

STRATA DYNAMICS IN UNDERGROUND MINES
A COMPARISON BETWEEN EUROPEAN AND U.S. COAL MINES

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ABSTRACT

This paper evaluates the strata dynamics associated with underground coal mining, particularly longwall mining, and compares mining and strata control practices for European and US operations. Addressed in the paper are the effects of depth of cover and geological disturbances on ground control. Both gateroad pillar design and face support are evaluated. Load development on shield supports is addressed as are considerations for shield selection and determination of setting pressure and yield capacity. A historical perspective of the evolution of longwall support and recent developments in shield design are described. Recommendations are made for methods to evaluate longwall ground control effectiveness and methods to alleviate ground control problems.

INTRODUCTION

In situ stresses in coal measure strata prior to mining depend upon the depth of cover and geological factors. In most conditions, vertical stress is a linear function of the mining depth (1 psi per foot of depth, 23 kPa per m), and horizontal stress is typically about one third of the vertical stress. However, horizontal stresses are dependent upon the tectonic forces that formed the local geology and in many areas may reach or even exceed the vertical stress. In multiple seam mining, vertical stresses may be divided, if the mining of one seam destressed the local strata, or multiplied if remnant pillars are left in place. When a void is created by mining, there is a suppression of horizontal stress in the beds in which the void is created, and simultaneously an increase in vertical stress in the abutments created around the void.

In summary, mining creates a void which modifies the in situ stress distribution and results in dynamic movements of the surrounding strata to reestablish a state of equilibrium. A good knowledge of the geological factors and distribution of stresses is essential to provide a safe working environment in underground coal mining. Horizontal stresses are a dominant factor in entry stability, while vertical stresses are more relevant to longwall face stability. The intent of this paper is to evaluate the dynamics of strata behavior associated with the differing geological conditions found in Europe and the United States in an effort to make the reader more familiar with effective ground control practices.

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STRATA DYNAMICS AROUND ENTRIES

When driving single or multiple entries in a coal seam, the local modification of stress is described as follows: (1) the vertical stress increases on each side of the entry and (2) the in situ horizontal stress is suppressed in the beds where the void is created. The horizontal stress can cause buckling of the immediate strata which is no longer supported by the coal seam. Laminated roof structures, typically shales, that are incapable of transferring this horizontal load without failure are most susceptible to damage from horizontal stress fields. Another common ground control problem manifested by the horizontal stresses is cutter roof (1). The most effective solution to horizontal stress-induced problems is to reorient the entries so that they are parallel to the major principal horizontal stress.

An appropriate pillar design depends upon knowledge of the pillar strength and stress distribution associated with the mining process. In room and pillar mining, pillars can be designed for relatively static loading associated with the increase in vertical stress as the entries are mined. However, in longwall mining, pillars must be designed to carry the much higher abutment loads associated with the extraction of the longwall panel. Several pillar design formulas have been developed, including the ALPS method developed by the Bureau of Mines (2). A primary factor in any pillar design formula is the depth of cover.

In shallow mines, pillars can be made large enough to resist the mining induced stresses and relatively little convergence occurs in the entries. The stability of the entries is mostly dependent upon the ability of the roof to span across the entry and the capacity to transfer horizontal stress. The roof is largely self supporting, although supplemental support in the form of roof bolting and cribbing is often used, particularly in longwall applications where the vertical stress is magnified several times by abutment loading associated with the extraction of the longwall panel.

In deeper mines, the vertical stress may exceed the compressive strength of a strata member or the remaining coal structure, and movement of the rock mass occurs which produces measurable convergence at the coal seam. In very deep mines, single entry design is the only practical solution since adequate pillar size and entry stability cannot be achieved in multiple entry designs. In longwall operations, entries are driven upon advance to minimize the exposure of the gateroads to the high abutment stresses. At very great depths when the size of the barrier pillar that could separate single entry panels from one another becomes prohibitive, the same single entry has to be used for both panels.

The following figures illustrate some effects of coal measure strata dynamics on entry stability.

Figure 1. The coal seam may be squeezed from the overburden pressure.

Figure 2. The floor may heave and fill the entry with debris. This typically occurs when the strength and loading of the pillars exceeds the load bearing capacity of the floor.

Figure 3. Cutter roof may develop from high horizontal stress.

Figure 4. A strong immediate roof or floor may be broken by the plastic deformation of a softer stratum located just above the immediate roof or under the floor.

Figure 5. An outburst of coal may be produced from dynamic loading caused by failure of the overburden strata or by excessive static loading of pillars.

In the United States, coal mines are developed under relatively shallow cover. There is little experience in dealing with excessive strata movements common to mining depths greater than 2000 feet, or in multiple seam conditions where stress concentrations are developed from remnant pillars in adjacent seams. In Europe, mining is hampered by greater depths and geologically disturbed deposits.

EVOLUTION OF LONGWALL SUPPORT

Longwall mining was first utilized in Europe as far back as the seventeenth century. The strata dynamics associated with this complete extraction technology required new support systems. Only through several evolutionary improvements in support technology has longwall mining become the most productive and safest coal mining method employed in the world.

Wood Timber

Longwall faces were first supported by wood timbers. Since these timbers were generally not strong enough to support the caving line, moveable wood cribs and strip packs built from caved rock were often employed to stabilize the face. These early faces used light weight face conveyors that were dismantled and manually moved as the face advanced.

Prop Free Front

Steel props were introduced to reduce consumption of wood timber and suppress strip packing. But the most important step was the use of steel link-bar systems that allowed some cantilever, and as a consequence, a "prop free front" (see figure 6). A prop free front allowed the use of an armored face conveyor which could be pushed in one piece without dismantling. This facilitated mechanization of coal winning, leading to the development of current extraction machinery.

While the steel props had higher capacities than the wood posts, the capacity was still small. The props were designed to support 20 tons, but generally held about 5 tons. The load was limited by the floor resistance as the props tended to punch into the strata.

In summary, serious roof control problems were encountered from the full caving and the inability of the steel props to control the strata. The props were particularly ineffective in controlling the horizontal movement of the roof associated with the caving process.

Hydraulic Props

A significant improvement in ground control came with the introduction of the hydraulic props towards the middle of the twentieth century. The hydraulic props provided not only a reliable yielding load but an active setting load as well. Another major advantage of the hydraulic props was that they could easily be moved and reused. The roof was generally supported by a line of two to three props. The distance between props was about 2 ft (60

can) with 3 to 4 feet (1 to 1.25 m) between prop lines. The maximum yield resistance provided by the props was 100 to 150 tons for five ft (1.5 m) of face length. These props significantly improved roof control, but still required a lot of skilled manpower working in hazardous conditions to recover and advance these supports.

Powered Roof Support

One of the first ideas of powered support was to assemble four of these hydraulic props in a box frame and to advance this chock using a horizontal hydraulic cylinder attached to the face conveyor. These powered support systems provided mechanization of the roof support operations. Another significant advantage was their larger contact area providing less tendency to penetrate into the floor. On the other hand, individual props could more easily accommodate horizontal roof movements than the more rigid frame and chock supports, which often experienced bending of the hydraulic props due to the dynamics of the caving strata.

