Effects of Pile Rigidity and Soil Stiffness on the Settlement of Piles

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Using RSPile for Understanding Pile Behavior

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This article is intended to show how RSPile is useful in research and parametric study.

Introduction

One of the likely benefits of having RSPile on your computer is conducting side research to have a better expectation to how your pile will behave. The following simple research work on RSPile will show you how we can optimize the stiffness of the pile to consume more of the skin resistance capacity and get shorter piles rather than having long stiff piles. Hence, this may lead to significant cost saving especially if the settlement was within the acceptable limits.

In the following example, different piles of two diameters 0.9 m and 0.3 m having the same length of 15 m are analyzed in addition to a series of piles of 0.9 m diameter but with a shorter length of 10 m. Piles have different modulus of elasticity varying from very stiff (rigid piles) of 2M MPa to only 200 MPa. The piles are analyzed embedded in three different soil layers with varying stiffness having skin resistances of 60 kPa, 90 kPa and 120 kPa, respectively. The user defined relative T-z curves are kept the same for the three soils to know exactly how the stiffness of the soil varies among the three cases.

The results will be discussed and presented to show how the piles are expected to behave under different stiffness conditions and how to use RSPile in handling such research work.

It is found that the stiffer the pile and the weaker the soil, the skin friction tends to be uniform along the depth with a smaller percentage of its ultimate capacity consumed. As the soil becomes stiffer or the pile becomes more flexible, the mobilized skin resistance approaches the ultimate values at the top parts of the pile and attenuates rapidly with depth leaving a long part of the pile useless. An introduction of the idea of effective length is then clearly noticed.

Defining the Soils

The soils used in the analysis are Soil 1, Soil 2, and Soil 3. To study the effect of soil stiffness and pile stiffness distinguished, the soil stiffness should not be dependent on pile size or length. That is why it is better to choose the user defined T-z curves instead of other models that are built in RSPile. The user defined T-z curves defines the soil skin friction mobilization level based on the "absolute displacement" of the soil instead of relative displacements. In this approach we can get different stiffness for the soil depending only on its ultimate skin resistance with reference to the same displacement value.

The soil T-z curve chosen following the points given in Table 1 and the relation is plotted in Fig.1.

Table 1. T-z curve defining points for the soils used in the study

Soil Displacement (mm)	Ratio of Mobilized (f_s/f_{sult})
0	0
5	0.5
10	0.75
15	0.9
20	1

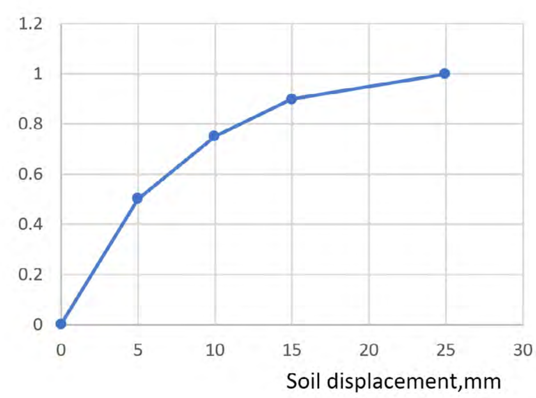


Figure 1. T-z curve defined for the soils in the study

All the three soils were set to have no tip resistance (end bearing capacity = 0). This will help to distribute the skin friction properly without interference of base to the load distribution. As mentioned in the introduction, the soils are given ultimate skin resistances of 60 kPa, 90 kPa, and 120 kPa, respectively.

The software needs to be run three times changing the soil type. Instead, a simple trick is followed here to define three zones of soils that are different from each other. Maximum diameter size used is 0.9m with a depth of 15 m. The soil is extended to 21 m to make sure no issues occur at the pile base. The trick is to define transition zones between the three soils where no piles will be installed. This is done using 18 boreholes to define the main zones where the piles are installed and the transition zone.

Fig.2 shows how the 18 boreholes are used to define the required soil zones to run the program one time for all cases. Boreholes 1–6 contain the zone for soil 1, 7–12 for soil 2, and 13–18 for soil 3, while the intermediate zones are transition zones to change the soils easily by defining zero thicknesses for the other soils and 21 m for the soil assigned to that zone. So, the soil layers are given thicknesses of 21 m as per the numbers of the boreholes in the sequence above and zero thicknesses for the other layers.

