Numerical analysis of a piled foundation in idealised granular material using slip element

Y. J. Lee, A. Swain and R. H. Bassett

Department of Civil and Environmental Engineering

University College London

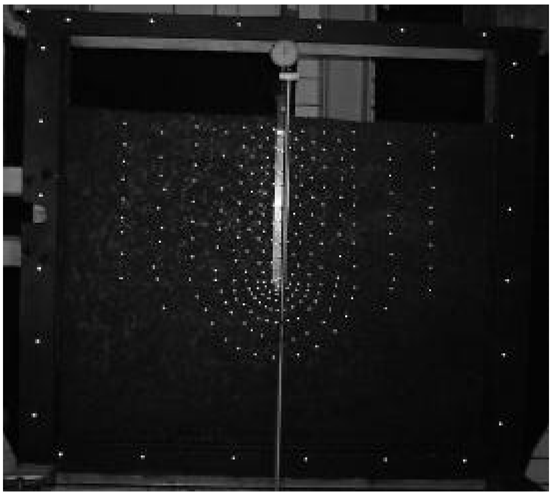
Gower Street, London WC1E 6BT

Introduction

The construction of a tunnel in a granular soil produces complex soil-structure interaction effect. This is compounded when the tunnel is constructed close to any existing below structures, especially piled foundations in urban city area. In an attempt to better understand the effect on buried structures due to adjacent tunnelling, research, both physical and analytical, is being carried at UCL. The first part of this research is aimed at modelling the basic case of a pile in a granular material. In this study, the pile was assumed to be an end bearing pile, not a friction pile. The slip elements were, therefore, applied around the pile in the numerical analysis using Crisp. The numerical analysis was carried out in order to compare the displacement patterns and failure mechanisms in terms of strain fields with the laboratory 2D pile load test using a photogrammetry technique. The New Mohr-Coulomb soil model based on linear elastic perfectly plastic model was used to introduce the dilation effect into this idealised granular material. In connection with the New Mohr-Coulomb soil model, all parameters were assumed. Stiffness and dilation angle were then changed to approach the real experimental behaviour of this idealised material. The aim of this study is to find an efficient mesh, which is related to low CPU time and to investigate the main factors, related to satisfaction of displacement norm convergence in connection with the MNR iterative solution scheme of SAGE CRISP. This paper finally presents experimental results in comparison with the numerical analysis.

Laboratory 2D pile load test

The pile load test is the most commonly adopted method of checking the performance of a pile. The pile load test may be either static or dynamic. In this study, static tests were carried out at laboratory scale. The aim of this laboratory 2D pile load test is to measure the pile head settlement using a dial gauge on the pile head resulting from pile loading (i.e. 5kg, 10kg, 15kg, 20kg, 25kg and 30kg) and to take a picture for the image processing using the photogrammetry technique. Fig 1 shows the laboratory 2D pile load test including reflective points (or/ bead marks) on the black aluminium rods and 25 reference points on the steel frame. The load against pile head displacement (P-S curve) is shown in Figure 2. In the P-S curve, plastic behaviour is evident after 20kg of pile loading.



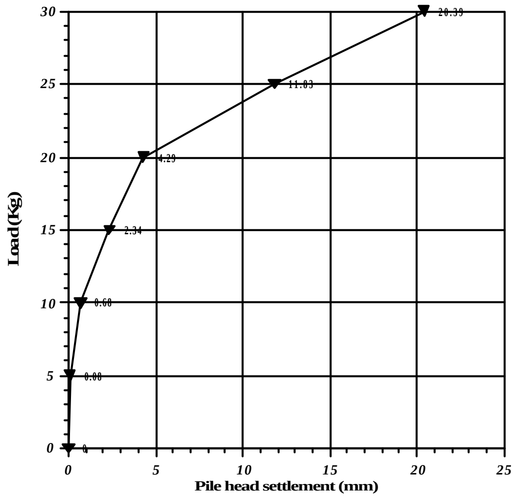


Figure 1. 2D model pile load test

Figure 2. P-S curve

Plane strain meshes

In this study, two meshes were constructed, shown in Figure 3 and 4, to compare the CPU time under the same parameters and the same analysis conditions. The mesh A has total 639 nodes and 1160 elements including 1132 LSTs (Linear Strain Triangle elements) and 28 LSQs (Linear Strain Quadrilateral elements). The mesh B has total 195 nodes and 176 elements including 4 LSTs and 172 LSQs. The boundary and geometry conditions were also shown in Figure 3.