An operational difference of significant consequence was also realized with the utilization of these powered roof support systems. Prior to the use of the powered supports, single props were advanced and reset so that partial roof support to the caving line was maintained at all times. Inherent in the chock system was the obligation of removing all support in an area from the coal face to the caving line and to repeat this process several times under the same roof area. This action limited the success of early powered support systems to relatively strong immediate roof strata that could maintain its integrity for a short period of time to accommodate the support advance.

The most significant development in powered roof support technology was the development of the shield support. First utilized in Russia in 1960, the shield system was attractive because of three major advantages: (1) the shield supported only a narrow three-foot band of roof along the face; (2) it provided good roof cover and protection from roof falls and invasive gob debris; and (3) the shield provided strong linkage between the canopy and base to resist horizontal roof movements without bending of the hydraulic leg cylinders. Modern shields are now very different from these early designs. The concept of supporting only a narrow band of roof was abandoned, but the advantages of a mechanical linkage between the base and canopy were fully exploited. This linkage results in a horizontal force resisting the movement of the strata towards the gob, which helps to limit the fissurization of the immediate roof. Shield supported faces are able to advance through geologically disturbed areas without damage and maintain effective ground control.

STRATA DYNAMICS AROUND A LONGWALL FACE

Strata dynamics associated with longwall mining are complicated, since complete extraction is permitted causing dynamic subsidence of the overburden into the void left by the extraction of the coal seam. In general, the extraction of the panel and caving of the roof into the void suppresses the horizontal stress in the coal seam, and after the first caving occurrence (first break), also alleviates the horizontal stresses in the immediate roof. At the same time, there is a multifold increase in the vertical stress as abutment loads are created as shown in figure 7 (3).

The front abutment loading generally reaches a maximum of three to four times the in situ virgin vertical stress within 10 to 30 feet (3 to 9 m) of the face (3). This loading is sufficient to cause failure of the coal, creating a destressed zone of yielded coal in the immediate face area. The free face caused by the extraction of the coal seam and caving of the roof produces an imbalance in confinement in the yield zone as shown in figure 8. This defines a plane of principal stress that is parallel to the coal face. The loss of confinement and expansion of the coal and strata towards the free face promotes fissurization along this plane (see figure 8), which facilitates roof caving as shown in figure 9. The movement of expansion towards the gob affects mainly the roof strata and coal seam, but the floor can also move. The degree of movement depends largely upon the material properties of each stratum and fissurization due to the loss of confinement. Differential movements between stratum layers also facilitates shear forces at the boundaries which help to fracture the coal and immediate strata.

The generation of load in the powered roof supports depends primarily on the caving dynamics of the immediate roof. Shields, once set actively against the roof, become passive supports and load generation is related to the displacement and stiffness of the support structure. Loads are developed in response to strata dynamics that result in displacements of the canopy relative to the base. The stiffness of current shield supports essentially remains constant at about 500 tons/in for all leg pressures (4). Debris on the canopy or soft floor also affects shield load development by reducing the stiffness of the shield strata combination. Less shield loading is generated since some of the roof convergence is consumed in compaction of the debris.

Generally, the immediate roof behaves as a beam of variable bending stiffness that cantilevers from a point somewhere between the front abutment loading and the coal face to or beyond the powered supports (see figure 10) (5). The deflection of the beam is controlled somewhat by the resistance (stiffness) of the supports. Higher setting pressures and increased shield resistance may help to bind the layers of the immediate roof together to improve the bending stiffness of the roof beam. An important factor is the time delay to support the newly exposed roof and the distance between the face and first point of support. In the worst case, the immediate roof forms a detached block, whose weight must be borne by the powered supports. This generally represents a worst case load condition and is the most difficult roof to control.

Recent measurements by the US Bureau of Mines confirm that total shield loading increased in proportion to increases in shield setting pressure as shown in figure 11, indicating a lower setting pressure would minimize support loading in this installation. While early longwall operations reported increased convergence with low setting forces, it appears that the benefits of active setting pressure have been fully exploited with the current high levels of setting force and that more optimum setting forces can be utilized.

The main roof generally retains sufficient integrity to bridge or arch and transfer load to other parts of the roof structure, so that its full weight is not borne by the face supports. However, the main roof does move as the face is advanced and this convergence is largely irresistible in terms of any practical shield capacity. The main roof will often fail periodically, creating periodic weighting on the powered supports.

COMPARISON OF US AND EUROPEAN MINING AND STRATA CONTROL PRACTICES

The differences in European and US mining practices and strata control techniques stems primarily from the differences in mining conditions. In Europe, coal mines are not only deep, 2000 to 4000 ft (610 to 1219 m), but the overburden is highly fractured with faults and strata disturbances. Major geological disturbances, such as faults, often limit the face and/or panel length in European mines. Still, 50 pct of the faces are crossing at least one fault. Occasionally, face directions are changed within a longwall panel to accommodate geological disturbances.

While a few American longwalls operate at depths below 2000 ft (610 m), the average depth of cover for American longwall installations is about 1100 ft (335 m) considering the maximum depth of cover at each mine site. Most American longwalls operate under 500 to 1000 ft (152 to 305 m) of cover. Average face length over 700 ft (215 m) with a trend towards wider faces. Face lengths exceeding 1000 ft (305 m) are being planned. The length of the panels are also increasing in American longwalls with six panels exceeding 10,000 ft (3045 m). Another major difference is that inclined seams are routinely mined in Europe, while most US longwalls operate in relatively flat coal seams.

Deep mining conditions make multiple entry developments unacceptable in Europe; nearly all European longwalls use single entry developments. All US longwalls employ at least two entry developments with three entry development used most often. The single entry European developments are supported extensively with steel arches, while wood and concrete cribbing are the primary supplemental entry support used in the United States. High vertical stresses associated with the deep cover conditions present a severe floor heave problem in European longwall operations. The high stresses also promote advancing longwall operations in Europe, as opposed to the predominant retreating practice employed in the United States.

An intermediate solution to single entry developments for deep cover longwall installations is to use multiple entries with yield pillar designs. The yield pillar approach rests on three fundamental assumptions: (1) the yield pillars must deform enough so that a pressure arch is created as the main roof bridges to transfer load elsewhere; (2) there must be solid abutments nearby to receive load shed by the yield pillars; and (3) the yield pillars must fail in a nonviolent manner and maintain enough residual strength to support the weight of the rock within the pressure arch. Yield pillar gateroad designs are commonly employed in US coal mines where the depth of cover approaches 2000 ft (610 m). They tend to be most effective when the immediate strata is relatively competent to transfer horizontal stress and bridge to more rigid coal structures.

Since the resource is less abundant in Europe than in the United States, many of the near surface seams have already been extracted. The extraction of these upper seams and high in situ stresses associated with the deeper coal seams that are currently being mined, generally results in easier and more regular caving of roof strata. This promotes the use of lower capacity face supports.

