11 Multistage Tunnel Excavation and Support

11.1 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 construction conditions and sequence of a shallow tunnel are illustrated in Figure 11.1 and Figure 11.2.

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

Stage I: right-side excavation;

Stage II: left-side excavation;

Stage III: top-heading excavation; and

Stage IV: bench excavation.

Each excavation stage is accomplished in three construction steps:

Step a: initial excavation;

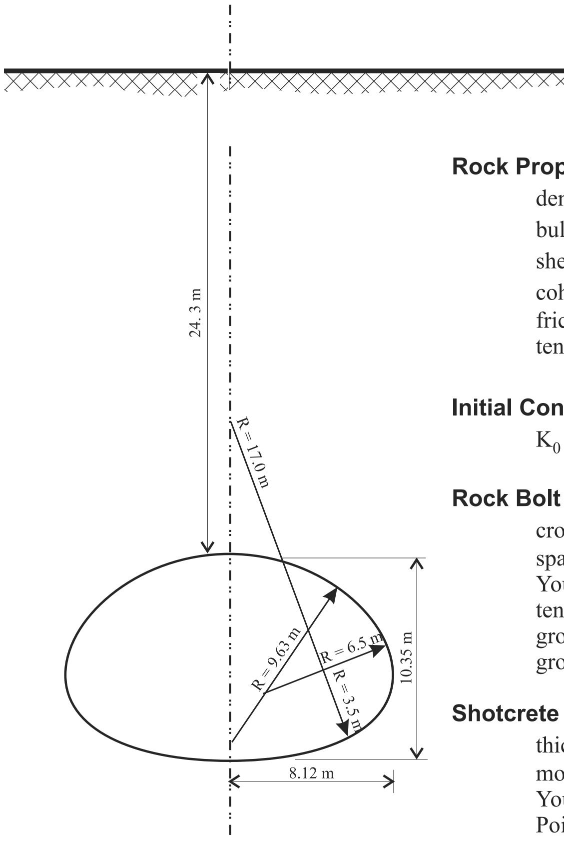
Step b: installation of rockbolt support; and

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 *FLAC3D* (Itasca 2012). 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.



Rock Properties

density	: 2700 kg/m^3
bulk modulus	: 0.555 GPa
shear modulus	: 0.417 GPa
cohesion	: 10 kPa
friction angle	: 33°
tensile strength	: 1 kPa

Initial Conditions

K_0	: 0.5

Rock Bolt Properties

cross section area	: 5.0×10^{-4} m^2
spacing	: 1.0 m
Young's modulus	: 2.05 GPa
tensile yield strength	: 0.5 MN
grout shear stiffness	: 15 GN/m/m
grout shear strength	: 800,000 N/m

Shotcrete Liner Properties

thickness	: 0.3 m
moment of inertia	: 2.25×10^{-3} m^4
Young's modulus	: 5.28 GPa
Poisson's ratio	: 0.2
compressive strength	: 10 MPa
tensile strength	: 1 MPa

Figure 11.1 Construction conditions for a multistage tunnel excavation and support

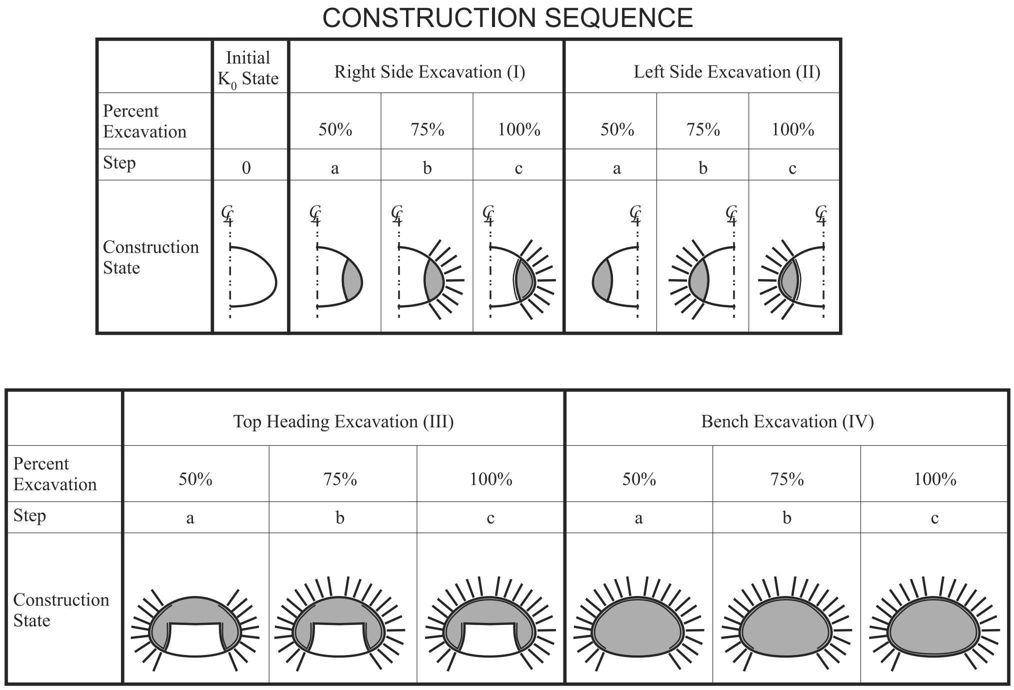


Figure 11.2 Construction sequence for a multistage tunnel excavation and support

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 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 11.1.

