User-Friendly Finite Element Design of Main Entries, Barrier Pillars, and Bleeder Entries

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ABSTRACT

This contribution describes development and application of a user-friendly finite element program, UT3PC, to address three important problems in underground coal mine design: (1) safety of main entries, (2) barrier pillar size needed for entry protection, and (3) safety of bleeder entries during the advance of an adjacent longwall panel. While the finite element method is by far the most popular engineering design tool of the digital age, widespread use by the mining community has been impeded by the relatively high cost of and the need for lengthy specialized training in numerical methods. Implementation of UT3PC overcomes these impediments in three easy steps: First, a material properties file is prepared for the considered site. Next, mesh generation is automatic through an interactive process. A third and last step is simply execution of the program. Examples using data from several western coal mines illustrate the ease of using the application for analysis of main entries, barrier pillars, and bleeder entry safety.

INTRODUCTION

Rational design of safe underground entries and crosscuts, barrier pillars, and bleeder entries begins with a site-specific analysis of stress. An analysis of stress identifies the critical regions of high-stress concentration where yielding is likely and additional or more focused ground control measures are needed. This analysis also identifies regions where stress concentration is low, and risk mitigation is less urgent. Displacements induced by mining, including roof sag, floor heave, and pillar squeeze, are also of importance to stability. The popular finite element method is well-suited for such analysis and has been in use for studying coal mine engineering problems since the late 1960s (Dahl, 1969). The method has been taught in undergraduate engineering curricula for many years and offers an alternative to existing design procedures based mostly on rules of thumb, empirical methods based on mine data, and predigital-age concepts of strata mechanics. However, despite the versatility of the finite element method, usage has been limited, mainly because of the cost of the software and the required training in numerical methods.

The program UT3PC (Pariseau, 2017) has evolved from early two-dimensional versions in the era of mainframe computers. These early versions were still quite limited using only a few hundred elements that required overnight turnaround times. Recent versions of UT3PC are convenient and efficient desktop programs that use several million elements. With the advent of personal computers in the mid-1980s and subsequent increase in computer speed, expanded memory, and lower costs, applications for mining increased in three-way cooperative projects among industry, the former U.S. Bureau of Mines, and academia. The Spokane Research Center of the U.S. Bureau of Mines, in cooperation with the University of Utah, developed a two-dimensional desktop finite element program, UT2PC, available to the mining community in 1991. This was a short course offered at the 1991 SME Annual Meeting in Denver, CO.

Reliability of the finite element method in general and UT3PC in particular is demonstrated in a long history of mining applications. An original software application was to hard rock mine slope stability (Pariseau and Stout, 1972). Another first was an application to cut-and-fill mining in the famous Coeur d'Alene mining district of northern Idaho (Pariseau and Kealy, 1973). Applications to underground coal mining were subsequently addressed (Pariseau 1977; 1979).

Numerous additional applications to problems in hard-rock and soft-rock mining have been done (Pariseau and Eitani, 1981; Pariseau et al., 1984; Pariseau, Corp, and Poad, 1985; Pariseau, Johnson, and Orr, 1990; Pariseau, McCarter, and McKenzie, 2008; Pariseau, 2012; Pariseau, Tesarik, and Trancynger, 2013; Pariseau, 2013; 2014; 2015; Pariseau and McCarter, 2016). Direct, quantitative comparisons of mine measurements with computer output, mainly through regression analysis of computed measured displacements, often gave correlation coefficients greater than 0.8. Stress measurements using the Australian hollow inclusion cell and stress changes using vibrating wire gauges have also correlated well with finite element analysis of various mining sequences.

Concurrent advances in finite element technology and computer capabilities at greatly reduced costs have allowed advances in applications to ground control problems with increasing realism. Current technology allows for analysis of stress based on first principles of mechanics taking into account the effects of joint sets and the variability of strata properties in situ. Elaborate calibration studies that involve adjusting input strata properties until a fit to a few mine measurements is achieved are now largely unnecessary. In any case, the user must supply the requisite strata properties.

PROBLEM STATEMENT

Mine design for strata control and safety begins with first principles: physical laws, kinematics, and material laws. The equations that allow for computing stress, strain, and displacements are fundamental (Fung, 1965; Jaunzemis, 1967; Malvern, 1969). Numerical solutions of the governing system of equations are almost certainly required and in finite element form (Zienkiewicz and Cheung, 1967; Desai and Abel, 1972; Oden, 1972; Cook, 1974; Bathe, 1982).

