

RSPile 2018

Pile Capacity and Loading Analysis

**Grouped Pile Analysis
Verification Manual**

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Introduction

This document contains a series of pile analysis problems that have been solved using *RSPile* 2018 and will serve as verification for the software. Verification test cases are derived from a literature review on grouped pile tests. All studies used in deriving the verification problems are cited at the end of the document.

RSPile results were computed and compared to GROUP software results, as well as study data. Comparison graphs are shown below each case.

For all examples, a description of the experimental procedure is given with material, soil, and pile properties shown in tables.

Finally, it should be noted that there is a degree of error associated with the results in these test cases which explains much of the comparisons' variability. The sources of error are derived from several factors:

1. Most, if not all, of the studies did not completely define the parameters necessary for the modelling in *RSPile*. This occurred predominantly in soil properties in which case typical values were assumed.
2. Several of the studies' pile wall thickness values differed from their reported moment of inertia values. The thicknesses that gave the specified moment of inertia were used.
3. Load values were often taken from study graphs by digitizing the data. There is a small amount of error inherent in this method.
4. There is some error inherent in the experimental bending moment and displacement values since the strain gauges and inclinometers used in testing do not represent exact values.

RSPile Verification Problem #1

Full Scale Static Lateral Load Test of a 9 Pile Group in Sand

1.1 Problem Description

This problem is based on the results of an experimental lateral load test conducted at Brigham Young University by Christensen (2006). Computer analysis was used to model the test and determine accurate p-multipliers for laterally loaded piles in sandy soils. The soil properties used to model the test were calibrated using the results from a test of a single laterally loaded pile. The group pile test was then modelled using this soil profile and p-multipliers were used to match the computed results to the experimental results. A diagram of the RSPile model is shown in Figures 1-1 and 1-2 below. The pile group is loaded in the positive Y' axis (to the right when looking at the plan view).

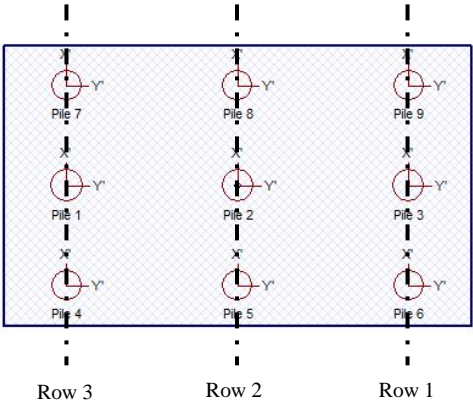


Figure 1-1: Plan View of RSPile Model

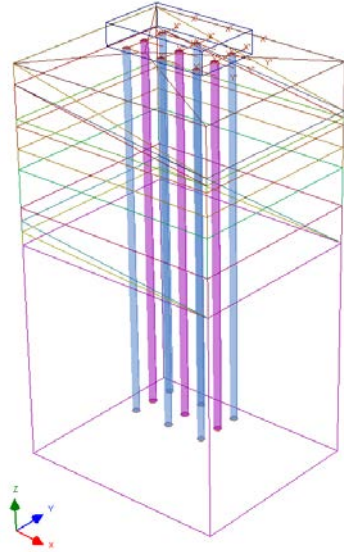


Figure 1-2: RSPile 3D Model

1.2 Material Properties

Separate soil profiles were used to model soil inside and outside of the pile group. The leading row of piles was modelled using the profile in Table 1-1, while the middle and trailing rows were modelled using the profile in Table 1-2. In GROUP, separate models had to be created to implement each soil profile while in RSPile, the varying soil profile could be modelled using the boreholes feature (Figure 1-2).

Table 1-1: Row 1 (leading row) Soil Profile

Soil Model	Depth (m)	Friction Angle (Degrees)	Effective Unit Weight (kN/m ³)	Subgrade Modulus (kN/m ³)	Max Side Friction (kN/m ³)	Max Tip Resistance (kN/m ³)	Undrained Shear Strength (kPa)	E50
API Sand	0 – 2.1	40	16.7	75,000	38	7660	-	-
API Sand	2.1 – 2.4	40	6.8	42,000	38	7660	-	-
Soft Clay	2.4 – 2.7	-	9.1	27,000	41	372	41	0.01
Soft Clay	2.7 – 3.7	-	9.1	140,000	50	450	50	0.01
Soft Clay	3.7 – 4.6	-	9.1	27,000	40	360	40	0.01
Sand	4.6 – 6.3	38	8.1	26,000	29	5743	-	-
Soft Clay	6.3 – 8	-	9.1	140,000	57	512	57	0.01
Sand	8 – 18	33	6.7	150,000	23	4599	-	-

Table 1-2: Row 2 and 3 (middle and trailing rows) Soil Profile

Soil Model	Depth (m)	Friction Angle (Degrees)	Effective Unit Weight (kN/m ³)	Subgrade Modulus (kN/m ³)	Max Side Friction (kN/m ³)	Max Tip Resistance (kN/m ³)	Undrained Shear Strength (kPa)	E50
API Sand	0 – 0.9	39	17.4	73,000	38	7660	-	-
API Sand	0.9 – 2.4	35	16.6	27,000	38	7660	-	-
Soft Clay	2.4 – 2.7	-	9.1	27,000	41	372	41	0.01
Soft Clay	2.7 – 3.7	-	9.1	140,000	50	450	50	0.01

Soft Clay	3.7 – 4.6	-	9.1	27,000	40	360	40	0.01
Sand	4.6 – 6.3	38	8.1	26,000	29	5743	-	-
Soft Clay	6.3 – 6.9	-	9.1	140,000	57	512	57	0.01
Soft Clay	6.9 – 7.4	-	9.1	27,000	25	225	25	0.01 5
Sand	8 – 18	33	6.7	150,000	23	4599	-	-

All piles had identical dimensions except for the center piles where strain gauges raised the moment of inertia and cross-sectional area. The pile properties are listed in Table 1-3. Bending moment in the pile was calculated at three pile head deflection values: 13 mm, 51 mm, and 25 mm.

Table 1-3: Pile and Loading Properties

Parameter	Value
Cross Section	Pipe
Outer Diameter	0.324 m
Wall Thickness	0.0095 m
Young's Modulus	200,000,000 kPa
Length	16.6 m
Load Point	0.48 m above ground level
Pile Head Deflections	13 mm, 25 mm, 51 mm
Moment of Inertia (center piles)	$1.43 \times 10^8 \text{ mm}^4$
Cross-Sectional Area (center piles)	$9.4 \times 10^3 \text{ mm}^2$
Pile Spacing (in loading direction)	1.83 m
Pile Spacing (perpendicular to loading direction)	1.07 m
Pile Head Connection	Pinned

Pile Cap Dimensions	Length: 4 m Width: 3 m Thickness: 1 m
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Table 1-4: P-multipliers Determined in Study

Row	P-Multiplier
Row 1 (leading)	1
Row 2 (middle)	0.7
Row 3 (trailing)	0.65

1.3 Results

RSPile predicted the experimental results accurately when the provided p-multipliers were used.