Historically, the European support capacity has been substantially less than the American. The typical support in Germany for example is a 400-ton two-leg shield providing 6 tons/sq ft (500 kN/m²) of

resistance at yield load. Support capacity in the United States varies over a wide range (250 to 900 tons). A survey of the 96 operating longwall operations in the United States reveals an average support capacity of 585 tons, although most new supports purchased in the past 3 years have been in the 600 to 800 ton range (6). The trend in the United States as shown in figure 12 is towards higher support capacities as older supports are replaced (7). This trend is also true for European practices. Support capacity in the American longwall installations has doubled during the past decade.

Nearly all shields in Germany are of the two-leg design while one-fourth of the US shields are four-legged constructions. However, the trend in shield selection in the United States is in favor of two-leg designs as higher capacity two-leg shields become available (see figure 13). Historically, four-leg shields have been employed in the United States in deep cover mines with a thick immediate sandstone roof structure that cantilevered well beyond the supports (7).

Differences of opinion in regards to setting pressures have also developed through the evolution of longwall mining. The British initially favored low setting pressures (25 pct of yield capacity) while the Germans and Americans have generally favored higher setting pressures (80 pct of yield capacity) (8). Setting forces have increased in proportion to the increase in yield capacity as the setting pressures have remained constant while the size (area) of the hydraulic legs has increased to accommodate the higher yield capacities. Optimum setting pressures as a function of geological conditions are generally not pursued.

The highly fractured and jointed strata in European mines creates more friable and often less stable immediate roof conditions. The trend in German support design is to use an articulated and extensible canopy (see figure 14) capable of being advanced while the support is set against the roof to provide immediate forward support. This design seems to provide good control of these friable roof structures. In the United States, the one-web-back system of support advance with rigid canopy designs is typically employed.

The most significant advancement in shield design in the past 10 years has been the use of electrohydraulic control systems to automate the support function (9). These systems are used more extensively in American longwall operations than European operations, but this technology is certain to be a world wide standard. One reported advantage of the electrohydraulic control is to provide programmable and consistent setting pressures across the face. However, recent studies by the US Bureau of Mines shows that consistent setting pressures are not routinely achieved. Examples of setting pressure inefficiency are shown in figure 15 from two state-of-the-art electrohydraulic American longwall operations. Apparently, the demand placed upon these systems is greater than the capability of the system for these installations. Inefficient hydraulic fluid distribution has plagued hydraulic supports since their inception and further improvements are still needed (10).

Two other developments in shield design are currently being evaluated by European operators. The recent trend in Germany has been to employ canopy wetting devices to control dust. If successful, this technology should be readily accepted in America,

where longwall productivity is often constrained by strict dust regulations. The other major advancement in shield design currently being pursued by the Europeans is wider supports. An increase in shield width from 1.5 m to 1.75 m (4.9 to 5.7 ft) is typical in recent German installations. It appears that 2 meter (6.6 ft) wide supports will be the standard for the next generation of shield supports. Since fracture developments tend to be parallel to the face, roof control should not be affected by the increase in shield width nor should a substantial increase in support capacity be required. The potential advantages of the wider design are: (1) reduced cost and (2) fewer supports to move.

CONCLUSIONS

Strata movements in entries become a major problem as mining depths increase beyond 1500 feet (450 m). In very deep mines, multiple entry developments with roof bolting and cribbing are replaced with single entry designs. At great depths, advancing longwall faces are used instead of retreating faces since the conditions in the gateroads deteriorate so rapidly. Eventually as the gateroad ground control becomes increasing difficult at greater depths, the cost of mining becomes prohibitive. The deepest longwalls currently in operation are at depths of about 4000 ft (1219 m).

In sharp contrast to gateroad ground control, depth has little direct effect on the mining of the longwall panel. In fact, roof caving is often better in deeper mines. The most difficult longwall mining is in shallow deposits with a competent overburden. In these conditions, low abutment loads cause less fissurization of the strata which leads to poor caving. The strata tends to cave in large blocks resulting in periodic weighting and excessive support loading. To improve caving in shallow mines, a minimum face length of 600 ft (183 m) is recommended to achieve maximum benefit from the abutment loading. From the point of view of caving and ground control, longer faces are not needed, but longer faces may be justified from the perspective of resource conservation and face productivity.

The shield support provides effective ground control and is able to withstand both the vertical and horizontal displacements associated with longwall strata dynamics. Roof control effectiveness can be assessed by observation of: (1) the formation of cavities in the immediate roof; (2) roof steps at the coal face; and (3) excessive convergence. Excessive face convergence can result in steps in the roof and support yielding. When the hydraulic travel of the legs is consumed, the supports cannot be advanced and are often abandoned. Roof steps make support advancement more difficult and are an indication of vertical fracture development in the strata that can seriously threaten face stability and increase face convergence. Finally, roof cavities make support advancement much more difficult and degrade the stability of the face area. Since the horizontal confinement in the strata is reduced, the cavities tend to increase in size, quickly resulting in poor roof control.

Face convergence is largely determined by the strata dynamics of the immediate and main roof. The shield will have minimal impact on face convergence if sufficient resistance is provided to maintain integrity of the immediate roof. Face convergence will largely be determined by the load bearing capability of the coal panel and the failure characteristics of the roof structure.

To prevent roof steps and excessive face convergence, experience has shown that the yield capacity of the shields is important (11). The shield should have sufficient capacity to equilibrate detached blocks of strata. In Europe, where the strata tends to cave regularly, smaller capacity supports (400 tons) are used, compared to the US where more competent strata cantilevers and caves periodically in larger blocks. Support capacities in the US are typically 600 to 800 tons.

To avoid roof cavities in the case of weak unstable immediate roof, an articulated and extensible canopy is a good solution. A long and rigid canopy may provide good protection from falling debris, but it does not provide good roof control since contact at the tip cannot be controlled. Studies have shown that the first point of contact is generally far from the face. With rigid canopy designs, the tip is often sloped upwards to promote roof contact. Articulated canopy tip designs are capable of ensuring tip contact and providing an active tip force of 5 tons by pressurization of a hydraulic cylinder at the joint.

Two-leg shield designs are preferred to four-leg shield constructions since the rear legs in four leg shields are not often set at full pressure. Therefore, the advantages of higher load capacity, resultant forces acting closer to the gob, and better load distribution are illusory in four-leg shield designs.

In the future, shield width should be increased up to at least 2 meters. This will reduce the total face cost since much of the expense in construction is due to hydraulics as opposed to the steel costs. Since the fracture development is generally parallel to the face, roof control is not affected by wider shield application, nor is there a need for substantially increased capacity with the wider supports.

Electrohydraulic shield controls permit faster cycle times and programmable setting pressures. However, consistent setting pressures are not routinely achieved, particularly when several supports are moved simultaneously. Fluid supply and pressure drop should be carefully calculated to provide the proper pump capacity and sizing of fluid distribution requirements.

American longwalls are among the most productive underground mining operations in the world. The average annual face production for the American longwalls is about 1.25 million tons. Daily production records exceeding 30,000 raw tons of coal have been reported. The productivity of European longwall operations is generally less than the American productivity because the Europeans are faced with more difficult mining conditions due to greater depths of cover, highly faulted strata, and inclined seams. As the American mining conditions become more difficult as deeper seams are mined, the European experience will bring solutions to the associated ground control problems.

