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USER-FRIENDLY FINITE ELEMENT ANALYSIS OF FIVE MINE DESIGN PROBLEMS

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ABSTRACT

Five important mine design problems are addressed by a user-friendly finite element package. Analyses of: (i) main entries, (ii) barrier pillars defending "mains", (iii) bleeder entries, and (iv) interpanel barrier pillars, all in longwall mining, and also (v) safety of rooms and pillars in room and pillar mining are readily accomplished. Distributions of stresses, displacements and local safety factors are obtained in three simple steps: (1) preparation of a strata properties file, (2) automatic, interactive mesh generation and (3) execution of a finite element program. The last is a simple "double-click"; the second is easy, while the first step is the most difficult because the elastic moduli and strengths of strata above and below the mining horizon must be known. A website http://ut3pc.net/ makes the UT3PC software and a User Manual available at no cost. Examples from coal, trona and other mines illustrate applications and results in extension of previous work (Pariseau, et al 2017).

INTRODUCTION

Safe, stable excavations are essential to profitability in the business of mining. Surface mines require stable slopes, neither too flat nor too steep. Underground mines require stable shafts, winzes, raises, drifts and crosscuts that are the lifelines to the underground. In strata-bound soft rock mines such as coal, trona, salt and potash and in hardrock mines in strata-bound lead-zinc, silver-copper deposits, entries, crosscuts, and pillars must be safe and stable by design. Safety is obtained mainly by natural support provided by the rock mass, usually with the aid of artificial support and reinforcement which are often necessary to ensure control of excavation roofs and pillar walls by preventing falls of roof rock and pillar spalls and by preventing raveling from progressing to extensive caved ground. Floor heave is also a serious challenge but is also subject to control by design.

While empirical and semi-empirical methods may be of some assistance in mine design, there is no substitute for rational design based on the fundamentals of a proper analysis of stress. For example, the semi-empirical tributary area method of pillar design is a helpful beginning of rational design. Introducing a requirement for equilibrium of forces in the vertical direction in case of pillars in flat seams is certainly a valid first step. However, the analysis is based on average vertical stress and in essence treats a full-scale mine pillar as if it were a uniaxial test specimen in the laboratory. Stress concentration at the pillar walls and the potential for spalling and progressive failure are not taken into account. Nor is the increase in horizontal confining pressure from pillar walls to the pillar core recognized. So called size effects formulas whether based on laboratory test data or statistical theory obscure the real design problem. There is simply no substitute for a proper engineering analysis of stress.

Advances in numerical methods of stress analysis and reduction in computer costs have brought stress analysis into easy reach of engineers with the appropriate training, computer hardware and software. The well-known finite element method (FEM) is perhaps the most popular method of analysis. Indeed, FEM has been in use in the mining industry since the early 1970's in application to ground control problems. The method is based on fundamentals: physical laws, kinematics, and material laws in the form of stress equations of equilibrium, strain displacement relations, and stress strain laws. Principles of the method have been taught at the undergraduate level for many years. However, an experienced user with advanced training is required for application of commercially available general purpose computer codes such Abaqus, Elfin, and FLAC which have numerous options and selections to be made during an application.

The user-friendly finite element code UT3PC overcomes training and availability obstacles and brings into easy reach five important strata-bound mine design problems: (i) safety of main entries, (ii) barrier pillar size needed for main entry safety in case of longwall mining, (iii) safety of bleeder entries associated with longwall mining, (iv) interpanel barrier pillar safety for longwall mining, and (v) pillar safety in room and pillar mining. Emphasis is on (iv) and (v); (i), (ii) and (iii) are discussed in detail by Pariseau, et al (2017). In brief, the material model is an anisotropic elastic-plastic model that combines a generalized Hooke's law with a non-linear yield criterion. The yield criterion takes into account all three principal stresses. Intact rock elastic moduli and strengths in combination with joint stiffnesses and strengths define strata properties. Initial response to load is purely elastic and may subsequently be elastic-plastic if the elastic limit is reached and loading is continued.

PROBLEM ANALYSIS

Three simple steps are all that are needed for problem analysis: (1) preparation of a strata properties file, (2) generation of a finite element mesh, and (3) execution of the finite element model. Output information that aids in design for safety and stability includes: (1) a file containing element stresses, (2) a file containing node displacements, and (3) a file containing element safety factors. Output file details are described in a User Manual.