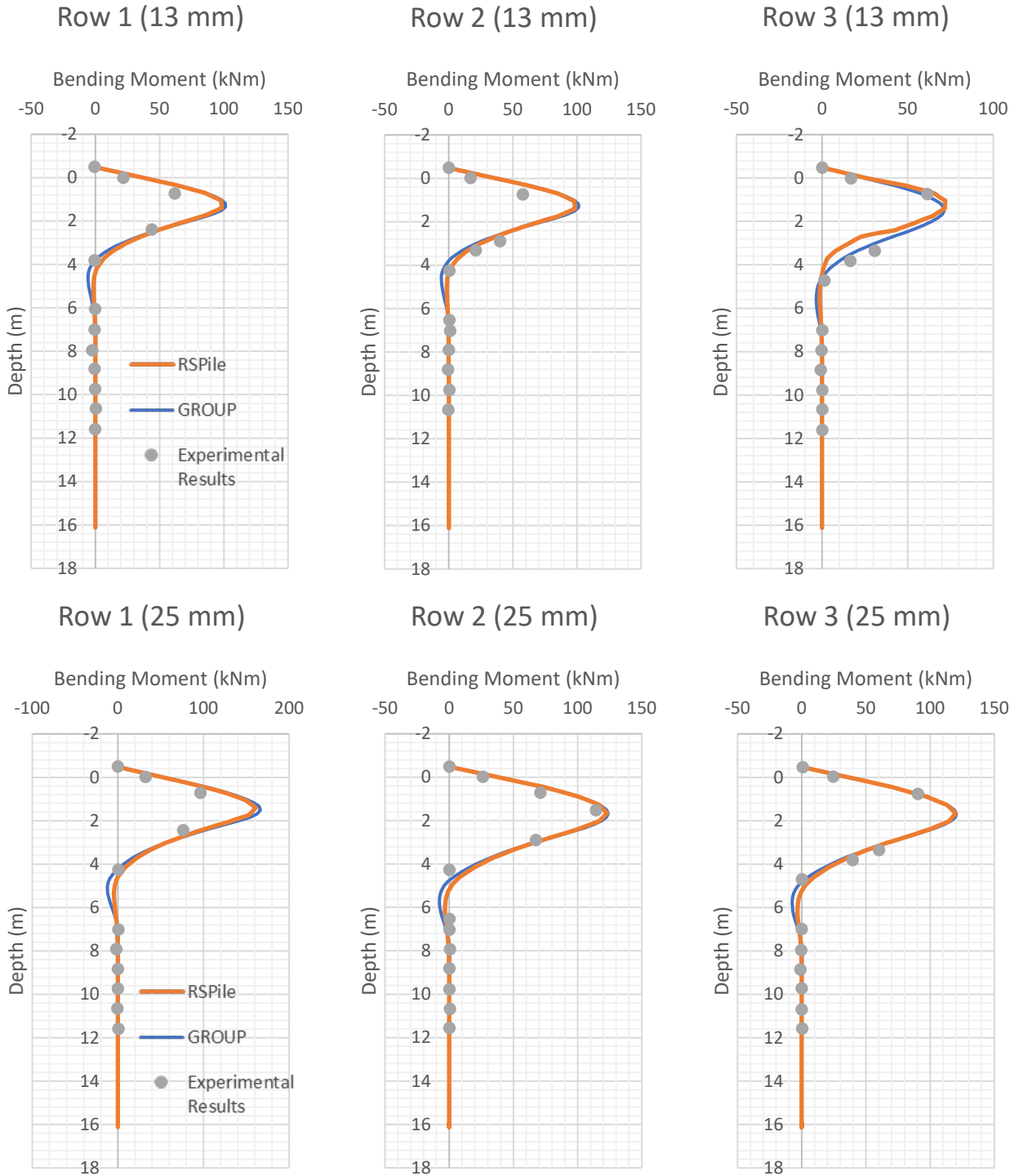


Figure 1-3: Comparison of the predicted and experimental bending moments in each row of piles at pile cap deflections of 13 mm and 25 mm. The p-multipliers provided in the article were used.

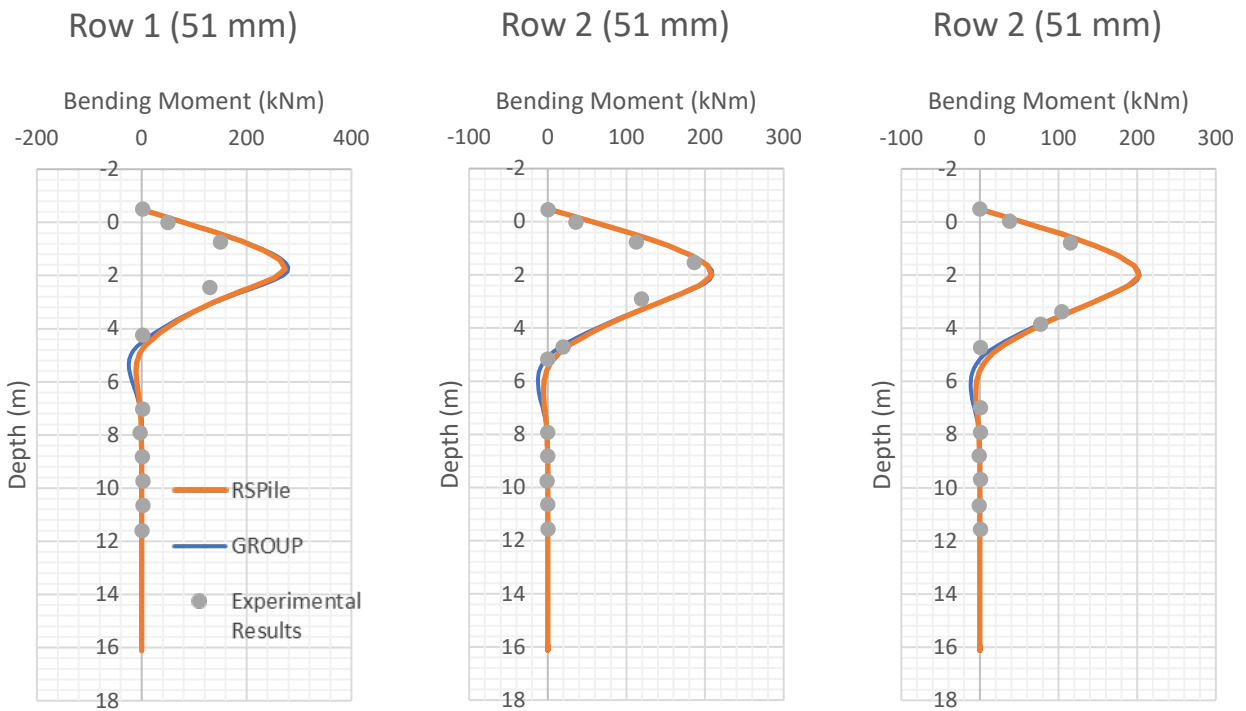


Figure 1-4: Comparison of the predicted and experimental bending moments in each row of piles at a pile cap deflection of 51 mm. P-multipliers provided in the article were used.

When p-multipliers generated automatically by each program are used, the results do not match the experimental results as closely.

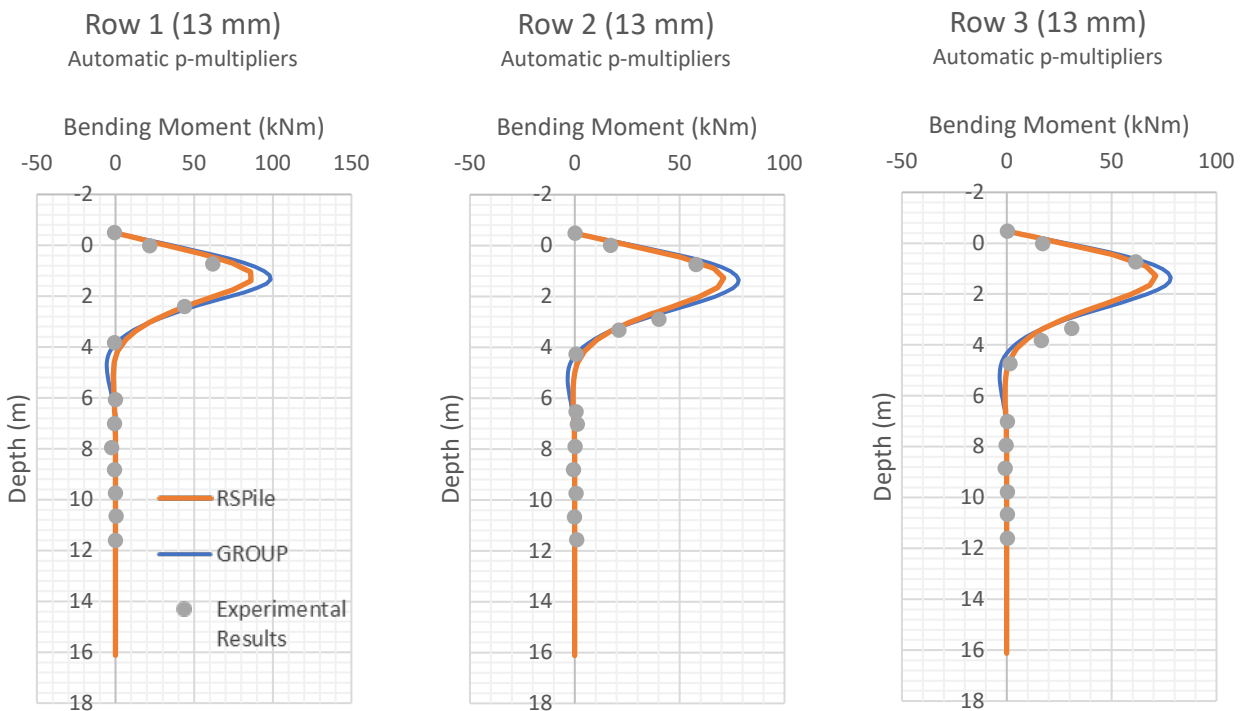


Figure 1-5: Comparison of the predicted and experimental bending moments in each row of piles at a pile cap deflection of 13 mm. P-multipliers generated automatically by *RSPile* were used.