Most rocks and soils respond elastically to an initial application of load, but the range of a purely elastic response is limited by strength of material. Indeed, strength of a material can be defined as the state of stress at the elastic limit. Any attempt to continue loading a material beyond the elastic limit induces yielding by fracture, flow, or a combination of both micro-mechanisms. The result, in any case, is plastic deformation. If flow or ductility is dominant, strain-hardening can occur with an increase in the yield point (strength) with further strain as illustrated in Figure 1. If fracture dominates, then strain-softening occurs with a decrease in the yield point (strength) with further strain. If neither strain hardening nor softening occurs, then the material response is ideally plastic. In a uniaxial compression test, the stress-strain plot rises, remains flat, or falls in case of work hardening, ideally plastic, or in strain softening, respectively. In three-dimensional analyses, an elastic zone generally contains yielding zones and thus constrains plastic components of strain to be of the same magnitude as the elastic part of strain. The total strain is still small or infinitesimal. In this regard, many materials fail in uniaxial stress at 0.1% to 1.0% strain. Squares of these strains are 10^{-6} and 10^{-4}, respectively, and thus are negligible. These failure strains are considered "small." "Large" or "finite" strain programs require much more elaborate, solid mechanics. Fortunately, many important practical problems in strata mechanics, including the three addressed here, fall within the small strain domain of material behavior.

In the elastic range, the stress-strain relations are a generalized Hooke's law. In matrix form for an anisotropic material

$$\{\varepsilon\}=[a]\{\sigma\} \text{ and } \{\sigma\}=[b]\{\varepsilon\} \tag{1}$$

where $[b]$ is the inverse of $[a]$. The 6x6 matrices $[a]$ and $[b]$ are symmetric, so there are, at most, 21 independent elastic constants in the most general case of anisotropy. An orthotropic material has nine independent elastic constants. Rocks with flow structures are often orthotropic. A transversely isotropic material has five independent elastic constants. Rocks that have a distinct layering or foliation may be transversely isotropic. Rocks that lack directional features are isotropic and have just two independent elastic constants, for example, Young's modulus and Poisson's ratio or Young's modulus and a shear modulus. Other property combinations are also possible in the isotropic case.

Hooke's law is only part of the stress-strain relations needed to describe material behavior beyond the elastic limit. First, the elastic limit must be defined, and then the computation of inelastic strains must be formulated. The elastic limit may be specified by a yield function or failure criterion, F, while the plastic part of strain may be computed using a plastic potential Y. Examples of failure criterion used in rock mechanics are the famous Mohr-Coulomb (MC) criterion, the popular Hoek-Brown (HB) criterion, and the well-known Drucker-Prager (DP) criterion. Nonlinear forms of MC (n-type) and DP (N-type) are almost sure to be required for rock over an extended range of stress. The subject of rock failure is a much discussed topic in the technical literature and is well beyond any detailed presentation here. However, some remarks are in order to complete the description of the stress-strain relations beyond the elastic range.

If one neglects complications caused by time- and rate-dependencies, heterogeneity, temperature dependency and so on, then failure may be described by an implicit function

$$F(\sigma_{xx},\ldots,\tau_{xy},\varepsilon^p_{xx},\ldots\gamma^p_{xy}) = 0 \tag{2a}$$

and if non-hardening or softening, then

$$F(\sigma_{xx},\ldots,\tau_{xy}) = 0 \tag{2b}$$

where superscript p in (2a) indicates a plastic component of strain.

When the intermediate principal stress effect is not negligible, then a nonlinear form of DP (N-type) may be used. In case of anisotropic strata, one has

$$J_2^{N/2} + I_1 - 1 = 0 \tag{3}$$

where

$$\begin{aligned} J_2 &= \{F(\sigma_{bb}-\sigma_{cc})^2 + G(\sigma_{cc}-\sigma_{aa})^2 + H(\sigma_{aa}-\sigma_{bb})^2 \\ &\quad + L(\tau_{bc})^2 + M(\tau_{ca})^2 + N(\tau_{ab})^2\} \\ \text{and } I_1 &= U\sigma_{aa} + V\sigma_{bb} + W\sigma_{cc} \end{aligned}$$

Here, the axes, a,b,c are the axes of anisotropy that may be skewed with respect to analysis coordinates x,y,z. The nine strength constants, F, G, etc., may be computed from unconfined compressive, tensile, and shear strength test data, although adjustments to excavations scales may be necessary to account for geological features, such as joints, that are absent in laboratory test specimens.

