NUMERICAL MODELING OF THE U1A COMPLEX AT THE NEVADA TEST SITE: MODEL DEVELOPMENT AND COMPARISON OF DIFFERENT DRIFT MINING OPTIONS

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ABSTRACT

Stress analysis programs such as MULSIM/NL, LAMODEL, MinSim 2000, and EXAMINE^{TAB} are used in the mining industry to analyze stresses and displacements in coal mines, platinum mines, gold reefs, and tabular-type deposits. These relatively simple numerical models can efficiently simulate yielding and failure of a rock mass near a mine opening and subsequent stress transfer. The main input parameters for these models are a family of nonlinear stress-strain curves for the in-seam material. For many applications of these models, such as in coal mining, extensive field measurements and observations exist from which to estimate these stress-strain curves and calibrate the numerical models; however, such measurements are lacking for other types of mines.

A three-step method is presented to determine nonlinear stress-strain curves for boundary-element (BE) programs used in many mining applications. The method requires a suite of laboratory-scale strength tests at various confining pressures. Note that this analysis uses laboratory-measured strength and modulus properties of alluvium. The dependency of the mechanical properties of alluvium on scale has not been established, although more tests are being planned. However, it is believed that the relative comparisons performed are valuable regardless of scale effects. First, the FLAC2D computer program is used to model the laboratory tests and determine cohesion (c) and friction angle (ϕ) for a Mohr-Coulomb material model. Second, another FLAC2D model uses the c and ϕ values to calculate vertical stress and strain around a single opening in the rock mass. This model calculates the stress-strain path of points at various distances from the opening boundary. Finally, based on these stress-strain paths, the stress-strain curves needed for a BE analysis are derived.

This three-step method was demonstrated in a large, flat-lying underground test facility in very weak rock. The BE analyses agreed well with observations of failure at the test facility and provided a basis for evaluating the behavior of alternative layouts.

INTRODUCTION

Background

The U1a complex is an underground physics laboratory at the Nevada Test Site (*1*). Figure 1 shows the general layout of the complex as of October 2001. The main features of the complex are the U1a shaft at the southern end, the new U1h shaft at the northern end, and the north-south U1a.01 drift that connects the two shafts. Main features of the facility are the vent drift and user's alcove east of the U1a.01 drift. Numerous alcoves used for physics experiments are located off the major drifts.

The facility is mined in a weakly cemented alluvium at a depth of 960 ft below the surface, where vertical stress is expected to be about 800 psi. Unfortunately, the unconfined compressive strength of the alluvium measured on 2-in-diam by 4-in-long specimens is only about 150 psi, which is roughly one-fifth of the vertical stress. Therein is the source of the facility's stability problems. When new drifts are mined close to existing drifts, the ground yields and induces excessive deformation around existing drifts. Yielding and excessive deformation results in deterioration of the support system, which consists of rock bolts, wire mesh, and shotcrete. The alcoves used for the physics experiments house expensive data collection systems. Any deterioration of the opening is unacceptable, and several areas in the facility have required rehabilitation.

The most serious damage resulted from mining crosscut D and the U1a.05 drifts off the U1a.02 drift and the U1a.102 drifts off the U1a.100 drift. Mining these drifts caused excessive deformation of the U1a.01 main drift, the U1a.02 drift, and the vent drift areas. Limited convergence and extensometer data are available from instruments installed in these areas. Unfortunately, these instruments were installed after most of the deformation had occurred, and they only recorded a limited amount of data.

Alternative Layouts

Keeping in mind these ground control problems, site managers considered two options for further facility development (figure 1). Option 1 locates the U1a.200 drift south of the U1h shaft, whereas option 2 locates it north of the shaft. The latter option

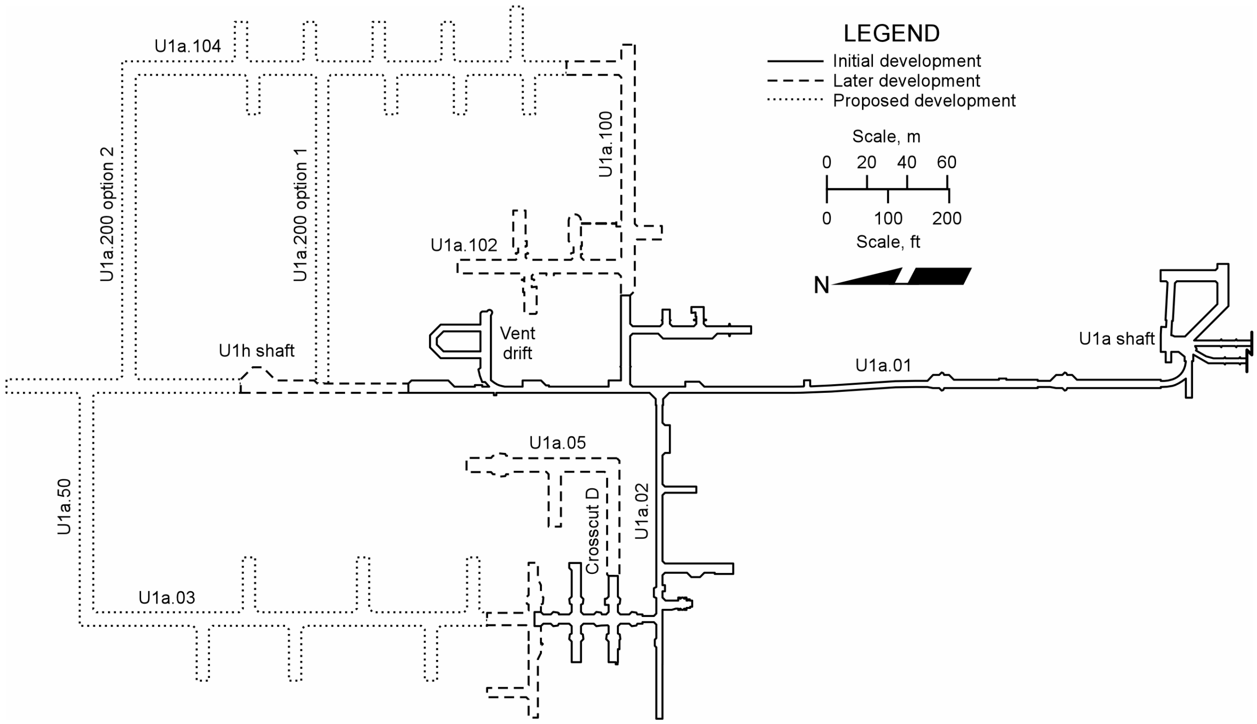

Figure 1. General layout of U1a complex.