1 Strata Properties

An example of a strata properties file is shown in abbreviated form in Figure 1. Each stratum has a name, elastic moduli, strengths, specific weights, orientation angle, depth and thickness. Strata may be isotropic, transversely isotropic or orthotropic with three mutually orthogonal axes of anisotropy, for example, down dip, on strike and normal to the plane of dip ("foliation"). An orthotropic stratum requires nine independent elastic constants and nine independent strength constants. Transverse isotropy requires five independent constants of elasticity and five for strength. Isotropy requires just two independent elastic constants, such as Young's modulus and Poisson's ratio and just two strength constants such as unconfined compressive and shear strengths.

Preparation of the material properties file is the most challenging task for the design engineer. The reason is the need to characterize strata at a meter scale of excavation in contrast to intact rock properties at a centimeter scale of laboratory test cylinders. Joints certainly influence strata response to excavation. Thus, strata properties are composite properties of joints and intact rock between joints. These properties are often determined by "scaling," that is, by adjusting input properties until a reasonable fit to mine measurements is obtained or by invoking a scaling law of some type. Another approach is through equivalent properties models which combine joint and rock properties into an equivalent material. This material responds to load on average in the same manner as the original jointed material.

An advantage of this latter approach is avoidance of the circularity of scaling by fitting analysis output displacements to measured displacements.

```
NLYRS = 9
NSEAM = 7
1 North Horn N=2
2.60E+06  2.60E+06  2.60E+06  0.26      0.26      0.26
1.75E+06  1.75E+06  1.75E+06  0.0       0.0  155.0
11803     11803     11803     696       696       696
1655      1655      1655
0         0         951
…
3 CASTLEGATE SANDSTONE
3.00E+06  3.00E+06  3.00E+06  0.22      0.22      0.22
1.92E+06  1.92E+06  1.92E+06  0.0       0.0       140.0
9585      9585      9585      435       435       435
1179      1179      1179
0         1499      568
…
6 ROOF SANDSTONE
3.39E+06  3.39E+06  3.39E+06  0.26      0.26      0.26
2.29E+06  2.29E+06  2.29E+06  0.0       0.0       140.0
14500     14500     14500     1088      1088      1088
2293      2293      2293
0         2549      158
7 COAL
4.06E+05  4.06E+05  4.06E+05  0.12      0.12      0.12
2.31E+05  2.31E+05  2.31E+05  0.0       0.0       78.0
4133      4133      4133      276       276       276
616       616       616
0         2707      11
…
9 MANCOS SHALE
2.20E+06  2.20E+06  2.20E+06  0.35      0.35      0.35
1.70E+06  1.70E+06  1.70E+06  0.0       0.0       145.0
10295     10295     10295     158       158       158
736       736       736
0         2927      73
```

Figure 1. Strata properties file in brief. NLYRS=number of strata, NSEAM=stratum; mined,1=stratum name; 3 Young's moduli, 3 Poisson's ratios; 3 shear moduli, specific weight components; 3 unconfined compressive strengths, 3 tensile strengths; 3 shear moduli; orientation angle (azimuth), depth to top of stratum, thickness.

2 Mesh Generation

Mesh generation is the second step. A double-click on an executable mesh generation file begins the process with a list of the five problems written to the screen and a request for selection by number. If the selected problem is the one of interest, then the next request is to enter the material properties file name. If the file is found, then the process proceeds with requests for entry and crosscut dimensions and so on. Pauses are present in the process which allow for changes because of a typing mistake without having to restart from the beginning, although that is always possible. All files necessary for the next and last step of finite element analysis are generated including a runstream file that may be edited. An example of a runstream file produced by the mesh generator is shown in Figure 2.

runstream title	inter = 100
matdoe1.txt	maxit = 1000
belms	nyeld = 2
bcrds	nelcf = 1832
brcte	nsol = 0
bsigi	mgob = 1
bnsps	error= 1.0000
bp1	orf = 1.8600
nelem = 379600	xfac = 12.0000
nnode = 413658	yfac = 12.0000
nspec = 65658	zfac = 12.0000
nmat = 15	efac = 1.0000
ncut = -1	cfac = 1.0000
ninc = 5	torl% = 0.0100
nisgo = 1	ENDRUN

Figure 2. An example finite element runstream file produced by mesh generation. All file names and numbers are explained in a User Manual.

