14 Pile-Supported Highway Embankment

14.1 Problem Statement

End-bearing piles can be used to support highway embankments constructed over soft foundation materials. This method of support can reduce the potential for excessive deformations and failure during the undrained stage of construction, when excess pore pressures are induced in the foundation materials by the embankment loading.

This example presents a *FLAC* analysis of the initial (undrained) construction stage for a highway embankment built over soft, saturated foundation clay and muck, using timber piles to support the embankment.* The piles extend through the soft materials and into underlying silty sands. The embankment includes foamed concrete engineered fill as part of the embankment materials. The lightweight foamed concrete is placed in lifts of approximately 0.6 m thickness. The first lift is placed over a wire mesh directly in contact with the top of the timber piles. Earth fill and pavement material are placed as cover over the foamed concrete. The analysis also includes a traffic surcharge of 11,500 Pa (240 psf). Figure 14.1 shows a section view of the embankment and foundation materials. The groundwater surface is at the top of the foundation materials.

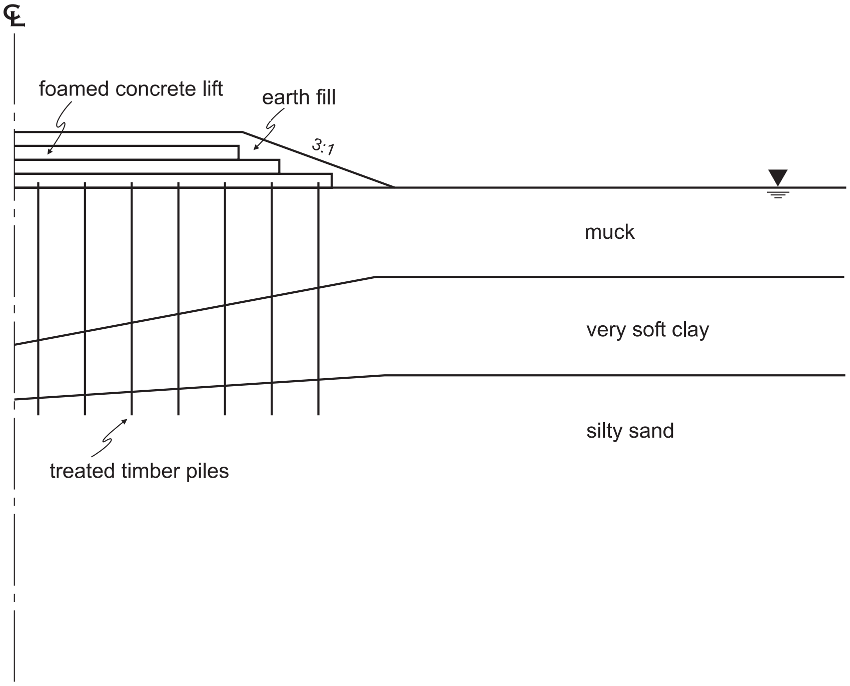

Figure 14.1 Half-section view of foamed concrete embankment on timber piles

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* This analysis is based on information provided by K. J. Kim of the North Carolina Department of Transportation on the design of a foamed concrete embankment supported on timber piles for the U.S. 64 widening project in Tyrrell County, North Carolina.

The properties assumed for the foundation and embankment materials are listed in Tables 14.1 and 14.2. Note that both saturated and dry densities are shown for the foundation materials. The embankment materials are assumed to remain dry. The *FLAC* simulation is an undrained analysis using the groundwater configuration mode. Consequently, the drained material bulk modulus and strength properties and the dry mass densities are input for this calculation mode, because the effect of water is incorporated in the *FLAC* calculation.

Table 14.1 Properties for foundation soils

	muck	very soft clay	silty sand
Saturated unit weight (N/m^3)	11,100	13,560	18,840
Porosity (%)	90	80	30
Dry density (kg/m^3)	231	582	1620
Drained Young’s modulus (MPa)	0.3	0.5	15.0
Drained Poisson’s ratio	0.49	0.45	0.3
Drained bulk modulus (MPa)	5.0	1.67	12.5
Shear modulus (MPa)	0.1	0.17	5.77
Drained cohesion (Pa)	3500	5000	0
Drained friction angle (degrees)	0	0	32
Dilation angle (degrees)	0	0	0
Horizontal permeability (m/day)	0.003	0.0003	2.4
Vertical permeability (m/day)	0.001	0.0001	0.8

Table 14.2 Properties for embankment materials

	foamed concrete	earth fill
Dry density (kg/m^3)	640	1920
Porosity (%)	30	30
Drained Young’s modulus (MPa)	600.0	10.0
Drained Poisson’s ratio	0.15	0.3
Drained bulk modulus (MPa)	286.0	8.33
Shear modulus (MPa)	261.0	3.85
Drained cohesion (Pa)	50,000	2400
Drained friction angle (degrees)	0	30
Dilation angle (degrees)	0	0
Horizontal permeability (m/day)	1.2	1.2
Vertical permeability (m/day)	0.4	0.4

Treated timber piles are located on a 2.5 m by 2.5 m rectangular spacing beneath the embankment materials. The length of each pile is 12.8 m (42 ft), and the average pile diameter is 0.3048 m (12 in). The properties of the timber piles are listed in Table 14.3.

Table 14.3 Properties for treated timber piles

Elastic modulus (GPa)	10.0
End-bearing capacity (KN)	250.0

14.2 Modeling Procedure

This analysis is performed as a parametric study to compare the deformation of an unsupported embankment to that of a pile-supported embankment. In both cases, we first determine the initial equilibrium state of the saturated foundation soils. Then, for the unsupported case, we add the embankment materials and monitor the vertical displacement along the foundation surface directly beneath the embankment. For the pile-supported case, we install the timber piles and then add the layers of embankment materials while monitoring the vertical displacements in the same locations as those for the unsupported case.

The model is created using *FLAC* 's graphical user interface. Upon entering the graphical interface, the groundwater flow option, structural elements and factor-of-safety calculation are activated in the *Model options* dialog. The SAVE PROJECT AS menu item is then selected from the FILE menu in order to set up a project file to save the model state at various stages of the simulation. We click on ? in this menu dialog to select a directory in which to save the project file. A record of the *FLAC* commands used to create this model can be saved after the analysis is complete, using the FILE/EXPORT RECORD menu item.

We generate the grid using the BUILD/GENERATE/GEOMETRY BUILDER tool to create the model geometry and add lines defining the excavation slope and the excavation and foundation material boundaries. The embankment is 3 m high and the pavement half-width is 12 m. The resulting grid is shown in Figure 14.2 and coincides with the half-section shown in Figure 14.1.