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Figure 1. - Coal seam being squeezed from the overburden pressure.

Figure 2. - Floor heave.

Figure 3. - Cutter roof development from high horizontal stress.

Figure 4. - Strong immediate roof and floor broken by softer adjacent strata.

Figure 5. - Coal outburst.

Figure 6. - Prop free front established with steel ^{bar and} link prop supports.

Figure 7. - Abutment stress development around a longwall panel.

Figure 8. - Imbalance in confinement at longwall face.

Figure 9. - Fissurization of face strata along plane parallel to face causing face-to-waste strata and coal movement.

Figure 10. - Immediate roof acting as a cantilevered beam.

Figure 11. - Correlation of final shield loading during a mining cycle to setting pressure.

Figure 12. - Trend of increased support capacity in American longwall operations.

Figure 13. - Trend in support selection showing preference to two-leg shield design (American longwall installations).

Figure 14. - Extensible and articulated canopy design is replacing rigid design in friable roof conditions.

Figure 15. - Inefficiency of electrohydraulic control systems to achieve consistent setting pressures.

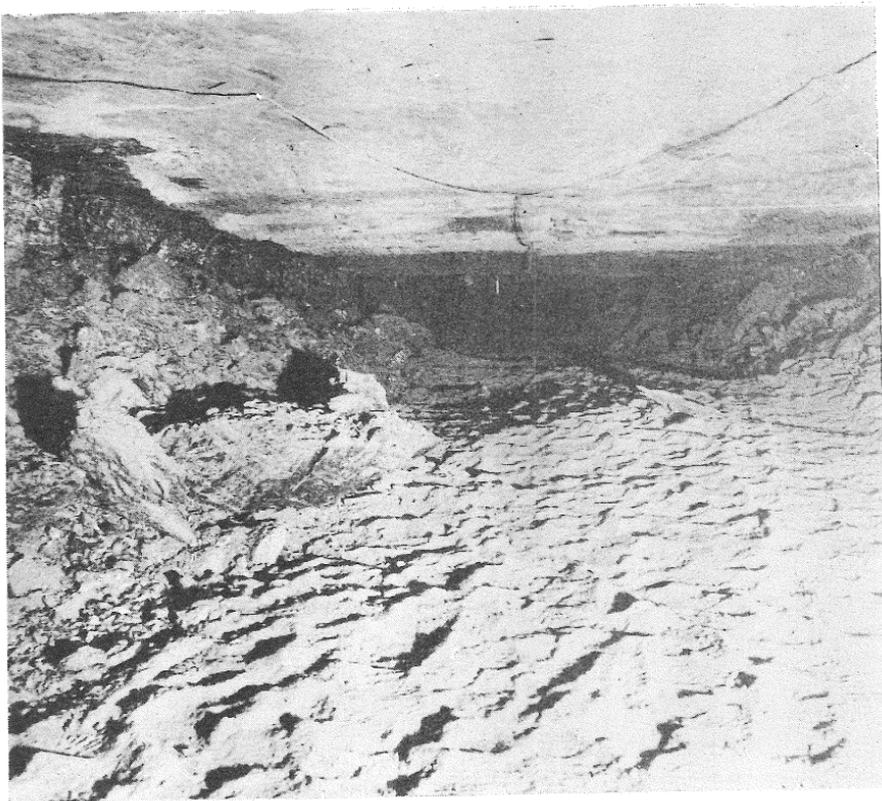


Figure 1. - Coal seam being squeezed from the overburden pressure.

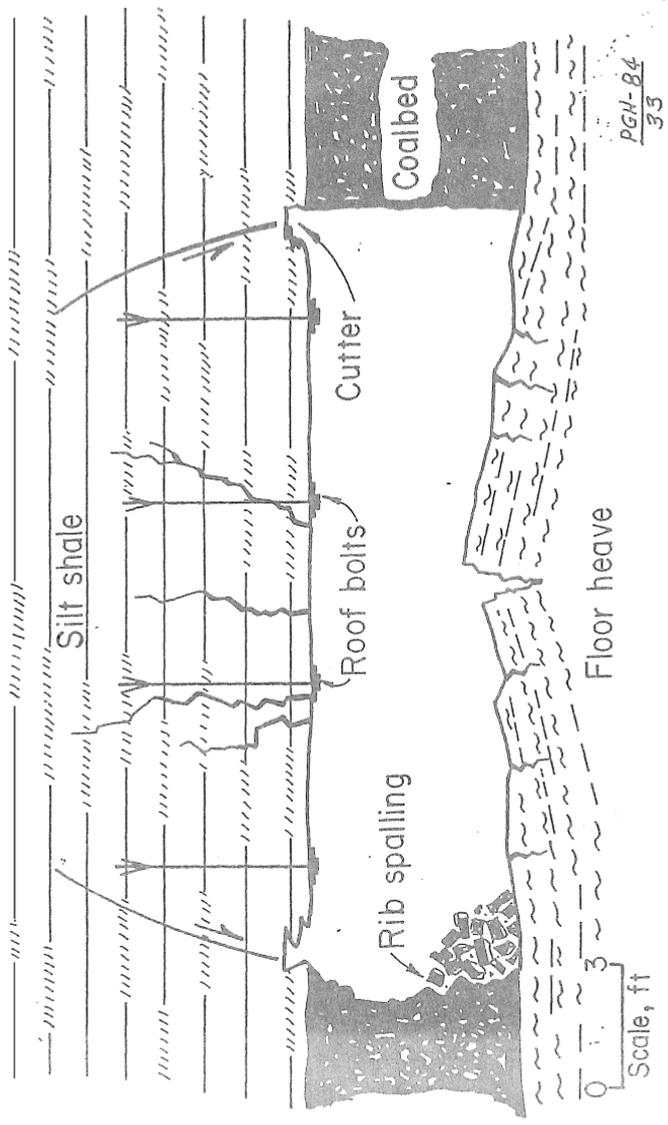
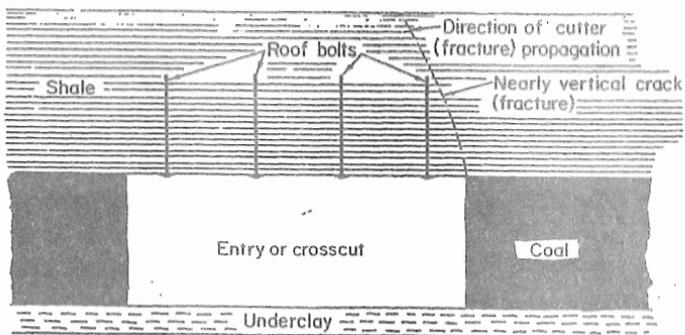
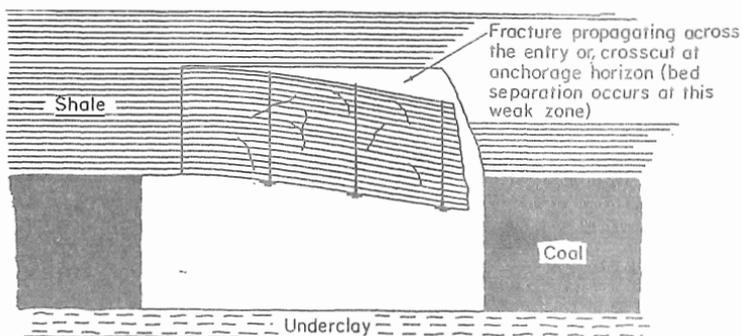


