor Capacity (kips)	Recommended Ultimate Capacity (kips)	Torque (ft-lbs)
Anchor 1	Angle: 90 Datum Depth: 0 Length: 49					
14" helix	SS 200	34.8	25.2t 30.3c			
14" helix	SS 200	38.3	33t 34.4c			
14" helix	SS 200	41	34.6t 36c			
12" helix	SS 200	44	26.7t 27.6c			
10" helix	SS 200	46.5	19.2t 17.6c	150.3t	150.3t	15029
8" helix	SS 200	48.5	11.3t 8.7c	154.9c	154.9c	

Soil Profile

Top of Layer Depth (ft)	Soil Type	Cohesion (lb/ft2)	N	Angle of Internal Friction (Degrees)	Unit Weight (lb/ft3)
0	Sand	0	12	30.7	102
3	Sand	0	8	29.6	100
11	Sand	0	8	29.6	100
19	Clay	2750	22	0	120
26	Mixed	500	9	28	100
35	Mixed	500	20	30	105
48	Clay	2875	23	0	120

HELICAL PULLDOWN™ Micropile Addendum: Friction Capacity

By inspection, the top portion of the helical foundation shaft will have to be enlarged to resist the applied shear load. Shaft diameter can be increased using the HELICAL PULLDOWN™ Micropile method, which replaces displaced soil with grout. The addition of a grout column contributes to pile capacity via skin friction. Table EX2-2 summarizes friction capacity calculations using the empirical method reported by Gouvenot (1973). See the HELICAL PULLDOWN™ Addendum for an explanation of the Gouvenot Method. For this example, an 8" diameter grout column is used to enlarge the helical foundation shaft. This is somewhat intuitive because sufficient diameter is required to provide the cross-sectional area to resist shear loads.

Table EX2-2 Friction Calculation

8" diameter grout column, 30'-0 long, B-2 soil boring

Depth (ft)	Soil	"N" blows/ft	Estimated		Effective Unit Weight (lb/ft^3)	Average Overburden (lb/ft^2)	Adhesion/ Friction (lb/ft^2)	Side Friction (lb)
			Cohesion (lb/ft^2)	ϕ				
0 – 3	Sand	12	-	30.7	102	153	91	571
3 – 11	Sand	8	-	29.6	37.6	456	259	4344
11 - 19	Sand	8	-	29.6	37.6	757	430	7207
19 - 26	Clay	22	2750	-	57.6	1109	2048	30025
26 - 30	Clay	9	500	-	37.6	1386	1092	9150

Total: 51297

The shear load will require the top portion of the grout column to be cased with a steel pipe for bending resistance. Therefore, the friction contribution due to the sand layers will be ignored in this example. This can be modified later if it is determined that the steel case does not have to extend to the full depth of the sand layers (19'-0). The net friction in the grout column in the clay is 51,297 – 12,122 = 39.2 kip

Total Capacity, $Q_t = \Sigma Q_h + Q_f = 155 + 39 =$ **194 kip = 97 ton**

Determine the number of helical screw piles required to support the ultimate compression capacity per silo column, 835 ton/97 ton = 8.61, **use 9 helical screw piles per silo column**. The nine helical piles can be arranged in a 3 x 3 pattern connected together into a common concrete pile cap. The dead weight of the pile cap is generally added to the total load. Assuming a 3'-0 center-to-center helical pile spacing, a 12'-0 x 12'-0 x 2½'-0 thick pile cap is required. The dead weight is 12'-0 x 12'-0 x 2.5'-0 x 150 lb/ft^3 = 54 kip = 27 ton. (835 ton + 27 ton)/97 ton = 8.9, **9 helical screw piles - OK**.

Steps 5 and 6: Lateral Capacity and Buckling

Lateral Capacity – the applied shear load per column can be equally divided between the 9 helical piles per silo column. Therefore, the ultimate lateral load per individual helical pile is 27 ton/9 piles per cap = 3 ton per helical pile. Figure EX2-2 is a soil-structure interaction model of a single helical pile in soil. The model is used as input for finite difference software like LPILE^PLUS or other programs used to predict soil-pile response to lateral loads. In this example, the top 30'-0 of the pile is the only section modeled, because the balance of the length (19'-0) will not be subjected to shear and bending forces. Figure EX2-3 is the cross-section of the helical pile section that is cased with an 8" nominal diameter steel pipe. The total stiffness of this composite section can be expressed by the following equation:

$$EI_{total} = EI_{case} + EI_{grout} + EI_{shaft} \qquad \text{Eq. EX2-1}$$

Equation EX2-1 can be solved for the total modulus to derive the necessary inputs for the soil-structure interaction computer model.