Piles Distribution

The piles are distributed in diameters lengths and loads to adequately study the stiffness effects on settlement. Forty-five piles are used with two diameters, 0.9 m and 0.3 m. The axial (vertical) load given to the 0.9m diameter piles is 300kN. To keep the same effect of length and perimeter on skin friction, a load of 100 kN is applied at pile heads of the 0.3 m diameter piles. Hence, we can study the effect of rigidity easily. Piles are divided to five levels of Young's modulus 2E10, 2E8, 2E6, 2E4 and 200 kPa from very stiff piles (almost fully rigid compared to the soils) to extremely flexible. Two rows of piles installed in each soil are given 15 m lengths. The third rows have shorter lengths of 10 m. The pile numbers and their properties are listed for all cases in Table 2.

The piles are spaced at 2 m for convenience. There is no interaction between them according to RSPile individual pile analysis. The piles layout is shown in Fig.3.

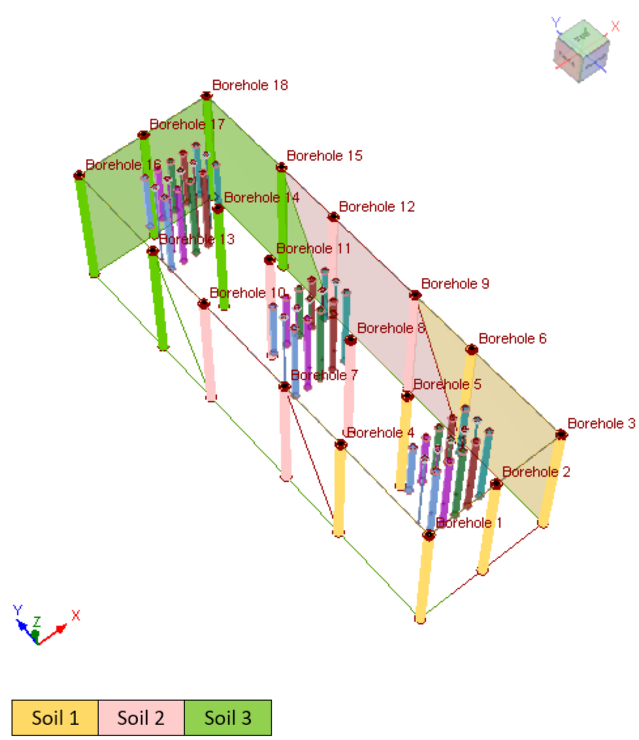


Figure 2. The distribution of the 18 boreholes to zone the soils

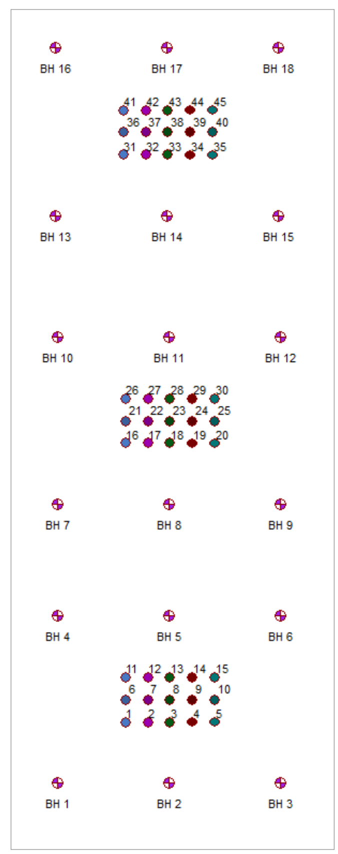


Figure 3. Piles and boreholes

Table 2. Dimensions, properties, and locations in soil zones of the piles in the study

Soil Zone	Pile Number	Diameter	Length	Young's Modulus	Axial Load
		m	m	kPa	kN
Soil 1	1	0.9	15	2.00E+10	300
	2	0.9	15	2.00E+08	300
	3	0.9	15	2.00E+06	300
	4	0.9	15	2.00E+04	300
	5	0.9	15	2.00E+02	300
	6	0.3	15	2.00E+10	100
	7	0.3	15	2.00E+08	100
	8	0.3	15	2.00E+06	100
	9	0.3	15	2.00E+04	100
	10	0.3	15	2.00E+02	100
	11	0.9	10	2.00E+10	300
	12	0.9	10	2.00E+08	300
	13	0.9	10	2.00E+06	300
	14	0.9	10	2.00E+04	300
	15	0.9	10	2.00E+02	300
Soil 2	16	0.9	15	2.00E+10	300
	17	0.9	15	2.00E+08	300
	18	0.9	15	2.00E+06	300
	19	0.9	15	2.00E+04	300
	20	0.9	15	2.00E+02	300
	21	0.3	15	2.00E+10	100
	22	0.3	15	2.00E+08	100
	23	0.3	15	2.00E+06	100
	24	0.3	15	2.00E+04	100
	25	0.3	15	2.00E+02	100
	26	0.9	10	2.00E+10	300
	27	0.9	10	2.00E+08	300
	28	0.9	10	2.00E+06	300
	29	0.9	10	2.00E+04	300
	30	0.9	10	2.00E+02	300
Soil 3	31	0.9	15	2.00E+10	300
	32	0.9	15	2.00E+08	300
	33	0.9	15	2.00E+06	300
	34	0.9	15	2.00E+04	300
	35	0.9	15	2.00E+02	300
	36	0.3	15	2.00E+10	100
	37	0.3	15	2.00E+08	100
	38	0.3	15	2.00E+06	100
	39	0.3	15	2.00E+04	100
	40	0.3	15	2.00E+02	100
	41	0.9	10	2.00E+10	300
	42	0.9	10	2.00E+08	300
	43	0.9	10	2.00E+06	300
	44	0.9	10	2.00E+04	300
	45	0.9	10	2.00E+02	300

