BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

LARGE OPEN PIT PROJECT

UNIVERSITY OF QUEENSLAND

HORIZONTAL DRAIN HOLE GUIDELINES

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF APPENDICES

LIMITATIONS

BGC Engineering Inc. (BGC) prepared this document for the account of University of Queensland and the Large Open Pit (LOP) III Project. The material in it reflects the judgment of BGC staff in light of the information available to BGC at the time of document preparation. Any use which a third party makes of this document or any reliance on decisions to be based on it is the responsibility of such third parties. BGC accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this document.

As a mutual protection to our client, the public, and ourselves all documents and drawings are submitted for the confidential information of our client for a specific project. Authorization for any use and/or publication of this document or any data, statements, conclusions or abstracts from or regarding our documents and drawings, through any form of print or electronic media, including without limitation, posting or reproduction of same on any website, is reserved pending BGC's written approval. A record copy of this document is on file at BGC. That copy takes precedence over any other copy or reproduction of this document.

1.0 INTRODUCTION

1.1. Terms of Reference

This project was sponsored by the Large Open Pit (III) Project based on BGC's proposal dated November 4, 2020. The scope of work was formally approved on November 10, 2020 and the contract for the work, administered by the University of Queensland, was fully executed on November 25, 2020.

1.2. Purpose of Study and Goals

Horizontal drain holes (HDHs) are commonly implemented in open pit mines to reduce pore pressures behind the pit slopes, where other methods of depressurization are ineffective or where passive drainage due to mining is insufficient to achieve depressurization targets required for pit slope stability. Guidance for the design, implementation, and monitoring of the effectiveness of HDHs specifically for open pit slope depressurization is included in Beale and Read (2013); however, there is an opportunity to update and enhance the concepts presented in that book with data from operating mines. The aims of this study and associated document are to:

- Summarize the current state of practice of HDH installations in open pits.
- Develop tools based on best practices to assist practitioners in designing, planning, implementing and maintaining HDH systems.
- Provide approximate planning and budgeting guidance.
- Present recommendations for defining and verifying the success of an HDH program.
- Present analytical and numerical modelling tools that can be used to estimate HDH requirements.
- Contribute to the science behind HDHs by exploring the importance of "getting the hydrogeology right".

1.3. Scope of Work and Methodology

The scope of work consisted of four main components:

I. A literature review focused on work not addressed by and/or published after Beale & Read (2013).
II. A survey of LOP sponsors and other selected mining operations on their practices.
III. Summarizing the results of the literature review and the survey data in a database for analysis of data trends to develop and verify analytical tools for HDH implementation.
IV. Publication of a guidance document that can be used by practitioners to justify the use of HDHs and assist with their design and implementation.

2.0 LITERATURE REVIEW

2.1. Information Sources

BGC reviewed various guidelines, conference proceedings, journal articles and university theses to compile a comprehensive list of references to HDH design, installation and monitoring. Thirty-seven references in total were located. The literature review was carried out in two stages, with the second stage of the review focused on references noted in papers and articles from the first review, and with an expanded scope to look for references on vertical passive drains and drain holes implemented from underground galleries. The references have been grouped in the following categories:

- Guideline documents (3)
- Publications/conference papers (33)
- Master's or Doctoral theses (1).

Several of the references reviewed were more appropriate to soil and civil engineering slopes than rock slopes in open pit mining operations, which is the purpose of this guidance document. However, all references providing useful guidance, regardless of their focus have been included in the bibliography at the back of the guidelines.

2.2. Existing Guidelines

The literature review yielded three key guideline documents that describe the use and design of horizontal drains for slope stabilization:

- Pohll, G.M., Carroll, R.W.H., Reeves., D.M., Parashar, R., Muhunthan, B., Thiyagarjah, S., Badger, T., Lowell, S. and Willoughby, K.A. (2013) Design Guidelines for Horizontal Drains used for Slope Stabilization (377-page manual)
- Beale, G. and Read, J., (2013) Guidelines for Evaluating Water in Pit Slope Stability (582-page book)
- Cashman, P.M. and Preene, M., (2020) Groundwater Lowering in Construction, A Practical Guide to Dewatering, 3rd Edition (857-page book).