Beyond the elastic limit, total strains are composed of an elastic and plastic part. Thus, in differential form

$$\{d\varepsilon\} = \{d\varepsilon^e\} + \{d\varepsilon^p\} \tag{4a}$$

The elastic part is given by Hooke's law; the plastic part is obtained from a plastic potential. Thus

$$\{d\varepsilon\} = [a]\{d\sigma\} + \lambda\{\partial Y/\partial\sigma\} \tag{4b}$$

where the scalar function λ is subsequently eliminated from consideration and where the assumption of perfect plasticity is made. Differentiation of the plastic potential Y is with respect to each of the nine components of stress (neglecting symmetry of shear stress). The plastic part has a geometric interpretation. When the plastic potential is plotted in principal stress space, the plastic strain increment vector is parallel to the gradient of the plastic potential surface and is thus normal to this surface. After some algebra, the stress-strain relations beyond the elastic limit are

$$\{d\sigma\} = [E^e - E^p]\{d\varepsilon\} \tag{5}$$

where the $[E^e]$ is a matrix of elastic moduli and $[E^p]$ is a plastic "correction" that is nil below the elastic limit. In the case where the failure criterion and the plastic potential coincide, the plasticity is associated and the plastic strain increments are obtained by associated rules of flow or normality. The form (of equation 5), anisotropic or not, is the same in case of strain-hardening or softening and is needed for finite element calculations.

A local element safety factor concept defined as the ratio of strength to stress requires definitions of suitable measures of strengths and stress for analysis. Both arise in the context of stress-strain relations. Strength may be defined as stress at the elastic limit, so, in the case of the famous Mohr-Coulomb criterion, one has

$$fs = \frac{\tau_m(strength)}{\tau_m(stress)} \tag{6a}$$

which reduces to $f_s = C_o/\sigma_c$ in unconfined compression and to $f_s = T_o/\sigma_t$ in uniaxial tension where C_o and T_o are unconfined compressive and tensile strengths, respectively. In case of an N-type yield condition (5)

$$fs = \frac{J_2^{1/2}(strength)}{J_2^{1/2}(stress)} \tag{6b}$$

that also reduces to the unconfined compression and tension cases. Much useful design guidance is obtained in plots of element safety factor distributions.

RESULTS: MINE EXAMPLES

User-friendly finite element analysis proceeds in three simple steps:

Step 1 is specification of a materials properties file. A material properties file containing just one material is shown in Figure 2 where the material is isotropic.

NLYRS=number of layers in the stratigraphic column, NSEAM=layer number of the mined seam, 2.4e+06=Young's moduli in three directions, 0.15=Poisson's ratio associated with three material directions, 1.0e+06=shear moduli in three directions, 158.0=specific weight in the vertical direction, 12000=unconfined compressive strengths, 1000=tensile strength, 2000=shear strength, 0.0=orientation angle, 0.0=depth to top of layer (*dpth*), 75.0=layer thickness. Units are pounds per square inch, pounds per cubic foot, and feet. Full details concerning the materials properties file are given in a user's manual.

Step 2 involves mesh generation that is done interactively. After typing in the name of the material properties file, requests for the number of entries follows. Additional information concerning widths of entries and crosscuts, as well as pillar widths and lengths, is typed in response to the screen request. Figure 3 illustrates the nomenclature used in mesh generation.

The mesh generator computes all the files needed for a finite element run, including an output file that serves as an input file for a run. An example is shown in Figure 4. There are 556,114 elements in this example. A nominal limit of one million elements is implied. The italics are explanatory and are not part of the file. To be sure, elements are three-dimensional and brick-shaped.

An initial stress field caused by strata weight is computed during mesh generation. However, an opportunity to modify the initial stress field is also presented during mesh generation. If high horizontal stresses exist, then the gravity stress field can be changed accordingly by addition of horizontal stress. In fact, any initial stress field can be obtained using the additional feature of the mesh generator.

Plotting meshes is an essential practice to allow for error checking and to allow for re-generation should a first mesh be considered inadequate. In this regard, mesh generation allows for specification of element size, although element aspect ratios are constrained to two (ratio of largest to smallest element dimension). This feature allows one to generate a relatively coarse mesh with few elements or a refined mesh with many elements. Again, details are given in a user's manual.

Step 3 is simplicity itself. All that is necessary is to click on the executable finite element program file and then type the name of the runstream file.

Main Entries

Step 1. The material properties for this example (Mine A) are given in Figure 5. The stratigraphic column is shown in Figure 6. Inspection of Figure 5 shows the mining depth to be 1,072 ft (322 m), indicated by the parameter *dpth* in the properties for Hiawatha Coal. This mine is in the Wasatch Plateau coal field in central Utah.

