

Design and remote construction of underground plugs

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ABSTRACT: Underground plugs are often required to isolate sections of previously mined or flooded underground areas for the opening or reworking of existing mines. Closure requirements also necessitate underground plugs for health, safety or environmental reasons. If access is still available, plugs can be constructed in situ. However, in flooded or previously abandoned locations where safe access is no longer possible, plugs must be constructed using remote methods, often working from the surface via small diameter boreholes. Various examples of underground plugs that have been designed and remotely constructed are presented, along with the challenges encountered and lessons learned. Emphasis is placed on selecting a working platform to reduce the amount of drilling, quality control methods and monitoring of the works during construction.

1 INTRODUCTION

Barriers, walls, seals, bulkheads or plugs are required to isolate various sections of a mine for closure requirements or to enable mining to continue adjacent to previously worked-out areas or abandoned workings.

The most common seals constructed in underground mines, particularly in bord and pillar mining, are stoppings or seals that are erected to control ventilation and/or provide explosion-proof barriers. The minimum design pressure for ventilation containment is a stopping capable of withstanding ~140kPa (20psi). In contrast, explosion-proof stoppings must be capable of withstanding pressures of up to 400kPa in areas that remain within the explosive range.

There is a significant disparity in the details of various walls constructed underground to meet these requirements. Walls designed as structural panels or bulkheads adhere to codes and applicable safety factors. In contrast, some walls, particularly those classified as explosion-proof and rated for 400kPa, are often specified based on empirical testing. When back analysed, these walls are repeatedly found inadequate to sustain a static pressure of 400kPa. Although they can endure impact loading and do not fail outright during testing, they may become overstressed and crack.

Therefore, where seals or plugs are required to retain static pressure, such as a head of water in flooded sections of a mine, the design of such plugs needs to

follow an engineered approach to account for uncertainties in loading, as well as the type and condition of the surrounding rock where the plug is to be located. Figure 1 shows a punching failure of a 900mm thick plug that failed due to a sudden increase in pressure above the design pressure.

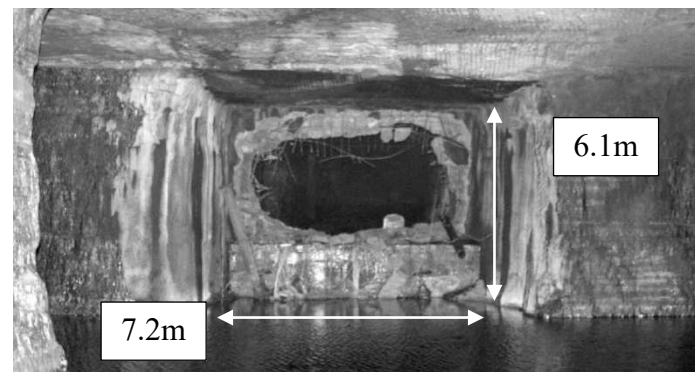


Figure 1. Punching shear failure of a 7.2m x 6.1m x 0.9m plug.

The aim of this paper is to present the steps to be followed for designing and constructing underground plugs, particularly those constructed remotely, which complicates the assessment of the location and quality control during construction. These factors are critical in the design, construction and verification process.

Although the construction method adopted does not involve grout intrusion, the general approach and recommendations given in the 1983 Code of Practice for the construction of underground plugs and bulkhead doors using intrusion concrete (Chamber of

Mines 1983) are applied to the design and construction of remote plugs.

Where the workings are still accessible, construction can proceed with proper preparation of the location, pre-treatment of the country rock and tight construction tolerances, resulting in more economical plugs with less material usage and shorter construction periods. In this case, the design of the plug is typically based on a relatively narrow structural plug that works in bending, arching and/or shear. The plug is anchored around its perimeter to transfer the resisted load into the surrounding rock through shear, often enhanced by rock dowels extending into the plug to provide additional shear and rotational fixity to the perimeter of the plug. Such walls or bulkheads are regularly constructed as part of ongoing mining operations.