Pohll et al. (2013) and Cashman et al. (2020) were prepared with a primary application toward civil engineering slopes, while Beale et al. (2013) was prepared specifically for open pit slopes. Pohll et al. (2013) is most applicable for soils, while Cashman et al. (2020) include slopes in both soil and rock. Each of the three documents provide comprehensive fundamentals of hydrogeology with different emphasis, depending on the intended application of the guidance document. However, the importance of and methods for site characterization, development of a site conceptual model, and the use of groundwater modeling to assist in the design process are universal themes in all of the guidelines. Additional details for each of them are provided below:

Pohll et al. (2013) Design Guidelines for Horizontal Drains used for Slope Stabilization

The purpose of this document is to provide a single reference to geotechnical engineers or hydrogeologists designing a horizontal drainage system to improve the stability of hillslopes for civil engineering projects.

The document presents analytical approaches to support horizontal drainage design that may be appropriate for hillslopes with simple geologic and hydrogeologic regimes. These approaches are generally most applicable for soils and smaller scale projects, or early scoping level work. In general, application of horizontal drains in open pit slopes target discrete features or anisotropic fractured bedrock systems for which analytical approaches tend to be overly simplistic.

Beale and Read (2013) Guideline for Evaluating Water in Pit Slope Stability

This document is an outcome of a previous LOP initiative and is considered the most relevant of the three guidelines with respect to mining open pit slopes and associated use of horizontal drains as part of a slope depressurization and management program. The book describes the outcome of hydrogeological research performed by the LOP since 2009 and provides open pit design practitioners with a roadmap to help them decide how to investigate and manage water pressures in pit slopes. The book is divided into six sections covering fundamentals of open pit hydrogeology, field data collection and characterization, importance of and methods for preparing a conceptual model, numerical groundwater modeling for open pits, implementation of slope depressurization systems, and monitoring and design reconciliation. In addition, seven appendices that include case studies and field data collection and interpretation guidelines are provided.

With specific regard to HDHs:

- Section 5.2 describes how to implement a groundwater control program for an open pit and includes description of the primary types of control systems available, including horizontal and vertical drains. Sixteen pages (comprising photos, figures, diagrams) are dedicated to describing the general use of horizontal drains, and provide guidance on determining targets, design, installation and monitoring of HDHs.
- The document highlights the importance of determining and understanding the objectives of the HDH program so that the objectives can be accomplished and a conceptual model can be developed that appropriately characterizes the hydrogeologic system.

Cashman and Preene (2020) Groundwater Lowering in Construction, A Practical Guide to Dewatering, 3rd Edition

This document is intended to provide practical guidance for groundwater control as it relates to civil engineering excavations and tunneling. Eleven project case histories are provided. Applications to mining are briefly discussed; however, the reader is generally referred to Beale and Read (2013) for further guidance. The document provides useful figures, diagrams and examples, as well as practical construction information for a range of dewatering systems.

2.3. Summary of Publications

Reference publications compiled and reviewed for the HDH guidance document have been listed in Appendix A and have been tabulated chronologically with the paper title, the authors and their affiliations, and the primary topic. The publications have been categorized as per the following topics, with the number of publications indicated in brackets:

- Case History/Study (20)
- Numerical Modeling (8)
- Novel Applications (5)
- Design Guidance/Specifications (17)
- Decision Making Process/Integration (11)
- Cost Benefit/Optimization (5).

The oldest publication found on the use of HDHs was written by Abrao (1978). Although the graphics in the paper were not very clear, it is noted that the guidance given on designing a HDH program and data presentation methods were useful and still applicable in many instances to current mining operations.

A novel application of HDHs involved the application of vacuum assistance to enhance the performance of the drains. This was applied with some success in the early 1980s on two mining projects in British Columbia, Canada at the Gibraltar and New Afton Mines. Although there are no recent applications of vacuum assistance to HDHs published in the literature, vacuums have successfully been used to increase the yield of vertical wells installed in low hydraulic conductivity formations (Zawadzki, et al., 2008; Fortin et al., 2011).