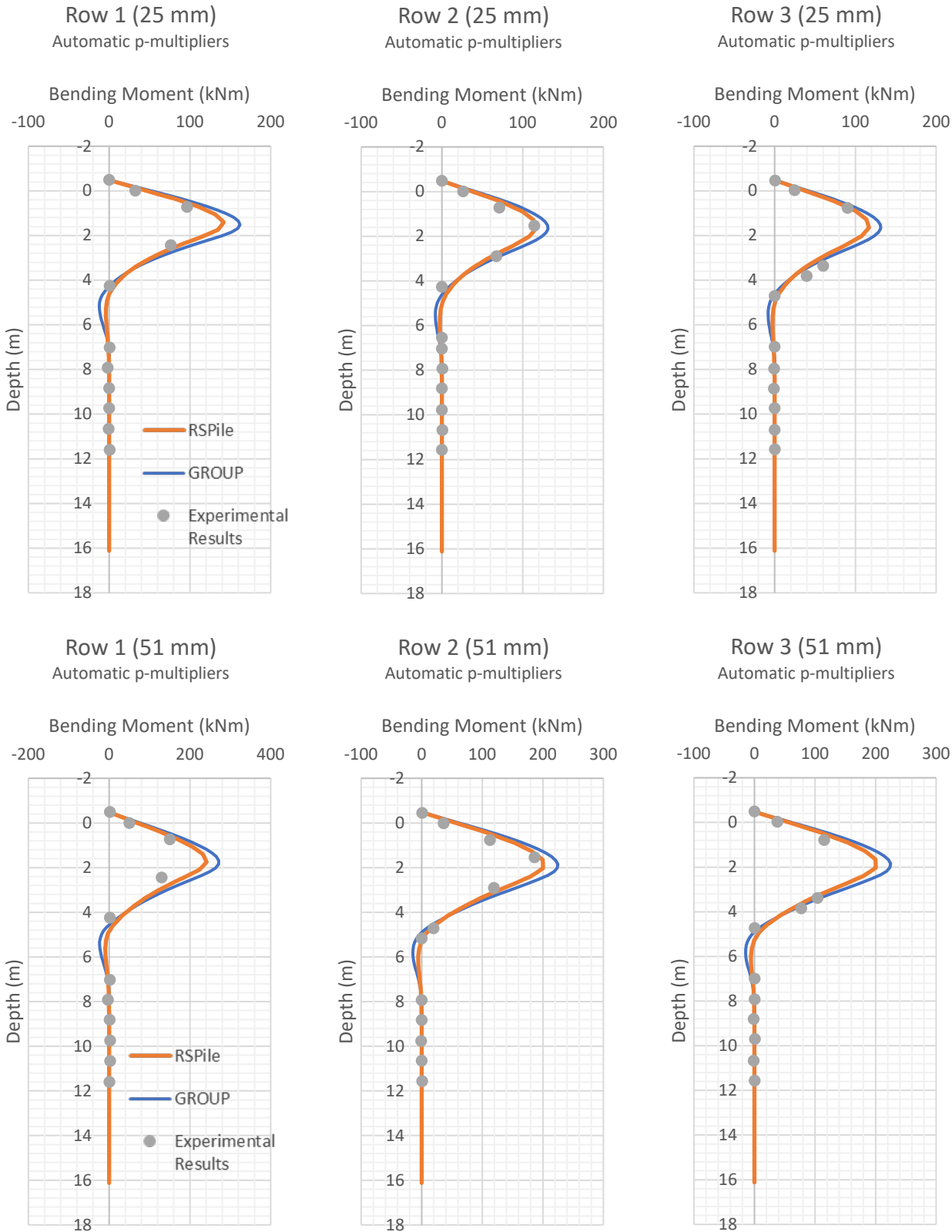


Figure 1-6: Comparison of the predicted and experimental bending moments in each row of piles at pile cap deflections of 25 mm and 51 mm.

RSPile Verification Problem #2

Full-Scale Lateral Load Test of a 3 x 5 Pile Group in Sand

2.1 Problem Description

This problem is based on Walsh (2005). This master’s thesis reports the results of an experimental lateral load test conducted at Brigham Young University. Computer analysis was used to model the test and determine accurate p-multipliers for laterally loaded piles in sandy soils. The soil properties used to model the test were calibrated using the results from a test of a single laterally loaded pile. The group pile test was then modelled using this soil profile and p-multipliers were used to match the computed results to the experimental results. The pile group is loaded in the positive Y’ axis (to the right when looking at the plan view).

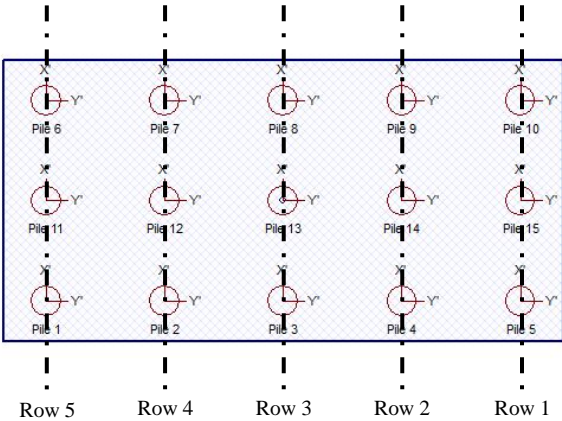


Figure 2-1: Plan View of RSPile Model

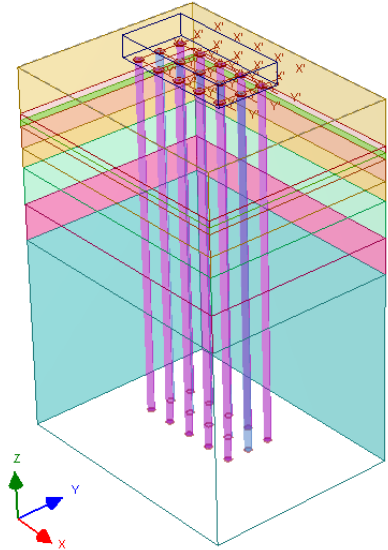


Figure 2-2: RSPile 3D Model

2.2 Material Properties

The soil properties of the system were modelled using the profile shown in Table 2-1. Pile dimensions and properties are shown in Table 2-2.

All piles had identical dimensions except for the center piles where strain gauges raised the moment of inertia and cross-sectional area values. The pile properties are listed in Table 1-3.

The bending moment in the pile was calculated at three pile head deflection values: 6 mm, 19 mm, and 38 mm.

Table 2-1: Soil Properties

Soil Model	Depth (m)	Friction Angle (Degrees)	Effective Unit Weight (kN/m ³)	Subgrade Modulus (kN/m ³)	Undrained Shear Strength (kPa)	E50
API Sand	0 – 2.1	40	16.7	75,000	-	-
API Sand Submerged	2.1 – 2.4	40	6.8	42,000	-	-
Submerged Stiff Clay	2.4 – 2.7	-	9.1	-	41	0.01
Submerged Stiff Clay	2.7 – 3.7	-	9.1	-	50	0.01
Submerged Stiff Clay	3.7 – 4.6	-	9.1	-	40	0.01
Sand	4.6 – 6.3	38	8.1	26,000	-	-
Submerged Stiff Clay	6.3 – 8	-	9.1	-	57	0.01
Sand	8 – 18	33	6.7	15,000	-	-

Table 2-2: Pile and Loading Properties

Parameter	Value
Cross Section	Pipe
Outer Diameter	0.324 m
Wall Thickness	0.0095 m
Young's Modulus	200,000,000 kPa
Length	16.6 m
Load Point	0.48 m above ground level
Applied Pile Head Deflections	6 mm, 19 mm, 38 mm
Moment of Inertia (center piles only)	$1.43 \times 10^8 \text{ mm}^4$

Cross-Sectional Area (center piles only)	9.4 x 10 ³ mm ²
Pile Spacing (in loading direction)	1.27 m
Pile Spacing (perpendicular to loading direction)	1.07 m
Pile Head Connection	Pinned
Pile Cap Dimensions	Length: 6 m Width: 3 m Thickness: 1 m
Pile Group Size	5 rows, 3 columns

Table 2-3: P-multipliers Determined in Study

Row	P-Multiplier
Row 1 (leading)	1
Row 2 (middle)	0.5
Row 3 (middle)	0.35
Row 4 (middle)	0.3
Row 5 (trailing)	0.4

2.3 Results

For all displacements, there was good agreement between *RSPile* and the experimental results reported in the study.