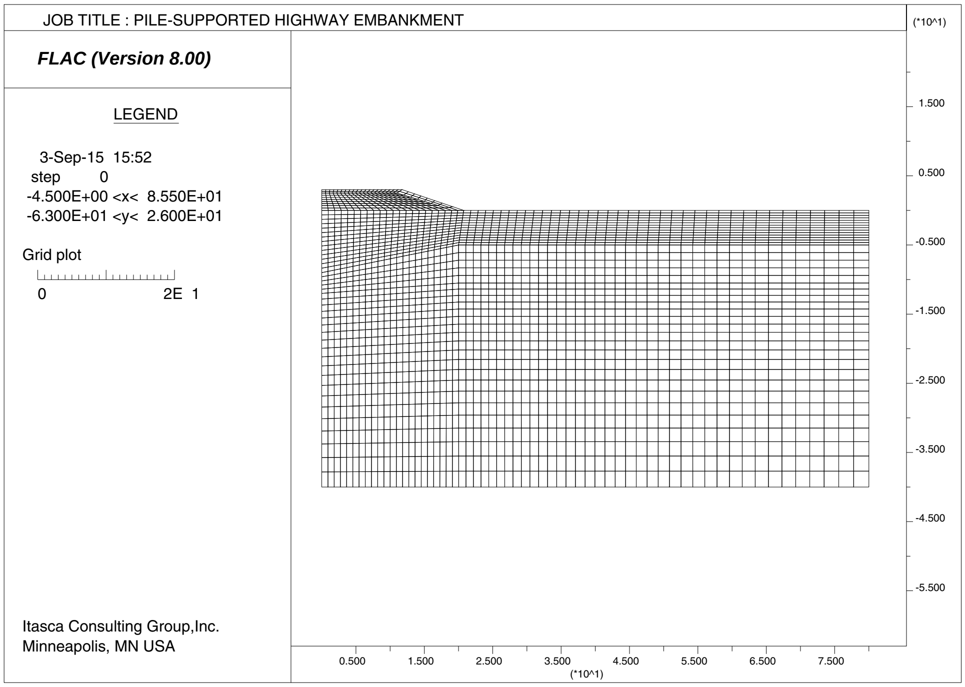
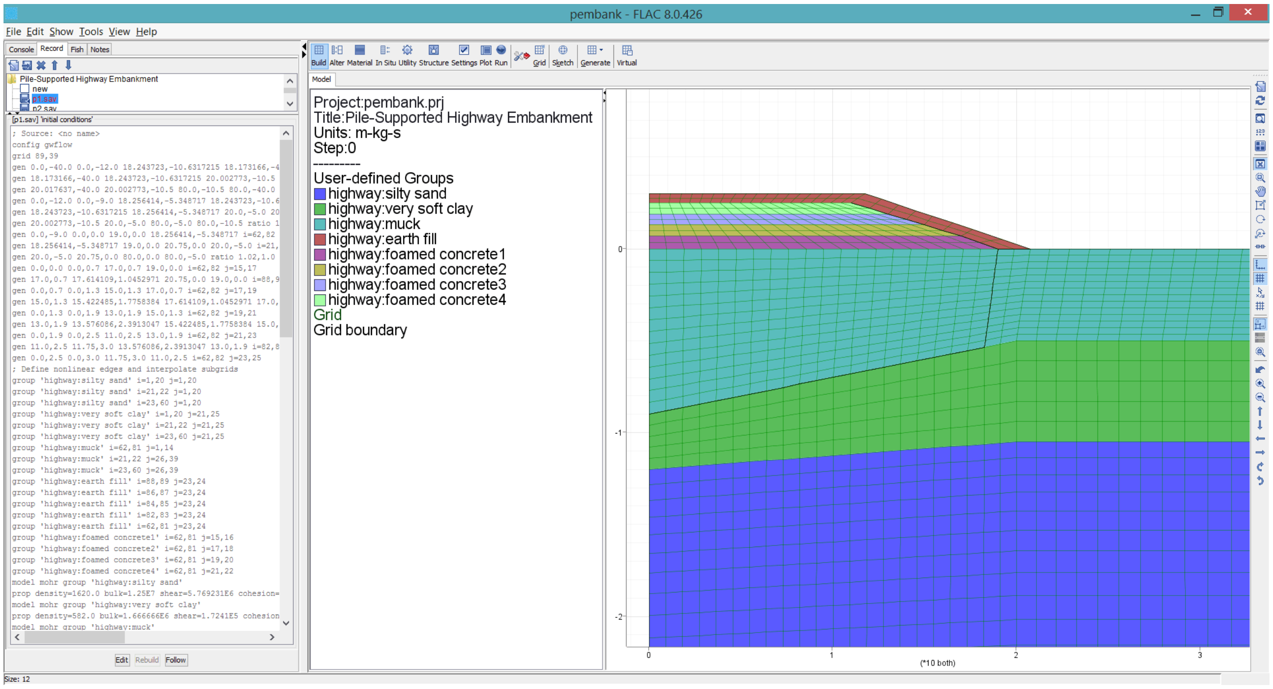


Figure 14.2 FLAC grid for highway embankment analysis

The different materials and their associated properties are assigned by group names. Three foundation soil groups are created: silty sand, very soft clay and muck. The embankment consists of four lifts of 0.6 m thick foamed concrete and the earth fill layer. All materials and associated properties are stored in the database file named “HIGHWAY.GMT” The groups defined for the embankment and foundation materials are shown in Figure 14.3. The groundwater properties are assigned using the Material/GWProp tool. The model is saved at this stage as “P1.SAV.”