For plugs where access is unavailable, either due to the plug location being flooded or deemed too costly or unsafe to access conventionally, a specifically engineered approach to the design and construction is required. Consequently, the design and construction of the plug must be adjusted to take into account the possible methods of achieving remote access and the unknowns regarding the location where the plug is to be constructed, such as the condition of the surrounding rock and the shape of the mined-out area within which the plug is to be constructed.

Therefore, contingency measures must be included in the construction of remote plugs to address possible unknowns that could affect the construction of the plug, ensuring that the design requirements are achieved.

2 REMOTE PLUG CONSTRUCTION

The design of remote plugs is closely linked to the construction process, as the access, geometry, condition and chosen location for the plug influence the design. For example, the force that a plug must withstand results from the contained water pressure, as well as the mined height and width at the plug location, which in turn determines the minimum length of the plug. However, the mined height and width at the plug location are only determined or confirmed during the probing phase of construction, after which they are used to update the design.

Initial concept designs are based on underground mining plans to estimate the size of the proposed plug according to the expected loading requirements, which are then finalised during construction.

2.1 Plug location

The selected location for constructing the plug must be accessible either from above (surface) or from the side through neighbouring underground workings. It is preferable to choose a point of access that has the

shortest drilled length to reach the plug location, as the cost of drilling often outweighs the material cost used in constructing the plug. Additionally, longer drill lengths require a larger plug to account for the achievable drilling tolerances. Once the point of access has been selected, probe drilling can commence.

2.2 Probe drilling

This process involves drilling a series of probe boreholes, initially set out according to the mine plans, to verify their accuracy. The aim of the probe boreholes drilled from the drilling platform is to either intersect the workings or unmined areas, to confirm the extent of the mined area and the location of the proposed plug by delineating the edges of the workings, defining the width of the openings and measuring the floor-to-roof height of the cavities. Additionally, the condition of the area is assessed, including the presence of debris on the footwall, potential flooding of the workings and any deviations from the mining plans. Borehole cameras and, if dry, Lidar surveys can also be undertaken inside the intersected cavities in order to gather more accurate information.

In cases where no mining plans exist, probe drilling is used to gather as much information as possible about the workings based on assumptions regarding the mining that was carried out. As more probing is carried out, these assumptions are gradually confirmed with each new piece of information.

There is no fixed method for undertaking probe drilling; however, a useful technique involves a halving approach. Initially, widely spaced probe holes are drilled using a grid pattern, followed by refining the grid by drilling at the midpoints and then at the quarter points, depending on the findings of the previous probe holes. This method helps to delineate mined-out and unmined areas. Adjustments or shifts in the underground mining plans are often required, which can be achieved by superimposing the plans over the drilling results to ensure alignment. It is important to note that some areas may be found to have been mined out more extensively than recorded on the plans. Additionally, larger unexpected openings may occur due to sidewall scaling and slaking, roof collapse, or unrecorded double bench mining. Similarly, areas indicated as mined are sometimes found to have either not been mined or to have been mined to a lesser extent than indicated on the plans, with narrower drives or bords established.

2.3 Plug Design

The parameters used in the concept design to determine the proposed size and location of the plug are verified based on confirmation received from the probe drilling, such as the rock strength of the country rock, the floor-to-roof height, width and available space.

The selected location for a plug is ideally positioned in the centre of a homogeneous area of approximately three plug lengths, which is free of structural weaknesses and other excavations, ensuring safe anchoring and watertightness.

Invariably, the loading is due to the hydrostatic pressure of the water retained by the plug within the flooded portion of the mine. It is important to note that the maximum or ultimate possible loading needs to be evaluated, as the retained water can continue to build up over time.

The minimum design length of the plug depends on the strength of the surrounding country rock in which the plug is constructed. Based on shear friction, the length of the plug is a function of the loading, with an applicable factor of safety (FOS). Additionally, considering the complexity introduced by remote construction, the minimum length must account for the tolerances achievable during the drilling and placement of the permanent shuttered ends.

Furthermore, the direction of loading must be considered in relation to the orientation of the “parallel” sides of the location. Due to the remote construction of the plug, access is limited for creating a shear key or taper plug to enhance the shear capacity of the plug with the surrounding rock. However, dowelling the plug in situ with the surrounding rock can be achieved by drilling through the plug to the rock on the far side and grouting in anchorage tendons that extend from the rock on one side of the plug, through the plug, and into the rock on the other side.

