16 Lined Tunnel Construction in Saturated Ground

16.1 Problem Statement

A circular tunnel with an excavated radius of 6 m, and with its center at a depth of 65 m below the surface, is constructed in saturated ground. The pre-construction water table is at a depth of 5 m below the surface. The ground is dewatered during the construction phase. The tunnel is supported by a temporary shotcrete liner, which is installed while the tunnel excavation advances, and a final cast-in-place 0.4 m-thick concrete liner. The analysis is required to determine the forces and moments that develop in the concrete liner both when the water level returns to its original elevation and when, at a later time, the temporary shotcrete liner loses its strength.

The construction sequence considered in this analysis is divided into six stages:

1. Before construction begins, the water table is lowered to approximately 10 m below the tunnel invert using dewatering wells. The initial in situ stress ratio, $K_o$, is 0.5 for the unsaturated state.

2. The excavation begins, and the tunnel advancement produces tunnel closure corresponding to a 30% relaxation of traction forces acting on the tunnel periphery before the shotcrete liner is installed.

3. The shotcrete is installed, the tunnel is advanced to produce 100% relaxation, and load develops in the shotcrete. Note that the shotcrete is sufficiently porous, such that it provides negligible resistance to fluid flow when the original water table is restored.

4. A permanent cast-in-place concrete liner is then placed inside the shotcrete lined tunnel. A plastic waterproof membrane covers the concrete liner; the concrete plus membrane is impermeable.

5. After the concrete liner is installed, the dewatering wells are stopped, and the water rises to the original level. Pore pressures are re-established throughout the ground and the outer liner, but fluid does not penetrate past the impermeable inner liner. The water exerts a pressure in the “gap” between the two liners; this pressure causes axial forces to develop within the liners.

6. Finally, the shotcrete liner degrades over time, and the ground relaxes into the inner liner.

Figure 16.1 illustrates the construction sequence that is simulated in the FLAC analysis. The figure also lists the rock, shotcrete and concrete liner properties assumed for the analysis.
**Example Applications**

**Figure 16.1** Conditions and sequence for the lined tunnel construction

### Rock Properties
- Density: 2240 kg/m³
- Elastic modulus: 275 MPa
- Poisson’s ratio: 0.3
- Cohesion: 20 kPa
- Friction angle: 20°
- Tensile strength: 0

### Shotcrete Properties
- Elastic modulus: 5 GPa
- Thickness: 20 cm

### Concrete Liner Properties
- Elastic modulus: 25 GPa
- Thickness: 40 cm
- Density: 2500 kg/m³

### Construction Sequence

<table>
<thead>
<tr>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
<th>Stage 5</th>
<th>Stage 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial $K_0$ state with lowered water table</td>
<td>Relax tractions 30%</td>
<td>Install shotcrete &amp; relax tractions 100%</td>
<td>Install concrete liner</td>
<td>Raise water table &amp; add water pressure in gap</td>
<td>Delete shotcrete</td>
</tr>
</tbody>
</table>

*Figure 16.1 Conditions and sequence for the lined tunnel construction*
16.2 Modeling Procedure

The six construction stages are simulated as separate steps in the FLAC analysis. Each step is described in the following sections. The model is created using FLAC’s graphical interface, the GIIC. Upon entering the GIIC, the groundwater flow option, adjust total stress option and structural elements facility are activated from the Model Options dialog. The option for automatic adjustment of total stresses is selected to facilitate the calculation for Stage 5, when the water table is raised in the model. Also, 5 extra grid variables are selected; these are available to store grid variables when creating FISH functions for this analysis. The Project Tree Record format and SI system of units are also selected for this example. The Model Options dialog is shown in Figure 16.2:

![Model options selected for lined tunnel example](image)

After the model options are selected, a Project File (*.prj) dialog opens. A working directory is selected for storing files related to this project, and a project title (“Lined tunnel construction in saturated ground”) and project filename (“LINER.PRJ”) are assigned in the dialog.

A record of all FLAC commands used to create and run this model are saved to file after the project is complete (using the File/Export Record menu item). A listing of the data record for this model is given in Section 16.4.
Example Applications

16.2.1 Step 1: Initial State with Lowered Water Table

The model creation takes advantage of the problem symmetry, as shown in Figure 16.1. The grid is constructed using the Build/Generate/Library tool. The Single tunnel-refined region grid type is selected, as shown in Figure 16.3. A fine mesh is created in the region of the tunnel, and a coarse grid extends away from the tunnel region. ATTACH commands are assigned automatically to connect the coarse mesh to the fine mesh. When this grid type is selected and a coordinate range is defined, a grid tool opens to prescribe mesh density and adjust the grid to the problem dimensions. Figure 16.4 shows the grid after adjustments have been made to the corner locations and mesh density. The grid extends from 0.0 to 120.0 in the x-direction, and from −80.0 to 65.0 in the y-direction. The x = 0 coordinate is the line of symmetry. The fine mesh region extends from 0.0 to 20.0 in the x-direction, and from −10.0 to 10.0 in the y-direction, and contains 36 × 36 zoning. The surrounding mesh is three times coarser than the fine mesh.

