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Structural Analysis of the NNWSI Exploratory Shaft

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STRUCTURAL ANALYSIS OF THE NNWSI EXPLORATORY SHAFT

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Abstract

The Exploratory Shaft is the first step involving mining at the actual geologic horizon of the proposed Nevada Nuclear Waste Repository. A three-dimensional finite element analysis of the Exploratory Shaft and a two-dimensional finite element analysis of an exploratory shaft cross section were performed to determine if excavation loads would produce any structural problems with the Exploratory Shaft. For the low extraction ratio seen in the Exploratory Shaft, it was not expected that the rock would be overstressed. The analyses confirmed this notion: Both studies showed that the lowest factors of safety against intact rock failure exceeded 4.0. The results should serve to aid in experimentation by providing information about the displacements and the stress fields expected in the excavated tunnels.

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TABLES

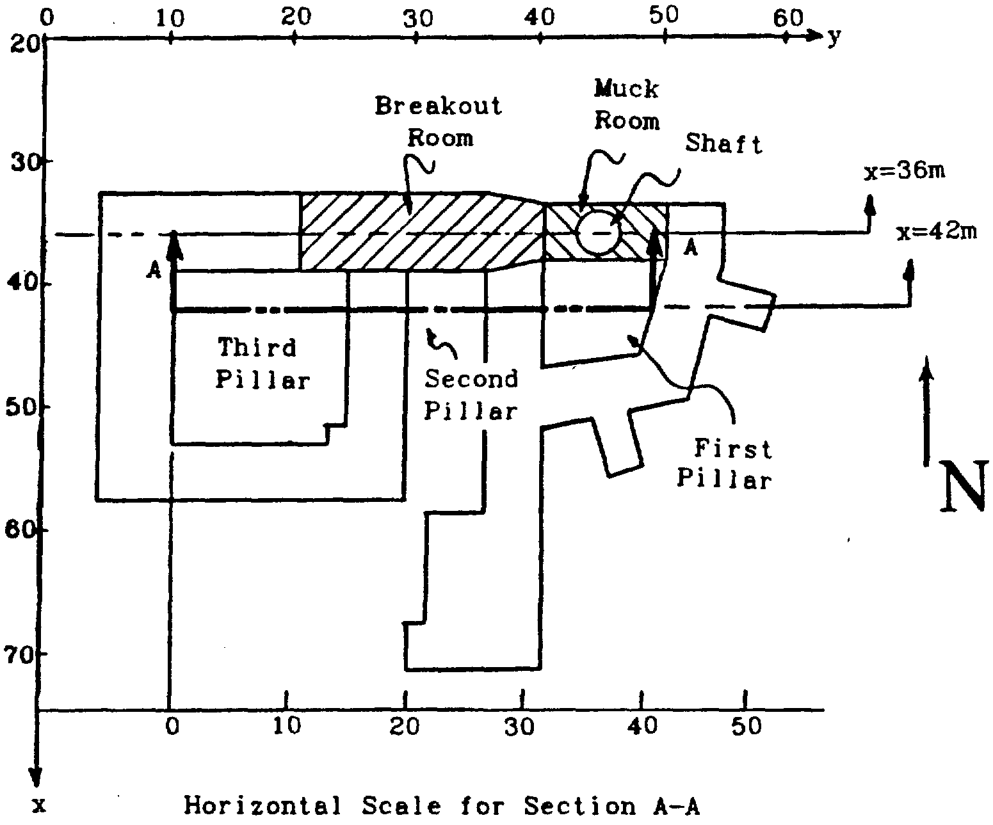
Introduction

Nuclear waste storage is a difficult engineering problem because the environment must be protected from radioactivity for thousands of years. Consequently, the problems involved with all aspects of repository development have been extensively analyzed mathematically and experimentally. The Exploratory Shaft is the first mining phase of the Nevada Nuclear Waste Storage Investigation in the actual geologic horizon of the planned waste repository. It will be used as an experimentation and demonstration facility to determine the feasibility of locating a nuclear waste repository at Yucca Mountain adjacent to the Nevada Test Site near Las Vegas, Nevada. Welded tuff at the Nevada Test Site has been studied extensively, particularly in another experimental mine (G-Tunnel); but, because the Exploratory Shaft is the first mined penetration of the tuff at the planned location of the repository, it is a critical step for determining the feasibility of locating a nuclear waste repository at Yucca Mountain (References 1 and 2).

This report discusses two finite element analyses of the Exploratory Shaft. Both analyses used the Sandia National Laboratory version of the ADINA non-linear finite element analysis code (References 3 and 5). One finite element analysis, performed by R. L. Johnson (Division 1524), was a two-dimensional parametric study of two drifts separated by a pillar. The other finite element analysis, performed by the author, was a three-dimensional analysis of a portion of one of the proposed Exploratory Shaft layouts. The drifts included are shown in the plan view in Figure 1 with the present Exploratory Shaft layout shown in Figure 2. Notice that the extraction ratio (volume of excavated rock to total volume of rock) is much lower in the present layout than in the analysis model. The present layout is much more spread out and has larger pillars between drifts, which will cause lighter loads on the pillars. Also, the in situ stress state is thought to be almost biaxial in nature, whereas the in situ stress conditions used in the finite element analyses had pronounced triaxiality. These differences all tend to make the finite element model conservative; i.e., factors of safety predicted should be lower than those actually observed in the field.

It is much harder to perform a three-dimensional analysis than a two-dimensional analysis. A three-dimensional mesh is hard to construct even with the finest facilities currently available. For similar resolution to a two-dimensional problem having n x n elements, a three-dimensional problem has n x n x n elements, causing a large increase in time and expense. However, for problems that do not lend themselves to two-dimensional solutions, that is, problems with indeterminate out-of-plane effects, a three-dimensional analysis may be the only way to predict the response of the system. In the case of the Exploratory Shaft analysis, the two-dimensional study and the three-dimensional analysis serve to complement each other. The three-dimensional analysis is used to resolve the three-dimensional effects throughout the area of the excavation, and the two-dimensional analysis (with a much higher mesh refinement) is then used to make more detailed predictions about the state of stress at certain locations.

Results from the Exploratory Shaft analysis should help the Nevada Nuclear Waste Storage Investigation in several ways. Since a numerical



(All dimensions in meters)

Figure 1

Plan View of Three-dimensional Analysis Model
Section A-A is the cross section for two-dimensional analysis.