Discussion of Results

Four points should be remembered before discussing the results.

1. The total mobilized skin friction must be equal to the applied axial load.
2. The settlement of a pile which mobilizes the skin resistance at any depth is the summation of the elastic shortening of the pile (the sum of the shortening in all pile segments above that level) and the rigid body movement of the pile due to the settlement of the surrounding soil.
3. The mobilized unit skin friction is a function of the soil movement (settlement of the soil regardless of the elastic shortening in the pile).
4. The main results that need to be looked at are the settlement, pile axial force distribution through the length, and the soil resistance distribution (skin friction).

Effect of Pile Stiffness on the Settlement:

Piles 1–5 have different Young's modulus. The results of these piles are shown in Fig.4. Piles 1–3 are plotted together while Pile 4 results are plotted in a different graph to get appropriate scaling as the settlement of Pile 4 increases tremendously due to the low rigidity of the pile. Pile 5 exceeds practical range of settlement and it is considered as a failed pile. It can never hold the load of 300 kN.

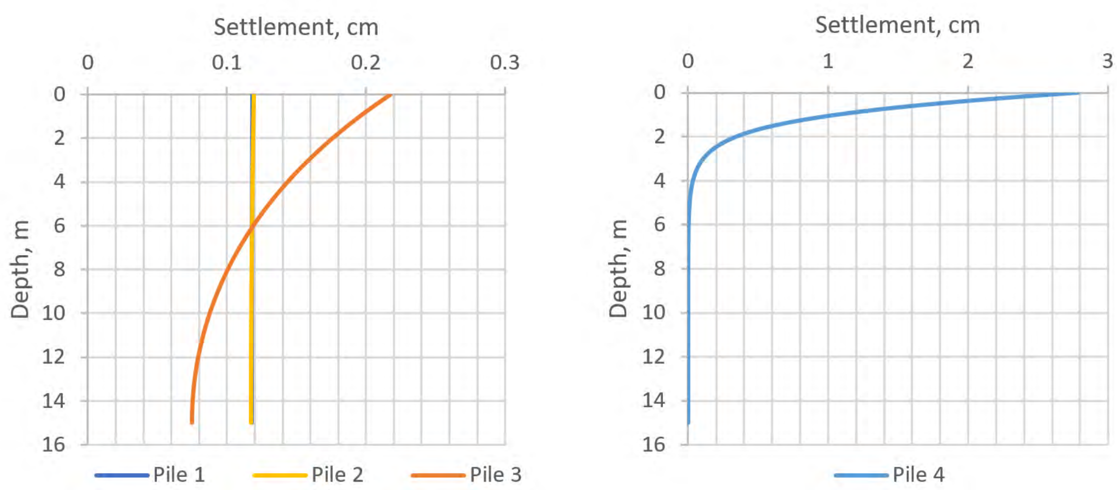


Figure 4. Settlement of Piles 1–4

It can be clearly noticed that although Piles 1 and 2 have 100 times difference in modulus the change in settlement can barely be noticed. These piles act rigid compared to soil stiffness. Hence the settlement will tend to be uniform along the depth and the skin friction as well. Skin friction in this case will be far away from reaching its ultimate values, as seen in Fig.5.

In Piles 1 and 2, the skin friction is around 20 kN/m * 15 m = 300 kN, the applied load. The uniform skin friction along the depth indicates a rigid body movement instead of having elastic shortening in the pile. Again when the rigidity decreases and the pile becomes flexible such as Pile 3 or 4—the skin friction gets consumed at the top part and the displacement stops at the bottom part of Pile 4, while in Pile 3 there is still some rigid pile movement participating to the settlement and the settlement tends to be uniform at the very bottom of the pile. Settlement in Pile 4 attenuates to zero at around 6m depth and similarly the skin friction goes down to nil. This length is the effective length of the pile where there is real resistance. Increasing the load will push this distribution down and the effective length increases for the same modulus of pile.