The grid in the fine-mesh region is then altered to match the periphery of the excavated tunnel, using the Alter/Shape tool. The Circle mode is selected to locate the tunnel with its center at x = 0.0, y = 0.0 and radius of 6.0. The third row of gridpoints from the top of the grid is adjusted slightly to the location y = 60.0, using the Line mode in the Shape tool. This is done to provide a more precise representation for the pore-pressure distribution (in Stage 5) when the water level is raised. The final grid is shown in Figure 16.5, and a close-up view of the tunnel region is shown in Figure 16.6. Note that the resources panes are turned off in the second figure (by checking off the Show/Resources menu item) to show a full model-view of the grid.

![Figure 16.3 Build/Generate/Library tool](image)
Lined Tunnel Construction in Saturated Ground

Figure 16.4  Grid tool for the “Single tunnel-refined region” grid type

Figure 16.5  Grid created for lined tunnel example
The material properties for the rock are entered using the MATERIAL ASSIGN tool. The properties are displayed in the Define Material dialog shown in Figure 16.7. The groundwater properties (porosity = 0.3, and permeability (i.e., mobility coefficient) = $10^{-10} \text{m}^2/(\text{Pa-sec})$) are also assigned, using the MATERIAL GWProp tool (see Figure 16.8). Units for groundwater properties in FLAC are discussed in Section 1.7 in Fluid-Mechanical Interaction.
The boundary conditions are applied using the In Situ tool. The left boundary is a line of symmetry. The right boundary is fixed from movement in the \(x\)-direction. The top boundary is a free surface, and the bottom boundary is fixed from movement in the \(y\)-direction. The In Situ tool with the boundary conditions assigned is shown in Figure 16.9.

The initial stress state is specified assuming that no water is present. The rock density listed in Figure 16.1 is considered to be the unsaturated value, and assuming a value of 10 m/sec\(^2\) for the gravitational magnitude, the calculated vertical stress at the bottom of the model (145 m depth) is then \(-3.248\) MPa. A linear variation based on this value is entered for the \(yy\)-stress component, using the In Situ tool. The \(xx\)-stress and \(zz\)-stress components are also entered, based on the lateral stress ratio, \(K_o = 0.5\). The input stresses are shown in the Initial tool displayed in Figure 16.10.
Figure 16.10 Initial stress state distribution entered in the INITIAL tool

The gravitational magnitude is entered using the Settings/Gravity tool, and the groundwater flow calculation is turned off using the Settings/GW tool. The Run/Solve tool is now used to calculate the initial stress state. The model should be very close to an equilibrium state. In order to ensure that a uniform stress distribution is developed in the model, the Solve Initial Equilibrium as Elastic Model check box is selected.

After the equilibrium state is calculated, the initial stress distribution is checked. Figure 16.11 displays the plot of the initial vertical stress distribution. Figure 16.12 shows the same result presented in a Postscript format. Different output formats can be selected from the FILE/PRINT PLOT SETUP menu item.
Figure 16.11 Vertical stress distribution at initial state

Figure 16.12 Vertical stress distribution at initial state – Postscript format
16.2.2 Step 2: Tunnel Excavation with 30% Relaxation of Tunnel Tractions

The tunnel region is excavated using the MATERIAL ASSIGN tool. The REGION radio button is selected to delineate the tunnel region, and then the null material is highlighted and the mouse is clicked within the tunnel region to null the zones in this region. Figure 16.13 shows the null tunnel region in the ASSIGN tool.

![Figure 16.13 Null tunnel zones in the ASSIGN tool](image)

If the SOLVE tool is executed at this point, the calculation corresponds to instantaneous excavation of the tunnel. In this exercise, we wish to simulate the installation of the temporary shotcrete liner after some change in the tunnel load has occurred due to the tunnel advancement. The effect of tunnel advancement is simulated by relaxing the tractions acting along the tunnel periphery incrementally. The relaxation tractions can be related to tunnel closure, which, in turn, can be related to the distance from the face of an advancing tunnel (e.g., see Panet 1979).

For this example, the tunnel tractions are relaxed by 30% before the shotcrete liner is installed. A relaxation FISH function, relax_hist, is used to control the rate of relaxation. The function is shown in Figure 16.14. Three FISH variables are input for this function: ninc specifies the step increment over which the tractions are relaxed; rstart is the starting multiplier for traction values; and rstop is the multiplier for traction values after ninc steps are completed. For a 30% relaxation, rstart = 1.0, rstop = 0.7, and we reduce the tractions over an interval of ninc = 100. The increment value is chosen such that inertial effects are minimized. (See Section 3.5.4 in the User's Guide for further discussion on minimizing inertial effects.)

FLAC Version 6.0
Lined Tunnel Construction in Saturated Ground

The *FLAC* function **apply_rf**, listed in Figure 16.15, is used to apply tractions along the tunnel boundary. Reaction forces are first calculated by fixing the boundary gridpoints, using the **APPLY xvelocity=0** and **APPLY yvelocity=0** commands, and taking a **STEP 1** to perform the calculation.* Then the function recovers the x- and y-reaction forces at the selected tunnel-boundary gridpoints, and assigns these forces as tractions (with an opposite sign) at the same boundary gridpoints, using the **APPLY xforce** and **APPLY yforce** commands. The **history** keyword is used to reduce the tractions linearly between the traction-multiplied limits (**rstart** and **rstop**) over the interval **ninc** specified in the *FISH* function **relax_hist**.