11.2 Modeling Procedure

11.2.1 Model Setup

FLAC is well-suited to model sequential excavation and construction problems. In this example, the four excavation stages and three construction steps within each stage are simulated as 12 sequential solutions. A procedure that demonstrates the process to develop a ground reaction curve for this model is also included. The project file, “mstunnel.prj”, contains all of the command data for each solution stage in this example.

The *FLAC* mesh is defined with the grid distorted to align with the boundaries of the four segments of the tunnel excavation. The Build/Generate/Geometry Builder tool is used to create the tunnel geometry with a fine mesh in the vicinity of the tunnel and a radially graded mesh extending to the model boundaries. The tunnel stage boundaries are defined in an imported geometry file, “tunnel.dxf”. This file can be directly obtained from a CAD drawing or drawn by hand in the Sketch tool. The *FLAC* grid for this example is shown in Figure 11.3. A close-up view of the four excavation stages is shown in Figure 11.4.

The rock behavior is represented by the Mohr-Coulomb model assigned the properties listed in Figure 11.1. The rockbolts are modeled using rockbolt elements, and the shotcrete is simulated with liner elements. Note that the 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. The initial stage is identified as Step 0 in Figure 11.1.

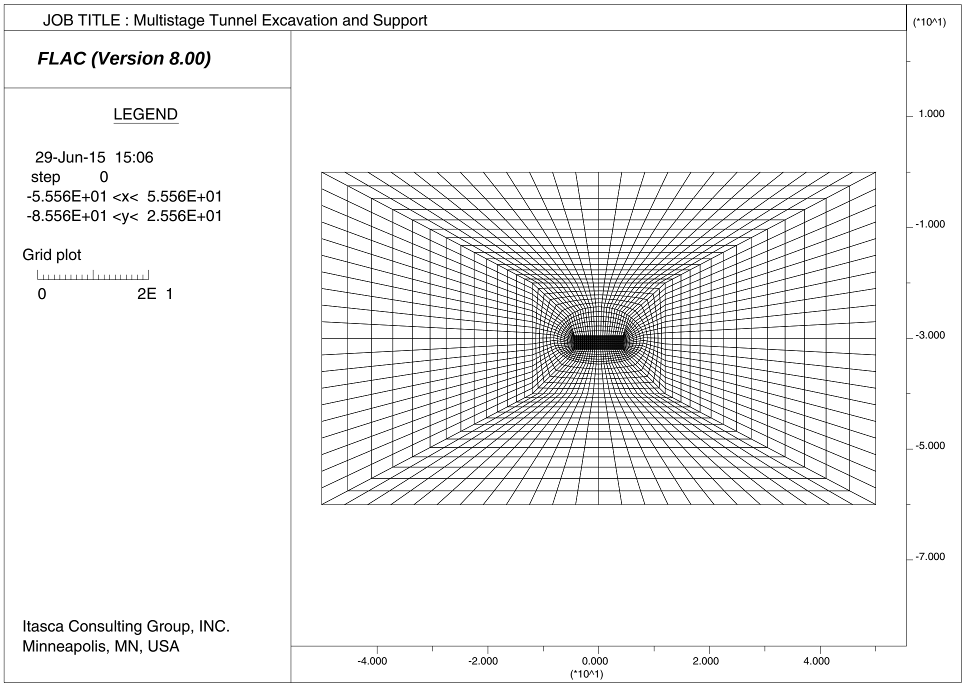


Figure 11.3 FLAC grid for a multistage tunnel construction

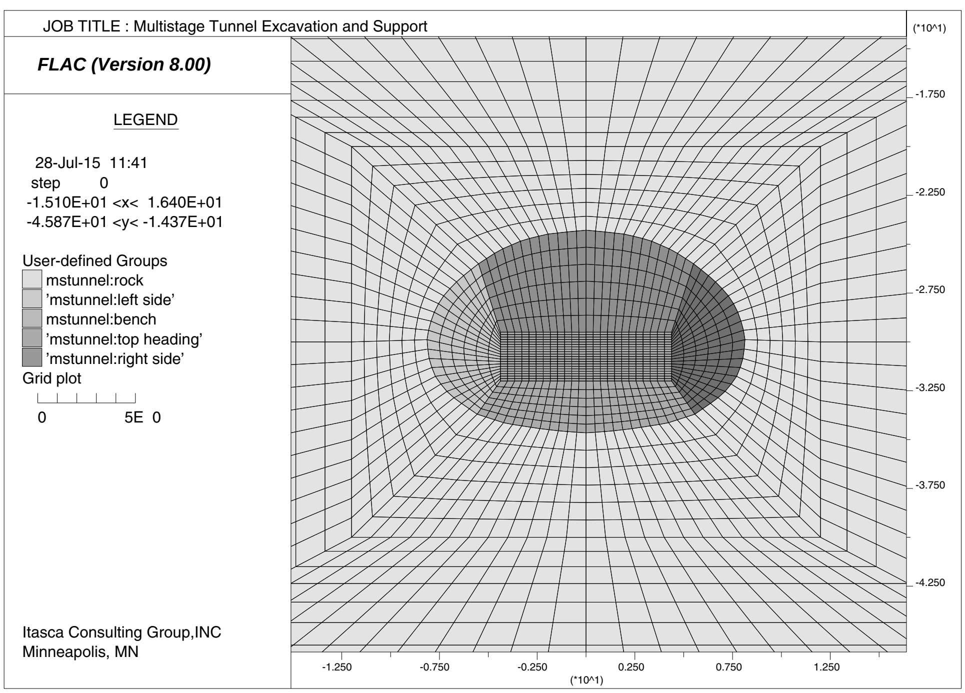


Figure 11.4 Close-up of excavation stage groups for multistage tunnel construction

11.2.2 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.

