ROCSCIENCE

RSPile

Helical Pile

Verification Manual

October 9, 2024

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1. Example #1

This example verifies the results of a helical pile embedded in a multi-layered soil profile, characterized through borehole data. Subsequent examples will present modifications to the initial model, assessing the impact of including or neglecting shaft adhesion, and determining the governing mechanism—either cylindrical shear or individual plate end bearing—for pile capacity. Tables 1-3 summarize the model specifications used in this analysis.

In addition:

- Groundwater is disabled
- Shaft adhesion will be ignored
- The height reduction factor in uplift will be 2
- 200 segments will be used. The total pile length is 15m

Table 1: Soil Properties

Material Name	Soil Type	Depth (m)	ɣ (kN/m3)	Su (kPa)	ϕ (°)	δ (°)	Kp
Sand 1	Cohesionless	0.5 - 4.5	20	-	32	20	0.5
Clay 1	Cohesive	4.5 - 9	20	70	-	-	-
Sand 2	Cohesionless	9 - 13.5	20	-	34	20	0.5
Clay 2	Cohesive	13.5 - 15	20	80	-	-	-
Sand 3	Cohesionless	15 - 19	20	-	36	20	0.5

Table 2: Shaft Section Properties

Pile Name	Pile Cross Section	Side Length (m)
SS1	Square Solid	0.1
SS2	Square Solid	0.1

Table 3: Helix Data – Example 1

#	Diameter (m)	Pitch (m)	Spacing (m)	Depth (m)	Elevation (m)	Area (m2)
1	0.3	0.1	-	7	-6.5	0.070685835
2	0.2	0.1	2	9	-8.5	0.031415927

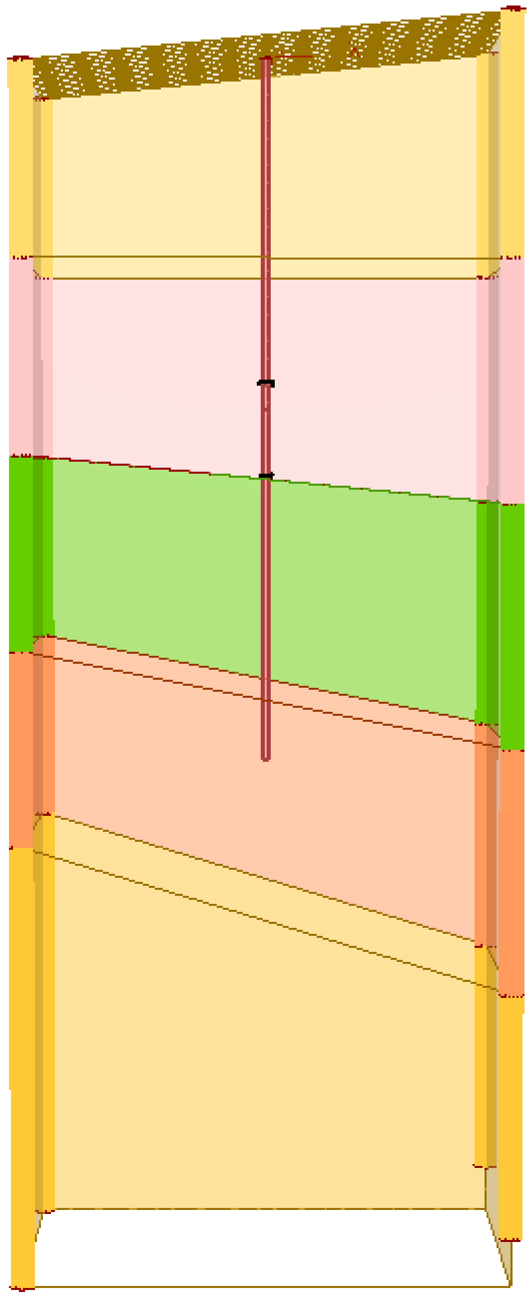

Figure 1: RSPile Helical Pile Model

1.1. Example 1a – Shaft Adhesion Neglected

1.1.1. Unit Skin Friction on the Shaft

With shaft adhesion ignored, the unit skin friction on the shaft is 0kPa for all segments above the first helix. The first helix is embedded in a cohesive soil type, *Clay 1*, where the unit skin friction is defined by the product of the adhesion factor and the undrained shear strength of the soil. Equation (1) depicts the method in calculating unit skin friction for cohesive soils:

$$f_s = \alpha * S_u \tag{1}$$

Since shaft adhesion is neglected, the default value of 1 is used for the adhesion factor α. The undrained shear strength for *Clay 1* is 70kPa. The unit skin friction of all segments in *Clay* 1 are calculated using Equation (1):

$$f_s = 1 * 70\,kPa = 70\,kPa$$

The segments between the first and second helix are also within the layer containing the clay (*Clay 1*), therefore the unit skin friction will be 70kPa for all the segments until the second helix. The second helix exists at an interface between the transition of two soil layers (*Clay 1* and *Sand 2*). The unit skin friction on the shaft will be calculated based on the soil type at the midpoint of the segment. In this case, the soil type is cohesionless (*Sand 2*) and skin friction on the shaft is calculated with Equation (2):

$$f_s = K * {q_H}' * \tan(\delta) \tag{2}$$

Where:

f_s: unit skin friction

${q_H}'$: effective overburden pressure at the midpoint elevation of the segment

δ: the friction angle between the soil and the shaft

The elevation of the second helix is -8.5m, therefore the effective overburden pressure at the midpoint is calculated as follows:

$${q_H}' = \left(0.5m - \left(-8.5m - \frac{0.075m}{2}\right)\right) * \frac{20kN}{m3} = 180.75kPa$$