The *FISH* input variables for **apply_rf** are the bounding range **i**- and **j**-gridpoints for the tunnel boundary. In this case, **ib_ap = 45**, **ie_ap = 56**, **jb_ap = 8** and **je_ap = 30**. These values can be identified from a grid plot that includes the gridpoint numbers (**PLOT grid gnum**), generated from the **Plot / Model** tool.

After **apply_rf** is executed, we need to re-fix the x-velocity of the gridpoints at the top and bottom of the tunnel; the fixity condition was removed during the execution of the function. We also select the large-strain calculation mode, using the **Settings / Mech** tool, and monitor displacements at the top of the model and around the tunnel periphery, using the **Utility / History** tool. The *FISH* function “**VERT_CLOSURE.FIS**” is executed from the *Fish Editor* to monitor the vertical closure/opening, calculated as the difference between the vertical displacement at the crown and invert of the tunnel. Before cycling, the application of the applied forces around the tunnel should be checked by creating a plot of applied forces using the **PLOT / Model** tool. See Figure 16.16.

* Note that the tunnel-boundary gridpoints are found by using the logical condition for identifying marked gridpoints (**and(flags(ii,jj), 128) = 128**). The tunnel gridpoints are the only marked gridpoints in this model.
We solve for the equilibrium solution at 30% relaxation of the tunnel tractions by invoking the \texttt{RUN/SOLVE} tool. The \texttt{APPLY} commands implemented in \texttt{apply_rf} relax the tunnel tractions during the calculation, and a new equilibrium state is found. The reduction is indicated by the applied-forces plot shown in Figure 16.17 (compare to Figure 16.16).
Lined Tunnel Construction in Saturated Ground

16-13

Figure 16.16 Applied forces added to tunnel-boundary gridpoints from `applyxf` FISH function

Figure 16.17 Applied forces after 30% relaxation of tractions
16.2.3 Step 3: Install Shotcrete and Relax Tunnel Traction 100%

The shotcrete is installed by using the Structure/Liner tool. The structural nodes are attached directly to the grid, as shown in Figure 16.18. The shotcrete properties are assigned in the Structure/SEPr tool. The property ID for the shotcrete liner elements is identified in the tool as “L1.” By clicking on this ID number, the Liner Element Properties dialog opens and properties are entered, as shown is Figure 16.19. Note that the weight of the shotcrete is neglected for this example.

![Figure 16.18 Shotcrete liner installed as liner elements attached to tunnel-boundary gridpoints](image)

Because only one-half of the liner is modeled, the structural nodes along the line of symmetry must be fixed from translation in the x-direction and from rotation. The fixity conditions for these nodes (node numbers 1 and 45) are set in the Structure/Node tool.
The tunnel loads are now relaxed completely around the tunnel. The FISH function “RELAX.FIS” is executed again from the FISH Editor with \( r_{\text{start}} = 1.0, \ r_{\text{stop}} = 0.0, \) and \( n_{\text{inc}} = 100. \) The tractions are then reduced 100% by executing “APPLY_RF.FIS” again over the same gridpoint range as before. The new equilibrium solution at 100% relaxation is found using RUN SOLVE.

Figure 16.20 displays the vertical and horizontal closure histories for the tunnel. The total vertical closure is approximately 11.5 cm, and the total horizontal closure approximately 2.5 cm, after 100% relaxation. The axial forces that develop in the shotcrete after total relaxation are shown in Figure 16.21. The maximum force corresponds to an axial stress of approximately 20 MPa.
Figure 16.20 Vertical and horizontal closures around tunnel

Figure 16.21 Axial forces in shotcrete after 100% relaxation of tunnel loads
16.2.4 Step 4: Install Concrete Liner

The cast-in-place concrete liner is installed in Step 4. The Structure/Liner tool is used, as shown in Figure 16.22. However, this time, an interface provides the connection between the new liner and the grid.* The liner elements for the concrete liner are created by first checking the Attach Nodes to an Interface radio button in the Structure/Liner tool. We also specify an initial gap of 1 cm between the liner elements and the grid, after checking the Add a gap from grid? radio button. When the new nodes are positioned, by dragging the mouse along the tunnel boundary, an Interface properties dialog opens to assign the interface properties. The interface is assumed to only provide frictional resistance, with a friction angle of 30°. The normal and shear stiffness values for the interface (4000 MPa/m) are selected to satisfy the condition that the deformability of the interface has minimal influence on both the compliance of the total model and the calculational speed (see Section 5.4.1 in Theory and Background).