Figure 7 shows a layout of five main entries. Solid coal exists to the left-hand and right-hand sides of the mains. The dotted lines are lines of symmetry in a long run of entries. Symmetry greatly reduces the number of elements needed in a mesh.

Step 2. The generated mesh is illustrated in Figures 8 and 9 for an eight-entry problem where the number of elements in the mesh is 556,114. The mesh generation output file resembles the finite element input file.

Figures 8 and 9 are plan and vertical section views of a mesh for the mains problem. The plots are obtained from output of the mesh generator. In this example, eight main entries were specified. These entries were spaced on 80-ft (24.4-m) centers. Crosscuts were spaced on 100-ft (30.0-m) centers. The mesh extends 580 ft (177 m) above and below the seam—a distance equal to the rib-to-rib width of the main entry set. Width of the mesh is equal to the width of the main entry set (580 ft (177 m)). The geometry of the main entries, crosscuts, and pillars are specified during mesh generation. Mesh extent is computed automatically in each case.

Step 3. Practical results of the finite element analysis are given in safety factor distributions. Such distributions show where safety is threatened by the presence of yielding elements with a safety factor of one and also by elements with safety factors near one. Figure 10 shows element safety factor distributions involving eight main entries according to equation 6b. As a reminder, entries and crosscuts are 20 ft (7-m) wide; mining height is 10 ft (3 m); pillars are 60 ft (18-m) wide and 80 ft (24-m) long. Because there is an even number of main entries, a vertical plane of symmetry passes through a pillar center, and only four entries are in the figure. Width of the half mains is 290 ft (87 m); width of the unmined coal to the left is also 290 ft (87 m). Total width is 580 ft (174 m). The mesh extends 580 ft (174 m) above and below the bottom of the coal seam of interest. However, the vertical extent shown in the figure is reduced for better detail at seam level. Seam height is 10 ft (3 m).

Element yielding is confined to thin regions at pillar walls. Safety factors increase rapidly with distance into the solid coal to *fs*=4 as seen in the green color in the pillar cores and to *fs*=5 farther into the solid coal on the left-hand side of the figure. Roof and floor safety factors are high, into blue and white, where *fs*>7. Safety factors above and below pillars are also high. Overall, the results indicate a safe, stable set of main entries where coal is mined at full seam height at a depth of 1,072 ft (321 m).

Barrier Pillars

A second example is an underground coal mine (Mine B) in the western United States but otherwise remains unidentified. There are just three main entries in this barrier pillar problem.

Step 1. The problem input for barrier mesh generation has 32 layers in the geologic column; the 11th layer is the mined coal seam 11 ft (3.3-m) thick at a depth of 2,250 ft (675 m). The order of strata is from the top down. As a reminder, the last line of each stratum properties set gives orientation angle, depth to the stratum top, and stratum thickness. Entries are aligned with the y-axis, so the orientation angle is zero. Depth to the top of the second stratum is simply the thickness of the first stratum. Entries and crosscuts are 20 ft (6-m) wide. Pillars are 170x180 ft (51x54 m). Barrier pillar width is 300 ft (90 m).

Step 2. The generated mesh is shown in Figure 11. There are 1,514,136 elements, which exceeds the 1-million-element limitation and will produce a relatively longer run time. The element aspect ratio is two. The mined panel to the left of the barrier pillar is twice the width of the barrier pillar. Hence, the mesh is 1,100 ft wide (330 m). Mesh height is 810 ft (243 m).

Step 3. Figure 12 shows a plan view of element safety factor distributions in this mine involving three main entries defended by a barrier pillar. Figure 13 shows element safety factor distribution in vertical section. Both indicate that the 300-ft-wide (90-m) barrier pillar is inadequate for defending against high stress imposed by longwall panel mining outside the barrier pillar. This inference is made in noting that more than half the barrier pillar is yielding (black), and the remainder is close to failure with a safety factor of 1.1 with the entry rib at failure. The entry pillar shows some failure near the entry crosscut intersection and shows low safety factors well into the pillar wall adjacent to the entry. Run time for this problem was 12-1/2 hrs.

Figure 13 confirms the inferences made from the seam level plan view distribution of element safety factors. Extensive yielding is present above and below the longwall panel to the left of the barrier pillar. The floor contact of the barrier pillar is also a yielding zone. Interestingly, a large yield zone exists in the upper right-hand side of the plot. This large black zone is associated with strata flexure and failure in horizontal tension.

