12 Multi-Stage Tunnel Excavation and Support

12.1 Problem Statement

Construction of large railroad, subway and road tunnels often involves multiple stages of excavation and support, particularly if the tunnels are located at shallow depth and/or in weak ground. A typical example for the construction sequence of a shallow tunnel is illustrated in Figure 12.1.

In this example, the construction sequence is divided into three major excavation stages:

- Stage I: side excavation;
- Stage II: top-heading excavation; and
- Stage III: bench excavation.

Each excavation stage is accomplished in three construction steps:

- Step a: initial excavation;
- Step b: installation of rockbolt support; and
- Step c: installation of a shotcrete lining.

The three steps occur at different times during the advancement of the tunnel face. Consequently, the loads acting on the tunnel will be changed at the time the support is installed, as a function of the tunnel advancement.

The stress and displacement fields in the vicinity of a tunnel construction change in the direction of the advancing tunnel face, and this is most rigorously analyzed using a three-dimensional program, such as FLAC\textsuperscript{3D} (Itasca 2006). However, advancing tunnel problems are often analyzed in two dimensions by neglecting displacements normal to the tunnel cross-section.

An important issue in the design of supports is the amount of change in the tunnel load that takes place, due to the tunnel advancement, before the support is installed. If no change is assumed to occur, the loads acting on the support will be overpredicted. If complete relaxation at the tunnel periphery is assumed to occur, zero load will develop in the support at the installation step, provided that the relaxation state is at equilibrium. In reality, some relaxation takes place. However, it is difficult to quantify relaxation with a two-dimensional program, because this depends on the distance behind the face at which the support is installed. One way to model the relaxation is to decrease the elastic moduli of the tunnel core, equilibrate, install the support and remove the core. This approach is typical of finite element codes. The main problem then becomes estimating how much to reduce the moduli.
Example Applications

Figure 12.1 Construction conditions and sequence for a multi-stage tunnel excavation and support

<table>
<thead>
<tr>
<th>CONSTRUCTION SEQUENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial K, State</td>
</tr>
<tr>
<td>Percent Relaxation</td>
</tr>
<tr>
<td>Step</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Construction State</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>8.12 m</td>
<td>10.5 m</td>
</tr>
</tbody>
</table>

Rock Properties
- Unit weight: 2700 kg/m³
- Bulk Modulus: 0.555 GPa
- Shear Modulus: 0.417 GPa
- Cohesion: 10 kPa
- Internal Friction Angle: 33°
- Tensile Strength: 1 kPa

Initial Conditions
- $K_u$: 0.5
- Gravity: 9.81 m/sec²

Shotcrete
- Young's Modulus: 5.56 GPa

Rock Bolt
- Diameter: 25 mm
- Young's Modulus: 205 GPa
An alternative approach to model the relaxation is based on the relation of the closure of the unsupported tunnel to the distance to the face. Panet (1979) published such an expression. (Also see Section 8.) Tunnel closure can also be related to traction forces acting on the tunnel periphery via a ground reaction curve. Thus, the tunnel relaxation as a function of the distance to the face can be specified in terms of tractions defined by a ground reaction curve, and an expression relating closure to distance to the face.

In order to simulate the relaxation, tractions are first applied to the tunnel boundary to provide an equilibrium condition at zero relaxation; then the tractions are gradually decreased to a value corresponding to a tunnel closure value that is related to a specified distance to the face. The support is then installed at this relaxation state. In this example, the rockbolt support is installed at an excavation stage corresponding to 50% relaxation of the tunnel load, and the shotcrete is installed at a stage corresponding to 75% relaxation, as illustrated in Figure 12.1.

12.2 Modeling Procedure

12.2.1 Model Setup

FLAC is well-suited to model sequential excavation and construction problems. In this example, the three excavation stages and three construction steps within each stage are simulated as nine sequential solutions. The data file for this analysis begins at “Branch: Multi-Stage Tunnel” in “MSTUNNEL.DAT,” listed in Section 12.5. The data file at “Branch: Ground Reaction Curve” in “MSTUNNEL.DAT” is included to demonstrate the process to develop a ground reaction curve for this model. In addition, several FISH functions, listed in Section 12.6, are provided to control the tunnel load relaxation process.

The FLAC mesh is defined with the grid distorted to align with the boundaries of the three segments of the tunnel excavation. The Build/Generate/Radial tool is used to create a fine mesh in the vicinity of the tunnel, and a radially graded mesh extending to the model boundaries. The model dimensions and zoning selected for the grid are shown in the Edit Radial Grid dialog, in Figure 12.2. The Arc mode in the Alter/Shape tool is then used to create the tunnel periphery based on the arc radii shown in Figure 12.1, and the Alter/Mark tool is used to mark the boundaries between the three excavation segments.