* Note that the concrete liner is connected to the grid via an interface, and not to the shotcrete liner. This is done because the shotcrete liner will be deleted later in the analysis (in Step 6). If the concrete and shotcrete liners are connected with an interface, and the shotcrete liner is deleted, then the interface is also deleted. A new interface would need to be created between the concrete liner and grid at Step 6. Because the shotcrete liner and grid are rigidly attached, it is sufficient to connect the concrete liner to the grid with the interface at Step 4.
In order to assign material properties for the concrete liner that are different from those for the shotcrete, a different property ID number must be prescribed for the new liner elements. The PropID radio button is selected while still in the Structure/Liner tool. An “L1” symbol will appear over the newly created liner elements. By clicking on this symbol, a dialog opens to rename the symbol, as shown in Figure 16.23. Select “L2” and all of the new segments are assigned “L2.”

The material properties for the concrete liner are assigned using the Structure/SEPrOp tool. Click on one of the “L2” symbols to open the dialog, as shown in Figure 16.24. (Note that “L2” property should be highlighted in the dialog.) The weight of the concrete liner is included for the concrete liner by assigning the mass density in this dialog. It is only necessary to assign the properties for one “L2” element; all elements with “L2” IDs will then be prescribed these properties.

The translation and rotation fixity conditions for the concrete-liner nodes along the centerline (nodes 46 and 90) must also be set, using the Structure/Node tool. This satisfies the symmetry condition as done previously for the shotcrete liner.

Figure 16.23 Reassigning liner property ID numbers to “L2” for the concrete liner elements
The model is stepped again to an equilibrium state using \textit{Run/Solve}. The concrete liner settles onto the grid at the invert of the tunnel, and normal stresses develop along the interface, as shown in Figure 16.25. The “alternate” interface normal stress plot is used, to clearly show those interface segments in contact. Note that stresses act mainly on alternate segments because slight shear movement on the interface causes geometrical mismatch for the contacting nodes on one side of the interface. This behavior is quite normal, and is illustrated in Figure 5.16 in Section 5.5.5 in Theory and Background.
16.2.5 Step 5: Reestablish Water Table

The water level is raised to the original elevation in Step 5. This stage of the simulation is performed in two steps (as an “uncoupled” analysis). First, a flow-only calculation is performed to establish the pore-pressure distribution. Then, a mechanical-only calculation is performed to establish the change in the stress state and the loading in the liners due to the water pressure acting on the liners.

The water level is raised by using the In Situ/Initial tool to specify a pore pressure distribution. For the water table located at \( y = 60 \) m in this model (5 m below the surface), and the bottom of the model located at \( y = -80 \) m, the pore pressure varies linearly from zero at \( y = 60 \) to 1.4 MPa at \( y = -80 \). Figure 16.26 shows the input for the pore-pressure distribution in the In Situ/Initial tool. Note that the tool must be applied twice to cover the model because the highlighted region cannot extend across attached gridpoints.
The mechanical-calculation mode is turned off in the Settings/Mech tool, and the flow calculation is turned on in the Settings/GW tool. The water modulus and water density are also required for the flow-only calculation. The modulus is set to 10,000 Pa; this low value speeds convergence for steady-state flow (see Section 1.7.5.3 in Fluid-Mechanical Interaction). The water density is set to 1000 kg/m³.

The pore-pressure distribution should correspond to a steady-flow state. Some stepping is necessary to satisfy steady flow due to the variation in zoning. The Run/Solve tool is executed to calculate this state. The resulting pore pressure distribution is shown in Figure 16.27.
The mechanical response resulting from raising the water level is now calculated. The flow-calculation mode is turned off and the water bulk modulus is set to zero in the \textit{Settings} tool. The mechanical-calculation mode is turned on in the \textit{Settings/Mech} tool.

When the water level is raised, the water is re-established throughout the ground and the permeable shotcrete liner, but not in the impermeable concrete liner. Thus, the water exerts a pressure in the gap between the two liners. The pressure acts on both the inner concrete liner and the outer shotcrete liner. The pressure applied to the shotcrete liner is applied using the \textit{In Situ/Apply} tool. For the water level raised to $y = 60$, the water pressure applied at the tunnel boundary varies from 660,000 Pa at the invert to 540,000 Pa at the crown. The application of this pressure in the \textit{In Situ/Apply} tool is illustrated in Figure 16.28.

\textit{Figure 16.27 Pore-pressure distribution after raising water table to $y = 60$ m}
Lined Tunnel Construction in Saturated Ground

In order to apply a pressure to the inner concrete liner, it is necessary to write a *FISH* function that calculates the forces at the liner nodes that correspond to the water pressure. The function “APPLY_GAP_PRESS.FIS,” listed in Section 16.5, performs this operation. This function accesses liner-element variables associated with the concrete liner. The file “STR.FIN” is used to identify and access the various structural data. (See Section 4 in the *FISH* volume for a description of the use of “.FIN” files to access the *FLAC* data structure.) The $x$- and $y$-direction forces are calculated corresponding to the water pressure at the depth of each liner node along the concrete liner. These forces are then added to the nodal forces at the offset locations identified by the symbols $\$kndlo1$ for the $x$-applied force, and $\$kndlo2$ for the $y$-applied force.

