T U N A Plus

Tunnel Analysis Program

Version 7.01

COMTEC RESEARCH

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Introduction

1.1. Overview

TUNA Plus is a fully automated computer program developed for tunnel analysis such as NATM (New Austrian Tunneling Method), TBM, Shield, etc. TUNA Plus employs SMAP-S2 which is a static, two-dimensional, nonlinear finite element program developed by COMTEC RESEARCH. Pre- and post-processors of TUNA Plus are built-in so that only the physical geometries and material properties associated with a proposed tunnel are required as input and graphical outputs can be obtained directly.

1.2 Features

Features of TUNA Plus include:

- Nonlinear Liner-Medium Interaction
- English and Metric Units
- Geometry of Tunnels;
  - Single Tunnel (Half Section)
  - Single Tunnel (Full Section)
  - Symmetric Two Tunnels
  - Unsymmetric Two Tunnels
- Multi-Layered Geological Medium
- Liner Loads
  - Weight
  - Water Pressure
  - Loosening Load
  - Support Degradation
- Circular, Horseshoe, or User Defined Tunnel Shapes
- Plain Concrete and Reinforced Concrete Liners

- Multi-Staged Excavations
- shotcrete and Rock Bolt Installation
- Graphical Outputs
  - Ground Surface Settlement
  - Tunnel Deformed Shape
  - Principal Stress in the Shotcrete and the Surrounding Medium
  - Contours of Safety Factor
  - Axial Stresses of Rock Bolt
  - Deformed Shape of Liner
  - Bending Moment, Thrust, and Shear in the Liner
  - Stresses in the Reinforcing Bars
  - Stresses in the Extreme Fibers of the Liner
  - Displacement History at Ground Surface, Tunnel Crown, Spring Line, and Invert

1.3 Assumptions

Assumptions for NATM tunnel analysis:

- Plane strain condition in the longitudinal tunnel direction.
- Each excavation stage involves three steps; the step for stress release before placing soft shotcrete or rock bolts, the step for which shotcrete remains in soft state, and the step for which shotcrete remains in hard state.
- Liners are installed when the tunnel excavation is completed. Liner deformations are due to self weight, ground water pressure, loosening load, and degradaion of primary supports.
- Surrounding medium and shotcrete are modeled by continuum element with Mohr-Coulomb material model.
- Rock bolts are modeled by nonlinear truss element.
- Liners are modeled by reinforced layered beam elements with Mohr-Coulomb material model.
- Interface between the liner and the surrounding medium is modeled by joint element with Mohr-Coulomb material model.

Installing TUNA Plus

2.1 Minimum System Requirements

✓ Windows 32 bit operating system
✓ Intel Pentium 4 or AMD processors
✓ 4 GB Ram with 30 GB free space in Drive C
✓ SVGA monitor

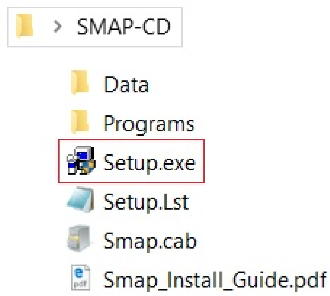
2.2 Installation Procedure

1. Uninstall if there are pre-existing SMAP programs.
   To uninstall SMAP programs, remove following program using Add/Remove in Control Panel:
   SMAP
   Delete following files if they are existing:
   C:\Program Files\Smap
   C:\Windows\Setup1.exe
   Rename or delete following folders if they are existing:
   C:\SMAP
   C:\SmapKey

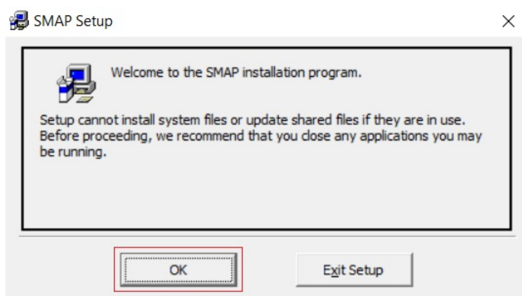
2. Download SMAP-CD.exe from the Download section of www.ComtecResearch.com

3. Run SMAP-CD.exe
   SMAP-CD folder will be created with SMAP installation programs

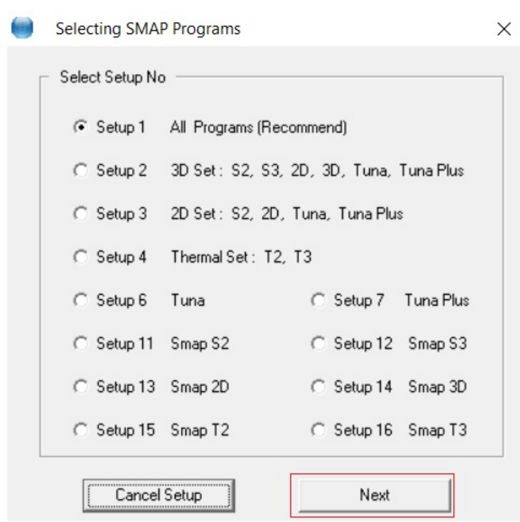
4. Double-click **Setup.exe**



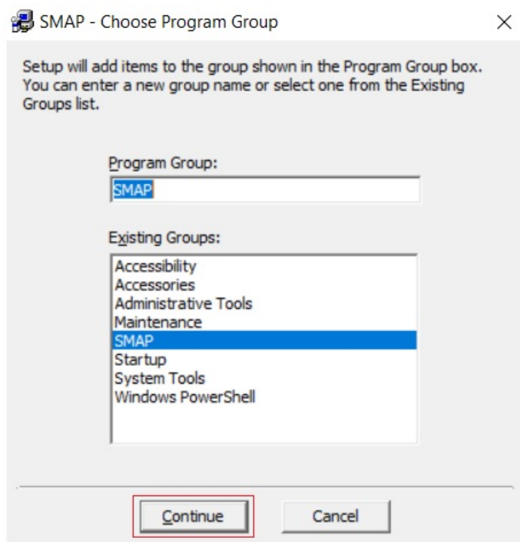
5. Click **OK**



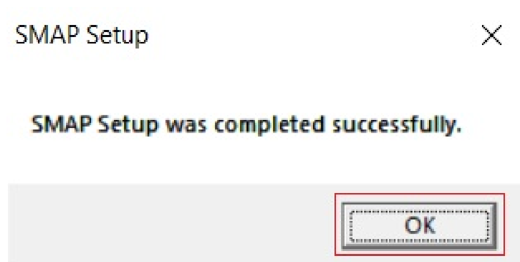
6. Click **Next**
   It will take few minutes.
   Wait until next step.



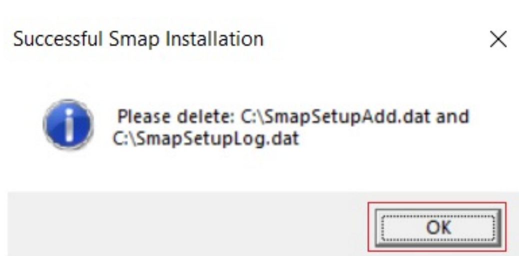
7. Click **Continue**



8. Click **OK**



9. Click **OK**



Note:

Following two log files will be generated once finished:
C:\SmapSetupAdd.dat
C:\SmapSetupLog.dat

If Smap Installation is successful, delete these two files.

If Smap Installation is not successful,
follow the instruction in SmapSetupAdd.dat.

If you still have problems with Smap Installation,
send these two files to info@ComtecResearch.com

Running Programs

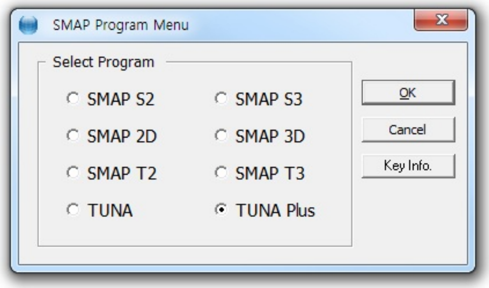
3.1 Introduction

Once you prepared the input file as described in Section 4, running **TUNA Plus** program is straightforward since finite element meshes and graphical instruction files are automatically generated.

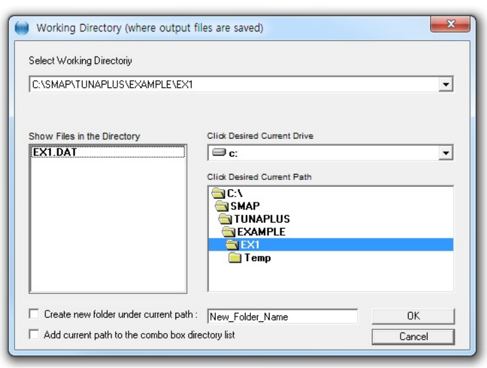
Accessing TUNA Plus Program

1. When it is the first time, you copy Smap.exe in C:\Ct\Ctmenu and setup a Shortcut to SMAP Icon on your computer desktop. Then You simply double-click SMAP Shortcut.

2. Select **TUNA Plus** radio button and then click **OK** button.

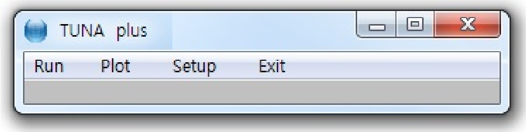


3. Next, you need to select **Working Directory**. Working Directory should be the existing directory where all the output files are saved. It is a good idea to have all your input files for the current project in this Working Directory. Click the disk drive, double-click the directory, and then **OK** button. Note that when you select **Working Directory**, a sub directory **Temp** is created automatically. All intermediate scratch files are saved in this sub directory **Temp**.

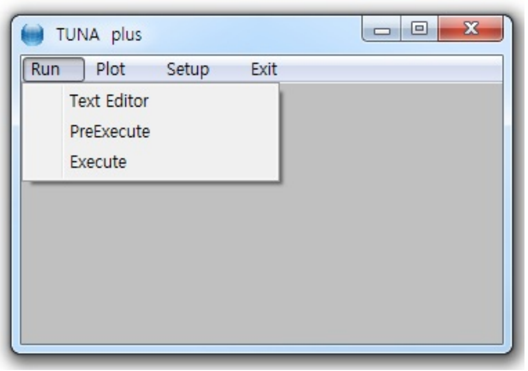


TUNA Plus Menu

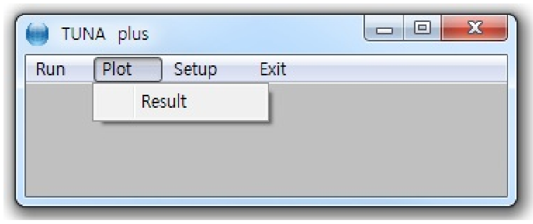
TUNA Plus provides the following Main Menus; Run, Plot, Setup and Exit.



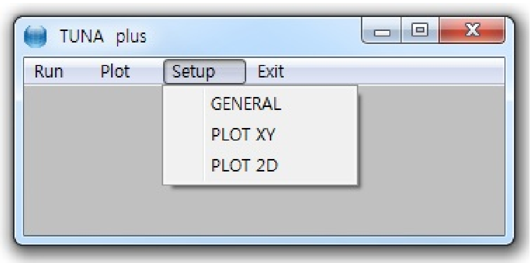
RUN executes main processing program and has following Sub Menus; Text Editor, Pre Execute and Execute.



PLOT executes Result. Result is associated with post-processing programs to show graphically the computed results.



SETUP is mainly used to set plotting control parameters for PLOT-XY and PLOT-2D and has the following Sub Menus; General, PLOT-XY and PLOT-2D.

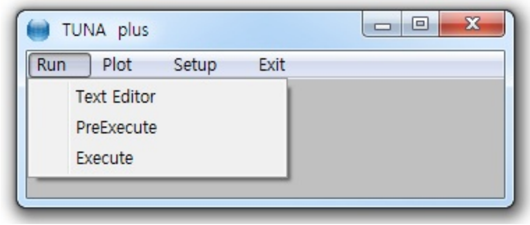


EXIT is used to end TUNA Plus.

3.2 RUN Menu

Once you have prepared the input file according to Section 4, you are ready to execute TUNA Plus main-processing program by selecting Execute.

RUN Menu has the following Sub Menus; Text Editor, Pre Execute, and Execute.



TEXT EDITOR is used to create or modify the input file using Notepad.

PRE EXECUTE is used either to check the input file or to generate plotting information files. **PRE EXECUTE** is especially useful when you want to check input data to see whether there is any input error. It is also useful when you have finished **EXECUTE** but you want to add or modify the Post File for plot. In this case, you edit the Post File as you want, run **PRE EXECUTE** and then run post-processing programs in **PLOT** menu.

EXECUTE executes TUNA Plus main-processing program.

TUNA Plus Output Files

Once you execute TUNA Plus, generally you can obtain following output files:

CONTSS.DAT	Contains stresses/strains in continuum element
BEAMSF.DAT	Contains section forces in beam element
TRUSS.DAT	Contains stresses/strains in truss element
DISPLT.DAT	Contains nodal displacements

It should be noted that all of your output files are saved in the Working Directory that you specified at the beginning.

TUNA Plus Graphical Output

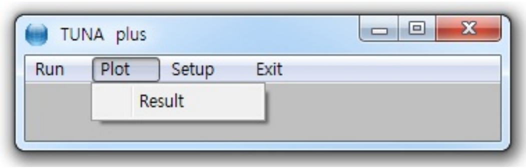
TUNA Plus Post-processing programs can generate the following graphical output:

- Finite element mesh
- Deformed shape
- Principal stress distribution
- Section forces in beam element
- Extreme fiber stresses/strains in beam elements
- Axial force/stress/strain in truss element
- Contours of stresses, strains and factor of safety
- Time histories of displacements

Graphical output can be followed by running RESULT from PLOT Menu.

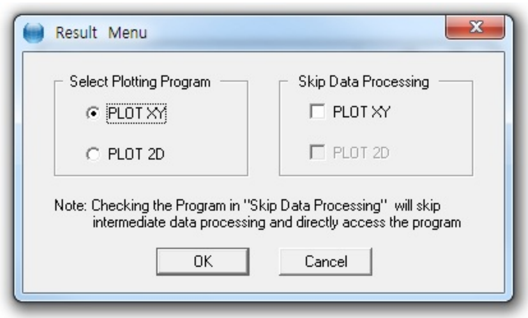
3.3 PLOT Menu

PLOT is to show graphically Computed Result.



Once you finished executing TUNA Plus main-processing program, you need to run post-processing programs to show graphically numerical results.

PLOT Menu contains PLOT-XY and PLOT-2D



PLOT-XY plots time histories of displacements at specified locations. Refer to PLOT-XY User's Manual in Section 13 in SMAP-S2 Manual

PLOT-2D plots contours of continuum stresses, beam section forces, truss axial force/stress/strain, principal stress vectors, and deformed shapes. Refer to PLOT-2D User's Manual in Section 14 in SMAP-S2 Manual.

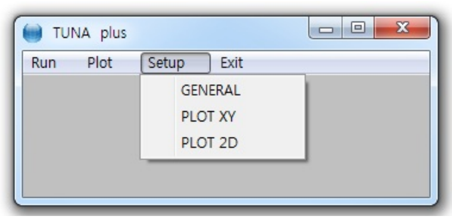
Note: When you first plot results, do not check the check box in Skip Data Processing. When you replot results, however, you can check the check box to skip intermediate data processing. This will save time and keep modified output data.

3.4 SETUP Menu

You need to run SETUP Menu

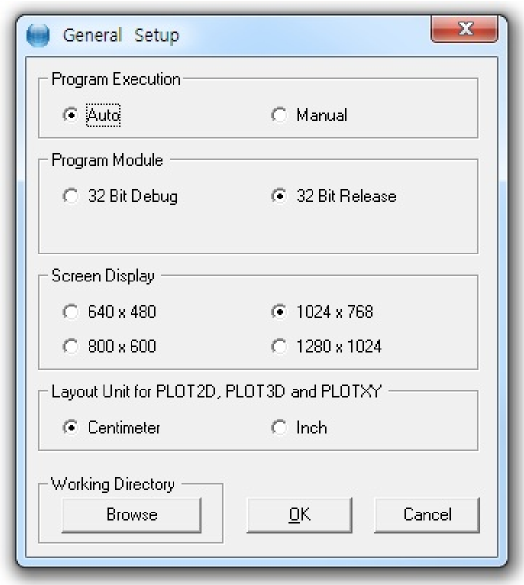
- To specify TUNA Plus main-processing program module.
- To adjust scales of graphical outputs from PLOT-XY and PLOT-2D.

SETUP Menu has three Sub Menus; General, PLOT-XY and PLOT-2D



3.4.1 General Setup

General Setup has five different items; Program Execution, Program Module, Screen Display, Layout Unit, and Working Directory.



Program Execution has two options; Auto and Manual.
For Manual Execution, refer to Section 3.5 in User's Manual.

Program Module has two options. 32 Bit Debug and 32 Bit Release. Debug program modules run slower but gives more detailed information when run time errors occur. For most cases, 32 Bit Release is recommended.

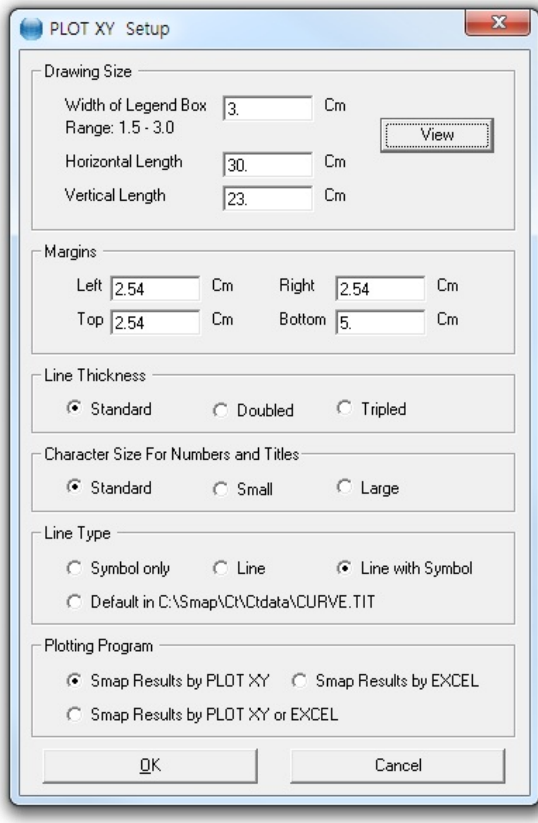
Screen Display has four options; 640x480, 800x600, 1024x768, and 1280x1024. This will affect the size of child window in PLOT-XY and PLOT-2D.

Layout Unit is used for PLOT-XY and PLOT-2D. You can select either Centimeter or Inch in specifying plot scales and dimensions.

Working Directory is to change the current working directory. When you click the Browse button, Working Directory dialog will be shown so that you can select new directory.

3.4.2 PLOT-XY Setup

PLOT-XY Setup is mainly used to specify scales and dimensions of post processing program PLOT-XY. It has six different items; Drawing Size, Margins, Line Thickness, Character Size, Line Type, and Plotting Program.



Drawing Size controls the size of output. Once you specify Legend Box Width, Horizontal and Vertical Length, you can click **View** button to see the scaled layout.

Margins is used to shift the drawing area. Left margin is the distance from the left edge of printer page to the left frame line. In the similar way, you can specify Top, Right, and Bottom margins.

Line Thickness specifies the thickness of lines. This option is not used.

Character Size for Numbers and Titles specifies the size of characters for numbers and titles. It has three options; Standard, Small, and Large.

Line type is used to specify default line type and has four options; Symbol only, Line, Line with Symbol, and Default in C:\Smap \Ct \Ctdata \Curve.tit.

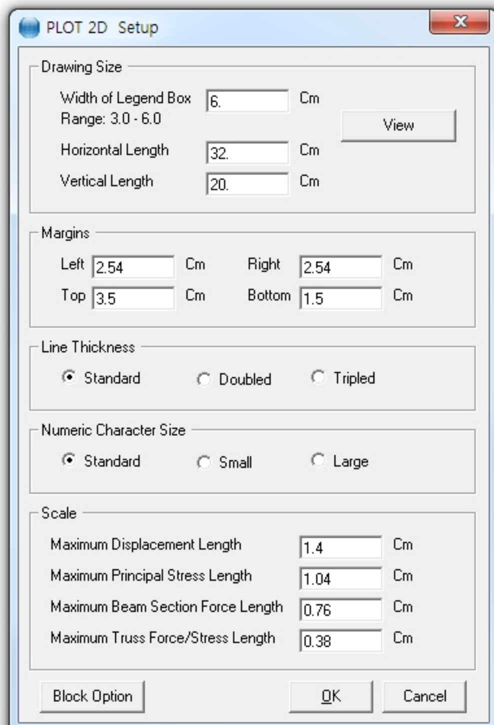
Plotting Program is used to specify default program to plot Smap results. It has three options; PLOT-XY, EXCEL, and PLOT-XY or EXCEL. Last option is to select either PLOT-XY or EXCEL at the time you plot results.

3.4.3 PLOT-2D Setup

PLOT-2D Setup is mainly used to specify scales and dimensions of post processing program PLOT-2D. It has six different items; Drawing Size, Margins, Line Thickness, Numeric Character Size, Scale and Block Option. The first four items are much similar to those described in PLOT-XY Setup.

Scale specifies Maximum Displacement Length, Maximum Principal Stress Length, Maximum Beam Section Force Length, and Maximum Truss Force/Stress Length, which will be shown on PLOT-2D.

Block Option specifies options to generate either PRESMAP Output or Block Diagram. This option is not available for TUNA Plus.



3.5 Manual Procedure to Run TUNA Plus

Occasionally, you need to execute TUNA Plus main-processing program manually to see what is going on each step, specially when terminated due to some errors.

Method 1

1. Select Setup -> General -> Manual in Program Execution
2. Select Run -> Execute
3. Select TUNA Plus input file when displaying file open dialog
4. Now TUNA Plus is running on Windows Command Line
5. Type Enter key to continue to next step or Control C to stop

Method 2

1. Select CMD and go to Working Directory
2. Change to Temp sub directory

   Create Temp sub directory if not existing.

   Type MD Temp

   Then change to this sub directory.

   Type CD Temp

   Now, the files in the Working Directory can be accessed by prefixing "..\" to the file name.
3. Type C:\Smap\Ct\Ctbat\TUNAPLUS.bat
4. Type ..\EX1.Dat to access input file in Working Directory, for example
5. Type Enter key to continue to next step or Control C to stop

3.6 Debugging TUNA Plus Main-Processing Program

Debug information would be helpful in the following cases:

- Having run time errors
- Extracting convergence
- Checking elapsed time

In order to get debug information, you need to modify the file "Smap_S2.dat" in the directory C:\Smap\Ct\Ctdata\Debug

```
     1,     11,       1,       1,      1,    100,         90
IDEBUG, NCLDEB, IOUTDEB, ICONVER, NELDEB, NO_MAX, NO_RESTART

   This "DEBUG.DAT" file allows listing of status with
   elapsed time information while running main process of
   SMAP programs.   This is the very useful features to see
   where it spends most time and where it stops.

   IDEBUG   =  0 : Do not print debug information.
               1 : Print debug information. Refer to IOUTDEB.
               2 : Print debug information in each individual
                   files based on NO_MAX and NO_RESTART and
                   save in C:\SMAP\SMAPS2\DEBUG (NOT AVAILABLE)

   NCLDEB        : Ending cycle number.
                   No printing debug information after NCLDEB.

   IOUTDEB =   0 : Debug information on screen.
               1 : Debug information on file,
                   Smap_S2.deb in Working Directory\Temp

   ICONVER =   0 : Do not print convergence information.
               1 : Print the ratio of displacement increment
                   to current displacement (DU/U)

   NELDEB   = -1 : Do not print element information in element
                   level operation.
            =  0 : Print current element number in element
                   level operation.
            >  0 : Print debug information for the element
                   number NELDEB in element level operation.

   NO_MAX        : Maximum number of individual files.
                   Used for IDEBUG = 2.

   NO_RESTART    : Restart number for individual file
                   once it reaches NO_MAX.
                   Used for IDEBUG = 2.
```

Description of Input Data

TUNA Plus consists of six major card groups.

The first card group includes general information; Job title (TITLE), Unit selection (IUNIT), Model selection (MODEL), and specification of Excavation order (IEXORDER, IEZ_I).

The second card group specifies tunnel analysis boundaries.

The third card group specifies soil/rock layer information, distributed surface load, and material properties of shotcrete, lining, rock bolt, and interface.

The fourth card group specifies dimensions of tunnels, shotcrete, lining, and rock bolts.

The fifth card group specifies stress release associated with excavation and shotcrete modulus change. It should be noted that each excavation involves three steps:

- Step for stress release before placing soft shotcrete or rock bolts
- Step for which shotcrete remains in soft state
- Step for which shotcrete remains in hard state

The last card group contains external loads for lining analysis; ground water pressure, loosening load (localized gravity load), and primary support degradation.

Program assumes that lining is placed after all tunnel deformations due to excavation are completed. Linings are assumed to be subjected to the following four different loadings in sequential order; weight, water pressure, loosening load, and support degradation.

Card Group	Input Data and Definitions
1 General Information See Figure 4.1	1.1 TITLE TITLE Any title (Max = 60 characters) TITLE will be shown on the graphical output
	1.2 IUNIT IUNIT Length Force Pressure Unit Weight 1 in lb lb/in^2 lb/in^3 2 cm kg kg/cm^2 kg/cm^3 3 m ton ton/m^2 ton/m^3
	1.3 MODEL, IGEN, IEXMESH, ILNCOUPL, IEXORDER, IRBP MODEL = 1 Single tunnel. Half section = 2 Single tunnel. Full section = 3 Two tunnels. Symmetric = 4 Two tunnels. Unsymmetric IGEN = 0 Line contour plot = 1 Color-filled contour plot = 2 Smooth color-filled contour plot IEXMESH = 0 No user supplied mesh ILNCOUPL = 0 Lining coupled with surrounding rock IEXORDER = 0 Built-in excavation order = 1 User specified excavation order IRBP = 0 Rock bolt placed during soft shotcrete = 1 Rock bolt placed during hard shotcrete = 2 Rock bolt not placed

Card Group	Input Data and Definitions
1 General Information	1.4 Excavation Order If IEXORDER = 0, go to next Card Group 2 MODEL = 1: IEZ_1, IEZ_2 = 2: IEZ_1, IEZ_2, IEZ_3, IEZ_4 = 3: IEZ_1, IEZ_2, IEZ_3, IEZ_4, IEZ_5, IEZ_6, IEZ_7, IEZ_8 = 4: IEZ_1, IEZ_2, IEZ_3, IEZ_4, IEZ_5, IEZ_6, IEZ_7, IEZ_8 IEZ_i Excavation order number for i^{th} zone. See Figure 4.3 Ex, IEZ_3 = 1 means that zone 3 is excavated first Note For IEXORDER= 0, tunnel cores are excavated in the following order: 1. Upper core in right tunnel 2. Lower core in right tunnel 3. Upper core in left tunnel 4. Lower core in left tunnel

Card Group	Input Data and Definitions
2 Tunnel Analysis Boundary See Figure 4.1	2.1 MODEL = 1: HT, HL, W, DX, DY, NY = 2: HT, HL, W, DX, DY, NY = 3: HT, HL, W, WP, DX, DY, NY = 4: HT, HL, W, WP, HP, DX, DY, NY HT Tunnel depth HL Depth from springline to bottom boundary W Horizontal distance from left to right boundary WP Horizontal distance from left tunnel center line to right tunnel center line HP Vertical distance from right tunnel springline to left tunnel springline. When HP is positive, left tunnel springline is above the right tunnel springline. DX Far-field horizontal element length DY Far-field vertical element length NY Maximum number of elements in vertical direction

<table>
<tr><th>Card Group</th><th>Input Data and Definitions</th></tr>
<tr><td rowspan="2">3

Soil / Rock Layer Information See Figure 4.1</td><td>3.1
NLAYER

NLAYER Total number of layers. Max = 10</td></tr>
<tr><td>3.2
NLAYER Cards: LAYERNO, H, GAMA, RKo, E, V, PHI [-m], C [s], T [sigc]
- - - - - - -
- - - - - - -

LAYERNO Soil/rock layer number
H Thickness of soil/rock layer
GAMA Unit weight
RKo Coefficient of earth pressure at rest
E Young's modulus
V Poisson's ratio
PHI [-m] Internal friction angle (°)
C [s] Cohesion
T [sigc] Tensile strength
Program takes absolute value of T as tensile strength. For negative value of T, stiffness reduction associated with tensile crack is considered.

Note: If a negative sign is prefixed to the value of PHI, program assumes Hoek and Brown material model. For m, s, and sigc, refer to SMAP-S2 User's Manual Page 4-25</td></tr>
</table>

<table>
<tr><th>Card Group</th><th colspan="2">Input Data and Definitions</th></tr>
<tr><td rowspan="2">3

Additional Top Soil / Rock Layers</td><td colspan="2">3.3.1

NATLAYER

NATLAYER — Number of additional top soil/rock layers. Maximum = 5.

If NATLAYER = 0, go to Card Group 3.4</td></tr>
<tr><td>3.3.2

For Each Specified Layer</td><td>3.3.2.1

GAMA, RKo, E, V, PHI, C, T

GAMA — Unit weight
RKo — Coefficient of earth pressure at rest
E — Young's modulus
V — Poisson's ratio
PHI — Internal friction angle (°)
C — Cohesion
T — Tensile strength. See Note in Card 3.2</td></tr>
</table>

<table>
<tr><th>Card Group</th><th colspan="2">Input Data and Definitions</th></tr>
<tr><td rowspan="2">3

Additional Top Soil / Rock Layers</td><td colspan="2">3.3.3

NUMSXP

NUMSXP   Number of specified x points. Max = 100</td></tr>
<tr><td>3.3.4

For Each X Point See Figure 4.4</td><td>3.3.4.1

X_i , H_{i1}, …, $H_{i\ NATLAYER}$

X_i X distance from left boundary
H_{ij} Height of j^{th} top layer at X_i</td></tr>
</table>

<table>
<tr><th>Card Group</th><th colspan="2">Input Data and Definitions</th></tr>
<tr><td rowspan="4">3
User Specified Soil / Rock Layers</td><td colspan="2">3.4.1
NUSLAYER

NUSLAYER Number of user specified soil/rock layers. Maximum = 10.

If NUSLAYER = 0, go to Card Group 3.5.1</td></tr>
<tr><td rowspan="3">For Each Specified Layer</td><td>3.4.2
LAYERNO

LAYERNO Layer number</td></tr>
<tr><td>3.4.3
X_1, Y_1, X_2, Y_2, X_3, Y_3, X_4, Y_4

X_i, Y_i X and Y coordinates defining soil/rock layer See Figure 4.5

Note: Original soil/rock material properties in this region will be replaced by the user specified properties provided in the next Card 3.4.4</td></tr>
<tr><td>3.4.4
GAMA, RKo, E, V, PHI [-m], C [s], T [sigc]

For the description of parameters, refer to the Note in Card 3.2</td></tr>
</table>

<table>
<tr><th>Card Group</th><th colspan="2">Input Data and Definitions</th></tr>
<tr><td rowspan="2">3

User Specified Distributed Surface Load</td><td colspan="2">3.5.1

NUSXPD

NUSXPD — Number of user specified x points for distributed surface load. Max = 100</td></tr>
<tr><td>For Each X Point</td><td>3.5.2.1

X_i, q_i

X_i — X distance from left boundary
q_i — Intensity of vertical distributed load at X_i

See Figure 4.6</td></tr>
</table>

<table>
<tr><th>Card Group</th><th>Input Data and Definitions</th></tr>
<tr><td rowspan="3">3
Shotcrete / Lining / Rock Bolt Material Property Data</td><td>3.6
Shotcrete Properties
E, V, PHI, C, T, GAMA
<table>
<tr><td>E</td><td>Young's modulus</td></tr>
<tr><td>V</td><td>Poisson's ratio</td></tr>
<tr><td>PHI</td><td>Internal friction angle (°)</td></tr>
<tr><td>C</td><td>Cohesion</td></tr>
<tr><td>T</td><td>Tensile strength. See Note in Card 3.2</td></tr>
<tr><td>GAMA</td><td>Unit weight</td></tr>
</table></td></tr>
<tr><td>3.7
Lining Properties
E_C, V_C, PHI, C, T, GAMA, E_R, V_R
<table>
<tr><td>E_C</td><td>Young's modulus of concrete</td></tr>
<tr><td>V_C</td><td>Poisson's ratio of concrete</td></tr>
<tr><td>PHI</td><td>Internal friction angle (°) of concrete</td></tr>
<tr><td>C</td><td>Cohesion of concrete</td></tr>
<tr><td>T</td><td>Tensile strength of concrete</td></tr>
<tr><td>GAMA</td><td>Unit weight</td></tr>
<tr><td>E_R</td><td>Young's modulus of reinforcing bar</td></tr>
<tr><td>V_R</td><td>Poisson's ratio of reinforcing bar</td></tr>
</table></td></tr>
<tr><td>3.8
Rock Bolt Properties
A, WL, E, STRSI, σ_y, ε_f
<table>
<tr><td>A</td><td>Cross section area</td></tr>
<tr><td>WL</td><td>Weight per unit length</td></tr>
<tr><td>E</td><td>Young's modulus</td></tr>
<tr><td>STRSI</td><td>Initial stress</td></tr>
<tr><td>σ_y</td><td>Yield stress</td></tr>
<tr><td>ε_f</td><td>Strain at rupture. For $\varepsilon_f \leq \sigma_y /E$, ε_f represents yield strain at tension</td></tr>
</table></td></tr>
</table>

Card Group	Input Data and Definitions
3 Interface Between Shotcrete and Lining (For ILNCOUPL = 0)	3.9 Interface Properties If ILNCOUPL = 1, go to next Card Group 4 Elastic Modulus and Joint Thickness NM, E, G, t NM = 0 Linear elastic joint = 2 Nonlinear joint E Elastic Young's modulus G Elastic shear modulus t Joint thickness Strength Parameters [Only for NM = 2] C, φ C Cohesion φ Friction angle (°) Normal Stress-Strain Relation [Only for NM = 2] ε_1, ε_2, ε_3, ε_4, σ_1, σ_2, σ_3, σ_4 ε_i, σ_i Pair of strain (ε_i) and stress (σ_i) to define normal stress-strain relation. Tension is positive

Card Group	Input Data and Definitions
4 Tunnel Dimension (Repeat this card group for left tunnel when MODEL = 4)	4.0 ISTYPE, GR, GA ISTYPE = 1 Horseshoe shape tunnel section = 2 Egg shape tunnel section = 3 User defined tunnel section GR Growing rate for near-field element. Use GR = 1 GA Normalized mid length. Use GA = 0.5

Card Group	Input Data and Definitions
4 Tunnel Dimension (Repeat this card group for the left tunnel when MODEL = 4)	4.1 For ISTYPE = 1 or 2 R_1, A_1, R_2, A_2, R_3, A_3, R_4 For ISTYPE = 3 NSEG, S_{HOR}, S_{TR}, S_{BR} NSEG Cards: For Straight Line 0, X_b, Y_b, X_e, Y_e, T_L, A_{SI}, A_{SO} For Circular Arc R, X_o, Y_o, θ_b, θ_e, T_L, A_{SI}, A_{SO} - - - - - - - - R_1, R_2, R_3, R_4 Radius as shown in Figure 4.2a or 4.2b A_1, A_2, A_3 Angle (°) as shown in Figure 4.2a or 4.2b NSEG Number of segments to define tunnel shape S_{HOR} Arc length at boundary of upper and lower cores S_{TR} Arc length at midpoint between crown and springline S_{BR} Arc length at midpoint between invert and springline X_b, Y_b Beginning X and Y coordinate of straight line X_e, Y_e Ending X and Y coordinate of straight line X_o, Y_o X and Y coordinate of circular arc orgin θ_b, θ_e Beginning and ending angle (°) of circular arc T_L Thickness of lining A_{SI} Area of inner reinforcing bar A_{SO} Area of outer reinforcing bar Note: For ISTYPE = 1 $R_4 = 0$: Invert is flat $R_4 < 0$: Invert depth is given as absolute value of R_4

<table>
<tr><th>Card Group</th><th>Input Data and Definitions</th></tr>
<tr><td rowspan="2">4

Tunnel Dimension (Repeat this card group for left tunnel when MODEL = 4)</td><td>4.2

INVSHOT, T_{S}, INVLN, T_{L}, D_{I}, A_{SI}, D_{O}, A_{SO}

INVSHOT = -1 No shotcrete
= 0 No shotcrete at invert
= 1 Full shotcrete

T_{S} Thickness of shotcrete

INVLN = -1 Lining is not placed
= 0 Lining is placed before tunnel excavation
= 1 Lining is placed after tunnel excavation

T_{L} Thickness of lining

D_{I}, Inner reinforcing bar cover depth
A_{SI}, Inner reinforcing bar area

D_{O}, Outer reinforcing bar cover depth
A_{SO} Outer reinforcing bar area</td></tr>
<tr><td>4.3

NUMRB, L_{RB}, $L_{SPACING}$, $T_{SPACING}$, NSRB

NUMRB Number of rock bolts
Example: NUMRB = 11 in Figure 4.2

L_{RB} Length of rock bolt
$L_{SPACING}$ Rock bolt spacing in longitudinal direction
$T_{SPACING}$ Rock bolt spacing in tangential direction

NSRB Number of elements between rock bolts
Use NSRB = 2 or 3</td></tr>
</table>

Card Group	Input Data and Definitions
5 Excavation Stress Release and Shotcrete Modulus Change	5.1 PSR, PASR, RESH PSR — Percent of stress release before placing soft shotcrete or rock bolts PASR — Percent of additional stress release from soft to hard shotcrete RESH — Ratio of the Young˙s modulus in soft shotcrete to the Young˙s modulus in hard shotcrete

Card Group	Input Data and Definitions
6 External Loads for Lining Analysis	6.1 LDTYPE LDTYPE = 0 Do not perform lining analysis = 1 Perform lining analysis If LDTYPE = 0, rest of cards are ignored
	6.2 Ground Water Pressure LGWINV, NWPSTEP, DGW, GAMAW LGWINV = 0 Ground water pressure is not included = 1 Ground water pressure on lining invert NWPSTEP Number of load steps for water pressure. Max=400. If NWPSTEP = 0, water pressure is not considered DGW Depth of ground water table from ground surface GAMAW Unit weight of water

<table>
<tr><th>Card Group</th><th colspan="2">Input Data and Definitions</th></tr>
<tr><td rowspan="3">External Loads for Lining Analysis</td><td colspan="2">6.3.1
<u>Loosening Load</u>
LSDADD, NLDSTEP, HPRES, VPRES

LSDADD: Additional vertical loosening load
= 0 Not included
= 1 Included

NLDSTEP: Number of load steps for loosening load. Max=400
If NLDSTEP = 0, loosening load is not considered

HPRES: Horizontal pressure due to loosening load
VPRES: Vertical pressure due to loosening load</td></tr>
<tr><td rowspan="2">Additional Vertical Loosening Load</td><td>6.3.2.1
<u>Additional Vertical Loosening Load for Right Tunnel</u>
If LSDADD = 0, skip this card

ΔX_{v1}, ΔX_{v2}, Q_{v1}, Q_{v0}, Q_{v2}

ΔX_{v1}, Δx_{v2}: X distance of left and right end of distributed load, measured from crown

Q_{v1}, Q_{v0}, Q_{v2}: Intensity of vertical distributed load at left end, center, and right end
See Figure 4.7</td></tr>
<tr><td>6.3.2.2
<u>Additional Vertical Loosening Load for Left Tunnel</u>
Required only for LSDADD = 1 and MODEL= 3 or 4

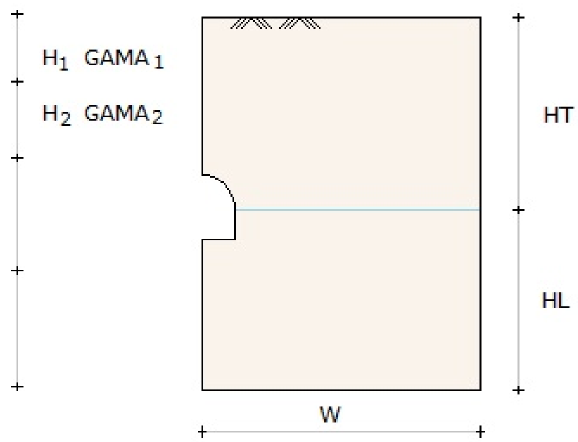
ΔX_{v1}, ΔX_{v2}, Q_{v1}, Q_{v0}, Q_{v2}

ΔX_{v1}, Δx_{v2}: X distance of left and right end of distributed load, measured from crown

Q_{v1}, Q_{v0}, Q_{v2}: Intensity of vertical distributed load at left end, center, and right end
See Figure 4.7</td></tr>
</table>

Card Group	Input Data and Definitions
6 External Loads for Lining Analysis	6.4 Primary Support Degradation LPSDEG, REDH LPSDEG = 0 No primary support degradation = 1 Include deactivation of rock bolt and degradation of shotcrete modulus REDH Ratio of Young's modulus in degraded shotcrete to the Young's modulus in hard shotcrete
	6.5 Subgrade and Lining Property If ILNCOUPL = 0, skip this card SUBGK, ITSPR, NUMSJ SUBGK Coefficient of subgrade reaction ITSPR = 0 No tangential spring = 1 Add tangential spring NUMSJ Number of segment joints Available for circular shape of MODEL 2
	6.6 Joint Locations If NUMSJ = 0, skip this card AJ_1, AJ_1, ... , AJ_{NUMSJ} AJ_i Angle (degrees) from crown top ($AJ_i \leq 180$)

MODEL = 1 Single Tunnel [Half Section]



MODEL = 2 Single Tunnel [Full Section]

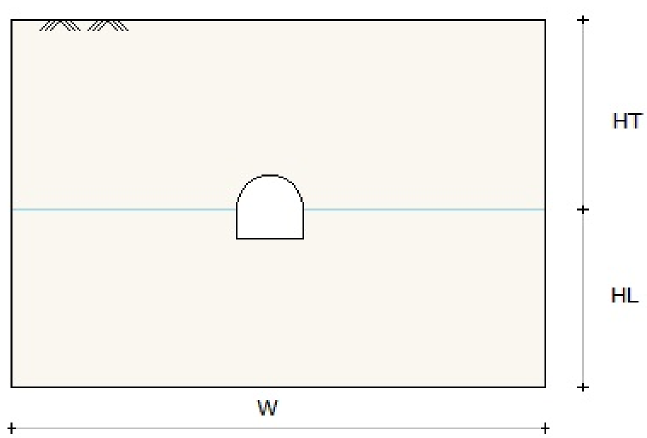
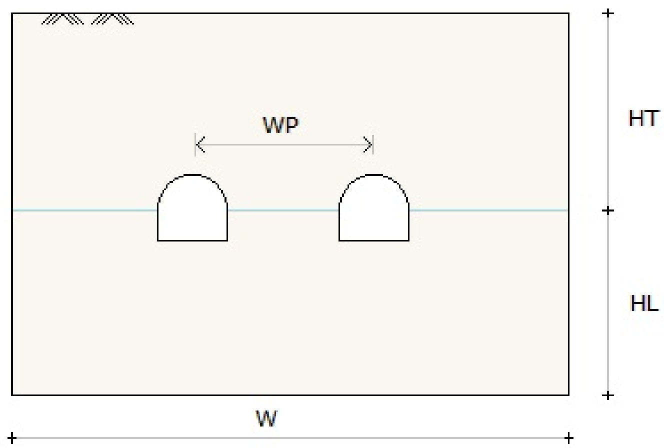


Figure 4.1 Schematic tunnel section for MODEL= 1 and 2

MODEL= 3 Two Tunnel [Symmetric Section]



MODEL= 4 Two Tunnel [Unsymmetric Section]

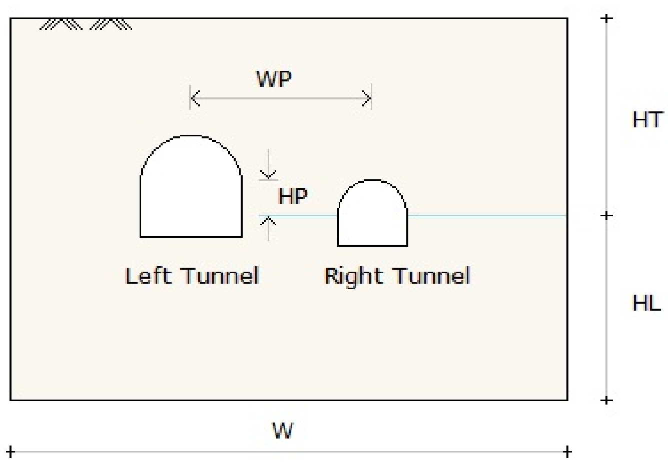


Figure 4.1 Schematic tunnel section for MODEL= 3 and 4

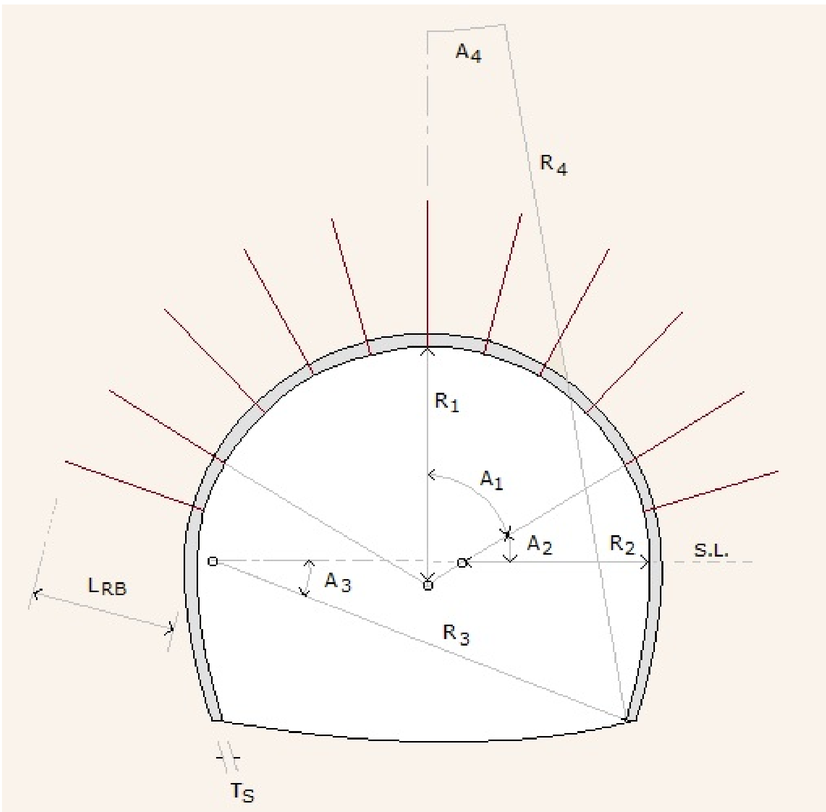


Figure 4.2a Horseshoe shape tunnel dimension
ISTYPE = 1 ($A_1 + A_2 = 90^{\circ}$)

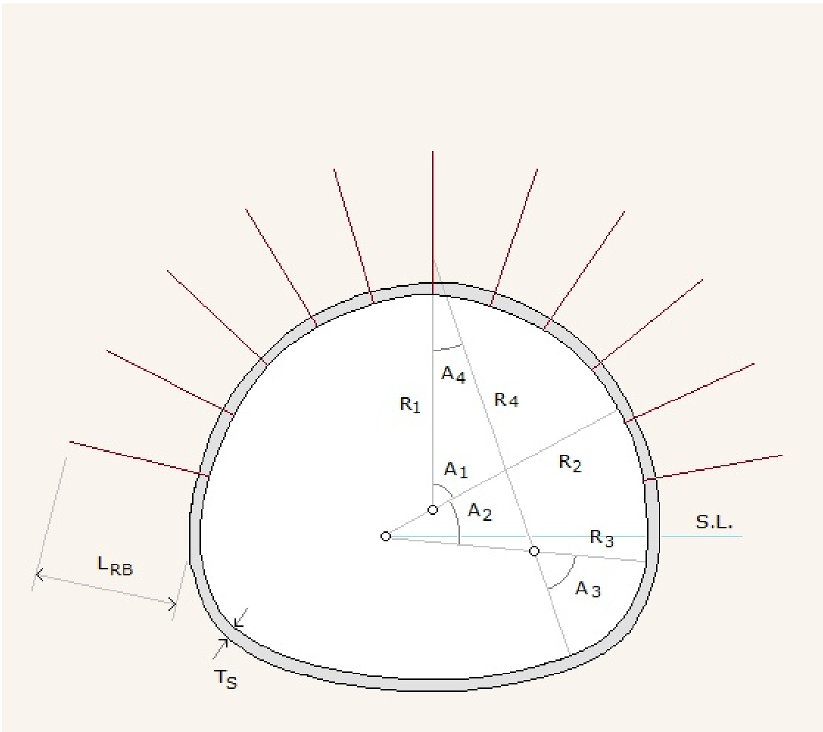


Figure 4.2b Egg shape tunnel dimension
ISTYPE = 2 ($A_1 + A_2 > 90^\circ$)

Note When arc length of a segment is less than $T_{spacing}$ / NSRB, that segment is considered as corner segment

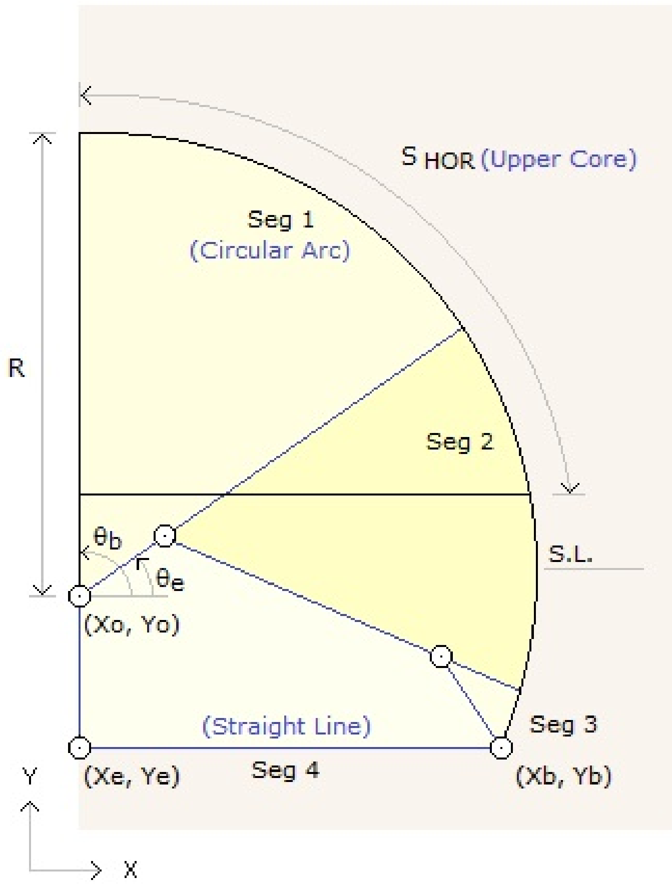


Figure 4.2c User defined tunnel dimension for ISTYPE = 3

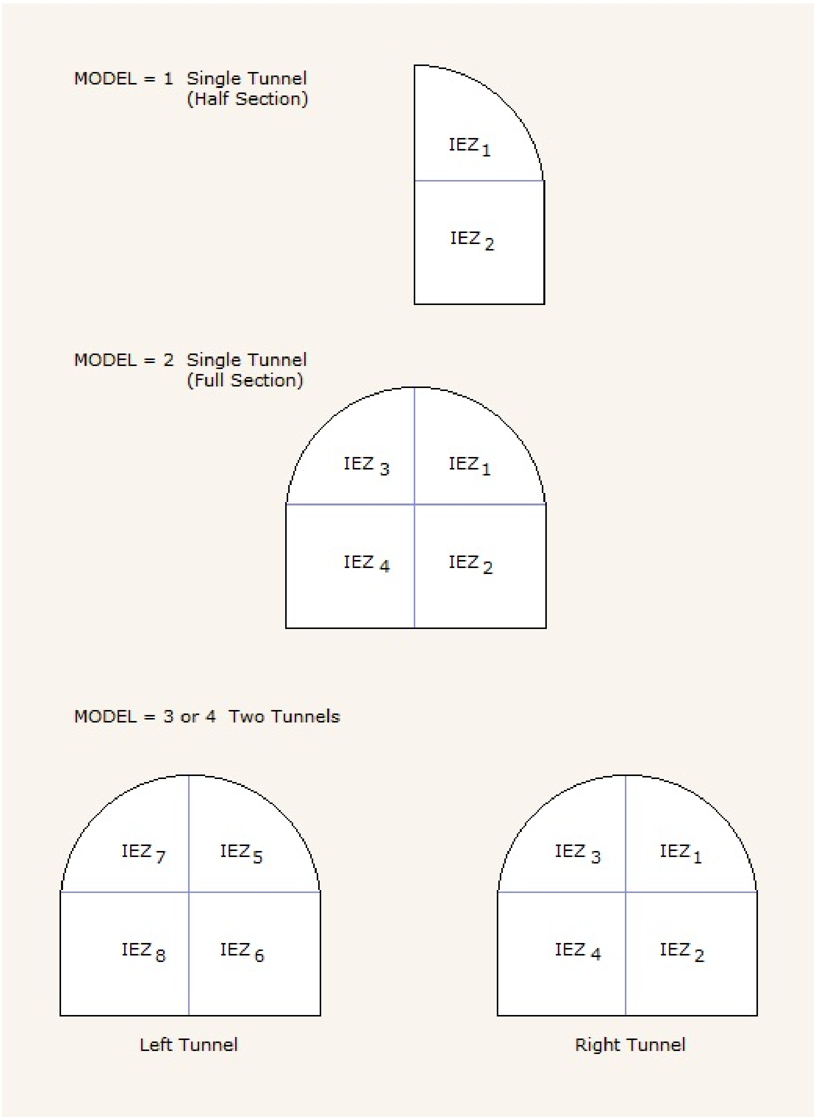


Figure 4.3 Designation of excavation zone

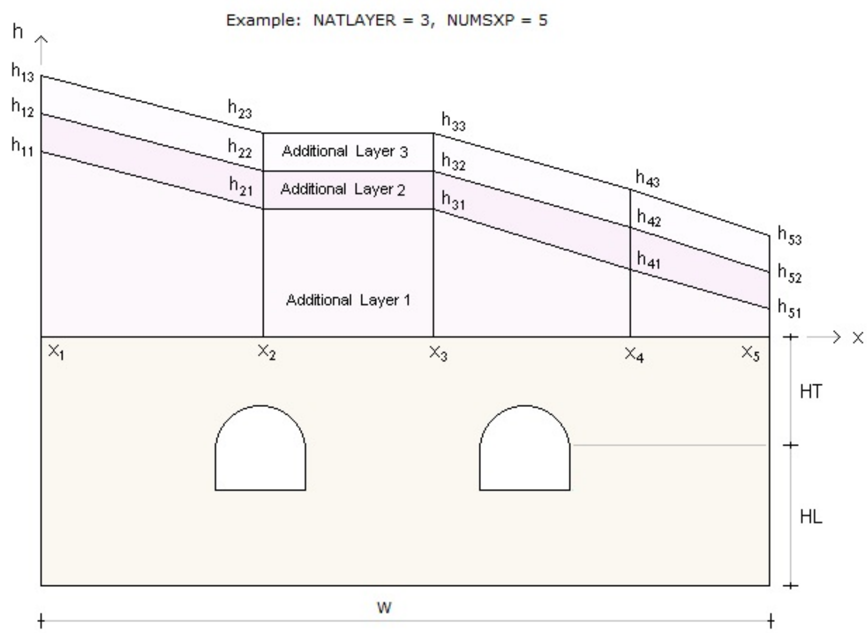


Figure 4.4 Specification of additional top soil/rock layers

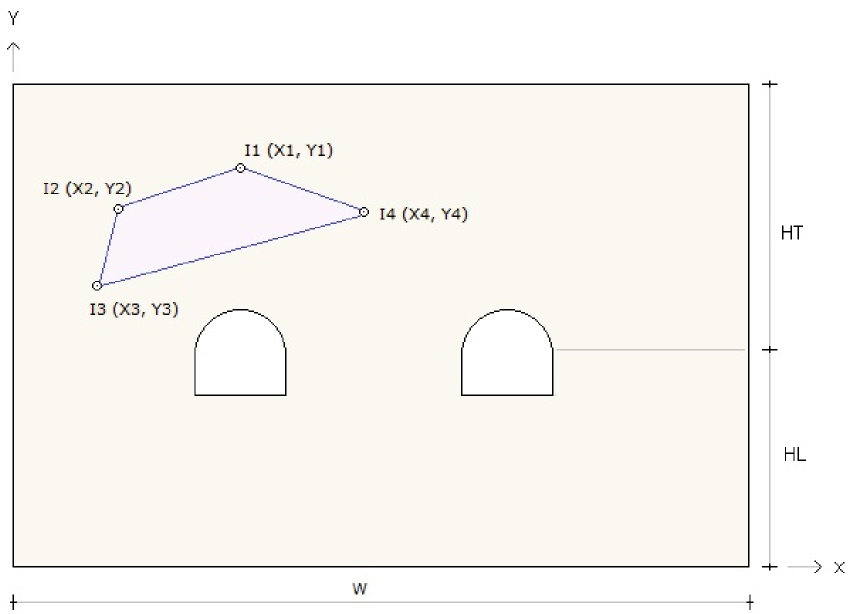


Figure 4.5 User specified soil/rock layers

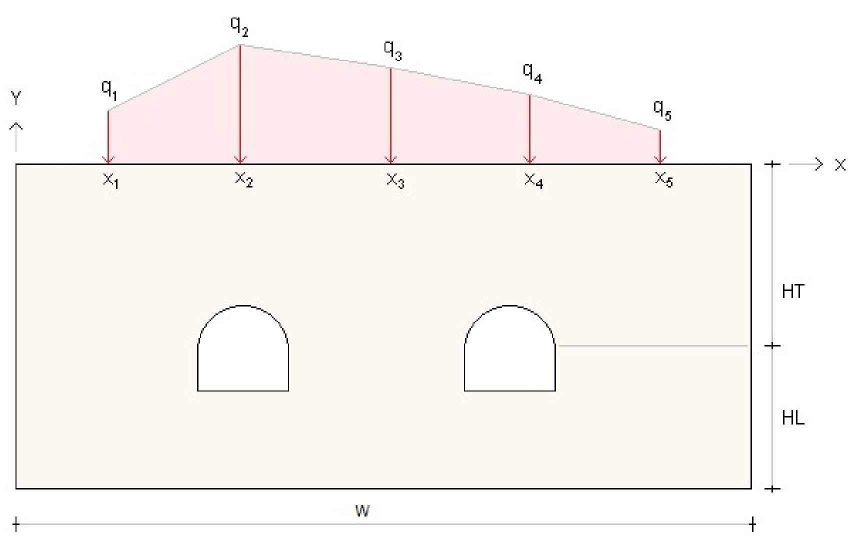


Figure 4.6 User specified distributed surface load

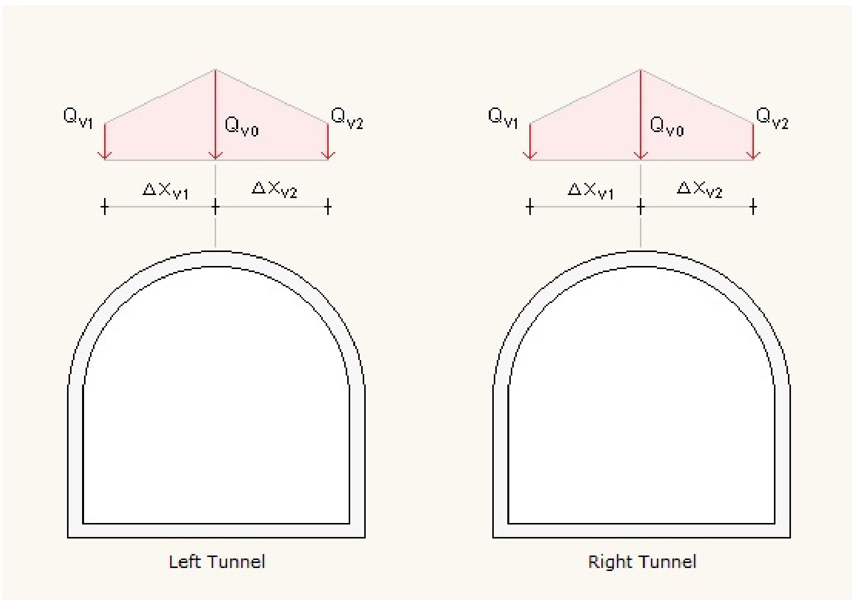


Figure 4.7 Additional vertical loosening load

Description of Output Data

Program TUNA Plus automatically generates graphical outputs once the calculation of tunnel analysis is completed. Graphical outputs from tunnel excavation and lining analysis are summarized in Tables 5.1 and 5.2 respectively. These graphical outputs can be obtained by executing PLOT-2D in PLOT Menu. Sign conventions and notations used for section forces and strains in the liner are shown in Figure 5.1.