Substituting 180.75kPa for effective overburden pressure and $\delta = 20°$ for *Sand 2* in Equation (2):

$$f_s = 0.5 * 180.75kPa * \tan(20°) = 32.8938\ kPa$$

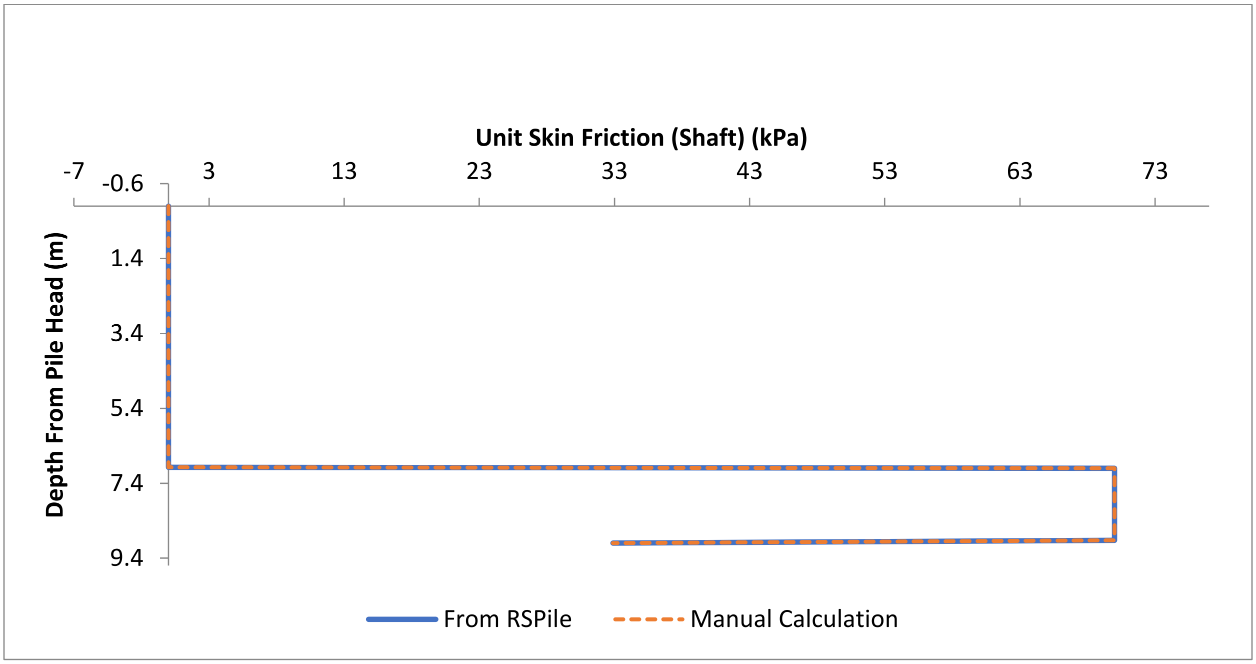

Figure 2: Example 1a Unit Skin Friction Comparison

1.1.2. Unit Cylindrical Shear

For cohesionless soils, unit cylindrical shear is determined using Perko's (2009) equation shown in Equation (3):

$$f_{s\,(soil\ cylinder)} = 0.09 * e^{(0.08*\,\phi_i)} * q_{H_i}{}' * \tan(\phi_i) \tag{3}$$

Where:

ϕ_i: the angle of internal friction of segment i

q_{H_i}: the effective overburden pressure of segment i

For cohesive soils, the unit cylindrical shear is assumed to be equal to the undrained shear strength of the soil (Equation 4):

$$f_{s\,(soil\ cylinder)} = S_u \tag{4}$$

In this example, the unit cylindrical shear will be calculated at the top and bottom of each soil layer.

Layer 1 (*Sand 1*) is a cohesionless soil with $\phi = 32°$. The top elevation of the layer is 0.5m. The effective overburden pressure at the midpoint of the segment is calculated as:

$$q_H{}' = 20\ \frac{kN}{m^3} * \left(0.5 - (0.5 - \frac{0.075}{2})\right) m = 0.75\ kPa$$

The corresponding unit cylindrical shear is calculated using Equation (3):

$$f_{s\ (soil\ cylinder)} = 0.09 * e^{(0.08*32)} * 0.75kPa * \tan(32°) = \ 0.5456\ kPa$$

At the layer's bottom elevation of -3.925 m, the effective overburden pressure increases to 89.25kPa:

$$q_H{}' = 20\ \frac{kN}{m^3} * \left(0.5 - (-3.925 - \frac{0.075}{2})\right) m = 89.25\ kPa$$

Equation (3) is used again to calculate the unit cylindrical shear at this elevation:

$$f_{s\ (soil\ cylinder)} = 0.09 * e^{(0.08*32)} * 89.25\ kPa * \tan(32°) = \ 64.9283\ kPa$$