spreads mine development over a wider area and decreases the risk of geomechanical problems due to ground yielding and stress transfer. However, option 2 also requires several hundred feet of additional mining at a cost of millions of dollars. Option 1 may carry some risk of geomechanical stability problems; however, the cost is substantially less.

This case study assessed potential ground yielding and stress transfer associated with the alternate locations for the U1a.200 drift. Any development option must ensure satisfactory stability of the new U1h shaft area and the nearby user's alcove and vent drift. MULSIM/NL (*2*, *3*), which is a pseudo-three-dimensional, boundary-element (BE) program, was used to examine the two options.

Objectives

This paper shows how to develop nonlinear stress-strain models used as input parameters for BE programs such as MULSIM/NL from a suite of laboratory-scale strength tests at various confining pressures. In brief, FLAC2D (*4*) is used to model the laboratory tests and determine cohesion (c) and friction angle (ϕ) for a Mohr-Coulomb material model. Next, another FLAC2D model of a single opening uses these material parameters to calculate the stress-strain path of points at various distances from the opening boundary. Finally, these calculated stress-strain paths become the required stress-strains curves for the BE analysis. Note that this analysis uses laboratory-measured strength and modulus properties of alluvium. The dependency of the mechanical properties of alluvium on scale has not been established, although more tests are being planned. However, it is believed that the relative comparisons performed are valuable regardless of scale effects. The three-step method presented here, in which laboratory strength data are used as required input parameters for BE analysis, should also be applicable to a variety of other mines, such as coal, gold, platinum, and other commodities where input parameters are poorly known.

REQUIRED INPUT PARAMETERS FOR 3-D BE MODELS

Stress analysis programs such as MULSIM/NL (*2*, *3*), LAMODEL (*5*, *6*), MinSim 2000 (*7*), and EXAMINE^{TAB} (*8*) are used in the mining industry to analyze stresses, displacements, yielding, and stress transfer around tabular bodies such as coal and gold-bearing reefs. MULSIM/NL uses the BE approach to calculate stresses and displacements around coal seams or, in the case reviewed here, the flat-lying U1a complex. The key abstraction underlying BE modeling is to analyze a tabular deposit as a thin crack or discontinuity in an otherwise homogeneous, isotropic, linear, elastic rock mass. Figure 2*A* shows this crack or seam plane in the surrounding rock mass. The top and bottom surfaces of the crack form the problem boundary (i.e., the roof and floor in coal mining or the hanging wall and footwall in metal mining). The next critical step is to divide the crack or seam plane into numerous square boundary elements. Figure 2*B* shows an actual mine plan (in this case, a plan view of coal mine gateroad entries) and a grid showing an approximation of the model. Individual elements are then assigned material properties to approximate mine geometry. Many of the stress analysis programs mentioned above feature stress-strain models for the in-seam material (figure 2*C*) that include (1) linear elastic for coal or rock, (2) strain-softening, (3) elastic-plastic, (4) bilinear-hardening, (5) strain-hardening, and (6) linear elastic gob or broken rock. The first three models are typically used for the unmined in-seam coal or rock material, while the last three are used for the broken rock or gob material left in the wake of full-extraction mining.