Graphical outputs of displacement history at key locations shown in Figure 5.2 can also be obtained by executing PLOT-XY in PLOT Menu.

Once the calculation of TUNA Plus is finished, you can obtain following three text files:

STEP.LST	Contains listing of major computational steps
PLTDS.LST	Contains listing of generated graphical outputs which are summarized in Tables 5.1 and 5.2. To get this file, select PLOT-2D in PLOT Menu.
PLTXY.LST	Contains listing of generated displacement history graphical outputs. To get this file, select PLOT-XY in PLOT Menu.

Table 5.1 Graphical output from tunnel excavation analysis

Plot Descriptions
Finite Element Mesh
Ground Surface Settlement
Tunnel Deformed Shape
Principal Stress Distribution in Surrounding Rock
Principal Stress Distribution in Shotcrete
Contours of Safety Factor in Surrounding Rock
Axial Stress in Rock Bolts

Table 5.2 Graphical output from tunnel lining analysis

Plot Descriptions
Lining Deformed Shape
Bending Moment
Thrust
Shear
Inner Extreme Fiber Stress
Outer Extreme Fiber Stress
Inner Reinforcing Bar Stress
Outer Reinforcing Bar Stress

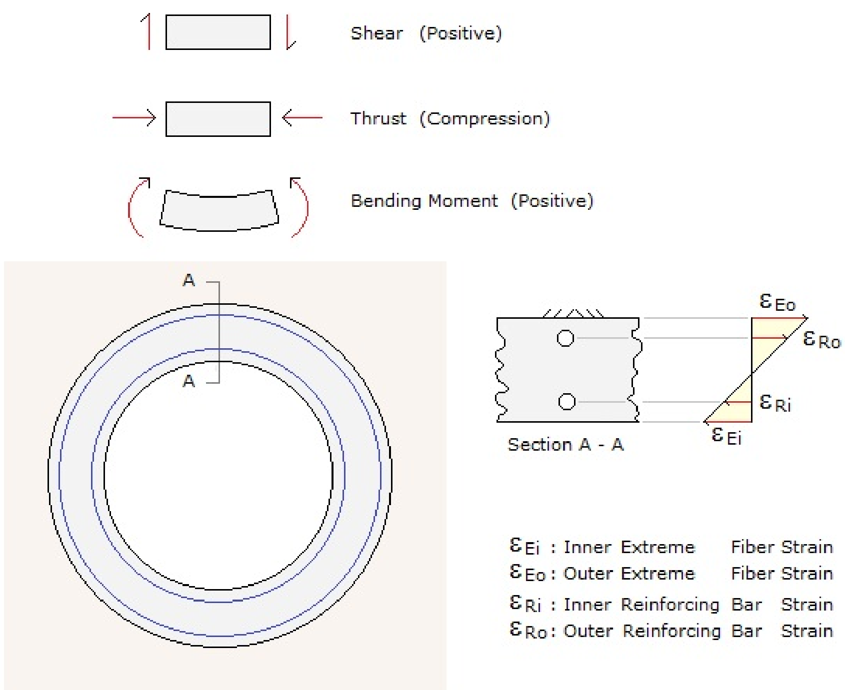


Figure 5.1 Sign conventions and notations used for section forces and strains in the liner

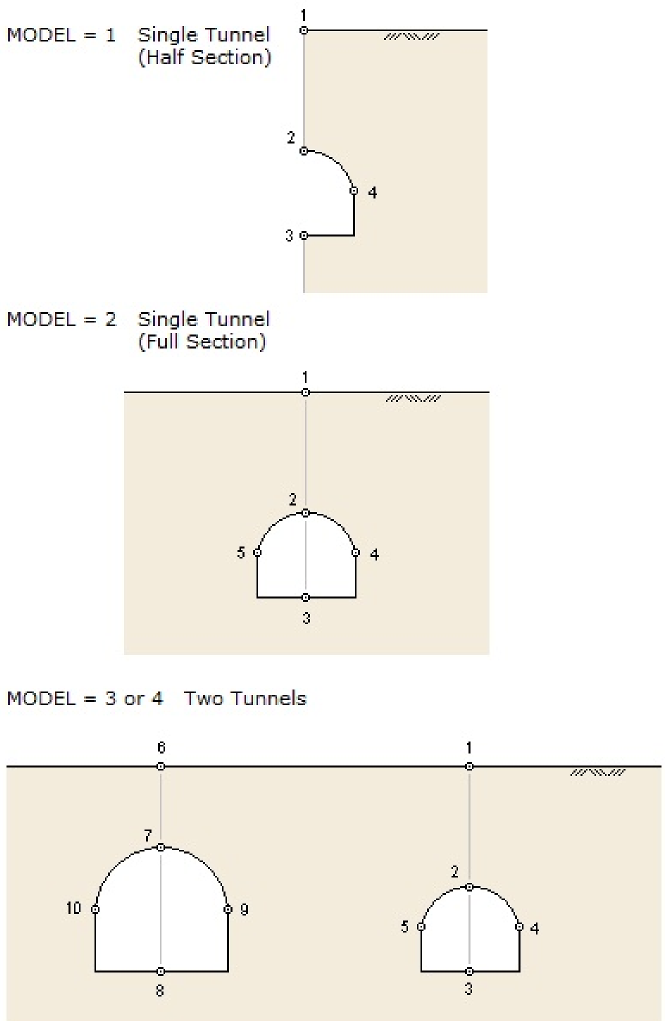


Figure 5.2 Locations for displacement history plot by PLOT-XY

Example Problems

This section is to illustrate how TUNA Plus can be applied for the analysis of tunnel problems. Main features of example problems are summarized in Table 6.1. First four example problems involve typical NATM tunnel excavation analysis followed by lining analysis. For each example problem, brief problem descriptions, listing of input files, and graphical outputs are presented.

Table 6.1 List of example problems

Problem Number	File Name	Run Time (min) PIII 850 MHZ	Description
1	EX1.DAT	0.47	Half section of single tunnel with reinforced concrete liner [MODEL 1]
2	EX2.DAT	4.78	Full section of single tunnel with reinforced concrete liner [MODEL 2]
3	EX3.DAT	5.42	Symmetric two tunnels with reinforced concrete liner [MODEL 3]
4	EX4.DAT	8.03	Unsymmetric two tunnels with reinforced concrete liner [MODEL 4]
5	EX5.DAT	0.88	Inclined top soil layer [Problem No. 2]
6	EX6.DAT	0.82	Inclined rock layer between soft and hard rocks [Problem No. 2]
7	EX7.DAT	0.72	Distributed surface load [Problem No. 5]
8	EX8.DAT	4.42	User defined tunnel shapes [MODEL 4]
9	EX9.DAT	2.08	Box tunnel liner subjected to full excavation load [Problem No. 8]

6.1 Example 1

Example 1 represents half section of a single tunnel as schematically shown in Figure 6.2.

A typical NATM tunnel shape is chosen here to be analyzed using program TUNA Plus. Geometric parameters related to tunnel shape, rock bolts, shotcrete, and liner are given in Figure 6.1. Geological profile, tunnel depth, and analysis boundaries are specified in Figure 6.2. Material properties of soil/rock layers and supports are summarized in Table 6.2.

As shown in Table 6.3, tunnel construction involves two major excavation stages; upper core excavation and lower core excavation. Each excavation stage is associated with three load steps; 50 % stress release, additional 25% stress release where soft shotcrete and rock bolts are installed, and the last 25% stress release where shotcrete is hardened. It should be noted that program TUNA Plus uses first two load steps to generate in situ K_o stress state.

For lining analysis, reinforced concrete liner is considered with interface joint element between the liner and the surrounding medium. The interface joint properties are set to allow separation when the tensile stress develops in the direction normal to the interface while full slippage is assumed along the interface.

For loads acting on the reinforced concrete liner, following four different load combinations are considered:
1. Weight
2. Weight+Water Pressure
3. Weight+Water Pressure+Loosening Load
4. Weight+Water Pressure+Loosening Load+Support Degradation

Ground water pressure is applied to the liner except the invert. As loosening load, a uniform vertical stress as shown in Table 6.3 is applied to liner. As support degradation, rock bolts are deactivated.

The input file EX1.DAT is listed in Table 6.4. Output file STEP.LST in Table 6.5 lists steps where major excavations take place and external lining loads are applied.

Graphical outputs from PLOT-2D are shown in Figures 6.3 to 6.47. Brief description of these plots are shown in the text output file PLTDS.LST in Table 6.6.

Displacement history graphical outputs from PLOT-XY are shown in Figures 6.48 to 6.51. Brief description of these plots are shown in the text output file PLTXY.LST in Table 6.7.

Table 6.2 Material property

Material Type	γ [t/m^3]	K_o	E [t/m^2]	ν	φ [°]	C [t/m^2]	T [t/m^2]
Weathered Soil	1.90	0.50	2.00×10^3	0.33	30	3	20
Weathered Rock	1.90	0.43	5.000×10^3	0.30	35	30	30
Soft Rock	2.40	0.33	2.00×10^4	0.25	40	70	40
Hard Rock	2.55	0.25	2.00×10^5	0.20	45	100	50
Shotcrete (Soft)	2.40		0.50×10^6	0.20	30	500	100
Shotcrete (Hard)	2.40		1.50×10^6	0.20	30	500	100
Rock Bolt			2.10×10^7				
Reinforced Concrete Lining	2.50		2.10×10^6	0.20	30	500	300
Reinforcing Bar			2.10×10^7	0.20			
Interface Joint			2.00×10^5		5	0.001	0.02

Table 6.3 Simulation of construction sequence

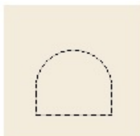
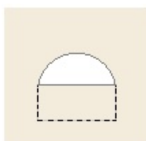
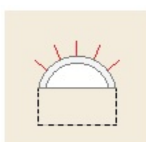
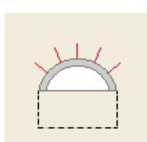
<table>
<tr><th>Step</th><th>Construction State</th><th colspan="2">Descriptions</th></tr>
<tr><td>1,2</td><td></td><td colspan="2">In Situ K_o State</td></tr>
<tr><td>3</td><td></td><td>50 % Stress Relief</td><td rowspan="3">Upper Core
Excavation</td></tr>
<tr><td>4</td><td></td><td>75 % Stress Relief
Soft Shotcrete
Rock Bolt</td></tr>
<tr><td>5</td><td></td><td>100 % Stress Relief
Hard Shotcrete
Rock Bolt</td></tr>
</table>

Table 6.3 Simulation of construction sequence (Continued)

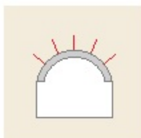
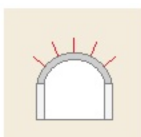
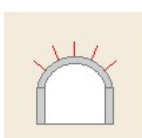
<table>
<tr><th>Step</th><th>Construction State</th><th colspan="2">Descriptions</th></tr>
<tr><td>6</td><td></td><td>50% Stress Relief</td><td rowspan="3">Lower Core
Excavation</td></tr>
<tr><td>7</td><td></td><td>75% Stress Relief
Soft Shotcrete
Rock Bolt</td></tr>
<tr><td>8</td><td></td><td>100% Stress Relief
Hard Shotcrete
Rock Bolt</td></tr>
</table>

Table 6.3 Simulation of construction sequence (Continued)

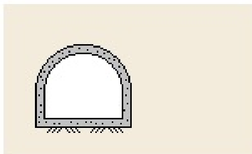
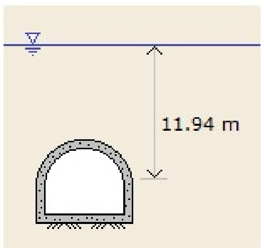
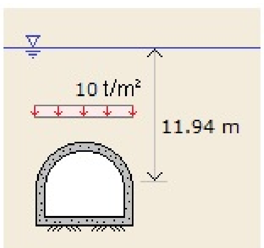
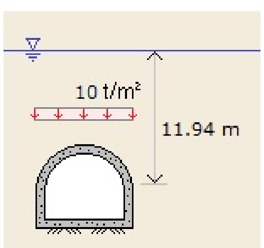
Step	Construction State	Descriptions
9		Lining Subjected to: Weight
12		Lining Subjected to: Weight + Water Pressure
15		Lining Subjected to: Weight + Water Pressure + Loosening Load
16		Lining Subjected to: Weight + Water Pressure + Loosening Load + Rock Bolt Deactivation

Table 6.4 Listing of input file EX1.DAT

```
*
* GENERAL INFORMATION
*
* CARD 1.1
* TITLE
  EXAMPLE PROBLEM ( MODEL 1 )
*
* CARD 1.2
* IUNIT
  3
*
* CARD 1.3
* MODEL  IGEN  IEXMESH  ILNCOUPL  IEXORDER IRBP
  1      0     0        0         0        0
*
* TUNNEL ANALYSIS BOUNDARY
*
* CARD 2.1
* HT    HL   W    DELTAX  DELTAY  NDYMAX
  21.94 30.  20.  2.0     2.0     40
*
* SOIL / ROCK LAYER INFORMATION
*
* CARD 3.1
* NLAYER
  4
* CARD 3.2
* LAYERNO   H     GAMA  RKO  E       V    PHI   C    T
  1         4.2   1.9   0.5  2000.   0.33 30.   3.   20.
  2         4.3   1.9   0.43 5000.   0.30 35.   30.  30.
  3         3.5   2.4   0.33 20000.  0.25 40.   70.  40.
  4         39.94 2.55  0.25 200000. 0.20 45.   100. 50.
*
* ADDITIONAL TOP SOIL / ROCK LAYER
*
* CARD 3.3.1
* NATLAYER
  0
*
* USER SPECIFIED SOIL / ROCK LAYER
*
* CARD 3.4.1
* NUSLAYER
  0
*
```

```
*
* USER SPECIFIED DISTRIBUTED SURFACE LOAD
*
* CARD 3.5.1
* NUSXPD
  0
*
* USER SPECIFIED DISTRIBUTED SURFACE LOAD
*
* CARD 3.5.1
* NUSXPD
  0
*
* SHOTCRETE PROPERTIES
*
* CARD 3.6
* E          V       PHI    C       T     GAMA
  1.5E+06    0.2     30.    500.    100.  2.4
*
* LINING PROPERTIES
*
* CARD 3.7
* E          V       PHI    C       T     GAMA   ER        VR
  2.1E+06    0.2     30.    500.    300.  2.5    2.1E+07   0.2
*
* ROCK BOLT PROPERTIES
*
* CARD 3.8
* A          WL         E          STRSI     SIGMAy     Ef
  0.000491   0.00383    2.1E+07    0.0       2.3E+04    1.0
*
* INTERFACE PROPERTIES BETWEEN SHOTCRETE AND LINING
*
* CARD 3.9
* NM        E       G        t
  2         200000. 2.0      0.001
* C         PHI
  0.001     5.0
* E1        E2      E3       E4      S1       S2      S3      S4
 -1.0       0.0     1.0E-7   1.0    -200000. 0.0      2.E-02  2.E-02
*
* TUNNEL DIMENSION
*
* CARD 4.0
* ISTYPE    GR      GA
  1         1.0     0.5
*
```

```
*
* CARD 4.1
* R1     A1    R2     A2   R3     A3      R4
  5.24   60.   4.24   30.  9.86   19.781  23.86
* CARD 4.2
* INVSHOT  TS       INVLN     TL      DI     ASI     DO    ASO
  0        0.15     1         0.3     0.05   0.0022  0.05  0.0022
* CARD 4.3
* NUMRB    LRB      LSPACING  TSPACING  NSRB
  11       3.0      1.35      1.2        2
*
* EXCAVATION STRESS RELEASE AND SHOTCRETE MODULUS CHANGE
*
* CARD 5.1
* PSR      PASR     RESH
  50.      25.      0.33
*
* EXTERNAL LOADS FOR LINING ANALYSIS
*
* CARD 6.1
* LDTYPE
  1
*
* WATER PRESSURE
*
* CARD 6.2
* LGWINV   NWPSTEP  DGW     GAMAW
  0        3        10.     1.0
*
* LOOSENING LOAD
*
* CARD 6.3.1
* LSDADD   NLDSTEP  HPRES   VPRES
  0        3        0.0     10.0
*
* PRIMARY SUPPORT DEGRADATION
*
* CARD 6.4
* LPSDEG   REDH
  1        1.0
*
* END OF DATA
```

Table 6.5 Listing of text output file STEP.LST

STEP NO	DESCRIPTIONS
5	Excavation of Upper Core
8	Excavation of Lower Core
9	<u>Lining Subjected to:</u> Weight
12	<u>Lining Subjected to:</u> Weight Water Pressure
15	<u>Lining Subjected to:</u> Weight Water Pressure Loosening Load
16	<u>Lining Subjected to:</u> Weight Water Pressure Loosening Load Rock Bolt Deactivation & Shotcrete Degradation

Table 6.6 Listing of text output file PLTDS.LST

PLOT NO	TITLE
1	FINITE ELEMENT MESH EXAMPLE PROBLEM (MODEL 1)
2	DEFORMED SHAPE AT LOAD STEP = 5 EXAMPLE PROBLEM (MODEL 1)
3	DEFORMED SHAPE AT LOAD STEP = 8 EXAMPLE PROBLEM (MODEL 1)
4	DEFORMED SHAPE AT LOAD STEP = 5 EXAMPLE PROBLEM (MODEL 1)
5	DEFORMED SHAPE AT LOAD STEP = 8 EXAMPLE PROBLEM (MODEL 1)
6	PRINCIPAL STRESS DISTRIBUTION AT LOAD STEP = 5 EXAMPLE PROBLEM (MODEL 1)
7	PRINCIPAL STRESS DISTRIBUTION AT LOAD STEP = 8 EXAMPLE PROBLEM (MODEL 1)
8	PRINCIPAL STRESS DISTRIBUTION AT LOAD STEP = 5 EXAMPLE PROBLEM (MODEL 1)
9	PRINCIPAL STRESS DISTRIBUTION AT LOAD STEP = 8 EXAMPLE PROBLEM (MODEL 1)
10	Contours of Safety Factor AT LOAD STEP = 5 EXAMPLE PROBLEM (MODEL 1)
11	Contours of Safety Factor AT LOAD STEP = 8 EXAMPLE PROBLEM (MODEL 1)

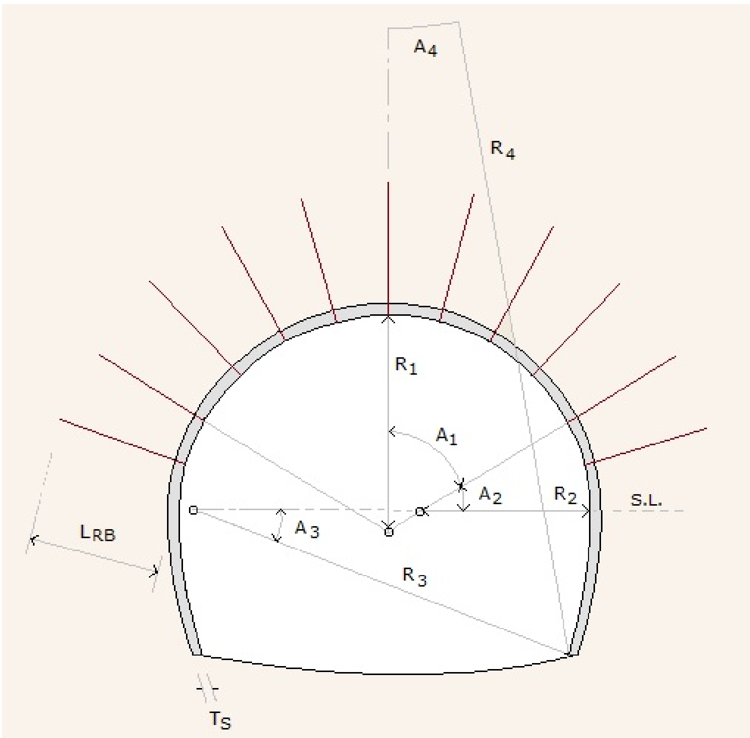
12	AXIAL STRESS AT LOAD STEP = 5 EXAMPLE PROBLEM (MODEL 1)
13	AXIAL STRESS AT LOAD STEP = 8 EXAMPLE PROBLEM (MODEL 1)
14	DEFORMED SHAPE AT LOAD STEP = 9 EXAMPLE PROBLEM (MODEL 1)
15	DEFORMED SHAPE AT LOAD STEP = 12 EXAMPLE PROBLEM (MODEL 1)
16	DEFORMED SHAPE AT LOAD STEP = 15 EXAMPLE PROBLEM (MODEL 1)
17	DEFORMED SHAPE AT LOAD STEP = 16 EXAMPLE PROBLEM (MODEL 1)
18	BENDING MOMENT AT LOAD STEP = 9 EXAMPLE PROBLEM (MODEL 1)
19	THRUST AT LOAD STEP = 9 EXAMPLE PROBLEM (MODEL 1)
20	SHEAR AT LOAD STEP = 9 EXAMPLE PROBLEM (MODEL 1)
21	INNER EXTREME FIBER STRESS AT LOAD STEP = 9 EXAMPLE PROBLEM (MODEL 1)
22	OUTER EXTREME FIBER STRESS AT LOAD STEP = 9 EXAMPLE PROBLEM (MODEL 1)

23	INNER REINFORCING BAR STRESS AT LOAD STEP = 9 EXAMPLE PROBLEM (MODEL 1)
24	OUTER REINFORCING BAR STRESS AT LOAD STEP = 9 EXAMPLE PROBLEM (MODEL 1)
25	BENDING MOMENT AT LOAD STEP = 12 EXAMPLE PROBLEM (MODEL 1)
26	THRUST AT LOAD STEP = 12 EXAMPLE PROBLEM (MODEL 1)
27	SHEAR AT LOAD STEP = 12 EXAMPLE PROBLEM (MODEL 1)
28	INNER EXTREME FIBER STRESS AT LOAD STEP = 12 EXAMPLE PROBLEM (MODEL 1)
29	OUTER EXTREME FIBER STRESS AT LOAD STEP = 12 EXAMPLE PROBLEM (MODEL 1)
30	INNER REINFORCING BAR STRESS AT LOAD STEP = 12 EXAMPLE PROBLEM (MODEL 1)
31	OUTER REINFORCING BAR STRESS AT LOAD STEP = 12 EXAMPLE PROBLEM (MODEL 1)
32	BENDING MOMENT AT LOAD STEP = 15 EXAMPLE PROBLEM (MODEL 1)
33	THRUST AT LOAD STEP = 15 EXAMPLE PROBLEM (MODEL 1)

34	SHEAR AT LOAD STEP = 15 EXAMPLE PROBLEM (MODEL 1)
35	INNER EXTREME FIBER STRESS AT LOAD STEP = 15 EXAMPLE PROBLEM (MODEL 1)
36	OUTER EXTREME FIBER STRESS AT LOAD STEP = 15 EXAMPLE PROBLEM (MODEL 1)
37	INNER REINFORCING BAR STRESS AT LOAD STEP = 15 EXAMPLE PROBLEM (MODEL 1)
38	OUTER REINFORCING BAR STRESS AT LOAD STEP = 15 EXAMPLE PROBLEM (MODEL 1)
39	BENDING MOMENT AT LOAD STEP = 16 EXAMPLE PROBLEM (MODEL 1)
40	THRUST AT LOAD STEP = 16 EXAMPLE PROBLEM (MODEL 1)
41	SHEAR AT LOAD STEP = 16 EXAMPLE PROBLEM (MODEL 1)
42	INNER EXTREME FIBER STRESS AT LOAD STEP = 16 EXAMPLE PROBLEM (MODEL 1)
43	OUTER EXTREME FIBER STRESS AT LOAD STEP = 16 EXAMPLE PROBLEM (MODEL 1)
44	INNER REINFORCING BAR STRESS AT LOAD STEP = 16 EXAMPLE PROBLEM (MODEL 1)
45	OUTER REINFORCING BAR STRESS AT LOAD STEP = 16 EXAMPLE PROBLEM (MODEL 1)

Table 6.7 Listing of text output file PLTXY.LST

PLOT NO	TITLE
1	DISPLACEMENT HISTORY AT LOCATION : 1 AT NODE 443
2	DISPLACEMENT HISTORY AT LOCATION : 2 AT NODE 1
3	DISPLACEMENT HISTORY AT LOCATION : 3 AT NODE 233
4	DISPLACEMENT HISTORY AT LOCATION : 4 AT NODE 14

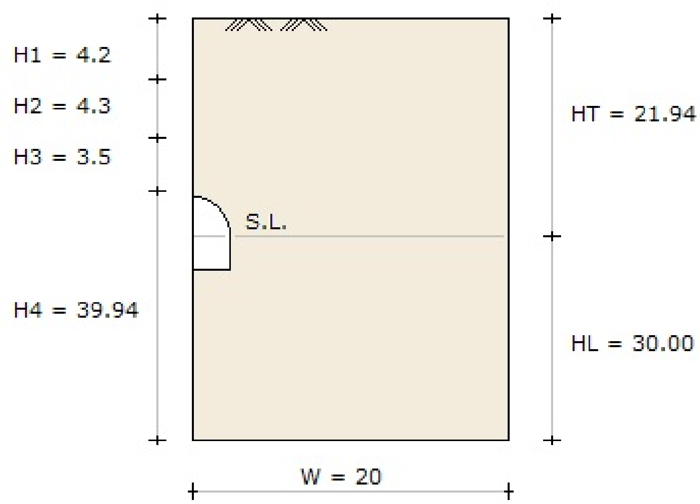


R_1	=	5.24 M	A_1	=	60°
R_2	=	4.24 M	A_2	=	30°
R_3	=	9.86 M	A_3	=	19.781°
R_4	=	23.86 M			

Number of Rock Bolts (NUMRB)	=	11
Length of Rock Bolts (LRB)	=	3.0 M
Spacing of Rock Bolts (TSPACING)	=	1.2 M
Thickness of Shotcrete (TS)	=	15 Cm
Thickness of Liner (TL)	=	30 Cm
Reinforcing Bar Area (ASI)	=	22 Cm^2
Reinforcing Bar Area (ASO)	=	22 Cm^2

Figure 6.1 Tunnel dimensions for Example 1

MODEL= 1 Single Tunnel [Half Section]



DELTAX = 2.0, DELTAY = 2.0, NDYMAX = 40

Figure 6.2 Schematic tunnel section for Example 1

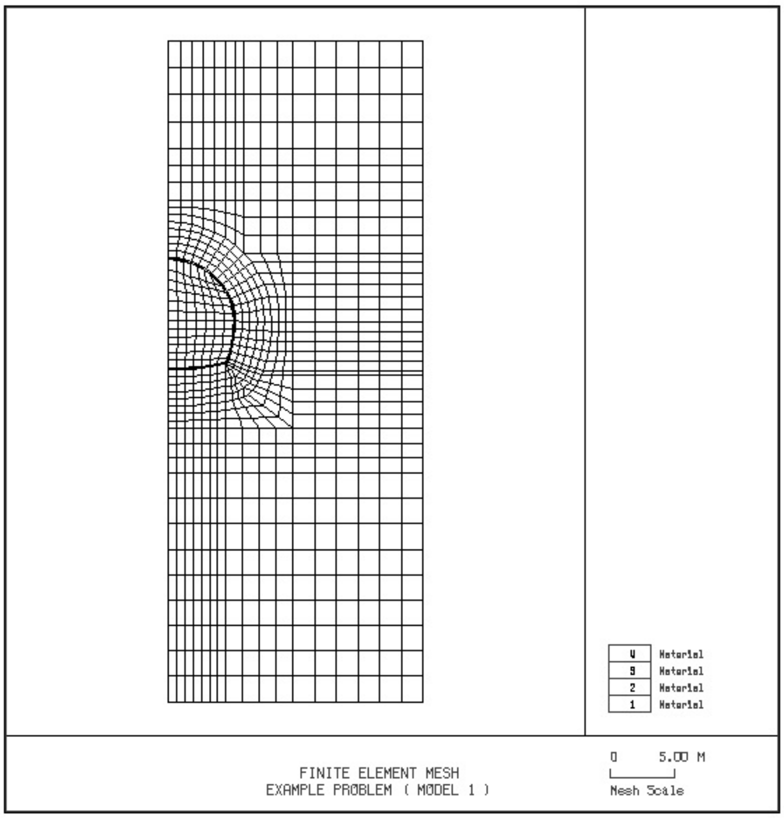

4 Material
3 Material
2 Material
1 Material
0 5.00 M
Mesh Scale
FINITE ELEMENT MESH
EXAMPLE PROBLEM (MODEL 1)

Figure 6.3

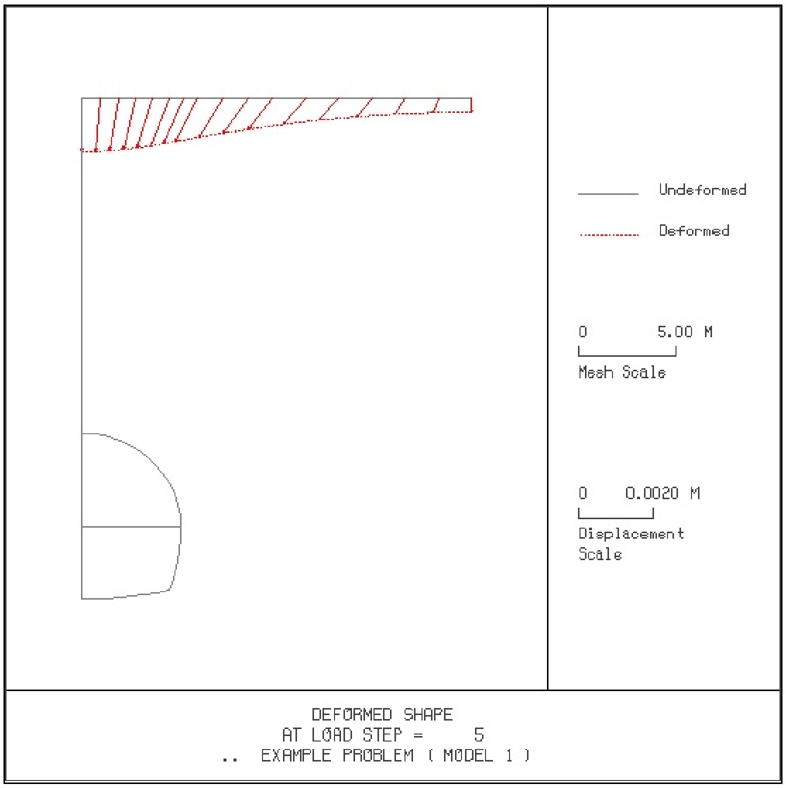

Undeformed
Deformed
0 5.00 M
Mesh Scale
0 0.0020 M
Displacement
Scale
DEFORMED SHAPE
AT LOAD STEP = 5
.. EXAMPLE PROBLEM (MODEL 1)

Figure 6.4

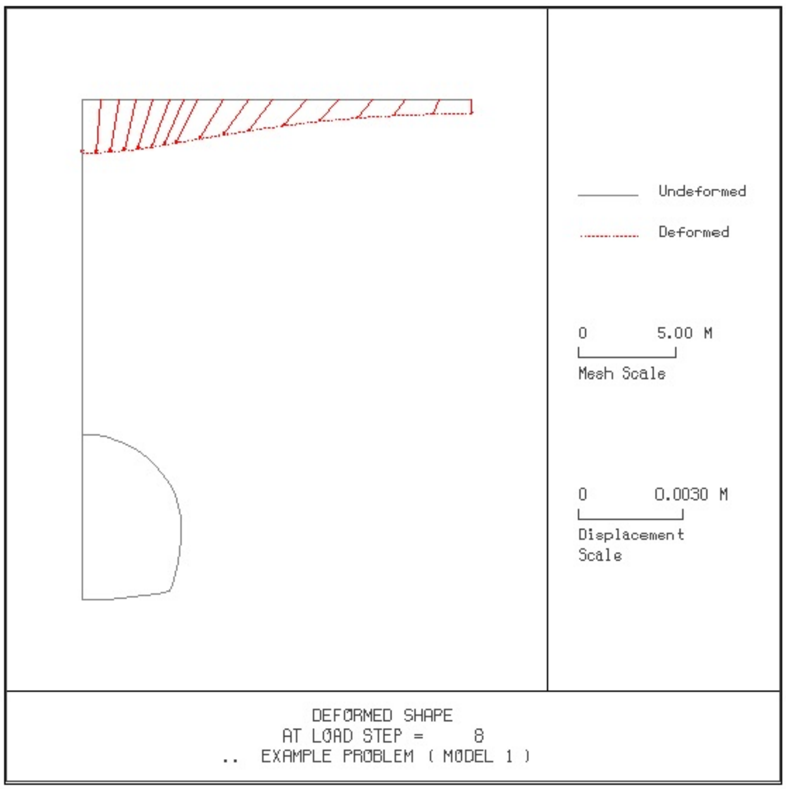

Undeformed
Deformed
0 5.00 M
Mesh Scale
0 0.0030 M
Displacement
Scale
DEFORMED SHAPE
AT LOAD STEP = 8
.. EXAMPLE PROBLEM (MODEL 1)

Figure 6.5

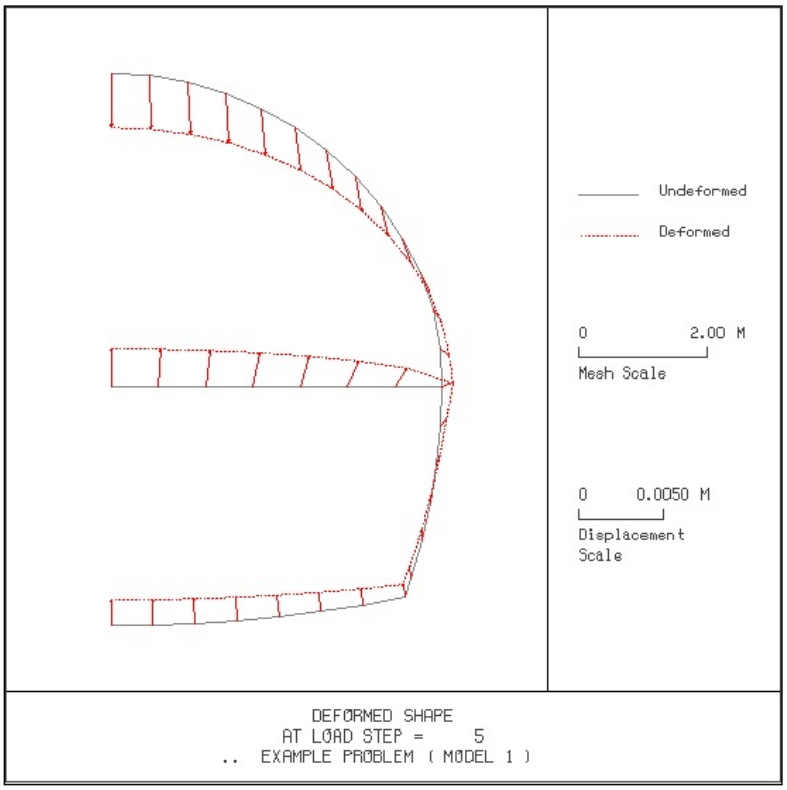

Undeformed
Deformed
0 2.00 M
Mesh Scale
0 0.0050 M
Displacement
Scale
DEFORMED SHAPE
AT LOAD STEP = 5
.. EXAMPLE PROBLEM (MODEL 1)

Figure 6.6

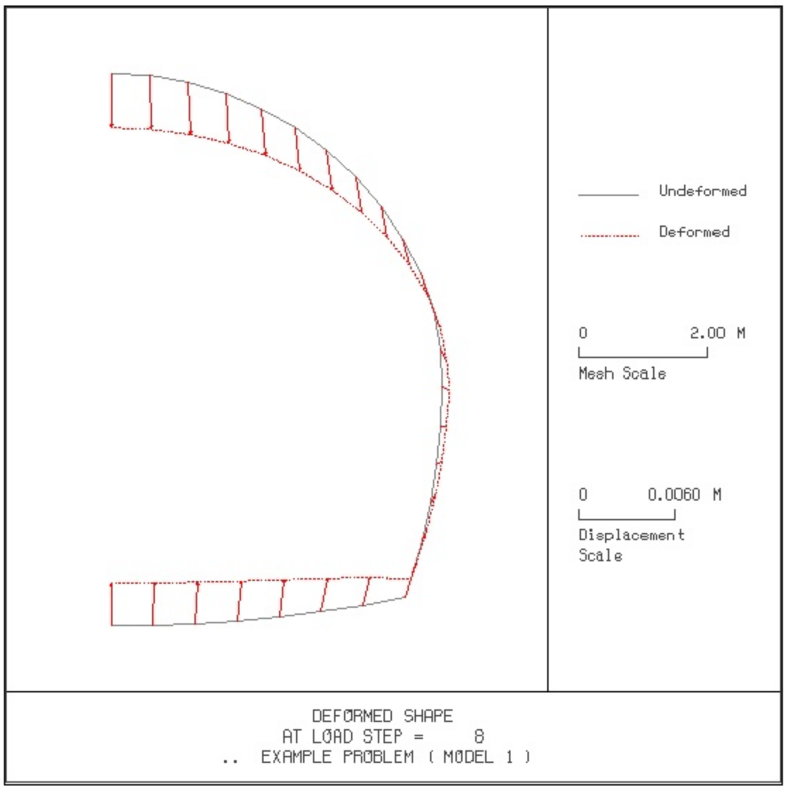

Undeformed
Deformed
0 2.00 M
Mesh Scale
0 0.0060 M
Displacement
Scale
DEFORMED SHAPE
AT LOAD STEP = 8
.. EXAMPLE PROBLEM (MODEL 1)

Figure 6.7

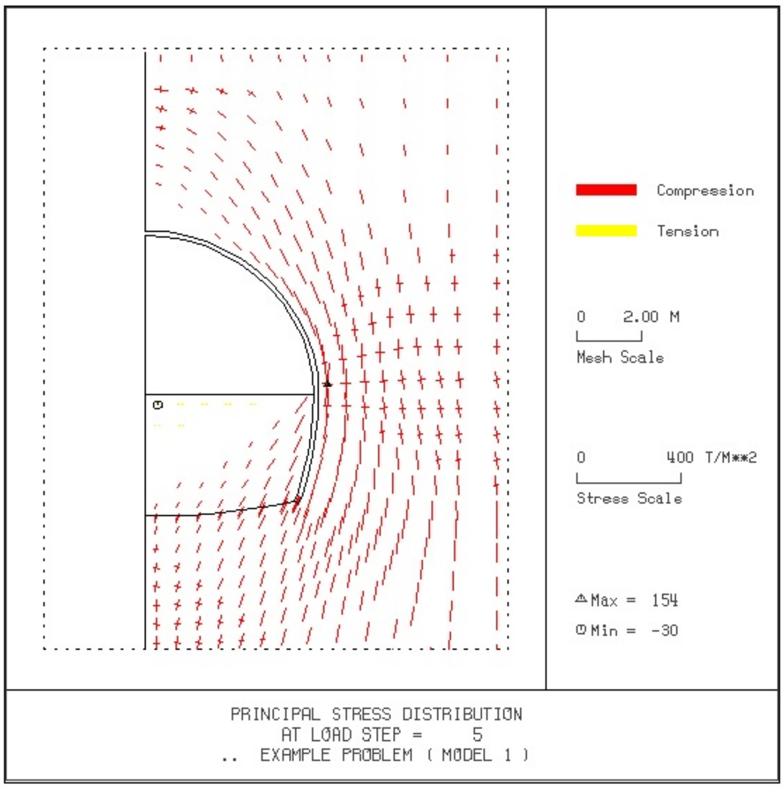

Compression
Tension
0 2.00 M
Mesh Scale
0 400 T/M**2
Stress Scale
Max = 154
Min = -30
PRINCIPAL STRESS DISTRIBUTION
AT LOAD STEP = 5
.. EXAMPLE PROBLEM (MODEL 1)

Figure 6.8

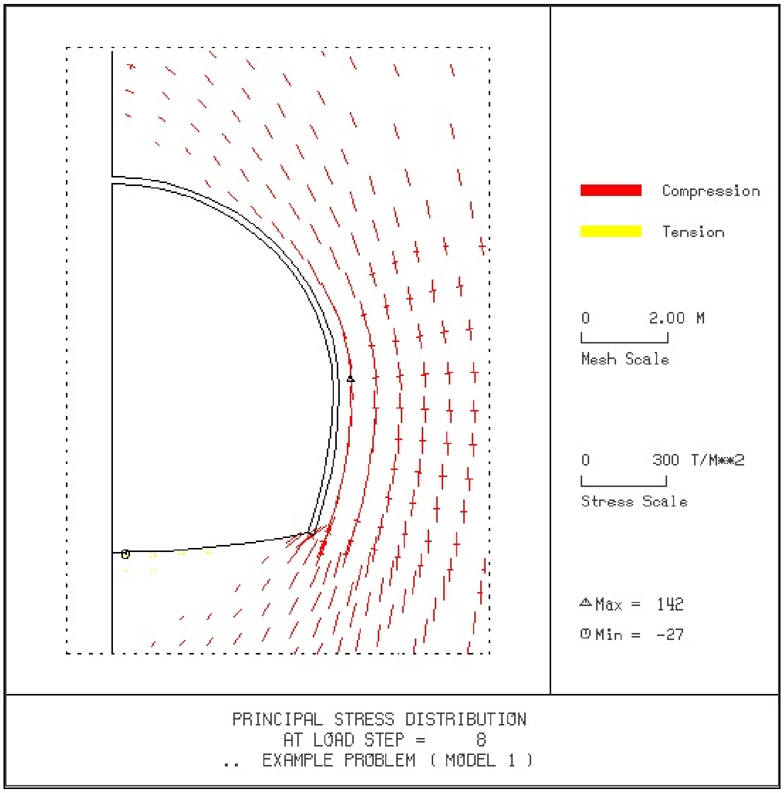

Compression
Tension
0 2.00 M
Mesh Scale
0 300 T/M**2
Stress Scale
Max = 142
Min = -27
PRINCIPAL STRESS DISTRIBUTION
AT LOAD STEP = 8
.. EXAMPLE PROBLEM (MODEL 1)

Figure 6.9

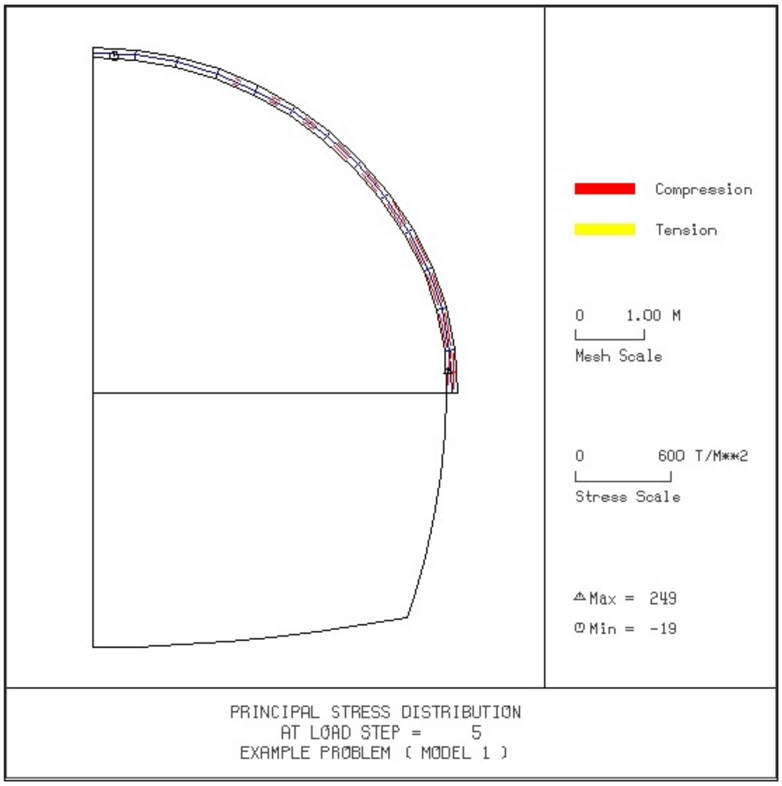

Compression
Tension
0 1.00 M
Mesh Scale
0 600 T/M**2
Stress Scale
Max = 249
Min = -19
PRINCIPAL STRESS DISTRIBUTION
AT LOAD STEP = 5
EXAMPLE PROBLEM (MODEL 1)

Figure 6.10

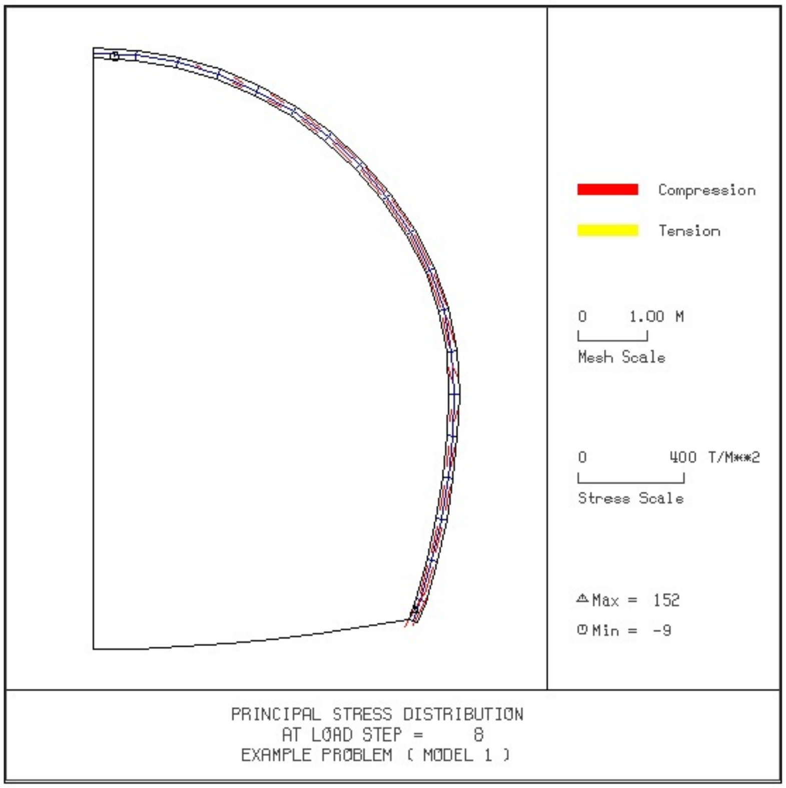

Compression
Tension
0 1.00 M
Mesh Scale
0 400 T/M**2
Stress Scale
Max = 152
Min = -9
PRINCIPAL STRESS DISTRIBUTION
AT LOAD STEP = 8
EXAMPLE PROBLEM (MODEL 1)

Figure 6.11

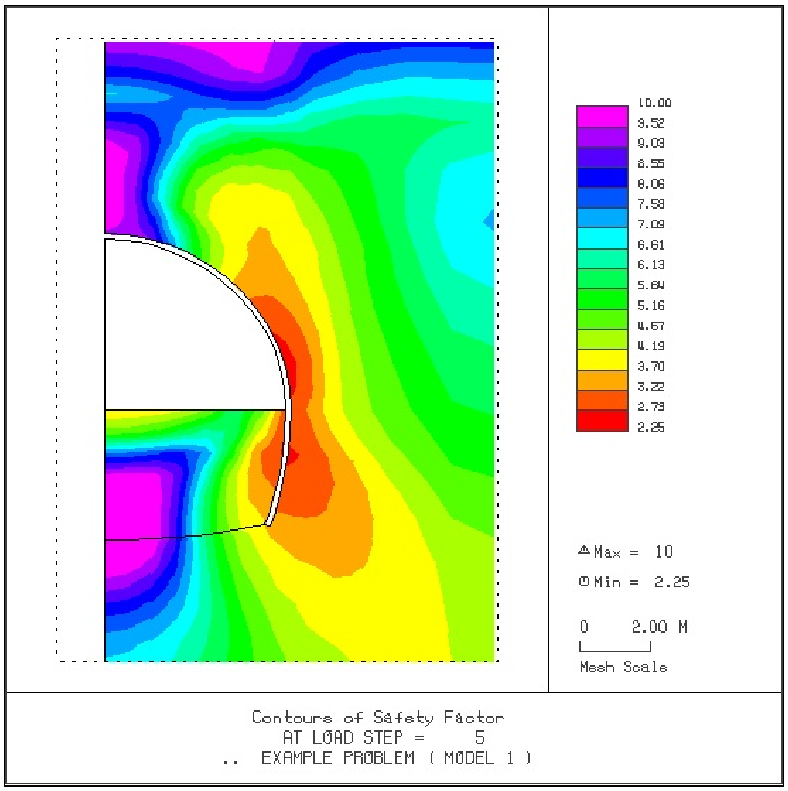

10.00
9.52
9.03
8.55
8.06
7.58
7.09
6.61
6.13
5.64
5.16
4.67
4.19
3.70
3.22
2.73
2.25
Max = 10
Min = 2.25
0 2.00 M
Mesh Scale
Contours of Safety Factor
AT LOAD STEP = 5
.. EXAMPLE PROBLEM (MODEL 1)

Figure 6.12

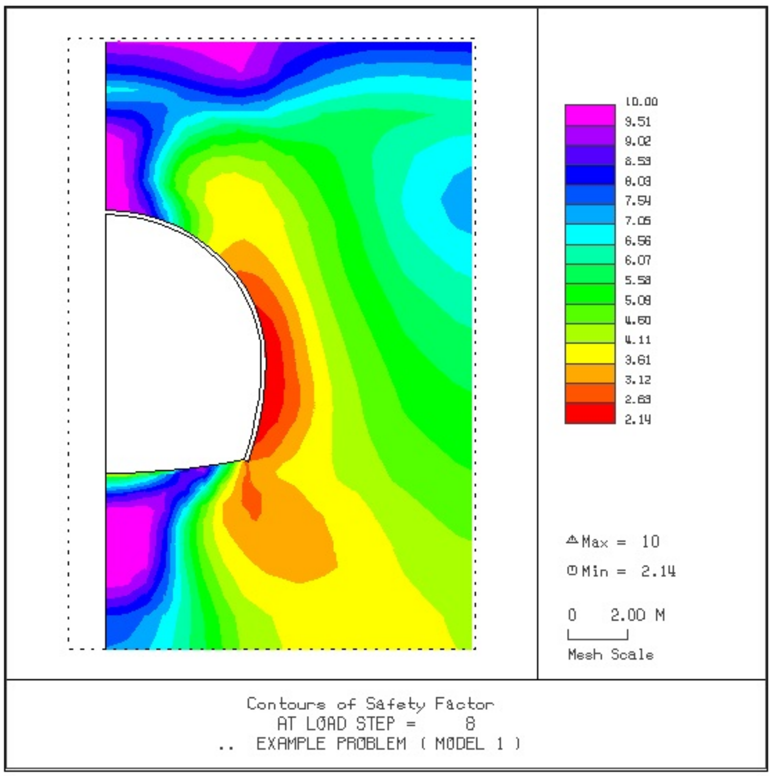

10.00
9.51
9.02
8.53
8.03
7.54
7.05
6.56
6.07
5.58
5.09
4.60
4.11
3.61
3.12
2.63
2.14
Max = 10
Min = 2.14
0 2.00 M
Mesh Scale
Contours of Safety Factor
AT LOAD STEP = 8
.. EXAMPLE PROBLEM (MODEL 1)

Figure 6.13

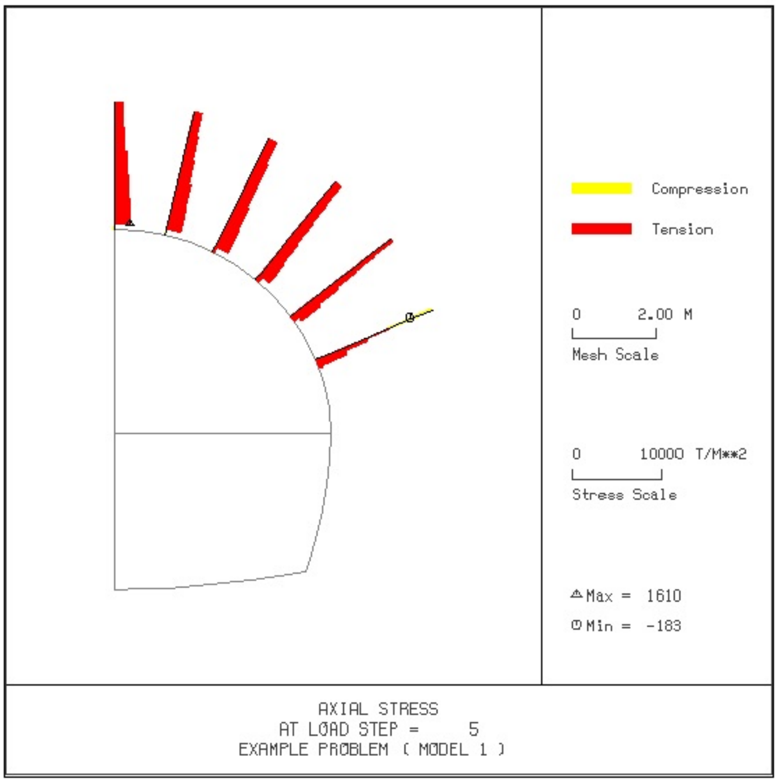

Compression
Tension
0 2.00 M
Mesh Scale
0 10000 T/M**2
Stress Scale
Max = 1610
Min = -183
AXIAL STRESS
AT LOAD STEP = 5
EXAMPLE PROBLEM (MODEL 1)

