# Slope Depressurisation at Sishen Mine, Northern Cape, South Africa


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## Abstract

Prior to 2014, the dewatering program at Sishen Mine focused exclusively on the deep fractured aquifer and neglected the upper shallow aquifer. In November 2014, increased pore pressures in the shallow aquifer led to slope instability with subsequent slope remediation measures costing more than USD9 million. This initiated the development of an active depressurisation program in its largest pit (GR80), to alleviate pore pressures. The system is an excellent example of the value of an effective depressurisation system which enabled slope design optimisation unlocking substantial value through a 24 million ton reduction in waste stripping and reduced production delays.



**Keywords:** slope depressurisation, pore pressure, slope design


## Introduction

The necessity for Sishen Mine's slope depressurisation system came about due to years of poor surface water management, geological variation in the northern mining area and delayed execution of capital projects. Mining was not affected by water induced slope instability in the past as mining tempos were slower and focussed in the southern part of the mine in areas with thinner clay units. When mining in the northern part of Sishen Mine commenced, where the clay unit is thicker and mining tempos were more aggressive, challenges with water seepage and subsequent bench scale failures began occurring. Exacerbating the situation were elevated water levels in the unconfined aquifer (calcrete). The presence of water within a rock mass reduces shear strength and detrimentally affects slope stability (Read and Stacey 2009). Initial attempts to mitigate the risks associated with water seepage involved the use of vertical drainage wells that would allow the shallow unconfined aquifer to drain into the deeper confined fractured aquifer, but the results were limited and a new approach was required. The new approach entailed four key focus areas:

1. Identify the water source causing the elevated water levels and establish controls to prevent further recharge of the unconfined aquifer.
2. Hydrogeological characterisation of the unconfined aquifer.
3. Review existing system and design a system to depressurise the pit slope more effectively.
4. Develop a monitoring network to establish baseline pore pressure and monitor efficacy of new system.

The outcome of the assessment of the four key focus areas above was as follows:

- The source of the elevated water levels was from the unlined storm water canal and surface water ponds near final pit wall perimeter boundaries.
- The unconfined aquifer has anisotropic hydraulic properties caused by geological heterogeneity.
- The existing system (vertical drainage wells) was not practical nor cost effective

in comparison to shallower wells with a solar pump system.

- The monitoring network gave valuable insight into the efficacy of the new depressurisation system and assisted in delineating potential problem areas that may be encountered in future which enabled proactive deployment in the expansion of the system.

The Sishen Mine depressurisation system has been continually developed since 2016 and is now being implemented in phases according to the mine plan. This paper aims to outline what caused the need for depressurisation, how the problem was resolved and the immense benefits of an effective depressurisation program.

## Methods

### *Identify the source*

A series of sample points were selected to determine the water source creating elevated pore pressure in the unconfined aquifer. The sample points were selected according to the spatial distribution of the potential sources. Samples were taken from the unlined canal, boreholes drilled in the unconfined aquifer, seepage ponds at the foot of the high wall and seepage directly out of the high wall.

### *Hydrogeological characterisation*

Quantifying hydraulic conductivity and specific yield is essential when assessing the potential depressurisation techniques to be considered for implementation. A series of ten boreholes were drilled and pump tests were performed on three of the boreholes in the project area. Each borehole was logged noting both primary and secondary lithofacies.

### *Review depressurisation design*

A review of the existing system involved assessing the results achieved to date, possible explanations for the limitations in efficacy, costs incurred, practicality and overall suitability of the design. There are various depressurisation techniques available which include grout curtains, horizontal drainage wells, vertical drainage wells, cut-off trenches and abstraction wells (Beale and Read 2013). Due to the size and complexity of the Sishen mining operation, vertical wells were the only practical and feasible option. With this constraint in mind, the implementation of deep-vertical drainage wells versus shallow-vertical abstraction wells was explored.

### *Establish baseline & monitoring network*

Prior to the review of the previous depressurisation system, there were no grouted vibrating wireline piezometers (VWPs) installed at Sishen Mine. Grouted VWPs are critical monitoring tools that are used to measure transient in situ pore pressures. A monitoring network of VWPs was installed around the project area to obtain a baseline pore pressure, per area, and measure progress of the depressurisation system. Each monitoring point is connected to a data logger which communicates wirelessly to a central gateway and transmits data which is then stored on Sishen Mine's Water Information Management System (WIMS).

## Data

### *Water samples*

Fourteen water samples were taken from various locations within the area of study. These include samples from boreholes representing the unconfined aquifer, the unlined canal, seepage from the high wall and seepage ponds at the foot of the high wall.