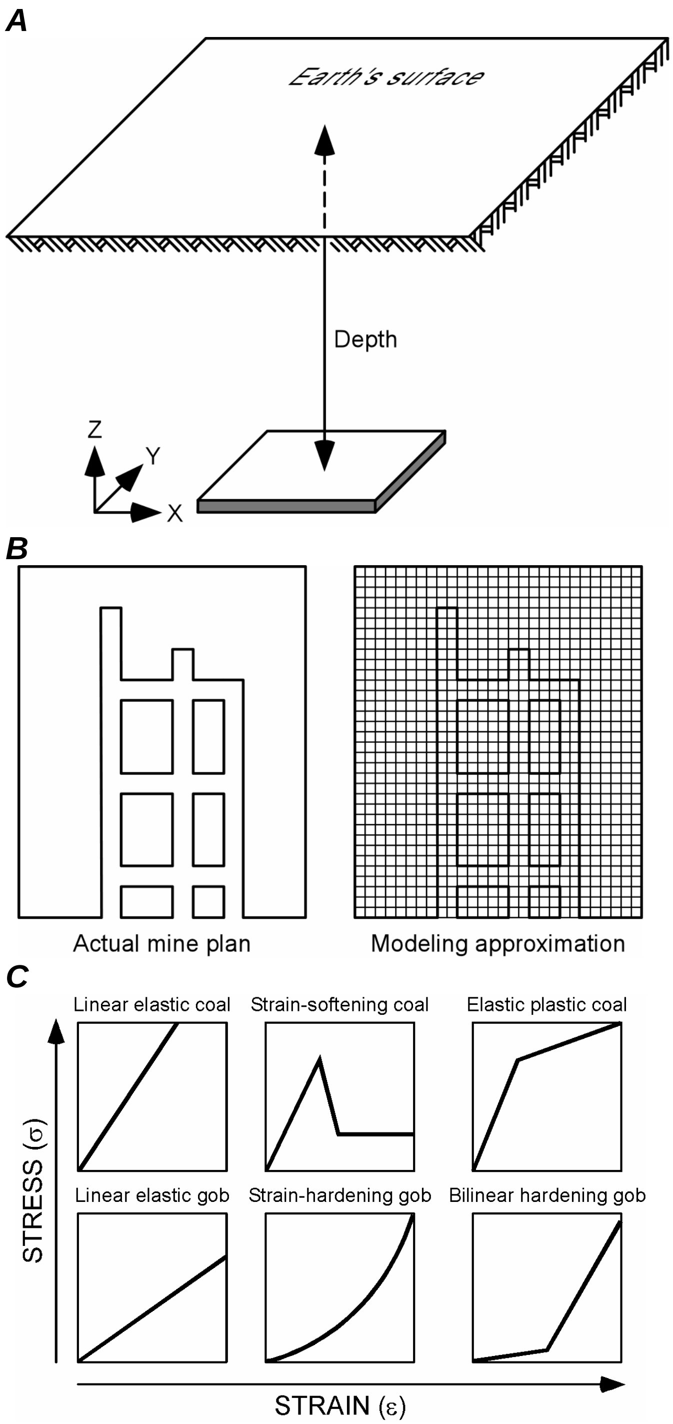

Figure 2. *A,* Boundary-element seam plane in surrounding rock mass; *B*, actual mine plan in-seam plane and grid of modeling approximation; *C*, six different stress-strain models available in MULSIM/NL.

In constructing a BE model similar to that shown in figure 2*B*, elements adjacent to an opening are assigned low strength properties. Progressively stronger properties are assigned to elements farther away from the opening to reflect increasing confinement. However, the elements do not truly confine each other. BE models of this type require knowledge of the nonlinear stress-strain behavior of the in-seam material. The stress path, and hence the failure path that a nonlinear in-seam material element will follow, is known a priori by virtue of the assigned material properties and through model construction. In other words, something is known about the stress and failure distribution away from the opening edges before the model is run. For coal mining, extensive field measurements of stress distributions and the stress path inside coal pillars are available. These observations have provided estimates of the nonlinear stress-strain relations required as input for the in-seam material elements of coal mine models. However, for the alluvium comprising the U1a complex, comparable observations and experience are unavailable.

The MULSIM/NL model of the U1a complex uses an elastic-plastic model for the in-seam material. In this material model, yield strength increases for elements farther from an opening. The next section describes development of these requisite stress-strain curves.

INPUT PARAMETER DEVELOPMENT–THREE-STEP METHOD

In the absence of extensive field measurements of deformation and stresses around the chambers, a method is described for using laboratory strength data and FLAC2D to develop MULSIM/NL input parameters. In the first step, an axisymmetric FLAC2D model with a simple Mohr-Coulomb failure criterion is used to approximate laboratory data. This FLAC2D model calculates the complete stress-strain curve for laboratory specimens at various confining pressures as measured with a stiff testing system. This model provides reliable estimates of the Mohr-Coulomb parameters cohesion (c) and friction angle (ϕ).

The second step uses these same Mohr-Coulomb parameters in another FLAC2D model of a tunnel in the alluvium at the U1a complex. By loading this tunnel model to stresses exceeding those expected in the field, information is obtained on the stress-strain response of the alluvium at various distances into the tunnel wall. In the third step, these calculated stress-strain responses become the basis for estimating the required stress-strain curves needed as input parameters to MULSIM/NL. This three-step procedure provides input parameters to MULSIM/NL that lead to the analyses of the U1a complex.

Friction Angle and Cohesion Estimates from Laboratory Data

Figure 3*A* shows all 21 complete stress-strain curves at various confining pressures as measured by TerraTek, Inc. (9). The laboratory data show the following general characteristics:

- Eight tests at 0 psi confinement exhibit strain-softening behavior with peak strength around 150 psi and residual strength of 100 psi or less at 2% strain.
- Three tests at 50 psi confinement also exhibit some strain-softening behavior; however, peak strength has increased to about 500 psi with a residual strength of about 300 psi.
- Four tests at 250 psi confinement are almost elastic-perfectly-plastic with a yield strength of about 1,000 psi.
- Five tests at 500 psi confinement show strain-hardening behavior with a yield strength of about 1,200 psi.
- One test at 750 psi confinement also shows strain-hardening behavior with a yield strength of about 1,100 psi.

Peak and residual strength data are extracted from these curves. Fitting a simple linear Mohr-Coulomb model to the data provided