$$E_{total} = (EI_{case} + EI_{grout} + EI_{shaft})/I_{total} \qquad \text{Eq. EX2-2}$$

Figure EX2-2
LPILE^{PLUS} Soil-Structure Interaction Model

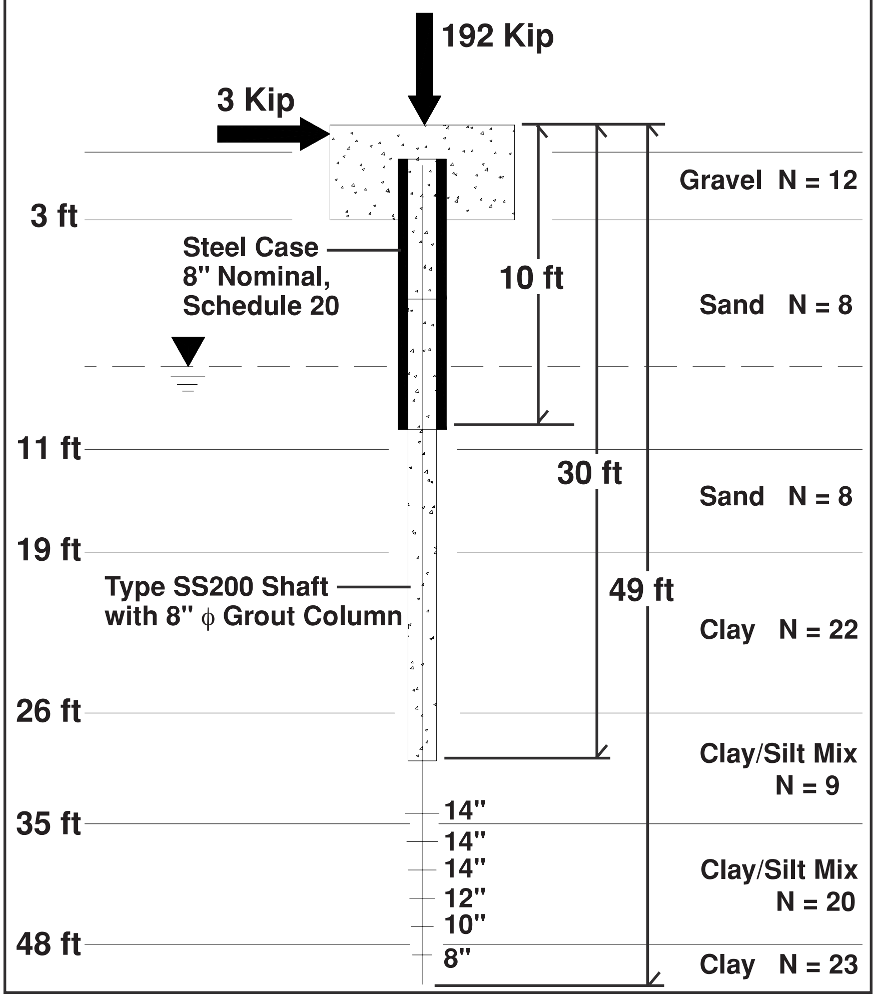


Figure EX2-3
Section Properties
Pile Section, Cased

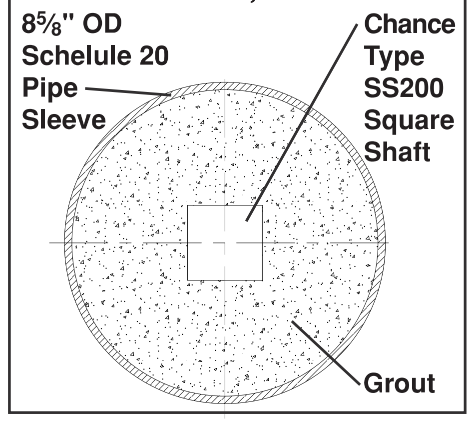


Figure EX2-4
Section Properties
Pile Section, Uncased

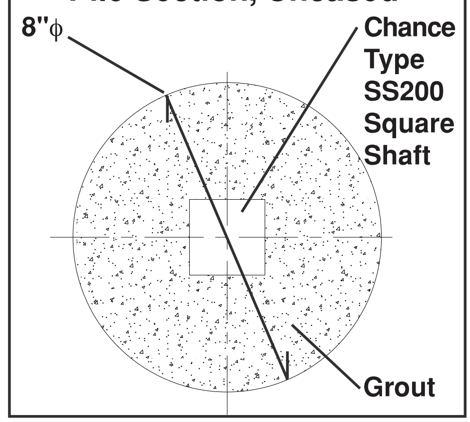


Figure EX2-4 is the cross-section of the helical pile section that is uncased. The total stiffness of this composite section can be calculated using Equation EX2-1 by dropping the EI_{case} term.