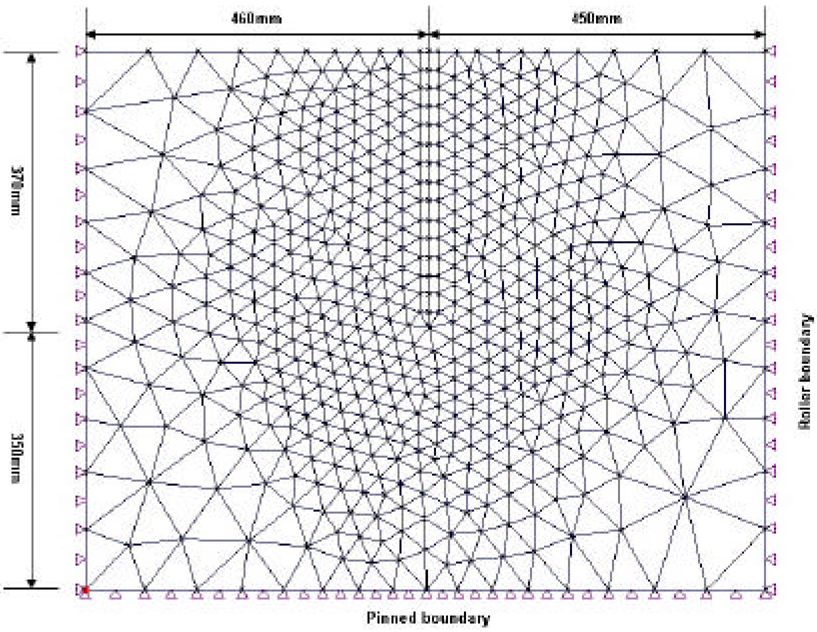


Figure 3. Mesh A

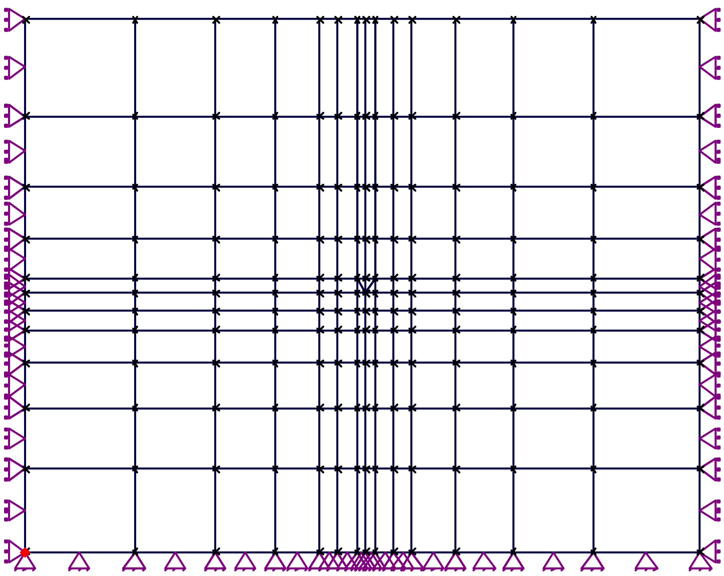


Figure 4. Mesh B

Hypothetical parameters

In drained condition, all parameters were summarised as below Table 1, 2 and 3 and material zones were also shown in Figure 5.

