# TECHNICAL CONSIDERATIONS FOR THE DESIGN AND CONSTRUCTION OF MINE SEALS TO WITHSTAND HYDRAULIC HEADS IN UNDERGROUND MINES

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**Abstract**. The practice of impounding mine water and liquid fine waste in underground mines is increasing. Often these underground impoundments are created by constructing seals or bulkheads designed to withstand the expected hydraulic pressures. Occasionally seals are built for another purpose, usually to act as explosion-resistant ventilation barriers. Due to factors such as clogged drain pipes or unexpectedly high inflow rates, these explosion-resistant seals sometimes become subjected to hydraulic pressures. The incidence of seal failures due to inadequate design and/or construction is also on the increase. Fortunately, to date, no lives have been lost by water seal failures, but a clearer understanding of the design and construction considerations specific to water seals is vital to keep this from occurring in the future. This paper presents technical considerations for the design and construction of seals which will specifically be required to withstand hydraulic pressures in underground mines.

## INTRODUCTION

Mining operations regularly find it necessary to handle large volumes of water both due to ground water infiltration into the mine and due to the need to dispose of liquid fine refuse or slurry generated by the preparation process. Treatment of the mine water and disposal of the plant generated fines usually involves the construction of surface impoundments. The high costs of design and construction of surface impoundments and the lack of available land on which to put them leads some mine operators to find other means of permanently storing this water. Many operators find it cost effective to create underground mine pools to permanently dispose of this water and/or fines. These mine pools are most often separated from the active mining areas through the construction of water seals.

There has recently been an increase in the number of cases where seals constructed as explosion-resistant seals have been subjected to hydraulic pressures. In many of these cases the impounding of water behind these seals is unintentional. On other occasions however, explosion-resistant ventilation seals are expected to withstand hydraulic pressures. This can happen because there is a belief that an explosion-resistant seal, which has been shown through testing to be capable of withstanding 137.9 kPa (20 psi) of air pressure, can withstand lower, long term hydraulic pressure. This frequently is not the case. There are many factors which must be considered when designing a seal to withstand hydraulic pressures in addition to the maximum pressure exerted on those seals.

There have been numerous studies on the construction of seals to control mine water. Most of the work in the United States has been related to water pollution control seals. Examples of this work include "New Mine Sealing Techniques For Water Pollution Abatement" (Halliburton, 1970) and "Evaluation of Bulkhead Seals" (Scott, 1972). The seals in these studies are designed for drainage and are exposed to heads of mine water only pooled to the mine roof. A study in South Africa (Garrett and Campbell Pitt, 1958) concentrated on mine seals installed in competent rock formations at large depths and designed to withstand large hydraulic heads. The conditions in this study obviously do not apply to conditions in most mines in the United States. A study in Great Britain (Auld, 1982) looked at seals designed against lower heads in mines with shallower cover. This study concluded that long hydraulic mine seals are necessary to prevent seepage through the rock strata, around the seal. Finally, a study by the U.S. Bureau of Mines (Chekan, 1985) looked at previous water seal studies and design methods and tested a solid concrete block seal against hydraulic heads.

MSHA's Coal and Metal and NonMetal district offices and the Mine Waste and Geotechnical Engineering Division of the Pittsburgh Safety and Health Technology Center are involved with the technical review of design plans for seals constructed in underground mines to withstand hydraulic pressures. Much has been learned about the critical considerations for the design and construction of these water seals underground. In this paper, the principal design and construction characteristics which are unique to seals expected to withstand hydraulic heads in underground mines will be discussed. Several types of mine seal materials and construction methods which are commonly used as water seals will be examined including some of the advantages and disadvantages of each.

## DESIGN HEAD

Water seals require a site specific determination of the design pressures which must be resisted. The maximum potential hydraulic pressure on a seal depends on factors such as rate of water infiltration, maximum ground water level, and the existence and level of boreholes, shafts or seam outcrops which will limit the head. Other factors which could affect the maximum head in a mine pool include the seasonal variation in the maximum groundwater level, increases in infiltration rates due to mining induced strata disturbance, changes in surface water flow or pooling patterns, and changes in water levels in adjacent flooded mines.

