The Use of Rock Mechanics in Mine Design at the Fairport Mine, Morton Salt Company

John D. Smith
C-I-M Consultants Ltd.
Kingston, Ontario, Canada

ABSTRACT

The Fairport Mine of the Morton Salt Company is considered to have good mining conditions and relatively stable rock formations in which to work. However, mining costs and safety conditions were being affected by significant amounts of rock movements expressed by floor heaving, pillar rib failure, and roof spalling.

Mine management recognizing these problems, authorized a rock mechanics programme to provide data on rock movement so that the improved mine design would result in a reduction or elimination of these problems.

This paper describes the rock mechanics study conducted by C-I-M Consultants Limited in conjunction with the mine staff. It describes the means of accumulating data and presents summaries of the measurements obtained and how these were used to determine optimum face width and orientation, optimum pillar size and orientation, and rock movement control.

The mine management has implemented several of the recommendations concerning mine design and the comparison of mining conditions, visual observations, and operational data is given between the older mining method and layout and the modified method and layout resulting from the study.

INTRODUCTION

The management of Morton Salt Company authorized C-I-M Consultants Limited to conduct a rock mechanics study to provide design criteria that could lead to the reduction or elimination of floor heaving, pillar spalling and roof deterioration at their Fairport Mine. This study was conducted over a period of six months, starting in July of 1963. Approximately twenty man days per month were spent on the project, half of which was used in field and travel time.

The Fairport Mine is a salt producer recovering about 4,000 tons per day from a gently dipping bed of about 20-foot thickness. The ore zone is bounded above and below by Silurian shales, limestones, and thinner salt beds. The regional dip is towards the southeast but locally there are rolls in the formations which change the dip over short distances. It appears that there has been little or no major tectonic movements in the region of the ore zone.

Mining is done by the room and pillar method laid out on a North-South and East-West grid. The rooms are approximately 40 feet wide and 17 feet high with pillars 100 ft. × 100 ft. The rate of advance is approximately ten feet every three weeks per room. In various sections of the mine floor heaving, roof spalling, and rib corner deterioration commences shortly after the creation of a new face. The mining is planned to leave two-three feet of salt in the roof immediately below the shale contact. This means that a variable amount of salt is left on the floor but where local "pinches" occur in the salt bed both roof and floor shales are exposed.

DEFINITION OF PROBLEM

The Fairport Mine was and is currently being mined with a very acceptable tons per man shift record and an excellent safety record. Mine operating personnel have evolved, during the life of the mine, techniques and mining procedures to cover most of the problems encountered by unexpected rock and salt movement. However, a continuous and significant number of man shifts was being spent on scaling, cleanup, and equipment maintenance caused by rock and salt movements expressed in floor heaving, roof spalling, and pillar deterioration. The basic problem, from a mining standpoint, was how to reduce this maintenance cost to a minimum and hence improve efficiency and decrease mining costs.

The problem, as viewed by a rock mechanic, was to determine the inherent directional and strain magnitude characteristics of the formations effected by the mining operation, to utilize this knowledge, on an engineering basis, in calculating design changes to reduce, eliminate, or minimize the various movements causing failure, and to monitor the changes in design underground in order to evaluate their effectiveness.

DATA ACCUMULATION

Any rock mechanics study for the purpose of improving mine design by considering the inherent properties of the mine structure evolves first of all into a sampling problem. The statistical force vector and inherent strain magnitudes must be determined by analyzing the required number of oriented samples in the laboratory. Further, "in situ" measurement must also be done in a sufficient number of places to attain the required confidence in the result. The following sections explain how this data was obtained, why it was required and how it was used in mine design.

INHERENT DIRECTIONAL CHARACTERISTICS

One of the most important properties of the materials affected by mining is their inherent force field. This is the vectorial sum or resultants of all forces acting on the material. This property must be determined for each geologic material that will be affected by the mining operation as their behavior and manner of movement is dependent upon this property.

Associated with the strain vectors acting in the various granular materials are curvilinear surfaces that possess higher orders of inherent energies than surrounding grains. These surfaces are called preferred shear planes.

The system of analysis used to determine the properties at the Fairport Mine involved the instrumentation of many oriented pieces of salt and shale. Oriented samples were taken from the ore zone and the roof shale on a statistical basis so that the area of influence of each sample gave the required confidence on a minewide scale. Each oriented sample had a cube cut from it with a diamond saw, three mutually perpendicular planes were then instrumented with two-inch diameter photoelastic strain gauges. As the time-dependent inherent energy stored in the grains and cement reoriented and strained them in order to reattain equilibrium, the photoelastic strain gauges recorded the directions and amount of movement. The vector components of the principal strains on each instrumented face were then combined using a stereonet to produce the force field vector (azimuth and dip). The preferred shear plane traces on each face also combined to produce the strike and dip of the various families of preferred shear. This work was also done using a stereonet.