“APPLY_GAP_PRESS.FIS” is executed from the *FISH Editor*. Three input parameters are required for this function: $y$ _wtab_, the $y$-coordinate of the water table; $tuncen_x$, the $x$-coordinate of the tunnel center; and $tuncen_y$, the $y$-coordinate of the tunnel center.

After “APPLY_GAP_PRESS.FIS” is executed, the new equilibrium state is calculated using the *Run/Solve* tool.

The tunnel moves upward and distorts slightly inward at the springline, as indicated by the magnified-mesh plot shown in Figure 16.29. The vertical distance between the crown and invert increases by approximately 2.5 cm due to the water pressure gradient, as shown in Figure 16.30. The resulting axial forces in the liners are shown in Figure 16.31. The maximum stress is approximately 17 MPa in the shotcrete liner and 10 MPa in the concrete liner. The moment distribution in the concrete liner and the normal stress along the interface are displayed in Figure 16.32. Some yielding of the rock occurs during the water table rise.
Figure 16.29  Exaggerated grid distortion after raising water table

Figure 16.30  Tunnel closure/opening after raising water table
Figure 16.31 Axial forces in liners after raising water table

Figure 16.32 Moments in concrete liner and normal stress along interface after raising water table
Example Applications

16.2.6 Step 6: Delete Shotcrete Liner

In the last step of this analysis, the shotcrete liner is deleted to represent the degradation of the liner. The shotcrete elements are deleted in the Structure/Segments tool. The shotcrete elements (elements 1 through 44) are highlighted with the mouse and deleted, as shown in Figure 16.33.

The final axial load in the concrete liner, after the shotcrete is deleted, is shown in Figure 16.34. The maximum force corresponds to an axial stress of approximately 17 MPa.

![Figure 16.33 Delete shotcrete-liner elements in Structure/Segments tool](image-url)


**Figure 16.34** Axial force in concrete liner after deleting shotcrete liner

### 16.3 Reference

16.4 Data File "LINER.DAT"

;Project Record Tree export
;Title:Lined tunnel construction

;... STATE: INITIAL ....
config gwf  ats extra 5
grid 80,60
gen 0.0,-80.0 0.0,-10.0 20.0,-10.0 20.0,-80.0 i 2 14 j 1 25
model elastic i=2,13 j=1,24
gen 20.0,-80.0 20.0,-10.0 120.0,-10.0 120.0,-80.0 i 14 44 j 1 25
model elastic i=14,43 j=1,24
gen 0.0,-10.0 0.0,10.0 20.0,10.0 20.0,-10.0 i 45 81 j 1 37
model elastic i=45,80 j=1,36
gen 20.0,-10.0 20.0,10.0 120.0,10.0 120.0,-10.0 i 14 44 j 25 37
model elastic i=14,43 j=25,36
gen 0.0,10.0 0.0,65.0 20.0,65.0 20.0,10.0 i 2 14 j 37 61
model elastic i=2,13 j=37,60
gen 20.0,10.0 20.0,65.0 120.0,65.0 120.0,10.0 i 14 44 j 37 61
model elastic i=14,43 j=37,60
attach aside from 2 25 to 14 25 bside from 45 1 to 81 1
attach aside from 45 37 to 81 37 bside from 2 37 to 14 37
attach aside from 81 37 to 81 1 bside from 14 37 to 14 25
gen circle 0.0,0.0 6.0
gen line 0.0,60.0 120.0 60.0
group 'ground' notnull
model mohr notnull group 'ground'
prop density=2240.0 bulk=2.29167E8 shear=1.05769E8 cohesion=20000.0 &
  friction=20.0 dilation=0.0 tension=0.0 notnull group 'ground'
prop por 0.3 perm le-10 notnull
fix y i 2 44 j 1
fix x i 44
fix x i 2 j 1 25
fix x i 45 j 1 37
fix x i 2 j 37 61
initial syy -3248000.0 var 0.0,3248000.0
initial sxx -1624000.0 var 0.0,1624000.0
initial szz -1624000.0 var 0.0,1624000.0
set gravity=10.0
set flow=off
history 999 unbalanced
solve elastic
save initial.sav

;... STATE: RELAX_30 ....
model null region 49 20
group 'null' region 49 20
set echo off
call relax.fis
set ninc=100 rstart=1.0 rstop=0.7
relax_ini
set echo off
call apply_rf.fis
set ib_ap=45 ie_ap=56 jb_ap=8 je_ap=30
apply_rf
fix x i 45 j 30
fix x i 45 j 8
set =large
history 1 ydisp i=2, j=61
history 2 ydisp i=45, j=30
history 3 ydisp i=45, j=8
history 4 xdisp i=56, j=19
set echo off
call vert_closure.fis
vert_closure
history 5 vert_closure
solve
save relax_30.sav

;... STATE: RELAX_100 ....
struct node 1 grid 45,8
struct node 2 grid 46,8
struct node 3 grid 47,8
struct node 4 grid 48,8
struct node 5 grid 48,9
struct node 6 grid 49,9
struct node 7 grid 50,9
struct node 8 grid 50,10
struct node 9 grid 51,10
struct node 10 grid 52,10
struct node 11 grid 52,11
struct node 12 grid 53,11
struct node 13 grid 53,12
struct node 14 grid 54,12
struct node 15 grid 54,13
struct node 16 grid 54,14
struct node 17 grid 55,14
struct node 18 grid 55,15
struct node 19 grid 55,16
struct node 20 grid 56,16
struct node 21 grid 56,17