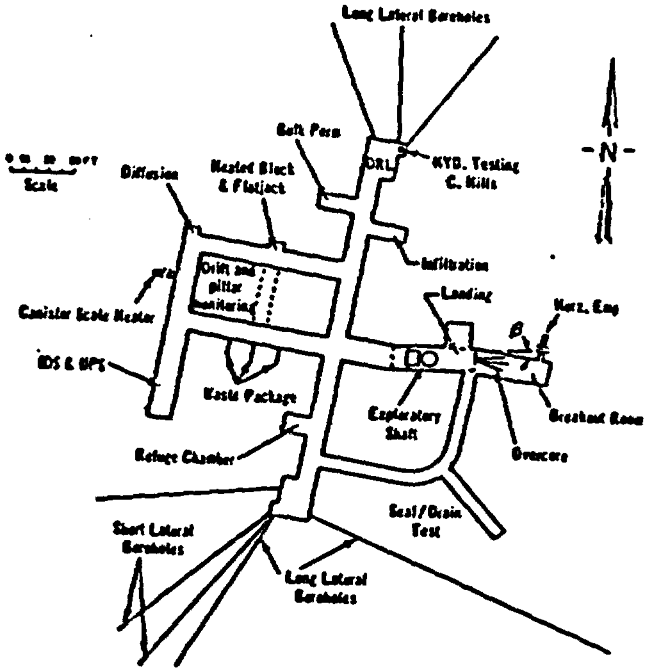


Figure 2

Plan View of Actual Exploratory Shaft

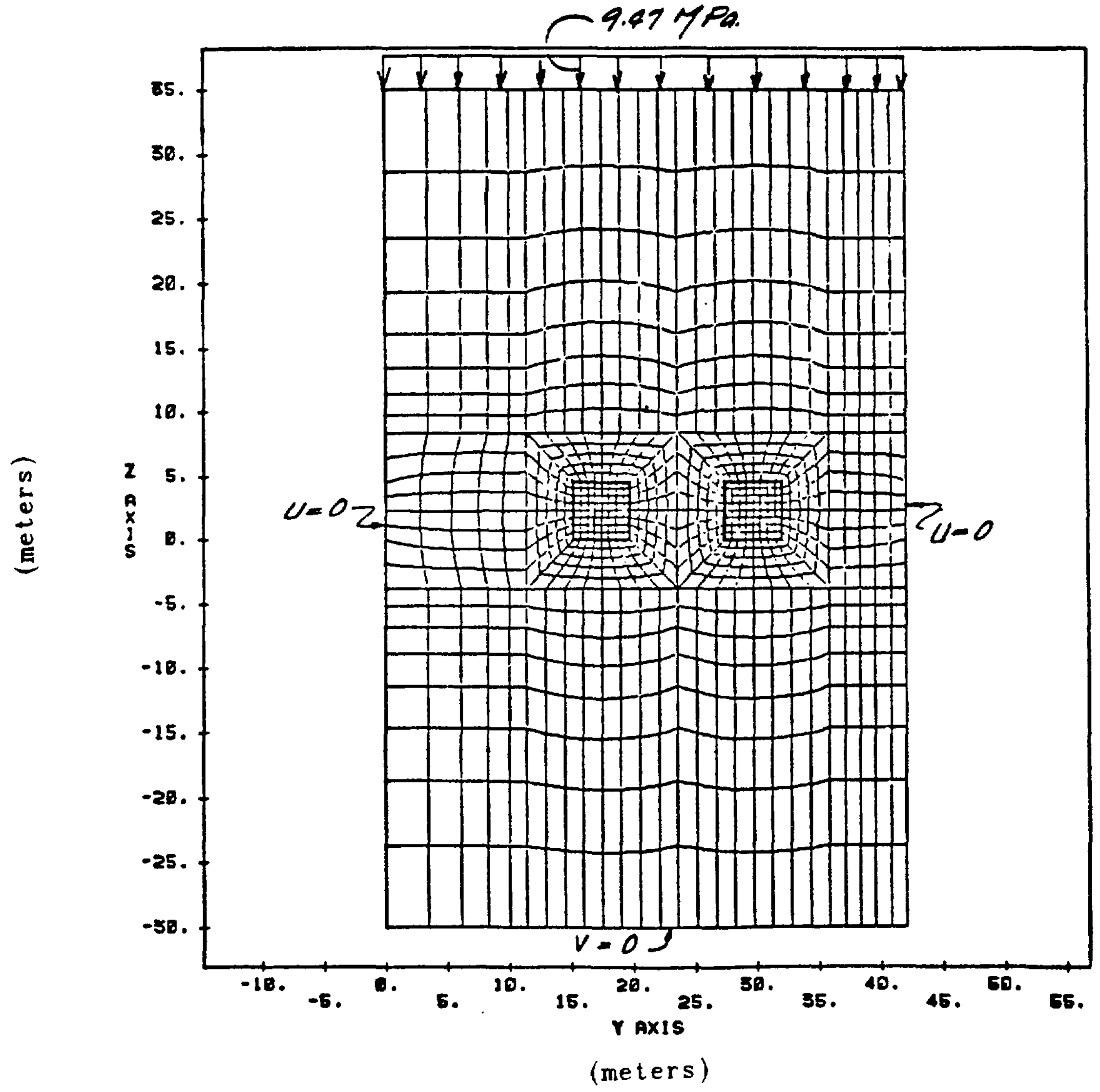


Figure 3

Finite Element Mesh of Section A-A, Figure 1, for Two-dimensional Analysis

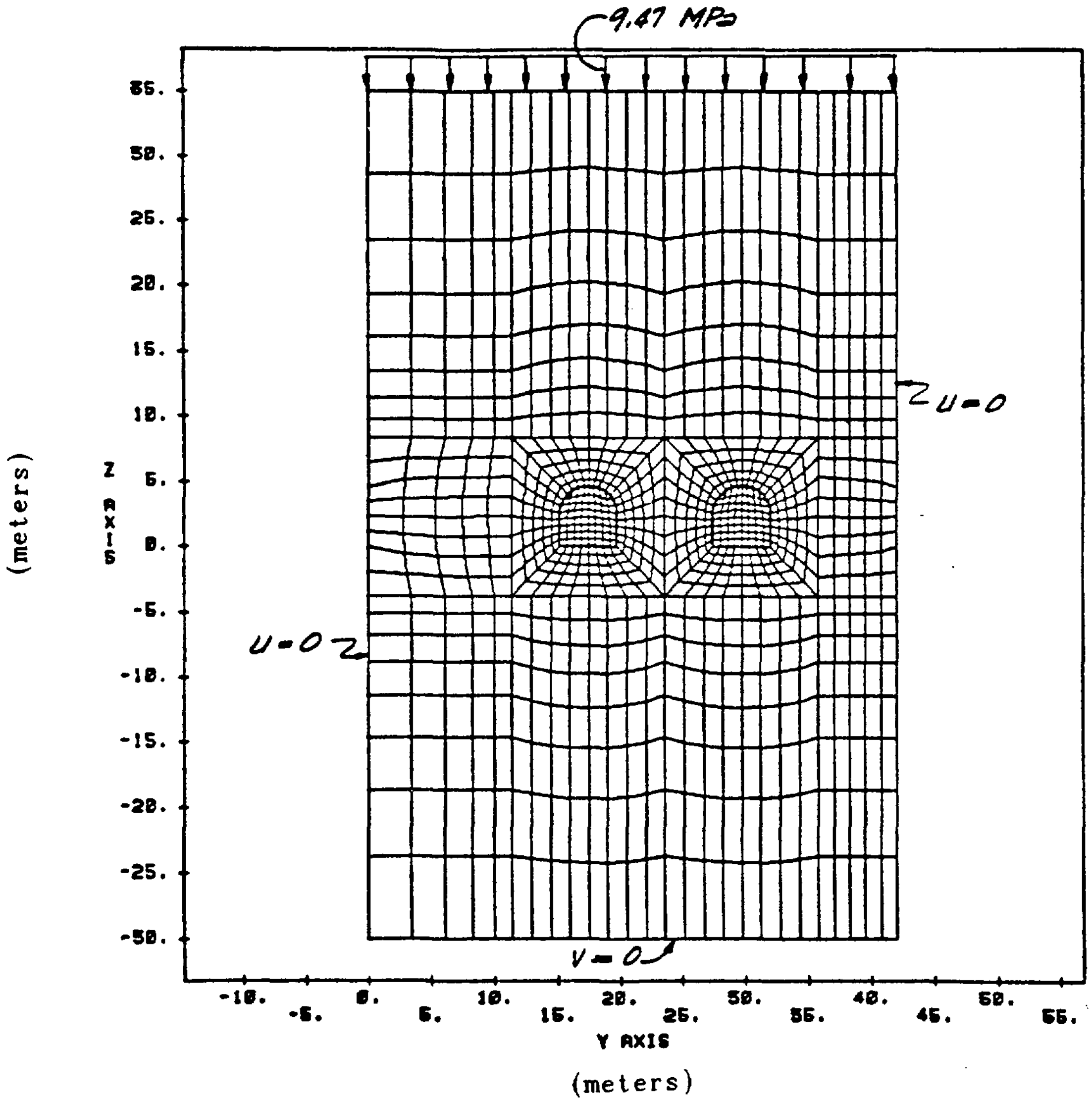


Figure 4

Finite Element Mesh of Section A-A, Figure 1, using Drifts with Arched Ceiling

