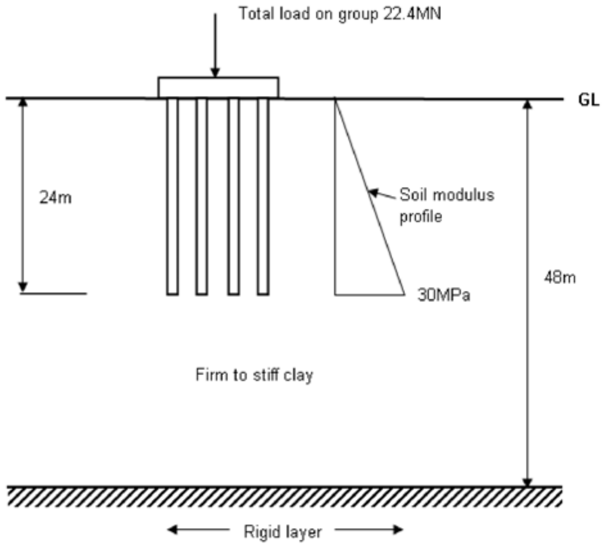
Repute benchmarks

4 x 4 pile group in firm to stiff clay

4 x 4 pile group embedded in firm to stiff clay, with an underlying rigid layer at 48m from ground level [1].

The piles are 24m long, 0.6m in diameter, and are spaced at 1.8m centre-to-centre, as shown below.



Results from Repute

The pile group settlement calculated by Repute is approximately 39 mm.

Comparison with benchmark

Tomlinson quotes the following results for pile group settlement, as obtained using other computer programs:

- DEFPIG = 42 mm
- PGROUP = 31 mm
- Equivalent Raft Method = 30 mm

Comments

None

Reference

[1] Tomlinson, M. J. (1994). Pile design and construction practice (4th edition). E & FN Spon, London

Downloads

Tomlinson(1994).rpx

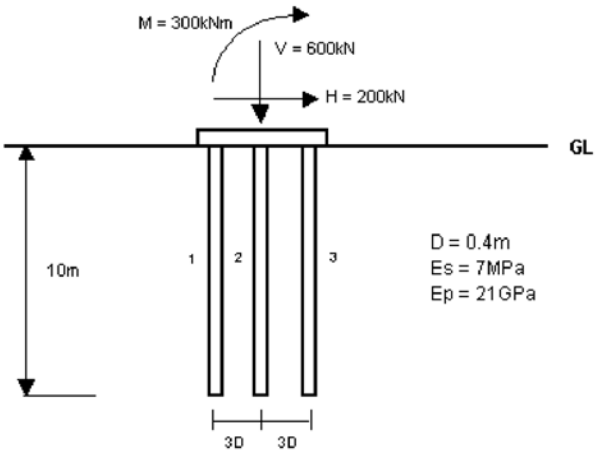
Repute benchmarks

3-pile group under general loading

The following example [1] describes a group of 3 piles under general loading conditions. Three types of analysis are described:

- A simple statical method that ignores the presence of soil and considers the pile group as a purely structural system
- The equivalent-bent method that reduces the pile group to a structural system but takes some account of the effect of the soil by determining equivalent free-standing lengths of the piles
- Pile group programs that consider the presence of the soil, including the interaction effects between the piles through the soil, specifically Repute, DEFPIG, Piglet, and GEPAN [2]

The 3-pile group is subjected to a combination of axial load, lateral load and moment. Results from the above methods are compared in the table (right) in which w3, u, and θ are the vertical head displacement of Pile 3, the horizontal cap displacement and the rotation of the cap, respectively. Resulting loads and bending moments at the pile heads are also reported.



Results from Repute

The results from Repute are given in the table below.