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 command **APPLY relax** performs this relaxation procedure automatically.

The **APPLY relax** command is applied to gridpoints along the entire tunnel boundary in this example. When the command is executed, x- and y-reaction forces at these gridpoints are recovered and then applied as tractions (with an opposite sign) at the same gridpoints. The **nsteps** keyword then defines the number of intervals over which the tractions are reduced. In this example, **nsteps** = 10, i.e., the tractions are reduced in 10% increments from the zero relaxation state. The keyword **rstop** sets the final reduced value of the traction. Tractions are defined as dimensionless relaxation factors between 1.0 and 0.0. For this example, the ending relaxation factor **rstop** is set to 0.2. If a lower value is specified, the tunnel collapses.

Tunnel closure is monitored as a history. The *FISH* function `closure` calculates the vertical closure of the tunnel. The closure is then recorded as **grhist** = 1 in the **APPLY relax** command. The ground reaction curve, which plots the reduction in relaxation factor versus the closure, is written to a table specified by **grtable** = 1 in the **APPLY relax** command. Figure 11.5 displays the result for load relaxation of the entire tunnel boundary from a relaxation factor of 1.0 to 0.2. This is the ground reaction curve.

By also relating the tunnel closure to the distance to the tunnel face (e.g., see Figure 8.6 in Section 8), relaxation factors can be selected to correspond to selected distances to the tunnel face.

For this multistage tunnel excavation/construction 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.

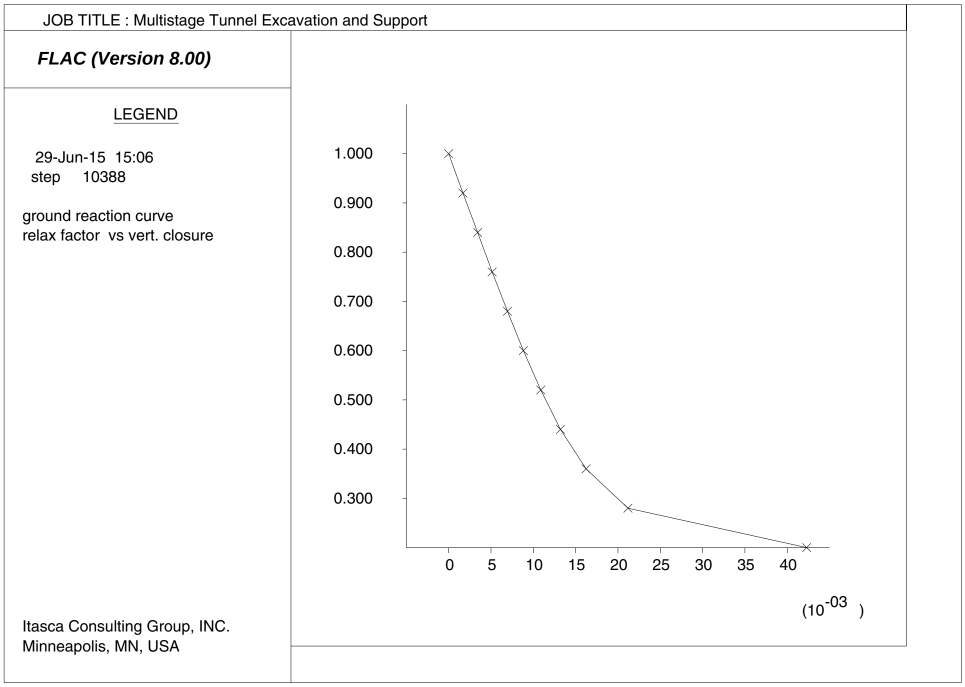


Figure 11.5 Ground reaction curve: relaxation factor versus vertical closure

11.2.3 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 the **APPLY relax** command is applied over that segment boundary to reduce the tractions in 20% increments (**nsteps** = 5) until the tractions are 50% of their starting value (**rstop** = 0.5). The model is brought to force equilibrium at 50% relaxation. This is Step a, as shown in Figure 11.1.

At this state, the rockbolt elements are added, representing the rockbolt support. The locations of the rockbolts are defined by a sketch of the rockbolt pattern. This geometry is imported into *FLAC* from the BUILD/SKETCH tool as the file "rockbolts.dxf". (The geometry can be imported as a CAD drawing or drawn in the SKETCH tool.) Using the sketch as a background image, the rockbolts are located around the boundary of each excavation, as shown in Figure 11.1. Each rockbolt is composed of five segments, which is sufficient to locate a rockbolt node within every zone along the bolt length.

The tunnel tractions around the excavation are now reduced again using **APPLY relax**. The relaxation increment, **nsteps** = 5 and the end factor **rstop** = 0.5. This results in the tractions relaxing an additional 50%. The model is then brought to force equilibrium at 75% relaxation. This is Step b in Figure 11.1.

At this state, the liner elements are added to represent installation of the shotcrete lining. The tunnel tractions are reduced by using **APPLY relax** with **nsteps** = 5 and **rstop** = 0.0. The tractions are now relaxed 100% and the model is brought to equilibrium.

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 in a five-step reduction (**nsteps** = 5), the effects of transient waves are minimized, and a gradual excavation of the tunnel is simulated. This is demonstrated by Figure 11.6, which displays vertical stress histories at the 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.)