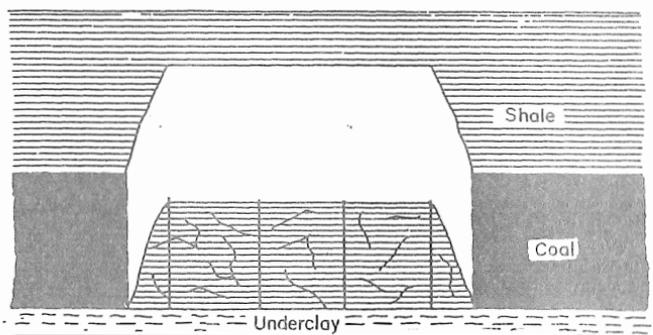
Figure 2. - Floor heave.



INITIAL CUTTER FAILURE



PROPAGATION OF CUTTER ALONG WEAK ZONE



CUTTER FALL

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Figure 3. - Cutter roof development from high horizontal stress.

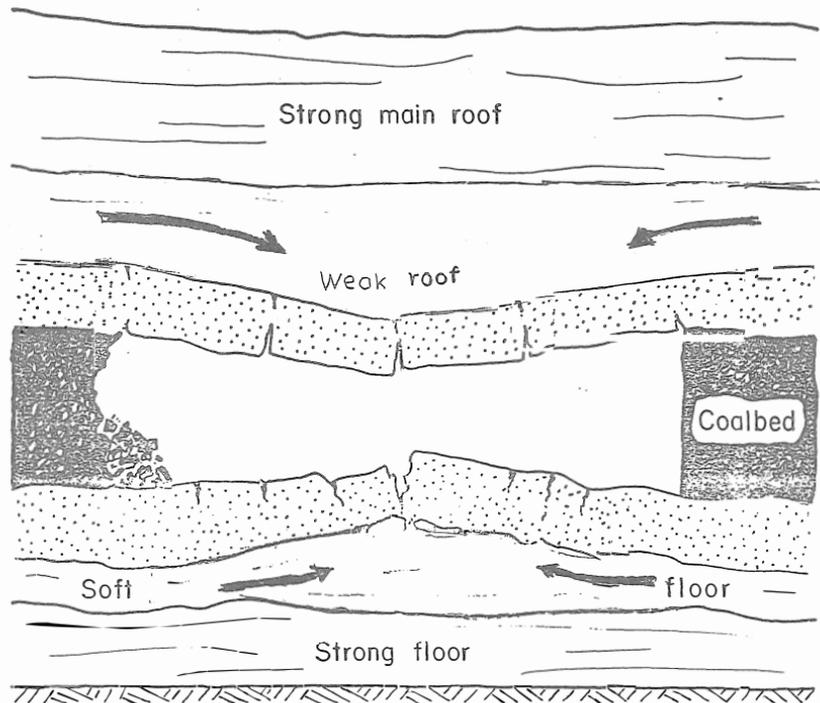


Figure 4. - Strong immediate roof and floor broken by softer adjacent strata.



Figure 5. - Coal outburst.

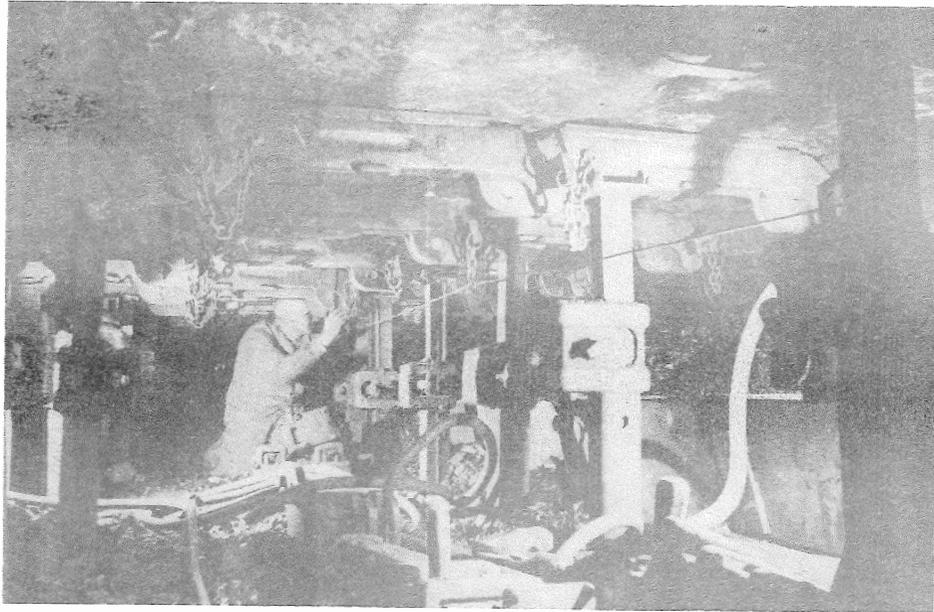


Figure 6. - Prop free front established with steel bar - link and prop supports.

