Shotcrete: Elements of a System – Bernard (ed)

Robotic shotcrete shaft lining—a new approach

K. Ford, L. Spence, D. McGarva & M. Calderwood
Macmahon Mining Services, Perth, Western Australia, Australia

ABSTRACT: Macmahon has recently designed and constructed its first robotic shotcrete shaft liner (hereafter referred to as "shaft liner"). The shaft liner was engineered with two principles in mind: enhancing the safety of operators working around an open hole, and improving the quality of the final shotcrete lining. The result is a state-of-the-art machine which has raised the standard in the industry for operator safety, rebound reduction and quality of lining.

Design and construction of the shaft liner winch deck platform enables the unit to be set up in close proximity to the collar of the hole without exposing personnel to the associated hazards. The shaft liner incorporates scanning technology to enable both pre and post scanning of the shaft surface area to gauge an accurate thickness measurement of the applied shotcrete. Recorded video footage of the shaft is also captured separately on DVD to allow close inspection of the condition of shaft walls and identification of any faults or over-break. Additionally, shotcrete application is monitored and recorded to demonstrate spray consistency. This paper will discuss all aspects of the design, engineering, commissioning and operation of the robotic shotcrete shaft liner.

1 INTRODUCTION

Macmahon Mining Services is a division within Macmahon that offers specialised underground services to the Australian and International mining industries. The division encompasses ground support installation in the form of cable bolting and shotcreting, raise drilling and specialised engineering services including shaft fit-out. In order to be able to provide clients with a full suite of options for the development and support of vertical openings, a remote shotcrete shaft liner has been developed. After reviewing the existing shaft liners operating in the mining industry, Macmahon drew on this collected experience and designed and constructed a state of the art machine.

2 HISTORY OF DEVELOPMENT

Historically, installation of surface support in shafts has been accomplished through man access to the shaft via a hoist and stage enabling direct installation of shotcrete, mesh or concrete lining. Working in shafts is a high risk activity in mining and also adds significant cost to the development of a shaft due to the specialised equipment and personnel that are required. An alternative to manual application that may be viable in some circumstances is to use a machine to remotely apply shotcrete within the shaft.

There is a paucity of published material in the industry concerning shotcrete shaft lining, making it difficult to examine the evolution of techniques and current practices. Hustrulid & Bullock (2001) refer to "Shelob shaft shotcreting units" developed by Caledonian Mining Co Ltd, but no further detail is given. Rispin et al (2005) refer briefly to "shaft robo" machines used for application of shotcrete, although this type of machine appears to be designed to be slung beneath a man-access stage rather than to operate remotely. An ITA/ATIA report in 2006 entitled "Shotcrete for Rock Support—A Summary of the State of the Art" refers to a submission from Canada detailing the "completely robotic, continuous placement of 75 mm of shotcrete in a 415 metre deep, 2.4 metre diameter shaft using wet mix materials and placement" but does not give further details.

An examination of websites from companies offering shotcrete shaft lining as a service perhaps gives a better idea of the technology on hand. These companies include Jetcrete Australia, Rix Group Australia and Multicrete systems in Canada. Jetcrete operates three shaft lining machines and the basic operation of their machine is described on their website. Rix group is another Australian company with remote shaft lining capability. Multicrete systems have developed a "Raise Robot" shotcrete machine and a basic description of its operation can be found on their website. Macmahon has drawn on the experience of all of these machines to design a shaft liner with a similar, but refined mode of operation to the above.

3 DESIGN CONSIDERATIONS

3.1 *General*

Raise boring of shafts has become a popular method of establishing vertical and sub-vertical openings in both mining and civil applications. In general, openings that are raise-bored are suited to being lined using a remote shotcrete shaft liner. Raise boring is only undertaken in competent ground due to the stand-up time required for the walls of the shaft. This usually means that the shaft will be competent enough to support with shotcrete alone and that it will remain open long enough to enable application of this shotcrete using a shaft liner. The use of a raise drill in combination with a remotely applied shotcrete lining reduces costs significantly.

Raise bored shafts are constructed both from a pre-existing underground opening to the surface or between underground openings. Thus the shaft liner had to be designed to either operate on the surface or from a shaft collar in a chamber underground. This requirement restricted the potential dimensions of the shaft liner.