The initial grid and marked gridpoints indicating the tunnel segment boundaries are shown in Figure 12.3. Note that because of the symmetry in the tunnel conditions, only half of the tunnel is modeled. The symmetry condition implies that the left- and right-side drifts are excavated simultaneously. If the effect of excavation sequence is considered an issue, then it may be necessary to model the entire tunnel.
**Figure 12.2** *Edit Radial Grid* dialog

**Figure 12.3** FLAC grid for a multi-stage tunnel construction
The rock behavior is represented by the Mohr-Coulomb model assigned the properties listed in Figure 12.1. The rockbolts are modeled using rockbolt elements, and the shotcrete is simulated with elastic liner elements. Note that structural element logic is a plane-stress formulation, so the value specified for the Young’s modulus, $E$, is divided by $(1 - \nu^2)$ to correspond to the plane-strain model (see Section 1.2.2 in Structural Elements).

The model is brought to an initial force-equilibrium state under gravitational loading, with the top boundary of the mesh representing the ground surface. This initial stage is identified as Step 0 in Figure 12.1.

12.2.2 Ground Reaction Curve

Before conducting the sequential excavation/support analysis, unsupported-tunnel calculations are performed, in order to develop ground reaction curves for this model. This procedure is demonstrated for the excavation of the entire tunnel in one stage. Separate ground reaction curves can also be developed for each tunnel segment. “Branch: Ground Reaction Curve,” in “MSTUNNEL.DAT,” lists the data file for this analysis.

The ground reaction curve is developed by measuring the force on the tunnel boundary at zero relaxation, and applying an incrementally decreasing amount of this force as a traction while measuring the corresponding tunnel closure.

The $FISH$ function $\text{apply\_rf}$, in “RELAX\_TRACTIONS.FIS” (Section 12.6.1), is used to apply tractions along the tunnel boundary. This function first recovers the $x$- and $y$-reaction forces at selected tunnel-boundary gridpoints, and then assigns these forces as tractions (with an opposite sign) at the same boundary gridpoints, using the $\text{APPLY\ xforce}$ and $\text{APPLY\ yforce}$ commands. The $\text{history}$ keyword is used to reduce the tractions linearly between user-selected traction-multiplier limits over a specified step interval, defined in $\text{relax\ hist}$.

Before applying $\text{apply\_rf}$, the tunnel-boundary gridpoints are identified by using the command $\text{APPLY\ xvel\ 0\ yvel\ 0}$ to assign $x$- and $y$-fixity conditions to the selected boundary gridpoints. The $x$- and $y$-fixity conditions identify the selected tunnel-boundary gridpoints to receive tractions. $\text{apply\_rf}$ applies the traction forces to only those fixed gridpoints. Note that the $\text{APPLY\ remove}$ command is first used to remove previous fixity conditions before assigning the new fixity conditions.

In order to create the ground reaction curve in this example, the tractions along the entire tunnel boundary are reduced in 20% increments from the zero relaxation state. At each increment, the calculated vertical displacement at the tunnel crown is stored in a table versus the relaxation factor (i.e., the ratio of the current tunnel traction to the initial tunnel traction). $FISH$ function $\text{grc}$ is used to store the results (see Section 12.6.2). Figure 12.4 displays the result for load relaxation of the entire tunnel boundary from a relaxation factor of 1.0 to 0.2. (Note that at a relaxation factor of approximately 0.2, the tunnel collapses. Figure 12.5 illustrates the collapse.)

By also relating the tunnel closure to the distance to the tunnel face (e.g., see Figure 8.4 in Section 8), relaxation factors can be selected to correspond to selected distances to the tunnel face.
**Figure 12.4** Ground reaction curve: vertical displacement at tunnel crown versus relaxation factor

**Figure 12.5** Displacement field during collapse for unsupported tunnel
For this example, we do not relate the relaxation factors to specific distances to the tunnel face. We arbitrarily choose a relaxation factor of 0.5 (50% relaxation) to define the tunnel loading state at which the rockbolt support is installed. The factor is then reduced to 0.25 (75% relaxation) to develop loads in the rockbolts. The relaxation factor of 0.25 corresponds to the state at which the shotcrete is installed, and then complete relaxation (100% relaxation) is allowed to develop loads in the shotcrete.

### 12.2.3 Construction Simulation

The construction steps of the excavation/support analysis follow the same sequence for each excavation stage. First, the excavation segment is nulled, and tractions are applied and relaxed by 50%. The tractions are reduced gradually over an interval of 1000 steps, and then the model is brought to a force-equilibrium state. At this state, indicated as Ia, IIa and IIIa in Figure 12.1, the rockbolt elements are added, representing the rockbolt support. The tunnel tractions are then reduced to 25% over a 1000 step interval, and the model is brought to equilibrium again. At this state, indicated as Ib, IIb and IIIb in Figure 12.1, the liner elements are added to represent installation of the shotcrete lining. The tunnel tractions are then reduced to zero over a 1000 step interval, and the model is brought to equilibrium. The loads that develop in the rockbolts result from tunnel-load relaxation from 50% to zero, and the loads that develop in the shotcrete result from relaxation from 25% to zero.