2.4 Plug Construction

Once the position of the plug has been determined, permanent shutters are constructed at either end. Various methods have been used to construct the required permanent shutters, including placing stockpiles of loose gravel and/or aggregate rock to form a barrier, using inflatable grout bags that are filled once secured in position, or constructing mass concrete barriers by placing batches of mass concrete as “cow patties”, piled on top of one another until the hanging wall is reached.

After the ends have been closed off, the central portion is filled with concrete or grout to form the plug. This is achieved by drilling a series of boreholes across the width of the opening to ensure the plug is filled across the entire width, extending up to the hanging wall. As the filling of the plug nears completion, interconnection between the boreholes can cause the pumped concrete or grout to be forced up neighbouring boreholes, indicating that the plug is completely filled up to the roof.

2.5 Plug tightening

Once construction of the plug is completed and the central portion between the two ends is fully filled, a series of tightening holes are drilled in a grid pattern

to intersect the contact between the plug and the surrounding rock. These holes serve two purposes: they verify intimate contact between the plug and the surrounding rock, and they also allow for pressure grouting to seal any openings that may exist, thereby tightening the contact between the plug and the surrounding rock. Small openings are often found against the roof, resulting from concrete shrinkage or from high spots that were not completely concreted.

The plug tightening boreholes are typically drilled in a sequence of primary widely spaced boreholes, followed by secondary boreholes midway between and then tertiary boreholes to address areas that may require additional treatment.

The boreholes are drilled at various inclinations to intersect the roof, floor or sidewalls, depending on the specific target area being addressed.

2.6 Verification

A series of verification boreholes are drilled to assess the condition of the surrounding country rock, determine if additional treatment is required, and evaluate the effectiveness of sealing and tightening the contact between the plug and the sides of the opening, as well as the plug itself.

The verification boreholes are often drilled as rotary core boreholes, allowing the cast concrete plug to be sampled, tested and logged. They can also be used for water testing and pressure grouting to seal off and improve any poor areas encountered.

2.7 Treatment of debris at the plug location

As the plugs are constructed remotely, any debris lying on the floor or against the sides of the workings due to slaking must be addressed during the construction of the remote plugs.

Typically, the muck and debris on the floor at the plug location are disturbed and sometimes partially removed during the probe drilling. As the workings are often flooded, the compressed air return up the annulus of the borehole airlifts some of the debris and muck as it is sucked out to the surface with the return flush.

Thereafter, during the placement of concrete or grout, the debris is either physically pushed aside by the pumped material, placed on the floor using a tremie pipe, or impregnated if voided. Occasionally, the debris is lifted, mixed in or entombed within the material being placed.

Finally, during the drilling of the tightening boreholes, the unconsolidated debris is treated by pressure grouting. Some of the remaining confined fine-grained debris is flushed out during the drilling process, while the rest is treated by permeation or impregnation through grouting. This process may require multiple downstage grouting treatments and advancing of the boreholes in stages until the footwall can be reached without borehole collapse.

Subsequent adjacent tightening holes and verification holes are then used to confirm that the entire horizon of debris trapped at the contact has been treated and acts as solidified material.

2.8 Treatment of the surrounding country rock

Where required, the rock surrounding the plugs can be treated by grouting, typically by installing a grout curtain. This is usually carried out concurrently with the tightening of the plug contacts or during the drilling of the verification boreholes.

Sections of the tightening and verification boreholes can be water tested and grouted using packers to treat the surrounding rock mass.

Depending on the specific requirements of the plug, the area can be sealed by creating a grout curtain that passes through the plug and extends outwards both above and below the plug, as well as on either side.

2.9 QA/QC and data pack

As with any geotechnical construction, it is critically important that a monitoring system is implemented to record and document all activities and the results thereof. This often overlooked process ensures that the design aims are achieved and provides an auditable record of all activities, which is compiled into an as-built data pack.