There are two commonly used shotcrete application methods: the use of dry mix shotcrete where water is added to the dry materials at the nozzle during spraying and the use of wet mix where the water is mixed into the concrete at batching. Dry mix offers significant advantages for a remote shaft lining application such as unlimited holding time for dry materials (provided they have not been predampened), long conveying distances possible and lower weight of material in lines down the shaft. Wet-mix also tends to segregate when used in these types of applications. Therefore a dry mix process was selected for use with the shaft liner.

3.2 *Hazard management*

Conducting shaft lining activities exposes personnel to several major hazards that need to be managed. The hazards which result in the greatest risk to personnel are working around open holes and working around moving lines. Working around an open shaft collar is necessitated both during the setup of the machine platform, the lowering of the robot into the hole and the operation of the machine when lengths of hose are being added. Both physical barriers and safe work procedures are necessary to mitigate the risk of falling.

During the lowering of the robot down into the shaft there is the requirement for feeding lengths of materials hose, water hose and communication and power cables over the collar and into the hole. Personnel are required to work in the same area as these moving lines, creating a hazard of interaction which could result in persons being dragged towards an open hole.

3.3 *Quality of application*

As with any shotcrete process, the quality of the final lining is dependent on the application method. The use of the dry mix method necessitates careful control of rebound and the water content of the mix. Controlling the water content of the applied shotcrete can be difficult as matching of the shotcrete machine speed and the water flow rate at the nozzle is required. Too little water can result in poor mixing and inadequate hydration of the cement, while too much water will lower the strength of the material.

The performance of any shotcrete lining is controlled by the thickness at which it is applied. The ability to accurately measure the final lining thickness is essential to ensure the quality of the application.

4 FINAL DESIGN

Following extensive research, construction of the shaft liner commenced in 2008 and it was completed and commissioned in January 2009. Research involved a comprehensive risk analysis, assessment of existing equipment within the industry and discussions with various shotcrete equipment manufacturers.

4.1 *Shaft liner elements*

The shaft liner consists of four main elements: the control room, the dry-mix shotcrete machine, the robot which is lowered down the shaft and the winch deck platform which houses the winch, boom, hose reels and associated equipment.

The control room is housed in a 3 m sea container and contains the operator control and monitoring system. The shaft liner operator can control all functions of the robot operation from this room including lowering and raising of the robot, rotation of the nozzle, water metering, spraying and scanning. The shotcrete machine used is a Reed Series 5 machine. The machine is typically fed directly by a concrete agitator truck but could also be loaded using 'bulkabags'. A machine operator is required to control the filling of the machine throughout operation.

The basic setup of the platform and robot is illustrated in Figure 1. The robot has three legs the length of which can be adapted to fit the diameter of the shaft that is being sprayed. The nozzle

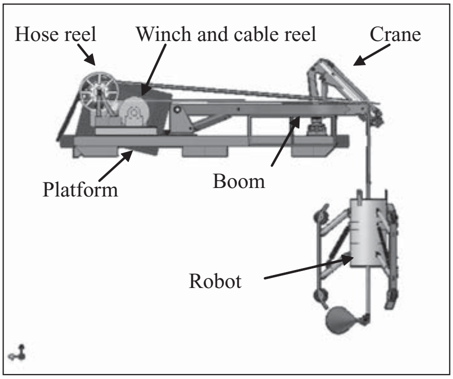

Figure 1. Setup of platform and robot.

is suspended below the main body of the robot and can rotate through 360 degrees. The robot is also fitted with cameras to monitor the spraying.

The boom of the platform can be extended, raised and lowered as required to position the robot within the hole. The hoses and cables run along the top of the boom and are contained within a covered channel. The winch and cable reel control the lowering and raising of the robot within the shaft. The water hose and power cables are stored on a hose reel, while the concrete hose is fed through from the rear of the platform. A crane is mounted at the front of the boom to enable the robot to be lifted into and out of the shaft collar.

