

T U N A Plus

Tunnel Analysis Program

Version 7.01

COMTEC RESEARCH

Copyright @2019 by COMTEC RESEARCH

All right reserved. No part of this manual may be reproduced in any form or by any means without a written permission of COMTEC RESEARCH.

Printed in the United States of America.

LICENSE AGREEMENT

LICENSE: COMTEC RESEARCH grants to Licensee a non-exclusive, non-transferable right to use the enclosed Computer Program only on a single computer. The use of the Computer Program is limited to the Licensee's own project. Licensee may not use the Computer Program to serve other engineering companies or individuals without prior written permission of COMTEC RESEARCH. Licensee may not distribute copies of the Computer Program or Documentation to others. Licensee may not rent, lease, or network the Computer Program without prior written permission of COMTEC RESEARCH.

TERM: The License is effective as long as the Licensee complies with the terms of this Agreement. The License will be terminated if the Licensee fails to comply with any term or condition of the Agreement. Upon such termination, the Licensee must return all copies of the Computer Program, Software Security Activator and Documentation to COMTEC RESEARCH within seven days.

COPYRIGHT: The Licensed Computer Program and its Documentation are copyrighted. Licensee agrees to include the appropriate copyright notice on all copies and partial copies.

USER SUPPORT: COMTEC RESEARCH will provide the Software Support for the Registered Users for a period of 90 days from the date of purchase. User support is limited to the investigation of problems associated with the correct operation of the Licensed Computer Program. The Licensee must return the Registration Card in order to register the Licensed Computer Program.

DISCLAIMER: COMTEC RESEARCH has spent considerable time and efforts in checking the enclosed Computer Program. However, no warranty is made with respect to the accuracy or reliability of the Computer Program. In no event will COMTEC RESEARCH be liable for incidental or consequential damages arising from the use of the Computer Program.

UPDATE POLICY: Update programs will be available to the Registered Licensee for a nominal fee. The Licensee must return all the Original Distribution Diskettes and Software Security Activator to receive the update programs.

GENERAL: The State of California Law and the U. S. Copyright Law will govern the validity of the Agreement. This Agreement may be modified only by a written consent between the parties. COMTEC RESEARCH, 12492 Greene Ave., Los Angeles, CA 90066, U.S.A

Contents

1. Introduction

1.1 Overview	1-1
1.2 Features	1-1
1.3 Assumptions.	1-2

2. Installing TUNA Plus

2.1 Minimum System Requirements.	2-1
2.2 Installation Procedure.	2-1

3. Running Programs

3.1 Introduction.	3-1
3.2 RUN Menu	3-4
3.3 PLOT Menu	3-6
3.4 SETUP Menu	3-7
3.4.1 General Setup	3-7
3.4.2 PLOT-XY Setup	3-9
3.4.3 PLOT-2D Setup	3-11
3.5 Manual Procedure to Run TUNA Plus	3-12
3.6 Debugging TUNA Plus Main-Processing Program	3-13

4. Description of Input Data 4-1

5. Description of Output Data. 5-1

6. Example Problems. 6-1

6.1 Example 1.	6-3
6.2 Example 2.	6-72
6.3 Example 3.	6-109
6.4 Example 4.	6-144
6.5 Example 5	6-179
6.6 Example 6	6-191
6.7 Example 7	6-203
6.8 Example 8	6-214
6.9 Example 9	6-240

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 degradation 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

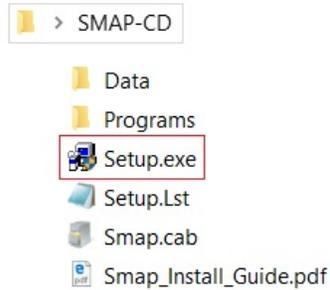
- ✓ Windows 32 bit operating system
- ✓ Intel Pentium 4 or AMD processors
- ✓ 4 GB Ram with 30 GB free space in Drive C
- ✓ SVGA monitor

2.2 Installation Procedure

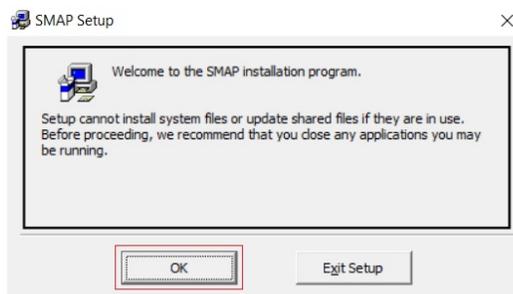
1. Uninstall if there are pre-existing SMAP programs.
To uninstall SMAP programs, remove following program using Add/Remove in Control Panel:
SMAP
Delete following files if they are existing:
C:\Program Files\Smap
C:\Windows\Setup1.exe
Rename or delete following folders if they are existing:
C:\SMAP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

2-2 Installing TUNA Plus

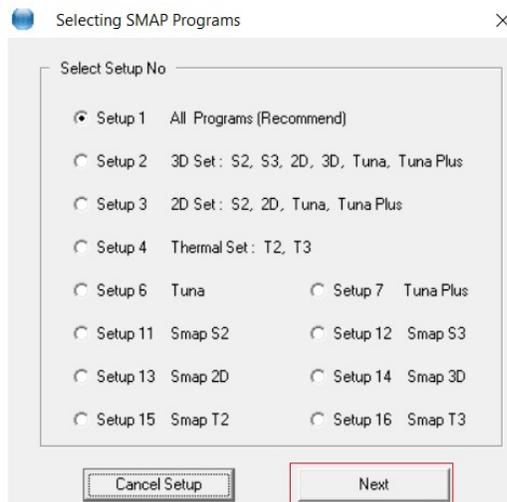
4. Double-click **Setup.exe**



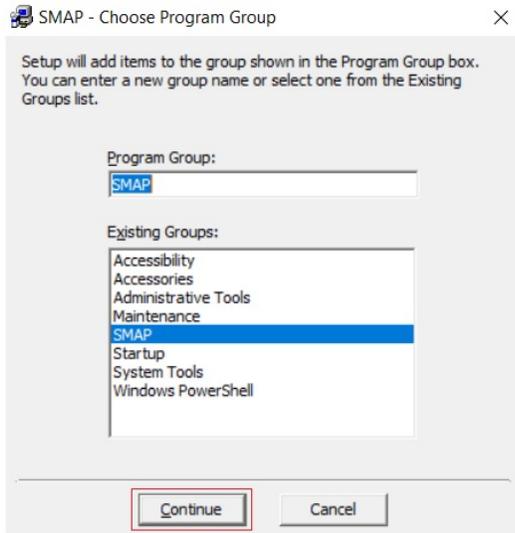
5. Click **OK**



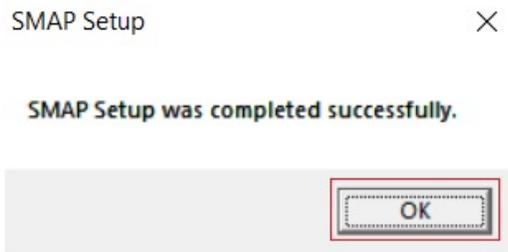
6. Click **Next**
It will take few minutes.
Wait until next step.



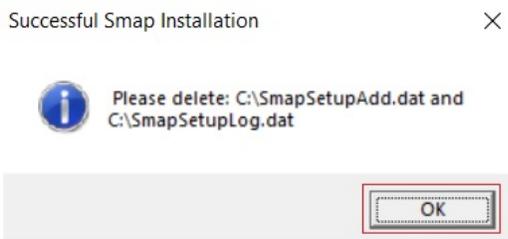
7. Click **Continue**



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

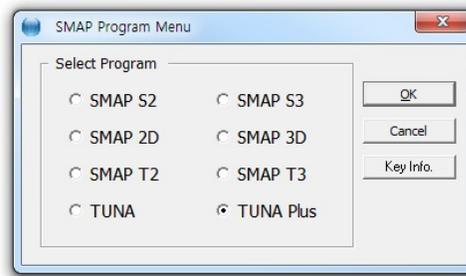
Running Programs

3.1 Introduction

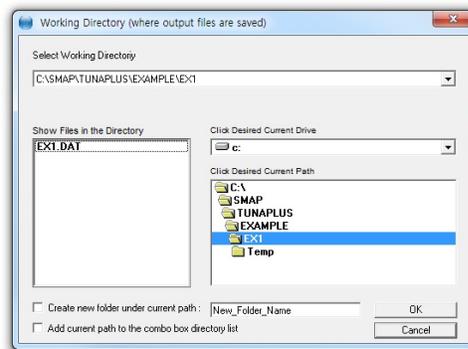
Once you prepared the input file as described in Section 4, running **TUNA Plus** program is straightforward since finite element meshes and graphical instruction files are automatically generated.

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.

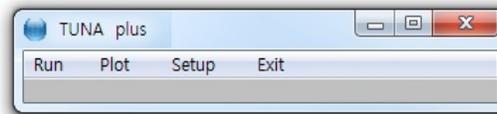


3. Next, you need to select **Working Directory**. Working Directory should be the existing directory where all the output files are saved. It is a good idea to have all your input files for the current project in this Working Directory. Click the disk drive, double-click the directory, and then **OK**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

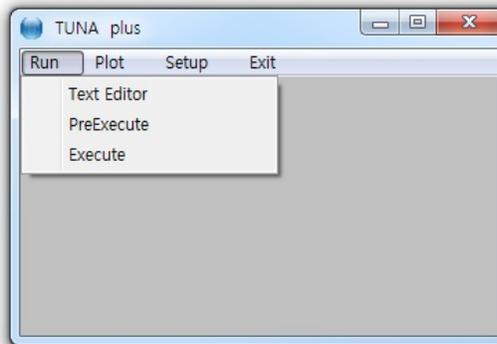


TUNA Plus Menu

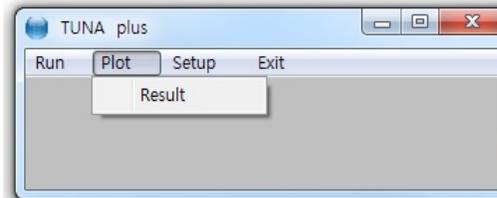
TUNA Plus provides the following Main Menu; Run, Plot, Setup and Exit.



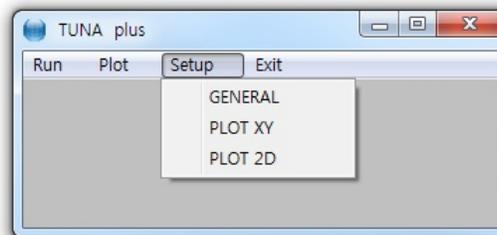
RUN executes main processing program and has following Sub Menus; Text Editor, Pre Execute and Execute.



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.

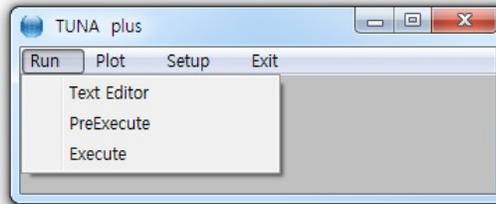


EXIT is used to end TUNA Plus.

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

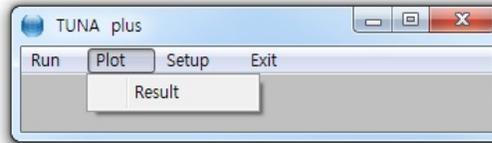
TUNA Plus Post-processing programs can generate the following graphical output:

- 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.

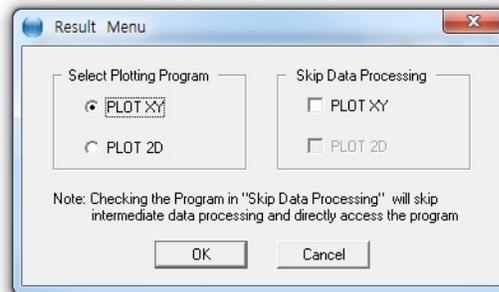
3.3 PLOT Menu

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.

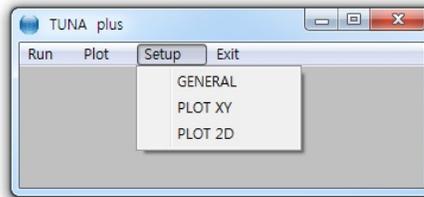
Note: When you first plot results, do not check the check box in Skip Data Processing. When you replot results, however, you can check the check box to skip intermediate data processing. This will save time and keep modified output data.

3.4 SETUP Menu

You need to run SETUP Menu

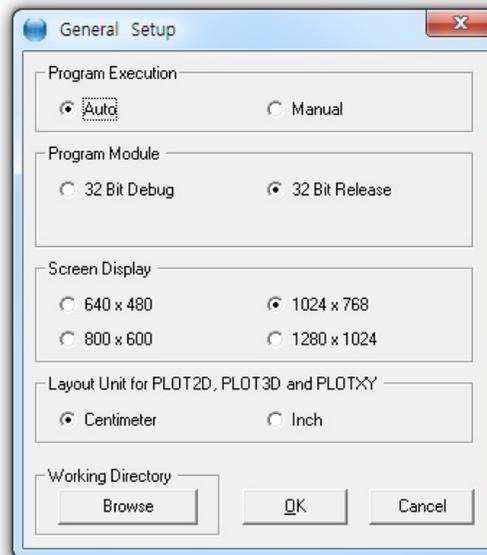
- To specify TUNA Plus main-processing program module.
- To adjust scales of graphical outputs from PLOT-XY and PLOT-2D.

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.

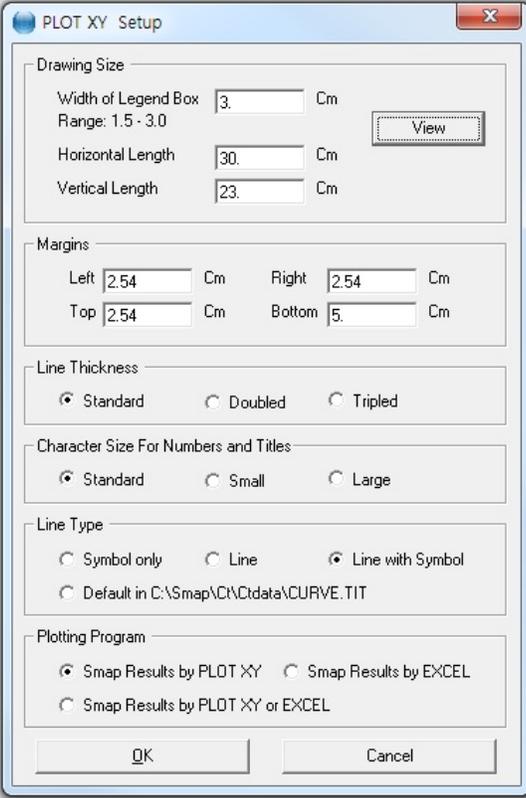
Screen Display has four options; 640x480, 800x600, 1024x768, and 1280x1024. This will affect the size of child window in PLOT-XY and PLOT-2D.

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.



The screenshot shows the 'PLOT XY Setup' dialog box with the following settings:

- Drawing Size:**
 - Width of Legend Box: 3.00 Cm (Range: 1.5 - 3.0)
 - Horizontal Length: 30.00 Cm
 - Vertical Length: 23.00 Cm
 - View button
- Margins:**
 - Left: 2.54 Cm
 - Right: 2.54 Cm
 - Top: 2.54 Cm
 - Bottom: 5.00 Cm
- Line Thickness:**
 - Standard
 - Doubled
 - Tripled
- Character Size For Numbers and Titles:**
 - Standard
 - Small
 - Large
- Line Type:**
 - Symbol only
 - Line
 - Line with Symbol
 - Default in C:\Smap\C\ctdata\CURVE.TIT
- Plotting Program:**
 - Smap Results by PLOT XY
 - Smap Results by EXCEL
 - Smap Results by PLOT XY or EXCEL

Buttons: OK, Cancel

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:\Smag\Ct\Ctdata\Curve.tit.

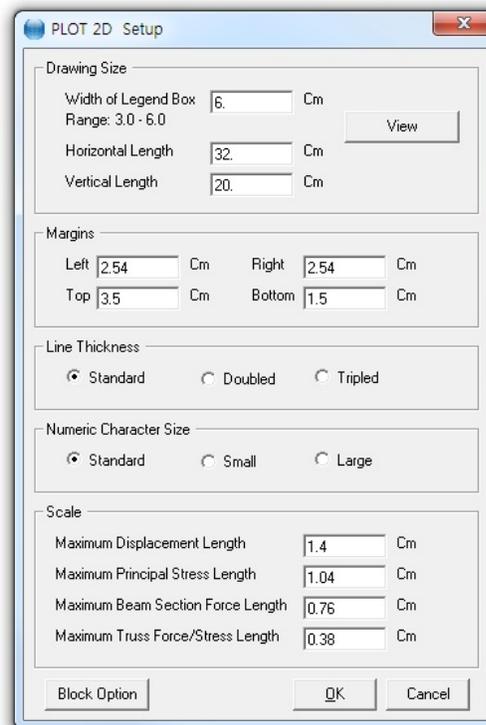
Plotting Program is used to specify default program to plot Smag results. It has three options; PLOT-XY, EXCEL, and PLOT-XY or EXCEL. Last option is to select either PLOT-XY or EXCEL at the time you plot results.

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.



The screenshot shows the 'PLOT 2D Setup' dialog box with the following settings:

- Drawing Size:**
 - Width of Legend Box: 6.00 Cm (Range: 3.0 - 6.0)
 - Horizontal Length: 32.00 Cm
 - Vertical Length: 20.00 Cm
- Margins:**
 - Left: 2.54 Cm
 - Right: 2.54 Cm
 - Top: 3.50 Cm
 - Bottom: 1.50 Cm
- Line Thickness:**
 - Standard
 - Doubled
 - Tripled
- Numeric Character Size:**
 - Standard
 - Small
 - Large
- Scale:**
 - Maximum Displacement Length: 1.40 Cm
 - Maximum Principal Stress Length: 1.04 Cm
 - Maximum Beam Section Force Length: 0.76 Cm
 - Maximum Truss Force/Stress Length: 0.38 Cm

Buttons at the bottom: Block Option, OK, Cancel.

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 "Smmap_S2.dat" in the directory C:\Smmap\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,
              Smmap_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, IEZ₁).

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.

4-2 Description of Input Data

Card Group	Input Data and Definitions																				
1	<p>1.1 TITLE</p> <p style="margin-left: 40px;">TITLE Any title (Max = 60 characters) TITLE will be shown on the graphical output</p> <hr/> <p>1.2 IUNIT</p> <table style="margin-left: 40px; border-collapse: collapse;"> <thead> <tr> <th style="text-align: left;">IUNIT</th> <th style="text-align: left;">Length</th> <th style="text-align: left;">Force</th> <th style="text-align: left;">Pressure</th> <th style="text-align: left;">Unit Weight</th> </tr> </thead> <tbody> <tr> <td>1</td> <td>in</td> <td>lb</td> <td>lb/in²</td> <td>lb/in³</td> </tr> <tr> <td>2</td> <td>cm</td> <td>kg</td> <td>kg/cm²</td> <td>kg/cm³</td> </tr> <tr> <td>3</td> <td>m</td> <td>ton</td> <td>ton/m²</td> <td>ton/m³</td> </tr> </tbody> </table> <hr/> <p>1.3 MODEL, IGEN, IEXMESH, ILNCOUPL, IEXORDER, IRBP</p> <p style="margin-left: 40px;">MODEL = 1 Single tunnel. Half section = 2 Single tunnel. Full section = 3 Two tunnels. Symmetric = 4 Two tunnels. Unsymmetric</p> <p style="margin-left: 40px;">IGEN = 0 Line contour plot = 1 Color-filled contour plot = 2 Smooth color-filled contour plot</p> <p style="margin-left: 40px;">IEXMESH = 0 No user supplied mesh</p> <p style="margin-left: 40px;">ILNCOUPL = 0 Lining coupled with surrounding rock</p> <p style="margin-left: 40px;">IEXORDER = 0 Built-in excavation order = 1 User specified excavation order</p> <p style="margin-left: 40px;">IRBP = 0 Rock bolt placed during soft shotcrete = 1 Rock bolt placed during hard shotcrete = 2 Rock bolt not placed</p>	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
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																	

General Information See Figure 4.1

4-4 Description of Input Data

Card Group	Input Data and Definitions
2	<p>2.1</p> <p> 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 </p> <p>HT Tunnel depth</p> <p>HL Depth from springline to bottom boundary</p> <p>W Horizontal distance from left to right boundary</p> <p>WP Horizontal distance from left tunnel center line to right tunnel center line</p> <p> HP Vertical distance from right tunnel springline to left tunnel springline. When HP is positive, left tunnel springline is above the right tunnel springline. </p> <p>DX Far-field horizontal element length</p> <p>DY Far-field vertical element length</p> <p>NY Maximum number of elements in vertical direction</p>

Tunnel Analysis Boundary See Figure 4.1

Card Group	Input Data and Definitions								
3	<p>3.1</p> <p>NLAYER</p> <p style="padding-left: 40px;">NLAYER Total number of layers. Max = 10</p> <hr/> <p>3.2</p> <table style="border-collapse: collapse; margin-left: 20px;"> <tr> <td style="padding-right: 10px;">NLAYER</td> <td style="border-left: 1px solid black; padding-left: 5px;">LAYERNO, H, GAMA, RKo, E, V,</td> </tr> <tr> <td style="padding-right: 10px;">Cards</td> <td style="border-left: 1px solid black; padding-left: 5px;">PHI [-m], C [s], T [sigc]</td> </tr> <tr> <td></td> <td style="border-left: 1px solid black; padding-left: 5px;">- - - - - -</td> </tr> <tr> <td></td> <td style="border-left: 1px solid black; padding-left: 5px;">- - - - - -</td> </tr> </table> <p>LAYERNO Soil/rock layer number</p> <p>H Thickness of soil/rock layer</p> <p>GAMA Unit weight</p> <p>RKo Coefficient of earth pressure at rest</p> <p>E Young's modulus</p> <p>V Poisson's ratio</p> <p>PHI [-m] Internal friction angle (°)</p> <p>C [s] Cohesion</p> <p>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.</p> <p>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</p>	NLAYER	LAYERNO, H, GAMA, RKo, E, V,	Cards	PHI [-m], C [s], T [sigc]		- - - - - -		- - - - - -
NLAYER	LAYERNO, H, GAMA, RKo, E, V,								
Cards	PHI [-m], C [s], T [sigc]								
	- - - - - -								
	- - - - - -								

Soil / Rock Layer Information See Figure 4.1

4-10 Description of Input Data

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

4-16 Description of Input Data

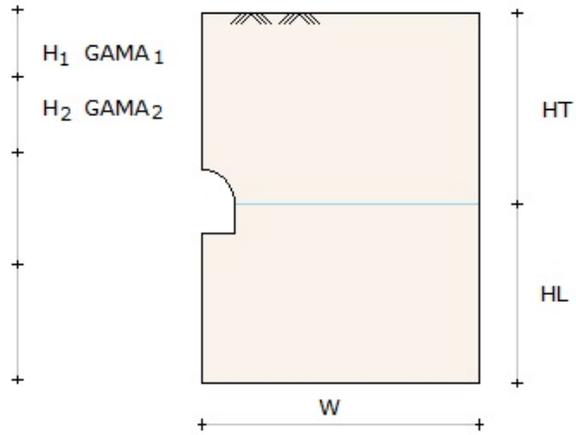
Card Group	Input Data and Definitions
External Loads for Lining Analysis	<p>6.1</p> <p>LDTYPE</p> <p>LDTYPE = 0 Do not perform lining analysis = 1 Perform lining analysis</p> <p>If LDTYPE = 0, rest of cards are ignored</p>
	<p>6.2</p> <p><u>Ground Water Pressure</u></p> <p>LGWINV, NWPSTEP, DGW, GAMAW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

Card Group	Input Data and Definitions		
External Loads for Lining Analysis		<p>6.3.1 <u>Loosening Load</u> LSDADD, NLDSTEP, HPRES, VPRES</p> <p> Additional vertical loosening load LSDADD = 0 Not included = 1 Included</p> <p>NLDSTEP Number of load steps for loosening load. Max=400 If NLDSTEP = 0, loosening load is not considered</p> <p>HPRES Horizontal pressure due to loosening load VPRES Vertical pressure due to loosening load</p>	
		Additional Vertical Loosening Load	<p>6.3.2.1 <u>Additional Vertical Loosening Load for Right Tunnel</u> If LSDADD = 0, skip this card</p> <p>ΔX_{v1r}, ΔX_{v2r}, Q_{v1r}, Q_{v0r}, Q_{v2r}</p> <p>ΔX_{v1r}, ΔX_{v2r} X distance of left and right end of distributed load, measured from crown</p> <p>Q_{v1r}, Q_{v0r}, Q_{v2r} Intensity of vertical distributed load at left end, center, and right end See Figure 4.7</p>
			<p>6.3.2.2 <u>Additional Vertical Loosening Load for Left Tunnel</u> Required only for LSDADD = 1 and MODEL= 3 or 4</p> <p>ΔX_{v1l}, ΔX_{v2l}, Q_{v1l}, Q_{v0l}, Q_{v2l}</p> <p>ΔX_{v1l}, ΔX_{v2l} X distance of left and right end of distributed load, measured from crown</p> <p>Q_{v1l}, Q_{v0l}, Q_{v2l} Intensity of vertical distributed load at left end, center, and right end See Figure 4.7</p>

4-18 Description of Input Data

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

MODEL = 1 Single Tunnel [Half Section]



MODEL = 2 Single Tunnel [Full Section]

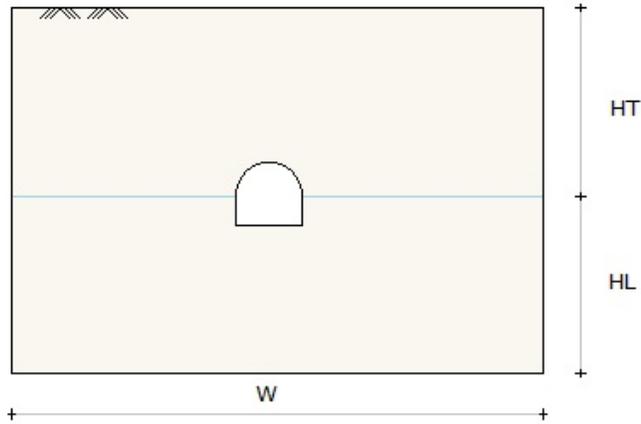
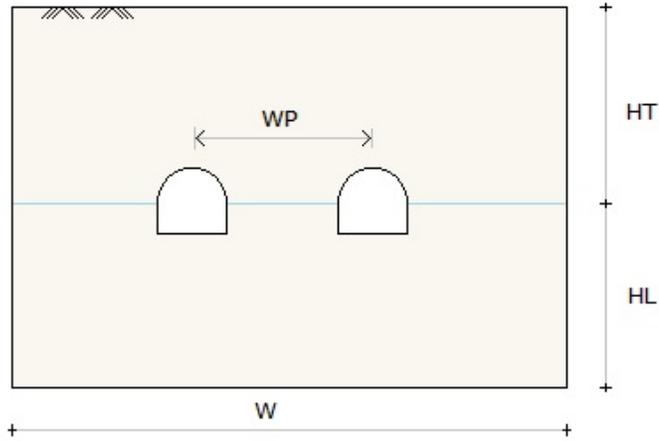


Figure 4.1 Schematic tunnel section for MODEL= 1 and 2

MODEL= 3 Two Tunnel [Symmetric Section]



MODEL= 4 Two Tunnel [Unsymmetric Section]

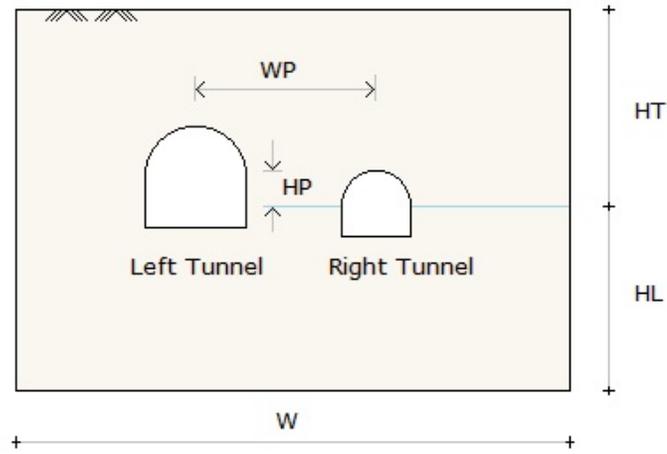


Figure 4.1 Schematic tunnel section for MODEL= 3 and 4

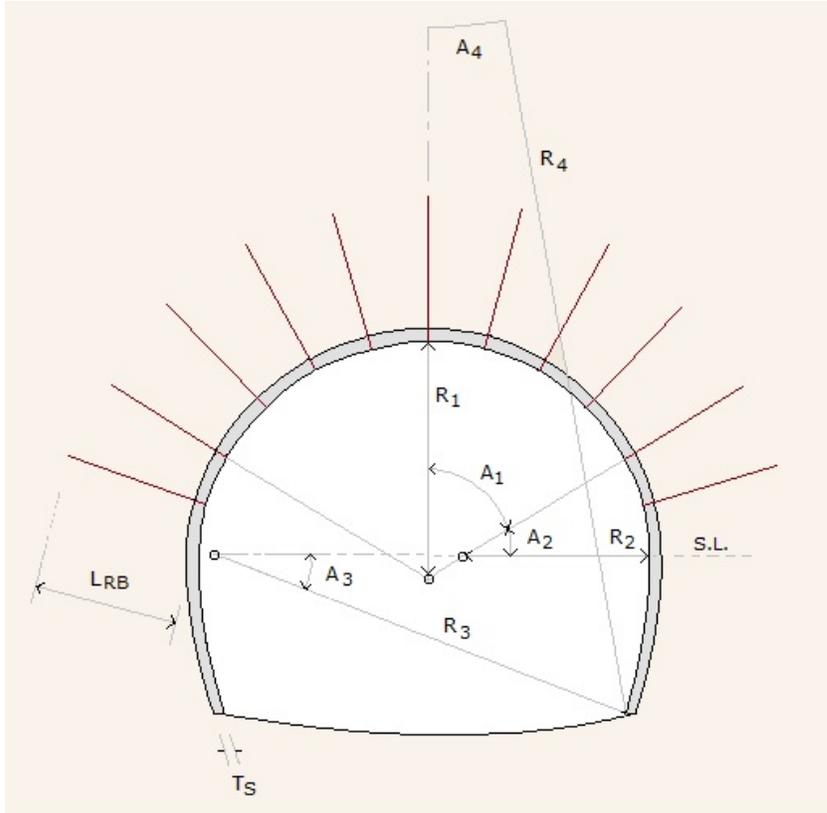


Figure 4.2a Horseshoe shape tunnel dimension
ISTYPE = 1 ($A_1 + A_2 = 90^\circ$)

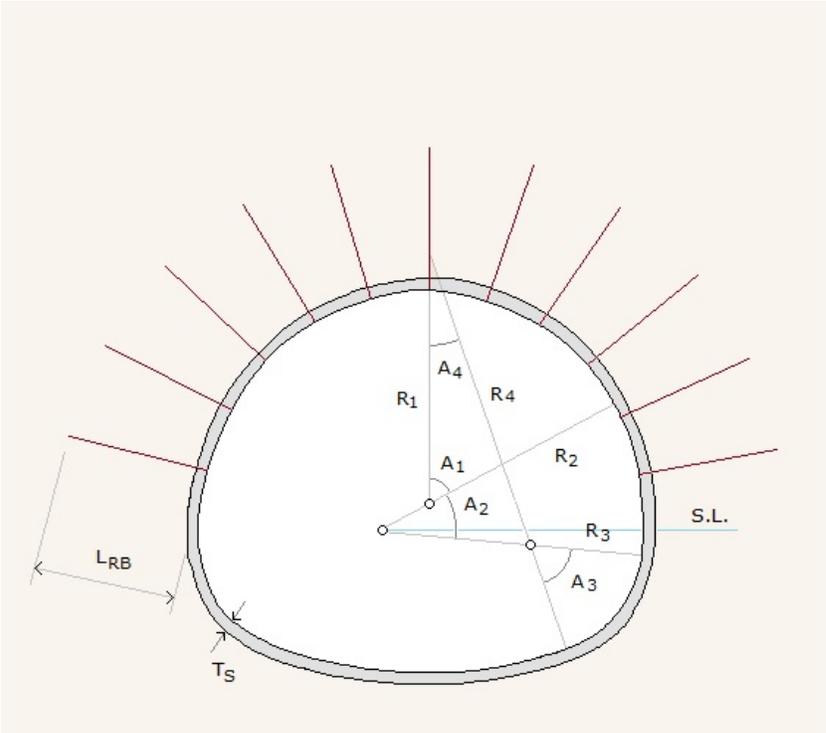


Figure 4.2b Egg shape tunnel dimension
 $ISTYPE = 2 (A_1 + A_2 > 90^\circ)$

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

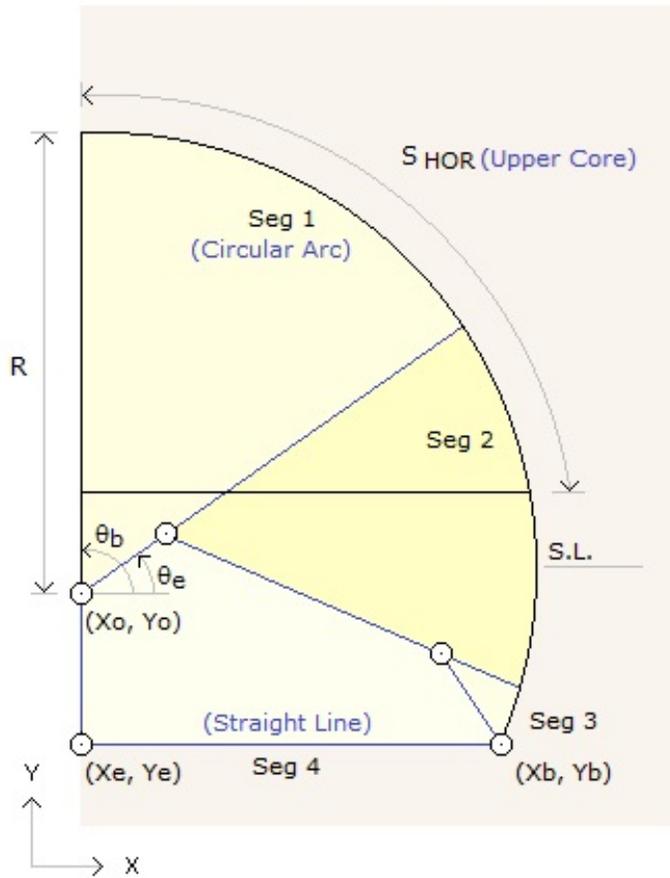


Figure 4.2c User defined tunnel dimension for ISTYPE = 3

4-24 Description of Input Data

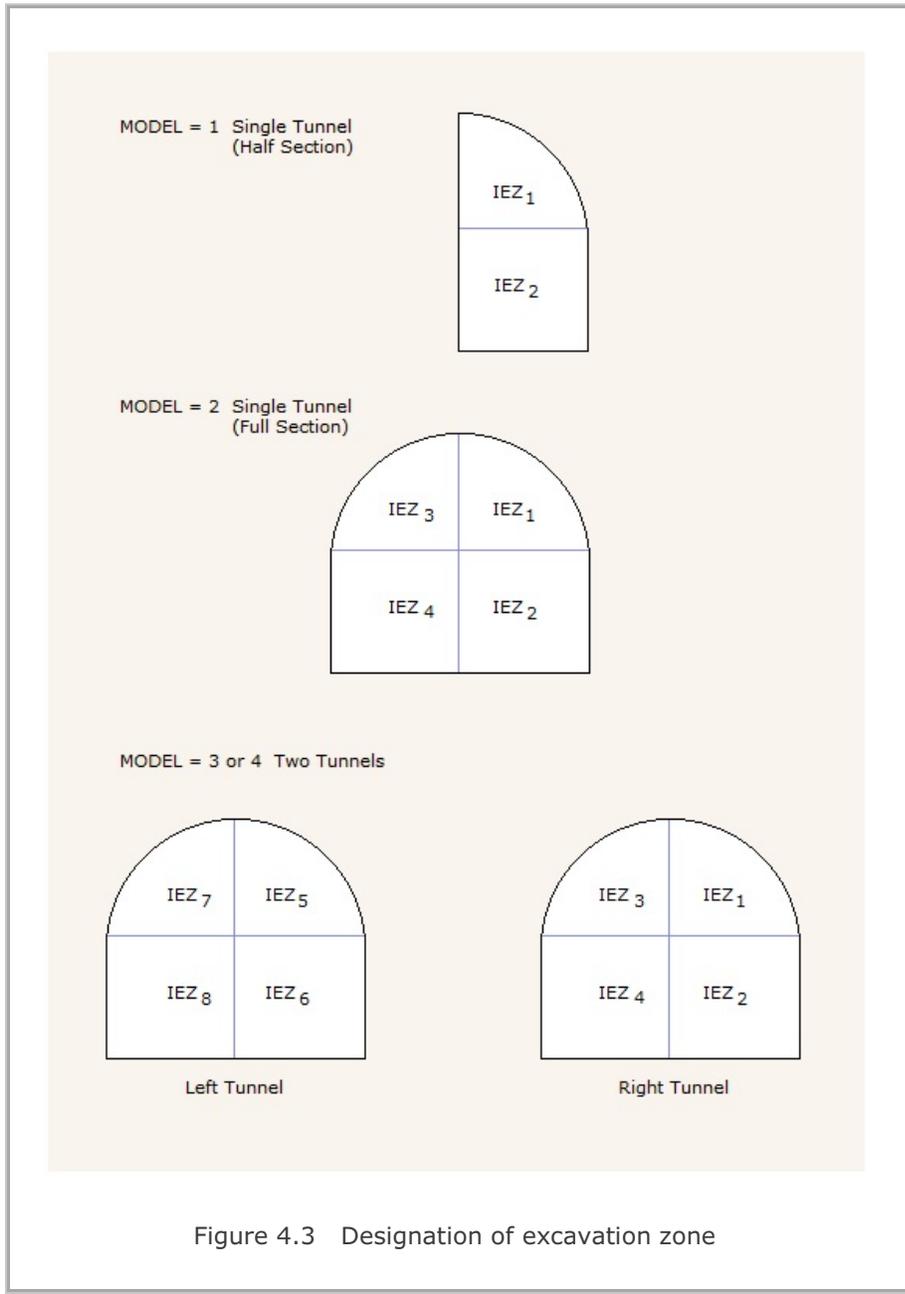


Figure 4.3 Designation of excavation zone

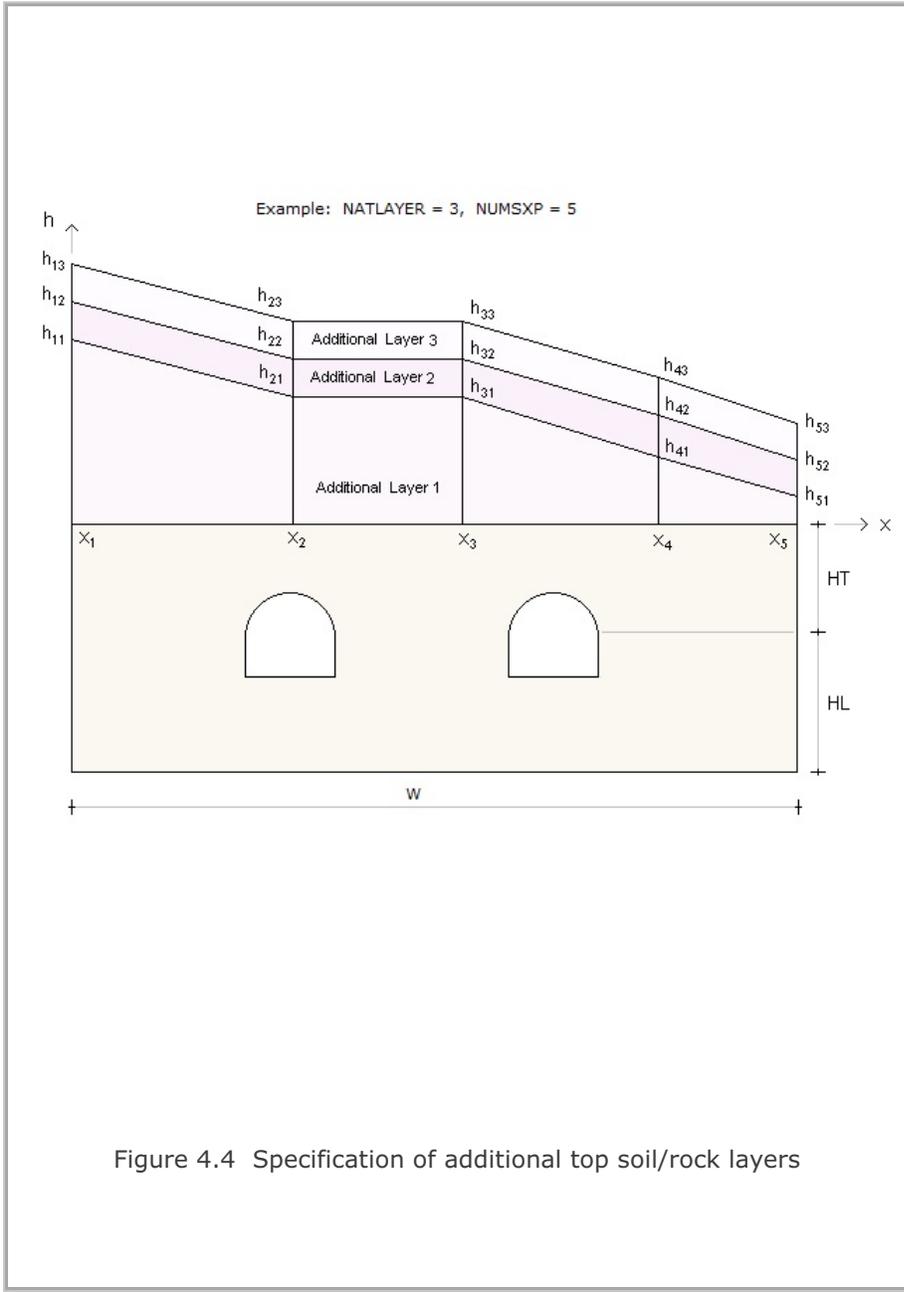


Figure 4.4 Specification of additional top soil/rock layers

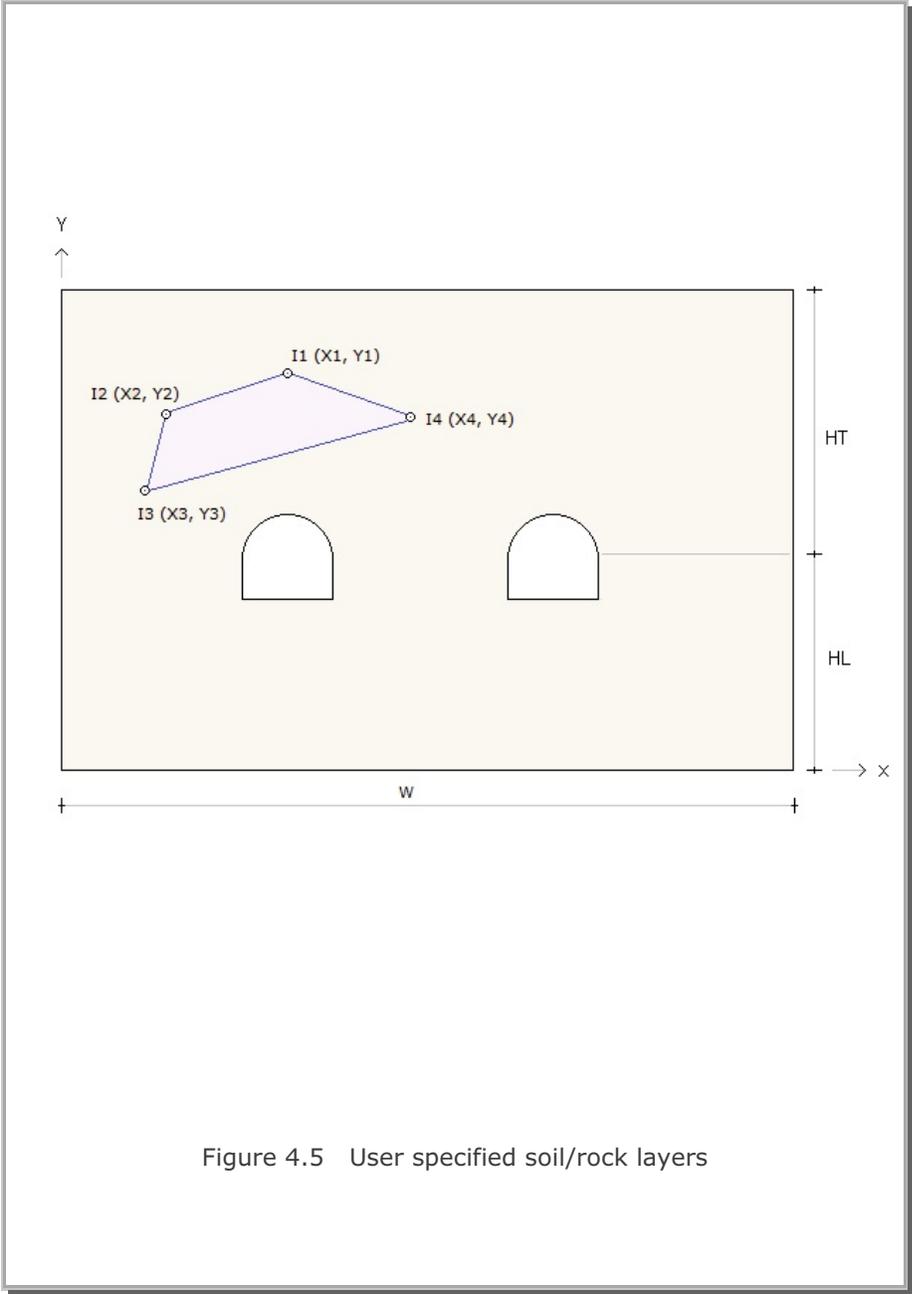


Figure 4.5 User specified soil/rock layers

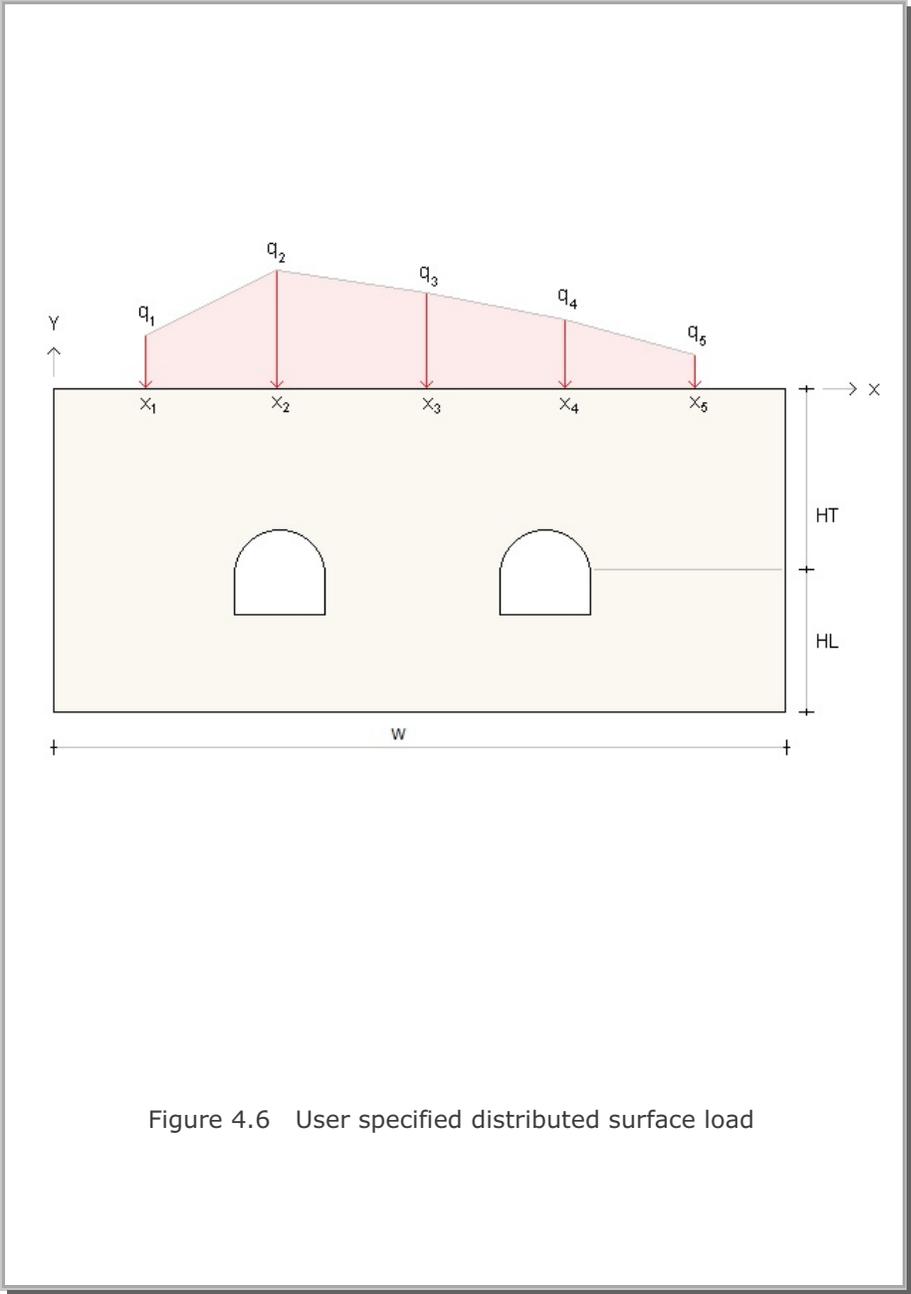


Figure 4.6 User specified distributed surface load

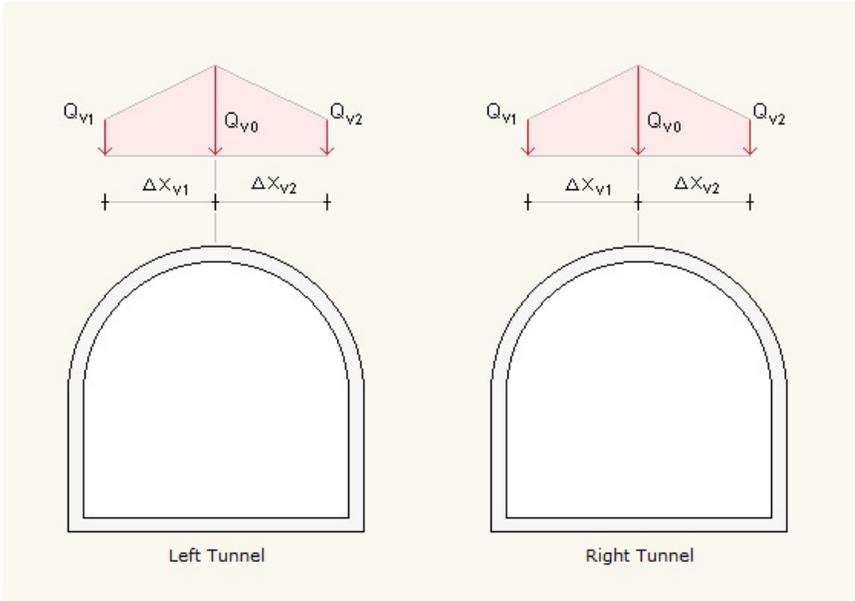


Figure 4.7 Additional vertical loosening load

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

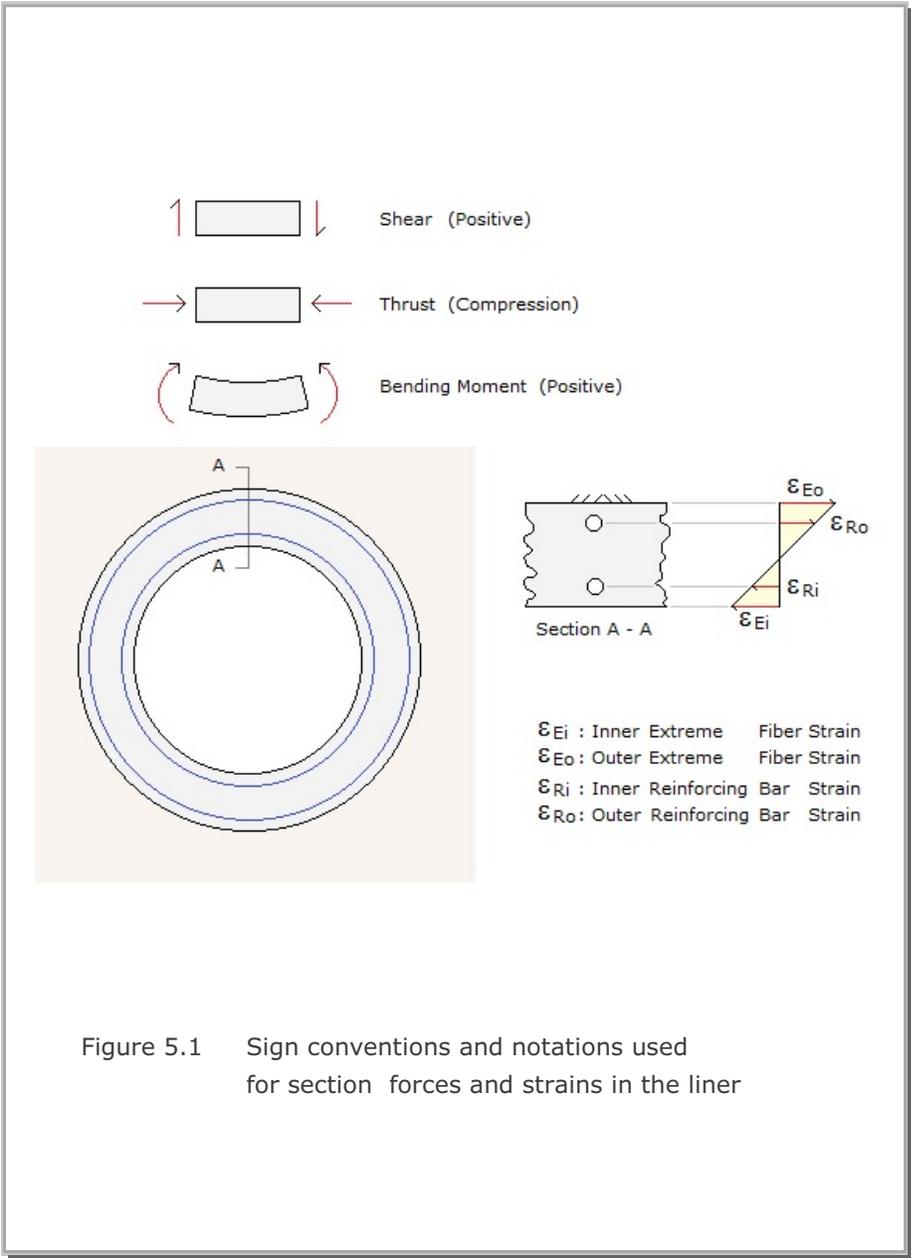


Figure 5.1 Sign conventions and notations used for section forces and strains in the liner

5-4 Description of Output Data

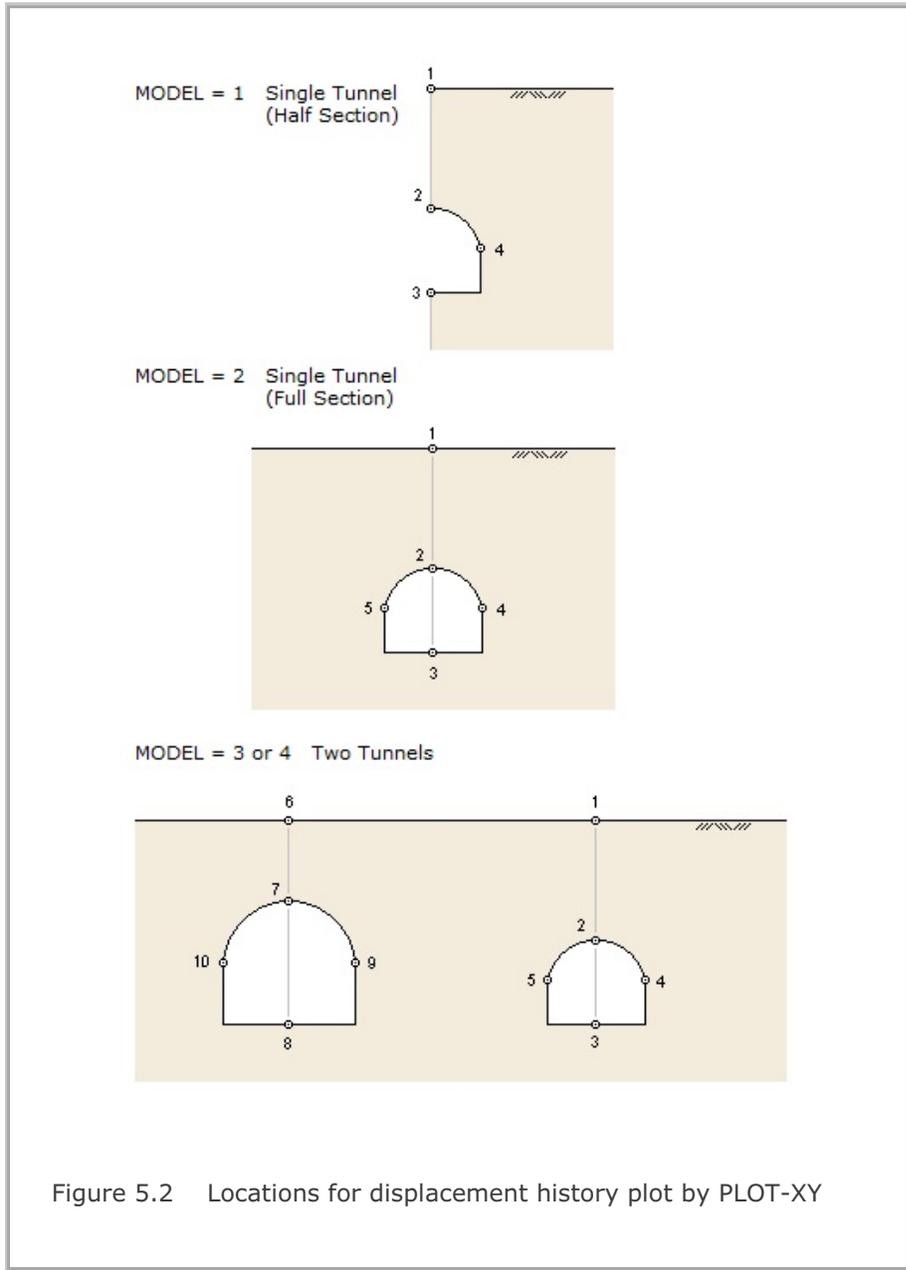


Figure 5.2 Locations for displacement history plot by PLOT-XY

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_0 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.