Figure 6.14

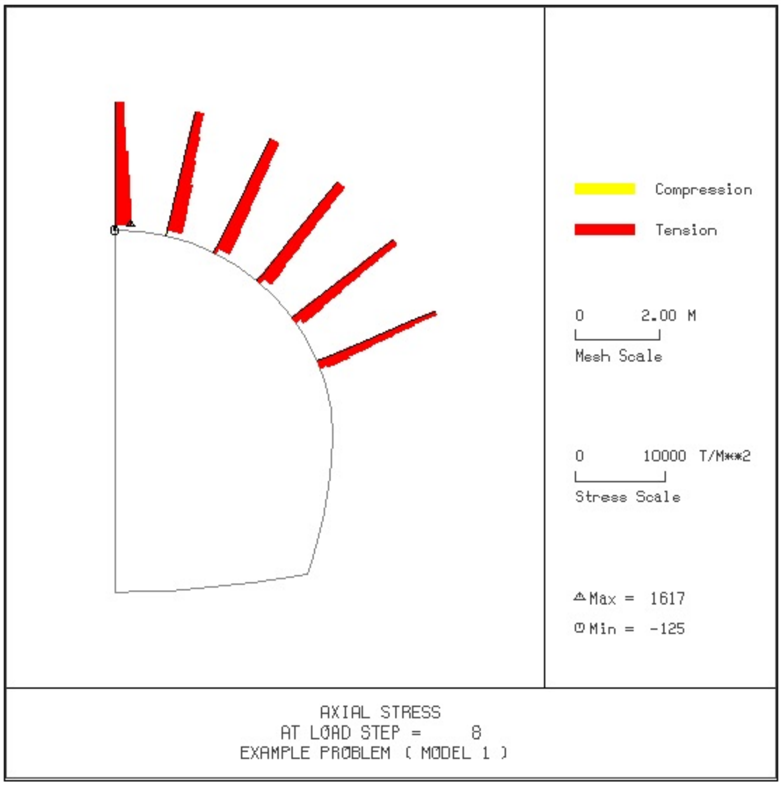

Compression
Tension
0 2.00 M
Mesh Scale
0 10000 T/M**2
Stress Scale
Max = 1617
Min = -125
AXIAL STRESS
AT LOAD STEP = 8
EXAMPLE PROBLEM (MODEL 1)

Figure 6.15

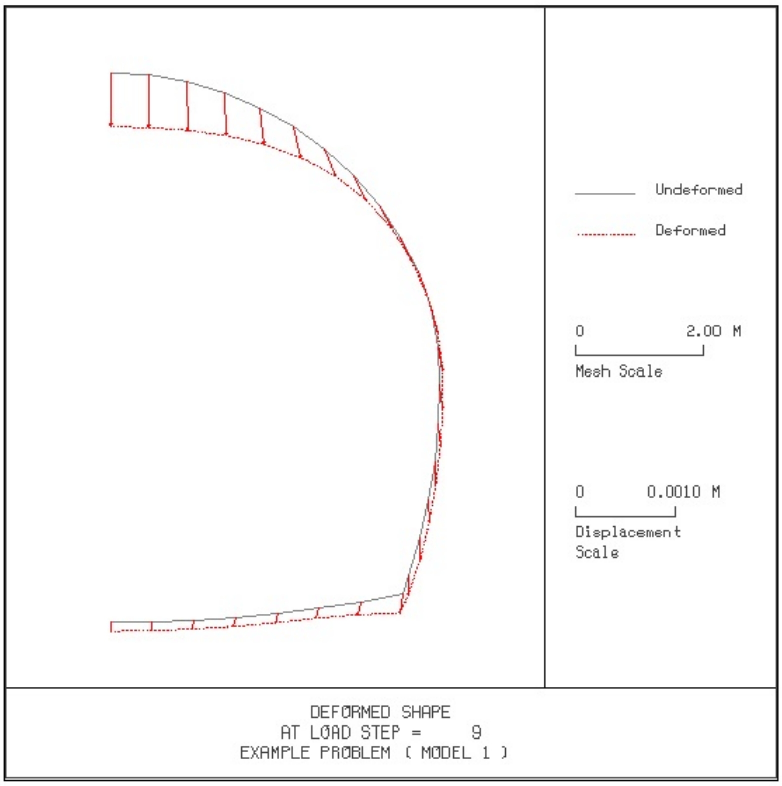

Undeformed
Deformed
0 2.00 M
Mesh Scale
0 0.0010 M
Displacement
Scale
DEFORMED SHAPE
AT LOAD STEP = 9
EXAMPLE PROBLEM (MODEL 1)

Figure 6.16

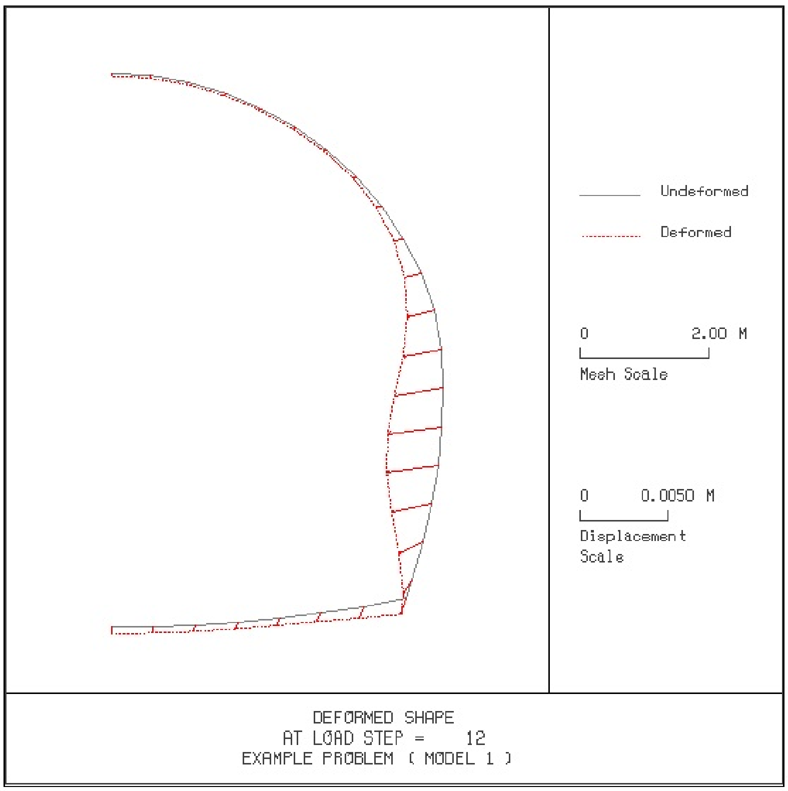

Undeformed
Deformed
0 2.00 M
Mesh Scale
0 0.0050 M
Displacement
Scale
DEFORMED SHAPE
AT LOAD STEP = 12
EXAMPLE PROBLEM (MODEL 1)

Figure 6.17

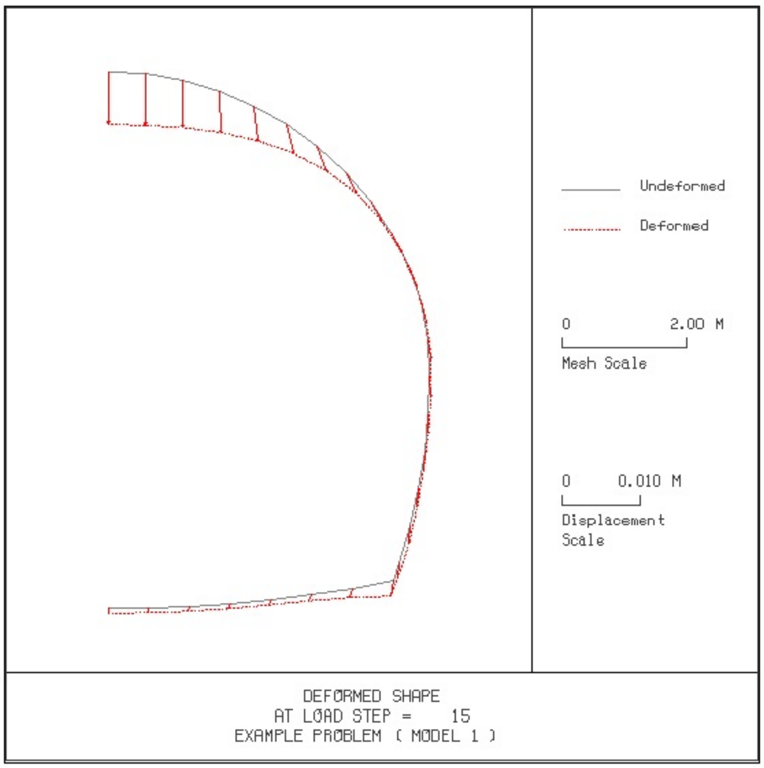

Undeformed
Deformed
0 2.00 M
Mesh Scale
0 0.010 M
Displacement
Scale
DEFORMED SHAPE
AT LOAD STEP = 15
EXAMPLE PROBLEM (MODEL 1)

Figure 6.18

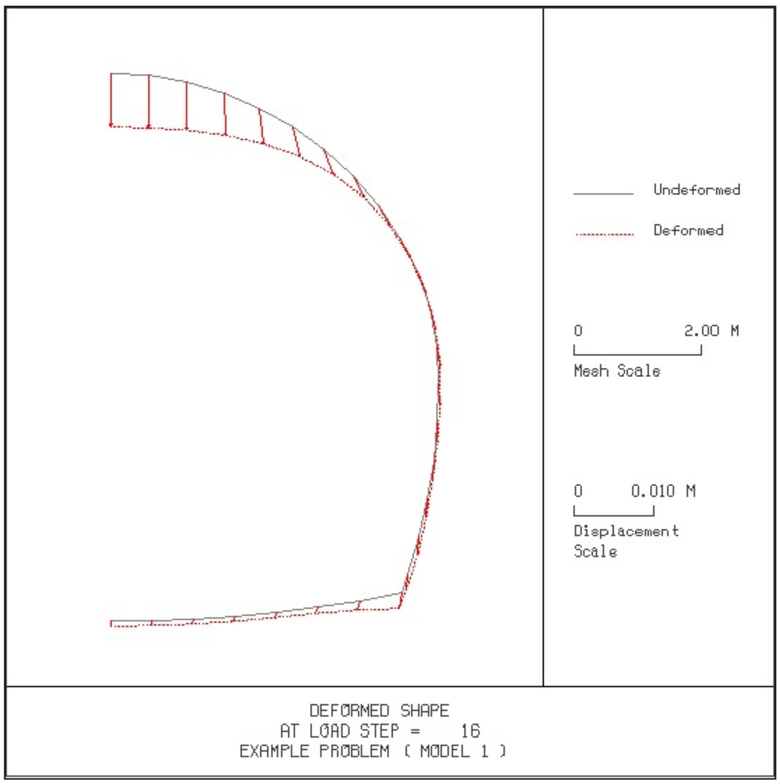

Undeformed
Deformed
0 2.00 M
Mesh Scale
0 0.010 M
Displacement Scale
DEFORMED SHAPE
AT LOAD STEP = 16
EXAMPLE PROBLEM (MODEL 1)

Figure 6.19

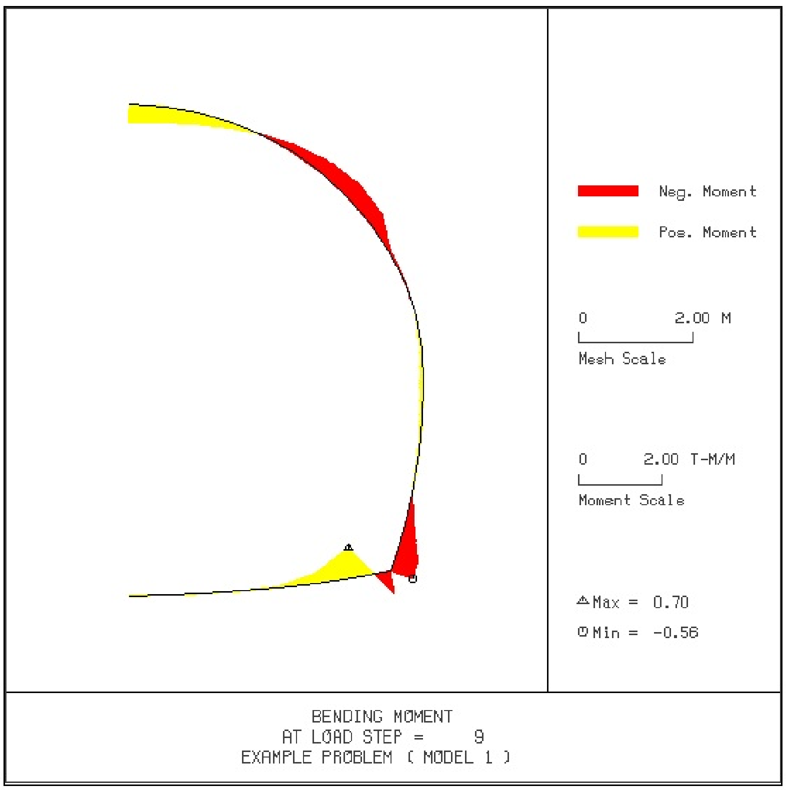

Neg. Moment
Pos. Moment
0 2.00 M
Mesh Scale
0 2.00 T-M/M
Moment Scale
Max = 0.70
Min = -0.56
BENDING MOMENT
AT LOAD STEP = 9
EXAMPLE PROBLEM (MODEL 1)

Figure 6.20

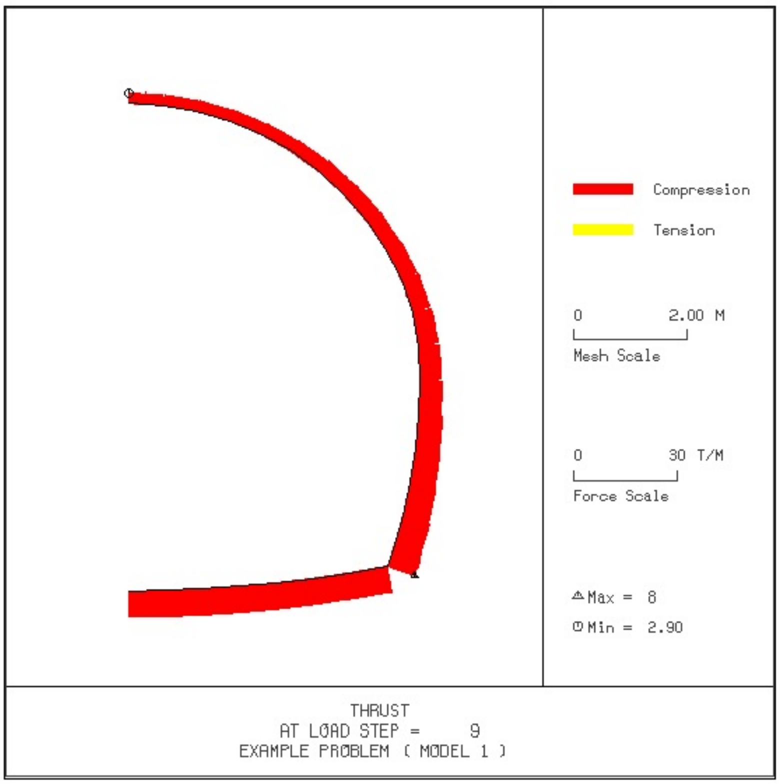

Compression
Tension
0 2.00 M
Mesh Scale
0 30 T/M
Force Scale
Max = 8
Min = 2.90
THRUST
AT LOAD STEP = 9
EXAMPLE PROBLEM (MODEL 1)

Figure 6.21

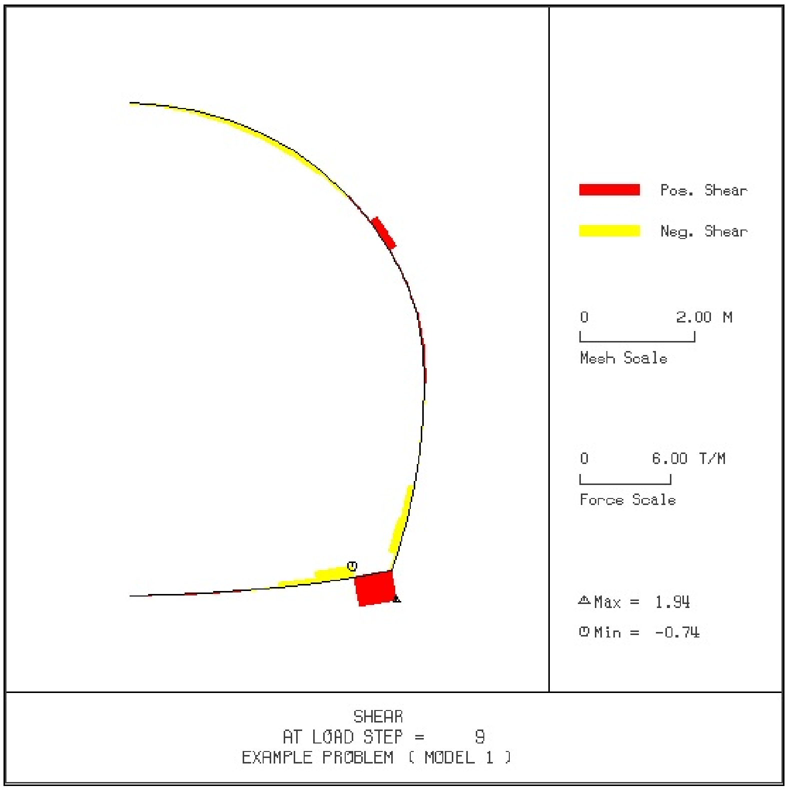

Pos. Shear
Neg. Shear
0 2.00 M
Mesh Scale
0 6.00 T/M
Force Scale
Max = 1.94
Min = -0.74
SHEAR
AT LOAD STEP = 9
EXAMPLE PROBLEM (MODEL 1)

Figure 6.22

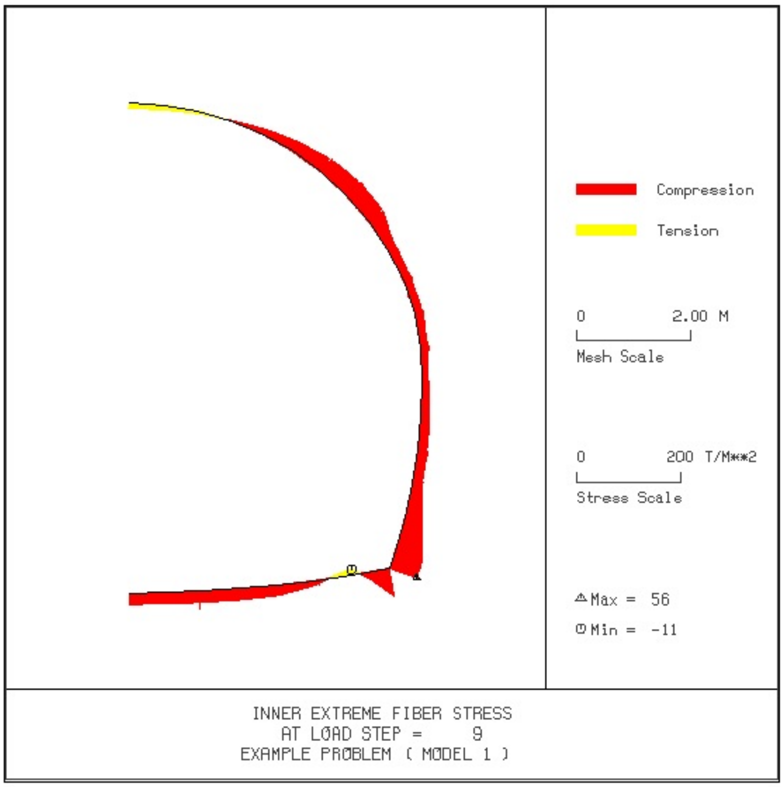

Compression
Tension
0 2.00 M
Mesh Scale
0 200 T/M**2
Stress Scale
Max = 56
Min = -11
INNER EXTREME FIBER STRESS
AT LOAD STEP = 9
EXAMPLE PROBLEM (MODEL 1)

Figure 6.23

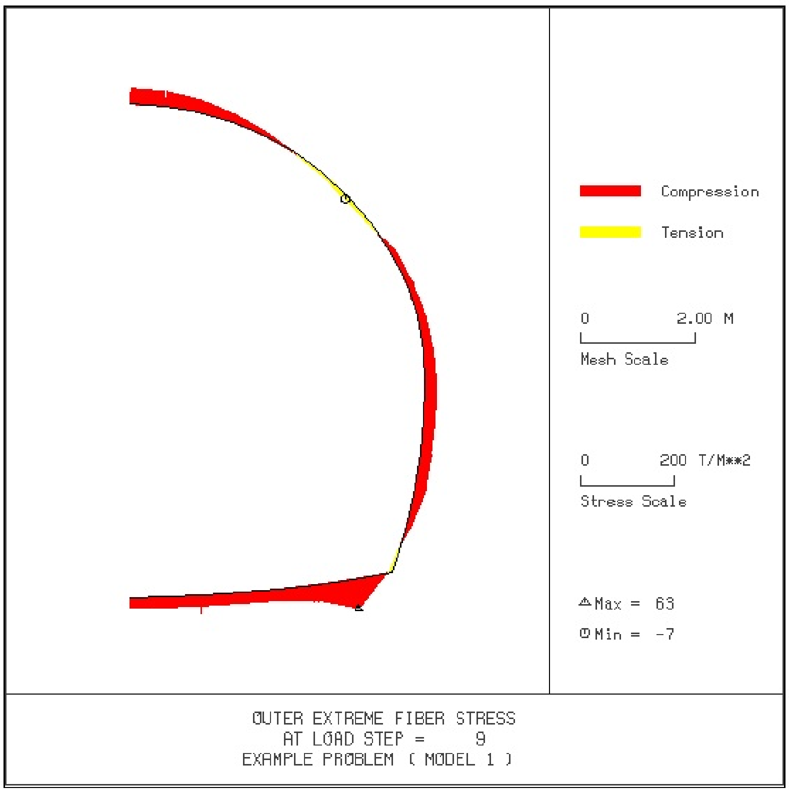

Compression
Tension
0 2.00 M
Mesh Scale
0 200 T/M**2
Stress Scale
Max = 63
Min = -7
OUTER EXTREME FIBER STRESS
AT LOAD STEP = 9
EXAMPLE PROBLEM (MODEL 1)

Figure 6.24

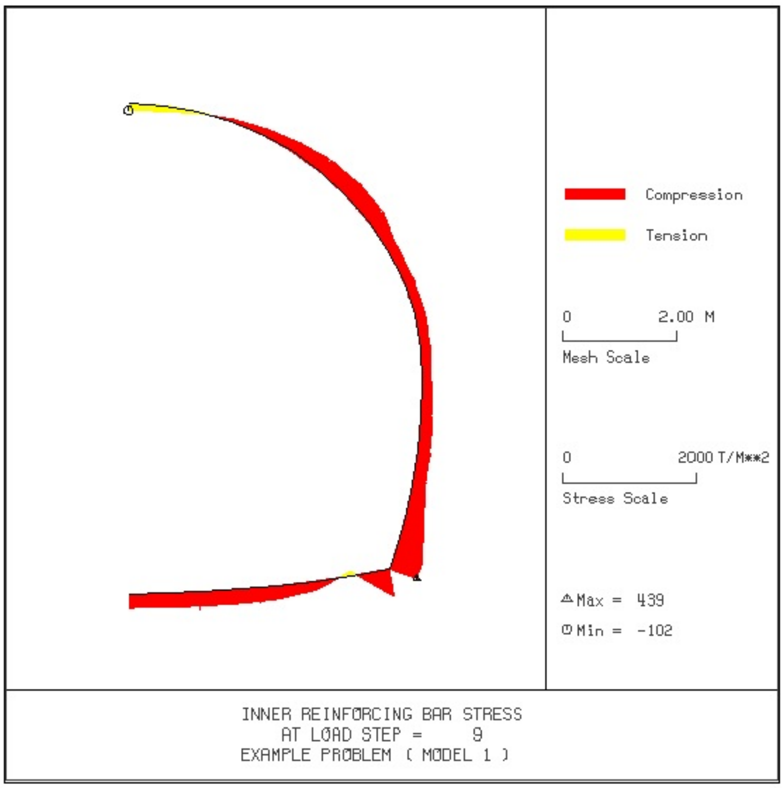

Compression
Tension
0 2.00 M
Mesh Scale
0 2000 T/M**2
Stress Scale
Max = 439
Min = -102
INNER REINFORCING BAR STRESS
AT LOAD STEP = 9
EXAMPLE PROBLEM (MODEL 1)

Figure 6.25

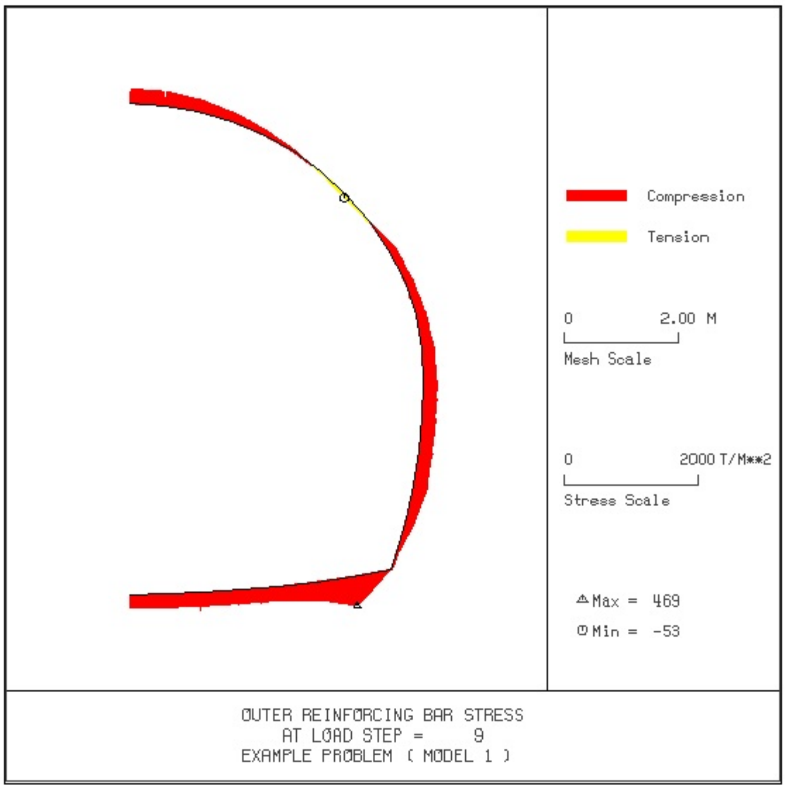

Compression
Tension
0 2.00 M
Mesh Scale
0 2000 T/M**2
Stress Scale
Max = 469
Min = -53
OUTER REINFORCING BAR STRESS
AT LOAD STEP = 9
EXAMPLE PROBLEM (MODEL 1)

Figure 6.26

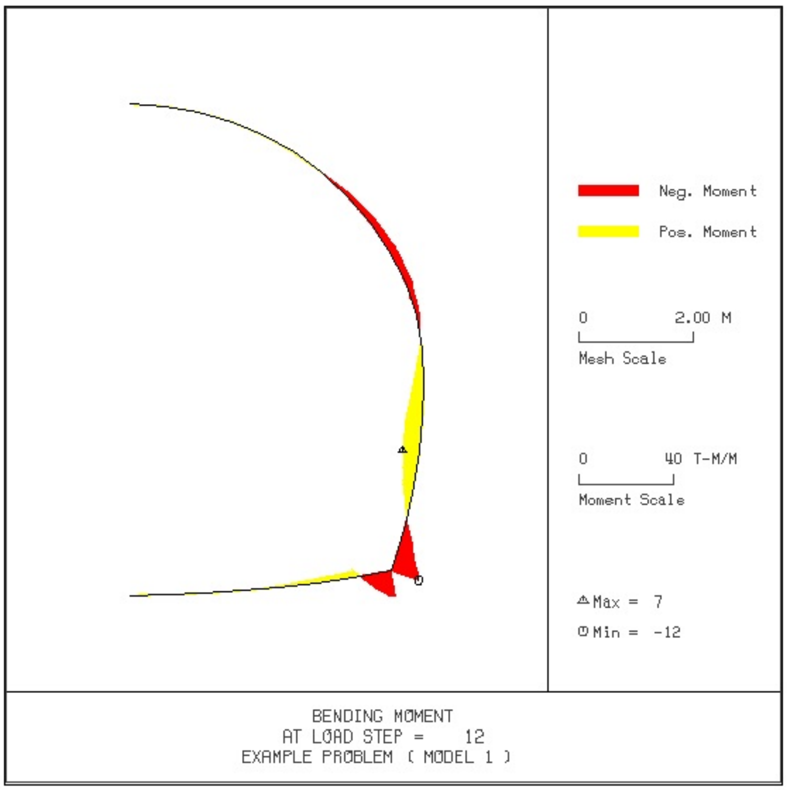

Neg. Moment
Pos. Moment
0 2.00 M
Mesh Scale
0 40 T-M/M
Moment Scale
Max = 7
Min = -12
BENDING MOMENT
AT LOAD STEP = 12
EXAMPLE PROBLEM (MODEL 1)

Figure 6.27

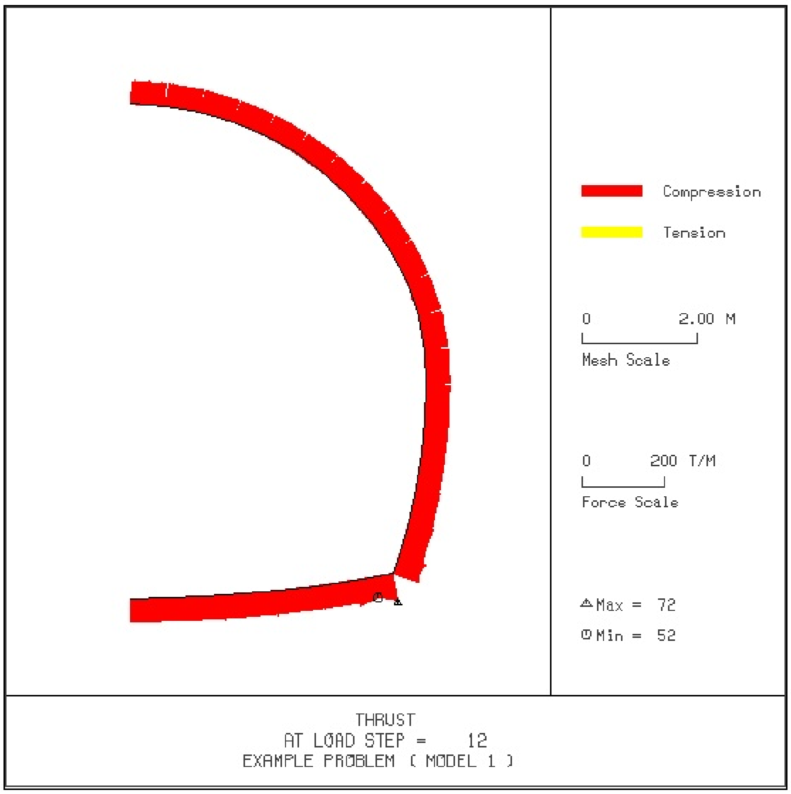

Compression
Tension
0 2.00 M
Mesh Scale
0 200 T/M
Force Scale
Max = 72
Min = 52
THRUST
AT LOAD STEP = 12
EXAMPLE PROBLEM (MODEL 1)

Figure 6.28

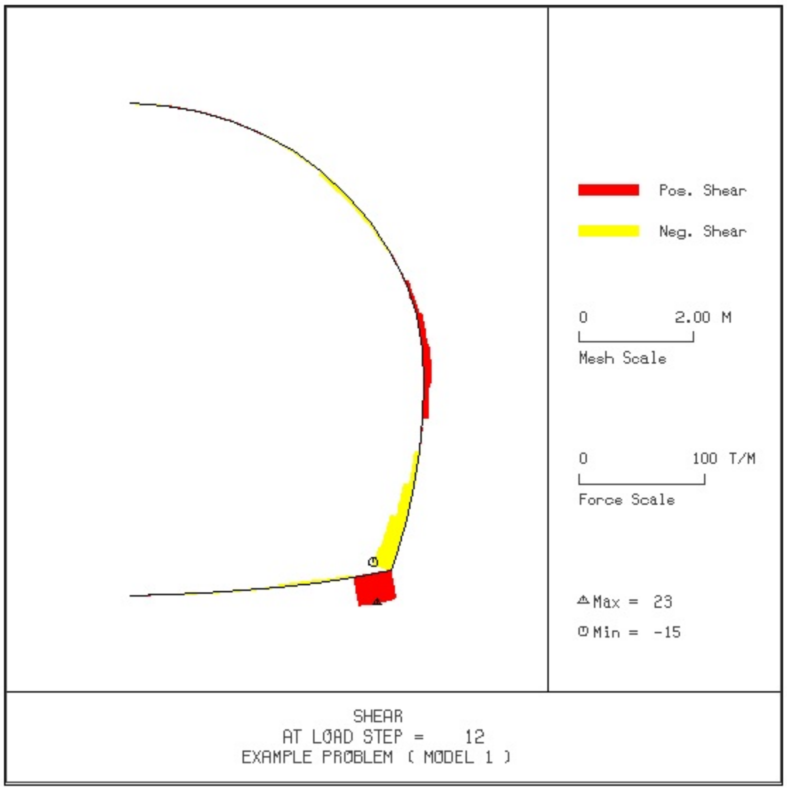

Pos. Shear
Neg. Shear
0 2.00 M
Mesh Scale
0 100 T/M
Force Scale
Max = 23
Min = -15
SHEAR
AT LOAD STEP = 12
EXAMPLE PROBLEM (MODEL 1)

Figure 6.29

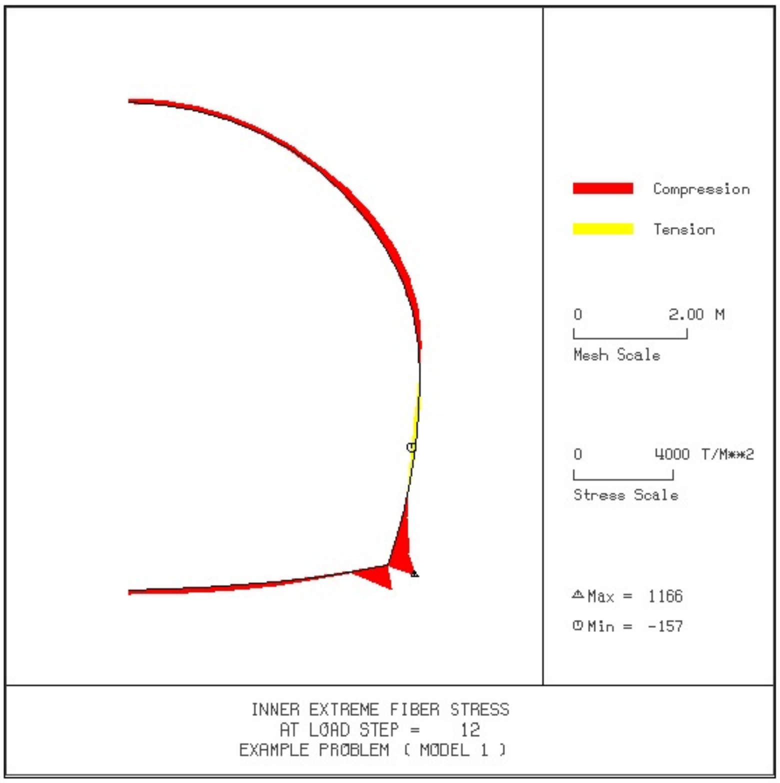

Compression
Tension
0 2.00 M
Mesh Scale
0 4000 T/M**2
Stress Scale
Max = 1166
Min = -157
INNER EXTREME FIBER STRESS
AT LOAD STEP = 12
EXAMPLE PROBLEM (MODEL 1)

Figure 6.30

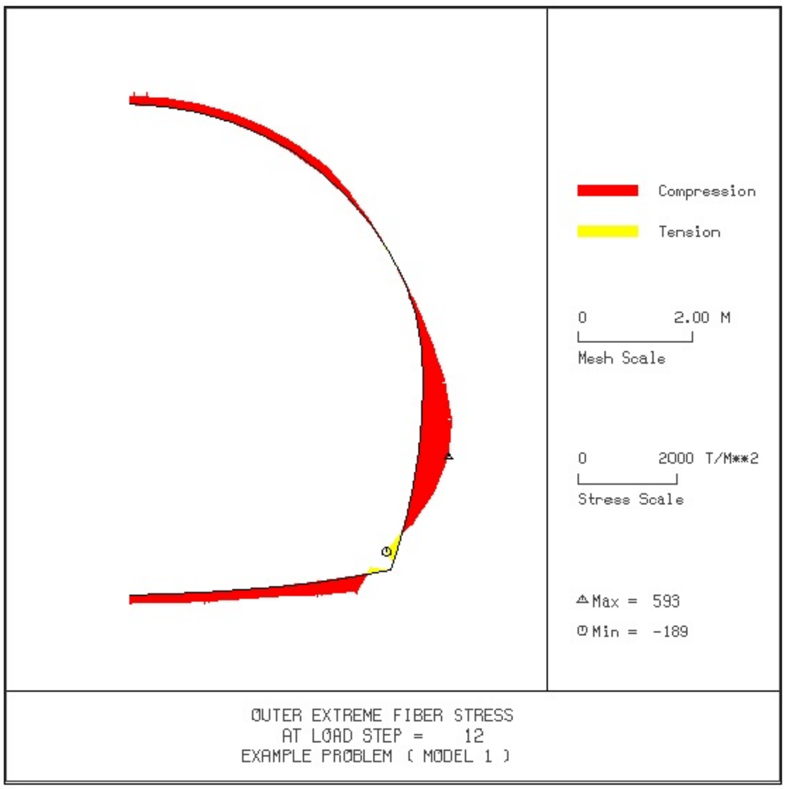

Compression
Tension
0 2.00 M
Mesh Scale
0 2000 T/M**2
Stress Scale
Max = 593
Min = -189
OUTER EXTREME FIBER STRESS
AT LOAD STEP = 12
EXAMPLE PROBLEM (MODEL 1)

Figure 6.31

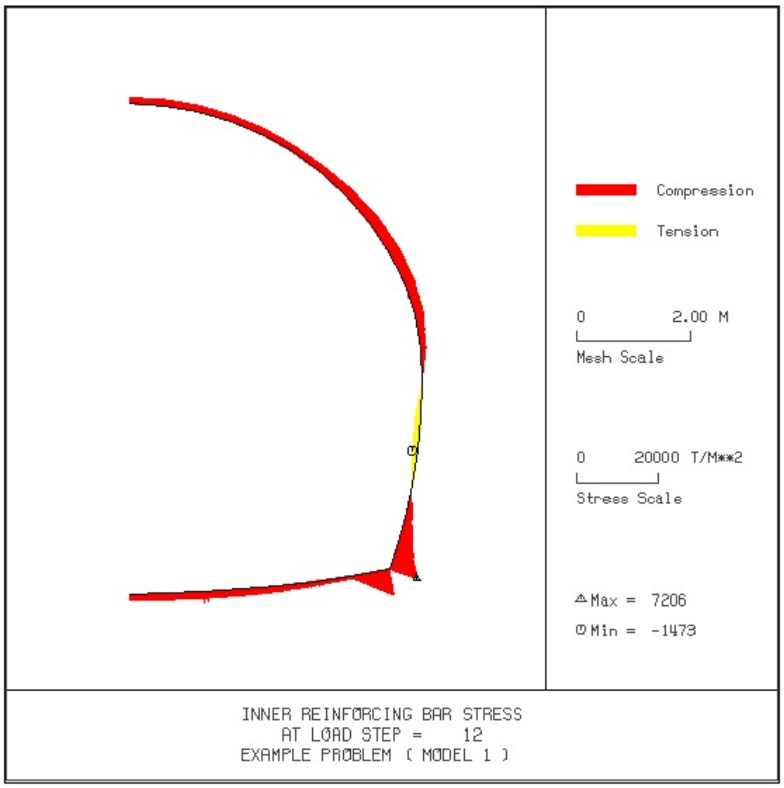

Compression
Tension
0 2.00 M
Mesh Scale
0 20000 T/M**2
Stress Scale
Max = 7206
Min = -1473
INNER REINFORCING BAR STRESS
AT LOAD STEP = 12
EXAMPLE PROBLEM (MODEL 1)

Figure 6.32

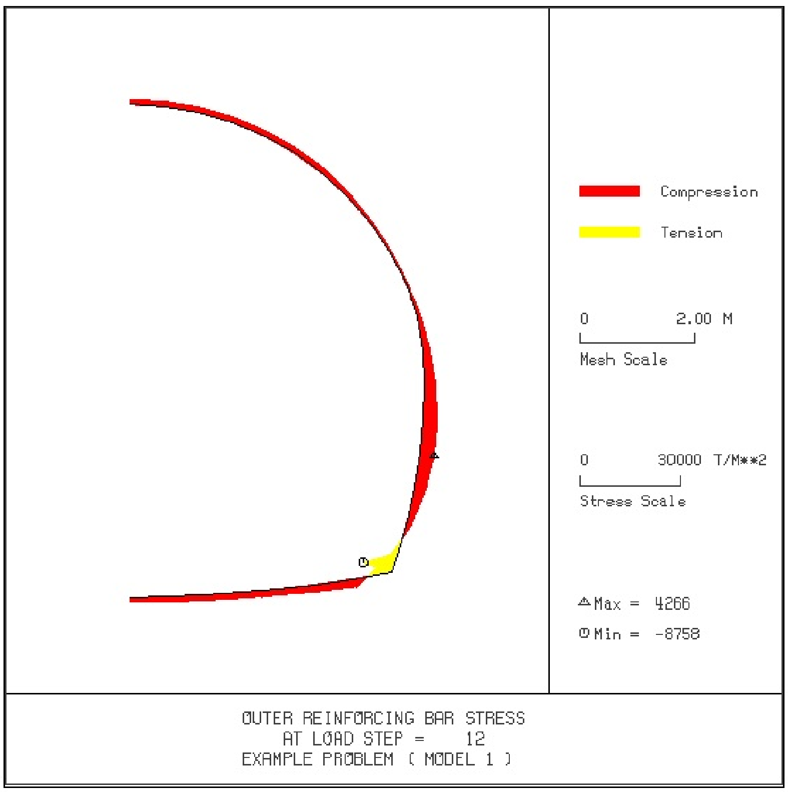

Compression
Tension
0 2.00 M
Mesh Scale
0 30000 T/M**2
Stress Scale
Max = 4266
Min = -8758
OUTER REINFORCING BAR STRESS
AT LOAD STEP = 12
EXAMPLE PROBLEM (MODEL 1)

Figure 6.33

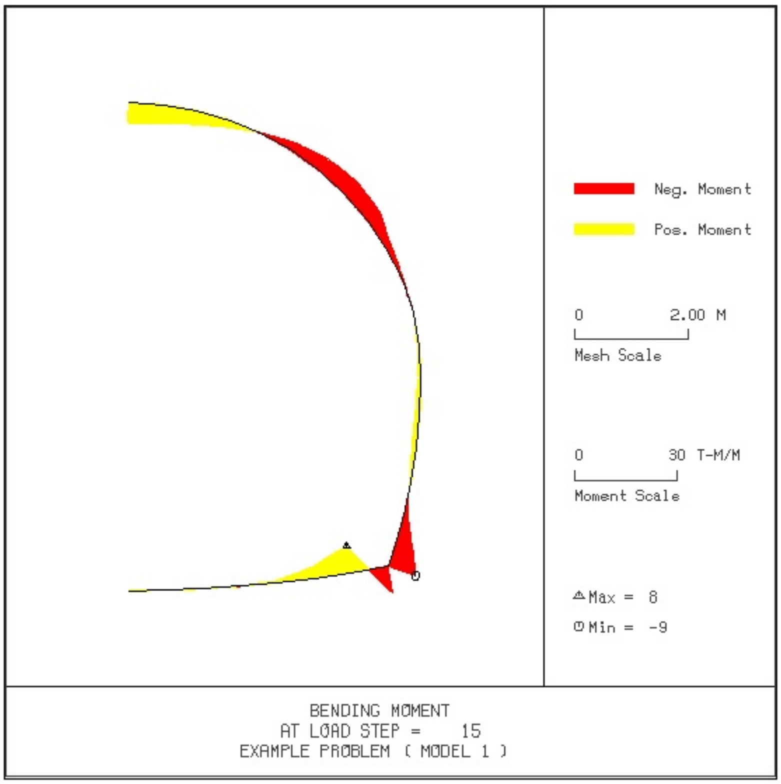

Neg. Moment
Pos. Moment
0 2.00 M
Mesh Scale
0 30 T-M/M
Moment Scale
Max = 8
Min = -9
BENDING MOMENT
AT LOAD STEP = 15
EXAMPLE PROBLEM (MODEL 1)

Figure 6.34

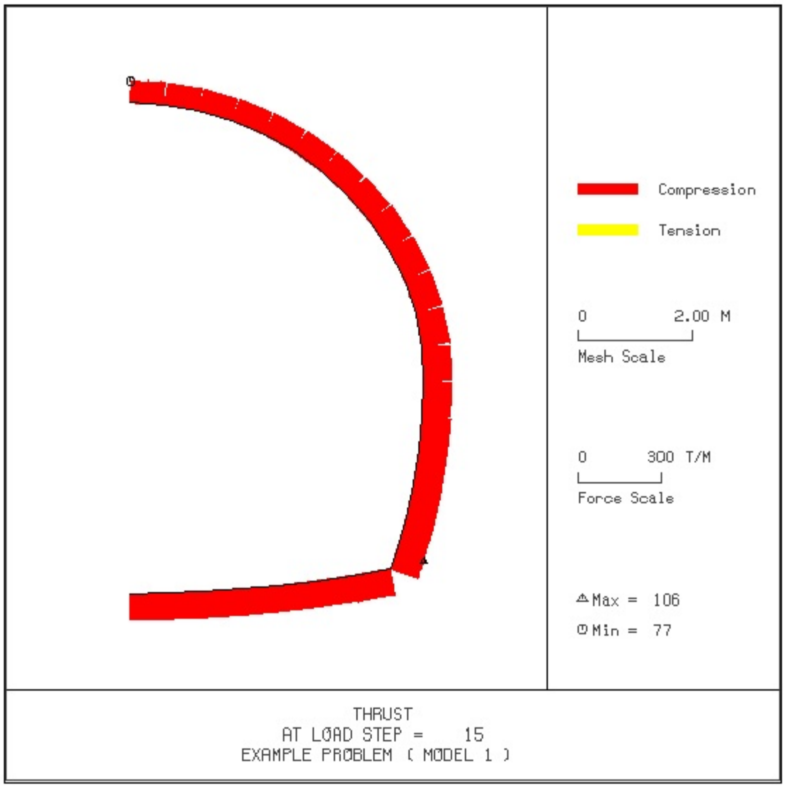

Compression
Tension
0 2.00 M
Mesh Scale
0 300 T/M
Force Scale
Max = 106
Min = 77
THRUST
AT LOAD STEP = 15
EXAMPLE PROBLEM (MODEL 1)

Figure 6.35

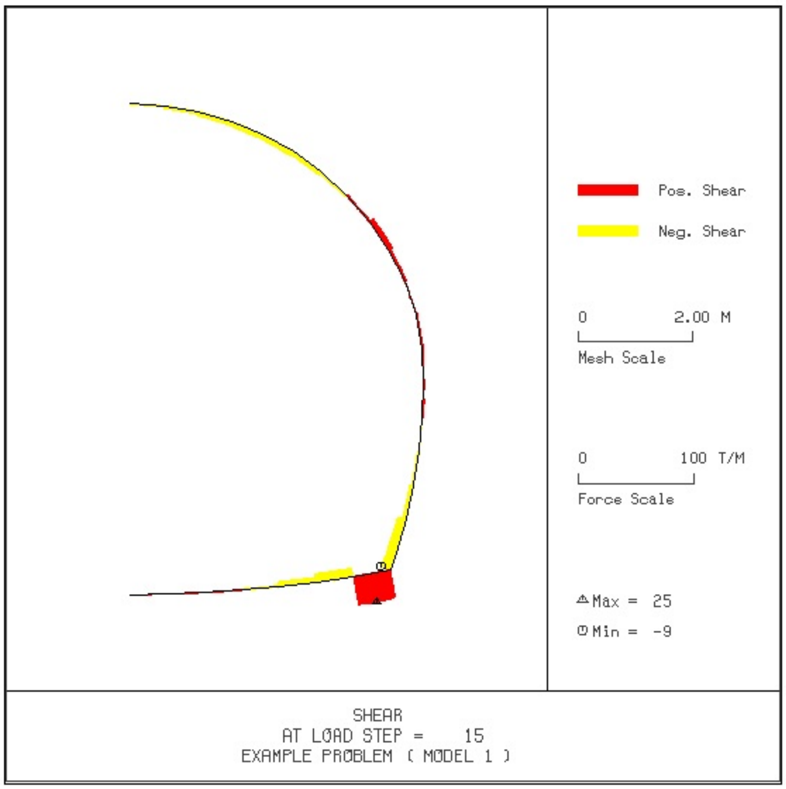

Pos. Shear
Neg. Shear
0 2.00 M
Mesh Scale
0 100 T/M
Force Scale
Max = 25
Min = -9
SHEAR
AT LOAD STEP = 15
EXAMPLE PROBLEM (MODEL 1)

Figure 6.36

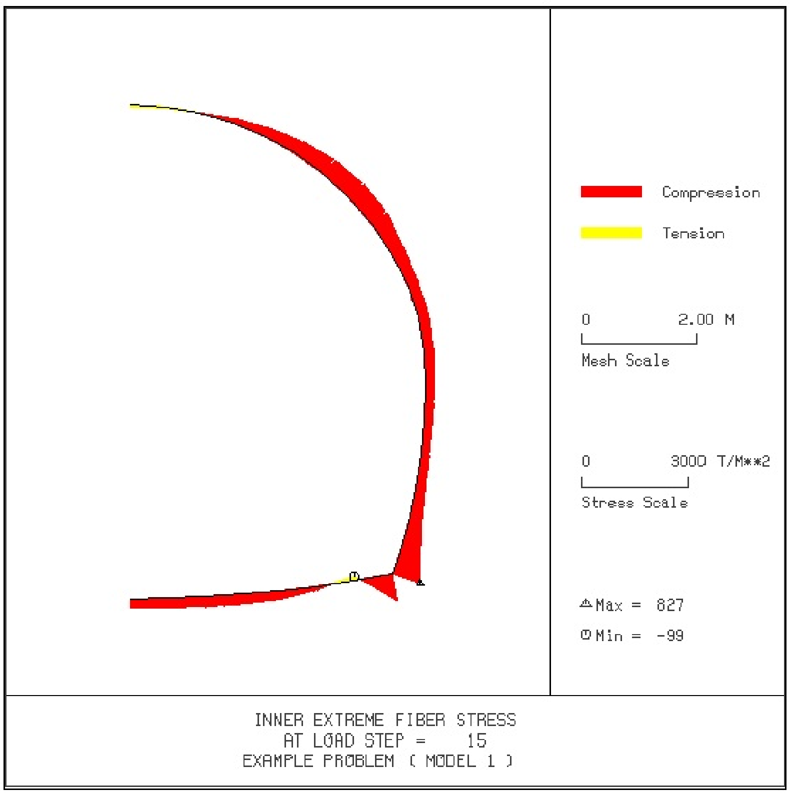

Compression
Tension
0 2.00 M
Mesh Scale
0 3000 T/M**2
Stress Scale
Max = 827
Min = -99
INNER EXTREME FIBER STRESS
AT LOAD STEP = 15
EXAMPLE PROBLEM (MODEL 1)

Figure 6.37

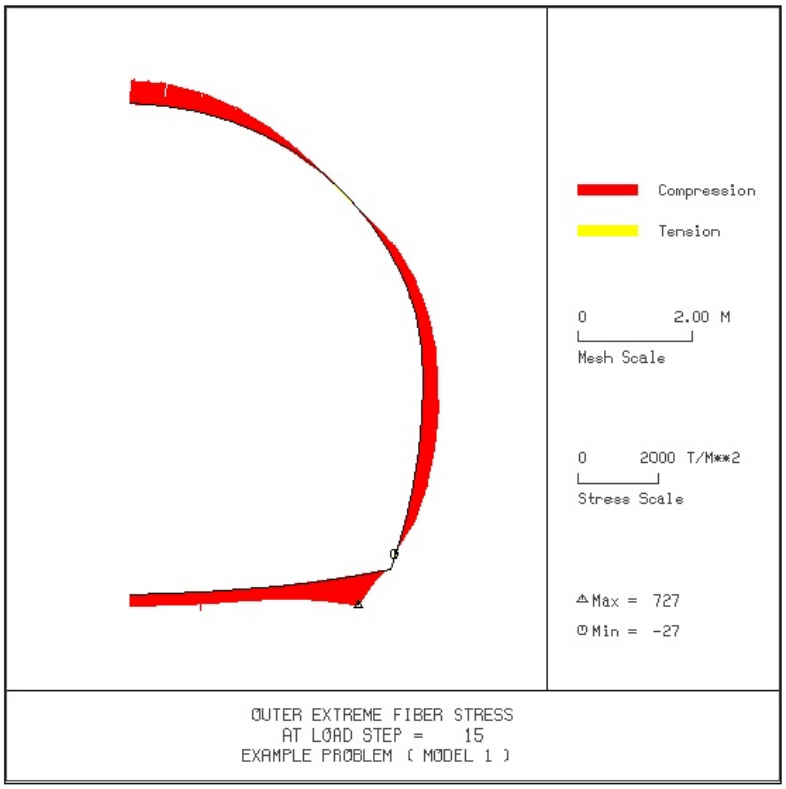

Compression
Tension
0 2.00 M
Mesh Scale
0 2000 T/M**2
Stress Scale
Max = 727
Min = -27
OUTER EXTREME FIBER STRESS
AT LOAD STEP = 15
EXAMPLE PROBLEM (MODEL 1)

Figure 6.38

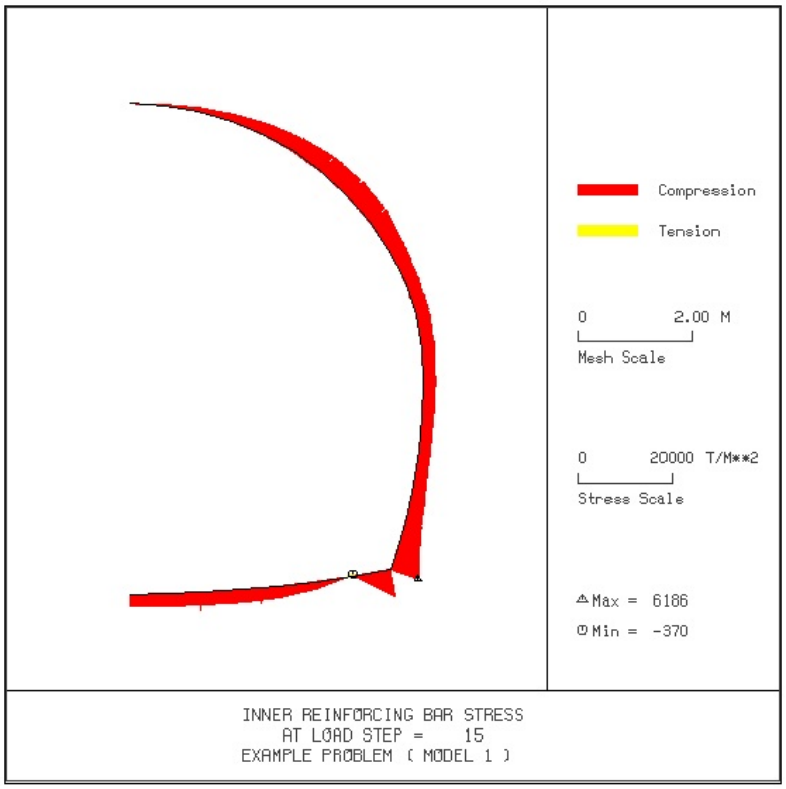

Compression
Tension
0 2.00 M
Mesh Scale
0 20000 T/M**2
Stress Scale
Max = 6186
Min = -370
INNER REINFORCING BAR STRESS
AT LOAD STEP = 15
EXAMPLE PROBLEM (MODEL 1)

Figure 6.39

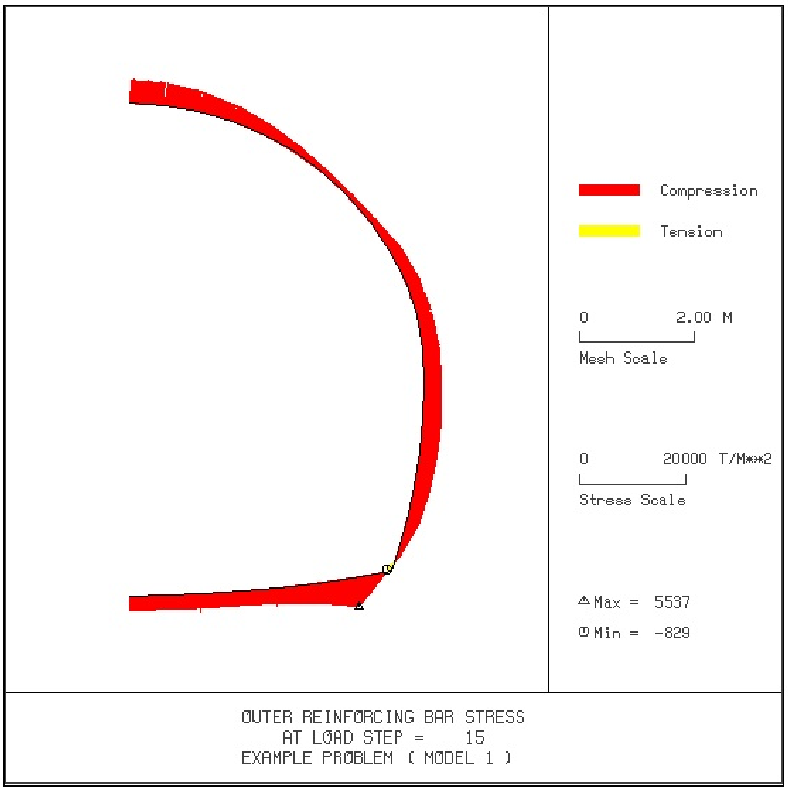

Compression
Tension
0 2.00 M
Mesh Scale
0 20000 T/M**2
Stress Scale
Max = 5537
Min = -829
OUTER REINFORCING BAR STRESS
AT LOAD STEP = 15
EXAMPLE PROBLEM (MODEL 1)