By applying the relaxation over a 1000 step interval, the effects of transient waves are minimized, and a gradual excavation of the tunnel is simulated. This is demonstrated by Figure 12.6, which displays radial stress histories at the crown, floor and springline of the tunnel. The histories show gradual changes in the stresses; if the relaxation loads were applied suddenly (i.e., in one step), sudden changes would be observed in these histories, and a different final state could result. (See Section 3.10.3 in the User’s Guide for further discussion on path-dependency effects of loading.)

The *FISH* function `apply_rf` is used to apply tractions along the tunnel boundary in the same manner as discussed previously in Section 12.2.2. For the side excavation, tractions are applied along the entire boundary of this tunnel segment. For the top-heading excavation, tractions are applied along the crown and the floor of this tunnel segment; for the bench excavation, tractions are applied along the floor. The model should remain in equilibrium after each tunnel segment is nulled and the tractions are applied, before they are relaxed.
12.3 Results

Typical results for this analysis are shown in Figures 12.7, 12.9 and 12.10. The settlement profile of the ground surface at the end of the analysis is shown in Figure 12.7. The profile is created with the FISH function `settle`: y-displacements at the gridpoints along the top of the model are stored in table 2. See Section 12.6.3.

The axial forces in the rockbolts at the end of each excavation stage are shown in Figure 12.9, and the axial forces in the shotcrete are shown in Figure 12.10. Note that the sense of the axial force plot depends on the order in which the structural elements are created. The sense can be changed by assigning a maximum value with opposite sign following the max keyword when issuing PLOT struct axial. Figure 12.8 shows the Plot Item Switches dialog, in which the maximum value is set to −2000000 to change the sense of the liner axial force plot.
Figure 12.7 Final settlement profile

Figure 12.8 Liner Plot Item Switches dialog; use the Maximum switch to change the plot sense
Figure 12.9 Axial forces in rockbolts at 100% relaxation for each excavation stage
Figure 12.10 Axial forces in shotcrete at 100% relaxation for each excavation stage
12.4 References


12.5 Data File “MSTUNNEL.DAT”

;Project Record Tree export
;Title: Multi-Stage Tunnel Excavation

; *** Branch: Ground Reaction Curve ****
new

;... State: ms_gr0.sav ....
config
grid 44,80
gen (0.0,-40.0) (0.0,-20.0) (12.0,-20.0) (12.0,-40.0) i 1 25 j 21 61
gen (0.0,-20.0) (0.0,0.0) (50.0,0.0) (12.0,-20.0) ratio 1.0,1.1 &
i 1 25 j 61 81
gen (0.0,-60.0) (0.0,-40.0) (12.0,-40.0) (50.0,-60.0) &
  ratio 1.0,0.9090909 i 1 25 j 1 21
gen (12.0,-40.0) (12.0,-20.0) (50.0,0.0) (50.0,-60.0) &
  ratio 1.1,1.0 i 25 45 j 21 61
model elastic i=1,24 j=21,60
model elastic i=1,24 j=61,80
model elastic i=1,24 j=1,20
model elastic i=25,44 j=21,60
attach aside from 25 1 to 25 21 bside from 45 21 to 25 21
attach aside from 25 81 to 25 61 bside from 45 61 to 25 61
gen arc 0.0,-33.93 5.5,-26.0 i 35
ngen arc 0.0,-17.65 0.0,-34.65 20
ini x 7.9 y -28.9 i 17 j 44
gen arc 2.0,-31.2 7.9,-28.9 35
ngen arc 4.6,-30.2 5.8,-33.55 90
gen arc 12.0,-30.0 5.5,-26.0 60
ini x 5.28 y -33.41 i 11 j 34
mark i 1 9 j 42
mark i 11 j 34

model mohr notnull group ‘rock’
prop density=2700.0 bulk=5.5550003E8 shear=4.166E8 cohesion=10000.0 &
  friction=33.0 dilation=0.0 tension=1000.0 notnull group ‘rock’
group ‘top heading’ region 5 47
model mohr group ‘top heading’
prop density=2700.0 bulk=5.5550003E8 shear=4.166E8 cohesion=10000.0 &
  friction=33.0 dilation=0.0 tension=1000.0 group ‘top heading’
group ‘bench’ region 6 36
model mohr group ‘bench’
prop density=2700.0 bulk=5.5550003E8 shear=4.166E8 cohesion=10000.0 &
  friction=33.0 dilation=0.0 tension=1000.0 group ‘bench’
group ‘side’ region 13 41
model mohr group 'side'
prop density=2700.0 bulk=5.5550003E8 shear=4.166E8 cohesion=10000.0 &
    friction=33.0 dilation=0.0 tension=1000.0 group 'side'
group 'top heading' i 11 j 48
model mohr group 'top heading'
prop density=2700.0 bulk=5.5550003E8 shear=4.166E8 cohesion=10000.0 &
    friction=33.0 dilation=0.0 tension=1000.0 group 'top heading'
group 'bench' i 11 j 33
model mohr group 'bench'
prop density=2700.0 bulk=5.5550003E8 shear=4.166E8 cohesion=10000.0 &
    friction=33.0 dilation=0.0 tension=1000.0 group 'bench'
fix y i 1 25 j 1
fix y i 45 j 21
fix x i 45 j 21 61
fix x i 25 j 1
fix x i 1
set gravity=9.81
initial syy -1589000.0 var 0.0,1589000.0
initial sxx -794600.0 var 0.0,794600.0
initial szz -794600.0 var 0.0,794600.0
save ms_gr0.sav