### *Hydrogeological characterisation*

A series of ten boreholes were drilled at 25 m spacing to 60 m depth. There is little variation in the primary lithofacies with calcrete from 0 m to 50 m and clay from 50 m to end of hole (EOH) but local variations in secondary lithofacies are evident. These variations occur in the calcrete where clay lenses appear erratically throughout the sequence and show no correlation from one borehole to the next. Historically, very little attention was given to the secondary lithofacies in the calcrete as it bears no economic importance. The erratic distribution of clay and sand lenses within the calcrete is noteworthy for depressurisation as this heterogeneity could influence ground water flow. The pump tests on the three wells were conducted over a period of four hours each at a constant discharge rate of 0.5 L/s.

Drawdown of 35 m was achieved in each well after two hours of abstraction and water level recovery (90% of initial water level) in each well varied from six hours to thirty hours.

*Shallow wells vs deep wells*

Possibly the most important part of the project was to perform a cost analysis on the existing system versus the implementation of a new system. To date, the vertical drainage wells have only achieved a total drawdown of 4 m and drawdown has been stagnant since. The vertical drainage wells used in the initial project area were drilled between 100 m and 150 m depth, through the calcrete, clay and into the banded iron formation (BIF) which forms part of the deeper fractured aquifer system (fig. 1). The clay is thicker in the northern part of the GR80 pit which would require deeper drainage wells to depths greater than 150 m to reach the deep aquifer. The unit cost of a vertical drainage well (>150 m) is approximately USD43,000 while a shallow well (60 m) costs USD14,000. This discernible difference in cost was the primary driver for reassessing the status quo and devising a more efficient and cost-effective system.

*Monitoring network*

Prior to 2016, Sishen Mine only made use of open standpipe piezometers to monitor water levels. Grouted VWPs were only introduced and used at the mine in 2016 as part of the depressurisation program. A single sensor VWP was installed as a trial in January 2016 after which a number of multi-level VWPs were installed. The multi-level VWPs comprise three sensors installed in an HQ diamond borehole; the lower sensor is installed in the clay, the middle sensor at the calcrete-clay contact and the upper sensor approximately 5 m above the contact.

## Results

*Water source*

Chemistry data for the fourteen water samples was assessed to distinguish different water species and observe any noticeable trends. Similarities in chemistry between the canal (surface water) and ground water samples (boreholes) supports the idea that the unlined canal was responsible for the elevated water levels in the unconfined aquifer. Increased chloride and sodium/potassium for the

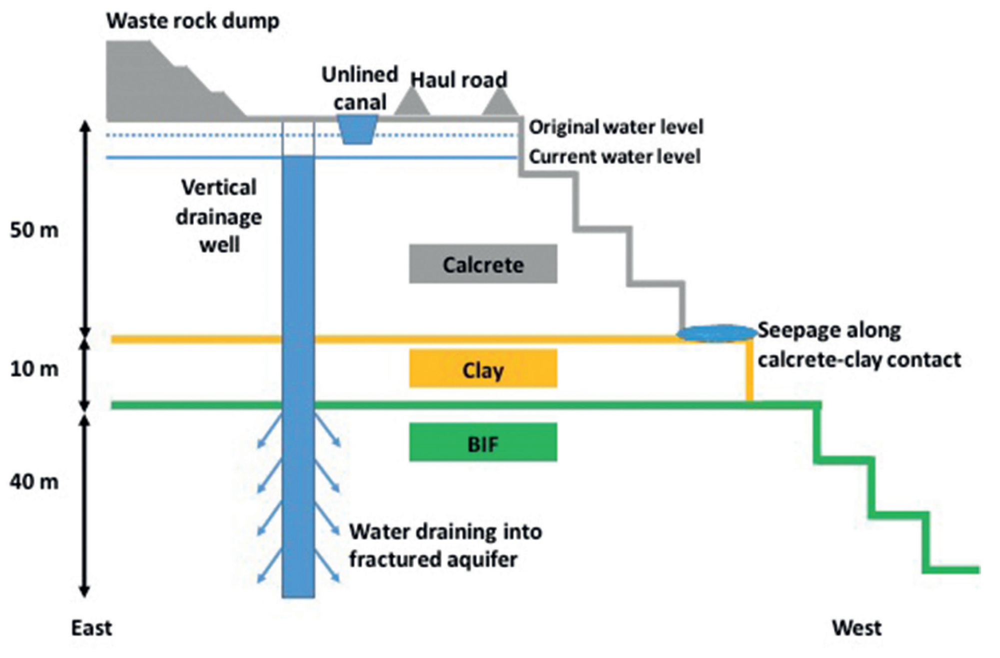


***Figure 1*** *East-West section through vertical drainage well depressurisation system.*

seepage samples can be explained by water-rock interaction and evaporation within the seepage ponds. The evolutionary trend of the seepage water species is toward the canal and borehole samples which suggests that the water chemistry (before water-rock interaction and evaporation) was similar to that of the source. Additional evidence that also supports the hypothesis are; normal water levels in areas with no canals, seepage more prominent when canal through flow was higher, background water chemistry for unconfined aquifer differs from project area and prominence of seepage issues aligned with timing of canal's construction.