Figure 6.40

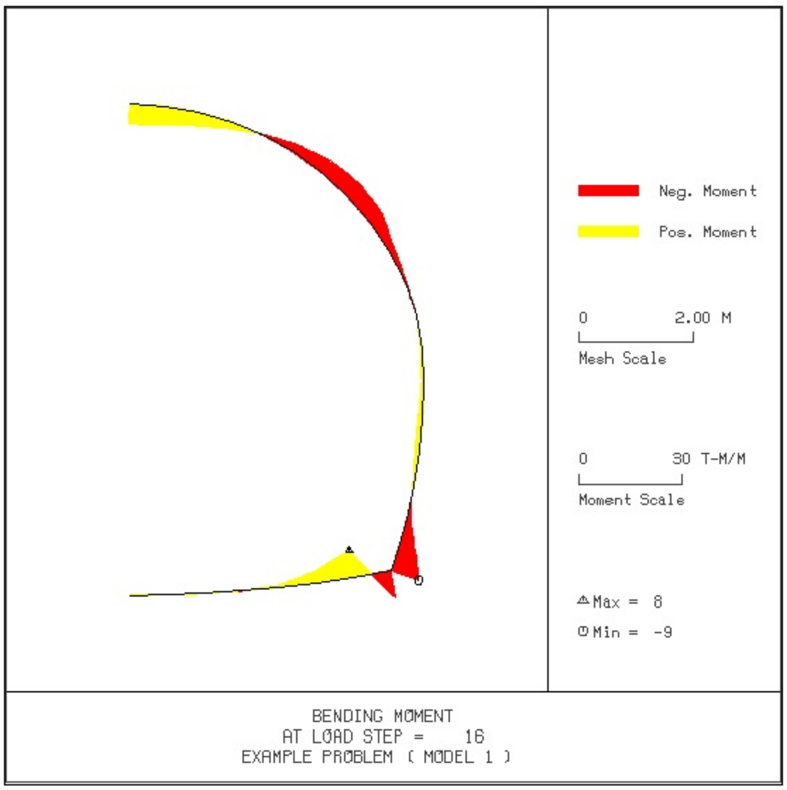

Neg. Moment
Pos. Moment
0 2.00 M
Mesh Scale
0 30 T-M/M
Moment Scale
Max = 8
Min = -9
BENDING MOMENT
AT LOAD STEP = 16
EXAMPLE PROBLEM (MODEL 1)

Figure 6.41

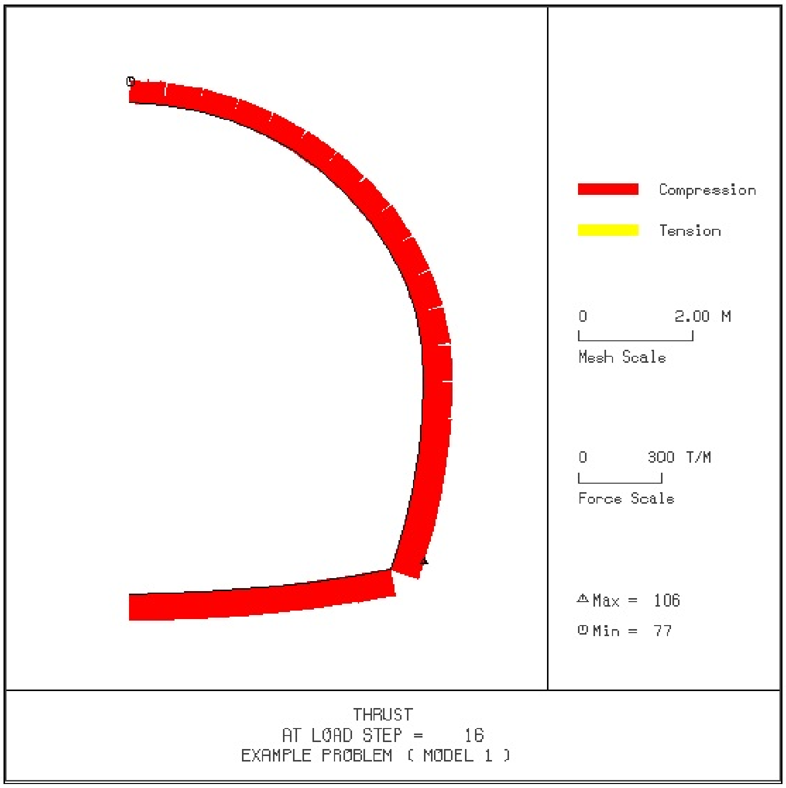

Compression
Tension
0 2.00 M
Mesh Scale
0 300 T/M
Force Scale
Max = 106
Min = 77
THRUST
AT LOAD STEP = 16
EXAMPLE PROBLEM (MODEL 1)

Figure 6.42

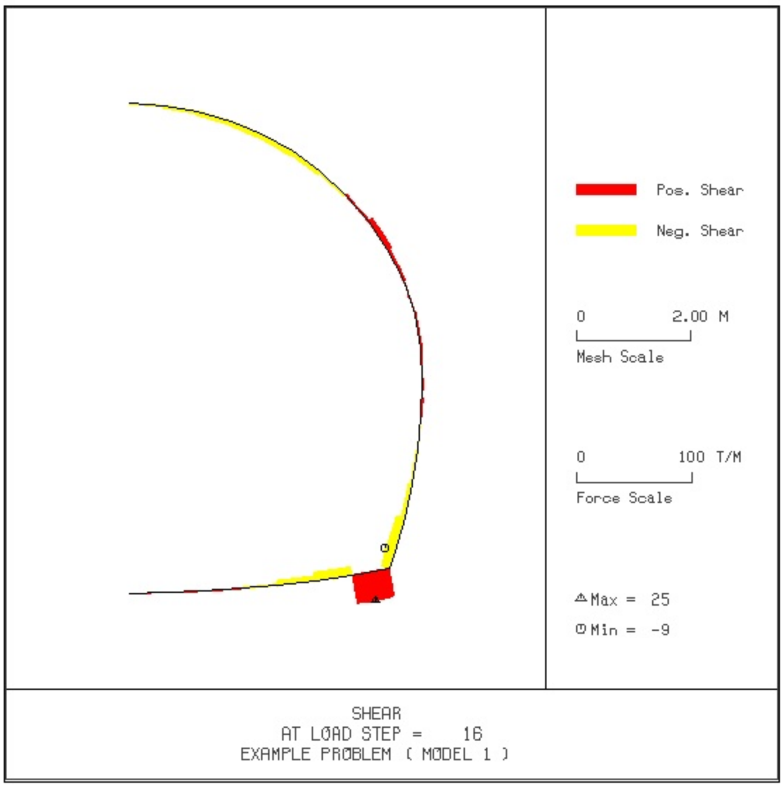

Pos. Shear
Neg. Shear
0 2.00 M
Mesh Scale
0 100 T/M
Force Scale
Max = 25
Min = -9
SHEAR
AT LOAD STEP = 16
EXAMPLE PROBLEM (MODEL 1)

Figure 6.43

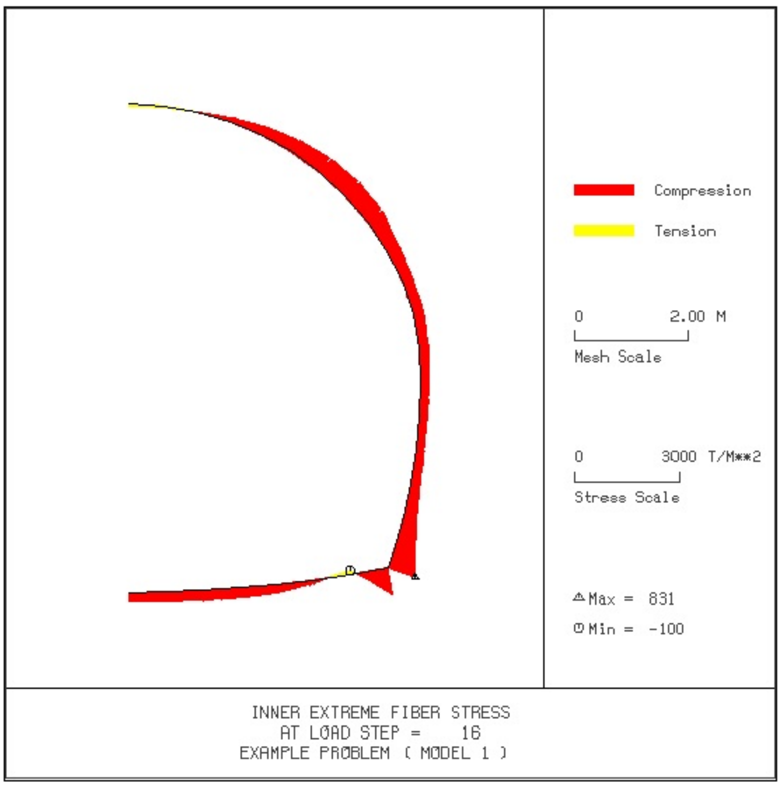

Compression
Tension
0 2.00 M
Mesh Scale
0 3000 T/M**2
Stress Scale
Max = 831
Min = -100
INNER EXTREME FIBER STRESS
AT LOAD STEP = 16
EXAMPLE PROBLEM (MODEL 1)

Figure 6.44

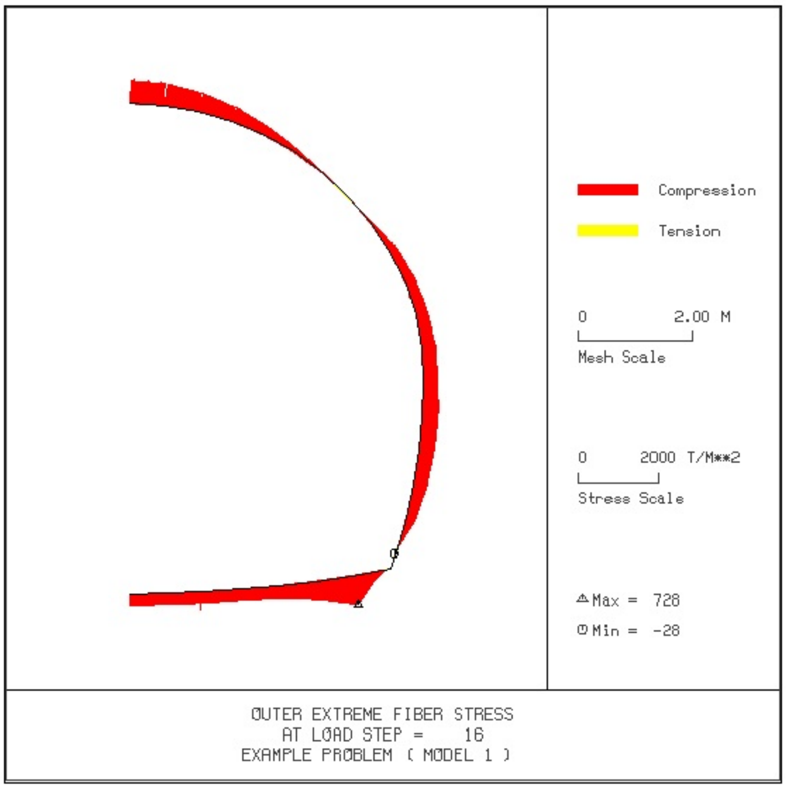

Compression
Tension
0 2.00 M
Mesh Scale
0 2000 T/M**2
Stress Scale
Max = 728
Min = -28
OUTER EXTREME FIBER STRESS
AT LOAD STEP = 16
EXAMPLE PROBLEM (MODEL 1)

Figure 6.45

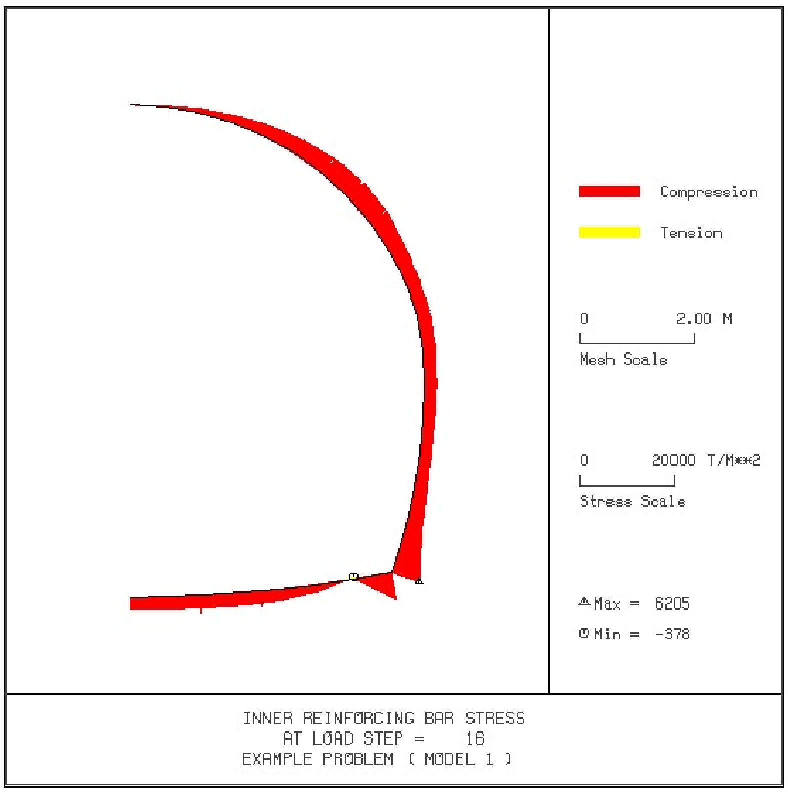

Compression
Tension
0 2.00 M
Mesh Scale
0 20000 T/M**2
Stress Scale
Max = 6205
Min = -378
INNER REINFORCING BAR STRESS
AT LOAD STEP = 16
EXAMPLE PROBLEM (MODEL 1)

Figure 6.46

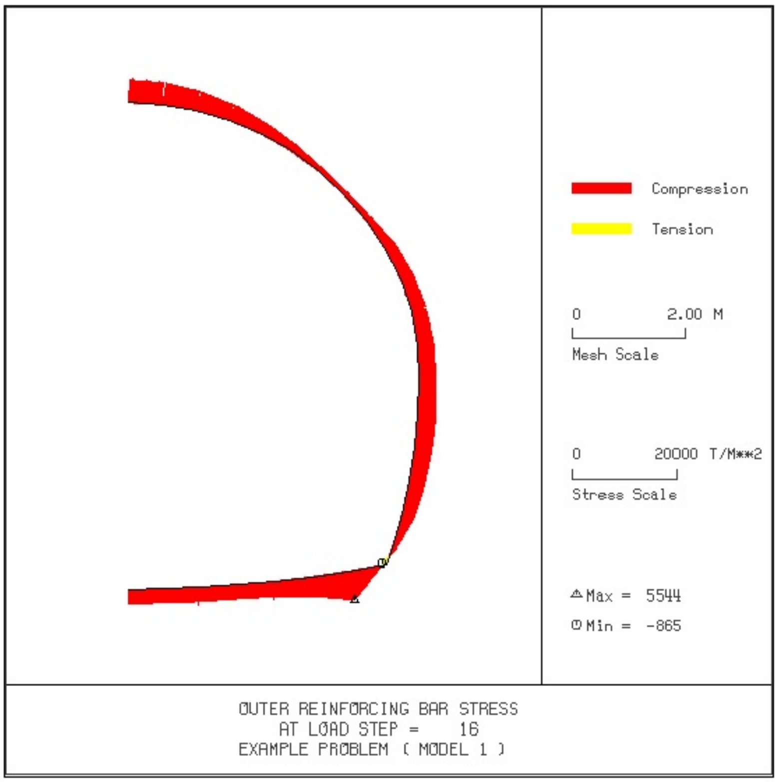

Compression
Tension
0 2.00 M
Mesh Scale
0 20000 T/M**2
Stress Scale
Max = 5544
Min = -865
OUTER REINFORCING BAR STRESS
AT LOAD STEP = 16
EXAMPLE PROBLEM (MODEL 1)

Figure 6.47

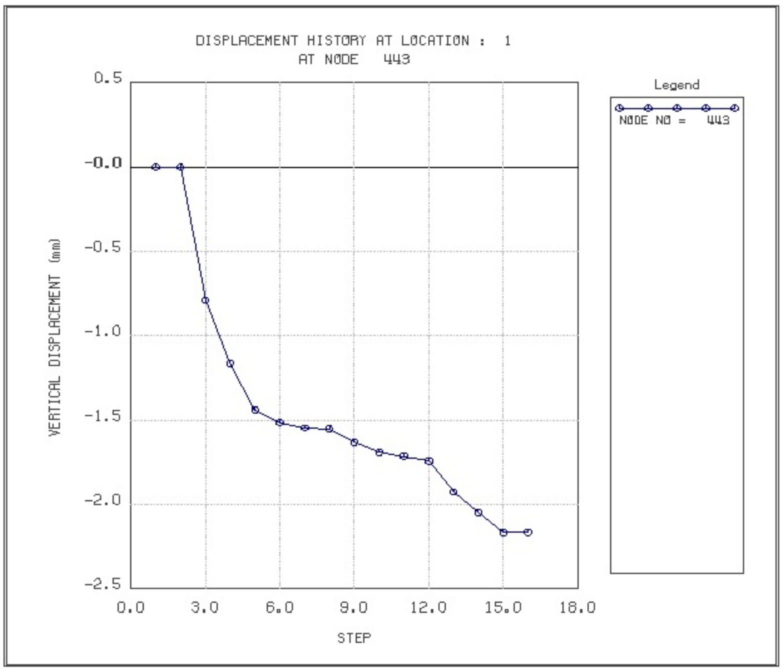

DISPLACEMENT HISTORY AT LOCATION : 1
AT NODE 443
Legend
NODE NO = 443
VERTICAL DISPLACEMENT (mm)
0.5
-0.0
-0.5
-1.0
-1.5
-2.0
-2.5
0.0
3.0
6.0
9.0
12.0
15.0
18.0
STEP

Figure 6.48

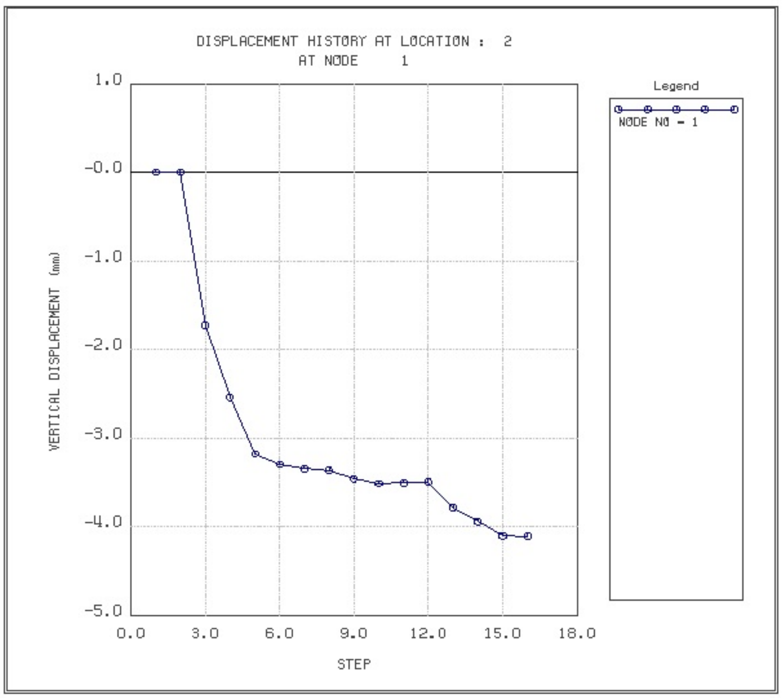

DISPLACEMENT HISTORY AT LOCATION : 2
AT NODE 1
Legend
NODE NO = 1
VERTICAL DISPLACEMENT (mm)
1.0
-0.0
-1.0
-2.0
-3.0
-4.0
-5.0
0.0
3.0
6.0
9.0
12.0
15.0
18.0
STEP

Figure 6.49

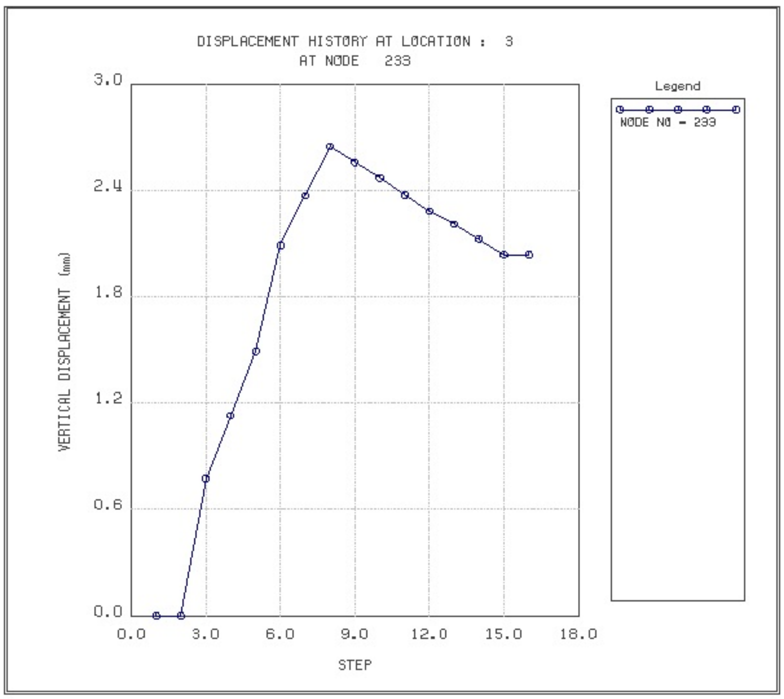

DISPLACEMENT HISTORY AT LOCATION : 3
AT NODE 233
VERTICAL DISPLACEMENT (mm)
3.0
2.4
1.8
1.2
0.6
0.0
0.0
3.0
6.0
9.0
12.0
15.0
18.0
STEP
Legend
NODE NO = 233

Figure 6.50

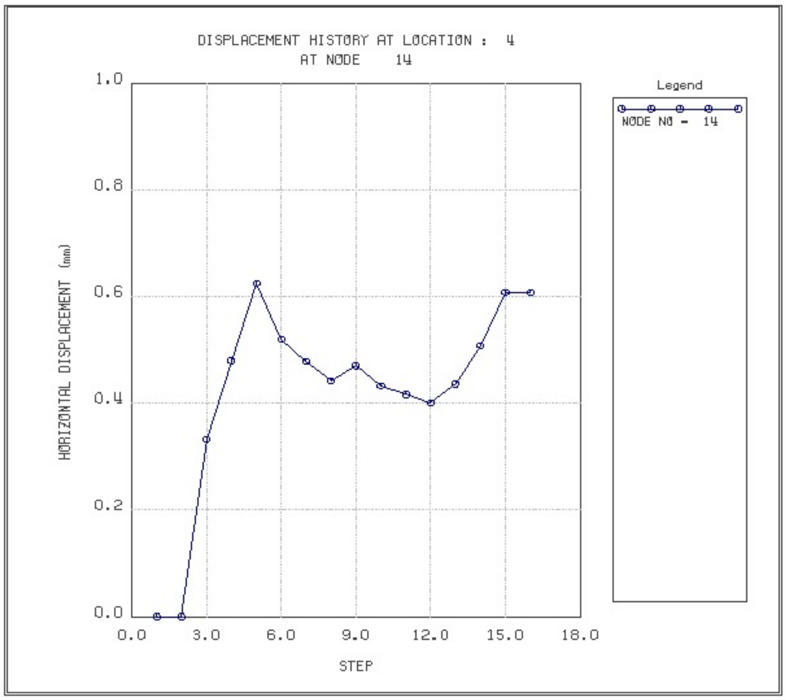

DISPLACEMENT HISTORY AT LOCATION : 4
AT NODE 14
HORIZONTAL DISPLACEMENT (mm)
1.0
0.8
0.6
0.4
0.2
0.0
0.0
3.0
6.0
9.0
12.0
15.0
18.0
STEP
Legend
NODE NO = 14

Figure 6.51

6.2 Example 2

Example 2 represents full section of a single tunnel as schematically shown in Figure 6.53.

A typical NATM tunnel shape is chosen here to be analyzed using program TUNA Plus. Geometric parameters related to tunnel shape, rock bolts, shotcrete, and liner are given in Figure 6.52. Geological profile, tunnel depth, and analysis boundaries are specified in Figure 6.53. Material properties of soil/rock layers and supports are summarized in Table 6.2.

As shown in Table 6.8, tunnel construction involves four major excavation stages; upper left core excavation, upper right core excavation, lower left core excavation, and lower right core excavation. Each excavation stage is associated with three load steps; 50% stress release, additional 25% stress release where soft shotcrete and rock bolts are installed, and the last 25% stress release where shotcrete is hardened. It should be noted that program TUNA Plus uses first two load steps to generate in situ K_o stress state.

For lining analysis, reinforced concrete liner is considered with interface joint element between the liner and the surrounding medium. The interface joint properties are set to allow separation when the tensile stress develops in the direction normal to the interface while full slippage is assumed along the interface.

For loads acting on the reinforced concrete liner, following four different load combinations are considered:

1. Weight
2. Weight + Water Pressure
3. Weight + Water Pressure + Loosening Load
4. Weight + Water Pressure + Loosening Load + Support Degradation

Ground water pressure is applied to the liner except the invert. As loosening load, an unsymmetric triangular vertical stress as shown in Table 6.8 is applied to the liner. As support degradation, rock bolts are deactivated.

The input file EX2.DAT is listed in Table 6.9. Text output file STEP.LST in Table 6.10 lists steps where major excavations take place and external lining loads are applied.

Figures 6.54 to 6.68 show PLOT-2D graphical outputs at the completion of excavation and at the last load step for lining. Brief description of these plots are shown in the text output file PLTDS.LST in Table 6.11.

Figures 6.69 to 6.71 show PLOT-XY graphical outputs at tunnel crown and springline. Brief description of these plots are shown in the text output file PLTXY.LST in Table 6.12.

Table 6.8 Simulation of construction sequence

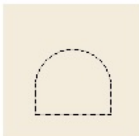
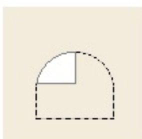
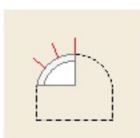
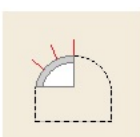
<table>
<tr><th>Step</th><th>Construction State</th><th colspan="2">Descriptions</th></tr>
<tr><td>1,2</td><td></td><td colspan="2">In Situ K_o State</td></tr>
<tr><td>3</td><td></td><td>50% Stress Relief</td><td rowspan="3">Upper Left Core Excavation</td></tr>
<tr><td>4</td><td></td><td>75% Stress Relief
Soft Shotcrete
Rock Bolt</td></tr>
<tr><td>5</td><td></td><td>100% Stress Relief
Hard Shotcrete
Rock Bolt</td></tr>
</table>

Table 6.8 Simulation of construction sequence (Continued)

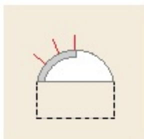
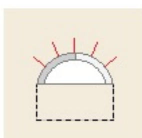
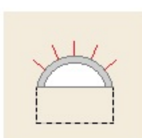
Step	Construction State	Descriptions	
6		50% Stress Relief	Upper Right Core Excavation
7		75% Stress Relief Soft Shotcrete Rock Bolt	
8		100% Stress Relief Hard Shotcrete Rock Bolt	

Table 6.8 Simulation of construction sequence (Continued)

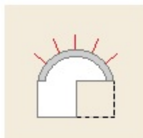
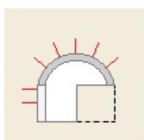
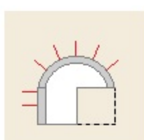
Step	Construction State	Descriptions	
9		50% Stress Relief	Lower Left Core Excavation
10		75% Stress Relief Soft Shotcrete Rock Bolt	
11		100% Stress Relief Hard Shotcrete Rock Bolt	

Table 6.8 Simulation of construction sequence (Continued)

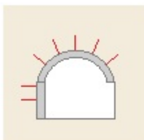
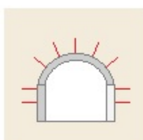
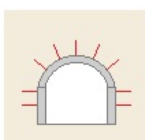
<table>
<tr><th>Step</th><th>Construction State</th><th colspan="2">Descriptions</th></tr>
<tr><td>12</td><td></td><td>50% Stress Relief</td><td rowspan="3">Lower Right Core Excavation</td></tr>
<tr><td>13</td><td></td><td>75% Stress Relief
Soft Shotcrete
Rock Bolt</td></tr>
<tr><td>14</td><td></td><td>100% Stress Relief
Hard Shotcrete
Rock Bolt</td></tr>
</table>

Table 6.8 Simulation of construction sequence (Continued)

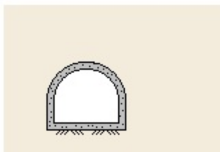
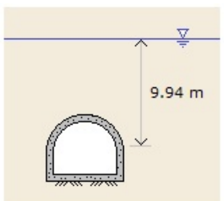
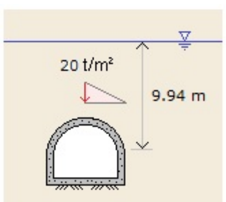
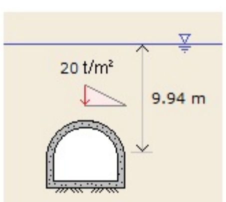
Step	Construction State	Descriptions	
15		Lining Subjected to: Weight	Lining Analysis
18		Lining Subjected to: Weight + Water Pressure	
21		Lining Subjected to: Weight + Water Pressure + Loosening Load	
22		Lining Subjected to: Weight + Water Pressure + Loosening Load + Rock Bolt Deactivation	

Table 6.9 Listing of input file EX2.DAT

```
*
* GENERAL INFORMATION
*
* CARD 1.1
* TITLE
  EXAMPLE PROBLEM ( MODEL 2 )
*
* CARD 1.2
* IUNIT
  3
*
* CARD 1.3
* MODEL  IGEN  IEXMESH  ILNCOUPL  IEXORDER  IRBP
  2      0     0        0         1         0
*
* CARD 1.4
* IEZ1   IEZ2  IEZ3  IEZ4
  2      4     1     3
*
* TUNNEL ANALYSIS BOUNDARY
*
* CARD 2.1
* HT    HL   W     DELTAX  DELTAY  NDYMAX
  19.94 30.  60.   2.0     2.0     40
*
* SOIL / ROCK LAYER INFORMATION
*
* CARD 3.1
* NLAYER
  4
* CARD 3.2
* LAYERNO   H     GAMA  RKO  E       V    PHI   C    T
  1         4.2   1.9   0.5  2000.   0.33 30.   3.   20.
  2         4.3   1.9   0.43 5000.   0.30 35.   30.  30.
  3         3.5   2.4   0.33 20000.  0.25 40.   70.  40.
  4         39.94 2.55  0.25 200000. 0.20 45.   100. 50.
*
* ADDITIONAL TOP SOIL / ROCK LAYER
*
* CARD 3.3.1
* NATLAYER
  0
*
* USER SPECIFIED SOIL / ROCK LAYER
*
* CARD 3.4.1
* NUSLAYER
  0
```

```
*
* USER SPECIFIED DISTRIBUTED SURFACE LOAD
*
* CARD 3.5.1
* NUSXPD
  0
*
* SHOTCRETE PROPERTIES
*
* CARD 3.6
* E         V      PHI       C         T        GAMA
  1.5E+06   0.2    30.       500.      100.     2.4
*
* LINING PROPERTIES
*
* CARD 3.7
* E         V      PHI       C         T        GAMA   ER        VR
  2.1E+06   0.2    30.       500.      300.     2.5    2.1E+07   0.2
*
* ROCK BOLT PROPERTIES
*
* CARD 3.8
* A          WL         E          STRSI      SIGMAy     Ef
  0.000491   0.00383    2.1E+07    0.0        2.3E+04    1.0
*
* INTERFACE PROPERTIES BETWEEN SHOTCRETE AND LINING
*
* CARD 3.9
* NM        E       G         t
  2         200000. 2.0       0.001
* C         PHI
  0.001     5.0
* E1        E2      E3        E4      S1       S2      S3      S4
  -1.0      0.0     1.0E-7    1.0    -200000. 0.0      2.E-02  2.E-02
*
* TUNNEL DIMENSION
*
* CARD 4.0
* ISTYPE  GR     GA
  1       1.0    0.5
*
* CARD 4.1
* R1     A1    R2    A2   R3    A3     R4
  7.24   60.   6.24  30.  11.86 21.781 25.86
* CARD 4.2
* INVSHOT  TS      INVLN     TL      DI    ASI    DO    ASO
  0        0.20    1         0.4     0.05  0.0033 0.05  0.0033
* CARD 4.3
* NUMRB    LRB     LSPACING  TSPACING  NSRB
  21       3.0     1.35      1.2        2
```

```
*
* EXCAVATION STRESS RELEASE AND SHOTCRETE MODULUS CHANGE
*
* CARD 5.1
* PSR       PASR     RESH
  50.       25.      0.33
*
* EXTERNAL LOADS FOR LINING ANALYSIS
*
* CARD 6.1
* LDTYPE
  1
*
* WATER PRESSURE
*
* CARD 6.2
* LGWINV    NWPSTEP DGW      GAMAW
  0         3       10.      1.0
*
* LOOSENING LOAD
*
* CARD 6.3.1
* LSDADD    NLDSTEP  HPRES    VPRES
  1         3        0.0      0.0
*
* ADDITIONAL VERTICAL LOOSENING LOAD
* CARD 6.3.2.1
* DXv1      DXv2     Qv1      Qvo      Qv2
  0.0       7.24     0.0      20.      0.0
*
* PRIMARY SUPPORT DEGRADATION
*
* CARD 6.4
* LPSDEG    REDH
  1         1.0
*
* SUBGRADE REACTION FOR ILNCOUPL = 1
*
* CARD 6.4
* SUBGK
* 1.0E+05
*
* END OF DATA
```

Table 6.10 Listing of text output file STEP.DAT

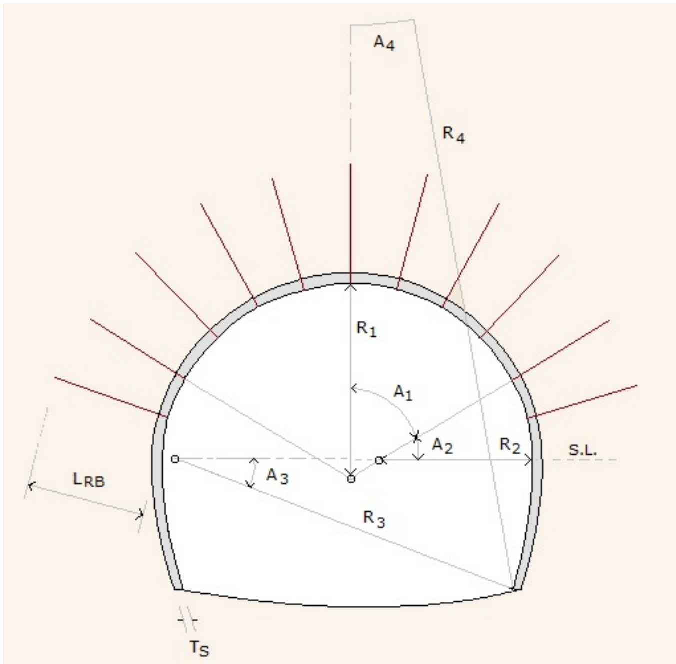
STEP NO	DESCRIPTIONS
5	Excavation of Upper Left Core
8	Excavation of Upper Right Core
11	Excavation of Lower Left Core
14	Excavation of Lower Right Core
15	<u>Lining Subjected to:</u> Weight
18	<u>Lining Subjected to:</u> Weight Water Pressure
21	<u>Lining Subjected to:</u> Weight Water Pressure Loosening Load
22	<u>Lining Subjected to:</u> Weight Water Pressure Loosening Load Rock Bolt Deactivation & Shotcrete Degradation

Table 6.11 Partial listing of text output file PLTDS.LST

```
PLOT NO   TITLE
   1      FINITE ELEMENT MESH
          EXAMPLE PROBLEM ( MODEL 2 )

   2      DEFORMED SHAPE
          AT LOAD STEP =     5
          EXAMPLE PROBLEM ( MODEL 2 )

   3      DEFORMED SHAPE
          AT LOAD STEP =     8
          EXAMPLE PROBLEM ( MODEL 2 )

   4      DEFORMED SHAPE
          AT LOAD STEP =    11
          EXAMPLE PROBLEM ( MODEL 2 )

   5      DEFORMED SHAPE
          AT LOAD STEP =    14
          EXAMPLE PROBLEM ( MODEL 2 )

   6      DEFORMED SHAPE
          AT LOAD STEP =     5
          EXAMPLE PROBLEM ( MODEL 2 )

   7      DEFORMED SHAPE
          AT LOAD STEP =     8
          EXAMPLE PROBLEM ( MODEL 2 )

   8      DEFORMED SHAPE
          AT LOAD STEP =    11
          EXAMPLE PROBLEM ( MODEL 2 )

   9      DEFORMED SHAPE
          AT LOAD STEP =    14
          EXAMPLE PROBLEM ( MODEL 2 )

  10      PRINCIPAL STRESS DISTRIBUTION
          AT LOAD STEP =     5
          EXAMPLE PROBLEM ( MODEL 2 )

  11      PRINCIPAL STRESS DISTRIBUTION
          AT LOAD STEP =     8
          EXAMPLE PROBLEM ( MODEL 2 )
```

Table 6.12 Listing of text output file PLTXY.LST

```
PLOT NO      TITLE

   1         DISPLACEMENT HISTORY AT LOCATION :  1
             AT NODE   609

   2         DISPLACEMENT HISTORY AT LOCATION :  2
             AT NODE     1

   3         DISPLACEMENT HISTORY AT LOCATION :  3
             AT NODE   310

   4         DISPLACEMENT HISTORY AT LOCATION :  4
             AT NODE    19

   5         DISPLACEMENT HISTORY AT LOCATION :  5
             AT NODE  1255
```

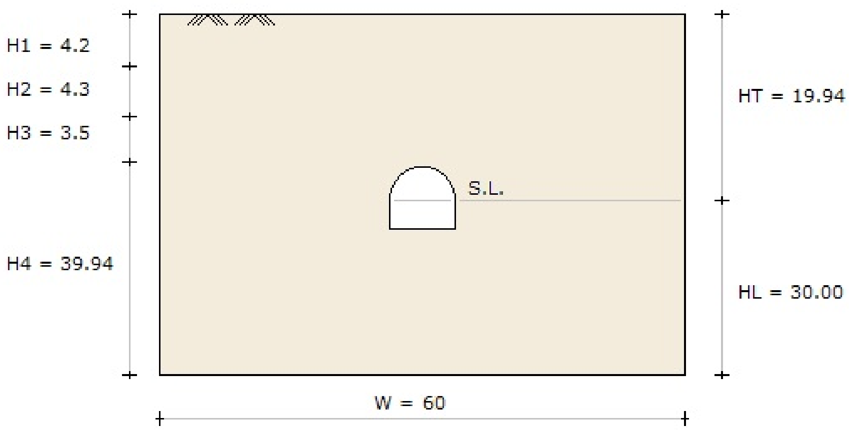


R_1	= 7.24 M	A_1	= 60°
R_2	= 6.24 M	A_2	= 30°
R_3	= 11.86 M	A_3	= 21.781°
R_4	= 25.86 M		

Number of Rock Bolts (NUMRB)	=	21
Length of Rock Bolts (LRB)	=	3.0 M
Spacing of Rock Bolts (TSPACING)	=	1.2 M
Thickness of Shotcrete (TS)	=	20 Cm
Thickness of Liner (TL)	=	40 Cm
Reinforcing Bar Area (ASI)	=	33 Cm^2
Reinforcing Bar Area (ASO)	=	33 Cm^2

Figure 6.52 Tunnel dimensions used for Example 2

MODEL= 2 Single Tunnel [Full Section]



DELTAX = 2.0, DELTAY = 2.0, NDYMAX = 40

Figure 6.53 Schematic tunnel section for Example 2

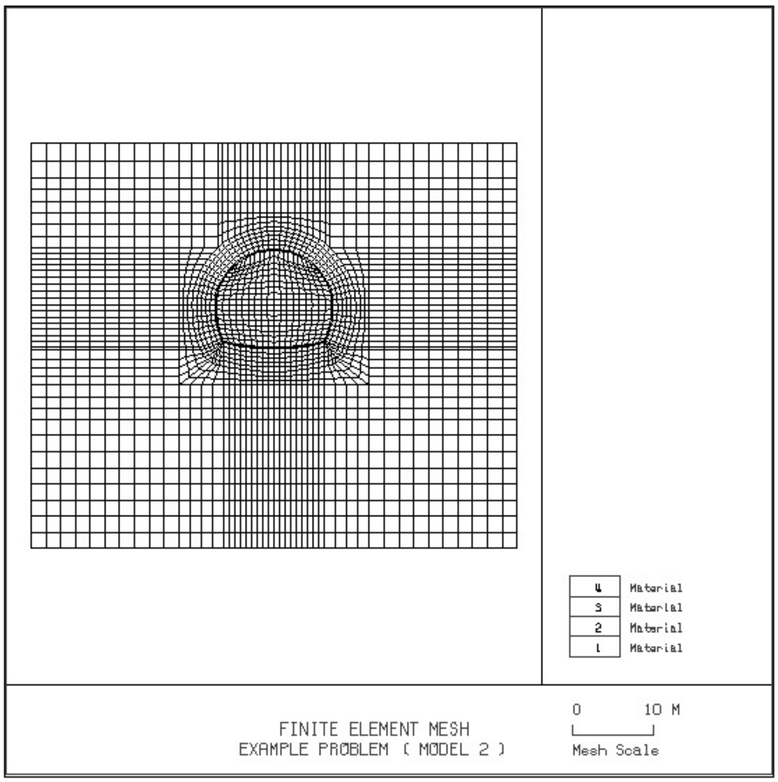

4 Material
3 Material
2 Material
1 Material
0 10 M
Mesh Scale
FINITE ELEMENT MESH
EXAMPLE PROBLEM (MODEL 2)

Figure 6.54

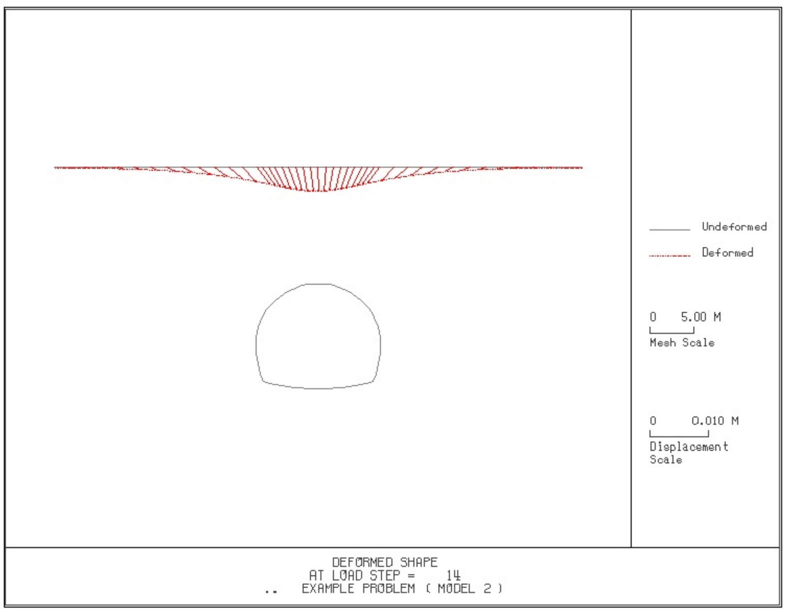

Undeformed
Deformed
0 5.00 M
Mesh Scale
0 0.010 M
Displacement Scale
DEFORMED SHAPE
AT LOAD STEP = 14
.. EXAMPLE PROBLEM (MODEL 2)

Figure 6.55

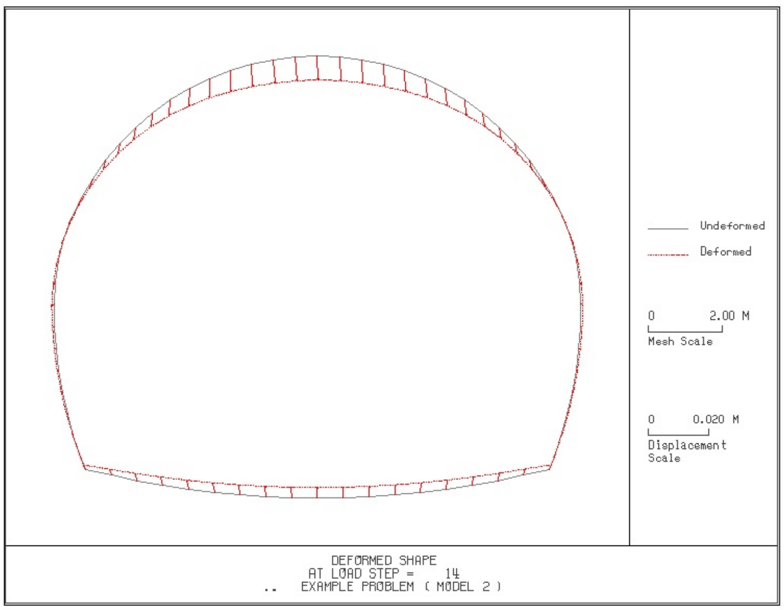

Undeformed
Deformed
0 2.00 M
Mesh Scale
0 0.020 M
Displacement
Scale
DEFORMED SHAPE
AT LOAD STEP = 14
.. EXAMPLE PROBLEM (MODEL 2)

Figure 6.56

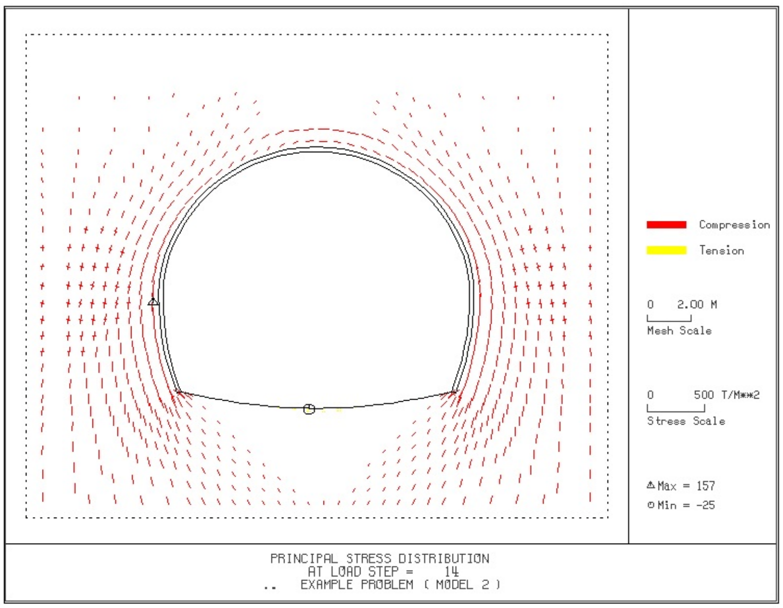

Compression
Tension
0 2.00 M
Mesh Scale
0 500 T/M**2
Stress Scale
Max = 157
Min = -25
PRINCIPAL STRESS DISTRIBUTION
AT LOAD STEP = 14
.. EXAMPLE PROBLEM (MODEL 2)

Figure 6.57

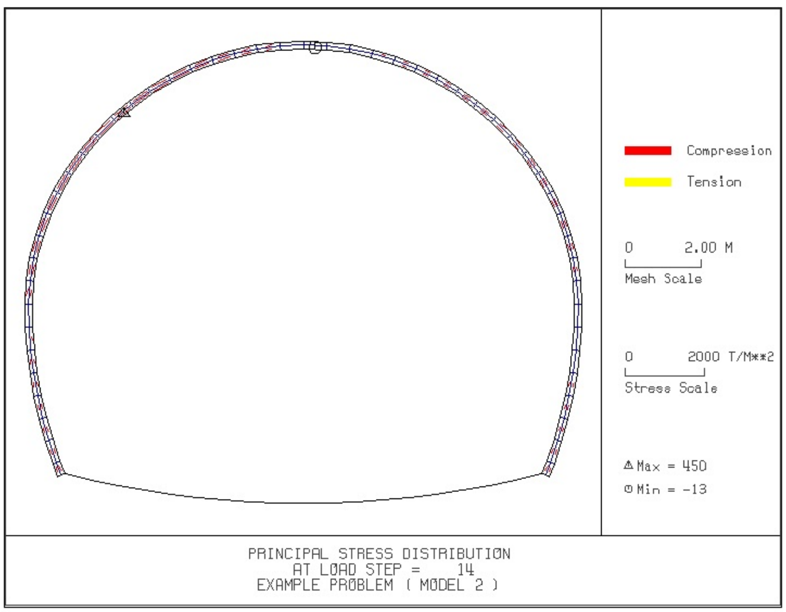

Compression
Tension
0 2.00 M
Mesh Scale
0 2000 T/M**2
Stress Scale
Max = 450
Min = -13
PRINCIPAL STRESS DISTRIBUTION
AT LOAD STEP = 14
EXAMPLE PROBLEM (MODEL 2)

Figure 6.58

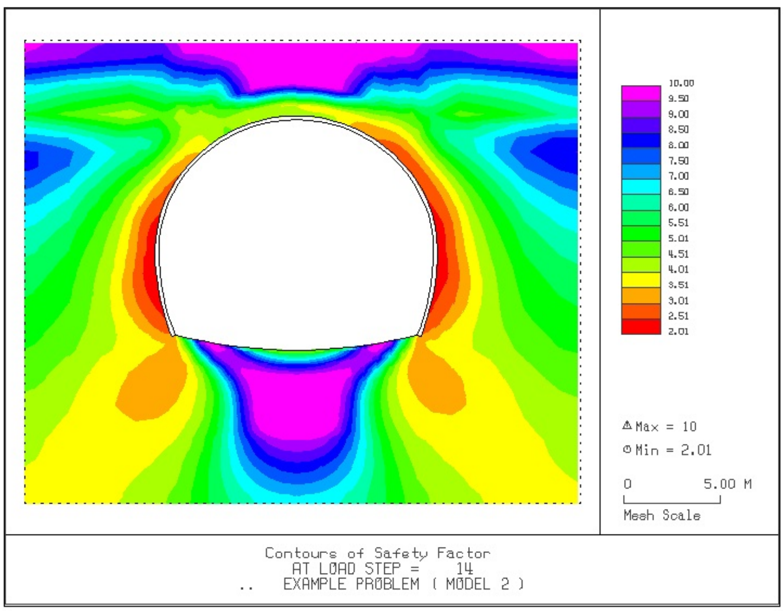

10.00
9.50
9.00
8.50
8.00
7.50
7.00
6.50
6.00
5.51
5.01
4.51
4.01
3.51
3.01
2.51
2.01
Max = 10
Min = 2.01
0
5.00 M
Mesh Scale
Contours of Safety Factor
AT LOAD STEP = 14
.. EXAMPLE PROBLEM (MODEL 2)

Figure 6.59

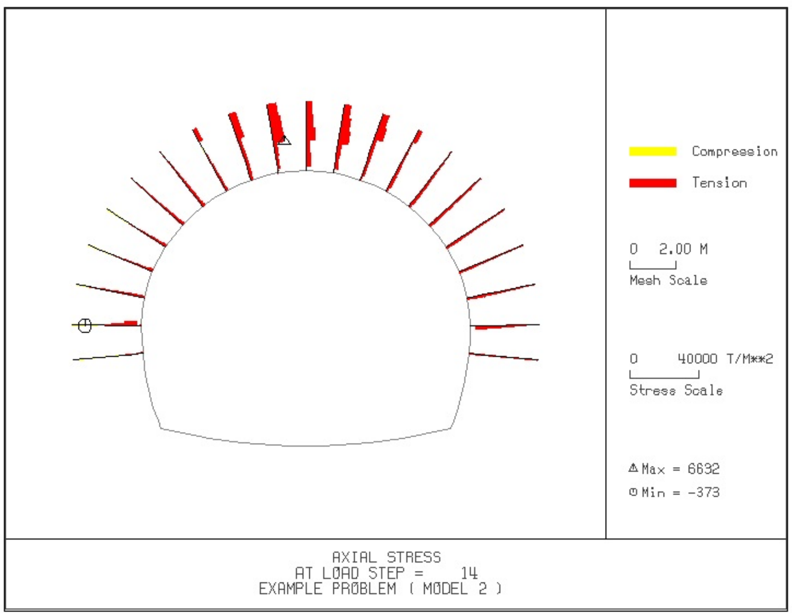

Compression
Tension
0 2.00 M
Mesh Scale
0 40000 T/M**2
Stress Scale
Max = 6632
Min = -373
AXIAL STRESS
AT LOAD STEP = 14
EXAMPLE PROBLEM (MODEL 2)

Figure 6.60

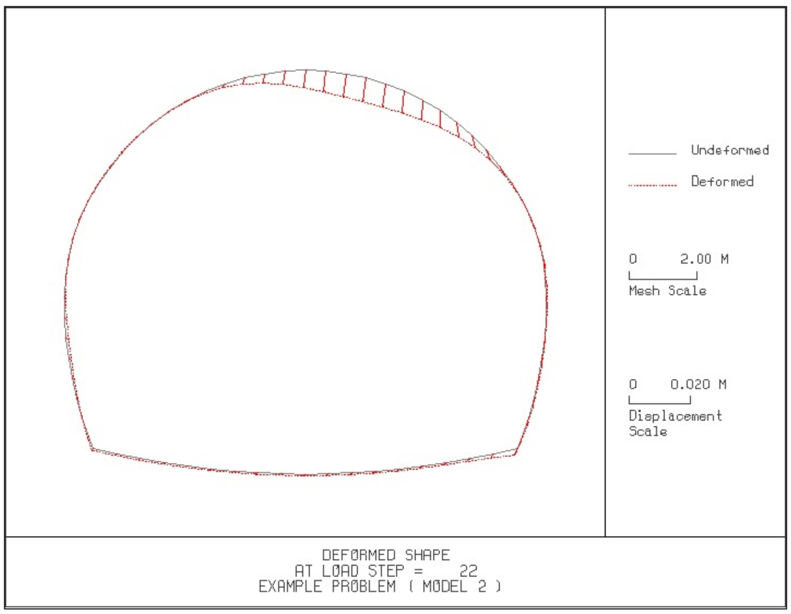

Undeformed
Deformed
0 2.00 M
Mesh Scale
0 0.020 M
Displacement
Scale
DEFORMED SHAPE
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 2)

Figure 6.61

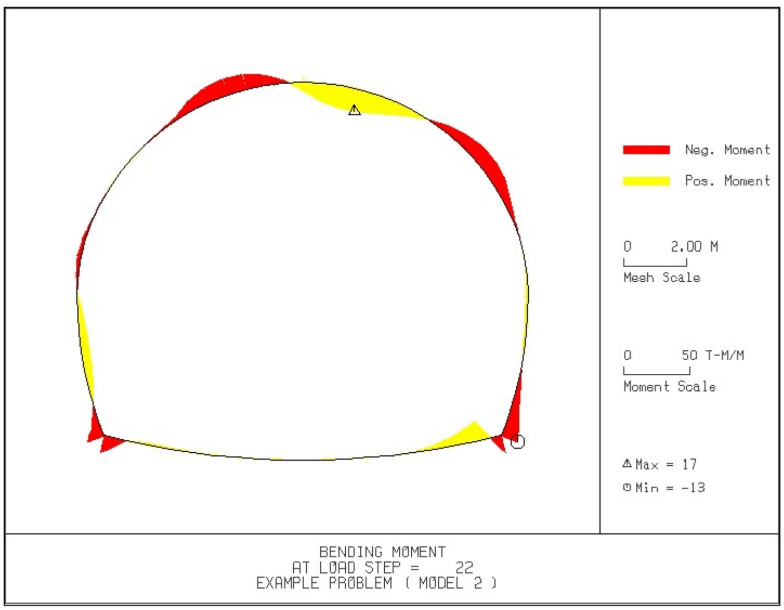

Neg. Moment
Pos. Moment
0 2.00 M
Mesh Scale
0 50 T-M/M
Moment Scale
Max = 17
Min = -13
BENDING MOMENT
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 2)

Figure 6.62

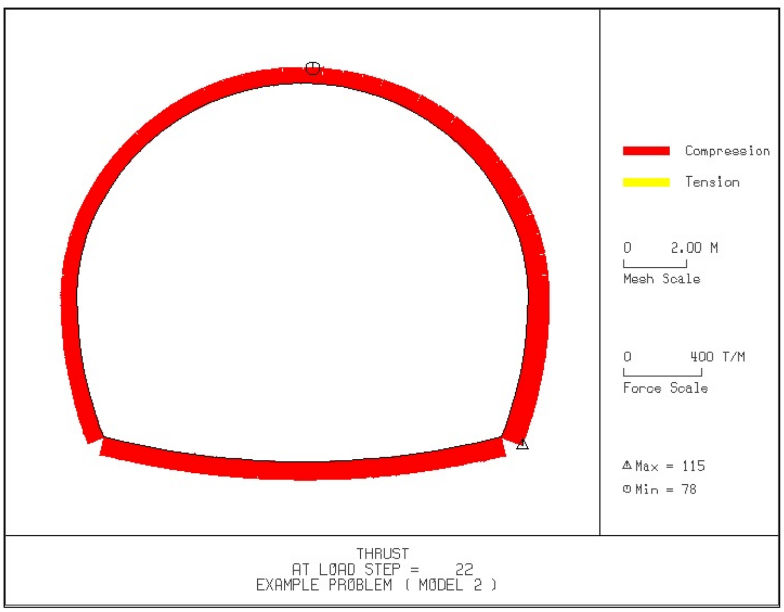

Compression
Tension
0 2.00 M
Mesh Scale
0 400 T/M
Force Scale
Max = 115
Min = 78
THRUST
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 2)