4.2 *Rig specifications*

The remote shaft liner has been designed to be able to operate either on the surface or in an underground chamber. The platform is 2 m in width, 6 m in length and has a maximum height of 2 m enabling it to be situated in most standard underground drives. The control cabin is housed in a sea container which is easily transported underground. The shaft dimensions that the shaft liner is able to operate in are:

- Shaft diameter from 1.8 m to 8 m,
- Shaft inclination from vertical to 50 degrees
- Shaft depth to 350 m

An air volume of 25 m^3/min at a pressure of 0.7 to 0.8 MPa is required for effective operation. The liner can be run on either 415 V or 1000 V power and sprays a nominal 10 mm dry mix shotcrete product. Shotcrete at a thickness between 10 mm and 100 mm can be applied in one pass.

4.3 *Safety enhancements*

A comprehensive risk assessment was conducted as part of the design of the shaft liner which has led to several innovations in the management of the hazards present.

4.3.1 *Open hole hazard management*

The platform of the shaft liner has been designed with a boom and a crane to ensure personnel are never required to work within 1.5 m of the hole collar during normal operation. The platform is secured to the ground using "gewi" type resin bolts. The crane can lift the robot into and out of the hole collar and the boom can be used to extend out over the hole as required. This functionality means that the platform can be located back from the collar of the hole, not over the top of the collar as with some shaft liners currently in operation.

As there is no requirement to be within the immediate vicinity of the open hole, effective guarding can be in place throughout the operation (Figure 2).

Maintenance and repairs on the robot can be carried out well away from the open hole with this platform setup. Other shaft liners in operation may require work to be performed on the robot while it is held by the winch in the collar of the hole with personnel wearing fall arrest gear to manage the hazard. An elevated anchor point is located at the centre of the platform to allow fall arrest or restraint devices to be anchored if work is required closer to the collar of the hole for any reason.

4.3.2 *Moving lines hazard management*

The hazard of working around moving lines has been reduced significantly in the design of the shaft liner. The hoses and cables run through a fully enclosed channel on the top of the boom (Figure 3). The water hose is housed on a reel at the rear of the platform, while the materials hose is fed through a set of rollers at the rear of the platform. The power cables are secured to the water hose and stored on the reel also.

Figure 2. Guarding around hole collar.

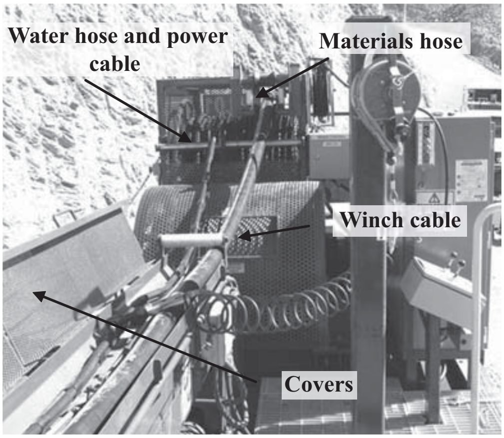

Figure 3. Enclosure of moving lines.

All hose reels are encased with wire mesh to prevent inadvertent access. Having the moving hoses and cables secured behind guarding also reduces the potential hazard presented by a broken hose as the free ends of the hose will be contained and unable to whip around.

Lengths of hose need only be added to the concrete line during operation. This operation is performed while the machine is shut down and hence no lines are moving while the operator clamps the hose on or off. As a safety precaution, an emergency pull stop cable has been installed on the platform which will shutdown all rig functions if activated in the event of an emergency.

4.3.3 *Other safety features*

The shaft liner has numerous other safety features including the shotcrete machine and winch deck being remotely controlled from the operator's cabin, removing the need for personnel to be in the vicinity of moving parts. Pressure gauges are located throughout the system and relay information through the Citect control system to the display in the operator's cabin. This information can be used to prevent over stressing of any part of the system.

A three point braking system has been fitted to the winch system to control rate of descent. To improve the ability of a single operator to control the entire process a moveable camera mounted on a pole relays images to the operator's cabin and can be used to monitor any area required. The robot is also fitted with methane sensors for working in underground coal mines. Laser barriers can be erected if required in access drives underground which will shutdown the rig if breached. These can be used to prevent inadvertent access to the bottom of the hole during spraying operations.

4.4 *Performance and quality*

The shaft liner was designed to offer benefits to clients in terms of its performance on site and the quality of the final lining achieved.