Comparison with benchmark

Variable	Equivalen beam	Staticalan alysis	DEFPIG	Piglet	GEPAN	Repute
V1 (kN)	67.2	75.0	55.8	55.7	54.0	49.6
V2 (kN)	200.0	200.0	155.1	155.0	156.0	153.0
V3 (kN)	332.8	325.0	389.1	389.3	390.0	397.3
H1 (kN)	66.6	66.7	72.0	80.4	73.7	68.9
H2 (kN)	66.7	66.7	56.0	39.3	50.9	53.5
H3 (kN)	66.6	66.7	72.0	80.4	75.4	77.6
M1 (kN)	-6.2	0	-35.8	-42.0	-38.5	-41.5
M2 (kN)	-6.2	0	-28.5	-16.3	-26.1	-31.8
M3 (kN)	-6.2	0	-35.8	-42.0	-38.6	-44.0
w3 (mm)	17.5	n/a	13.4	9.9	10.8	10.9
u (mm)	8.9	n/a	11.6	11.4	10.5	11.5
θ (rad)	0.00581	n/a	0.00242	0.00242	0.00241	0.00263

Comments

There is a good agreement between the solutions which consider pile-soil-pile interaction (even if with different degrees of rigour), whereas the statical and equivalent-bent analyses give quite different results, thereby showing the pitfall of attempting to model a complex pile-soil system by means of a simple structural frame.

References

[1] Poulos H. G. & Davis, E. H. (1980). Pile foundation analysis and design. Wiley, New York.

[2] Xu K. J. & Poulos H. G. (2000). General elastic analysis of pile groups. Int. J. Numer. Anal. Meth. Geomechs 24, 1109-1138.

Downloads

Poulos-Davis(1980).rpx

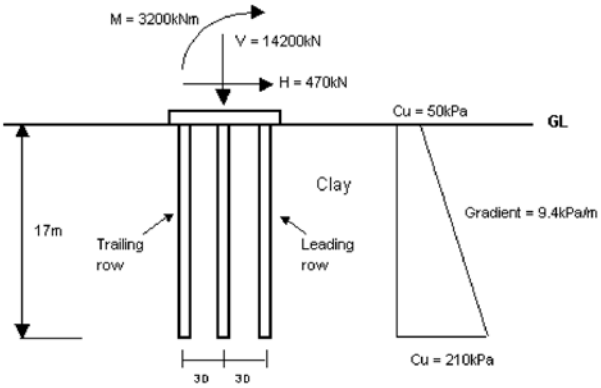
3 x 3 pile group for railway viaduct in North London

This benchmark describes the design of a 3x3 pile group subjected to a combination of vertical loads, horizontal loads and moments, and embedded into the stiff London Clay [1].

The bored cast-in-situ reinforced concrete piles are 17m long, 0.9m in diameter, with a centre-to-centre spacing of three pile diameters, and with the underside of the pile cap assumed at the top of the London Clay. A profile of undrained shear strength (C_u) of 50 + 9.4z kPa has been adopted, where z is the depth in m below the top of the London Clay.

For the axial response, the profile of soil modulus has been derived from the correlation $E_s = 400C_u$ for the linear analyses and from $E_s = 1500C_u$ for the non-linear analysis. For the lateral response, the profile of soil modulus has been assumed to increase linearly with depth from a value of zero at the top of the London Clay at a rate of 4.14MN/m^3 for the linear analyses and 6.15MN/m^3 for the non-linear analysis.

The applied vertical loads (V) result from the combined effect of live and dead loads, whereas the horizontal loads (H) and moments (M) are generated by the high-speed trains braking and accelerating. The loads acting on the cap have been estimated as V = 14200kN, H = 470kN and M = 3200kNm.



Results from Repute

The results from Repute are given in the table below

Comparison with benchmark

The table below summarises results obtained from various programs. In the linear elastic range, there is a reasonably good agreement between the group deformations and axial load distribution predicted by the different codes.