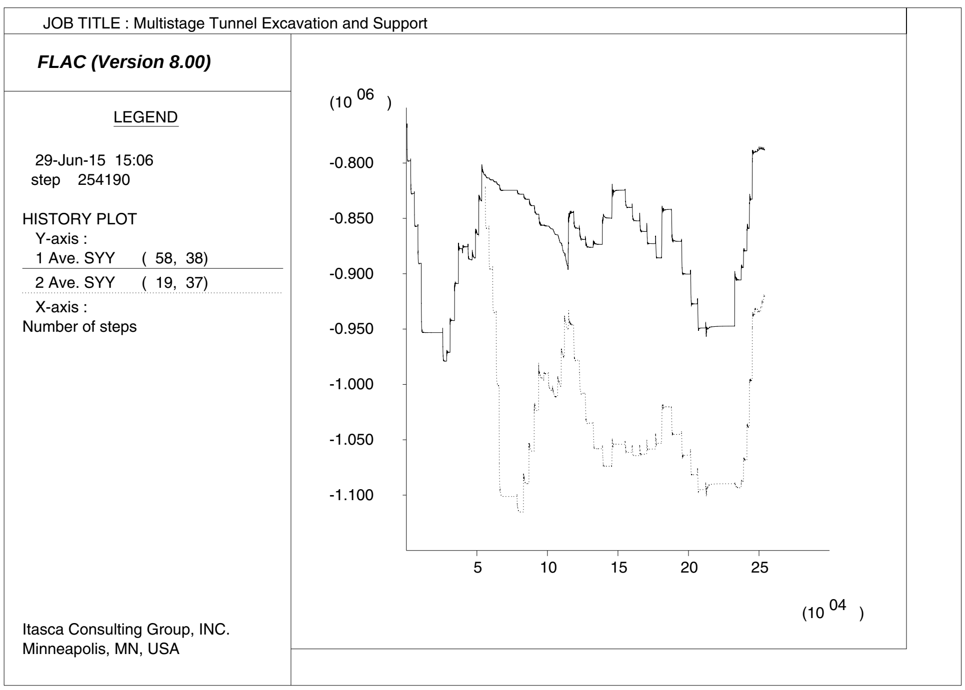


Figure 11.6 Vertical stress histories at the springline

11.3 Results

Typical results for this analysis are shown in Figures 11.7, 11.9, 11.10 and 11.11. The settlement profile of the ground surface at the end of the analysis is shown in Figure 11.7. The profile is created with *FISH* function **settle**; *y*-displacements at the gridpoints along the top of the model are stored in table 2.

The axial forces in the rockbolts at the end of each excavation stage are shown in Figure 11.9, and the axial forces in the shotcrete are shown in Figure 11.10. 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 the command **PLOT structure axial**. Figure 11.8 shows the *Plot Item Switches* dialog, in which the maximum value is set to −800000.0 to change the sense of the liner axial force plot.