Figure 6.63

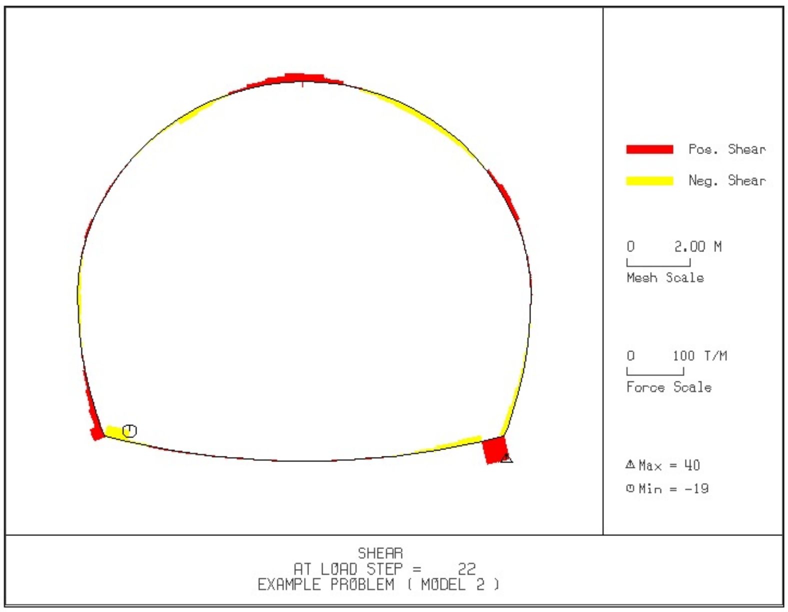

Pos. Shear
Neg. Shear
0 2.00 M
Mesh Scale
0 100 T/M
Force Scale
Max = 40
Min = -19
SHEAR
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 2)

Figure 6.64

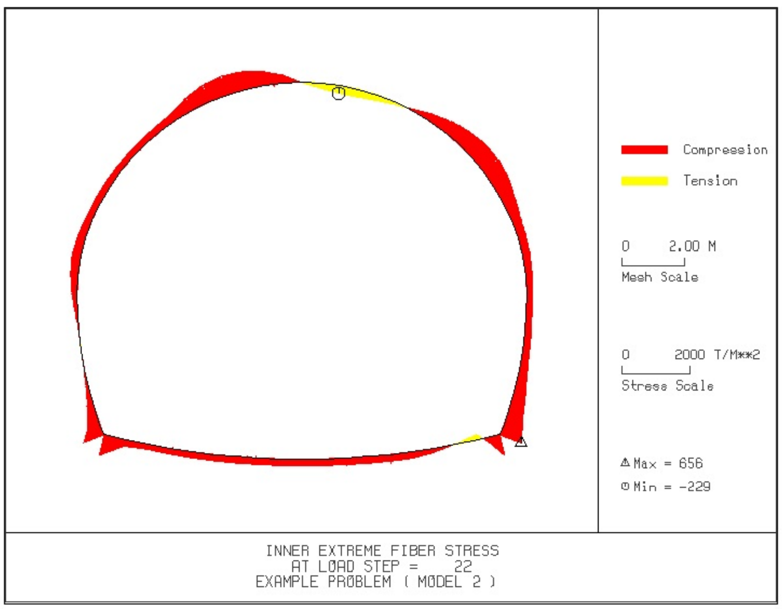

Compression
Tension
0 2.00 M
Mesh Scale
0 2000 T/M**2
Stress Scale
Max = 656
Min = -229
INNER EXTREME FIBER STRESS
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 2)

Figure 6.65

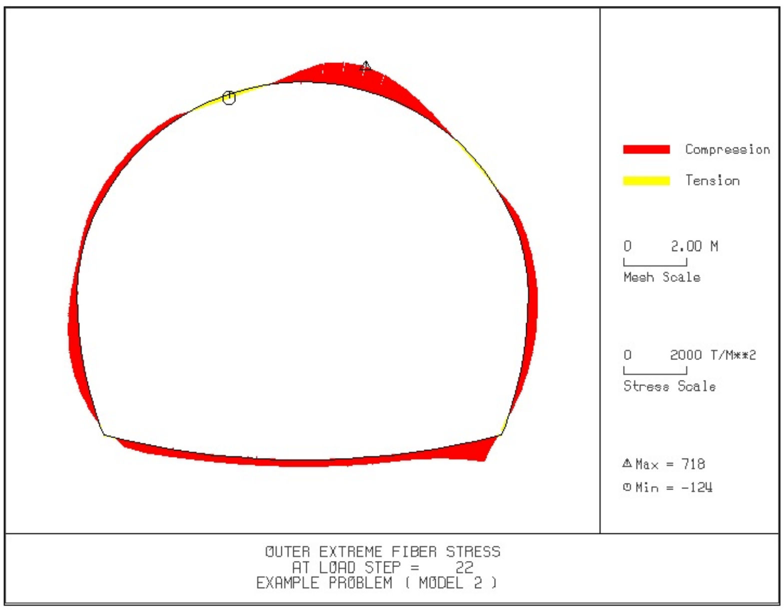

Compression
Tension
0 2.00 M
Mesh Scale
0 2000 T/M**2
Stress Scale
Max = 718
Min = -124
OUTER EXTREME FIBER STRESS
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 2)

Figure 6.66

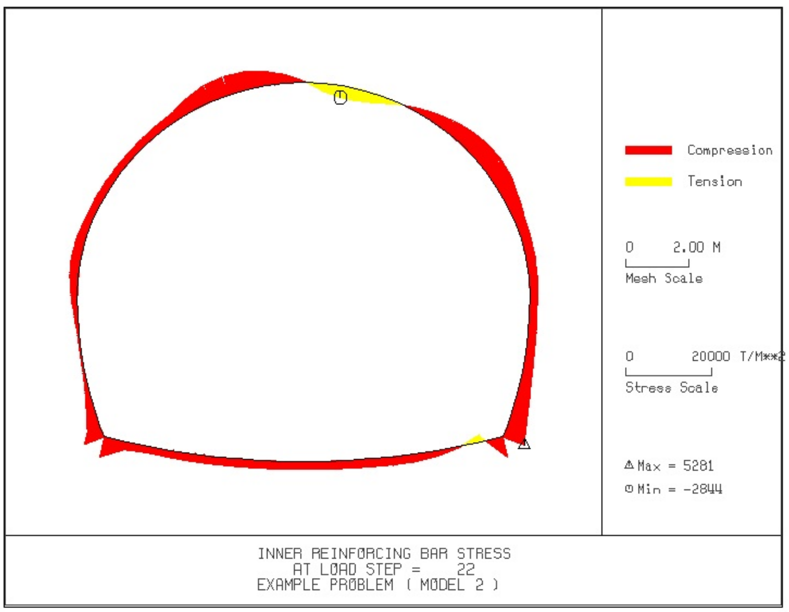

Compression
Tension
0 2.00 M
Mesh Scale
0 20000 T/M**2
Stress Scale
Max = 5281
Min = -2844
INNER REINFORCING BAR STRESS
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 2)

Figure 6.67

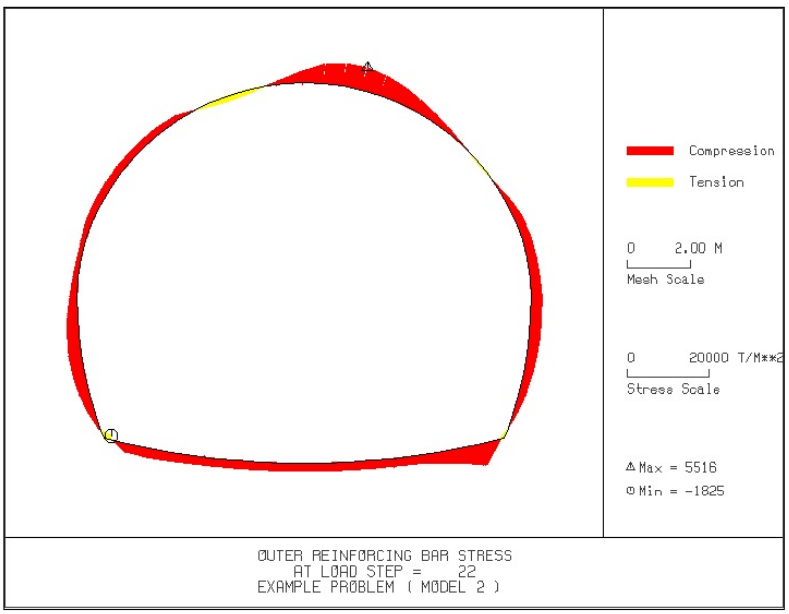

Compression
Tension
0 2.00 M
Mesh Scale
0 20000 T/M**2
Stress Scale
Max = 5516
Min = -1825
OUTER REINFORCING BAR STRESS
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 2)

Figure 6.68

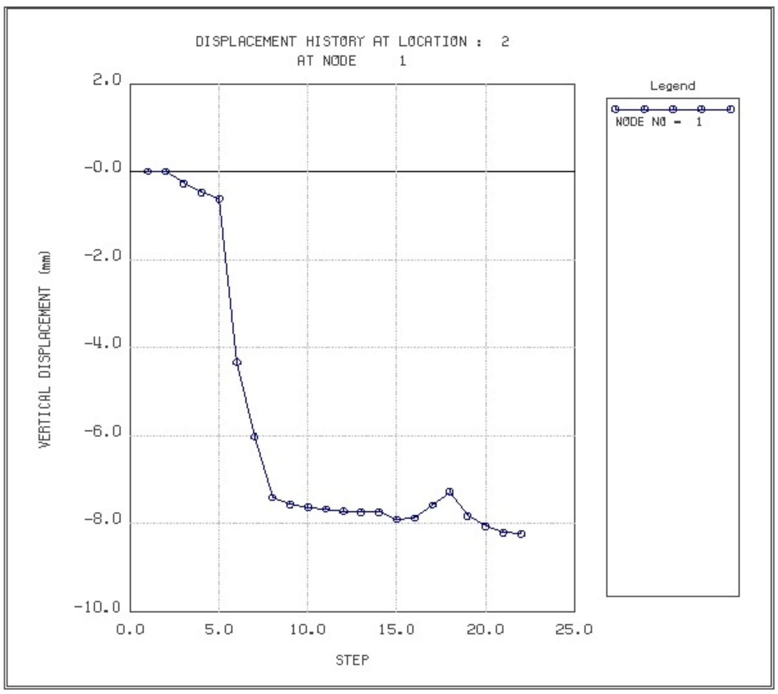

DISPLACEMENT HISTORY AT LOCATION : 2
AT NODE 1
VERTICAL DISPLACEMENT (mm)
STEP
2.0
-0.0
-2.0
-4.0
-6.0
-8.0
-10.0
0.0
5.0
10.0
15.0
20.0
25.0
Legend
NODE NO = 1

Figure 6.69

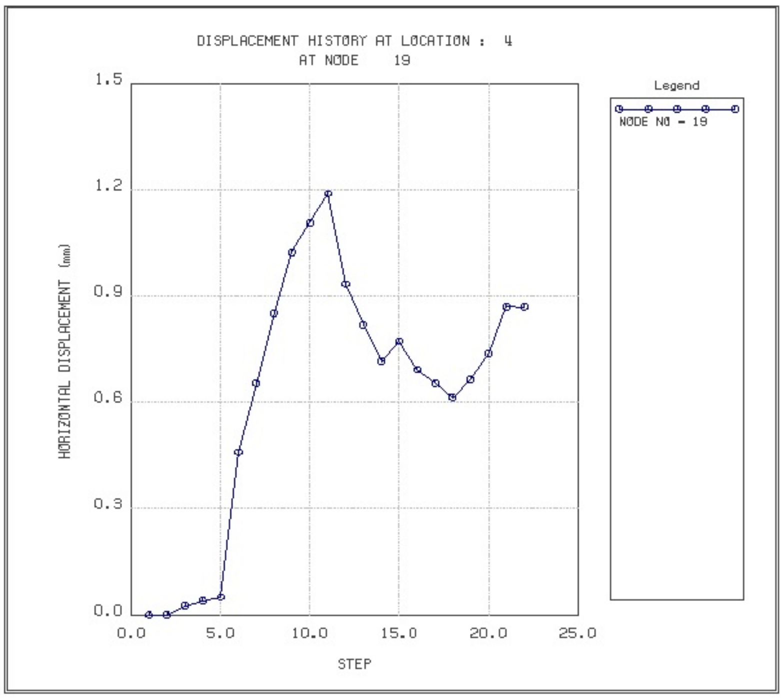

DISPLACEMENT HISTORY AT LOCATION : 4
AT NODE 19
HORIZONTAL DISPLACEMENT (mm)
STEP
1.5
1.2
0.9
0.6
0.3
0.0
0.0
5.0
10.0
15.0
20.0
25.0
Legend
NODE NO = 19

Figure 6.70

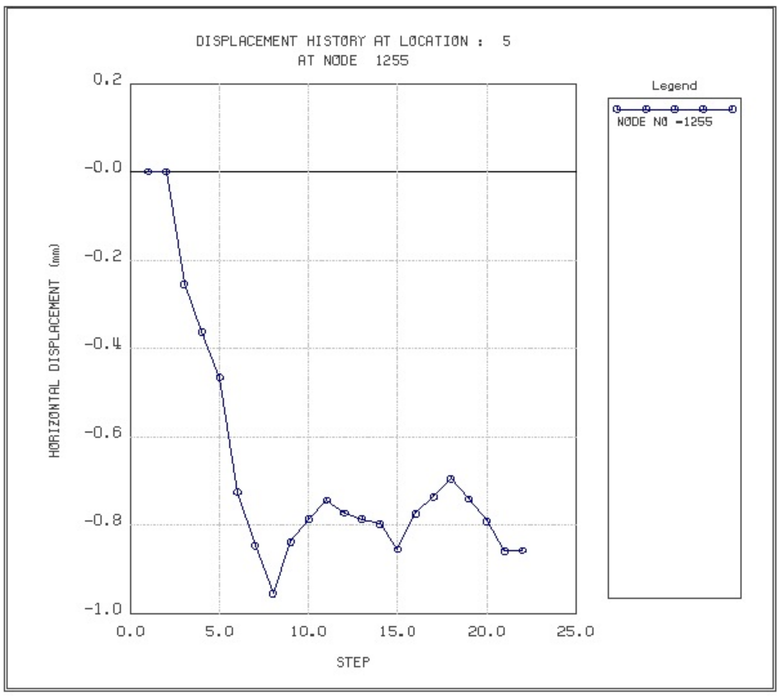

DISPLACEMENT HISTORY AT LOCATION : 5
AT NODE 1255
HORIZONTAL DISPLACEMENT (mm)
0.2
-0.0
-0.2
-0.4
-0.6
-0.8
-1.0
0.0
5.0
10.0
15.0
20.0
25.0
STEP
Legend
NODE NO =1255

Figure 6.71

6.3 Example 3

Example 3 represents two identical tunnels as schematically shown in Figure 6.72.

A typical NATM tunnel shape is chosen here to be analyzed using program TUNA Plus. Geometric parameters related to tunnel shape, rock bolts, shotcrete, and liner are given in Figure 6.1. Geological profile, tunnel depth, and analysis boundaries are specified in Figure 6.72. Material properties of soil/rock layers and supports are summarized in Table 6.2.

As shown in Table 6.13, tunnel construction involves four major excavation stages; upper core excavation in right tunnel, lower core excavation in right tunnel, upper core excavation in left tunnel, and lower core excavation in left tunnel. Each excavation stage is associated with three load steps; 50% stress release, additional 25% stress release where soft shotcrete and rock bolts are installed, and the last 25% stress release where shotcrete is hardened. It should be noted that program TUNA Plus uses first two load steps to generate in situ K_o stress state.

For lining analysis, reinforced concrete liner is considered with interface joint element between the liner and the surrounding medium. The interface joint properties are set to allow separation when the tensile stress develops in the direction normal to the interface while full slippage is assumed along the interface.

For loads acting on the reinforced concrete liner, following four different load combinations are considered:

1. Weight
2. Weight + Water Pressure
3. Weight + Water Pressure + Loosening Load
4. Weight + Water Pressure + Loosening Load + Support Degradation

Ground water pressure is applied to the liner except the invert. As loosening load, a uniform vertical stress as shown in Table 6.13 is applied to the liner in the left tunnel. As support degradation, rock bolts are deactivated.

The input file EX3.DAT is listed in Table 6.14. Text output file STEP.LST in Table 6.15 lists steps where major excavations take place and external lining loads are applied.

Figures 6.73 to 6.87 show PLOT-2D graphical outputs at the completion of excavation and at the last load step for lining. Brief description of these plots are shown in the text output file PLTDS.LST in Table 6.16.

Figures 6.88 and 6.89 show PLOT-XY graphical outputs at tunnel crowns. Brief description of these plots are shown in the text output file PLTXY.LST in Table 6.17.

Table 6.13 Simulation of construction sequence

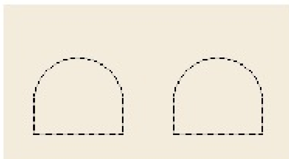
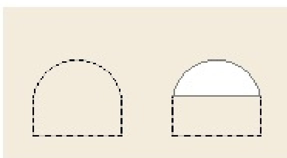
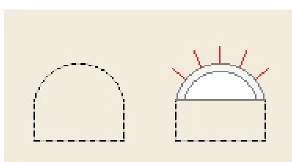
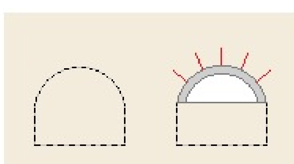
<table>
<tr><th>Step</th><th>Construction State</th><th colspan="2">Descriptions</th></tr>
<tr><td>1,2</td><td></td><td colspan="2">In Situ K_o State</td></tr>
<tr><td>3</td><td></td><td>50% Stress Relief</td><td rowspan="3">Upper Core Excavation (Right Tunnel)</td></tr>
<tr><td>4</td><td></td><td>75% Stress Relief
Soft Shotcrete
Rock Bolt</td></tr>
<tr><td>5</td><td></td><td>100% Stress Relief
Hard Shotcrete
Rock Bolt</td></tr>
</table>

Table 6.13 Simulation of construction sequence (Continued)

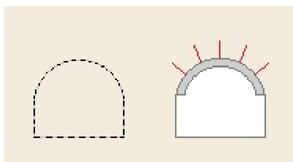
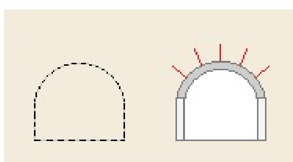
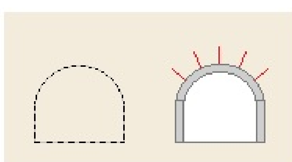
Step	Construction State	Descriptions	
6		50% Stress Relief	Lower Core Excavation (Right Tunnel)
7		75% Stress Relief Soft Shotcrete	
8		100% Stress Relief Hard Shotcrete	

Table 6.13 Simulation of construction sequence (Continued)

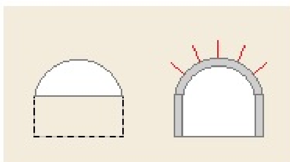
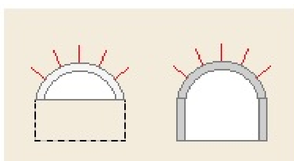
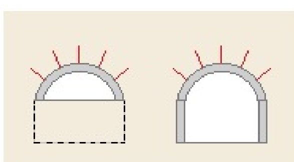
Step	Construction State	Descriptions	
9		50% Stress Relief	Upper Core Excavation (Left Tunnel)
10		75% Stress Relief Soft Shotcrete Rock Bolt	
11		100% Stress Relief Hard Shotcrete Rock Bolt	

Table 6.13 Simulation of construction sequence (Continued)

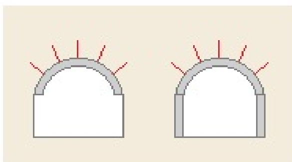
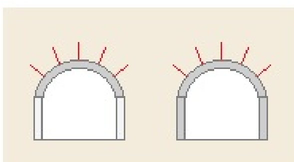
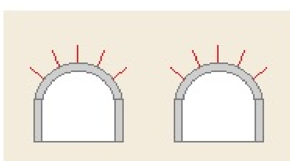
Step	Construction State	Descriptions	
12		50% Stress Relief	Lower Core Excavation (Left Tunnel)
13		75% Stress Relief Soft Shotcrete	
14		100% Stress Relief Hard Shotcrete	

Table 6.13 Simulation of construction sequence (Continued)

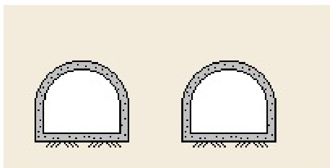
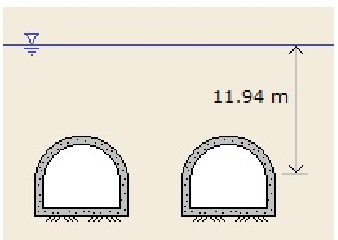
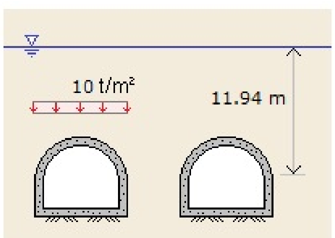
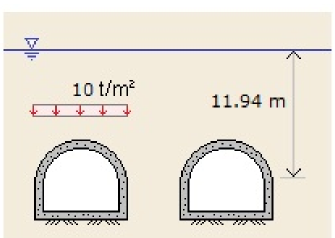
Step	Construction State	Descriptions	
15		Lining Subjected to: Weight	Lining Analysis
18		Lining Subjected to: Weight + Water Pressure	
21		Lining Subjected to: Weight + Water Pressure + Loosening Load	
22		Lining Subjected to: Weight + Water Pressure + Loosening Load + Rock Bolt Deactivation	

Table 6.14 Listing of input file EX3.DAT

```
*
* GENERAL INFORMATION
*
* CARD 1.1
* TITLE
  EXAMPLE PROBLEM ( MODEL 3 )
*
* CARD 1.2
* IUNIT
  3
*
* CARD 1.3
* MODEL  IGEN  IEXMESH  ILNCOUPL  IEXORDER  IRBP
  3      0     0        0         0         0
*
* TUNNEL ANALYSIS BOUNDARY
*
* CARD 2.1
* HT    HL   W    WP    DELTAX  DELTAY  NDYMAX
  21.94 30.  60.  20.   2.0     2.0     40
*
* SOIL / ROCK LAYER INFORMATION
*
* CARD 3.1
* NLAYER
  4
* CARD 3.2
* LAYERNO   H     GAMA  RKO  E       V    PHI   C    T
  1         4.2   1.9   0.5  2000.   0.33 30.   3.   20.
  2         4.3   1.9   0.43 5000.   0.30 35.   30.  30.
  3         3.5   2.4   0.33 20000.  0.25 40.   70.  40.
  4         39.94 2.55  0.25 200000. 0.20 45.   100. 50.
*
* ADDITIONAL TOP SOIL / ROCK LAYER
*
* CARD 3.3.1
* NATLAYER
  0
*
* USER SPECIFIED SOIL / ROCK LAYER
*
* CARD 3.4.1
* NUSLAYER
  0
*
* USER SPECIFIED DISTRIBUTED SURFACE LOAD
*
* CARD 3.5.1
* NUSXPD
  0
```

```
*
* SHOTCRETE PROPERTIES
*
* CARD 3.6
* E          V      PHI    C      T     GAMA
  1.5E+06    0.2    30.    500.   100.  2.4
*
* LINING PROPERTIES
*
* CARD 3.7
* E          V      PHI    C      T     GAMA   ER        VR
  2.1E+06    0.2    30.    500.   300.  2.5    2.1E+07   0.2
*
* ROCK BOLT PROPERTIES
*
* CARD 3.8
* A          WL         E          STRSI      SIGMAy     Ef
  0.000491   0.00383    2.1E+07    0.0        2.3E+04    1.0
*
* INTERFACE PROPERTIES BETWEEN SHOTCRETE AND LINING
*
* CARD 3.9
* NM        E       G       t
  2         200000. 2.0     0.001
* C         PHI
  0.001     5.0
* E1        E2      E3      E4    S1       S2    S3      S4
 -1.0       0.0     1.0E-7  1.0  -200000. 0.0   2.E-02  2.E-02
*
* TUNNEL DIMENSION
*
* CARD 4.0
* ISTYPE    GR      GA
  1         1.0     0.5
*
* CARD 4.1
* R1    A1    R2    A2  R3    A3     R4
  5.24  60.   4.24  30. 9.86  19.781 23.86
* CARD 4.2
* INVSHOT   TS      INVLN     TL      DI    ASI    DO    ASO
  0         0.15    1         0.3     0.05  0.0022 0.05  0.0022
* CARD 4.3
* NUMRB     LRB     LSPACING  TSPACING  NSRB
  11        3.0     1.35      1.2         2
*
* EXCAVATION STRESS RELEASE AND SHOTCRETE MODULUS CHANGE
*
* CARD 5.1
* PSR       PASR    RESH
  50.       25.     0.33
```

```
*
* EXTERNAL LOADS FOR LINING ANALYSIS
*
* CARD 6.1
* LDTYPE
  1
*
* WATER PRESSURE
*
* CARD 6.2
* LGWINV   NWPSTEP DGW     GAMAW
  0        3       10.     1.0
*
* LOOSENING LOAD
*
* CARD 6.3.1
* LSDADD   NLDSTEP  HPRES   VPRES
  1        3        0.0     0.0
*
* ADDITIONAL VERTICAL LOOSENING LOAD FOR RIGHT TUNNEL
* CARD 6.3.2
* DXv1     DXv2     Qv1     Qvo     Qv2
  5.2      5.2      0.0     0.0     0.0
*
* ADDITIONAL VERTICAL LOOSENING LOAD FOR LEFT  TUNNEL
* CARD 6.3.2
* DXv1     DXv2     Qv1     Qvo     Qv2
  5.2      5.2      10.     10.     10.
*
* PRIMARY SUPPORT DEGRADATION
*
* CARD 6.4
* LPSDEG   REDH
  1        1.0
*
* SUBGRADE REACTION FOR ILNCOUPL = 1
*
* CARD 6.5
* SUBGK
* 1.0E+05
*
* END OF DATA
```

Table 6.15 Listing of Text output file STEP.LST

```
STEP NO  DESCRIPTIONS

   5
         Excavation of Upper Right Core in Right Tunnel
         Excavation of Upper Left  Core in Right Tunnel
   8
         Excavation of Lower Right Core in Right Tunnel
         Excavation of Lower Left  Core in Right Tunnel
  11
         Excavation of Upper Right Core in Left  Tunnel
         Excavation of Upper Left  Core in Left  Tunnel
  14
         Excavation of Lower Right Core in Left  Tunnel
         Excavation of Lower Left  Core in Left  Tunnel
  15
         Lining Subjected to:
         Weight
  18
         Lining Subjected to:
         Weight
         Water Pressure
  21
         Lining Subjected to:
         Weight
         Water Pressure
         Loosening Load
  22
         Lining Subjected to:
         Weight
         Water Pressure
         Loosening Load
         Rock Bolt Deactivation &
          Shotcrete Degradation
```

Table 6.16 Partial listing of text output file PLTDS.LST

```
PLOT NO    TITLE

    1
           FINITE ELEMENT MESH
           EXAMPLE PROBLEM ( MODEL 3 )

    2      DEFORMED SHAPE
           AT LOAD STEP = 5
           EXAMPLE PROBLEM ( MODEL 3 )

    3      DEFORMED SHAPE
           AT LOAD STEP = 8
           EXAMPLE PROBLEM ( MODEL 3 )

    4      DEFORMED SHAPE
           AT LOAD STEP = 11
           EXAMPLE PROBLEM ( MODEL 3 )

    5      DEFORMED SHAPE
           AT LOAD STEP = 14
           EXAMPLE PROBLEM ( MODEL 3 )

    6      DEFORMED SHAPE
           AT LOAD STEP = 5
           EXAMPLE PROBLEM ( MODEL 3 )

    7      DEFORMED SHAPE
           AT LOAD STEP = 8
           EXAMPLE PROBLEM ( MODEL 3 )

    8      DEFORMED SHAPE
           AT LOAD STEP = 11
           EXAMPLE PROBLEM ( MODEL 3 )

    9      DEFORMED SHAPE
           AT LOAD STEP = 14
           EXAMPLE PROBLEM ( MODEL 3 )

   10      PRINCIPAL STRESS DISTRIBUTION
           AT LOAD STEP = 5
           EXAMPLE PROBLEM ( MODEL 3 )

   11      PRINCIPAL STRESS DISTRIBUTION
           AT LOAD STEP = 8
           EXAMPLE PROBLEM ( MODEL 3 )
```

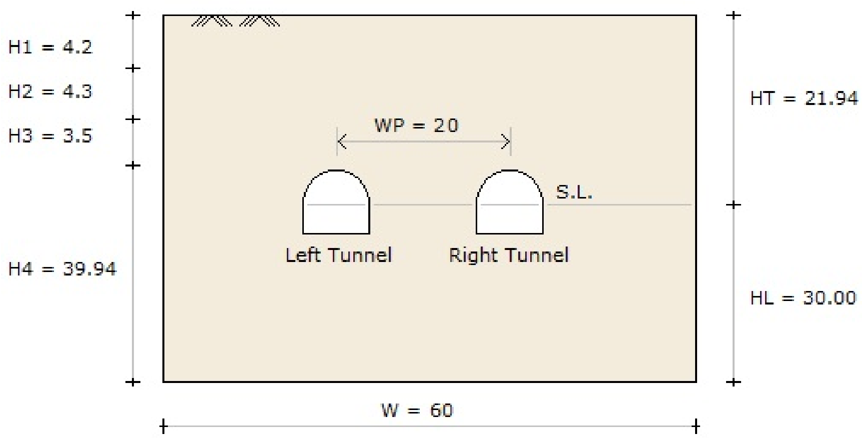
```
12      PRINCIPAL STRESS DISTRIBUTION
        AT LOAD STEP = 11
        EXAMPLE PROBLEM ( MODEL 3 )

13      PRINCIPAL STRESS DISTRIBUTION
        AT LOAD STEP = 14
        EXAMPLE PROBLEM ( MODEL 3 )

14      PRINCIPAL STRESS DISTRIBUTION
        AT LOAD STEP = 5
        EXAMPLE PROBLEM ( MODEL 3 )

15      PRINCIPAL STRESS DISTRIBUTION
        AT LOAD STEP = 8
        EXAMPLE PROBLEM ( MODEL 3 )

16      PRINCIPAL STRESS DISTRIBUTION
        AT LOAD STEP = 11
        EXAMPLE PROBLEM ( MODEL 3 )

17      PRINCIPAL STRESS DISTRIBUTION
        AT LOAD STEP = 14
        EXAMPLE PROBLEM ( MODEL 3 )

18      Contours of Safety Factor
        AT LOAD STEP = 5
        EXAMPLE PROBLEM ( MODEL 3 )

19      Contours of Safety Factor
        AT LOAD STEP = 8
        EXAMPLE PROBLEM ( MODEL 3 )

20      Contours of Safety Factor
        AT LOAD STEP = 11
        EXAMPLE PROBLEM ( MODEL 3 )

21      Contours of Safety Factor
        AT LOAD STEP = 14
        EXAMPLE PROBLEM ( MODEL 3 )
22      AXIAL STRESS
        AT LOAD STEP = 5
        EXAMPLE PROBLEM ( MODEL 3 )

23      AXIAL STRESS
        AT LOAD STEP = 8
        EXAMPLE PROBLEM ( MODEL 3 )
```

```
48      OUTER EXTREME FIBER STRESS
        AT LOAD STEP = 21
        EXAMPLE PROBLEM ( MODEL 3 )

49      INNER REINFORCING BAR STRESS
        AT LOAD STEP = 21
        EXAMPLE PROBLEM ( MODEL 3 )

50      OUTER REINFORCING BAR STRESS
        AT LOAD STEP = 21
        EXAMPLE PROBLEM ( MODEL 3 )

51      BENDING MOMENT
        AT LOAD STEP = 22
        EXAMPLE PROBLEM ( MODEL 3 )

52      THRUST
        AT LOAD STEP = 22
        EXAMPLE PROBLEM ( MODEL 3 )

53      SHEAR
        AT LOAD STEP = 22
        EXAMPLE PROBLEM ( MODEL 3 )

54      INNER EXTREME FIBER STRESS
        AT LOAD STEP = 22
        EXAMPLE PROBLEM ( MODEL 3 )

55      OUTER EXTREME FIBER STRESS
        AT LOAD STEP = 22
        EXAMPLE PROBLEM ( MODEL 3 )

56      INNER REINFORCING BAR STRESS
        AT LOAD STEP = 22
        EXAMPLE PROBLEM ( MODEL 3 )

57      OUTER REINFORCING BAR STRESS
        AT LOAD STEP = 22
        EXAMPLE PROBLEM ( MODEL 3 )
```

Table 6.17 Listing of text output file PLTXY.LST

```
PLOT NO  TITLE

   1     DISPLACEMENT HISTORY AT LOCATION :  1
         AT NODE   443

   2     DISPLACEMENT HISTORY AT LOCATION :  2
         AT NODE     1

   3     DISPLACEMENT HISTORY AT LOCATION :  3
         AT NODE   233

   4     DISPLACEMENT HISTORY AT LOCATION :  4
         AT NODE    14

   5     DISPLACEMENT HISTORY AT LOCATION :  5
         AT NODE   910

   6     DISPLACEMENT HISTORY AT LOCATION :  6
         AT NODE  1951

   7     DISPLACEMENT HISTORY AT LOCATION :  7
         AT NODE  1509

   8     DISPLACEMENT HISTORY AT LOCATION :  8
         AT NODE  1741

   9     DISPLACEMENT HISTORY AT LOCATION :  9
         AT NODE  2418

  10     DISPLACEMENT HISTORY AT LOCATION : 10
         AT NODE  1522
```

MODEL = 3 Two Tunnels [Symmetric Section]



DELTAX = 2.0, DELTAY = 2.0, NDYMAX = 40

Figure 6.72 Schematic tunnel section for Example 3

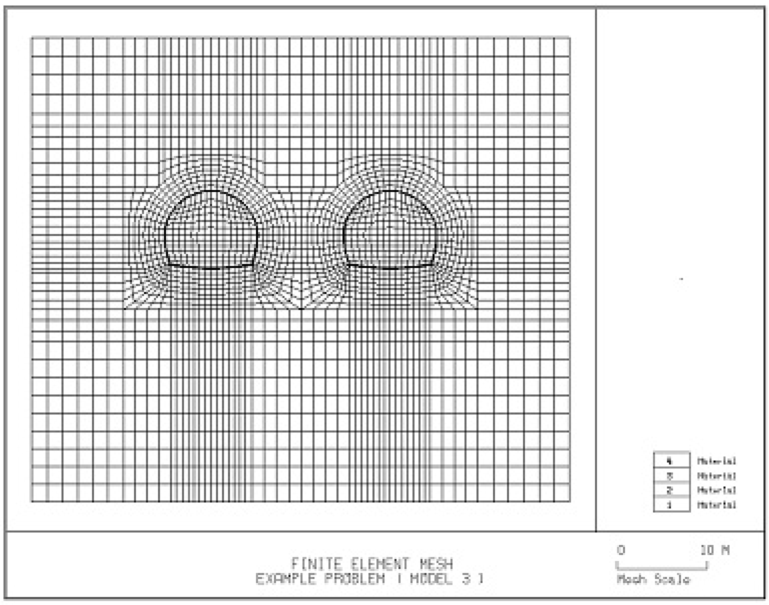

4 Material
3 Material
2 Material
1 Material
FINITE ELEMENT MESH
EXAMPLE PROBLEM (MODEL 3)
0
10 M
Mesh Scale

Figure 6.73

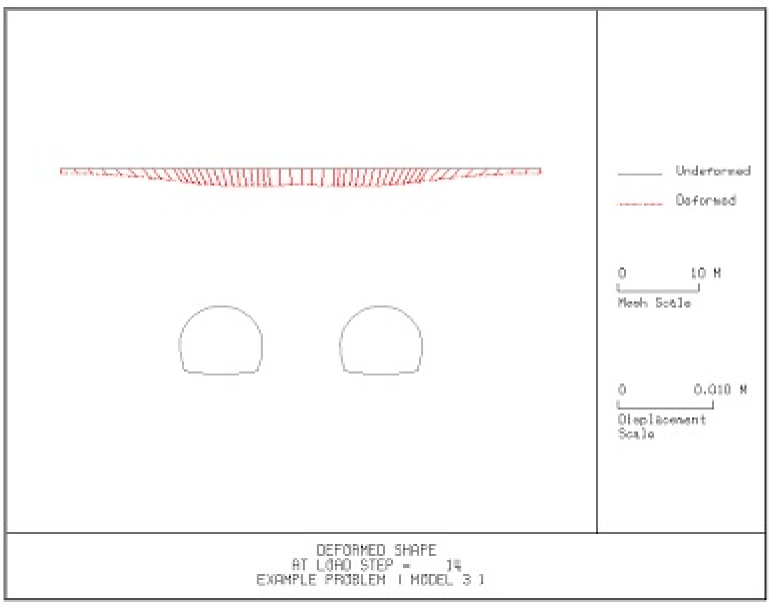

Undeformed
Deformed
0 10 M
Mesh Scale
0 0.010 M
Displacement
Scale
DEFORMED SHAPE
AT LOAD STEP = 14
EXAMPLE PROBLEM (MODEL 3)

Figure 6.74

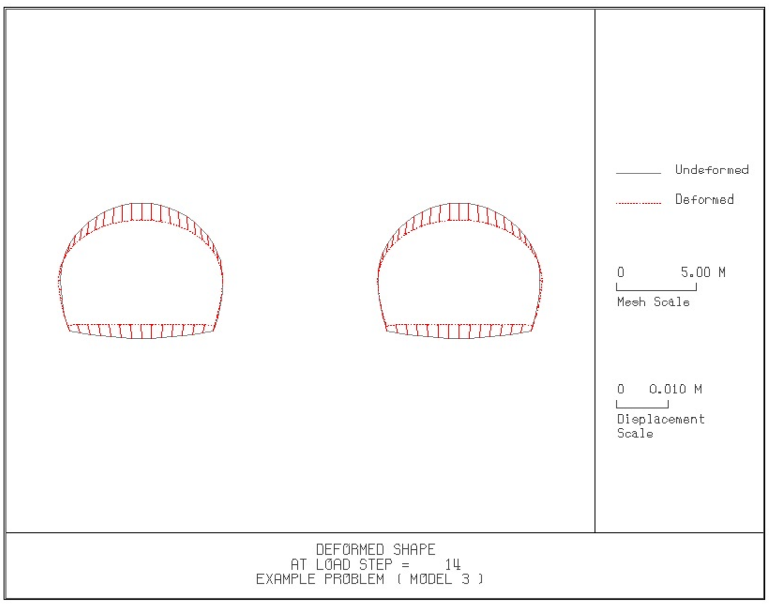

Undeformed
Deformed
0 5.00 M
Mesh Scale
0 0.010 M
Displacement
Scale
DEFORMED SHAPE
AT LOAD STEP = 14
EXAMPLE PROBLEM (MODEL 3)

Figure 6.75

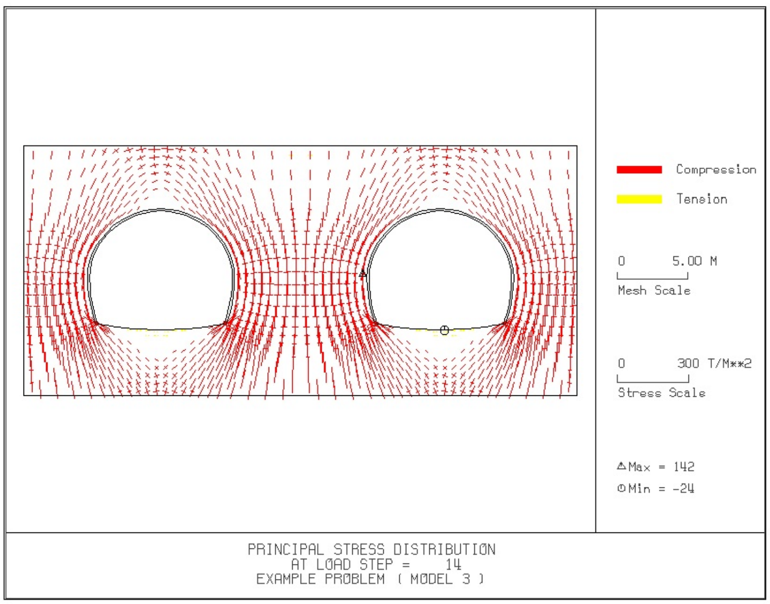

Compression
Tension
0 5.00 M
Mesh Scale
0 300 T/M**2
Stress Scale
Max = 142
Min = -24
PRINCIPAL STRESS DISTRIBUTION
AT LOAD STEP = 14
EXAMPLE PROBLEM (MODEL 3)

Figure 6.76

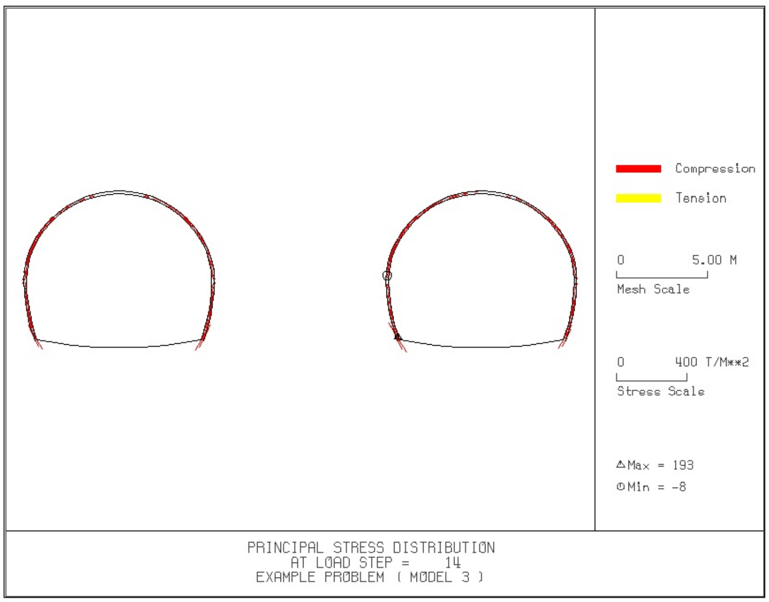

Compression
Tension
0 5.00 M
Mesh Scale
0 400 T/M**2
Stress Scale
Max = 193
Min = -8
PRINCIPAL STRESS DISTRIBUTION
AT LOAD STEP = 14
EXAMPLE PROBLEM (MODEL 3)

Figure 6.77

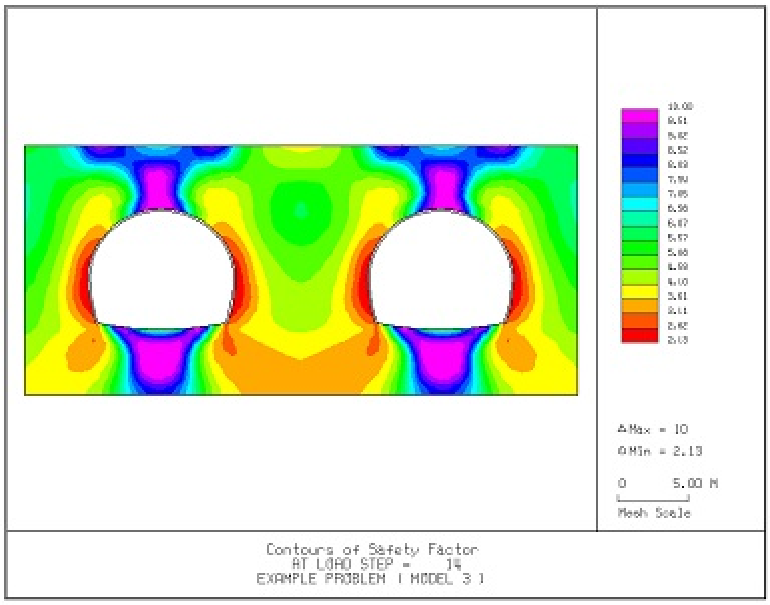

Max = 10
Min = 2.13
0 5.00 M
Mesh Scale
Contours of Safety Factor
AT LOAD STEP = 14
EXAMPLE PROBLEM (MODEL 3)

Figure 6.78

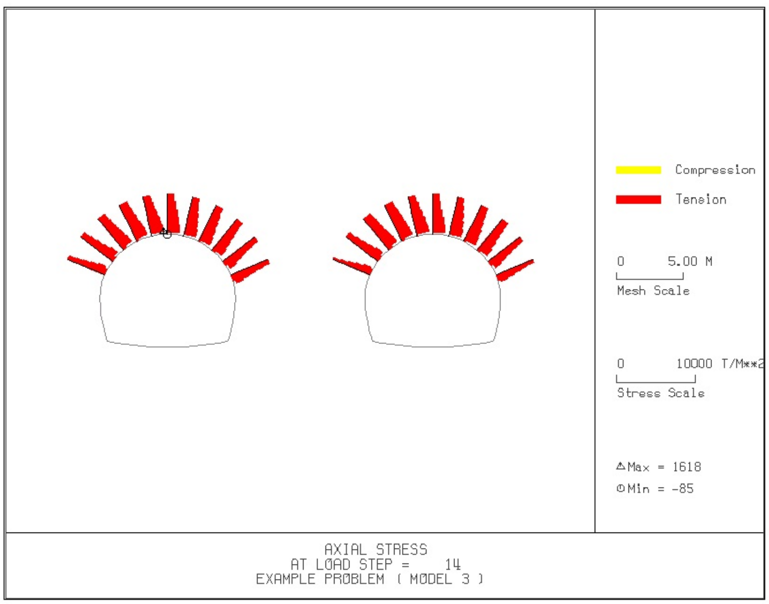

Compression
Tension
0 5.00 M
Mesh Scale
0 10000 T/M**2
Stress Scale
Max = 1618
Min = -85
AXIAL STRESS
AT LOAD STEP = 14
EXAMPLE PROBLEM (MODEL 3)

Figure 6.79

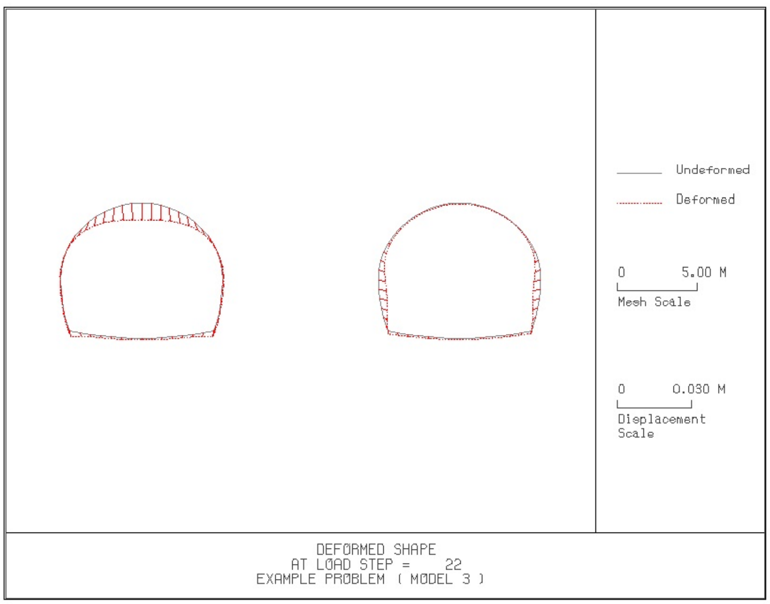

Undeformed
Deformed
0 5.00 M
Mesh Scale
0 0.030 M
Displacement Scale
DEFORMED SHAPE
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 3)

Figure 6.80

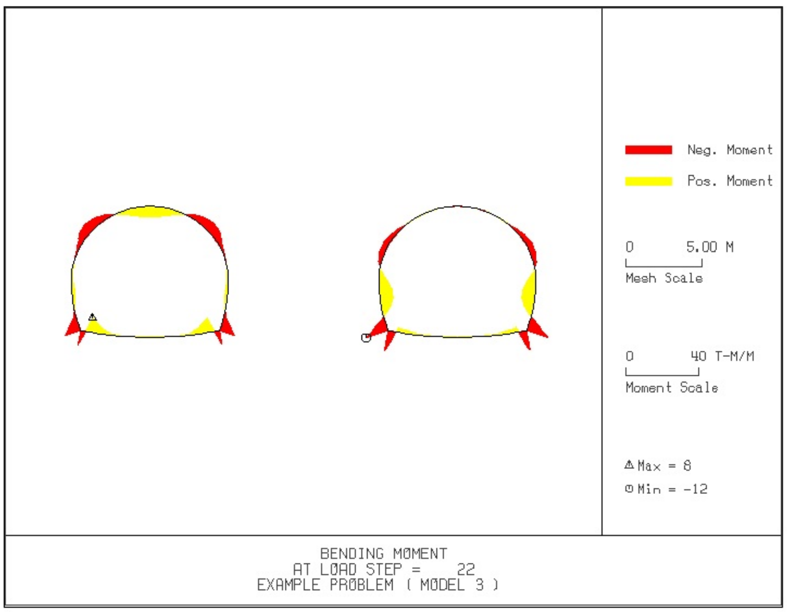

Neg. Moment
Pos. Moment
0 5.00 M
Mesh Scale
0 40 T-M/M
Moment Scale
Max = 8
Min = -12
BENDING MOMENT
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 3)

Figure 6.81

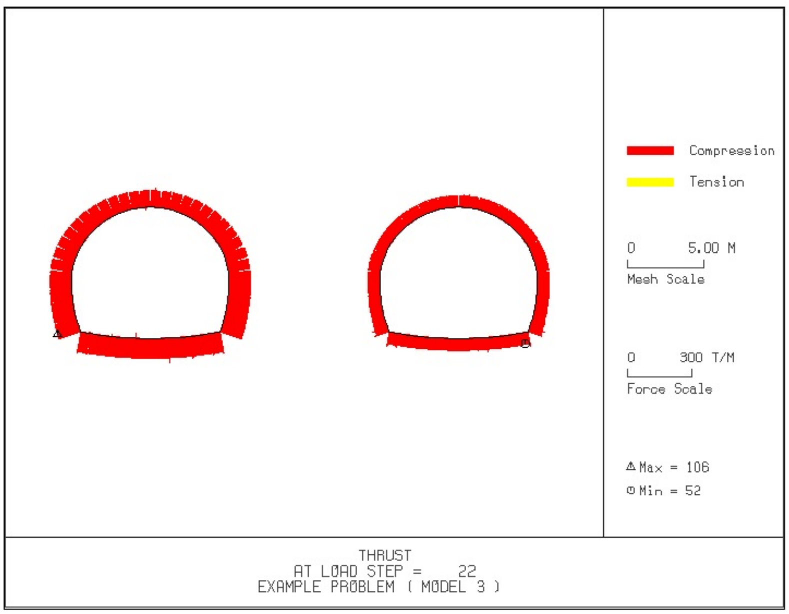

Compression
Tension
0 5.00 M
Mesh Scale
0 300 T/M
Force Scale
Max = 106
Min = 52
THRUST
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 3)

Figure 6.82

Pos. Shear
Neg. Shear
0 5.00 M
Mesh Scale
0 100 T/M
Force Scale
Max = 26
Min = -26
SHEAR
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 3)

Figure 6.83

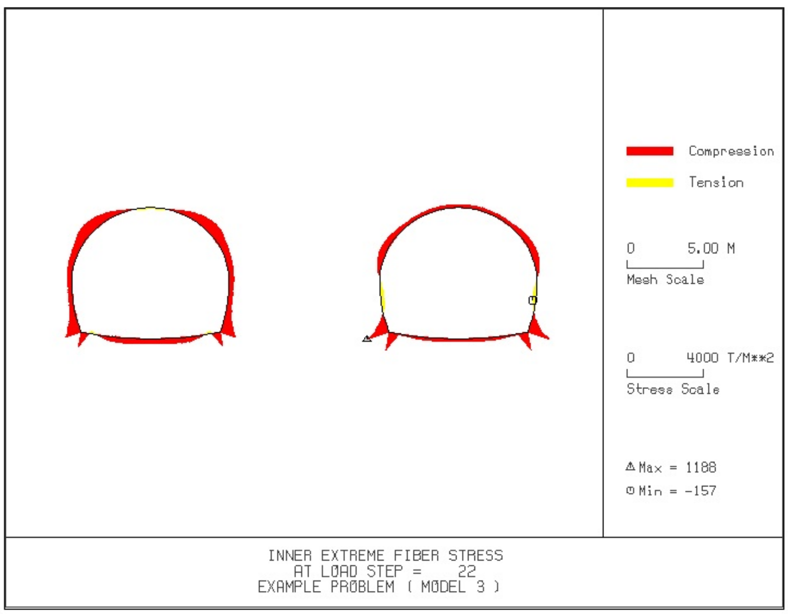

Compression
Tension
0 5.00 M
Mesh Scale
0 4000 T/M**2
Stress Scale
Max = 1188
Min = -157
INNER EXTREME FIBER STRESS
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 3)

Figure 6.84

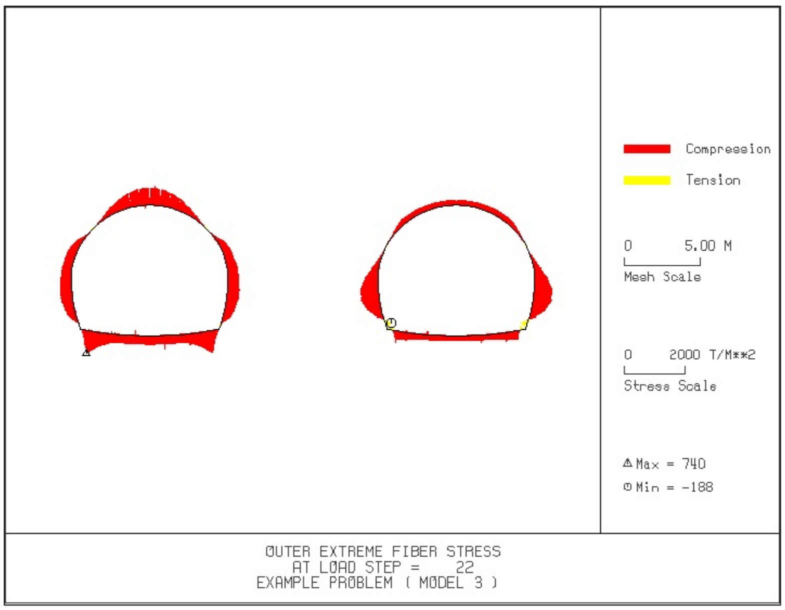

Compression
Tension
0 5.00 M
Mesh Scale
0 2000 T/M**2
Stress Scale
Max = 740
Min = -188
OUTER EXTREME FIBER STRESS
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 3)

Figure 6.85

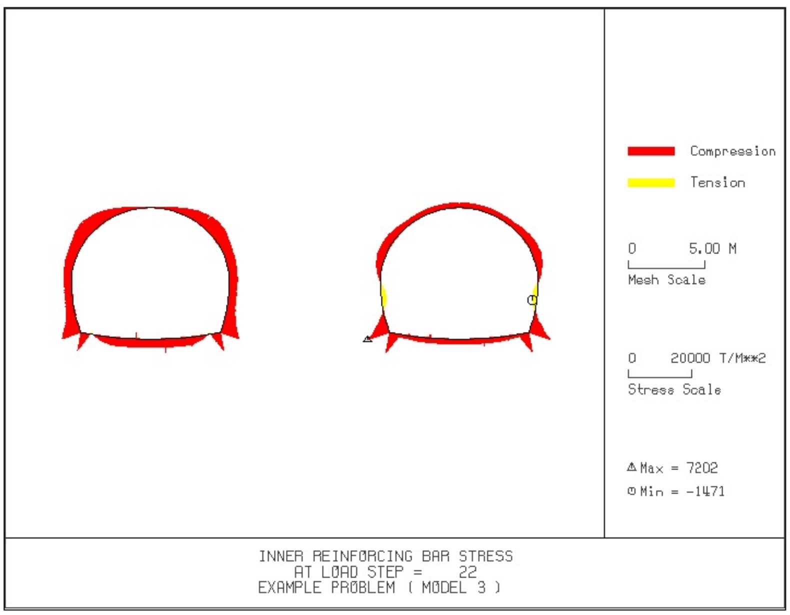

Compression
Tension
0 5.00 M
Mesh Scale
0 20000 T/M**2
Stress Scale
Max = 7202
Min = -1471
INNER REINFORCING BAR STRESS
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 3)

Figure 6.86

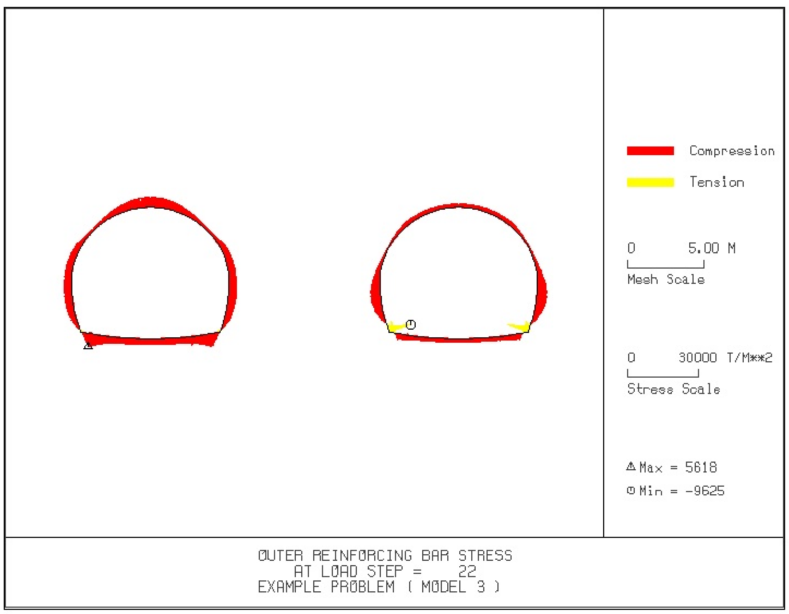

Compression
Tension
0 5.00 M
Mesh Scale
0 30000 T/M**2
Stress Scale
Max = 5618
Min = -9625
OUTER REINFORCING BAR STRESS
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 3)

Figure 6.87

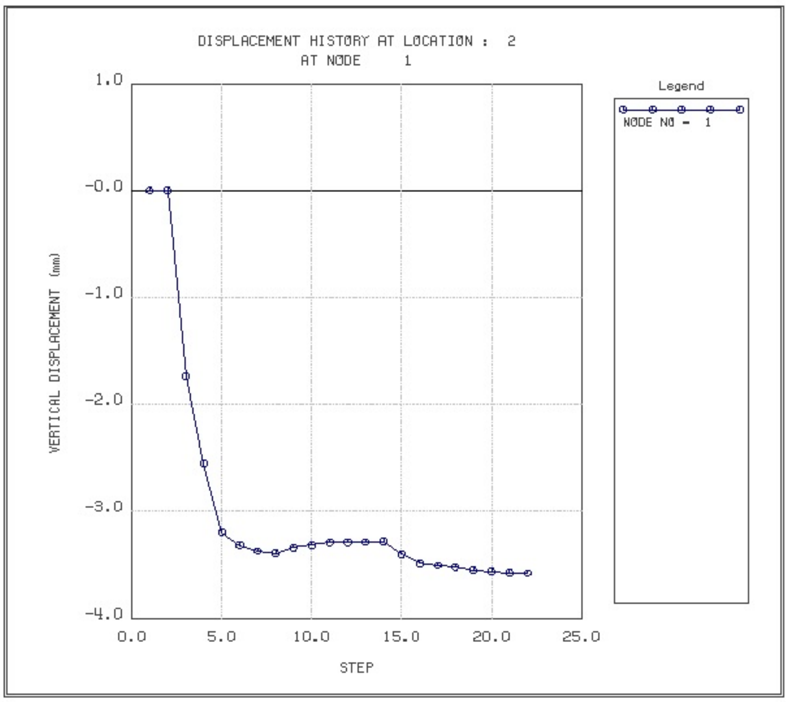

DISPLACEMENT HISTORY AT LOCATION : 2
AT NODE 1
VERTICAL DISPLACEMENT (mm)
1.0
-0.0
-1.0
-2.0
-3.0
-4.0
0.0
5.0
10.0
15.0
20.0
25.0
STEP
Legend
NODE NO = 1

Figure 6.88

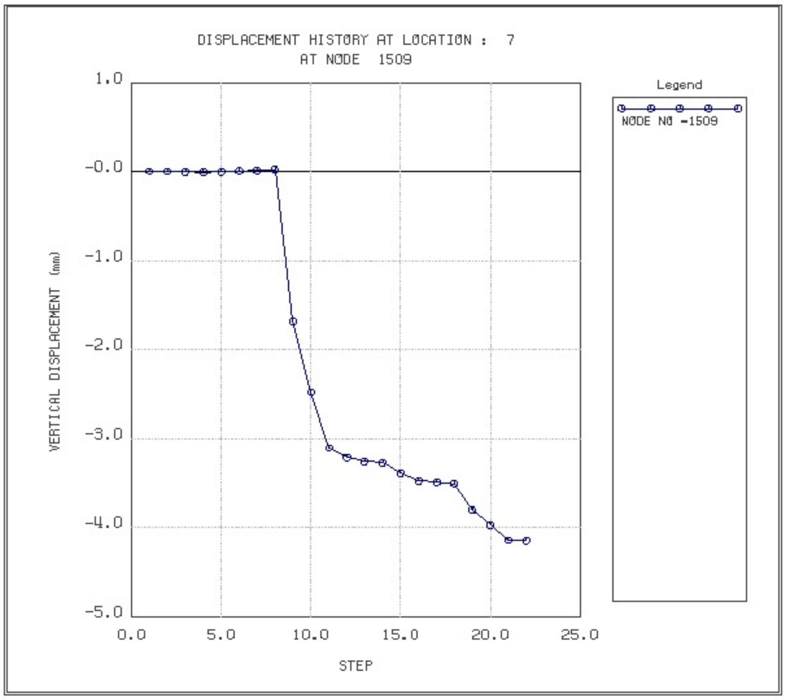

DISPLACEMENT HISTORY AT LOCATION : 7
AT NODE 1509
VERTICAL DISPLACEMENT (mm)
1.0
-0.0
-1.0
-2.0
-3.0
-4.0
-5.0
0.0
5.0
10.0
15.0
20.0
25.0
STEP
Legend
NODE NO -1509

Figure 6.89

6.4 Example 4

Example 4 represents two different tunnels as schematically shown in Figure 6.90.