6-4 Example 1

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.

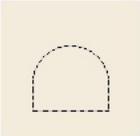
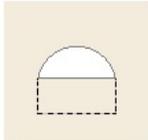
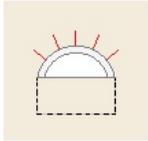
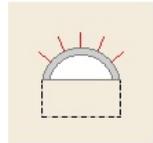
Graphical outputs from PLOT-2D are shown in Figures 6.3 to 6.47. Brief description of these plots are shown in the text output file PLTDS.LST in Table 6.6.

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 PLTX.Y.LST in Table 6.7.

Table 6.2 Material property

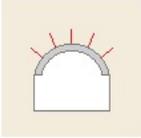
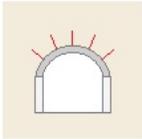
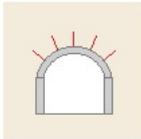
Material Type	γ [t/m ³]	K_o	E [t/m ²]	ν	ϕ [°]	C [t/m ²]	T [t/m ²]
Weathered Soil	1.90	0.50	2.00×10^3	0.33	30	3	20
Weathered Rock	1.90	0.43	5.000×10^3	0.30	35	30	30
Soft Rock	2.40	0.33	2.00×10^4	0.25	40	70	40
Hard Rock	2.55	0.25	2.00×10^5	0.20	45	100	50
Shotcrete (Soft)	2.40		0.50×10^6	0.20	30	500	100
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

Step	Construction State	Descriptions	
1,2		In Situ K_0 State	
3		50 % Stress Relief	Upper Core Excavation
4		75 % Stress Relief Soft Shotcrete Rock Bolt	
5		100 % Stress Relief Hard Shotcrete Rock Bolt	

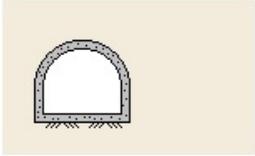
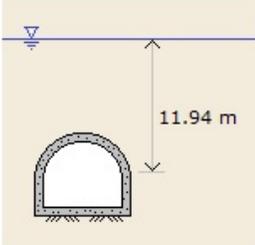
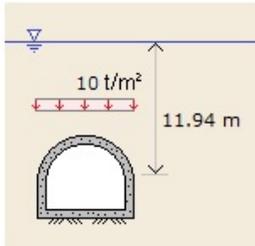
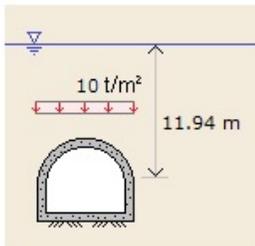
6-6 Example 1

Table 6.3 Simulation of construction sequence (Continued)

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

Lower Core
Excavation

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

6-8 Example 1

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
* N LAYER
* 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
*

```

6-10 Example 1

```
*
* 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

6-12 Example 1

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)

6-14 Example 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)

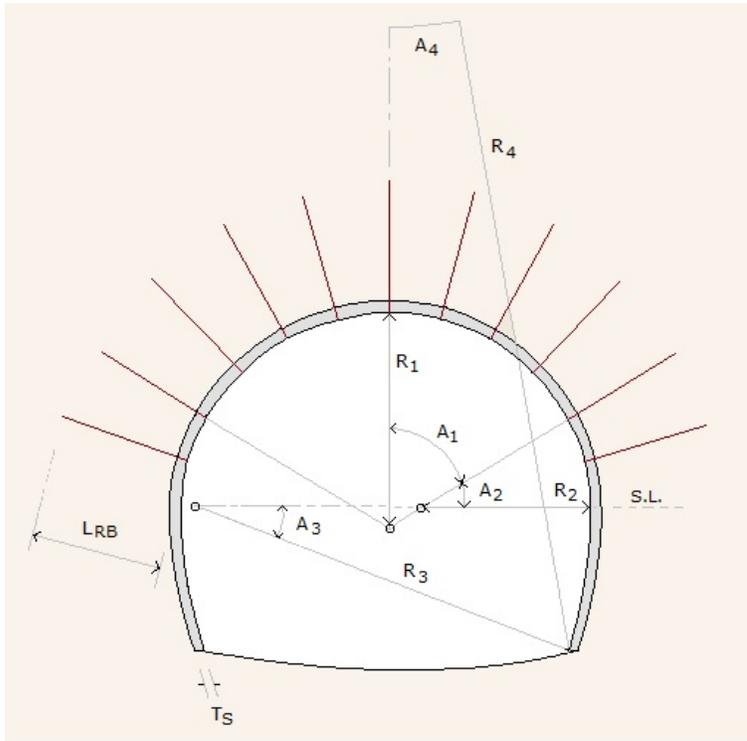
43 OUTER EXTREME FIBER STRESS
 AT LOAD STEP = 16
 EXAMPLE PROBLEM (MODEL 1)

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

6-18 Example 1

MODEL= 1 Single Tunnel [Half Section]