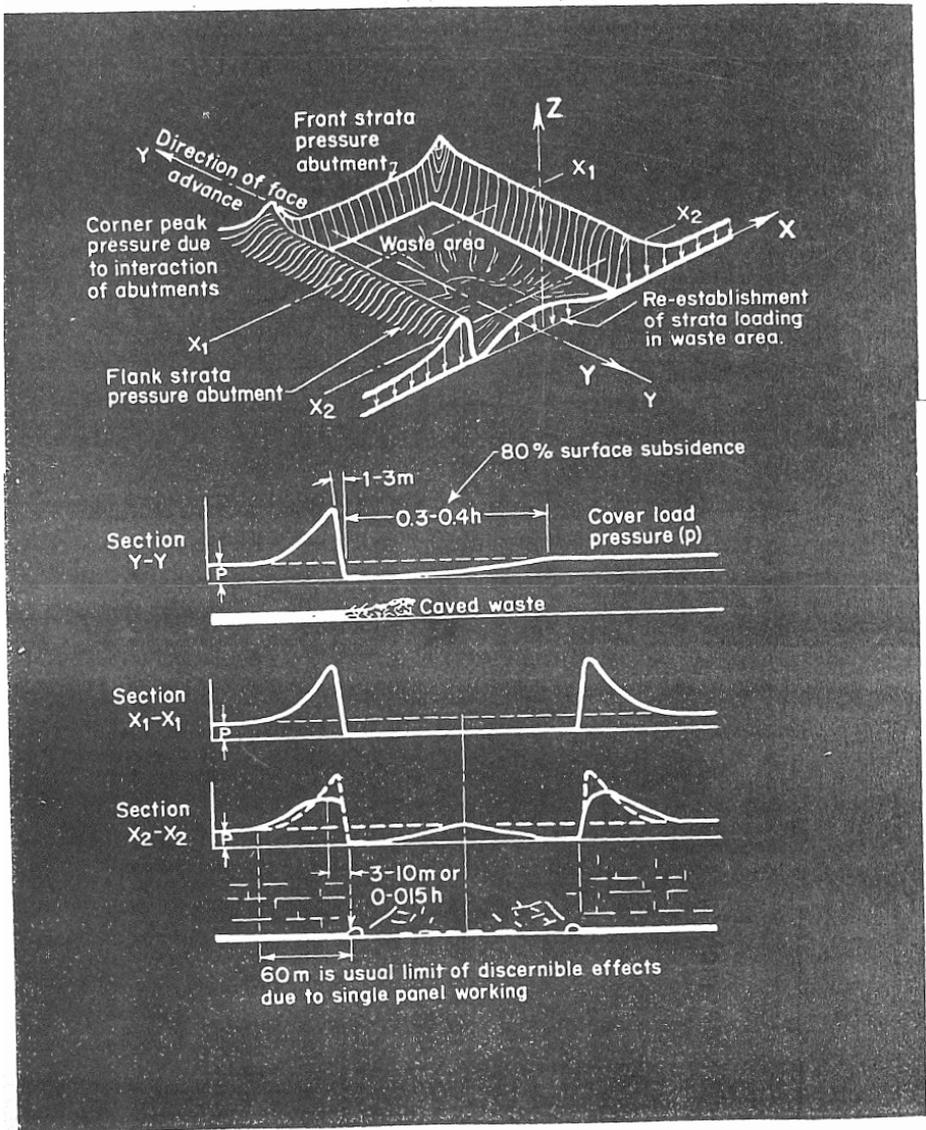
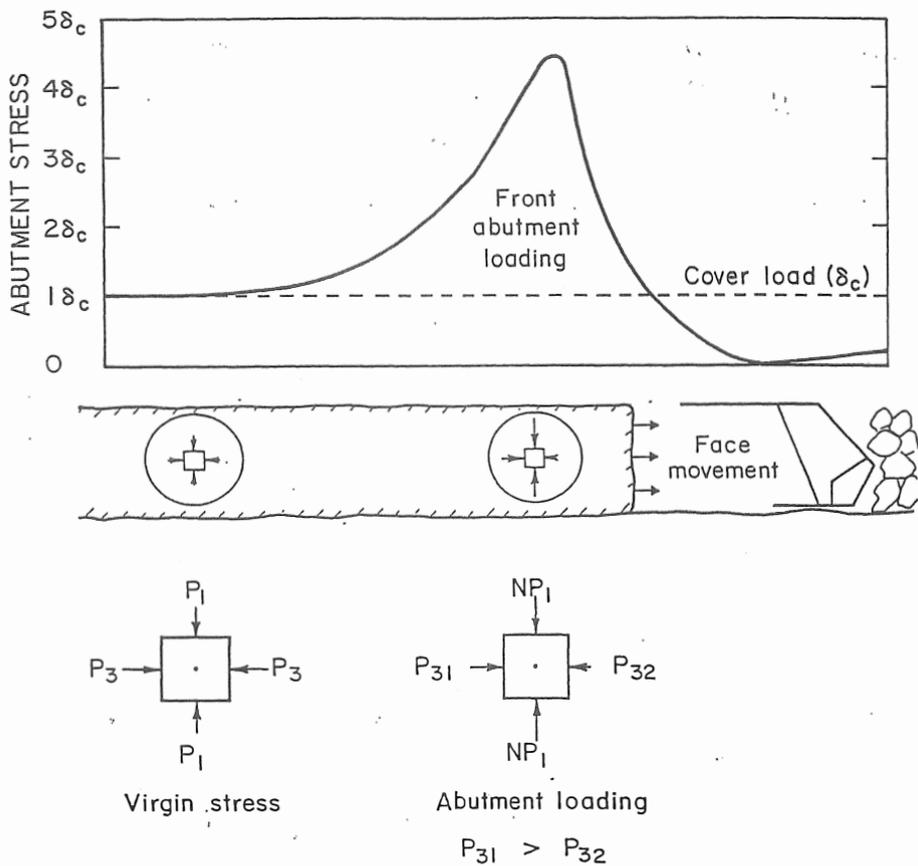


Figure 7. - Abutment stress development around a longwall panel.



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Figure 8. - Imbalance in confinement at longwall face.