FLAC Version 6.0
struct node 22 grid 56,18
struct node 23 grid 56,19
struct node 24 grid 56,20
struct node 25 grid 56,21
struct node 26 grid 56,22
struct node 27 grid 55,22
struct node 28 grid 55,23
struct node 29 grid 55,24
struct node 30 grid 54,24
struct node 31 grid 54,25
struct node 32 grid 54,26
struct node 33 grid 53,26
struct node 34 grid 53,27
struct node 35 grid 52,27
struct node 36 grid 52,28
struct node 37 grid 51,28
struct node 38 grid 50,28
struct node 39 grid 50,29
struct node 40 grid 49,29
struct node 41 grid 48,29
struct node 42 grid 48,30
struct node 43 grid 47,30
struct node 44 grid 46,30
struct node 45 grid 45,30
struct liner begin node 1 end node 2 seg 1 prop 5001
struct liner begin node 2 end node 3 seg 1 prop 5001
struct liner begin node 3 end node 4 seg 1 prop 5001
struct liner begin node 4 end node 5 seg 1 prop 5001
struct liner begin node 5 end node 6 seg 1 prop 5001
struct liner begin node 6 end node 7 seg 1 prop 5001
struct liner begin node 7 end node 8 seg 1 prop 5001
struct liner begin node 8 end node 9 seg 1 prop 5001
struct liner begin node 9 end node 10 seg 1 prop 5001
struct liner begin node 10 end node 11 seg 1 prop 5001
struct liner begin node 11 end node 12 seg 1 prop 5001
struct liner begin node 12 end node 13 seg 1 prop 5001
struct liner begin node 13 end node 14 seg 1 prop 5001
struct liner begin node 14 end node 15 seg 1 prop 5001
struct liner begin node 15 end node 16 seg 1 prop 5001
struct liner begin node 16 end node 17 seg 1 prop 5001
struct liner begin node 17 end node 18 seg 1 prop 5001
struct liner begin node 18 end node 19 seg 1 prop 5001
struct liner begin node 19 end node 20 seg 1 prop 5001
struct liner begin node 20 end node 21 seg 1 prop 5001
struct liner begin node 21 end node 22 seg 1 prop 5001
struct liner begin node 22 end node 23 seg 1 prop 5001

FLAC Version 6.0
struct liner begin node 23 end node 24 seg 1 prop 5001
struct liner begin node 24 end node 25 seg 1 prop 5001
struct liner begin node 25 end node 26 seg 1 prop 5001
struct liner begin node 26 end node 27 seg 1 prop 5001
struct liner begin node 27 end node 28 seg 1 prop 5001
struct liner begin node 28 end node 29 seg 1 prop 5001
struct liner begin node 29 end node 30 seg 1 prop 5001
struct liner begin node 30 end node 31 seg 1 prop 5001
struct liner begin node 31 end node 32 seg 1 prop 5001
struct liner begin node 32 end node 33 seg 1 prop 5001
struct liner begin node 33 end node 34 seg 1 prop 5001
struct liner begin node 34 end node 35 seg 1 prop 5001
struct liner begin node 35 end node 36 seg 1 prop 5001
struct liner begin node 36 end node 37 seg 1 prop 5001
struct liner begin node 37 end node 38 seg 1 prop 5001
struct liner begin node 38 end node 39 seg 1 prop 5001
struct liner begin node 39 end node 40 seg 1 prop 5001
struct liner begin node 40 end node 41 seg 1 prop 5001
struct liner begin node 41 end node 42 seg 1 prop 5001
struct liner begin node 42 end node 43 seg 1 prop 5001
struct liner begin node 43 end node 44 seg 1 prop 5001
struct liner begin node 44 end node 45 seg 1 prop 5001
struct prop 5001
struct prop 5001 e 5E9 area 0.2 I 6.667E-4 thickness 0.2 pratio 0.2
struct node 1 fix r
struct node 45 fix r
set echo off
call relax.fis
set ninc=100 rstart=1.0 rstop=0.0
relax_ini
set echo off
call apply_rf.fis
set ib_ap=45 ie_ap=56 jb_ap=8 je_ap=30
apply_rf
fix  x i 45 j 30
fix  x i 45 j 8
solve
save relax.100.sav

