Rock Mechanics—Can It Pay Its Way?

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ABSTRACT

The decision to apply any of the tools or techniques of rock mechanics to a mining operation must be made on the same basis as any other engineering decision. The basic criteria are economy and efficiency. Mine operators lack information about what is available in rock mechanics and the returns which reasonably can be expected.

Theoretical elastic analysis and laboratory physical specimen testing can be used to predict rock response to excavation and to indicate potential problem areas. Because of the geologic complexity of rock masses instrumentation must be used to measure the actual response of a rock mass.

The greatest potential dollars and cents application today is probably measurement verification of existing mine designs. It is not necessary to accept a room and pillar pattern as the best optimum design. Pillar sizes and roof spans can be tested, changed, and tested again. Effectiveness of support reinforcement as well as its design can be determined. A proper program of rock mechanics serves also to detect impending failure.

As a statistician might say, "Rock mechanics is the combination of two mutually exclusive conditions."

Rock is a complex material, which ranges from imperfectly elastic to imperfectly plastic. The best that can be said is that while some rocks approach ideal materials the majority, if not all, conform to the "Universal law of natural cussedness." Whenever we look at a rock we must remember we are looking at one instant in its geologic history. Conclusions must be drawn for a material which has undergone millions of years of environmental conditioning which is unknown, or at best only dimly perceived.

Mechanics, on the other hand, is ideally the engineering application of elasticity. The goal of mechanics is the rigorous mathematical solution of engineering structures.

I am moved to quote from my notes from the first lecture of Hank Babcock in his elasticity course (Babcock, 1965). "If the world had waited for the elasticians to solve the mechanics of a beam, man would still be living in caves!" To which I would add ". . . . and, he wouldn't know why the roof stayed up."

Someday rock mechanics will offer rigorous solutions to mining problems. It offers some approximate solutions to the practical mining man with a problem today. The practical mining man with a problem is perfectly willing to accept an approximate answer to some simple question like "How can we stop these . . . . roof falls?" As a matter of fact, the miner would be pleased to know where and when the next roof fall was going to occur. These are the areas where rock mechanics can be, has been, and is of great potential value.

Let me take the time for an example of the development of one such acceptable approximate solution. The problem was selecting depths and widths of underground openings such that convergence would not force the removal of an 8-ft. high building in a 15-ft. high opening for at least 5 years. THAT is convergence. We had to come up with a set of equations to relate depth, to room width, to convergence rate (Abel, 1961). Figure 1 shows one of the sets of curves we developed from

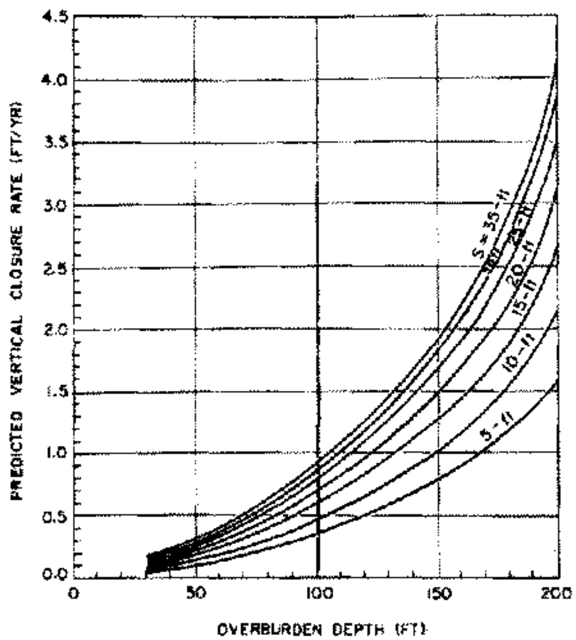

Figure 1. Predicted vertical closure rates. Prediction equation: (Abel, 1961)

$$CR_v = \sqrt{S}(8.77 \times 10^{-4} H + 6.56 \times 10^{-8} H_3)$$

S = Span; H = Depth

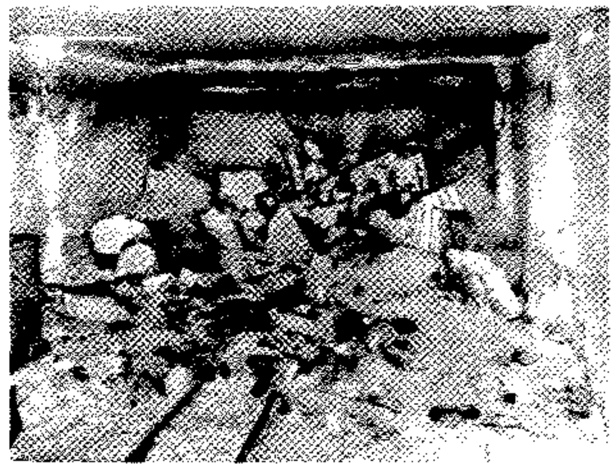

Figure 2. Ice tunnel as driven (12 ft. wide by 7 1/2 feet high).

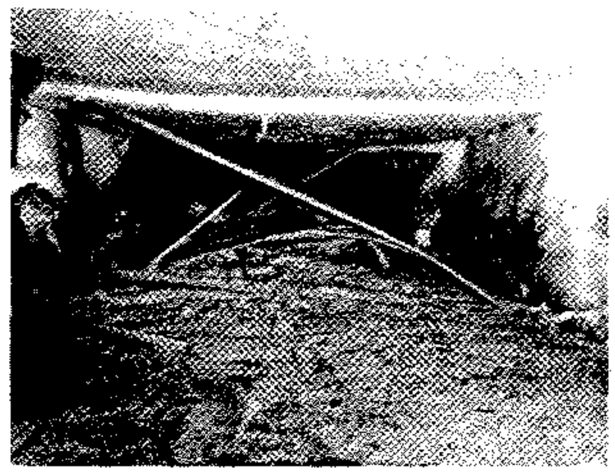

Figure 3. Standard tunnel section 2 years after mining, depth 170 ft., average 1 1/2 ft/yr convergence rate.