Force Field. A total of 21 oriented samples were taken from the salt ore zone and 37 oriented ore and hand samples from the roof shale. Two samples from the floor shale were also studied. The azimuth of the principal strains in the horizontal plane for the different materials is presented in Table 1. G_1 is the major strain direction and G_2 is the minor strain direction. The azimuths are corrected for the local magnetic declination. It is apparent that there is little difference in force field direction in the different formations. The approximate force field dip is down towards the southeast at about 20°. The local variations in force field direction are best shown by a strain trajectory which is a plot of how the principal strains are propagated through a given plane and is a visual representation of how the rocks are strained directionally. The most useful representation for a bedded deposit with a slightly dipping force field is to show the strain

TABLE 1

Average Force Field Directions

Rock Type	No. of Samples	Principal Strain Directions in Horizontal Plane -- Az. G_1	G_2
Salt	21	133°	043°
Roof Shale	37	135°	045°
Floor Shale	2	137°	047°

trajectory in the horizontal plane. This has been done for the roof shale bed and is presented in Fig. 1 on the following page.

The major and minor force field has been determined and defined by an azimuth and dip. The determination of the thrust direction or the placement of the arrowhead on the vector cannot b determined adequately from oriented samples. "In Situ" measurement was used to determine this characteristic. Both north-south and east-west openings were instrumented around their periph- ery's with photoelastic gauges bonded to the surface as well as bolt tension meters placed on rock bolts. The manner of load build-up on these instruments indicated that one wall of the openings was moving into the void at a faster rate than the other. This indicated that the thrust vector was thrusting downward at 20° on an azimuth of 135°.

Preferred Shear Planes. It is believed that these approximate planes of inherent weakness in a granular material are a function of the grain packing patterns, the type of "glue" cementing grains together and the tectonic forces that created its present configuration. These planes are very useful both in designing restraint and for drilling and blasting functions. These points will be discussed later. There are several families of preferred shear planes in both the roof shale and the salt bed. The following Table 2 shows the general agreement between these families.

TABLE 2

Preferred Shear Plane Families

Rock Type	Preferred Shear Planes -- Az. and Dip 1	2	3	4
Roof Shale	153° -- 22° N.E.	122° -- 43° S.W.	050° -- 30° N.W.	0° -- 19° S.E.
Salt Bed (upper 2nd Salt)	142° -- 48° N.E.	138° -- 42° S.W.	052° -- 56° N.W.	067° -- 48° S.E.

From the table it is evident that families one and two have similar azimuths but opposite dips while families 3 and 4 have the same characteristic with their azimuths being approximately 90° from 1 and 2. An attempt was made to correlate the families of preferred shear planes with the local variation in salt bed thickness. It was found that in a "pinch" region of the salt bed that preferred shear plane families of 052° az. -- 56° N.W. dip and 142° az. -- 48° N.E. dip predominate while in "swells" and relatively undisturbed parts of the bed families of 052° az. -- 56° N.W., 067° az. -- 48° S.E. and 138° az. -- 42° S.W. predominate.

Shear Strain and Strain Magnitudes. Only the time-dependent portion of the total elastic recoverable strain is recorded by the instruments on the oriented samples. These show the distribution of the time-dependent shear strain when viewed with the correct optical instrument. The graph presented in Fig. 2 shows a typical relaxation rate for an oriented salt sample.