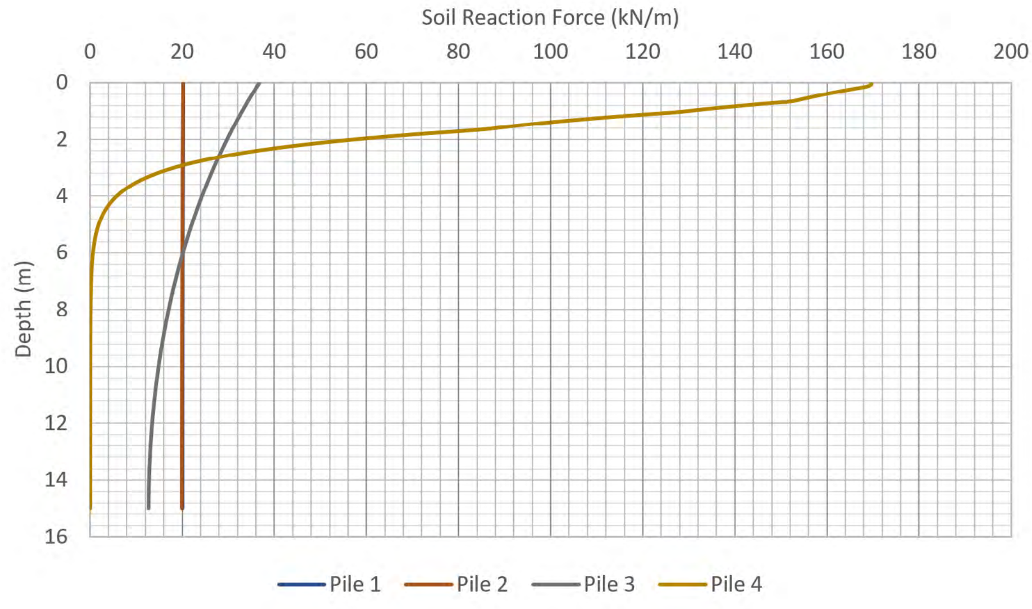


Figure 5. Distribution of skin friction along the depth, Piles 1–4

Effect of Pile Diameter

The second row of piles, Pile 6–10 are having lesser diameter of 0.3 m with similar variation in modulus. The results are compared with row 1. Piles 1 and 6, and Piles 3 and 8, are plotted in Fig.6. The resulting skin friction along the piles is illustrated in Fig.7.