;... State: ms_gr1.sav ....
initial xdisp 0 ydisp 0
initial xvel 0 yvel 0
model null group 'side'
model null group 'top heading'
model null group 'bench'
set echo off
  call grc.fis
set relax_value=1.0 isn=1
grc
apply xvelocity 0.0 from 1,32 to 1,52
apply yvelocity 0.0 from 1,32 to 1,52
history 999 unbalanced
cycle 1
set echo off
  call relax_tractions.fis
set ninc=1000 rstart=1.0 rstop=0.8 ib_ap=1 ie_ap=17 jb_ap=32
set je_ap=52
relax_tractions
history 1 relax_hist
fix x i 1 j 52
fix x i 1 j 32
solve
set echo off
call grc.fis
set relax_value=0.8 isn=2
grc
save ms_gr1.sav

;... State: ms_gr2.sav ....
apply remove mech from 1,32 to 1,52
apply xvelocity 0.0 from 1,32 to 1,52
apply yvelocity 0.0 from 1,32 to 1,52
cycle 1
set echo off
call relax_tractions.fis
set ninc=1000 rstart=1.0 rstop=0.8 ib_ap=1 ie_ap=17 jb_ap=32 je_ap=52
relax_tractions
fix x i 1 j 52
fix x i 1 j 32
solve
set echo off
call grc.fis
set relax_value=0.64 isn=3
grc
save ms_gr2.sav

;... State: ms_gr3.sav ....
apply remove mech from 1,32 to 1,52
apply xvelocity 0.0 from 1,32 to 1,52
apply yvelocity 0.0 from 1,32 to 1,52
cycle 1
set echo off
call relax_tractions.fis
set ninc=1000 rstart=1.0 rstop=0.8 ib_ap=1 ie_ap=17 jb_ap=32 je_ap=52
relax_tractions
fix x i 1 j 52
fix x i 1 j 32
solve
set echo off
call grc.fis
set relax_value=0.512 isn=4
grc
save ms_gr3.sav

;... State: ms_gr4.sav ....
apply remove mech from 1,32 to 1,52
apply xvelocity 0.0 from 1,32 to 1,52
apply yvelocity 0.0 from 1,32 to 1,52
cycle 1
Example Applications

```
set echo off
call relax_tractions.fis
set ninc=1000 rstart=1.0 rstop=0.8 ib_ap=1 ie_ap=17 jb_ap=32 je_ap=52
relax_tractions
fix x i l j 52
fix x i l j 32
solve
set echo off
call grc.fis
set relax_value=0.410 isn=5
grc
save ms.gr4.sav

;... State: ms_gr5.sav ....
apply remove mech from 1,32 to 1,52
apply xvelocity 0.0 from 1,32 to 1,52
apply yvelocity 0.0 from 1,32 to 1,52
cycle 1
set echo off
call relax_tractions.fis
set ninc=1000 rstart=1.0 rstop=0.8 ib_ap=1 ie_ap=17 jb_ap=32 je_ap=52
relax_tractions
fix x i l j 52
fix x i l j 32
solve
set echo off
call grc.fis
set relax_value=0.328 isn=6
grc
save ms.gr5.sav

;... State: ms_gr6.sav ....
apply remove mech from 1,32 to 1,52
apply xvelocity 0.0 from 1,32 to 1,52
apply yvelocity 0.0 from 1,32 to 1,52
cycle 1
set echo off
call relax_tractions.fis
set ninc=1000 rstart=1.0 rstop=0.8 ib_ap=1 ie_ap=17 jb_ap=32 je_ap=52
relax_tractions
fix x i l j 52
fix x i l j 32
solve
set echo off
call grc.fis
set relax_value=0.26 isn=7
```

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grc
save ms_gr6.sav

;... State: ms_gr7.sav ....
apply remove mech from 1.32 to 1.52
apply xvelocity 0.0 from 1.32 to 1.52
apply yvelocity 0.0 from 1.32 to 1.52
cycle 1
set echo off
call relax_tractions.fis
set ninc=1000 rstart=1.0 rstop=0.8 ib_ap=1 ie_ap=17 jb_ap=32 je_ap=52
relax_tractions
fix  x  i  1  j  52
fix  x  i  1  j  32
cycle 5000
set echo off
call grc.fis
set relax_value=0.21 isn=8
grc
save ms_gr7.sav