[p1.sav] 'initial conditions'

```
; Source: <no name>
config gwflow
grid 89,39
gen 0.0,-40.0 0.0,-12.0 18.243723,-10.6317215 18.173166,-4
gen 18.173166,-40.0 18.243723,-10.6317215 20.002773,-10.5
gen 20.017637,-40.0 20.002773,-10.5 80.0,-10.5 80.0,-40.0
gen 0.0,-12.0 0.0,-9.0 18.256414,-5.348717 18.243723,-10.6
gen 18.243723,-10.6317215 18.256414,-5.348717 20.0,-5.0 20
gen 20.002773,-10.5 20.0,-5.0 80.0,-5.0 80.0,-10.5 ratio 1
gen 0.0,-9.0 0.0,0.0 19.0,0.0 18.256414,-5.348717 i=62,82
gen 18.256414,-5.348717 19.0,0.0 20.75,0.0 20.0,-5.0 i=21,
gen 20.0,-5.0 20.75,0.0 80.0,0.0 80.0,-5.0 ratio 1.02,1.0
gen 0.0,0.0 0.0,0.7 17.0,0.7 19.0,0.0 i=62,82 j=15,17
gen 17.0,0.7 17.614109,1.0452971 20.75,0.0 19.0,0.0 i=88,9
gen 0.0,0.7 0.0,1.3 15.0,1.3 17.0,0.7 i=62,82 j=17,19
gen 15.0,1.3 15.422485,1.7758384 17.614109,1.0452971 17.0,
gen 0.0,1.3 0.0,1.9 13.0,1.9 15.0,1.3 i=62,82 j=19,21
gen 13.0,1.9 13.576086,2.3913047 15.422485,1.7758384 15.0,
gen 0.0,1.9 0.0,2.5 11.0,2.5 13.0,1.9 i=62,82 j=21,23
gen 11.0,2.5 11.75,3.0 13.576086,2.3913047 13.0,1.9 i=82,8
gen 0.0,2.5 0.0,3.0 11.75,3.0 11.0,2.5 i=62,82 j=23,25
; Define nonlinear edges and interpolate subgrids
group 'highway:silty sand' i=1,20 j=1,20
group 'highway:silty sand' i=21,22 j=1,20
group 'highway:silty sand' i=23,60 j=1,20
group 'highway:very soft clay' i=1,20 j=21,25
group 'highway:very soft clay' i=21,22 j=21,25
group 'highway:very soft clay' i=23,60 j=21,25
group 'highway:muck' i=62,81 j=1,14
group 'highway:muck' i=21,22 j=26,39
group 'highway:muck' i=23,60 j=26,39
group 'highway:earth fill' i=88,89 j=23,24
group 'highway:earth fill' i=86,87 j=23,24
group 'highway:earth fill' i=84,85 j=23,24
group 'highway:earth fill' i=82,83 j=23,24
group 'highway:earth fill' i=62,81 j=23,24
group 'highway:foamed concrete1' i=62,81 j=15,16
group 'highway:foamed concrete2' i=62,81 j=17,18
group 'highway:foamed concrete3' i=62,81 j=19,20
group 'highway:foamed concrete4' i=62,81 j=21,22
model mohr group 'highway:silty sand'
prop density=1620.0 bulk=1.25E7 shear=5.769231E6 cohesion=
model mohr group 'highway:very soft clay'
prop density=582.0 bulk=1.666666E6 shear=1.7241E5 cohesion
model mohr group 'highway:muck'
```

Project:pembank.prj
Title:Pile-Supported Highway Embankment
Units: m-kg-s
Step:0

User-defined Groups
- 🟦 highway:silty sand
- 🟩 highway:very soft clay
- 🟦 highway:muck
- 🟥 highway:earth fill
- 🟪 highway:foamed concrete1
- 🟨 highway:foamed concrete2
- 🟦 highway:foamed concrete3
- 🟩 highway:foamed concrete4

Grid
Grid boundary

Figure 14.3 Groups defined for embankment and foundation materials

After all of the material groups are assigned, the foamed concrete lifts and earth fill groups are "excavated" using the MATERIAL/CUT&FILL tool. The initial stress state for the saturated foundation soils is then calculated. We use the *FISH* function "ININVT.FIS" to set the pore pressure, effective stress and total stress distributions. This function automatically calculates the pore pressures and total stresses that are compatible for a model containing a phreatic surface. The groundwater density and water bulk modulus are specified before applying this *FISH* function. We use the SETTINGS/GW tool to set the groundwater density to 1000 kg/m^3 and the groundwater bulk modulus to 10,000 Pa (to speed convergence to steady-state flow). We specify the total stress distribution for the three foundation layers using the UTILITY/TABLE tool. Table 1 is created with x, y pairs designating elevation and total vertical stress: (0,0), (-5,-55,500), (-10.5,-130,080), (-40,-685,860). We then use the UTILITY/FISHLIB tool to access the "ININVT.FIS" *FISH* function. We enter the phreatic surface elevation (**`wth`** = 0), the K_o ratios (**`k0x`** = 0.5 and **`k0z`** = 0.5) and the total stress distribution defined by Table 1 (**`syytab`** = 1) in the dialog, and press OK. The *FISH* function is called into *FLAC* and executed. The pore-pressure distribution and total stress adjustment are then calculated automatically. We now solve for the new equilibrium state, using the RUN/SOLVE tool and running in coupled mechanical-groundwater flow mode. The pore-pressure distribution is shown in Figure 14.4. The model is saved at this state as "P2.SAV."