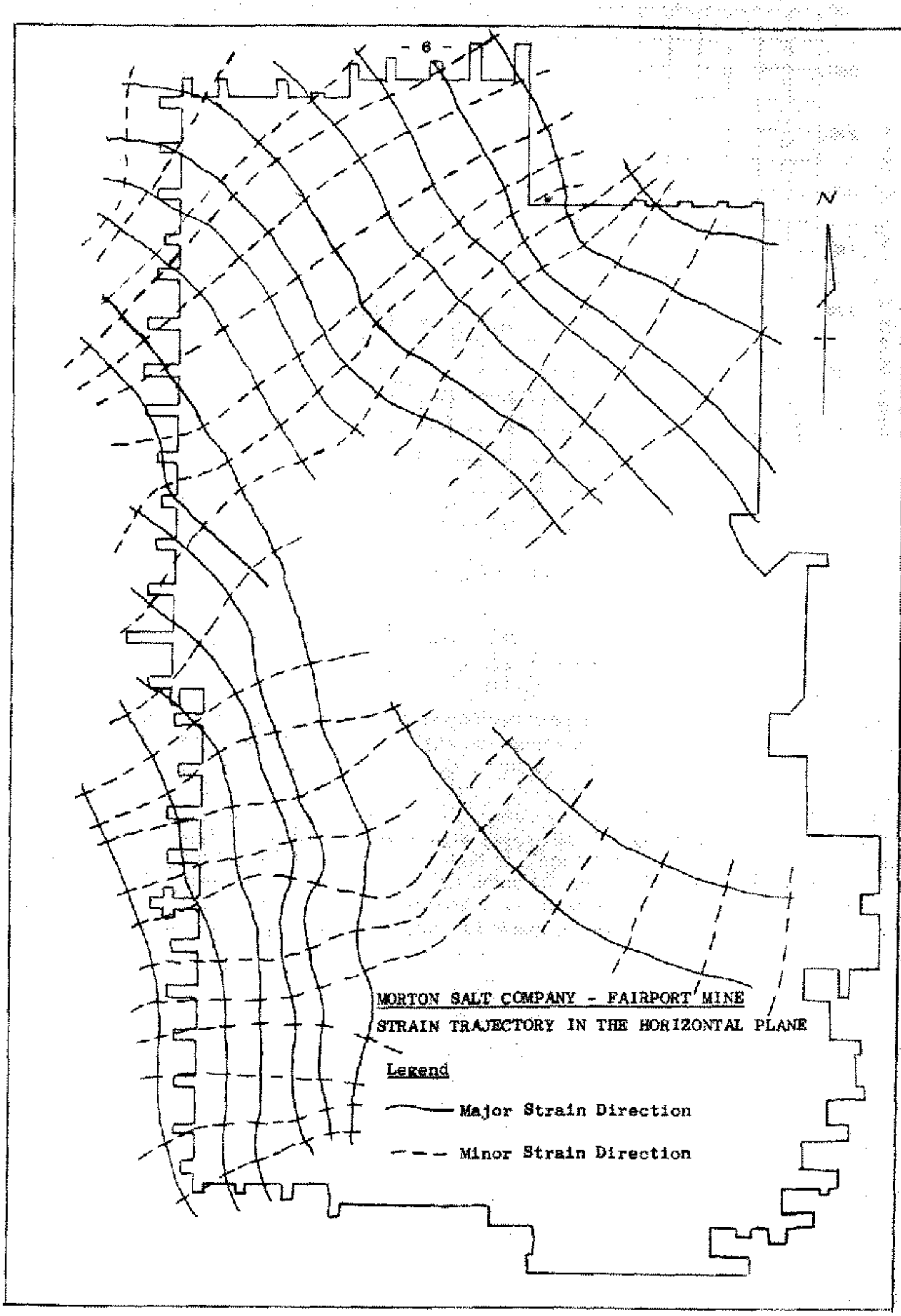

Figure 1. Strain Trajectory in the Horizontal Plane, Fairport Mine, Morton Salt Company.

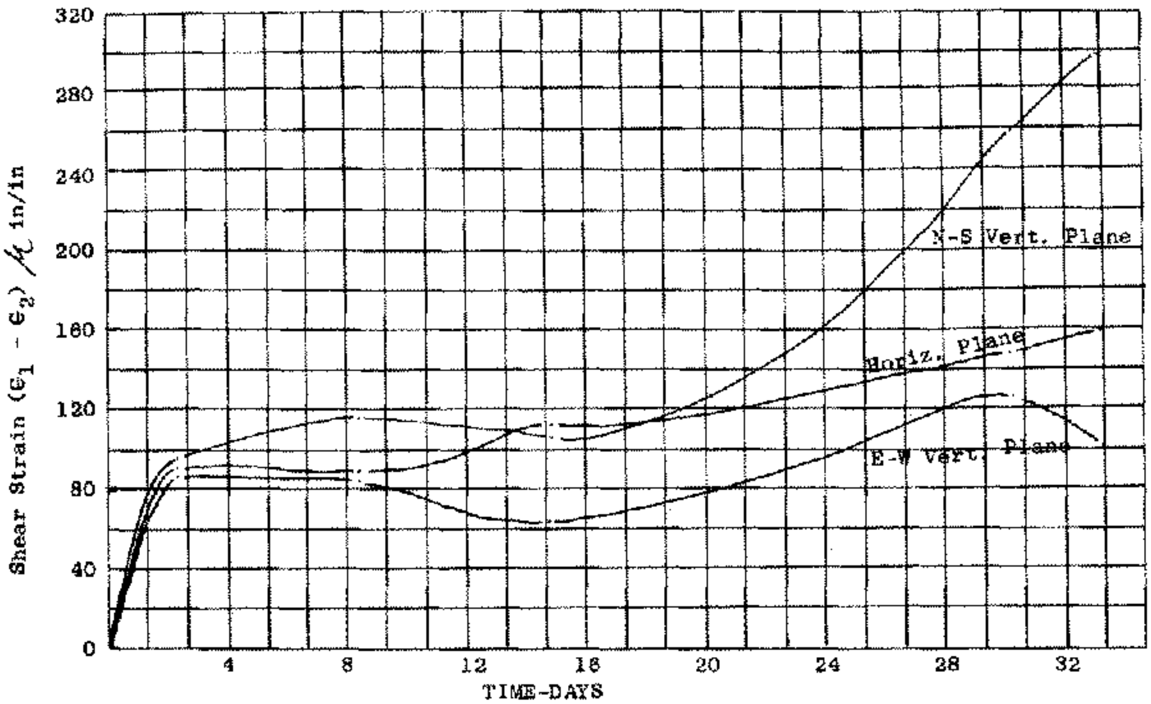

Figure 2. Typical Relaxation Rate -- Salt Sample.