As a practical matter, plotting a generated mesh before taking the next and last step is suggested. A plot allows for an easy visual check on the model. If a mistake has been made or if a change is desired, such can be addressed before spending time on an analysis proper.

3 Program Execution

This is the easiest step of the three and requires just a double-click on the executable file containing the finite element program (UT3PC). Upon execution, a request written to the screen will ask for the runstream file name. Execution proper begins after entering the runstream file name. Information pertaining to the analysis is written to the screen from time to time as explained in the User Manual. Run time varies mainly with problem size, but also with the computer (a 64-bit machine is needed). Several hours are usually necessary to complete a relatively small problem, say, one with less than 350,000 elements. Overnight turnaround time, say, more than eight hours, may be necessary for problems with 1,000,000 elements or more (but less than 2,000,000).

PROBLEM EXAMPLES

The expanded offering of problems to five from three now includes interpanel barrier pillar safety in longwall mining and safety of pillars and rooms in room and pillar mining.

Interpanel Barrier Pillar Safety

This example is from a deep, underground coal mine in central Utah which is no longer operating (Pariseau et al 2008). The stratigraphic column is shown in part in Figure 3. The full column with strata properties (step 1) is omitted for brevity but is similar to the file shown in Figure 1. This file is the input strata properties file required for mesh generation (step 2). Figure 4 is one of the mesh generation output files, InData. The second mesh generation output file is similar to the file shown in Figure 2. The InData file tracks input parameters such as entry width WE and so on. The RunStrm file is used as the input file for a finite element analysis after editing such as the file name and output file prefix bp1. A detailed explanation of the RunStrm file parameters is given in a User Manual.

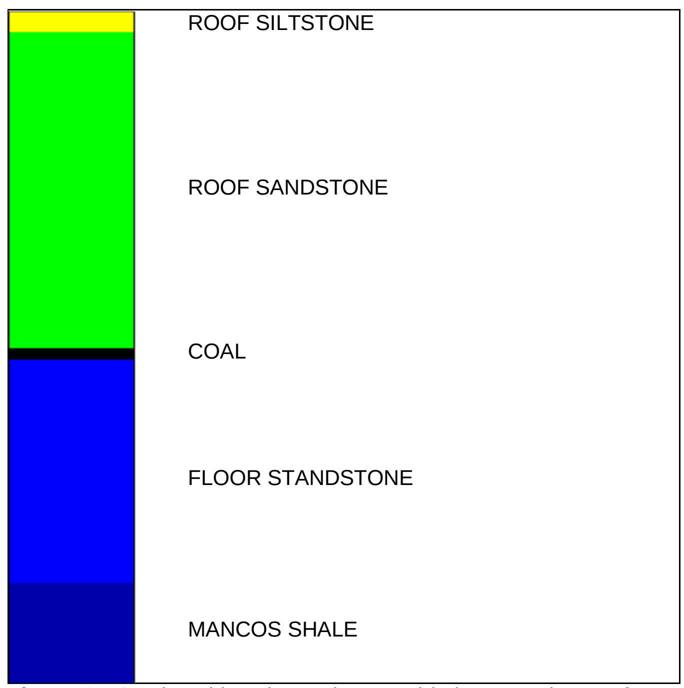
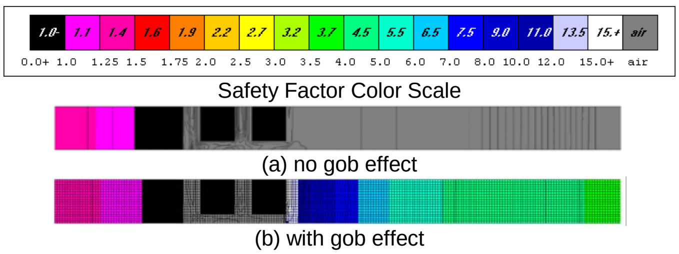


Figure 3. Stratigraphic column above and below a coal seam for an interpanel barrier pillar analysis of a deep coal mine in central Utah. The coal seam is 3.3 m (11 ft) thick. Top of the coal seam is 825 m (2,707 ft) below ground surface.