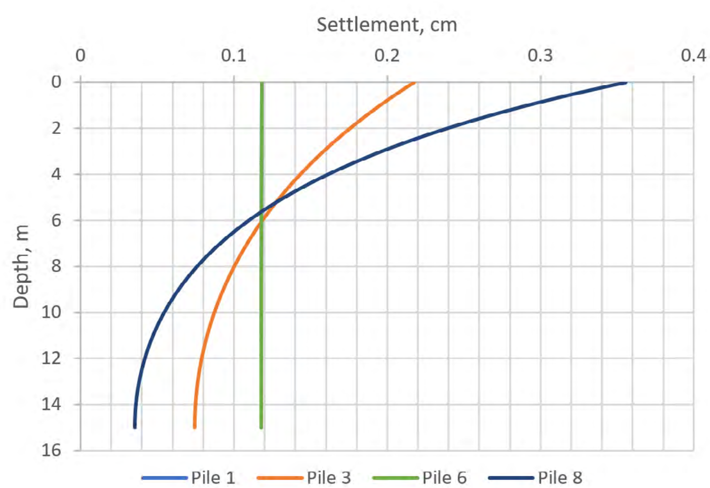


Figure 6. Settlement of Piles 1, 3, 6, and 8

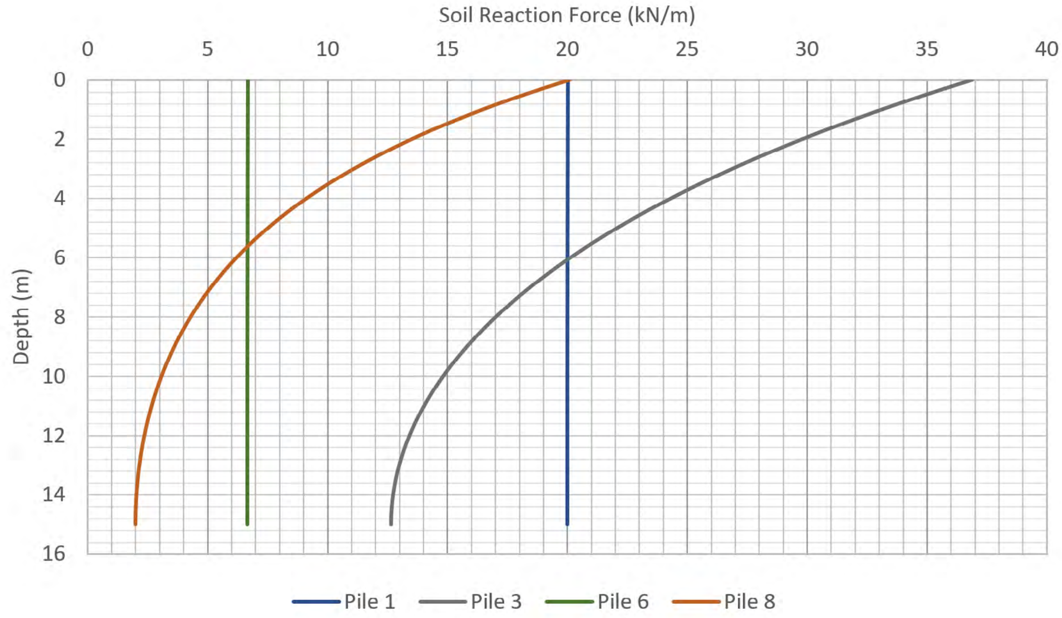


Figure 7. Distribution of skin friction along the pile length for Piles 1,3, 6, and 8

From these figures, it can be seen that pile modulus will not be the only factor that affects the settlement even if the soil stiffness and the load to perimeter ratio are the same. The real factor that affects the settlement response is the rigidity of the pile EA. Piles are the same length, hence, the diameter has a role here. Having less diameter, Pile 8 consumes more unit skin friction at the top than Pile 3 (divide the values 20 kN/m and 37 kN/m by the corresponding perimeters). This means the effect of elastic shortening of the pile is more in the smaller diameter pile (having less rigidity) and accordingly the settlement of Pile 8 is more than the settlement of Pile 3. This effect decreases as rigidity values compared to soil stiffness gets high enough for Pile 1 and 6 where the settlement becomes almost equal due to the dominating rigid body movement. That is also why the skin friction at Pile 6 is one third the skin friction of Pile 1 (the load on Pile 6 is 100 kN while on Pile 1 is 300 kN). As the pile rigidity diameter decreases, the skin friction mobilized more rapidly at the top than for a larger pile due to the increased elastic shortening of the pile with less diameter. Remember that elastic shortening of a pile segment is directly related to EA/L, where L and E are the same for both piles in comparison.

Pile 9 has the same modulus as Pile 4 but of course lower by 100 times than Pile 3 and Pile 8. Fig.4, showed that the skin friction at the top of Pile 4 reached 170 kN/m which means the unit skin friction reached its ultimate value (169.65/0.9/pi= 60 kN/m^2). In fact, following the result table it is found that only the first pile segment (out of 100 segments) arrived at the ultimate skin resistance level, while Pile 9 in Fig.8 shows that a longer part at the top is at the maximum ultimate skin resistance. This is a confirmation of the discussion above. The settlement increases markedly in Pile 9 reaching 6.94 cm.

Note that although the skin friction decreases to zero at about 4.2 m, this length cannot be considered as an effective length for design as the pile failed at the top already.

Figure 8. Skin friction along Pile 9

Effect of Pile Length

To check the effect of length on settlement, Piles 11–15, 26–30, and 41–45 are given a 10 m length instead of 15 m. These piles are all similar to Piles 1–5 in diameter and modulus and all subject to a vertical load of 300 kN.