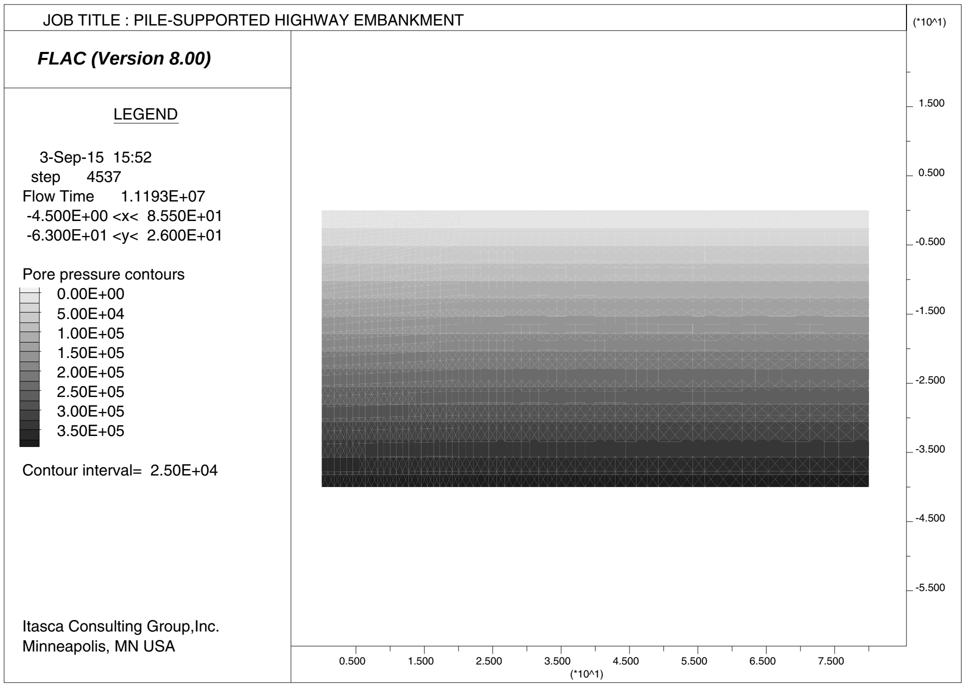
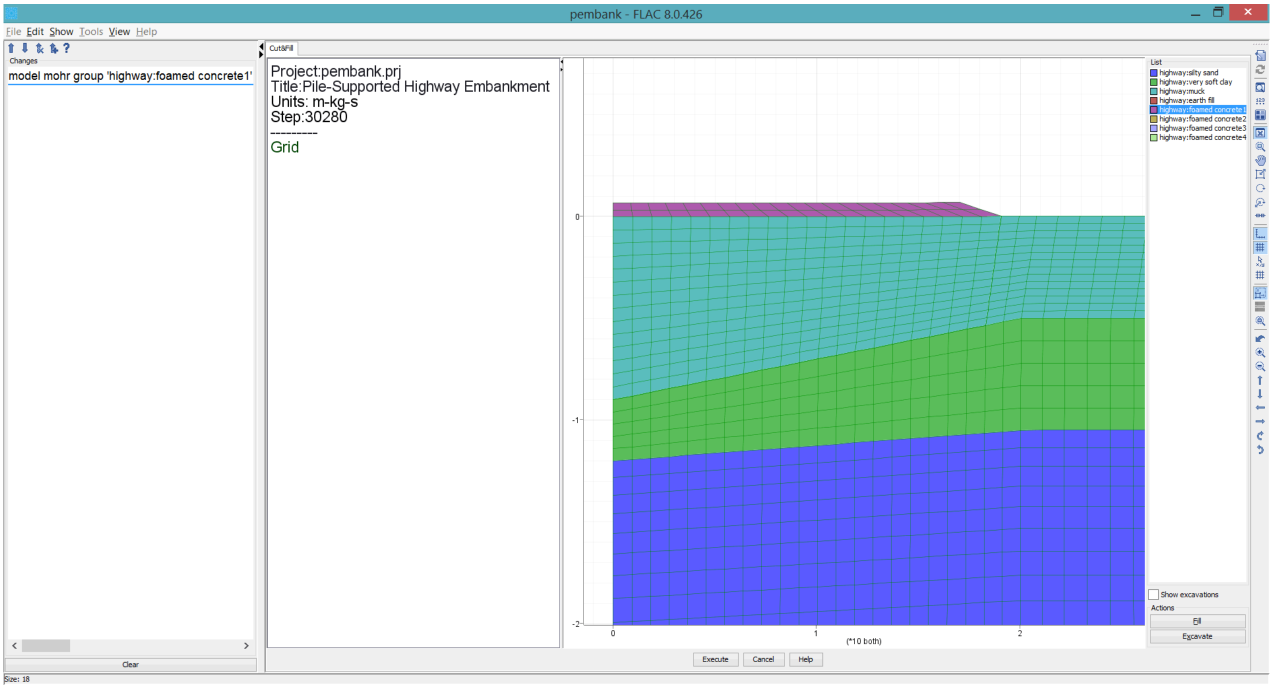


Figure 14.4 Initial pore-pressure distribution in foundation soils

The embankment construction is analyzed assuming undrained conditions. This is accomplished by setting the groundwater flow calculation mode off, and increasing the water bulk modulus to approximate a nearly incompressible fluid. We increase the water bulk modulus to 0.2 GPa and set flow off using the Settings/GW tool. Also, because we anticipate large deformations during the construction, we perform this stage in large-strain mode and set this option on in the Settings/Mech tool.

The unsupported embankment construction is simulated by adding each embankment-lift group individually (via the Material/Cut&Fill tool), and then solving for the equilibrium state with this lift in place. As each group is added, the saturation values of the gridpoints in the group are set to zero (using the In Situ/Initial tool) to simulate the unsaturated condition of the embankment materials. Figure 14.5 shows the Material/Cut&Fill tool with the "foamed concrete1" lift added (filled). (We note that if the Show Excavations? box is checked, then the excavated groups are shown grayed-out in this tool.) These steps are repeated for each of the three remaining foamed concrete lifts and the earth-fill lift. Finally, the traffic surcharge is applied along the top of the embankment, using the In Situ/Apply tool. Each of the unsupported construction stages is saved as a separate save state in "P3.SAV" through "P8.SAV."



```
model mohr group 'highway:foamed concrete1'
```

```
Project:pembank.prj
Title:Pile-Supported Highway Embankment
Units: m-kg-s
Step:30280
---------
Grid
```

Figure 14.5 Addition of first embankment lift "foamed concrete1"

Vertical displacement histories are recorded at four locations along the base of the embankment, at ($x = 0$, $y = 0$), ($x = 6.5$, $y = 0$), ($x = 11.5$, $y = 0$) and ($x = 17$, $y = 0$). The displacements are monitored throughout the embankment construction; the results are shown in Figure 14.6. The extent of the displacements induced by the unsupported construction is shown in Figure 14.7. The maximum vertical displacement beneath the embankment is approximately 0.7 m (2.3 ft).

The displacements are associated with excess pore pressures that develop in the muck and very soft clay. This is evident from the pore-pressure histories recorded along the centerline of the embankment at $y = 0$ and $y = -6.5$ (in the muck), and at $y = -10.5$ (in the very soft clay). The plots of pore-pressure histories are given in Figure 14.8.

A factor-of-safety calculation is performed at this stage by selecting the RUN/SOLVE FOS tool. The safety factor for the unsupported embankment is calculated to be 1.02. Figure 14.9 shows the failure surface that develops if cohesion and friction of the embankment and foundation materials are reduced by this factor.