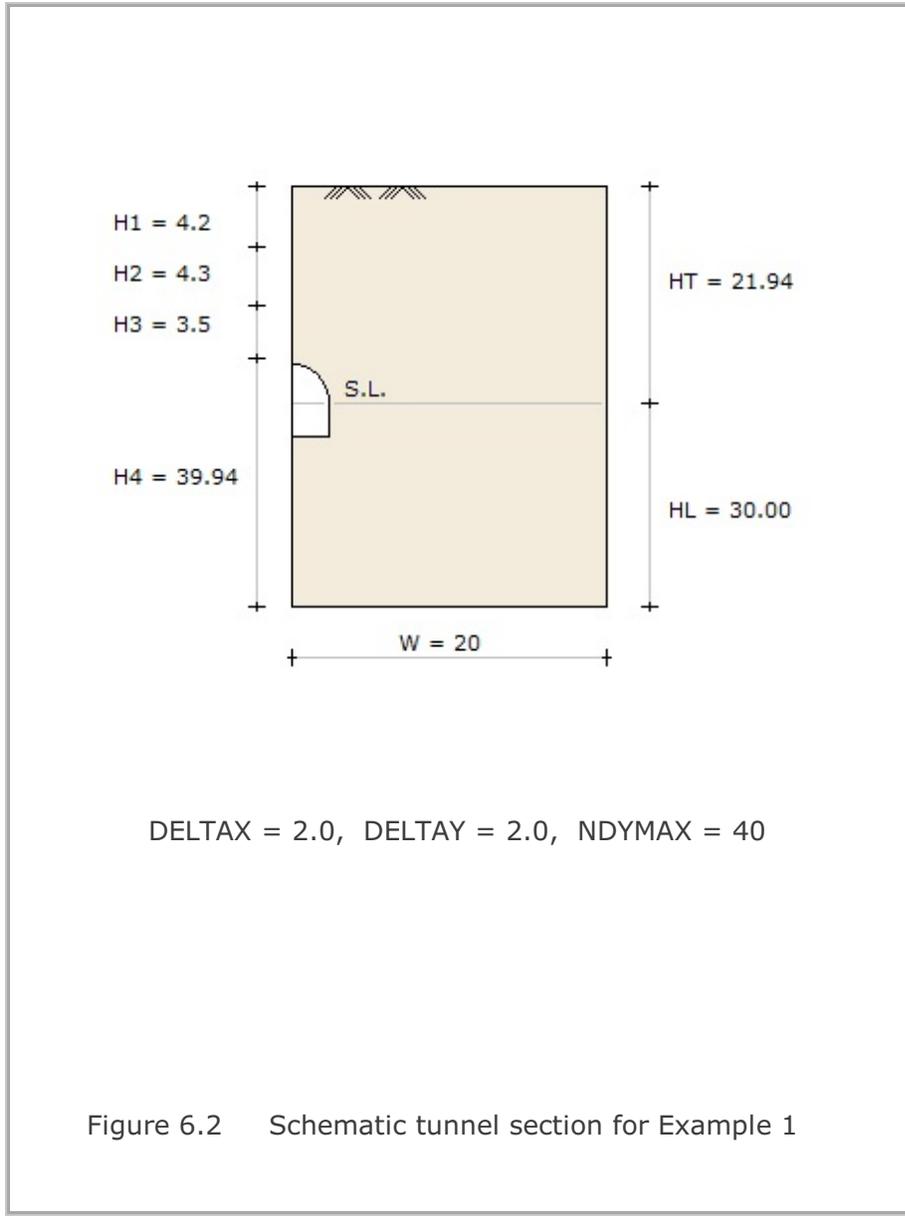


Figure 6.2 Schematic tunnel section for Example 1

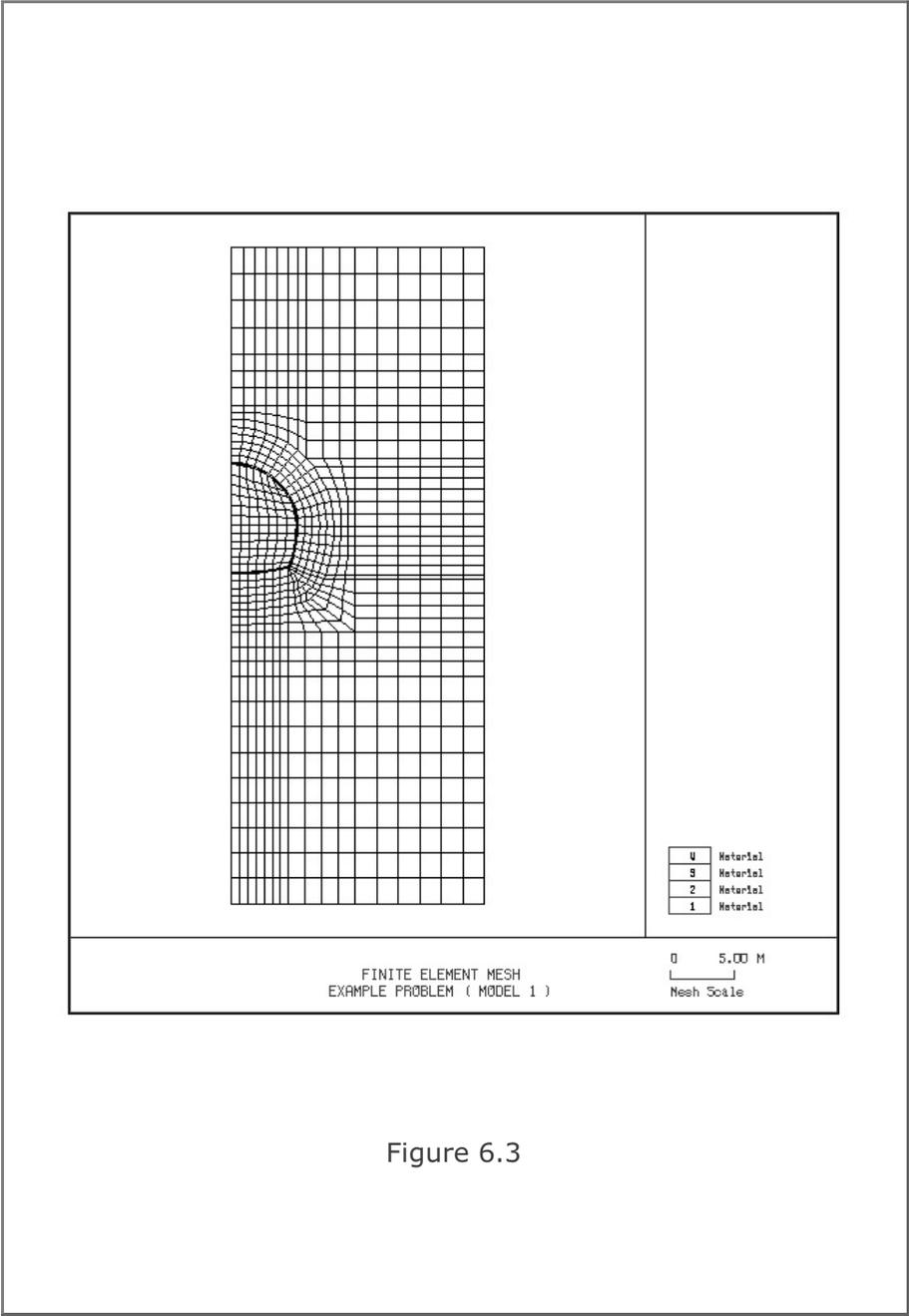


Figure 6.3

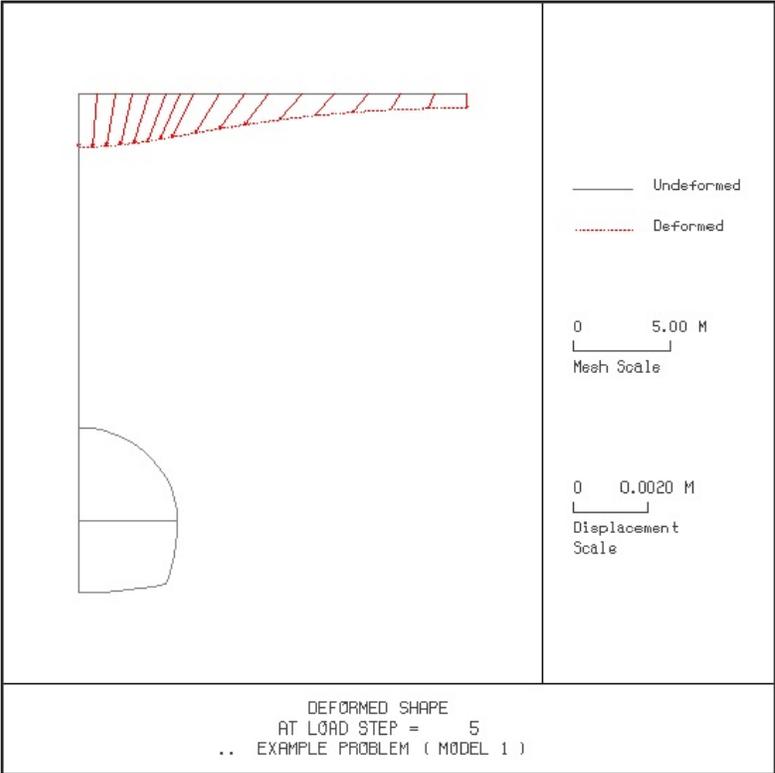


Figure 6.4

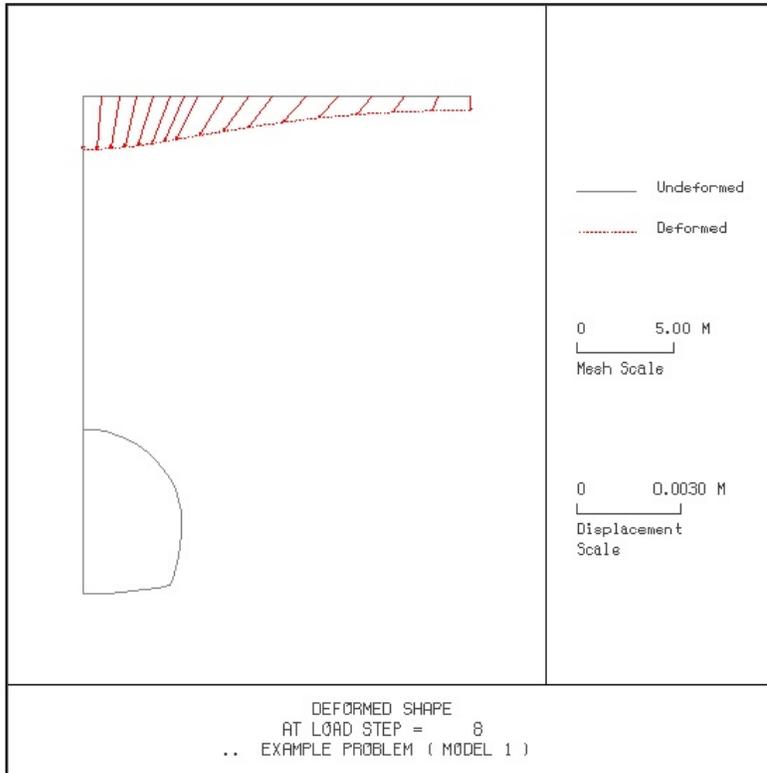


Figure 6.5

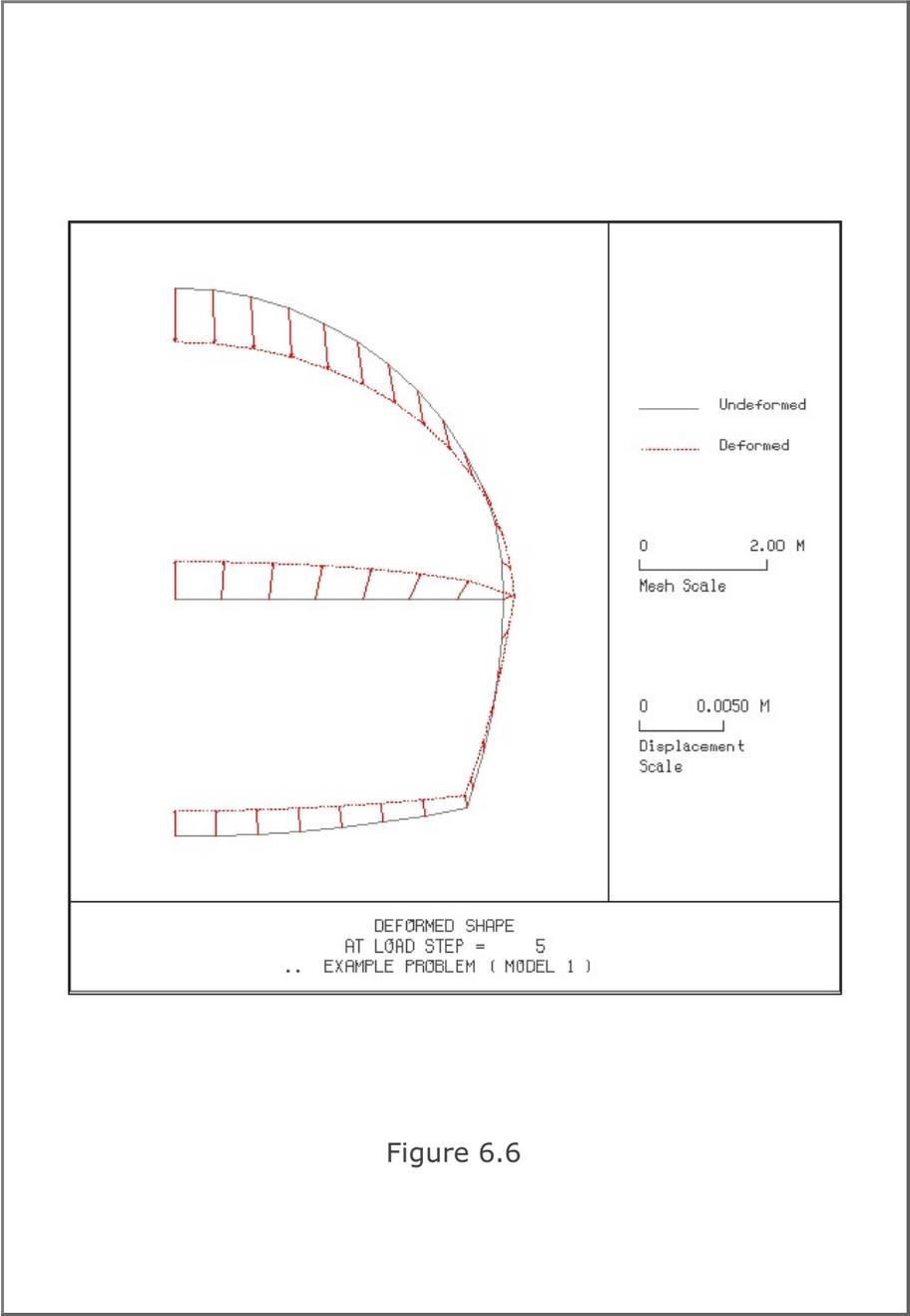


Figure 6.6

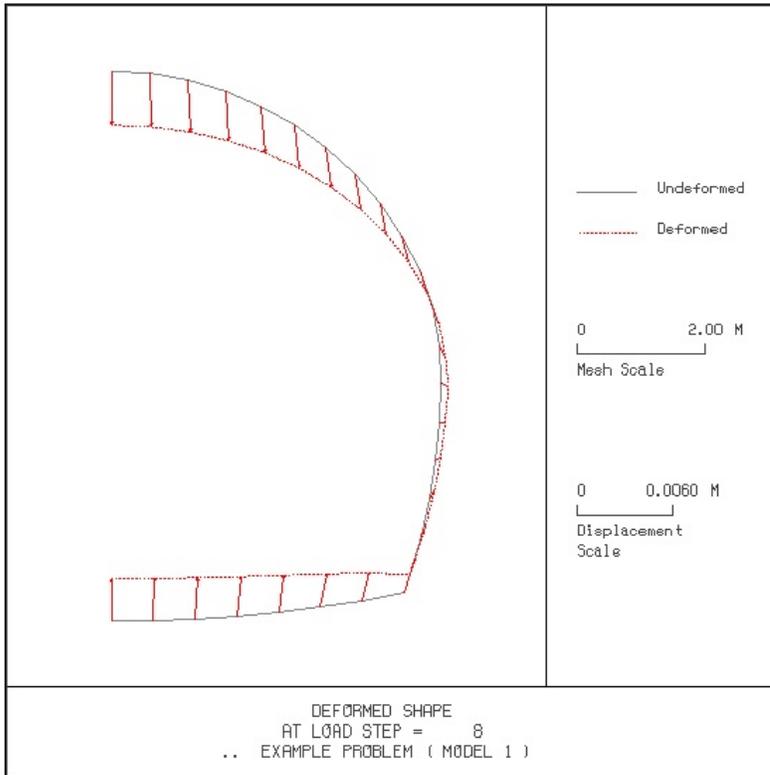


Figure 6.7

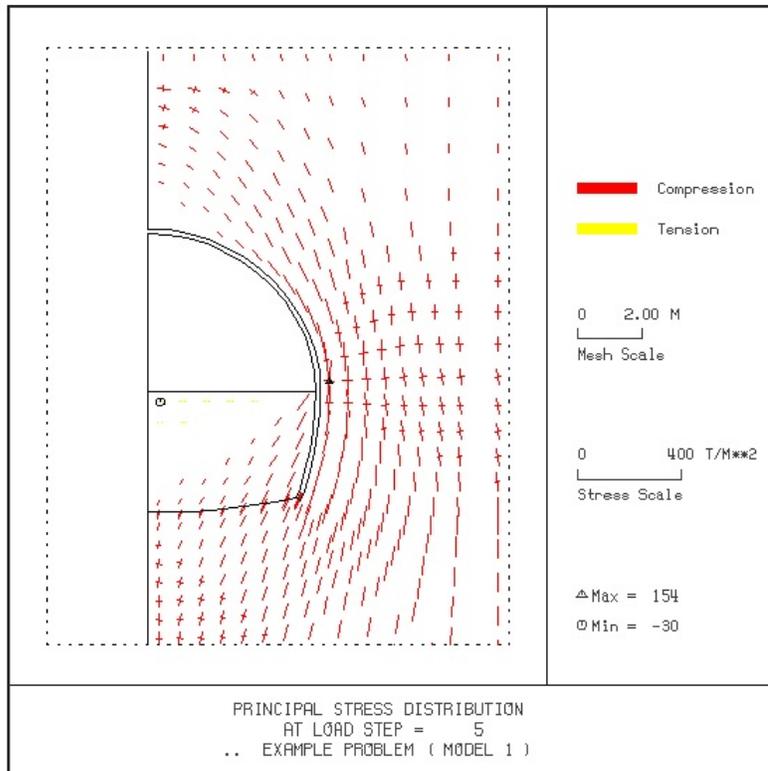


Figure 6.8

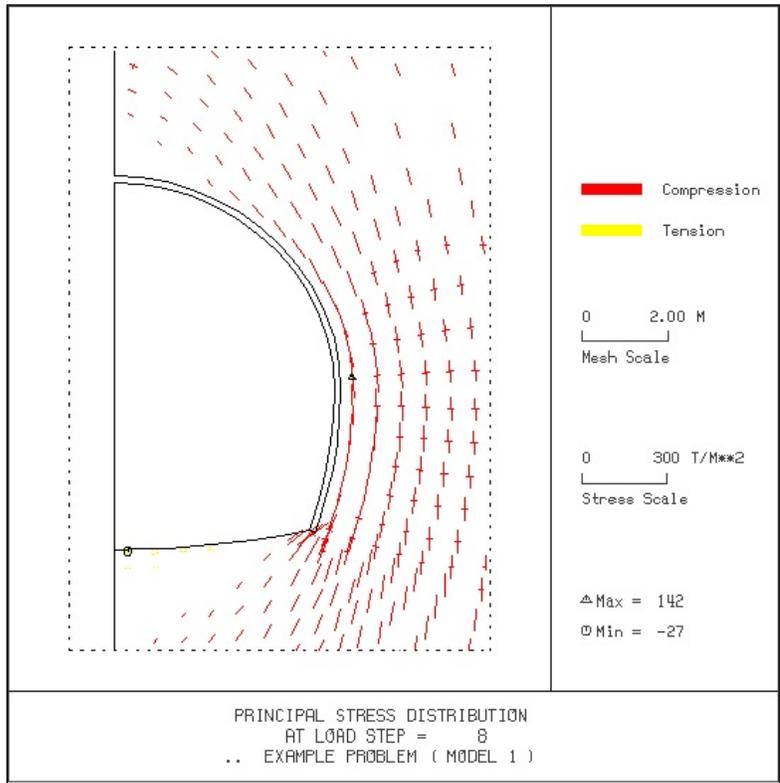


Figure 6.9

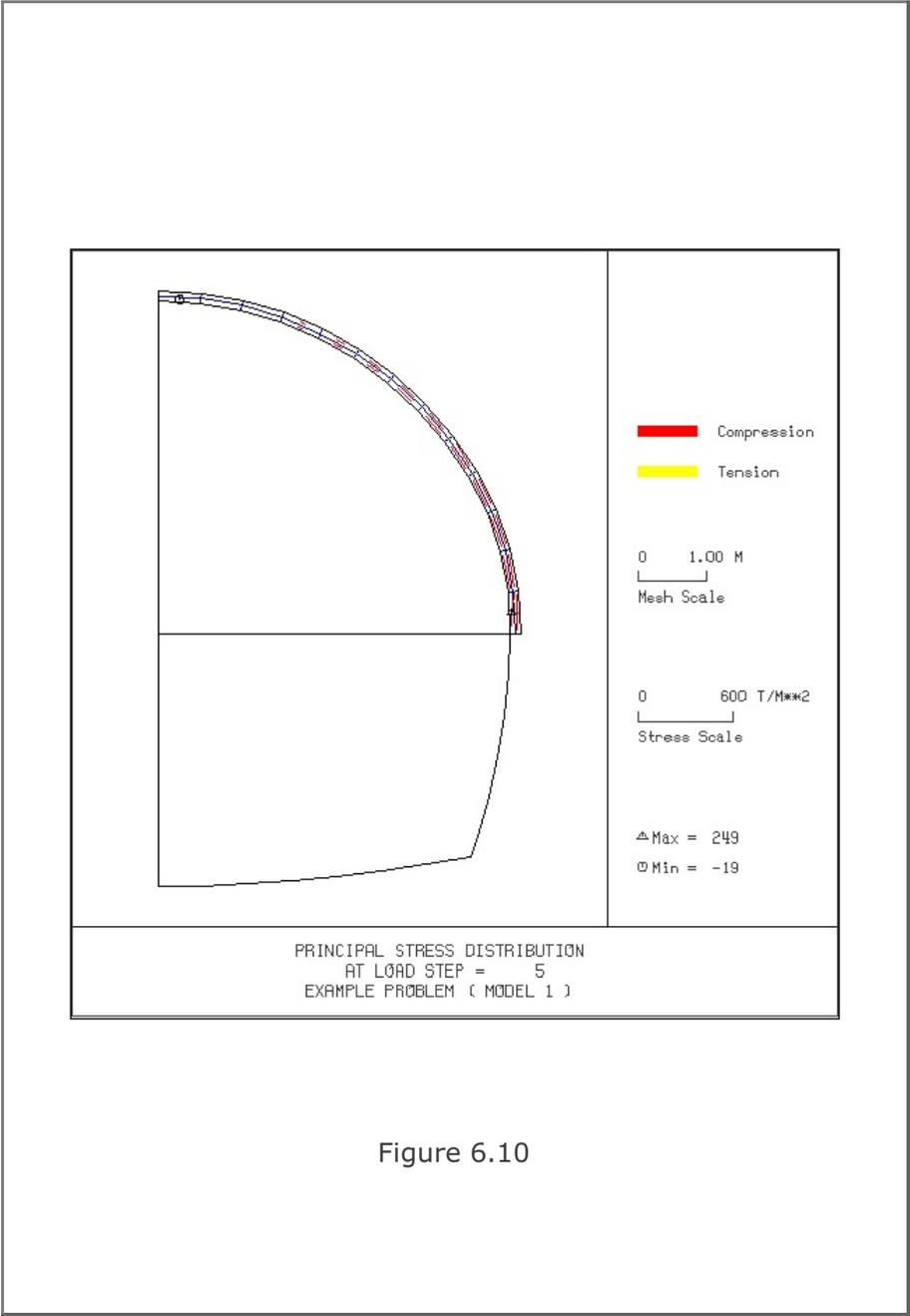


Figure 6.10

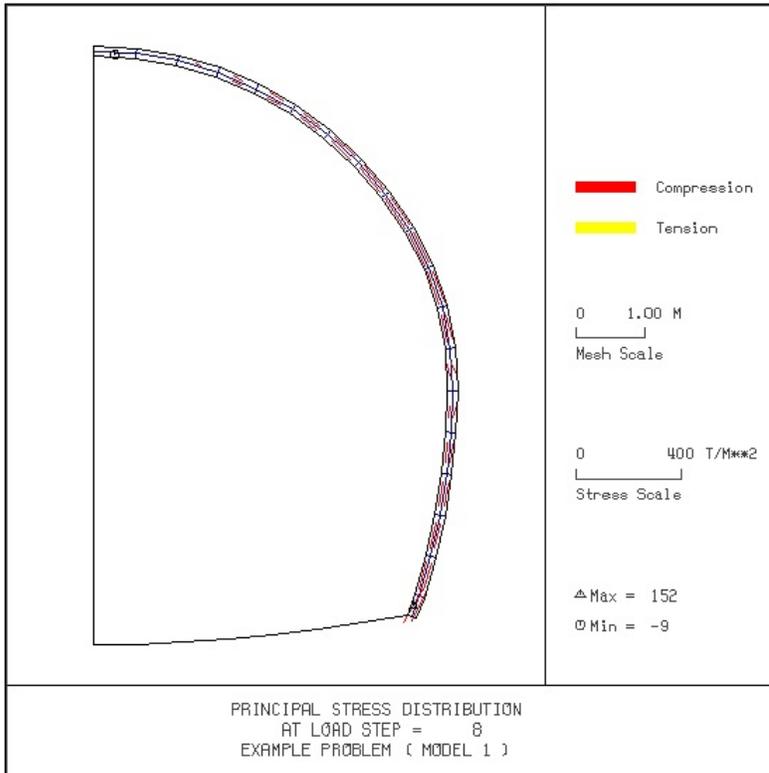


Figure 6.11

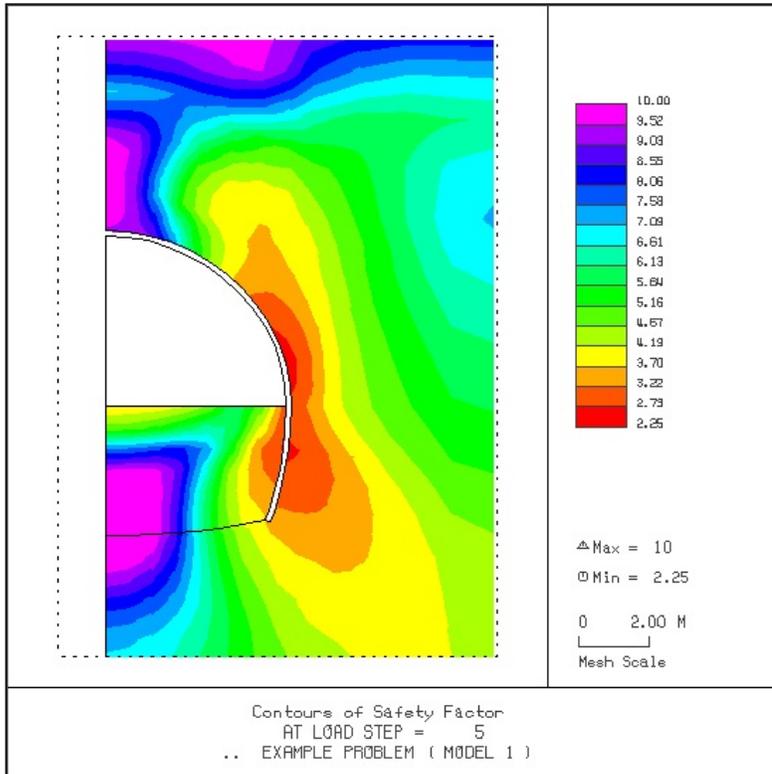


Figure 6.12

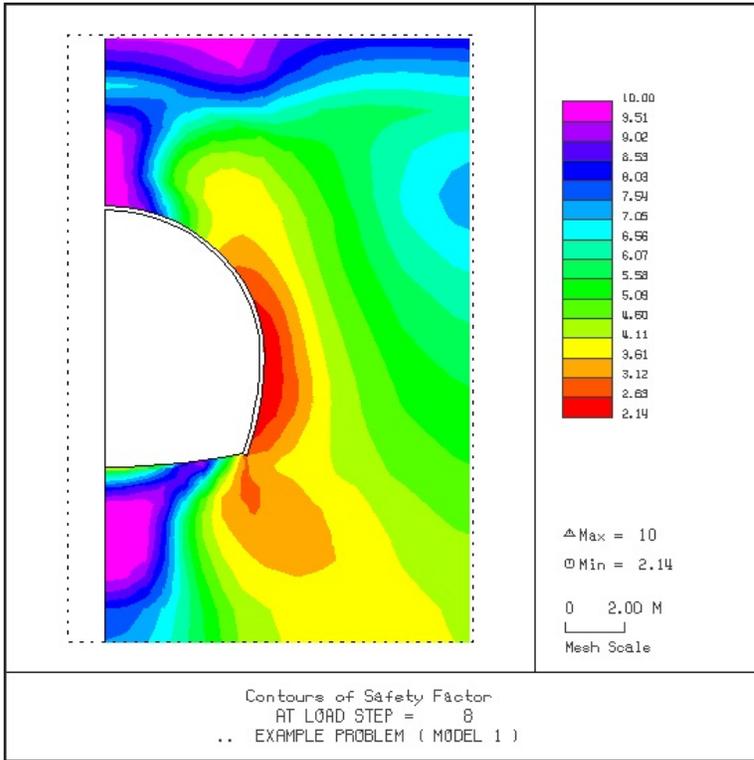


Figure 6.13

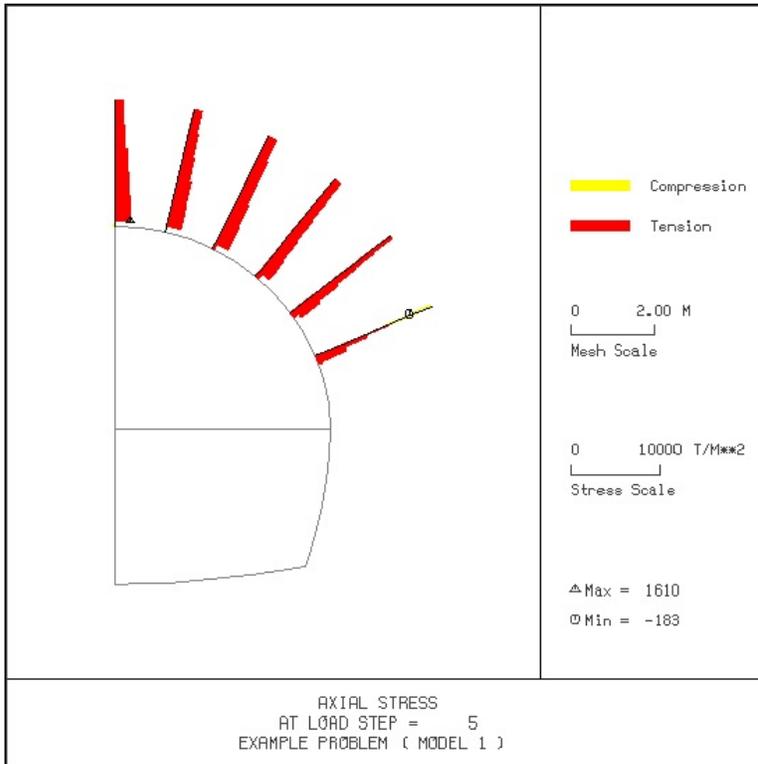


Figure 6.14

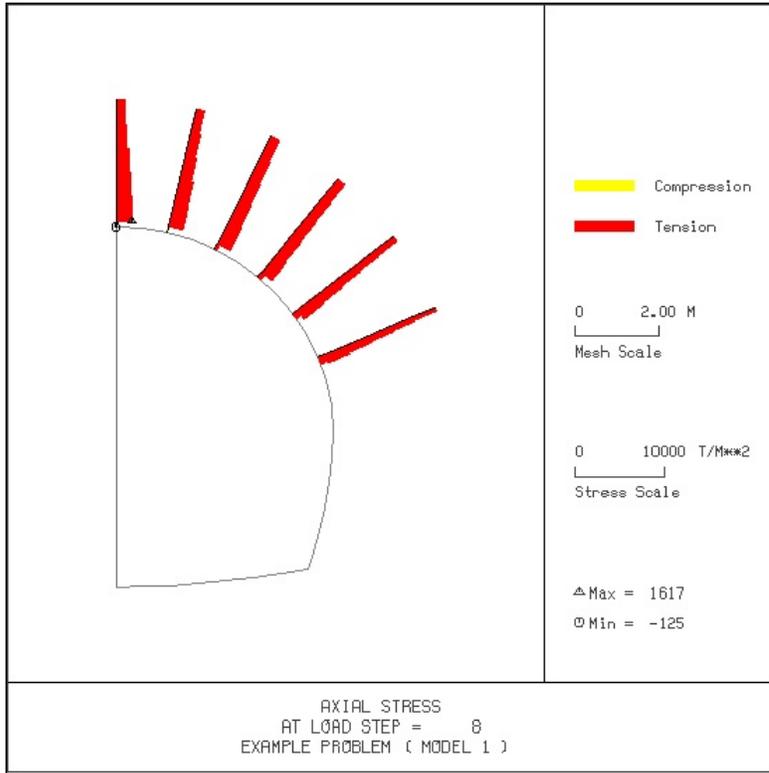


Figure 6.15

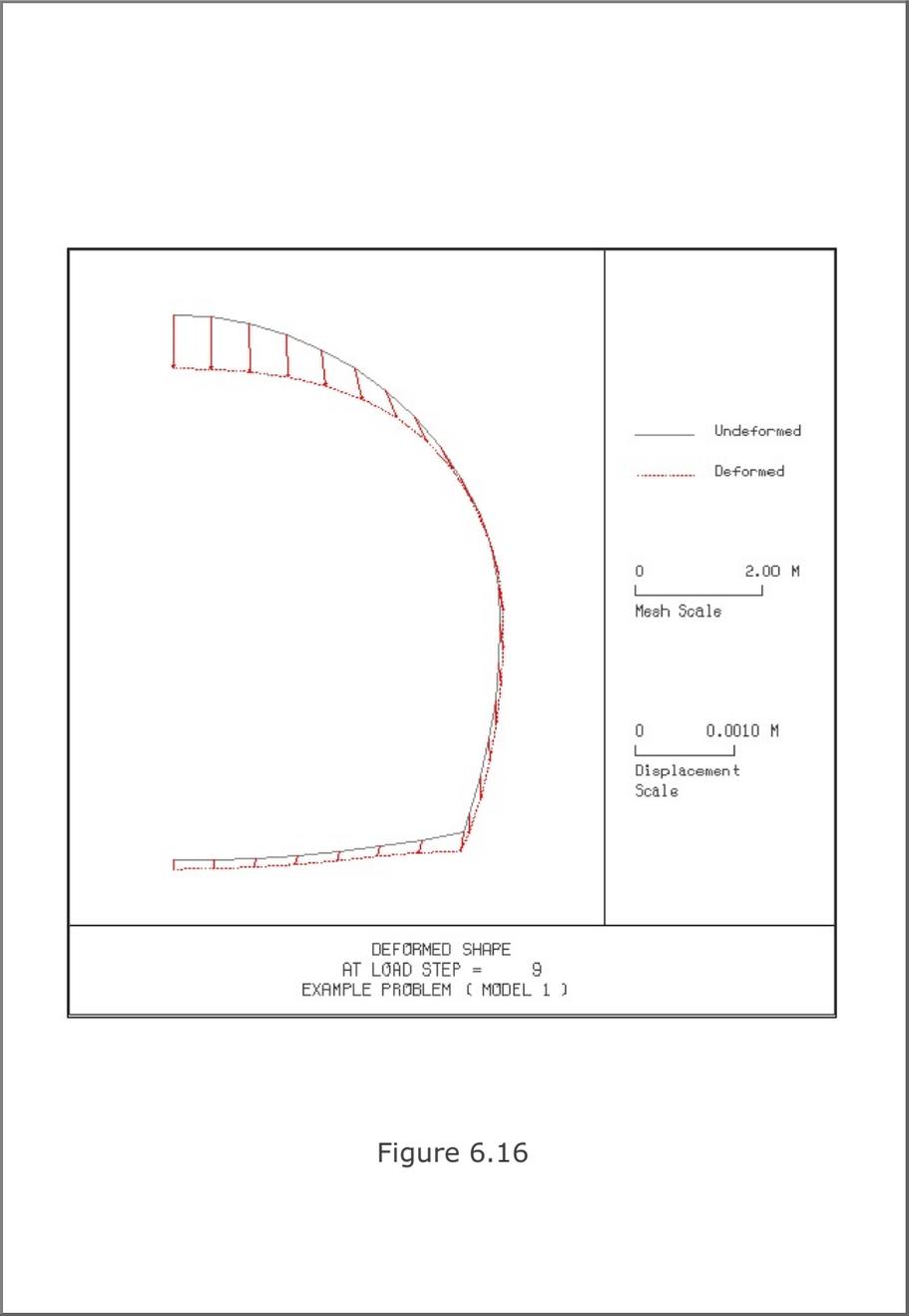


Figure 6.16

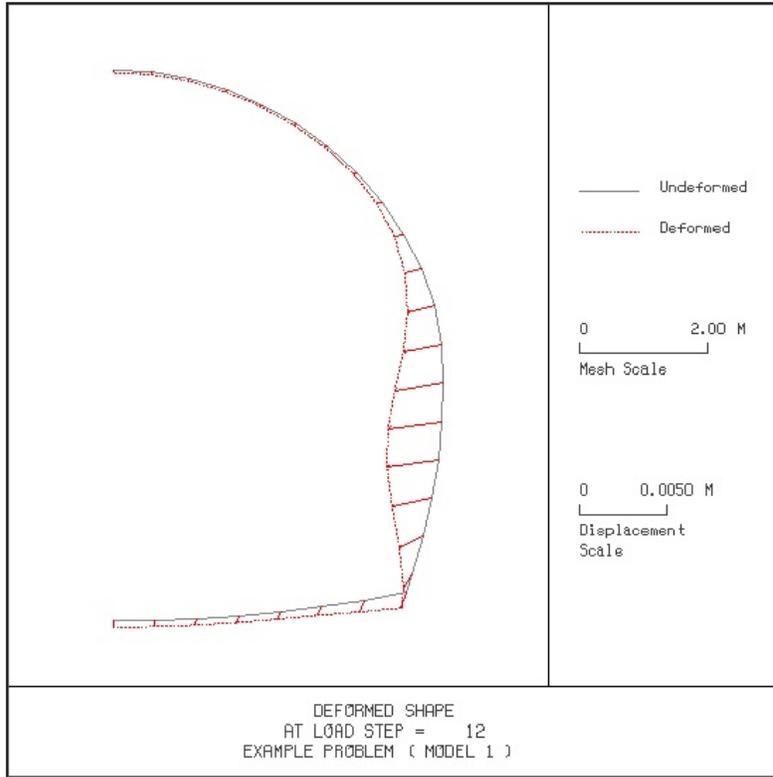


Figure 6.17

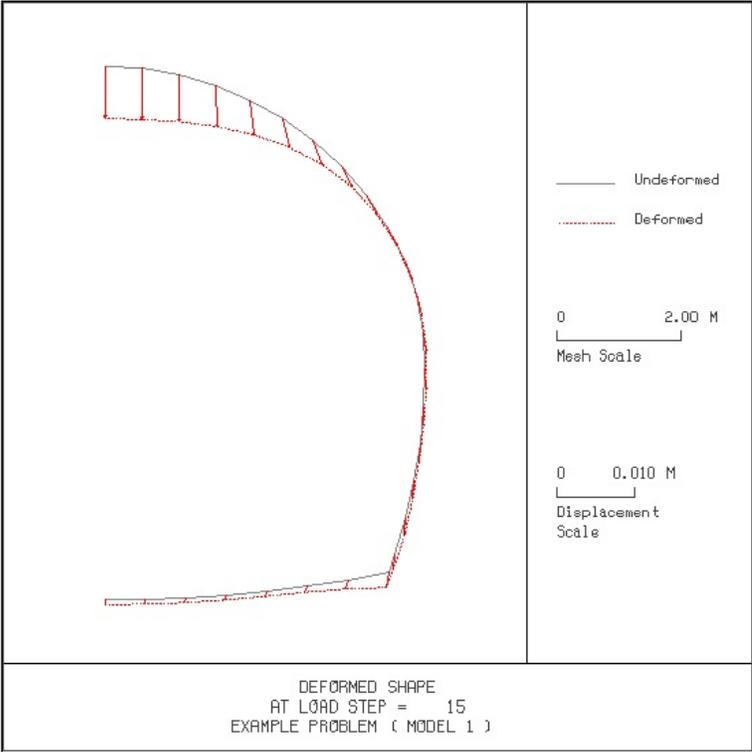


Figure 6.18

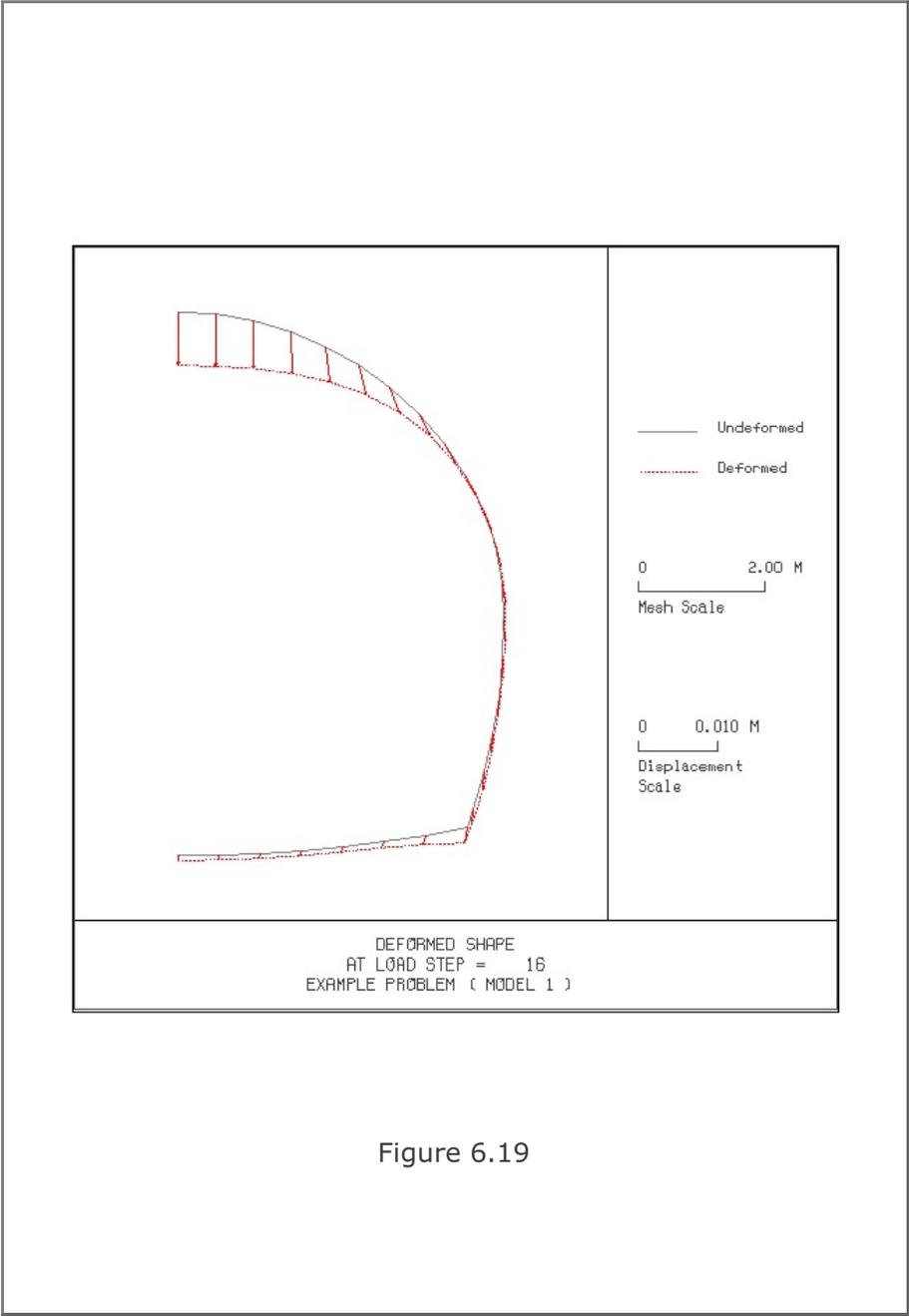


Figure 6.19

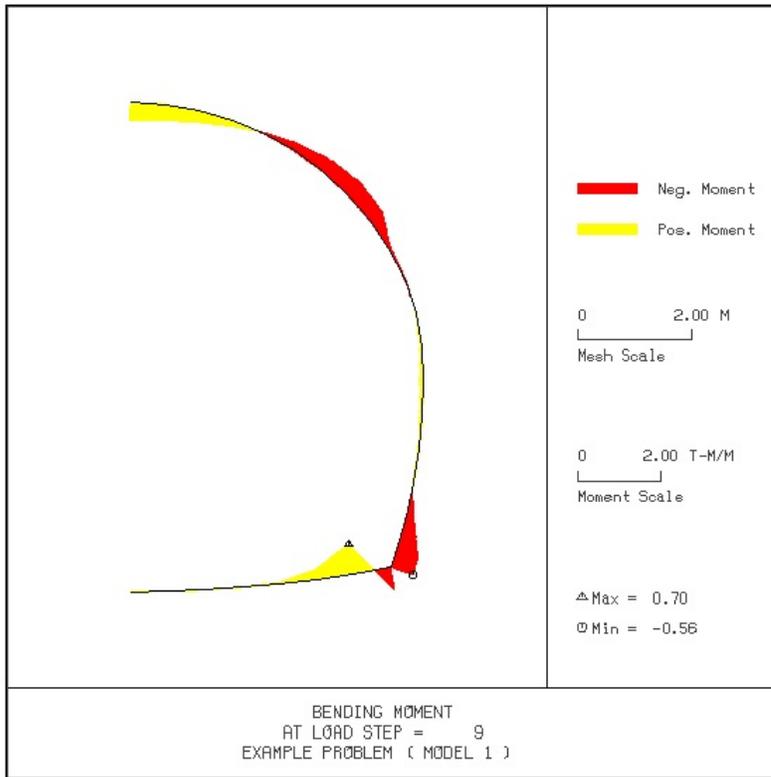


Figure 6.20

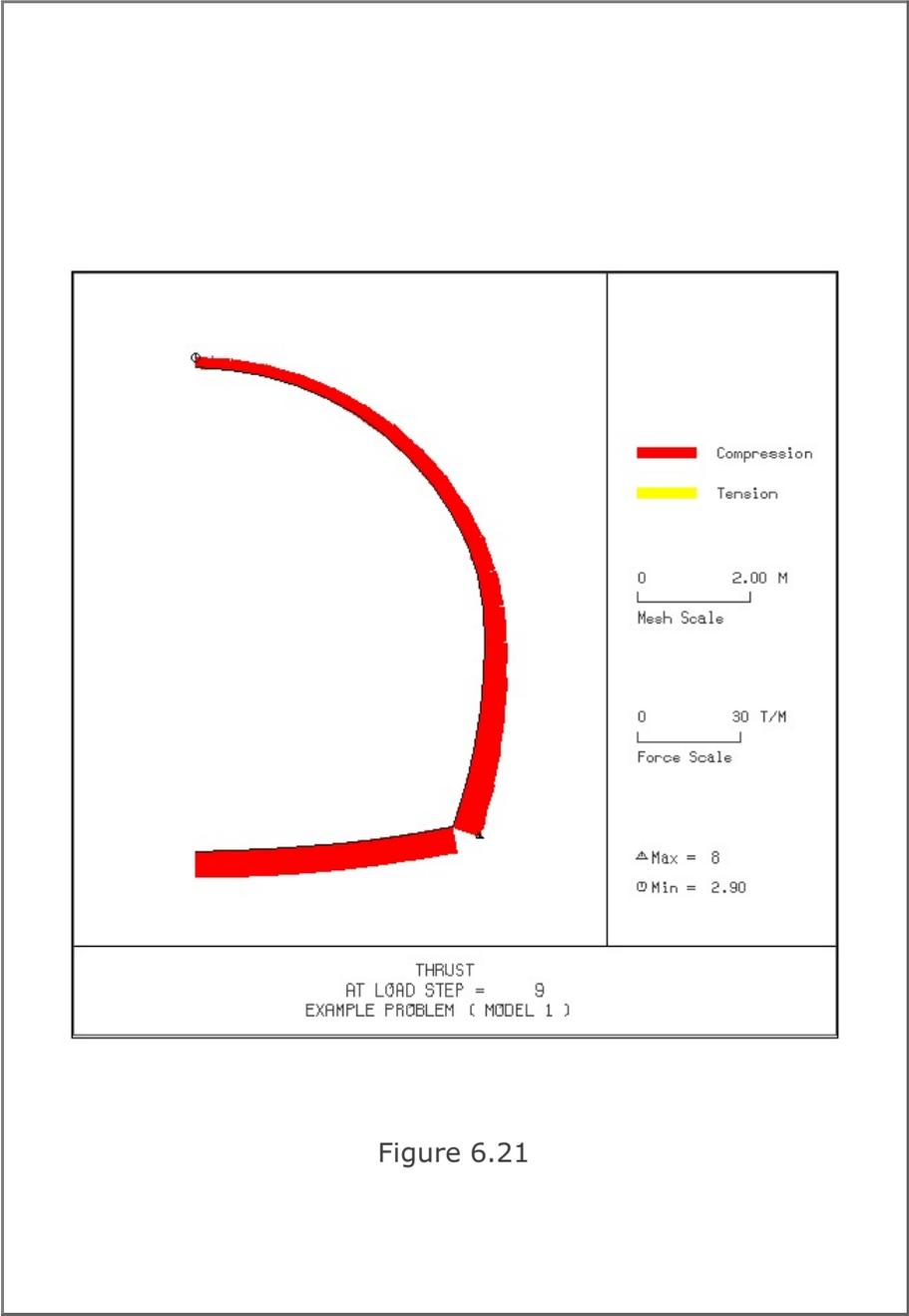


Figure 6.21

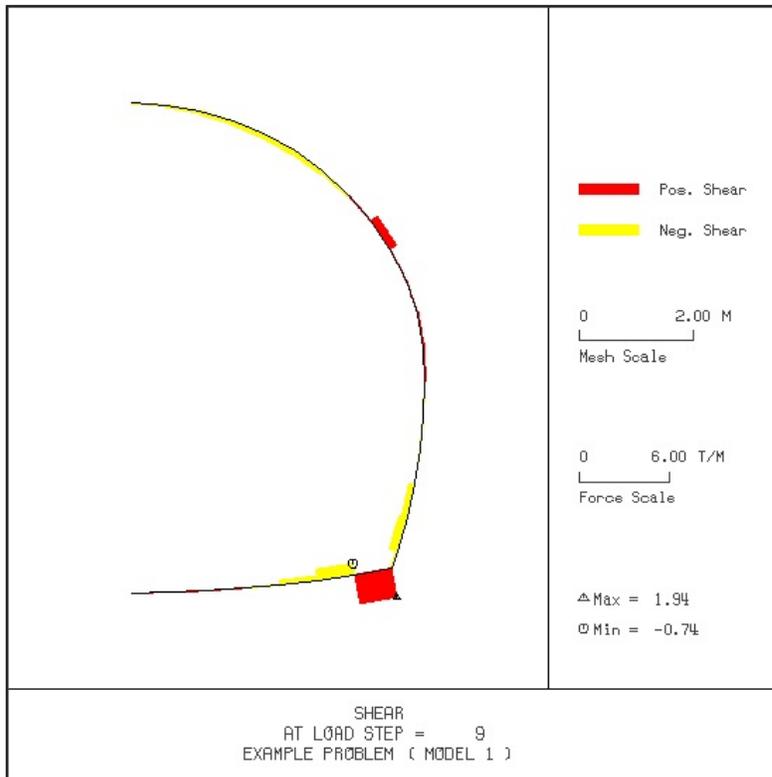


Figure 6.22

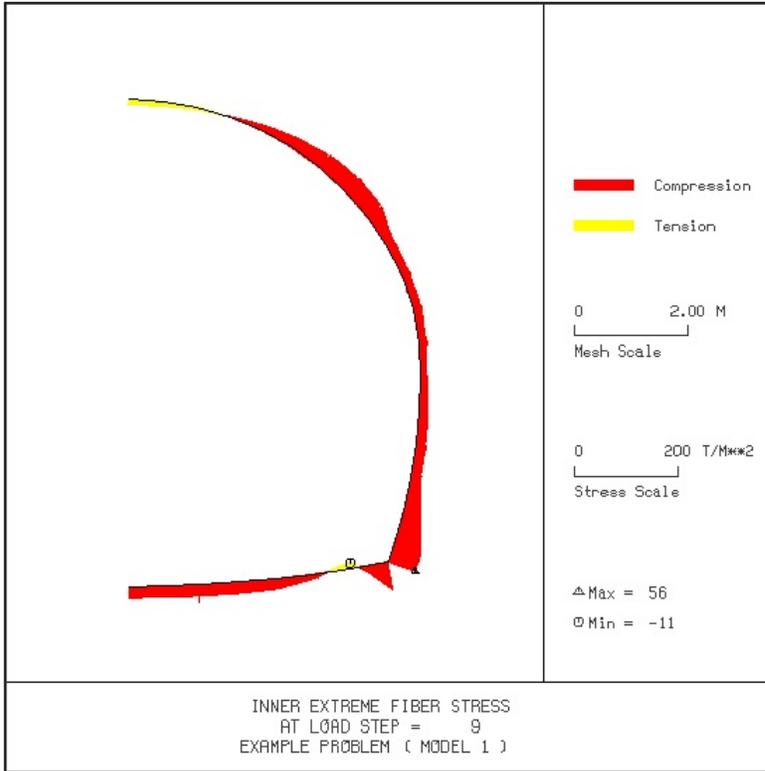


Figure 6.23

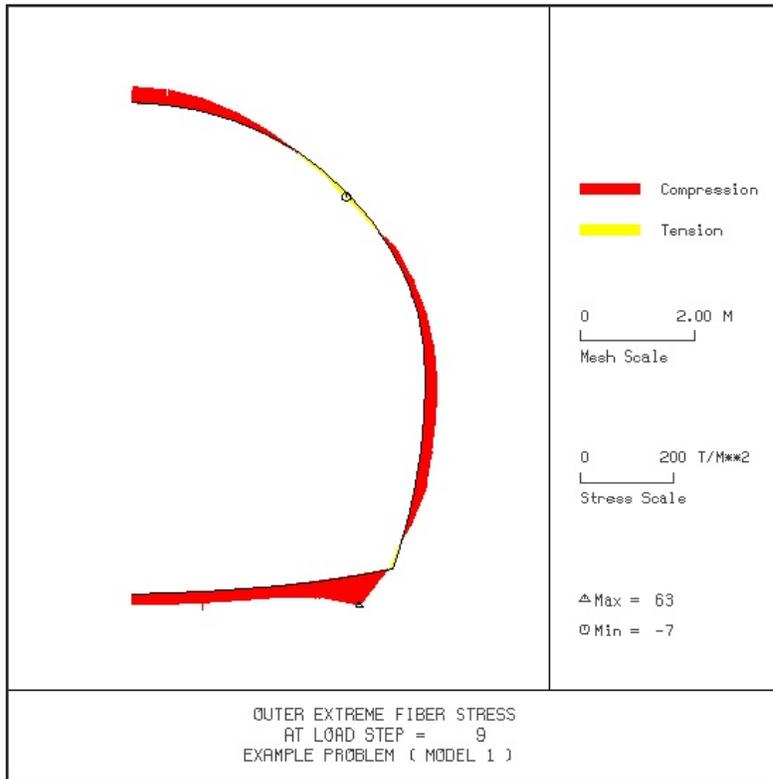


Figure 6.24

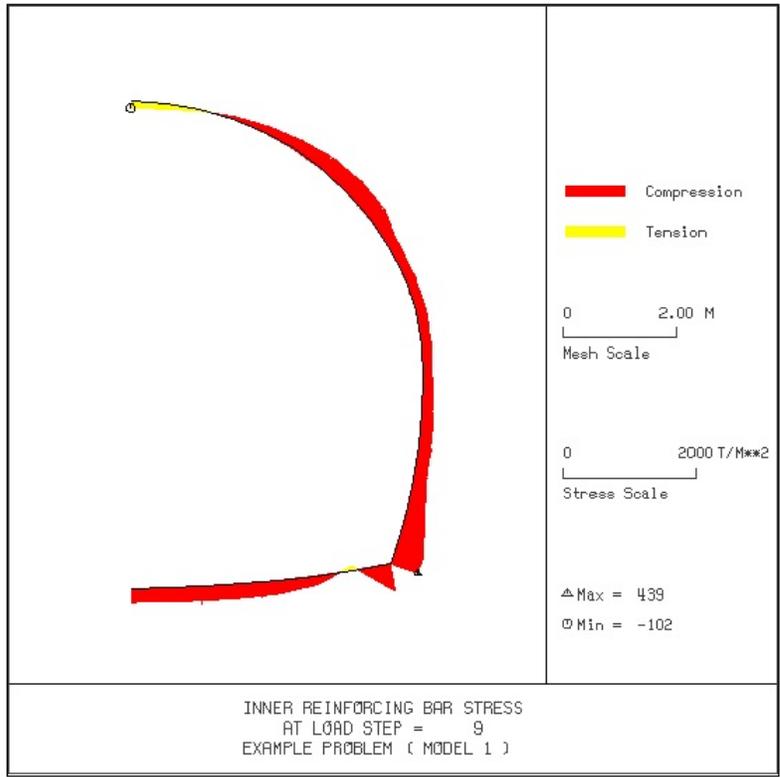


Figure 6.25

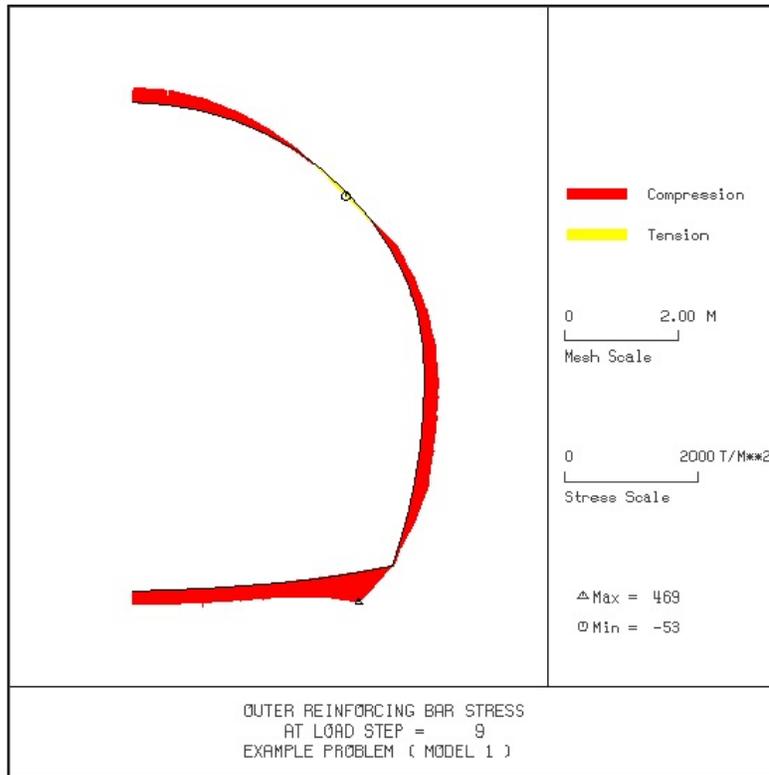


Figure 6.26

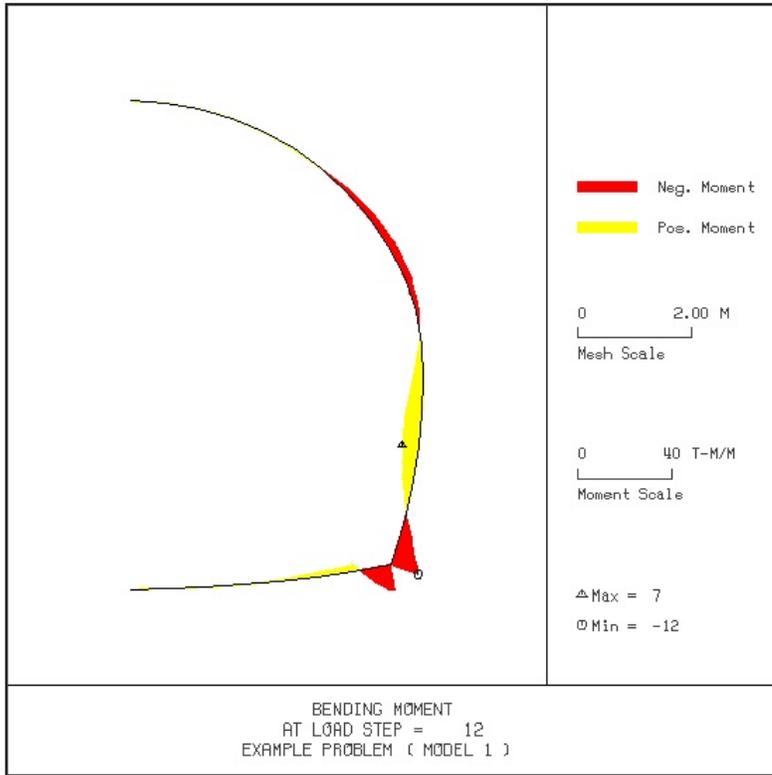


Figure 6.27

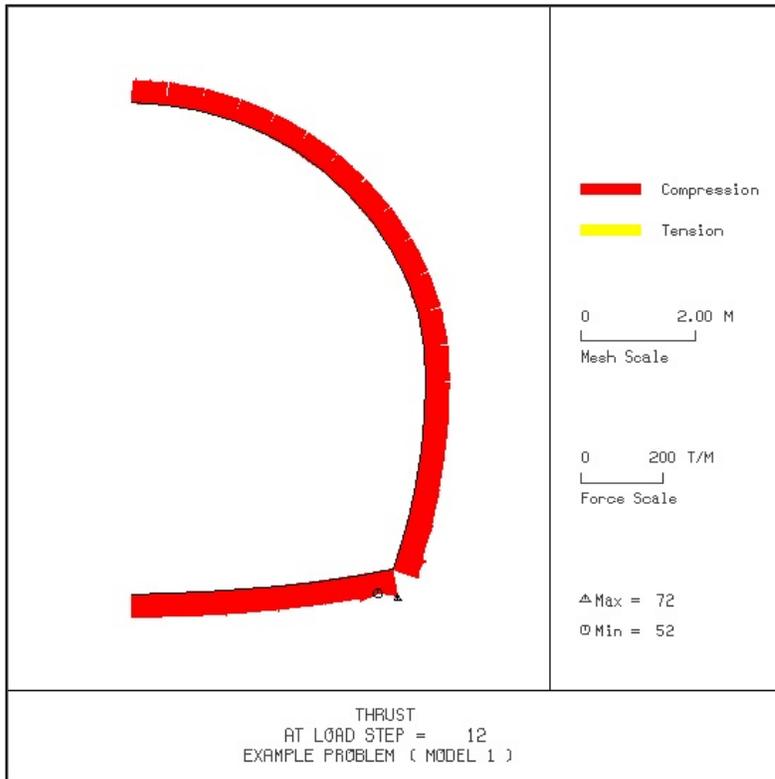


Figure 6.28

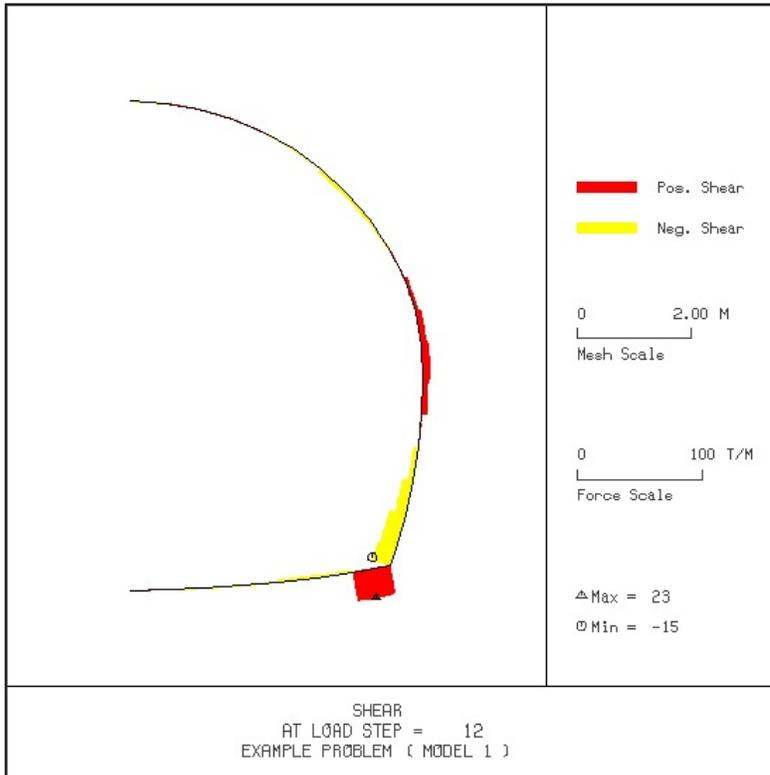


Figure 6.29

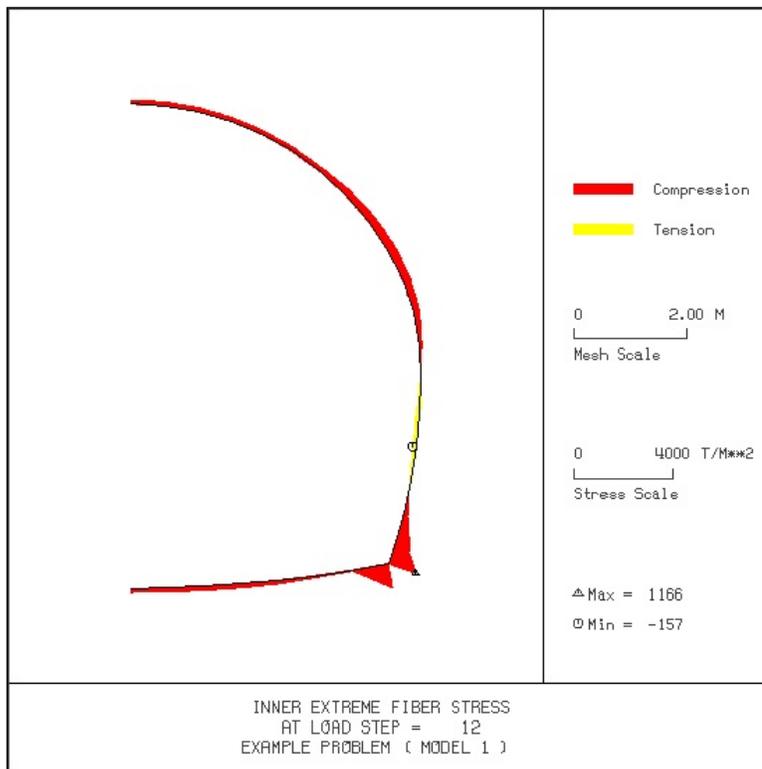


Figure 6.30

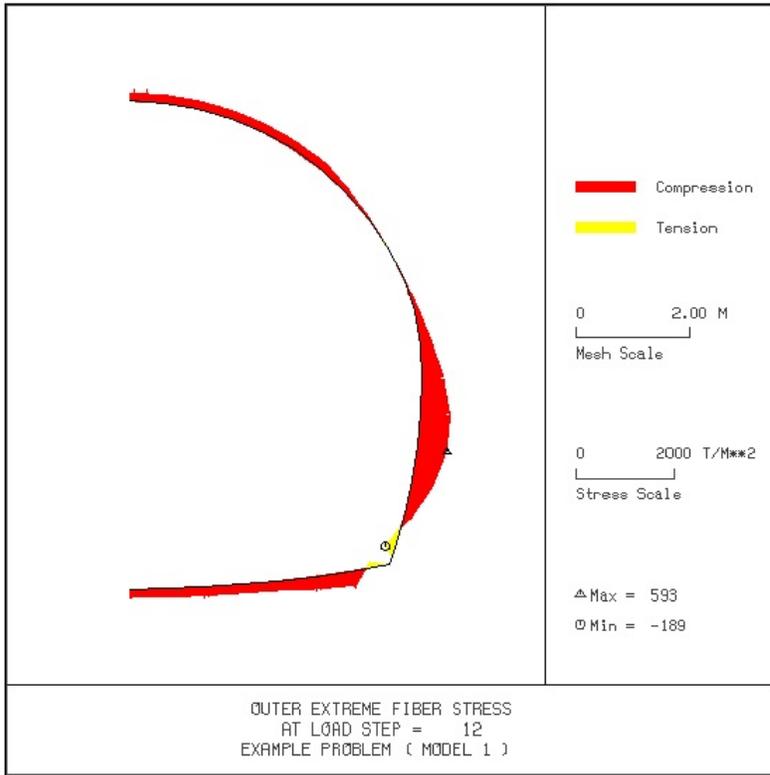


Figure 6.31

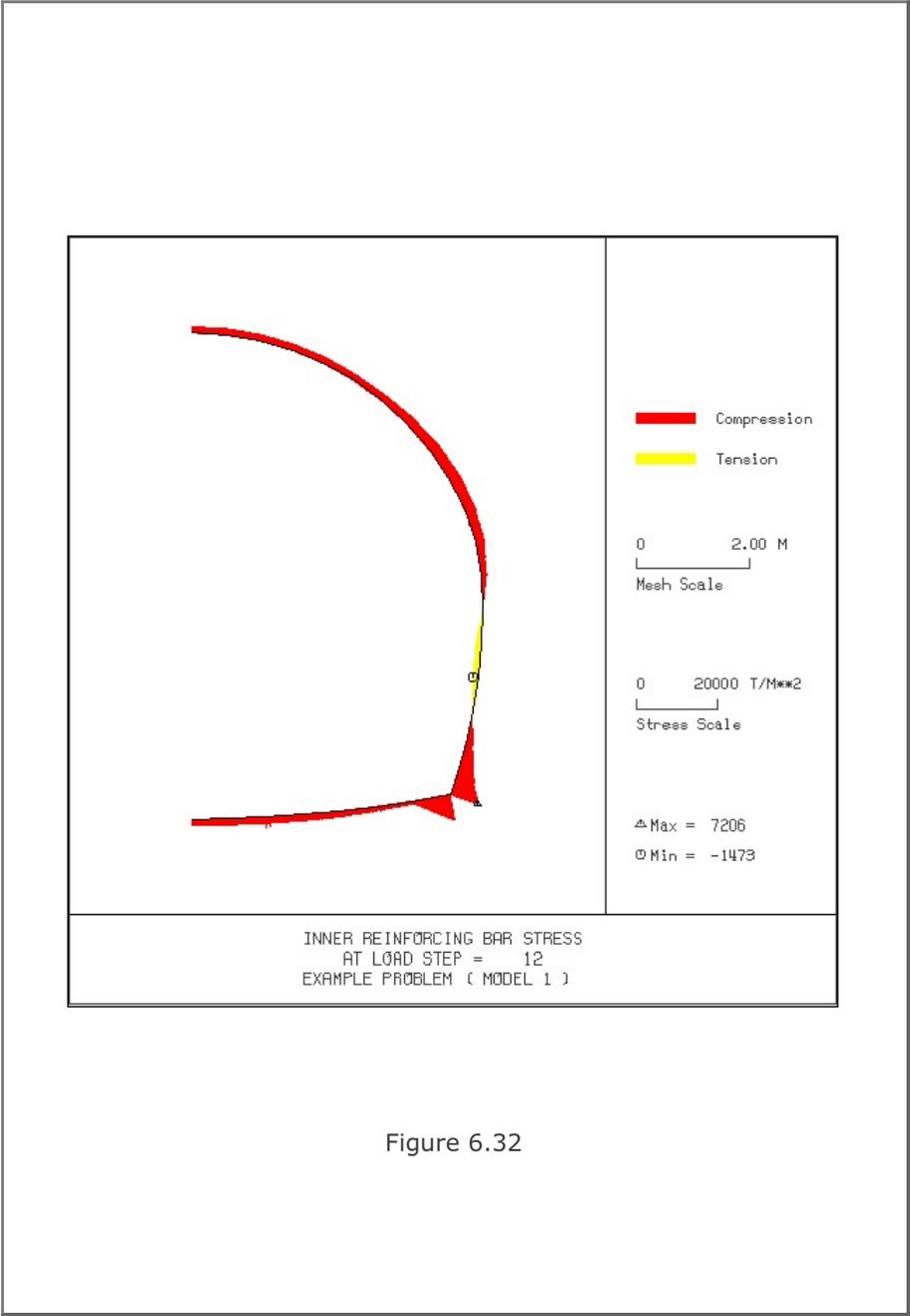


Figure 6.32

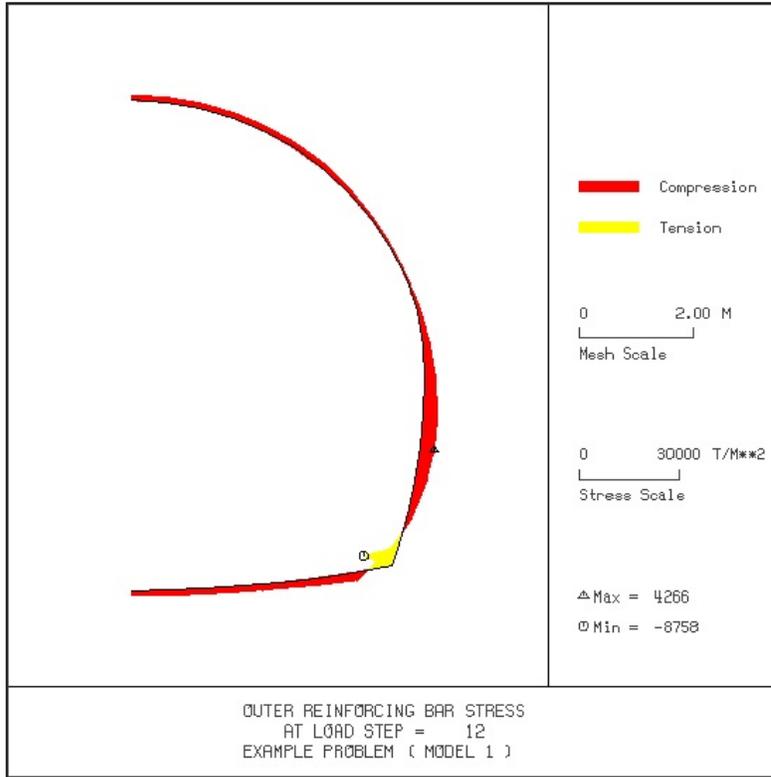


Figure 6.33

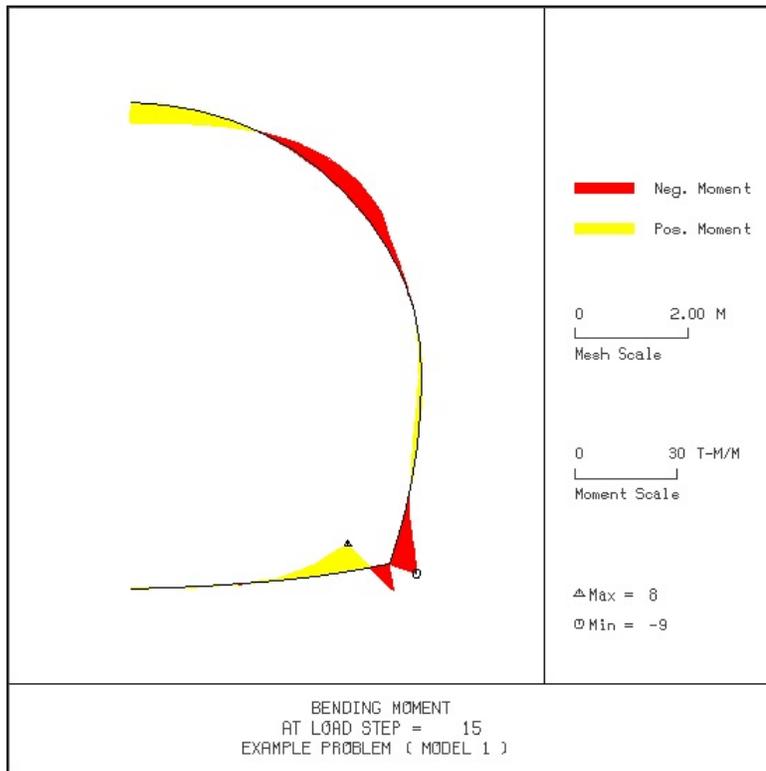


Figure 6.34

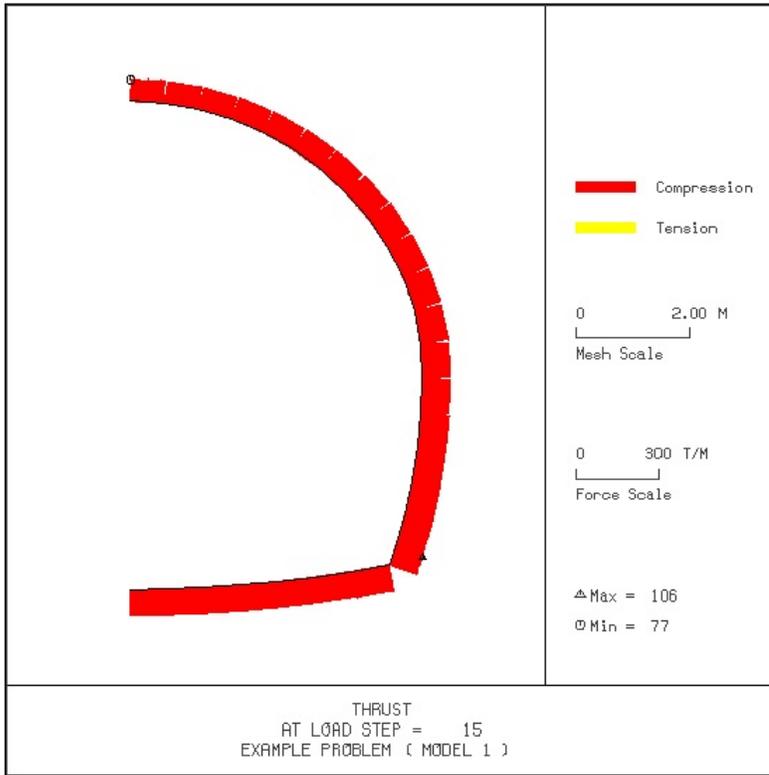


Figure 6.35

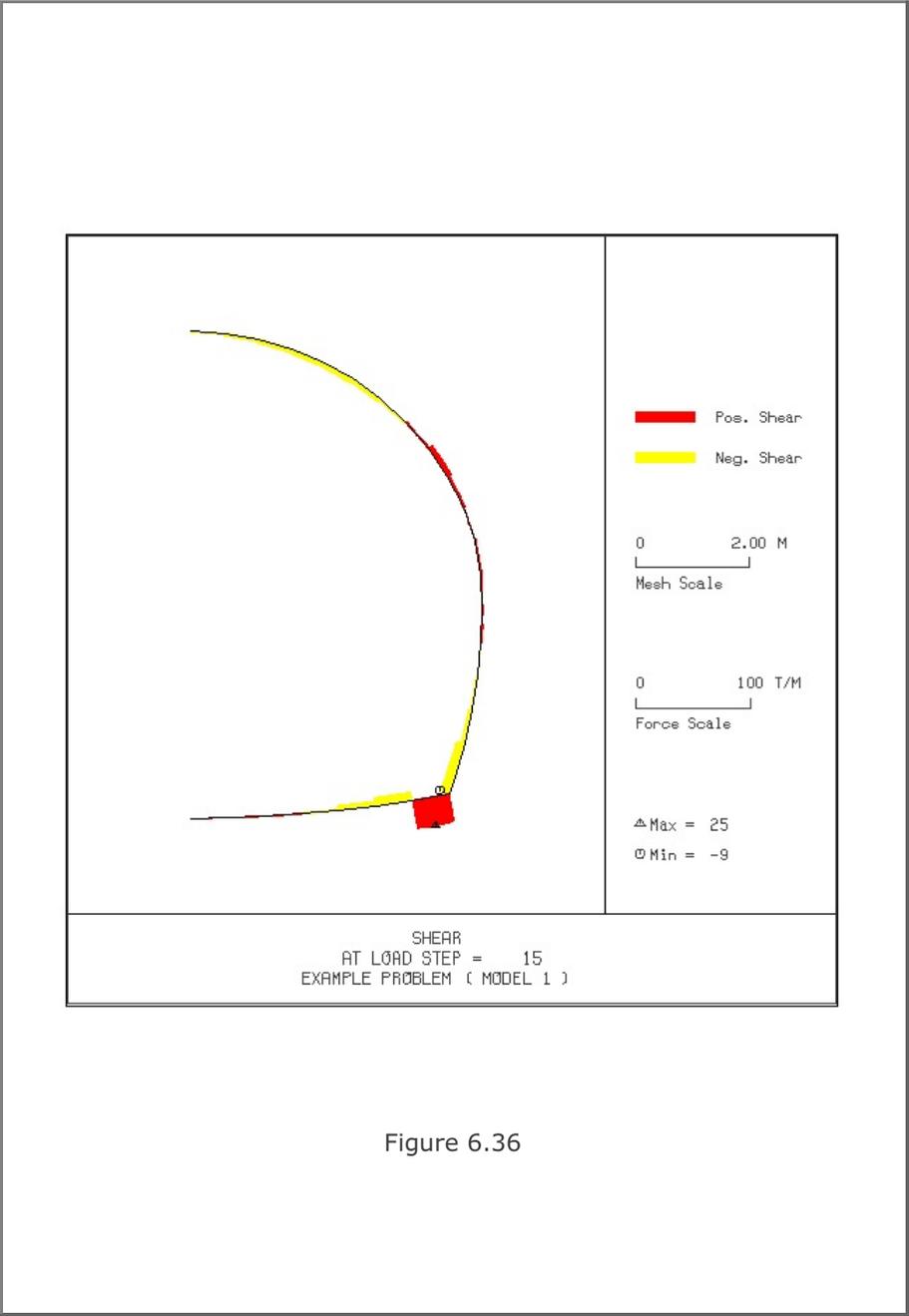


Figure 6.36

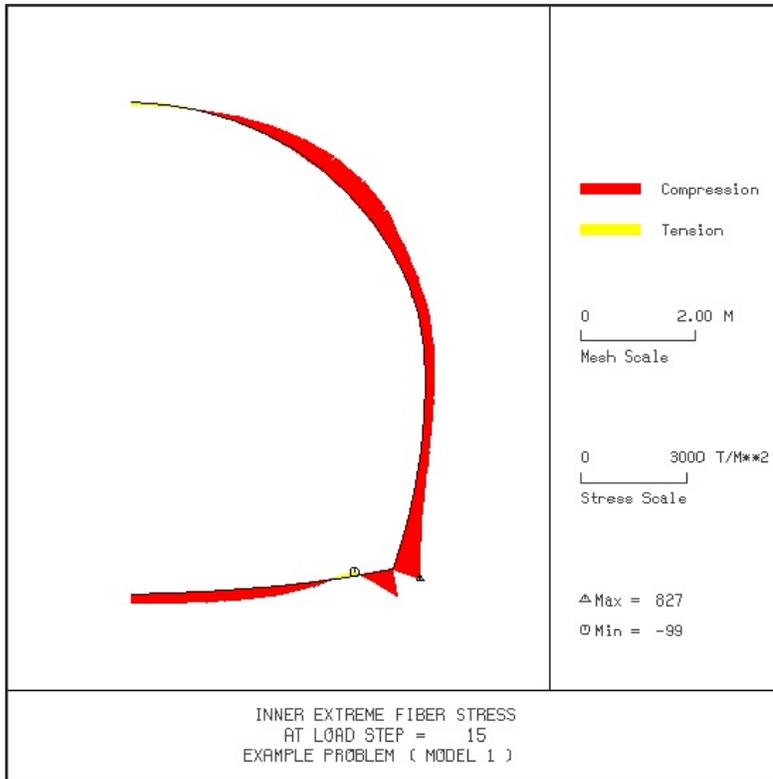


Figure 6.37

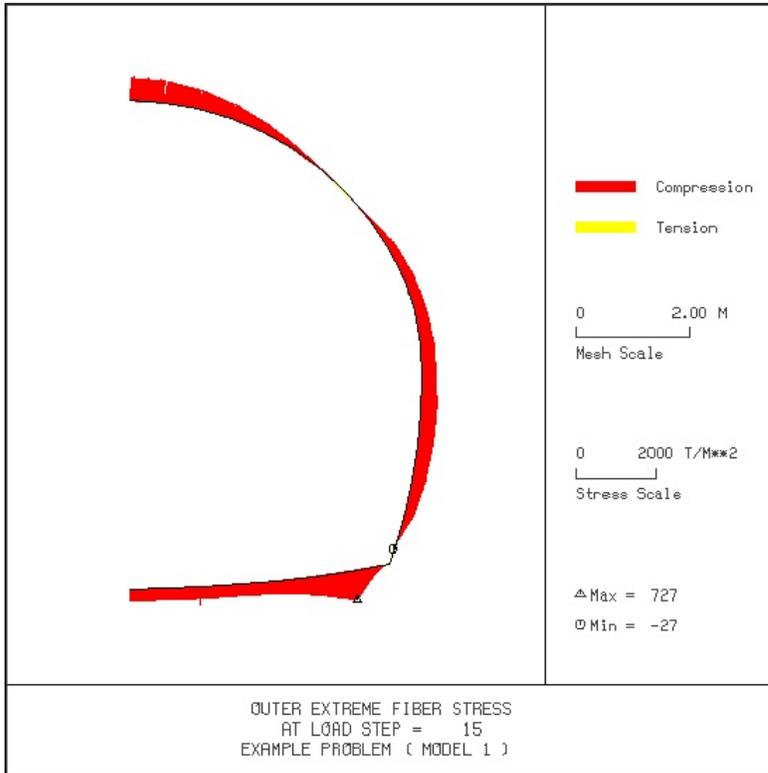


Figure 6.38

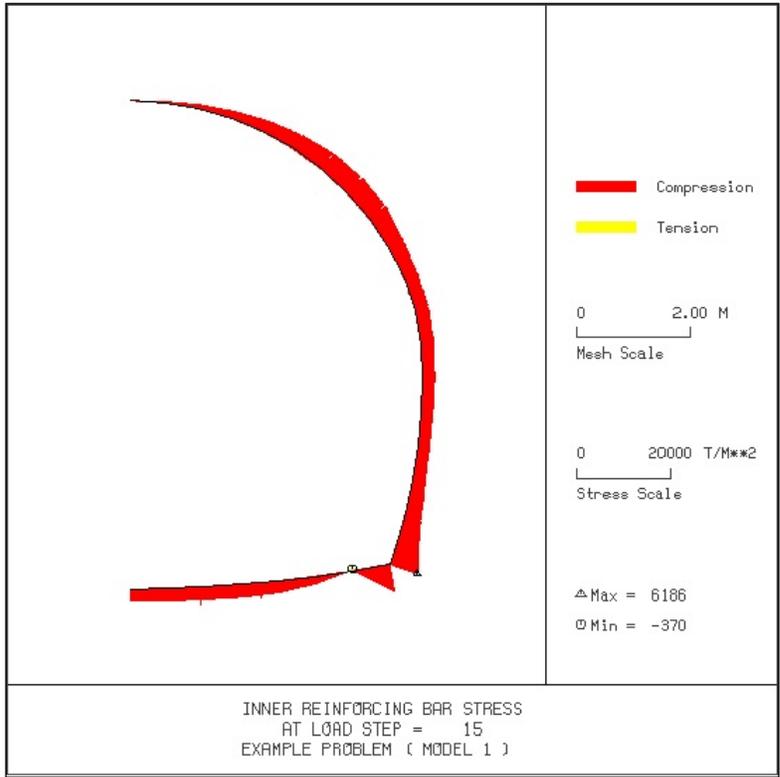


Figure 6.39

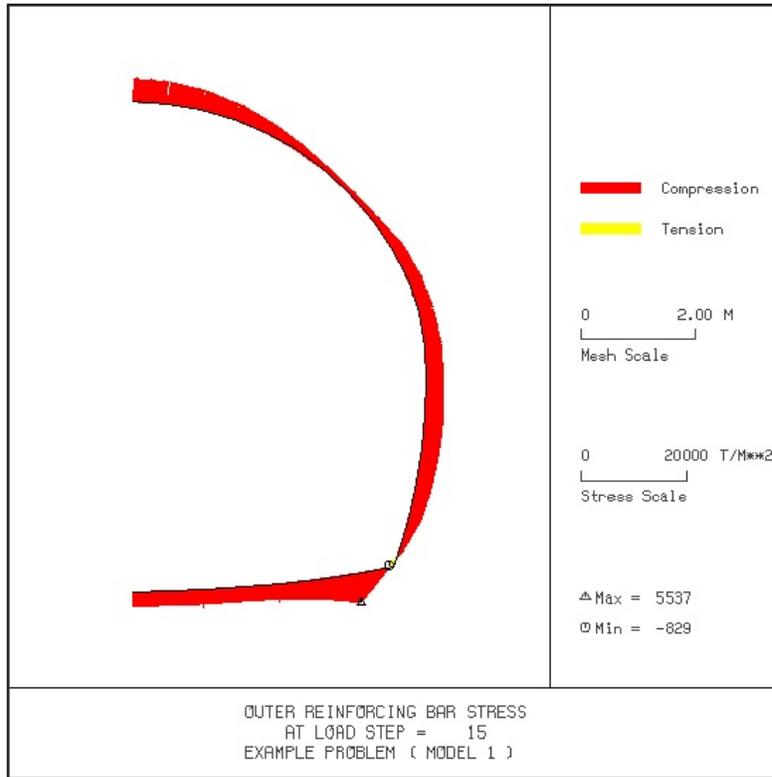


Figure 6.40

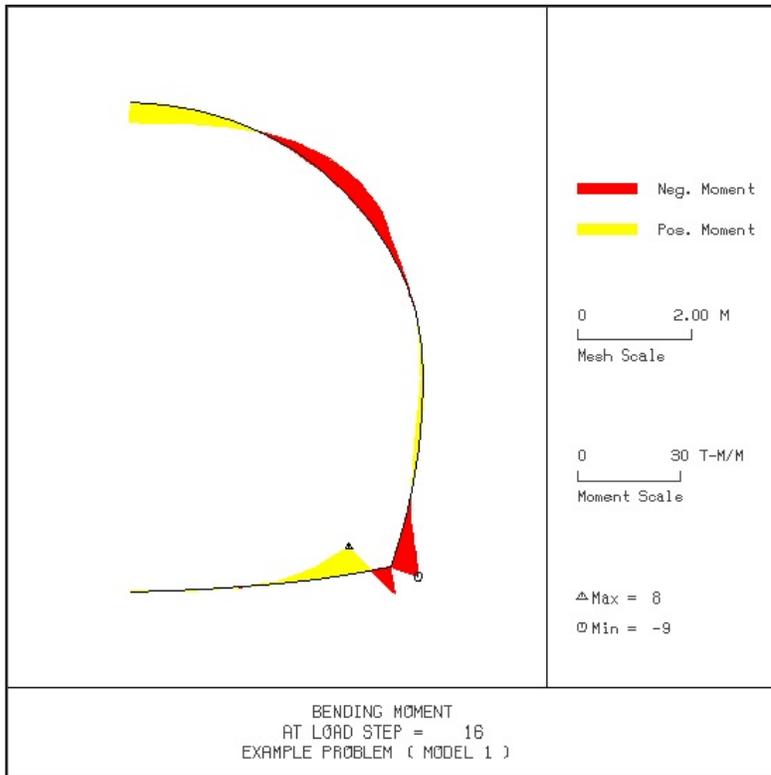


Figure 6.41

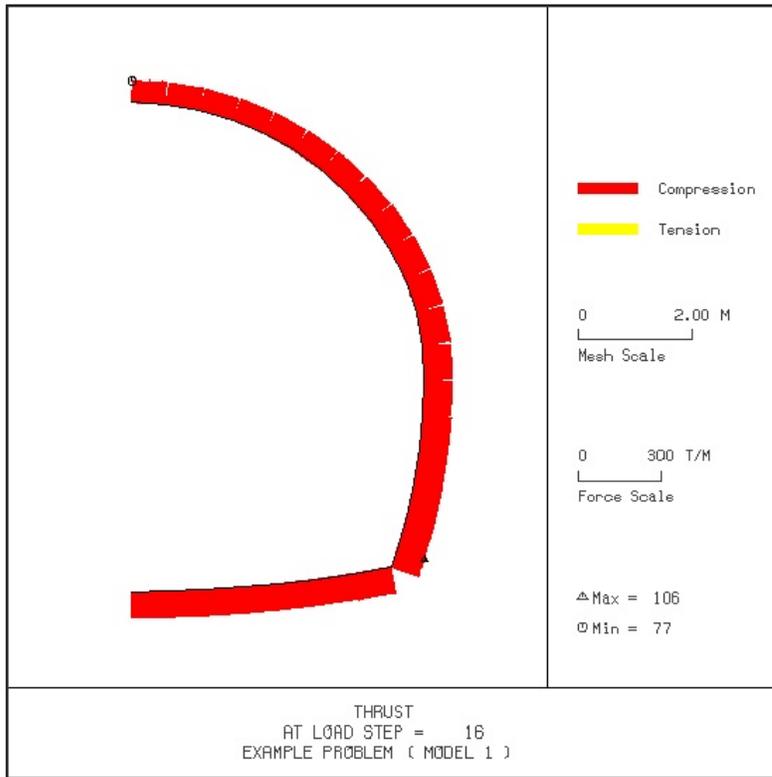


Figure 6.42

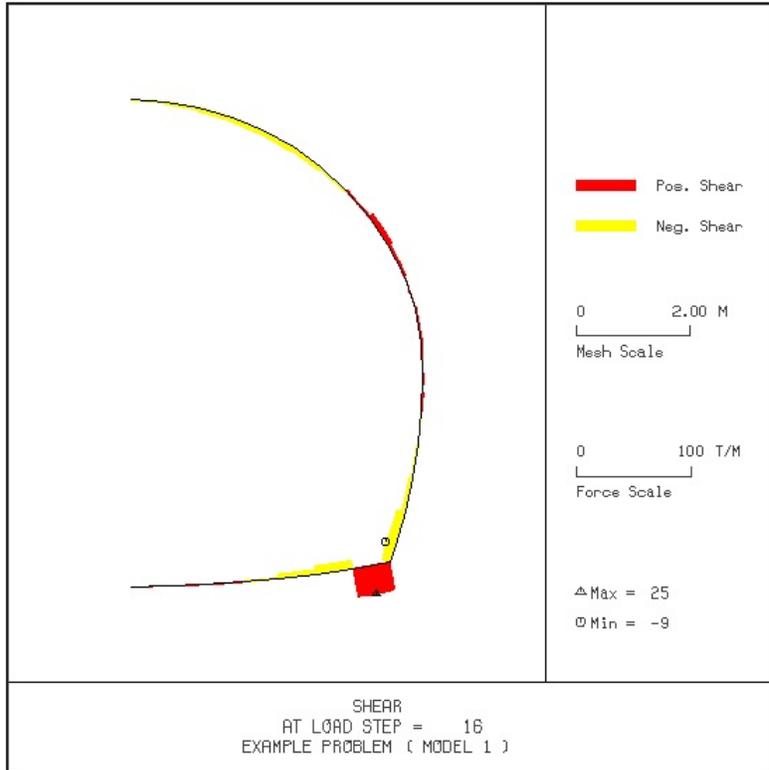


Figure 6.43

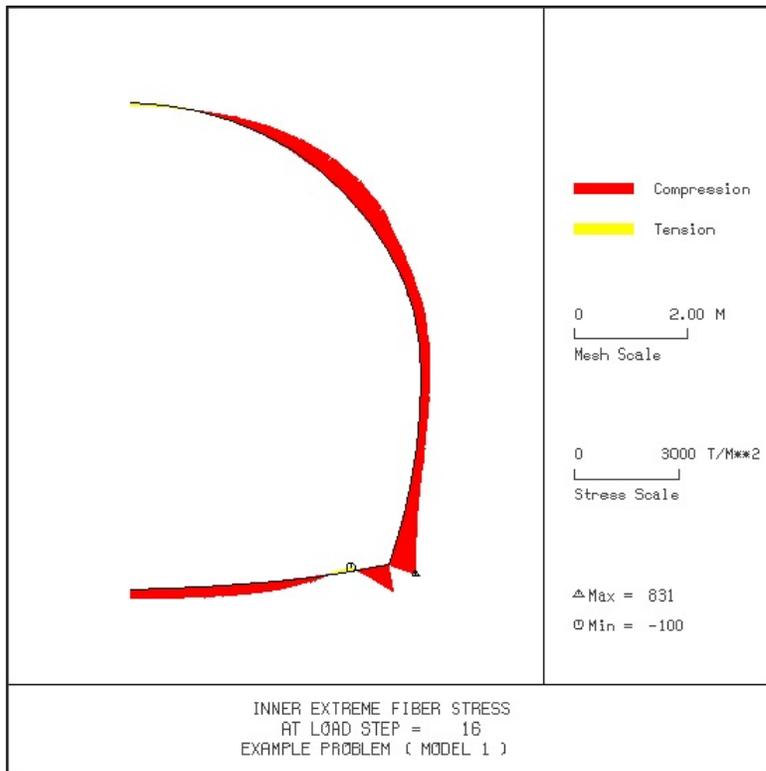


Figure 6.44

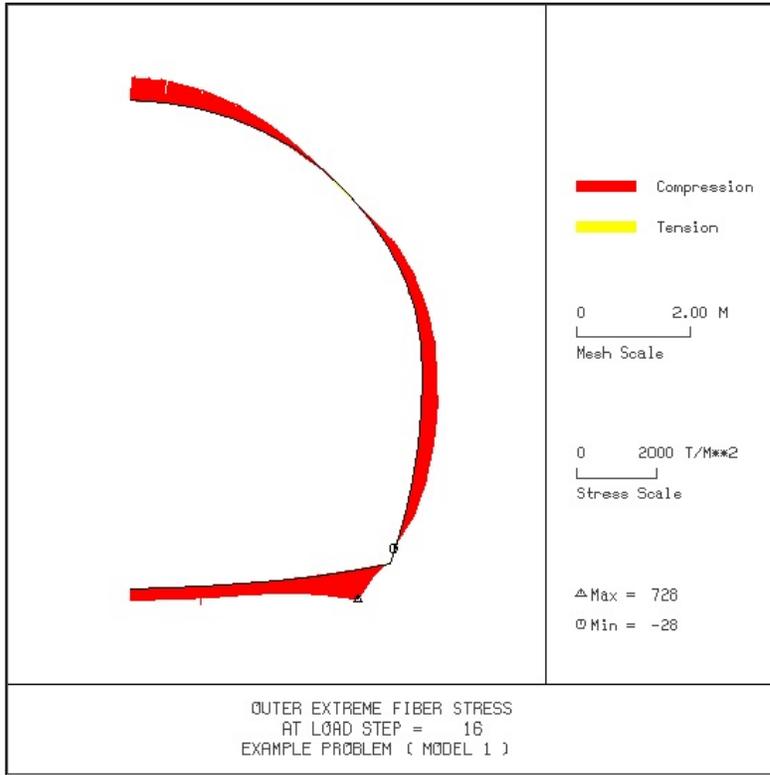


Figure 6.45

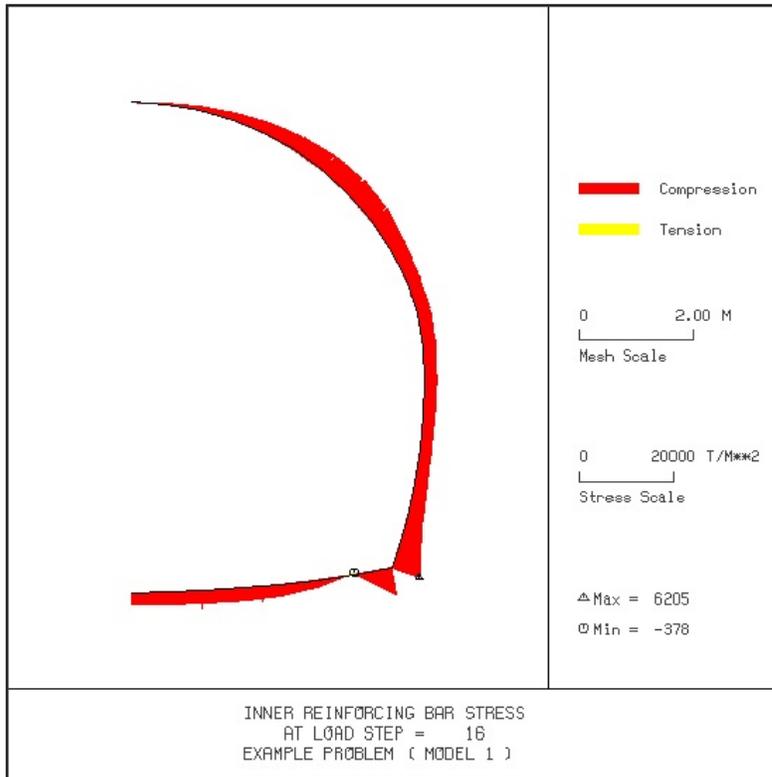


Figure 6.46

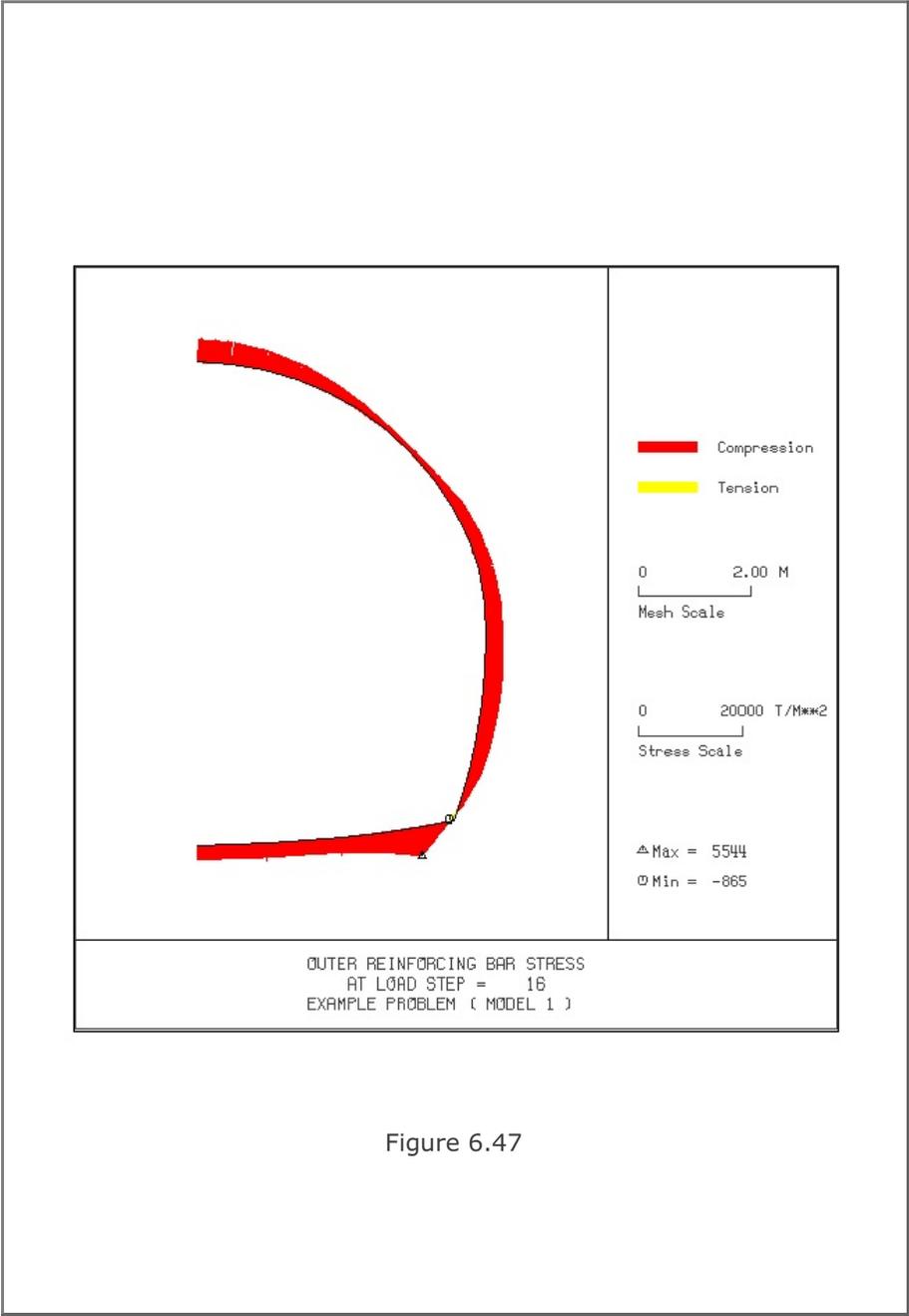


Figure 6.47

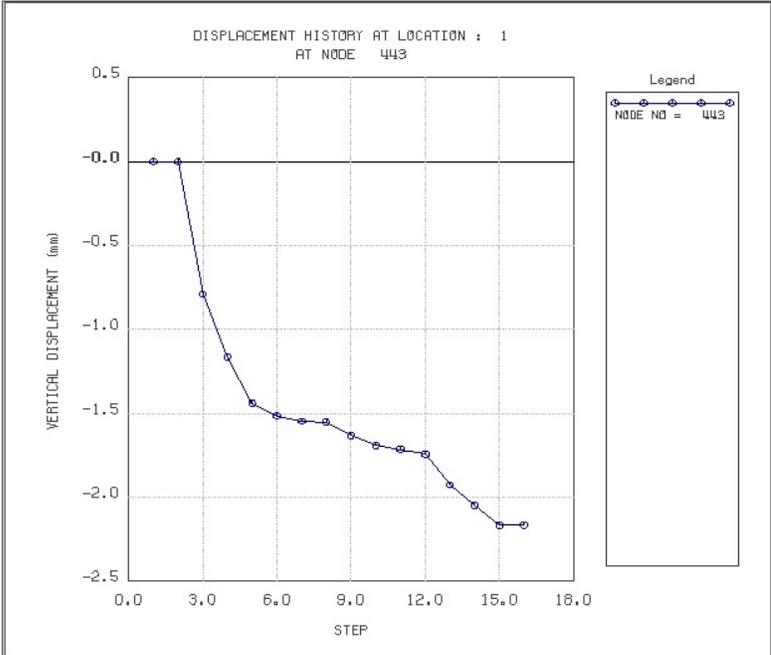


Figure 6.48

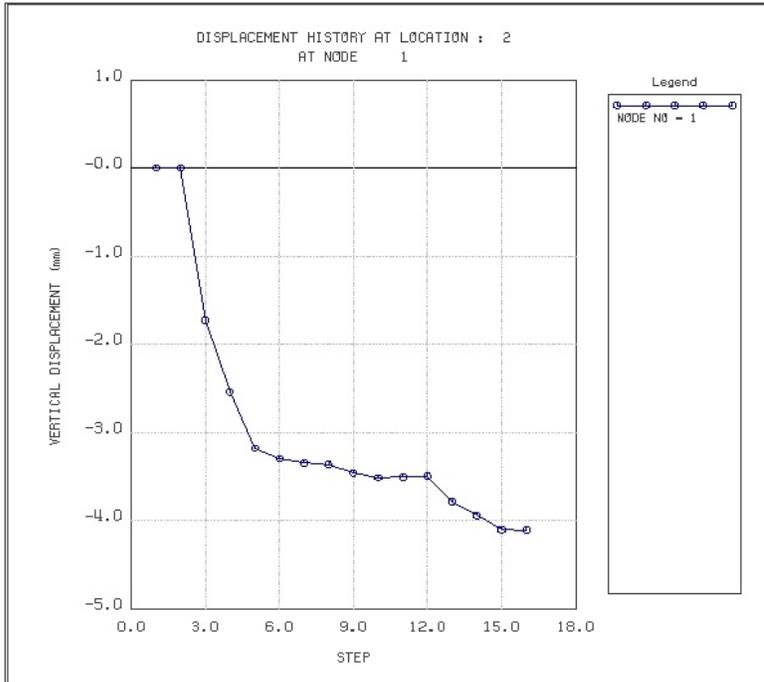