Figure 4. Standard tunnel section 2 years after mining, depth 208 ft., average 2 1/2 ft/yr convergence rate.

a six-month convergence measurement program. Our approximate equation of relationship was infinitely far from a rigorous mechanical solution. We were only able to predict the convergence rate to a standard error of plus or minus 0.09 ft/yr.

The error is easily explained. We were working in an almost ideal rock, ice; but we were unable to make a precise prediction of convergence rate because of the influence of impurities in the ice. Figure 2 shows a part of one of the experimental tunnels. Notice the banding in the walls of this tunnel. Figures 3 and 4 show sections of this same tunnel after two years. The inward wall movement is variable. The movement rate was dependent on the percentage of debris in the individual beds. To put this another way, the geologic variations in the rock influenced its response.

In this business we never seem to be able to obtain an exact solution. We are bedeviled by geologic variations and approximate answers. This need not necessarily affect the application of rock mechanics, so long as the errors involved are both known and acceptable.

The history of rock mechanics is really a record of observational hypotheses which were tested by measurements to prove or disprove them. Fayol (1885) proposed an observational theory of harmless depth in 1885 (Fig. 5). His theory was that if the opening were small enough and (or) deep enough the surface would not be affected. Precise surface measurements have been demonstrating the error of that theory almost ever since. But his

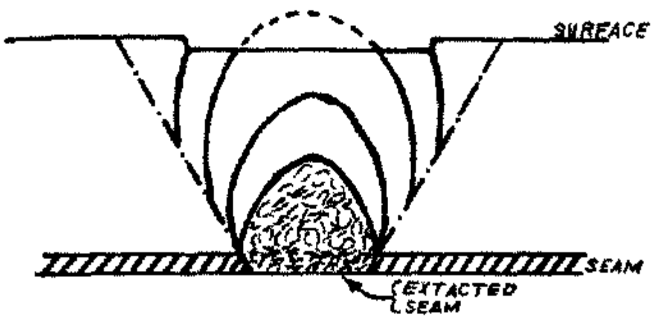

Figure 5a. Arch-collapse theory of Fayol (1885).

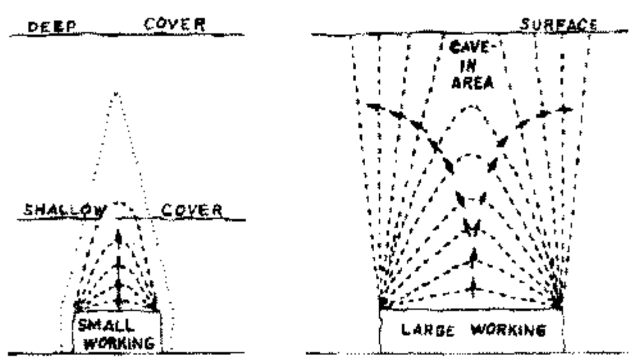

Figure 5b. Vertical section, showing how failure of roof of workings affects overlying rock. (Modified from IC 6501; Crane, W.R., 1931).

theory still lives (Crane, 1931). There may be no engineering consequences but the surface responds to any excavation. No damage means harmless, right? The evidence to disprove Fayol's theory came as the result of damage to buildings on the surface above and outward from mine workings (Dartmund Board of Mines, 1897). Measurements by men in the field supplied the evidence, in this case to disprove a theory based on initial superficial observational field evidence.

Scholarly arguments are going on today in rock mechanics. Many are relatively pointless academic discussions to operators. One such controversy, or tempest in a teapot, concerns the theories of how the rock loads are carried across the workings at a longwall face comes closest to matching field evidence.

Haack (1928) proposed a "two abutment theory" based on the observation of damage in galleries driven in the solid coal ahead of and in roadways maintained through the cave area behind longwall faces. Figure 6 shows Haack's theory. It was based on the distress observed in mine supports ahead of and behind a longwall face. The "two abutment theory" assumes the load from above the working area is transferred in both directions, ahead of and behind the longwall face.

Several investigators questioned the existence of the rear abutment assuming instead that the beam in the roof was cantilevered out from the solid face, and not fixed at its ends, as it would be in the "two abutment theory." Precise survey measure-

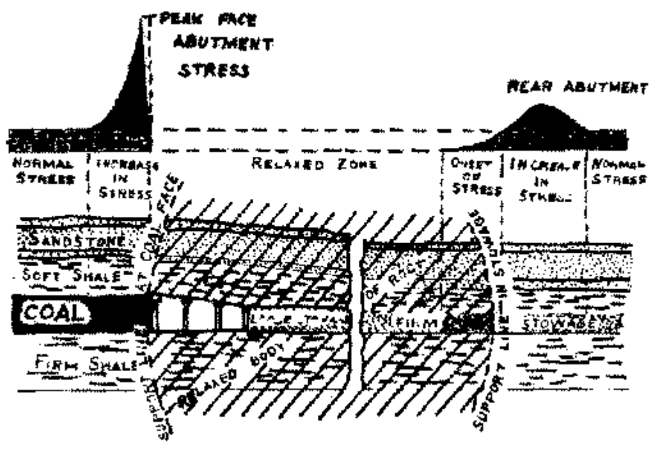

Figure 6. The pressure vault or arch with abutments. (Modified from Haak, 1928).

ments by various investigators, including Grond's (1957), shown on Figure 7, lent some support to this cantilever or "face abutment theory." The support distress zone in the cave area using this theory merely coincides with the zone of maximum reconsolidation of the caved material as it picks up the overlying rock load shed by the progressively collapsing cantilevered roof beam. What operator really cares? He must live through all of it anyhow, both distress zones!

The difficulty in obtaining rock load measurements in the cave area has prevented the resolution of this controversy. At this time we have only one set of reported measurements, Jacobi's, (1956) shown on Figure 8. This set of results tends to confirm the cantilever concept. We await more measurements.