4.4.1 *Performance considerations*

Performance has been considered in terms of independence of operation on site, control of spraying process and efficiency of application.

Independent operation is beneficial for clients to minimise disruption to mine production. Minimal use of cranes is required with the setup of the shaft liner, with the only lifting required being that to remove the platform and sea containers from the truck and into position over the hole. The robot can then be correctly positioned using the lifting crane and adjustment using the boom. Control of the spraying operation is facilitated using a Citect control system and a graphic display in the control room (Figure 4).

The Citect system monitors all aspects of the spraying operation including depth of the robot, (which is measured using cable counters on the sheave wheel), nozzle rotation (which is measured using a proximity switch), winch speed, oil temperature, shotcrete machine speed, air pressure, water flow rate and any faults that occur. This system provides precise, real time feedback to the operator on all aspects of the spraying operation. Fault diagnosis is also provided by the Citect system enabling identification of the issue by the operator and promoting quick rectification with minimal downtime. Fully automated spraying is possible using this system.

There are four infra-red cameras (Figure 5) mounted on the robot facing the shaft walls at 90 degrees to each other. The use of infra red cameras means that only low light levels are required. Light is supplied using several LED lights mounted at the top of the robot. Infra-red cameras have the

Figure 4. Graphic display in operator cabin.

Figure 5. Infra red camera mounted on robot.

benefit of providing a clear picture to the operator in all working conditions as the picture is less affected by dust and water vapour. The cameras are mounted within an enclosed housing for protection and are kept free of dust by air and water sprays.

Having a clear view of the spraying is vital for the operator to assess the consistency of the mix being attained, the amount of rebound that is occurring and where any variances in shaft wall conditions may necessitate further spraying. The footage from the cameras is recorded and can be copied to a disc and given to clients for review if required.

4.4.2 *Quality of final lining*

The quality of the final applied lining is, of course, the most important performance consideration. As with any dry mix process, the control of accelerator and water dosing is critical to the quality of the product. The thickness of the lining obtained is the other major factor affecting the behavior of the lining.

Water metering is finely controlled to an accuracy of 0.05 L/min by the operator via the Citect system in the control room. The water meter is mounted on the robot as opposed to being on the water line at the surface meaning that the true water being delivered to the nozzle is measured. Liquid accelerator is used in place of the powdered accelerators traditionally used in this type of application. Liquid accelerator is added at the nozzle whereas powder accelerator is added at the shotcrete machine with the dry mix. The advantage of using liquid accelerator is that an even dose rate of accelerator can be achieved.

The shaft liner is equipped with a thickness scanning system using an ultrasonic distance measurement device. The scanner is set up to measure 20 points at each depth with the nozzle rotation and depth being indexed against each measurement. A scan of the entire shaft is conducted prior to spraying and a second scan is conducted post spraying. The difference in distance measurement at each point can then be calculated to give a thickness of lining and indicate any areas of possible under-spray that require additional spraying. The rate of rotation of the robot must be determined at the start of spraying to enable the desired thickness of lining to be achieved. This is done by spraying a small section of the shaft, scanning that section and adjusting the required parameters to suit.

5 COMMISSIONING

Commissioning of the shaft liner was carried out in January 2009 on a 3.5 m diameter shaft designed to be lined to a depth of 74 m at a thickness of 50 mm. The shaft collar was located in the floor of an open pit. The commissioning was used to calibrate the various measuring devices on the shaft liner, though several other issues emerged with the operation of the shaft liner during this time. These included:

- Nozzle getting caught up during rotation
- There were originally no lights installed on the robot, resulting in the infra-red cameras having difficulty in judging the depth of field for focus
- There was some brake chattering evident.

The nozzle rotation issue was solved by replacing the swivel at the top of the robot with an alternative type that allowed free rotation. With the installation of the LED lights on the robot, the cameras were able to judge depth of field correctly and focus appropriately providing clear images to the operator. The brake chattering issue was overcome through circuit changes.

The commissioning of the shaft liner was completed in seven days with a total of 43.5 m^3 of fibre reinforced shotcrete being sprayed in the shaft. The shaft liner performed well, achieving a consistent and smooth lining with minimal rebound. Figure 6 shows the shaft liner robot suspended in the shaft during commissioning.