Variable	MPILE	DEFPIG	Repute linear	Repute non-linear
Group centre settlement (mm)	9.0	11.3	11.6	4.0
Group deflection (mm)	3.2	4.3	3.9	2.7
Axial load at top of corner piles of leading row (kN)	2220	2210	2230	2100
Axial load at top of corner piles of trailing row (kN)	1700	1670	1640	1520
Lateral load at top of corner piles of leading row (kN)	66	62	94	76
Lateral load at top of corner piles of trailing row (kN)	66	62	23	35
Bending moment at top of corner piles of leading row (kNm)	120	177	225	179
Bending moment at top of corner piles of trailing row (kNm)	120	177	87	124

Comments

If the effects of soil non-linearity are considered using Repute, we obtain lower group deformations (due to the higher value of soil modulus adopted) and a decrease of predicted loads on the most heavily loaded row of piles (i.e. the leading row), thereby resulting in a more uniform load distribution between the piles.

Reference

[1] Basile F. (2003). Analysis and design of pile groups. In Numerical Analysis and Modelling in Geomechanics, E & FN Spon (eds J. W. Bull), Chapter 10, in press.

Downloads

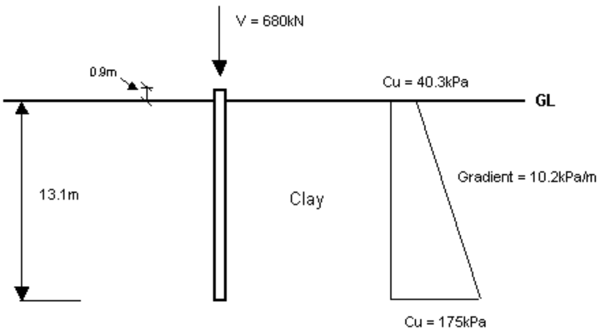
Basile-linear(2003).rpx
Basile-non-linear(2003).rpx

Repute benchmarks

Axial loading tests on single piles and pile groups in stiff overconsolidated clay

Reference [1] reports the results of axial loading tests on single piles and pile groups driven into a stiff overconsolidated clay at a site located in Houston, as shown below. The piles were closed end tubular steel pipes with Young's modulus of 210GPa, external diameter 274mm, wall thickness 9.3mm, penetration depth of 13.1m, and with a clearance of 0.9m from the groundline.

A non-linear soil model has been adopted within Repute. The soil parameters are based on the data presented in reference [2] i.e. a profile of initial soil modulus of 100MPa at ground level, increasing linearly to 400MPa at the pile base level (as deduced from seismic cross-hole data), and a profile of undrained shear strength of about 40kPa at the surface, increasing linearly to 175kPa at the level of the pile base (as deduced from laboratory triaxial tests).

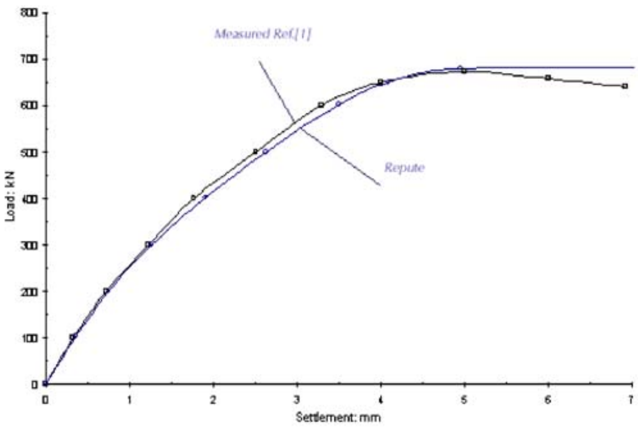


Results from Repute

The results from Repute are shown in the graph below.

Comparison with benchmark

The graph below shows a favourable agreement between the computed and measured load-settlement behaviour for the single pile.



Comments

Further details on this comparison may be found in [3].

References

[1] O'Neill, M. W., Hawkins, R. A. & Mahar, L. J. (1982). Load transfer mechanism in piles and pile groups. J. Geotech. Engng, Am. Soc. Civ. Engrs, 108, No. GT12, 1605-1623.