Figure 6.49

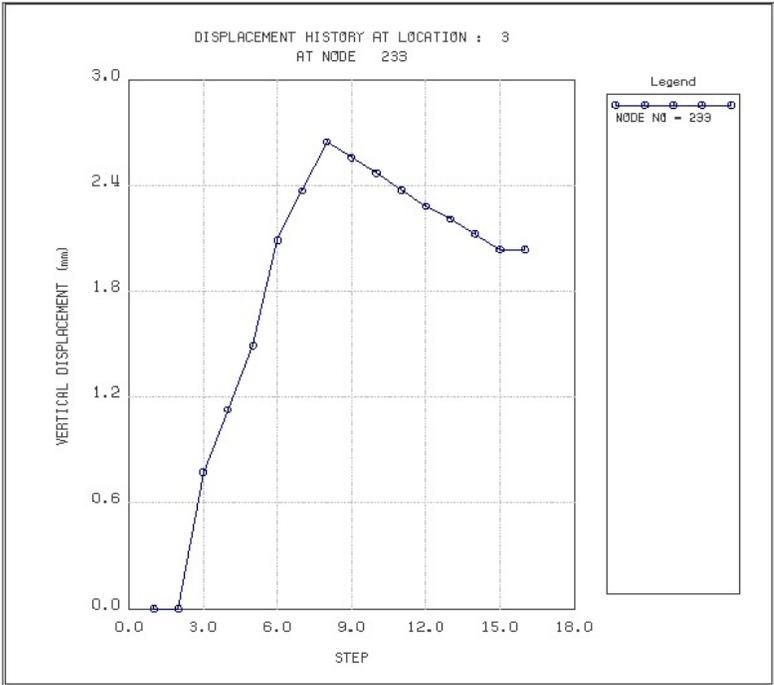


Figure 6.50

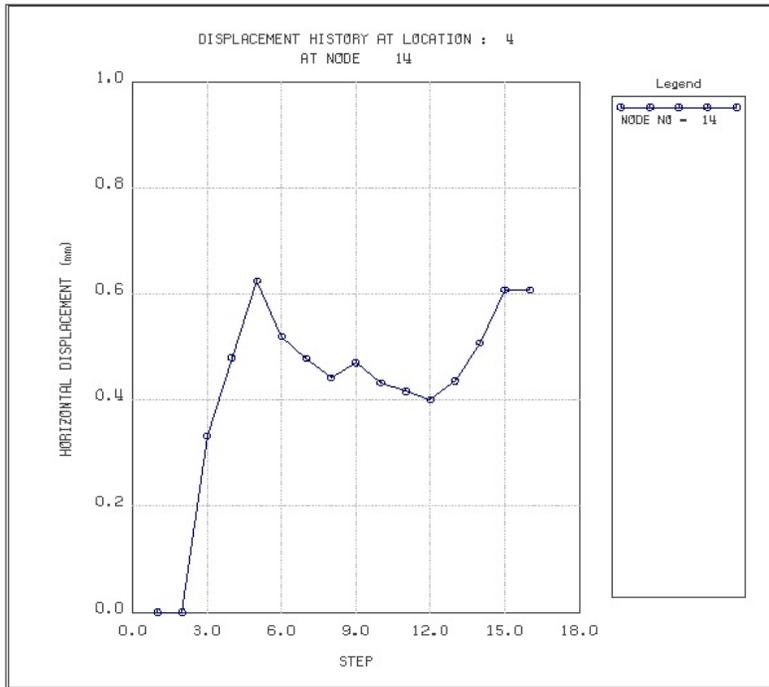


Figure 6.51

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_0 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

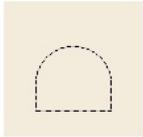
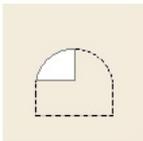
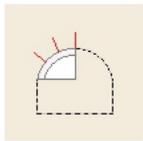
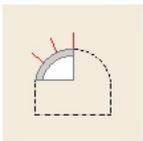
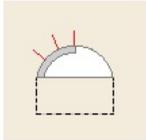
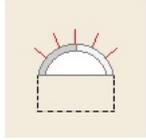
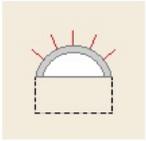
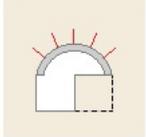
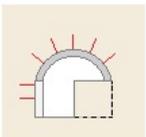
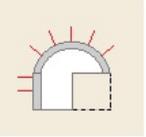
Step	Construction State	Descriptions
1,2		In Situ K_0 State
3		50% Stress Relief
4		75% Stress Relief Soft Shotcrete Rock Bolt
5		100% Stress Relief Hard Shotcrete Rock Bolt
Upper Left Core Excavation		

Table 6.8 Simulation of construction sequence (Continued)

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

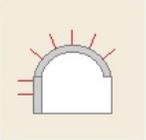
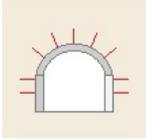
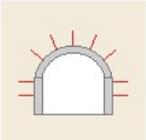
Upper Right Core Excavation

Table 6.8 Simulation of construction sequence (Continued)

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

Lower Left Core Excavation

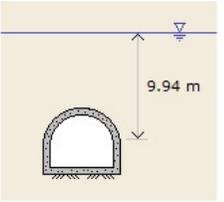
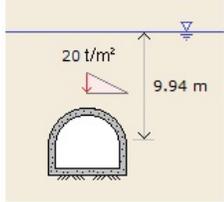
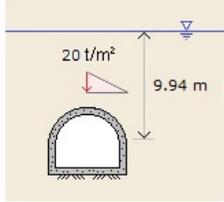
Table 6.8 Simulation of construction sequence (Continued)

Step	Construction State	Descriptions
12		50% Stress Relief
13		75% Stress Relief Soft Shotcrete Rock Bolt
14		100% Stress Relief Hard Shotcrete Rock Bolt

Lower Right Core Excavation

6-74 Example 2

Table 6.8 Simulation of construction sequence (Continued)

Step	Construction State	Descriptions
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

Lining Analysis

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
* N LAYER
  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

```

6-76 Example 2

```
*
* 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

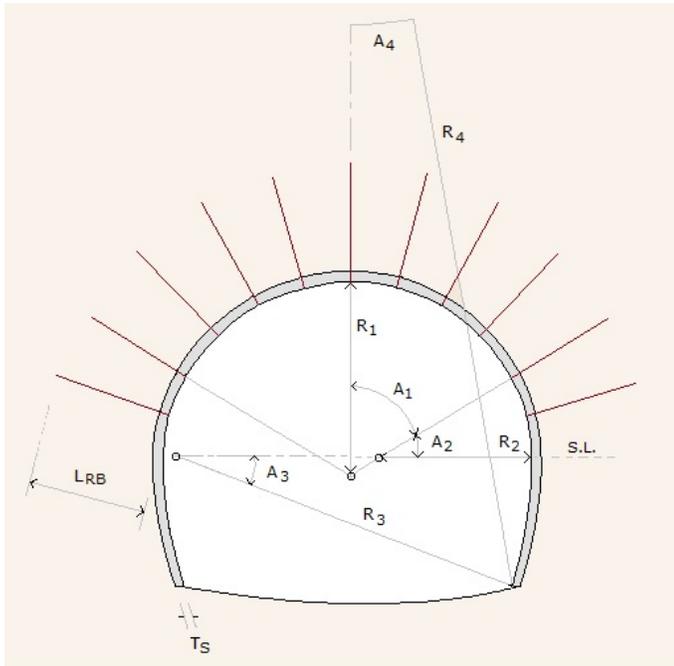
STEP NO	DESCRIPTIONS
5	Excavation of Upper Left Core
8	Excavation of Upper Right Core
11	Excavation of Lower Left Core
14	Excavation of Lower Right Core
15	<u>Lining Subjected to:</u> Weight
18	<u>Lining Subjected to:</u> Weight Water Pressure
21	<u>Lining Subjected to:</u> Weight Water Pressure Loosening 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



$R_1 = 7.24 \text{ M}$ $A_1 = 60^\circ$
 $R_2 = 6.24 \text{ M}$ $A_2 = 30^\circ$
 $R_3 = 11.86 \text{ M}$ $A_3 = 21.781^\circ$
 $R_4 = 25.86 \text{ M}$

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 Cm²
 Reinforcing Bar Area (ASO) = 33 Cm²