Since all activities are carried out remotely, verifying the final details of the constructed plug relies heavily on the results of the probing, water testing, volumes of concrete placed, and grout takes, as well as the inspection of retrieved core samples during the verification process. The integrity of the plug is assessed based on the interpretation of these measured results.

3 REMOTELY CONSTRUCTED PLUGS

The reasons and requirements for constructing plugs vary significantly. Below are examples of three different types of remote plugs, each constructed in a unique way, to highlight that there is not one single method for plug construction; rather, each location must be assessed individually. Based on the specific circumstances, a plug should be designed and constructed to best meet the design requirements and access constraints.

3.1 Adit entrance plugs

Two different methods were used to construct plugs in adit entrances to underground mines that were no longer accessible due to flooding. Despite the different construction methods, both types were required to retain water in the flooded mined-out areas and prevent water from discharging out of the adits from the flooded workings behind.

The main factors influencing the choice of construction methods were the thickness of the material above the plug locations and the accessibility of the area directly above the plugs.

In the first case, the plugs were installed in the adit entrances at the base of an open pit highwall, with no safe working access to the area directly above the plugs, at the top of the highwall. Instead of working from above, the mass concrete plugs were installed inside the partially flooded adit entrances by working remotely from inside the open pit, without having to enter the adits and while maintaining a safe working distance from the highwall. See Figure 2.

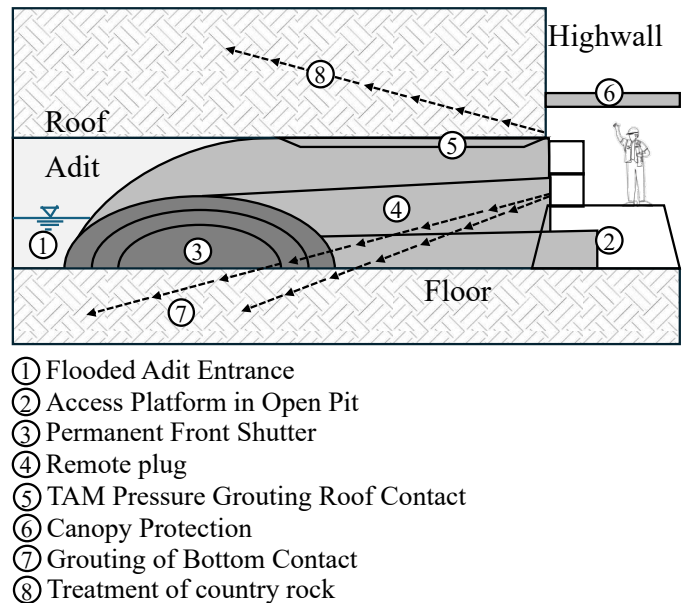


Figure 2. Mass Concrete Adit Plug (not to scale).

In the second case, the adits were located in the side of a mountain, and the plugs needed to be inserted relatively far back into the adit entrances, where there was sufficient competent surrounding country rock to withstand the expected water pressure as a result of the flooded mine extending back into the hillside. In this case, a working platform could be created directly above the plug locations by cutting a bench into the mountainside, with the depth from the bench to the adits below being approximately 10m. See Figure 3.

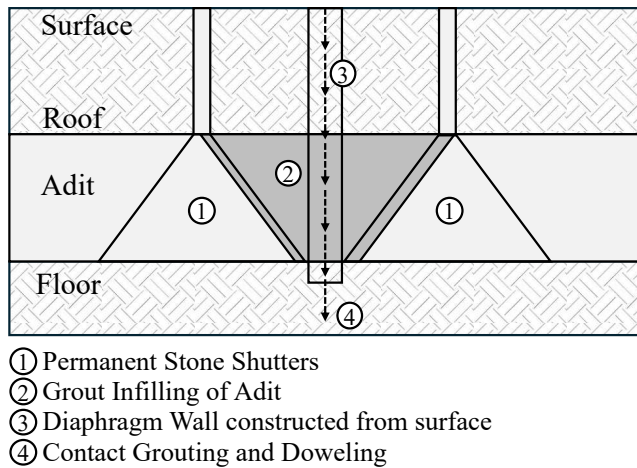


Figure 3. Diaphragm Wall Adit Plug (not to scale).