[2] Poulos, H. G. (1989). Pile behaviour-theory and application. 29th Rankine Lecture, Géotechnique, 39, No. 3, 365-415.

[3] Basile, F. (2003). Analysis and design of pile groups. In Numerical Analysis and Modelling in Geomechanics, E & FN Spon (eds J. W. Bull), Chapter 10, in press.

Downloads

ONeill(1982).rpx

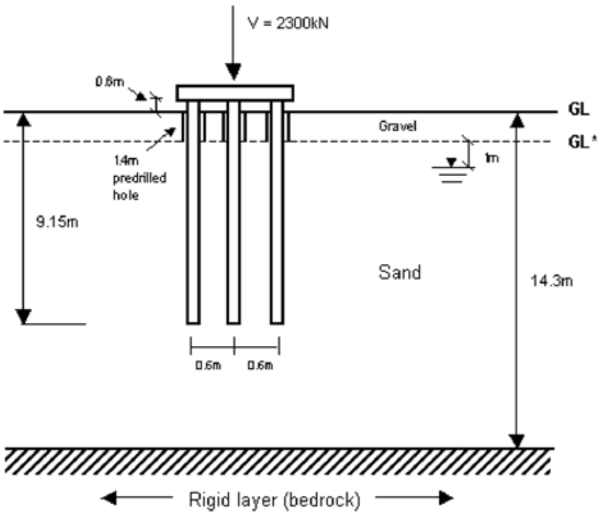
Repute benchmarks

Axial loading tests on driven piles in medium dense sand

Reference [1] describes the results of axial loading tests on a group of five driven piles in medium dense sand at a site located in San Francisco, as shown below. The piles were tubular steel pipes with Young's modulus of 160GPa, external diameter 273mm, wall thickness 9.3mm, driven to a depth of 9.15m through a 300mm diameter hole predrilled to a depth of 1.4m. The piles were arranged in the configuration shown in the inset to the graph to the right, and connected by a rigid cap with a clearance of 0.6m from the ground level.

The soil profile consists of medium dense sand, overlain by 1.4m of sandy gravel and underlain by bedrock at a depth of 14.3m below ground level. The water table is 2.4m deep.

A non-linear soil model has been adopted within Repute. The assumed soil parameters are based on a subsoil idealisation with two layers resting on a rigid base, as shown on the diagram to the left. Considering that the predrilled hole disconnects the piles from the top 1.4m of gravelly soil, the ground level (GL*) used within Repute is taken at 1.4m below the actual ground level (GL). Thus, the embedded length of piles will be taken as 7.75m, and the free-standing length as 2m (i.e. 1.4 + 0.6m).

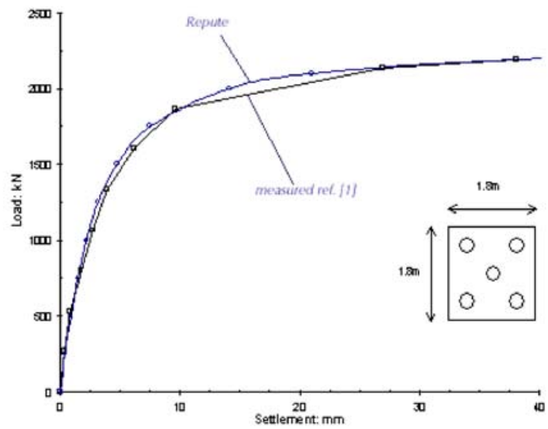


Results from Repute

The pile group settlement calculated by Repute is approximately 39 mm.

Comparison with benchmark

The computed and measured load-settlement curves are reported in the graph below and show a good agreement.



Comments

Further details on this comparison may be found in [2].

References

[1] Briaud, J. L., Tucker, L. M. & Ng, E. (1989). Axially loaded 5 pile group and single pile in sand. Proc. 12th Int. Conf. Soil Mech. Fdn Engng, Rio de Janeiro 2, 1121-1124.