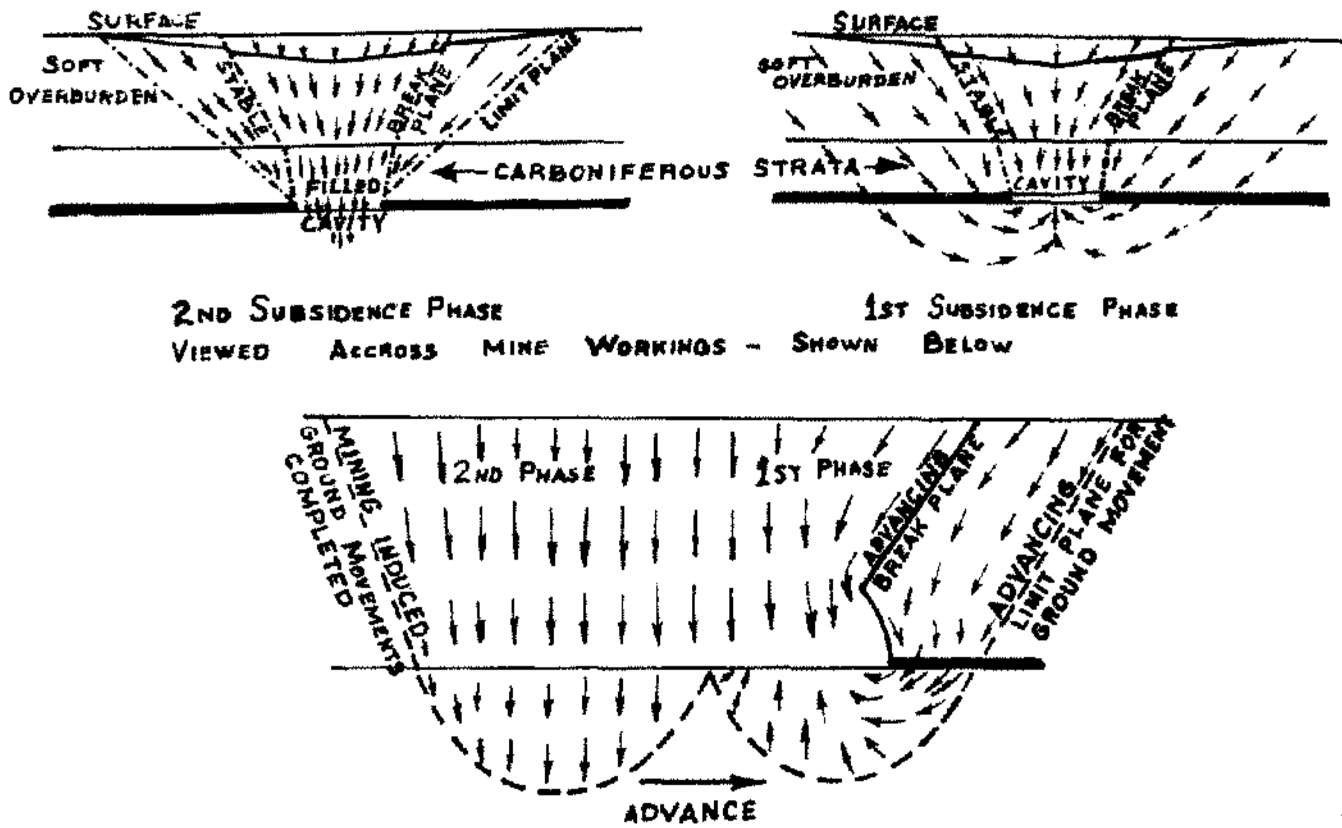

Figure 7. Movement trajectories around a longwall face. (Modified from Grond, 1957).

The first published paper on rock mechanics applied to salt is probably Bernard Busch's (1907) where he reported on borehole deformation measurements made in 1899 and 1900. One is tempted to guess why he waited seven years to report. He had obviously hoped to measure the convergence rate for an entire mining level with a very limited number of measurements of borehole closure. He obtained some very informative and valuable measurements, but not the ones he sought. He showed that the deformation of the salt into boreholes varied from location to location within any borehole and on the level and that at any given location the deformation rate for the salt decreased with time.

Subsequent investigations have demonstrated other valuable facts about the response of salt to mining. Mohr (1956) measured the apparent stresses in salt pillars and demonstrated stress concentrations near their edges, such as would be predicted elastically (Fig 9.). Potts (1964) reported similar results from other measurements (Fig. 10). The report of Baar (1953) and McClain (1964) presented evidence to verify the elastic prediction that movements induced by mining are present in the rock below salt mine workings as well as above the mining horizon.

The measurement programs cited have been helpful in understanding the response of salt and associated strata to mining. They have been used to estimate in a qualitative manner the deformational response of these rocks under changed, or different, stress conditions. If we stay in the same geologic environment, real, economic use can be made of the results. For example Mohr's and Potts' peak stress levels indicate the true short-term load carrying capability of the pillar. It should at least be possible to temporarily raise the stress in any particular pillars to the peak level measured in that pillar. This opens up the prospect of controlling pillar sizes, and that means dollars!

This brings us to the concept of buying time in which to complete any particular part of the mining plan. In the case of a room and pillar salt mine, various pillars must stand different periods of time. Room pillars must stand long enough to mine out the salt in the particular panel. Main entry pillars must stand the life of the mine. Failure of either

