A Comparative Analysis of a Laterally Loaded Pile Group Using Different Software

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Abstract. This paper presents a comparative analysis of a laterally loaded pile group using the computer programs PIGLET, RSPile and RS3. To enable the construction of a new road by-pass, a 24-inch diameter watermain serving 10,000 residents needed to be diverted. The diversion alignment generated out of balance horizontal forces within the pipe requiring a thrust block to resist these forces. Due to site constraints, the thrust block was located in an area of weak alluvial and tidal flat deposits necessitating a piled foundation. To help develop a robust and cost-effective pile group design, a comparative study using three different commercial computer programs was undertaken. Some pros and cons of the three programs are discussed and the results are compared.

Keywords: PIGLET · RSPile · RS3 · pile · pile group

1 Introduction

From time to time the Geotechnical Engineer is called upon to design pile groups where interaction between the piles can influence the forces generated in the individual piles. Pile group design must therefore incorporate such interaction effects and nowadays the designer has recourse to a choice of commercially available computer programs to carry out these complex calculations. In the commercial design environment, the pile group design process must provide reliable results in a time- and cost-efficient manner.

Important factors to consider when deciding what software to use include the following.

- The reliability and transparency of the software in implementing well documented calculation methods incorporating all necessary interaction effects.
- Transparency of input parameters and results to allow for third party checking.
- Use with standard geotechnical parameters from routine ground investigation.
- Flexibility in respect of different pile arrangements and load cases for efficient optioneering to identify the most economic design.
- Ease of learning and use.

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2 Design Problem

A plan describing the geometry of the pile group and pile cap is shown on Fig. 1. The pile cap is rectangular in plan with side dimensions of 4.9 m × 7.4 m and a thickness of 1.58 m. The base of pile cap is 2.4 m below ground level (BGL).

The pile group consists of eight, 16.5m long, 600 mm diameter piles installed vertically with a pile cutoff level (PCOL) at 2.4 m BGL and full rotational fixity into the pile cap. The piles therefore extend 14.1 m below the pile cap base.

2.1 Loading

The working loads applied to the pile cap comprised a 2,420 kN vertical point load and a 400 kN horizontal point load together with a moment of 440 kNm. These resultant loads were all applied at the geometrical centroid of the pile cap at the PCOL.

2.2 Ground and Groundwater Conditions

Beneath a thin mantle of topsoil, the site is underlain by a succession of loose alluvial sand, glacio-fluvial sand and predominantly fine-grained glacial till. The ground stratigraphy adopted for design is summarized in Table 1.

The groundwater regime is hydrostatic with a phreatic surface at a depth of 0.3 m BGL.

2.3 Geotechnical Design Parameters

The characteristic geotechnical parameters were derived from the ground investigation data and are summarized in Table 2.

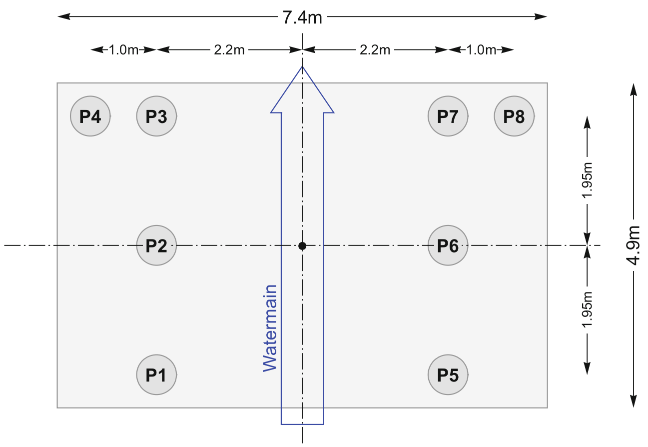


Fig. 1. Plan showing pile group and pile cap geometry

Table 1 Design stratigraphy

Stratum Name	**Depth (m BGL)**	**Description**
Sand 1a	0.0 - 5.2	Very loose to loose silty SAND. *Tidal Flat Deposits*
Sand 1b	5.2 - 8.0	Loose becoming medium dense silty SAND. *Tidal Flat Deposits.*
Sand 2	8.0 - 13.0	Loose to medium dense clayey SAND. *Glacio-fluvial Sand.*
Till 1	13.0 - 24.0 +	Very stiff gravelly CLAY. *Glacial Till.*