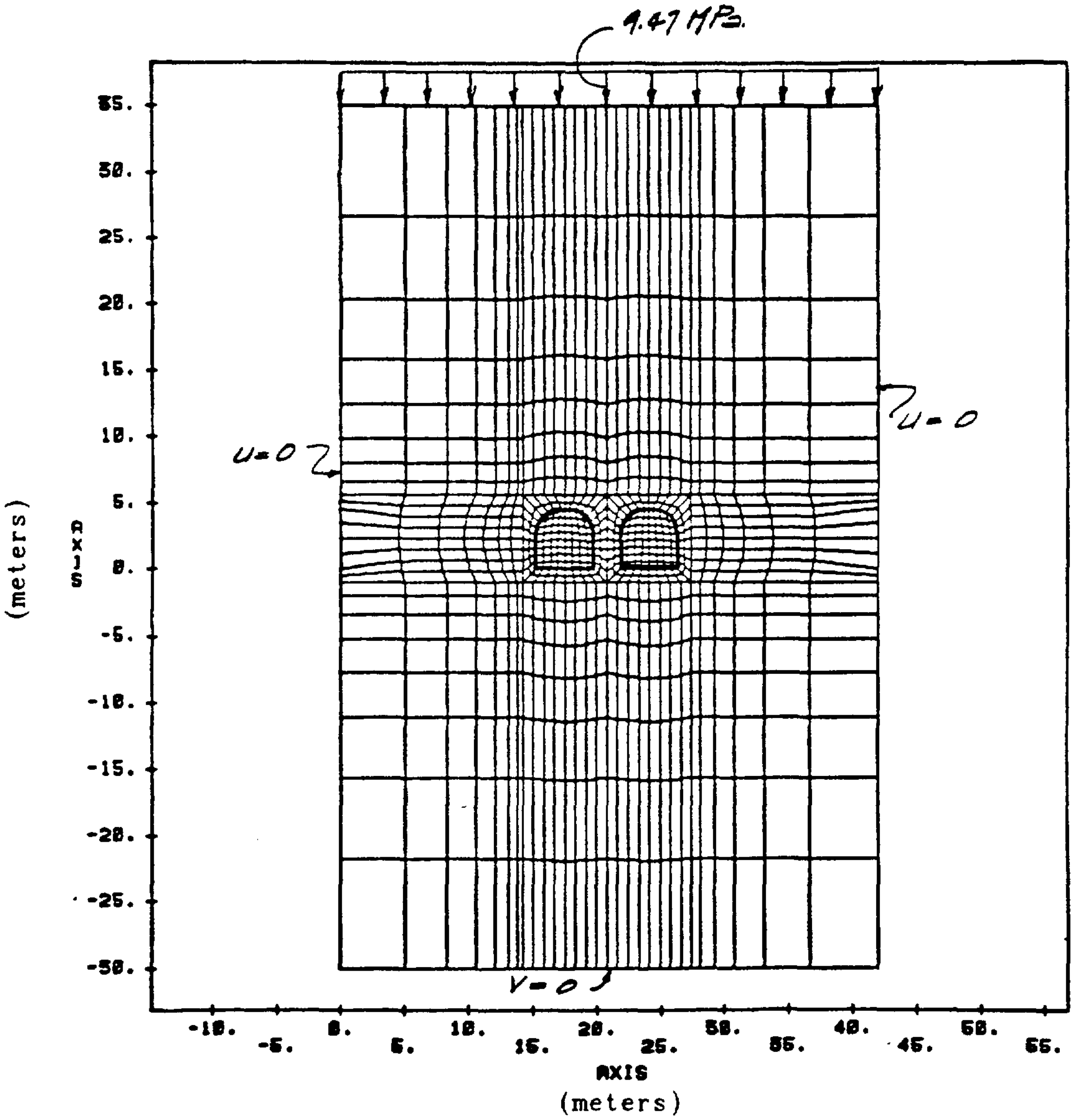


Figure 5

Finite Element Mesh of Section A-A, Figure 1, for Pillar Width Parametric Study

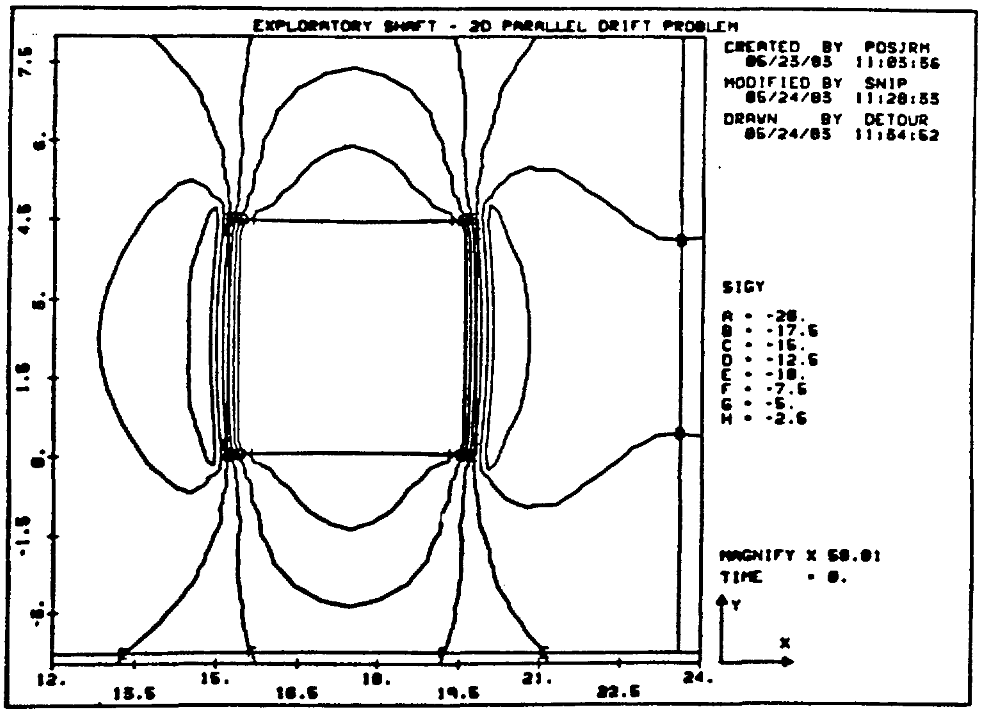


Figure 6

Vertical Stress Contours - Jointed Rock Model (MPa)

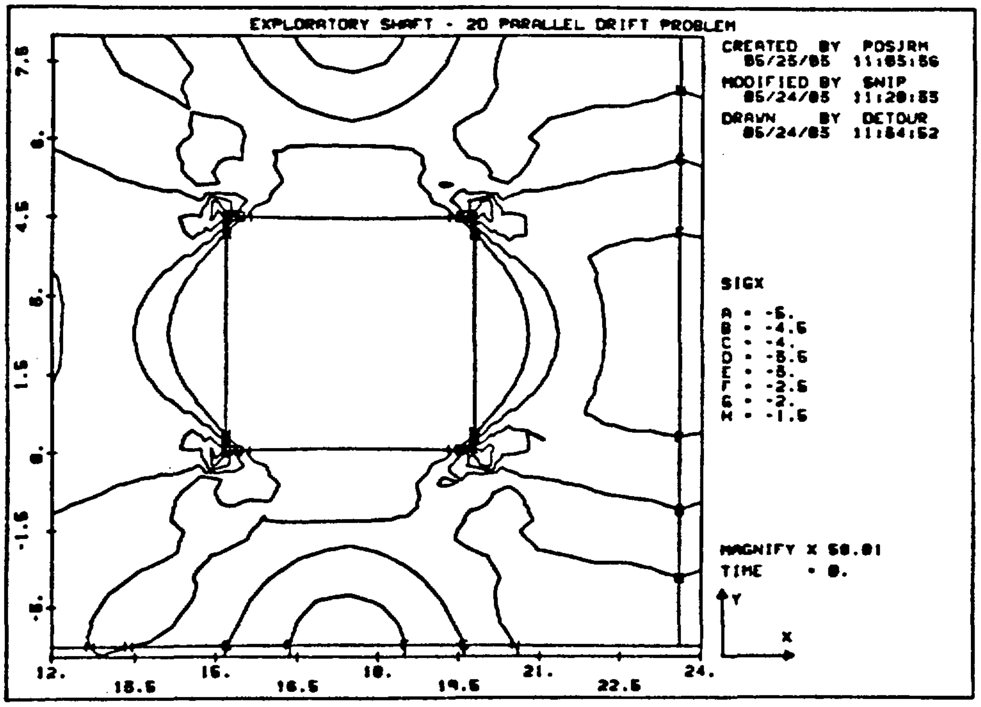


Figure 7

Horizontal Stress Contours - Jointed Rock Model (MPa)