Figure 6.52 Tunnel dimensions used for Example 2

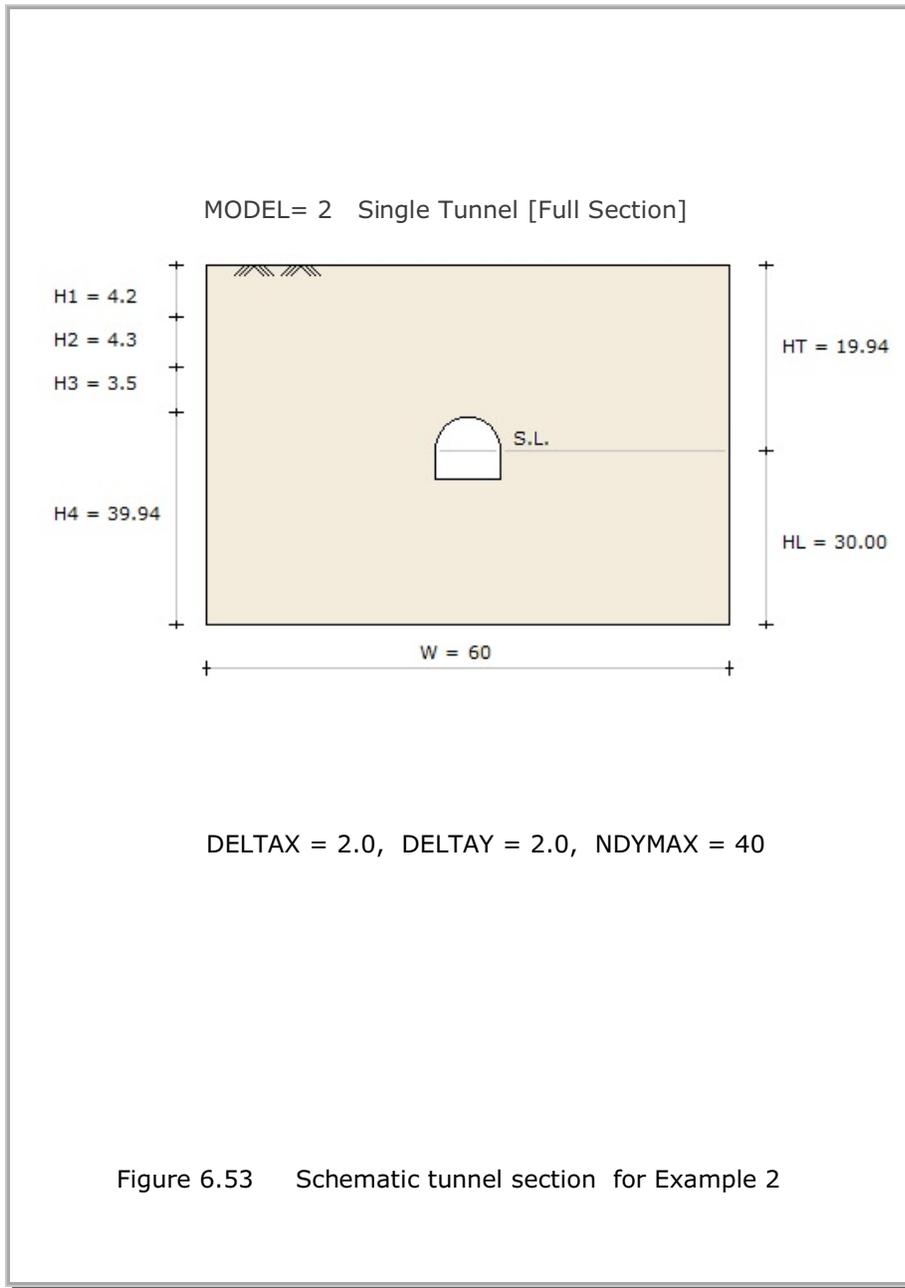


Figure 6.53 Schematic tunnel section for Example 2

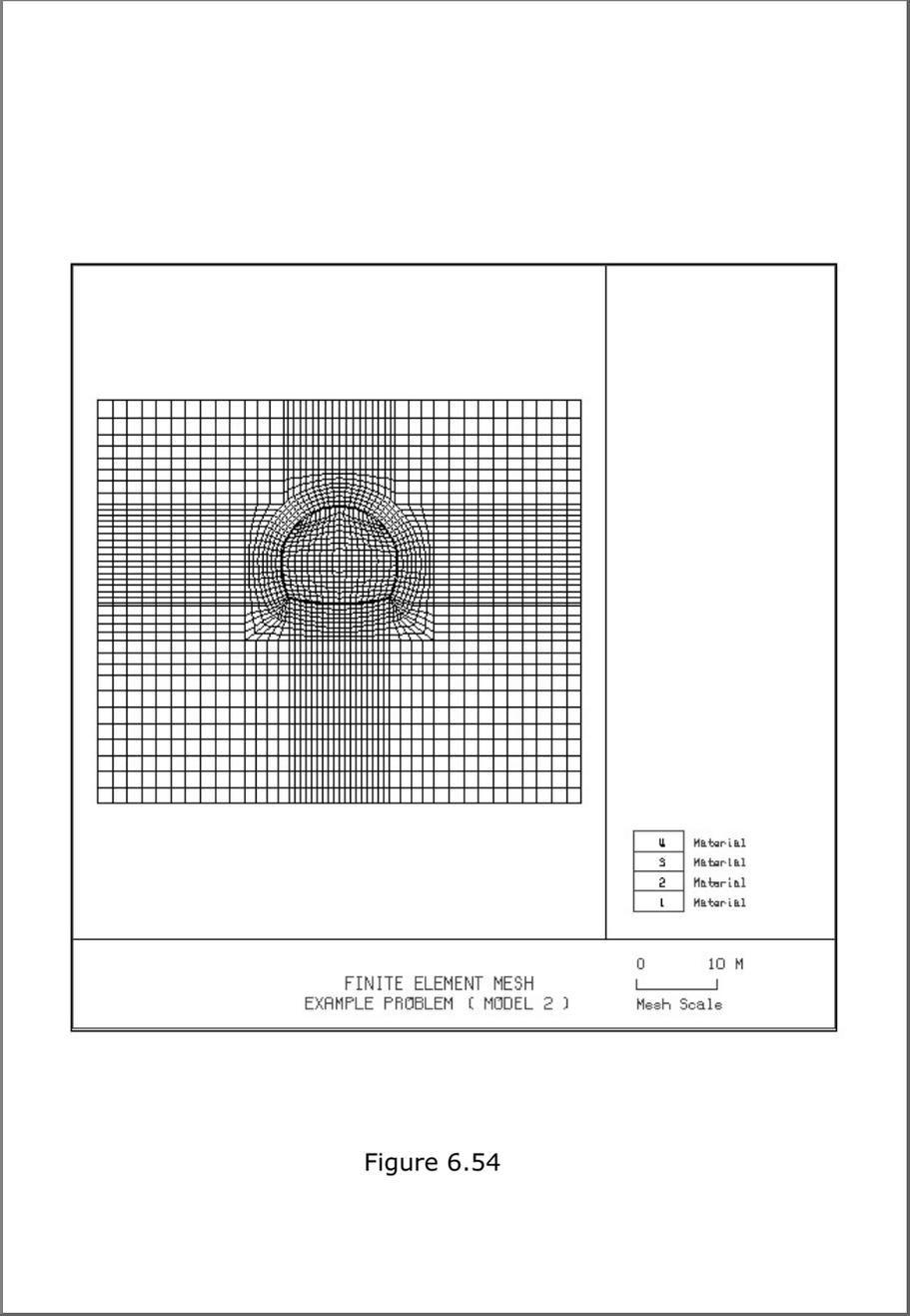


Figure 6.54

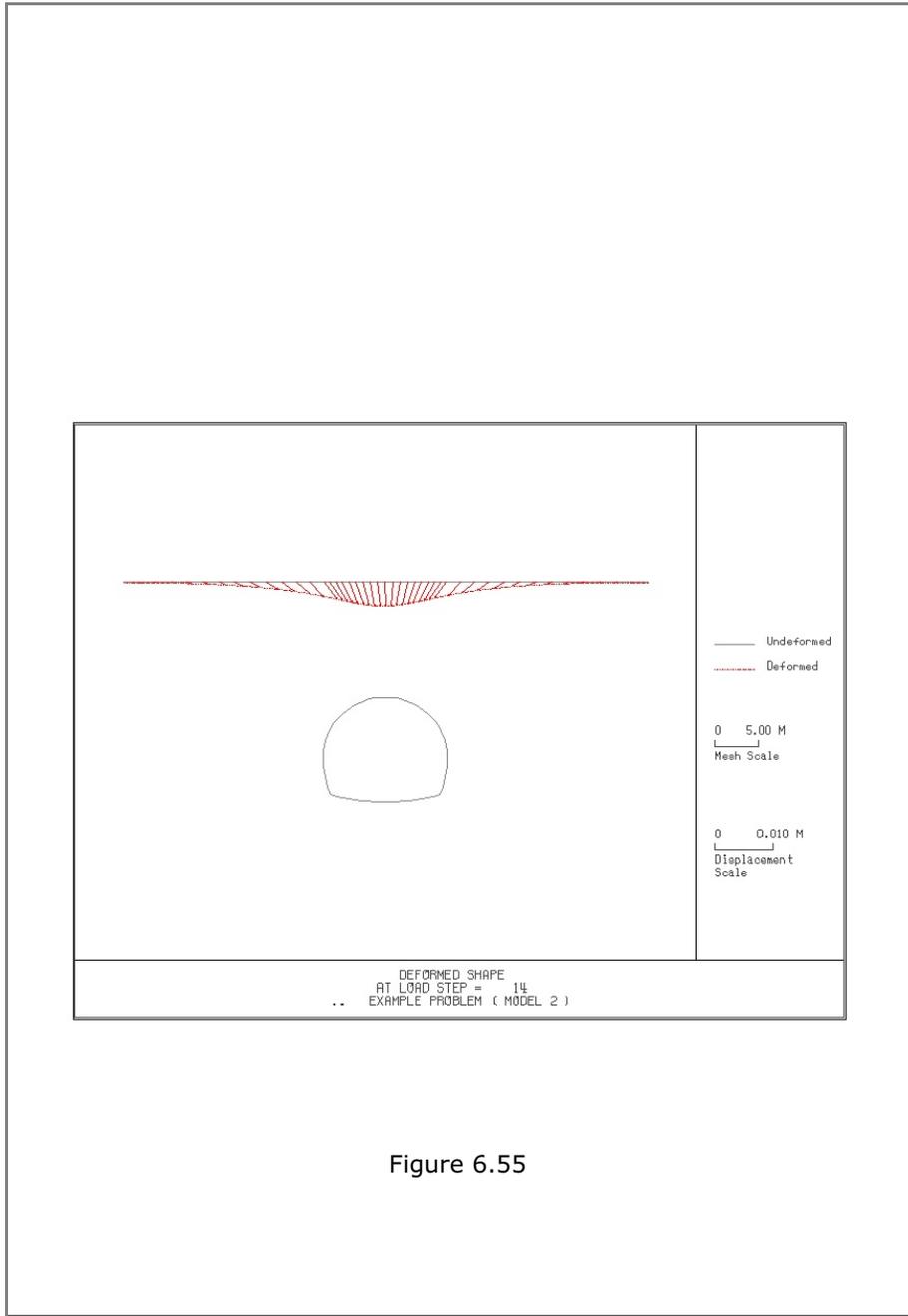


Figure 6.55

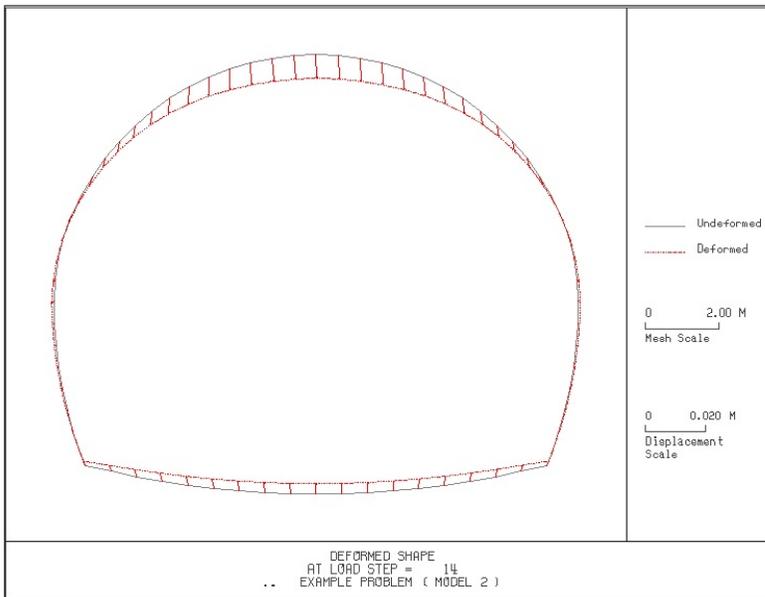


Figure 6.56

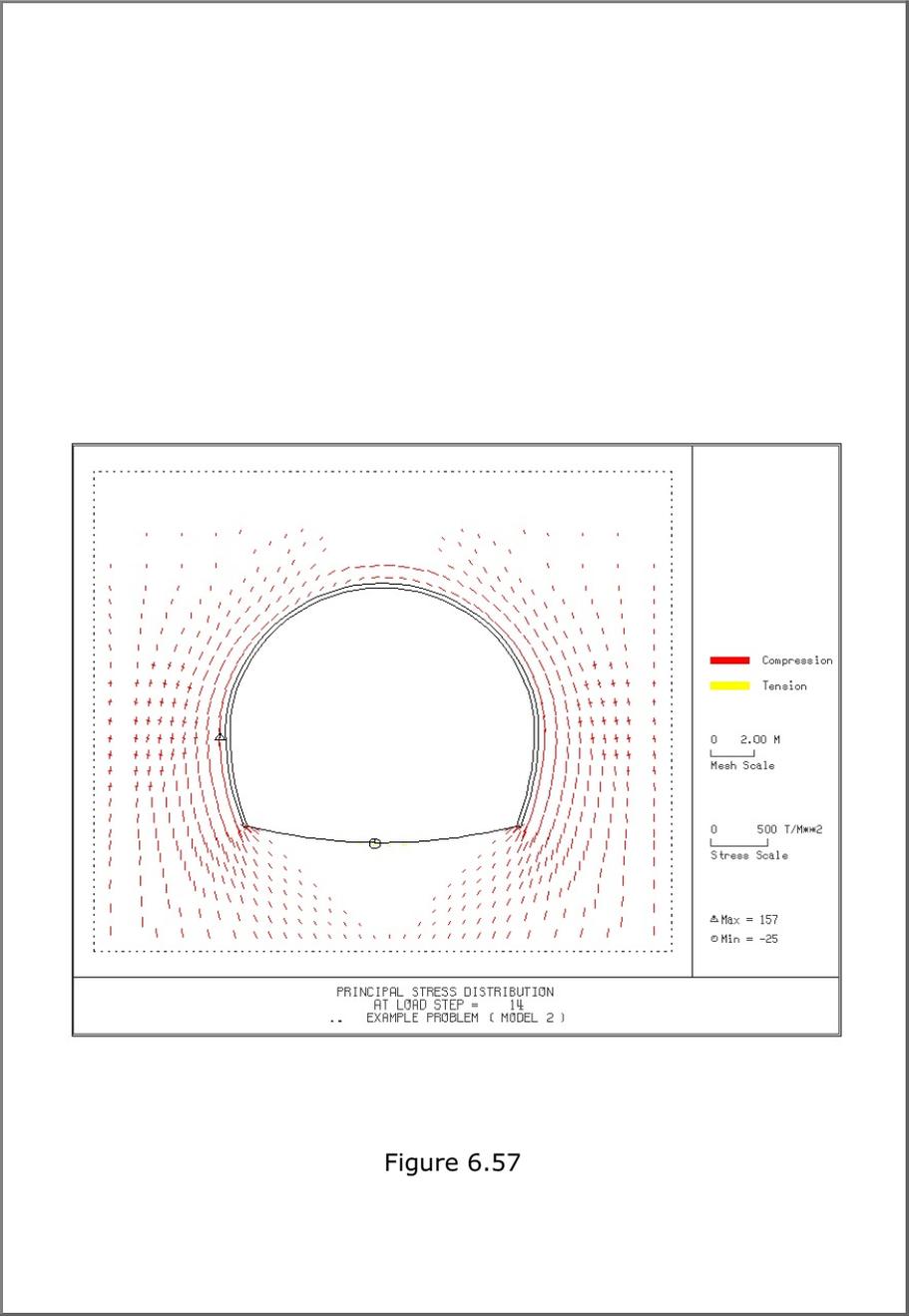


Figure 6.57

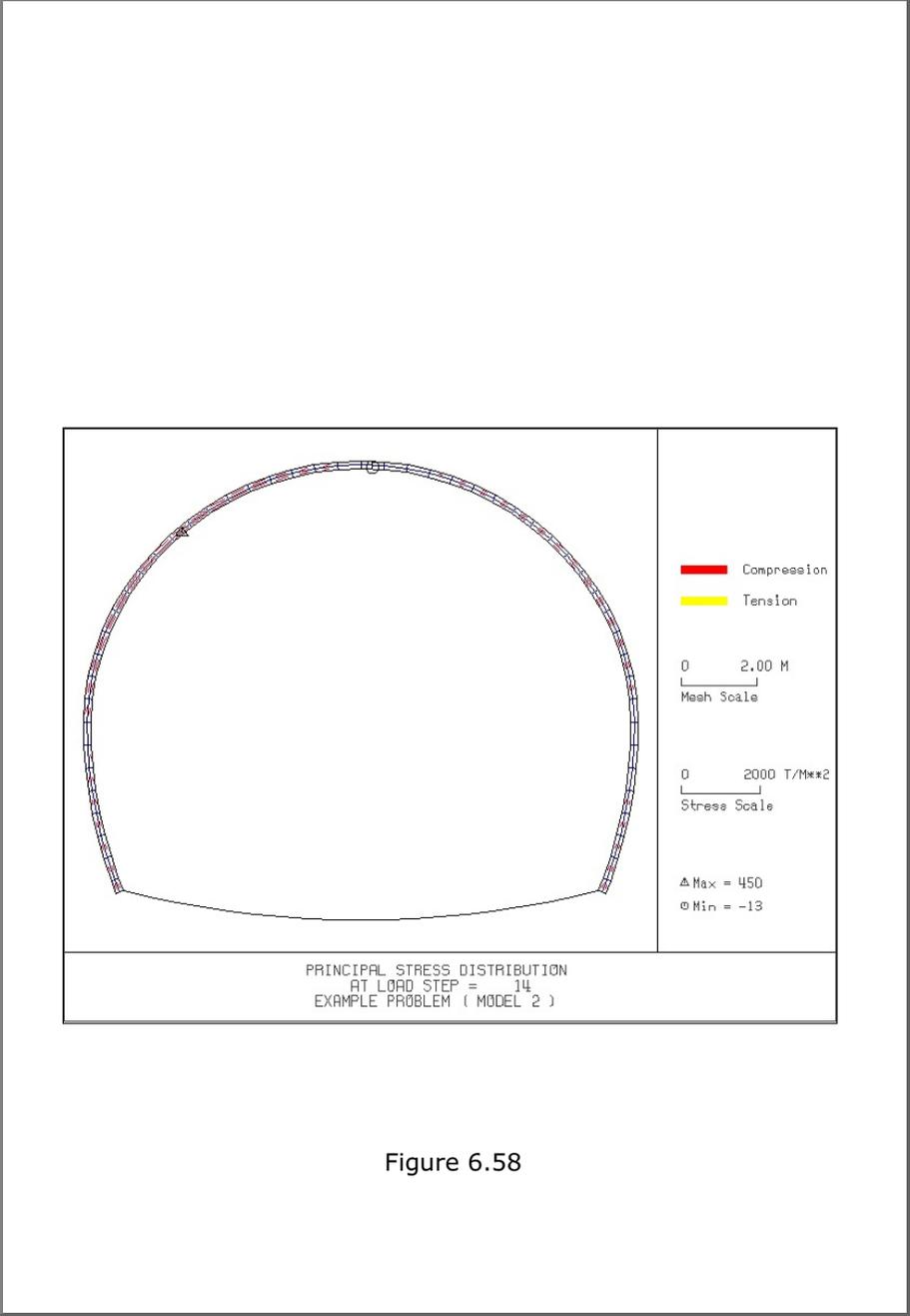


Figure 6.58

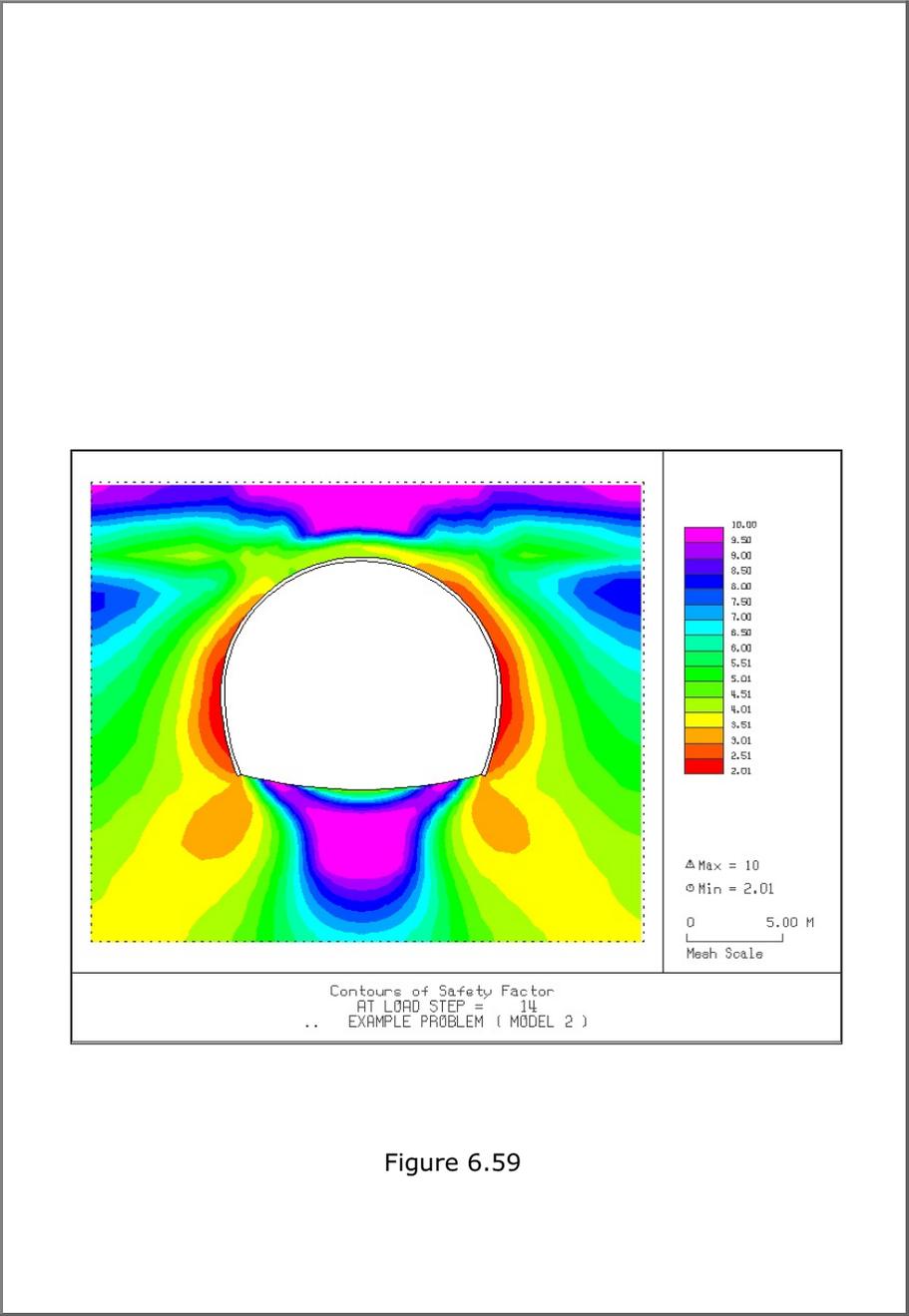


Figure 6.59

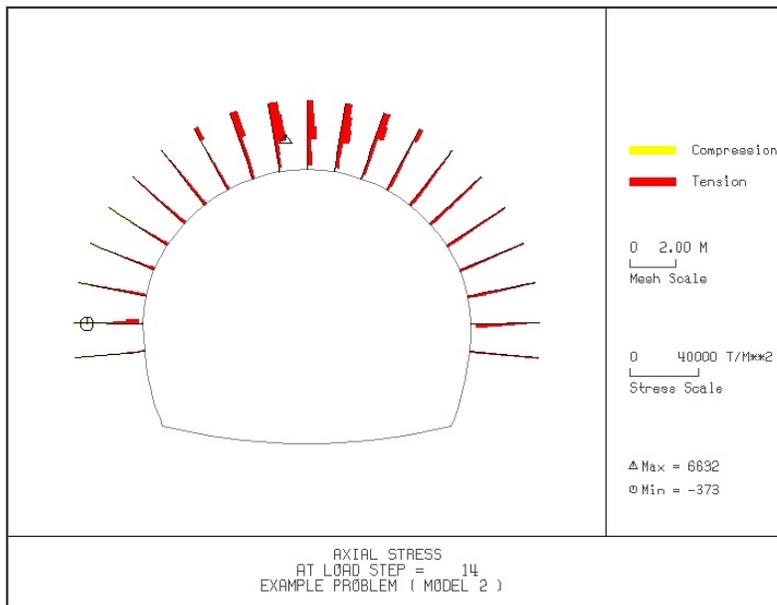


Figure 6.60

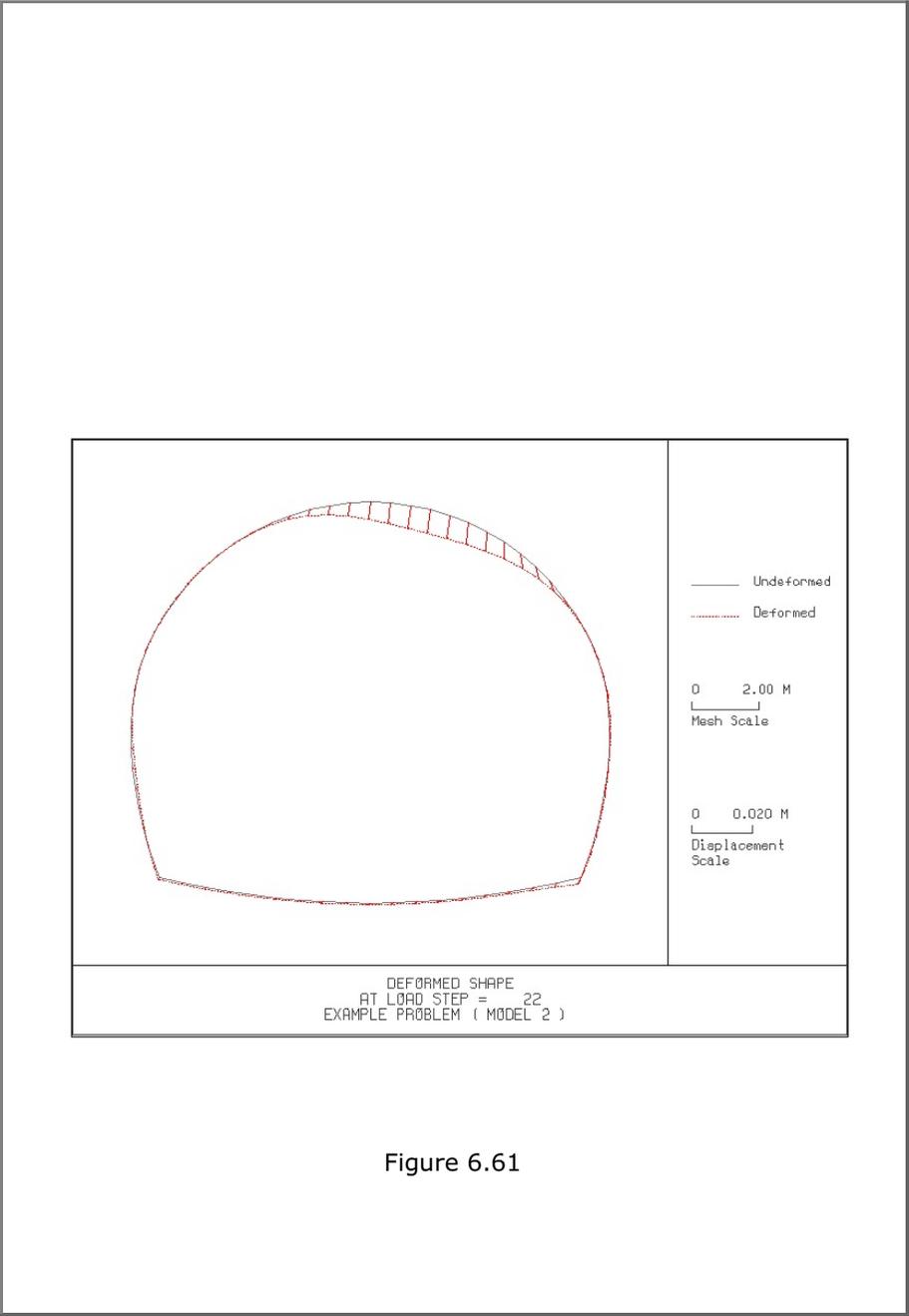


Figure 6.61

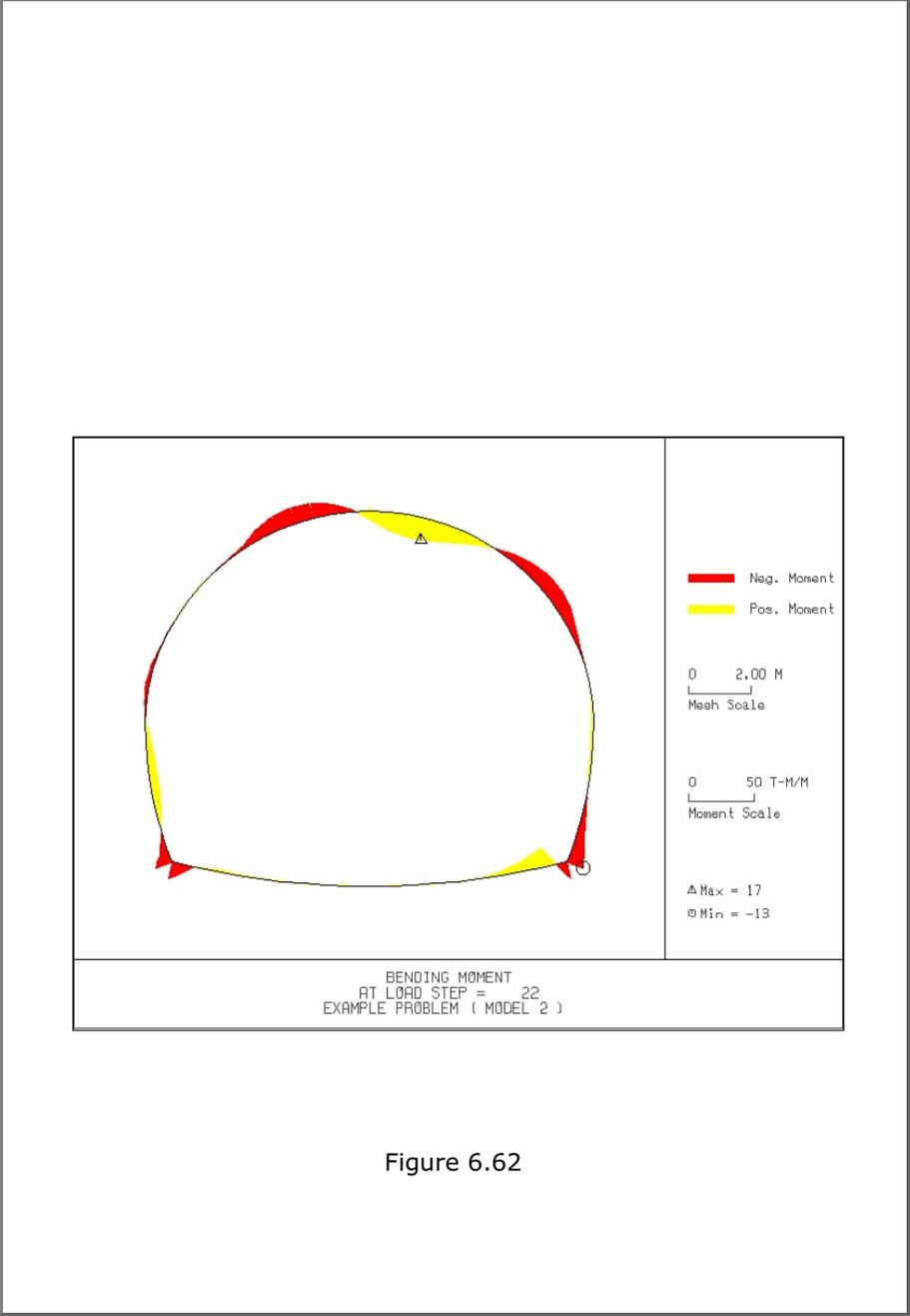


Figure 6.62

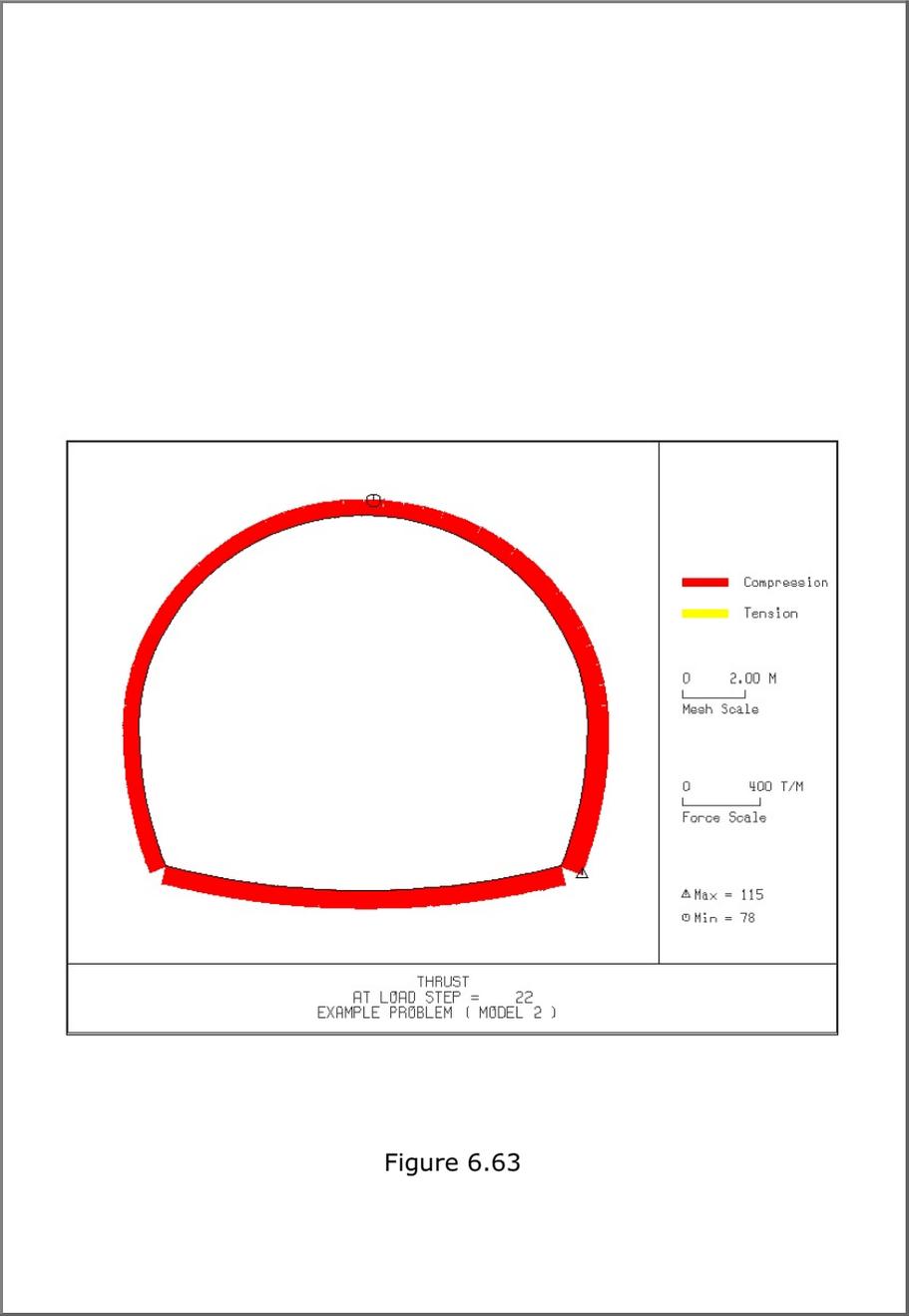


Figure 6.63

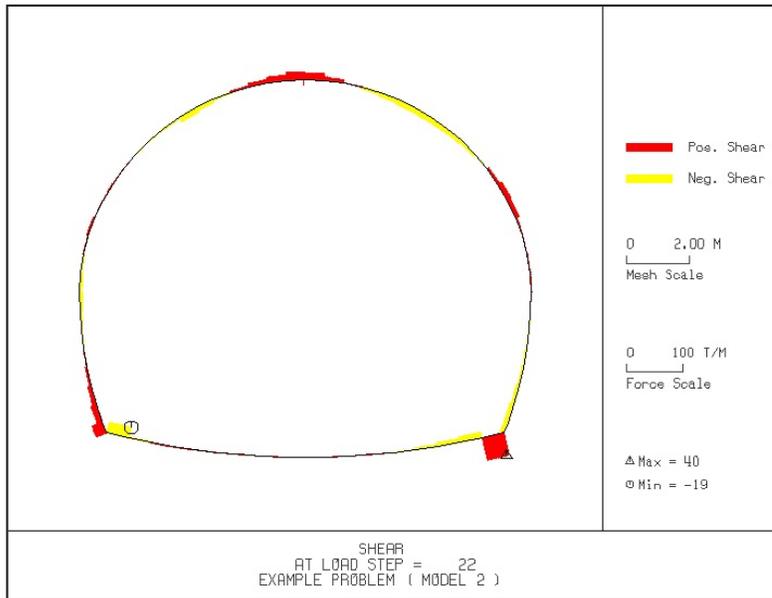


Figure 6.64

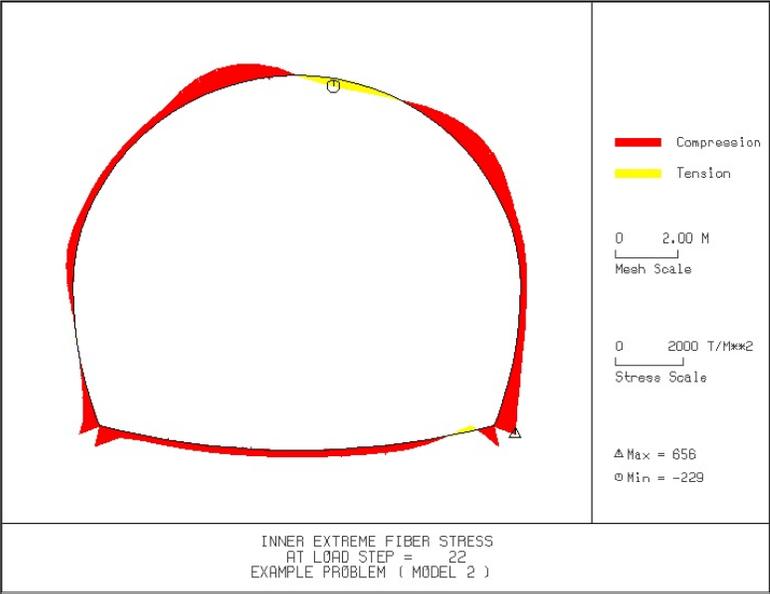


Figure 6.65

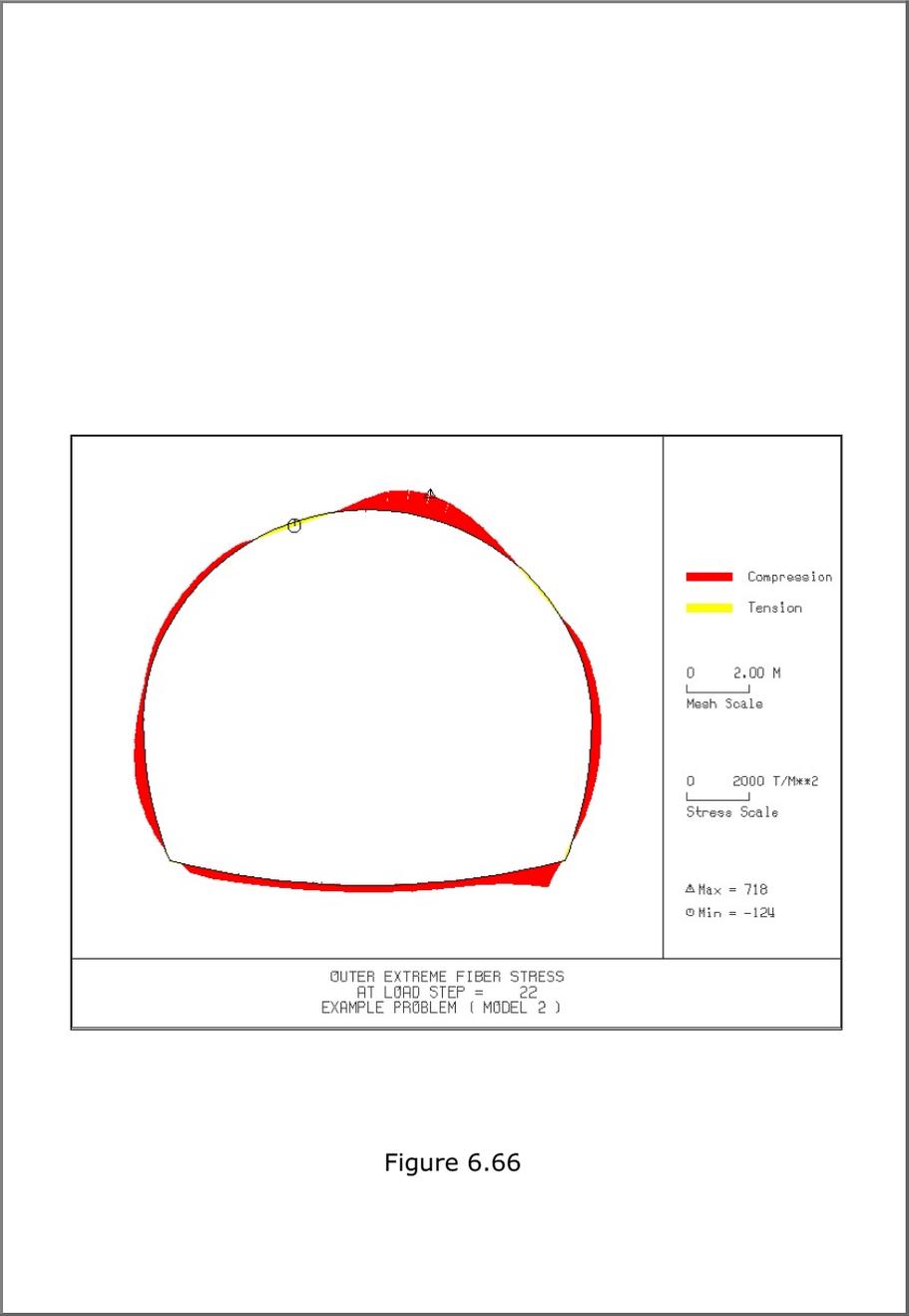


Figure 6.66

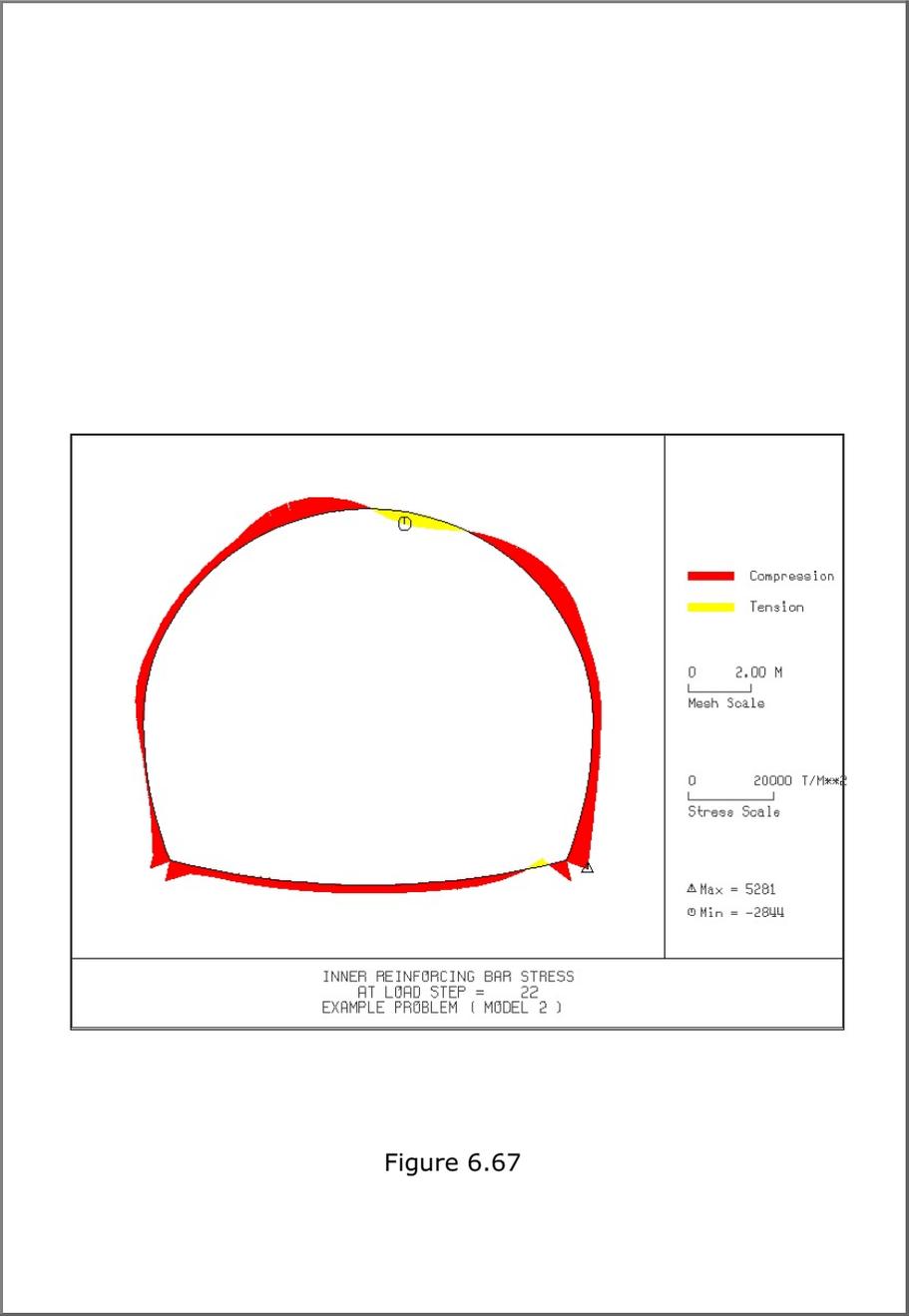


Figure 6.67

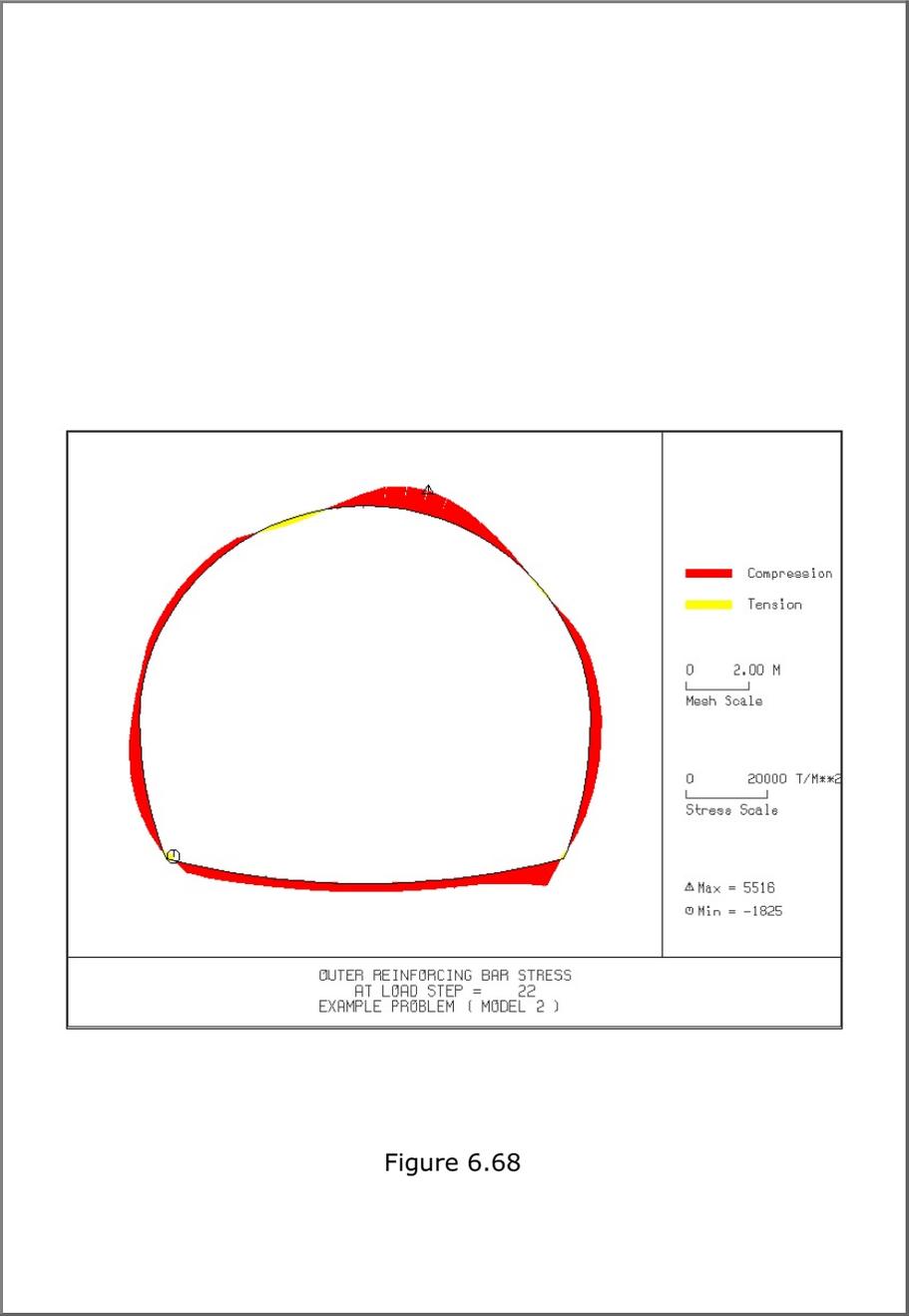


Figure 6.68

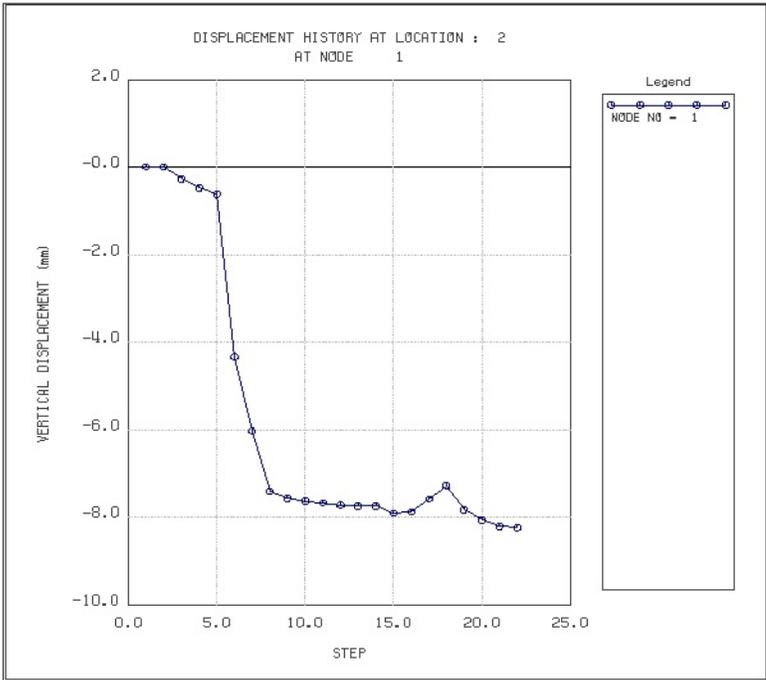


Figure 6.69

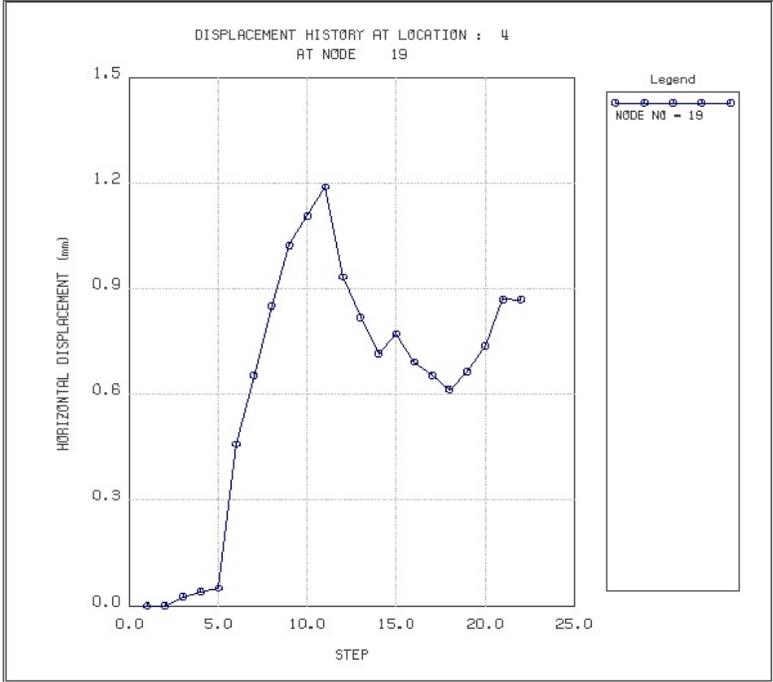


Figure 6.70

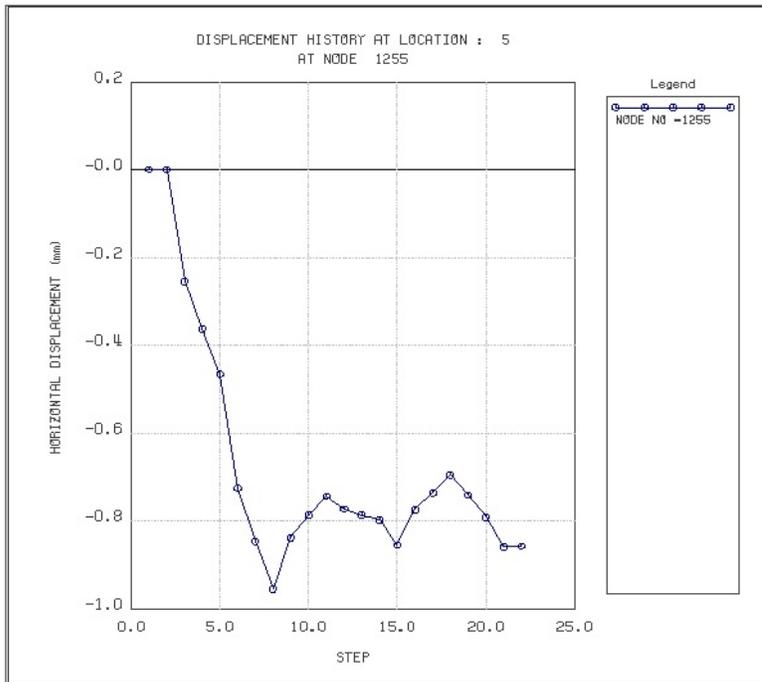


Figure 6.71

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_0 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

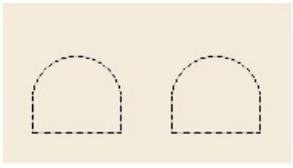
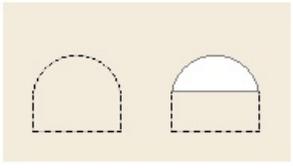
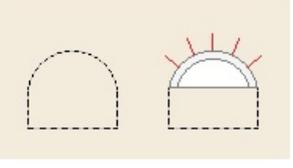
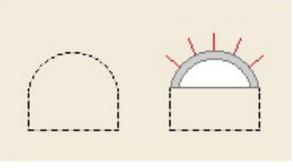
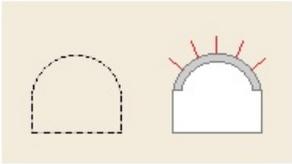
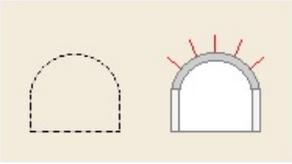
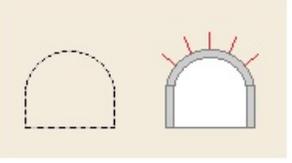
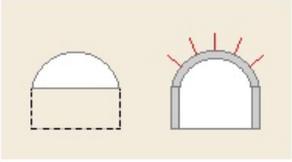
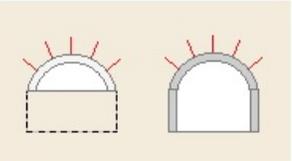
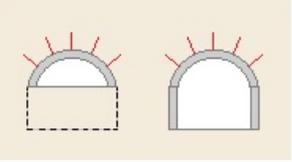
Step	Construction State	Descriptions
1,2		In Situ K_0 State
3		50% Stress Relief
4		75% Stress Relief Soft Shotcrete Rock Bolt
5		100% Stress Relief Hard Shotcrete Rock Bolt
		Upper Core Excavation (Right Tunnel)

Table 6.13 Simulation of construction sequence (Continued)

Step	Construction State	Descriptions
6		50% Stress Relief
7		75% Stress Relief Soft Shotcrete
8		100% Stress Relief Hard Shotcrete

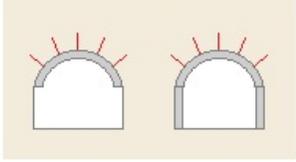
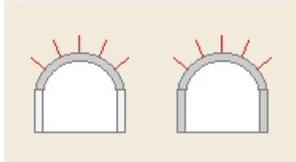
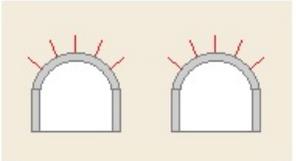
Lower Core Excavation (Right Tunnel)

Table 6.13 Simulation of construction sequence (Continued)

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

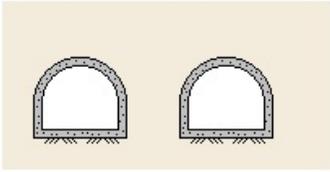
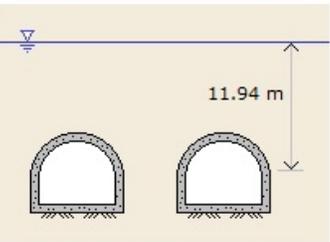
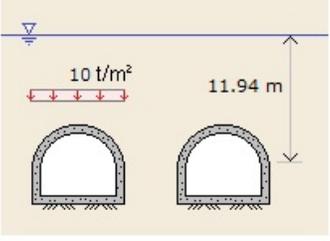
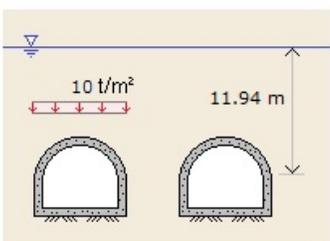
Upper Core Excavation (Left Tunnel)

Table 6.13 Simulation of construction sequence (Continued)

Step	Construction State	Descriptions
12		50% Stress Relief
13		75% Stress Relief Soft Shotcrete
14		100% Stress Relief Hard Shotcrete

Lower Core Excavation (Left Tunnel)

Table 6.13 Simulation of construction sequence (Continued)

Step	Construction State	Descriptions
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

Lining Analysis

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
* N LAYER
  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

```

6-110 Example 3

```
*
* 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	<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 6.16 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 )
```

6-114 Example 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

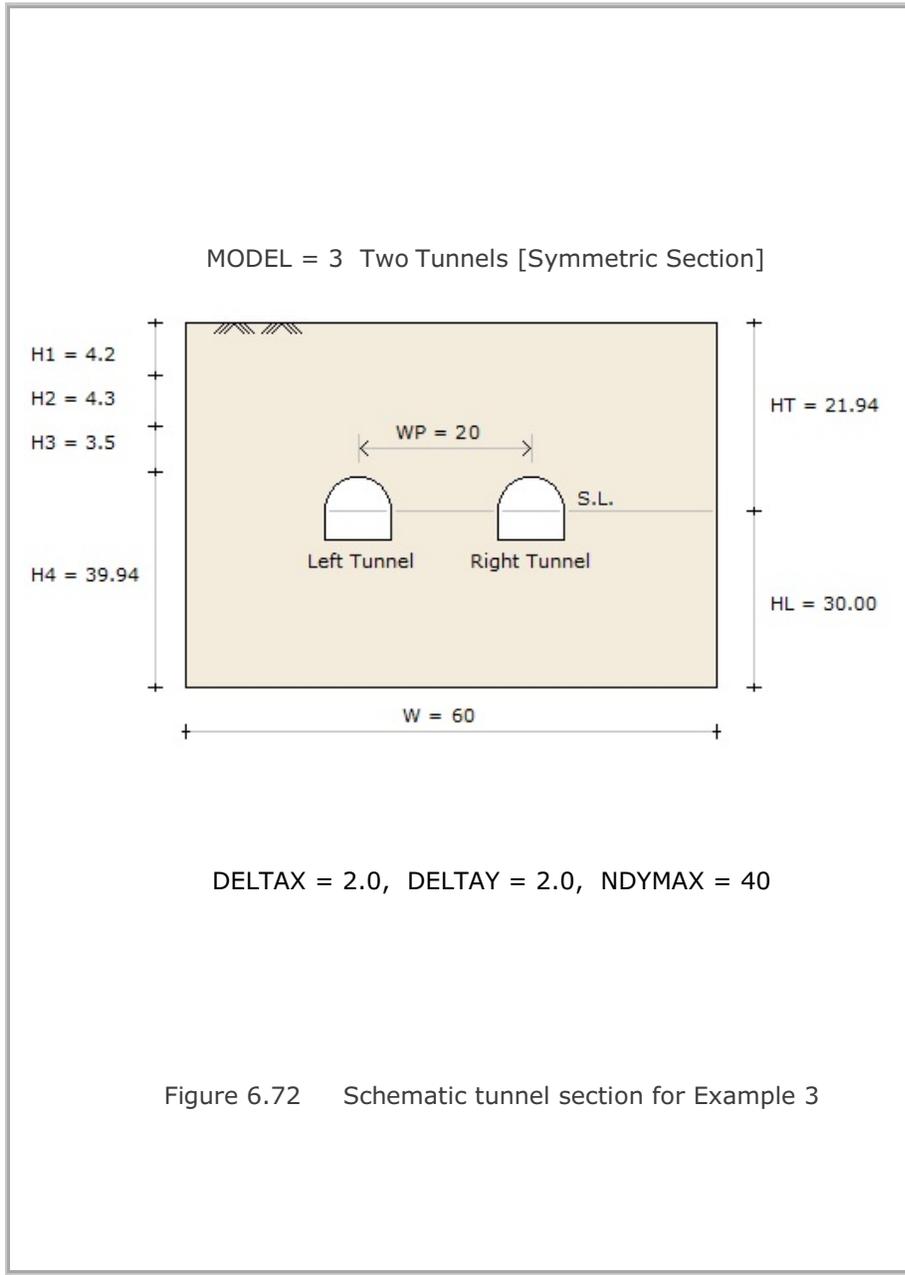


Figure 6.72 Schematic tunnel section for Example 3

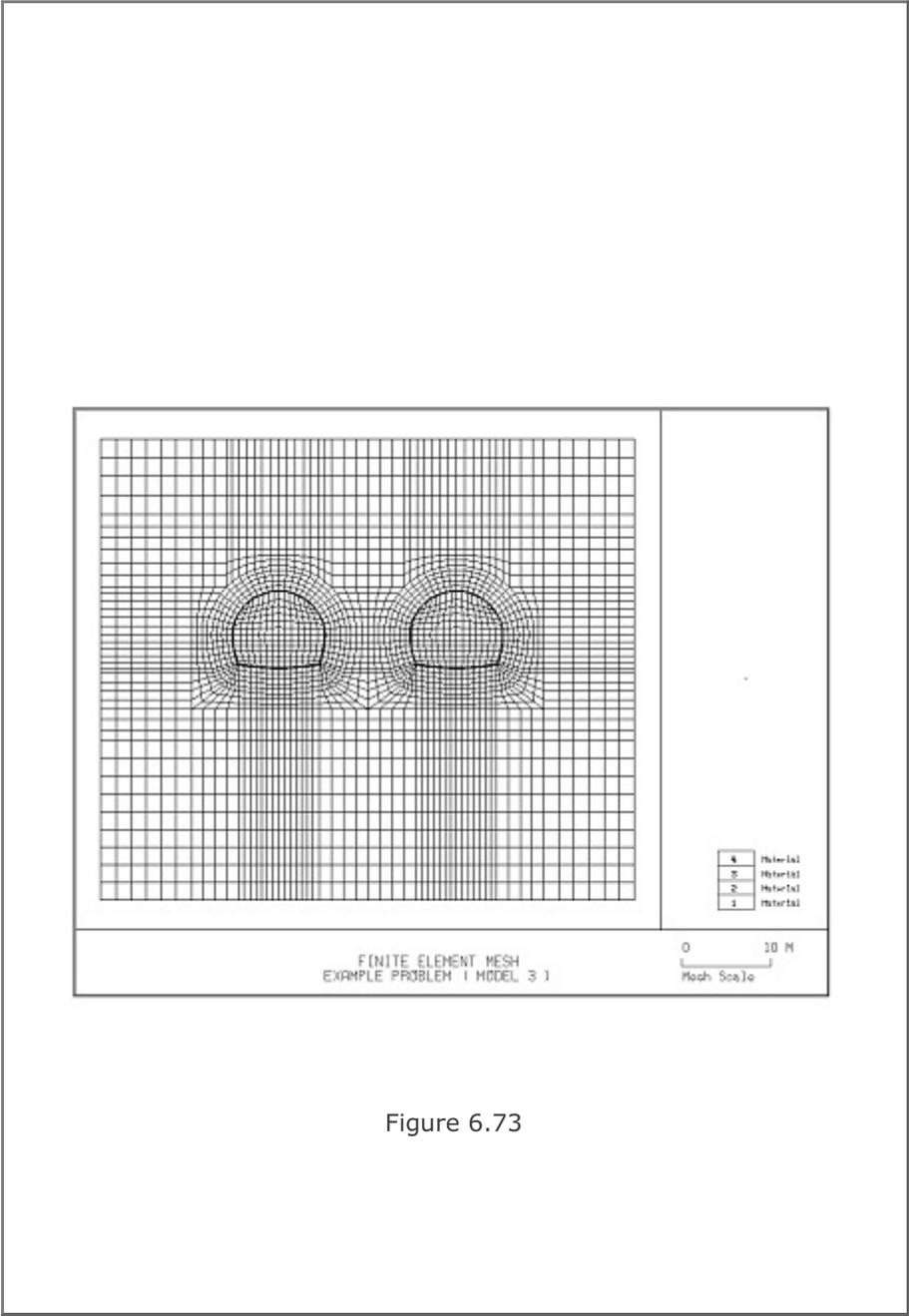


Figure 6.73

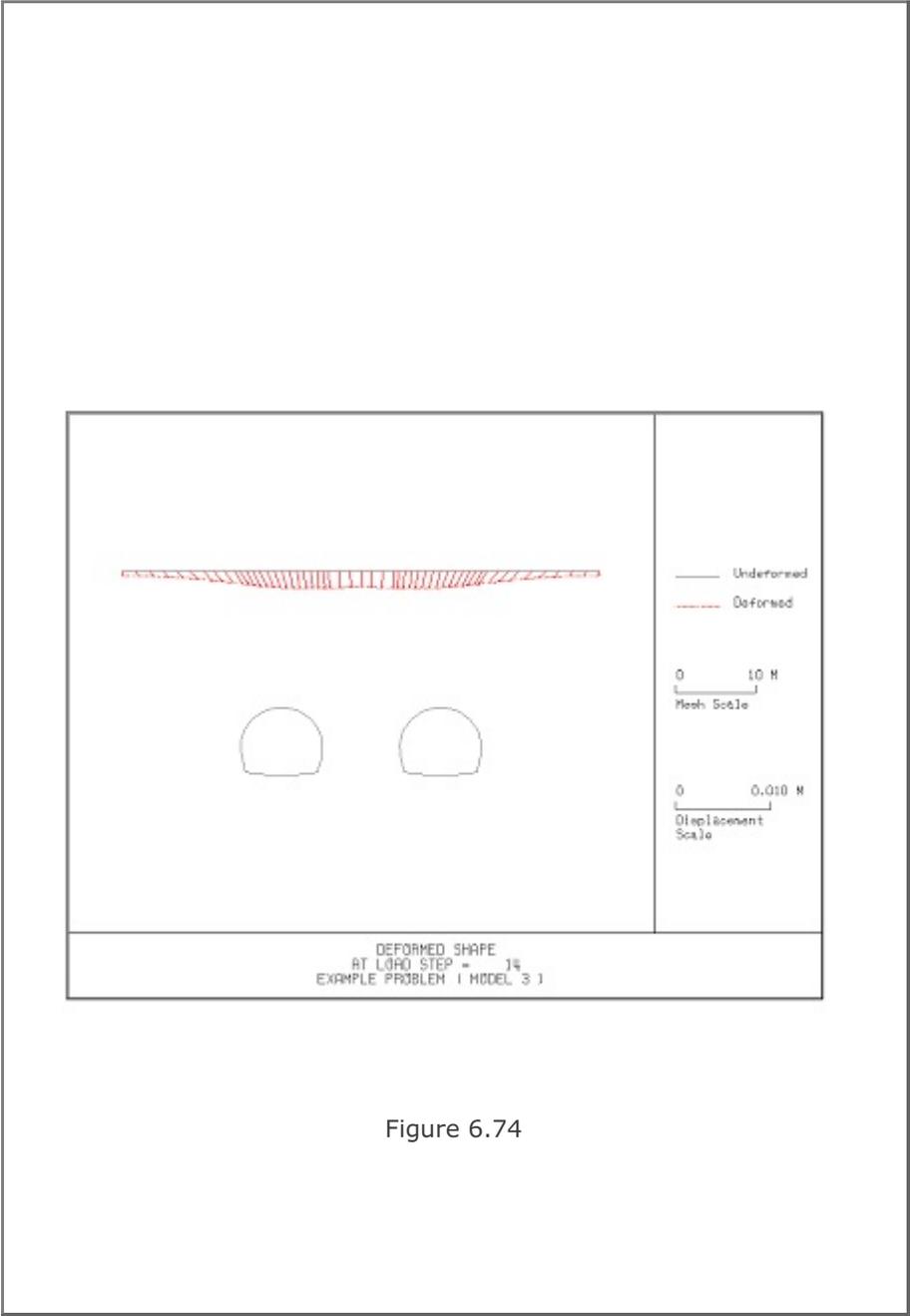


Figure 6.74

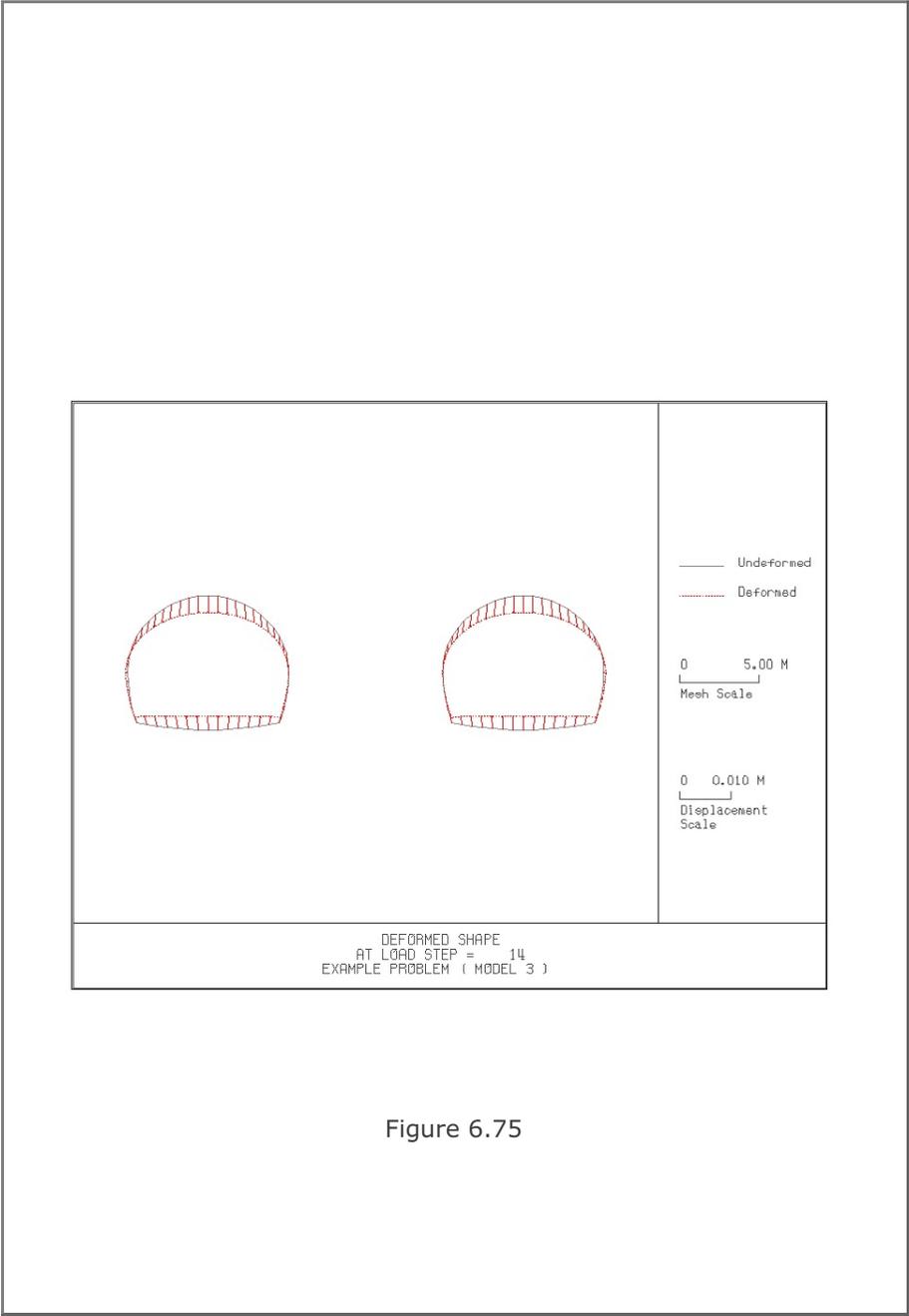


Figure 6.75

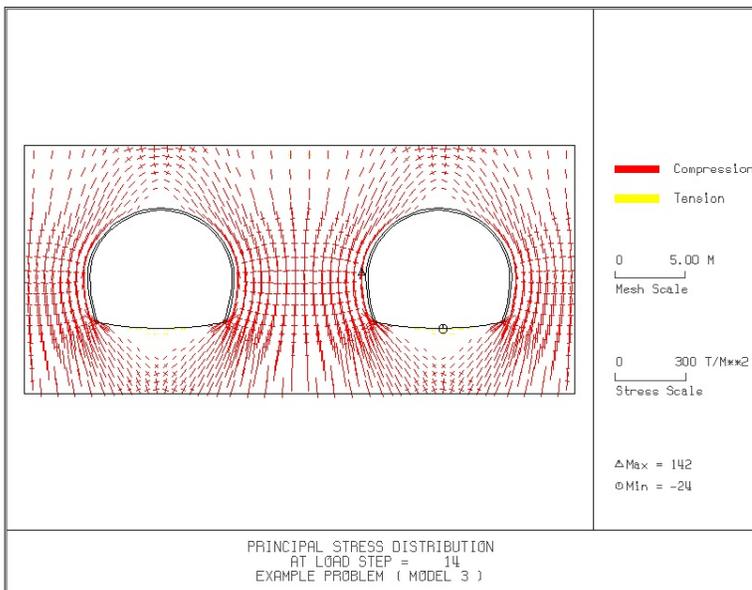


Figure 6.76

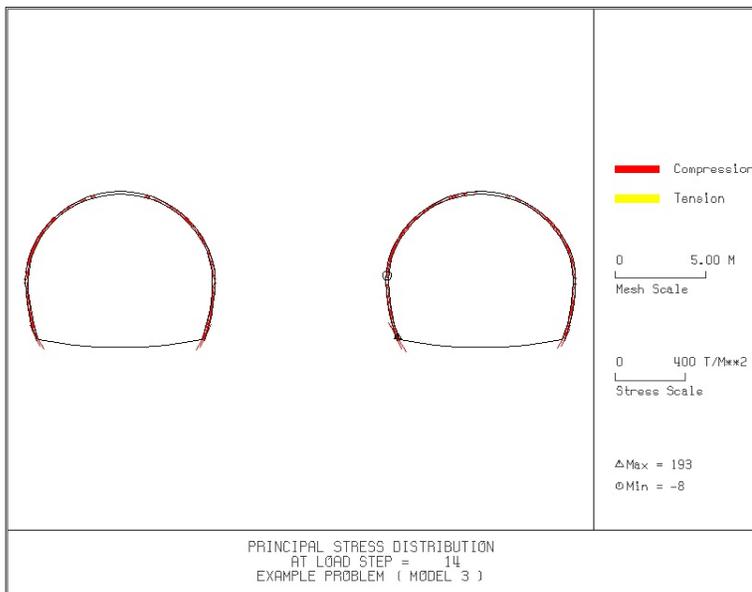


Figure 6.77

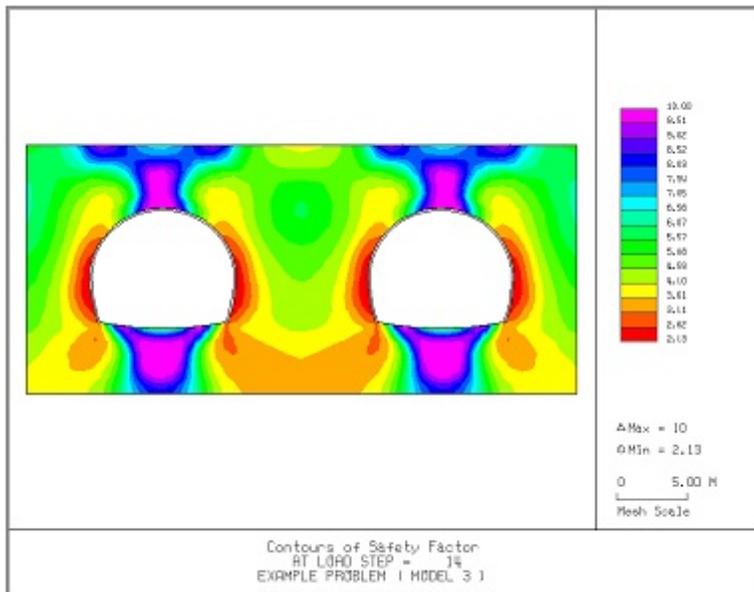


Figure 6.78

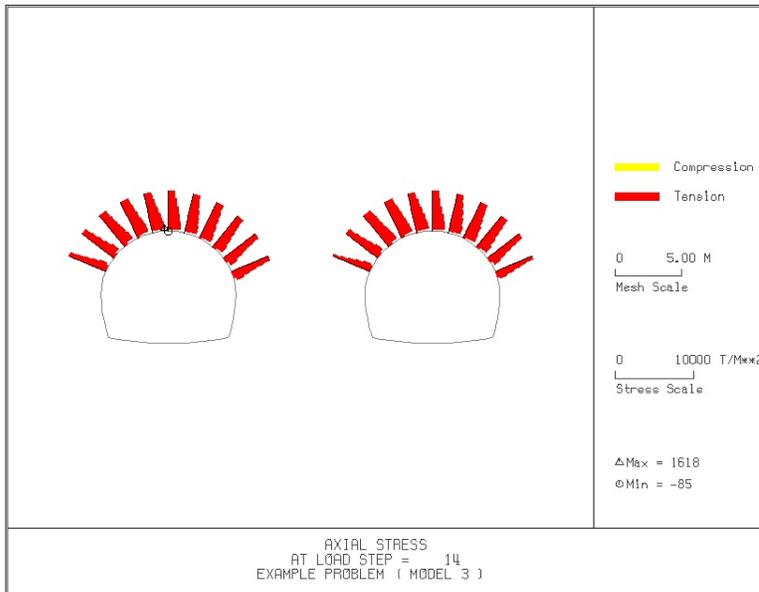


Figure 6.79

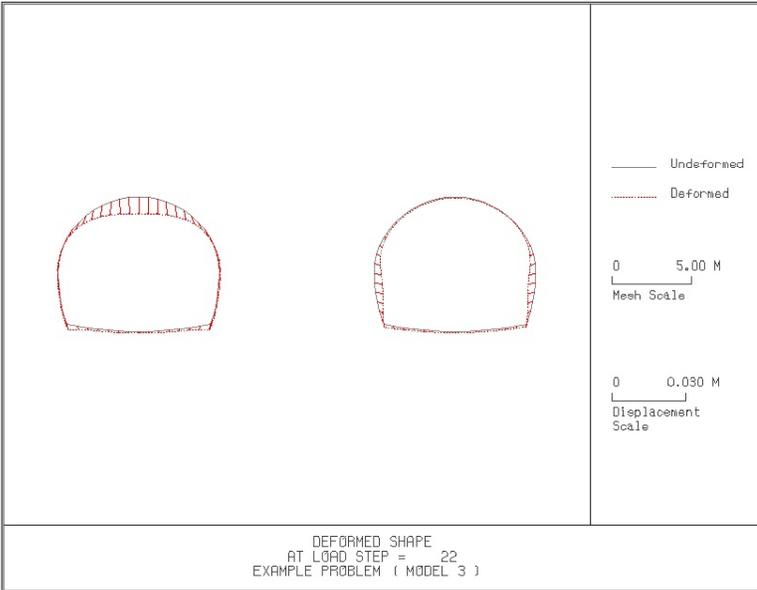


Figure 6.80

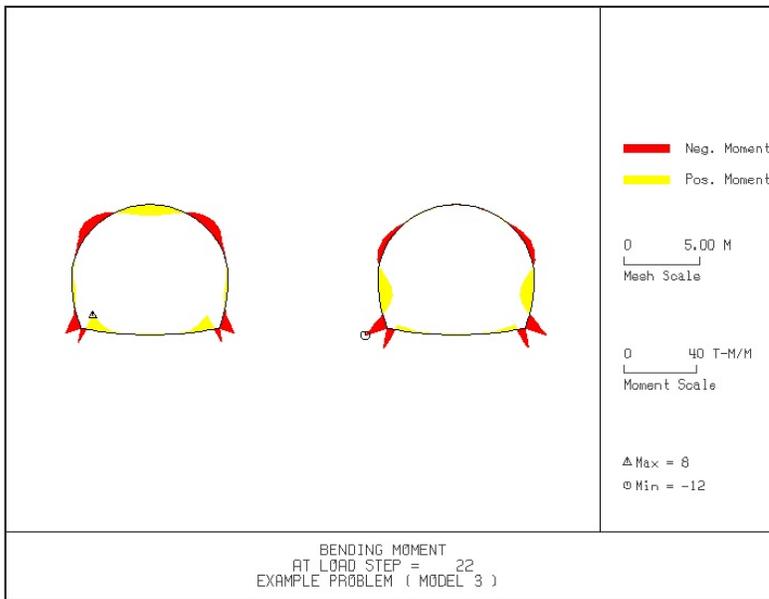


Figure 6.81

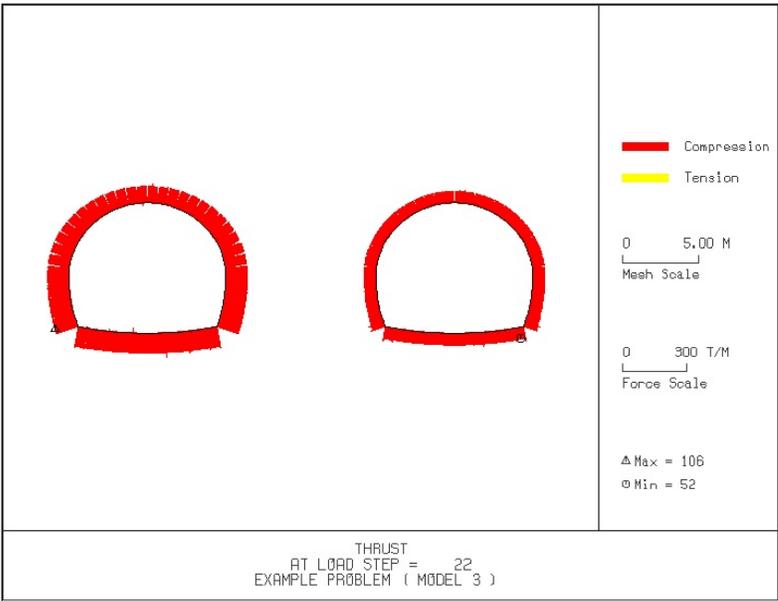


Figure 6.82

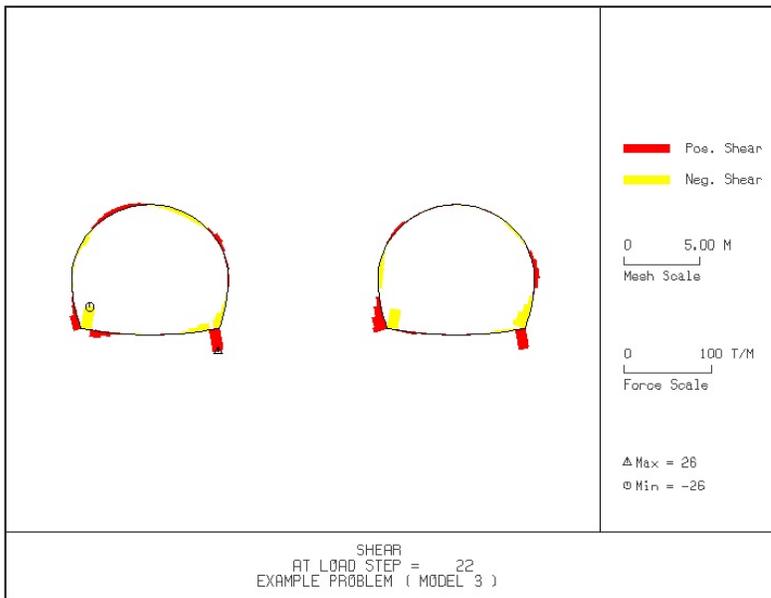


Figure 6.83

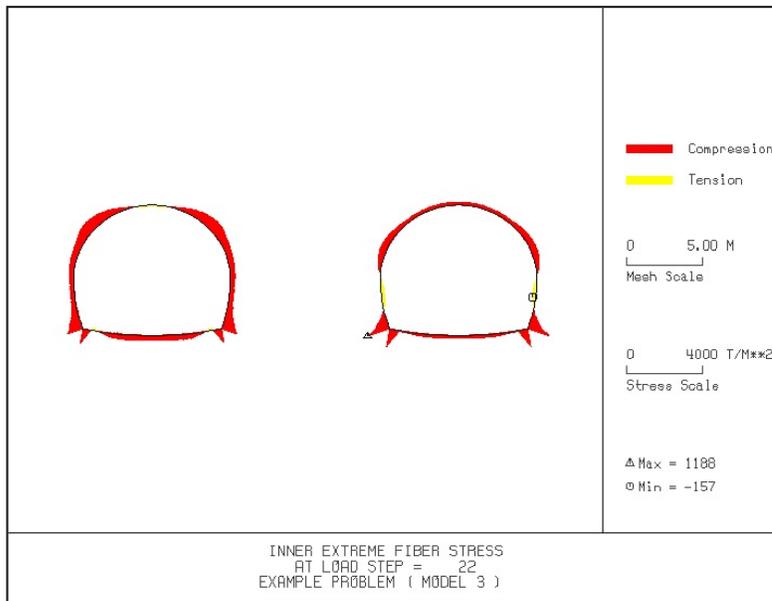


Figure 6.84

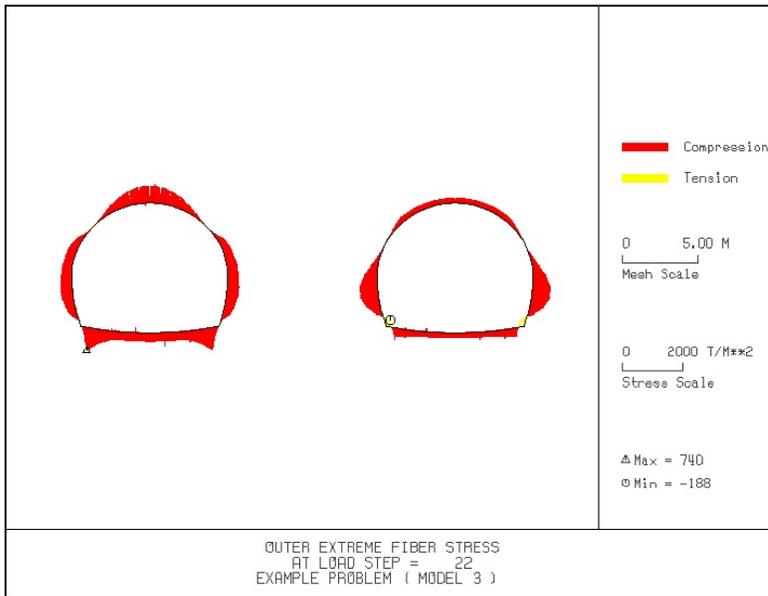


Figure 6.85

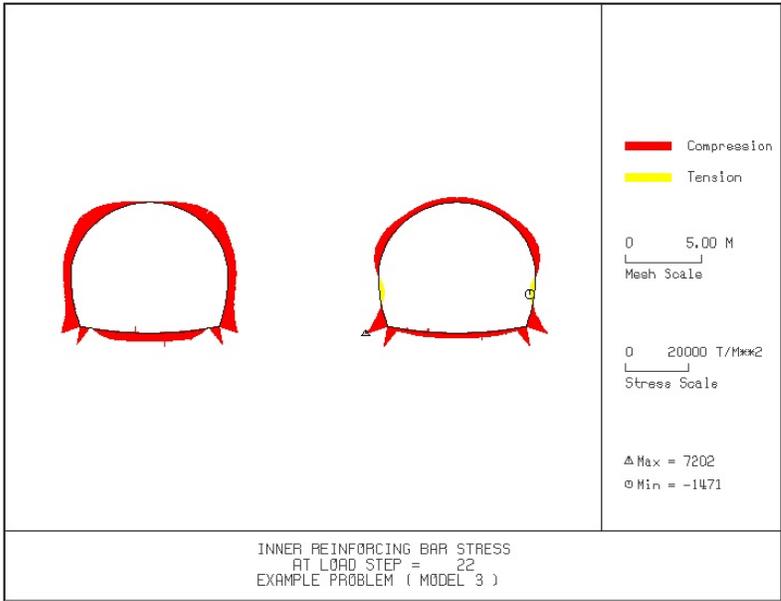


Figure 6.86

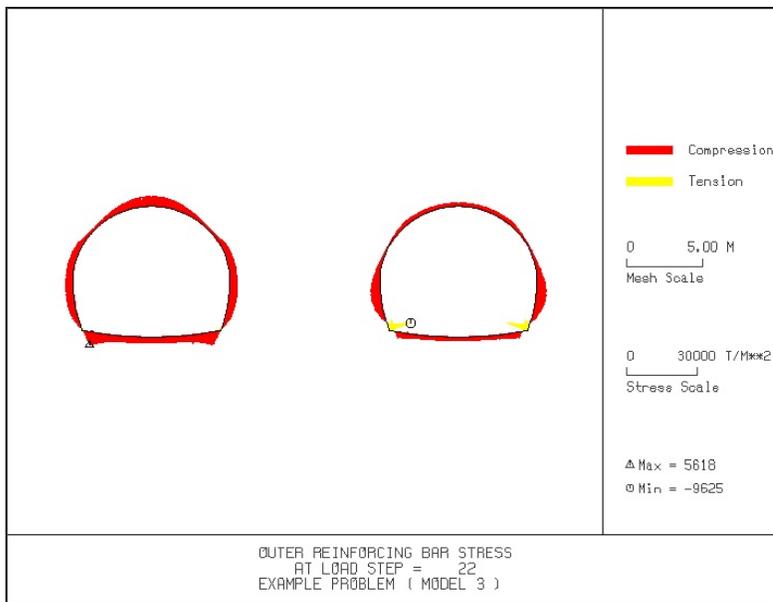


Figure 6.87

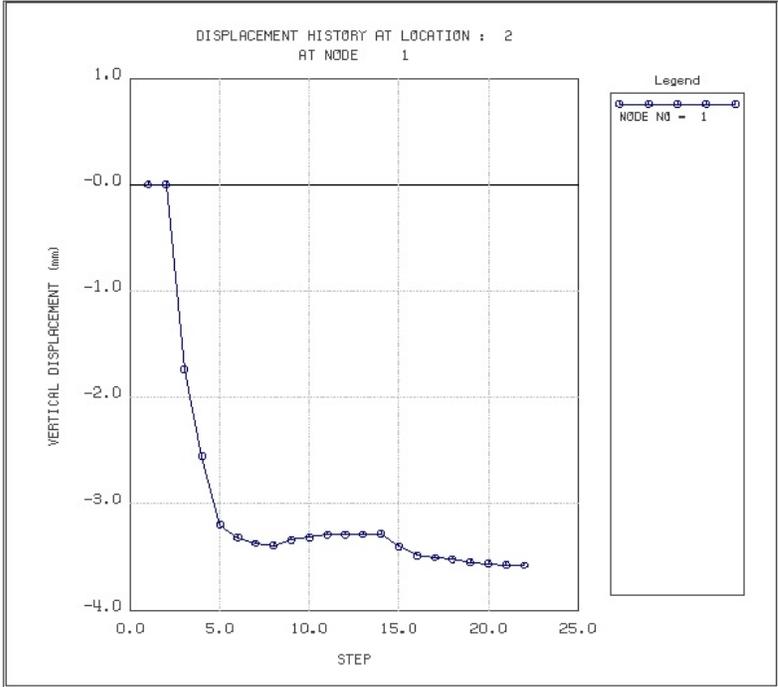


Figure 6.88

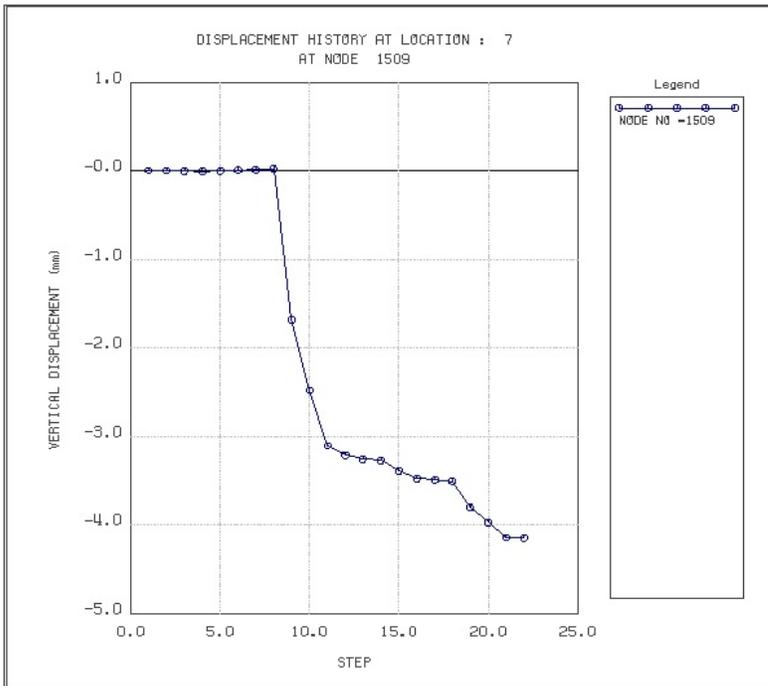


Figure 6.89

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_0 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

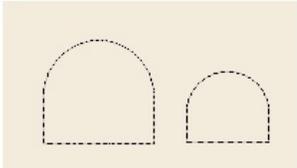
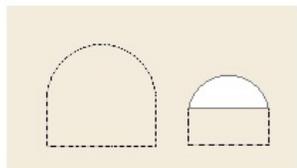
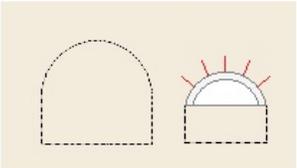
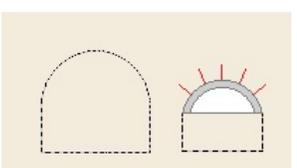
Ground water pressure is applied to the liner except the invert. As loosening load, a uniform vertical stress to the right tunnel liner and a symmetric triangular vertical stress to the left tunnel liner as shown in Table 6.18 are applied. As support degradation, rock bolts are deactivated.

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.

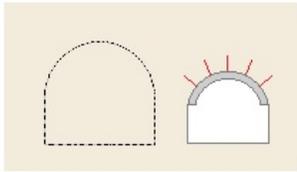
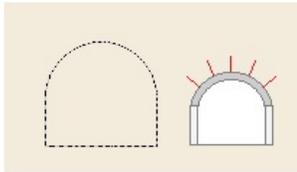
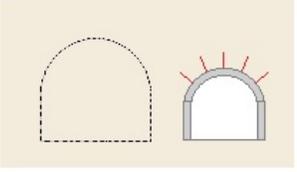
Figures 6.106 and 6.107 show PLOT-XY graphical outputs at tunnel crowns. Brief description of these plots are shown in the text output file PLTX.Y.LST in Table 6.22.

Table 6.18 Simulation of construction sequence

Step	Construction State	Descriptions
1,2		In Situ K_0 State
3		50% Stress Relief
4		75% Stress Relief Soft Shotcrete Rock Bolt
5		100% Stress Relief Hard Shotcrete Rock Bolt

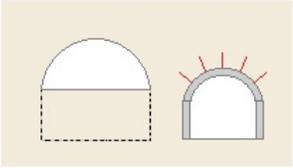
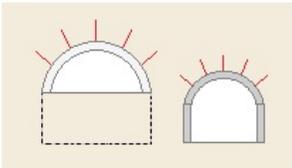
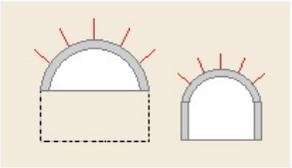
Upper Core Excavation (Right Tunnel)

Table 6.18 Simulation of construction sequence (Continued)

Step	Construction State	Descriptions
6		50% Stress Relief
7		75% Stress Relief Soft Shotcrete
8		100% Stress Relief Hard Shotcrete

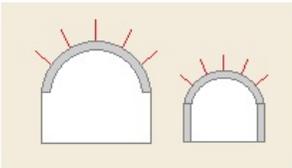
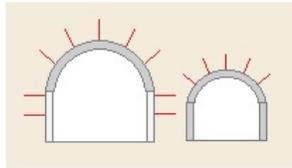
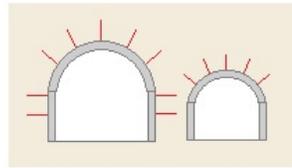
Lower Core Excavation (Right Tunnel)

Table 6.18 Simulation of construction sequence (Continued)

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

Upper Core Excavation (Left Tunnel)

Table 6.18 Simulation of construction sequence (Continued)

Step	Construction State	Descriptions
12		50% Stress Relief
13		75% Stress Relief Soft Shotcrete Rock Bolt
14		100% Stress Relief Hard Shotcrete Rock Bolt

Lower Core Excavation (Left Tunnel)

Table 6.18 Simulation of construction sequence (Continued)

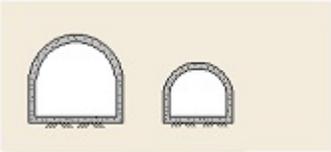
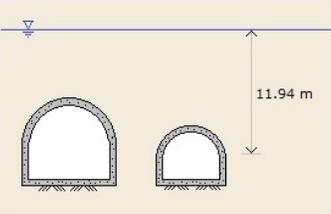
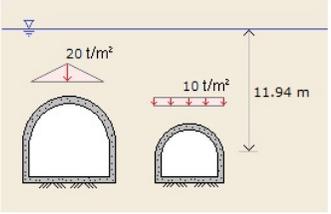
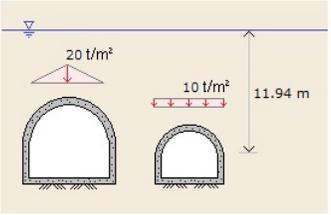
Step	Construction State	Descriptions	Lining Analysis
15		Lining Subjected to: Weight	
18		Lining Subjected to: Weight + Water Pressure	
21		Lining Subjected to: Weight + Water Pressure + Loosening Load	
22		Lining Subjected to: Weight + Water Pressure + Loosening Load + Rock Bolt Deactivation	

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