3 Modelling

3.1 Piglet

PIGLET is an Excel-based program that analyses the load deformation response of pile groups under general loading regimes. The program incorporates a number of approximate, but compact, solutions for the response of single and 3D groups of piles to axial, torsional and lateral loading, with automatic allowance for the effects of interaction between piles in the group. The soil and the piles are modelled as a linear elastic material and the soil stiffness can either be constant or vary linearly with depth. The pile cap is assumed to be rigid and piles are modeled as either pinned or built-in to the cap. All applied loads go into the piles with no support from the ground at the underside of the pile cap.

The soil stiffness is characterized by an elastic shear modulus, G, and Poisson's ratio, ν, and the pile stiffness by a Young's modulus and pile geometry. A limitation of PIGLET is that individual strata with different shear moduli can not be discretely modeled.

The input parameters adopted for the PIGLET analysis are shown in Table 2.

PIGLET allows the independent treatment of axial and lateral response. In accordance with guidance given in [1], the horizontal ground stiffness was set to half that of the vertical stiffness to allow for the high lateral strains that occur in the soil close to the pile.

3.2 RSPile

RSPile models the piles using beam finite elements with vertical and horizontal components of soil resistance represented at discrete points along the piles' embedded lengths by t-z and p-y springs respectively. Different t-z and p-y springs can be specified for each soil stratum such that any variation in soil stiffness and/or strength with depth may be modelled. Table 2 shows some key input parameters and the soil/spring models used. Further details on the soil/spring models can be found in RSPile's online documentation [2].

By default, RSPile assumes that the piles are spaced far enough apart to render pile-soil-pile interaction effects insignificant. Such interactions can, however, be accounted for by specifying multipliers for the soil resistance curves. RSPile provides an option to automatically calculate interaction multipliers for horizontal p-y curves and that option was used for the work presented here. Interaction factors for vertical t-z curves, however, must be specified manually for individual piles and were not used for this study.

Like PIGLET, RSPile assumes that the pile cap is rigid with no direct transfer of load into the ground. Piles can be modeled with pinned, restrained or full moment connections to the pile cap. Full moment connections were used for the work presented here.

3.3 Rs3

RS3 is a three-dimensional finite element program for ground engineering modelling and is the most sophisticated of the three programs used in this study. It can represent simple to complex 3D geometries and includes a wide range of material models together with joints to simulate interface characteristics at soil-structure discontinuities. Provided representative material models and parameters are used, RS3 should therefore be able to capture the key behavioral characteristics of the laterally loaded pile group.

The RS3 model of the pile group is shown on Fig. 3. Due to the symmetrical nature of the pile group and loading regime only half of the pile group needed to be modelled (namely, piles 1 to 4 in Fig. 1). The half-model was discretized using 677,819 ten-node tetrahedral elements with edge dimensions increasing from 0.1 m at the piles to 1.0 m at the model boundary. The piles and the pile cap were modelled as linear elastic material and the soil strata were modelled as elastic-perfectly-plastic material with a Mohr-Coulomb yield surface. Material parameters were based on the geotechnical parameters given in Table 2. The piles were assumed fully bonded to the soil (Fig. 2).

To replicate assumptions inherent in the PIGLET and RSPile models, the RS3 model incorporates an effectively rigid pile cap and a small (0.1 m high) air gap between the pile cap base and underlying formation soils (to prevent load transfer).

The RS3 analysis was performed in the following three stages: (1) initialize the in-situ effective stress field; (2) construct the pile group and apply the vertical load; and (3) apply the horizontal load and moment.