3.0 SURVEY

3.1. Design

The survey was developed using the Survey Monkey® online platform and a link was forwarded to the Deputy Manager of the LOP Project in the School of Engineering at the University of Queensland. The survey link was subsequently distributed to the LOP III sponsor representatives from the various mining companies financially supporting LOP III. The company representatives were directed to forward the link to their operations employing HDHs. Due to confidentiality, BGC was not involved in the latter part of the process and thus there is no record of which operations the survey was actually sent to and what the response rate was. BGC was responsible for sending the survey to non-LOP III operations and the response rate of those operations was tracked.

The survey was menu driven to facilitate input and subsequent data management and interpretation. A brief introduction page outlined the purpose of the survey. The survey was broken down into the following sub-sections and associated themes:

- General Information – Confidentiality, contact information, depressurization methods employed in open pits and confirmation of use of HDHs, purpose of HDHs, limitations and advantages, respondent's primary interest in the outcome of the survey and subsequent guidance document, physiographic and geologic setting
- State of Practice – Size of open pit(s), extent of depressurization efforts, maturity of efforts, who is responsible, HDH layout and completion details, depressurization targets, validation of success, and costs
- Mine Site Hydrogeology – Characterization methods, monitoring methods, hydrogeologic model and water balance, groundwater management, data presentation
- HDH Program Details – Frequency of depressurization efforts, extent of efforts within pit(s), number of HDHs, total length, minimum/maximum/average lengths, geologic and slope performance considerations, drain performance criteria, drilling equipment and methods employed, drain hole targets, HDH locations, outflow management
- Monitoring and Validation of Depressurization Systems – Validation criteria, location of pore pressure monitoring points, flow monitoring details, data presentation details, how data are used
- Lessons learned – open ended question allowing respondents to provide more information on their experience with HDHs.

3.2. Data Quality

Due to the nature of the survey, respondent entries were self-reported, including both qualitative and quantitative answers, and the results could not be entirely verified. Many of the respondents only filled out partial surveys and some questions were misinterpreted. The results of the survey were corrected, adjusted and organized for the purpose of reviewing trends, ranges and other meaningful statistics. Examples of corrections and/or adjustments to allow more data to be incorporated into the statistics are given below:

- Data written in different formats (i.e., 10.5 vs. 10,5) were corrected to the North American format.
- Where possible, data were verified using available information from the public domain (i.e., climatological data, open pit area or footprint).
- Typographic errors were corrected using judgement and experience (e.g., a hole diameter of 115 cm was corrected to 11.5 cm).
- Where erroneous answers could not be corrected without additional verification from the respondents they were omitted from the dataset.

3.3. Statistics & State of Practice

The following discussions and statistics quoted are primarily based on the survey responses and are considered to reasonably represent a cross-section of industry practice. However, not all of the fields in the database had responses and the percentages reported have ignored blank entries or obviously invalid values. In some instances the responses given cover more than one open pit operation. The compiled database of operations includes 31 entries from 24 online survey responses, and 7 entries from published case studies. Approximately half of the entries are from LOP III sponsor companies. The geographic distribution of entries includes representation from North and South America, the Indo-Pacific Region, Asia, Australia and Africa (Figure 1).

Nearly 90% of the survey respondents are actively using HDHs, with the following breakdown on how their use is integrated into the mine's dewatering and/or depressurization efforts (Figure 2):