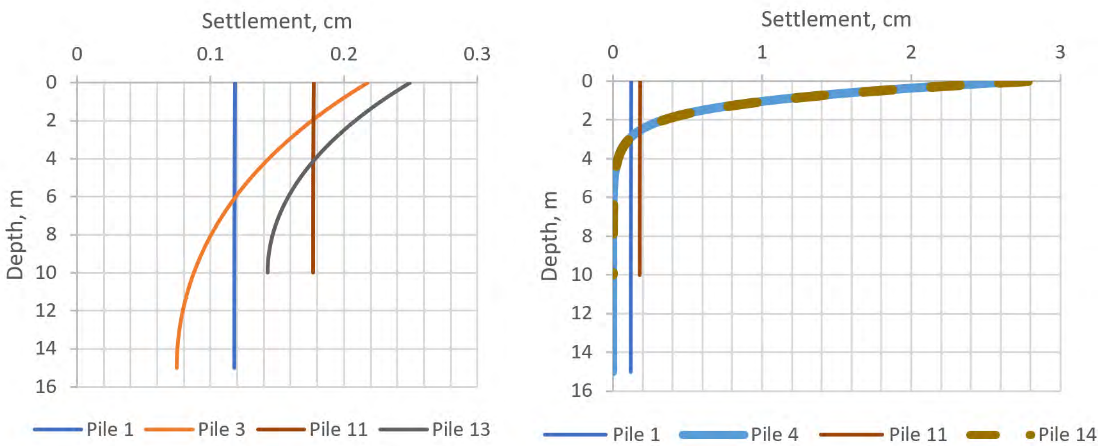


Figure 9. Settlement of Piles 1, 3, 11, 13, 4, and 14

The settlements of some of these piles are plotted against depth in Fig.9. The behavior in the short Pile 11 gives uniform movement along its depth but the value of settlement is higher than the rigid Pile 1 which is longer having a length of 15 m. This is attributed to how more skin friction is mobilized along Pile 11 than in Pile 1 to balance the applied load of 300 kN. **Increase in skin friction increases the settlement of a rigid pile regardless of the length of the pile.**

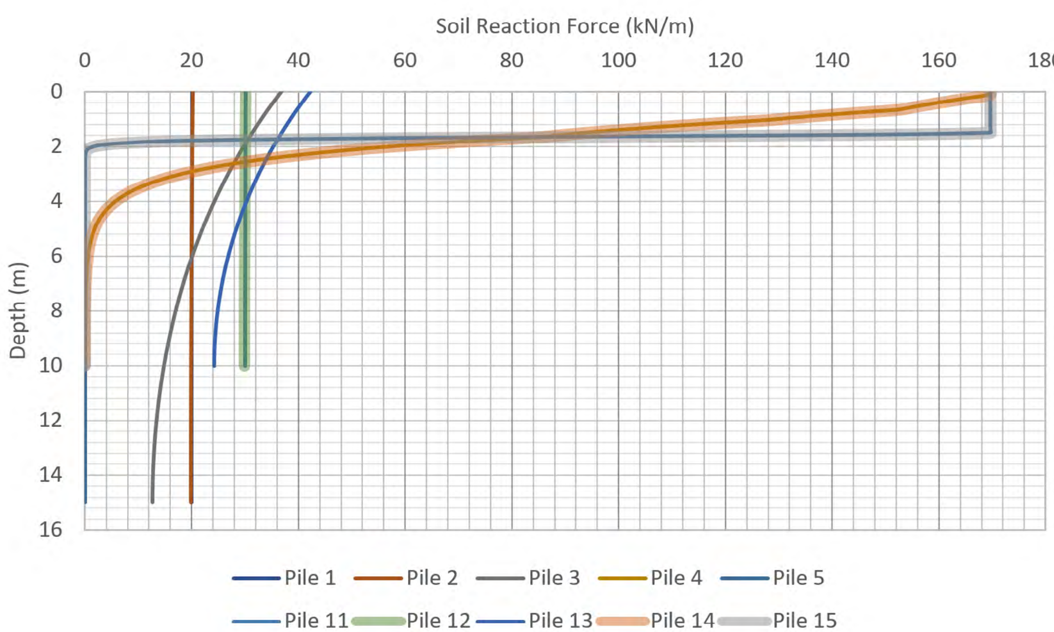


Figure 10. Distribution of skin friction along the depth of Piles 1–5 and Piles 11–15. The shown curves are coinciding for Piles 1 and 2, Piles 11 and 12 (rigid piles), and curves of Piles 13, 14, and 15 are coinciding with the first 10 m of Piles 3, 4 and 5.

Decreased rigidity in Piles 3 and 13 showed tendency of the settlement of the shorter pile, Pile 13, to become closer to the settlement of the longer pile although the longer pile still has less settlement. In the right side the comparison between Piles 4 (15 m long) and 14 (10 m long) shows that the settlement curves of the two piles coincide. The effect of elastic shortening of the pile (piles having lesser modulus) governed the skin friction mobilization.

Decrease of rigidity EA after a certain limit will control the skin friction distribution regardless of length of the pile provided that the length available is greater than the effective length. It can be seen from the curves of Piles 4 and 14 that the effective length did not change, but in both piles it is still less than the pile length. Piles 5 and 15 both fail, and the settlement exceeds the practical range. See Fig.10 for the skin friction distribution.

Effect of Soil Stiffness

Additional series of piles from Pile 16–45 were added in a similar way to Soil 2 and Soil 3, see Table 2. These two series are executed to compare with rows in Soil 1 to depict the effect of soil stiffness on the settlement of piles having different rigidity. Soil 2 and Soil 3 have the same T-z (normalized for T as T/T_{ult}) curves as Soil 1. The soils differ in their ultimate skin resistance; hence, their stiffness will change as the level of friction will increase for the same displacement with increased ultimate values.