Although the volume impounded behind the seals can have a major impact on the potential hazard to miners, the design pressure on the seal is dependent solely on the vertical head above the seal, usually 9.81 kPa per meter (.43 psi per foot) of water depth. The design pressure or head is derived by conservatively estimating the maximum practical elevation of the mine pool above the seal. The maximum mine pool elevation is set at either the elevation where water would drain out of the mine drift opening, the shaft collar elevation, or the highest recorded groundwater elevation above the area behind the seal. Occasionally, seals are constructed at the seam outcrop and are intended to protect the mine from water in a surface impoundment. In these cases, design head corresponds to the maximum water level in the impoundment under design storm conditions.

## STRATA SURROUNDING THE SEAL

The condition of the strata into which the water seal will be constructed is critical. Problems with seepage commonly occur near the interface between the seal and the roof, ribs, or floor around the seal. These conditions are characterized by a gradual deterioration of the strata and a steady increase in water seepage through the strata. The gradual deterioration of the strata surrounding the seal is the aspect of water seal design which differs most from the design of explosion-resistant seals. Explosion-resistant seals are expected to withstand a short pressure pulse from a blast lasting a second or less. The pressures used in the testing on explosion-resistant seals reach a maximum of approximately 137.9 kPa (20 psi). Under these test conditions the explosion-resistant seal must not permit any pressure air transfer across the seal.

In contrast, seals expected to withstand water heads will have the hydraulic pressure exerted for months or more commonly for years. It is this long period of time over which the hydraulic pressure is exerted which results in a deterioration of the surrounding strata. Even when a seal is built to impound water, it often takes years for the head to reach its maximum value. It's difficult to determine if there will be significant leakage through the roof, ribs, or floor until the area behind the seal is flooded and the pressure builds. It can take many months before it is known whether a seal will adequately withstand the expected hydraulic head. Typically, some seepage appears long before a significant head builds behind the seal and increases as the head increases. If it is found that the seal or the surrounding strata leak significantly, repair of the seal or surrounding strata may have to be attempted while the head is still against the seal, since drawing down the water could take many months.

The water seal must be constructed in a location in which the ground is stable and the strata is relatively unfractured. Even when a stable, unbroken area of the mine is chosen in which to construct the seal, care must be taken when preparing the area so as not to damage the surrounding strata. Usually, some preparation is also necessary to improve the condition of the strata. This can include removing severely broken rock, pressure grouting cracks or open areas within the rock, and surface treatment of the face of the rock with low permeability and/or strength enhancing materials. If the roof rock is pressure grouted the possibility of the grout pressures causing a roof fall needs to be taken into account. Additional supports should be provided to minimize roof sag and separation caused by the grouting pressures. Care should be taken to minimize additional strata movement in the area of the seals. This will include limiting mining in the area of the water seals and installing supplemental roof supports at each seal location.

The strength of the surrounding strata is also an important factor, particularly if the water seal will be relied upon to withstand large hydraulic pressures. Roof, rib, and floor materials should be sampled and tested for shear strength along planes of weakness and for compressive strength. Although the typical mechanism of water seal failure is the seepage and deterioration described above, there are cases where the seal has failed suddenly due to the strength of the strata being exceeded by the hydraulic pressures. These cases are far more hazardous than the ones involving gradual deterioration since there is little warning that the failure is imminent. For this reason and because of the variability in the in-situ rock mass and the possible deterioration from strata movement, saturation, and/or seepage forces, a conservative safety factor should be applied to the tested rock strength. The pillars adjacent to the seals should have a conservative factor of safety against yielding and floor punching.