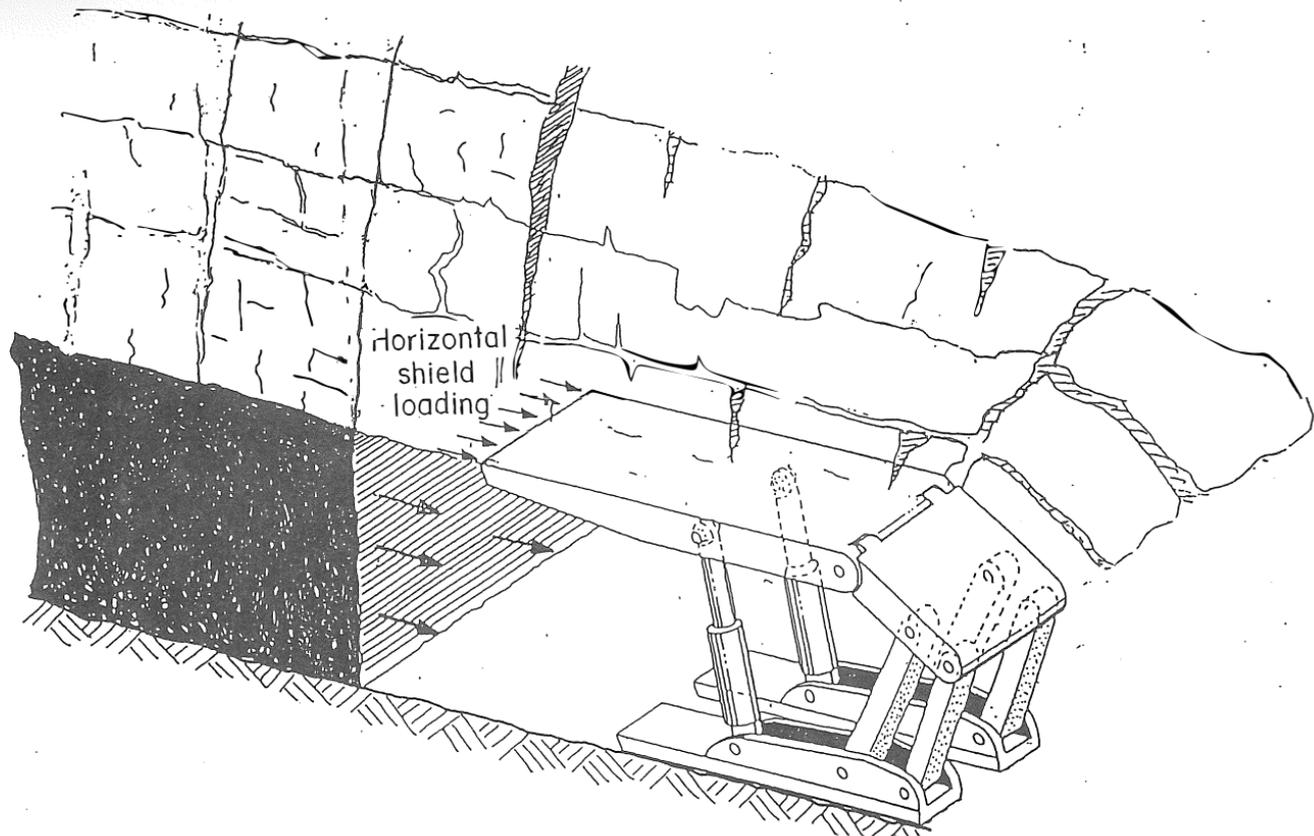
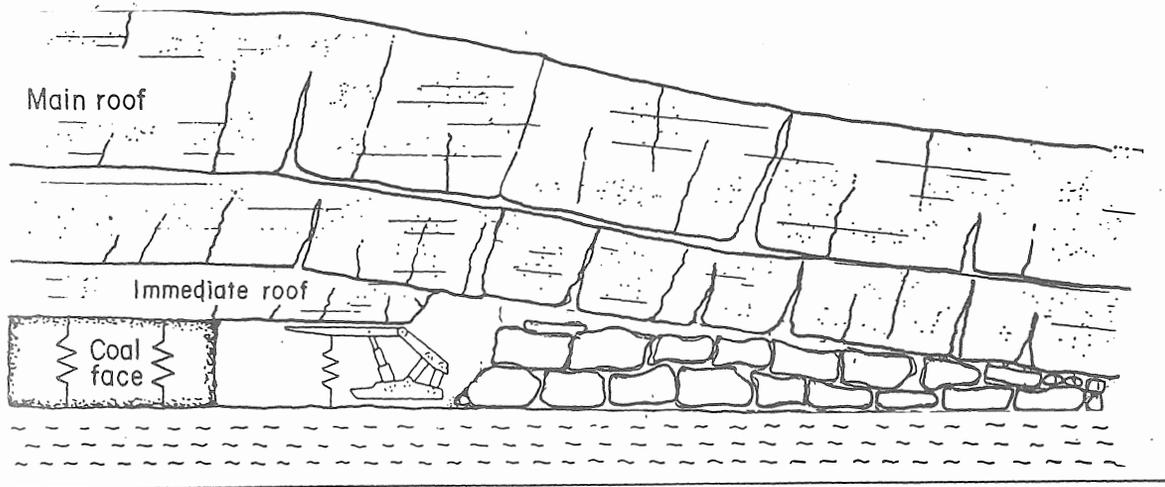
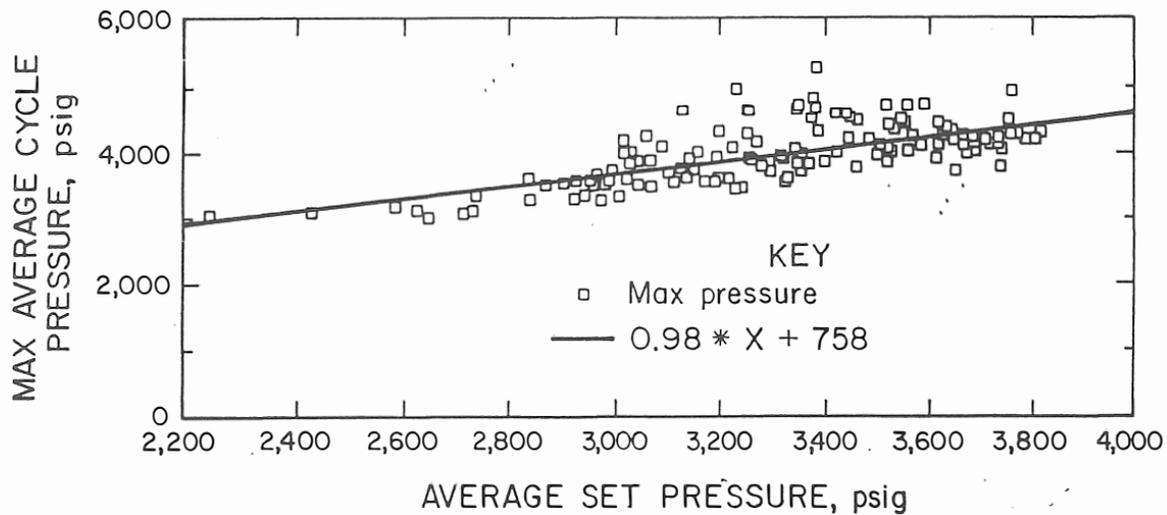


Figure 9. - Fissurization of face strata along plane parallel to face causing face-to-waste strata and coal movement.



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Figure 10. - Immediate roof acting as a cantilevered beam.

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Figure 11. - Correlation of final shield loading during a mining cycle to setting pressure.

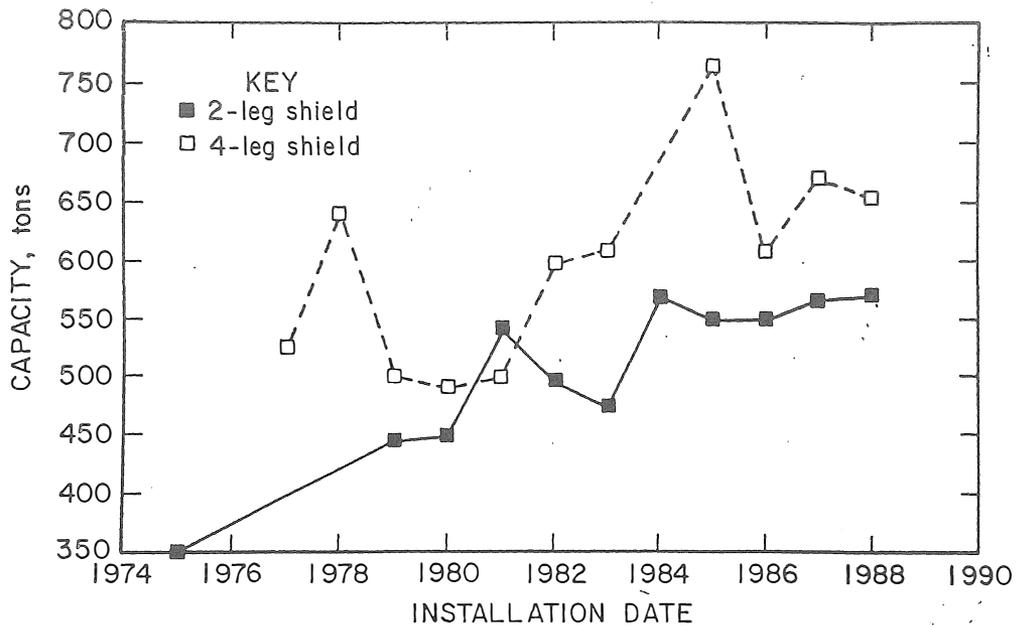


Figure 12. - Trend of increased support capacity in American longwall operations.