### *Hydrogeological characterisation*

The pump test data from the three wells and heterogeneity in geological logs indicate that the unconfined aquifer is hydraulically anisotropic which is supported by qualitative evidence in the pit. Sporadic and irregularly distributed seepage can be explained by the variations in secondary lithofacies. Though some fracturing is present in the calcrete, the primary control of ground water flow appears to be the presence, or absence, of paleochannels which vary in composition from clay/silt to sand and pebbles/gravel. Seepage is prominent along the calcrete-clay contact and above clay lenses that daylight in the high wall as the clay is an aquitard. The specific yield for each of the depressurisation wells varies from as low as 0.05 to 0.5 L/s with very low hydraulic conductivity (K) in the range of 10-7 to 10-8 m/s in the calcrete.

### *Cost comparison*

Upon reviewing the existing design of the depressurisation system, it was clear that vertical drainage wells would be capital intensive, would take longer to implement and the required reduction in pore pressure was not guaranteed. Taking the above into consideration, the continuation of the vertical drainage well configuration would be futile and the option of using shallow wells equipped with submersible pumps was pursued.

## Design

### *Lining of canal and shallow well solar pump system*

To comply with legal and regulatory requirements, the canal was lined with concrete in 2016 which mitigated artificial recharge of the shallow aquifer. Though the water source for the elevated water table was resolved, the calcrete remained saturated and seepage would persist unless the water was intercepted before reaching the high wall.

The pumps for the wells were sized according to the maximum total head (60 m) and specific yield of each well which ranged from 0.05 to 0.5 L/s. The pump set selected for the wells was a Grundfos SQF0,6-2 which has a 0.75 kW motor powered by three 100 W solar panels. The unit cost for the complete solar powered submersible pump set per well (pump, motor, solar panels, switch box, electrical cable, riser pipe, valves, flow meter, well cap and fittings) is USD2,750 which brings the total cost per depressurisation well to USD16,750 which is 60% less than the cost of a vertical drainage well. Figure 2 illustrates the configuration of the solar pump system and VWP installation to monitor performance.

The project area for the depressurisation system covers a linear distance of 5.5 km. Establishing the necessary infrastructure (electrical power lines and pipe work) in an active mining area over such a large distance is challenging and expensive. Recent advances in solar technology has made solar products cheaper, more efficient and easily accessible for both commercial and domestic use. The decision to implement a solar powered submersible pump system was based on the following factors;

1. Solar power would be cheaper than mainline electrical power distribution.
2. The low yields on the wells meant that the effective abstraction duration for each well was 4 to 8 hours per day.
3. Sishen Mine has more than 330 sun days per year which offers excellent potential for exploitation of solar energy.

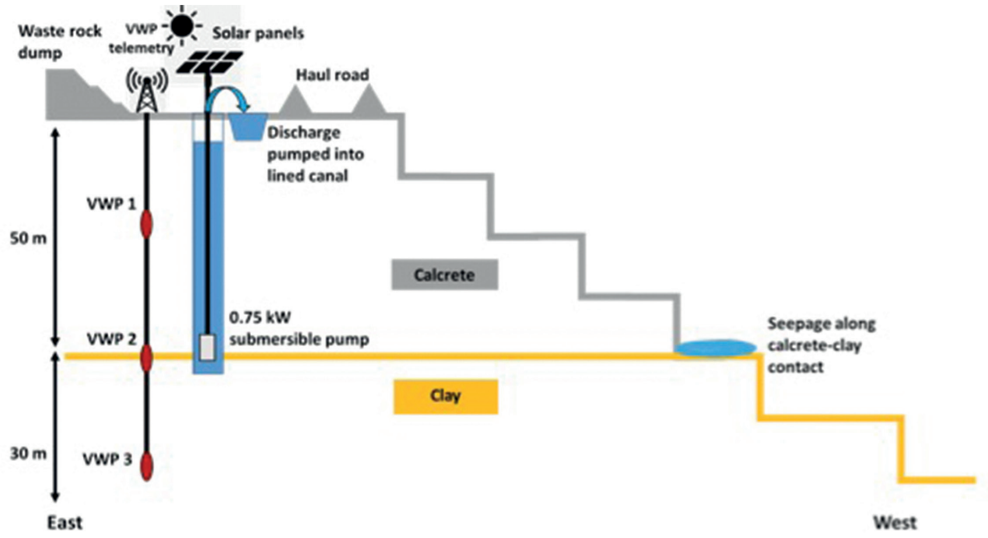


*Figure 2* *East-West section of solar powered submersible pump system with VWP configuration.*

4. Solar systems are modular and manufacturers offer ready built solutions rapid and easy deployment.
5. Modern solar systems require little to no maintenance.
6. Solar powered systems are mobile and offer flexibility in a confined working area.