Figure 6. Shaft liner robot suspended in shaft during commissioning.

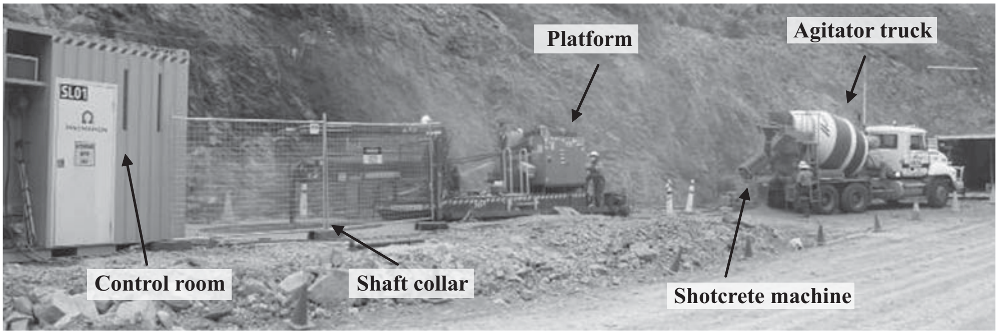

Figure 7. Shaft liner setup during commissioning showing major components.

6 PERFORMANCE TO DATE

To date four shafts have been lined using the robotic shotcrete shaft liner. Shaft diameters between 3.1 m and 5.4 m have been successfully lined with the maximum design depth of lining required being 185 m. Lining thicknesses applied to date have been either 50 mm or 75 mm nominal thickness.

From this experience it has been found that application rates of up to 16 m^3 in a 12 hour shift can be achieved with an overall average of approximately 13 m^3/shift. To give an idea of the rate of coverage that the maximum application rate equates to, for a 50 mm lining applied to a 5 m diameter shaft with 20% rebound allowance, 17 m of depth in the shaft would be lined per shift.

Rebound varies with the concrete mix supplied, but is within the range of 10–20% which is exceedingly good for dry-mix shotcrete. The reason for this low rebound is thought to be the effect of the high degree of control of water and accelerator dosage during spraying. The aggregate type and grading is the factor found to have the most effect on the variance in rebound experienced.

7 FUTURE WORK

The robotic shotcrete shaft liner developed by Macmahon represents a new approach in terms of safety and quality assurance to remote lining of vertical and inclined openings with shotcrete. Future development of the shaft liner is planned to increase its application and refine the control systems.

The current depth that the shaft liner is thought to operate effectively at is 350 m. This is due to the amount of air volume that can be supplied to keep the dry mix moving in the lines and prevent compaction of the mix and hence blockages at the robot. This maximum depth restriction will be investigated by Macmahon as shaft lining opportunities arise and further work is undertaken in an attempt to achieve operation at greater depth. The braking system is planned to be improved by adding a dynamic brake to operate along with the three point braking system. This enhancement will provide additional redundancy in the braking system and also facilitate greater control of the rate of descent at depth.

Further work is also planned on the scanning system to translate point data into three dimensional images and point data files that may be imported into mine survey software for analysis. Further feedback on shaft geometry will be provided by the installation of pneumatically controlled legs on the robot. These legs will adjust to the contours of the shaft and relay changes in the diameter of the shaft back to the operator as the robot travels in the shaft.

Macmahon anticipates that the safety features and performance of this shaft liner will help to raise the standards in the industry for remote shotcrete lining of shafts.

REFERENCES

Hustrulid, W.A., & Bullock, R.C., Editors, 2001 *Underground Mining Methods: Engineering Fundamentals and International Case Studies.* Society for Mining Metallurgy and Exploration, Littleton, Colorado, 728 p., www.smenet.org

Rispin, M., Gause, C., & Kurth, T. 2005. "Robotic Shotcrete Applications for Mining and Tunneling". *Shotcrete* Vol. 7, No. 3 Summer 2005, pp. 4–9.

Shotcrete for rock support—A summary report on state-of-the-art. 2006. ITA-AITES. www.ita-aites.org/cms.

www.jetcrete.com.au/Services/Shaft-Lining-with-Shotcrete.aspx

www.multicretesystems.com/images/Equipment%20-%20Robotic/Raise%20Robot.pdf

www.therixgroup.com.au/