Output files of element stresses, node displacements and element safety factors are produced during finite element program execution (step 3). An element safety factor is simply a ratio of "strength" to "stress", that is, *fs=strength/stress* where appropriate measures of strength and stress are used in the three-dimensional finite element analysis. Again, details are given in a User Manual that has two examples of each of five mine design problems. Figure 5 shows the distribution of element safety factors in plan view at seam level, without and with the effects of gob formation in the mined panel. Grey elements are excavated entries, crosscuts and panel elements. Black elements are yielding! In this example both panel entry pillars are yielding. Yielding (black) also extends into the interpanel barrier pillar. Figure 6 shows element safety factors in vertical section where, again, pillars are yielding as are roof and floor elements about the longwall panel. Flexure over the interpanel barrier pillar also induces yielding above the barrier. Run time for this analysis was approximately 10-1/2 hours.

Input Data
INTERPANEL
Number of panel entries, NES = 3
Width of entries, WE (ft) = 20.0
Width of crosscuts, WC (ft) = 20.0
Width of pillars, WP (ft) = 40.0
Length of pillars, LP (ft) = 80.0
Longwall panel width, LPW (ft) = 750.0
Interpanel Barrier pillar width WBR (ft) = 300.0
EX, EY, EZ, (ft)= 3.0 3.0 3.0
Additional Sxx,Syy,Szz,Tyz,Tzx,Txy, tension +=
0.0 0.0 0.0 0.0 0.0 0.0
No gob effects

Figure 4. An InData file from mesh generation of an interpanel barrier pillar problem.



Safety Factor Color Scale

(a) no gob effect

(b) with gob effect

Figure 5. Element safety factor distribution in plan view of the interpanel barrier pillar.

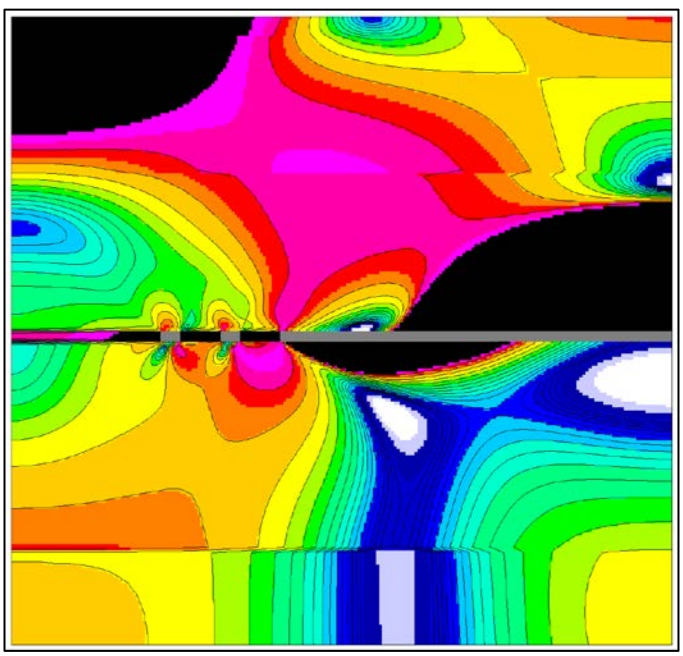


Figure 6. Element safety factor distribution on a long section of the interpanel barrier pillar. Sudden changes in contour directions are a consequence of stratigraphic changes. The seam (gray) is 3.3 m (11 ft) thick.

A non-linear gob model is an option in this problem type. Effects of gob are shown in Figure 5b which indicates a reduction in the extent of yielding of the interpanel barrier pillar on the left-hand side. The gob safety factor decreases away from the panel pillar towards the center of the longwall panel face on the right-hand side.

Ground control difficulties led to closure of this deep coal mine operation and also to a question of whether interpanel mine design is practical, not only from the engineering perspective of ground control, but also from the conservation perspective of resource recovery. Simply making pillars wider does not make pillars "safer." Attention to rib control, possibly bolting and screening, may be a feasible design alternative. Detailed design study and field trials would be needed for proof of concept, of course.

Room and Pillar Safety

This example is from an underground lead-zinc mine in southeast Missouri.(Pariseau et al 1995). The stratigraphic column is shown in abbreviated form in Figure 7 (step 1). Figure 8 is a mesh generation (step 2) output file, InData.

Figure 7 Stratigraphic column for a room-and-pillar problem near the mine level.