## SEAL CONSTRUCTION METHODS AND MATERIALS

A wide variety of materials and fabrication methods have been used for the construction of water seals. Some of the more common materials used to construct water seals are discussed below, along with some of the advantages and disadvantages of each.

### **Solid Concrete Block Seals**

The simplest design used for water seals is the construction of a double row of 15 cm by 20 cm by 40 cm (6 in x 8 in x 16 in) solid concrete blocks as seen in Figure 1. This seal was tested with maximum water pressures of 275.8 kPa (40 psi) by the U.S. Bureau of Mines (Chekan, 1985). The concrete blocks were mortared in an alternating pattern, and a pilaster or buttress was provided at the center of the seal to add bending stiffness. The seal is notched or hitched into the ribs 30.5 cm to 61 cm (12 in to 24 in). When the seal is intended to withstand hydraulic pressures, the floor is notched. Shotcrete, gunite, or some other material is applied to both faces of the block wall to add flexural strength to the wall and/or to reduce permeability through the mortar joints. Pipes for pressure gauges and drainage are sometimes grouted into the roof or floor rather than through the blocks or mortar joints.

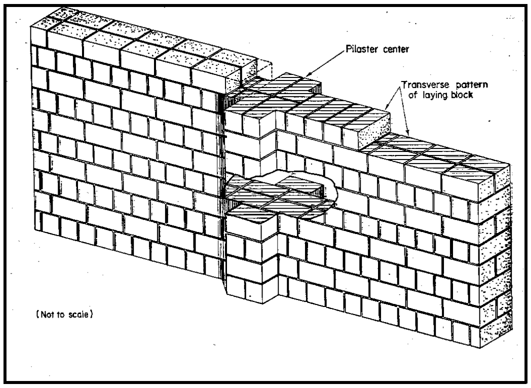

**Figure 1**
**Solid Concrete Block Seal**
**(Chekan, 1985)**

The evaluation of a solid concrete block seal, as with most seal installations, requires an estimation of the shear strength around the perimeter of the seal. The assessment of the wall focuses on the bending stresses near the center of the entry. Since the seal has no steel reinforcement, the wall has relatively poor flexural strength. The flexural strength of the solid block wall limits the maximum hydraulic head more so than the strength of the surrounding strata, except in the case of very narrow entry widths. The flexural stress on the seal can be estimated from the following equation (Kendorski, Khosla, and Singh, 1979):

$$\sigma_f = \beta f H^2 / T^2$$

where $\sigma_f$ is flexural stress
$\beta$ is a correction factor (function of seals width to height ratio)
f is the max. force on the seal =PBH
B is the seal width
H is the seal height
T is the seal thickness
and P is the hydrostatic pressure against the seal

A solid concrete block wall was tested against hydraulic pressures in the Bruceton Research Mine by the U.S. Bureau of Mines and the results were reported in their I.C. 9020 (Chekan, 1985). This seal was 5.5 m (18 ft) wide and 1.8 m (6 ft) high. The seal was trenched into each rib 40.6 cm (16 in) and 55.9 cm (22 in) into the floor. A 10 cm (4 in) concrete footer was poured into the floor notch before the blocks were laid. The roof, ribs, floor behind the seal and both sides of the wall were sprayed with gunite. When testing began, water immediately leaked from the roof, ribs, and floor. Polyurethane was then pressure grouted into the strata. As mentioned earlier, the solid block seal withstood a maximum pressure of 275.8 kPa (40 psi). However, the test was run for a very short time, a total of 9 hours. It was concluded in IC 9020 that the maximum allowable pressure that the bulkhead can safely withstand is approximately 17.9 kPa (6 ft of water head). This low recommended maximum head was arrived at by analyzing the seal considering the limits of the ACI Building Code and ignoring the effects of the pilaster, the gunite coating, and the transverse pattern of laying the blocks. Although this recommended maximum head appears extremely conservative, given the load that the test seal actually withstood, this apparent conservatism is necessary due to the largely unknown long term effects of strata movement and deterioration surrounding the seal.