;... STATE: CONCRETE_LINER ....
struct node 46 -0.009999999,-5.934354
struct node 47 0.5403872,-5.909409
struct node 48 1.0677705,-5.83766
struct node 49 1.3934847,-5.7689834
struct node 50 1.7148663,-5.6822453
struct node 51 2.2164936,-5.507348
Example Applications

```
struct node 52 2.6691952,-5.3049097
struct node 53 2.9959185,-5.12955
struct node 54 3.3110964,-4.934328
struct node 55 3.6289055,-4.7082486
struct node 56 3.9312108,-4.4618177
struct node 57 4.2217777,-4.1916423
struct node 58 4.4936547,-3.9028683
struct node 59 4.741998,-3.6024983
struct node 60 4.9692087,-3.2874517
struct node 61 5.1648974,-2.975049
struct node 62 5.3416204,-2.650305
struct node 63 5.543802,-2.2015164
struct node 64 5.71753,-1.7040727
struct node 65 5.803216,-1.384472
struct node 66 5.870646,-1.0615453
struct node 67 5.9404373,-0.53864527
struct node 68 5.9640603,-0.003078309
struct node 69 5.9402924,0.5325633
struct node 70 5.870383,1.0556496
struct node 71 5.8029413,1.3787708
struct node 72 5.717355,1.6985627
struct node 73 5.5437098,2.196513
struct node 74 5.3415146,2.645681
struct node 75 5.1648083,2.9705613
struct node 76 4.969033,3.2831426
struct node 77 4.741786,3.598347
struct node 78 4.4934635,3.8988612
struct node 79 4.221613,4.187811
struct node 80 3.9311185,4.4582114
struct node 81 3.6289046,4.70485
struct node 82 3.311182,4.931169
struct node 83 2.9960687,5.1266155
struct node 84 2.6694071,5.30218
struct node 85 2.2167227,5.504829
struct node 86 1.7150635,5.6798687
struct node 87 1.3936529,5.7666674
struct node 88 1.0678986,5.8353524
struct node 89 0.54044735,5.907067
struct node 90 -0.010000001,5.931989
struct liner begin node 46 end node 47 seg 1 prop 5002
struct liner begin node 47 end node 48 seg 1 prop 5002
struct liner begin node 48 end node 49 seg 1 prop 5002
struct liner begin node 49 end node 50 seg 1 prop 5002
struct liner begin node 50 end node 51 seg 1 prop 5002
struct liner begin node 51 end node 52 seg 1 prop 5002
struct liner begin node 52 end node 53 seg 1 prop 5002
```

FLAC Version 6.0
struct liner begin node 53 end node 54 seg 1 prop 5002
struct liner begin node 54 end node 55 seg 1 prop 5002
struct liner begin node 55 end node 56 seg 1 prop 5002
struct liner begin node 56 end node 57 seg 1 prop 5002
struct liner begin node 57 end node 58 seg 1 prop 5002
struct liner begin node 58 end node 59 seg 1 prop 5002
struct liner begin node 59 end node 60 seg 1 prop 5002
struct liner begin node 60 end node 61 seg 1 prop 5002
struct liner begin node 61 end node 62 seg 1 prop 5002
struct liner begin node 62 end node 63 seg 1 prop 5002
struct liner begin node 63 end node 64 seg 1 prop 5002
struct liner begin node 64 end node 65 seg 1 prop 5002
struct liner begin node 65 end node 66 seg 1 prop 5002
struct liner begin node 66 end node 67 seg 1 prop 5002
struct liner begin node 67 end node 68 seg 1 prop 5002
struct liner begin node 68 end node 69 seg 1 prop 5002
struct liner begin node 69 end node 70 seg 1 prop 5002
struct liner begin node 70 end node 71 seg 1 prop 5002
struct liner begin node 71 end node 72 seg 1 prop 5002
struct liner begin node 72 end node 73 seg 1 prop 5002
struct liner begin node 73 end node 74 seg 1 prop 5002
struct liner begin node 74 end node 75 seg 1 prop 5002
struct liner begin node 75 end node 76 seg 1 prop 5002
struct liner begin node 76 end node 77 seg 1 prop 5002
struct liner begin node 77 end node 78 seg 1 prop 5002
struct liner begin node 78 end node 79 seg 1 prop 5002
struct liner begin node 79 end node 80 seg 1 prop 5002
struct liner begin node 80 end node 81 seg 1 prop 5002
struct liner begin node 81 end node 82 seg 1 prop 5002
struct liner begin node 82 end node 83 seg 1 prop 5002
struct liner begin node 83 end node 84 seg 1 prop 5002
struct liner begin node 84 end node 85 seg 1 prop 5002
struct liner begin node 85 end node 86 seg 1 prop 5002
struct liner begin node 86 end node 87 seg 1 prop 5002
struct liner begin node 87 end node 88 seg 1 prop 5002
struct liner begin node 88 end node 89 seg 1 prop 5002
struct liner begin node 89 end node 90 seg 1 prop 5002
struct prop 5002
interface 1 aside from 45,8 to 45,30 bside from node 90,89 to node 46
interface 1 unglued kn=4.0E9 ks=4.0E9 cohesion=0.0 dilation=0.0 &
  friction=30.0 tbond=0.0 bslip=off
struct prop 5002 density 2500.0 e 2.5E10 area 0.4 I 0.05333 &
  thickness 0.4 pratio 0.2
struct node 46    fix x r
struct node 90    fix x r
solve

FLAC Version 6.0
save concrete_liner.sav

;... STATE: WATER ....
initial pp 1400000.0 var 0.0,-1400000.0 i 2 44 j 1 59
initial pp 700000.0 var 0.0,-200000.0 i 45 81 j 1 37
set mechanical=off
set flow=on
water bulk=10000.0
water density=1000.0
solve
save water.sav