A typical NATM tunnel shape is chosen here to be analyzed using program TUNA Plus. Geometric parameters related to tunnel shape, rock bolts, shotcrete, and liner are given in Figure 6.1 for the right tunnel and Figure 6.52 for the left tunnel. Geological profile, tunnel depth, and analysis boundaries are specified in Figure 6.90. Material properties of soil/rock layers and supports are summarized in Table 6.2.

As shown in Table 6.18, tunnel construction involves four major excavation stages; upper core excavation in right tunnel, lower core excavation in right tunnel, upper core excavation in left tunnel, and lower core excavation in left tunnel. Each excavation stage is associated with three load steps; 50% stress release, additional 25% stress release where soft shotcrete and rock bolts are installed, and the last 25% stress release where shotcrete is hardened. It should be noted that program TUNA Plus uses first two load steps to generate in situ K_o stress state.

For lining analysis, reinforced concrete liner is considered with interface joint element between the liner and the surrounding medium. The interface joint properties are set to allow separation when the tensile stress develops in the direction normal to the interface while full slippage is assumed along the interface

For loads acting on the reinforced concrete liner, following four different load combinations are considered:

1. Weight
2. Weight + Water Pressure
3. Weight + Water Pressure + Loosening Load
4. Weight + Water Pressure + Loosening Load + Support Degradation

Ground water pressure is applied to the liner except the invert. As loosening load, a uniform vertical stress to the right tunnel liner and a symmetric triangular vertical stress to the left tunnel liner as shown in Table 6.18 are applied. As support degradation, rock bolts are deactivated.

The input file EX4.DAT is listed in Table 6.19. Text output file STEP.LST in Table 6.20 lists steps where major excavations take place and external lining loads are applied.

Figures 6.91 to 6.105 show PLOT-2D graphical outputs at the completion of excavation and at the last load step for lining. Brief description of these plots are shown in the text output file PLTDS.LST in Table 6.21.

Figures 6.106 and 6.107 show PLOT-XY graphical outputs at tunnel crowns. Brief description of these plots are shown in the text output file PLTXY.LST in Table 6.22.

Table 6.18 Simulation of construction sequence

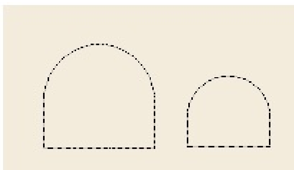
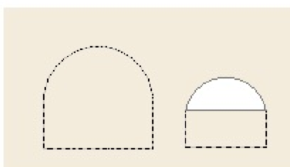
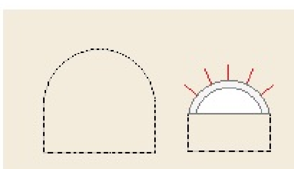
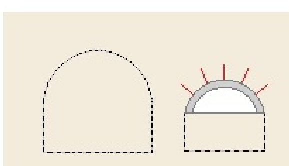
<table>
<tr><th>Step</th><th>Construction State</th><th colspan="2">Descriptions</th></tr>
<tr><td>1,2</td><td></td><td colspan="2">In Situ K_o State</td></tr>
<tr><td>3</td><td></td><td>50% Stress Relief</td><td rowspan="3">Upper Core Excavation (Right Tunnel)</td></tr>
<tr><td>4</td><td></td><td>75% Stress Relief
Soft Shotcrete
Rock Bolt</td></tr>
<tr><td>5</td><td></td><td>100% Stress Relief
Hard Shotcrete
Rock Bolt</td></tr>
</table>

Table 6.18 Simulation of construction sequence (Continued)

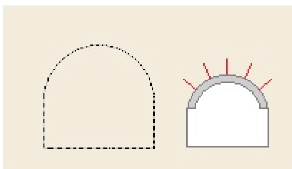
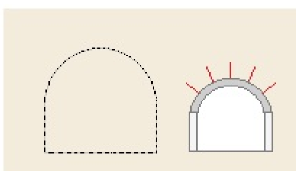
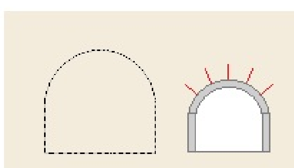
Step	Construction State	Descriptions	
6		50% Stress Relief	Lower Core Excavation (Right Tunnel)
7		75% Stress Relief Soft Shotcrete	
8		100% Stress Relief Hard Shotcrete	

Table 6.18 Simulation of construction sequence (Continued)

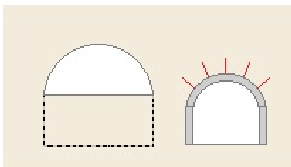
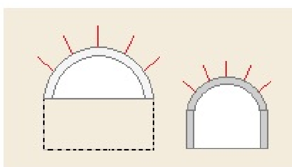
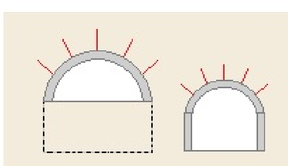
Step	Construction State	Descriptions	
9		50% Stress Relief	Upper Core Excavation (Left Tunnel)
10		75% Stress Relief Soft Shotcrete Rock Bolt	
11		100% Stress Relief Hard Shotcrete Rock Bolt	

Table 6.18 Simulation of construction sequence (Continued)

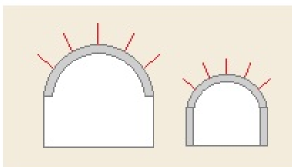
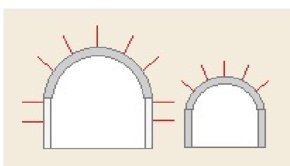
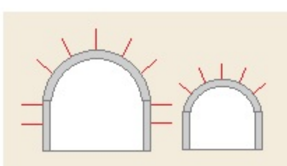
Step	Construction State	Descriptions	
12		50% Stress Relief	Lower Core Excavation (Left Tunnel)
13		75% Stress Relief Soft Shotcrete Rock Bolt	
14		100% Stress Relief Hard Shotcrete Rock Bolt	

Table 6.18 Simulation of construction sequence (Continued)

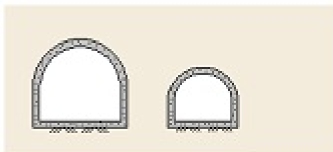
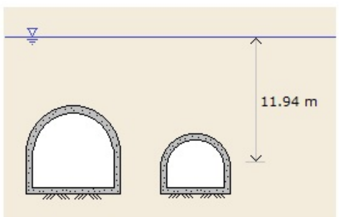
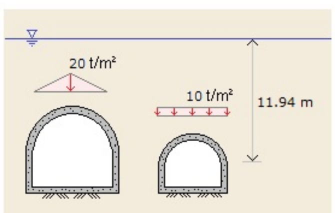
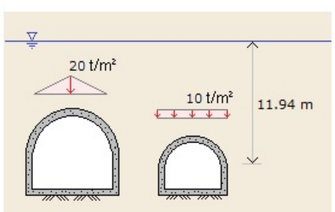
Step	Construction State	Descriptions	
15		Lining Subjected to: Weight	Lining Analysis
18		Lining Subjected to: Weight + Water Pressure	
21		Lining Subjected to: Weight + Water Pressure + Loosening Load	
22		Lining Subjected to: Weight + Water Pressure + Loosening Load + Rock Bolt Deactivation	

Table 6.19 Listing of input file EX4.DAT

```
*
* GENERAL INFORMATION
*
* CARD 1.1
* TITLE
  EXAMPLE PROBLEM ( MODEL 4 )
*
* CARD 1.2
* IUNIT
  3
*
* CARD 1.3
* MODEL  IGEN  IEXMESH  ILNCOUPL  IEXORDER  IRBP
  4      0     0        0         1         0
*
* CARD 1.4
* IEZ1  IEZ2  IEZ3  IEZ4  IEZ5  IEZ6  IEZ7  IEZ8
  1     2     1     2     3     4     3     4
*
* TUNNEL ANALYSIS BOUNDARY
*
* CARD 2.1
* HT    HL   W    WP    HP   DELTAX  DELTAY  NDYMAX
  21.94 30.  80.  25.   2.0  2.0     2.0     40
*
* SOIL / ROCK LAYER INFORMATION
*
* CARD 3.1
* NLAYER
  4
* CARD 3.2
* LAYERNO   H     GAMA  RKO  E       V    PHI   C    T
  1         4.2   1.9   0.5  2000.   0.33 30.   3.   20.
  2         4.3   1.9   0.43 5000.   0.30 35.   30.  30.
  3         3.5   2.4   0.33 20000.  0.25 40.   70.  40.
  4         39.94 2.55  0.25 200000. 0.20 45.   100. 50.
*
* ADDITIONAL TOP SOIL / ROCK LAYER
*
* CARD 3.3.1
* NATLAYER
  0
*
* USER SPECIFIED SOIL / ROCK LAYER
*
* CARD 3.4.1
* NUSLAYER
  0
```

```
*
* USER SPECIFIED DISTRIBUTED SURFACE LOAD
*
* CARD 3.5.1
* NUSXPD
  0
* SHOTCRETE PROPERTIES
*
* CARD 3.6
* E         V      PHI     C       T      GAMA
  1.5E+06   0.2    30.     500.    100.   2.4
*
* LINING PROPERTIES
*
* CARD 3.7
* E         V      PHI     C       T      GAMA   ER        VR
  2.1E+06   0.2    30.     500.    300.   2.5    2.1E+07   0.2
*
* ROCK BOLT PROPERTIES
*
* CARD 3.8
* A         WL        E          STRSI     SIGMAy     Ef
  0.000491  0.00383   2.1E+07    0.0       2.3E+04    1.0
*
* INTERFACE PROPERTIES BETWEEN SHOTCRETE AND LINING
*
* CARD 3.9
* NM       E       G        t
  3        200000. 2.0      0.001
* C        PHI
  0.001    5.0
* E1       E2      E3       E4      S1       S2      S3      S4
 -1.0      0.0     1.0E-7   1.0    -200000. 0.0     2.E-02  2.E-02
*
* TUNNEL DIMENSION (FOR RIGHT TUNNEL)
*
* CARD 4.0
* ISTYPE  GR    GA
  1       1.0   0.5
*
* CARD 4.1
* R1    A1    R2    A2  R3    A3     R4
  5.24  60.   4.24  30. 9.86  19.781 23.86
* CARD 4.2
* INVSHOT  TS      INVLN     TL      DI    ASI    DO    ASO
  0        0.15    1         0.3     0.05  0.0022 0.05  0.0022
* CARD 4.3
* NUMRB    LRB     LSPACING  TSPACING  NSRB
  11       3.0     1.35      1.2         2
*
```

```
*
* TUNNEL DIMENSION (FOR LEFT  TUNNEL)
*
* CARD 4.0
* ISTYPE  GR    GA
  1       1.0   0.5
*
* CARD 4.1
* R1    A1    R2    A2   R3    A3     R4
  7.24  60.   6.24  30.  11.86 21.781 25.86
* CARD 4.2
* INVSHOT  TS       INVLN      TL       DI     ASI     DO    ASO
  0        0.20     1          0.4      0.05   0.0033  0.05  0.0033
* CARD 4.3
* NUMRB    LRB      LSPACING  TSPACING  NSRB
  21       3.0      1.35      1.2        2
*
* EXCAVATION STRESS RELEASE AND SHOTCRETE MODULUS CHANGE
*
* CARD 5.1
* PSR      PASR     RESH
  50.      25.      0.33
*
* EXTERNAL LOADS FOR LINING ANALYSIS
*
* CARD 6.1
* LDTYPE
  1
*
* WATER PRESSURE
*
* CARD 6.2
* LGWINV   NWPSTEP DGW      GAMAW
  0        3       10.      1.0
*
* LOOSENING LOAD
*
* CARD 6.3.1
* LSDADD   NLDSTEP  HPRES   VPRES
  1        3        0.0     0.0
*
* ADDITIONAL VERTICAL LOOSENING LOAD FOR RIGHT TUNNEL
* CARD 6.3.2
* DXv1     DXv2     Qv1     Qvo     Qv2
  5.09     5.09     10.     10.     10.
*
* ADDITIONAL VERTICAL LOOSENING LOAD FOR LEFT  TUNNEL
* CARD 6.3.2
* DXv1     DXv2     Qv1     Qvo     Qv2
  7.24     7.24     0.0     20.     0.0
```

```
*
* PRIMARY SUPPORT DEGRADATION
*
* CARD 6.4
* LPSDEG   REDH
  1        1.0
*
* SUBGRADE REACTION FOR ILNCOUPL = 1
*
* CARD 6.4
* SUBGK
* 1.0E+05
*
* END OF DATA
```

Table 6.20 Listing of text output file STEP.LST

```
STEP NO  DESCRIPTIONS
   5
             Excavation of Upper Right Core in Right Tunnel
             Excavation of Upper Left  Core in Right Tunnel
   8
             Excavation of Lower Right Core in Right Tunnel
             Excavation of Lower Left  Core in Right Tunnel
  11
             Excavation of Upper Right Core in Left  Tunnel
             Excavation of Upper Left  Core in Left  Tunnel
  14
             Excavation of Lower Right Core in Left  Tunnel
             Excavation of Lower Left  Core in Left  Tunnel
  15
             Lining Subjected to:
              Weight
  18
             Lining Subjected to:
             Weight
             Water Pressure
  21
             Lining Subjected to:
             Weight
             Water Pressure
             Loosening Load
  22
             Lining Subjected to:
             Weight
             Water Pressure
             Loosening Load
             Rock Bolt Deactivation &
             Shotcrete Degradation
```

Table 6.21 Partial listing of text output file PLTDS.LST

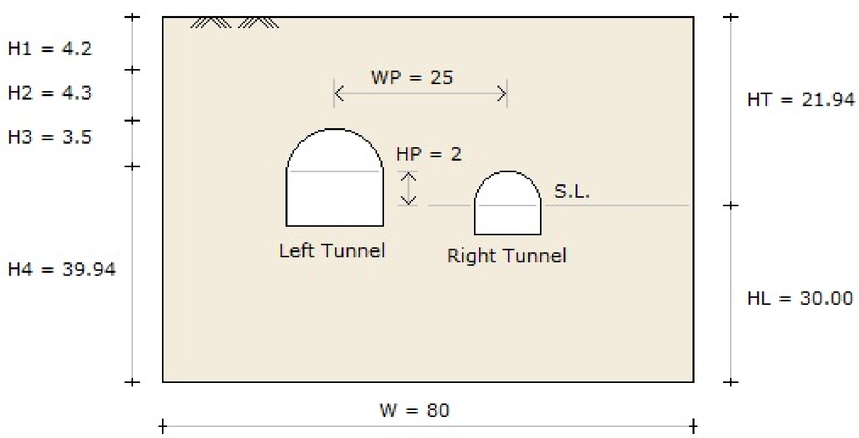
```
PLOT NO   TITLE

   1
          FINITE ELEMENT MESH
          EXAMPLE PROBLEM ( MODEL 4 )

   2      DEFORMED SHAPE
          AT LOAD STEP =     5
          EXAMPLE PROBLEM ( MODEL 4 )

   3      DEFORMED SHAPE
          AT LOAD STEP =     8
          EXAMPLE PROBLEM ( MODEL 4 )

   4      DEFORMED SHAPE
          AT LOAD STEP =    11
          EXAMPLE PROBLEM ( MODEL 4 )

   5      DEFORMED SHAPE
          AT LOAD STEP =    14
          EXAMPLE PROBLEM ( MODEL 4 )

   6      DEFORMED SHAPE
          AT LOAD STEP =     5
          EXAMPLE PROBLEM ( MODEL 4 )

   7      DEFORMED SHAPE
          AT LOAD STEP =     8
          EXAMPLE PROBLEM ( MODEL 4 )

   8      DEFORMED SHAPE
          AT LOAD STEP =    11
          EXAMPLE PROBLEM ( MODEL 4 )

   9      DEFORMED SHAPE
          AT LOAD STEP =    14
          EXAMPLE PROBLEM ( MODEL 4 )

  10      PRINCIPAL STRESS DISTRIBUTION
          AT LOAD STEP =     5
          EXAMPLE PROBLEM ( MODEL 4 )
```

```
48      OUTER EXTREME FIBER STRESS
        AT LOAD STEP =    21
        EXAMPLE PROBLEM ( MODEL 4 )

49      INNER REINFORCING BAR STRESS
        AT LOAD STEP =    21
        EXAMPLE PROBLEM ( MODEL 4 )

50      OUTER REINFORCING BAR STRESS
        AT LOAD STEP =    21
        EXAMPLE PROBLEM ( MODEL 4 )

51      BENDING MOMENT
        AT LOAD STEP =    22
        EXAMPLE PROBLEM ( MODEL 4 )

52      THRUST
        AT LOAD STEP =    22
        EXAMPLE PROBLEM ( MODEL 4 )

53      SHEAR
        AT LOAD STEP =    22
        EXAMPLE PROBLEM ( MODEL 4 )

54      INNER EXTREME FIBER STRESS
        AT LOAD STEP =    22

        EXAMPLE PROBLEM ( MODEL 4 )

55      OUTER EXTREME FIBER STRESS
        AT LOAD STEP =    22
        EXAMPLE PROBLEM ( MODEL 4 )

56      INNER REINFORCING BAR STRESS
        AT LOAD STEP =    22
        EXAMPLE PROBLEM ( MODEL 4 )

57      OUTER REINFORCING BAR STRESS
        AT LOAD STEP =    22
        EXAMPLE PROBLEM ( MODEL 4 )
```

Table 6.22 Listing of text output file PLTXY.LST

```
PLOT NO  TITLE

   1     DISPLACEMENT HISTORY AT LOCATION :  1
         AT NODE   443

   2     DISPLACEMENT HISTORY AT LOCATION :  2
         AT NODE     1

   3     DISPLACEMENT HISTORY AT LOCATION :  3
         AT NODE   233

   4     DISPLACEMENT HISTORY AT LOCATION :  4
         AT NODE    14

   5     DISPLACEMENT HISTORY AT LOCATION :  5
         AT NODE  1107

   6     DISPLACEMENT HISTORY AT LOCATION :  6
         AT NODE  2354

   7     DISPLACEMENT HISTORY AT LOCATION :  7
         AT NODE  1746

   8     DISPLACEMENT HISTORY AT LOCATION :  8
         AT NODE  2055

   9     DISPLACEMENT HISTORY AT LOCATION :  9
         AT NODE  2962

  10     DISPLACEMENT HISTORY AT LOCATION : 10
         AT NODE  1764
```

MODEL= 4 Two Tunnels [Unsymmetric Section]



DELTAX = 2.0, DELTAY = 2.0, NDYMAX = 40

Right tunnel dimensions shown in Figure 6.1
Left tunnel dimensions shown in Figure 6.52

Figure 6.90 Schematic tunnel section for Example 4

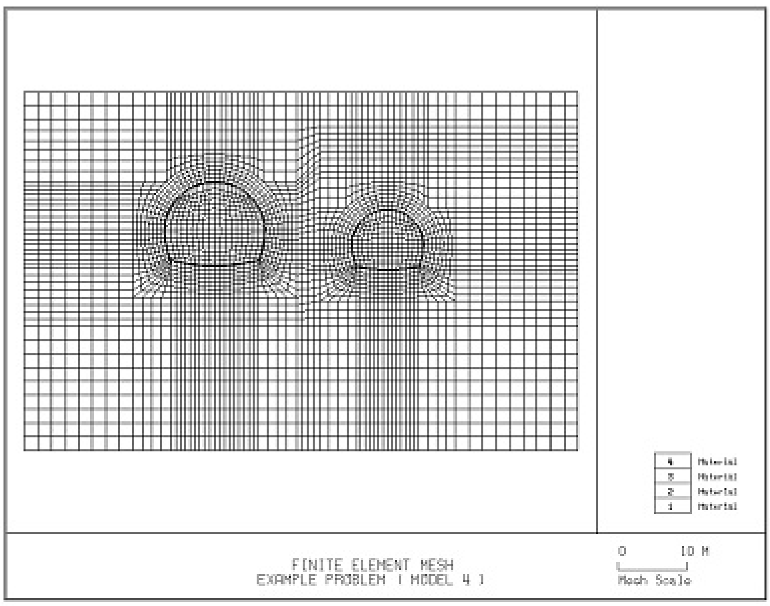

4 Material
3 Material
2 Material
1 Material
FINITE ELEMENT MESH
EXAMPLE PROBLEM (MODEL 4)
0 10 M
Mesh Scale

Figure 6.91

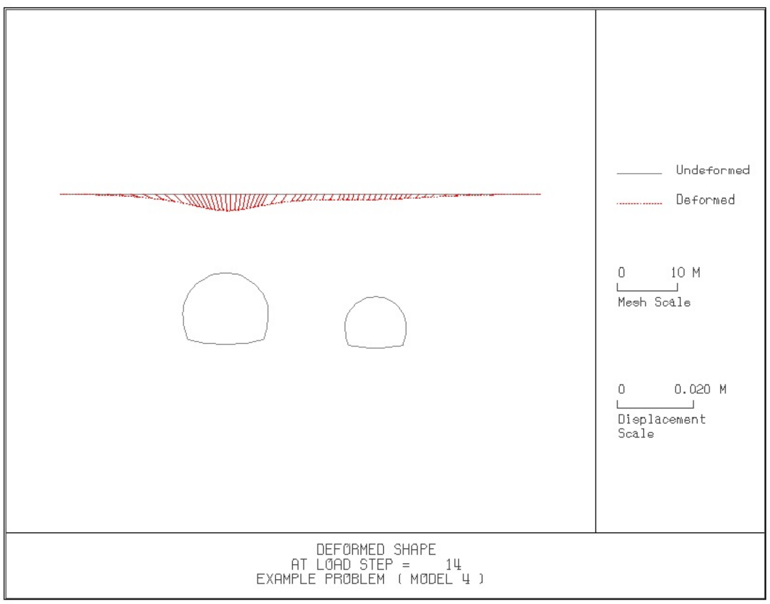

Undeformed
Deformed
0 10 M
Mesh Scale
0 0.020 M
Displacement
Scale
DEFORMED SHAPE
AT LOAD STEP = 14
EXAMPLE PROBLEM (MODEL 4)

Figure 6.92

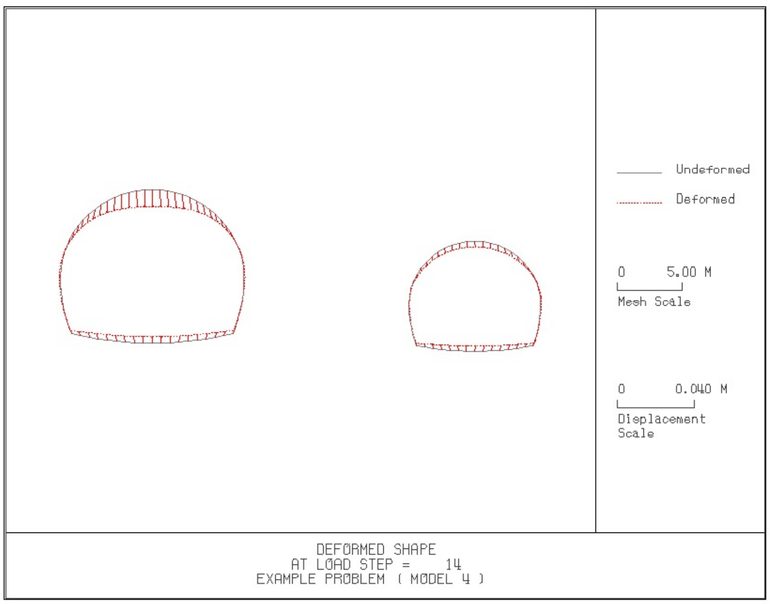
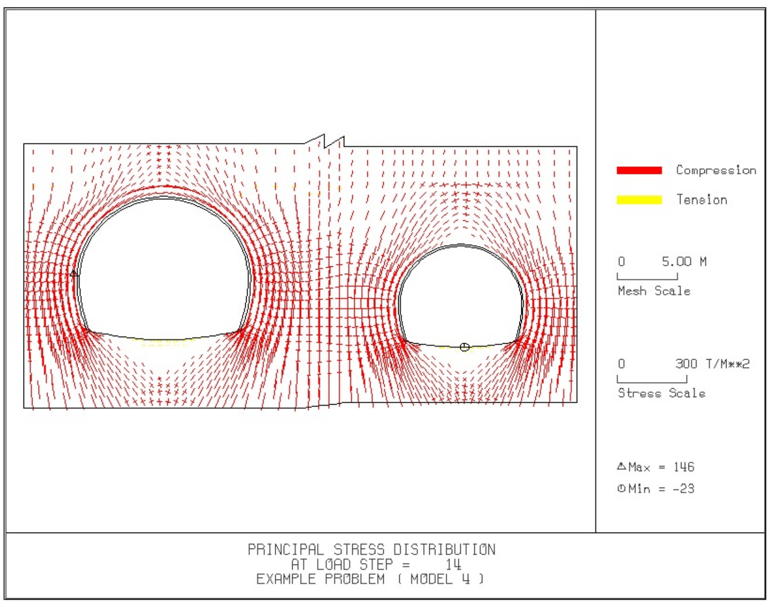

Undeformed
Deformed
0 5.00 M
Mesh Scale
0 0.040 M
Displacement
Scale
DEFORMED SHAPE
AT LOAD STEP = 14
EXAMPLE PROBLEM (MODEL 4)

Figure 6.93



Compression
Tension
0 5.00 M
Mesh Scale
0 300 T/M**2
Stress Scale
Max = 146
Min = -23
PRINCIPAL STRESS DISTRIBUTION
AT LOAD STEP = 14
EXAMPLE PROBLEM (MODEL 4)

Figure 6.94


Compression
Tension
0 5.00 M
Mesh Scale
0 400 T/M**2
Stress Scale
Max = 202
Min = -16
PRINCIPAL STRESS DISTRIBUTION
AT LOAD STEP = 14
EXAMPLE PROBLEM (MODEL 4)

Figure 6.95

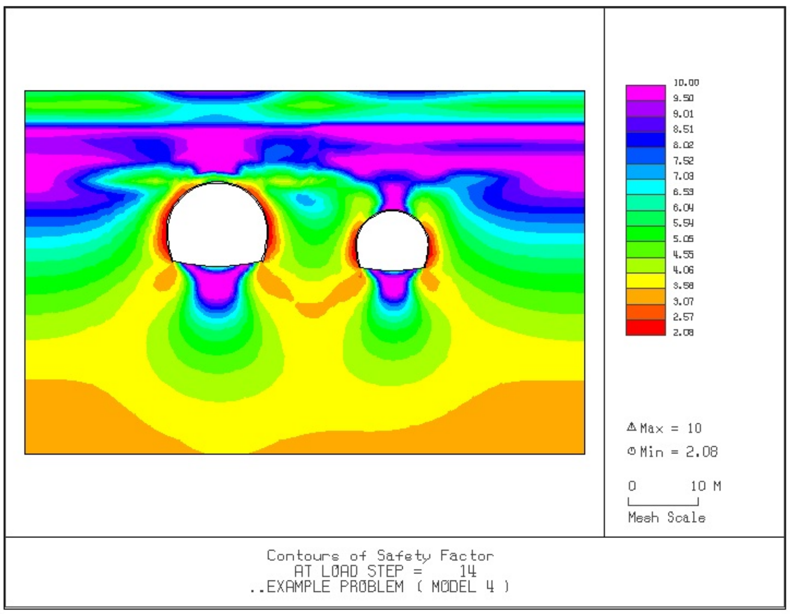

10.00
9.50
9.01
8.51
8.02
7.52
7.03
6.53
6.04
5.54
5.05
4.55
4.06
3.58
3.07
2.57
2.08
Max = 10
Min = 2.08
0
10 M
Mesh Scale
Contours of Safety Factor
AT LOAD STEP = 14
..EXAMPLE PROBLEM (MODEL 4)

Figure 6.96

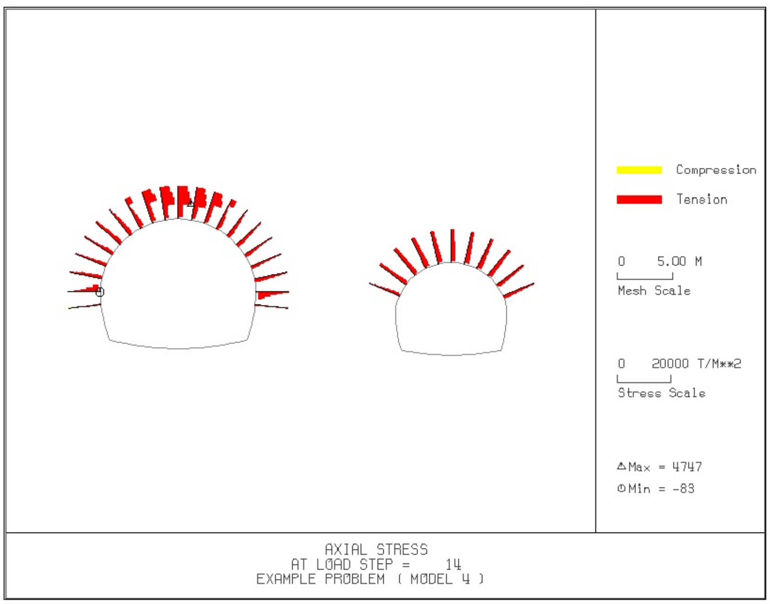

Compression
Tension
0 5.00 M
Mesh Scale
0 20000 T/M**2
Stress Scale
Max = 4747
Min = -83
AXIAL STRESS
AT LOAD STEP = 14
EXAMPLE PROBLEM (MODEL 4)

Figure 6.97

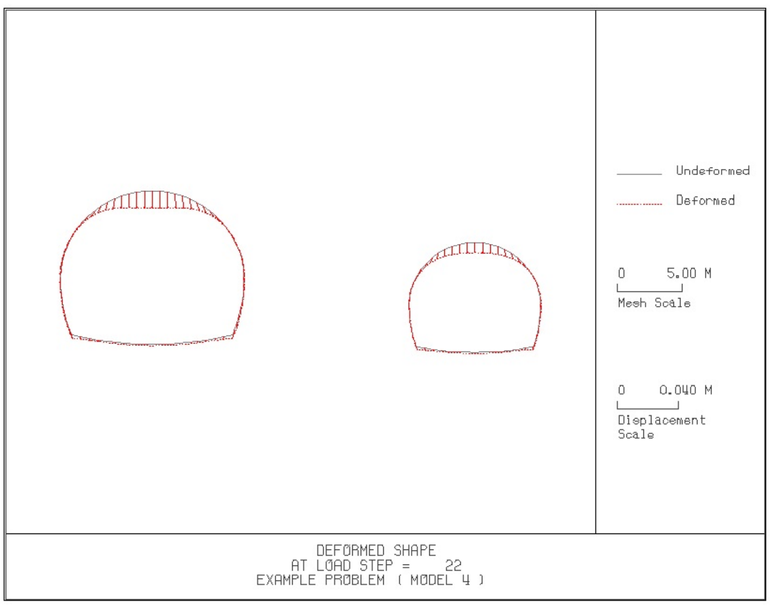

Undeformed
Deformed
0 5.00 M
Mesh Scale
0 0.040 M
Displacement
Scale
DEFORMED SHAPE
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 4)

Figure 6.98

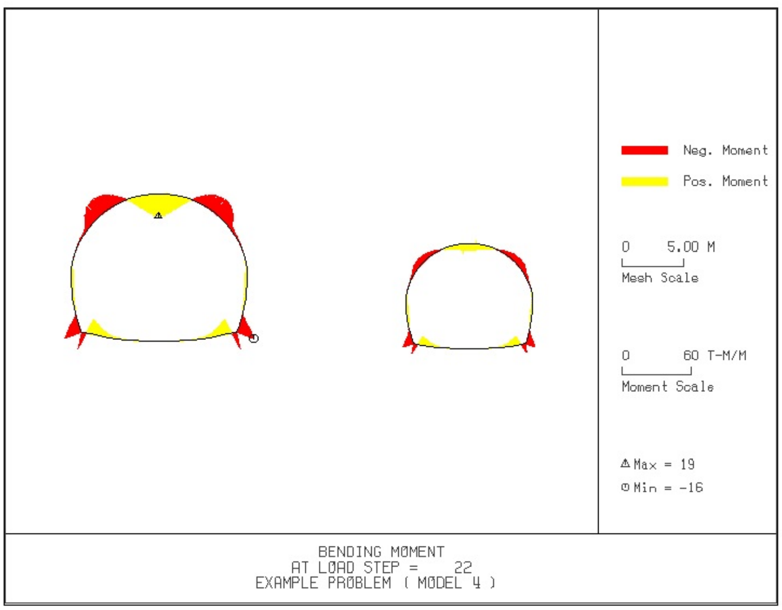

Neg. Moment
Pos. Moment
0 5.00 M
Mesh Scale
0 60 T-M/M
Moment Scale
Max = 19
Min = -16
BENDING MOMENT
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 4)

Figure 6.99

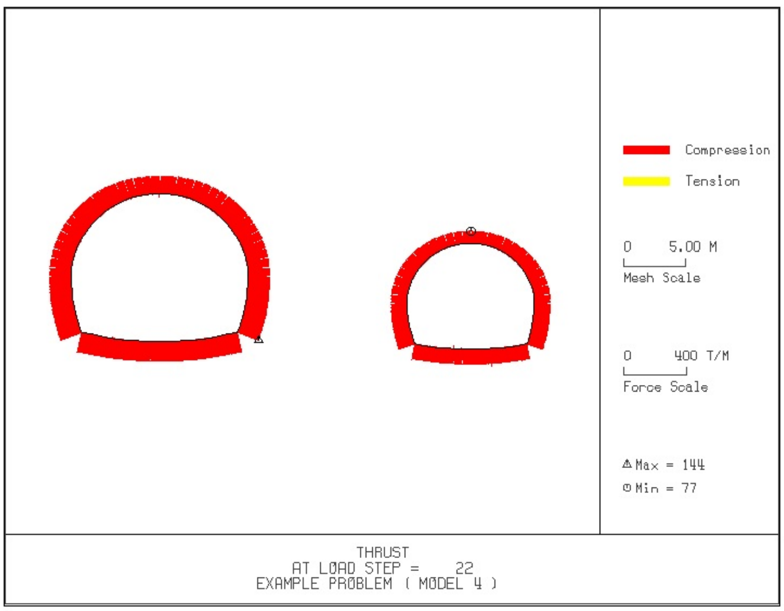

Compression
Tension
0 5.00 M
Mesh Scale
0 400 T/M
Force Scale
Max = 144
Min = 77
THRUST
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 4)

Figure 6.100

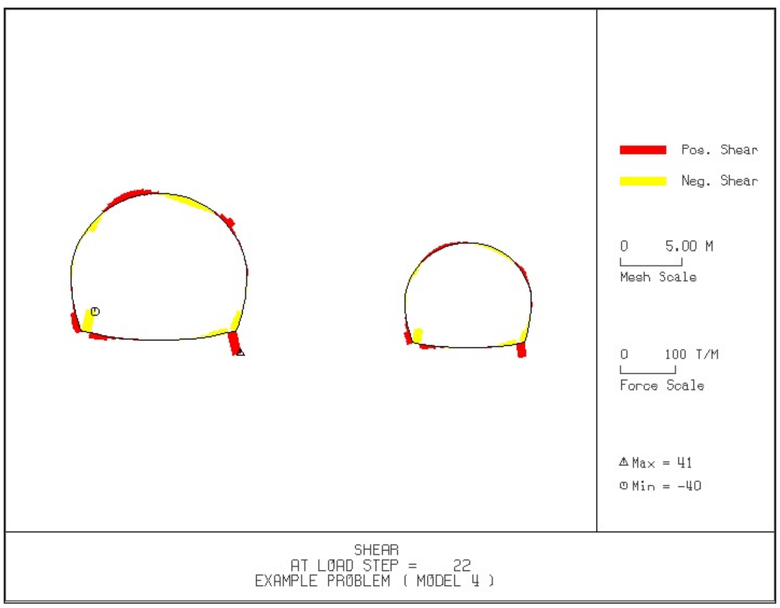

Pos. Shear
Neg. Shear
0 5.00 M
Mesh Scale
0 100 T/M
Force Scale
Max = 41
Min = -40
SHEAR
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 4)

Figure 6.101

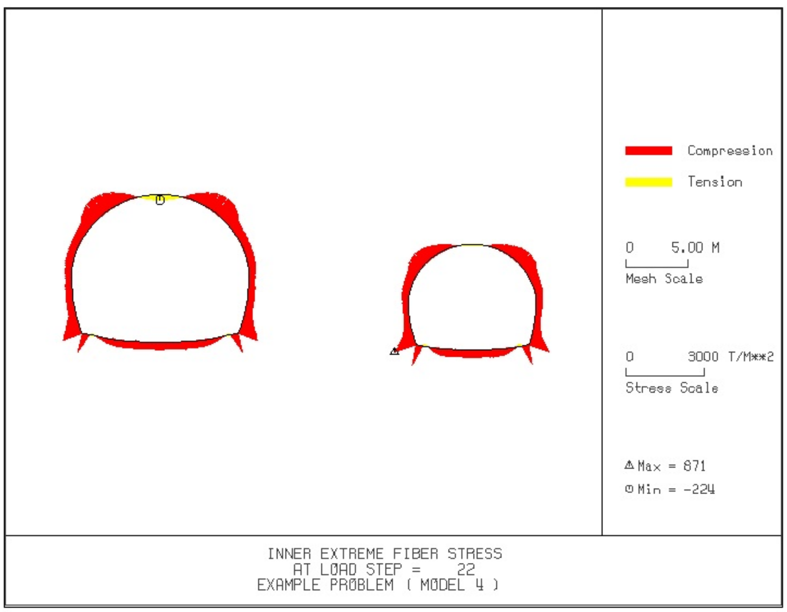

Compression
Tension
0 5.00 M
Mesh Scale
0 3000 T/M**2
Stress Scale
Max = 871
Min = -224
INNER EXTREME FIBER STRESS
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 4)

Figure 6.102

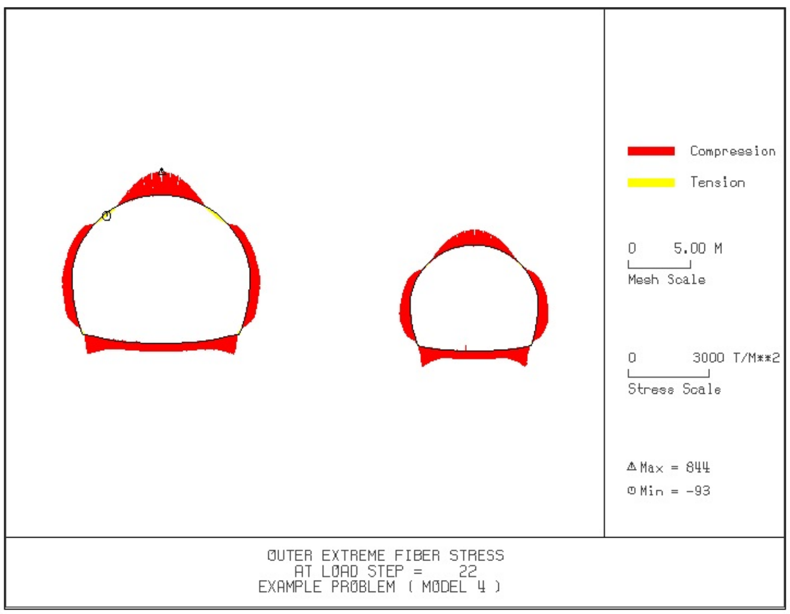
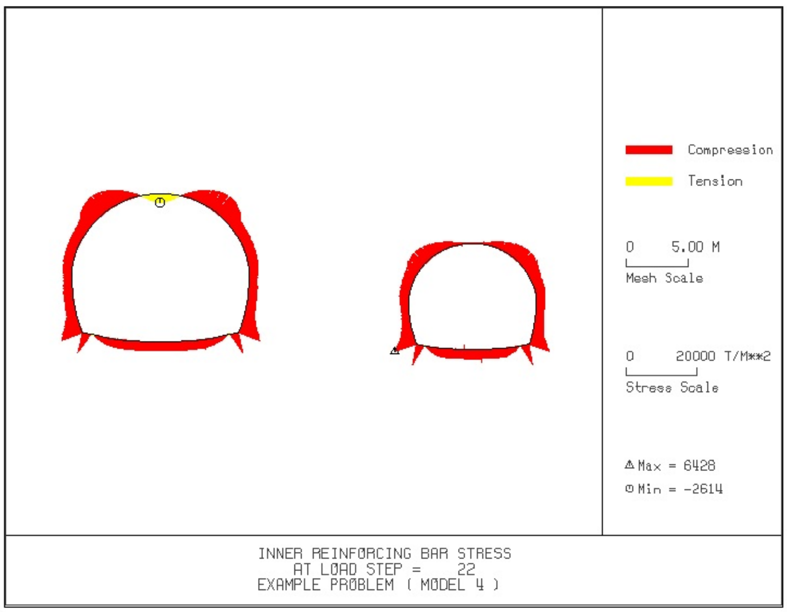

Compression
Tension
0 5.00 M
Mesh Scale
0 3000 T/M**2
Stress Scale
Max = 844
Min = -93
OUTER EXTREME FIBER STRESS
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 4)

Figure 6.103



Compression
Tension
0 5.00 M
Mesh Scale
0 20000 T/M**2
Stress Scale
Max = 6428
Min = -2614
INNER REINFORCING BAR STRESS
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 4)

Figure 6.104

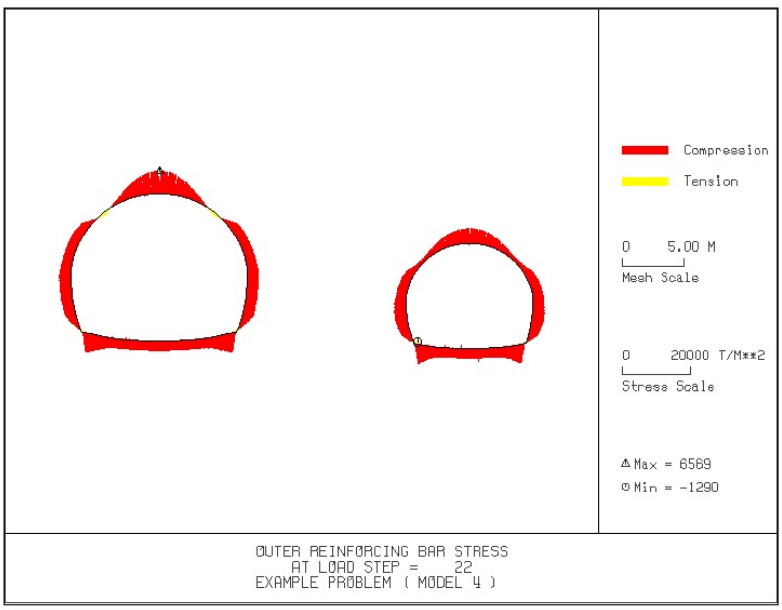

Compression
Tension
0 5.00 M
Mesh Scale
0 20000 T/M**2
Stress Scale
Max = 6569
Min = -1290
OUTER REINFORCING BAR STRESS
AT LOAD STEP = 22
EXAMPLE PROBLEM (MODEL 4)

Figure 6.105

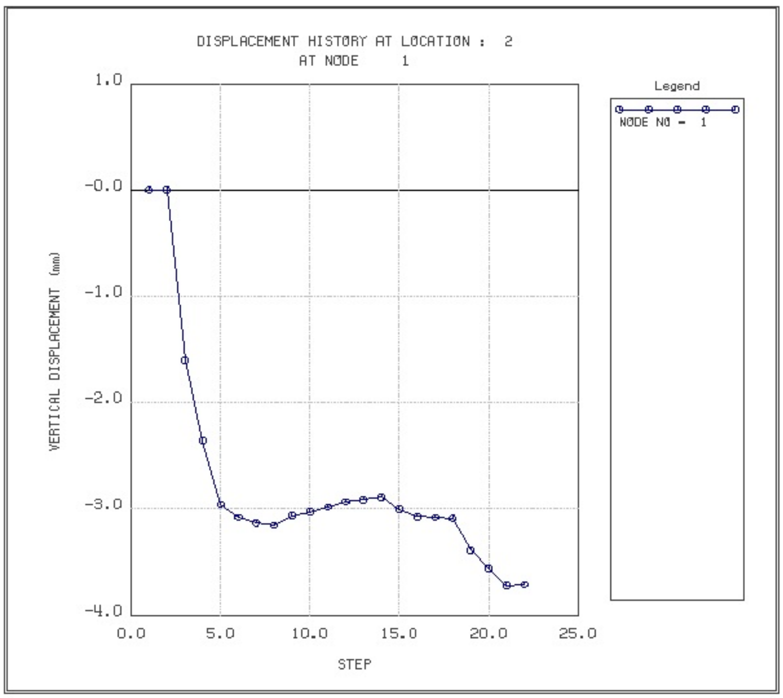
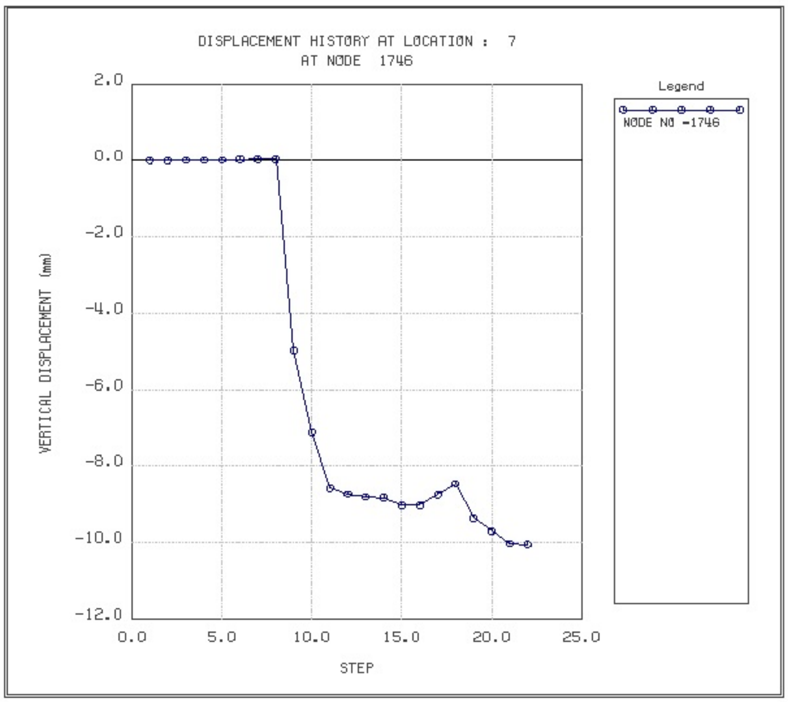

DISPLACEMENT HISTORY AT LOCATION : 2
AT NODE 1
VERTICAL DISPLACEMENT (mm)
1.0
-0.0
-1.0
-2.0
-3.0
-4.0
0.0
5.0
10.0
15.0
20.0
25.0
STEP
Legend
NODE NO = 1

Figure 6.106



DISPLACEMENT HISTORY AT LOCATION : 7
AT NODE 1746
VERTICAL DISPLACEMENT (mm)
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
-12.0
0.0
5.0
10.0
15.0
20.0
25.0
STEP
Legend
NODE NO =1746

Figure 6.107

6.5 Example 5

Example 5 is the same as Example 2 in Section 6.2 except that the top soil layer is replaced by the inclined soil layer as schematically shown in Figure 6.108. The inclined top soil layer is modeled using NATLAYER=2 in Card Group 3.3. Lining analysis is not performed.

Table 6.23 lists the input data for Example 5.

Finite element mesh generated by TUNA Plus is shown in Figure 6.109. Summarized in the following are the results at the completion of tunnel excavation.