The shear strain pattern is useful in two ways. First it gives the traces of the preferred shear plane families on each instrumental face and second, it aids in calculating the multiplication factor for the force field due to mine "geometry."

This "n" factor is an important part of the prestressed beam-column formula used to calculate room spans. Its determination involves the analysis of underground instrumentation as well as the relaxation rates from oriented samples. Disc "rings" (which consist of a two-inch diameter photoelastic gauge bonded to the salt at each corner of the opening as well as in the centre of the roof) are installed in the two mining directions. The shear strain magnitudes from these instruments can be compared directly with the shear strains measured on the appropriate planes of the oriented samples provided the instruments in both cases are installed at the same time after creation of a new face and are read during the same time interval. The following Table 3 summaries the shear strain readings from both sources. Results are presented for the horizontal plane as this plane is of greatest importance for span calculations in this type of deposit.

TABLE 3

Time-Dependent

Average Shear Strain Magnitudes

Plane of Measurement	Shear Strain -- μ in/in				
	Oriented Samples	Disc Rings			
		N -- S Rings		E -- W Rings	
		Disc C	Disc E	Disc C	Disc E
Horiz. Plane	120	813	783	323	1,095

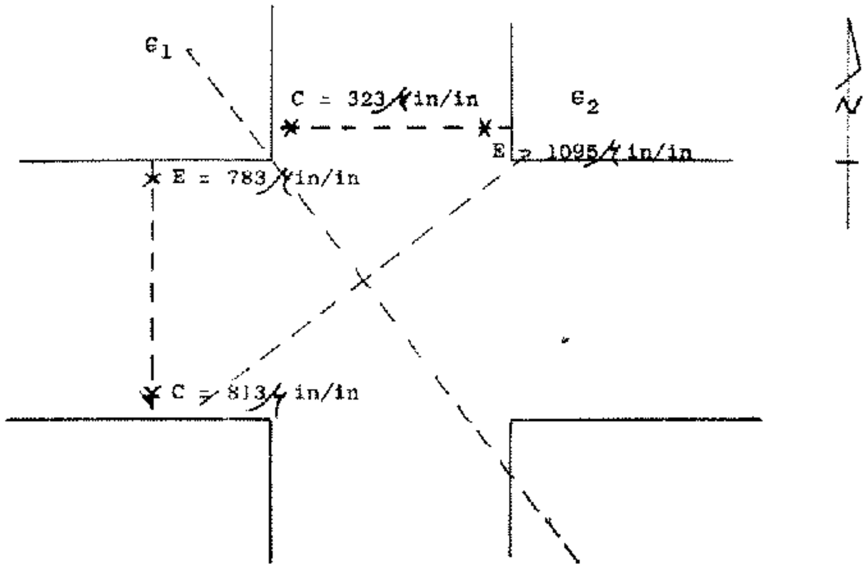

Figure 3. Typical Instrument Locations -- Plan View of Workings.

It is evident that the force field thrust can cause rotational moments to act on an opening if it is incorrectly oriented. One would expect the angle at the corner of the opening at E for the N-S ring and at C for the E-W ring to be opening and to have decreasing strain. The reverse should be true for the opposite corners of the openings. The shear strain readings confirm this concept. For design purposes the least value of shear strain was used in each case to provide a safety factor. The high compression corners at C for the N-S ring and at E for the E-W ring are not used because these high shear strain values represent the sum of shear strain energy due to relaxation into the opening and compression at the corners due to rotation of the opening. The values at the tension corners are conservative because relaxation into the openings is decreased by the tensional effect due to rotation.

The multiplication factors required were obtained by dividing the average inherent shear strain magnitude obtained from the oriented samples into the average shear strain values from disc E and disc C from the N-S and E-W rings respectively. The multiplication factor for openings of azimuth 135° is approximately six and for openings of azimuth 045° is three. The major strain direction has the largest multiplication factor because it has the greatest inherent shear strain.

The magnitudes of the individual strains, G_1 and G_2, were determined from the oriented samples. It must be understood that the values presented in Table 4 are a measure of the time-dependent elastically recoverable strains and hence are known to be conservative. The measured strains in the plastic are equal to the strains in the shale and can be converted into stresses for the shale by using the approximate physical constants. These measurements were done on the shale as the amount of prestress in this formation was required for structural design. The appropriate physical constants measured in the roof shale using the dynamic testing method developed by Obert, Windes and Duvall are $E = 12.88 \times 10^6$ p.s.i. and $\mu = 0.74$ for the 090° direction and $E = 11.40 \times 10^6$ p.s.i. and $\mu = 0.61$ for the 000° direction. All measurements were taken in the horizontal plane. The photoelastic theory applicable to this discussion can be found in (Emery, 1960) and (Roberts, 1962, pp. 583-596).

In calculating stresses from the measured strains the following should be considered:

1. The measured strains are a portion of the time-dependent reorientation strains and should be extrapolated back to zero time for a newly created face.
2. The immediate elastic rebound component has been lost by the act of preparing the sample.