For layer 2, the soil type is cohesive with undrained shear stress, S_u, equal to 70kPa. The unit cylindrical shear will remain constant at the top and bottom of the layer and is directly determined by the undrained shear strength, yielding:

$$f_{s\ (soil\ cylinder)} = S_u = 70\ kPa$$

The segment containing Helix #2 is between two soil layers with a midpoint elevation falling in *Sand 2* with $\phi = 34°$. The effective overburden pressure at the midpoint of Helix #2 was previously found to be 180.75kPa. The cylindrical shear at this elevation is:

$$f_{s\ (soil\ cylinder)} = 0.09 * e^{(0.08*34°)} * 180.75\ kPa * \tan(34°) = \ 166.657\ kPa$$

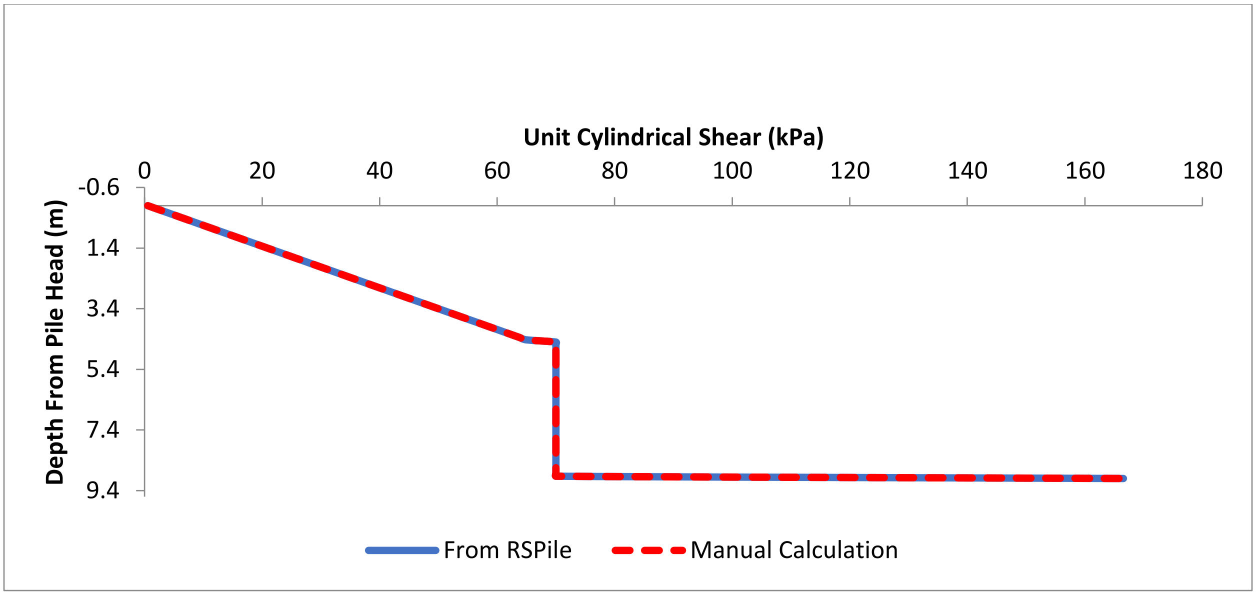

Figure 3: Example 1a Unit Cylindrical Shear Comparison

1.1.3. Unit End Bearing

In RSPile, unit end bearing is calculated using Meyerhof's (1951) modified version of Terzaghi's (1943) formula:

For compression,

$$q_{bult} = cN_c' + q_H'(N_q' - 1) + 0.5\gamma D N_\gamma' \tag{5}$$

For uplift,

$$q_{bult} = cN_c' + q_H' N_q' + 0.5\gamma D N_\gamma' \tag{6}$$

Where:

c: Cohesion (undrained shear strength if ϕ = 0).

q_H': Effective overburden pressure, calculated by:

N_c', N_q', N_γ': Meyerhof's (1951) modified bearing capacity factors

For more information on Meyerhof's (1951) method and the modified bearing capacity factors, please see the *RSPile Helical Pile Theory Manual*.

Compression

In this section, the unit end bearing of both helices will be calculated for compression. For the first helix at an elevation of -6.5m, the effective overburden stress is calculated as:

$$q_H{}' = 20\frac{kN}{m3} * \left(0.5m - (-6.5m)\right) = 140\ kPa$$

Since Helix #1 is embedded in a cohesive soil (*Clay 1*) where ϕ = 0°, the following simplifications can be made for the modified bearing capacity factors $N_q{}'$ and $N_\gamma{}'$:

$$Nq' = 1$$

$$N_\gamma' = 0$$

For *Clay 1*, N_c' is 9 and the unit end bearing can be computed as follows:

$$q_{bult} = cN_c' = 70kPa * 9 = 630\ kPa$$

The effective overburden pressure for Helix #2 at an elevation of -8.5m is calculated as 180kPa:

$$q_H{}' = 20\frac{kN}{m3} * \left(0.5m - (-8.5m)\right) = 180\ kPa$$

Since Helix #2 is located at the interface of the transition between two layers, the soil properties of the layer beneath the helix will be used for calculating the unit end bearing of the helix. This is due to the soil below the helix resisting the downward force. The soil beneath the helix is *Sand 2* with ϕ = 34°. Since $\phi \neq 0°$, the shape, depth, and bearing capacity factors must be calculated. For cohesionless soils, $c = 0$, simplifying the equation of unit end bearing to:

$$q_{bult} = q_H'\left(N_q{}' - 1\right) + 0.5\gamma D N_\gamma'$$

The calculations of the shape, depth, and bearing capacity factors N_q, N_γ, and N_c are shown below:

$$N_q = e^{\pi \tan\phi}\tan^2\left(45° + \frac{\phi}{2}\right) = e^{\pi\tan(34°)}\tan^2\left(45° + \frac{34°}{2}\right) = 29.43979$$

$$N_\gamma = \left(N_q - 1\right)\tan(1.4\phi) = (29.43979 - 1) * \tan(1.4 * 34°) = 31.1455$$

$$sq = 1 + \tan(\varphi) = 1 + \tan(34°) = 1.6745$$

$$s_\gamma = 1 - 0.4 * \frac{B}{L} = 1 - 0.4 = 0.6$$

The depth factors require a scaling factor, K, which is a ratio of the depth of the helix from the ground surface to its diameter.

$$K = \begin{cases} \frac{d_H}{B}, & for \ \frac{d_H}{B} \leq 1 \\ \arctan\left(\frac{d_H}{B}\right), & for \ \frac{d_H}{B} > 1 \end{cases} \quad (7)$$

$$\frac{d_H}{B} = \frac{0.5 - (-8.5)}{0.2} = 45 > 1, \therefore K = \arctan(45) = 1.5486$$

After the scaling factor is determined, the depth factors can be calculated:

$$d_q = 1 + 2K\tan\phi(1 - \sin\phi)^2 = 1 + 2(1.5486) * \tan(34)\,(1 - \sin(34))^2 = 1.40593$$

$$d_\gamma = 1$$

The modified bearing capacity factors are calculated as follows:

$$Nq' = Nq * sq * dq = 29.43979 * 1.6745 * 1.40593 = 69.308$$

$$N_\gamma' = N_\gamma * s_\gamma * d_\gamma = 31.1455 * 0.6 * 1 = 18.6873$$

Substituting the values into the simplified Equation (5), the unit end bearing of Helix #2 in compression is:

$$q_{bult} = 180kPa(69.308 - 1) + 0.5\left(\frac{20kN}{m3}\right)(0.2m)(18.687) = 12332.814\ kPa$$

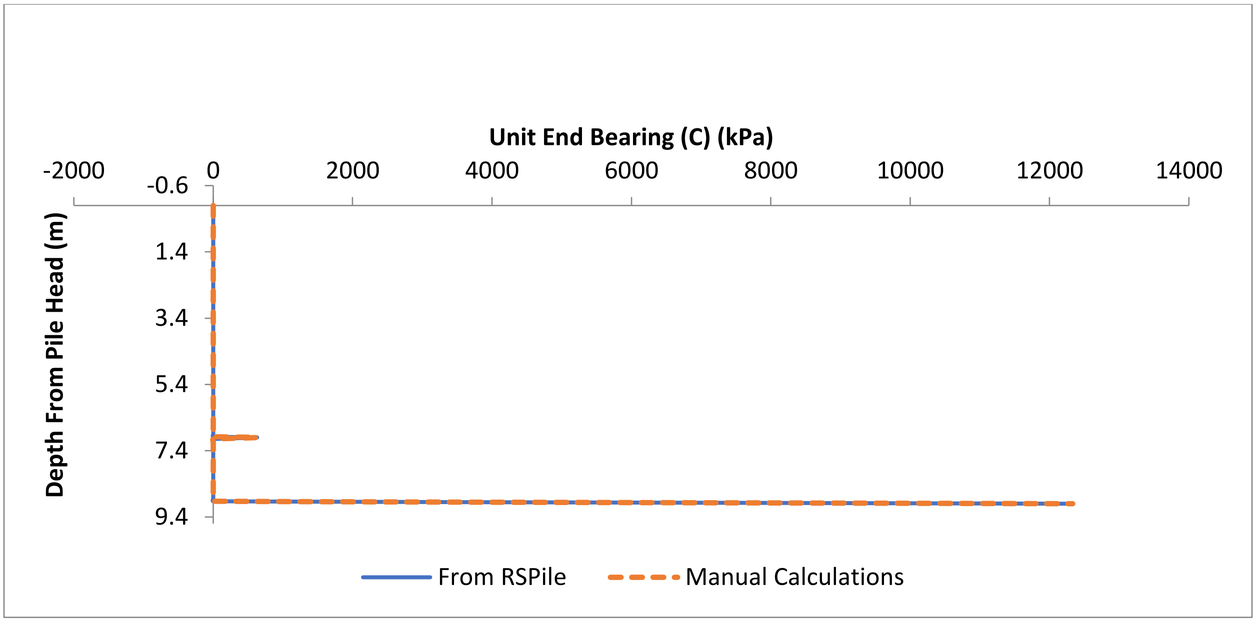

Figure 4: Example 1a Unit End Bearing Comparison

Uplift

For Helix #1, it was previously found that $N'_\gamma = 0$, $N'_q = 1$, and $N'_c = 9$. Therefore, unit end bearing can be directly calculated based off the simplified version of Equation (6):

$$q_{bult} = cN'_c + q'_H N'_q$$

Substituting the values into the equation yields:

$$q_{bult} = (70kPa * 9) + (140kPa * 1) = 770\ kPa$$

In compression, the soil property beneath Helix #2 was used since it is at the transition of two soil layers. In uplift, the soil property above will be used. In this case, the soil property is *Clay 1* for which the values of N'_γ, N'_q, and N'_c were previously determined for Helix #1. The unit end bearing will be:

$$q_{bult} = cN'_c + \ q'_H\left({N_q}'\right) = (70 * 9) + (180 *\ 1) = \ 810kPa$$