The control of water seepage from around the solid concrete block test seal required a comprehensive grouting program. Without the grout, the water flowed freely from the surrounding strata. Had the grouting not been done, the pressure behind the seal might have been considerably limited due to water flow through the strata, around the seal. This flow around the seal could, if it continued for a long enough period, have eroded material from strata further limiting the seals ability to withstand large heads. This illustrates the critical nature of the strata surrounding the seal. If a stable, unbroken area cannot be found, in which to install the seal, even a quality grouting program might be unable to prevent the seal from failing.

Explosion-resistant mine seals, often solid concrete block, are constructed with a water trap installed through the seal. A pipe, usually 10.3 cm (4 in) diameter or less, is used for that purpose. Many mines find that the pipe doesn't have sufficient flow area to prevent water from accumulating behind the seal. The result is an explosion-resistant seal with impounded water behind it. The water can build up high enough behind these explosion-resistant seals to fail them. In an attempt to correct this problem, some mines have considered explosion-resistant seals with a two row high block wall built on the inby and outby sides of the seal and a single block missing from the bottom course of the seal. This creates a water trap much larger than that provided by the pipe. MSHA's Industrial Safety Division, in cooperation with the U.S. Bureau of Mines, is testing this design against 137.9 kPa (20 psi) explosions and checking for air exchange. An alternative configuration is being tested by the U.S. Bureau of Mines (Taylor, 1994)and MSHA's Industrial Safety and Mine Waste and Geotechnical Engineering Divisions. This seal, seen in Figure 2, provides baffles to dissipate the force of the 137.9 kPa (20 psi) explosion and to prevent air exchanges during that explosion. To date, this baffle design has not been installed in any mines. The baffle design does allow substantially more flow to pass by the seal than a 10.3 cm diameter pipe, considerably reducing the chance that the explosion-resistant seal would unintentionally impound water.

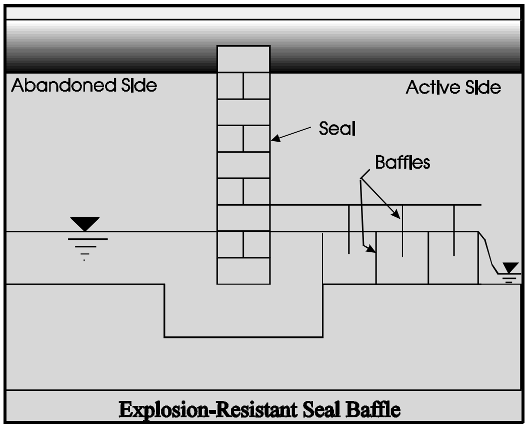

**Figure 2**

**Reinforced Concrete Seals**

Singularly or doubly reinforced concrete walls are commonly used for water seals. Figure 3 shows a simple, singularly reinforced concrete water seal. The entry is first cleaned and then floor and ribs, and occasionally the roof, are notched. Reinforcement is placed in the entry and grouted into the roof and floor. Forms are then constructed on either side of the reinforcement and the concrete is poured through the top of the forms or through the roof above the forms, until concrete begins to flow out of the vent pipes. The forms should be built of sufficient strength to bear the weight from the entire height of wet concrete and pumping pressures. Additives are often mixed in the concrete to prevent shrinkage and to provide better resistance to sulfate induced deterioration. Pressurized cement grout is then injected through the vent pipes to fill any remaining voids.