3.1.1 Mass Concrete Adit Plugs (First Case)

The construction of a series of remote plugs to seal off a line of adit entrances was required, as access to a partially flooded underground mine and adit entrances was no longer possible from inside.

Although the adit entrances and the base of the open pit mine were partially flooded, there was sufficient spoil material nearby to create a working platform on the floor of the open pit, in front of the adit entrances, in order to construct the plugs remotely. The working platform, constructed above the water level, was set back from the highwall to provide a drop zone for any possible falling objects dislodged from the unsecured vertical face of the open pit highwall. Fortunately, the tops of the adit entrances remained visible above the rising water that had flooded the mine and open pit.

Some adit entrances had been sealed off by falling debris or purposely by shotcrete walls installed during mining to control ventilation. Using an excavator while maintaining a safe distance from the highwall, the fronts of all the adit entrances could be opened, allowing all the plugs to be constructed remotely from the working platform.

As the openings to the adit entrances were still visible from the working platform, probe drilling was not required to confirm their location or width.

The concrete plugs were created by inserting the long arm of a concrete boom pump into the open adit entrances, which was then used to place a limited volume of low slump concrete along the rear line of the proposed plugs, deep inside the entrances. The end of the concrete boom pump pipe was placed on the floor of the flooded adit, allowing the extruded concrete to be tremied into place while the end of the pipe remained submerged in the wet concrete. By repeatedly placing limited volumes of low slump concrete at the rear of the proposed plug, forming a series of “cow patties” placed one on top of the other, a permanent shutter was built up, creating a mass concrete barrier at the rear of the plug.

The front of the adit was sealed using spoil, dozed in from the working platform, which was then raised further as a vertical wall across the opening using bulk bags placed one on top of another by a long-arm teleporter while maintaining a safe distance from the highwall.

Once the rear barrier had nearly reached the roof of the adit entrances, the remaining centre of the plug was filled by pumping flowable concrete between the rear barrier and the front wall of bulk bags. Just before the bulk filling reached the roof, a series of parallel 25mm diameter High-Density Polyethylene (HDPE) grout pipes fitted with Tube-a-Manchettes (TAM) valves at regular intervals were positioned into the open adit on top of the rising bulk concrete. Concreting continued, pushing the grout pipes against the roof as more pumped concrete was forced to fill the adit right up to the roof, squeezing out of the adit and over the top of the bulk bag wall.

Pressure grouting was then carried out through the TAM valves to ensure intimate contact between the concrete plug and the roof, as well as to treat any high spots.

To facilitate safe drilling and grouting at the adit entrances, protection canopies were erected against the highwall, consisting of thick concrete lintels placed above the openings to the adits and propped on the sides. Inclined grout tightening boreholes were drilled from beneath the protective canopy into the highwall to intersect the roof, sidewalls and floor of the remotely constructed plug, which was situated further in from the entrance. The boreholes were drilled as a sequence of primaries, secondaries and tertiary (verification) holes. As expected, the secondary boreholes took less grout than the primary boreholes, with the tertiary boreholes used to verify that the area had been sealed.

The boreholes were also drilled deeper beyond the plug/rock contact into the surrounding country rock to treat any fractures or delaminations around the adit opening.

Surprisingly, most adit floors were found to have very little debris or muck, except for one adit. The debris was mainly a result of a roof collapse at the adit entrance. At this adit, the grout tightening boreholes drilled into the footwall needed to be redrilled multiple times with repeated downstage grouting of relatively high takes so that the drilling could advance a little further each time until the footwall was reached. The debris was relatively porous, consisting of angular slabs lying on top of one another, making it easy to grout. Subsequent secondary boreholes drilled between the primaries encountered no issues and easily reached the intersection with the footwall. Pressure grouting of the secondary boreholes confirmed the grouted debris was tight.

3.1.2 Diaphragm Wall Adit Plugs (Second Case)

Water accumulating in the underground workings of a mine had bypassed the initially constructed bulkheads, installed on cessation of mining, and was seeping from three adit entrances. A new line of plugs was therefore installed in more competent material further back to accommodate the expected increase in water pressure due to further filling of the mine. The new plugs were installed in each of the adits, in line with each other, with a grout curtain between the adit plugs that extended some distance on the outside to prevent water from bypassing the area.