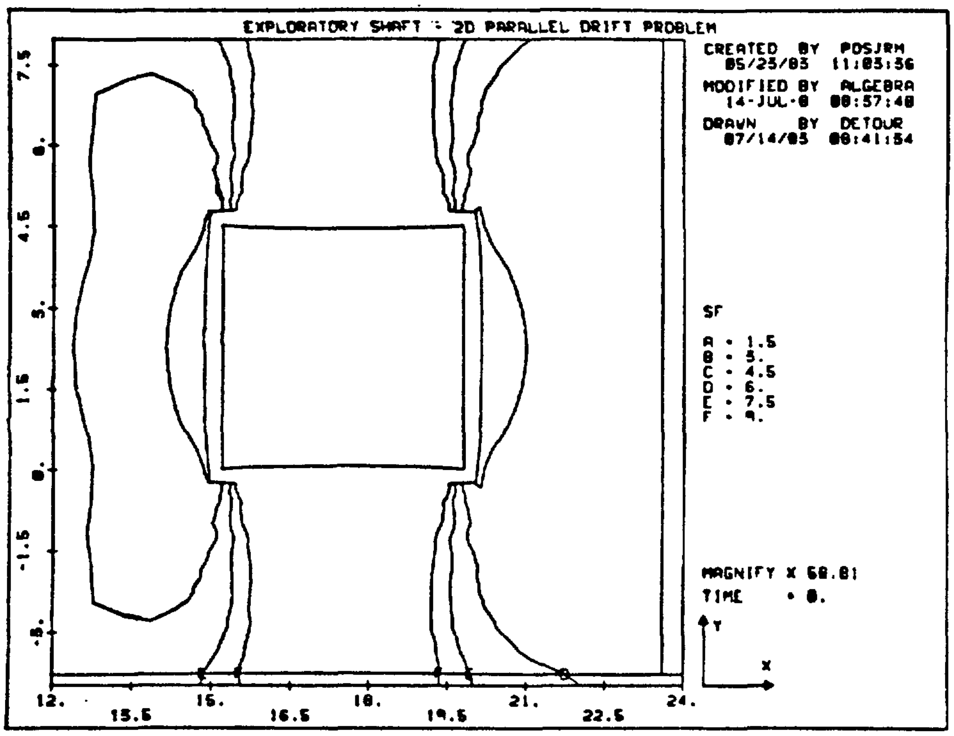


Figure 8

Factor of Safety Against Intact Rock Failure - Jointed Rock Model

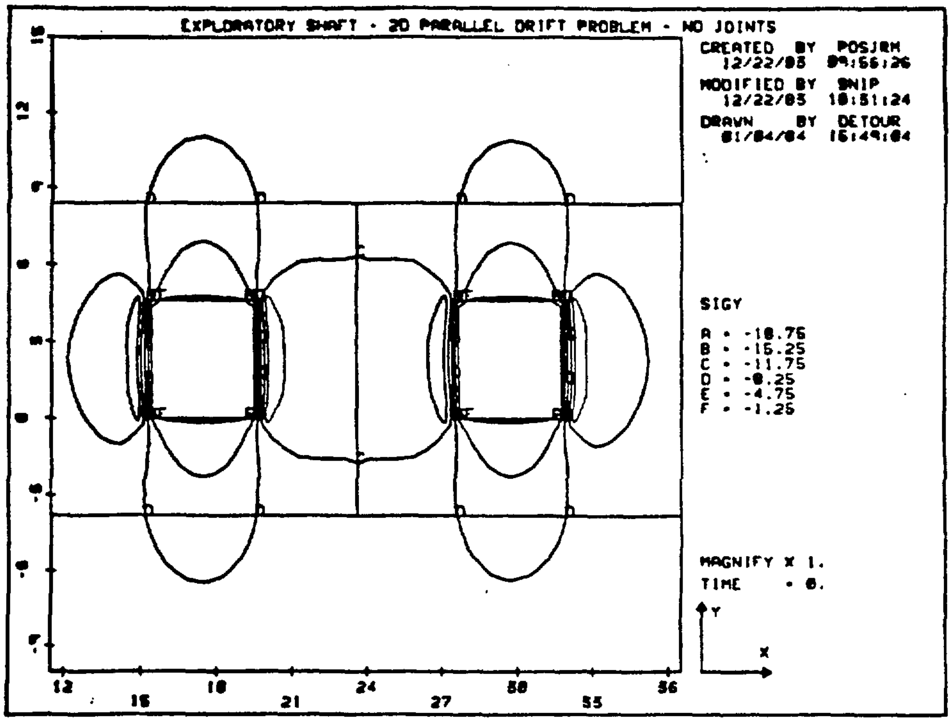


Figure 9

Vertical Stress Contours - Linear Elastic Material (MPa)

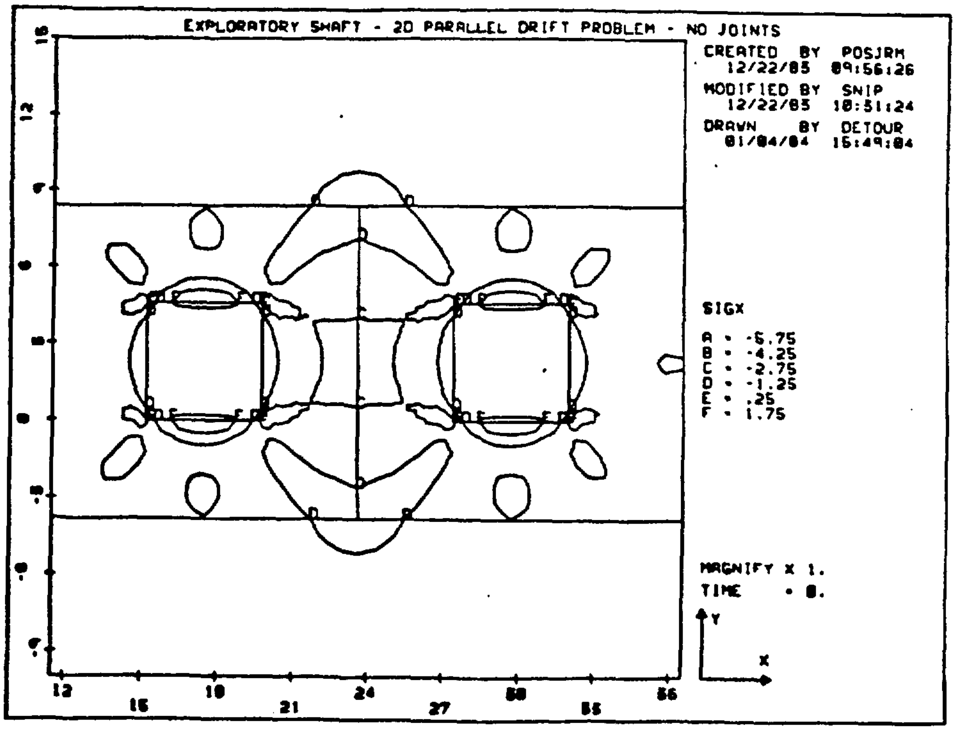


Figure 10

Horizontal Stress Contours - Linear Elastic Material (MPa)

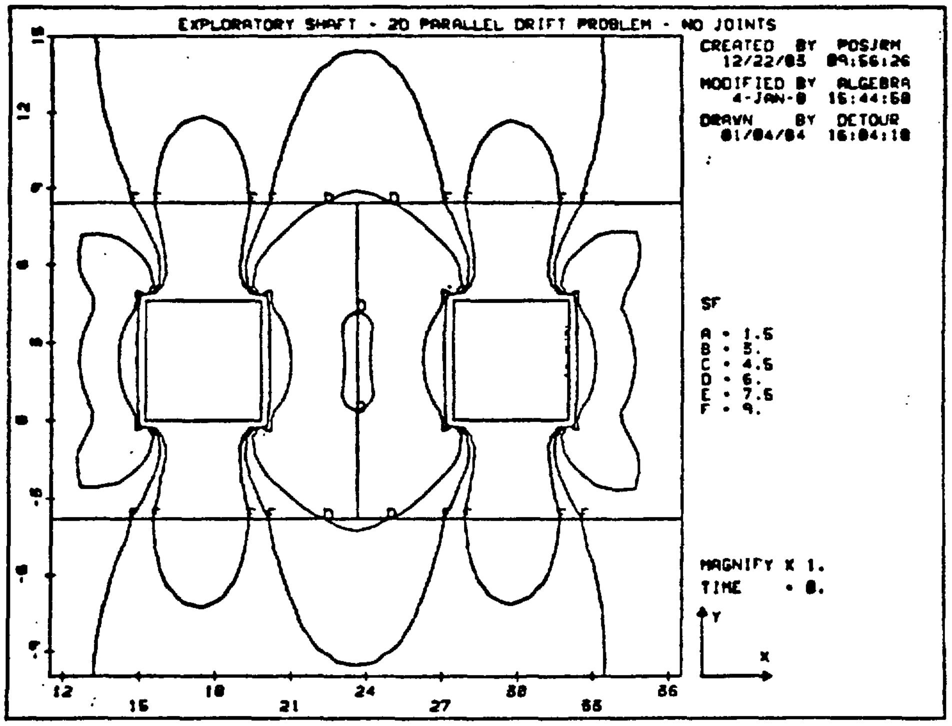


Figure 11

Factor of Safety Against Intact Rock Failure -
Linear Elastic Material

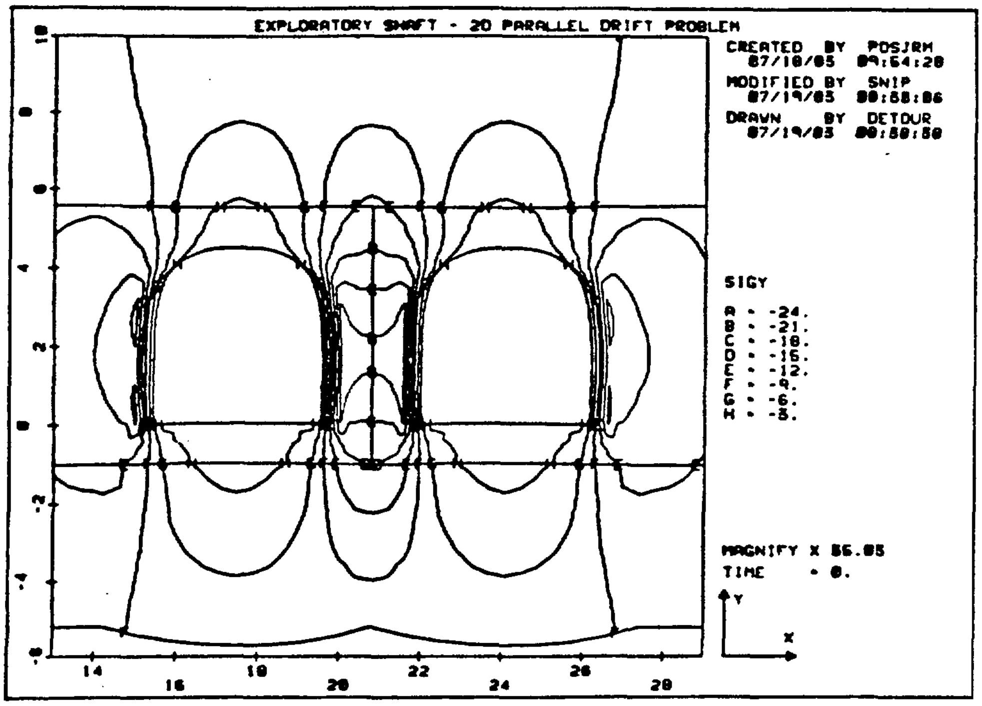


Figure 12

Vertical Stress Contours - Narrow Pillar Study (MPa)