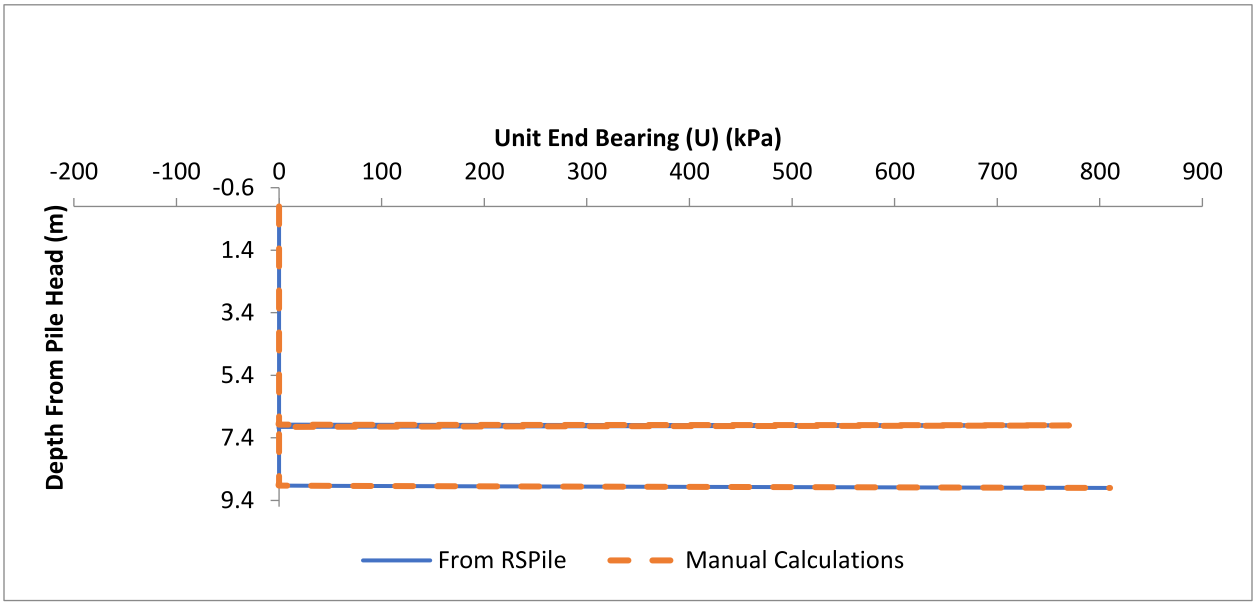

Figure 5: Example 1a Unit End Bearing in Uplift Comparison

1.1.4. Total Ultimate Capacity

The total ultimate capacity of helical piles depends on whether the individual end bearing capacity of the helix plates or the cylindrical shear on the soil cylinder between the helices is the governing limit state. This example will demonstrate the case where the individual end bearing of the helices governs the capacity. Example 1c will show how cylindrical shear will govern the capacity.

The skin friction for each segment on the pile is calculated by taking the multiplying the unit skin friction/cylindrical shear by the segment's perimeter and thickness as shown in Equation (7):

$$Q_{s_{ult}} = f_{s_{ult}} P t \tag{7}$$

Where:

$f_{s_{ult}}$ = unit skin friction or unit cylindrical shear

P = perimeter of the segment

t = thickness of the segment

For segments above the first helix (on the shaft), the perimeter is calculated based on the diameter or side length of the shaft's cross section. However, the perimeter of segments between the helices where the soil cylinder may exist is calculated by interpolating the diameter of the soil cylinder between the helices.

At each helix, the individual end bearing of the plate is calculated from the product of the unit end bearing and the helix area:

$$Q_{bult} = q_{bult} A_{helix} \tag{8}$$

At each helix, the limit state will be checked to determine if the individual end bearing of the helix or the cylindrical shear between the helices will govern. As the unit skin friction is computed for each segment, RSPile keeps track of the accumulated shaft skin friction or cylindrical shear until that segment. If cylindrical shear governs the capacity, the cylindrical shear will continue to act along the length of the pile until the next helix, where the limit state is checked again. If cylindrical shear is acting, then the individual plate end bearing of that helix does not contribute to the capacity. Conversely, if end bearing governs, the accumulation of cylindrical shear stops, and end bearing is accumulated instead.

The ultimate capacity of the pile is calculated by taking the sum of the total shaft friction/cylindrical shear and the total accumulated individual plate end bearing at the last helix, after the limit states have been considered.