4 Results of Analyses

4.1 Pile Displacements and Forces

Computed pile displacements and forces from the three analyses are compared on Fig. 3 with the maximum values of displacement and pile forces compared in Tables 3 and 4. It should be noted that the pile displacements given by PIGLET (as plotted on Fig. 3) are relative soil-pile displacements, not absolute pile displacements: the pile displacements derived from PIGLET are therefore not directly comparable with the displacements from RSPile and RS3. The PIGLET pile cap displacements reported in Table 3, however, are absolute values.

4.2 Pile Shadowing

The locations of yielded soil elements from the RS3 analysis are shown on Fig. 4. This visualization indicates that the in-situ horizontal earth pressures reduce to active pressures over the top 6 to 7 m of pile (a length of about 10 pile diameters). However, passive earth pressures are not mobilized in front of the piles where the soil remains in an elastic state. This is consistent with the PIGLET assumption that the resisting soil (and piles) remains effectively within the elastic range.

Figure 4 also indicates that the development of active earth pressure zones at the rear of piles 2 and 3, and to a lesser extent at Pile 4, is suppressed by compressive (passive) pressures induced by the piles behind them moving forwards. These observations highlight one of the benefits arising from the additional effort required to model the problem in RS3: namely, complex mechanisms that are assumed and represented by idealized models in the other programs are inherently captured by RS3 and can be visualized.

5 Comparison and Discussion of Results

5.1 Horizontal Pile Deflections

Figure 3(a) shows that horizontal pile deflections from RSPile and RS3 are comparable in magnitude and distribution with depth. Whilst the relative pile deflections given by PIGLET are not directly comparable to the RSPile and RS3 results, the shape of curvature is similar. The PIGLET results terminate at the calculated critical depth (approximately 8.7 mBGL), which compares well with the attenuation of deflection given by RSPile. In contrast, the RS3 results show appreciable deflections extending to greater depth. The reason for this difference has not been investigated. However, it is probably due to the continuum nature of the RS3 model and could likely be addressed by increasing the soil stiffness values to reflect the reduction in soil shear strain magnitudes with increasing depth. These larger lateral displacements at depth are probably not important in practical terms as they do not appear to significantly affect the pile bending moments or shear forces (when compared to the forces given by PIGLET and RSPile).

RSPile and RS3 both give 2.4 mm of horizontal displacement at the pile cap whereas PIGLET gives 4.0 mm. The almost exact match between RSPile and RS3 is surprising given the different calculation models and is probably somewhat fortuitous. Whilst the PIGLET displacement is around 67% greater than RSPile and RS3, the difference is just 1.6 mm so is inconsequential in practical terms.

5.2 Pile Bending Moments and Shear Forces

Figure 3 shows that despite their different levels of sophistication, all three programs give reasonably similar pile bending moment and shear force distributions. The maximum force values summarized in Table 4 are also reasonably similar, varying by only around 13 to 19%. Based on these results, the amount of steel reinforcement in the piles would be the same whichever analysis software was used.

One point to note is that RSPile and RS3 give appreciable bending moments and shear forces extending below the PIGLET critical depth of 8.7 m. The critical depth given by PIGLET may be a consequence of the simplified stiffness profile adopted for the PIGLET analysis, a feature that may not always adequately capture the influence of soil layering and associated stiffness variations.

6 Conclusions

The purpose of this paper was to provide a comparative study of a real-life pile group design using three different commercially available computer programs. Whilst the three programs gave different results, the differences are very modest and do not affect the amount of steel reinforcement in the piles. Given the varying sophistication levels of the calculation models implemented in the three programs, this is an encouraging finding. It serves to verify the results of each program and suggests that simple models can provide results that are adequate in a commercial design environment. However, these conclusions are not generally applicable and the suitability of any software must be critically assessed on a case-by-case basis.

Some of the pros and cons that the authors (subjectively) consider apply to each program are summarised in Table 5.

The key conclusions emerging from this study are summarized as follows.