[2] Basile, F. (2003). Analysis and design of pile groups. In Numerical Analysis and Modelling in Geomechanics, E & FN Spon (eds J. W. Bull), Chapter 10, in press.

Downloads

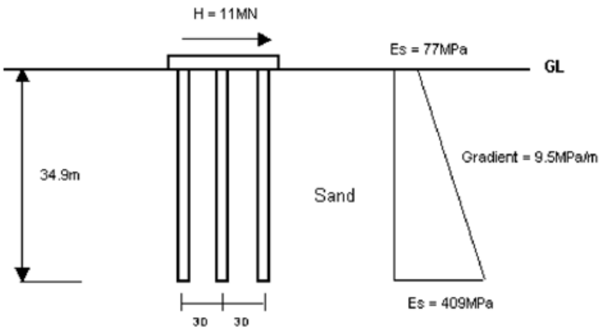
Briaud(1989).rpx

Repute benchmarks

Lateral load tests on single piles and pile groups

As part of the design of the high-speed rail system in Taiwan, reference [1] reports the results of lateral load tests on single piles and pile groups installed at a site located in Taipao Township, as shown below. The bored cast-in-situ reinforced concrete piles are 34.9m long, 1.5m in diameter, with a Young's modulus of 27.6GPa. The group piles were connected by a massive reinforced concrete cap and arranged in a 2x3 configuration with centre-to-centre spacing of three pile diameters, as shown in the inset to the graph to the right. A lateral load of 11MN was applied at the level of the ground surface.

The soil was generally classified as silty sand or silt with occasional layers of silty clay. The soil profile has been idealised as a single cohesionless layer with a friction angle of 30˚. A non-linear soil model has been adopted within Repute, and the assumed soil modulus was 77MPa at the level of the pile cap underside, increasing linearly at the rate of 9.5MPa/m.

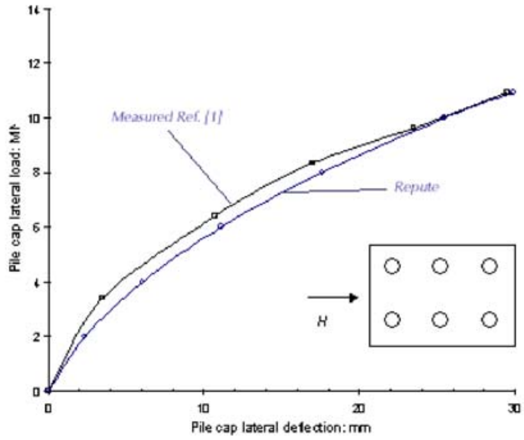


Results from Repute

The results from Repute are shown in the graph below.

Comparison with benchmark

The graph below shows a favourable agreement between the computed and measured load-deflection behaviour of the 6-pile group.



Comments

Further details on this comparison may be found in [2].

References

[1] Huang, A. B., Hsueh, C. K., O'Neill, M. W., Chern, S. & Chen, C. (2001). Effects of construction on laterally loaded pile groups. J. Geotech. and Geoenv. Engng, Am. Soc. Civ. Engrs 127, No. 5, 385- 397.

[2] Basile, F. (2003). Analysis and design of pile groups. In Numerical Analysis and Modelling in Geomechanics, E & FN Spon (eds J. W. Bull), Chapter 10, in press.