;*** Branch: Multi-Stage Tunnel ****
new

;... State: ms_0.sav ....
config
grid 44,80
gen (0.0,-40.0) (0.0,-20.0) (12.0,-20.0) (12.0,-40.0) i 1 25 j 21 61
gen (0.0,-20.0) (0.0,0.0) (50.0,0.0) (12.0,-20.0) ratio 1.0,1.1 &
  i 1 25 j 61 81
gen (0.0,-60.0) (0.0,-40.0) (12.0,-40.0) (50.0,-60.0) &
  ratio 1.0,0.909090909 i 1 25 j 1 21
ngen (12.0,-40.0) (12.0,-20.0) (50.0,0.0) (50.0,-60.0) &
  ratio 1.1,1.0 i 25 45 j 21 61
model elastic i=1,24 j=21,60
model elastic i=1,24 j=61,80
model elastic i=1,24 j=1,20
model elastic i=25,44 j=21,60
attach aside from 25 1 to 25 21 bside from 45 21 to 25 21
attach aside from 25 81 to 25 61 bside from 45 61 to 25 61
gen arc 0.0,-33.93 5.5,-26.0 35
gen arc 0.0,-17.65 0.0,-34.65 20
ini x 7.9 y -28.9 i 17 j 44
gen arc 2.0,-31.2 7.9,-28.9 35
gen arc 4.6,-30.2 5.8,-33.55 90
gen arc 12.0,-30.0 5.5,-26.0 60
ini x 5.28 y -33.41 i 11 j 34
mark i 1 9 j 42
mark i 11 j 34

Example Applications

group 'rock' notnull
model mohr notnull group 'rock'
prop density=2700.0 bulk=5.5550003E8 shear=4.166E8 cohesion=10000.0 &
  friction=33.0 dilation=0.0 tension=1000.0 notnull group 'rock'

model mohr group 'top heading'
prop density=2700.0 bulk=5.5550003E8 shear=4.166E8 cohesion=10000.0 &
  friction=33.0 dilation=0.0 tension=1000.0 group 'top heading'

model mohr group 'bench'
prop density=2700.0 bulk=5.5550003E8 shear=4.166E8 cohesion=10000.0 &
  friction=33.0 dilation=0.0 tension=1000.0 group 'bench'

model mohr group 'side'
prop density=2700.0 bulk=5.5550003E8 shear=4.166E8 cohesion=10000.0 &
  friction=33.0 dilation=0.0 tension=1000.0 group 'side'

model mohr group 'top heading'
prop density=2700.0 bulk=5.5550003E8 shear=4.166E8 cohesion=10000.0 &
  friction=33.0 dilation=0.0 tension=1000.0 group 'top heading'

model mohr group 'bench'
prop density=2700.0 bulk=5.5550003E8 shear=4.166E8 cohesion=10000.0 &
  friction=33.0 dilation=0.0 tension=1000.0 group 'bench'

fix y i 1 25 j 1
fix y i 45 j 21
fix x i 45 j 21 61
fix x i 25 j 1
fix x i 1
set gravity=9.81

initial syy -1589000.0 var 0.0,1589000.0
initial sxx -794600.0 var 0.0,794600.0
initial szz -794600.0 var 0.0,794600.0
save ms_0.sav

;... State: ms_ia.sav ....
initial xdisp 0 ydisp 0
initial xvel 0 yvel 0
model null group 'side'
apply xvelocity 0.0 long from 11,34 to 11,34
apply yvelocity 0.0 long from 11,34 to 11,34
cycle 1
set echo off

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call relax_tractions.fis
set ninc=1000 rstart=1.0 rstop=0.5 ib_ap=10 ie_ap=17 jb_ap=34
set je_ap=49
relax_tractions
history 1 relax_hist
history 2 syy i=1, j=52
history 3 syy i=1, j=31
history 4 sxx i=17, j=40
solve
save ms_Ia.sav

;... State: ms_Ib.sav ....
struct node 1 5.79,-33.6
struct node 2 7.1,-37.4
struct node 3 6.81,-33.0
struct node 4 9.1,-36.3
struct node 5 7.74,-32.2
struct node 6 10.65,-34.5
struct node 7 8.05,-31.2
struct node 8 11.75,-32.25
struct node 9 8.27,-30.0
struct node 10 12.12,-30.0
struct node 11 7.95,-29.0
struct node 12 11.4,-27.6
struct node 13 7.47,-27.95
struct node 14 10.75,-25.95
struct node 15 6.85,-27.0
struct node 16 9.7,-24.4
struct node 17 6.0,-26.27
struct node 18 8.55,-23.1
struct rockbolt begin node 1 end node 2 seg 5 prop 4001
struct rockbolt begin node 3 end node 4 seg 5 prop 4001
struct rockbolt begin node 5 end node 6 seg 5 prop 4001
struct rockbolt begin node 7 end node 8 seg 5 prop 4001
struct rockbolt begin node 9 end node 10 seg 5 prop 4001
struct rockbolt begin node 11 end node 12 seg 5 prop 4001
struct rockbolt begin node 13 end node 14 seg 5 prop 4001
struct rockbolt begin node 15 end node 16 seg 5 prop 4001
struct rockbolt begin node 17 end node 18 seg 5 prop 4001
struct prop 4001
struct prop 4001 e 2.04999999E11 area 5.0E-4 cs_sstiff 1.50000005E10 &
cs_scoh 800000.0 yield 500000.0 perimeter 0.0785
apply remove mech long from 11,34 to 11,34
apply xvelocity 0.0 long from 11,34 to 11,34
apply yvelocity 0.0 long from 11,34 to 11,34
cycle 1
Example Applications