Compression

The individual end bearing of the first plate (Helix #1) is calculated by substituting the helix radius and unit end bearing into Equation (9):

$$Q_{bult} = q_{bult} * A_{helix} = 630kPa * \pi * 0.15^2 = 44.5321kN$$

Once the helix's individual plate end bearing is calculated, the limit state is determined by comparing it to the difference in the total accumulated shear between the current helix (with $Q_{bult} = 44.53kN$) and the next helix (Helix #2). Since shaft friction is neglected, the accumulated shaft friction/cylindrical shear above the first helix is 0kPa. For segments between the helices, the diameter of the soil cylinder is interpolated using Equation (8). A sample calculation for the soil cylinder diameter at the midpoint elevation of the segment containing the first helix is shown below:

$$D = 0.3 + \left(\frac{0.2 - 0.3}{(-8.5) - (-6.5)}\right)\left((-6.5 - (\frac{0.05}{2}) - (-6.5)\right) = 0.29875m$$

The ultimate cylindrical shear on this segment is calculated using the unit cylindrical shear at that elevation:

$$Q_{s_{ult}} = f_{s_{ult}} \pi D t = 70kPa * \pi * 0.29875m * 0.05m = 3.28493kN$$

This calculation is repeated for each segment between the helices. As RSPile computes the ultimate cylindrical shear or shaft friction, it continuously tracks the accumulated cylindrical shear for all segments up to the current elevation.

The difference between the accumulated cylindrical shear at the current and subsequent helix is:

$$109.9557kN - 0kN > 44.53kN$$

Since the capacity of the individual helix plate is less than the cylindrical shear, the individual end bearing of the helix plate governs the capacity at the first helix. In compression, the bottom-most helix will always contribute to the compressive capacity of the helical pile. In this example, there are only two helices, therefore the capacity is completely governed by the individual end bearing of the helices.

The total accumulated end bearing of the helical pile is the sum of each helix's individual plate end bearing:

$$Q_{bult\ (helices)} = \sum_{j}^{m} q_{bult\,j} A_j \tag{10}$$

The end bearing of the second plate Helix #2 is calculating using Equation (8);

$$Q_{bult} = q_{bult} * A_{helix} = 12332.855\ kPa * \pi * 0.1m^2 = 387.448kN$$

The total ultimate compression capacity is calculated as follows:

$$Q_{bult\ (helices)} = 44.53\text{kN} + 387.448\text{kN} = 431.98kN$$

Uplift

In uplift calculations for shaft friction, the length determined by the product of the height reduction factor and the first helix diameter is neglected from uplift calculations. If the depth of the helix from the ground surface is less than this length, the helix is shallow (See Example #2). In this example, the helix is deep, and therefore skin friction on the shaft will work above the first helix. However, shaft friction is neglected in this example and skin friction above the first helix is 0kPa.

In uplift, the limit state is determined by comparing the individual plate end bearing of the lower helix with the total accumulated cylindrical shear between the helices. The individual plate end bearing of the lower helix is calculated using Equation (9):

$$Q_{bult} = 810kPa * \pi * 0.10^2 = 25.4469kN$$

The total accumulated cylindrical shear of the segments between the helices was found previously to be 109.95578kN (Table 4). Since the individual end bearing of the plate is less than the total cylindrical shear between the helices, the plate will govern the capacity at the helix. The total ultimate uplift capacity is once again the sum of both helix's individual plate end bearing using Equation (10):

$$Q_{ult} = 54.4281kN + 25.5569kN = 79.875kN$$

1.2. Example 1b – Shaft Adhesion Included

Adhesion on the shaft will not affect the unit cylindrical shear and unit end bearing results calculated in Example 1a. If shaft adhesion is included, the unit skin friction above the first helix will no longer be 0 kPa. The pile's capacity is expected to slightly increase due to the added adhesion effects along the length of the shaft. In the previous example, the adhesion factor was not considered because shaft adhesion was neglected. Here, an adhesion factor of 0.7 is applied in Clay 1 to demonstrate its impact on unit skin friction.

1.2.1. Unit Skin Friction on Shaft

At the top of the first layer, *Sand 1*, the effective overburden pressure was previously determined to be $0.75\ kPa$ (See *Example 1a*). Therefore, unit skin friction on the shaft at the top of the layer is calculated using the Equation (2):

$$f_s = 0.5 * 0.75\ kPa * \tan(20°) = 0.136489\ kPa$$

At the bottom of the layer, the effective overburden pressure is $89.25kPa$ (See *Example 1a*). The unit skin friction at the bottom of the layer is:

$$f_s = 0.5 * 89.25kPa * \tan(20°) = 16.2422\ kPa$$

The first helix is embedded in Clay 1, a cohesive soil, and therefore unit skin friction at the helix is equal to the undrained shear strength of that soil type (Equation 1):