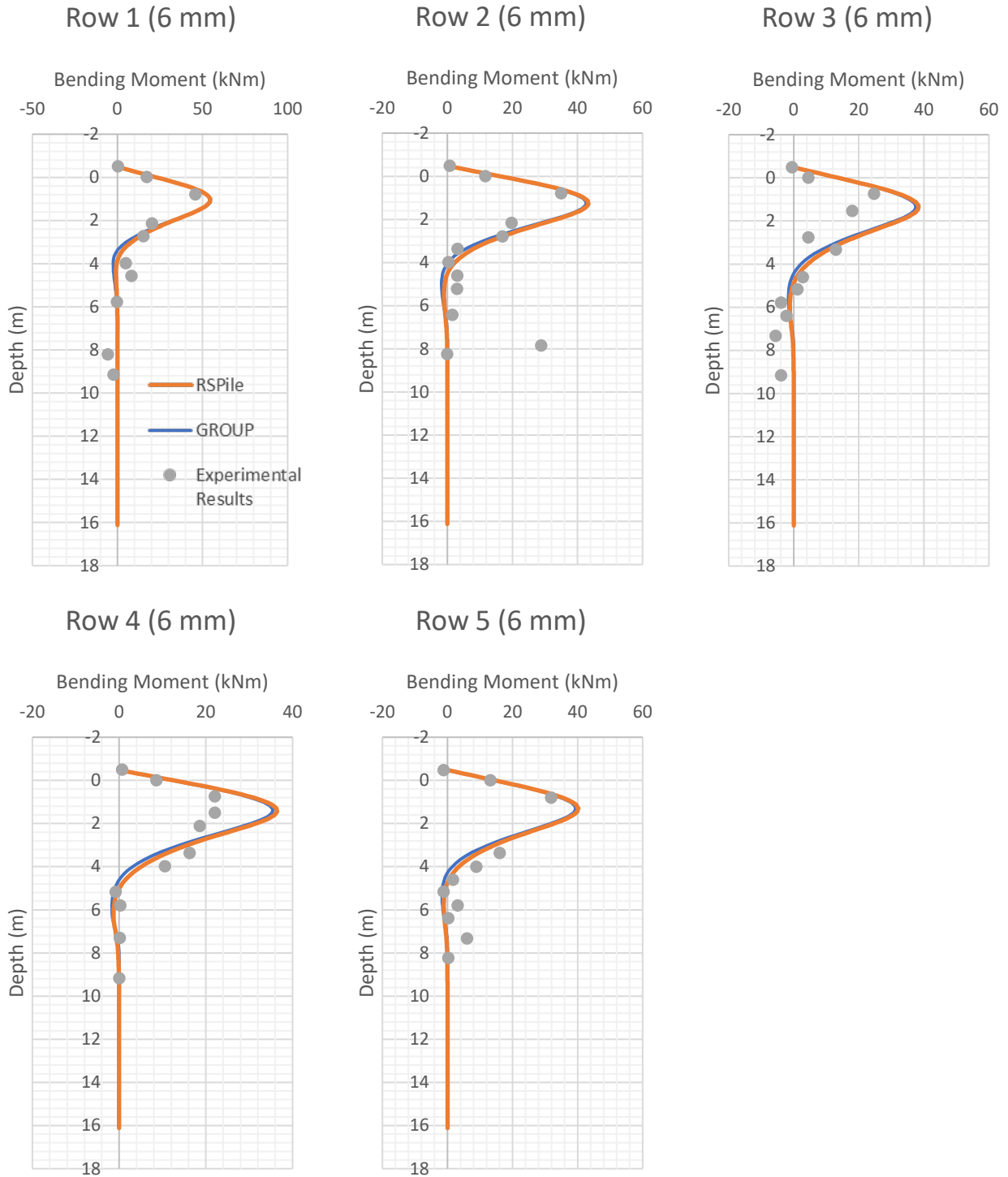


Figure 2-5: Comparison of the predicted and experimental bending moments in each row of piles at a pile cap deflection of 6 mm.

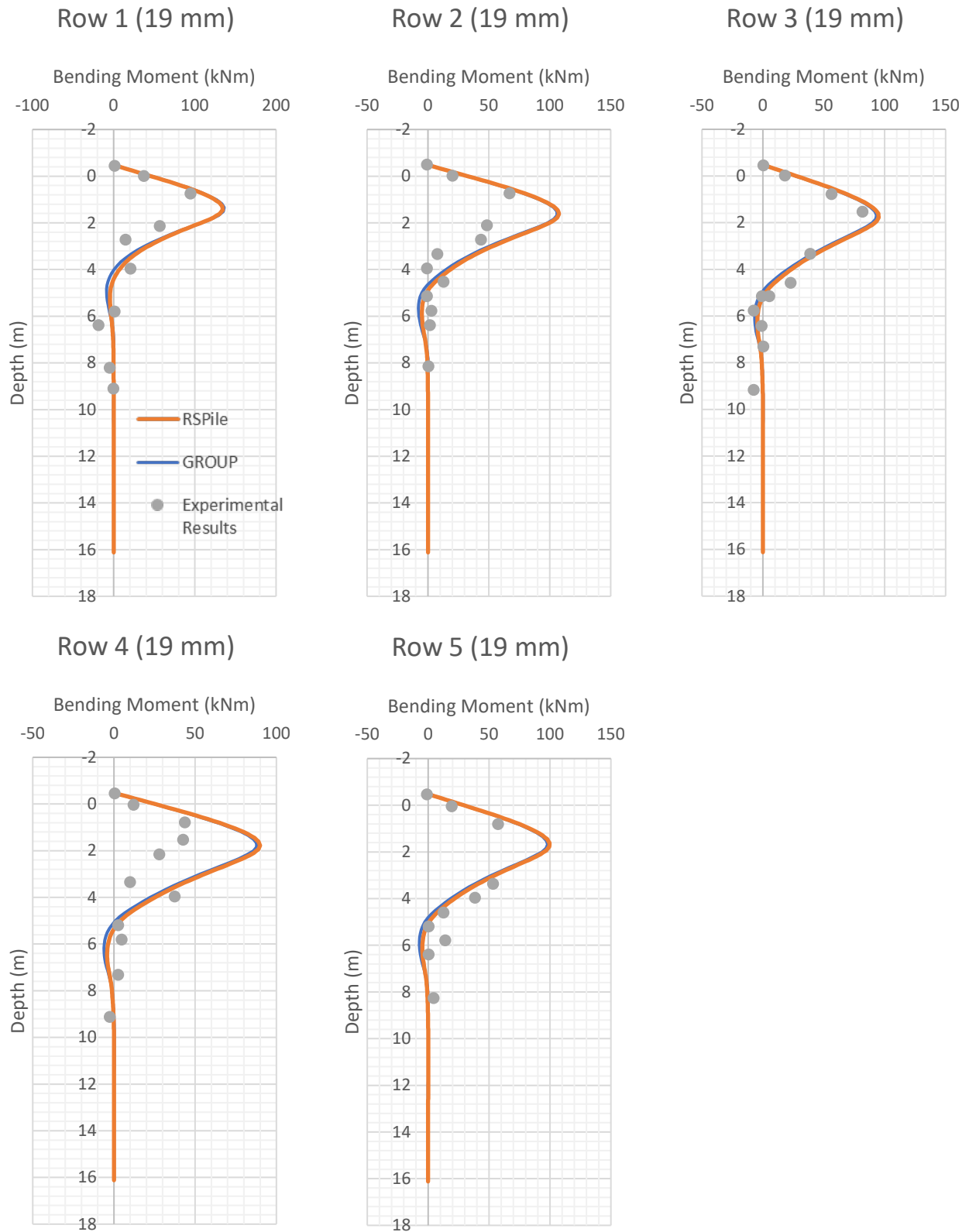


Figure 2-6: Comparison of the predicted and experimental bending moments in each row of piles at a pile cap deflection of 19 mm.