TABLE 4

Average Time-Dependent Strain Magnitudes and Calculated Stresses

Roof Shale Samples

	Measured Strain Magnitudes μ in/in		Calculated Principal Stresses p. s. i.	
	G_1	G_2	G_1	G_2
Horizontal Plane	55	30	900	630

3. The material has different values of Young's Modulus and Poisson's ratio in different directions.
4. Young's Modulus varies with stress.
5. Strains in the plastic gauges are recalculated in terms of stresses in the gauges. These are then multiplied by a suitable factor to determine approximate stresses in the rock.

These factors will be considered in the section on mine design to arrive at more accurate figures for the probable inherent stresses in the rock. Only item 3 above has been used in the table.

MINE DESIGN

The first phase of the study was spent in determining the characteristics of the granular material affected by the mining operation. The knowledge of the rock movements was then used to modify the mine design and layout. The following sections explain how this was done and what the recommendations were.

Room and Pillar Orientation. To minimize rotational moments (Emery, 1964, p. 3), which can be one of the major reasons for rock failure, all mine openings and pillars should be oriented in one of the principal strain directions. Rooms and the long axis of the pillars should be aligned with the major strain direction and crosscuts and the short axis of pillars should be aligned with the minor strain directions. In this type of deposit it is only practical to orient these in the horizontal plane. The force field dip is small (about 20°) and so rotational moments are minimized and are resisted by the long axis of the pillars.

The oriented cores from the roof shale were taken primarily to provide the variation of the force field thrust on a minewide scale. The principal strain directions in the horizontal plane were plotted on a mine map and strain trajectories were prepared from this. The strain trajectory shown in Fig. 1 is a visual representation of how the roof shale is loaded. Since the roof shale movement, upon removal of restraint by mining, is what acts upon the pillars, the strain trajectory of the shale provides the room and pillar orientation directly.

The strain trajectory was determined from samples obtained from existing mine workings. To orient rooms and pillars at any location involved the extrapolation of the strain trajectory into the solid ahead of the mining face. On a statistical minewide basis, the statistically optimum room and long axis direction of pillars is 135° azimuth and crosscut direction is 045° azimuth.

The mine staff decided to implement these recommendations by opening panels at the southwest and northwest corners of the mine. The panels were started approximately 3, 400 feet apart. The northwest panel was advanced toward the northwest with crosscut faces advancing in this direction. The southwest panel was advanced with room faces moving towards the southwest. To check on the variation of the principal strains as mining progressed in these panels, disc rings were installed at appropriate intervals. The data obtained from these instruments showed where and by how much the force field had turned from the average direction determined. They also measured the amount of variation in direction needed to increase the rotational moments to cause failure.

Room Span Calculation. Details of the beam-column theory used in this section to calculate safe room and crosscut spans are to be found in (Smith, 1963, p. 27).

The beam-column is visualized as a flat slab of rock in the roof of an opening with effective depth equal to the rock bolt lengths used or to the depth of some competent bed above the roof. The worst possible case would be to consider uniformly loaded, simply supported beams of one foot width, placed side by side and supported or loaded on the ends by the force field prestress. Using these conditions, a safety factor is immediately provided as the roof material is almost never simply supported. These conditions are illustrated in Fig. 4.

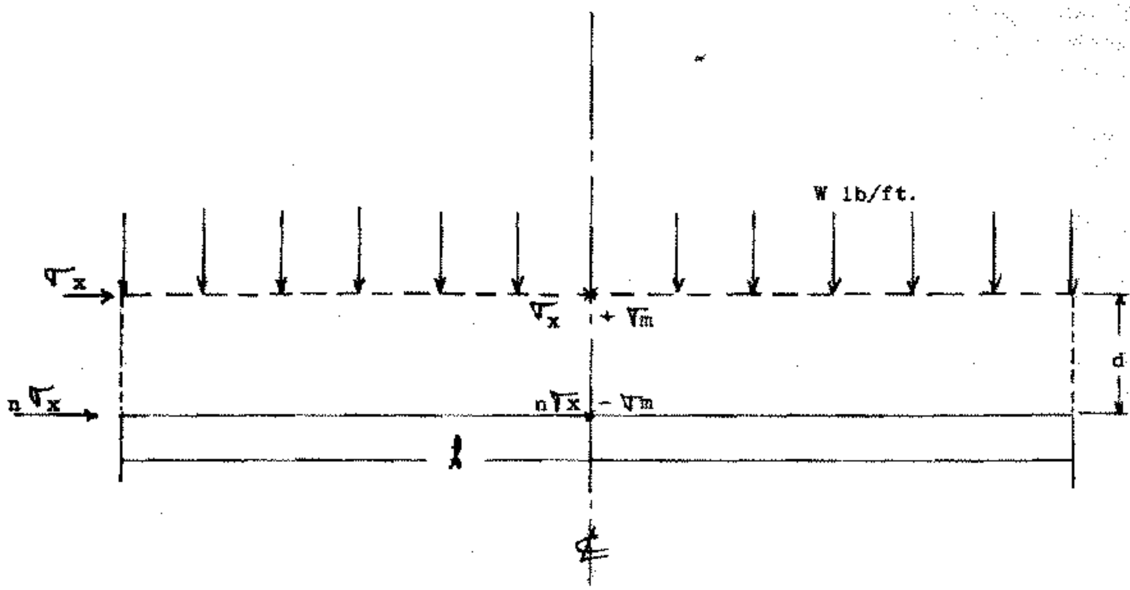

Figure 4. Uniformly Loaded Prestressed Beam-Column.