Table 1. Granular soil based on the New Mohr-Coulomb model

C(Kpa)	ϕ(°)	ψ(°)	ν	E_0(Kpa)	m_E(Kpa/m)	m_C(Kpa/m)	γ_{bulk}(KN/m^3)	Y_0(m)
0.1	30	20	0.35	1600	40,000	0	24	0.72

Table 2. Slip element

C(Kpa)	δ(°)	K_n(Kpa)	K_s(Kpa)	K_{sres}(Kpa)	t(m)
0.005	5	16,000	8,000	0.8	0.1

Table 3. Concrete pile based on the isotropic elastic model

E(Kpa)	ν	γ_{bulk}(KN/m^3)
1.55e7	0.2	23

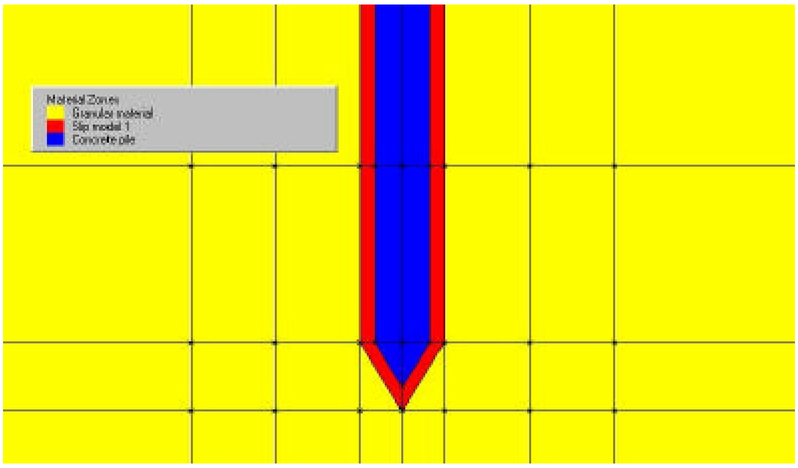


Figure 5. Material zones (drained condition)

Analysis conditions

For the analysis of pile loading, the experimental values of pile head settlement were applied on the centre node point of the pile head as shown in Figure 6. In this study, the author focused on the DCM (Displacement Control Method) rather than LCM (Load Control Method)

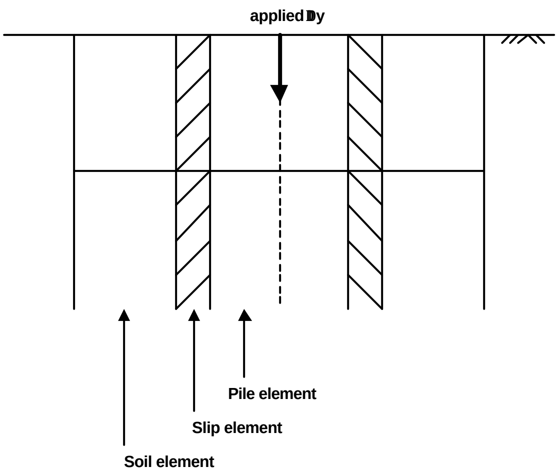


Figure 6. DCM according to the pile head settlements

MNR (Modified Newton-Raphson) iterative solution was used in association with a tolerance of 0.05 and maximum iteration number of 40. K_0 =0.5 was used for the in-situ stress conditions. For the displacement norm convergence in the MNR, total 320 increments were used as summarised below Table 4.

Table 4. Increment block parameters

Increment block No.	Increment block list	Pile head settlements (mm)	Time-Step (sec)	Number of increments			
				Case 1	Case 2	Case 3	Case 4
1	Install pile	0	1	5	5	5	5
2	Δy_1=0.08mm	0+0.08=0.08	1	5	10	20	5
3	Δy_2=0.6mm	0.08+0.6=0.68	1	5	10	20	20
4	Δy_3=0.32mm	0.68+0.32=1	1	5	10	20	40
5	Δy_4=1.34mm	1+1.34=2.34	1	5	10	20	50
6	Δy_5=1.95mm	2.34+1.95=4.29	1	5	10	20	50
7	Δy_6=3.71mm	4.29+3.71=8	1	5	10	20	50
8	Δy_7=3.83mm	8+3.83=11.83	1	5	10	20	50
9	Δy_8=8.56mm	11.83+8.56=20.39	1	5	10	20	50
	Total	20.39	9	45	85	165	**320**

Results

1. Displacement norm convergence check for the MNR

Table 5 shows the displacement norm convergence according to the number of increments. The convergence is clearly dependent on the number of increments (or/ increment size) in this study (i.e. with slip elements). However, if the slip elements are not applied around the piled foundation (i.e. without slip elements), the convergence is independent of the number of increments.