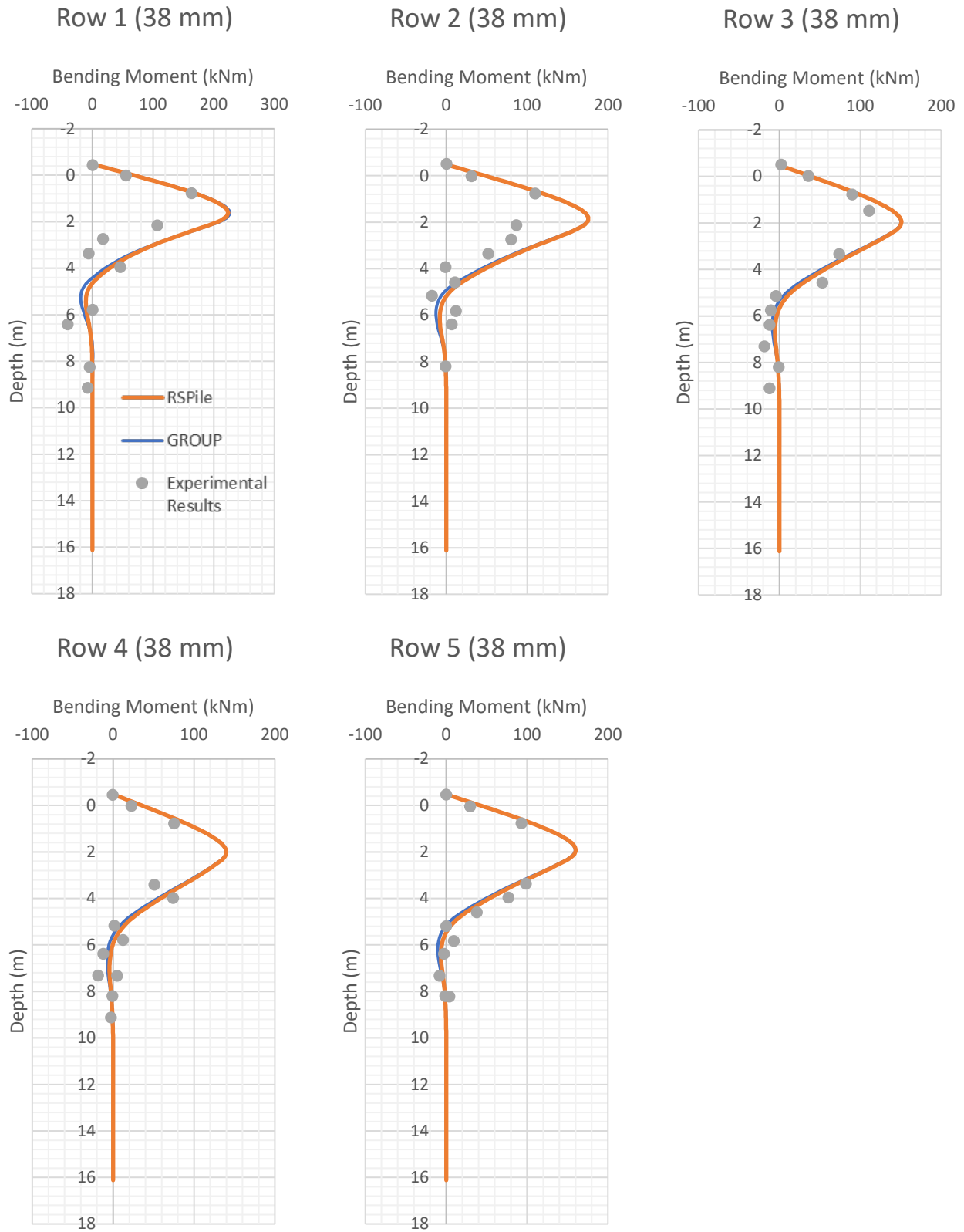


Figure 2-7: Comparison of the predicted and experimental bending moments in each row of piles at a pile cap deflection of 38 mm.

RSPile Verification Problem #3

Simulating Centrifuge Model Tests of Laterally Loaded Pile Groups in CDSM Improved Soft Clay Using a Nonlinear Winkler Model

3.1 Problem Description

This problem is based on Taghavi and Muraleetharan (2014). This technical paper describes a centrifuge test of a laterally loaded pile group. The paper tests the technique of cement deep soil mixing (CDSM), which is used to improve pile foundations to meet stricter seismic design criteria. CDSM can be used as a more cost-effective alternative to the addition of extra piles to a pile group.

Three different models were tested in the study: one model with a large CDSM block, one with a smaller CDSM block, and one with no CDSM block. There was insufficient information provided to model the pile groups with improved soils. Therefore, only the model with no CDSM block was modelled. The *RSPile* model can be seen in Figure 3-1, 3-2 and the pile group is loaded in the positive Y' axis (to the right when looking at the plan view).

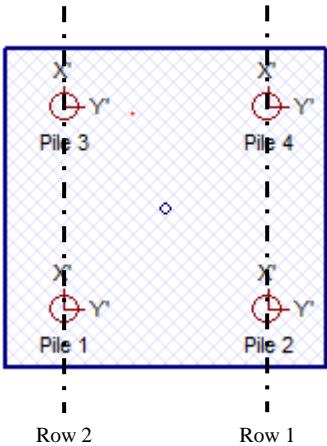


Figure 3-1: Plan View of *RSPile* Model

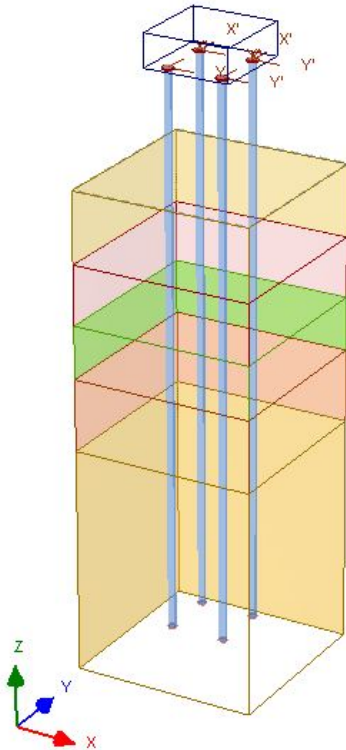


Figure 3-2: *RSPile* 3D Model

3.2 Material Properties

Table 3-1: Soil Profile

Soil Model	Depth (m)	Undrained Cohesion (kPa)	E50	Friction Angle (degrees)	Subgrade Modulus (kN/m ³)	Submerged Unit Weight (kN/m ³)
Soft Clay	0 – 2.58	Top: 4.26 Bottom: 5.41	0.02	-	8.14	8.18
Soft Clay	2.58 – 4.73	Top: 8.66 Bottom: 9.78	0.02	-	8.14	8.69
Soft Clay	4.73 – 6.64	Top: 13.92 Bottom: 14.9	0.02	-	8.14	9.05
Soft Clay	6.64 – 9.22	Top: 19.02 Bottom: 20.32	0.02	-	8.14	9.28
Sand	9.22 – 17.25	-	-	38	33.9	10.33

The centrifuge model was tested at an acceleration of 30g. Therefore, the model dimensions were multiplied by 30 to obtain the prototype dimensions. The prototype dimensions are listed in Table 3-3 below.

The pile group was loaded with a sinusoidal displacement time history. The bending moment in the pile was calculated at a pile head deflection of 45 mm.

Table 3-3: Pile and Loading Properties

Parameter	Value
Cross Section	Pipe
Outer Diameter	0.285 m
Wall Thickness	0.027 m
Young's Modulus	182,000,000 kPa
Length	19.998 m
Load Point	5.1 m above ground level
Applied Pile Head Deflections	45 mm

Pile Spacing (in loading direction)	1.995 m
Pile Spacing (perpendicular to loading direction)	1.995 m
Pile Cap Dimensions	Width: 3.135 m Length: 3.135 m Thickness: 1.2 m
Cap Elevation Above Ground	3.9 m
Pile Head Connection	Fixed
Pile Group Size	2 rows and 2 columns

3.3 Results

Due to the large pile spacing, there is very little observable reduction in soil resistance due to group effects. This is consistent with the results of experimental lateral load tests in soft clay soil. There is good agreement between *RSPile* and the experimental data.