τ m is the extreme fibre stress due to the uniform load of the beam and $\tau m = \pm \frac{Mc}{I}$ where $M = \frac{Wl^2}{8} \times 12$ in.-lb. and $\frac{I}{c} = \frac{bd^2}{6}$ where b and d are in inches. The inherent force field, τ x, is multiplied by a factor n due to the geometry of the opening. Theoretically, n should be infinity at the corners but in actual practice the rock flows and readjusts to within its yield point. For stability and to reduce high horizontal shears in this beam, the span is adjusted such that the top and bottom extreme fibres are strained an equal amount. This is expressed by $n\,\tau x - \tau m = \tau x + \tau m$. The variables n and τx are measured underground and so this equation can be solved for τ m. But $\tau m = \pm \frac{Mc}{I} = \pm \frac{Wl^2}{8} \times 12 \times \frac{6}{bd^2}$.

Solving this equation for ℓ one obtains:

$$\ell = \sqrt{\frac{\tau m \times 8 \times bd^2}{W \times 12 \times 6}} \text{ ft.}$$

The effect of geometry was determined from disc rings installed on salt. It was considered safe to use these factors for the roof shale after comparing the physical properties of salt and shale. The multiplication factor of n = 6 for openings of azimuth 135° and n = 3 openings of azimuth 045° will be used.

The roof shale is hard, competent and interbedded with thin salt stringers and beds. There is a good parting in the shale, about four feet above the shale-salt contact. When the "skin" of salt left on the roof gets too thin, bolts are used to tie it to the shale. The beam depth will be considered as four feet because this is the approximated shale bed thickness and if bolting is required four bolts should be used.

The sonic tests required the determination of the shale density. This was found to be 130 lb./cu.ft. and hence for a beam one foot wide and four feet deep this means a uniform load of 720 lb./ft. of beam.

The measured field force τx was determined from oriented hand samples and hence reflec short time relaxation strain only. The variations of Young's Modulus and Poisson's ratio under r load have been considered in calculating τ_1 = 900 p.s.i. and τ_2 = 630 p.s.i. from the measure strains. These strains should be extrapolated back to zero time in order to attain a more accura time-dependent strain magnitude. An examination of the short time relaxation rates for the roof shale samples provided a multiplication factor of 1.25 for the time-dependent strains. An examp of a relaxation graph is given in Fig. 2. The immediate inherent elastic rebound of the shale wa not measured by the photoelastic gauges due to the method of analysis. Overcoring techniques us on similar materials tested indicated that the elastic rebound was approximately one-fourth of th total inherent strain energy. The time-dependent strains should then be multiplied by a factor of 1.33 to obtain a more accurate figure. It is an established fact that Young's Modulus increases with applied load. Since this figure was determined under a no load condition a factor must be ap plied to compensate. Experience indicated that a reasonable figure for this type of material was a 1.33 increase in Young's Modulus due to a load of the magnitude measured. Probable values of τ_1 and τ_2 are 900 × 1.3 × 1.3 × 1.25 and 630 × 1.3 × 1.3 × 125 respectively. The values used i the following calculations are τ_1 = 1,900 p.s.i. and τ_2 = 1,330 p.s.i.

Spans of rooms running in the 045° direction (supported by the major strain) are calculated as follows:

$n = 6 \qquad W = 720$ lb./ft. $\qquad d = 48$ inches

$b = 12$ inches $\qquad \tau_1 = 1{,}900$ p.s.i.

$$n \tau x - \tau m = \tau x + \tau m$$

$$m = \frac{n \tau x - \tau x}{2}$$

$$= \frac{6 \times 1{,}900 - 1{,}900}{2}$$

$$= 4{,}750 \text{ p.s.i.}$$

$$l = \sqrt{\frac{\tau m \times 8 \times bd^2}{W \times 12 \times 6}}$$

$$= \sqrt{\frac{4{,}750 \times 8 \times 12 \times 48^2}{720 \times 12 \times 6}}$$

$$l = 142 \text{ ft.}$$

Similarly, the calculated span of the proposed crosscuts running in an azimuth of 135° is calculated.

$$n \tau x - \tau m = \tau x + \tau m.$$

$$\tau m = \frac{n \tau x - \tau x}{2} = \frac{3 \times 1{,}330 - 1{,}330}{2} = 1{,}330 \text{ p.s.i.}$$

$$l = \sqrt{\frac{1{,}330 \times 8 \times 12 \times 48^2}{720 \times 12 \times 6}}$$

$$l = 75 \text{ ft.}$$

The measured spans of 142 and 75 feet are considered conservative. These spans would be safe only if the rooms are driven in the principal strain directions. Due to the problem of maintaining a clean, unbroken back to aid in beam stability, it is imperative that the faces be advanced uniformly. In other words, the whole breast, after undercutting, should be drilled off and blasted at one time. The best sequence would be to drive the rooms ahead of the crosscuts so that beam equilibrium could be established before the crosscut mining disturbed the condition.