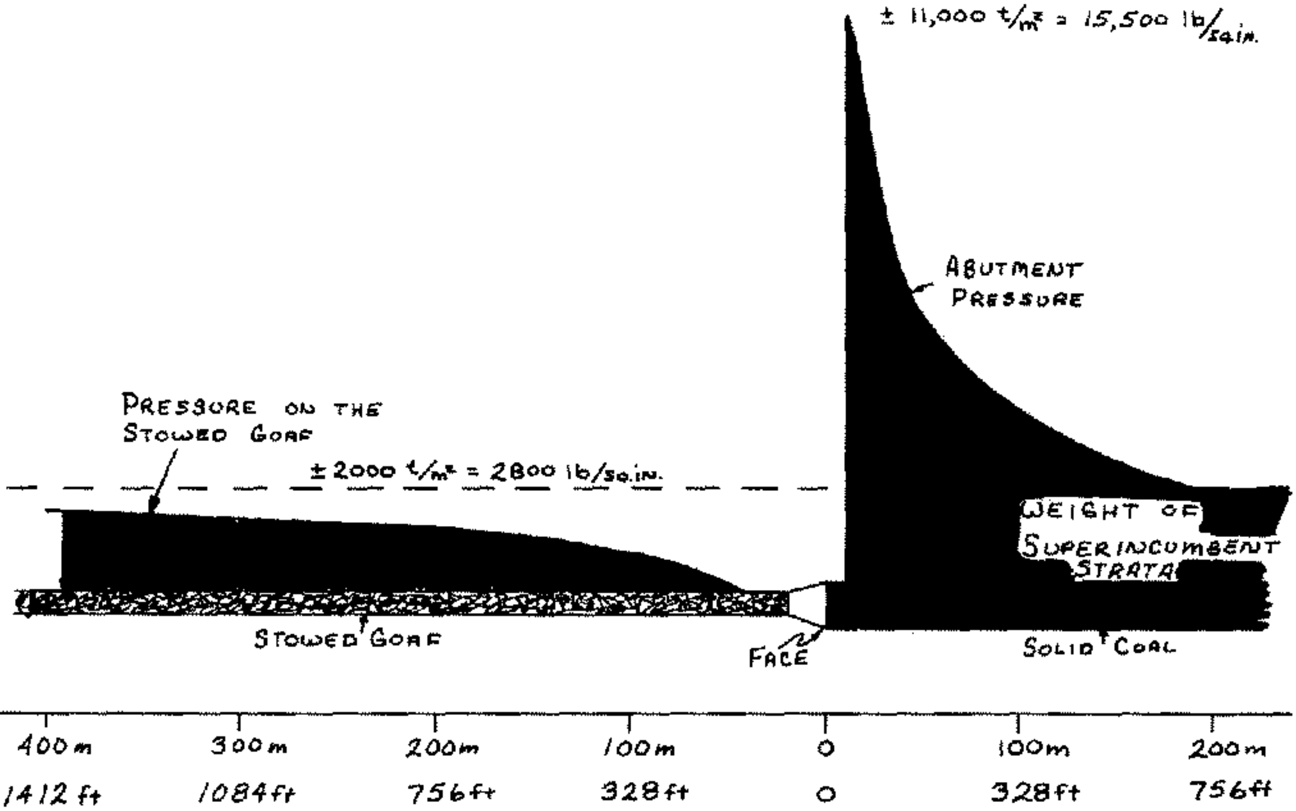

Figure 8. Pressure measurements Girondelle Seam Neumühl Colliery (after Denkhaus, 1965).

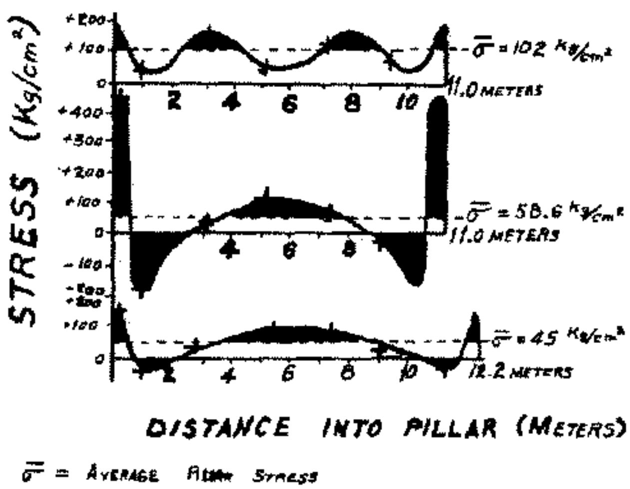

Figure 9. Stress Profiles for three pillars in rock salt—strain gage overcoring (Modified from Mohr, 1900).

type of pillar after its usefulness is complete does not usually represent a hazard. Two diagrams (Figs. 11 and 12) represent this concept, even if determined only for physical test specimens in the laboratory. The critical point here is the ability to predict approaching failure by measureable acceleration prior to failure. Unfortunately, this does not appear to be the universal situation, even for such a relatively non-elastic material as salt. Particular salts burst as well as creep. The ice shown in Figure 13 demonstrates that even ice can be pushed too hard, and that brittle failure and plastic flow can take place side by side.

Figure 14 is a representation I have for rock. It is the result more of theft than originality, but, I feel it has been instructive to develop a feeling for what is rock. Failure of a particular rock may skip one part of this stress strain curve. With salt the elastic zone is drastically limited in extent; whereas, the progressive deterioration zone and the acceleration zone are extensive.

The response of a rock specimen in the lab can differ drastically from rock mass response to a major mined opening. For one thing the specimen in the lab starts in an unloaded condition; the rock in the field is pre-loaded, or pre-stressed. The mined opening changes the previous stress field.

Secondly, the magnitude and direction of stresses applied to a specimen are known. In the vicinity of a mining operation the actual three-dimensional stress field is usually only estimated. It can be measured, but at a price. Finally, the laboratory

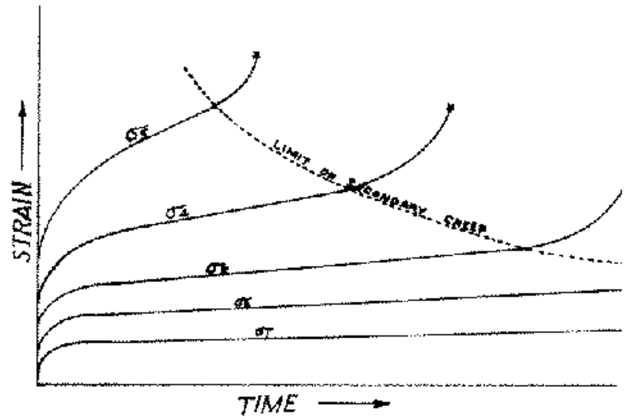

Figure 12. Deriviation of "time-safe strain" (McClain, 1963).