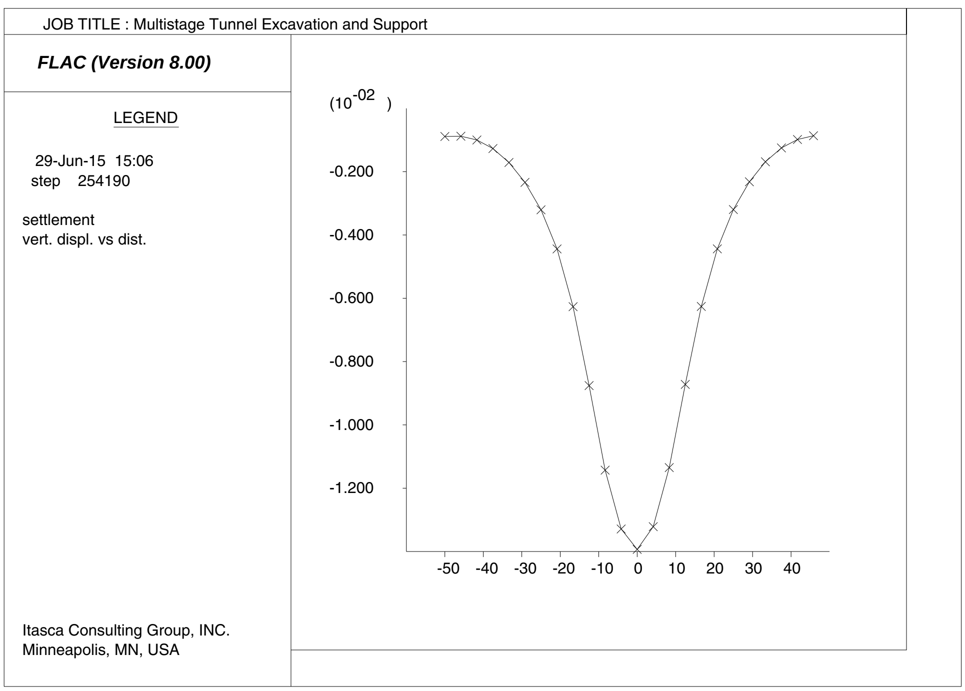


Figure 11.7 Final settlement profile

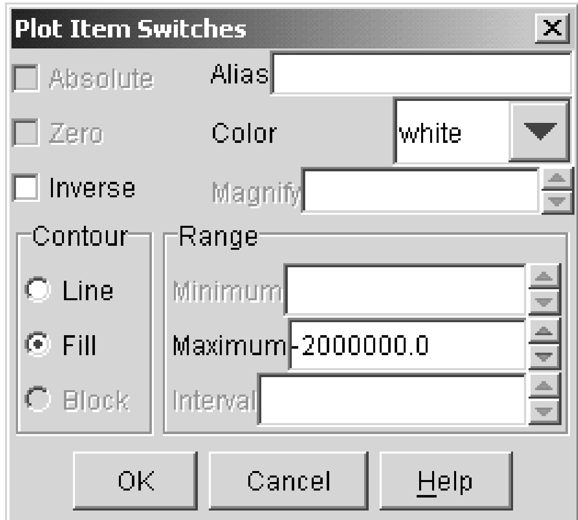
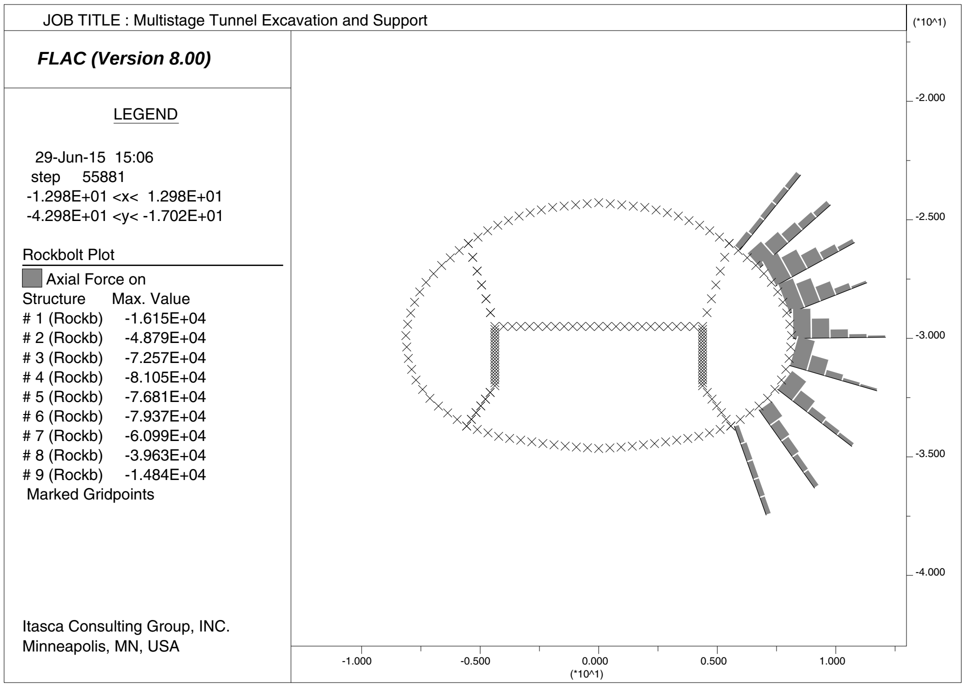
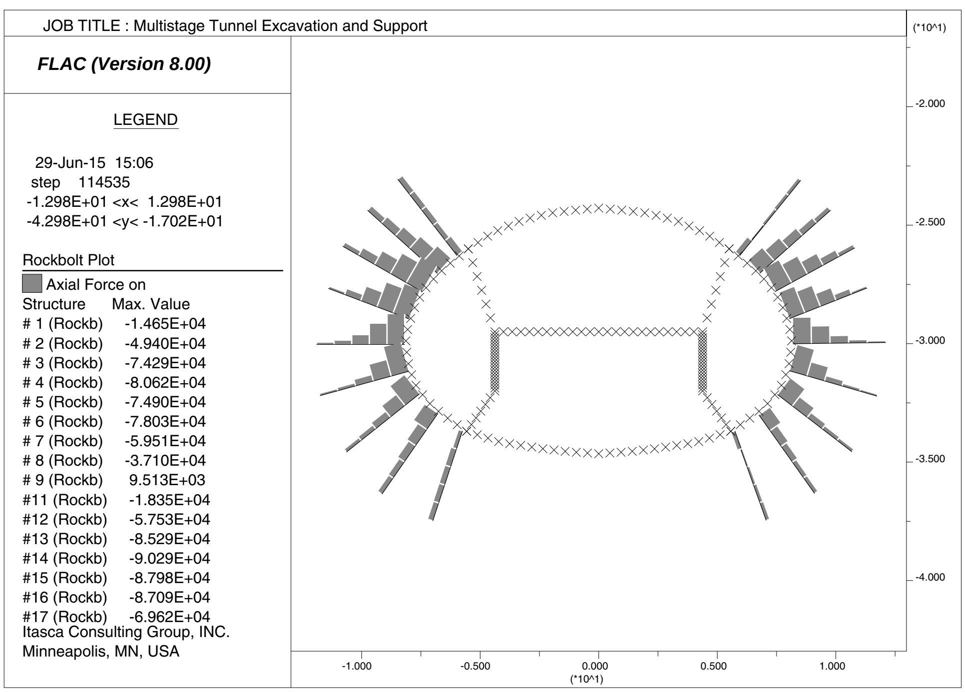