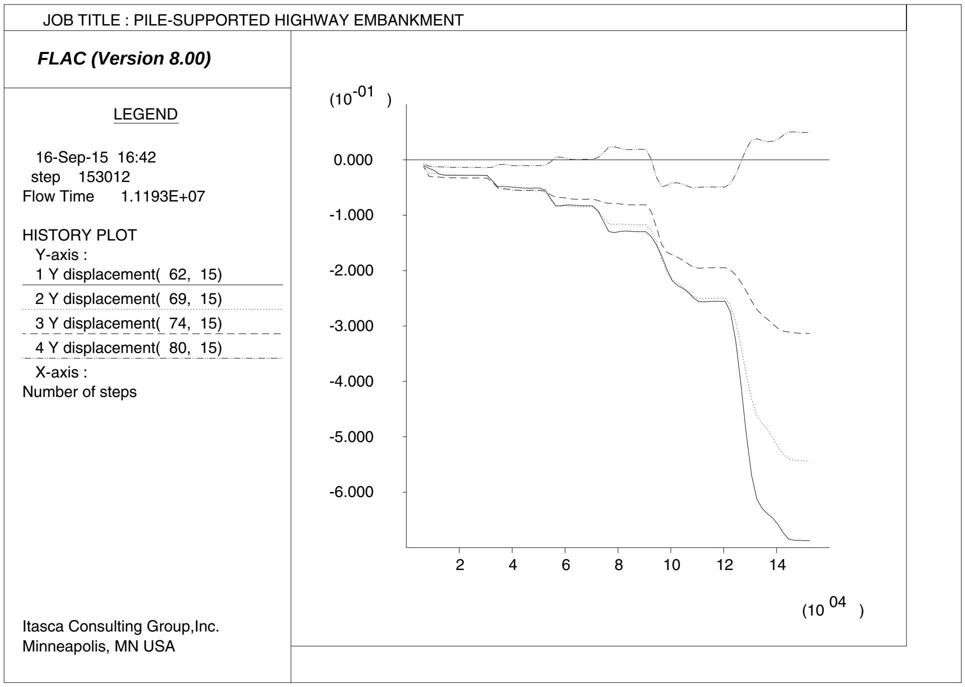


Figure 14.6 Vertical displacements along base of embankment for unsupported embankment construction

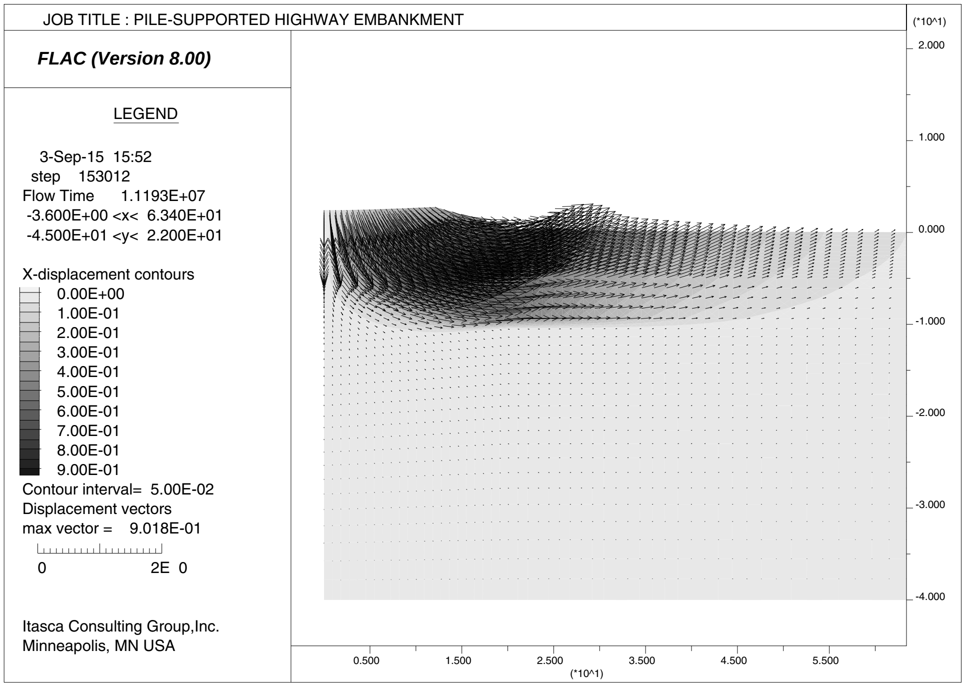


Figure 14.7 Displacement vectors and x-displacement contours for unsupported embankment construction

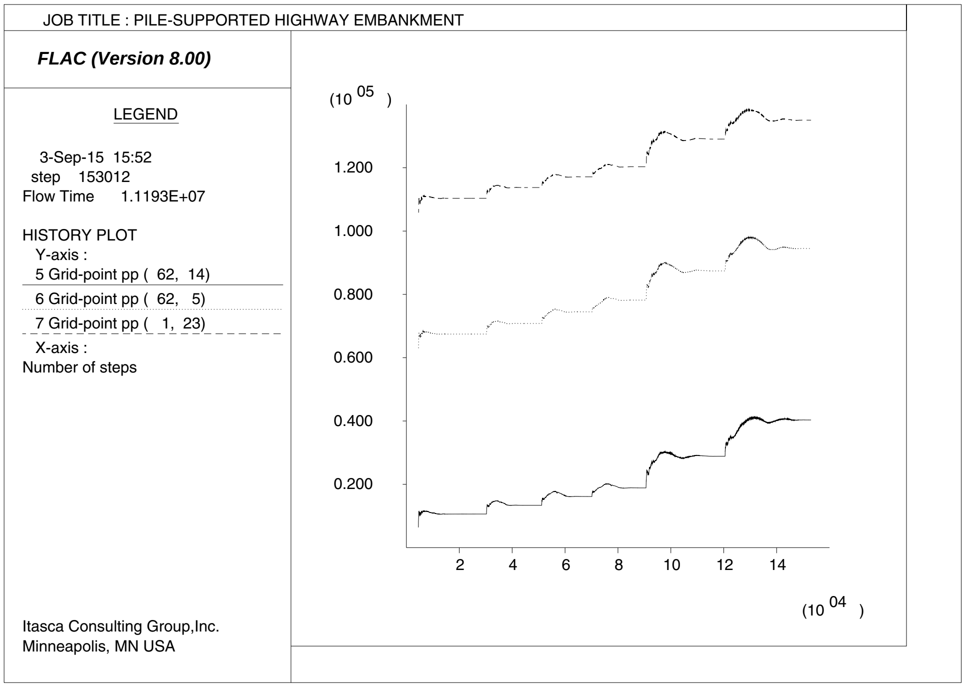


Figure 14.8 Pore pressures beneath center of embankment for unsupported embankment construction