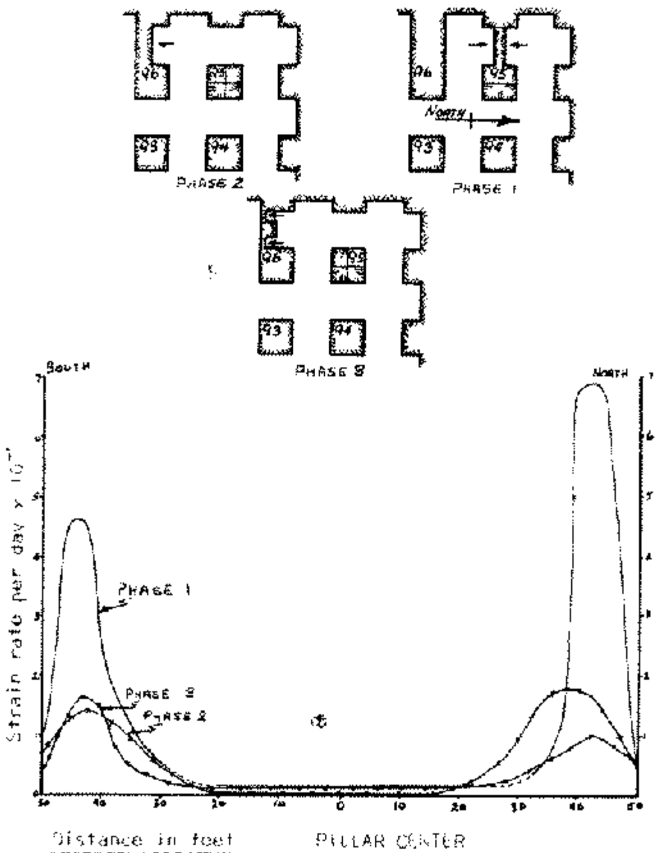

Figure 10. Strain rate measurements in pillar 95 (after Potts, 1964).

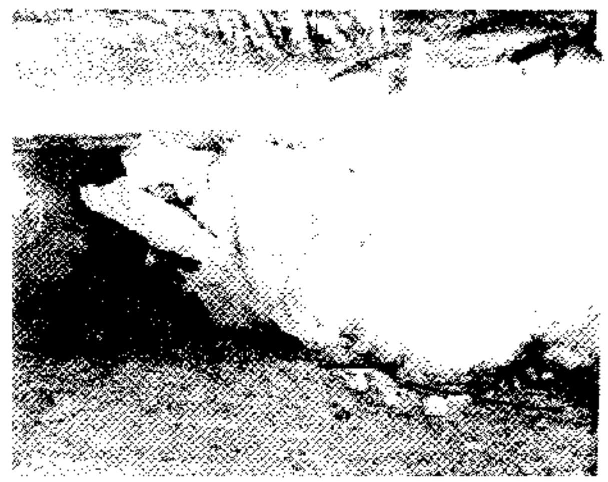

Figure 13. Combined brittle failure and plastic flowage on pillar point in ice, original opening height 7 1/2 ft., depth 200 ft.

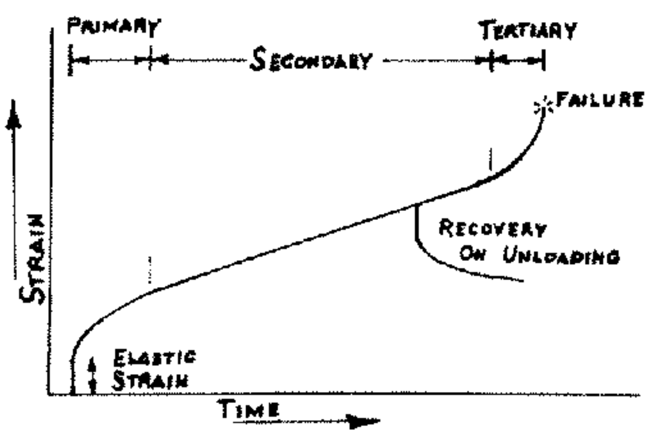

Figure 11. Generalized creep curve for sediments and evaporites. (Modified from Potts, 1964).

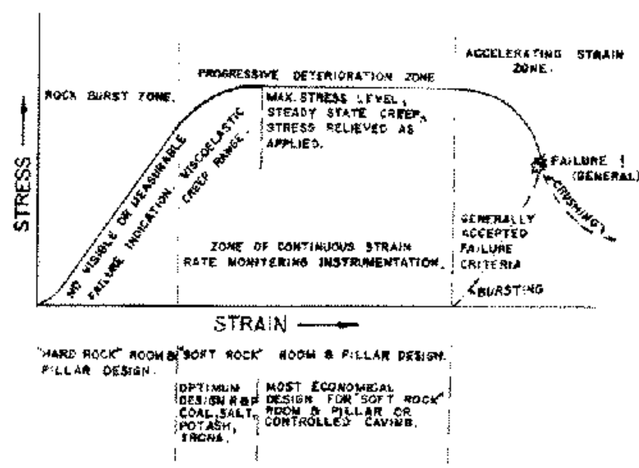

Figure 14. Rock Representation.

rock specimen is restricted in size; it cannot contain any but the smallest of the weaknesses in the rock mass. This problem is not so serious with a lab specimen of rock salt since generally the mass of rock salt is not extensively fractured. Rock salt does occasionally contain such features as old fractures filled with pure crystalline salt, anhydrite bands, and clay partings; these features may locally change the load-carrying capacity of the mass. It has been demonstrated that changes in the crystal size can drastically change the strength of evaporite specimens.

Theoretical analysis and physical testing can provide advance information about a planned mining operation. It is possible to predict which salt bed or what part of a salt bed is more prone to deformation or failure. Geometric shapes of openings and mining layouts which produce high stress concentrations can be avoided. How much is this worth?

If the mining operation is already underway a theoretical analysis and physical testing program can define the sequence of a complex failure pattern. The pillars may be expanding and putting an axial load on the salt in the roof causing it to buckle. The salt/marl contact at the base of the pillars may, on the other hand, provide a lubricated surface on which the pillars expand and deteriorate, ultimately destroying the roof beam. Rock reinforcement can be directed to buy time at the critical part of the structure, provided you have an idea what part is critical.

To reiterate: (1) Theoretical elastic analysis can be employed to estimate where high stress locations are probable. (2) Physical specimen testing can be employed to indicate where rock strength is low, or where viscoelastic mobility is high. The combination of stress and strength, or creep rate, in the case of salt, is critical to the stability of a mine opening.

There comes a time in any program or rock mechanics when the tie and white coat have to come off, and one must prove the predictions in the mine. This means instrumentation. The best preliminary mine design has a lot of fat. Many factors of uncertainty are involved in selecting room widths and pillar sizes.