There are several methods that we've encountered in the analysis of reinforced concrete walls. These include simply supported one-way slab design, fixed one-way slab design, and two-way slab design. For a simply supported one-way slab design, the wall is assumed to be a series of vertical beams of unit width, simply supported on either end. The analysis, therefore, involves determining the maximum bending moment in the center of the beam, calculating the flexural stress, and determining if the wall thickness and reinforcement are adequate. The simply supported one-way slab design is the most conservative of the three analyses mentioned for reinforced concrete walls. The maximum bending moment, which occurs at the center, in the simply supported beam is given by:

$$M_{\max}=0.125PW^{2}$$

where $P$ is hydrostatic pressure
$W$ is seal length

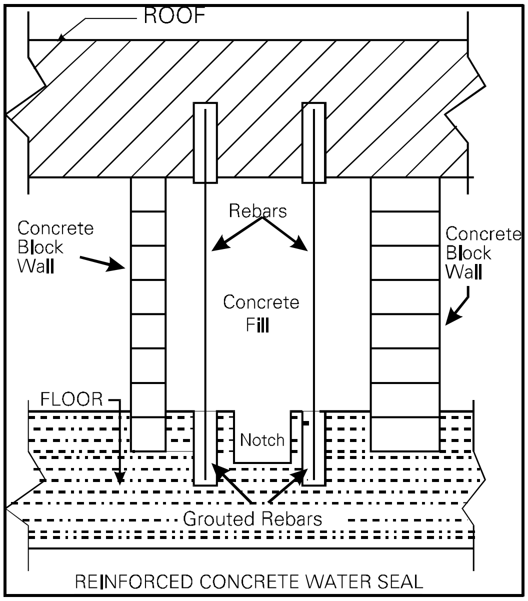

**Figure 3**

The one-way slab analysis with two fixed sides, like the simply supported one-way slab analysis, assumes a series of vertical beams of unit width. The beams are assumed to be fixed on both ends in this analysis. The maximum bending moment, which occurs near the ends, in the one-way slab with two fixed sides can be computed by:

$$M_{\max}=0.083PW^2$$

The singularly reinforced concrete seals should not be analyzed with a two-way slab analysis since the lack of substantial steel reinforcing in the second direction prevents the slab from truly acting as a two-way slab. The doubly reinforced concrete seal can be analyzed using either of the three methods, the two-way slab analysis being the least conservative. The exact analysis of a two-way slab is more formidable than the one-way slab analyses and appropriate text (Winter and Nilson, 1979) should be consulted when doing the two-way slab design.

The strength of the reinforced concrete wall can be adjusted by varying the width of the wall and the size and location of reinforcement. The limiting factor in this design is the shear strength of the rock surrounding the seal. This is because the reinforced concrete is normally much stronger than the surrounding strata.

Reinforced concrete water seals are routinely built only .3 to .9 meters (1 to 3 feet) thick. This limited thickness can create a relatively short path for water to flow around the seal through the roof, ribs, or floor. Locating these seals in a stable, unbroken area and performing a quality strata grouting program is necessary for these thin bulkheads. Reinforced concrete seals are rarely able to take full advantage of their superior wall strength because the maximum safe head is controlled by the ability of the surrounding strata to withstand the long term hydraulic pressure. The shear strength of the surrounding rock, as with all other types of seals, must be sufficient to withstand the hydraulic pressures. The rock shear strength will be concentrated over a much shorter length than for very thick seals. Notching the seal into the surrounding strata will help to increase the total shearing resistance provided by the surrounding rock and will increase the seepage path around the seal and force the seepage through more competent rock. In addition, the limited thickness of these seals makes a bearing capacity type failure on the ribs or floor more of a concern. This is especially true for seals constructed on fireclay floors or on other shales that deteriorate when exposed to water.

Another limitation of this design is the difficulty in pouring the concrete tight against the roof and the limited access for working the concrete around the reinforcement. These conditions can result in voids that weaken the seal and create water flow paths through the seal. Also, the concrete is quite rigid in comparison with the adjacent ribs, and the design should consider some roof loading due to compression of the pillars. If the pillars yield significantly, the concrete may actually act as a stress abutment concentrating the loads. If the seal will be subjected to roof loading, it will be necessary to analyze the seal as a wall subjected to axial load and flexure.