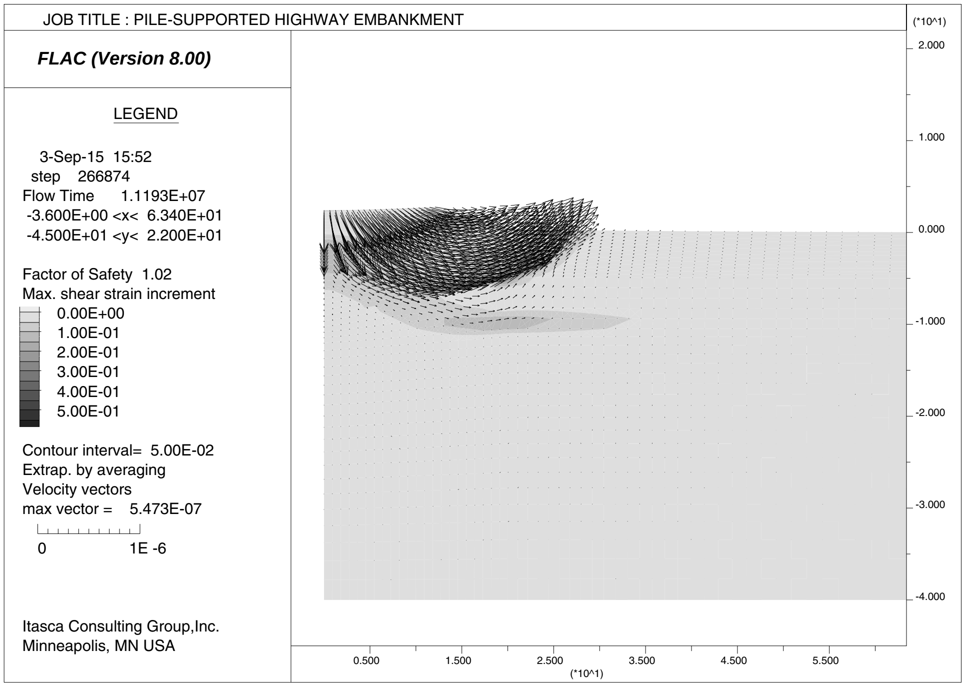
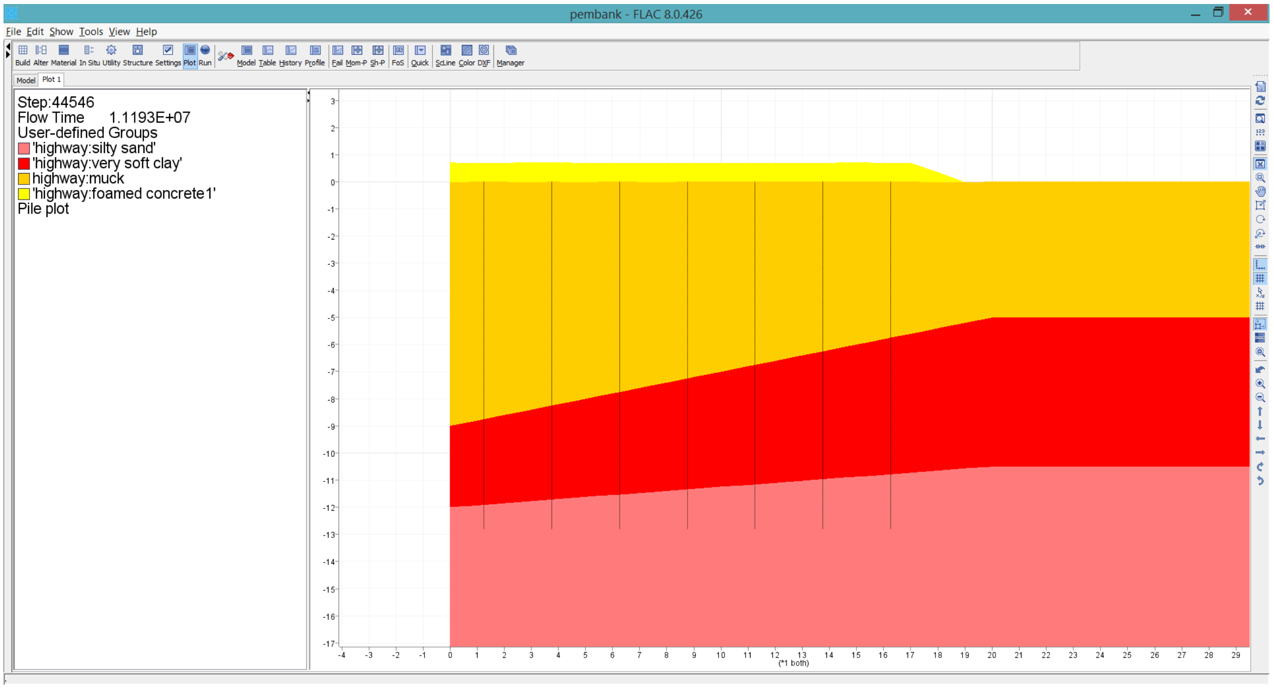


Figure 14.9 Factor of safety and failure surface plot for unsupported embankment

The pile-supported embankment construction is simulated by first installing pile elements in the *FLAC* model. The model state at “P3.SAV” (the initial equilibrium state) is cloned, and seven piles of 12.8 m length are positioned at a 2.5 m spacing within the foundation soils. Before the piles are placed in the model, the first foamed concrete lift is added. This is done so that the top of the piles can be connected to the embankment materials. Then, the piles are positioned as shown in Figure 14.10.

In order to represent the three-dimensional effect of the 2.5 m pile spacing, we scale the pile properties by dividing by the pile spacing. This is done automatically by specifying the **spacing** property when assigning pile properties. In this analysis, only the elastic modulus and the end-bearing capacity are scaled to account for the spacing. Note that we neglect the weight of the piles; the pile density would also be scaled if this weight is included. (See Section 1.9.4 in **Structural Elements** for additional information on scaling properties to simulate the three-dimensional effect.)

The properties of the pile coupling springs are selected to simulate an end-bearing capacity and zero skin friction. The cohesive strengths of the shear coupling springs at the top and bottom elements of each pile are set to 2.5 MN/m, while all other shear and normal coupling-spring strength values are set to zero. The value for cohesive strength is derived from a simulation of axially loaded piles at 2.5 m spacing to produce an end-bearing ultimate capacity of 250 KN in the silty-sand foundation material. The value for coupling-spring shear stiffness is selected at approximately ten times the equivalent stiffness of the stiffest neighboring zone. By doing this, the deformability at the pile/soil interface will have minimal influence on both the compliance of the total model and the calculational speed (see Section 3.4.1 in **Theory and Background**). The properties used for the pile elements in this model are summarized in Table 14.4. The model is saved at this stage as ‘PILES_P3.SAV.”