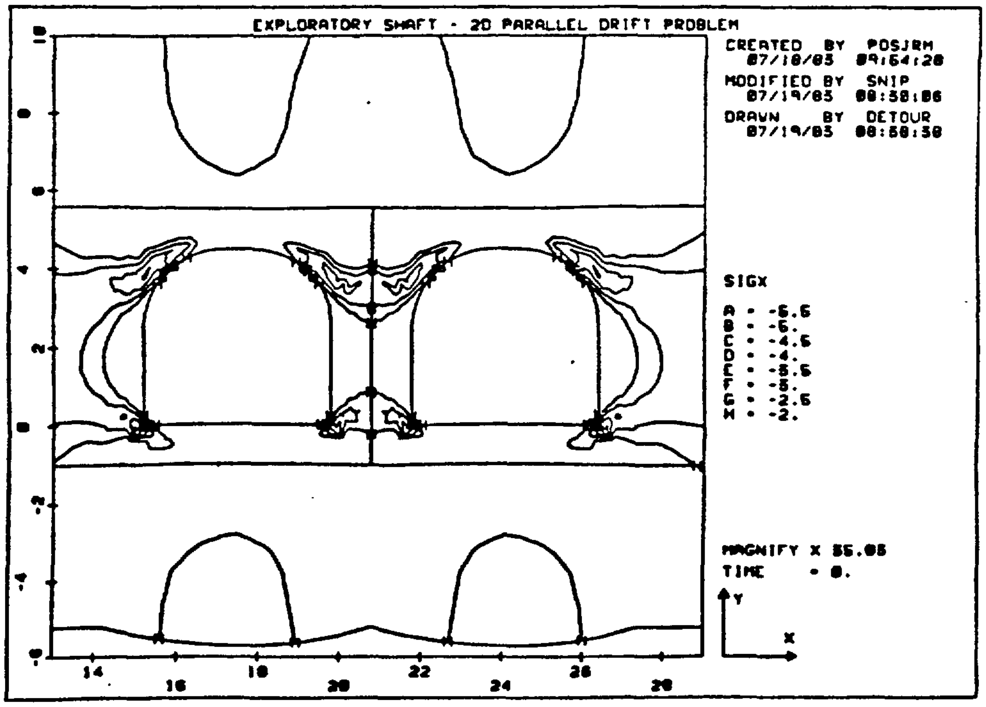


Figure 13

Horizontal Stress Contours - Narrow Pillar Study (MPa)