```

6-142 Example 4

```

*
* 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

```

6-144 Example 4

```
*
* 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 )

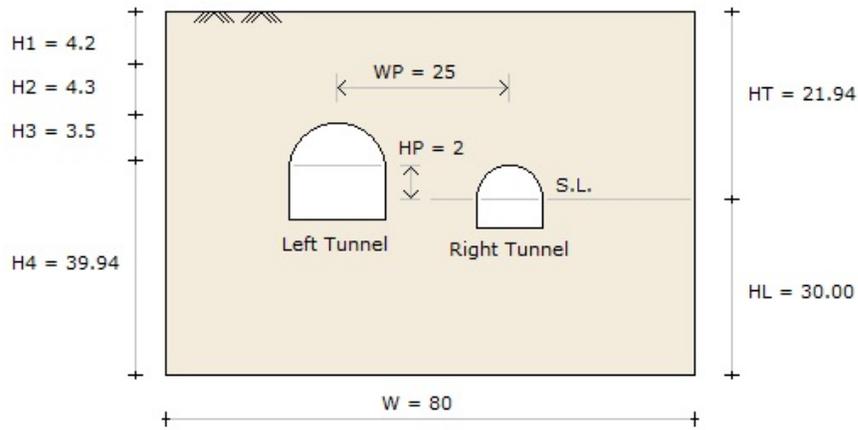
56      INNER REINFORCING BAR STRESS
        AT LOAD STEP =    22
        EXAMPLE PROBLEM ( MODEL 4 )

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]



DELTA X = 2.0, DELTA Y = 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

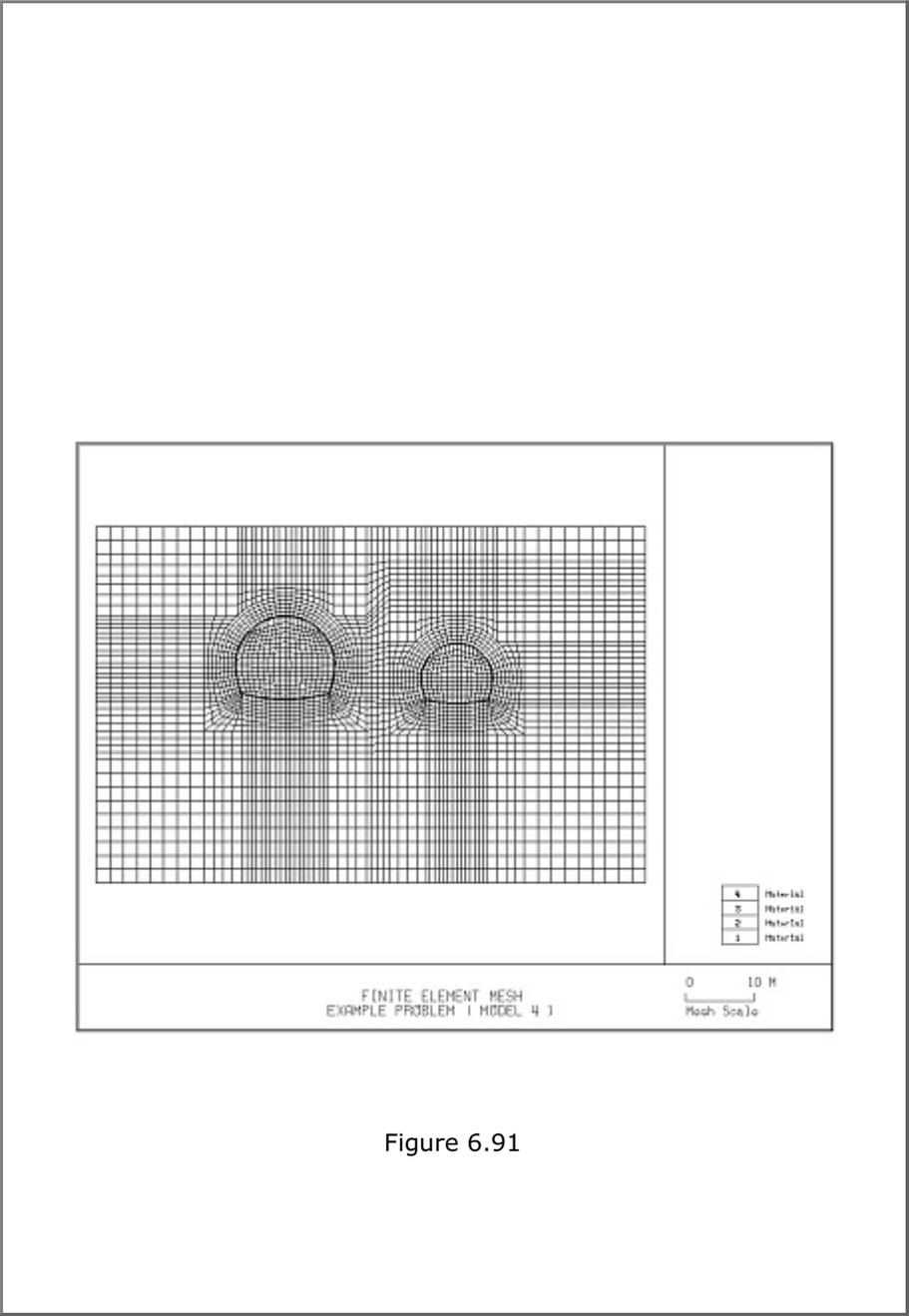


Figure 6.91

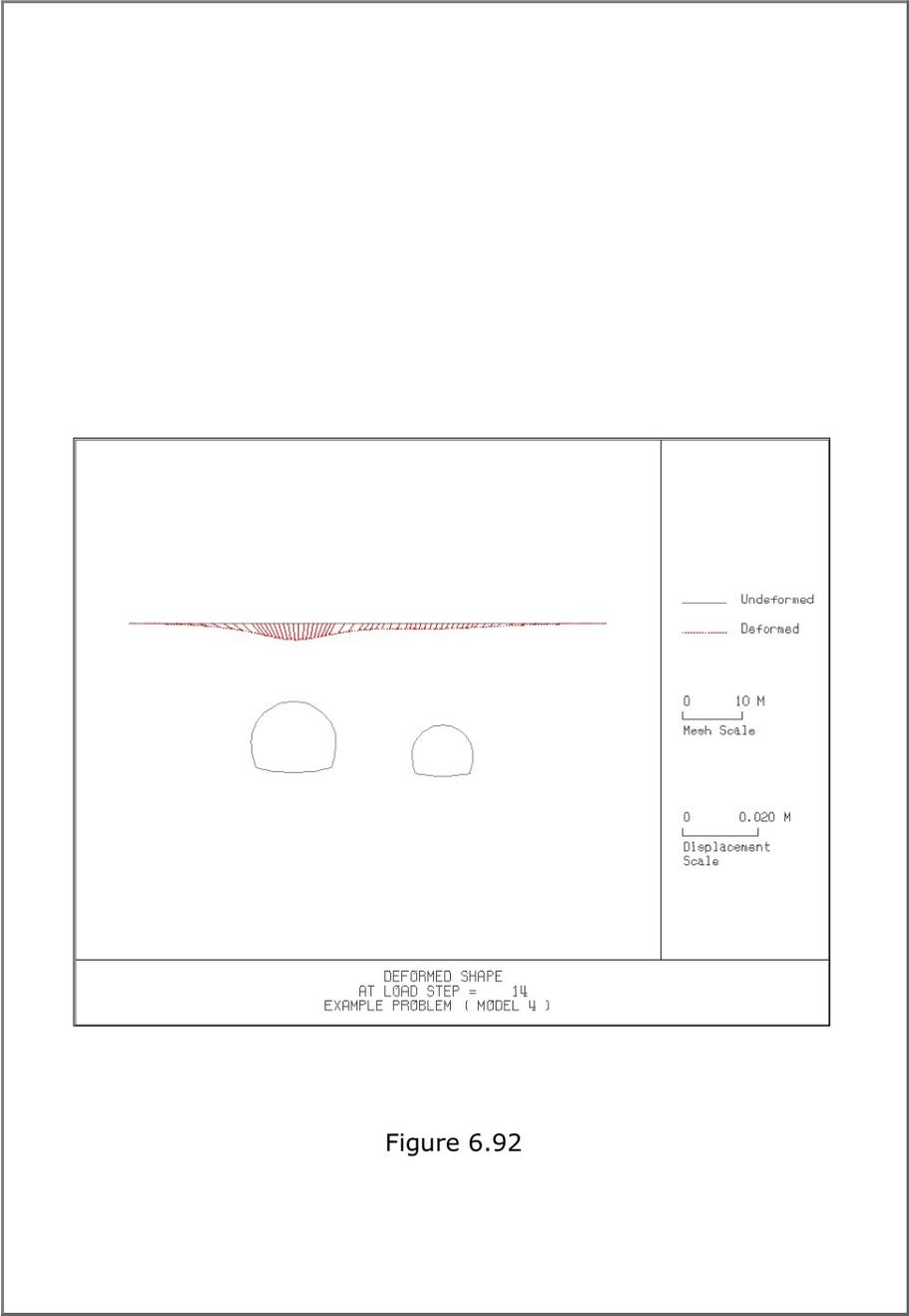


Figure 6.92

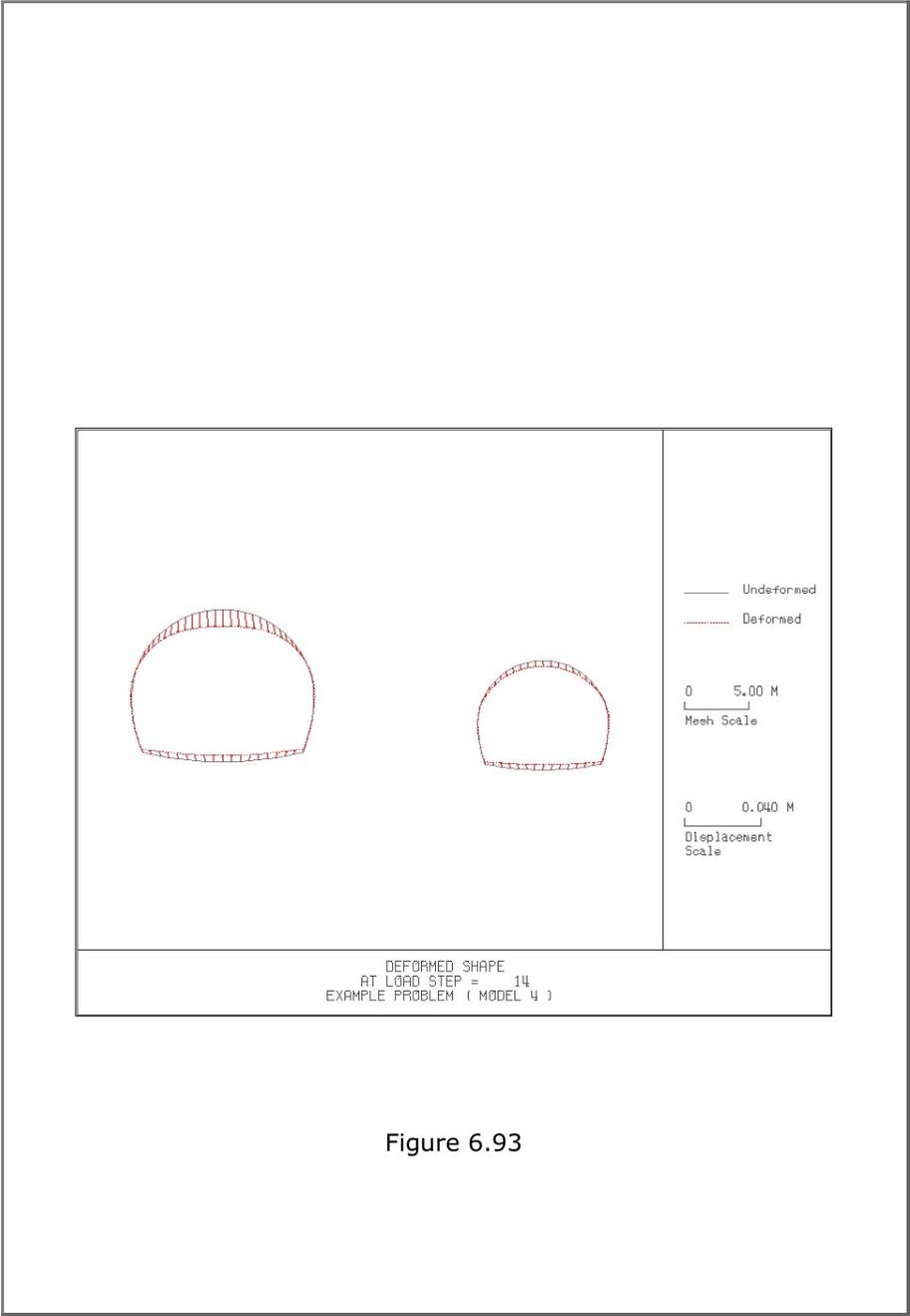


Figure 6.93

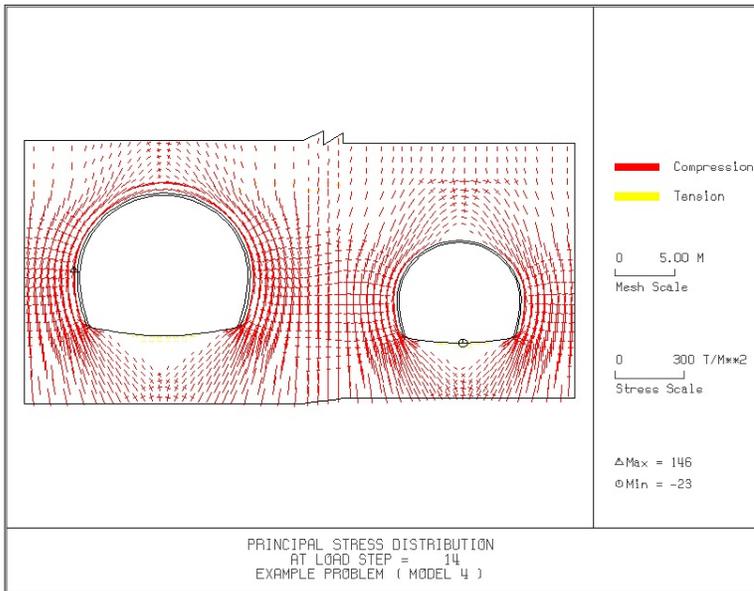


Figure 6.94

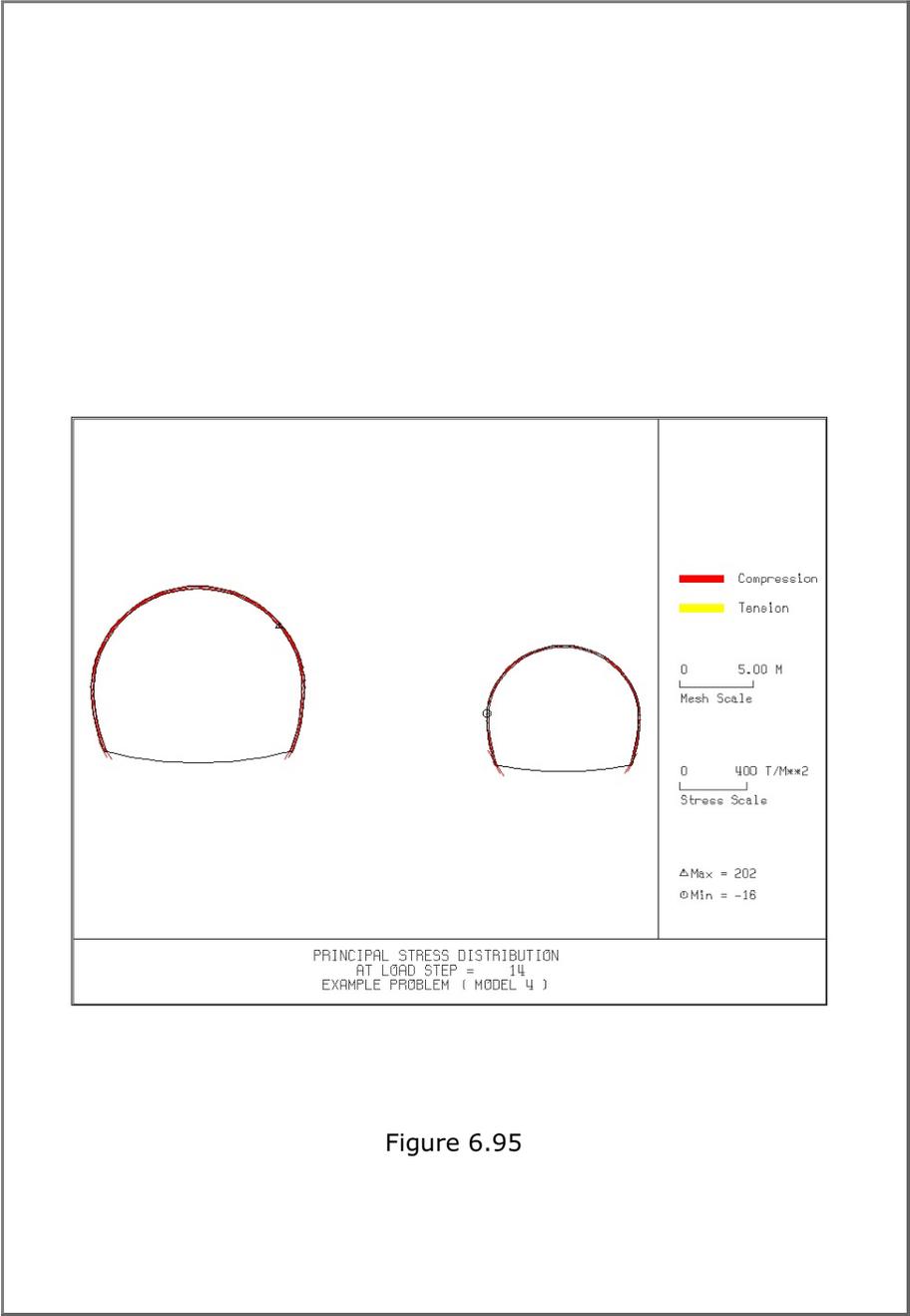


Figure 6.95

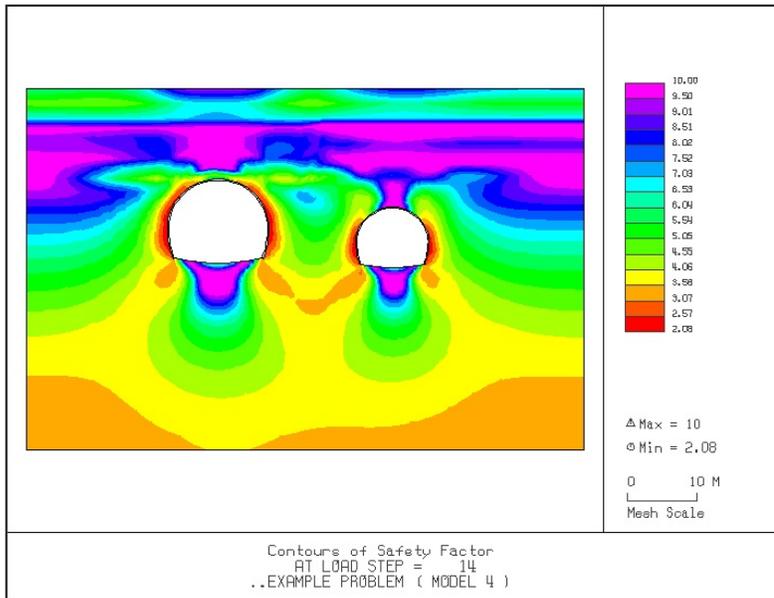


Figure 6.96

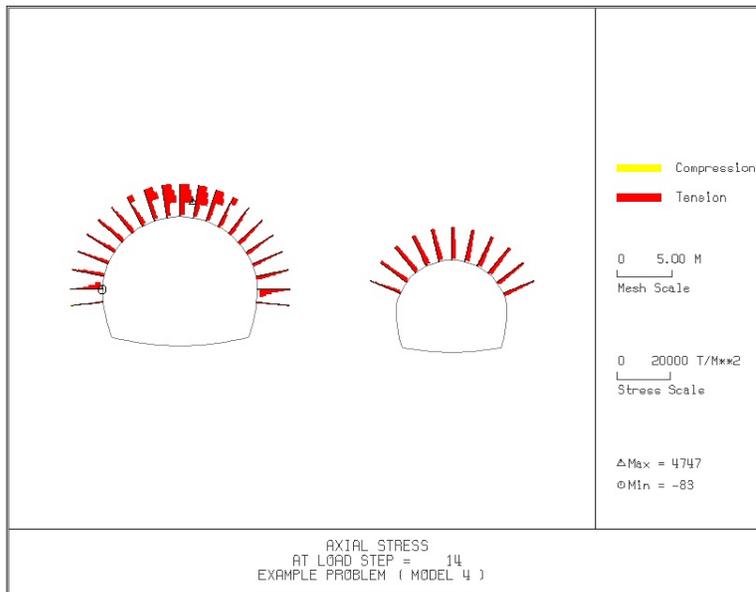


Figure 6.97

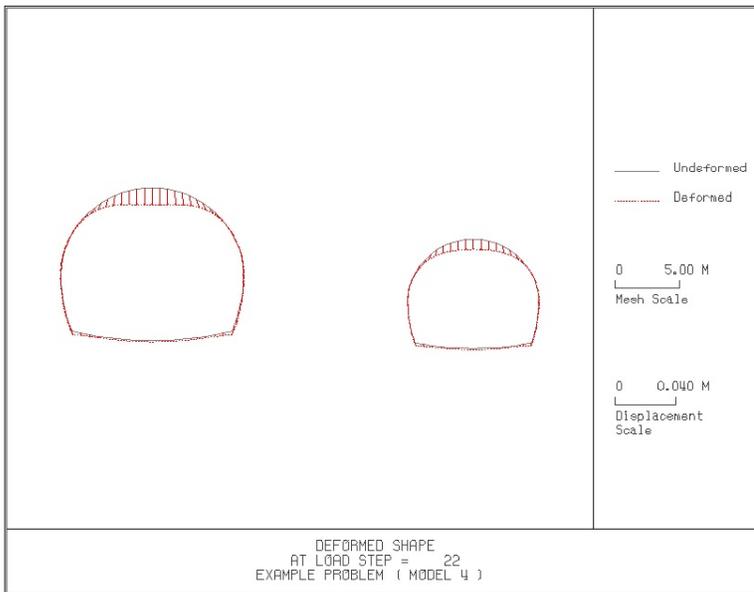


Figure 6.98

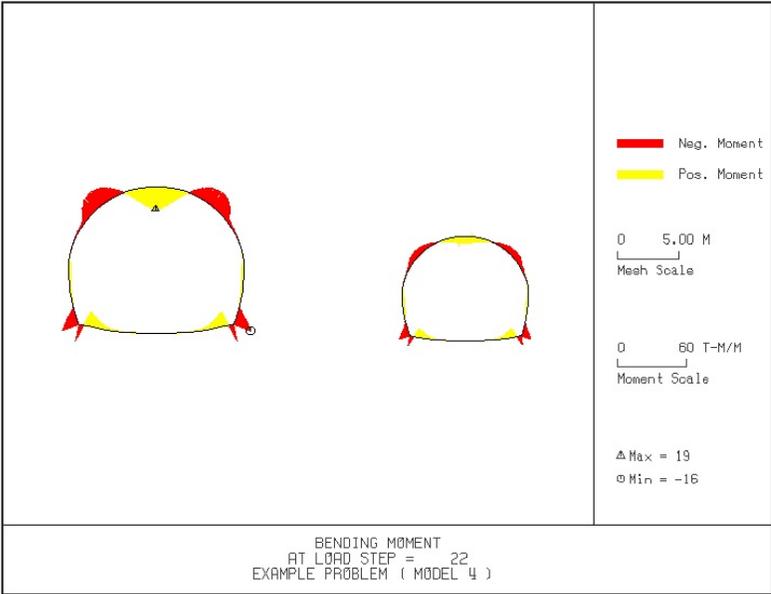


Figure 6.99

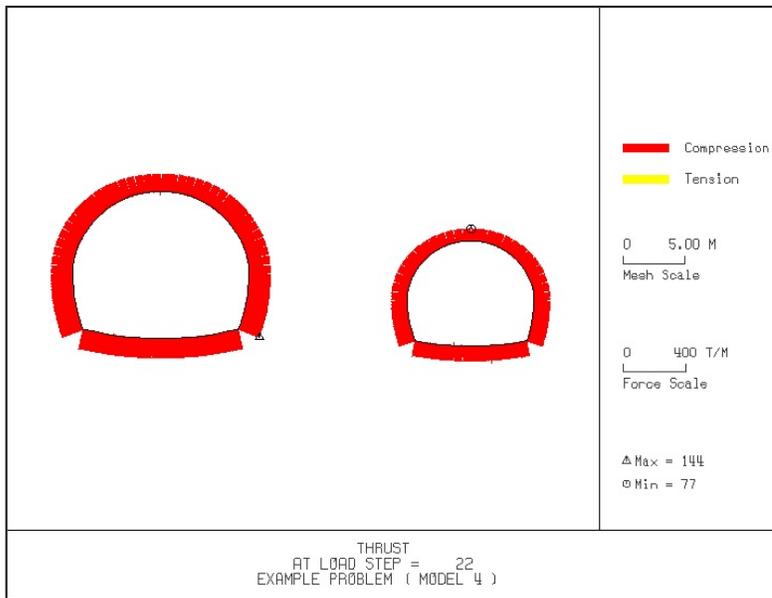


Figure 6.100

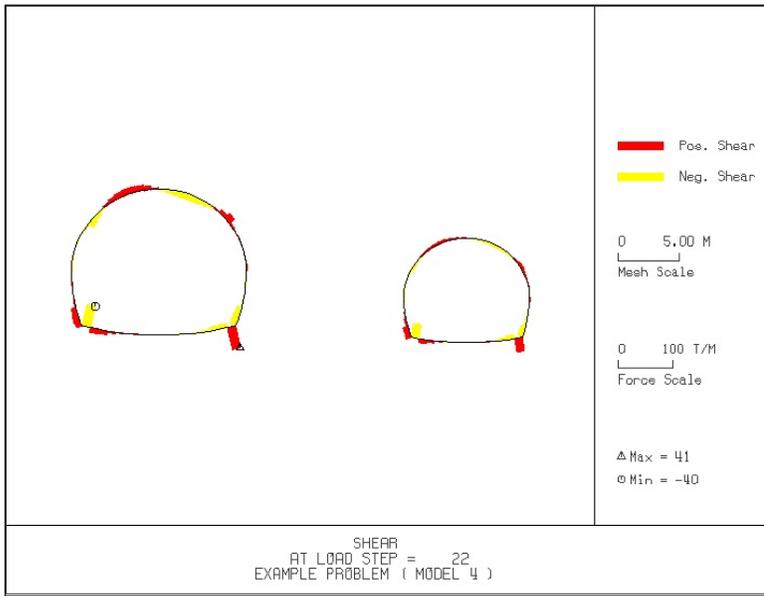


Figure 6.101

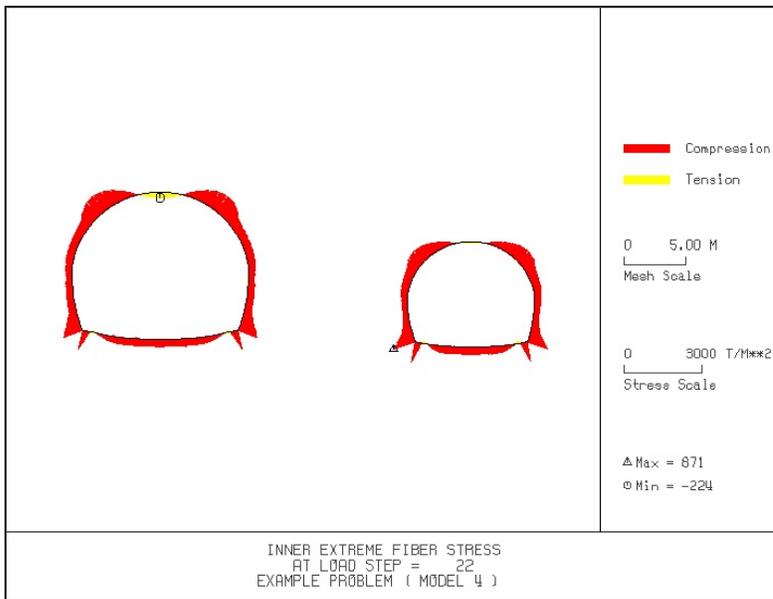


Figure 6.102

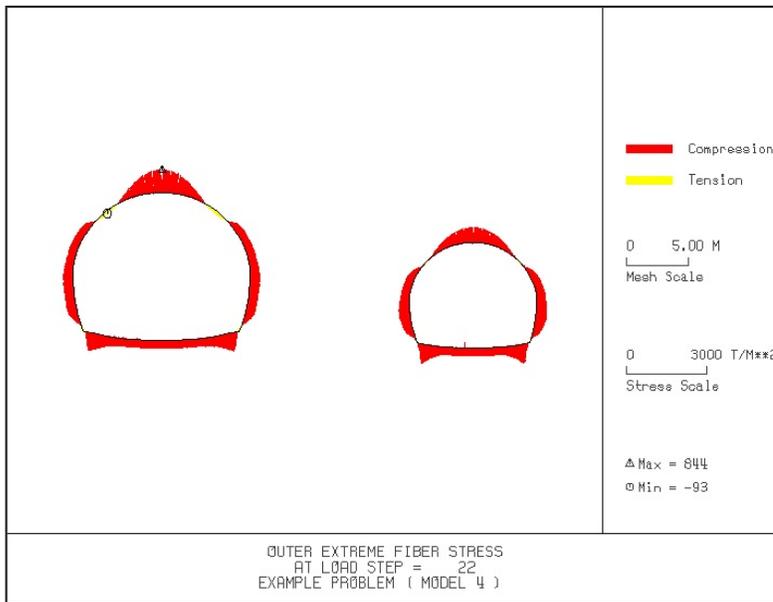


Figure 6.103

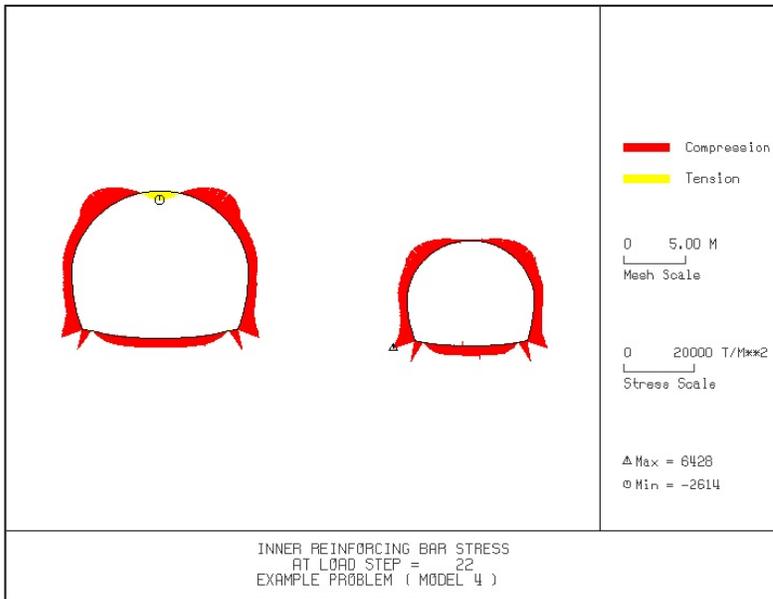


Figure 6.104

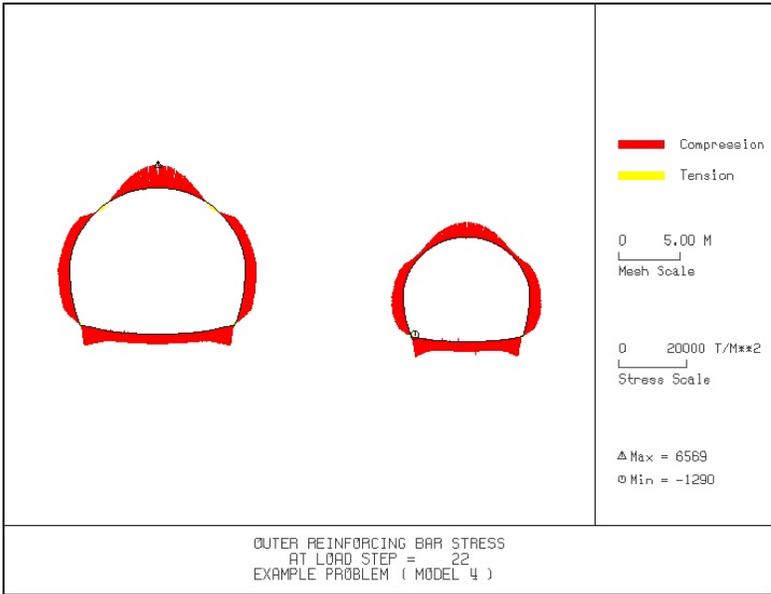


Figure 6.105

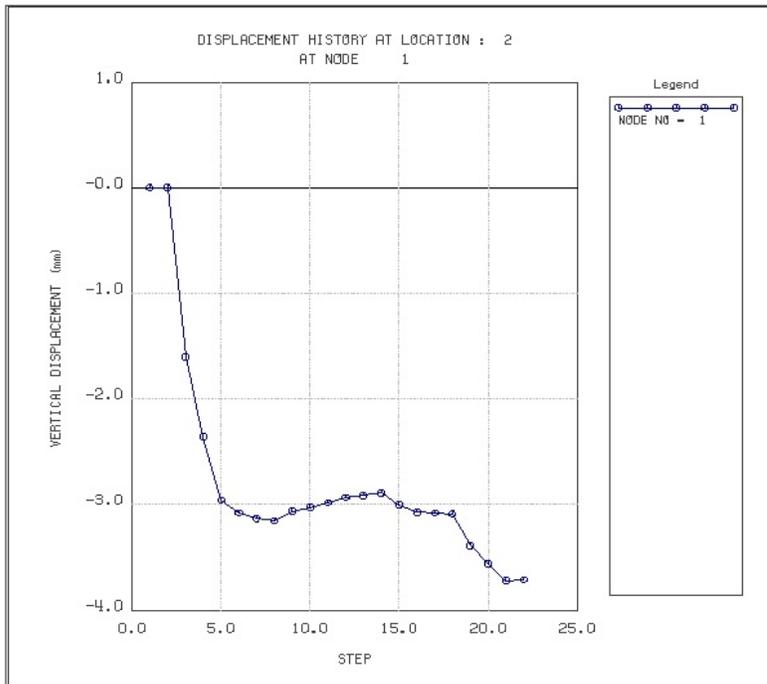


Figure 6.106

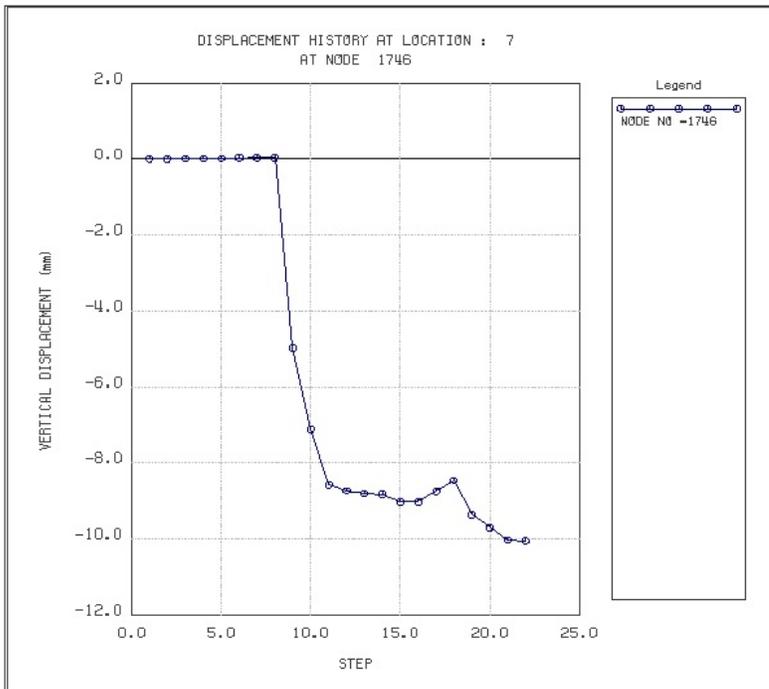


Figure 6.107

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
* N_LAYER
* 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
* NAT_LAYER
* 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
*

```

6-170 Example 5

```
*
* 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
```