Pillar Size. The regional force field thrusts from the northwest to the southeast at about 20°. For maximum stability, the long axis of pillars should run in this direction to offset the overturning moment of the force field caused by the downward dip. The pillar should have sufficient mass so that it doesn't crush and also so that it doesn't punch into the roof or floor. These things are possible depending upon the pillar size and relative hardness and strengths of the roof, ore, and floor materials. A physical examination of the mine showed that there was no pillar failure as such. The only evidence of failure was noted at pillar corners and this was attributed to rotation of the pillar caused by improper orientation. The size of the pillars in the older sections of the mine is 100 feet by 100 feet. The dimensions of the pillar should be in relation to the ratio of the principal strains. In this case, the ratio of the principal strains is 1.43:1. If the long axis of the pillars is 100 feet, then the short axis should be 70 feet. It was felt that this would provide a pillar with sufficient mass in the correct direction to withstand the forces acting upon it. Recommended pillar sizes, provided they are oriented correctly, are 100 feet by 70 feet. Since this study, more sophisticated means of calculating pillar sizes have been developed. Using these methods, the above mentioned size is still considered safe.

General. Preferred shear planes can be utilized in determining the best direction of mining, fragmentation, and ease of break as well as to aid in designing restraint in the form of rock bolts. In this particular case there are two families of preferred shear planes roughly parallel to the proposed room and crosscut direction. Because of this and their dips, good fragmentation should result in both directions. Whether the rooms are driven in an azimuth of 045° or in 225° should make no difference to the fragmentation and drilling rates. However, crosscuts should be driven in an azimuth of 125° and not 315°. In this way, the force field thrust will be cut off and the drilling rates should improve. For optimum fragmentation, drill holes should be drilled perpendicular to preferred shear planes. In this way, explosive energy adds to the high inherent shears in a wedging action.

Consider restraint. These same preferred shear planes or planes of inherent weakness, if their attitudes in relation to mine openings produce a low angle, can be the source of shear failure in roof, floor and pillars. To prevent this, short high tensile steel rock bolts should be placed in holes drilled perpendicular to the planes of preferred shear. These bolts should be placed in rows along the strike of these planes. For rooms, the azimuth of these rows should be about 060°. A compromise direction for the bolts would be to place them vertically to allow for all families of planes.

SUMMARY OF RECOMMENDATIONS

1. On a minewide basis the rooms should be driven in an 045° direction and crosscuts driven in a 135° direction. These directions should be altered locally to conform to the strain trajectory variations.
2. The calculated safe mining width for rooms is 140 feet and for crosscuts is 75 feet.
3. Salt pillars should be oriented with their long axis parallel to azimuth 135° and their size should not be smaller than 100 feet by 70 feet.
4. Rooms could be driven in 045° or in 225° directions without altering fragmentation, drilling rates, and powder costs. Crosscuts should be driven in 135° direction only. An improvement should be noted in drilling rate and powder cost.
5. Mining faces should be advanced uniformly and each round of advance should be blasted at one time. Rooms should be driven ahead of crosscuts.
6. If rock bolts are required they should be placed vertically in rows parallel to the azimuths of the preferred shear planes. Short bolts will be more effective than long bolts.

RESULTS OF TEST PANEL MINING

The mine management, treating this study as a research project decided to evaluate each major recommendation separately. During 1964 a test panel shown in Fig. 5 was started from the southwest corner of that mine. This panel was laid out in the recommended directions of 135° and 045° azimuth but nothing further was changed. The following results show the effect of changing directions only.

During the first two months of mining this section the following changes were noted by underground supervision:

1. Slightly faster drilling rates.
2. Better fragmentation and lower powder factor.
3. Less bootleg and angle of faces more nearly vertical.
4. No floor heaving. This was the longest time an area had been open without some evidence of floor heaving.
5. Roof control and pillar slabbing reduced.
6. Both rooms and crosscuts have squarer corners and the ribs are more uniform.
7. An average of 50 tons per round increase in break was noted.
8. The corners of the pillars still slabbed, but incidence and size of slabs reduced.