As the workings were already flooded and access to the adit entrances was blocked by the initially constructed bulkheads, the new plugs were installed remotely from the surface, directly above the adit entrances. The plugs were positioned approximately 50m back from the existing bulkheads. This chosen location was determined by a geotechnical investigation, ensuring that the adits were surrounded by competent material (not backfill) and that the depth of the workings was shallow enough to be remotely accessed from the surface.

The chosen location was checked to confirm that there was sufficient restraining force from the surrounding soil to withstand the expected water pressure exerted on the plugs once the mine was flooded to the selected decant level. The positions of the adits were verified by probe drilling, which confirmed the width and height of the adits.

The method of construction selected for the remote installation of the permanent plugs involved creating vertical concrete cut-offs from the surface through the adits using the under-slurry technique as "diaphragm walls". Additionally, core samples and water pressure testing of the different horizons indicated a real possibility of seepage along the joints and bedding planes of the coal seam, carbonaceous siltstone, and sandstone between the adits. Therefore, a grout curtain was installed between the three permanent concrete cut-off walls and extended beyond the outer two adits by 16m.

Along either side of the proposed plugs/walls, the three adits were filled to the roof by discharging coarse aggregate stone through the probe holes drilled. The V-shaped space formed between the two lines of stockpiled stone along the line of the plugs was then filled across the entire width of the adits with weak cement grout. The adits were then sealed by excavating vertical diaphragm walls from surface through the low strength grout filled adits. The bottoms of the excavated diaphragm walls were keyed into the hard rock sandstone footwall by approximately 300 to 500mm, using chiselling techniques. The ends of the diaphragm walls were keyed in by approximately 2m on both sides into the sidewalls of

the adits. The new plugs were constructed as fully reinforced concrete walls over their full depth, with concrete placed using a tremie pipe in a single pour.

The bottom contact or key of the concrete walls was pressure grouted through vertical ducts cast into the walls at 500mm centres. These ducts were then extended a further three metres below the bottom of the concrete walls by drilling into the hard rock sandstone, followed by additional pressure grouting. The boreholes were then used to install vertical Y32mm dowel bars along the bottom contact of the walls.

The area between the new concrete plugs and the outside of the outer two was sealed using a grout curtain that extended from surface to a depth of ~3m to 4m below the footwall of the adits.

The concrete plugs were designed to rely solely on edge support at the sides of the walls and shear from the dowels installed along the base. Any additional restraint achieved by keying in the walls along the side edges, as well as shear along the bottom, was not relied upon during the design stage. Each plug was designed as a single, fully reinforced wall, concreted in one pour to prevent any cold joints.

To verify the integrity of the plugs, diamond cored boreholes were drilled vertically through the full height of the concrete plugs and into the hard rock sandstone below. The core samples showed that the concrete throughout the plugs was uniform and that the interface between the bottom of the plugs and the underlying hard rock sandstone was intimate.

3.2 Remote Bord Plugs

To mine out a previously excavated bord and pillar panel using opencast methods, five bords connecting the panel to the rest of the flooded underground mine were sealed off by constructing remote plugs from the surface. With the panel sealed off by the completed plugs, the overburden will be removed, and the pillars extracted in the dry by opencast mining.

The positions of the existing bords to be plugged were pegged out on surface according to the underground mining plans. Using the pegged out layout, probe drilling was undertaken from surface to verify the expected position of the bords and pillars. The underground workings were intercepted at a depth of between 27m and 32m.