Figure 6.110	Ground surface settlement
Figure 6.111	Tunnel deformed shape
Figure 6.112	Principal stresses around tunnel
Figure 6.113	Shotcrete stresses
Figure 6.114	Contour of safety factor
Figure 6.115	Rock bolt axial stresses

Table 6.23 Listing of input file EX5.DAT

```
*
* GENERAL INFORMATION
*
* CARD 1.1
* TITLE
  EXAMPLE PROBLEM 5  ( MODEL 2 )
*
* CARD 1.2
* IUNIT
  3
*
* CARD 1.3
* MODEL  IGEN  IEXMESH  ILNCOUPL  IEXORDER  IRBP
  2      0     0        0         1         0
*
* CARD 1.4
* IEZ1  IEZ2  IEZ3  IEZ4
  1     2     1     2
*
* TUNNEL ANALYSIS BOUNDARY
*
* CARD 2.1
* HT    HL    W     DELTAX  DELTAY  NDYMAX
  15.74 30.   60.   2.0     2.0     40
*
* SOIL / ROCK LAYER INFORMATION
*
* CARD 3.1
* NLAYER
  3
* CARD 3.2
* LAYERNO    H     GAMA  RKO  E       V    PHI   C    T
  1          4.3   1.9   0.43 5000.   0.30 35.   30.  30.
  2          3.5   2.4   0.33 20000.  0.25 40.   70.  40.
  3          37.94 2.55  0.25 200000. 0.20 45.   100. 50.
*
* ADDITIONAL TOP SOIL / ROCK LAYER
*
* CARD 3.3.1
* NATLAYER
  2
*
* CARD 3.3.2
*
* FIRST LAYER
*
* CARD 3.3.2.1
* GAMA   RKO  E       V    PHI   C    T
  1.9    0.5  2000.0  0.33 30.   3.   20.
*
```

```
*
* CARD 3.3.2
*
* SECOND LAYER
*
* CARD 3.3.2.1
* GAMA   RKO  E       V    PHI   C    T
   1.9   0.5  2000.0  0.33 30.   3.   20.
*
* CARD 3.3.3
* NUMSXP
   3
* CARD 3.3.4.1
* Xi   H1j  H2j
  0.0  2.0  14.2
  30.  2.0  4.2
  60.  2.0  4.2
*
*
* USER SPECIFIED SOIL / ROCK LAYER
*
* CARD 3.4.1
* NUSLAYER
  0
*
* USER SPECIFIED DISTRIBUTED SURFACE LOAD
*
* CARD 3.5.1
* NUSXPD
  0
*
* SHOTCRETE PROPERTIES
*
* CARD 3.6
* E         V      PHI    C      T       GAMA
  1.5E+06   0.2    30.    500.   100.    2.4
*
* LINING PROPERTIES
*
* CARD 3.7
* E         V      PHI    C      T       GAMA   ER        VR
  2.1E+06   0.2    30.    500.   300.    0.0    2.1E+07   0.2
*
* ROCK BOLT PROPERTIES
*
* CARD 3.8
* A         WL        E          STRSI   SIGMAy     Ef
  0.000491  0.00383   2.1E+07    0.0     2.3E+04    1.0
*
```

```
*
* INTERFACE PROPERTIES BETWEEN SHOTCRETE AND LINING
*
* CARD 3.9
* NM        E       G        t
  2         200000. 2.0      0.001
* C         PHI
  0.001     5.0
* E1        E2      E3       E4      S1      S2      S3      S4
 -1.0       0.0     1.0E-7   1.0    -200000. 0.0     2.E-02  2.E-02
*
* TUNNEL DIMENSION
*
* CARD 4.0
* ISTYPE  GR    GA
  1       1.0   0.5
*
* CARD 4.1
* R1    A1    R2    A2   R3    A3     R4
  7.24  60.   6.24  30.  11.86 21.781 25.86
* CARD 4.2
* INVSHOT  TS      INVLN     TL      DI    ASI     DO    ASO
  0        0.20    1         0.4     0.05  0.0033  0.05  0.0033
* CARD 4.3
* NUMRB    LRB     LSPACING  TSPACING  NSRB
  21       3.0     1.35      1.2        2
*
* EXCAVATION STRESS RELEASE AND SHOTCRETE MODULUS CHANGE
*
* CARD 5.1
* PSR      PASR    RESH
  50.      25.     0.33
*
* EXTERNAL LOADS FOR LINING ANALYSIS
*
* CARD 6.1
* LDTYPE
  0
* END OF DATA
```

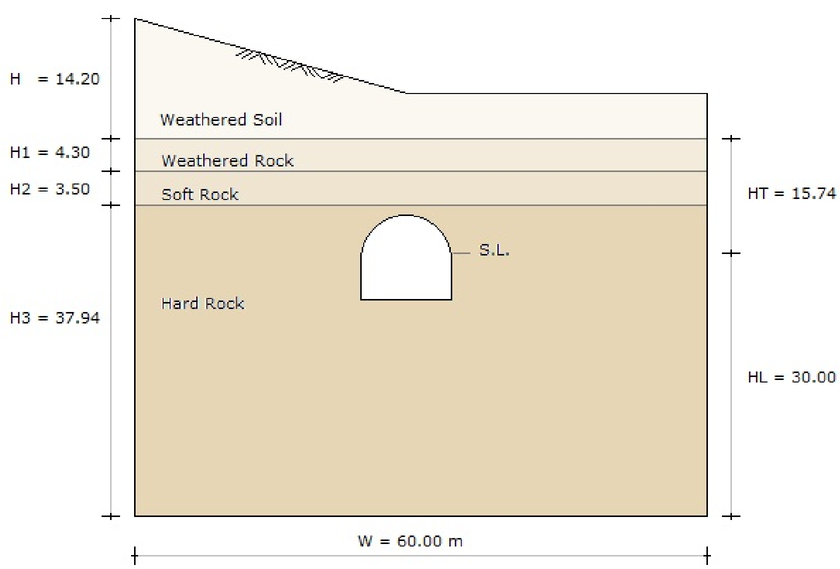


Figure 6.108 Schematic tunnel section for example 5

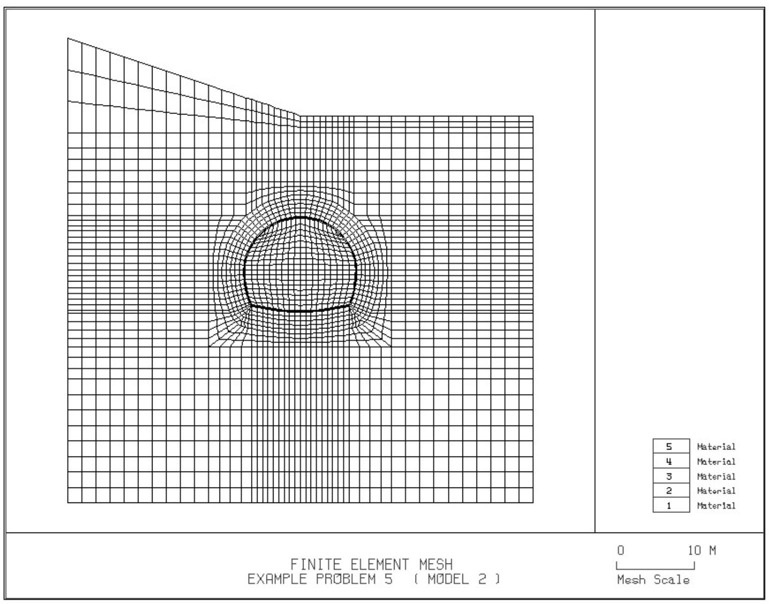


Figure 6.109 Finite element mesh

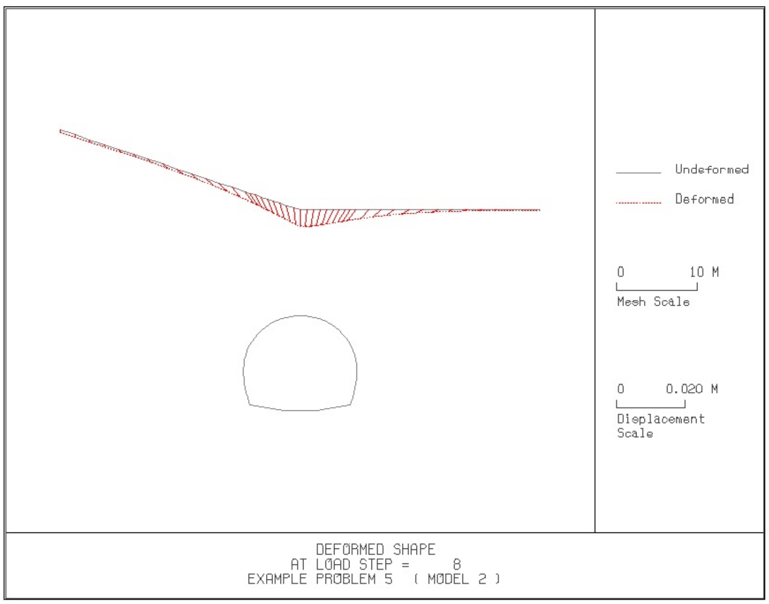


Figure 6.110 Ground surface settlement

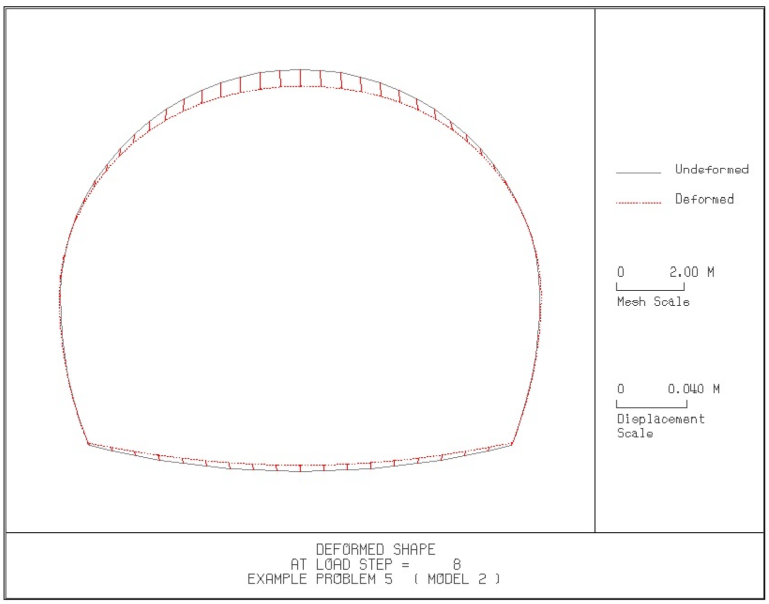


Figure 6.111 Tunnel deformed shape

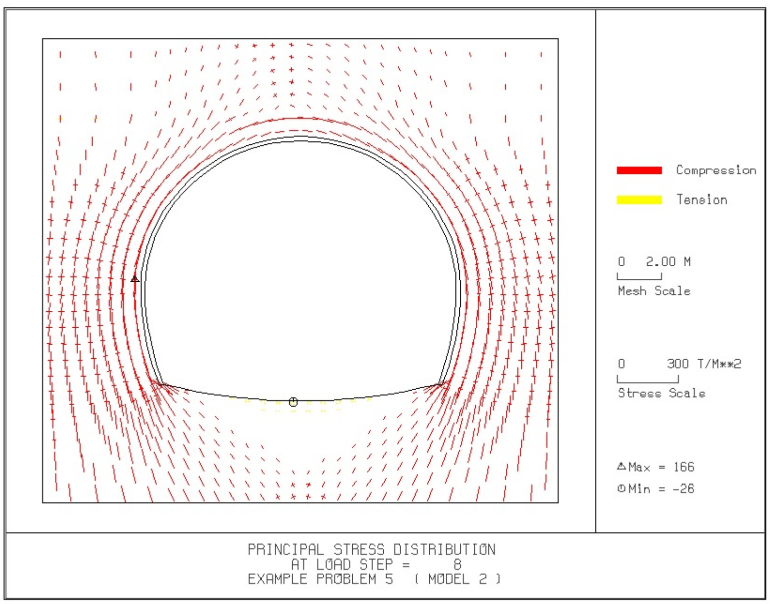


Figure 6.112 Principal stresses around tunnel

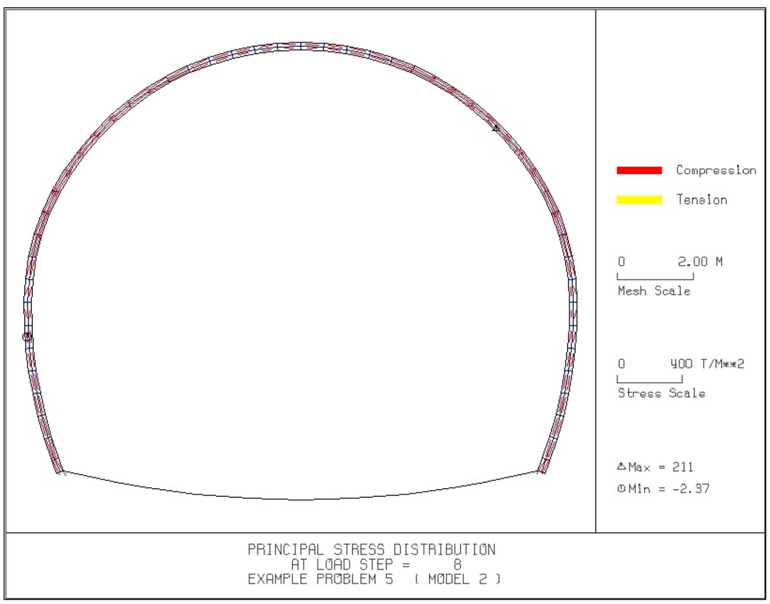


Figure 6.113 Shotcrete stresses

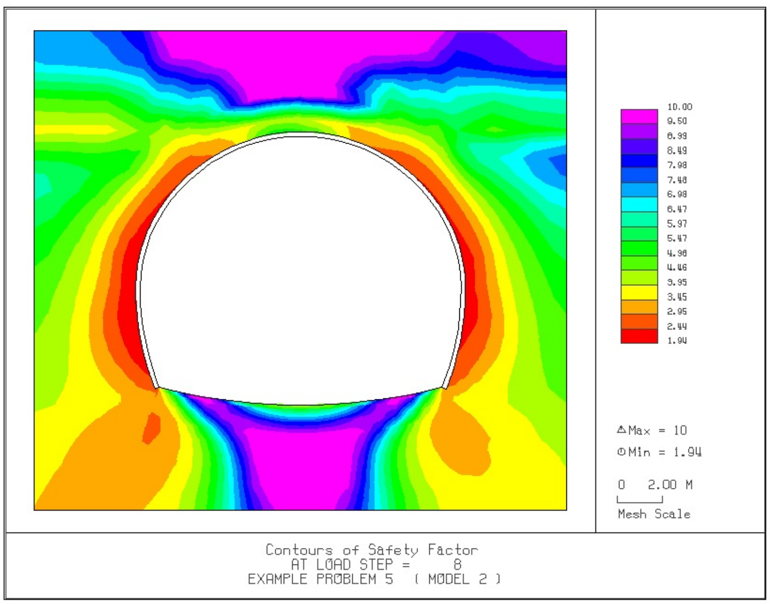


Figure 6.114 Contour of safety factor

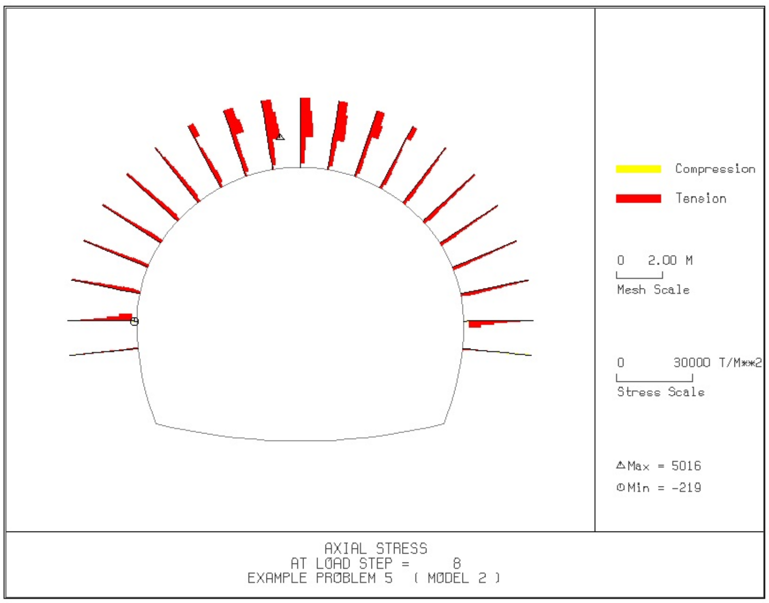


Figure 6.115 Rock bolt axial stresses

6.6 Example 6

Example 6 is the same as Example 2 in Section 6.2 except that there is an additional inclined rock layer (E=100,000 t/m^2) between soft and hard rocks as schematically shown in Figure 6.116. The inclined additional rock layer is modeled using NUSLAYER=1 in Card Group 3.4. Lining analysis is not performed.

Table 6.24 lists the input data for Example 6.

Finite element mesh generated by TUNA Plus is shown in Figure 6.117. Summarized in the following are the results at the completion of tunnel excavation.

Figure 6.118	Ground surface settlement
Figure 6.119	Tunnel deformed shape
Figure 6.120	Principal stresses around tunnel
Figure 6.121	Shotcrete stresses
Figure 6.122	Contour of safety factor
Figure 6.123	Rock bolt axial stresses

Table 6.24 Listing of input file EX6.DAT

```
*
* GENERAL INFORMATION
*
* CARD 1.1
* TITLE
  EXAMPLE PROBLEM 6   ( MODEL 2 )
*
* CARD 1.2
* IUNIT
  3
*
* CARD 1.3
* MODEL  IGEN  IEXMESH  ILNCOUPL  IEXORDER  IRBP
  2      0     0        0         1         0
*
* CARD 1.4
* IEZ1  IEZ2  IEZ3  IEZ4
  1     2     1     2
*
* TUNNEL ANALYSIS BOUNDARY
*
* CARD 2.1
* HT    HL   W     DELTAX  DELTAY  NDYMAX
  19.94 30.  60.   2.0     2.0     40
*
* SOIL / ROCK LAYER INFORMATION
*
* CARD 3.1
* NLAYER
  4
* CARD 3.2
* LAYERNO   H     GAMA  RKO  E       V    PHI   C    T
  1         4.2   1.9   0.5  2000.   0.33 30.   3.   20.
  2         4.3   1.9   0.43 5000.   0.30 35.   30.  30.
  3         3.5   2.4   0.33 20000.  0.25 40.   70.  40.
  4         37.94 2.55  0.25 200000. 0.20 45.   100. 50.
*
* ADDITIONAL TOP SOIL / ROCK LAYER
*
* CARD 3.3.1
* NATLAYER
  0
*
* USER SPECIFIED SOIL / ROCK LAYER
*
* CARD 3.4.1
* NUSLAYER
  1
*
* CARD 3.4.2
* LAYERNO
   1
* CARD 3.4.3
* X1    Y1    X2    Y2    X3    Y3    X4    Y4
  60.   37.94 0.0   37.94 0.0   10.00 30.   23.94
```

```
* CARD 3.4.4
* GAMA  RKO  E       V    PHI   C    T
  2.55  0.25 100000. 0.20 45.   100. 50.
*
* USER SPECIFIED DISTRIBUTED SURFACE LOAD
*
* CARD 3.5.1
* NUSXPD
  0
*
* SHOTCRETE PROPERTIES
*
* CARD 3.6
* E         V      PHI    C      T     GAMA
  1.5E+06   0.2    30.    500.   100.  2.4
*
* LINING PROPERTIES
*
* CARD 3.7
* E         V      PHI    C      T     GAMA   ER        VR
  2.1E+06   0.2    30.    500.   300.  0.0    2.1E+07   0.2
*
* ROCK BOLT PROPERTIES
*
* CARD 3.8
* A         WL         E          STRSI     SIGMAy     Ef
  0.000491  0.00383    2.1E+07    0.0       2.3E+04    1.0
*
* INTERFACE PROPERTIES BETWEEN SHOTCRETE AND LINING
*
* CARD 3.9
* NM       E       G        t
  2        200000. 2.0      0.001
* C        PHI
  0.001    5.0
* E1       E2      E3       E4      S1       S2      S3      S4
 -1.0      0.0     1.0E-7   1.0    -200000. 0.0     2.E-02  2.E-02
*
* TUNNEL DIMENSION
*
* CARD 4.0
* ISTYPE   GR      GA
  1        1.0     0.5
*
* CARD 4.1
* R1    A1    R2    A2   R3    A3     R4
  7.24  60.   6.24  30.  11.86 21.781 25.86
* CARD 4.2
* INVSHOT  TS      INVLN     TL      DI    ASI    DO    ASO
  0        0.20    1         0.4     0.05  0.0033 0.05  0.0033
* CARD 4.3
* NUMRB    LRB     LSPACING  TSPACING  NSRB
  21       3.0     1.35      1.2        2
*
* EXCAVATION STRESS RELEASE AND SHOTCRETE MODULUS CHANGE
*
* CARD 5.1
* PSR      PASR    RESH
  50.      25.     0.33
```

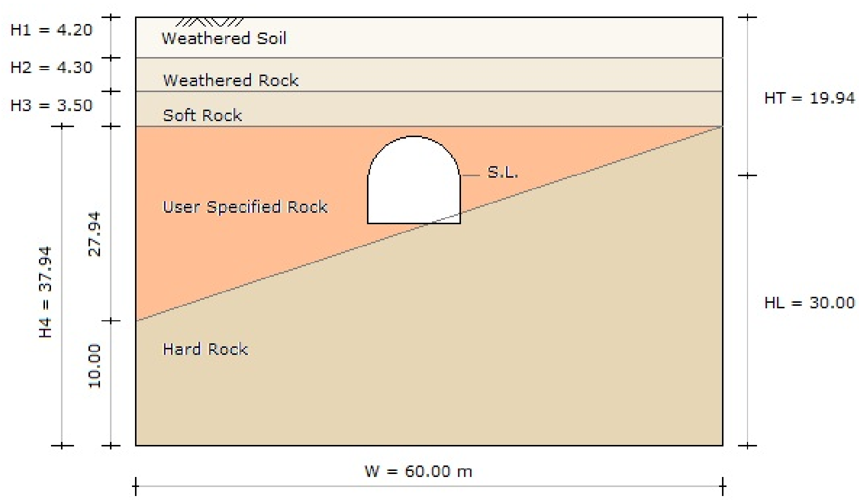


Figure 6.116 Schematic tunnel section for Example 6

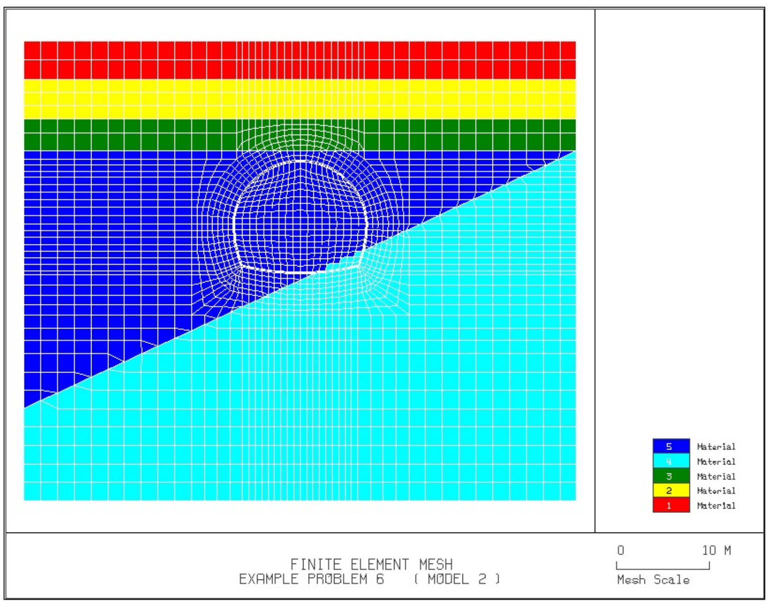


Figure 6.117 Finite element mesh

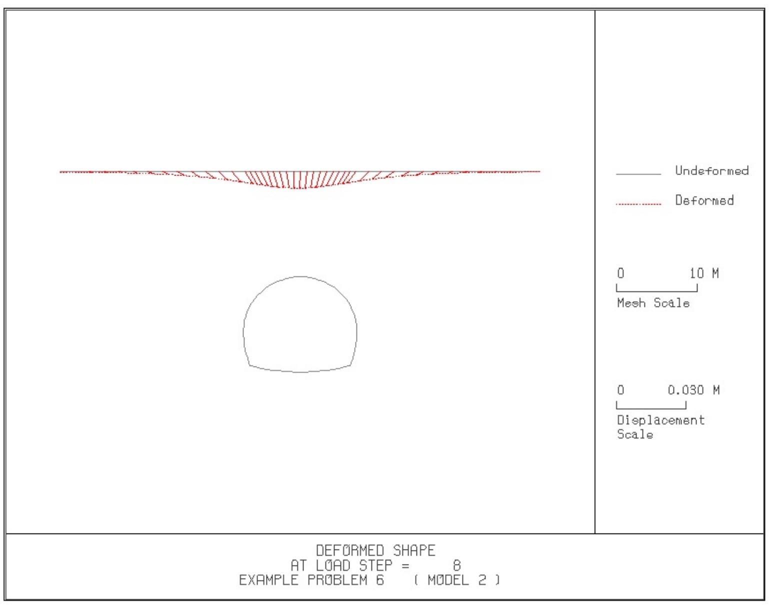


Figure 6.118 Ground surface settlement

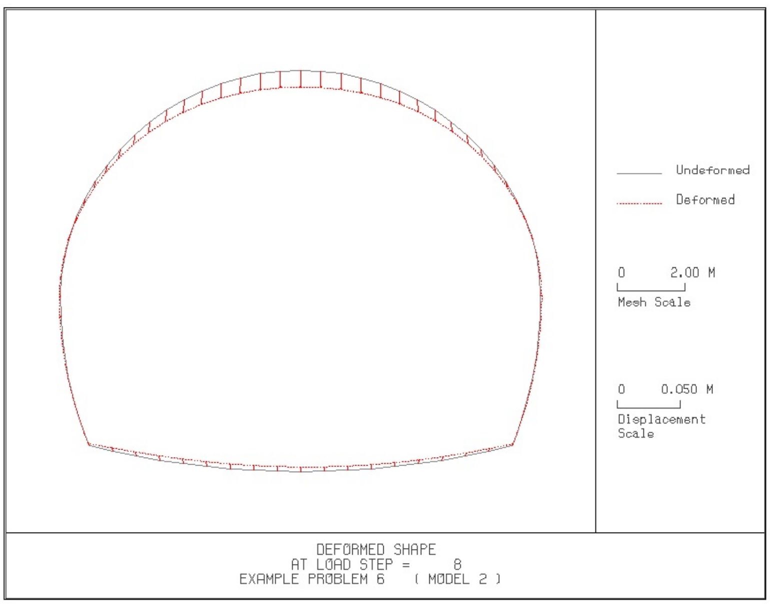


Figure 6.119 Tunnel deformed shape

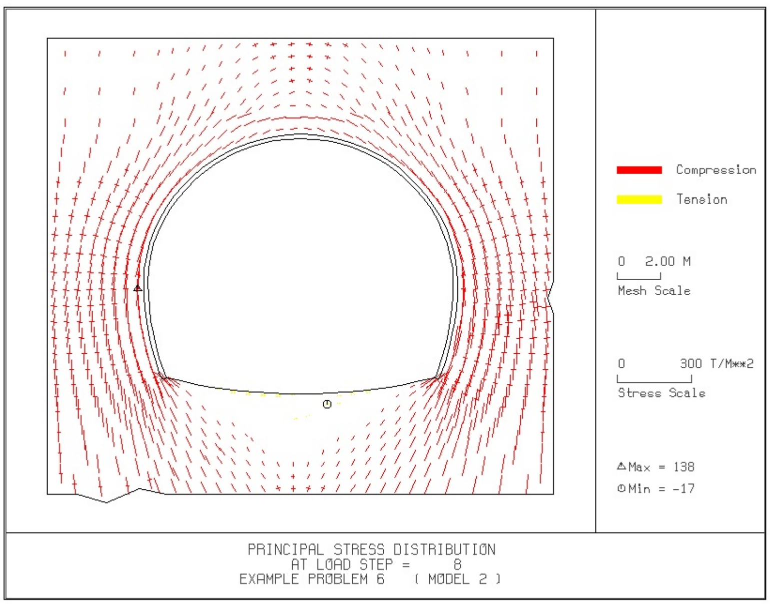


Figure 6.120 Principal stresses around tunnel

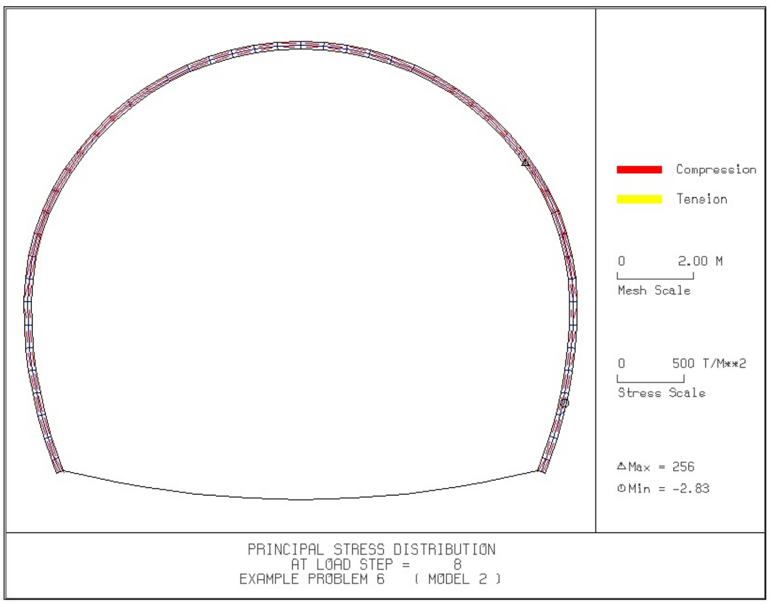


Figure 6.121 Shotcrete stresses

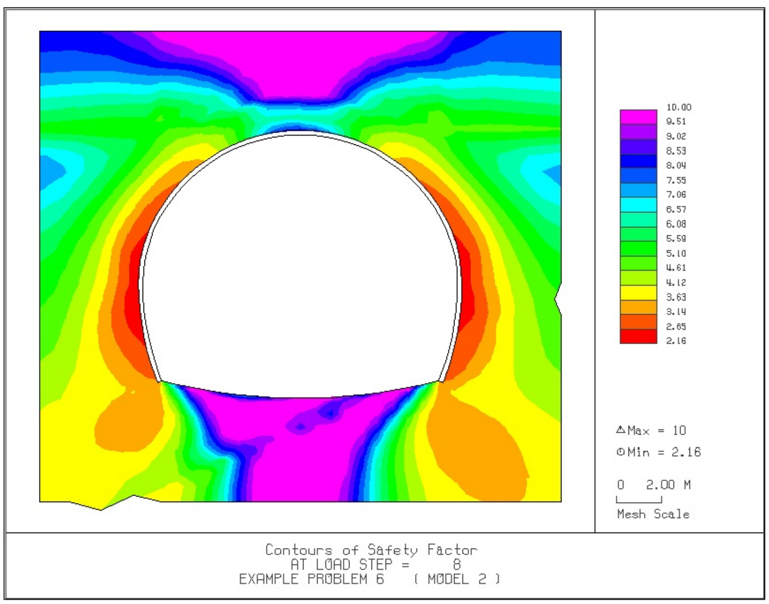


Figure 6.122 Contour of safety factor

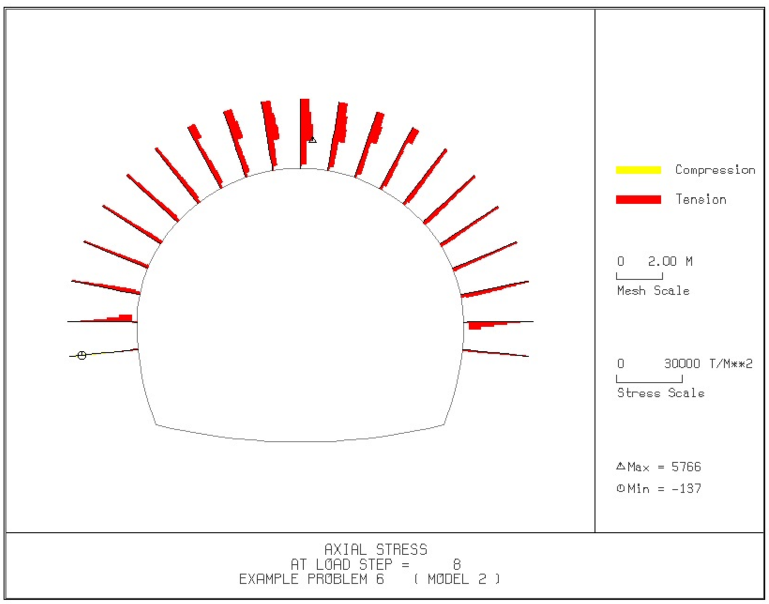


Figure 6.123 Rock bolt axial stresses

6.7 Example 7

Example 7 is the same as Example 5 in Section 6.5 except that the inclined top soil layer is replaced by the equivalent distributed surface load as schematically shown in Figure 6.124. The inclined distributed load is modeled using NUSXPD=3 in Card Group 3.5. Lining analysis is not performed.

Table 6.25 lists the input data for Example 7.

Finite element mesh generated by TUNA Plus is shown in Figure 6.125. Summarized in the following are the results at the completion of tunnel excavation.

Figure 6.126	Ground surface settlement
Figure 6.127	Tunnel deformed shape
Figure 6.128	Principal stresses around tunnel
Figure 6.129	Shotcrete stresses
Figure 6.130	Contour of safety factor
Figure 6.131	Rock bolt axial stresses

Table 6.25 Listing of input file EX7.DAT

```
*
* GENERAL INFORMATION
*
* CARD 1.1
* TITLE
  EXAMPLE PROBLEM 7   ( MODEL 2 )
*
* CARD 1.2
* IUNIT
  3
*
* CARD 1.3
* MODEL  IGEN  IEXMESH  ILNCOUPL  IEXORDER  IRBP
  2      0     0        0         1         0
*
* CARD 1.4
* IEZ1  IEZ2  IEZ3  IEZ4
  1     2     1     2
*
* TUNNEL ANALYSIS BOUNDARY
*
* CARD 2.1
* HT    HL   W     DELTAX  DELTAY  NDYMAX
  15.74 30.  60.   2.0     2.0     40
*
* SOIL / ROCK LAYER INFORMATION
*
* CARD 3.1
* NLAYER
  3
* CARD 3.2
* LAYERNO   H     GAMA  RKO  E       V    PHI   C    T
  1         4.3   1.9   0.43 5000.   0.30 35.   30.  30.
  2         3.5   2.4   0.33 20000.  0.25 40.   70.  40.
  3         37.94 2.55  0.25 200000. 0.20 45.   100. 50.
*
* ADDITIONAL TOP SOIL / ROCK LAYER
*
* CARD 3.3.1
* NATLAYER
  0
*
* USER SPECIFIED SOIL / ROCK LAYER
*
* CARD 3.4.1
* NUSLAYER
  0
*
* USER SPECIFIED DISTRIBUTED SURFACE LOAD
*
* CARD 3.5.1
* NUSXPD
  3
* CARD 3.5.2.1
* X    Q
  0.0  26.98
  30.  7.98
```

```
  60.  7.98
*
* SHOTCRETE PROPERTIES
*
* CARD 3.6
* E          V       PHI     C       T      GAMA
  1.5E+06    0.2     30.     500.    100.   2.4
*
* LINING PROPERTIES
*
* CARD 3.7
* E          V       PHI     C       T      GAMA    ER        VR
  2.1E+06    0.2     30.     500.    300.   0.0     2.1E+07   0.2
*
* ROCK BOLT PROPERTIES
*
* CARD 3.8
* A          WL         E           STRSI   SIGMAy     Ef
  0.000491   0.00383    2.1E+07     0.0     2.3E+04    1.0
*
* INTERFACE PROPERTIES BETWEEN SHOTCRETE AND LINING
*
* CARD 3.9
* NM        E       G         t
  2         200000. 2.0       0.001
* C         PHI
  0.001     5.0
* E1        E2      E3        E4      S1       S2       S3       S4
 -1.0       0.0     1.0E-7    1.0    -200000.  0.0      2.E-02   2.E-02
*
* TUNNEL DIMENSION
*
* CARD 4.0
* ISTYPE  GR     GA
  1       1.0    0.5
*
* CARD 4.1
* R1    A1     R2     A2    R3    A3     R4
  7.24  60.    6.24   30.   11.86 21.781 25.86
* CARD 4.2
* INVSHOT   TS       INVLN      TL       DI     ASI    DO     ASO
  0         0.20     1          0.4      0.05   0.0033 0.05   0.0033
* CARD 4.3
* NUMRB     LRB      LSPACING   TSPACING   NSRB
  21        3.0      1.35       1.2         2
*
* EXCAVATION STRESS RELEASE AND SHOTCRETE MODULUS CHANGE
*
* CARD 5.1
* PSR       PASR     RESH
  50.       25.      0.33
*
* EXTERNAL LOADS FOR LINING ANALYSIS
*
* CARD 6.1
* LDTYPE
  0
* END OF DATA
```

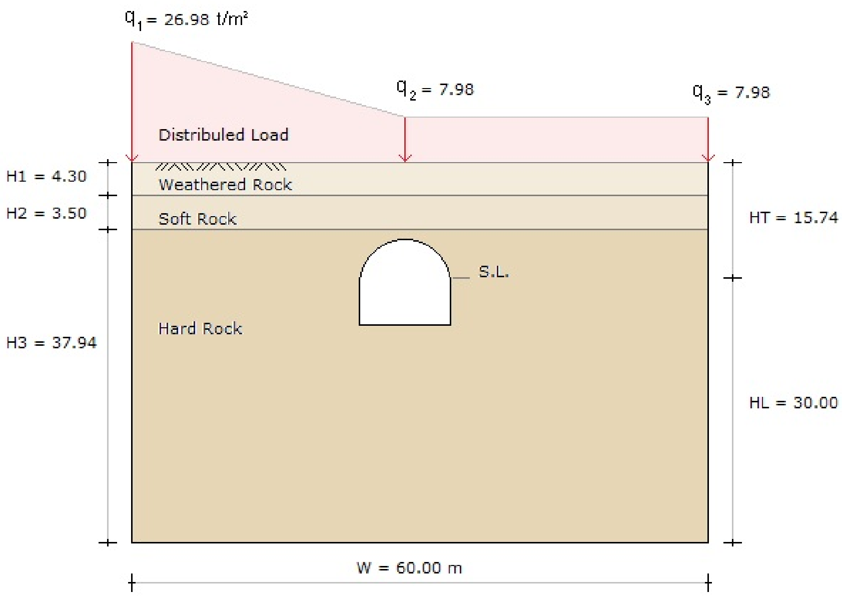


Figure 6.124 Schematic tunnel sectionfor example 7

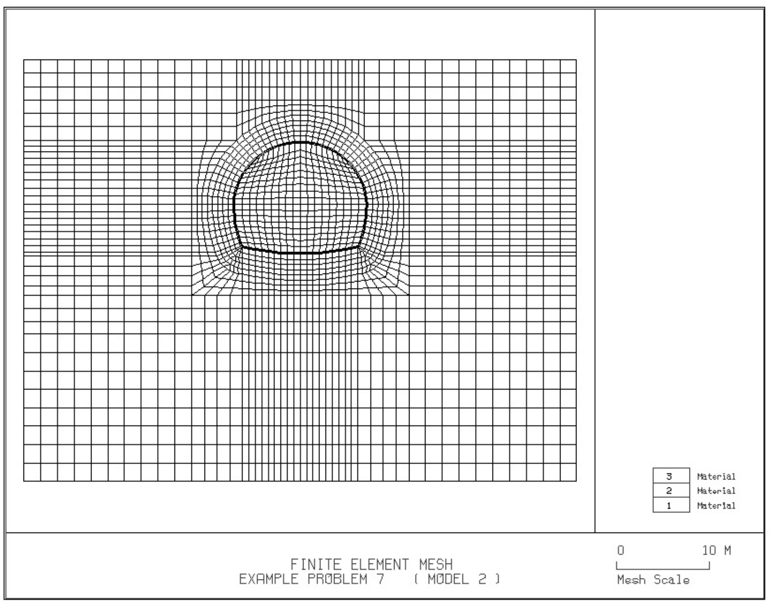


Figure 6.125 Finite element mesh

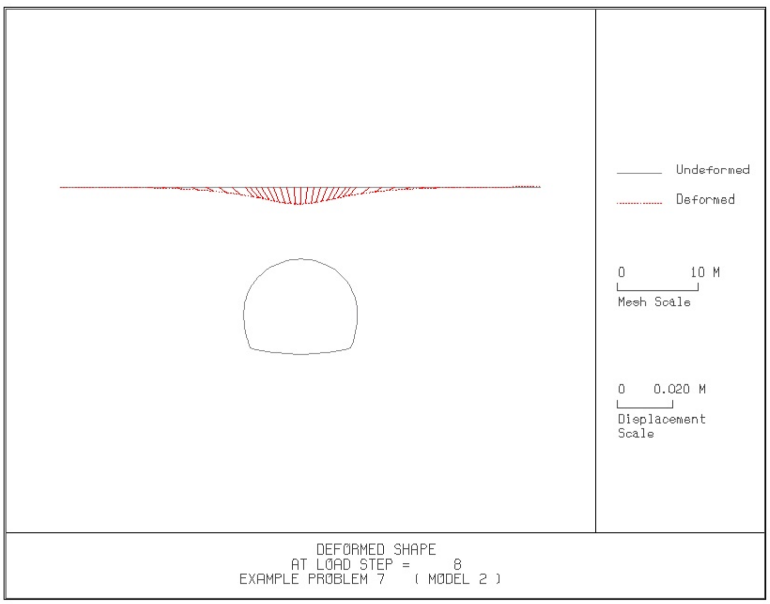


Figure 6.126 Ground surface settlement

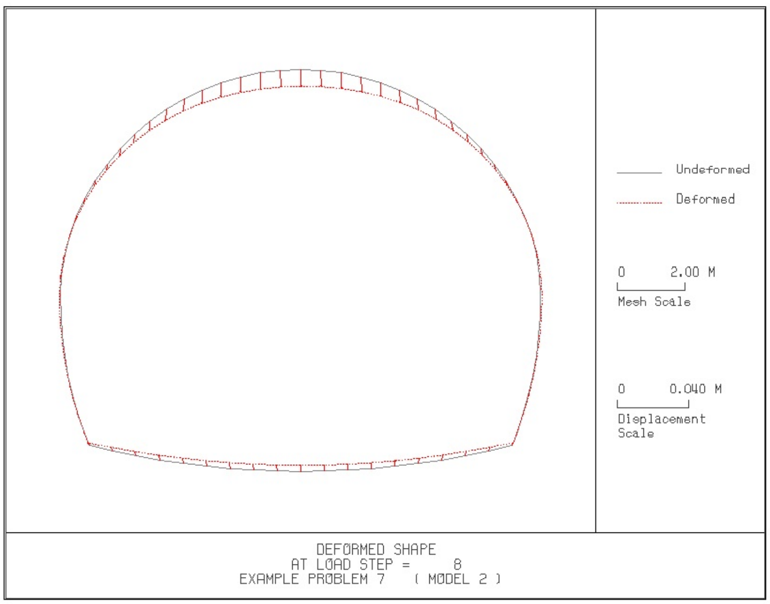


Figure 6.127 Tunnel deformed shape

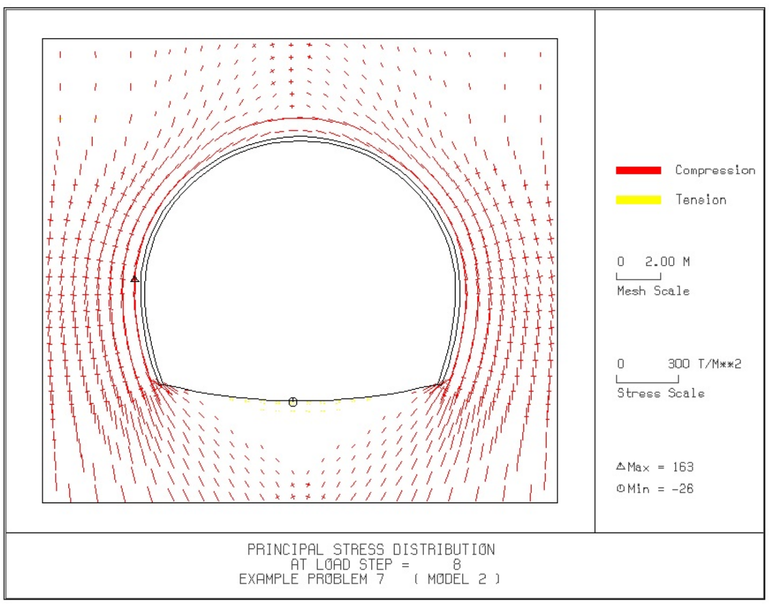


Figure 6.128 Principal stresses around tunnel

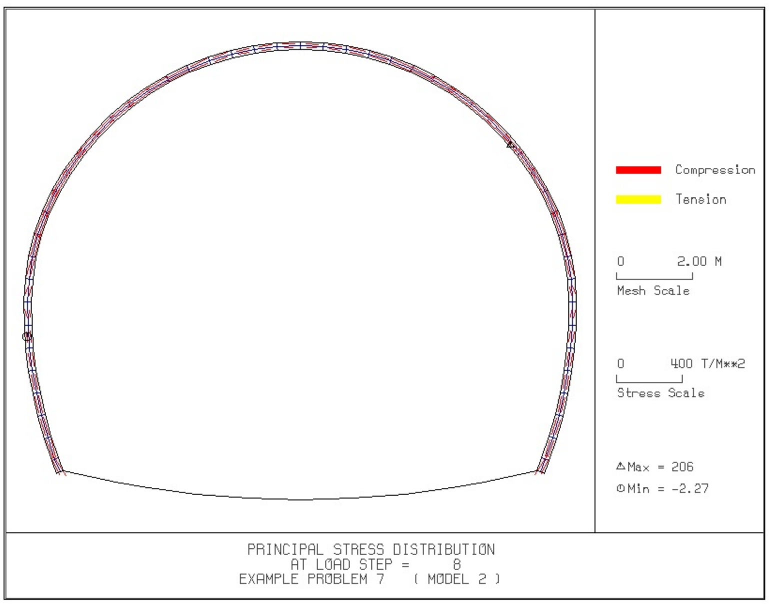


Figure 6.129 Shotcrete stresses

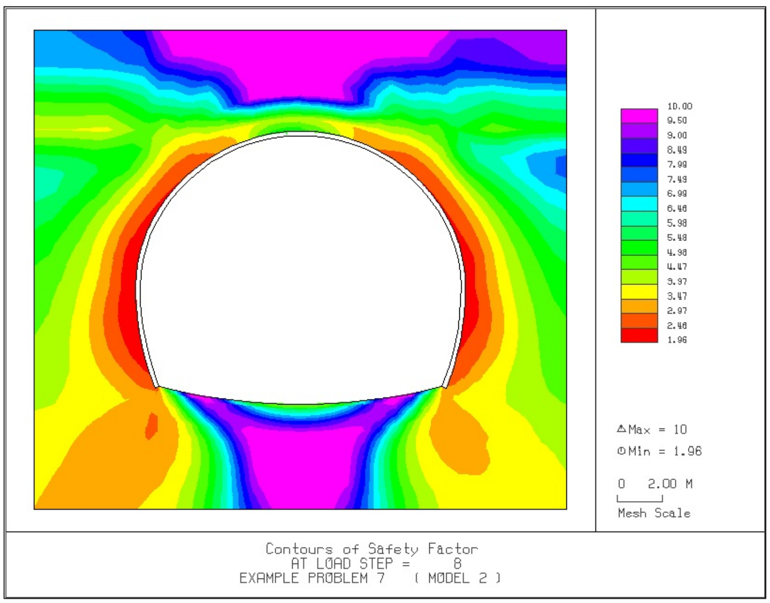


Figure 6.130 Contour of safety factor

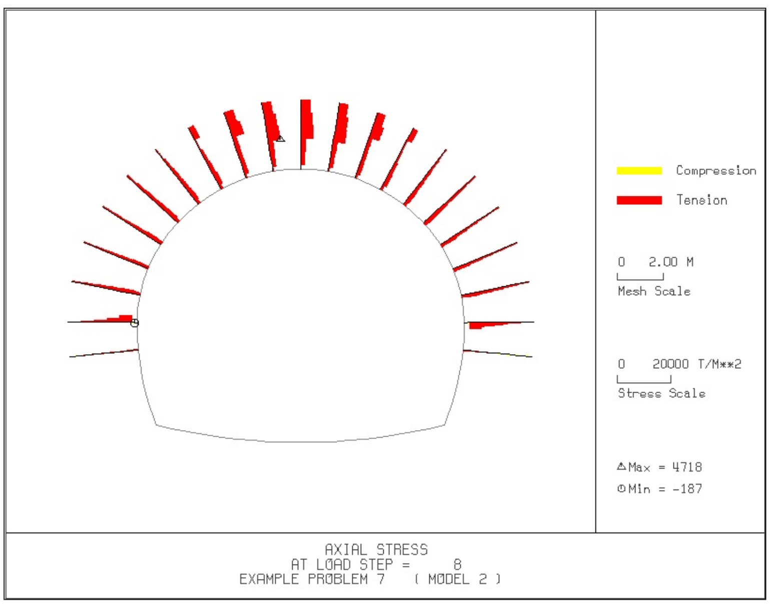


Figure 6.131 Rock bolt axial stresses

6.8 Example 8

Example 8 represents two different tunnels as schematically shown in Figure 6.134.

Shapes of both tunnels are specified using the user defined tunnel section (ISTYPE=3). Geometric parameters related to tunnel shapes are given in Figure 6.132 for the right tunnel and Figure 6.133 for the left tunnel. Geological profile, tunnel depth, and analysis boundaries are specified in Figure 6.134. Material properties of soil/rock layers and supports are summarized in Table 6.2.

As shown in Table 6.26, tunnel construction involves four major excavation stages; upper core excavation in right tunnel, lower core excavation in right tunnel, right core excavation in left tunnel, and left core excavation in left tunnel. Each excavation stage is associated with three load steps; 50% stress release, additional 25% stress release where soft shotcrete and rock bolts are installed, and the last 25% stress release where shotcrete is hardened. It should be noted that program TUNA Plus uses first two load steps to generate in situ K_o stress state.

For lining analysis, reinforced concrete liner is considered with interface joint element between the liner and the surrounding medium. The interface joint properties are set to allow separation when the tensile stress develops in the direction normal to the interface while full slippage is assumed along the interface.

For loads acting on the reinforced concrete liner, only ground water pressure is considered.

The input file EX8.DAT is listed in Table 6.27. Text output file STEP.LST in Table 6.28 lists steps where major excavations take place and external lining loads are applied.

Selected graphical outputs from PLOT-2D are shown in Figures 6.135 to 6.140. Brief description of PLOT-2D plots is given in the text output file PLTDS.LST in Table 6.29.

Selected displacement history graphical outputs from PLOT-XY are shown in Figures 6.141 to 6.144. Brief description of PLOT-XY plots is given in the text output file PLTXT.LST in Table 6.30.

Table 6.26 Simulation of construction sequence

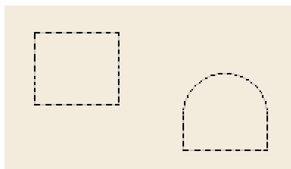
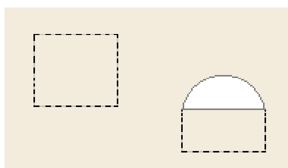
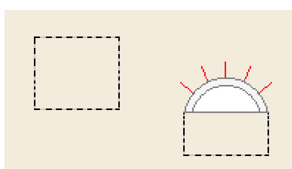
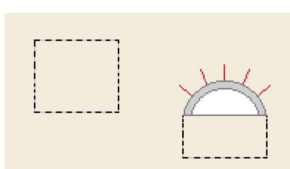
Step	Construction State	Descriptions	
1,2		In Situ K_o State	
3		50 % Stress Relief	Upper Core Excavation (Right Tunnel)
4		75 % Stress Relief Soft Shotcrete Rock Bolt	
5		100% Stress Relief Hard Shotcrete Rock Bolt	

Table 6.26 Simulation of construction sequence (Continued)

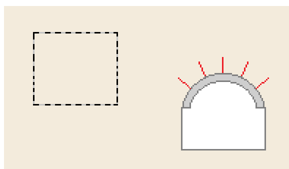
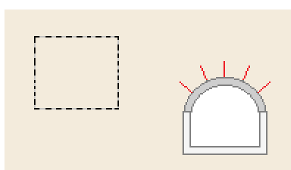
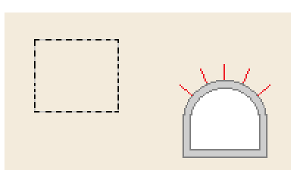
Step	Construction State	Descriptions	
6		50% Stress Relief	Lower Core Excavation (Right Tunnel)
7		75% Stress Relief Soft Shotcrete Rock Bolt	
8		100% Stress Relief Hard Shotcrete Rock Bolt	

Table 6.26 Simulation of construction sequence (Continued)

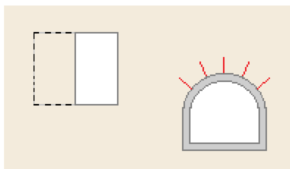
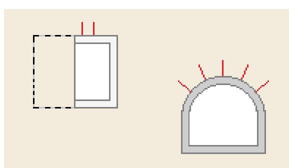
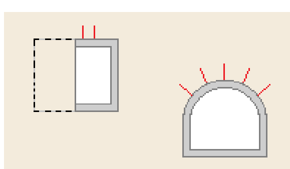
Step	Construction State	Descriptions	
9		50% Stress Relief	Right Core Excavation (Left Tunnel)
10		75% Stress Relief Soft Shotcrete Rock Bolt	
11		100% Stress Relief Hard Shotcrete Rock Bolt	

Table 6.26 Simulation of construction sequence (Continued)

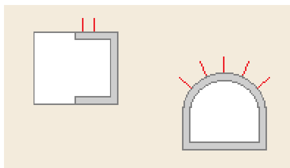
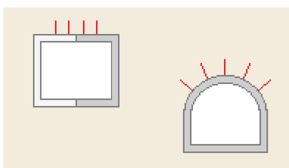
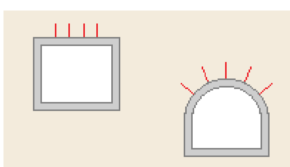
Step	Construction State	Descriptions	
12		50 % Stress Relief	Left Core Excavation (Left Tunnel)
13		75 % Stress Relief Soft Shotcrete Rock Bolt	
14		100 % Stress Relief Hard Shotcrete Rock Bolt	

Table 6.26 Simulation of construction sequence (Continued)

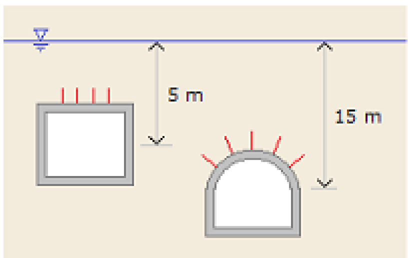
Step	Construction State	Descriptions	
18		Lining Subjected to: Water Pressure	Lining Analysis

Table 6.27 Listing of input file EX8.DAT

```
*
* GENERAL INFORMATION
*
* CARD 1.1
* TITLE
  EXAMPLE PROBLEM 8 (USER DEFINED TUNNEL SECTION)
*
* CARD 1.2
* IUNIT
  3
*
* CARD 1.3
* MODEL  IGEN  IEXMESH  ILNCOUPL  IEXORDER  IRBP
  4      0     0        0         1         0
*
* CARD 1.4
* IEZ1  IEZ2  IEZ3  IEZ4  IEZ5  IEZ6  IEZ7  IEZ8
  1     2     1     2     3     3     4     4
*
* TUNNEL ANALYSIS BOUNDARY
*
* CARD 2.1
* HT    HL   W     WP    HP    DELTAX  DELTAY  NDYMAX
  25.0  30.  70.   25.   10.   2.0     3.0     40
*
* SOIL / ROCK LAYER INFORMATION
*
* CARD 3.1
* NLAYER
  3
* CARD 3.2
* LAYERNO   H     GAMA  RKO  E       V    PHI   C    T
  1         5.0   1.9   0.43 5000.   0.30 35.   30.  30.
  2         5.0   2.4   0.33 20000.  0.25 40.   70.  40.
  3         45.0  2.55  0.25 200000. 0.20 45.   100. 50.
*
* ADDITIONAL TOP SOIL / ROCK LAYER
*
* CARD 3.3.1
* NATLAYER
  0
*
* USER SPECIFIED SOIL / ROCK LAYER
*
* CARD 3.4.1
* NUSLAYER
  0
*
* USER SPECIFIED DISTRIBUTED SURFACE LOAD
*
```

```
*
* CARD 3.5.1
* NUSXPD
  0
*
* SHOTCRETE PROPERTIES
*
* CARD 3.6
* E          V       PHI     C       T      GAMA
  1.5E+06    0.2     30.     500.    100.   2.4
*
* LINING PROPERTIES
*
* CARD 3.7
* E          V       PHI     C       T      GAMA   ER        VR
  2.1E+06    0.2     30.     500.    300.   0.0    2.1E+07   0.2
*
* ROCK BOLT PROPERTIES
*
* CARD 3.8
* A          WL         E          STRSI     SIGMAy     Ef
  0.000491  0.00383    2.1E+07    0.0       2.3E+04    1.0
*
* INTERFACE PROPERTIES BETWEEN SHOTCRETE AND LINING
*
* CARD 3.9
* NM        E       G        t
  2         200000. 2.0      0.001
* C         PHI
  0.001     5.0
* E1     E2     E3      E4     S1      S2     S3      S4
 -1.0    0.0    1.0E-7  1.0   -200000. 0.0    2.E-02  2.E-02
*
* -------------------------------------------------------------
*
* TUNNEL DIMENSION
*
* CARD 4.0
* ISTYPE  GR     GA
  3        1.0    0.5
*
* CARD 4.1-1
* NSEG    SHOR    STR    SBR
  4       8.0     6.0    0.0
* SEGMENT 1 (CIRCULAR ARS)
* R       XO      YO     TB      TE     TL       ASI    ASO
  6.1683 0.0     1.85   90.     30.    0.30     0.0020 0.0020
* SEGMENT 2 (CIRCULAR ARS)
* R       XO      YO     TB      TE     TL       ASI    ASO
  4.9413 1.062   2.463  30.    -26.0   0.32     0.0022 0.0022
* SEGMENT 3 (CIRCULAR ARS)
* R       XO      YO     TB      TE     TL       ASI    ASO
  0.51   5.045   0.521 -26.0  -90.    0.34     0.0024 0.0024
*
```

```
*
* SEGMENT 4 (STRAIGHT LINE)
* 0      XB     YB     XE     YE     TL     ASI    ASO
  0      5.045  0.0    0.0    0.0    0.40   0.0030 0.0030
* CARD 4.2
* INVSHOT  TS      INVLN     TL     DI     ASI    DO     ASO
  1        0.20    1         0.4    0.05   0.0030 0.05   0.0030
* CARD 4.3
* NUMRB    LRB     LSPACING  TSPACING  NSRB
  11       3.0     1.35      1.2       2
*
* --------------------------------------------------------------
* TUNNEL DIMENSION
*
* CARD 4.0
* ISTYPE  GR     GA
  3       1.0    0.5
* CARD 4.1-1
* NSEG    SHOR   STR    SBR
  5       0.0    0.0    0.0
* SEGMENT 1 (STRAIGHT LINE)
* 0      XB     YB     XE     YE     TL       ASI    ASO
  0      0.0    6.0    5.5    6.0    0.40     0.0066 0.0044
* SEGMENT 2 (CIRCULAR ARC)
* R      XO     YO     TB     TE     TL       ASI    ASO
  0.5    5.5    5.5    90.    0.0    0.40     0.0066 0.0066
* SEGMENT 3 (STRAIGHT LINE)
* 0      XB     YB     XE     YE     TL       ASI    ASO
  0      6.0    5.5    6.0    0.5    0.32     0.0024 0.0024
* SEGMENT 4 (CIRCULAR ARS)
* R      XO     YO     TB     TE     TL       ASI    ASO
  0.5    5.5    0.5    0.0   -90.    0.36     0.0026 0.0026
* SEGMENT 5 (STRAIGHT LINE)
* 0      XB     YB     XE     YE     TL       ASI    ASO
  0      5.5    0.0    0.0    0.0    0.38     0.0028 0.0028
* CARD 4.2
* INVSHOT  TS      INVLN     TL      DI     ASI    DO     ASO
  1        0.20    1         0.48    0.05   0.0028 0.05   0.0028
* CARD 4.3
* NUMRB    LRB     LSPACING  TSPACING  NSRB
  7        3.0     1.35      1.6        2
*
* ---------------------------------------------------------------
*
* EXCAVATION STRESS RELEASE AND SHOTCRETE MODULUS CHANGE
*
* CARD 5.1
* PSR      PASR    RESH
  50.      25.     0.33
*
*
* EXTERNAL LOADS FOR LINING ANALYSIS
*
```

```
*
* CARD 6.1
* LDTYPE
  1
*
* WATER PRESSURE
*
* CARD 6.2
* LGWINV   NWPSTEP DGW     GAMAW
  0        3       10.     1.0
*
* LOOSENING LOAD
*
* CARD 6.3.1
* LSDADD   NLDSTEP  HPRES   VPRES
  0        0        0.00    0.0
*
* PRIMARY SUPPORT DEGRADATION
*
* CARD 6.4
* LPSDEG   REDH
  0        1.0
*
* END OF DATA
```

Table 6.28 Listing of text output file STEP.LST

```
STEP NO   DESCRIPTIONS
    5
          Excavation of Upper Right Core in Right Tunnel
          Excavation of Upper Left  Core in Right Tunnel
    8
          Excavation of Lower Right Core in Right Tunnel
          Excavation of Lower Left  Core in Right Tunnel
   11
          Excavation of Upper Right Core in Left  Tunnel
          Excavation of Lower Right Core in Left  Tunnel
   14
          Excavation of Upper Left  Core in Left  Tunnel
          Excavation of Lower Left  Core in Left  Tunnel
   18
          Lining Subjected to:
          Water Pressure
```