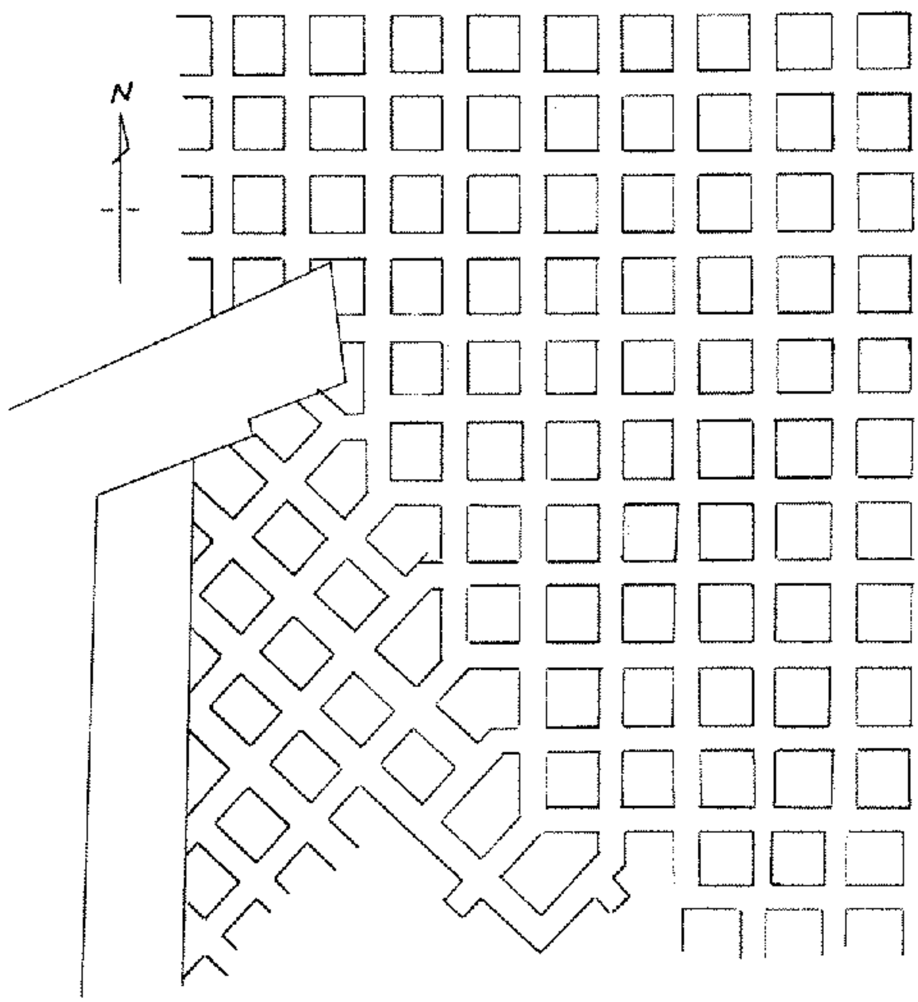

Figure 5. Test Panel Mining Layout, Fairport Mine, Morton Salt Company.

As mining advanced towards the west some floor heaving developed in several sections. These heaves had their axes parallel to the room and crosscut directions and were not at an approximate 45° angle as in the older mining method of N-S and E-W drives. The correct alignment of rooms and crosscuts does not eliminate the forces causing such failure, it merely eliminates the moments acting on the roof and floor slabs. The changing of directions did not completely eliminate floor heaving. To do this required the use of wider spans and larger pillar combinations as well as correct directions.

Several mine openings were instrumented with bolt tension meters and disc rings to determine whether the openings were being driven in the optimum direction. The measurements indicate that statistically the panel is in the correct direction but locally some portions of openings are a little off. A significant thing is that the bolt tension meters are recording much higher readings in this new panel in the same relative period of time than instruments in the older parts of the mine. This indicates that the salt bed has increased inherent energy characteristics in this region. In the conventional mining directions, floor heaves are occurring two to three rounds back from the face.

It became important to consider wider rooms and crosscuts as well as larger pillars. Mine management are currently planning such changes in the near future. To provide some data for such changes, in 1965, four rooms were widened to 50 feet. The floors have not heaved in the rooms as yet but they have not been opened long enough to draw positive conclusions.

During the past year some tests were conducted by the mine staff to improve the blasting efficiency and powder requirements. The overall results of the rock mechanics study include these results. The overall results of all changes incorporated during the past year and a half can be summarized as follows:

1. Better fragmentation and lower powder factor.
2. Less bootleg and angle of faces more nearly vertical.
3. Openings have squarer corners and more uniform ribs.
4. Pillar corners squarer with less slabbing.
5. Overall decrease in maintenance and scaling costs.
6. Average increase in tons broken per round is 40 to 50 tons.
7. Floor heaving is continuing but at a reduced rate. Where it occurs the axes of the heaves are parallel to the room and crosscut directions, proving the directions are correct.

LIST OF REFERENCES

Emery, C.L., 1960, Photoelastic Coatings on Granular Materials: Institute of Physics, London, England.

Emery, C.L., 1964, "In Situ" Measurements Applied to Mine Design, Rock Mechanics Symposium, Missouri School of Mines, Rolla, October 1964.

Roberts, A., Emery, C.L., and Chakravarty, P.K., Photoelastic Coating Technique Applied to Research in Rock Mechanics, Trans. Institute Mining and Metallurgical, vol. 71, part 10, 1961-62, pp. 583-596.

Smith, J.D., 1963, The Condition of Stress Surrounding a Simulated Mine Opening, Proc. Rock Mechanics Symposium, Queen's University, December 6-7, 1963, p. 27.