Step:44546
Flow Time 1.1193E+07
User-defined Groups
🟥 'highway:silty sand'
🟥 'highway:very soft clay'
🟧 highway:muck
🟨 'highway:foamed concrete1'
Pile plot

Figure 14.10 Location of piles in FLAC model

Table 14.4 Properties for pile elements

	middle segments	top & bottom segments
Elastic modulus (GPa)	10.0	10.0
Radius (m)	0.1524	0.1524
Perimeter (m)	0.976	0.976
Spacing (m)	2.5	2.5
Shear coupling spring stiffness (GN/m/m)	0.0	1.0
Shear coupling spring cohesion (MN/m)	0.0	2.5
Shear coupling spring friction (degrees)	0.0	0.0
Normal coupling spring stiffness (GN/m/m)	0.0	0.0
Normal coupling spring cohesion (N/m)	0.0	0.0
Normal coupling spring friction (degrees)	0.0	0.0

The embankment construction steps are now performed following the same sequence of steps as in the unsupported case. Each of the pile-supported stages is saved as a separate save state in “PILES_P4.SAV” through “PILES_P8.SAV”.

The vertical displacements are monitored as before; the histories are shown in Figure 14.11. The maximum vertical displacement beneath the embankment is now approximately 0.04 m (1.5 in).

Also, we note that for this case there is an insignificant change in pore pressures in the muck and very soft clay, as seen in Figure 14.12.

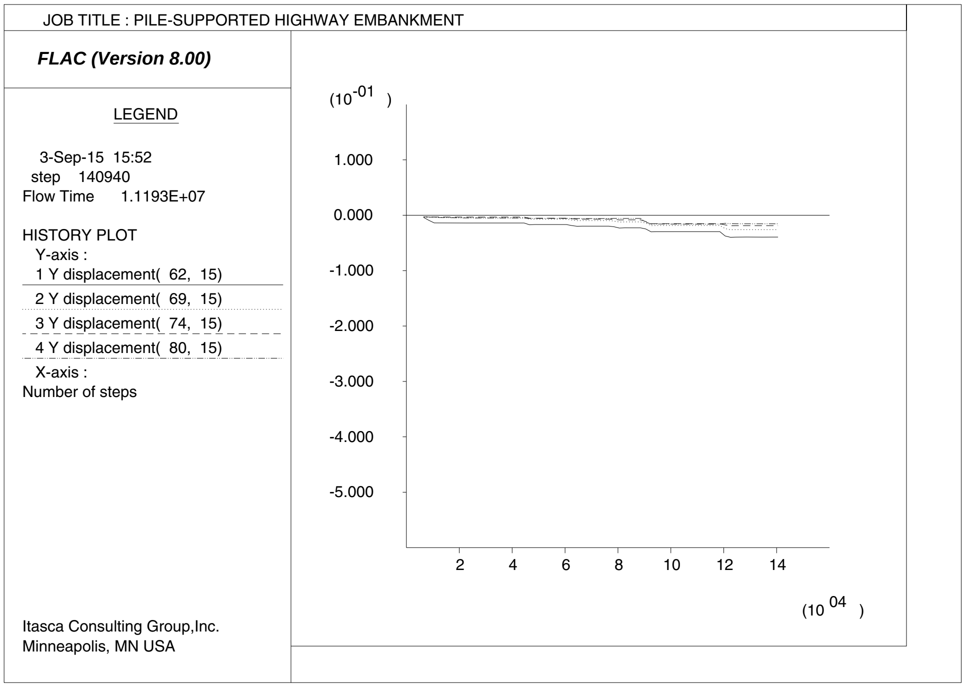


Figure 14.11 Vertical displacements along base of the embankment for pile-supported embankment construction

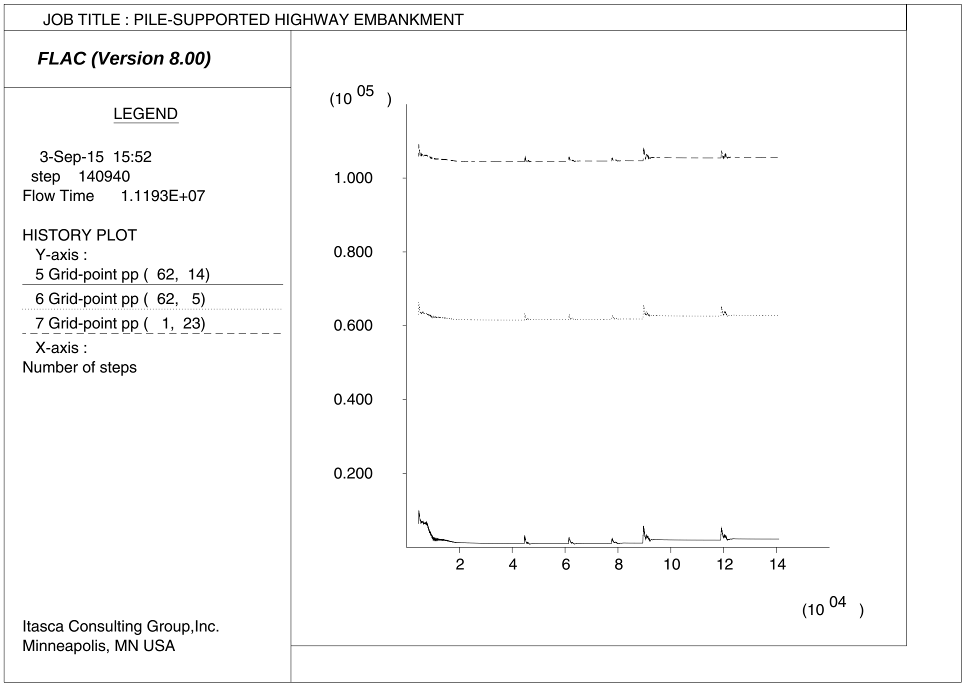
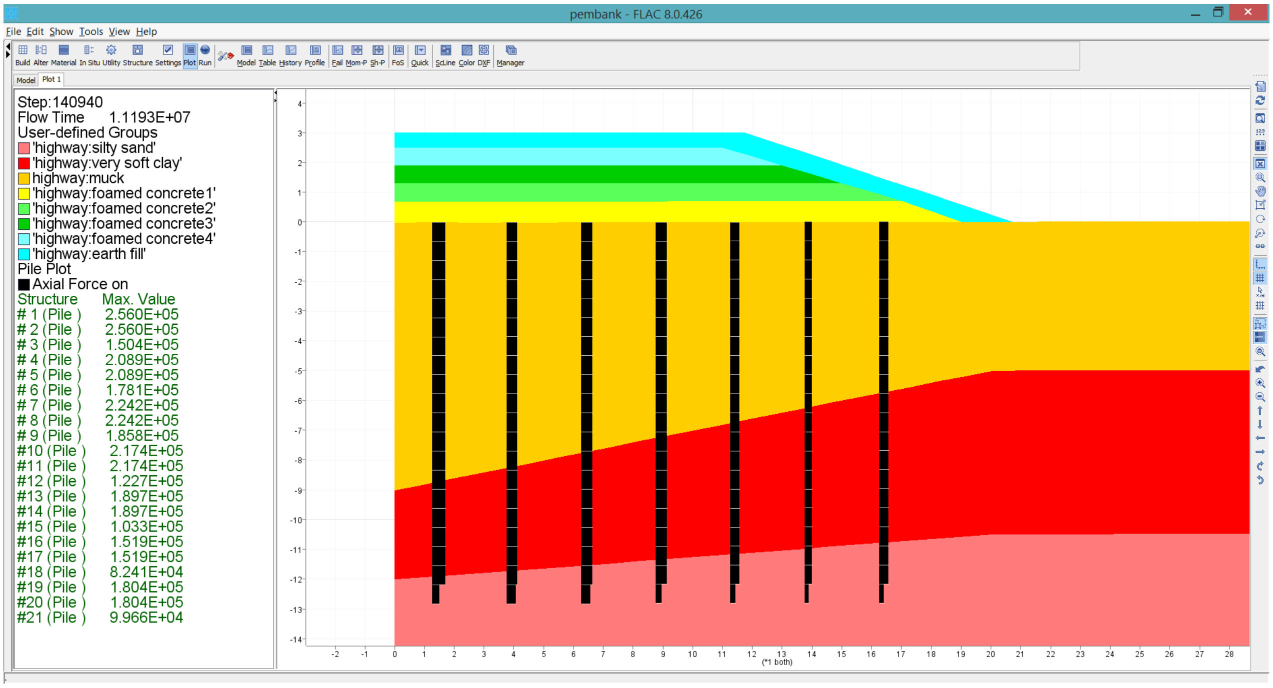