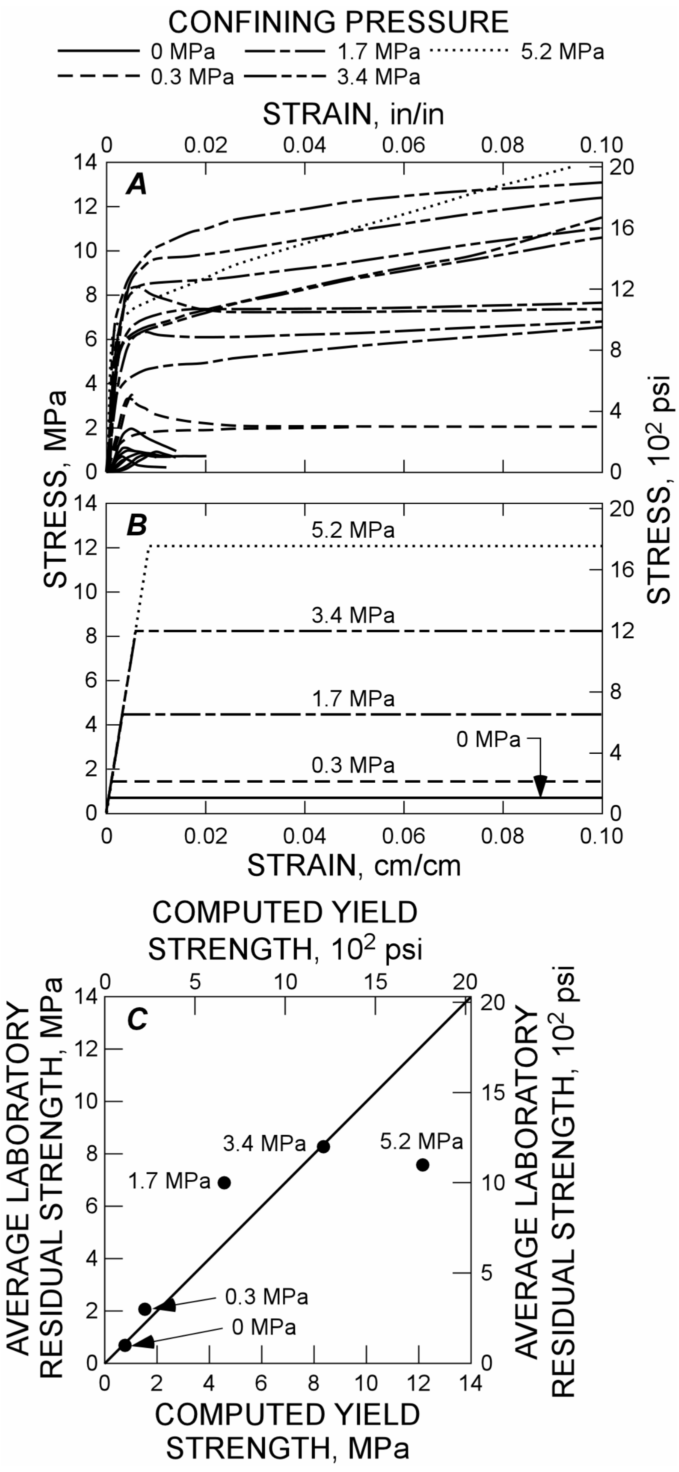

Figure 3. *A*, Complete stress-strain curves from laboratory tests at various confining pressures on U1a alluvium; *B*, stress-strain curves from FLAC2D models with friction angle of 22° and cohesion of 35 psi; *C*, measured versus computed yield strength.

Peak friction angle ϕ_p = 18.9° ≈ 19°.

Peak cohesion = 93.3 ≈ 90 psi.

Residual friction angle ϕ_r = 20.4° ≈ 20°. (The residual range is defined as post-yield.)

Residual cohesion = 64.3 ≈ 60 psi.

Correlation coefficients (R^2) for these curve-fitting exercises exceeded 0.8, which is good for geotechnical data. Note that the post-peak behavior of this alluvium is not typical of brittle rock.

Step 1 – Friction Angle and Cohesion Estimates from FLAC2D Model

An axisymmetric FLAC2D (*4*) model was developed using the laboratory data. Boundary conditions on the model are as follows:

- The left side is the line of axisymmetry.
- The right side is subject to the desired normal confinement pressure.
- The bottom edge is fixed in the vertical direction and free in the horizontal direction.
- The grid points along the top edge move downward with constant velocity of 4 × 10^{-6} in/sec. This downward velocity applies strain to the model at the rate of 10^{-6} strains per second. Thus, the FLAC2D model simulates testing in a perfectly stiff test frame.

Models were run at confining pressures of 0, 50, 250, 500, and 750 psi. Each FLAC2D model produced an elastic-perfectly-plastic stress-strain curve in which yield stress increased with confining pressure. In the numerical studies, friction angle and cohesion were varied systematically until the family of elastic-perfectly-plastic stress-strain curves approximated the laboratory data. Increasing cohesion tended to shift the family of curves upward as a group, whereas increasing friction angle tended to spread the curves apart.

The best fit of the laboratory data occurs with a friction angle of 22° and cohesion of 35 psi. This estimate compares favorably with the residual strength estimate for a friction angle of 20° and cohesion of 60 psi. Figure 3*B* shows this family of computed stress-strain curves. Computed yield strengths at confining pressures of 0, 50, 250, 500, and 750 psi were 100, 210, 650, 1,200, and 1,550 psi, respectively.

For the various confining pressures indicated, figure 3*C* compares the approximate average residual strength as determined from figure 3*A* to the computed yield strength as shown in figure 3*B*. The simple Mohr-Coulomb failure model used by FLAC2D reproduced the laboratory data at an acceptable level.

Step 2 - Stress-Strain Behavior of Tunnel Wall with FLAC2D Model

Excavation of an underground opening redistributes stresses in the rock around the opening. In a linear elastic material, the redistributed stresses are highest at the opening boundary and decrease further into the rock mass. The stress concentration at the excavation boundary typically exceeds the in situ stress by a factor of 2 to 3. The stress typically returns to the in situ condition about three excavation widths into the rock.

Depending on conditions, most rocks will fail or yield near the excavation boundary. At this facility, stress concentration into the tunnel wall deviated considerably from the ideal linear elastic case. Rock failure at the excavation boundary caused the stress concentration there to fall to zero. The vertical stress concentration then rose and reached a maximum some distance away from the excavation boundary before declining to the in situ value far into the rock mass. For nonlinear elastic rock that is failing, maximum stress concentration is normally less than the elastic case; however, the region of elevated stress concentration always extends much farther into the rock mass. That distance may exceed five or more opening widths. Such rock failure and the ensuing stress redistribution explains the so-called "load transfer" away from underground openings.

Use of MULSIM/NL and other similar stress analysis programs requires knowledge of the nonlinear elastic behavior of the failing rock mass surrounding an underground opening. Using the same material model as used in the laboratory data simulations, additional FLAC2D models examined the stress-strain behavior of a single tunnel in the alluvium at the U1a complex. The model consists of a 70- by 100- (or 7,000-) element array containing a tunnel 25 ft wide by 17 ft high, which is a typical size for many of the larger excavations at the U1a complex. Boundary conditions were as follows:

- Along the bottom edge, displacements were fixed in the y-direction.
- The left edge was a symmetry plane where displacements in the x-direction were fixed.
- The right edge was considered a remote boundary, and the x displacements were fixed there as well.
- The top edge of the model was subject to a constant downward displacement or velocity to load the model.
- Each element was a linear elastic material subject to a simple Mohr-Coulomb failure criterion.
- The tunnel models used a friction angle of 22° and cohesion of 35 psi as determined from prior FLAC2D models of the laboratory tests.