Some of the results may be enough to understand the differences. Note that the behavior among the piles of the same series are in line with what has been discussed above for piles installed in Soil 1.

Settlements of Piles 2, 3, and 4 are plotted against depth in the three graphs of Fig.11 along with their corresponding piles of similar modulus installed in Soil 1, Soil 2, and Soil 3.

Pile 2 is relatively still rigid, but the rigidity becomes less in Soil 2 and even lesser in Soil 3. Still, the change in settlement is insignificant, Fig.11 (a). An interesting coincidence occurred between settlements of Piles 2, 7, and 27 as for this specific case the ratio of lengths 10/15 equal the ratio of f_{sult}(Soil 1)/f_{sult}(Soil 2) and all are almost rigid piles. The soil stiffness effect can be clearly found in Fig.11 (b) where the piles are in the intermediate flexibility. The piles show less settlement in stiffer soils and the behavior of 0.3 m diameter piles is obviously different than the behavior of 0.9 m diameter piles where the effect of the elastic shortening takes a role in shaping the skin friction distribution per meter length of the pile.

Fig.11 (c) collects the piles of high flexibility where the settlement exceeds the acceptable usual limits although the stiffer the soil the less the settlement. The reason is that the effective length shortens in stiffer soils causing less elastic shortening of the pile.

Similar to previous sections, the soil reaction (the mobilized skin friction per meter length of the pile) is plotted against the depth for all piles in two scales in Fig.12. Again, the increase in soil stiffness decreased the settlement and decreased the effective length, while for the highly rigid pile the effect of soil stiffness was insignificant.

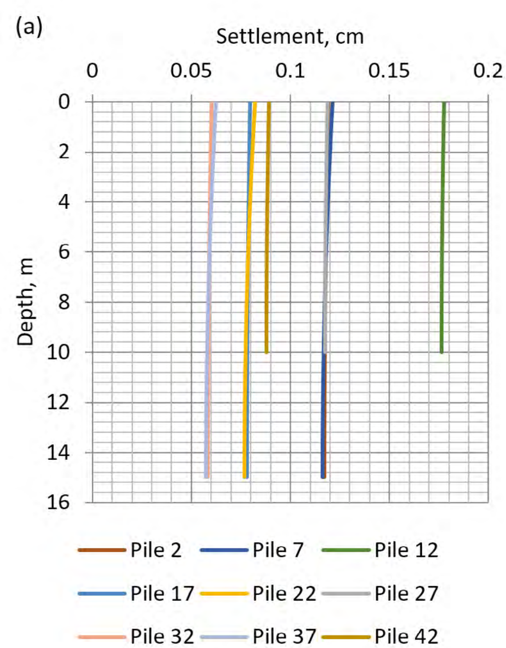
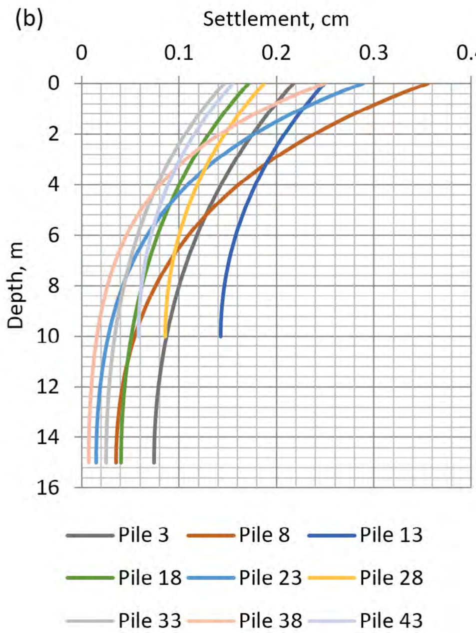