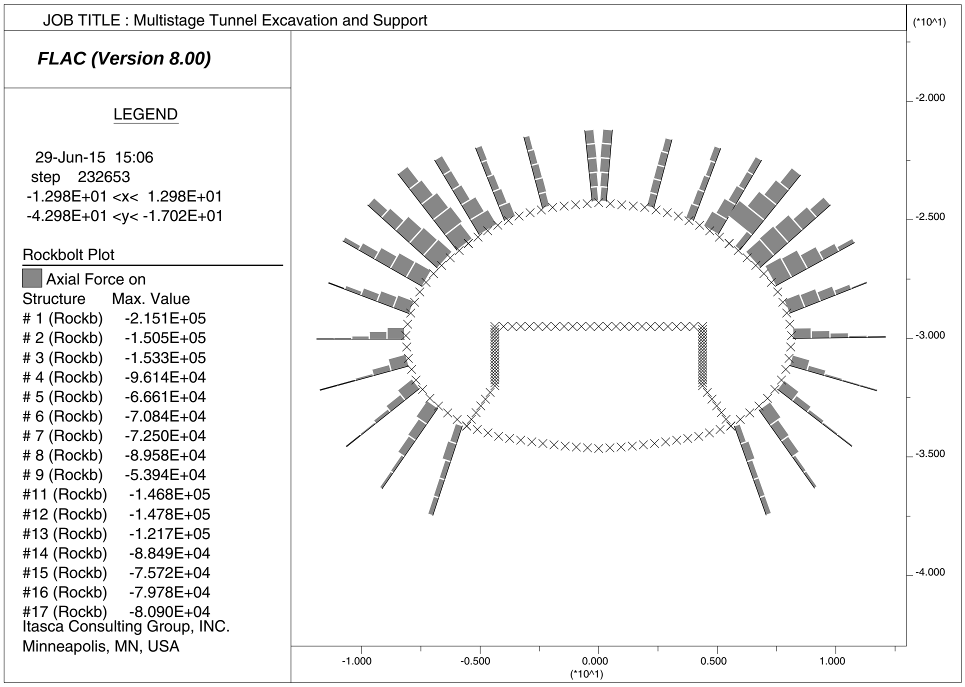
Figure 11.8 Plot Item Switches dialog; use the MAXIMUM ***switch to change the plot sense***