Table 5. Increment size effect (based on ψ = 20°)

Number of increments	Convergence	
	With slip elements	Without slip elements
45	No	Yes
85	No	Yes
165	Yes	Yes
320	Yes	Yes

Table 6 also shows the displacement norm convergence according to the values of dilation angle in the New Mohr-Coulomb soil model. The convergence with slip elements is only satisfied at the dilation angle of 20 degrees. However, the convergence without slip elements is satisfied except for the dilation angle of 0 and 5 degrees.

Table 6. Dilation angle effect (based on 320 increments)

Dilation angles (°)	Convergence	
	With slip elements	Without slip elements
0	No	No
5	No	No
10	No	Yes
15	No	Yes
20	Yes	Yes

2. Comparison of CPU times

CPU time was compared between the mesh A and mesh B as shown in Figure 7. The mesh B is most cost effective in terms of computer resources.

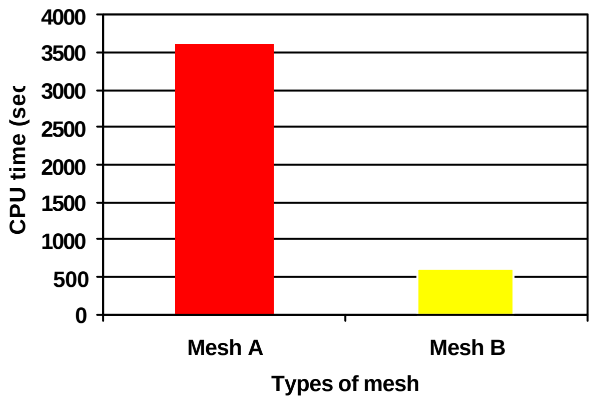


Figure 7. Comparison of CPU times

3. Comparison of MNR methods

According to Potts et al. (1999), the MNR results are insensitive to increment size as shown in Figure 8. However, in Crisp, the MNR results are dependent on increment size in connection with the slip elements. The MNR solution in Crisp was not fully implemented in connection with relationship between load norm and displacement norm, being based only on the displacement norm convergence checking system at the moment. Therefore, Crisp needs to add the load (or/ force) norm convergence checking system in association with stress point algorithms.

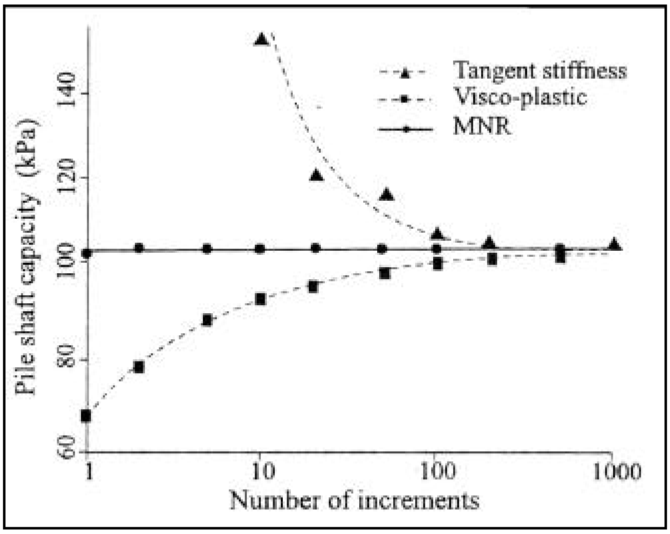


Fig. 8. Pile problem (After Potts et al., 1999)

4. Comparison of results between the experiment and the numerical analysis

The experimental results are plotted using the photo image processing as follows:

(1) Vector movements; (2) Horizontal displacements; (3) Vertical displacements: (4) Dilatant volumetric strains; (5) Maximum shear strains; (6) Major principal strain directions; (7) Zero extension line directions (or slip line directions).