Figure 14.12 Pore pressures beneath center of embankment for pile-supported embankment construction

We are also interested in the axial loading that develops in the piles. When the **spacing** property is assigned, the axial force values that are printed and plotted output are the actual values (i.e., they account for the pile spacing). We plot the actual axial forces in the piles in Figure 14.13. (The 21 pile numbers shown in the plot legend correspond to the top, middle and bottom pile segments, which are assigned different material property numbers.) The maximum pile loading is approximately 256 KN.

A factor-of-safety calculation is also performed at this stage. The calculated factor is 2.49, and the failure surface is shown by the plot in Figure 14.14. Note that the critical failure surface for the supported embankment is now along the slope of the earthfill berm. The safety factor for the foundation material beneath the embankment is greater than 2.49, as a result of the support provided by the piles.



```
Step:140940
Flow Time     1.1193E+07
User-defined Groups
🟥 'highway:silty sand'
🟥 'highway:very soft clay'
🟧 highway:muck
🟨 'highway:foamed concrete1'
🟩 'highway:foamed concrete2'
🟩 'highway:foamed concrete3'
🟦 'highway:foamed concrete4'
🟦 'highway:earth fill'
Pile Plot
■ Axial Force on
Structure     Max. Value
# 1 (Pile )    2.560E+05
# 2 (Pile )    2.560E+05
# 3 (Pile )    1.504E+05
# 4 (Pile )    2.089E+05
# 5 (Pile )    2.089E+05
# 6 (Pile )    1.781E+05
# 7 (Pile )    2.242E+05
# 8 (Pile )    2.242E+05
# 9 (Pile )    1.858E+05
#10 (Pile )    2.174E+05
#11 (Pile )    2.174E+05
#12 (Pile )    1.227E+05
#13 (Pile )    1.897E+05
#14 (Pile )    1.897E+05
#15 (Pile )    1.033E+05
#16 (Pile )    1.519E+05
#17 (Pile )    1.519E+05
#18 (Pile )    8.241E+04
#19 (Pile )    1.804E+05
#20 (Pile )    1.804E+05
#21 (Pile )    9.966E+04
```

Figure 14.13 Actual loads in piles for pile-supported embankment construction

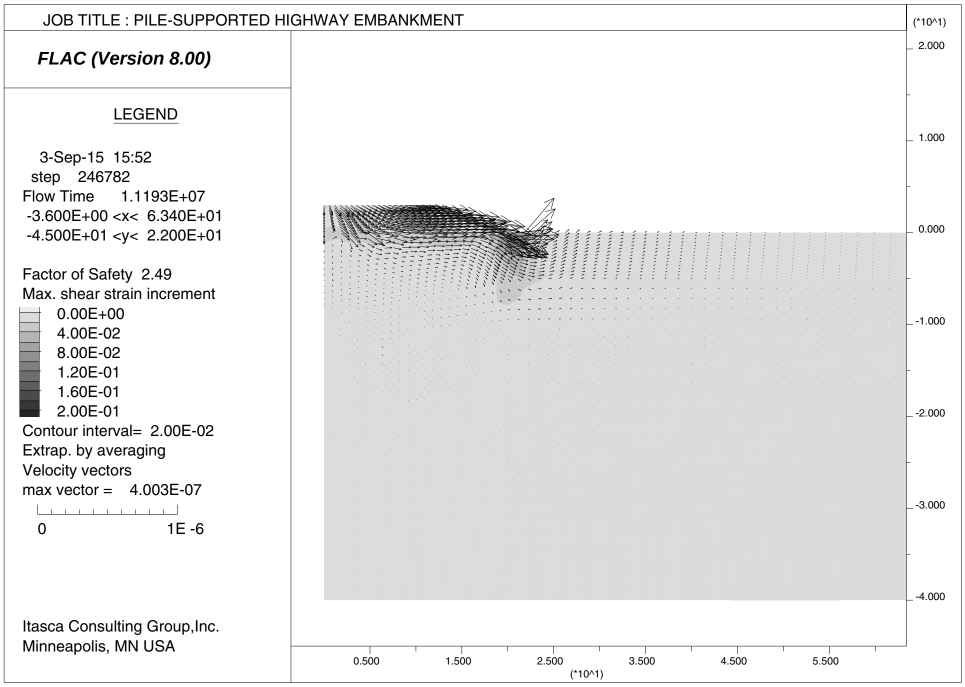


Figure 14.14 Factor of safety and failure surface plot for supported embankment