- PIGLET is likely to be adequate for many routine design situations, including initial/preliminary analysis and optioneering. The approximate formulation of pile forces may warrant additional margins of safety being applied to the design outputs which, in practical terms, are unlikely to significantly affect the sizing or structural design of pile groups.
- RSPile can provide greater flexibility than PIGLET, but its use is less time-efficient, especially at the optioneering stage. RSPile is therefore probably best suited to cases where the simplifying assumptions of PIGLET invalidate the results or to check a final design.
- RS3 is not advocated for routine design, but does have a place in modelling particularly complex design problems or in verifying results given by other methods/programs.
- If time and budget permits, it will always be beneficial to check the results of any analysis using alternative methods.
- Irrespective of which program is used, it is essential to select appropriate input parameters and to critically evaluate the outputs. In this context, the importance of experience and engineering judgement is paramount.

References

1. Randolph, M. F.: PIGLET, Analysis and Design of Pile Groups. Version 6.2. (August 2021).
2. Rocscience, RSPile online documentation, https://www.rocscience.com/help/rspile.

Table 2 Ground parameters

	Pile Cap	**Piles**	**Sand 1a**	**Sand 1b**	**Sand 2**	**Till 1**
Depth range (m BGL)	0.9–2.4	2.4–16.5	2.4–5.2	5.2–8.0	8–13	13–24
Weight density, γ (kN/m^3)	24	24	17	17	18	19
Young's modulus, E (MPa)	30×10^3	30×10^3	-	-	-	-
Shear modulus at small strain, G_o (MPa) §1	-	-	5.0	22.5	80.0	80.0
Change of G_o with depth, dG_o/dz (MPa/m)	-	-	6.25	6.25	-	-
Poisson's ratio, ν	0.15	0.15	0.3	0.3	0.3	0.3
Effective cohesion, c' (kPa)	-	-	0	0	0	-
Effective friction angle, ϕ' (°)	-	-	29.5	30.5	35.0	-
Undrained shear strength, c_u (kPa) §1	-	-	-	-	-	170
Change of c_u with depth, dc_u/dz (kPa/m)	-	-	-	-	-	11.8
PIGLET						
Axial shear modulus, G_{axial} (MPa) §1	-	-	2.0	9.0	32.0	32.0
Change of G_{axial} with depth, dG_{axial}/dz (MPa/m)	-	-	2.5	2.5	-	-
Lateral shear modulus, G_{lat} (MPa) §1	-	-	1.0	3.5	16.0	16.0
Change of G_{lat} with depth, dG_{lat}/dz (MPa/m)	-	-	1.25	1.25	-	-
RSPile						
Soil model, Axial	-	-	Drilled Sand	Drilled Sand	Drilled Sand	Drilled Clay