Bending Moment vs Depth for All Rows (45 mm)

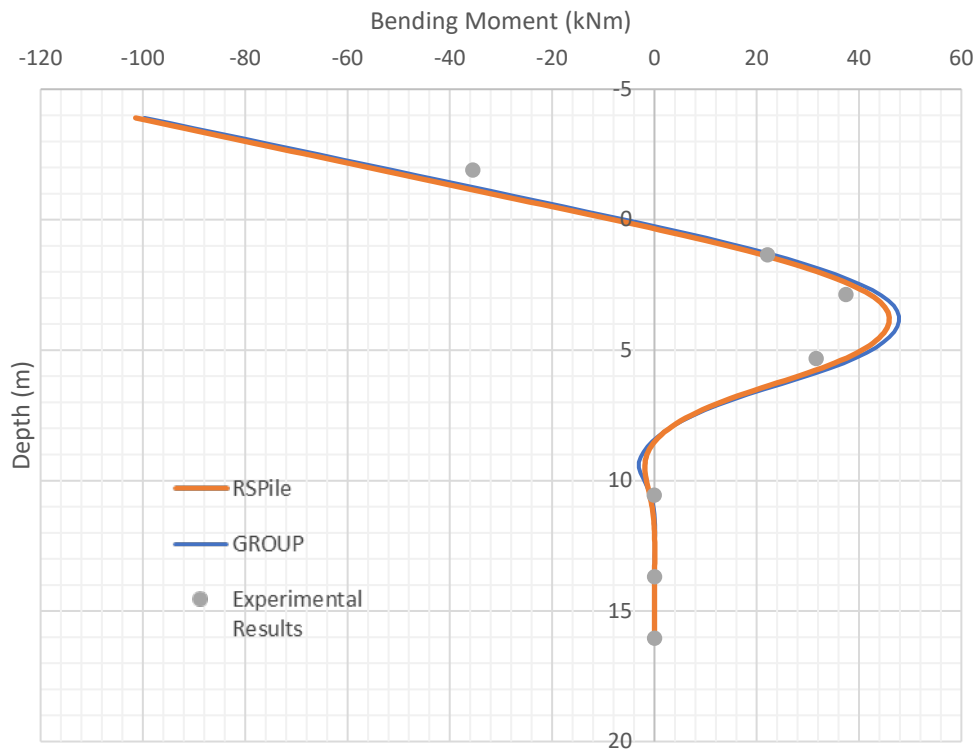


Figure 3-3: Comparison of the predicted and experimental bending moments in the pile group at a pile cap deflection of 45 mm. All rows had very similar results due to the small group effects.

RSPile Verification Problem #4

Response, Analysis, and Design of Pile Groups Subjected to Static and Dynamic Lateral Loads

4.1 Problem Description

This problem is taken from a report by Rollins et al. (2003) in which a 3 x 3 pile group was subjected to lateral loading to determine effective p multipliers for the arrangement. Loading is in the positive Y' direction (to the right when looking at the plan view).

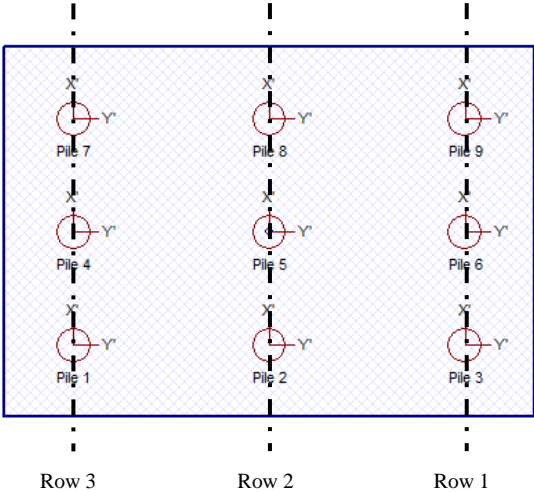


Figure 4-1: Plan view of RSPile model

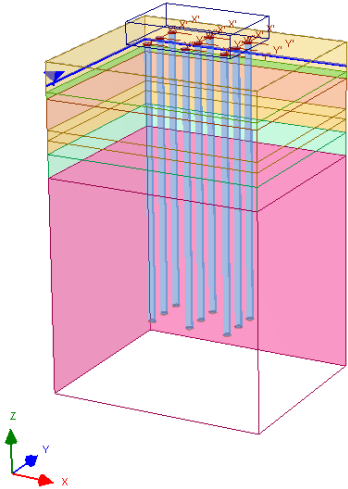


Figure 4-2: 3D view of RSPile model

4.2 Material Properties

For the RSPile model used in this verification, the soil properties of the system were taken as the profile shown below in Table 4-1.

All piles had identical dimensions which are listed in Table 4-2.

The bending moment in the pile was calculated at a pile cap load of 1420 kN.

Table 4-1: Soil Properties

Soil Model	Depth (m)	Friction Angle (Degrees)	Effective Unit Weight (kN/m ³)	Subgrade Modulus (kN/m ³)	Undrained Shear Strength (kPa)	E50
Submerged Stiff Clay	0 - 1.34	-	14.9	-	70	0.005
Sand	1.34 – 1.65	36	16.18*	26,000	-	-
Submerged Stiff Clay	1.65 – 3.02	-	16.5	-	105	0.005
Sand	3.02 – 3.48	36	16.18*	26,000	-	-
Submerged Stiff Clay	3.48 – 4.09	-	16.5	-	105	0.005
Sand	4.09 -5.15	38	16.18*	30,000	-	-
Soft Clay Soil	5.15 – 9.8	-	14.9	-	35	0.01
Submerged Stiff Clay	9.8 – 15	-	16.5	-	105	0.005

*Values not specified in the study, assumed in model.

**The water table was defined at a depth of 1.07 m and saturated unit weights were assumed by *RSPile*'s standard charts.

Table 4-2: Pile and Loading Properties

Parameter	Value
Cross Section	Pipe
Outer Diameter	0.324 m
Wall Thickness	0.0127 m
Young's Modulus	200,000,000 kPa
Length	12.59 m
Load Point	0.39 m above ground level
Applied Pile Cap Load	1420 kN

<p> Pile Spacing (in loading direction) </p>	<p> 1.83 m </p>
<p> Pile Spacing (perpendicular to loading direction) </p>	<p> 1.07 m </p>
<p> Pile Cap Dimensions </p>	<p> Length: 5 m Width: 5 m Thickness: 1 m </p>
<p> Pile Group Size </p>	<p> 3 rows, 3 columns </p>

Table 4-3: Group Effect P-multipliers

Row	P-Multiplier
Row 1 (leading)	0.94
Row 2 (middle)	0.88
Row 3 (trailing)	0.77

4.3 Results

The graph below illustrates good agreement between *RSPile* and study data with regards to pile cap deflection and total group load.

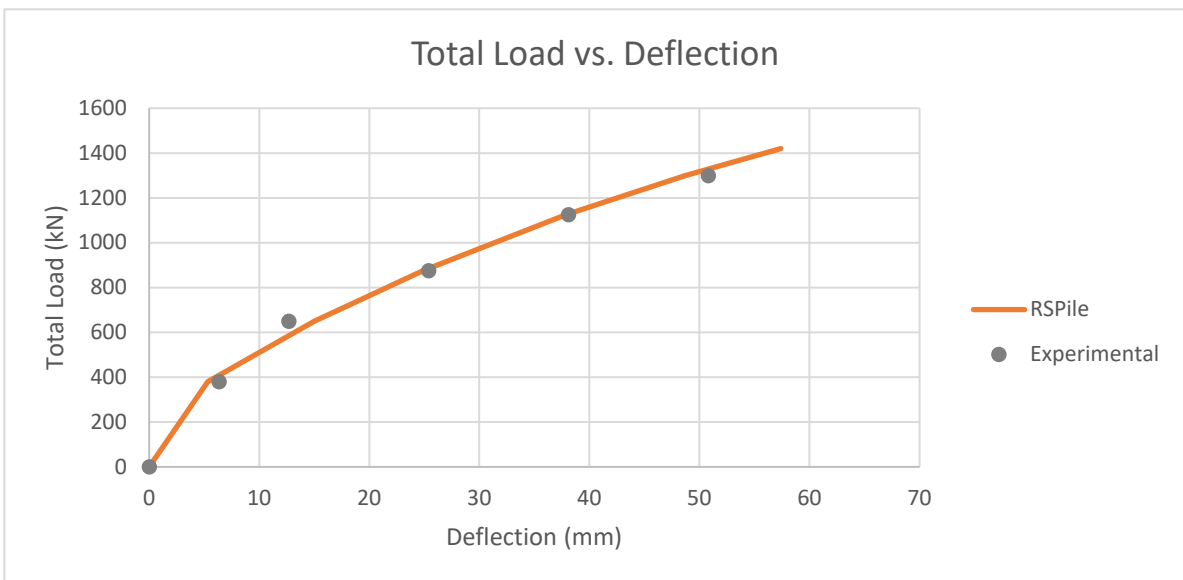


Figure 4-3: Comparison of the predicted and experimental pile cap load vs deflection curves for the pile group.

The following bending moment vs depth graphs are representative of the maximum load applied in the experiment (1420 kN). Results from *RSPile* are compared with study results.