With various instrumentation techniques available it is possible to verify how good the mine design is.

A case can be made for or aginst any particular type of instrumentation, or instrument. My experience, and that of many others, indicates that different instrumentation techniques produce strikingly similar results when applied to the same mining problem. This results naturally from measuring the same rock mass response by different means. In any case, my purpose here is to describe the application of instruments for certifying a mine design, not to argue their individual merits.

INSTRUMENTATION

Instrumentation techniques are dead simple. They generally consist of periodic precise measurement of the distance between two points, or the measurement of the load being carried by a support. The real problems are encountered in the installation, the protection, and the maintenance of instruments.

Internal instrumentation.

The largest, simplest, and most useful group of instruments are those designed to be used inside underground openings. There are two classes of these: those which measure the distance between the points on the exposed rock around the opening and those which measure loads on supports. Typical locations for these internal instruments can be seen on Figure 15. Results from such a group of surface strain measurements is shown on Figure 16.

Opening convergence is determined from periodic precision measurements of the distance between anchors placed in the rock on opposite sides of an opening (Fig. 17). Surface rock strains are determined from similar periodic measurements of the distance between anchors along the same surface of the opening. Support loads are commonly measured by inserting load cells between the

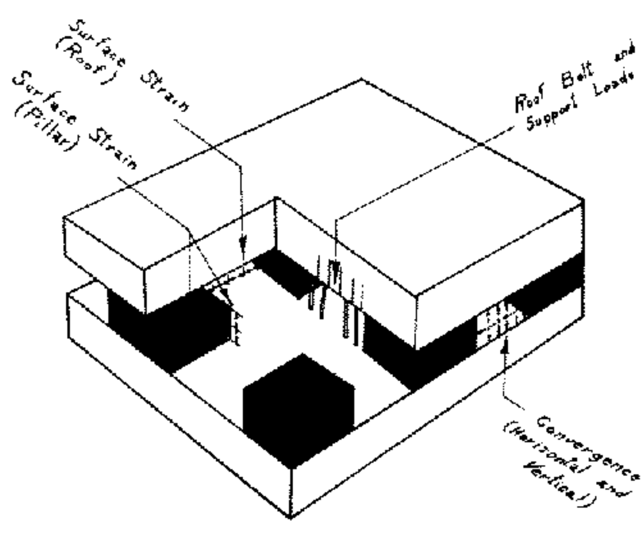

Figure 15. Internal rock mechanics instrumentation. (Abel, 1966).

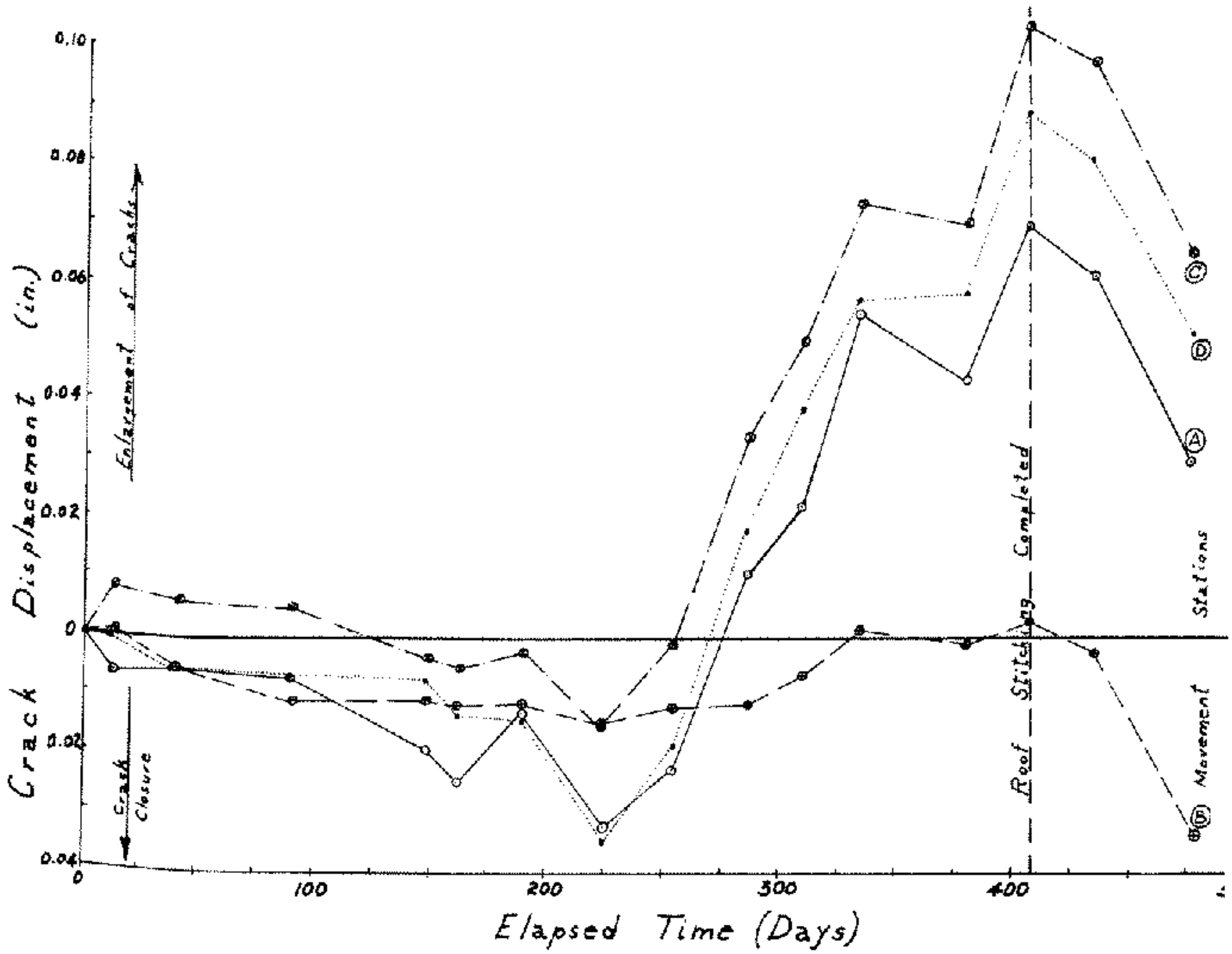

Figure 16. Crack movement histories (Abel, 1966).

support and the rock. This is generally true for steel, timber, or rock bolt supports (Fig. 18).