set echo off
call relax_tractions.fis
set ninc=1000 rstart=1.0 rstop=0.5 ib_ap=10 ie_ap=17 jb_ap=34
set je_ap=49
relax_tractions
solve
save ms_Ib.sav

;... State: ms_Ic.sav ....
apply remove mech long from 11,34 to 11,34
apply yvelocity 0.0 long from 11,34 to 11,34
apply xvelocity 0.0 long from 11,34 to 11,34
cycle 1
set echo off
call relax_tractions.fis
set ninc=1000 rstart=1.0 rstop=0.0 ib_ap=10 ie_ap=17 jb_ap=34
set je_ap=49
relax_tractions
struct node 55 grid 10,42
struct node 56 grid 10,41
struct node 57 grid 10,40
struct node 58 grid 10,39
struct node 59 grid 10,38
struct node 60 grid 10,37
struct node 61 grid 10,36
struct node 62 grid 11,36
struct node 63 grid 11,35
struct node 64 grid 11,34
struct node 65 grid 12,34
struct node 66 grid 13,34
struct node 67 grid 14,34
struct node 68 grid 14,35
struct node 69 grid 15,35
struct node 70 grid 15,36
struct node 71 grid 16,36
struct node 72 grid 16,37
struct node 73 grid 17,37
struct node 74 grid 17,38
struct node 75 grid 17,39
struct node 76 grid 17,40
struct node 77 grid 17,41
struct node 78 grid 17,42
struct node 79 grid 17,43
struct node 80 grid 16,44
struct node 81 grid 16,45

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struct node 83 grid 16,46
struct node 84 grid 15,46
struct node 85 grid 15,47
struct node 86 grid 14,47
struct node 87 grid 14,48
struct node 88 grid 13,48
struct node 89 grid 13,49
struct node 90 grid 12,49
struct node 91 grid 12,48
struct node 92 grid 11,48
struct node 93 grid 11,47
struct node 94 grid 11,46
struct node 95 grid 10,46
struct node 96 grid 10,45
struct node 97 grid 10,44
struct node 98 grid 10,43
struct liner begin node 55 end node 56 prop 5001
struct liner begin node 56 end node 57 prop 5001
struct liner begin node 57 end node 58 prop 5001
struct liner begin node 58 end node 59 prop 5001
struct liner begin node 59 end node 60 prop 5001
struct liner begin node 60 end node 61 prop 5001
struct liner begin node 61 end node 62 prop 5001
struct liner begin node 62 end node 63 prop 5001
struct liner begin node 63 end node 64 prop 5001
struct liner begin node 64 end node 65 prop 5001
struct liner begin node 65 end node 66 prop 5001
struct liner begin node 66 end node 67 prop 5001
struct liner begin node 67 end node 68 prop 5001
struct liner begin node 68 end node 69 prop 5001
struct liner begin node 69 end node 70 prop 5001
struct liner begin node 70 end node 71 prop 5001
struct liner begin node 71 end node 72 prop 5001
struct liner begin node 72 end node 73 prop 5001
struct liner begin node 73 end node 74 prop 5001
struct liner begin node 74 end node 75 prop 5001
struct liner begin node 75 end node 76 prop 5001
struct liner begin node 76 end node 77 prop 5001
struct liner begin node 77 end node 78 prop 5001
struct liner begin node 78 end node 79 prop 5001
struct liner begin node 79 end node 80 prop 5001
struct liner begin node 80 end node 81 prop 5001
struct liner begin node 81 end node 82 prop 5001
struct liner begin node 82 end node 83 prop 5001
struct liner begin node 83 end node 84 prop 5001
struct liner begin node 84 end node 85 prop 5001
struct liner begin node 85 end node 86 prop 5001
struct liner begin node 86 end node 87 prop 5001
struct liner begin node 87 end node 88 prop 5001
struct liner begin node 88 end node 89 prop 5001
struct liner begin node 89 end node 90 prop 5001
struct liner begin node 90 end node 91 prop 5001
struct liner begin node 91 end node 92 prop 5001
struct liner begin node 92 end node 93 prop 5001
struct liner begin node 93 end node 94 prop 5001
struct liner begin node 94 end node 95 prop 5001
struct liner begin node 95 end node 96 prop 5001
struct liner begin node 96 end node 97 prop 5001
struct liner begin node 97 end node 98 prop 5001
struct liner begin node 98 end node 55 prop 5001
struct prop 5001
deprop 5001 e 5.5000003E9 area 0.1 I 8.333E-5 thickness 0.1 pratio 0.2
history 999 unbalanced
solve
save ms_Ic.sav