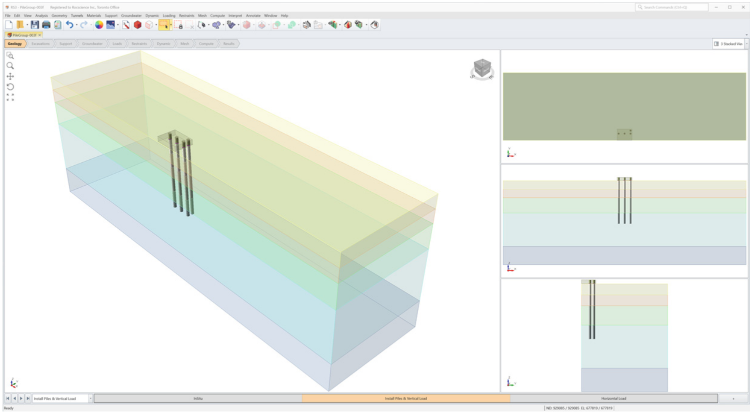
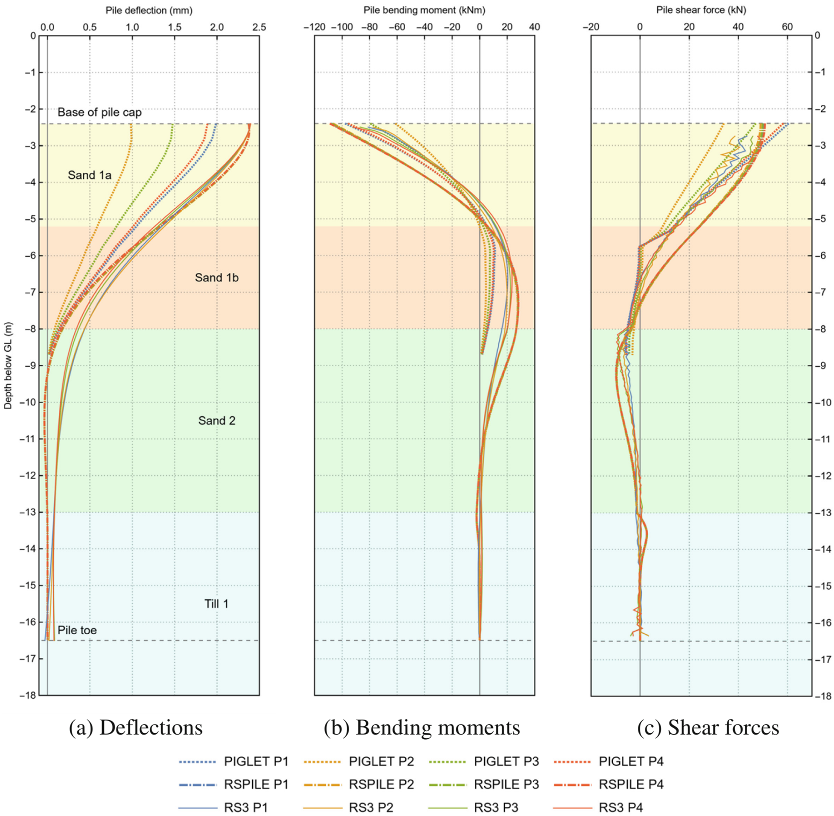


Fig. 2. The RS3 model showing the (half) pile group and soil layers.



(a) Deflections (b) Bending moments (c) Shear forces

Fig. 3. Pile deflection and force profiles

Table 3. Comparison of pile cap displacements, (x) – pile number

	PIGLET		**RSPILE**		**RS3**	
	Min	Max	Min	Max	Min	Max
Vertical, δ_z (mm)	-	3.8	-	1.0	1.4 (1)	1.6 (3)
Horizontal, δ_x (mm)	-	4.0	-	2.4	-	2.4

Table 4. Comparison of pile forces (x) – Pile Number

	PIGLET		**RSPILE**		**RS3**	
	Min	Max	Min	Max	Min	Max
Moment, M (kNm)	61.3 (2)	97.9 (1)	106.6 (2)	108.9 (4)	77.4 (2)	92.1 (4)
Shear force, V (kN)	34.6 (2)	60.4 (1)	49.0 (2)	50.8 (4)	40.5 (2)	49.2 (4)
Axial force, N (kN)	221.8 (2)	371.3 (4)	243.8 (3&4)	399.3 (1)	286.8 (2)	(1)