Convergence and surface measurements made at intervals permit a calculation of either the rock deformation or the rock displacement rate, and the acceleration or deceleration of the rock exposed at the walls of the excavation. Of course, the rock adjacent to an excavation indicates the stability of the basic structure only if continuity exists between the rock exposed and that at depth, within the pillar or roof.

The support load measurements are related to the design load for the particular support. Accurate support load measurements have been employed for research and support design in England since the early 1950's. More rough and ready load measurements were made on tunnel supports by Karl Terzaghi in Austria in the 1920's.

External instrumentation.

The development of borehole instruments in th 1950's permitted the monitoring of the dynami rock response to mining operations that occurs a depth into the rock and external to the opening These types of instruments give us a chance to lool into a pillar, the back, or floor and see how an where "it" is carrying the imposed load.

The two basic types of borehole instrument (Fig. 19) measure either the axial extension of al or a portion of a drillhole or the change in diam eter of one point in a drillhole.

The simplest and most valuable of these instru ments is the single position type of borehole ex tensometer. Such extensometers measure axia movements of the rock between the toe and th collar of the borehole (Fig. 20). Since the to

a. Extension rod method. b. Steel tape method. c. Dial indicator method.

Figure 17a. Tunnel closure measurement methods. (Abel, 1961).

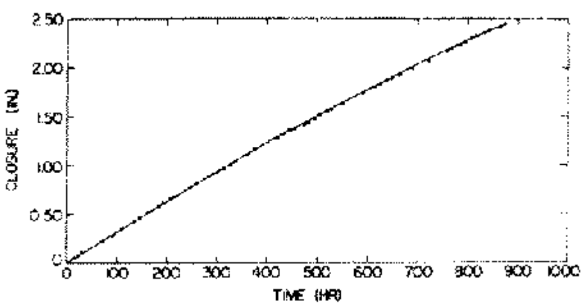

Figure 17b. Vertical closure in center of 32-ft. experimental room. The downward curve indicates the decreasing closure rate as the result of decrease in size of the room due to the closure. (From Butkovich, 1969, p. 14).

anchor of such a device can be some distance from the borehole collar (Potts has reported employing these instruments in 700-ft. drillholes) a considerable zone of rock can be checked, for stability or instability, by such a device. One drawback of this group of instruments is the expense of the drillhole. The results must, at least partially, justify the cost. The geologic information gained from the borehole will also have a value.

A logical extension of the single-position borehole extensometer was the placement of several anchors in the same borehole. This permits the measurement of axial rock displacements at several positions along a single borehole (Fig. 21). From such measurements strain variation along the borehole can be calculated: indicating such things as bed separation locations within the roof, variations in rock competency or active sliding surfaces—in addition to the general reading or stability or instability as measured by a single position extensometer.

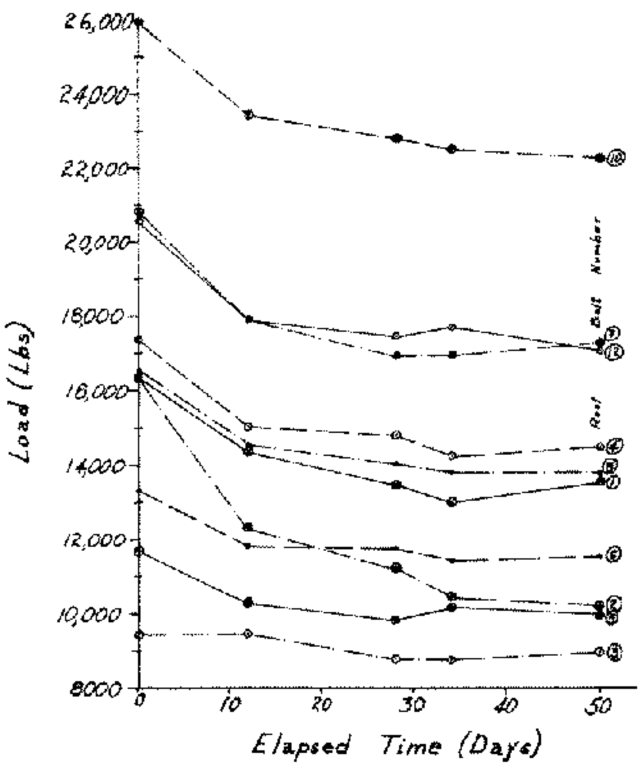

Figure 18. Roof bolt load histories (Abel, 1966).

Another type of borehole instrument is the borehole deformation gauge, which records changes in the shape or diameter of a borehole. This class of instruments includes the ones designed to measure the force required to prevent deformation of the borehole. These instruments are probably under the most intense investigation at present. This is logical since the borehole deformation gauge provides the only proven technique