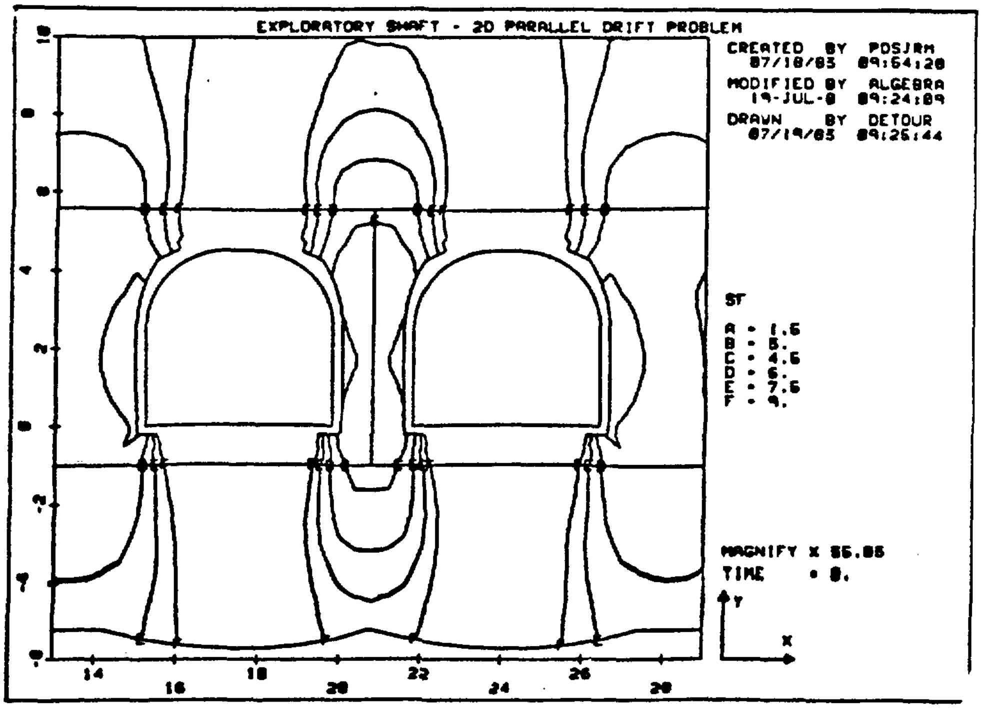


Figure 14

Factor of Safety Against Intact Rock Failure - Narrow Pillar Study

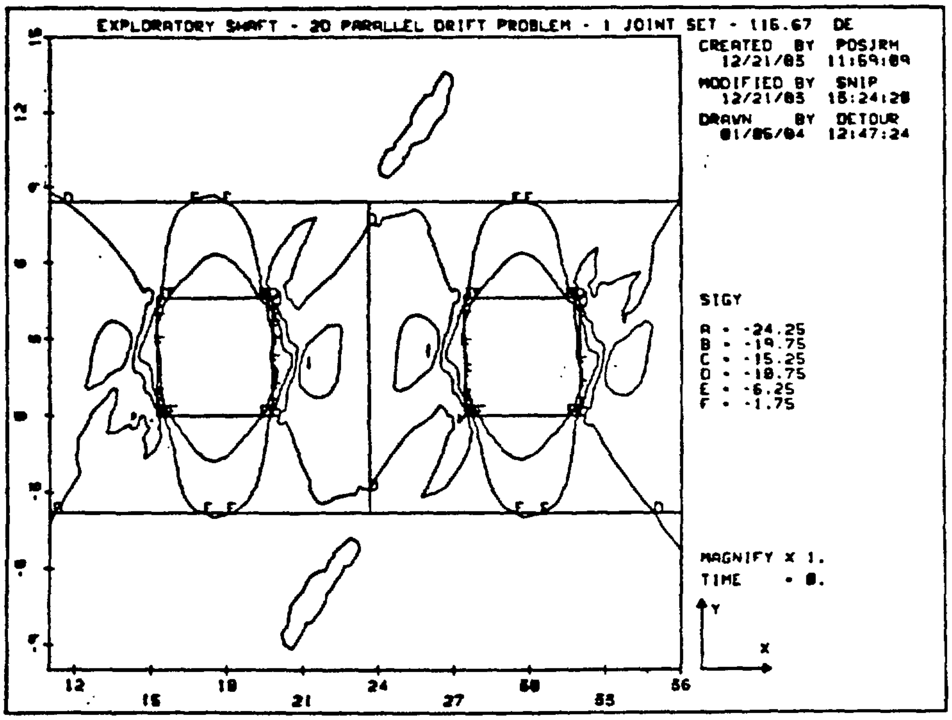


Figure 15

Vertical Stress Contours – Jointed Rock Model, Joint Angle 115.670

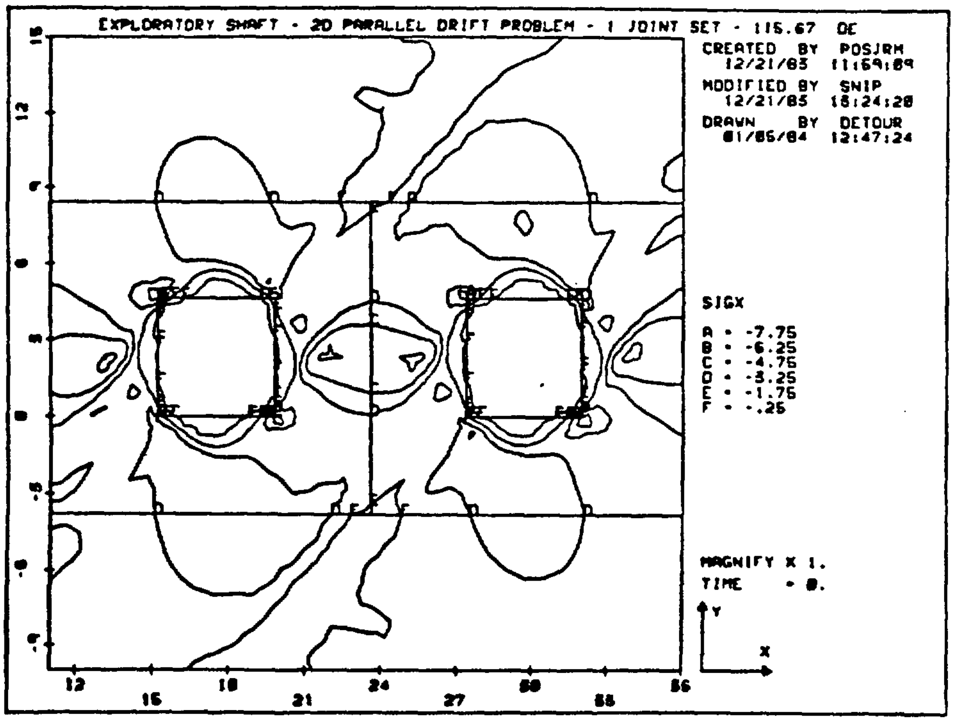


Figure 16

Horizontal Stress Contours – Jointed Rock Model, Joint Angle 115.670 (MPa)

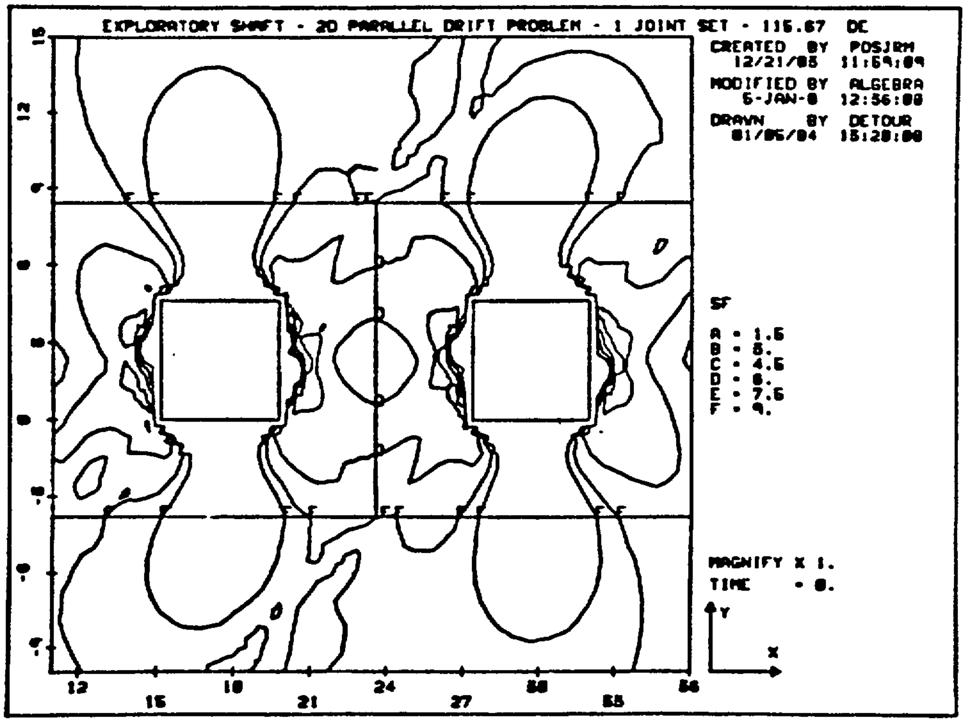


Figure 17

Factor of Safety Against Intact Rock Failure -
Jointed Rock Model, Joint Angle 115.670

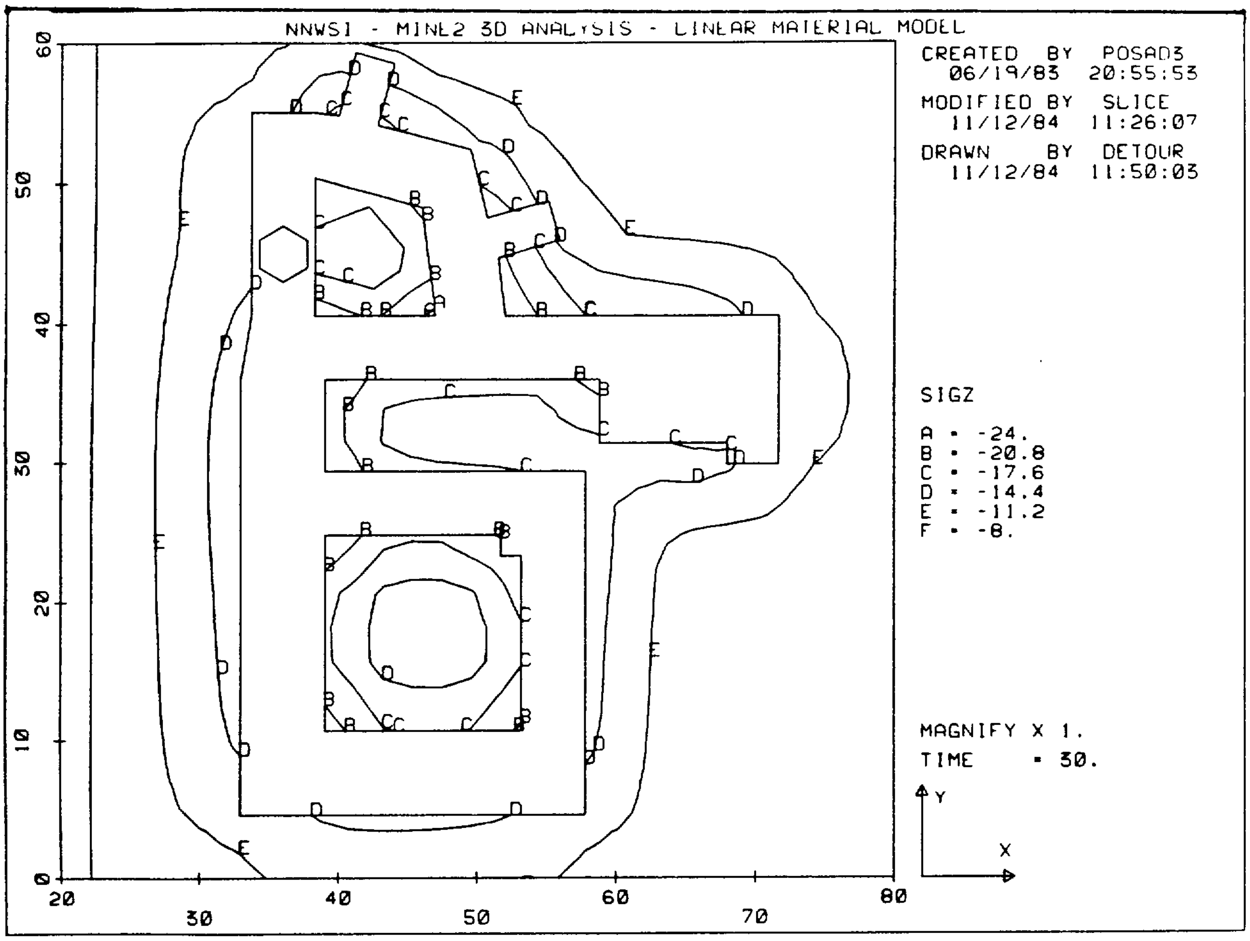


Figure 18

Vertical Stress Contours - Three-dimensional Analysis (MPa)