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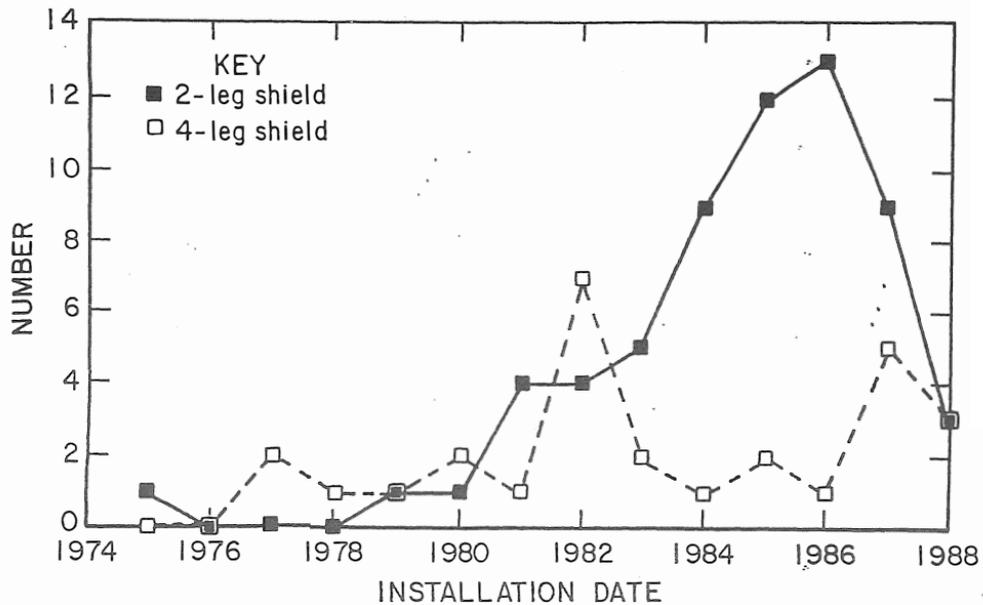


Figure 13. - Trend in support selection showing preference to two-leg shield design (American longwall installations).

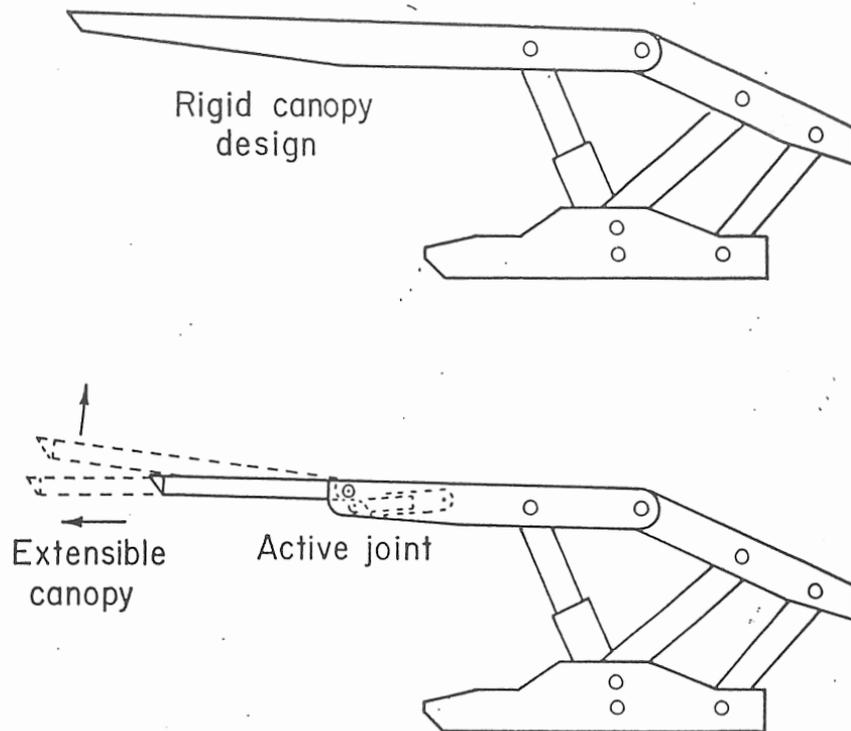
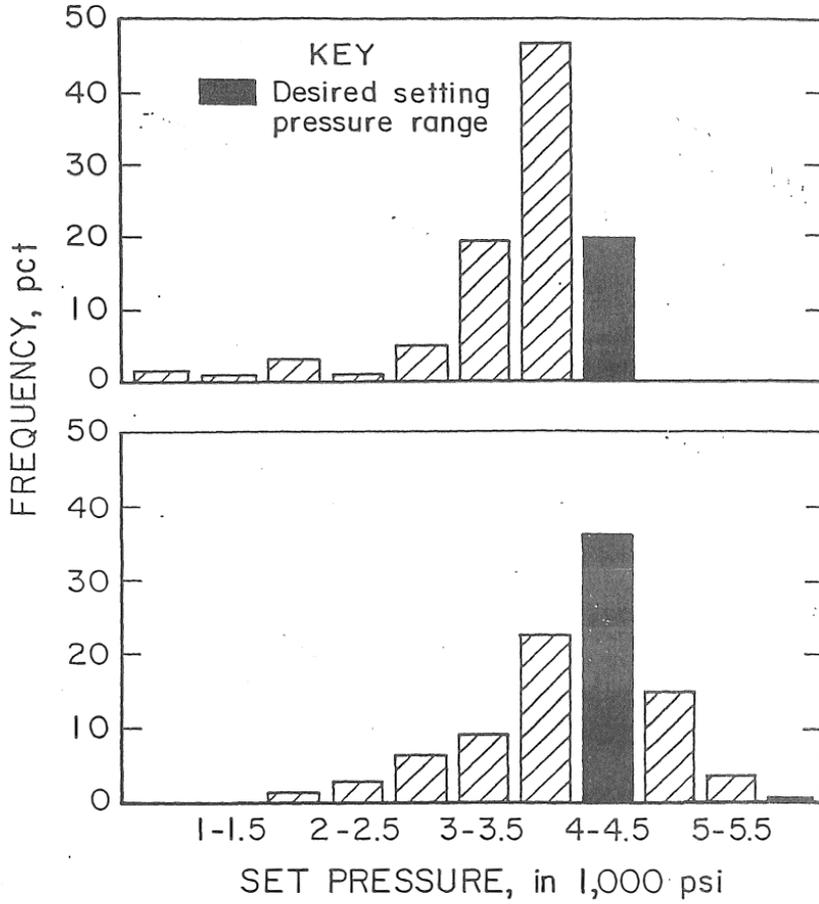


Figure 14. - Extensible and articulated canopy design is replacing rigid design in friable roof conditions.



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Figure 15. - Inefficiency of electrohydraulic control systems to achieve consistent setting pressures.