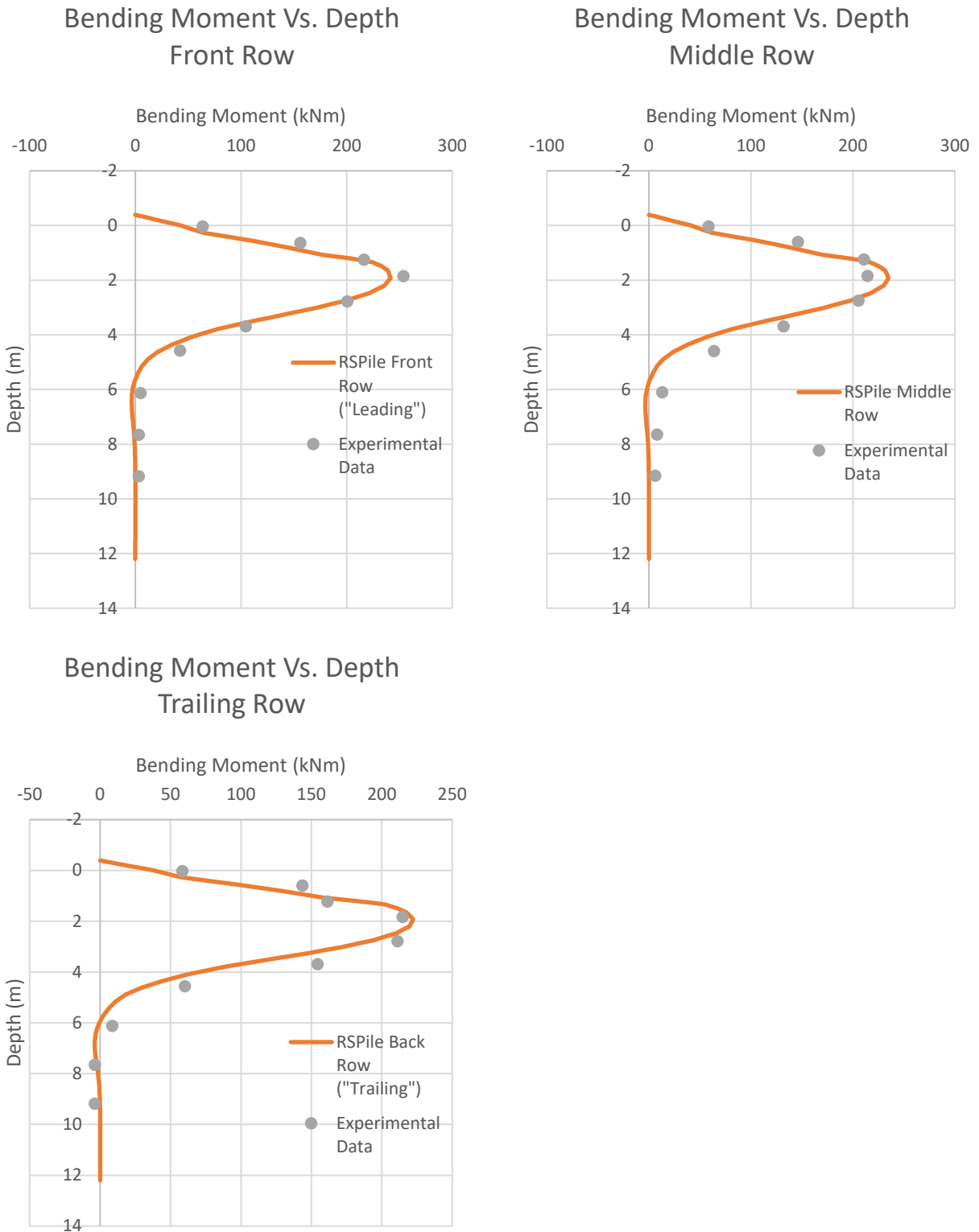


Figure 4-4: Comparison of the predicted and experimental bending moments in each row of piles at a pile cap load of 1420 kN.

The following graphs display maximum bending moment for various displacements.

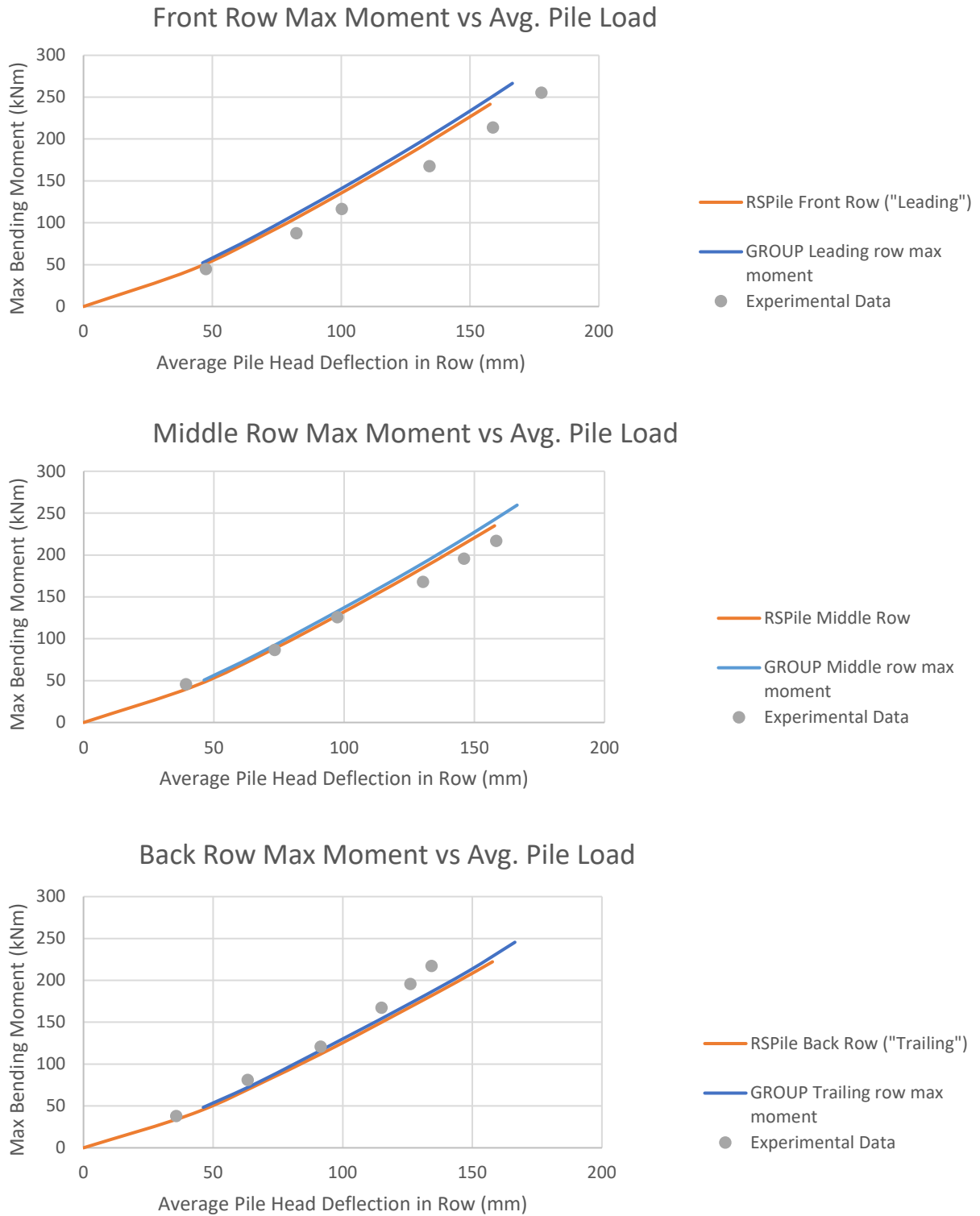


Figure 4-5: Comparison of the predicted and experimental maximum bending moment in each row of piles at different pile head deflections.