## Concrete Plug Seals

Another common type of water seal is unreinforced concrete or cement grout poured between forms or solid concrete block walls as shown in Figure 4. The forms are erected at both ends of the seal. Vent pipes are placed through the forms and into the seal area, near the roof. The concrete is then poured between the forms either through the pipes left in the forms or through boreholes drilled from the surface. Due to the large amount of concrete required to build a concrete plug seal, filling from the surface through boreholes is more common. Pumping continues until concrete flows from the vent pipes and, as with the reinforced concrete seal, pressurized grout is injected through the vent pipes to fill any remaining voids. Additives are sometimes mixed with the concrete to reduce shrinkage and minimize the effects of sulfate on the concrete. The concrete plug seals are normally quite thick and thicknesses of 6.1 meters (20 feet) or more are not unusual where large hydraulic pressures are expected. Keying into the floor, ribs, and the roof is common. The mine entries are often tapered such that the seal width and/or height increases towards the water side of the seal. This configuration better mobilizes the strength of the surrounding strata. Pipes for gauges and drainage are frequently installed through the seals.

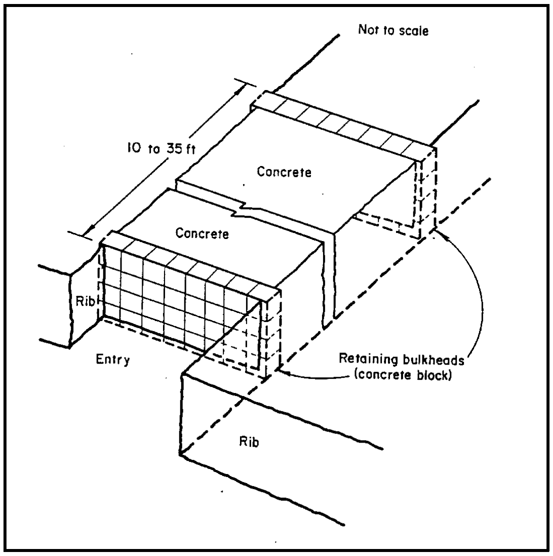

**Figure 4**
**Concrete Plug Seal**
**(Chekan, 1985)**

Concrete plug seals can be analyzed in several ways. The simplest method of evaluating the plugs adequacy involves ensuring that the total weight of the plug exceeds the total hydraulic force exerted on it.

$$L=\frac{PWH}{WH\gamma}=\frac{P}{\gamma}$$

where L is required plug length
W is plug width
H is plug height
$\gamma$ is unit wt. of plug material
P is the hydraulic pressure exerted on the plug

This analysis is conservative since it neglects the friction, adhesion and shearing resistance between the plug and the surrounding strata. These factors can be considered by assuming that the shearing resistance around the plug perimeter is the lowest value of the shear strength of the roof, ribs, floor, concrete or the adhesion between the concrete and the surrounding strata. Unless the surrounding strata is particularly weak, the adhesive strength will be lower than the shear strength of the surrounding strata. If the plug is tapered or keyed into the surrounding strata, then more of the shear strength of that strata can be relied on.

Another formula used to analyze a concrete plug seal is the South African or Parallel Plug formula (Garrett and Campbell Pitt, 1961). In this analysis, the required length of the plug is based on shearing resistance, bearing capacity, and resistance to leakage. It is concluded that the plug should be sized to prevent leakage around it. That is, it should be made longer than is necessary for structural strength purposes. However, determining the necessary length to prevent leakage requires knowledge of the resistance of the strata to the passage of water. This is not only difficult to quantify, but the resistance to flow of the strata will likely change in many mine environments. The required plug length based on shearing resistance is given as:

$$L=\frac{PWH}{2\,(W+H)\,p_{pe}}$$

where $p_{pe}$ is the permissible punching shear stress of the rock

The concrete plug seal suffers less than other seal types from the deteriorating effects of water flow through the roof, ribs, and floor, due to its greatly increased thickness. The greater thickness also tends to reduce the maximum potential pressure from roof loading on the seal, making the installation of supplemental roof supports less critical. The longer seepage path can also reduce the need for grouting of the surrounding strata. Key trenches can be excavated into the roof, ribs, and floor further increasing the seepage path and making better use of the rock strength.