A constant downward velocity along the top edge loaded the model and provided a picture of the evolving stress and strain away from the tunnel wall. Figure 4 shows the vertical stress distribution in the vicinity of the tunnel at a stage when the applied vertical stress was over 1200 psi, which was much larger than the expected vertical stress. Vertical stress increased from zero and reached a maximum value of 1,800 psi about 80 ft (960 in) into the tunnel wall. Horizontal stress also increased from zero and reached a maximum of 750 psi about 100 ft (1,200 in) into the wall. Vertical stress and therefore yield strength of the alluvium increased nearly linearly at a rate of about 20 psi/ft into the tunnel wall for an opening 25 ft wide by 17 ft high.

The FLAC2D model of a single tunnel recorded average stress and strain within elements 0 to 5, 5 to 10, etc., up to 40 to 50 ft into the tunnel wall as the model was subjected to a constant downward displacement along the top edge. Figure 5 shows the computed stress-strain response of these 10 selected points. For a 25- by 17-ft opening, material at the tunnel edge yielded at about 125 psi and material 45 to 50 ft from the rib yielded at 1,100 psi.

Step 3 - Stress-Strain Curves for MULSIM/NL Input

The computed stress-strain responses shown in figure 5 are the basis for the stress-strain curves in figure 6, which were used as input to MULSIM/NL. Note that for materials A and B, the MULSIM/NL stress-strain curves are adjusted somewhat to better reflect the laboratory data, which exhibit strain-hardening at high confining pressure. In creating a MULSIM/NL model of the U1a complex, elements adjacent to an excavation boundary will follow stress-strain curve J, elements 5 to 10 ft from an excavation boundary will follow curve I, and so forth, to elements more than 45 ft from an excavation boundary, which will follow curve A.

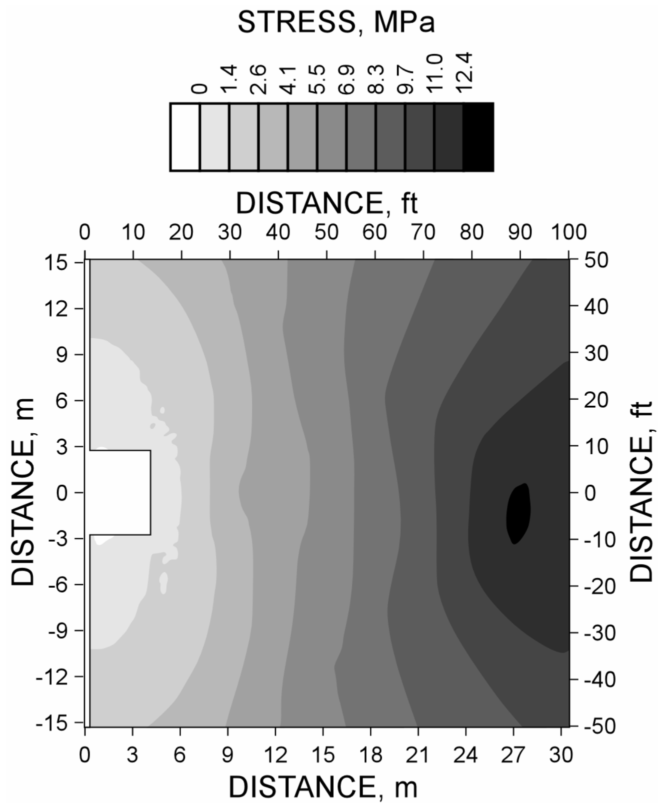

Figure 4. Vertical stress distribution in vicinity of tunnel 25 ft wide by 17 ft high when applied vertical stress equals 1200 psi.

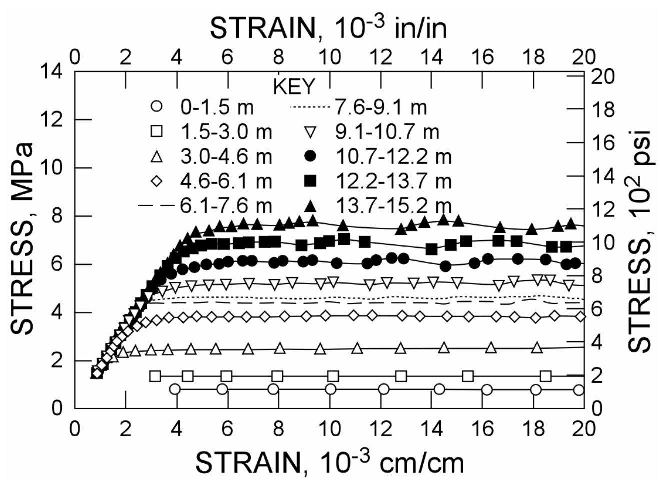

Figure 5. Computed stress-strain response into wall of 25- by 17-ft opening.

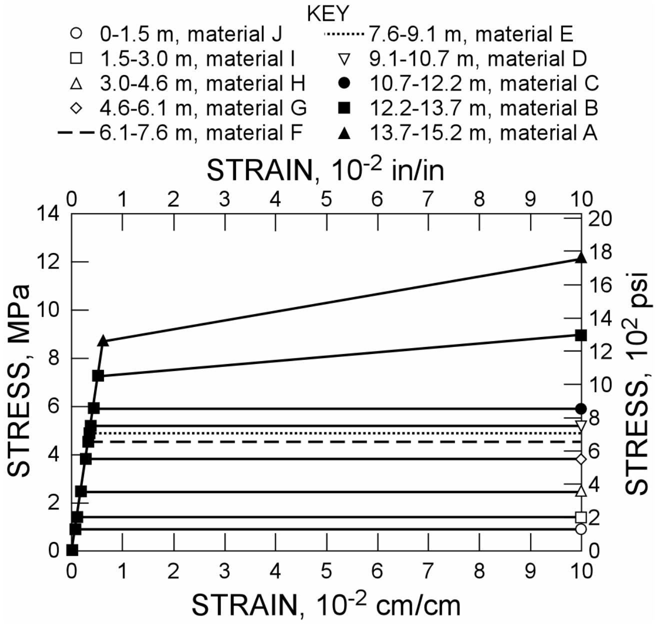

Figure 6. Ten nonlinear elastic-plastic stress-strain models for in-seam material used in MULSIM/NL models of U1a complex