Input Data
PILLARS
Width of entries, WE (ft) = 20.0
Width of crosscuts, WC (ft)= 30.0
Width of pillars, WP (ft) = 40.0
Length of pillars, LP (ft) = 50.0
Height of pillars, HP (ft) = 30.0
EX, EY, EZ, (ft)= 2.0 2.0 2.0
Additional Sxx,Syy,Szz,Tyz,Tzx,Txy, tension +=
0.0 0.0 0.0 0.0 0.0 0.0

Figure 8. An InData file from mesh generation in case of room and pillar mining.

Figure 9 shows the distribution of element safety factors in vertical section and in plan view at seam level (step 3). Element boundaries are also shown in the figure. Grey elements are excavated entries, crosscuts, and panel elements. No yielding is evident in this example, although the pillar corner is "hot" with a red color indicating an element safety factor of approximately 1.5. The pillar core shows green, indicating a safety factor of approximately 4.5. These results suggest an increase in extraction may be feasible. Further analysis with varying entry, crosscut, and pillar dimensions would aide in establishing a new mining plan.

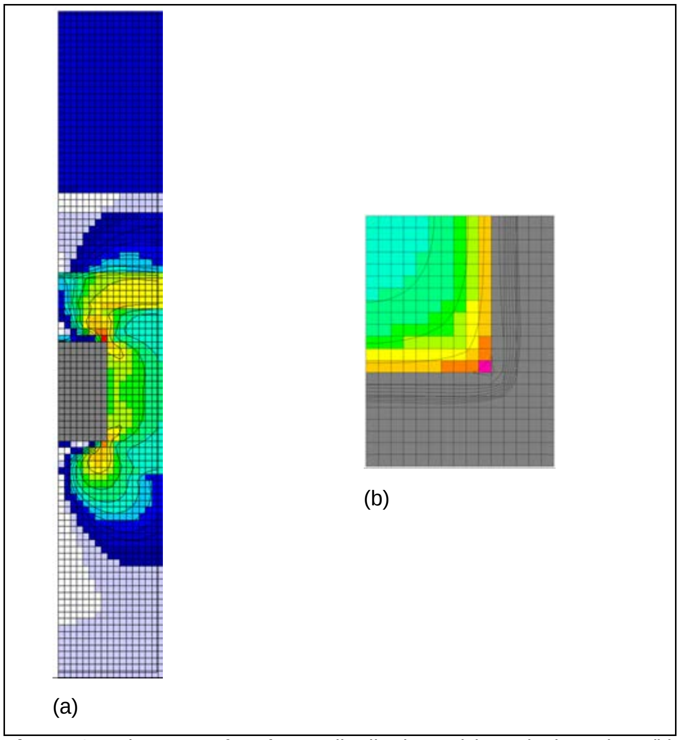


Figure 9. Element safety factor distributions: (a) vertical section, (b) horizontal section at floor level at a different scale (elements are cubes). Mining height is 9 m (30 ft). Entries and crosscuts are 9 and 12 m (30 and 40 ft), respectively. Only one-fourth of the pillar is shown and only one-half of the entry and crosscut are shown.

CONCLUSION

A user-friendly finite element approach to mine design has been extended to five from three important problems. These problems involve safety in longwall mining of: (1) main entries, (2) barrier pillars, (3) bleeder entries, and (4) interpanel barrier pillars. Problem (5) involves safety of pillars, entries and crosscuts in room and pillar mining. The approach has the advantage of being based on fundamentals of physical laws, kinematics, and material laws, and on the well-known finite element method of stress analysis. Each of the five problems is addressed in the same easy step by step manner: step 1 = development of a strata graphic column with strata properties (elastic moduli and strengths), step 2 = mesh generation, automatic and interactive, and step 3 = finite element program execution, a simple double-click. An example of an interpanel barrier pillar design from a deep, longwall coal mine in central Utah and a room and pillar mine in southeast Missouri illustrate the ease of the approach and the reliability of results. Future work may address graphics availability for mesh checking and output data plotting and perhaps user-friendly finite element analysis of shafts, raises, drifts and crosscuts in three easy steps. In the meantime, website http://ut3pc.net/ makes the UT3PC software and a User Manual available at no cost.

DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention or the University of Utah. Mention of any company or product does not constitute endorsement by NIOSH.

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