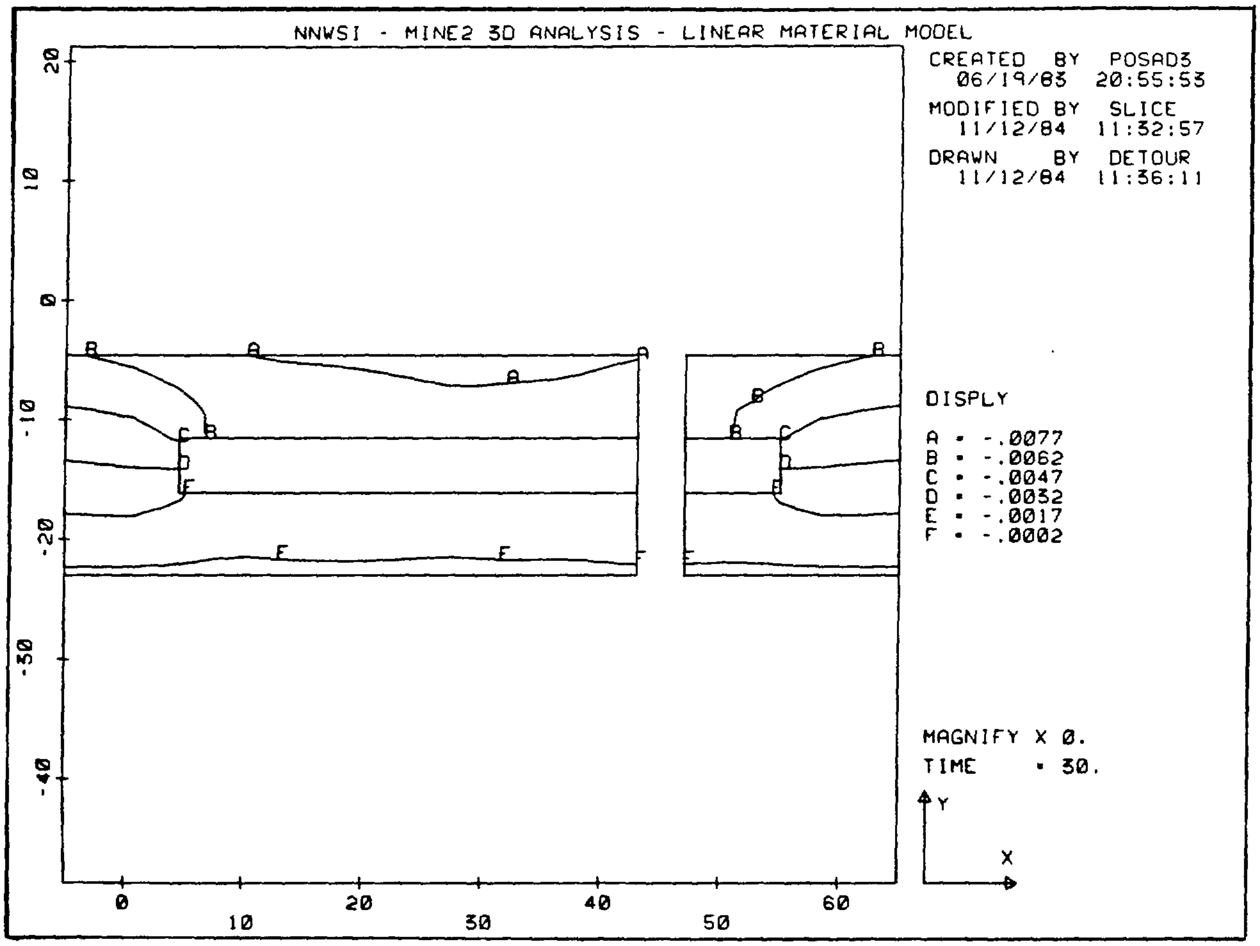


Figure 19

Vertical Displacement Contours for Drift at x = 36 m (Figure 1)

(meters)

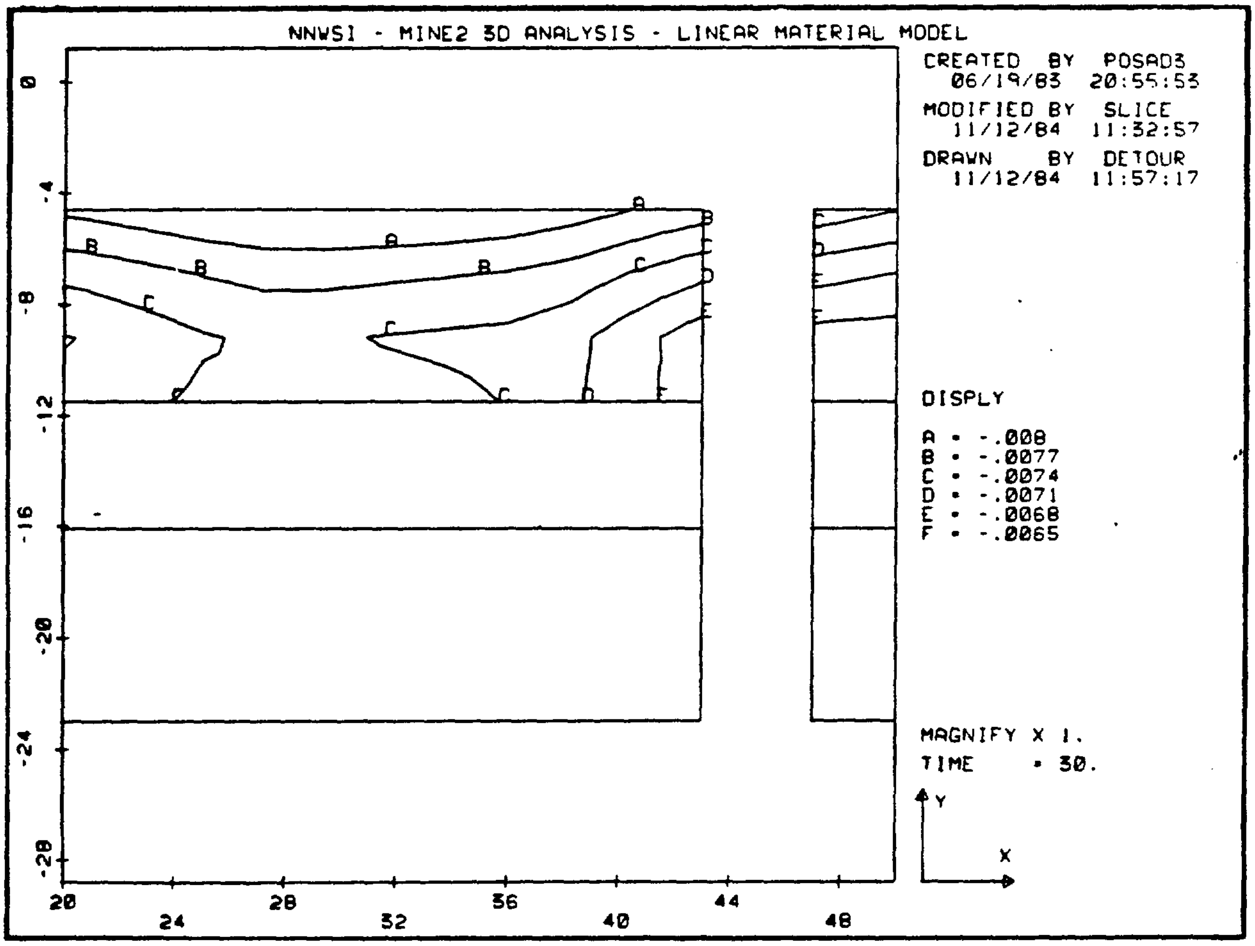


Figure 20

Vertical Displacement Contours (meters) at Muck Room and Breakout Room analysis represents an idealized case, particularly in a geologic media where there are many unknowns, it can be made to represent a worst case, a best case, or something in between, thus giving a range of solutions and possibly pointing out major design flaws. With the results of the two analyses, the overall effects of mining on the rock mass can be quantified. This will enable predictions to be made about the near-field effects and safety of the Exploratory Shaft. The results allow the investigator to have an idea of what to expect when the shaft is excavated, and will then be able to better instrument the drifts. Finally, the comparison of actual versus predicted conditions should provide a basis for confirming or redirecting this general analysis procedure.

Analysis Methods

Modeling the Exploratory Shaft in Three Dimensions

For the three-dimensional analysis, the welded tuff of the geologic horizon was considered to be a linear elastic material with material properties shown in Table 1. A block of tuff (25 meters thick and 90 by 90 meters in plan view) located 427 meters below the surface was modeled as 10 layers of 788 finite elements each for a total of 7880 eight-noded hexahedral finite elements, commonly called "bricks." The average element size was about 3 meters by 3 meters in plan view with a volume of ~20 cubic meters; a slight mesh refinement occurred at the drifts (average element volume ~12 cubic meters).

Table 1

MATERIAL PROPERTIES FOR THE THREE-DIMENSIONAL ANALYSIS

Young's Modulus	26.7 GPa
Poisson's Ratio	0.14
Grain Density	2.55
Unconfined Compressive Strength	91.1 MPa

The Exploratory Shaft was to be "mined" from the mesh by sequentially removing elements from the mesh room by room; so, the first room "mined" would be the muck room, followed by the breakout room, and so on around the Exploratory Shaft model until excavation was complete. After each room full of elements was removed, the problem would be solved statically to determine the equilibrium stress state. With this method, it was hoped that the deflections and stresses that would be seen as mining progressed could be predicted, thus enabling the experimenters to better instrument the Exploratory Shaft. Unfortunately, numerical problems discussed later allowed analysis of only the final excavated state of the shaft.