;... State: ms_IIa.sav ....
apply remove mech long from 12,34 to 12,34
model null group ‘top heading’
struct liner delete 81
struct liner delete 82
struct liner delete 83
struct liner delete 84
struct liner delete 85
struct liner delete 86
struct liner delete 87
struct liner delete 88
struct liner delete 89
apply xvelocity 0.0 from 1,42 to 10,42
apply yvelocity 0.0 from 1,42 to 10,42
apply xvelocity 0.0 from 1,52 to 12,49
apply yvelocity 0.0 from 1,52 to 12,49
cycle 1
set echo off
call relax_tractions.fis
set ninc=1000 rstart=1.0 rstop=0.5 ih_ap=1 ie_ap=12 jb_ap=42 je_ap=52
relax_tractions
fix x i 1 j 52
fix x i 1 j 42
solve
save ms_IIa.sav

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 construed node 99 4.75,-25.5
 construed node 100 6.8,-21.85
 construed node 101 3.44,-24.9
 construed node 102 5.0,-21.0
 construed node 103 2.13,-24.5
 construed node 104 3.05,-20.4
 construed node 105 0.7,-24.3
 construed node 106 1.0,-20.1

 construed rockbolt begin node 99 end node 100 seg 5 prop 4001
 construed rockbolt begin node 101 end node 102 seg 5 prop 4001
 construed rockbolt begin node 103 end node 104 seg 5 prop 4001
 construed rockbolt begin node 105 end node 106 seg 5 prop 4001

 apply remove mech from 1,42 to 10,42
 apply remove mech from 1,52 to 12,49
 apply xvelocity 0.0 from 1,42 to 10,42
 apply yvelocity 0.0 from 1,42 to 10,42
 apply xvelocity 0.0 from 1,52 to 12,49
 apply yvelocity 0.0 from 1,52 to 12,49

 cycle 1
 set echo off
 call relax_tractions.fis
 set ninc=1000 rstart=1.0 rstop=0.5 ib_ap=1 ie_ap=12 jb_ap=42 je_ap=52
 relax_tractions
 fix x i 1 j 52
 fix x i 1 j 42
 solve
 save ms_IIb.sav

 ;... State: ms_IIc.sav ....
 apply remove mech from 1,42 to 10,42
 apply remove mech from 1,52 to 12,49
 apply xvelocity 0.0 from 1,42 to 10,42
 apply yvelocity 0.0 from 1,42 to 10,42
 apply xvelocity 0.0 from 1,52 to 12,49
 apply yvelocity 0.0 from 1,52 to 12,49

 cycle 1
 set echo off
 call relax_tractions.fis
 set ninc=1000 rstart=1.0 rstop=0.0 ib_ap=1 ie_ap=12 jb_ap=42 je_ap=52
 relax_tractions
 fix x i 1 j 52
 fix x i 1 j 42
 construed node 123 grid 11,49
 construed node 124 grid 11,50
 construed node 125 grid 10,50
struct node 126 grid 9,50
struct node 127 grid 9,51
struct node 128 grid 8,51
struct node 129 grid 7,51
struct node 130 grid 7,52
struct node 131 grid 6,52
struct node 132 grid 5,52
struct node 133 grid 4,52
struct node 134 grid 3,52
struct node 135 grid 2,52
struct node 136 grid 1,52
struct liner begin node 90 end node 123 prop 5001
struct liner begin node 123 end node 124 prop 5001
struct liner begin node 124 end node 125 prop 5001
struct liner begin node 125 end node 126 prop 5001
struct liner begin node 126 end node 127 prop 5001
struct liner begin node 127 end node 128 prop 5001
struct liner begin node 128 end node 129 prop 5001
struct liner begin node 129 end node 130 prop 5001
struct liner begin node 130 end node 131 prop 5001
struct liner begin node 131 end node 132 prop 5001
struct liner begin node 132 end node 133 prop 5001
struct liner begin node 133 end node 134 prop 5001
struct liner begin node 134 end node 135 prop 5001
struct liner begin node 135 end node 136 prop 5001
struct node 136 fix r
solve
save ms_IIc.sav

;... State: ms_IIa.sav ....
apply remove mech from 1,42 to 10,42
apply remove mech from 1,52 to 12,49
model null group ‘bench’
struct liner delete 46
struct liner delete 47
struct liner delete 48
struct liner delete 49
struct liner delete 50
struct liner delete 51
struct liner delete 52
struct liner delete 53
struct liner delete 54
struct liner delete 55
apply xvelocity 0.0 from 1,32 to 12,34
apply yvelocity 0.0 from 1,32 to 12,34
cycle 1
set echo off
call relax_tractions.fis
set ninc=1000 rstart=1.0 rstop=0.5 ib_ap=1 ie_ap=12 jb_ap=32 je_ap=34
relax_tractions
fix  x  i  l  j  32
solve
save ms_IIIa.sav