These displacements are associated with strain fields in soil mechanics problems. In connection with above displacement plots, the results of the numerical analysis based on the mesh B were compared with the experimental results. There is good agreement between both results in connection with displacement patterns and failure mechanisms through the slip line directions as shown in Figure 9.

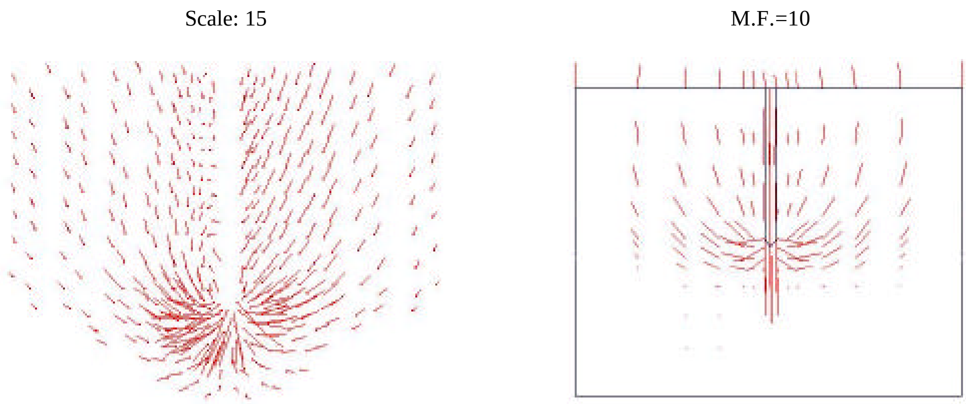


Figure 9. (a) Vector movements

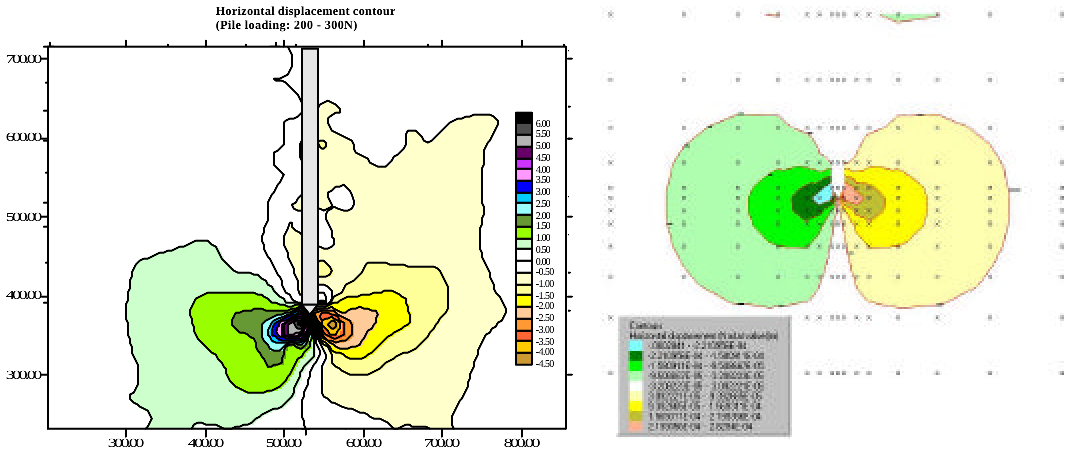


Figure 9. (b) Horizontal displacements