In order to prevent cold joints in the concrete, which can be a path for seepage, the plugs are poured as rapidly as possible. This can be a problem for large plugs underground and often requires filling through boreholes from the surface. The quality of the pour can be lower than for other critical concrete structures. This is mainly due to the difficult access to the pour. If the pour is made through a borehole, from the surface, the possibility of segregation of the sand and gravel in the mixture must be considered. Voids are difficult to find and difficult to fill. The detrimental effect of voids left in the seal is offset by the size of the plug. These plugs are much thicker than they would be if shear through the concrete were the determining design factor. Voids, therefore, are rarely a major factor in either strength reduction or potential flow through the seal itself. Small seeps through a large concrete plug seal, especially around vent pipes, monitoring pipes, etc., are not always critical. Seeps should be monitored and if the seepage increases significantly, remedial action may be necessary. Finally, as with thinner, reinforced concrete seals, insuring that the concrete is tight against the roof is difficult, and additional grouting is may be necessary.

Cement grouts and pumpable cement foam materials are also used to construct these plug seals. The cement foam material varies but its strength is much less than the strength of concrete yet higher than the strength of chemical grouts. Some concerns have been raised about the consistency of plugs, the potential for cracking and therefore seepage through the plugs, and the effect of acidic water on the plugs. Some testing has been done and more testing is being conducted to answer some of these questions. The strength of the plug must be considered in the design of these seals. Supplemental roof support is necessary when the plugs are filled with grouts and cement foams.

## Grouted Rock Seals

Grouted rock seals are constructed by installing a solid concrete block wall or form on the water side of the seal location. A partial concrete block wall or form is then built at the other end. Grouted rock seals are usually as thick or thicker than the concrete plug seals. The entry is then filled to a predetermined height with rocks. The size of the rocks in the fill depends on the size of the seal and the grout material and ranges from gravel to large hand placed rocks. Grout injection pipes and vent pipes are then laid on top of the rock to varying distances from the forms. The partial wall is then raised and the rock and grout pipe installation sequence is repeated until the area between the forms is filled. The rock is then grouted until grout material flows out of the vent pipes. After the grout sets, the perimeter of the seal is regrouted to seal it against the rock. The grout material varies from cement grout to rigid polyurethane foam.

The analyses used for grouted rock seals are similar to those used for the concrete plug seals. Comparing the weight of the seal to the total water force is the simplest and most conservative. The South African or Parallel Plug formula is also used.

Grouting of these seals is typically done from the mine level because of the number of grout pipes involved and the horizontal orientation of these pipes. The compressive strength of a seal grouted with cement grout would theoretically be equivalent to that of the concrete plug seal. However, in practice, it is found that filling all of the voids within the rock fill in the seal is extremely difficult, and the actual compressive strength is likely to be less. Chemical grout has lower compressive and shear strength than cement. Compression of the seal by roof movements can create cracks in the grout, reducing the shear strength of the plug and opening paths for seepage. The lower shear strength must be accounted for in the design.

The inability to fill all of the voids within the rock fill can allow seepage through the plug and occasionally erosion of plug material by seepage forces. The chemical grouts, because of their expansive quality, can do a somewhat better job of filling the voids, but total filling may not be possible with either type of grout.

## GENERAL CONSIDERATIONS

There are some water seal construction and design considerations which are common to many, if not most, designs. Some of these common considerations include:

### Grouting of the Roof and/or Ribs

The most common mode of failure of many water seals is broken or deteriorated rock strata surrounding the seal. The use of supplemental roof supports and the restriction of mining in the area of the seals can help to prevent additional damage. The remedies for existing cracks and voids include sealing the strata at its face and/or pressure grouting the cracks and voids within the rock. For a pressure grouting program to be successful, there must be an understanding of the rock conditions at the location of the seal. Factors such as in situ stresses and joint orientations are vital. Pressure grouting, if not done carefully, can damage the strata and result in reduced rock strength and possibly opening new seepage paths. Grouting of the strata becomes more critical for thinner seal designs due to the reduced flow path length.