;... STATE: GAP_PRESSURE ....
set flow=off
water bulk=0.0
set mechanical=on
apply pressure 660000.0 var 0.0,-120000.0 from 45,8 to 45,30
set echo off
call apply_gap_press.fis
set y_wtab=60.0 tuncen_x=0.0 tuncen_y=0.0
apply_gap_press
history reset
history 1 ydisp i=2, j=61
history 2 ydisp i=45, j=30
history 3 ydisp i=45, j=8
history 4 xdisp i=56, j=19
history 5 vert Closure
initial xdisp 0 ydisp 0
initial xvel 0 yvel 0
history 999 unbalanced
solve
save gap_pressure.sav

;... STATE: DELETE_SHOTCRETE ....
struct liner delete 1
struct liner delete 2
struct liner delete 3
struct liner delete 4
struct liner delete 5
struct liner delete 6
struct liner delete 7
struct liner delete 8
struct liner delete 9
struct liner delete 10
struct liner delete 11
struct liner delete 12
struct liner delete 13
struct liner delete 14
struct liner delete 15
struct liner delete 16
struct liner delete 17
struct liner delete 18
struct liner delete 19
struct liner delete 20
struct liner delete 21
struct liner delete 22
struct liner delete 23
struct liner delete 24
struct liner delete 25
struct liner delete 26
struct liner delete 27
struct liner delete 28
struct liner delete 29
struct liner delete 30
struct liner delete 31
struct liner delete 32
struct liner delete 33
struct liner delete 34
struct liner delete 35
struct liner delete 36
struct liner delete 37
struct liner delete 38
struct liner delete 39
struct liner delete 40
struct liner delete 41
struct liner delete 42
struct liner delete 43
struct liner delete 44
solve
save delete_shotcrete.sav

;*** plot commands ****
;plot name: applied tractions
plot hold bound apply max 500000.0
;plot name: tunnel disp
plot hold history 4 line 5 line
;plot name: shotcrete axial forces
plot hold struct liner axial fill max 5.0E7 white bound
;plot name: interface stresses
plot hold bound struct liner moment 2 fill max 2000000.0 iface 1 altns & fill white
;plot name: pp contours

FLAC Version 6.0
plot hold pp fill bound
;plot name: grid
plot hold grid magnify 10.0 bound
16.5 Data File “APPLY_GAP_PRESS.FIS”

;Name: apply_gap_press
;Diagram:
;Input: y_wtab/float/60.0/y-coordinate of water table
;Input: tuncen_x/float/0.0/x-coordinate of tunnel center
;Input: tuncen_y/float/0.0/y-coordinate of tunnel center

call str.fin

def Apply_Gap_Press
  strp = str.pnt
  sp=imem(strp+$ksels) ;pointer to struc element list
  loop while sp # 0 ;loop through all struc elements
    if imem(sp+$kelcod2)=5 ;check if it is a liner element
      pn1=imem(sp+$keln1) ;node 1 of liner elem.
      pn2=imem(sp+$keln2) ;node 2 of liner elem.
      if imem(pn1+$kndcod) = 1 ;not linked to gridpoint means inner liner
        n1id=imem(pn1+$kndid)
        n2id=imem(pn2+$kndid)
        n1xcord=fmem(pn1+$kndx)
        n1ycord=fmem(pn1+$kndy)
        n2xcord=fmem(pn2+$kndx)
        n2ycord=fmem(pn2+$kndy)
        nxdif=abs(n1xcord-n2xcord)
        nxdif=abs(n1ycord-n2ycord)
        sslope=atan(nxdif/nydif) ;slope of liner
        shlength=fmem(sp+$kell)/2. ;half-length of liner
        if n1xcord>=tuncen_x
          unx_=-cos(sslope)
        else
          unx_=-cos(sslope)
        end_if
        if n1ycord>=tuncen_y
          uny_=-sin(sslope)
        else
          uny_=-sin(sslope)
        end_if
      ;node 1
        n1depth=y_wtab-n1ycord ;depth of node
        n1pp = -ygrav*n1depth*wdens ;pore pressure
        n1fmag = shlength * n1pp ;equivalent force on node
        ;from half of liner element
        n1xforce = n1fmag * unx_
        n1yforce = n1fmag * uny_
        fmem(pn1+$kndlo1)=fmem(pn1+$kndlo1)+n1xforce ;add xforce
        fmem(pn1+$kndlo2)=fmem(pn1+$kndlo2)+n1yforce ;add yforce
      ;node 2
n2depth=y_wtab-n2ycord
n2pp = -ygrav*n2depth*wdens
n2fmag = shlength * n2pp
n2xforce = n2fmag * unx_
n2yforce = n2fmag * uny_

fmem(pn2+$kndlo1)=fmem(pn2+$kndlo1)+n2xforce ;add xforce
fmem(pn2+$kndlo2)=fmem(pn2+$kndlo2)+n2yforce ;add yforce

end_if
end_if
sp = imem(sp)
end_loop
end

FLAC Version 6.0