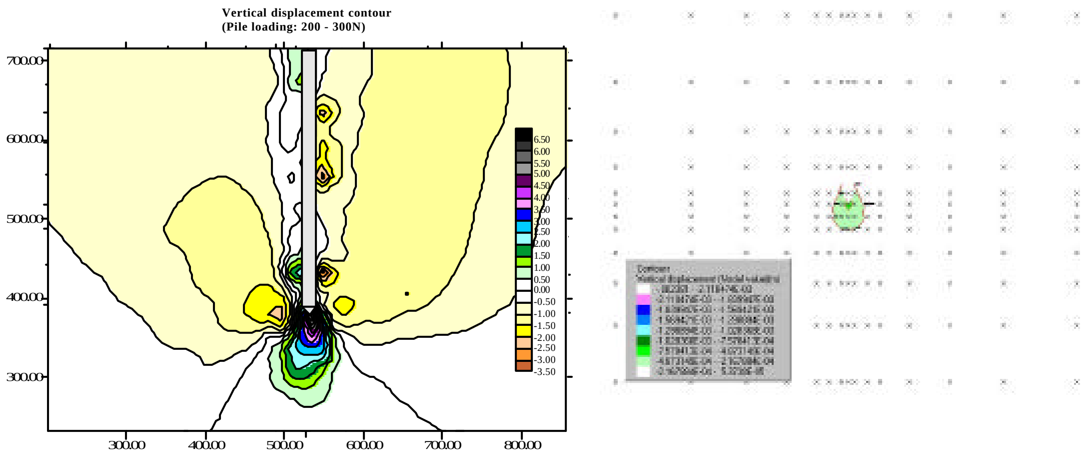


Figure 9. (c) Vertical displacements

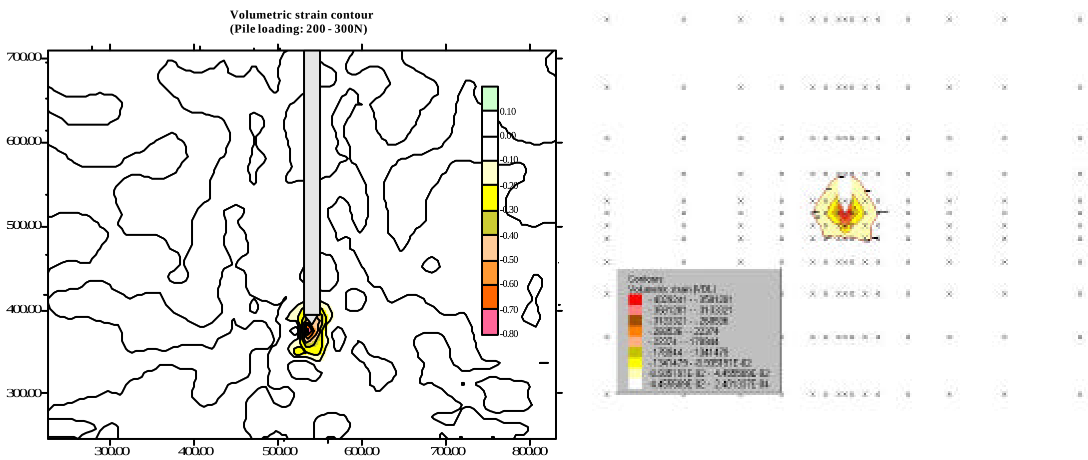


Figure 9. (d) Dilatant volumetric strains

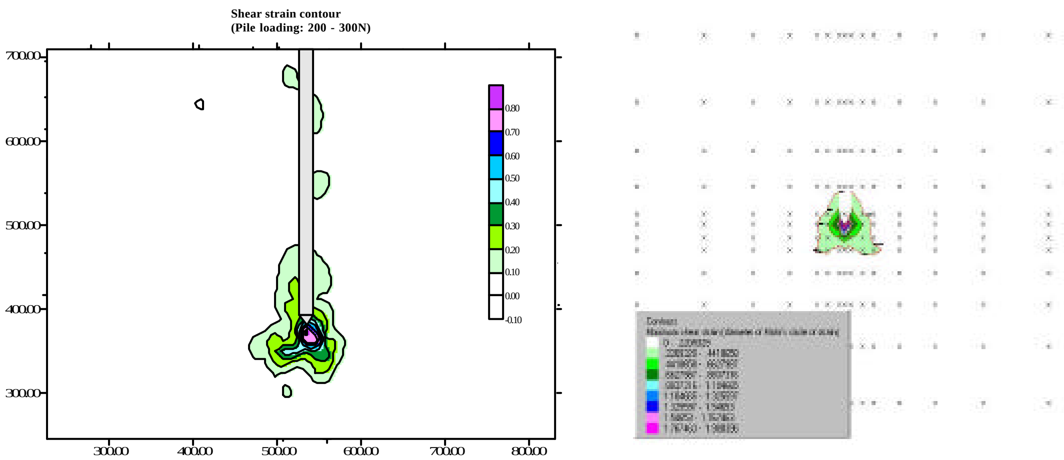


Figure 9. (e) Max. shear strains

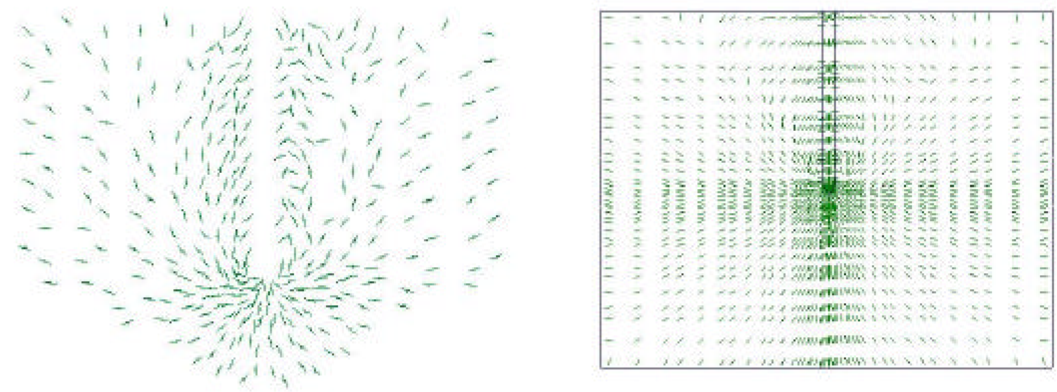


Figure 9. (f) Major principal strain directions

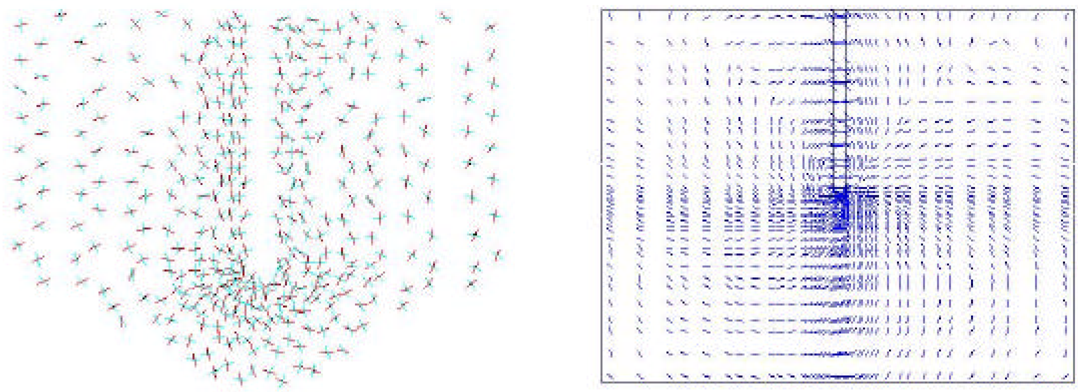


Figure 9. (g) Slip line directions

Conclusions

The CPU time can be improved using the linear strain quadrilateral elements (i.e. LSQs) rather than the linear strain triangular elements (i.e. LSTs). This does not mean that quadrilateral elements are in any way superior to triangular elements. In the numerical analysis of the pile load test using the slip elements, the displacement norm convergence of the MNR is very sensitive to the number of increments (or/ increment size) in contrast to the comment by Potts et al. (1999). In the New Mohr-Coulomb linear elastic perfectly plastic soil model, the value of dilation angle (ψ) is a key factor in order to satisfy the displacement norm convergence using the MNR solution.