### Face Sealants

A sealant material, usually shotcrete or gunite, is applied to the roof and ribs behind a water seal, prior to its construction. This is done to restrict water flow through this strata. The faces of the seal itself are treated to restrict seepage.

### Supplemental Roof Supports

Supplemental roof supports are placed on both sides of a water seal. These supports include combinations of crib sets, additional roof bolting, meshing, steel beams, and timbers or steel columns. This additional roof support helps prevent increases in the roof load on the seal due to roof convergence. The reduction of convergence can reduce roof strata separation and the resulting water flow paths.

### Notching of the Roof, Ribs, and/or Floor

The seal design frequently calls for the notching of the roof, ribs and/or floor. This notching can improve the seals ability to mobilize the strength of the surrounding rock. Notching can also increase the flow path and reduce seepage around the seal. Notching, if not done with extreme care, can also further damage the rock leading to additional seepage around the seal.

### Doweling into the Floor and/or Roof

Dowels or grouted reinforcement rods are often installed into the floor and less commonly into the roof (Figure 2). These dowels are grouted several feet into the rock and are left extended into the seal area. Dowels are normally used with reinforced concrete seals, where they are welded to the reinforcement. The installation of dowels can significantly increase the shearing strength at the interface between the seal and the roof and floor.

### Pressure Gauge

A pipe, open at both ends, is often installed through the seal. A pressure gauge can then be installed on the end of the pipe and the pressure behind the seal can be monitored. It is useful to monitor mine pool changes and to assess the adequacy of design pressure assumptions. At least one pressure gauge should be installed for each set of seals.

### Relief Valve

As with the pressure gauge, the open pipes can be fitted with relief valves. These valves can be very useful if, due to serious deterioration of the seal and/or surrounding rock or due to an unexpected increase in the mine pool level, it is decided that in the interest of safety the water level should be reduced behind the seal. The valved pipes can also be used to monitor air quality behind the seal if water does not accumulate behind it. Finally, the open pipe can be used for emergency grouting or filling of the entry behind the seal in the event of rapid deterioration.

### Alarms

Alarms are sometimes included with a water seal design. The alarms are set to sound if there is a sudden drop in the mine pool. Alarms are only used in extremely critical situations.

### Evacuation Plans

Evacuation plans have to be included with any seal design that will accumulate a sufficient volume of water to pose a hazard to miners. Evacuation would be triggered when an alarm sounds or when some predetermined water level or water pressure behind the seal is reached. This predetermined water level would be a function of the maximum design head of the seal.

## SUMMARY

The use of seals to impound water in underground mines is increasing. The water pressure that these seals are being designed for is also increasing. New construction materials and methods are constantly being proposed for seal installations. Water seal design and construction is very site specific because in many installations the limiting factor is the condition of the surrounding strata and not the seal material. The strata around the seal is also subject to long term deterioration due to a continuation of strata movement from previous mining, the effects of additional mining, and the potential effects of pressurized water flowing through the cracks and voids within the strata. When seals are built to withstand hydraulic heads and when the failure of these seals would pose a hazard to miners, their design should be very conservative since the long term condition of the surrounding strata can not be adequately predicted. Furthermore, a regular inspection and monitoring program should be developed to verify the continued adequacy of the seals. Finally, a remedial action and evacuation plan should be developed in case it is found that the seals are not performing as expected.

This paper has been an overview of the design and construction considerations for the water seals most used in the United States. The goal has been to increase awareness of specific areas of concern so that the actual level of risk is better understood and hopefully can be reduced.

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