Downloads

Huang(2001).rpx

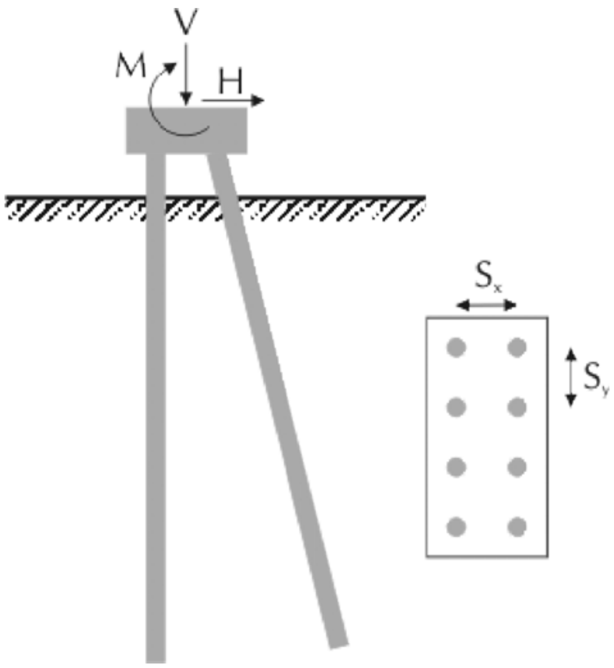
Repute benchmarks

Bridge abutment on two rows of piles, one raked

This is Example 2 from the PIGLET User Manual [1]. It deals with a 2 x 4 pile group, in which one row of piles is raked in the direction of the horizontal load.

The concrete piles (17m long, 0.6m in diameter) are spaced at either 2 or 3m centres in the X-direction (S_x) and at 2m centres in the Y-direction (S_y). Young's modulus of the piles is assumed to be 24GPa axially and laterally. The bottom of the pile cap is 1.5m above the ground surface.

The ground itself has a shear modulus G = 1z MPa (where z is the depth below the bottom of the pile cap) and Poisson's ratio = 0.2.



The loads applied to the pile cap are V = 8MN, H = 1.2MN, and M = 2.4MNm.

References

[1] Randolph, M. F. (1996). PIGLET analysis and design of pile groups, University of Western Australia.

[2] Basile, F. (2003). Analysis and design of pile groups. In Numerical Analysis and Modelling in Geomechanics (ed. J. W. Bull), Spon press, London, Chapter 10, pp 278-315.

Results from Repute

Spacing S_x (m)	Pile rake	Deflection (mm)		Max. mom't (kNm)	
		Vert'l	Horiz'l	Vert'l	Horiz'l
2	None	17.0	33.5	-389	-354
	1:8	15.1	16.1	-151	-130
	1:6	15.0	11.9	-81	-64
	1:4	15.1	5.3	+43	+62
3	None	16.3	29.4	-417	-377
	1:8	14.7	14.8	-191	-164
	1:6	14.6	11.0	-122	-98
	1:4	14.9	4.7	+5	+30

Comparison with benchmark

Spacing S_x (m)	Pile rake	Deflection (mm)		Max. mom't (kNm)	
		Vert'l	Horiz'l	Vert'l	Horiz'l
2	None	17.2	33.8	-339	-339
	1:8	15.4	15.4	-90	-158
	1:6	15.3	11.1	+42	-101
	1:4	15.4	4.3	+132	+44
3	None	16.6	29.5	-370	-370
	1:8	15.1	14.3	-133	-195
	1:6	14.9	10.4	-57	-137
	1:4	15.1	3.9	+90	+32

Comments

Repute and PIGLET give very similar deflections for this example, but Repute generally gives higher bending moments. PIGLET does not account for load-deformation coupling, i.e. the interaction between the axial and lateral response of the piles. This behaviour is important when a pile group is subjected to a combination of vertical and horizontal loads. Proper consideration of this interaction (as in the Repute analysis) increases bending moments in the leading/raked piles and decreases moments in the trailing/vertical row [2].