CASE HISTORY - U1a COMPLEX MODEL CALIBRATION AND RESULTS

Ten-Step Model Up to Present

Table 1 summarizes the major input parameters used in the MULSIM/NL model of the U1a complex. The model uses a 5-ft element width and is centered along the U1a.01 drift near the vent drift. The fine mesh extends 240 elements north-south and 250 elements east-west, which is an area 1,200 by 1,250 ft. This fine-mesh grid adequately covers all the existing and proposed U1a complex drifts from south along U1a.01 to north beyond the proposed U1a.50 and U1a.200 drifts, and from west well beyond the U1a.03 drift and alcoves to east well beyond the U1a.104 drift and alcoves.

Table 1. Input parameter summary for MULSIM/NL model of U1a complex

Element width	5 ft
Model size	70-by-68 coarse mesh blocks 250-by-240 fine-mesh elements
Seam thickness	16 ft
Rock mass moduli	E = 200,000 psi, ν = 0.25
Vertical stress on-seam	800 psi
Number of in-seam materials	10 (A through J)

The first analysis involved 10 mining steps and simulated development of the U1a complex to its present state. Figure 7 (top) shows computed vertical stress and convergence as they evolved during mining. Note that the vertical stress scale always ranges from 0 to 1,500 psi and the convergence scale always ranges from 3 to 18 in. Calculated convergence includes a pre-excavation in situ component of about 1 in induced by an in situ stress of 800 psi.

The calculations shown in figure 7 (top) agree well with visually observed damage to the U1a workings. Ground control problems in the U1a.01, U1a.02, U1a.100, and vent drifts began to develop with excavation of the U1a.03 D crosscut, the U1a.105 drift, and the U1a.102 drift. The MULSIM/NL calculations showed that the new large excavations induced an additional 2 to 4 in of convergence on the existing support system, resulting in flaking of alluvium, cracking of shotcrete, and bagging of wire mesh. Elevated stresses developed in the pillars between the U1a.01 and U1a.05 drifts and the U1a.01 and U1a.102 drifts. However, elevated stresses in the interiors of pillars were not the cause of ground control problems at the U1a complex. More likely is that induced convergence on the support system in existing workings was caused by additional excavation nearby.

The MULSIM/NL models showed that 1 in of additional convergence correlated with the onset of visually observed damage to nearby drifts at the U1a facility. Most of the convergence occurred shortly after initial development and before the application of shotcrete. When a MULSIM/NL model predicts more than 1 in of additional convergence due to nearby mining, that area is likely to experience flaking ground and spalling shotcrete. In this case study, model areas with less than 1 in of additional convergence are not likely to have significant ground control problems.

Pressure cells installed in the tunnel wall along U1a.01 prior to mining the connection to the U1h shaft provided some information that supported the validity of the calculated stresses from MULSIM/NL and the model's input parameters. As shown in figure 8, MULSIM/NL predicted a maximum pressure increase of about 380 psi about 50 ft into the tunnel wall. Measurements indicated a maximum pressure increase of about 260 psi at a distance of 35 ft into the tunnel wall. Thus, the pressure cell data provided some confirmation of the stresses and pressure changes calculated by MULSIM/NL and the model's input parameters. The depth of the measured maximum pressure increase is less than that predicted by MULSIM/NL; therefore, the model is conservative in that it may predict load transfer over distances greater than what may actually be the case.

In summary, value of the MULSIM/NL model of the U1a complex was established by three considerations:

1. Good correlation between calculated additional convergence and visual observation of tunnel distress;
2. Similarity between the pressure arch resulting from minethrough of the U1a.01 drift as estimated by MULSIM/NL and as measured by hydraulic pressure cells, both of which are consistent with theory; and
3. Careful definition of input parameters.

Thus, the MULSIM/NL models can be used as a basis to compare the relative merits of alternate mine plans. Evaluation of alternative mine plans will use the additional convergence threshold criterion of 1 in.

Options Analysis for U1a.200 Drift

The calibrated MULSIM/NL model enabled analyses of two options for the U1a complex.

1. U1a.200 drift located south of the U1h shaft, and
2. U1a.200 drift located north of the U1h shaft.

In both options, the U1a.200 drift will extend east about 500 ft where it will join the U1a.104 drift. The analyses provided comparative stress and convergence data for a critical area of the