Table 6.29 Partial listing of text output file PLTDS.LST

```
PLOT NO  TITLE
    1
         FINITE ELEMENT MESH
         EXAMPLE PROBLEM 8 (USER DEFINED TUNNEL SECTION)

    2    DEFORMED SHAPE
         AT LOAD STEP = 5
         EXAMPLE PROBLEM 8 (USER DEFINED TUNNEL SECTION)

    3    DEFORMED SHAPE
         AT LOAD STEP = 8
         EXAMPLE PROBLEM 8 (USER DEFINED TUNNEL SECTION)
         -
         -
   30    INNER EXTREME FIBER STRESS
         AT LOAD STEP = 18
         EXAMPLE PROBLEM 8 (USER DEFINED TUNNEL SECTION)

   31    OUTER EXTREME FIBER STRESS
         AT LOAD STEP = 18
         EXAMPLE PROBLEM 8 (USER DEFINED TUNNEL SECTION)

   32    INNER REINFORCING BAR STRESS
         AT LOAD STEP = 18
         EXAMPLE PROBLEM 8 (USER DEFINED TUNNEL SECTION)

   33    OUTER REINFORCING BAR STRESS
         AT LOAD STEP = 18
         EXAMPLE PROBLEM 8 (USER DEFINED TUNNEL SECTION)
```

Table 6.30 Listing of text output file PLTXY.LST

```
PLOT NO   TITLE
     1     DISPLACEMENT HISTORY AT LOCATION :  1
           AT NODE   498

     2     DISPLACEMENT HISTORY AT LOCATION :  2
           AT NODE    34

     3     DISPLACEMENT HISTORY AT LOCATION :  3
           AT NODE    66

     4     DISPLACEMENT HISTORY AT LOCATION :  4
           AT NODE    15

     5     DISPLACEMENT HISTORY AT LOCATION :  5
           AT NODE  1065

     6     DISPLACEMENT HISTORY AT LOCATION :  6
           AT NODE  2226

     7     DISPLACEMENT HISTORY AT LOCATION :  7
           AT NODE  1831

     8     DISPLACEMENT HISTORY AT LOCATION :  8
           AT NODE  1859

     9     DISPLACEMENT HISTORY AT LOCATION :  9
           AT NODE  2797

    10     DISPLACEMENT HISTORY AT LOCATION : 10
           AT NODE  1816
```

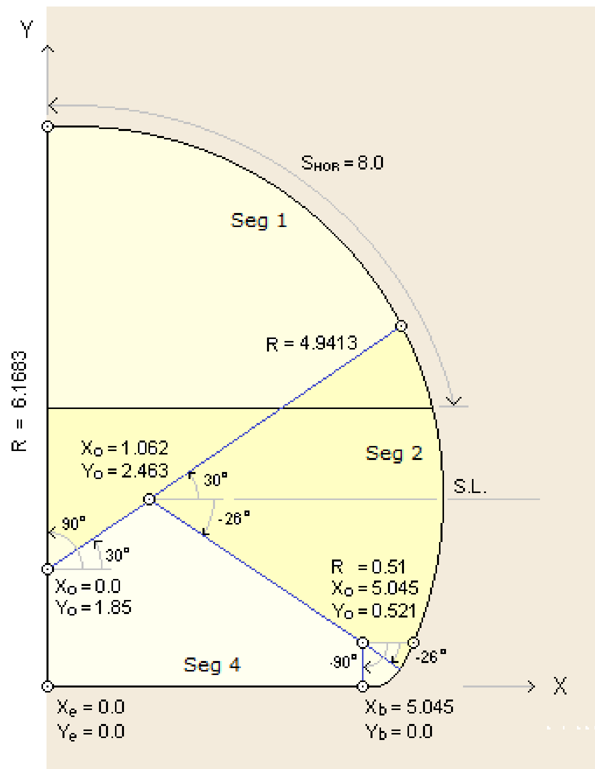


Figure 6.132 Dimensions of right tunnel for Example 8

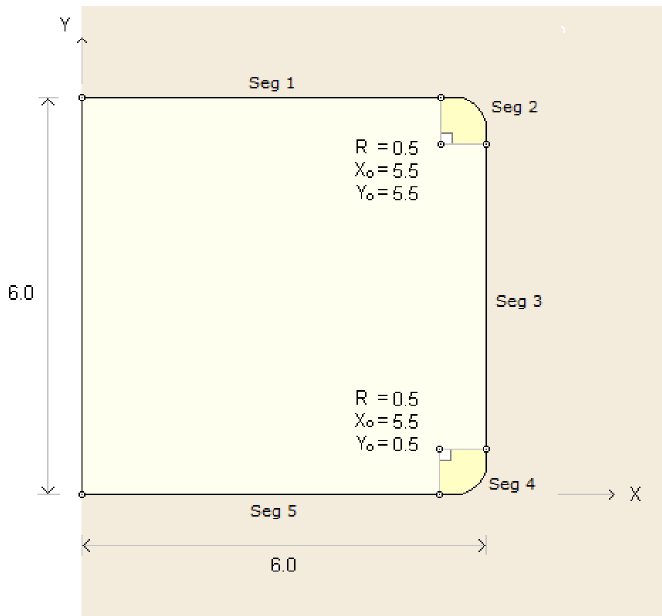
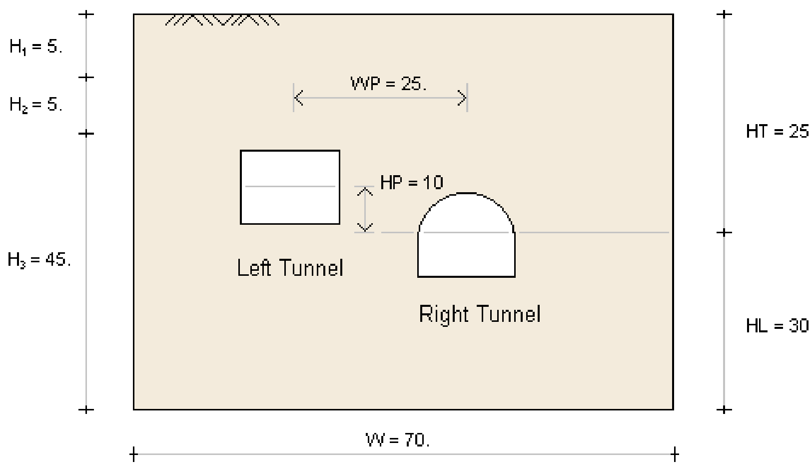


Figure 6.133 Dimensions of left tunnel for example 8

MODEL = 4 Two Tunnels [Unsymmetric Section]



DELTAX = 2.0, DELTAY = 3.0, NDYMAX = 40

Right tunnel dimensions shown in Figure 6.132
Left tunnel dimensions shown in Figure 6.133

Figure 6.134 Schematic tunnel section for Example 8

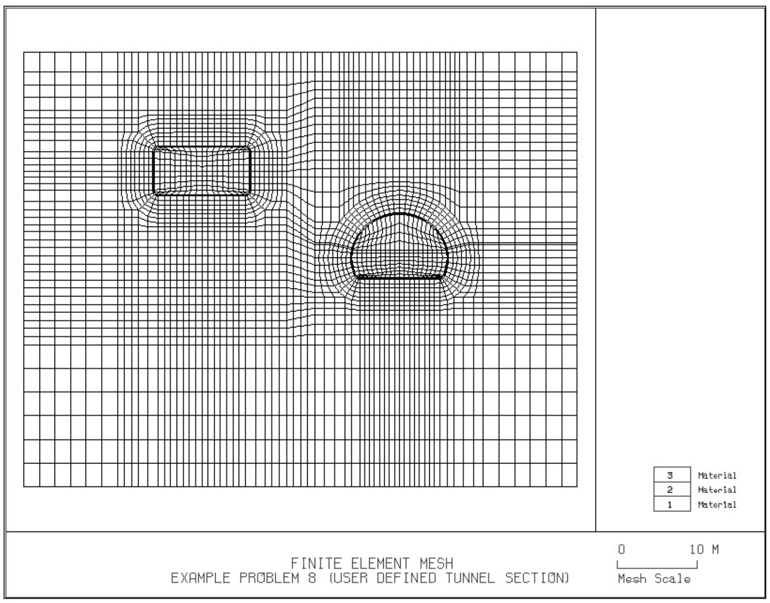

3 Material
2 Material
1 Material
0 10 M
Mesh Scale
FINITE ELEMENT MESH
EXAMPLE PROBLEM 8 (USER DEFINED TUNNEL SECTION)

Figure 6.135

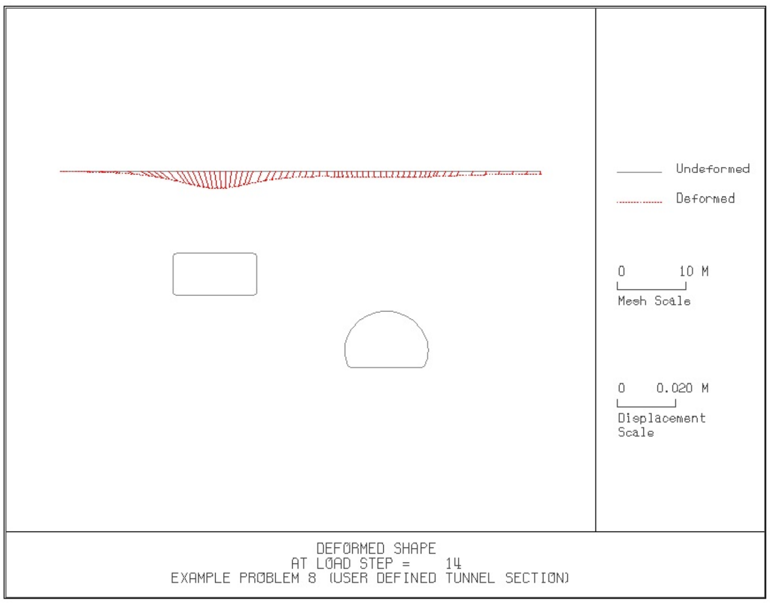

Undeformed
Deformed
0 10 M
Mesh Scale
0 0.020 M
Displacement Scale
DEFORMED SHAPE
AT LOAD STEP = 14
EXAMPLE PROBLEM 8 (USER DEFINED TUNNEL SECTION)

Figure 6.136

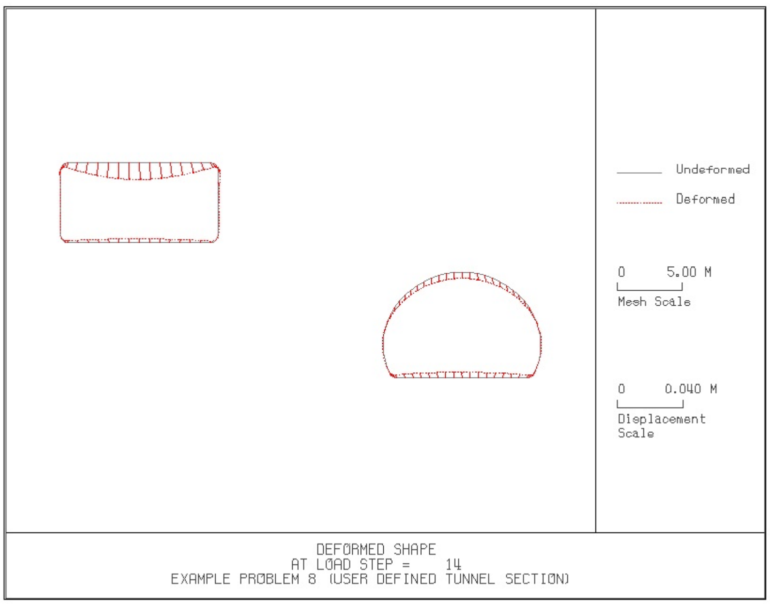

Undeformed
Deformed
0 5.00 M
Mesh Scale
0 0.040 M
Displacement
Scale
DEFORMED SHAPE
AT LOAD STEP = 14
EXAMPLE PROBLEM 8 (USER DEFINED TUNNEL SECTION)

Figure 6.137

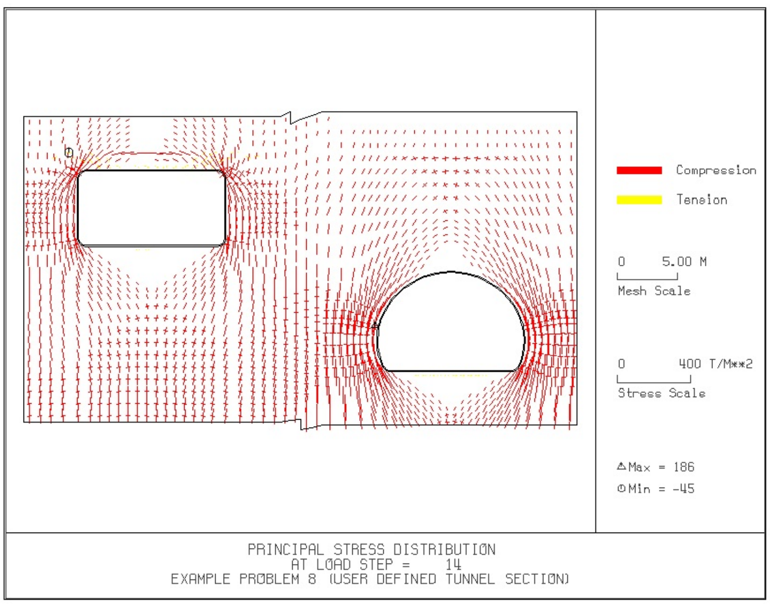

Compression
Tension
0 5.00 M
Mesh Scale
0 400 T/M**2
Stress Scale
Max = 186
Min = -45
PRINCIPAL STRESS DISTRIBUTION
AT LOAD STEP = 14
EXAMPLE PROBLEM 8 (USER DEFINED TUNNEL SECTION)

Figure 6.138

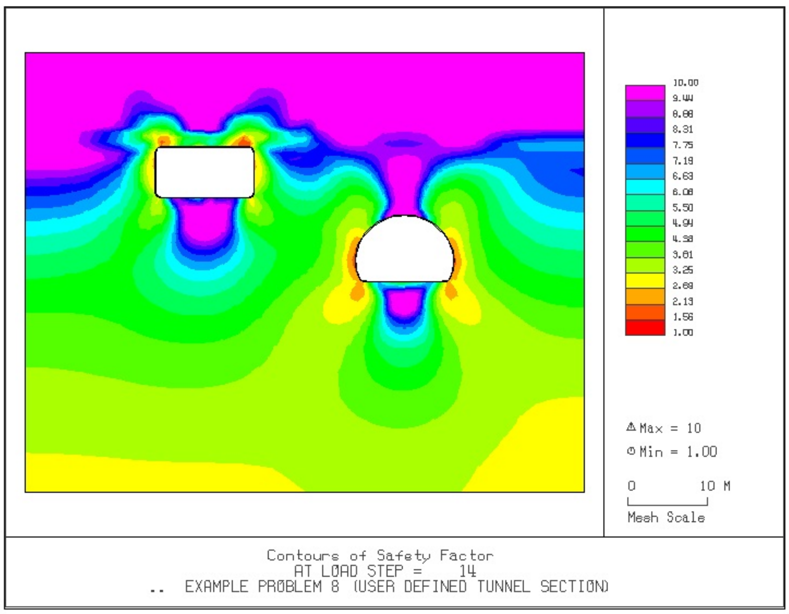

10.00
9.44
8.88
8.31
7.75
7.19
6.63
6.06
5.50
4.94
4.38
3.81
3.25
2.69
2.13
1.56
1.00
Max = 10
Min = 1.00
0 10 M
Mesh Scale
Contours of Safety Factor
AT LOAD STEP = 14
.. EXAMPLE PROBLEM 8 (USER DEFINED TUNNEL SECTION)

Figure 6.139

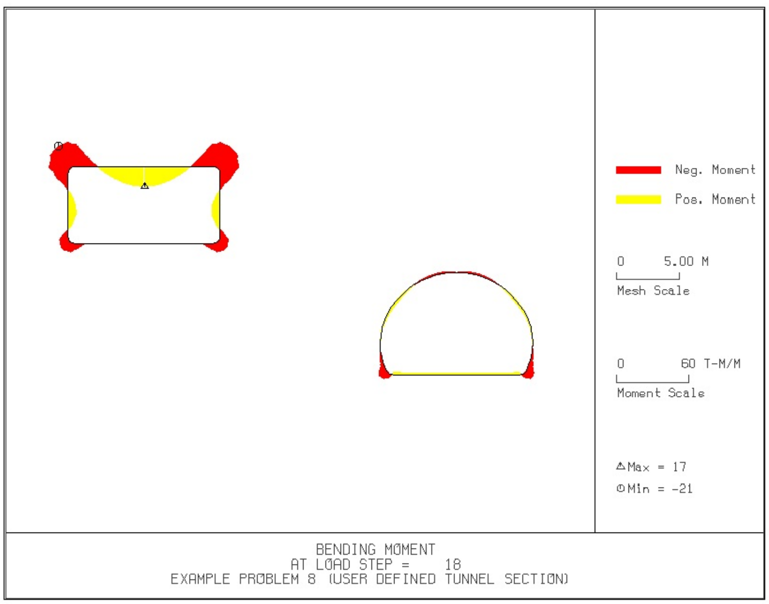

Neg. Moment
Pos. Moment
0 5.00 M
Mesh Scale
0 60 T-M/M
Moment Scale
Max = 17
Min = -21
BENDING MOMENT
AT LOAD STEP = 18
EXAMPLE PROBLEM 8 (USER DEFINED TUNNEL SECTION)

Figure 6.140

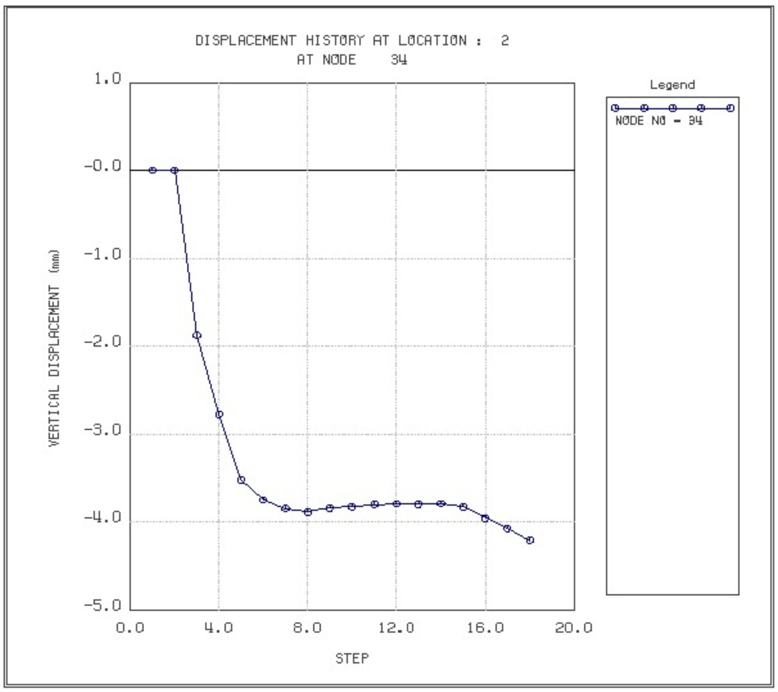

DISPLACEMENT HISTORY AT LOCATION : 2
AT NODE 34
Legend
NODE NO = 34
VERTICAL DISPLACEMENT (mm)
1.0
-0.0
-1.0
-2.0
-3.0
-4.0
-5.0
0.0
4.0
8.0
12.0
16.0
20.0
STEP

Figure 6.141

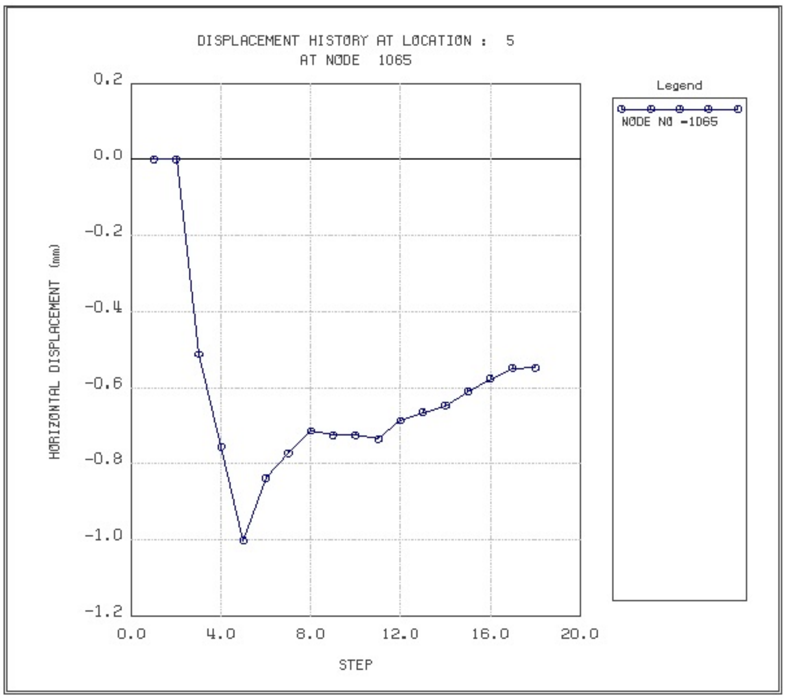

DISPLACEMENT HISTORY AT LOCATION : 5
AT NODE 1065
Legend
NODE NO =1065
HORIZONTAL DISPLACEMENT (mm)
STEP
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
0.0
4.0
8.0
12.0
16.0
20.0

Figure 6.142

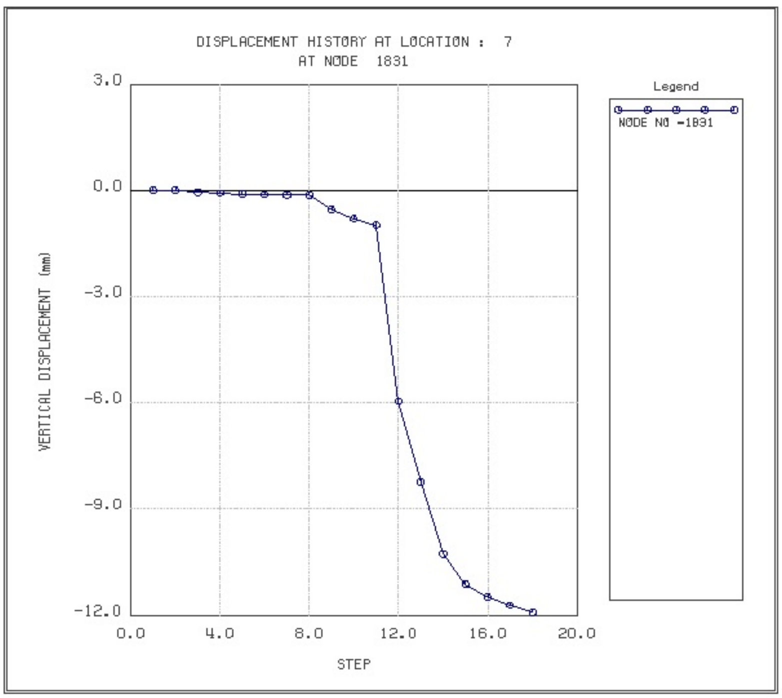

DISPLACEMENT HISTORY AT LOCATION : 7
AT NODE 1831
Legend
NODE NO =1831
3.0
0.0
-3.0
-6.0
-9.0
-12.0
VERTICAL DISPLACEMENT (mm)
0.0
4.0
8.0
12.0
16.0
20.0
STEP

Figure 6.143

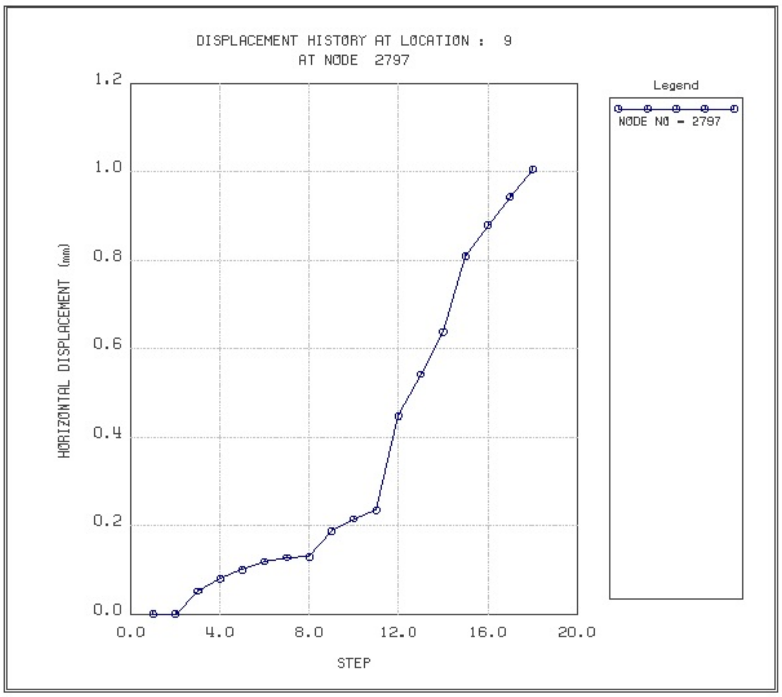

DISPLACEMENT HISTORY AT LOCATION : 9
AT NODE 2797
HORIZONTAL DISPLACEMENT (mm)
STEP
Legend
NODE NO = 2797
0.0
0.2
0.4
0.6
0.8
1.0
1.2
4.0
8.0
12.0
16.0
20.0

Figure 6.144

6.9 Example 9

Example 9 is the same as Example 8 in Section 6.8 except that the excavation and liner installation for the left box tunnel are assumed to occur instantaneously and simultaneously so that the liner interacts with the surrounding medium immediately after excavation and resists full tunnel displacement. Shotcrete and rock bolts are not included for the left box tunnel. Lining analysis after tunnel excavation is not performed for this example problem.

Table 6.31 lists the input data for Example 9. Text output file STEP.LST in Table 6.32 shows steps where major excavations and liner installation for the box tunnel take place. Finite element mesh generated by TUNA Plus is shown in Figure 6.145.

Selected graphical outputs from PLOT-2D at the completion of tunnel excavation are shown in Figures 6.146 to 6.153.

Selected displacement history graphical outputs from PLOT-XY are shown in Figures 6.154 to 6.157.

Table 6.31 Listing of input file EX9.DAT

```
*
* GENERAL INFORMATION
*
* CARD 1.1
* TITLE
  EXAMPLE PROBLEM 9 (USER DEFINED TUNNEL SECTION)
*
* CARD 1.2
* IUNIT
  3
*
* CARD 1.3
* MODEL  IGEN  IEXMESH  ILNCOUPL  IEXORDER  IRBP
  4      0     0        0         1         0
*
* CARD 1.4
* IEZ1   IEZ2  IEZ3  IEZ4  IEZ5  IEZ6  IEZ7  IEZ8
  1      2     1     2     3     3     4     4
*
* TUNNEL ANALYSIS BOUNDARY
*
* CARD 2.1
* HT    HL   W     WP    HP    DELTAX  DELTAY  NDYMAX
  25.0  30.  70.   25.   10.   2.0     3.0     40
*
* SOIL / ROCK LAYER INFORMATION
*
* CARD 3.1
* NLAYER
  3
* CARD 3.2
* LAYERNO   H     GAMA  RKO  E       V    PHI   C    T
  1         5.0   1.9   0.43 5000.   0.30 35.   30.  30.
  2         5.0   2.4   0.33 20000.  0.25 40.   70.  40.
  3         45.0  2.55  0.25 200000. 0.20 45.   100. 50.
*
* ADDITIONAL TOP SOIL / ROCK LAYER
*
* CARD 3.3.1
* NATLAYER
  0
*
* USER SPECIFIED SOIL / ROCK LAYER
*
* CARD 3.4.1
* NUSLAYER
  0
*
* USER SPECIFIED DISTRIBUTED SURFACE LOAD
*
* CARD 3.5.1
* NUSXPD
  0
*
```

```
*
* SHOTCRETE PROPERTIES
*
* CARD 3.6
* E         V      PHI    C      T     GAMA
  1.5E+06   0.2    30.    500.   100.  2.4
*
* LINING PROPERTIES
*
* CARD 3.7
* E         V      PHI    C      T     GAMA  ER        VR
  2.1E+06   0.2    30.    500.   300.  0.0   2.1E+07   0.
*
* ROCK BOLT PROPERTIES
*
* CARD 3.8
* A         WL         E          STRSI     SIGMAy     Ef
  0.000491  0.00383    2.1E+07    0.0       2.3E+04    1.0
*
* INTERFACE PROPERTIES BETWEEN SHOTCRETE AND LINING
*
* CARD 3.9
* NM        E       G        t
  2         200000. 2.0      0.001
* C         PHI
  0.001     5.0
* E1        E2      E3       E4      S1      S2    S3      S4
 -1.0       0.0     1.0E-7   1.0    -200000. 0.0   2.E-02  2.E-02
*
* TUNNEL DIMENSION [ RIGHT TUNNEL ]
*
* CARD 4.0
* ISTYPE  GR    GA
  3       1.0   0.5
*
* CARD 4.1-1
* NSEG   SHOR   STR   SBR
  4      8.0    6.0   0.0
* SEGMENT 1 (CIRCULAR ARS)
* R      XO     YO    TB     TE    TL      ASI    ASO
  6.1683 0.0    1.85  90.    30.   0.30    0.0020 0.0020
* SEGMENT 2 (CIRCULAR ARS)
* R      XO     YO    TB     TE    TL      ASI    ASO
  4.9413 1.062  2.463 30.   -26.0  0.32    0.0022 0.0022
* SEGMENT 3 (CIRCULAR ARS)
* R      XO     YO    TB     TE    TL      ASI    ASO
  0.51   5.045  0.521 -26.0 -90.   0.34    0.0024 0.0024
* SEGMENT 4 (STRAIGHT LINE)
* 0      XB     YB    XE     YE    TL      ASI    ASO
  0      5.045  0.0   0.0    0.0   0.40    0.0030 0.0030
* CARD 4.2
* INVSHOT  TS      INVLN     TL      DI     ASI    DO    ASO
  1        0.20    1         0.4     0.05   0.0030 0.05  0.0030
* CARD 4.3
* NUMRB    LRB     LSPACING  TSPACING  NSRB
  11       3.0     1.35      1.2        2
*
```

```
*
* TUNNEL DIMENSION [ LEFT TUNNEL ]
*
* CARD 4.0
* ISTYPE  GR    GA
  3       1.0   0.5
* CARD 4.1-1
* NSEG   SHOR   STR   SBR
  5      0.0    0.0   0.0
* SEGMENT 1 (STRAIGHT LINE)
* 0      XB     YB    XE     YE    TL      ASI     ASO
  0      0.0    6.0   5.5    6.0   0.40    0.0066  0.0044
* SEGMENT 2 (CIRCULAR ARC)
* R      XO     YO    TB     TE    TL      ASI     ASO
  0.5    5.5    5.5   90.    0.0   0.40    0.0066  0.0066
* SEGMENT 3 (STRAIGHT LINE)
* 0      XB     YB    XE     YE    TL      ASI     ASO
  0      6.0    5.5   6.0    0.5   0.32    0.0024  0.0024
* SEGMENT 4 (CIRCULAR ARS)
* R      XO     YO    TB     TE    TL      ASI     ASO
  0.5    5.5    0.5   0.0   -90.   0.36    0.0026  0.0026
* SEGMENT 5 (STRAIGHT LINE)
* 0      XB     YB    XE     YE    TL      ASI     ASO
  0      5.5    0.0   0.0    0.0   0.38    0.0028  0.0028
* CARD 4.2
* INVSHOT  TS      INVLN     TL      DI     ASI     DO    ASO
 -1        0.20    0         0.48    0.05   0.0028  0.05  0.0028
* CARD 4.3
* NUMRB    LRB     LSPACING  TSPACING  NSRB
  0        3.0     1.35      1.6       2
*
* ---------------------------------------------------------------
*
* EXCAVATION STRESS RELEASE AND SHOTCRETE MODULUS CHANGE
*
* CARD 5.1
* PSR      PASR    RESH
  50.      25.     0.33
*
* EXTERNAL LOADS FOR LINING ANALYSIS
*
* CARD 6.1
* LDTYPE
  0
*
* WATER PRESSURE
*
* CARD 6.2
* LGWINV   NWPSTEP DGW     GAMAW
  0        3       10.     1.0
*
```

```
*
* LOOSENING LOAD
*
* CARD 6.3.1
* LSDADD   NLDSTEP  HPRES   VPRES
  0        0        0.00    0.0
*
* PRIMARY SUPPORT DEGRADATION
*
* CARD 6.4
* LPSDEG   REDH
  0        1.0
*
* END OF DATA
```

Table 6.32 Listing of text output file STEP.LST

```
STEP NO    DESCRIPTIONS

     9
          Installation of Lining in Left  Tunnel
     5
          Excavation of Upper Right Core in Right Tunnel
          Excavation of Upper Left  Core in Right Tunnel
     8
          Excavation of Lower Right Core in Right Tunnel
          Excavation of Lower Left  Core in Right Tunnel
    11
          Excavation of Upper Right Core in Left  Tunnel
          Excavation of Lower Right Core in Left  Tunnel
    14
          Excavation of Upper Left  Core in Left  Tunnel
          Excavation of Lower Left  Core in Left  Tunnel
```

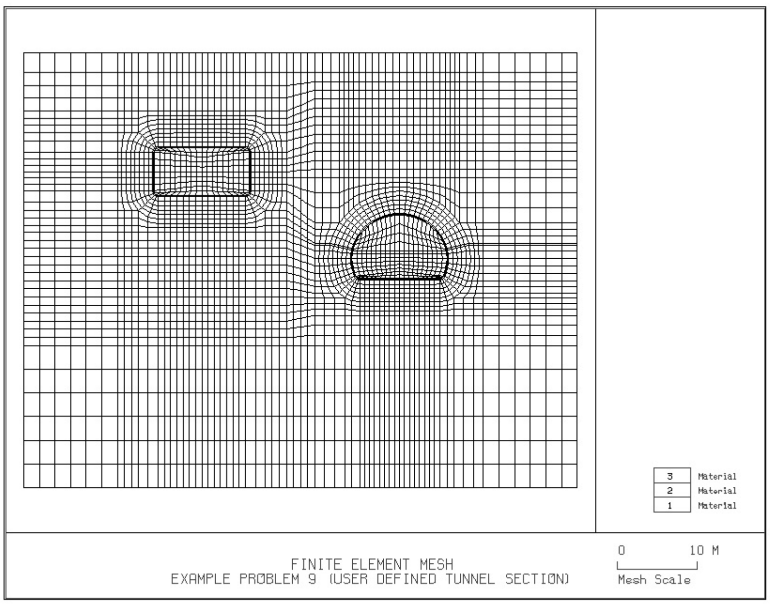

3 Material
2 Material
1 Material
FINITE ELEMENT MESH
EXAMPLE PROBLEM 9 (USER DEFINED TUNNEL SECTION)
0 10 M
Mesh Scale

Figure 6.145

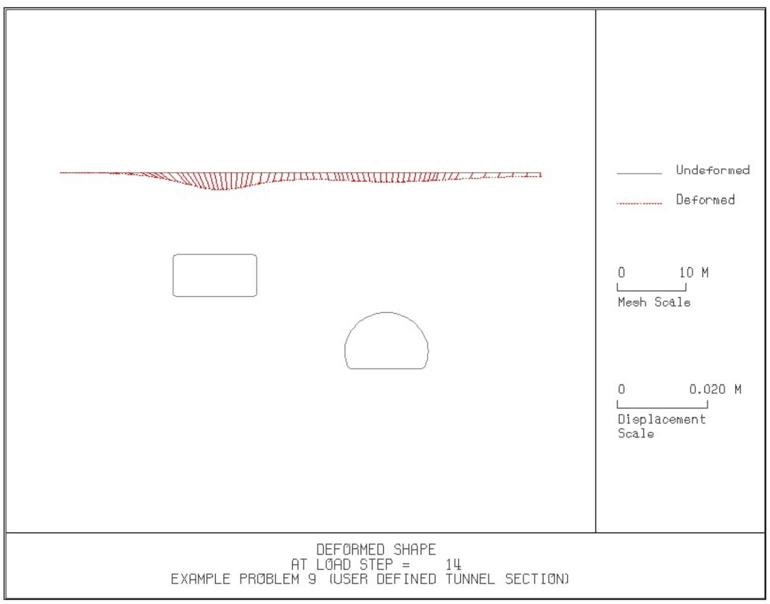

Undeformed
Deformed
0 10 M
Mesh Scale
0 0.020 M
Displacement Scale
DEFORMED SHAPE
AT LOAD STEP = 14
EXAMPLE PROBLEM 9 (USER DEFINED TUNNEL SECTION)

Figure 6.146

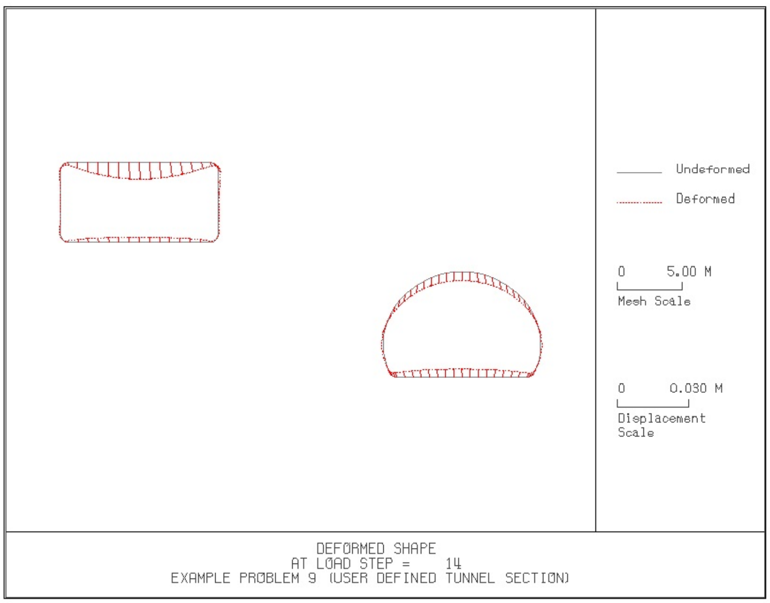

Undeformed
Deformed
0 5.00 M
Mesh Scale
0 0.030 M
Displacement
Scale
DEFORMED SHAPE
AT LOAD STEP = 14
EXAMPLE PROBLEM 9 (USER DEFINED TUNNEL SECTION)

Figure 6.147

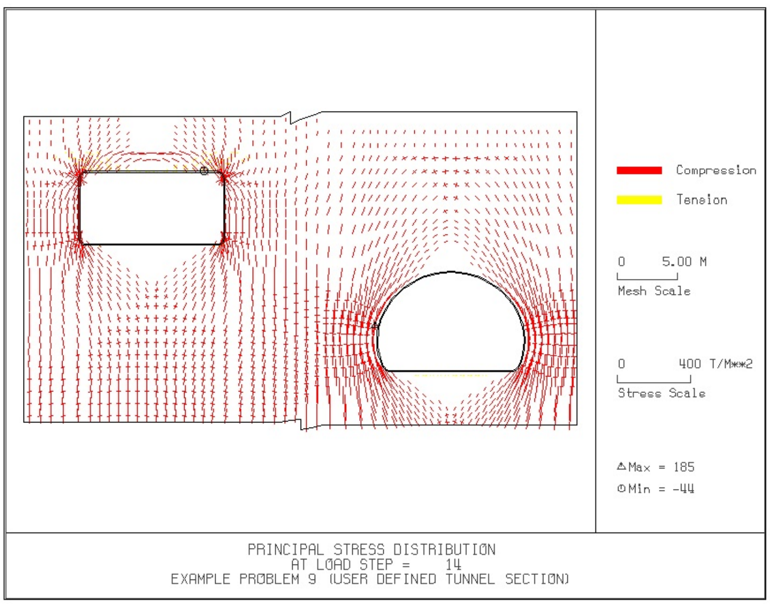

Compression
Tension
0 5.00 M
Mesh Scale
0 400 T/M**2
Stress Scale
Max = 185
Min = -44
PRINCIPAL STRESS DISTRIBUTION
AT LOAD STEP = 14
EXAMPLE PROBLEM 9 (USER DEFINED TUNNEL SECTION)

Figure 6.148

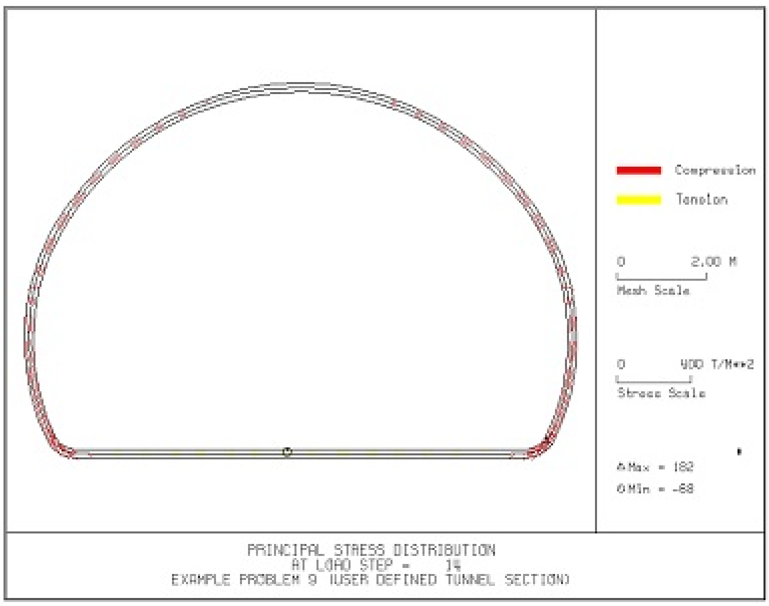

Compression
Tension
0 2.00 M
Mesh Scale
0 400 T/M**2
Stress Scale
Max = 182
Min = -68
PRINCIPAL STRESS DISTRIBUTION
AT LOAD STEP = 14
EXAMPLE PROBLEM 9 (USER DEFINED TUNNEL SECTION)

Figure 6.149

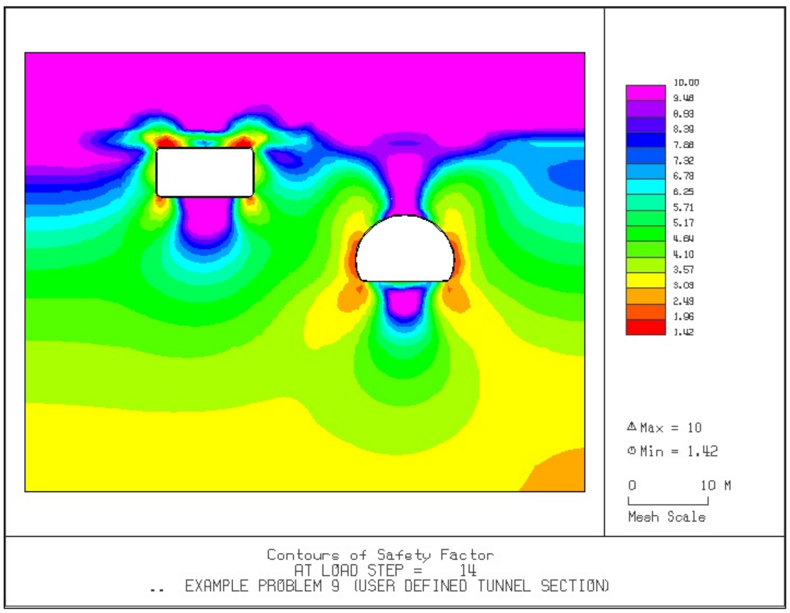

10.00
9.46
8.93
8.39
7.86
7.32
6.78
6.25
5.71
5.17
4.64
4.10
3.57
3.03
2.49
1.96
1.42
Max = 10
Min = 1.42
0 10 M
Mesh Scale
Contours of Safety Factor
AT LOAD STEP = 14
.. EXAMPLE PROBLEM 9 (USER DEFINED TUNNEL SECTION)

Figure 6.150

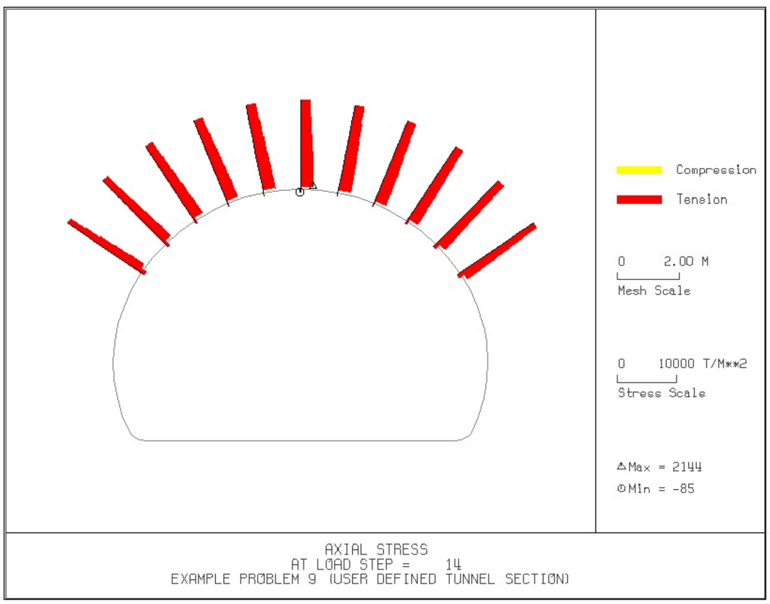

Compression
Tension
0 2.00 M
Mesh Scale
0 10000 T/M**2
Stress Scale
Max = 2144
Min = -85
AXIAL STRESS
AT LOAD STEP = 14
EXAMPLE PROBLEM 9 (USER DEFINED TUNNEL SECTION)

Figure 6.151

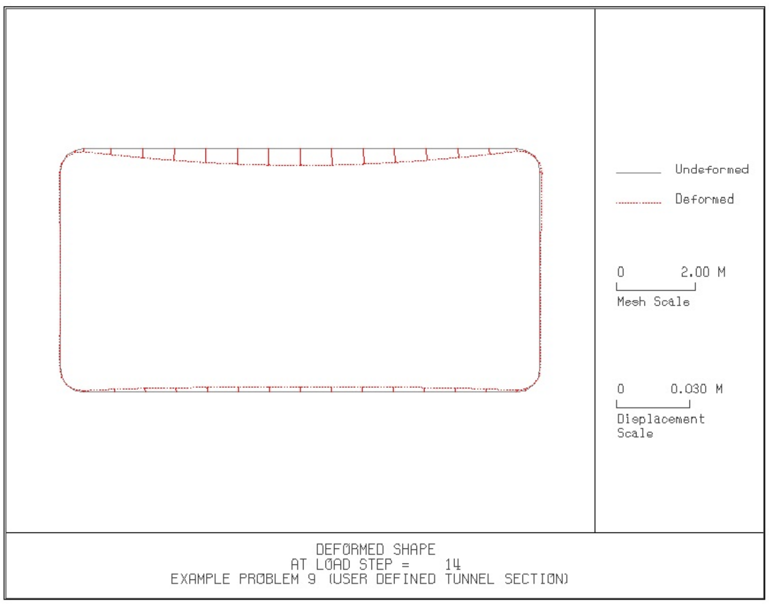

Undeformed
Deformed
0 2.00 M
Mesh Scale
0 0.030 M
Displacement
Scale
DEFORMED SHAPE
AT LOAD STEP = 14
EXAMPLE PROBLEM 9 (USER DEFINED TUNNEL SECTION)

Figure 6.152

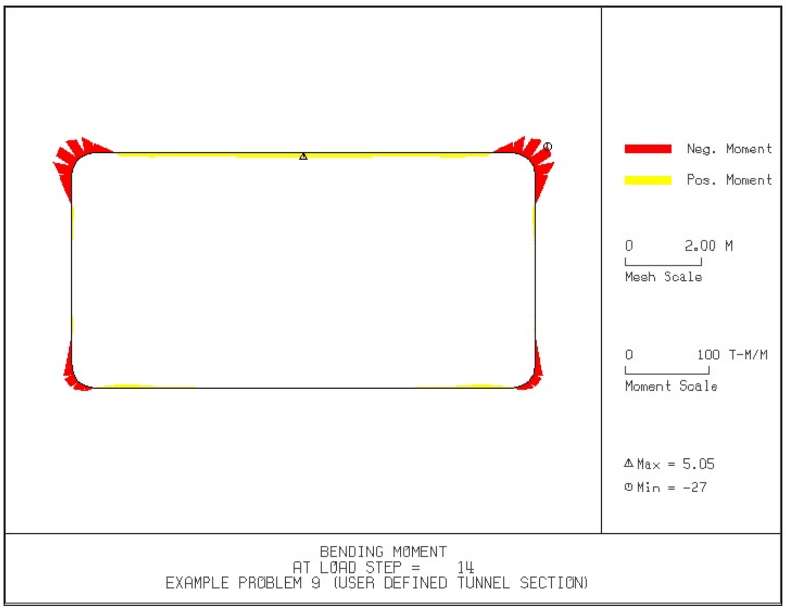

Neg. Moment
Pos. Moment
0 2.00 M
Mesh Scale
0 100 T-M/M
Moment Scale
Max = 5.05
Min = -27
BENDING MOMENT
AT LOAD STEP = 14
EXAMPLE PROBLEM 9 (USER DEFINED TUNNEL SECTION)

Figure 6.153

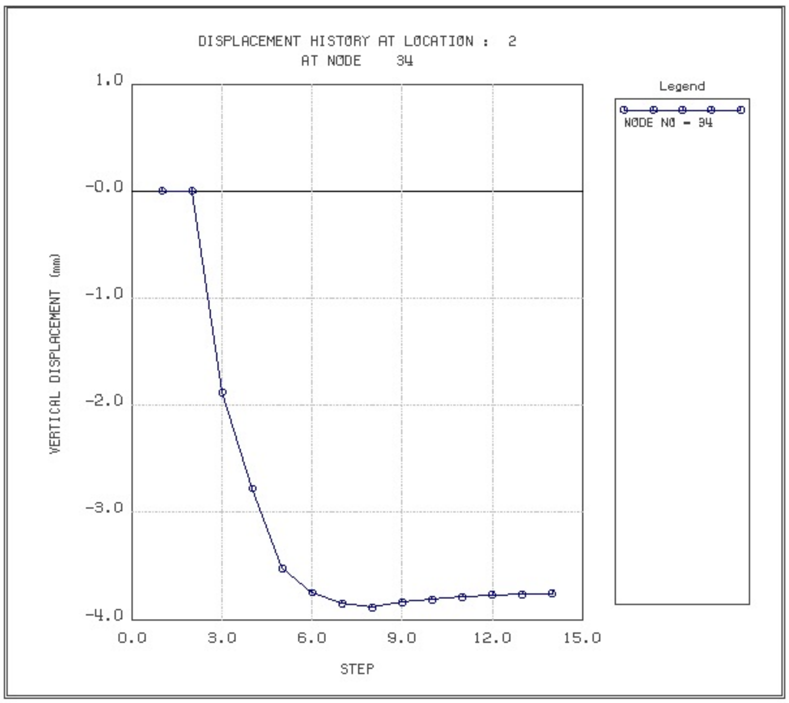

DISPLACEMENT HISTORY AT LOCATION : 2
AT NODE 34
Legend
NODE NO = 34
VERTICAL DISPLACEMENT (mm)
1.0
-0.0
-1.0
-2.0
-3.0
-4.0
0.0
3.0
6.0
9.0
12.0
15.0
STEP

Figure 6.154

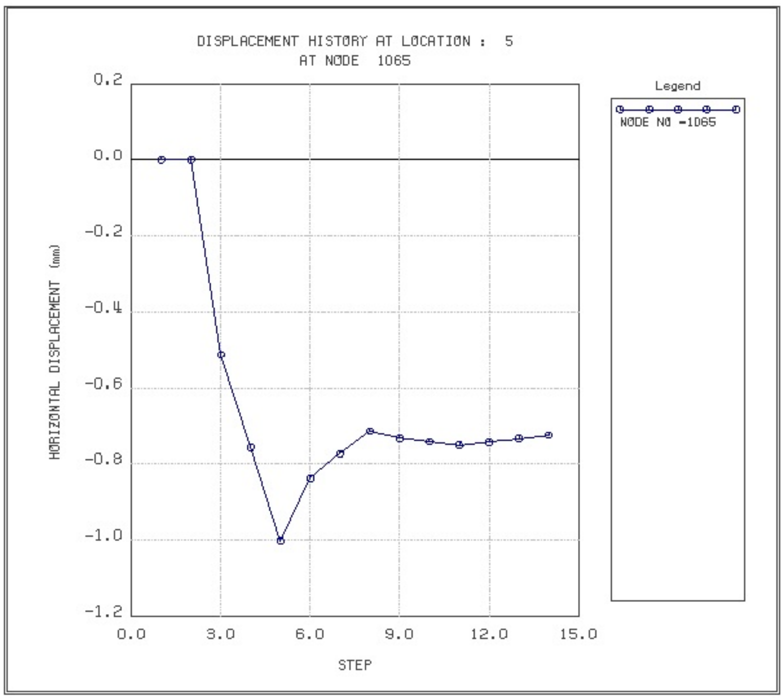

DISPLACEMENT HISTORY AT LOCATION : 5
AT NODE 1065
HORIZONTAL DISPLACEMENT (mm)
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
0.0
3.0
6.0
9.0
12.0
15.0
STEP
Legend
NODE NO =1065

Figure 6.155

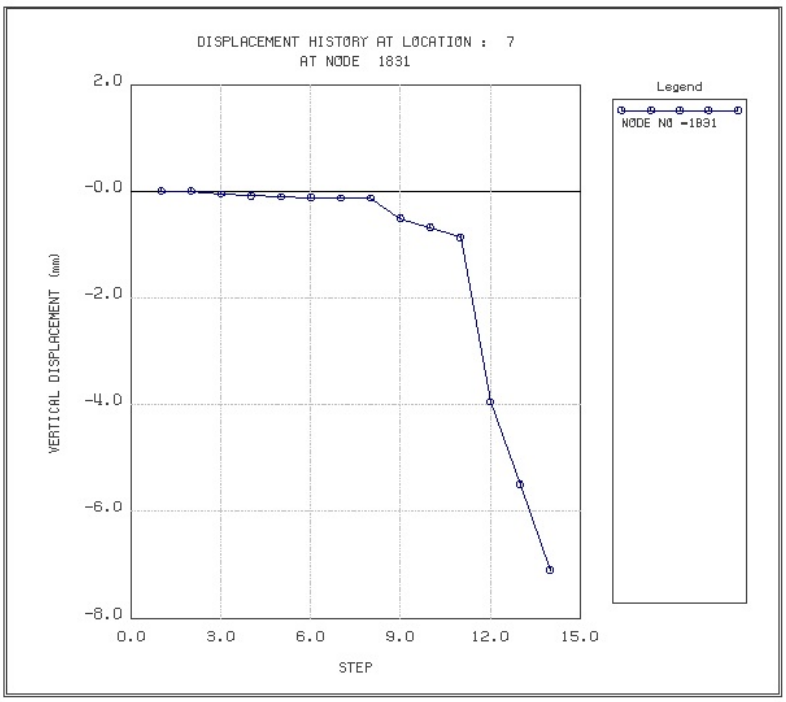

DISPLACEMENT HISTORY AT LOCATION : 7
AT NODE 1831
VERTICAL DISPLACEMENT (mm)
STEP
Legend
NODE NO =1831
2.0
-0.0
-2.0
-4.0
-6.0
-8.0
0.0
3.0
6.0
9.0
12.0
15.0

Figure 6.156

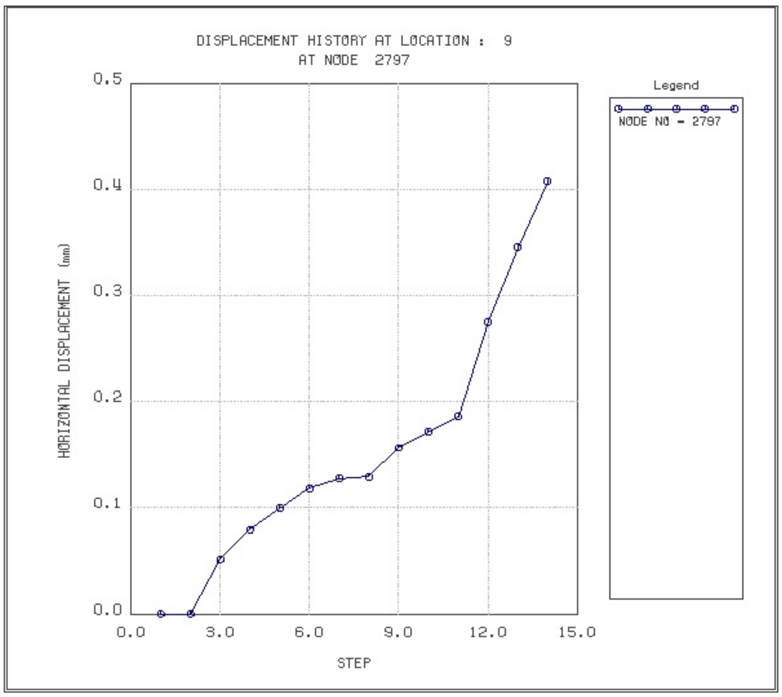

DISPLACEMENT HISTORY AT LOCATION : 9
AT NODE 2797
HORIZONTAL DISPLACEMENT (mm)
0.0
0.1
0.2
0.3
0.4
0.5
0.0
3.0
6.0
9.0
12.0
15.0
STEP
Legend
NODE NO - 2797

Figure 6.157