;... State: ms_IIIb.sav ....
apply remove mech from 1,32 to 12,34
apply xvelocity 0.0 from 1,32 to 12,34
apply yvelocity 0.0 from 1,32 to 12,34
cycle 1
set echo off
call relax_tractions.fis
set ninc=1000 rstart=1.0 rstop=0.5 ib_ap=1 ie_ap=12 jb_ap=32 je_ap=34
relax_tractions
fix  x  i  l  j  32
solve
save ms_IIIb.sav

;... State: ms_IIIC.sav ....
apply remove mech from 1,32 to 12,34
apply xvelocity 0.0 from 1,32 to 12,34
apply yvelocity 0.0 from 1,32 to 12,34
cycle 1
set echo off
call relax_tractions.fis
set ninc=1000 rstart=1.0 rstop=0.0 ib_ap=1 ie_ap=12 jb_ap=32 je_ap=34
relax_tractions
fix  x  i  l  j  32
struct node 137 grid 12,33
struct node 138 grid 11,33
struct node 139 grid 10,33
struct node 140 grid 9,33
struct node 141 grid 8,33
struct node 142 grid 8,32
struct node 143 grid 7,32
struct node 144 grid 6,32
struct node 145 grid 5,32
struct node 146 grid 4,32
struct node 147 grid 3,32
struct node 148 grid 2,32
struct node 149 grid 1,32
struct liner begin node 65 end node 137 prop 5001
struct liner begin node 137 end node 138 prop 5001
struct liner begin node 138 end node 139 prop 5001
struct liner begin node 139 end node 140 prop 5001
struct liner begin node 140 end node 141 prop 5001
struct liner begin node 141 end node 142 prop 5001
struct liner begin node 142 end node 143 prop 5001
struct liner begin node 143 end node 144 prop 5001
struct liner begin node 144 end node 145 prop 5001
struct liner begin node 145 end node 146 prop 5001
struct liner begin node 146 end node 147 prop 5001
struct liner begin node 147 end node 148 prop 5001
struct liner begin node 148 end node 149 prop 5001
struct node 149 fix r
solve
save ms_IICc.sav

;... State: ms_settle.sav ....
set echo off
call settle.fis
settle
save ms_settle.sav

;*** plot commands ****
;plot name: rockbolt forces
plot hold struct rockbolt axial fill max 1000000.0 mark
;plot name: shotcrete forces
plot hold struct liner axial fill max -2000000.0 mark
;plot name: tractions
plot hold apply max 170000.0 bound liner iwhite
;plot name: stress histories
plot hold history 2 3 line 4 line
;plot name: SE numbers
plot hold bound struct liner node struct liner element
;plot name: settlement profile
label table 2
Vert. Dist. vs Dist.
plot hold table 2 both
;plot name: y-displacement
plot hold ydisp fill inv displacement bound
;plot name: ground reaction curve
label table 1
Relax Factor vs Vert. Disp.
plot hold table 1 both
12.6 *FISH Functions*

12.6.1 *"RELAX_TRACIONS.FIS"*

;Name:relax_tractions
;Diagram:
;Input:ninc/int/1000/relaxation steps
;Input:rstart/float/1.0/beginning relaxation ratio
;Input:rstop/float/0.5/ending relaxation ratio
;Input:ib_ap/int/10/beginning i gridpoint for traction range
;Input:ie_ap/int/17/ending i gridpoint for traction range
;Input:jb_ap/int/34/beginning j gridpoint for traction range
;Input:je_ap/int/49/ending j gridpoint for traction range
; FISH functions to control relaxation of tunnel tractions

def relax_ini
   nstart = step
   nstop = nstart + ninc
end

def relax_hist
   if step < nstop
      step_inc = float(step - nstart)
      relax_hist = rstart - ((rstart - rstop)/ float(ninc)) * step_inc
   else
      relax_hist = rstop
   endif
end

def apply_rf
   loop ii (ib_ap,ie_ap)
      loop jj (jb_ap,je_ap)
         if and(flags(ii,jj), 2) = 2 then
            if and(flags(ii,jj), 4) = 4 then
               xftmp = -xforce(ii,jj)
               yftmp = -yforce(ii,jj)
               command
                  apply xforce=xftmp hist relax_hist i=ii j=jj
                  apply yforce=yftmp hist relax_hist i=ii j=jj
               end_command
            endif
         endif
      endloop
   endloop
end
Example Applications

12.6.2 “GRC.FIS”

;Name:grc
;Diagram:
;Input:relax_value/float/1.0/relaxation factor
;Input:isn/int/1/step number
def grc
  xtable(1,isn) = -ydisp(1,52)
  ytable(1,isn) = relax.value
end

12.6.3 “SETTLE.FIS”

;Name:settle
;Diagram:
; generate a settlement profile plot
def settle
  loop il (1,25)
    xtable(2,il) = x(il,jgp)
    ytable(2,il) = ydisp(il,jgp)
  end.loop
end