## Implementation

### *Installation of solar powered submersible pumps*

Before full scale implementation of the solar powered system was commissioned, a trial system comprising 7 wells was deployed along the eastern pit boundary of GR80 pit and was monitored over a period of 2 years. Seven wells were equipped and the system delivered approximately 20,000 litres per day. A single sensor VWP with a data logger, for barometric correction and remote monitoring, was used to obtain a baseline and monitor the performance of the trial system. The improved efficiency of the new system was clear upon commissioning and the results are presented in figure 3. Diurnal fluctuations in pore pressure are due to the operating times of the solar system.

With these productive results, the full-scale depressurisation system was deployed and to date there are 36 depressurisation wells in production with 13 multi-level VWPs monitoring their performance. Expansion of the project will continue as mining of the GR80 pit expands to the west of the current mining area.

## Discussion and conclusion

The solar powered submersible depressurisation system at Sishen Mine has been incredibly successful in reducing the pore pressure behind the GR80 pit slope. The success of the system is the result of adhering to basic scientific principles with a practical approach in developing and implementing an effective solution. The hydrogeological aspects of the geotechnical model together with the geological, structural and rock mass aspects, proved to be critical in the successful management of geotechnical risk at Sishen Mine.

Successful depressurisation and mine dewatering together with other advancements in geotechnical engineering and operational mine to design adherence, not only led to more effective risk mitigation, but also to the launch of a slope optimisation initiative to unlock value. This is based on the principle that addressing geological uncertainty in potential risk areas, increases the confidence in the slope design. Optimisation initiatives focused on design sectors with favourable interaction of slope geometry with geology, lithologies with favourable strength characteristics where stability analysis indicate optimisation potential as well as

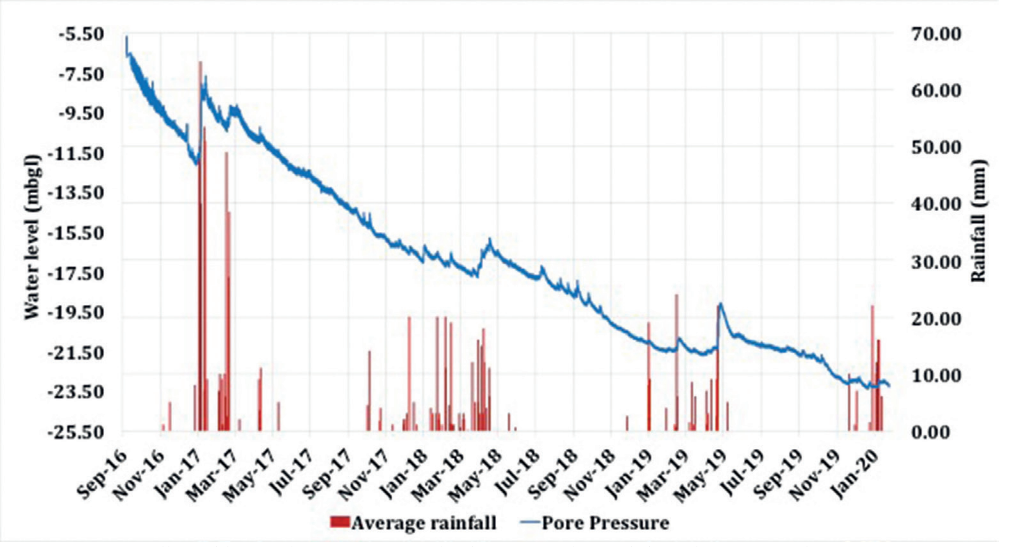


*Figure 3 Data collected by single sensor VWP displaying accelerated drawdown in trial area.*

layout optimisation aspects (geotechnical berms and ramps). Options were evaluated that determine cost saving by decreasing waste stripping for the same amount of ore as well as accessing additional deeper ore at equivalent strip ratios.

Phase 1 of the slope optimisation project was included in the Sishen 2018 Life of Mine (LOM) plan. This work unlocked substantial value for Kumba Iron Ore and was the major contributor to an increase in NPV from 2017 to 2018 of approximately USD720,000,000 from an additional 50 million tons of ore (Anglo American 2019) which would not have been possible without the success of the depressurisation program.

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