RSPile Verification Problem #5

Pile Spacing Effects on Lateral Pile Group Behaviour: Analysis

5.1 Problem Description

This problem was taken from Rollins, Olsen, Jensen, et. al (2006). This study analyzed the results of full scale tests of pile groups of varying configurations to determine p multipliers for each row of piles. Each case was then modelled using computer software to determine if the computed results matched the measured results once the p multipliers were applied. The case of a 3x3 pile group was used for this problem. The difference in appearance of model centre piles is due to the adjusted moment of inertia (Table 5-2). Loading is in the Y' direction (to the right when looking at the plan view)

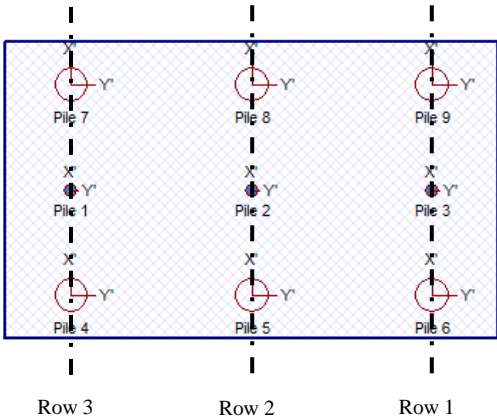


Figure 5-1: Plan view of RSPile model

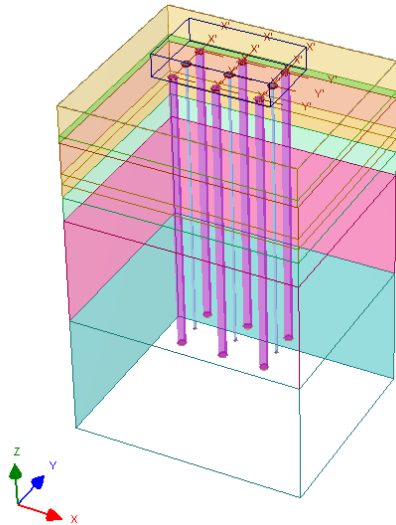


Figure 5-2: 3D view of RSPile model

5.2 Material Properties

Table 5-1: Soil Profile

Soil Model	Depth (m)	Unit Weight (kN/m ³)	E50	Friction Angle (degrees)	Subgrade Modulus (kN/m ³)	Undrained Shear Strength (kPa)
Dry Stiff Clay	0 – 1.34	14.9	0.005	-	136,000	70
Sand	1.34 – 1.65	16.18*	-	36	26,000	-
Dry Stiff Clay	1.65 – 3.02	16.5	0.005	-	271,000	105
Sand	3.02 – 3.48	16.18*	-	36	26,000	-
Dry Stiff Clay	3.48 – 4.09	16.5	0.005	-	271,000	105
Sand	4.09 – 5.15	16.18*	-	38	30,000	-
Soft Clay	5.15 – 9.8	14.9	0.01	-	27,000	35
Dry Stiff Clay	9.8 – 15	16.5	0.005	-	271,000	105

*Values not specified in the study, assumed in model.

Table 5-2: Pile and Loading Properties

Parameter	Value
Cross Section	Pipe
Outer Diameter	0.324 m
Wall Thickness	0.0095 m
Moment of Inertia (center piles only)	$1.43 \times 10^8 \text{ mm}^4$
Cross-Sectional Area (center piles only)	0.01 m^2
Young's Modulus	200,000,000 kPa*

Length	12.28 m
Load Point	0.38 m above ground level
Applied Pile Head Deflections	64 mm
Pile Spacing (in loading direction)	1.8306 m
Pile Spacing (perpendicular to loading direction)	1.0692 m
Pile Cap Dimensions	Length: 5 m Width: 3 m Thickness: 1 m
Pile Group Size	3 rows, 3 columns

*Values not specified in the study, assumed in model.

Table 5-3: Group Effect P-multipliers

Row	P-Multiplier
Row 1 (leading)	0.95
Row 2 (middle)	0.88
Row 3 (trailing)	0.77

5.3 Results

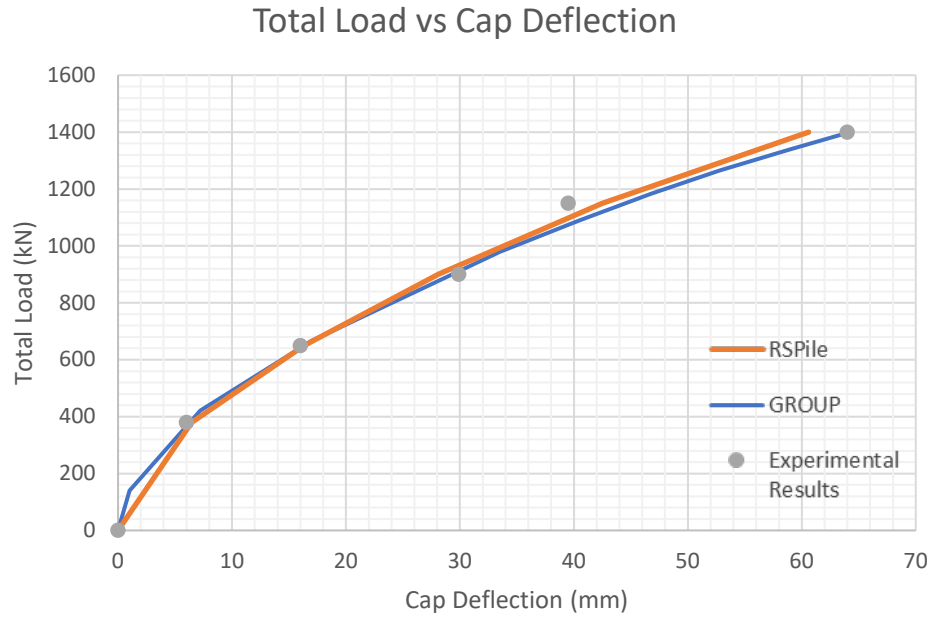


Figure 5-3: Comparison of the predicted and experimental pile cap load vs deflection curves for the pile group.

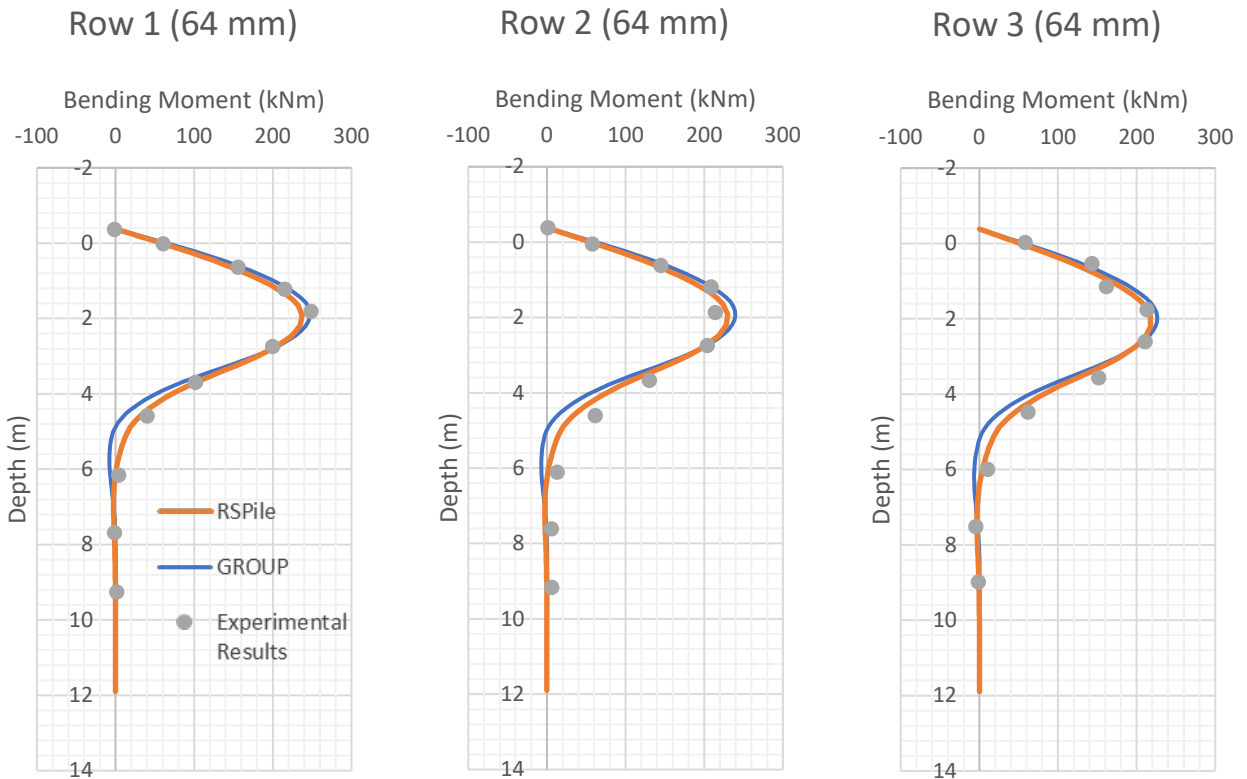


Figure 5-2: Comparison of the predicted and experimental bending moments in each row of piles at a pile cap deflection of 64 mm.

References

1. Christensen, D. (2006), "Full Scale Static Lateral Load Test of a 9 Pile Group in Sand." BYU Scholars Archive
2. Walsh, J. (2005), "Full-Scale Lateral Load Test of a 3x5 Pile Group in Sand." BYU Scholars Archive
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