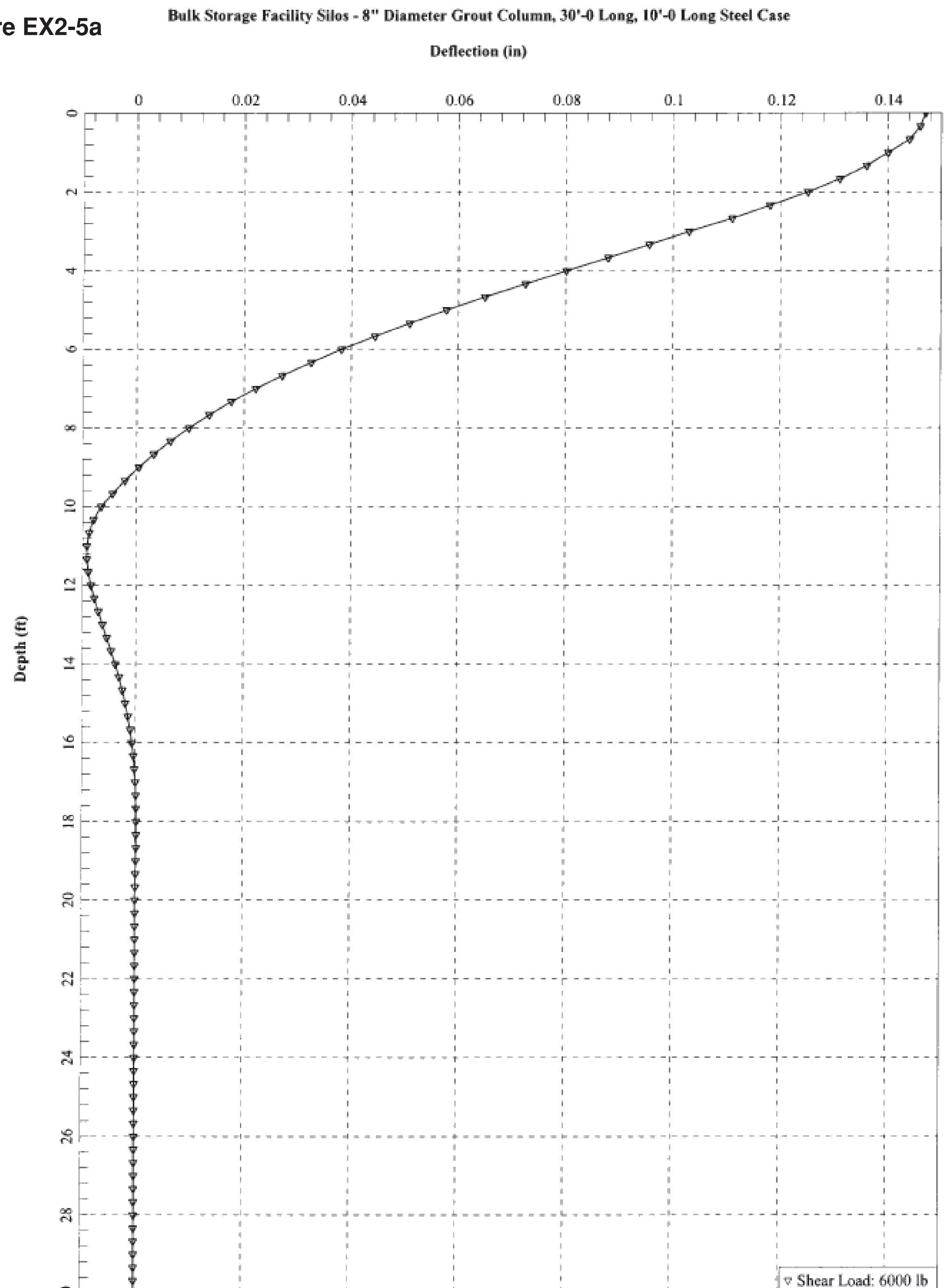
The length of 8" diameter steel pipe case required can be determined by observing at what point the reinforcement provided by the steel pipe is no longer required to resist the shear-induced bending moment in the helical pile shaft. In other words, at what point along the shaft is the bending moment reduced to a level that can be adequately resisted by the grouted shaft only? An estimation of this can be accomplished by determining the “cracking moment” of the grout column. The tensile strength of normal-weight concrete has been experimentally established, and can be expressed as:

$$F_r = 7.5\sqrt{f'_c}\ \text{psi} \qquad \text{Eq. EX2-3}$$

For 6,000 psi grout, the tensile strength is 581 psi, say **600 psi**. The “cracking moment” can then be defined as the bending moment which results in a bending stress that equals the tensile strength of the grout. For an 8" diameter grout column, the cracking moment is approximately 30.2 in-kip.

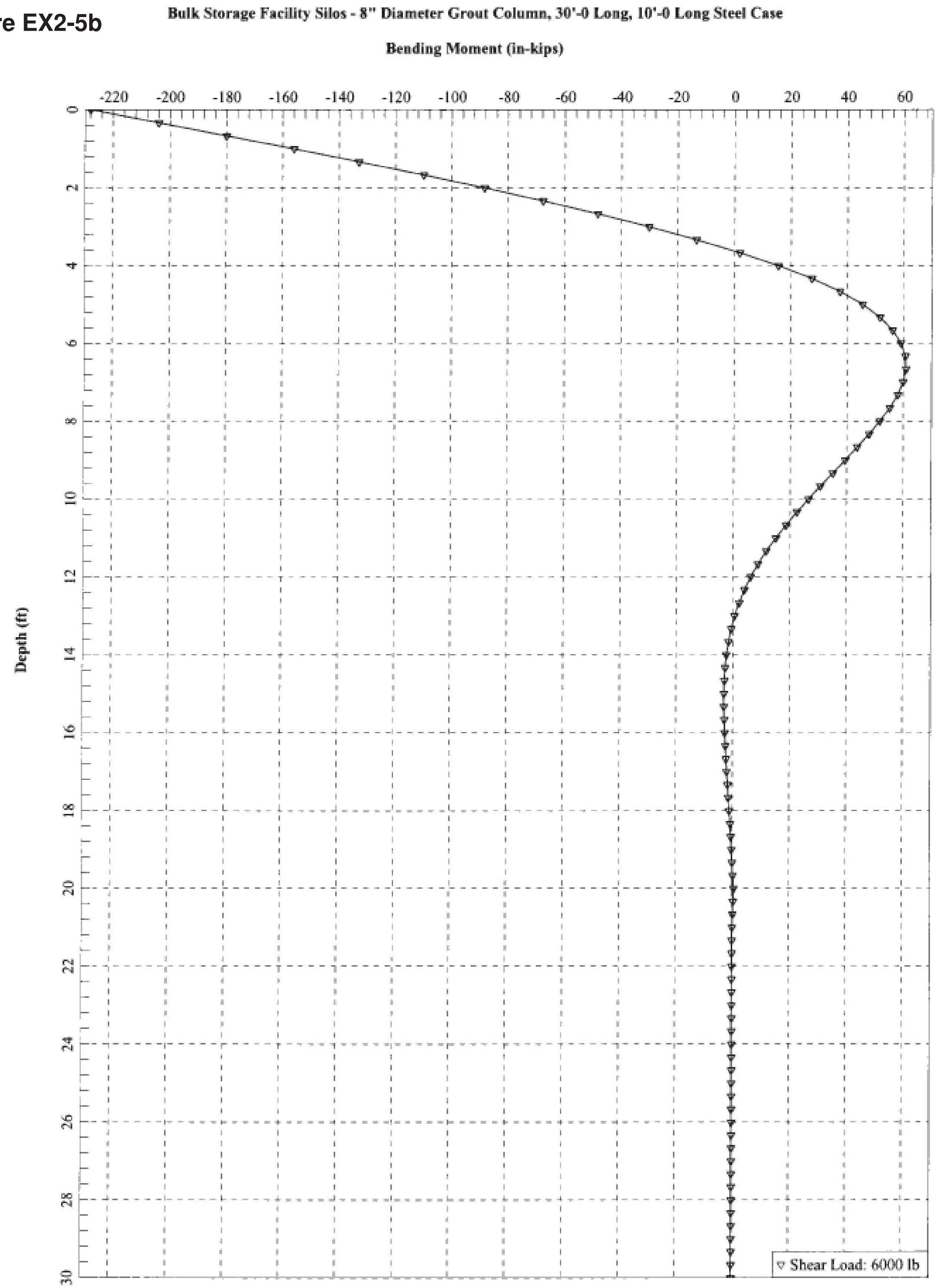
Figures EX2-5a and EX2-5b are a sample LPILE^{PLUS} output plots of lateral shaft deflection and bending moment vs. depth where the top of the helical pile is fixed against rotation, i.e. in a concrete pile cap. Results indicate the top of the pile will translate about 0.144 inches, and the cracking moment is reached around the 9'-0 to 10'-0 depth. **Use a 10'-0 case length**.