Figure 14 is a close-up view of element safety factors about the entry (grey) adjacent to the barrier pillar. The asymmetry of the distribution caused by mining a longwall panel to the left is clearly evident. Loading of the entry tends to be diagonal in the sense that a high compressive force acts across the entry (black to black), while unloading tends to occur at right angles (green to green). One concludes that the barrier pillar is inadequate for entry protection.

Bleeder Entries

A third example problem involves bleeder entry safety. A longwall panel advances away from the bleeder entries illustrates the processes of mesh generation and finite element analysis for this problem type. As a reminder, bleeder entries are for ventilation and safety; they provide a secondary escapeway from the mine. By law, bleeder entries must be maintained in a passable condition. This mine is an underground coal mine in the western United States (also Mine B). There are three main entries in this bleeder entry mine problem.

Step 1. The problem input for bleeder entries mesh generation is lengthy. There are 26 layers in the geologic column; the 10th layer is the mined coal seam 11 ft (3.3-m) thick at a depth of 2,250 ft (675 m). The thinnest layer is 4 ft (1.2-m) thick. Order of strata is from the top down. As a reminder, the last line of each stratum properties set gives the orientation, depth to the stratum top, and stratum thickness. Depth to the top of the second stratum is simply the thickness of the first stratum. Entries and crosscuts are 20 ft (6-m) wide. Pillars are 73x180 ft (22x54 m).

Step 2. The generated mesh is shown in Figure 15. There is a relatively small total number of elements in the mesh (188,748). The element aspect ratio is two. The mesh is 824 ft (247-m) wide and 100 ft (30-m) long. Mesh height is 927 ft (278 m).

Step 3. Run time for this mesh was 1-1/2 hrs. Plan and vertical section views of the distribution of element safety factors are shown in Figure 16. Element boundaries are shown. The plan view in the figure indicates yielding entry pillar ribs and pillar cores with low safety factors (*fs*<1.3). Indeed, the pillar adjacent to the longwall panel is yielding to the core. Entry ribs also show some yielding. The result is conservative because the panel is fully excavated—currently there is no gob model in UT3PC.

In vertical section, large zones of yielding extend above and below the longwall panel mined to the right. A large zone of yielding also extends above the left abutment of the panel and far into the roof where an abrupt termination of the yield zone occurs. Abrupt changes in contours are caused by abrupt changes in strata properties that indirectly reveal stratigraphy. Floor yielding below the abutment corner is also indicated in vertical section. Low pillar safety factors are again indicated in vertical section where entry corners are yielding and threaten roof and floor safety.

A close-up vertical section in Figure 17 reveals more clearly the details of element safety factor distribution about the bleeder entries. Yielding is evident at entry ribs and corners where some yielding extends into the roof and floor. A suggestion of diagonal loading is present that is caused by mining the adjacent longwall panel. Pillars are under high stress, as indicated by low safety factors in the pillar cores. The large yielding zone (black) that extends back over the abutment pillar threatens to extend retrograde over the bleeder entries in consideration of the large expanse of low safety factors over the entry adjacent to the abutment pillar.

The evidence from the finite element analysis in the form of safety factor distributions at seam level and in vertical section indicates the bleeder entries are marginally safe at best and likely to require considerable maintenance. Although the bleeder entry mesh is relatively coarse, the lesson learned from a coarse mesh - fine mesh comparison is that the conclusions would be similar if a finer mesh were used. Figure 18 is a vertical section showing element safety factors from a mesh containing over three million elements that required two-days run time. Element density would obscure the view, so element borders are removed in the figure. The similarity to Figure 17 is evident, indicating the conclusion about bleeder entry safety would be much the same.

CONCLUSION

Improved safety of underground coal mine openings follows from better informed design decisions enabled by improved tools for engineering analysis. Using a design tool based on fundamental engineering principles is especially important in new geological settings and as mining methods evolve in new coal basins and at depths beyond past situations where empirical data no longer apply. The popular finite element method is well suited for use in the design of safe, stable mine openings. This method is a significant advance over simple rules of thumb and predigital-age empirical methods. However, general purpose software is costly and requires extensive training by potential users. The UT3PC program is a user-friendly, publicly available finite element program developed especially for coal mine design. The program allows for analysis of main entry safety, safety provided by barrier pillars, and bleeder entry safety in three easy steps including automatic, interactive mesh generation. A user's manual accompanies the program, and a graphic plotting capability is under development. Applications were made to three underground coal mines in the western United States. Distributions of element safety factors were particularly useful in providing guidance to safe design. UT3PC thus promises to be a reliable alternative and cost-effective approach to mine design. The software is expected to become available after review is completed.

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of any company or product does not constitute endorsement by NIOSH.

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