Downloads

See table of downloads at Randolph(1996).html

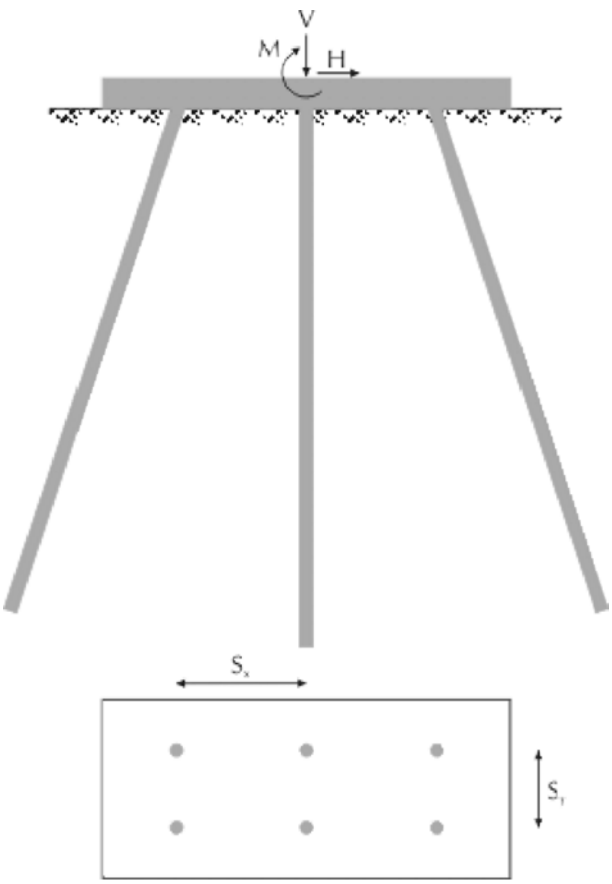
Repute benchmarks

Six model piles in sand

This is a test case from the PIGLET User Manual [1], which compares analytical results with those obtained from model tests in sand [2]. It deals with a 2 x 3 pile group, with the end rows of piles raked at 1 in 3 outwards from the pile cap.

The piles (533mm long, 12.7mm diameter, 0.8mm wall thickness) are spaced at 127mm centres in the X-direction (S_x) and at 75mm centres in the Y-direction (S_y). The piles' equivalent solid Young's moduli are assumed to be 16.3GPa axially and 28.9GPa laterally. The bottom of the pile cap is in contact with the ground surface.

The sand has a shear modulus G = 4.2z MPa (where z is the depth below the ground surface) and Poisson's ratio = 0.25.



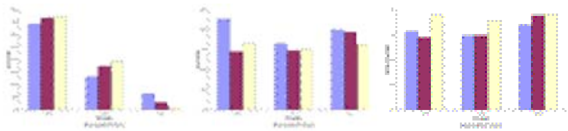
The loads applied to the pile cap are V = 222N, H = 138N, and M = 6Nm.

Downloads

Davisson-Salley(1970).rpx

Results from Repute

The thumbnail images below give the results obtained from Repute (yellow), PIGLET (red), and the physical model tests (blue). Visit Davisson-Salley(1970).html to see these diagrams at full size.



Comparison with benchmark

The axial loads predicted by Repute are within 5% of those predicted by PIGLET [1], which in turn differ from the measured loads [2] by up to 12%.

The shear loads predicted by Repute are typically 10% different from those predicted by PIGLET, which in turn are typically 15% less than the measured loads.

The bending moments predicted by Repute are typically 13% higher than those predicted by PIGLET, which in turn differ typically from the measured moments by 6%.

Comments

The agreement between Repute, PIGLET, and Davisson and Salley's model tests is remarkably good, given the different assumptions made in the two methods of analysis [1, 3] and the inherent inaccuracies in physical modelling.

Better agreement between PIGLET's predictions and the measured results is expected because the shear modulus adopted by Randolph [1] for the soil was backfigured from test results for a single pile.

References

[1] Randolph, M. F. (1996). PIGLET analysis and design of pile groups, University of Western Australia.

[2] Davisson, M.T. and Salley, J.R (1970). Model study of laterally loaded piles. J. Soil Mechanics and Foundation Engineering Division, American Society of Civil Engineers, vol 96, no SM5.

[3] Basile, F. (2003). Analysis and design of pile groups. In Numerical Analysis and Modelling in Geomechanics (ed. J. W. Bull), Spon press, London, Chapter 10, pp 278-315.