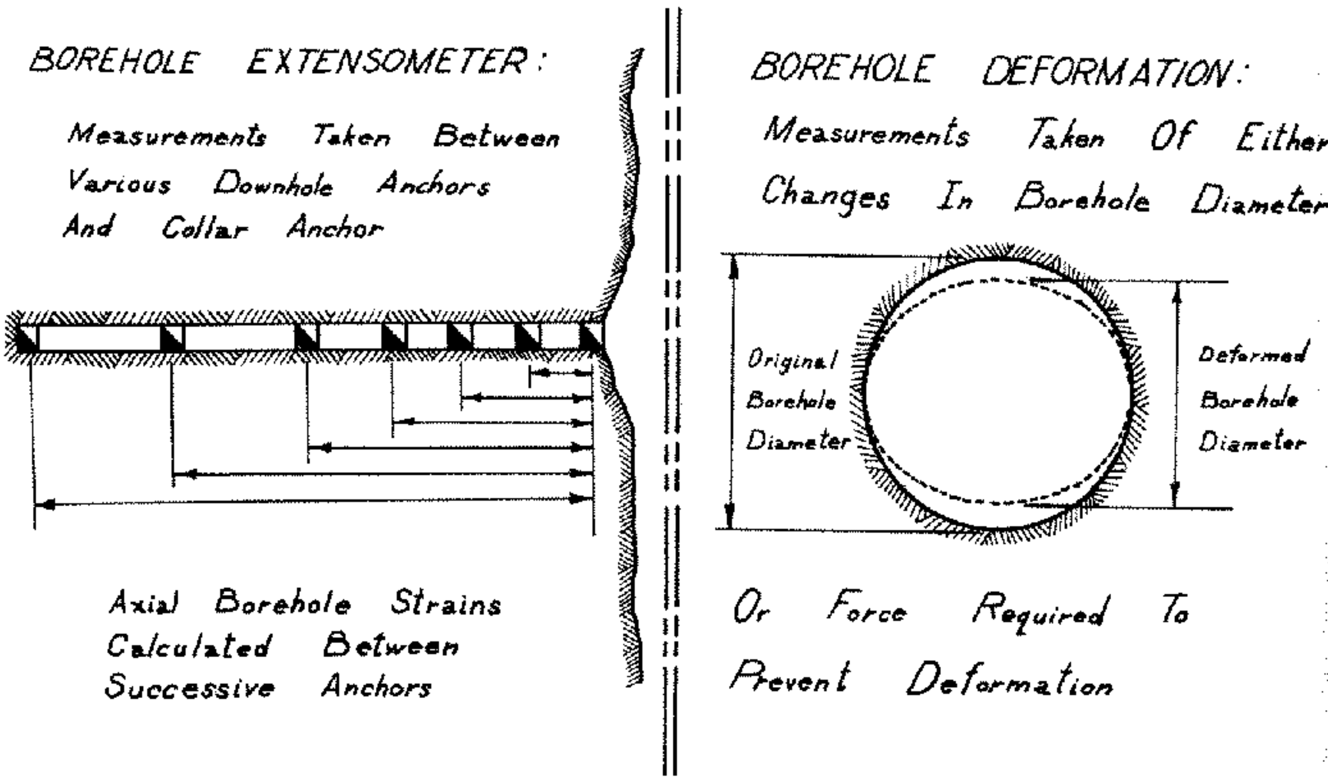

Figure 19. External rock mechanics instrumentation. (Abel, 1966).

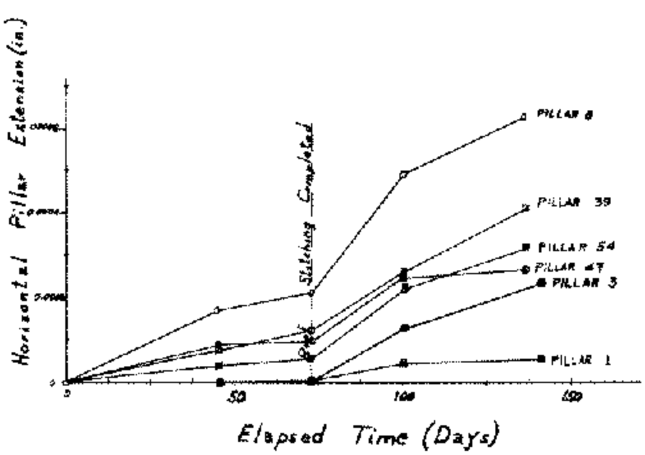

Figure 20. Pillar extension histories. (Abel, 1966).

for obtaining a quantitative indication of the stress conditions or changes in the stress conditions at a point in a rock mass.

The selection of a particular instrument type is dependent on several factors. The precision of the readout may require a more sensitive electronic sensing device. If large movements are anticipated, in the range of inches, cheaper and simpler mechanical instruments will probably be satisfactory. Mechanical instruments require the occupation of the instrumented location each time a reading is taken. This may not be possible in a 30-ft. high room. Electronic instruments can be

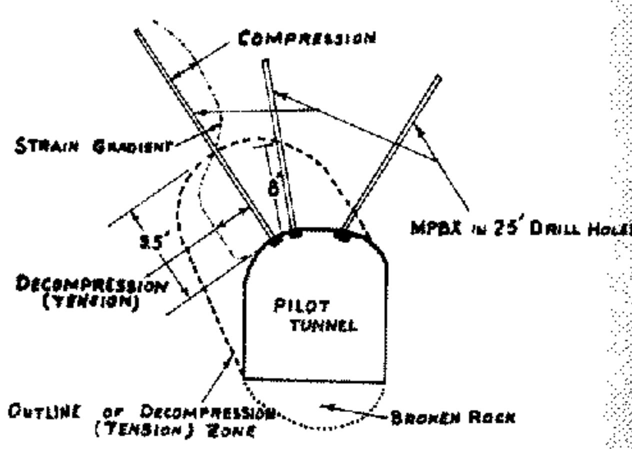

Figure 21. Extensometer readings outlining decompression zone in rock of tunnel roof, Straight Creek Tunnel, Pilot Bore. (Modified from Hartman, 1966).

remotely read. The period of time over which readings are to be taken may dictate the use of less expensive mechanical instruments. The load carry capacity of the support will govern the capacity of the load cells employed. The simple lack of an electronics technician may prevent the use of electronic instrumentation.

Even after instrumentation has been selected it is necessary to determine a reading frequency. As I have found out every time I've played the game, readings were generally taken more frequently than necessary. As a result, a mountain of data was collected. At this point I want to recommend, in the strongest way possible, that a computer capability be made available. Don't waste technical personnel reducing data, let the computer do it. One partial out, but no substitute, is the combined taking and plotting of the data on graph paper. This technique provides an instantaneous visual display that demonstrates continued stability, or the onset of acceleration and instability. It also permits changes in reading frequency to be made on the spot.

CONCLUSION

If you are interested in determining how efficient a mine design is, rock mechanics provides an avenue of approach, maybe the only one! Rock mechanics is not, however, a magic wand which can be waved over a 50-ft. pillar to turn it into a 150-ft pillar. Rock mechanics, if it is to be given a fair chance to make its maximum contribution, must be included from mine planning right through mine production. It should include theoretical analysis, physical testing, instrument verification, and all the geologic information you can get.

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