Figure EX2-5a



Buckling Concerns
– The soil density and shear strength is sufficient to provide lateral confinement to the helical pile shaft. The necessity to enlarge the pile shaft to resist lateral loads and the subsequent lateral analysis demonstrates that buckling is not a practical concern.

Figure EX2-5b



Step 7: Corrosion
No electrochemical properties were given for the soil. The top three feet is noted as fill, so it can be assumed that it is disturbed material. The rest of the profile appears to be a combination of transported and residual material that probably can be considered undisturbed. Step 7 suggests that undisturbed material is so deficient in oxygen at levels a few feet below the ground line or below the water table zone that steel pilings are not appreciably affected by corrosion. In addition, the grout column provides double corrosion protection to the central steel shaft, which in turn has a hot dip galvanized coating.

Step 8: Product Selection
Step 4 Bearing Capacity indicates the need to use the A.B. Chance Type SS200 product family. SS225 material could be used, but since the shaft section above the helix plates has to be enlarged to resist shear and moment loads, the additional axial load capacity derived from the grout column in skin friction make Type SS200 material a better economic choice.

The six-helix configuration and overall length of 49'-0 can be achieved by using a four-helix lead section (8"-10"-12"-14") and a twin-helix (14"-14") extension, followed by three 10'-0 plain extensions followed by one 5'-0 plain extension. This configuration will locate the helix plates in the stiff to very-stiff silts and clays with the top-most helix located 35'-0 below grade and the bottom helix located 48.5'-0 below grade. The exact catalog items to use for a specific project are usually the domain of the contractor. The A.B. Chance Company certified contractor is familiar with the standard catalog items and is best able to determine which items to use based on availability and project constraints.

Step 9: Field Production Control
For a project of this scale, pre-production tests are recommended to verify total capacity and to determine the appropriate K_t. If pre-production testing is not done, use $K_t = 10 \text{ ft}^{-1}$ for Hubbell/A.B. Chance Type SS200 material. The minimum depth and minimum installing torque must both be achieved during production. If the minimum torque requirement is not achieved, the contractor should have to right to load test the helical screw pile to determine if K_t is greater than 10 ft^{-1}.

Estimate Installing Torque for field production control and specifying the minimum allowable without testing.

$Q_{ult} = K_t T$, or $T = Q_{ult}/K_t$ Eq. 9.1

$T = Q_{ult}/K_t = 155{,}000 \text{ lb}/10^{-1 \text{ ft}} = 15{,}500$ ft-lb - say 15,000 ft-lb for the minimum average torque taken over the last three readings.

Note that the torque rating for Hubbell/A.B. Chance Type SS200 product family is 15,000 ft-lb – OK.

Step 10: Product Specifications
See Step 10 for MANU-SPEC™ or Hubbell/A.B. Chance model specifications. NOTE: It is recommended the specifier use the Internet version available from www.abchance.com for the latest revisions. The minimum depth and torque requirements should be noted on the construction documents. In this example, the specified minimum torque is 15,000 ft-lb and the minimum depth is 49'-0. The specifier should note that variation in soil profiles may necessitate a change to the minimum specified depth, i.e. an acceptable overall length may be less than 49'-0, depending on verification factors such as installation torque or proof tests.

Step 11: Load test
As mentioned in Step 9 above, a project of this scale justifies pre-production tests to verify total capacity (both axial and lateral) and to determine a site specific K_t. The number of pre-production tests should be

based on the total quantity of production piles, the physical size of the job site, and the anticipated variation in soil profile. Test budgets are another factor since full-scale compression load tests are relatively expensive. The torque correlation method typically reduces the need to conduct a large number of pre-production tests. See section 6 of the model specification located in Step 10 for an explanation of pre-production and production testing procedures and acceptance criteria. Step 11 provides more detail on static load testing.

For large projects such as described in this example, a certain number of proof tests should be conducted on the production helical piles. The number of piles tested is typically less than 2% of the total with a minimum of 1.

Soil Boring B-2