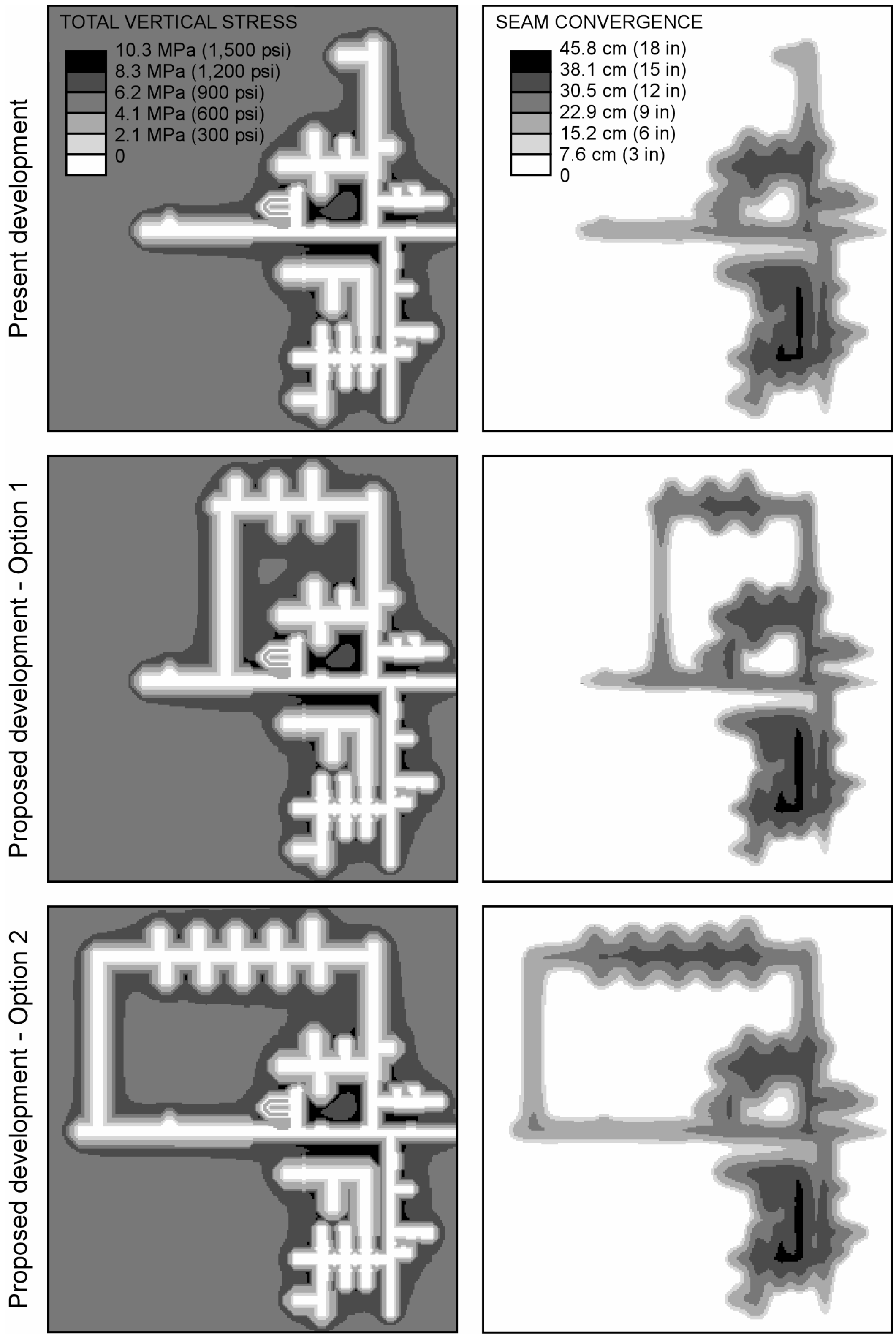

Figure 7. Comparison of computed vertical stress and convergence.

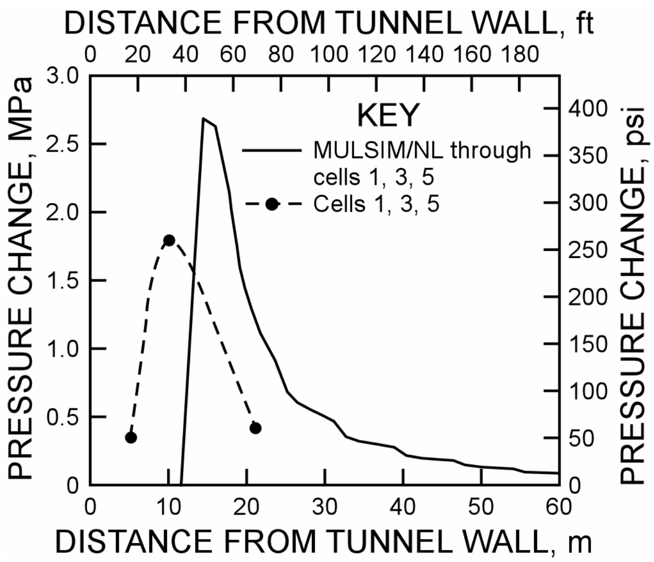

Figure 8. Comparison of measured pressure changes to predicted pressure changes with MULSIM/NL along U1a.01.

U1a complex that is near the user's alcove and vent drift area east of the U1a.01 drift. The critical question is whether constructing the U1a.200 drift south of the U1h shaft will have a significant adverse impact on the user's alcove, vent drift, or U1h shaft area.

Figure 7 (middle and bottom) shows computed stress and convergence for option 1 (south of the U1h shaft) and option 2 (north of the U1h shaft). Close examination of stresses in the vicinity of the user's alcove, vent drift, and U1h shaft areas shows that no appreciable differences exist between the two options. Slightly higher values are seen in the vent drift area, but no differences are discernable elsewhere.

For closer examination of the differences, figure 9*A* and 9*B* shows stress and convergence profiles looking east along a north-south section just east of the U1a.01 drift and passing through the pillar between the east and west user's alcoves. Figure 9*A* shows slightly higher stress (50 to 100 psi) for option 1 between the user's alcove and the U1a.200 drift. Stresses under both options are the same elsewhere, such as in the user's alcove pillar and between the vent drift and the U1a.100 drift. More importantly, figure 9*B* shows no appreciable difference in convergence. With option 1, convergence is greater than with option 2 by about 0.5 in. in the user's alcove, by about 0.3 in. in the user's alcove pillar, and by about 0.2 in. in the vent drift. The additional convergence above the base case associated with option 1 is less than 1 in (remember that the convergence threshold criterion is 1 in). In summary, the MULSIM/NL analysis shows that locating the U1a.200 drift south of the U1h shaft will not induce significant additional convergence and associated ground control problems in the user's alcove and vent drift area.

CONCLUSIONS

MULSIM/NL (*2, 3*) and related stress analysis programs such as LAMODEL (*5, 6*), MinSim 2000 (*7*), and EXAMINE^{TAB} (*8*) have become standard tools in the mining industry for analyzing stresses and displacement in coal mines, platinum mines, gold reefs, and tabular-type deposits. Early versions of these programs had linear elastic capability only. Zipf (*2, 3*) introduced a suite of six nonlinear material models that enabled realistic simulation of coal mines. MULSIM/NL and LAMODEL have been applied to a wide variety of longwall coal mines, room-and-pillar coal mines, trona mines, and underground stone mines.