A uniform pressure of 9.2 MPa was applied to the upper surface of the block to simulate the effect of the overburden. Gravitational effects within the block were neglected. A uniform pressure of 2.6 MPa was applied in the north-south direction, and a uniform pressure of 1.9 MPa was applied in the east-west direction to simulate the in situ conditions thought to exist at the horizon.

Cross-Section Modeling in Two Dimensions

For the two-dimensional finite element analysis, a nonlinear, jointed rock constitutive law was usually used (Reference 3) to model welded tuff. Table 2 summarizes the material properties (from Reference 4). The meshes used are shown in Figures 3-5 and consist entirely of four-noded, quadrilateral, plane strain elements. Note that the two-dimensional mesh has eight elements along each wall of the drifts, whereas the three-dimensional mesh has only two elements along each wall.

In the analysis, two pillar widths were compared to determine the effects on factors of safety against intact rock failure. Also, the effects of joint orientation were compared to determine the maximum extent of joint slip possible due to excavation. Lastly, a linear elastic material was used to compare the analysis with one of the cross sections of the three-dimensional analysis. The in situ conditions (Table 2) are identical to those used for the three-dimensional analysis to enable comparison of the two analyses. All of the above analyses were performed statically to determine the equilibrium stress state at the completion of excavation.

Analysis Problems

There were two major problems with the three-dimensional analysis. Both problems are related to the architecture of the SANDIA-ADINA finite element code.

SANDIA-ADINA forms the entire active (nonzero) portion of the stiffness matrix for solution at each solution step. With over 9000 nodes, the three-dimensional problem has about 25,000 degrees of freedom which causes the stiffness matrix to be very large. When the problem was run, it used approximately two-thirds of a storage disk, causing the CRAY-1 machine operator to repeatedly terminate the job. Fortunately, the analysis of the final (complete Exploratory Shaft) solution step was accomplished, but none of the intermediate, sequential mining time steps were completed.

The second problem is the lack of spatial resolution built into the finite element mesh. Even with over 9000 nodes, the mesh is very coarse. The typical element is about 3 meters square and 2.3 meters high; and, due to the method of mesh construction, only a slight refinement of the mesh exists near the excavation. As a result, the overall performance and general state of stress of the Exploratory Shaft is determined, but near-field effects are not accurately portrayed. Refining the mesh is not a viable option at this writing as it would exacerbate the storage problems discussed above.

Table 2

MECHANICAL PROPERTIES OF TUFF

Property	Symbol	Value	Units
Young's Modulus	E	26,700	MPa
Poisson's Ratio	ν	.14	–
Shear Modulus	G	11,711	MPa
Matrix Internal Friction	μ_i	.488	–
Matrix Cohesion	C_{oi}	28.5	MPa
Matrix Tensile Strength	σ_{ti}	12.8	MPa
Joint Friction Coefficient	μ_i	.8	–
Joint Cohesion	C_{oj}	1.0	MPa
Joint Tensile Strength	σ_{tj}	0.1	MPa
Horizontal In-Plane In-Situ Stress	σ_y	-1.87	MPa
Vertical In-Plane In-Situ Stress	σ_z	-9.47	MPa
Horizontal Out-of-Plane In-Situ Stress	σ_x	-2.62	MPa
Joint Angle*	β	90	degrees

*The preferred joint angle varied for "effects of joint angle" study

The third pillar is larger than the first and second pillars and much wider in both directions than the drifts surrounding it. Consequently, the center region of the pillar is close to in situ conditions and would be an ideal region for experimentation since there is access to four sides of the pillar.

Another important aspect of the analysis is the closure (relative displacement of floor and ceiling) of the mined drifts. Although the analysis cannot be expected to predict the precise deflection of the ceiling, it should give results which are qualitatively similar to field measurements. Figures 19 and 20 show a contour mapping of the deflection in the drift cut by the section line at x = 36 meters (see Figure 1 for section lines), as well as a closeup of the muck room and breakout room in the same drift. Note that the maximum deflection is about 8 mm on the roof, while the floor below it deflects about 1 mm, giving a relative closure of ~7 mm. (This downward motion of the floor is an artificial phenomenon attributable to the compression of the mesh when in situ pressures are applied. However, the motion of the floor relative to the roof is correctly reported.) Unfortunately, since the sequential mining runs were not completed, it is not possible to say at what stage of mining the displacements occur. However, most of the displacement probably occurs gradually as the drift face being excavated recedes from the point of interest and is probably complete when the excavated face is a few drift widths away. There should be some slight secondary displacement at drift intersections at the time the intersection is made. Since the relative displacement is so slight and occurs gradually as the drift progresses, it is not likely to be detected by unaided visual observation and may even be difficult to detect with instruments. Displacements of selected points in the floor and ceiling along the centerline of the drift are tabulated in Table 3. Note that the geometry of the muck room and breakout room in the model are similar to the planned geometry of the same rooms of the current planned configuration for the Exploratory Shaft (Figure 2).

Comparative Results

The linear elastic material model used for the three-dimensional analysis and the two-dimensional study were identical. Taking a cross section of the three-dimensional Exploratory Shaft model shows virtually identical stress states and factors of safety against intact rock failure when compared to the two-dimensional linear elastic material model analysis. The factor of safety against intact rock failure is about 4.5 for both. Using the jointed rock material model in the two-dimensional study produced a factor of safety of about 4.0. This magnitude did not vary appreciably with joint angle orientation. Since the second pillar shows stress patterns similar to the other pillars, it is unlikely that the factor of safety anywhere within the Exploratory Shaft as modeled will be less than 4.0.

In the worst case for rock jointing considered by the two-dimensional analysis, it is worth noting that the redistribution of stress is quite localized. One would not, therefore, expect to see gross redistribution of stress in a three-dimensional worst case analysis. As a result, it is unlikely that a combination of design and bad jointing could create a catastrophic failure. If the design has a reasonable factor of safety when analyzed with a linear material model, then the worst possible jointing scheme would be most unlikely to cause failure.

Conclusion

Several differences between the actual Exploratory Shaft and the modeled Exploratory Shaft reported here have been mentioned. The actual Exploratory Shaft will have a much lower extraction ratio as shown by Figures 1-2. The in situ stress state is thought to be more biaxial in nature (9.2 MPa vertical, 9.2 MPa N30E, 4.6 MPa N60W) than the pronounced triaxial state used for the analysis reported here (9.2 MPa vertical, 2.6 MPa due S, 1.9 MPa due E).

With a lower extraction ratio, the Exploratory Shaft will have even higher factors of safety. Conventional mines do not generally have such a low extraction ratio since they are designed to remove as much mineral as possible. Also, a conventional mine generally remains open only as long as it produces; so, the life of the mine is short compared to that of the Exploratory Shaft and that of the Nevada Nuclear Waste Repository, which should remain open for perhaps 100 years. The high factors of safety due to the low extraction ratio help in this regard by reducing stresses and therefore lessening the time-dependent effects that would exist if the rock were more highly stressed.

A biaxial stress state is closer to hydrostatic loading condition than the triaxial stress state reported herein and should reduce effects caused by deviatoric stresses (such as the joint slippage reported in the two-dimensional analysis). If the biaxial stress state is as it is thought to be, the response of the welded tuff to excavation should be very benign. In either case, the near-term effects of mining should be inconsequential; the long-term effects would be better with a biaxial stress state but should not be severe in either case.

Conclusions from the two-dimensional study tend to reinforce those made from the three-dimensional analysis and vice versa. Since the rock only a few meters from drifts of this size is unaware of the excavation, any three-dimensional effects change the response of a local region only, not the Exploratory Shaft as a whole. The lower extraction ratio of the actual Exploratory Shaft will further diminish three-dimensional effects, causing two-dimensional cross section analysis to represent the actual response better.

It is difficult to perform a three-dimensional analysis. Three-dimensional analysis can be a valuable analysis tool, but the increased difficulty should be weighed against the potential engineering information to be gained over performing one or several two-dimensional analyses. A typical finite element analysis involves three steps: generating the finite element mesh and input file, executing the finite element code, and postprocessing the results into useable form. At this writing, the first and last steps are the most difficult. Pre- and post-processors for finite element codes are still in their development stage. Until more sophisticated systems are developed, three-dimensional analysis will be very difficult and expensive to perform.

The Exploratory Shaft should be a very safe excavation and no structural problems should occur. Even if all of the worst possible conditions existed at the geologic horizon of the Exploratory Shaft simultaneously, the drifts would still be safe. Since the overall stresses are quite low, time-dependent effects should also be minimal.

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