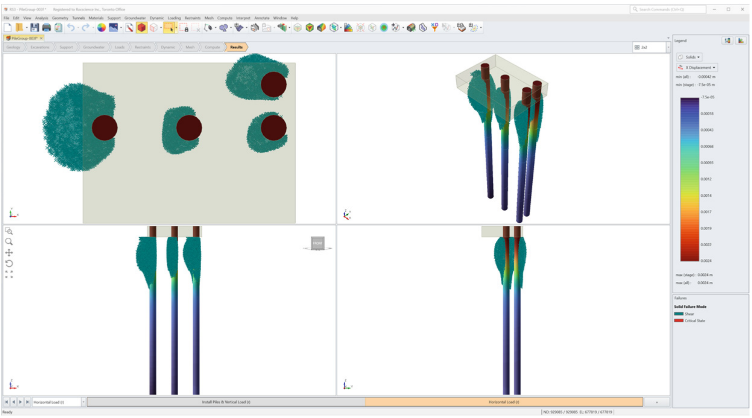


Fig. 4. Locations of yielded elements

Table 5. Some pros and cons of the three programs

	PIGLET	**RSPile**	**RS3**
Modelling the ground	Uses familiar geotechnical stiffness parameters, G & ν. But, only suitable for soil profiles that can be approximated a constant or linearly increasing stiffness with depth profile. Difficulties can arise in determining a representative stiffness profile where soil layers of varying stiffness are interleaved over the effective depth of the pile.	The ground and groundwater profile can be discreetly modelled to accommodate layered strata with different properties. But relies on the use of t-z and p-y curves which may be unfamiliar to some geotechnical practitioners.	Uses familiar geotechnical parameters: E, ν, c′, ϕ′. The ground and groundwater profile can be discreetly modelled to accommodate layered strata with different properties.
Modelling pile-ground interaction	Axial and torsional pile-ground interaction is modelled using closed form solutions for single piles. For lateral loading, single piles are modelled by treating the soil as an idealised elastic continuum in a similar way to a coefficient of subgrade reaction model. For pile groups, interaction factors are applied. Although highly simplified, the method is appropriate for many routine design applications.	Pile-ground interaction is modelled via the use of t-z and p-y curves. A number of standard curves are provided within the software. However, knowledge and experience of pile behaviour is required to ensure that appropriate curves are being used for a given problem.	Pile-ground interaction effects are inherently captured. The pile and ground are modelled as a continuum with a range of available material models and facilities for modelling ground-structure interfaces. Non-rigid pile caps can be modelled and imposed loads can be transmitted into the soil via the pile cap as well as via the piles.
Modelling pile-pile interaction	Pile to pile influences are considered through the use of interaction factors embedded in the software (no additional consideration by the user is necessary).	Interaction effects for closely spaced piles are catered for by coefficients assigned to individual piles. Whilst lateral group effect coefficients can be automatically calculated using built-in formulae, vertical group effect coefficients must be specified manually for each pile.	Pile-to-pile interactions are inherently captured. The pile and ground are modelled as a continuum with a range of available material models and facilities for modelling ground-structure interfaces.

(*continued*)

Table 5. (*continued*)

	PIGLET	**RSPile**	**RS3**
Pile deflections	Pile deflections *relative to the immediately surrounding ground* are output and only down to the pile's critical depth. The upshot is that the relative deflections at the pile heads do not match the absolute deflection of the pile cap.	The program provides a clear output of pile deflections.	Pile displacement profiles are easily obtained.
Bending moments & shear forces	Pile forces are given directly, but only down to the critical depth. The PIGLET manual states that pile forces and deflections are indicative and should not be taken as having accuracy greater than 10–15%.	The program provides a clear output of pile forces.	Pile forces are not given directly. They need to be estimated from the pile displacements or stress fields. This is a relatively complicated and time-consuming process.
Ease of use	The program is very easy to use with a short learning curve.	Slightly longer learning curve than PIGLET. Moderately easy to use, but requires understanding and experience in the application of t-z and p-y curves.	Relatively long learning curve. Building/changing models, running analyses and processing results is relatively time consuming. Specialist staff and hardware may be required.
Use for optioneering	Very easy/quick to use for optioneering.	Moderately easy/quick to use for optioneering.	Unsuitable for optioneering.
Overall comments	Very easy/quick to use and expected to give reasonably reliable results for pile groups operating in the elastic range in non-complex ground conditions.	Moderately easy/quick to use and versatile with good graphical output. However, modelling of pile-pile interaction could be better catered for.	A sophisticated and highly versatile program. But is overkill for routine design and is best reserved for particularly complex cases. Can provide valuable insights.