$$f_s = \alpha * S_u = 0.7 * 70\ kPa = 49\ kPa$$

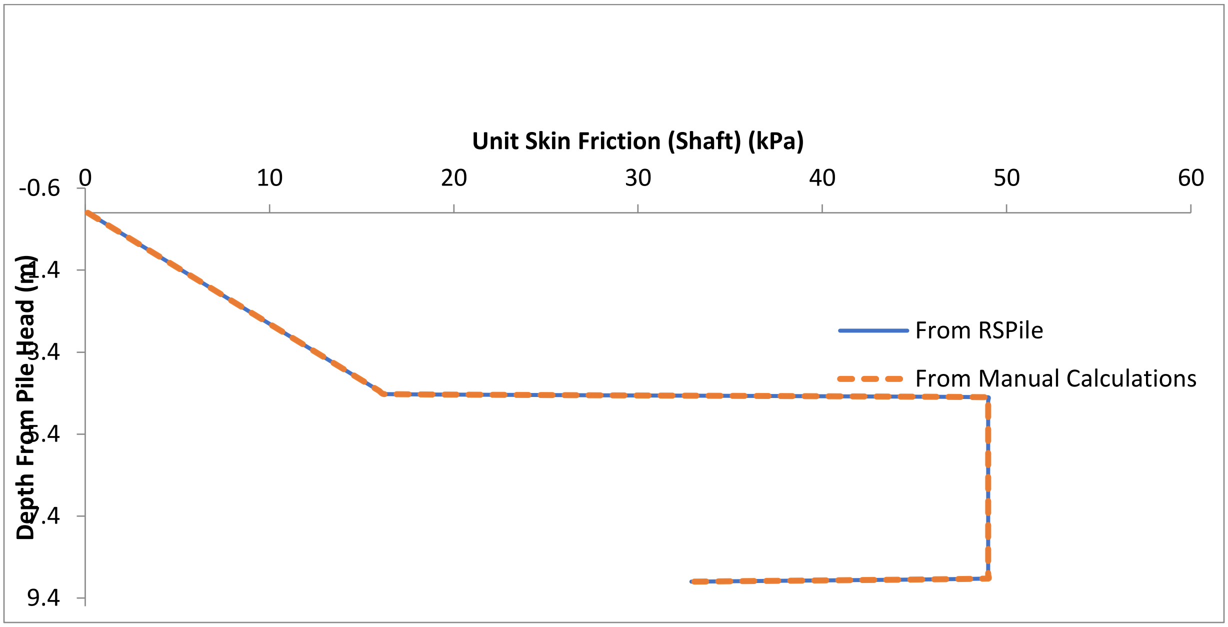

Figure 6: Example 1b Unit Skin Friction with Shaft Comparison

1.2.2. Total Ultimate Capacity

Since the skin friction on the shaft is included, there are additional contributions to the accumulated skin friction/cylindrical shear from the segments above the first helix.

Compression

To determine the limit state of the pile's capacity in compression at the helix, the difference between the cylindrical shear at the current and subsequent helix is compared to the plate's bearing capacity:

$$173.697kN - 63.7408kN = 109.9562 > 44.53kN$$

Since the individual end bearing of the helix plate is less than the cylindrical shear, there will no longer be any accumulation between the helices. The cylindrical shear will remain constant at its last accumulated value at the helix, 63.741kN. Therefore, the ultimate compressive capacity of the pile is calculated by taking the sum of the skin friction and individual plate end bearing of both helices (previously calculated).

$$Q_{ult} = 431.98kN + 63.741kN = 495.721kN$$

Uplift

To determine the limit state in uplift, the total accumulate cylindrical shear must be calculated between the helices.

The individual end bearing of the lower helix plate was previously determined to be 25.446kN. Since it is less than the total cylindrical shear of 109.96kN, the end bearing of the helices will govern once again. Skin friction remains constant after the effective shaft height. In this case, friction is limited to 52.961kN.

The ultimate capacity is the sum of both plates with the value of the total skin friction/cylindrical shear at the last helix:

$$Q_{ult} = 52.961\text{kN} + 79.875kN = 132.84kN$$

1.3. Example 1c – Cylindrical Shear

In this example, Helix #2 will be placed closer to Helix #1 to demonstrate the effects of cylindrical shear working between the helices. In addition to closer spacing, the diameters of Helix #1 and Helix #2 will be modified to 0.6m and 0.5m, respectively. Shaft adhesion will be neglected above the first helix. The updated helix configuration, unit end bearings, and plate end bearings are shown in Table 4:

Table 4: Updated Helix Data

#	Diam. (m)	Depth (m)	Elevation (m)	Area (m2)	Unit End Bearing Compression (kPa)	Plate End Bearing Compression (kPa)	Unit End Bearing Uplift (kPa)	Unit End Bearing Uplift (kPa)
1	0.6	7	-6.5	0.282743339	630	178.1283035	770	217.7123709
2	0.5	7.5	-7	0.196349541	630	123.7002107	780	153.1526419

1.3.1. Compression

In Example 1a, the individual end bearing on the plate was calculated by multiplying the area of the helix by the unit end bearing, yielding 44.53kN. Table 5 shows the tabulated results of the accumulated cylindrical shear for each segment between the helices:

The difference in cylindrical shear at the top and bottom of the helices is 60.476kN. The limit state can now be determined:

$$60.476kN < 178.128kN$$

Since the cylindrical shear between the helices is less than the individual plate end bearing of Helix #1, cylindrical shear governs the capacity at the location of the first helix. As a result, the individual end bearing of Helix #1 will not contribute to the capacity and cylindrical shear will continue to accumulate until the last helix. The last helix will always contribute to the capacity in compression; therefore, the total ultimate compressive capacity will be the sum of the total cylindrical shear and individual end bearing of the last helix:

$$Q_{ult} = 60.47kN + 123.7kN = 184.176kN$$

1.3.2. Uplift

Since the depth of the helix from the ground surface is deep, the individual end bearing of the top plate (Helix #1) will contribute to the capacity. The limit state still needs to be checked, and it can be found by comparing the previously determined total accumulated cylindrical shear between the helices (Table 8) and the individual plate end bearing of the bottom helix:

$$60.476kN < 153.15kN$$

Cylindrical shear will govern the capacity in uplift, and the total ultimate uplift capacity will be the sum of the total cylindrical shear at the bottom helix and the individual plate end bearing of the top helix:

$$Q_{ult} = 60.47kN + 217.7kN = 278.188kN$$

2. Example 2 – Shallow Embedment

This example will demonstrate the case where a soil cylinder forms above the first helix in uplift. The helix data is summarized in Table 5:

Table 5: Helix Data

#	Diameter (m)	Spacing (m)	Depth from Pile Head (m)	Elevation from Ground Surface (m)
1	0.6	-	3	-1
2	0.5	0.5	3.5	-1.5
3	0.4	0.5	4	-2

In this example, there is only one borehole with top elevation of 0m. The soil type is *cohesionless* with the default RSPile values:

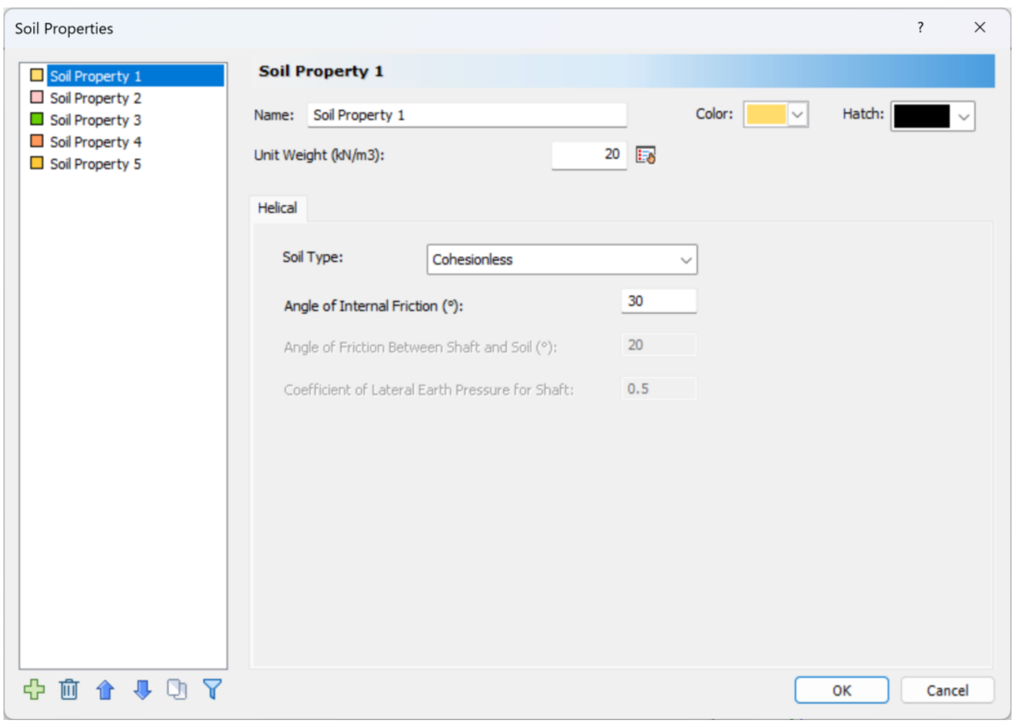

Figure 7: Soil Properties from RSPile

If the depth of the first helix from ground surface is less than Heff, then the helix is shallow. Heff is calculated as shown:

$$H_{eff} = \mu * D_T$$

Where:

μ = height reduction factor

D_T = diameter of top helix

For uplift calculations, if the helix is shallow then cylindrical shear will act completely above the first helix, and shaft adhesion will be ignored (even if it is enabled in **Project Settings**).

In this example, suppose there is a single borehole at (0,0) with top elevation of 0m. If the pile head elevation is at 4.5m and the helix elevation is at -0.5m, the effective length for this scenario is:

$$H_{eff} = \mu * D_T = 2 * 0.6m = 1.2m$$

The depth of the helix from ground surface is 1m, therefore the helix is shallow and a soil cylinder will form from the first helix to the ground surface. A comparison of the cylindrical shear in compression and uplift are shown in Figures 2 and 3. Observe the additional cylindrical shear acting above the first helix in uplift (Figure 3).

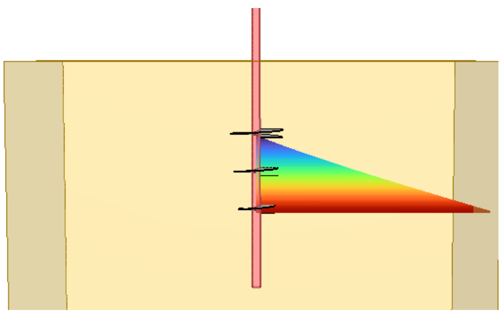

Figure 8: Cylindrical Shear in Compression

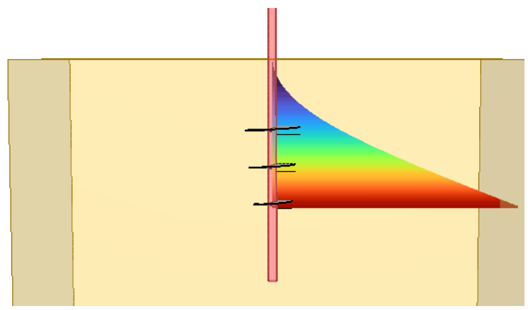

Figure 9: Cylindrical Shear in Uplift