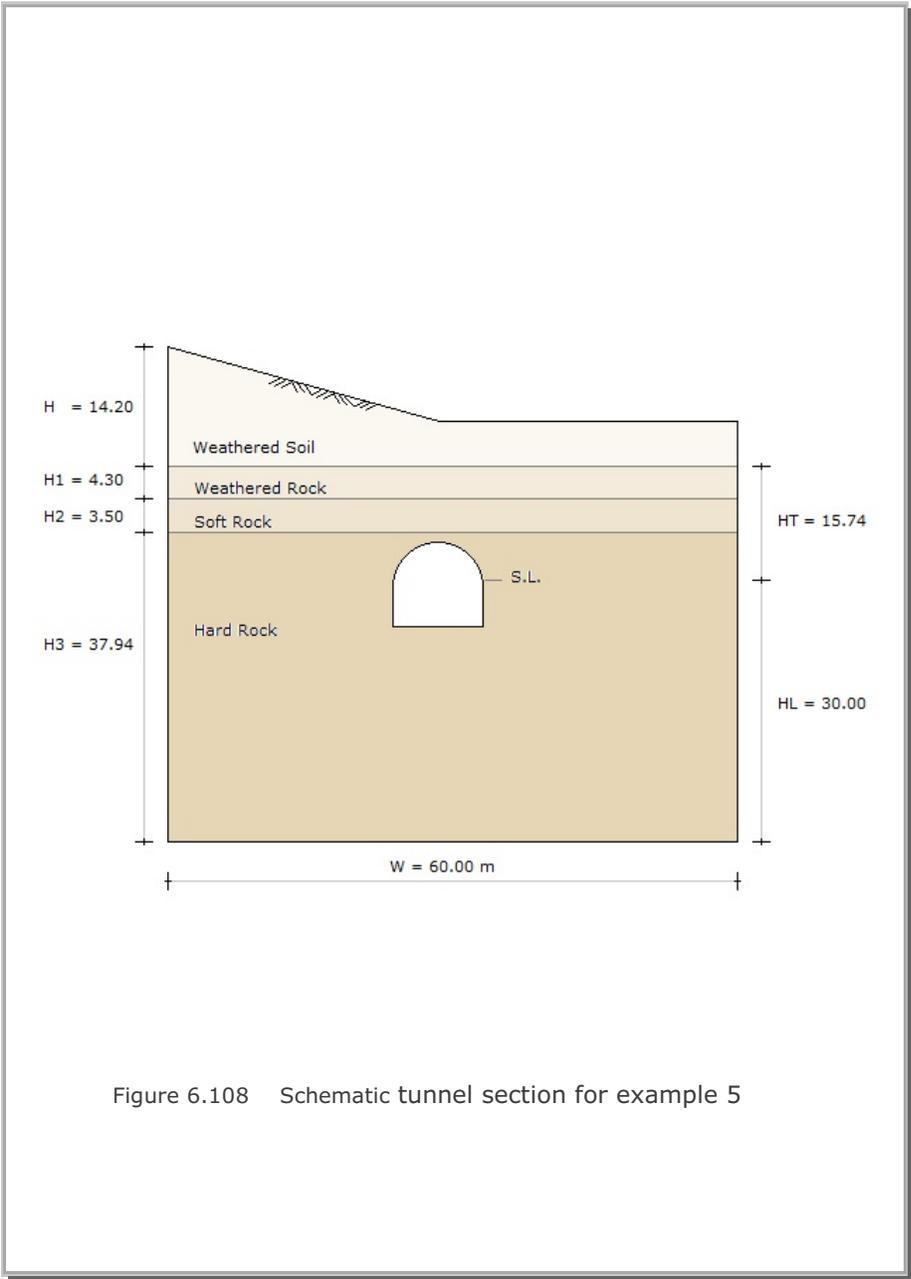


Figure 6.108 Schematic tunnel section for example 5

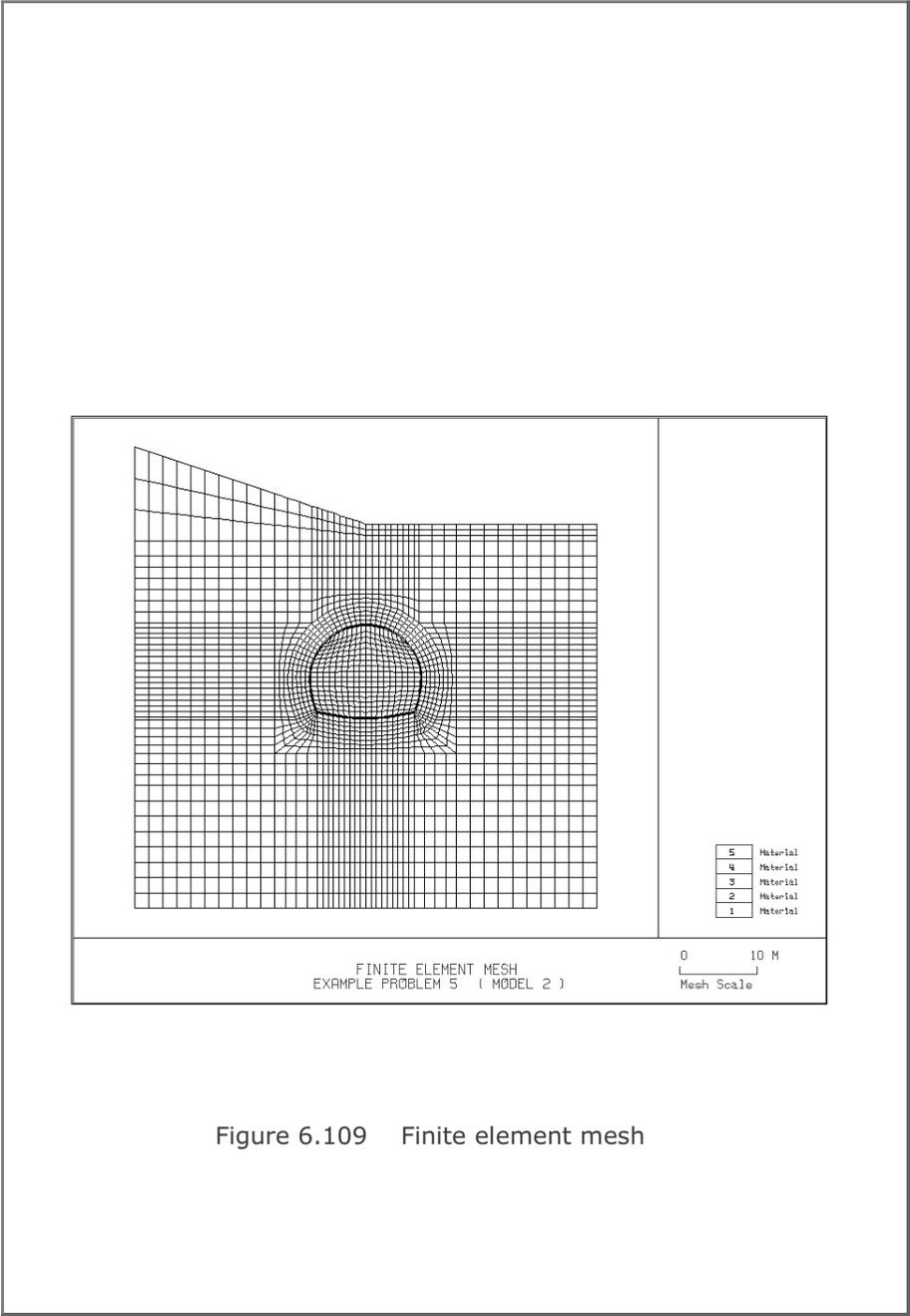


Figure 6.109 Finite element mesh

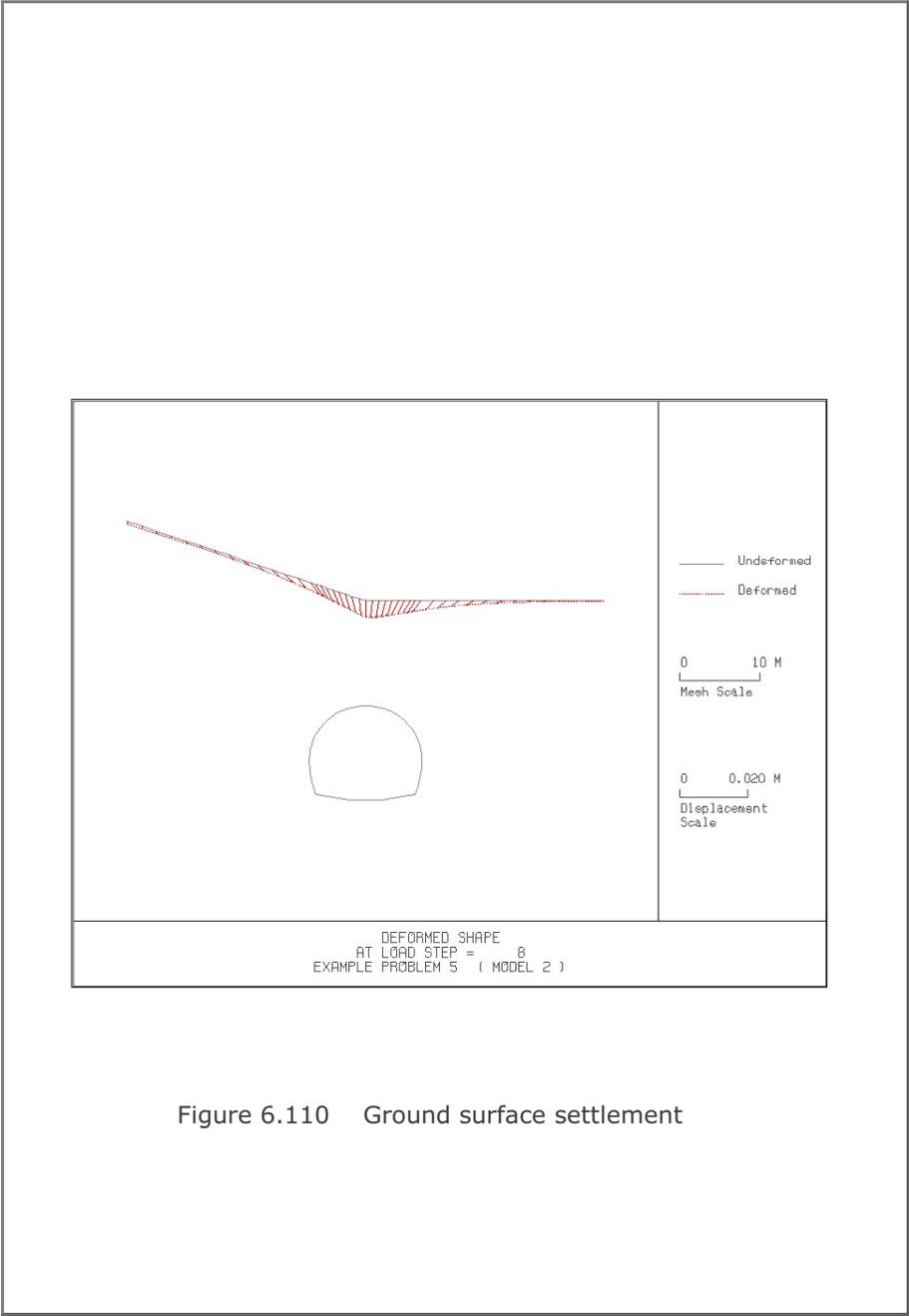


Figure 6.110 Ground surface settlement

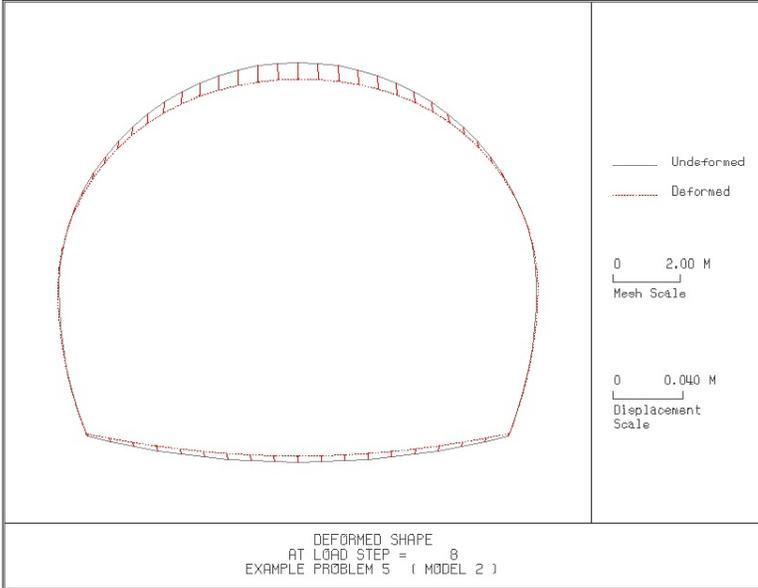


Figure 6.111 Tunnel deformed shape

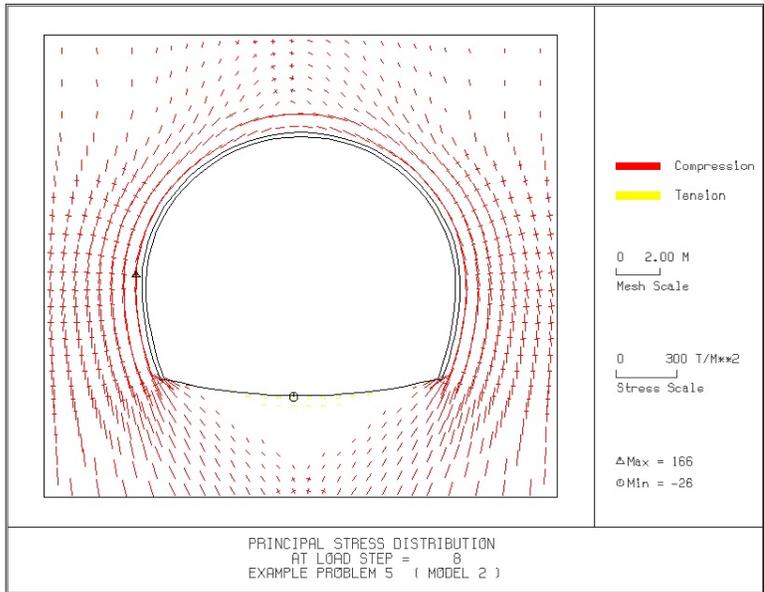


Figure 6.112 Principal stresses around tunnel

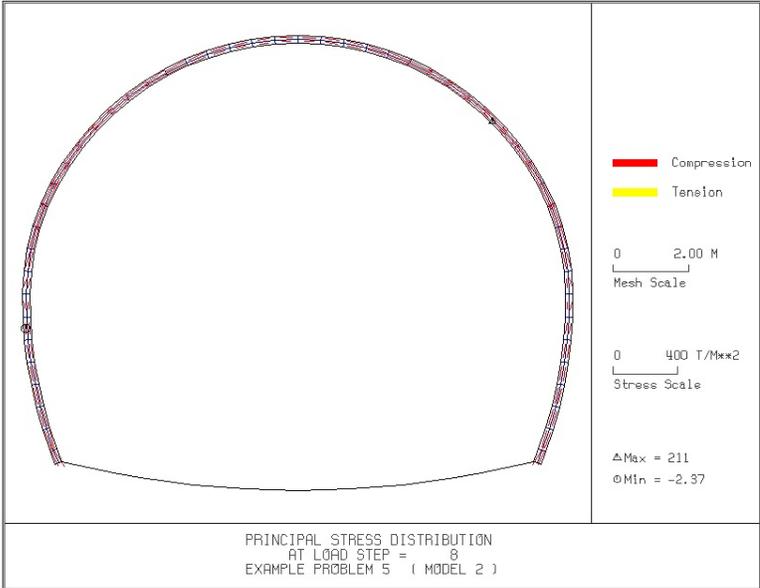


Figure 6.113 Shotcrete stresses

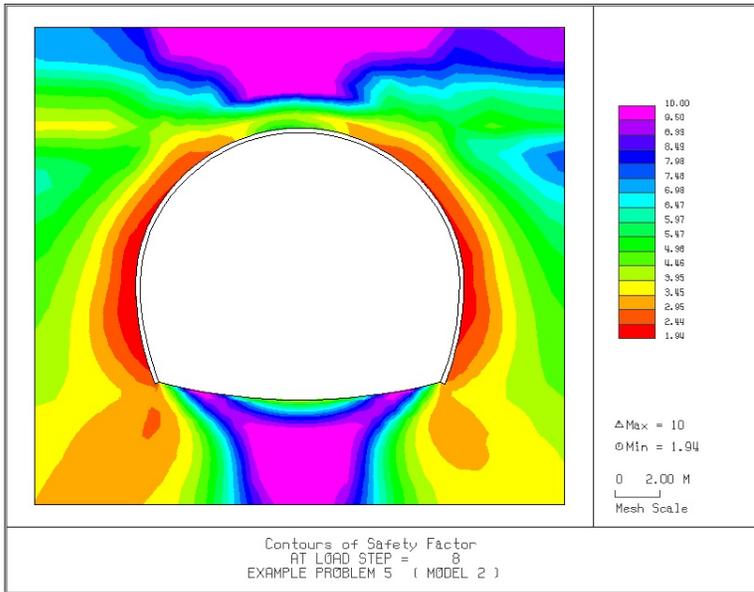


Figure 6.114 Contour of safety factor

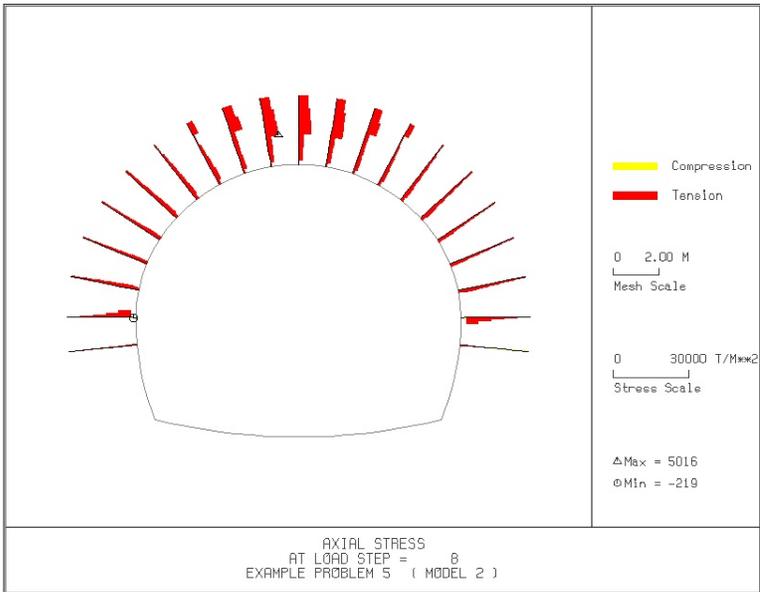


Figure 6.115 Rock bolt axial stresses

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 ($E=100,000 \text{ t/m}^2$) 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

```

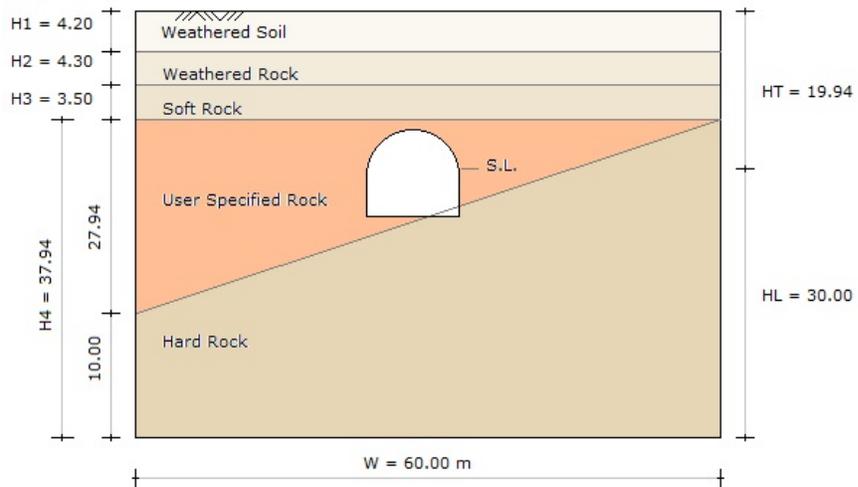


Figure 6.116 Schematic tunnel section for Example 6

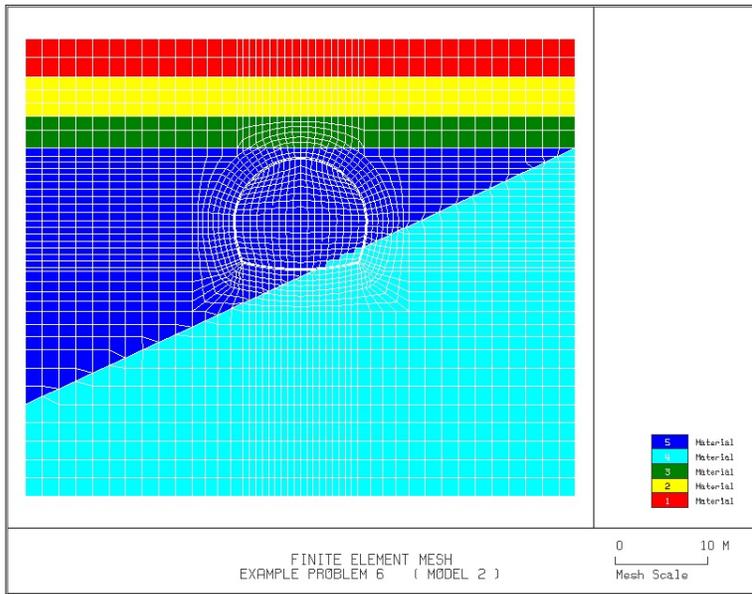


Figure 6.117 Finite element mesh

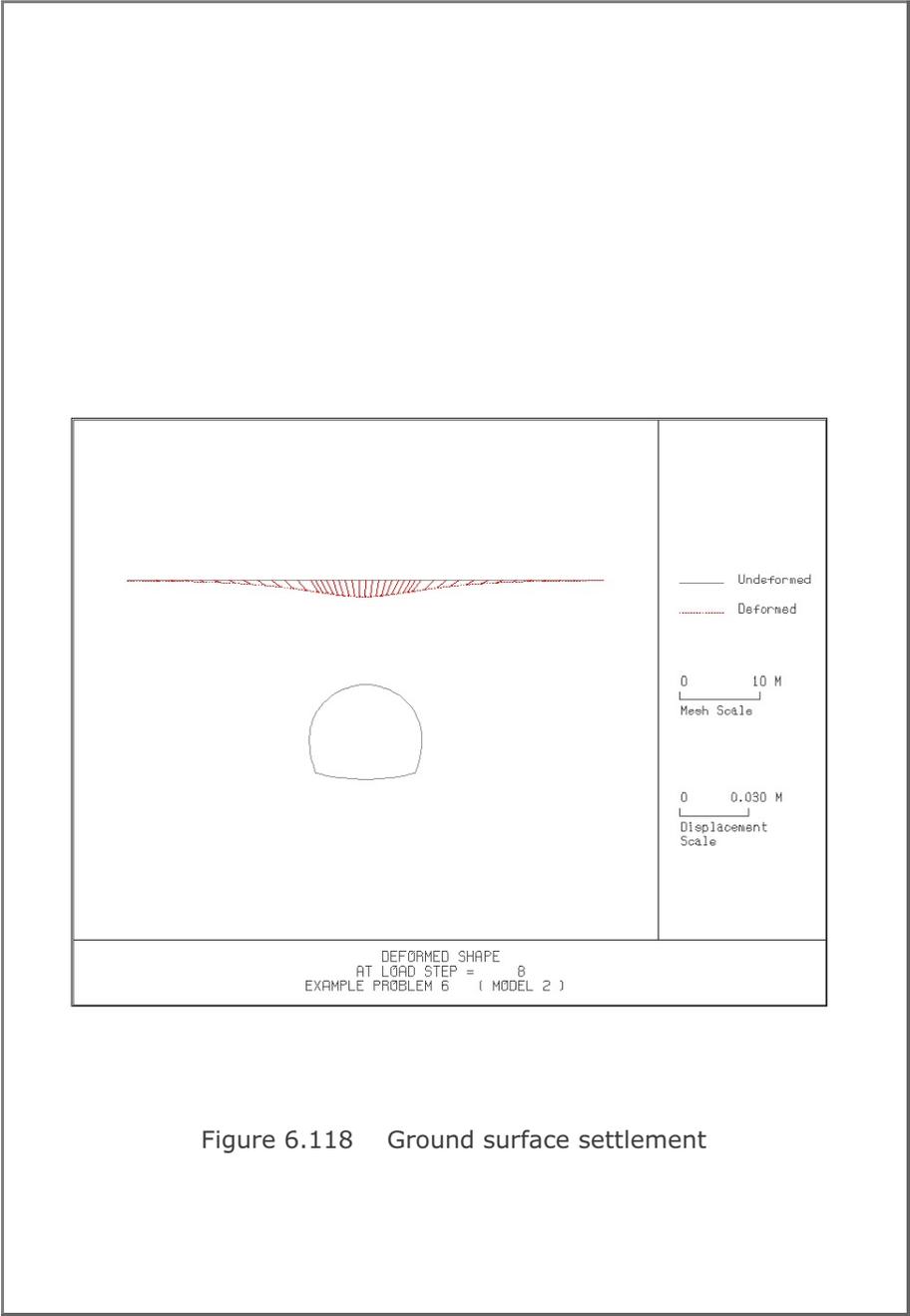


Figure 6.118 Ground surface settlement

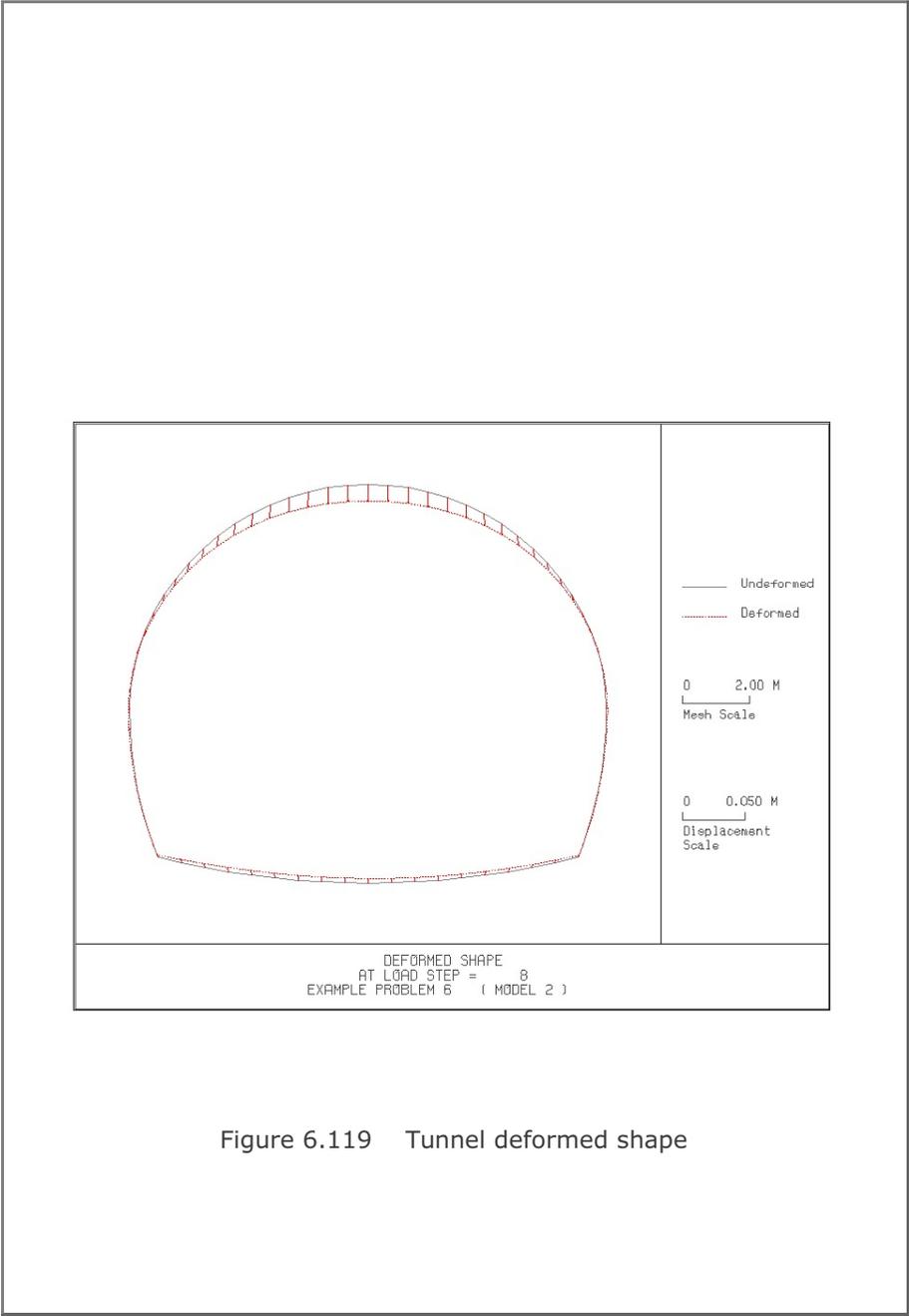


Figure 6.119 Tunnel deformed shape

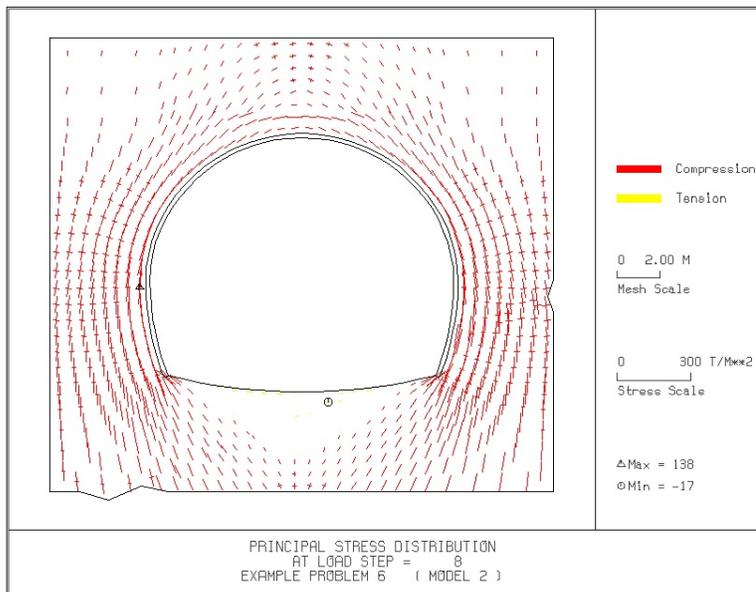


Figure 6.120 Principal stresses around tunnel

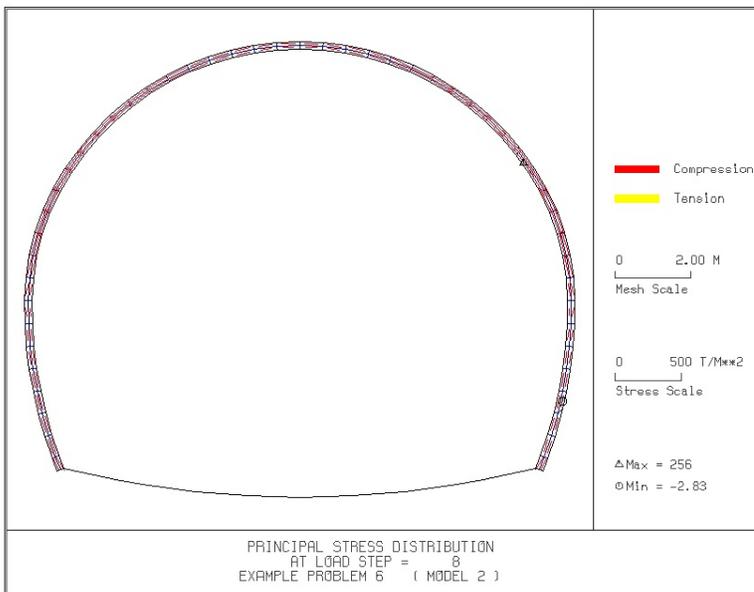


Figure 6.121 Shotcrete stresses

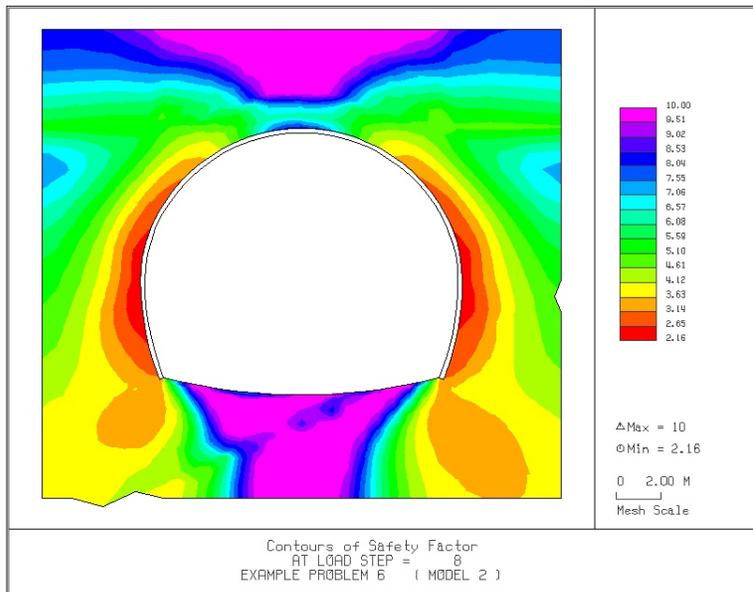


Figure 6.122 Contour of safety factor

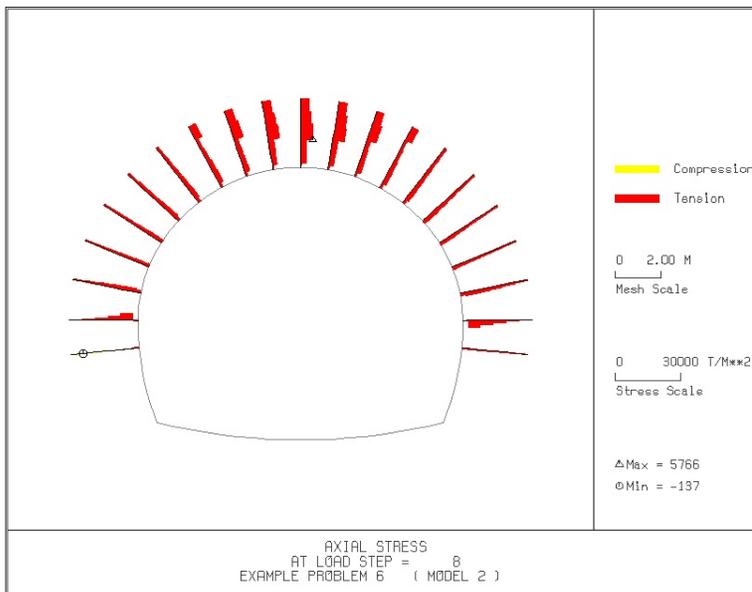


Figure 6.123 Rock bolt axial stresses

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
* N LAYER
* 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

```

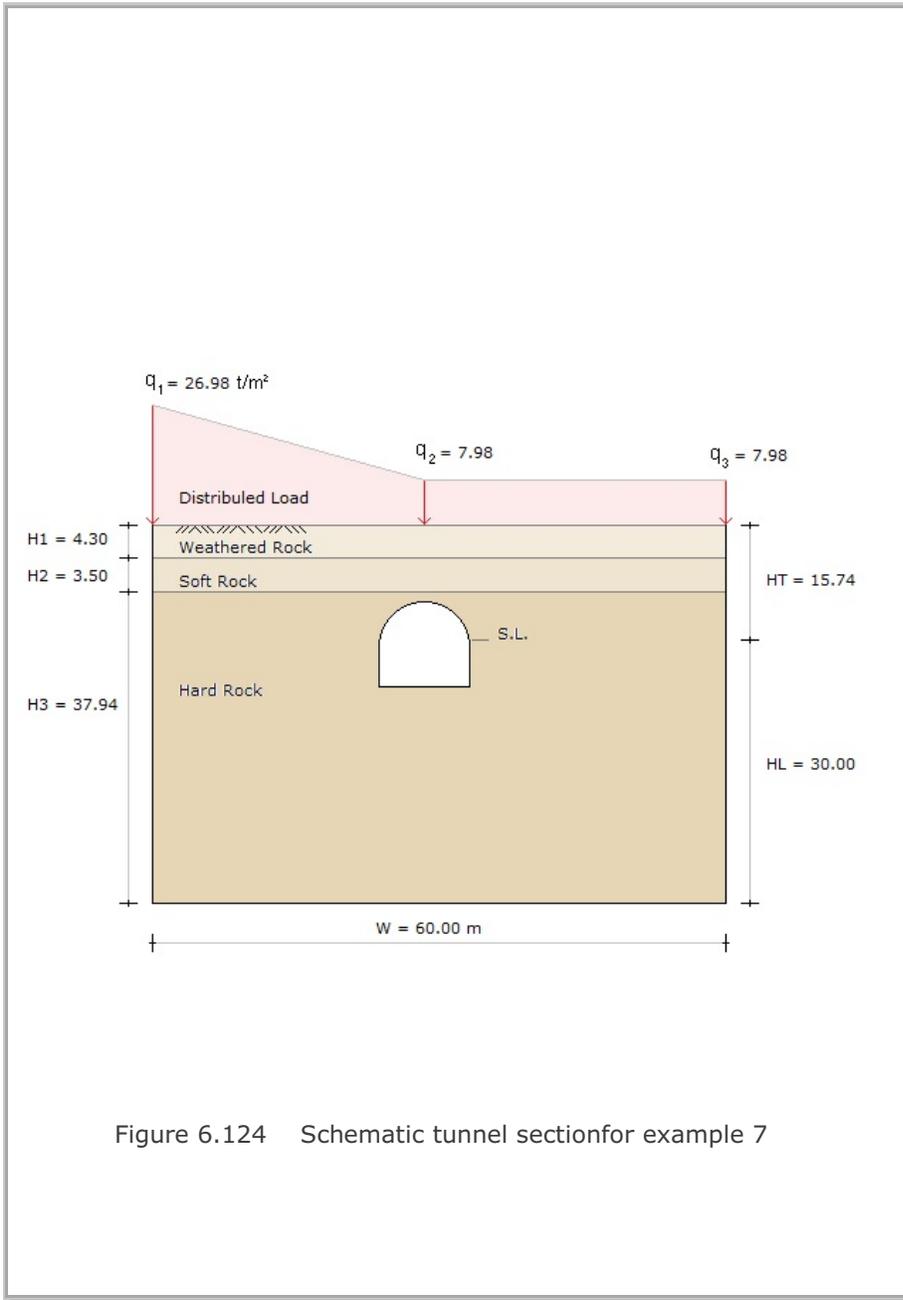


Figure 6.124 Schematic tunnel section for example 7

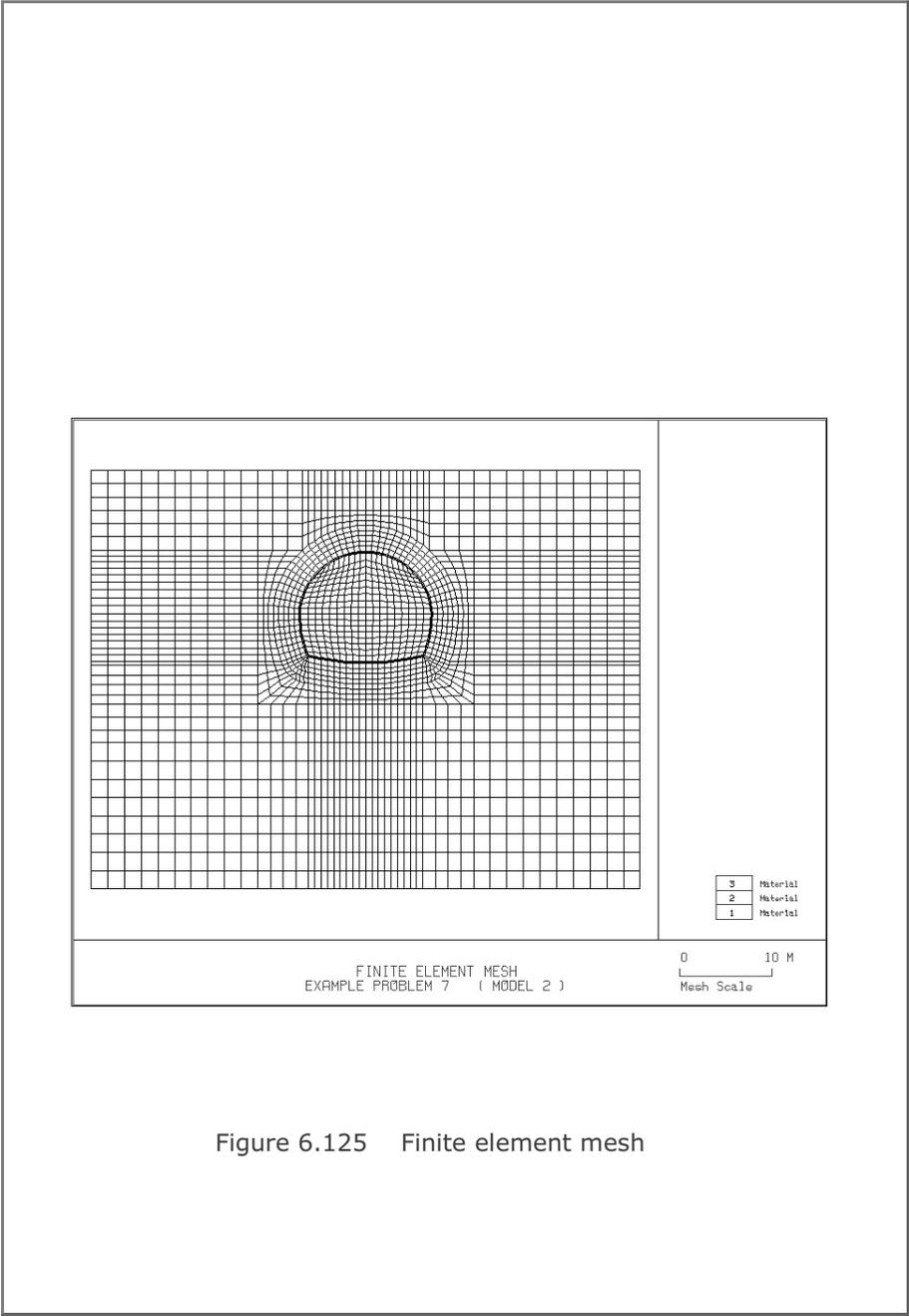


Figure 6.125 Finite element mesh

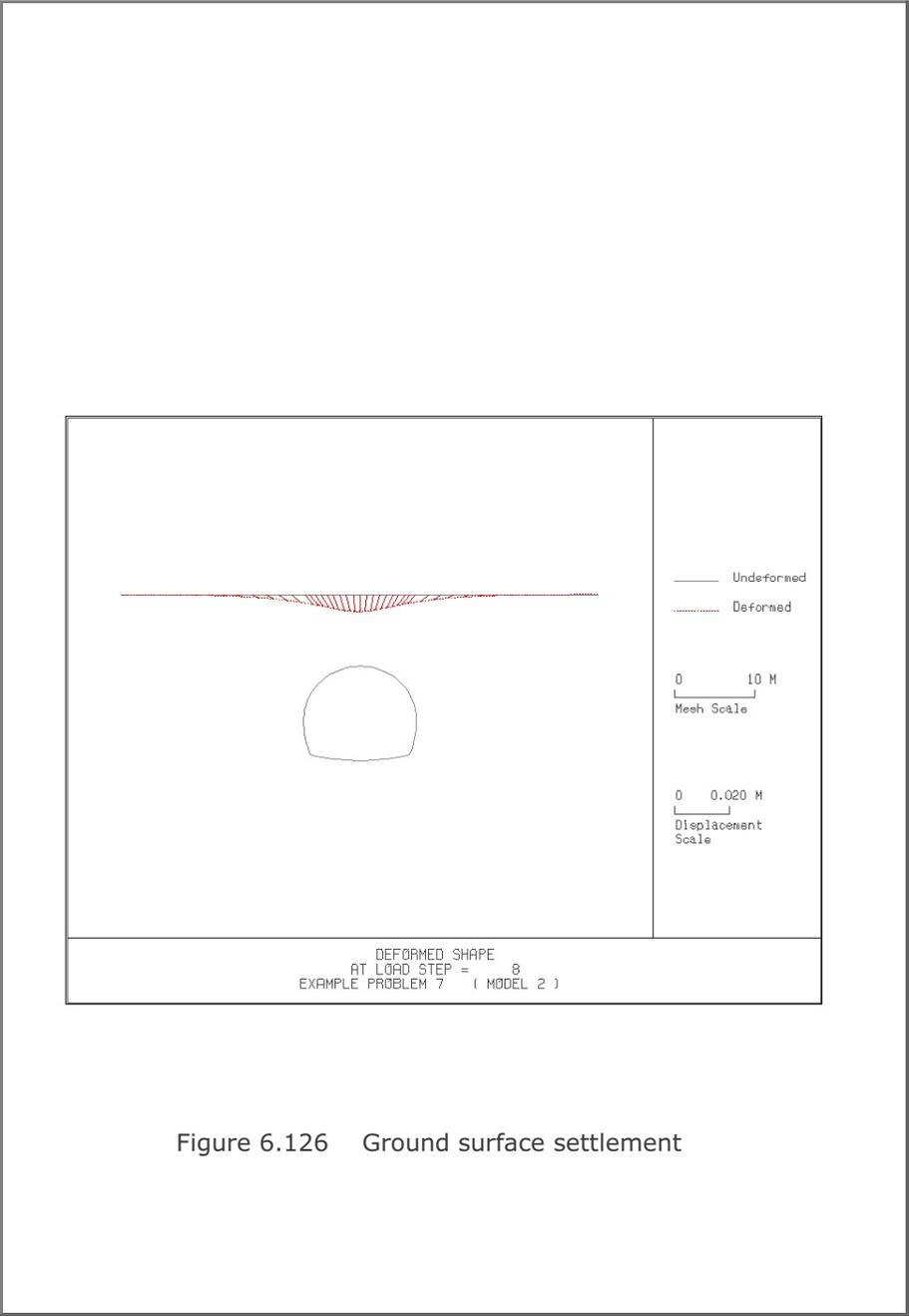


Figure 6.126 Ground surface settlement

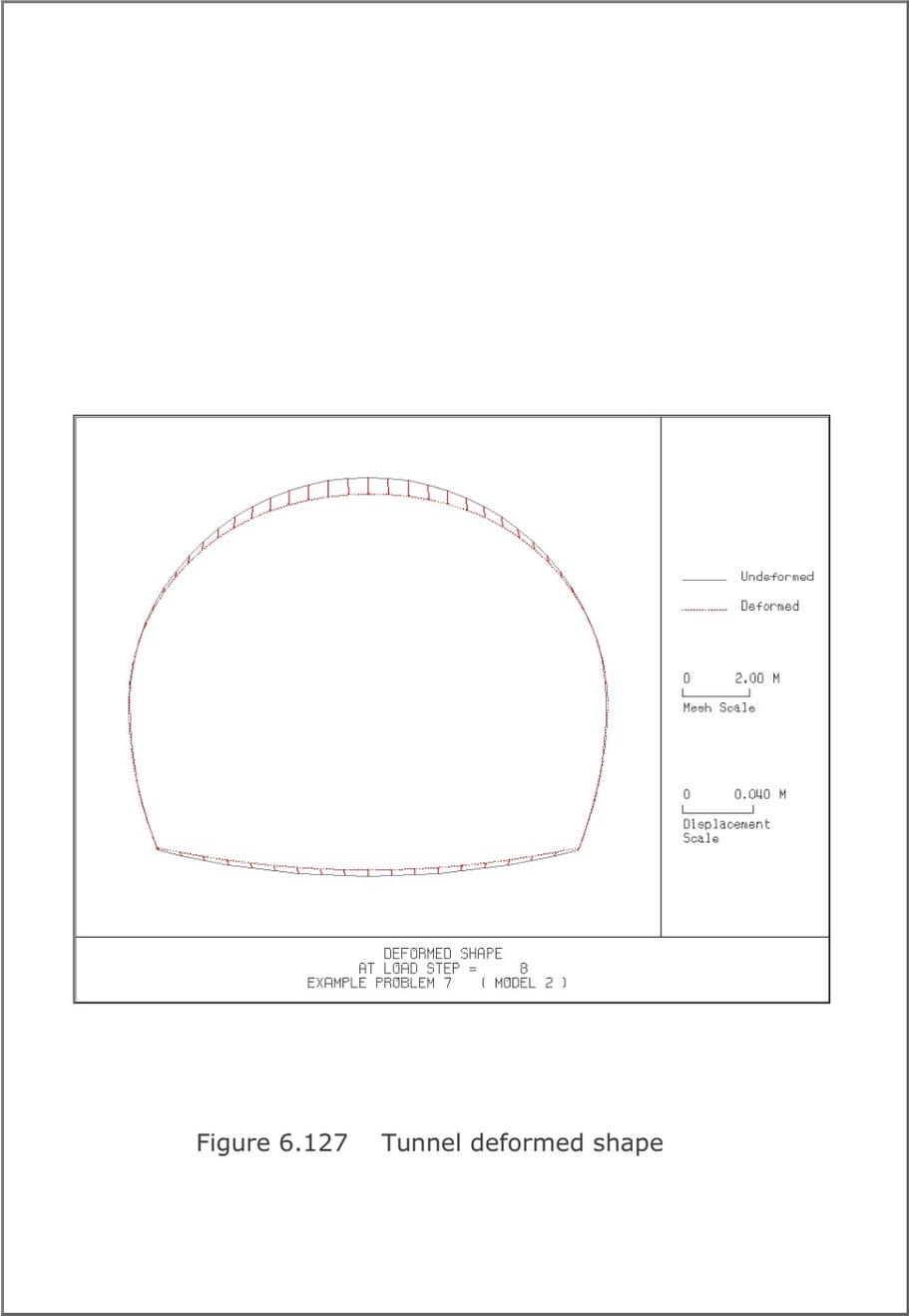


Figure 6.127 Tunnel deformed shape

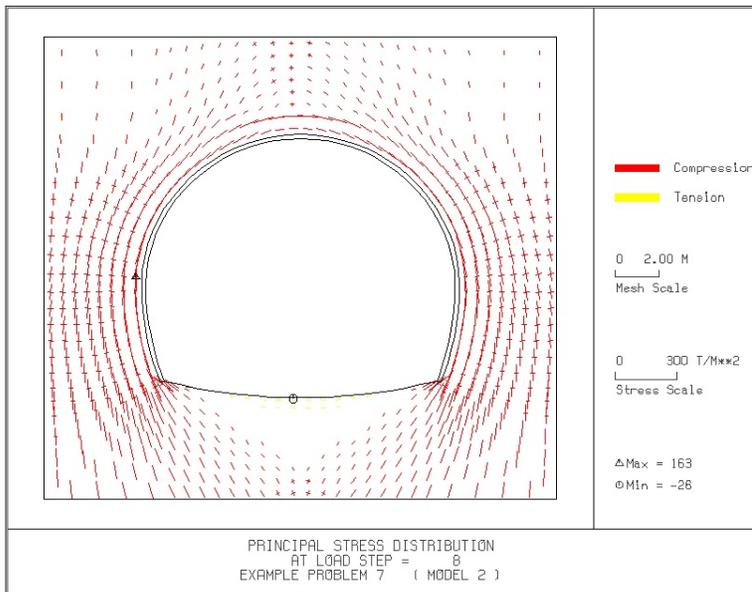


Figure 6.128 Principal stresses around tunnel

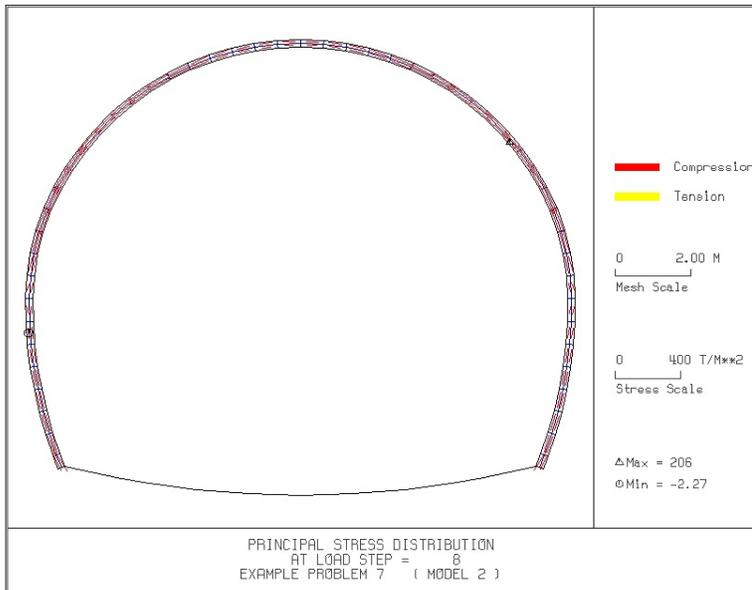


Figure 6.129 Shotcrete stresses

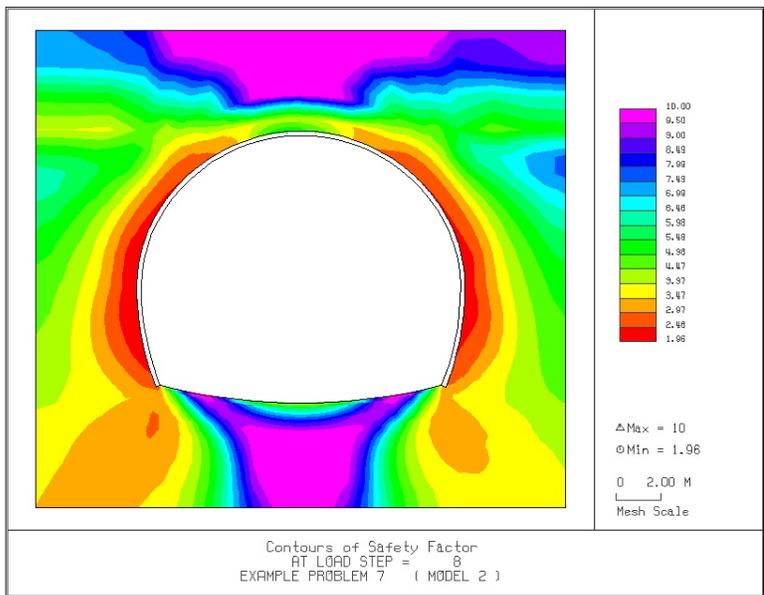


Figure 6.130 Contour of safety factor

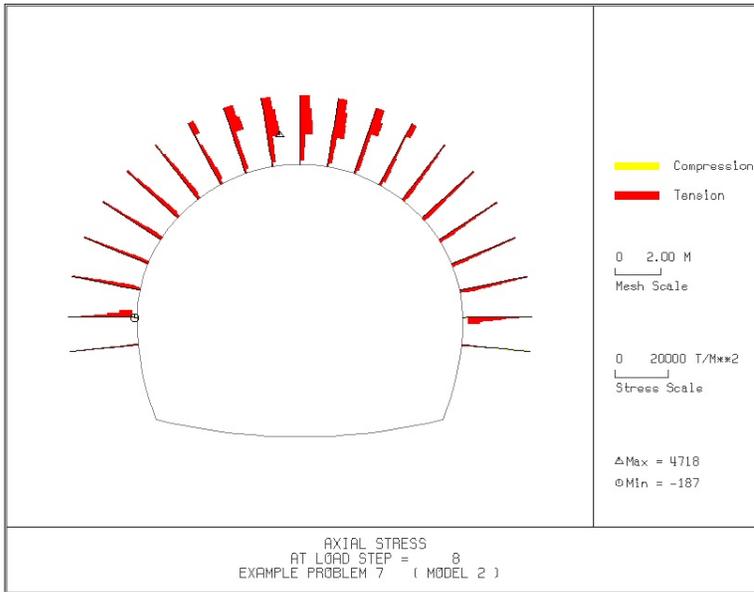


Figure 6.131 Rock bolt axial stresses

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_0 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

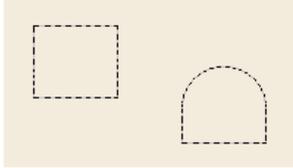
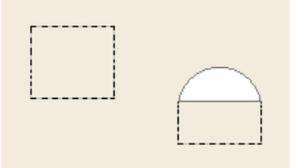
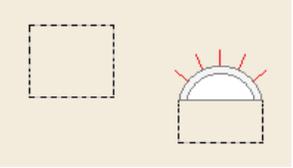
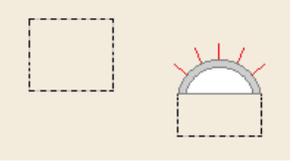
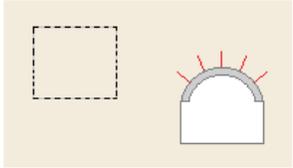
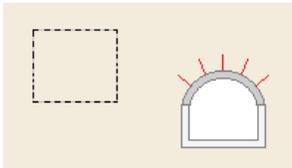
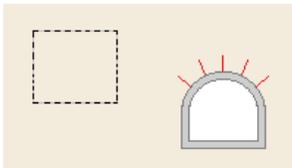
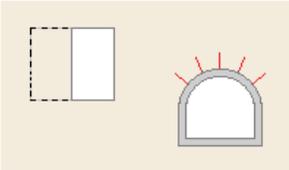
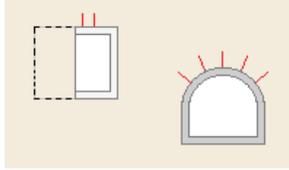
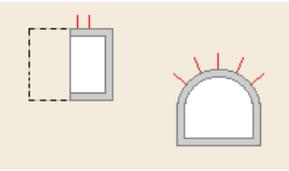
Step	Construction State	Descriptions
1,2		In Situ K_0 State
3		50 % Stress Relief
4		75 % Stress Relief Soft Shotcrete Rock Bolt
5		100% Stress Relief Hard Shotcrete Rock Bolt
		Upper Core Excavation (Right Tunnel)