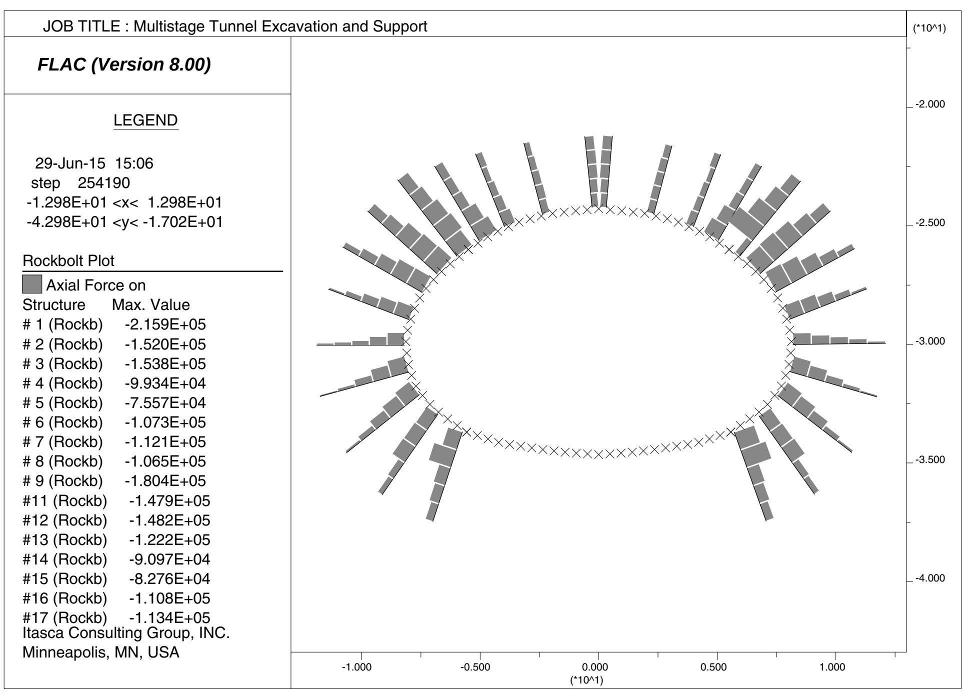
(a) right-side excavation



(b) left-side excavation

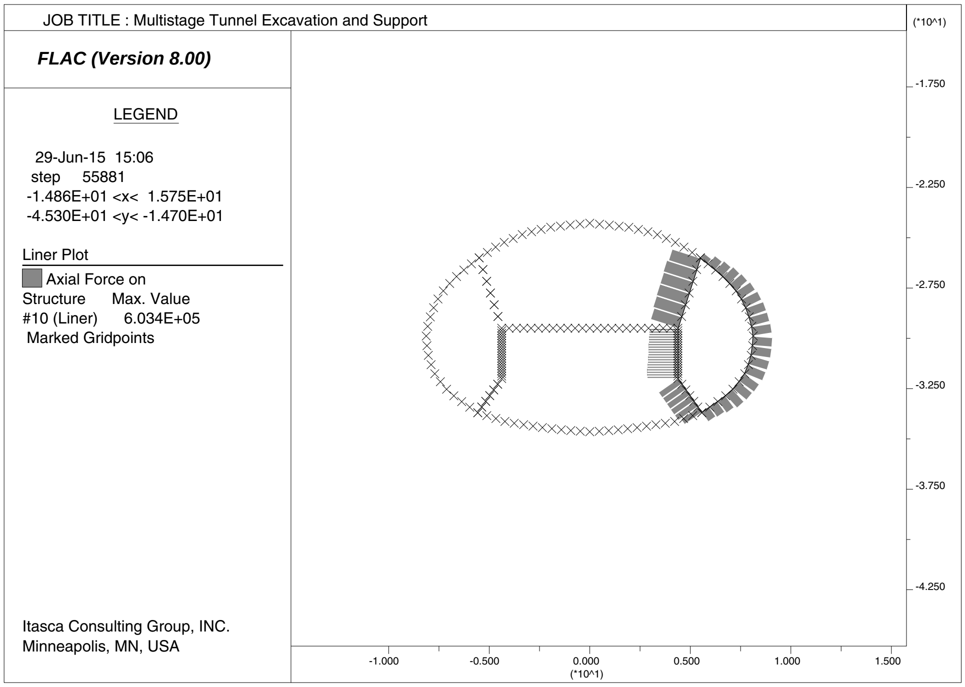


(c) top-heading excavation

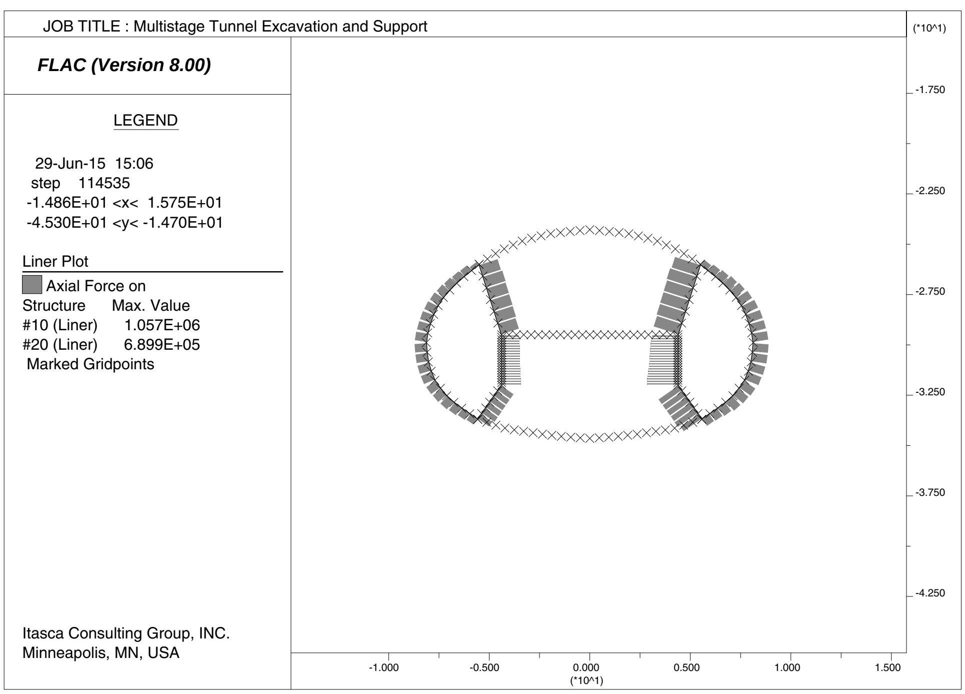


(d) bench excavation

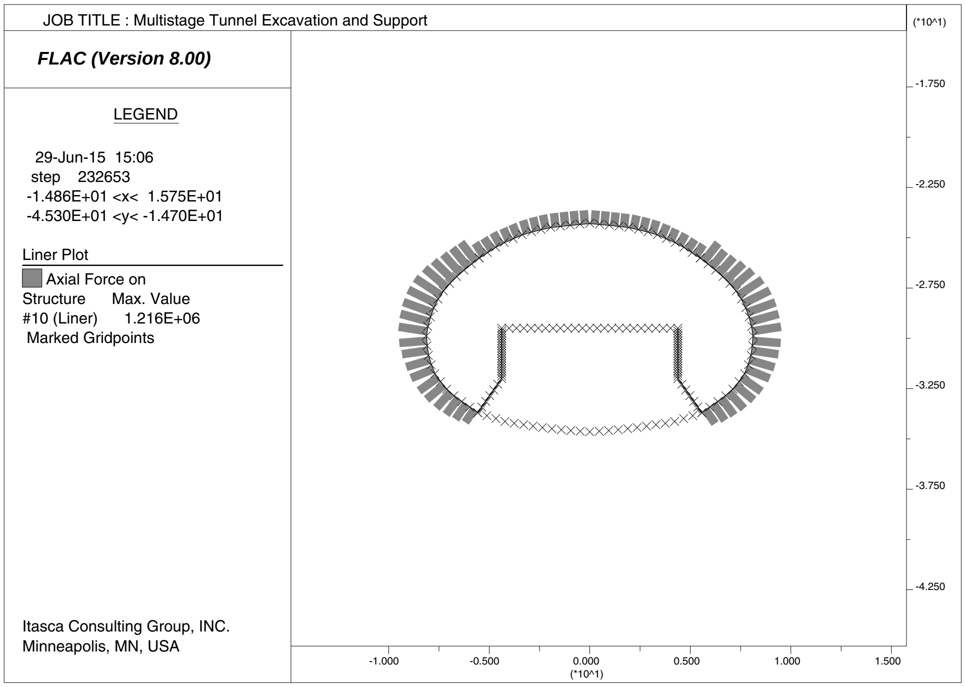
Figure 11.9 Axial forces in rockbolts at 100% relaxation for each excavation stage