These relatively simple numerical models can efficiently simulate yielding and failure of a rock mass near mine openings and subsequent stress transfer. The main input parameters for these models are nonlinear stress-strain curves for in-seam materials. Extensive field measurements and observations from many types of mines allow stress-strain curves to be calculated and numerical models to be calibrated. However, for many mines, such measurements are lacking.

A three-step method is presented to determine the nonlinear stress-strain curves for quasi-three-dimensional BE programs. The method requires a suite of laboratory-scale strength tests at various confining pressures. In the first step, FLAC2D is used to model the laboratory tests and determine cohesion (c) and friction angle (ϕ) for a Mohr-Coulomb material model. In the second step, another FLAC2D model uses the c and ϕ values to calculate vertical stress and strain around a single opening in the rock mass. This model calculates the stress-strain path of points at various distances from the opening boundary. In the third step, the stress-strain curves needed for a BE stress analysis are derived.

A case study demonstrated the practicality of this three-step method for determining input parameters for BE programs. The BE analyses shown in figure 7 (top) agreed well with failure observations at a test facility. The MULSIM/NL model showed clearly that extension of the U1a.03 D crosscut and development of the U1a.05 drift would lead to additional induced convergence of 1 in or more along the U1a.01 and U1a.02 drifts and the user's alcove and the vent drift areas. Unacceptable ground conditions at the U1a complex have occurred at these locations.

Subsequent analyses predicted the behavior of alternative layouts. From a geomechanics viewpoint, locating the U1a.200 drift south of the U1h shaft (option 1) is feasible. This location results in additional induced convergence of 0.9 inch in the user's alcove and vent drift area, which is less than the threshold of an acceptable additional induced convergence of 1 in. Option 2 results in additional induced convergence of about 0.5 in. in these critical areas. However, the expense that would be incurred with the additional excavation footage required for option 2 is not justified from a ground control perspective.

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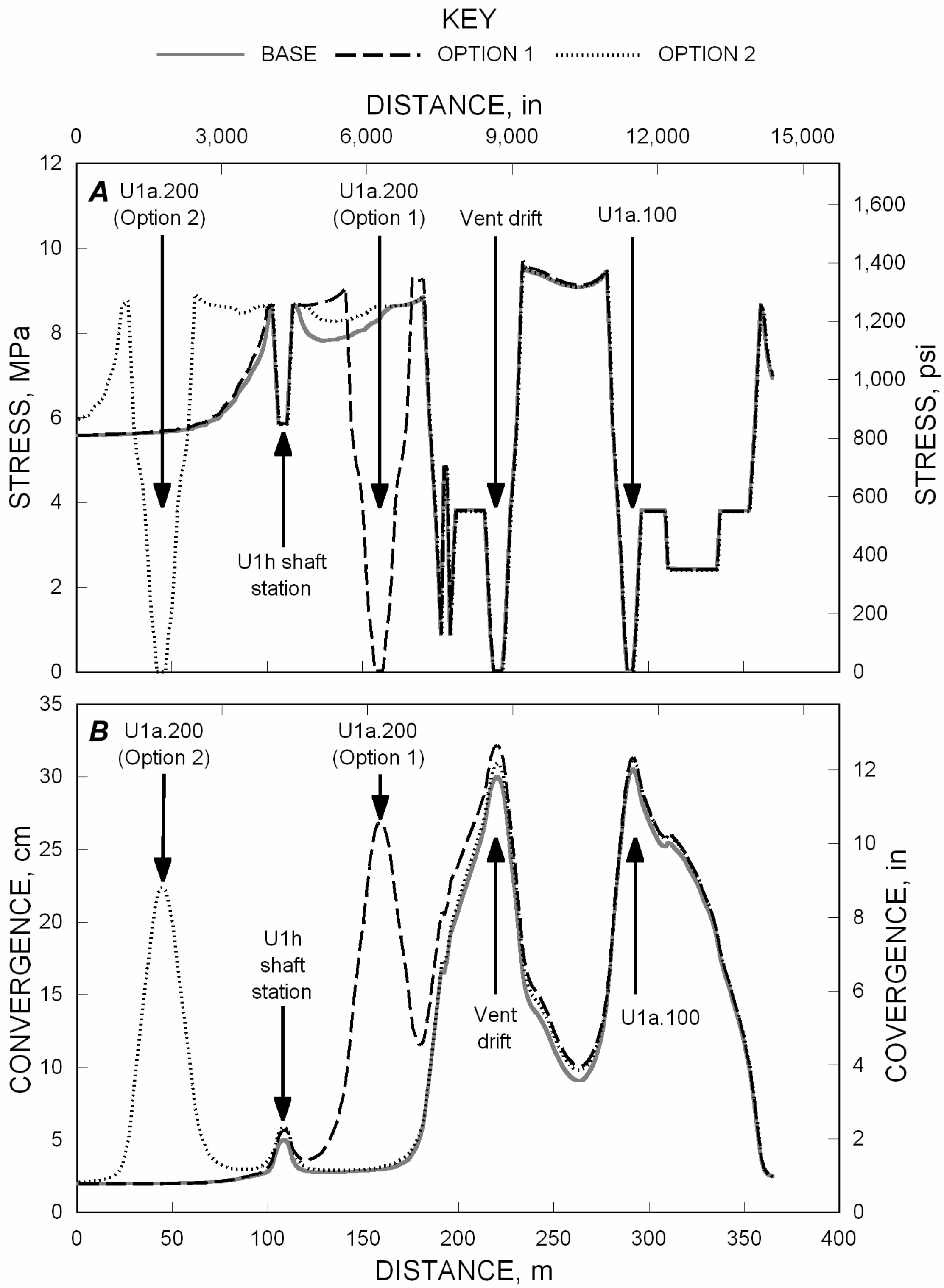

Figure 9. (*A*) Stress and (*B*) convergence profile parallel to U1a.01 drift and through user's alcove.

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