Table 6.26 Simulation of construction sequence (Continued)

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

Lower Core Excavation (Right Tunnel)

Table 6.26 Simulation of construction sequence (Continued)

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

Right Core Excavation (Left Tunnel)

Table 6.26 Simulation of construction sequence (Continued)

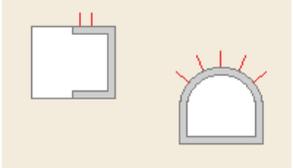
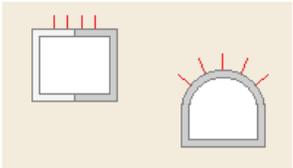
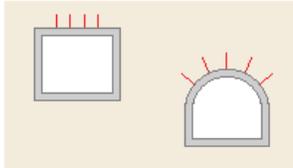
Step	Construction State	Descriptions	Left Core Excavation (Left Tunnel)
12		50 % Stress Relief	
13		75 % Stress Relief Soft Shotcrete Rock Bolt	
14		100 % Stress Relief Hard Shotcrete Rock Bolt	

Table 6.26 Simulation of construction sequence (Continued)

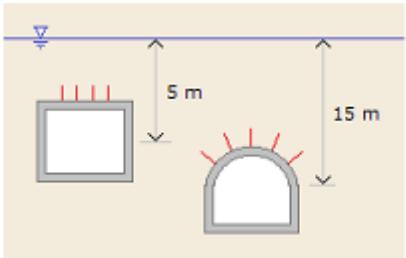
Step	Construction State	Descriptions
18		<p>Lining Subjected to: Water Pressure</p> <p style="writing-mode: vertical-rl; transform: rotate(180deg);">Lining Analysis</p>

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
*

```

6-210 Example 8

```

*
* 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
*

```

6-212 Example 8

```
*
* 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	<u>Lining Subjected to:</u> 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

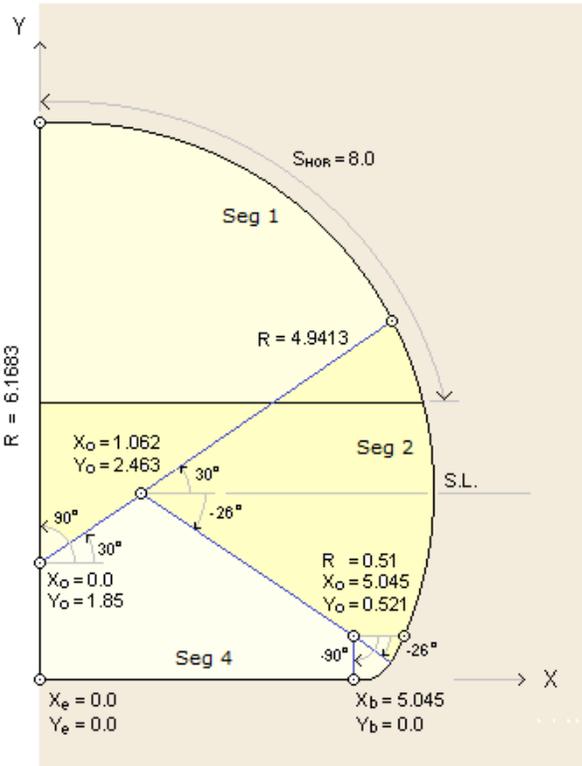


Figure 6.132 Dimensions of right tunnel for Example 8

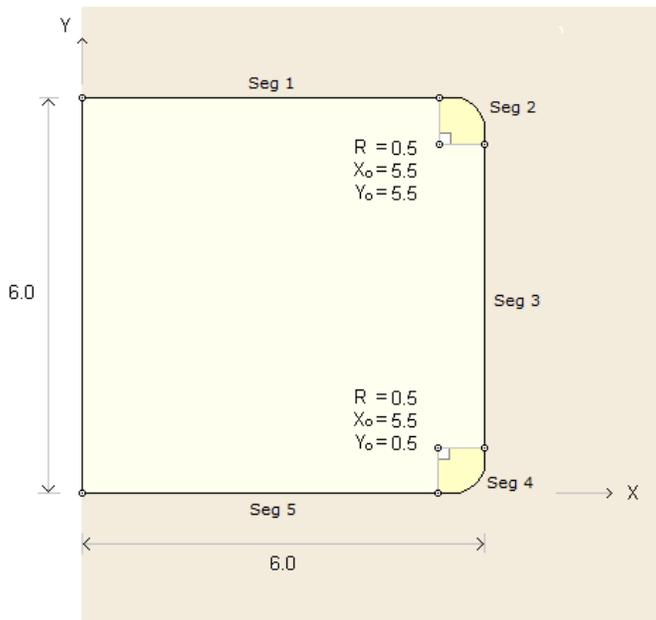
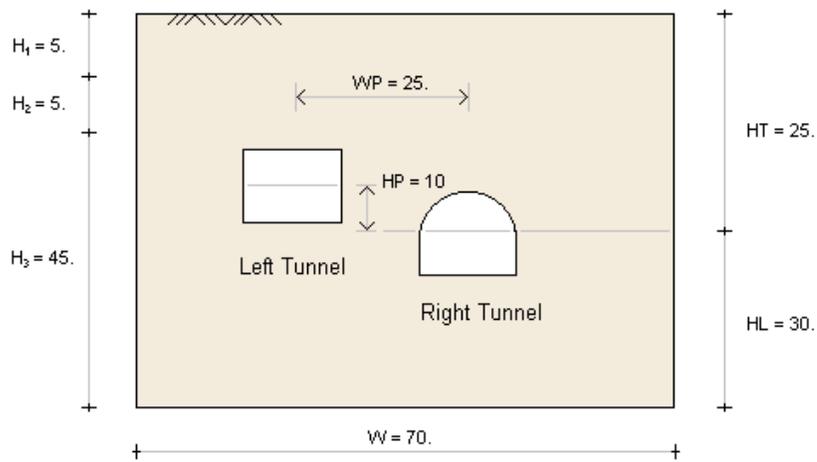


Figure 6.133 Dimensions of left tunnel for example 8

MODEL = 4 Two Tunnels [Unsymmetric Section]



DELTA X = 2.0, DELTA Y = 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

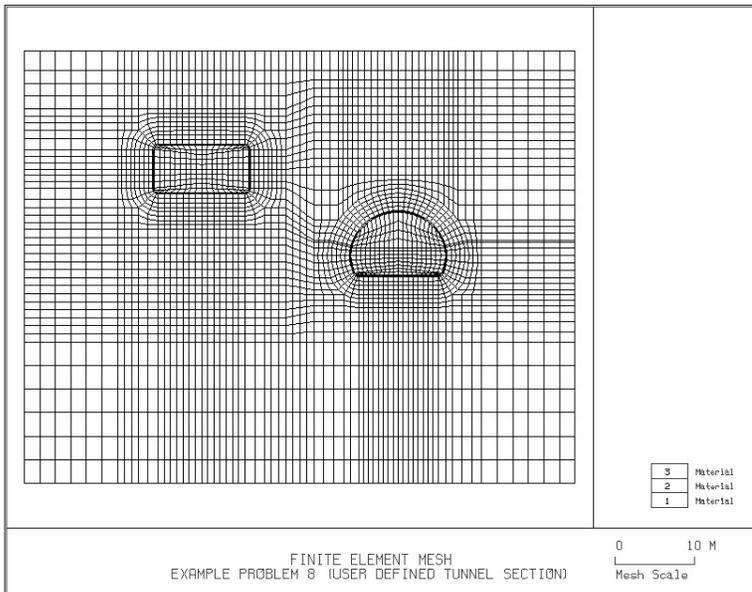


Figure 6.135

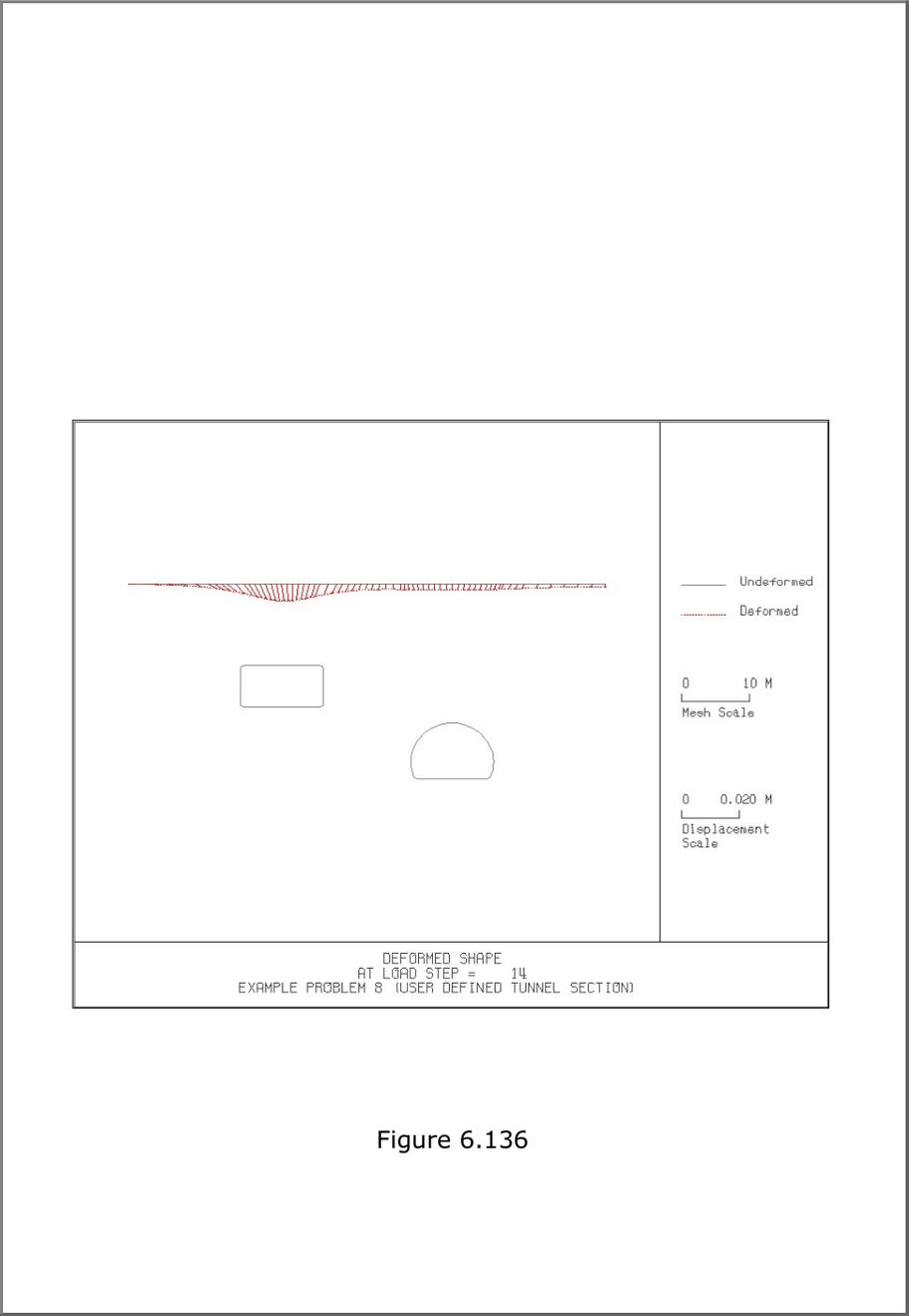


Figure 6.136

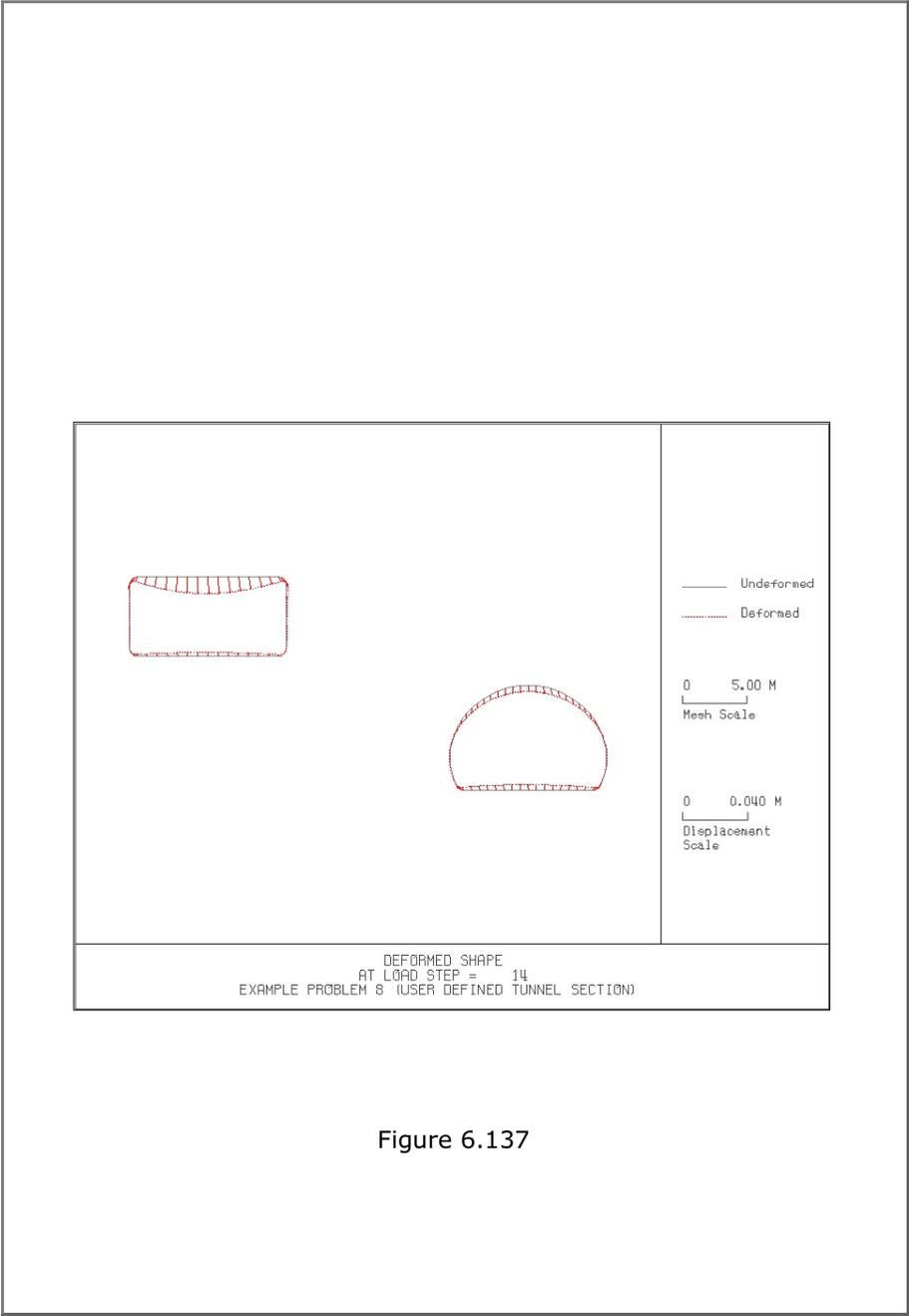


Figure 6.137

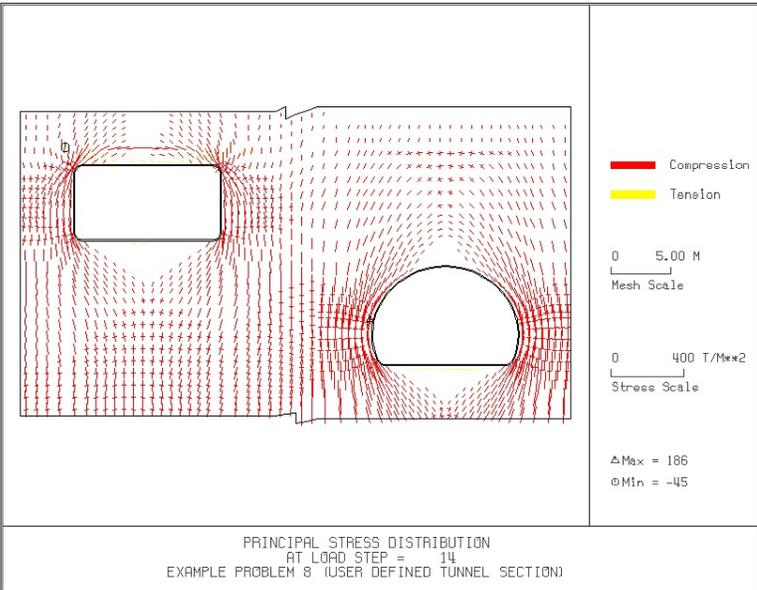


Figure 6.138

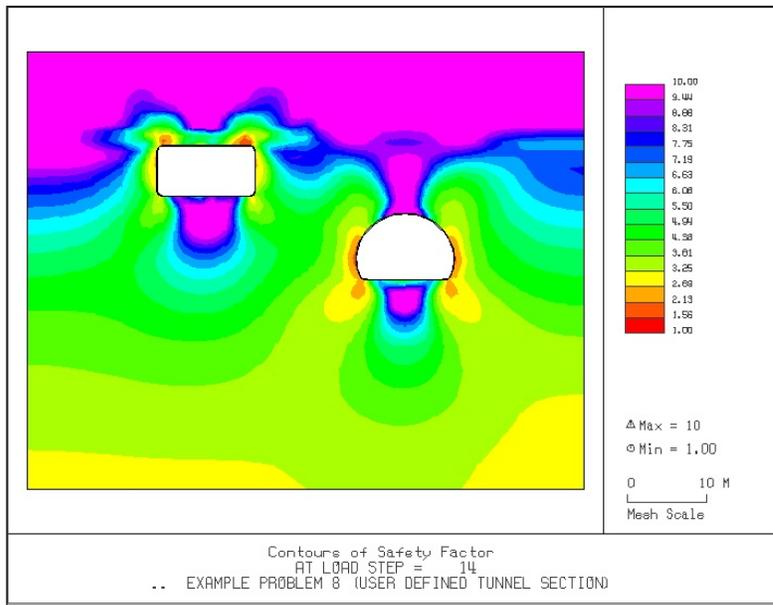


Figure 6.139

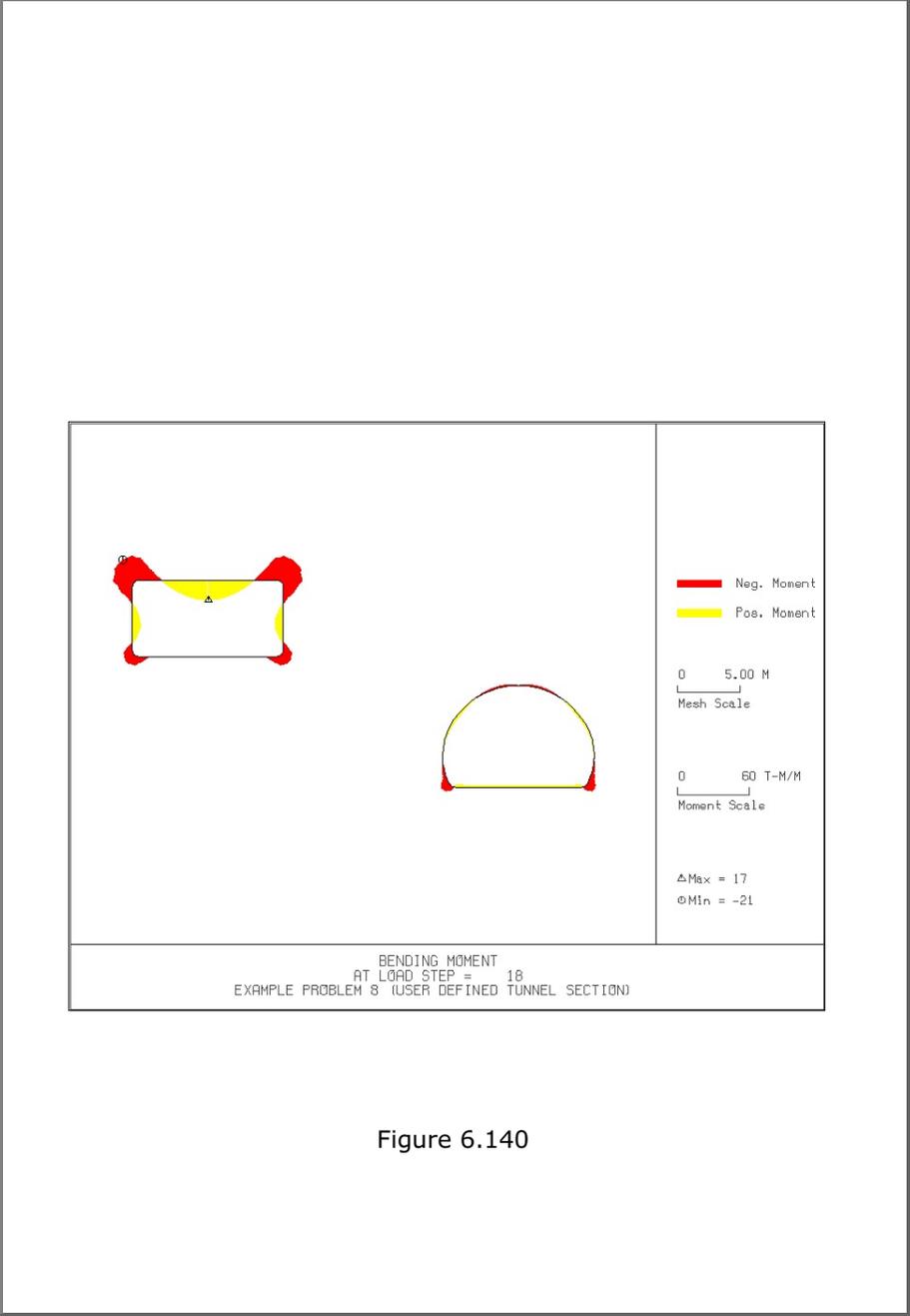


Figure 6.140

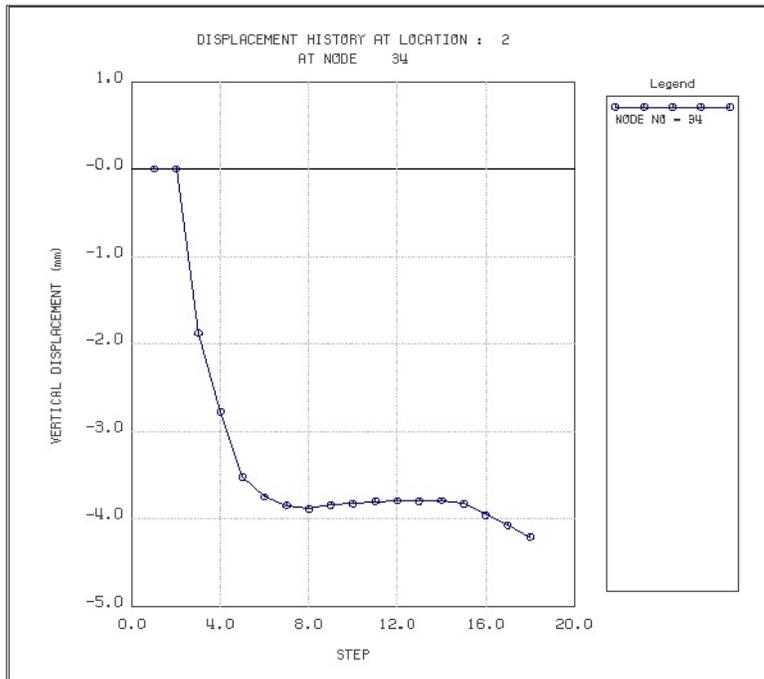


Figure 6.141

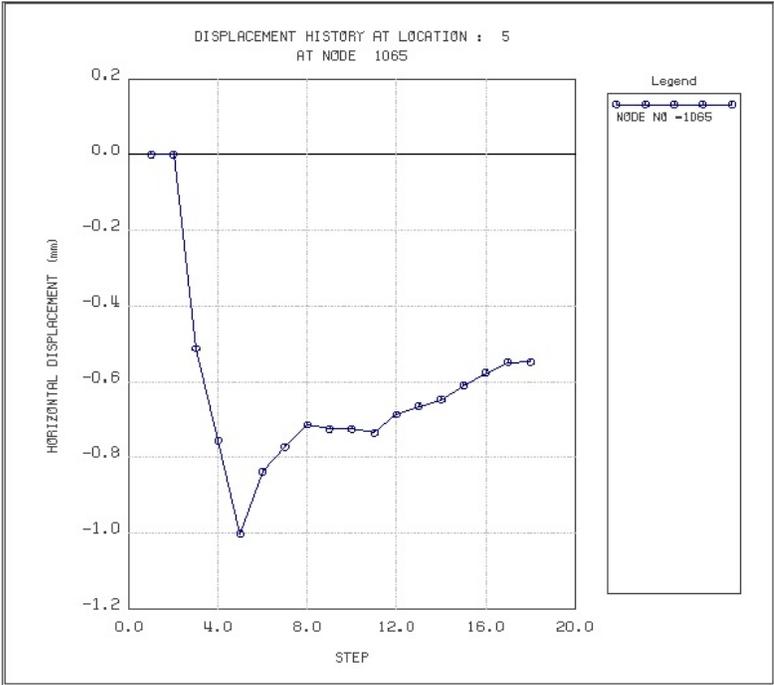


Figure 6.142

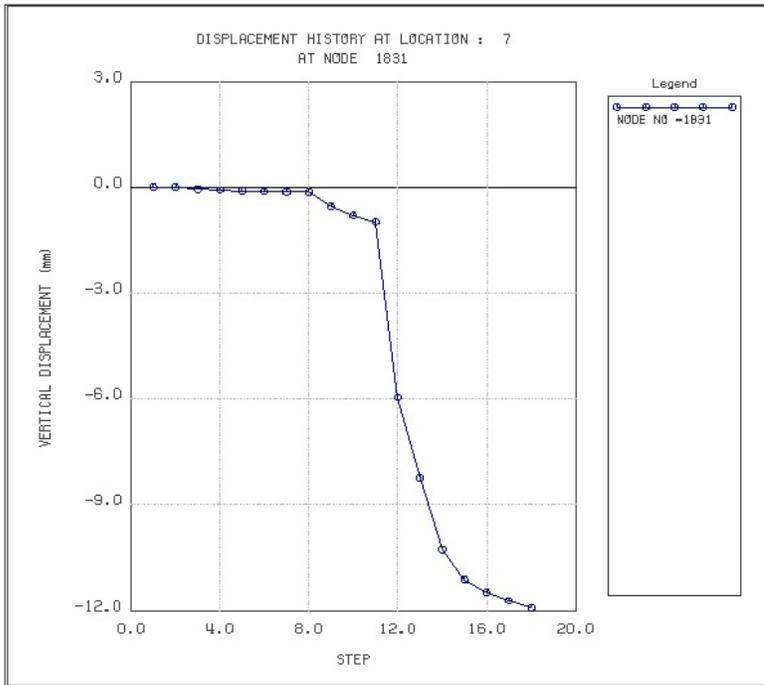


Figure 6.143

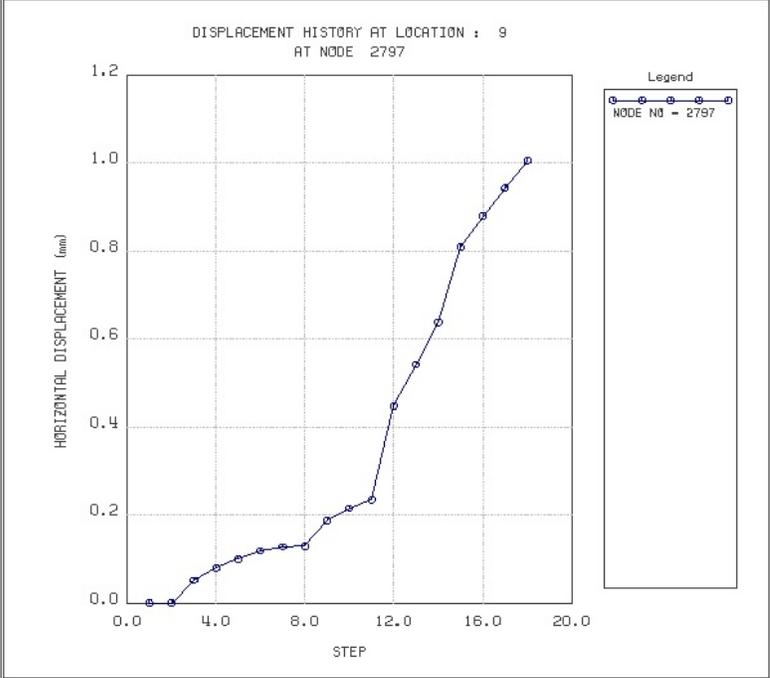


Figure 6.144

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
* N LAYER
  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
*

```

6-232 Example 9

```

*
* 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
*

```

6-234 Example 9

```
*
* 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

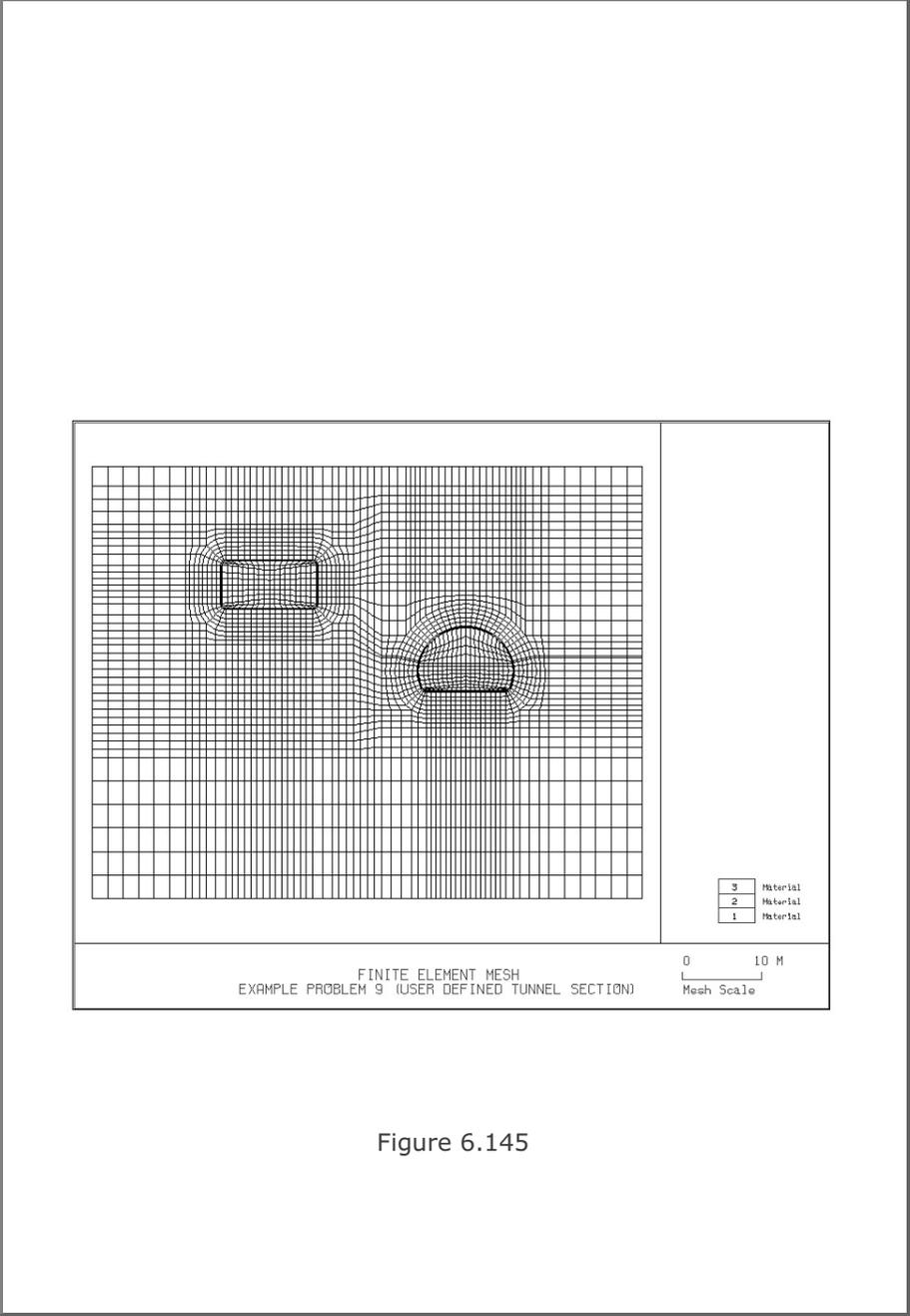


Figure 6.145

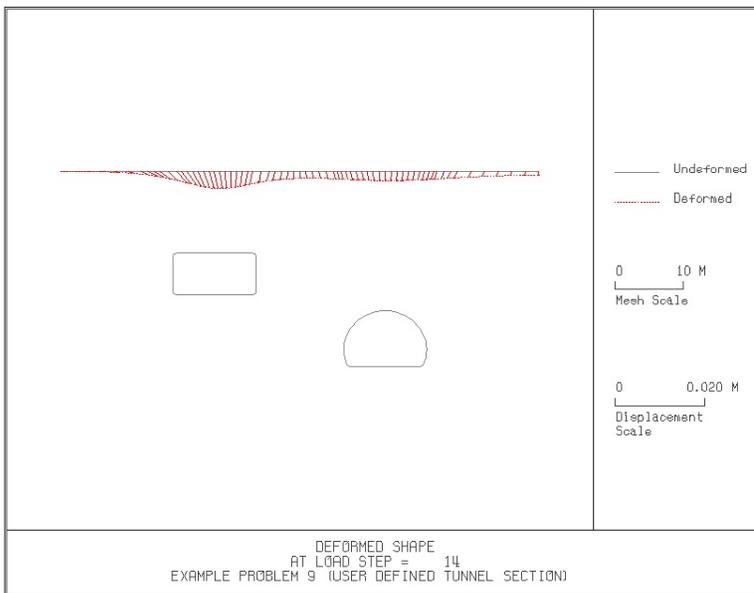


Figure 6.146

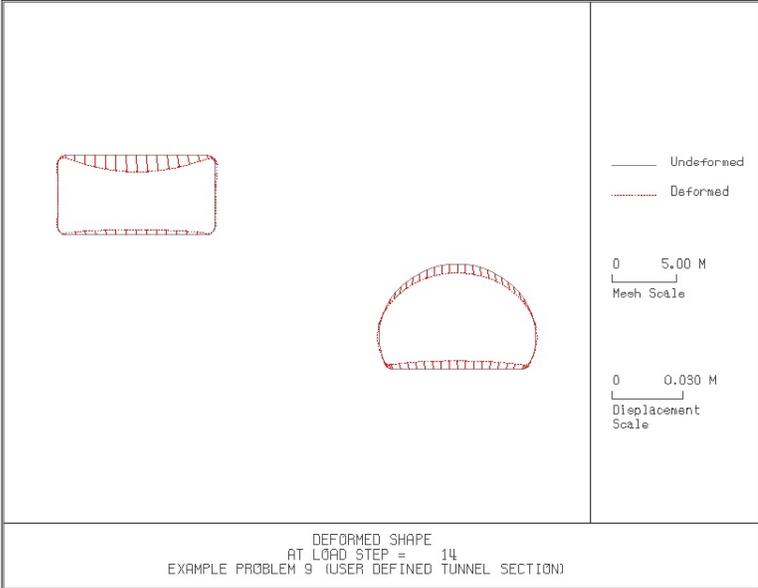


Figure 6.147

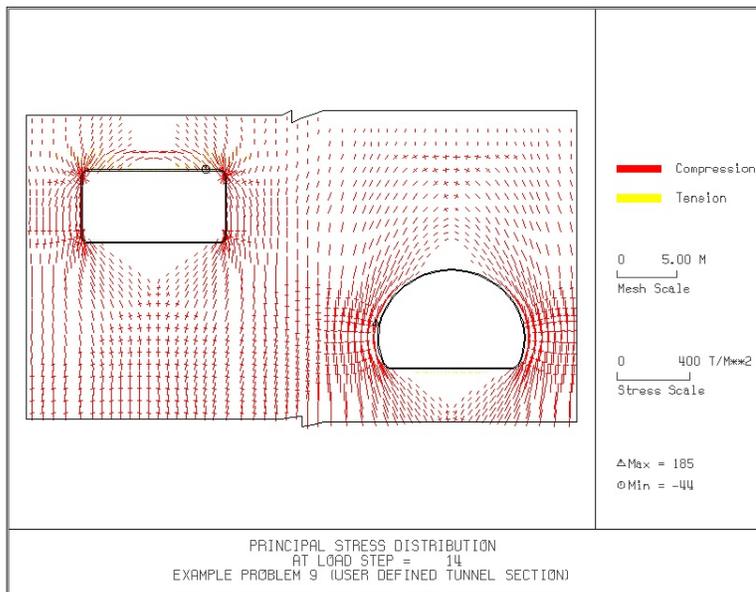


Figure 6.148

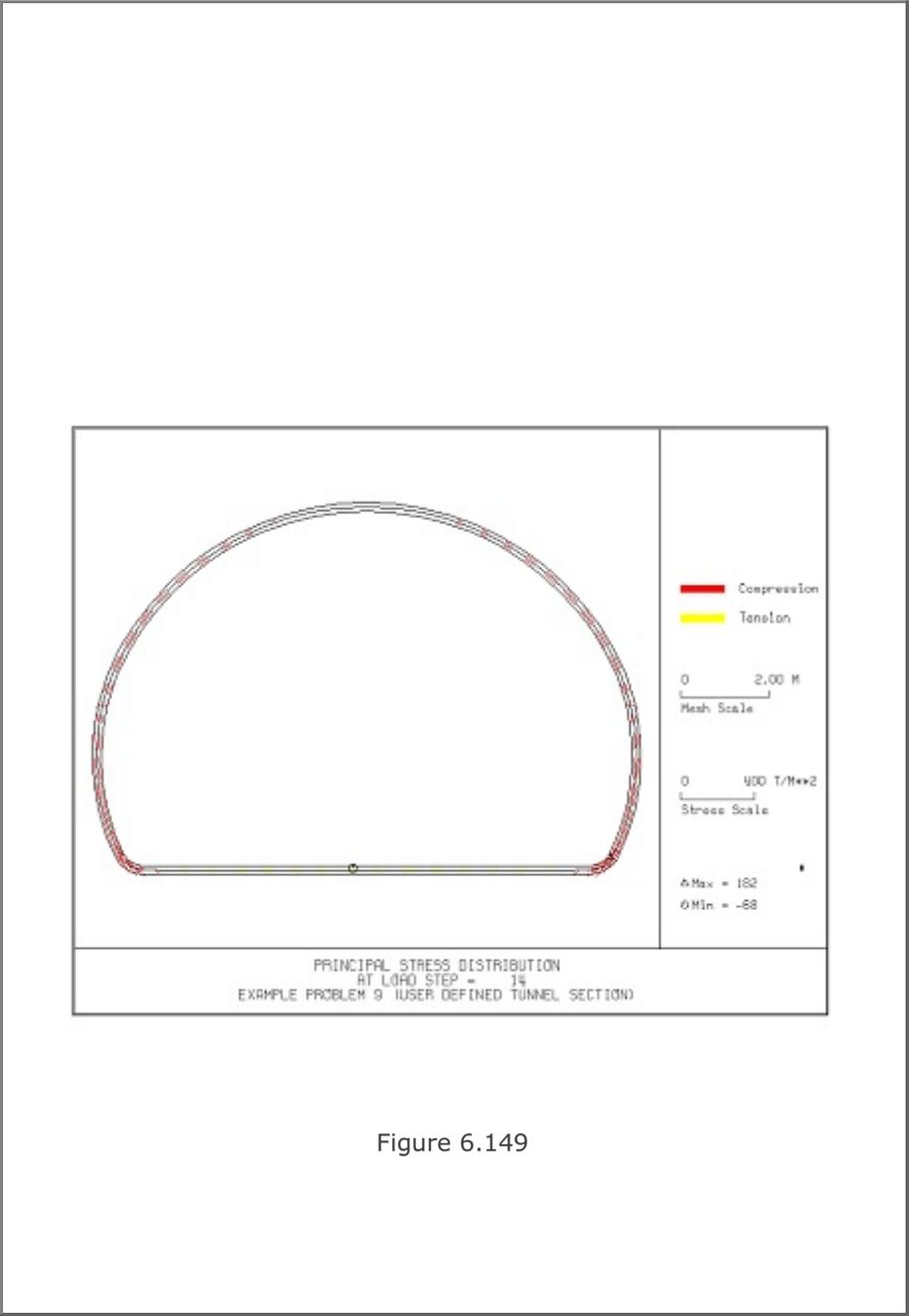


Figure 6.149

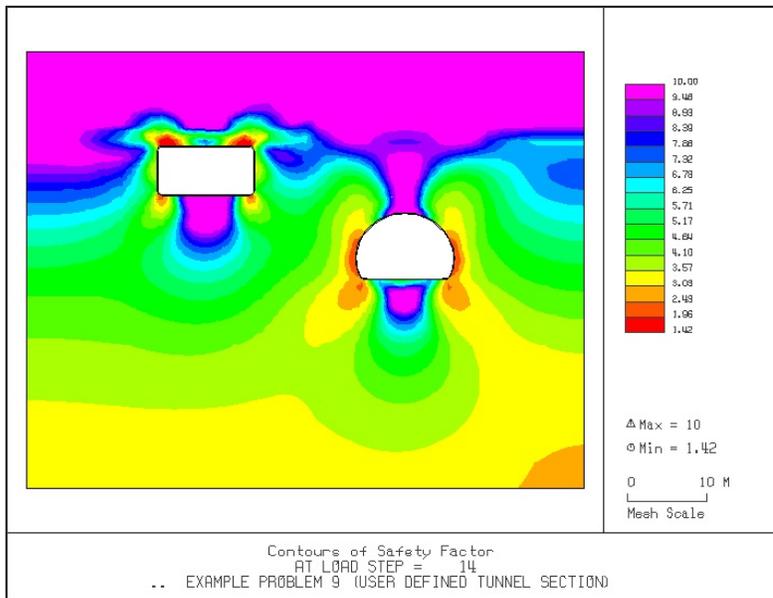


Figure 6.150

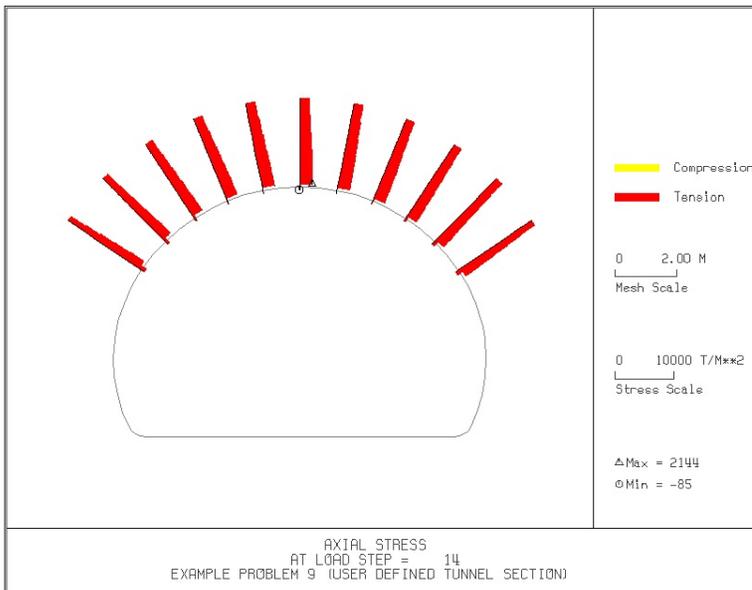


Figure 6.151

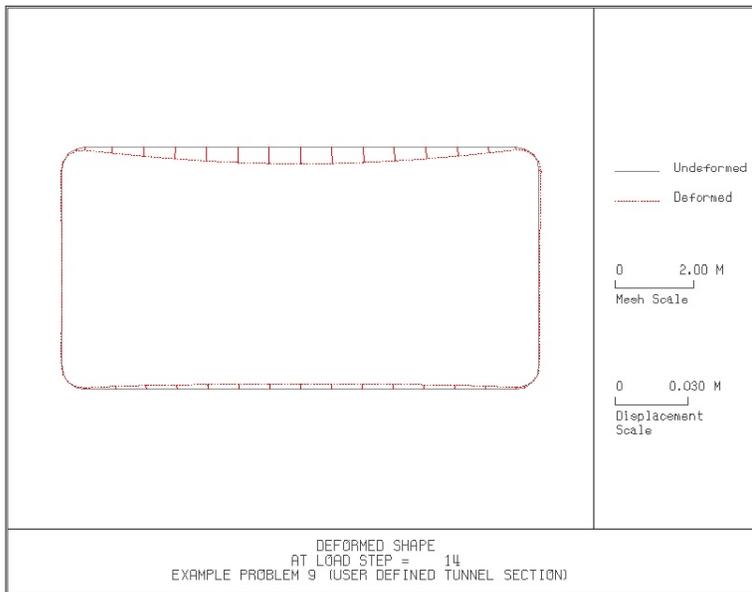


Figure 6.152

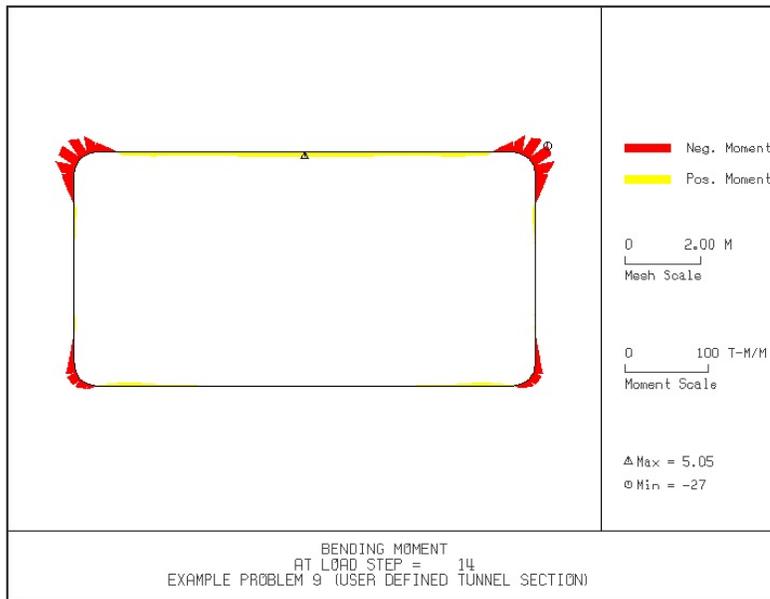


Figure 6.153

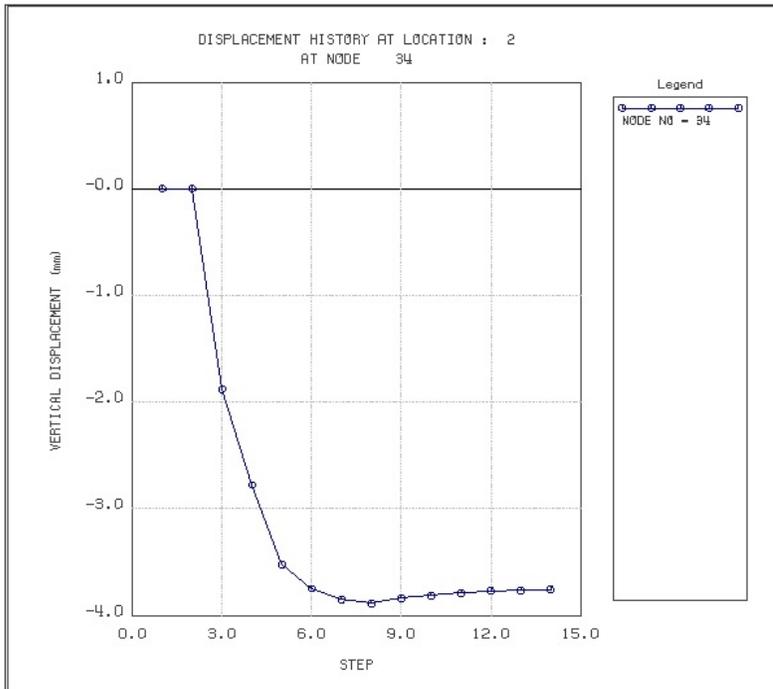


Figure 6.154

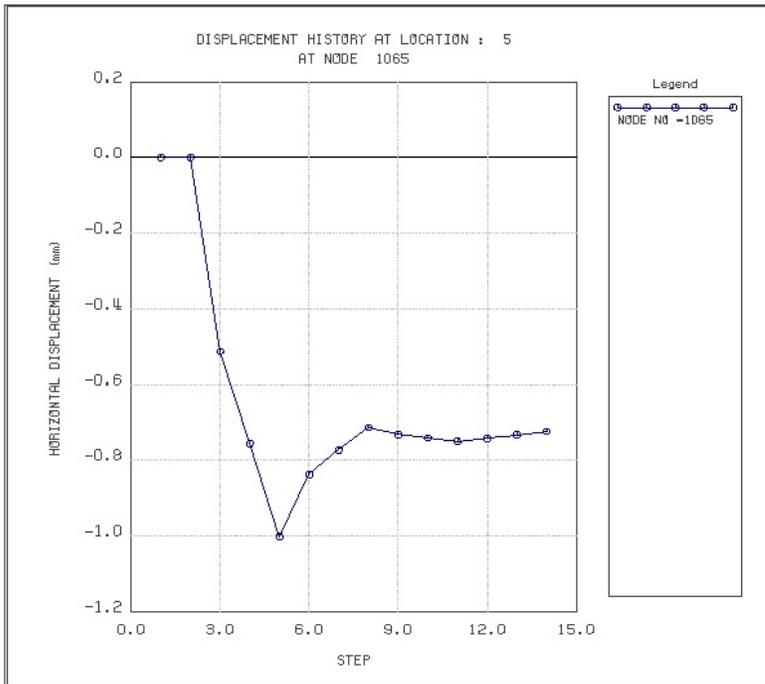


Figure 6.155

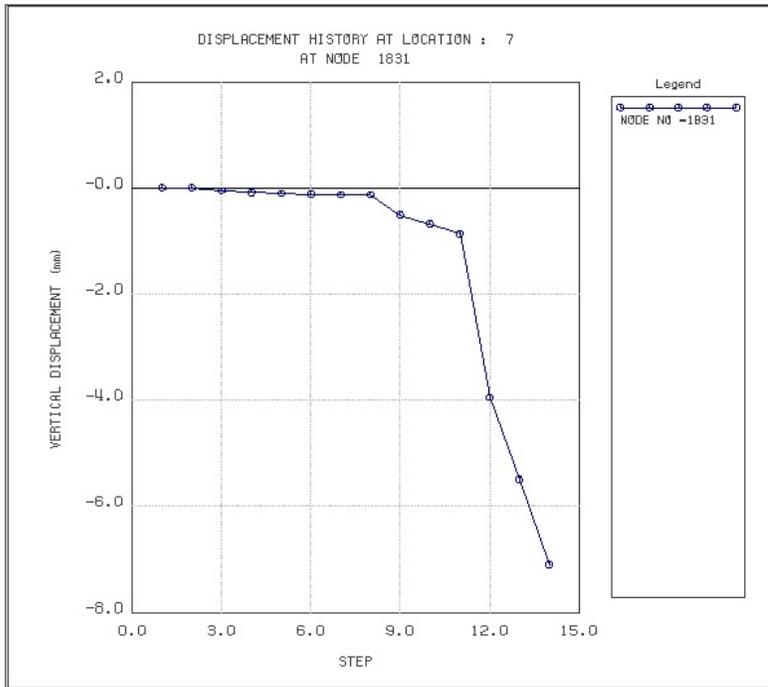


Figure 6.156

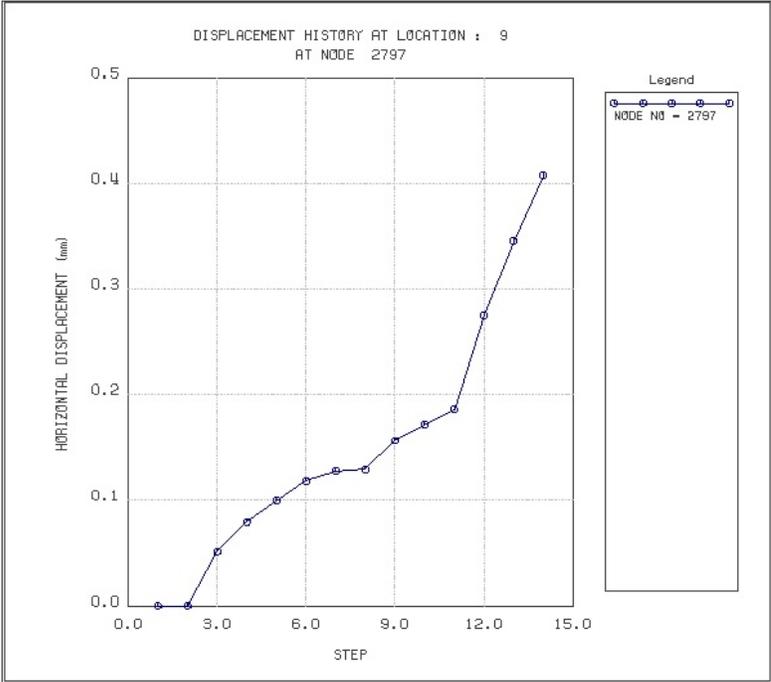


Figure 6.157