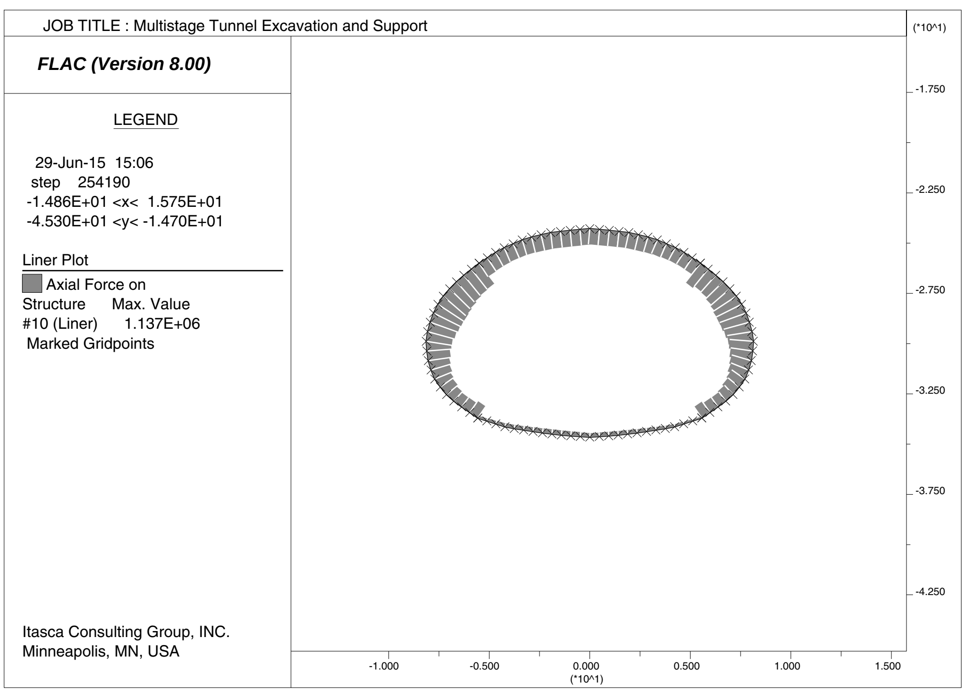
(a) right-side excavation



(b) left-side excavation



(c) top-heading excavation



(d) bench excavation

Figure 11.10 Axial forces in shotcrete at 100% relaxation for each excavation stage

Figure 11.11 plots a moment-thrust diagram for the shotcrete liner at 100% relaxation at the last excavation stage. The plot indicates that all segments along the liner have a factor of safety greater than 1.4.

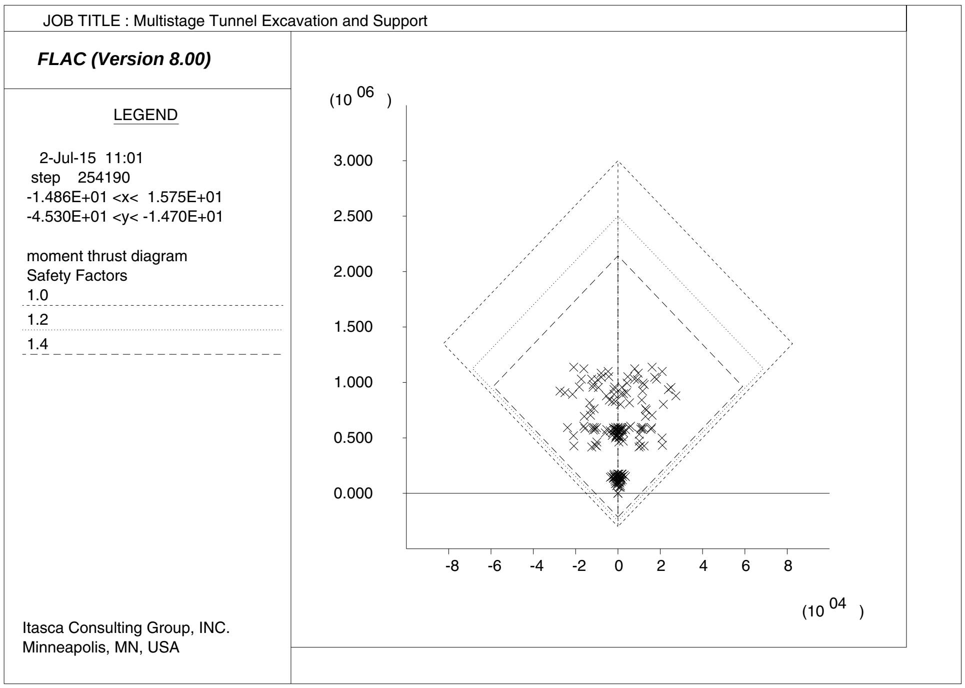


Figure 11.11 Moment-thrust diagram (tensile yield strength = 1 MPa, compressive yield strength = 10 MPa) for shotcrete liner at 100% relaxation at the last excavation stage

11.4 References

Itasca Consulting Group, Inc. ***FLAC^{3D} (Fast Lagrangian Analysis of Continua in 3 Dimensions)***, Version 5.0. Minneapolis: ICG (2012).

Panet, M. "Time-Dependent Deformations in Underground Works," in ***Proceedings of the 4th ISRM Congress (Montreux)***, Vol. 3, pp. 279-289. Rotterdam: A. A. Balkema and the Swiss Society for Soil and Rock Mechanics (1979).