Figure 11 (a). The effect of soil stiffness on the pile settlements



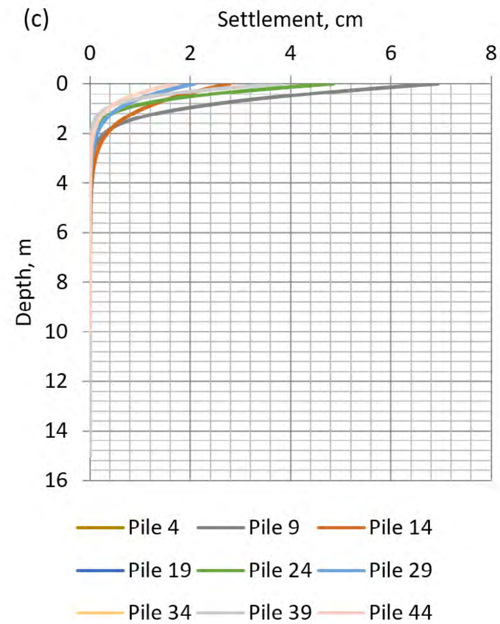
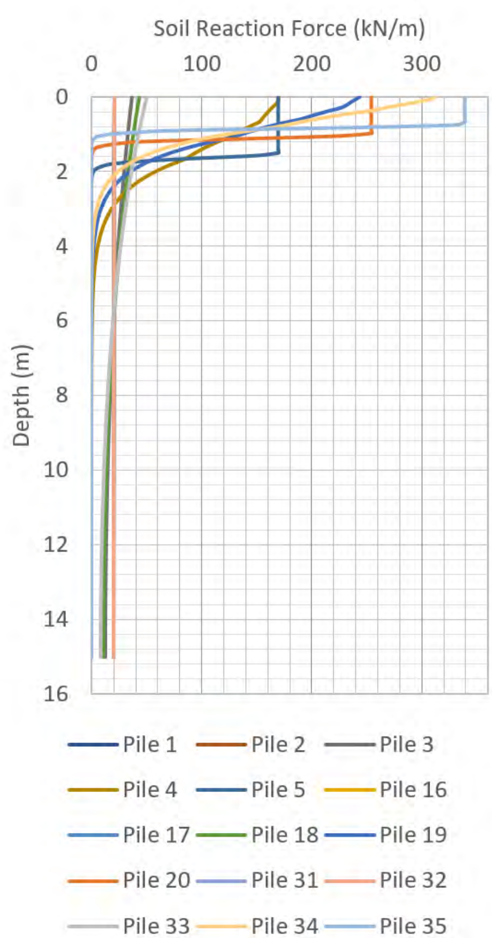


Figure 11 (b) and (c). The effect of soil stiffness on the pile settlements



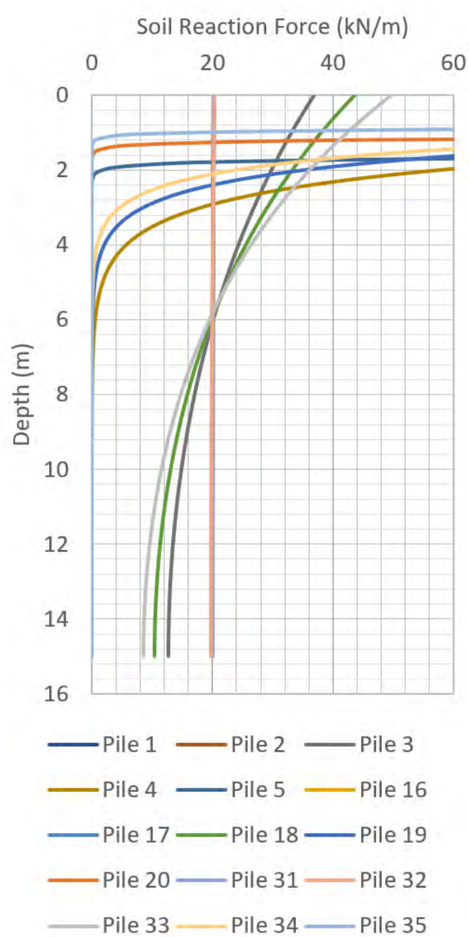


Figure 12. The skin friction distribution in kN per unit length of pile for the piles A and C of 15 m length (first rows of each series)

Concluding Remarks

A tricky way to represent zones of different soils in one RSPile model is presented. Piles of different rigidity, diameter, and lengths have been studied to show how the rigidity of a pile may affect the settlement and skin friction distribution in soils of different stiffness.

The article showed how rigid piles distribute the skin resistance uniformly along the pile depth.

The idea of the effective length was presented at which the mobilized skin friction attenuates practically to nil. The more flexible the pile the shorter the effective length is.

The skin friction and settlement of relatively flexible piles may not be affected significantly by the length of the piles provided that the piles are longer than the effective length.

The use of absolute displacement T-z curves may cause confusion in the values of settlement for equal load/diameter ratio. The reason is that the elastic shortening depends on the area and not the diameter. It is possible that some soil-pile interactions may follow normalized displacement z/D instead of z only.

As expected, it is found that the stiffer the soil, the more skin friction accumulates at the top yielding shorter effective length and less settlement. ■

Note: General controls on the model analysis by RSPile

- The program was executed using Axial/Lateral analysis using general loading option.
- No water table was added.
- The number of pile segments chosen was 100.
- Accuracy limit (tolerance) was fixed to 0.001.
- Any method of interpolation for ground layers (standard option) may be used provided that the boreholes are defined as shown in Fig.1.
- To ensure convergence, the maximum number of iterations was set to 200.