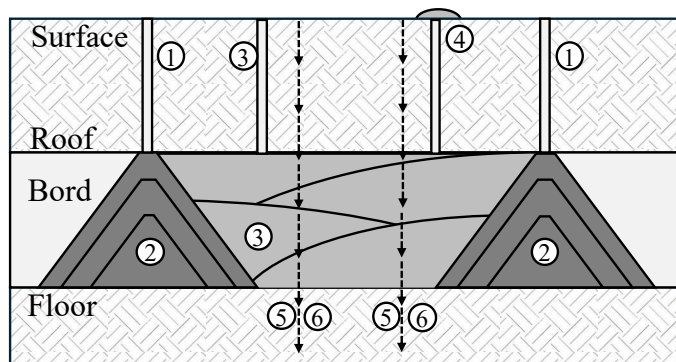
Initial probe drilling revealed that the underground mining was not properly aligned with the points set out, based on the original mining plans, requiring a shift of approximately 3m to the calculated positions. After applying the shift, further probe holes were drilled to confirm the adjustments made. Once verified, the sizes of the plugs were re-analysed based on the actual mining heights and widths of the bords determined from the probe drilling.

Using some of the existing probe holes and additional boreholes, the front and back shutters were systematically constructed. Batches of concrete were

placed by tremie at each of the plugs and allowed to set before the next batch was added on top, creating a series of “cow patties” stacked one on top of another until the roof of the bords was reached.

After the front and rear of each plug had been shuttered, the central portion of the plug was cast by pumping concrete between the two ends using a tremie pipe inserted through a series of boreholes drilled across the width of the bord, along the centre of the plug. As the filling of the plug neared completion, interconnections between the boreholes sometimes caused the pumped concrete to be forced up the neighbouring boreholes to surface, indicating that the plug was fully filled to the roof. Once the casting of the plug was complete, the concrete was allowed to set.

Based on the location of the plug, a line of grout tightening boreholes and treatment holes for the surrounding rock were drilled. The contact between the plug and surrounding rock on all sides, including the base, was checked by water testing and pressure grouted to treat any areas requiring improvement. See Figure 4.



- ① Probe drilling
- ② Permanent Shutters
- ③ Infill Plug Construction from surface
- ④ Concrete Return
- ⑤ Contact Grouting and Grout Curtain
- ⑥ Verification Boreholes

Figure 4. Remote plug constructed in a bord (not to scale).

A final check was carried out by coring several boreholes through the concrete plug and the contact interfaces on both sides of the plugs to assess the integrity of the cast concrete plug and the contacts. The last step involved sealing off all open boreholes by pressure grouting. Based on the results from the probe drilling, concrete and grout takes, water test results, and cube strengths, a comprehensive data pack of all the records was compiled for each of the completed plugs.

4 CONCLUSIONS AND LESSONS LEARNT

Before the design and construction of plugs commence, it is important that the purpose of the plug is clearly understood, as well as what is achievable. Often, the plug is a small component in a larger system, and it is critical that the surrounding areas are capable of providing the same or better function as the plug. For example, if the plug is intended to limit seepage, it is important that the country rock around the plug does the same; otherwise, the seepage will bypass both the plug and the surrounding treated area.

Where possible, it is more economical to construct plugs underground in mined-out workings while access is available, rather than doing so remotely. When access is still possible, the plugs can be designed and constructed to tighter tolerances, resulting in less material usage and shorter construction periods.

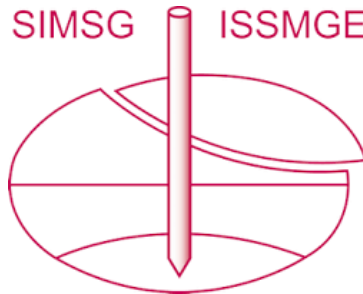
However, if access to the location where plugs are required is not possible, it is feasible to construct plugs remotely with a relatively high degree of accuracy. A crucial point is that one must remain flexible to adjust the design and construction process to accommodate the conditions encountered and any variations that need to be implemented, as illustrated in this paper by providing three different construction methods adopted and plug types for the case studies presented.

From recent projects undertaken, the cost of drilling increases exponentially with the distance to the plug, due to the length and the additional boreholes required to accommodate the reduced confidence in the accuracy of the drilling, whether for probing, construction, or verification. The increased drilling not only costs more but is normally on the critical path and also increases the construction period. Therefore, the working platform should be selected to minimise the amount of drilling required. Additionally, one can consider placing excess amounts of material through fewer boreholes based on the assumption that the higher “wastage” of materials warrants a reduction in the number and length of boreholes drilled, leading to a shorter construction programme.

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