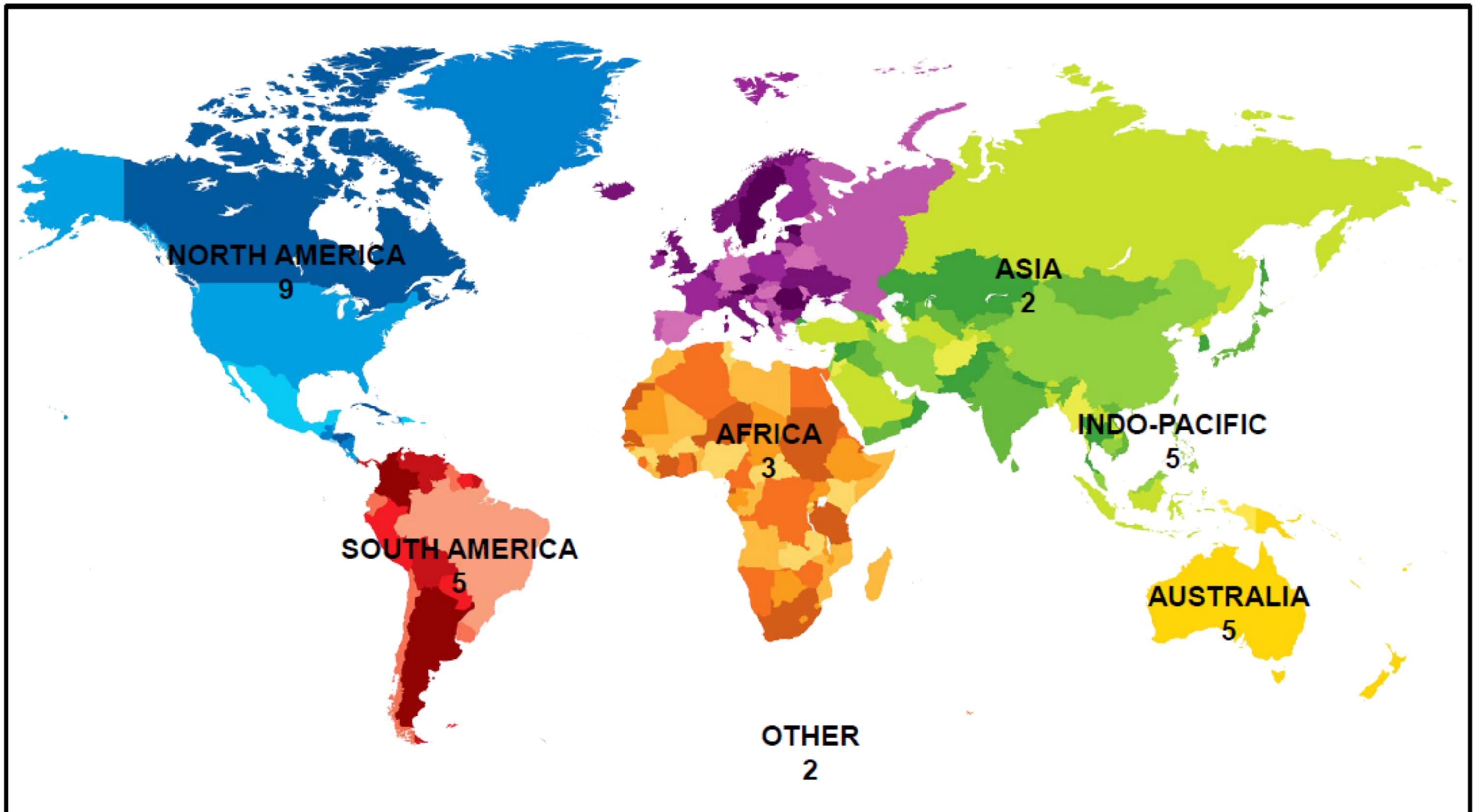
- Approximately one in seven (13%) of respondents reported HDHs as their only water management/dewatering method
- Over half (58%) combine HDHs with other subsurface depressurization methods
- Approximately two-thirds (65%) combine HDHs with surface water management/dewatering methods
- The most common surface water management methods used to dewater open pits in conjunction with HDHs are in-pit sumps, surface water diversions and dewatering wells.

The various water management tools typically employed at an open pit mine and their locations relative to the pit slopes are depicted schematically in Figure 3. Terminology used in the guidelines are consistent with those shown in Figure 3.

The configuration of HDH installations varied significantly amongst the respondents, reflecting the different geology, climate and operational requirements. These variations also reflect the utility of HDHs to be able to remove water from mined slopes in a wide range of settings. HDHs may be built into mine plans from the earliest planning stages or implemented to respond to geotechnical issues that develop during operations. They are commonly deployed in a range of geometries fit for purpose and/or specific site conditions. The most common configurations (Figure 4) in order of increasing application were:

- Fan – to minimize the depressurization system footprint
- Linear – exclusively perpendicular (as opposed to angled) to the open pit face for even coverage of the pit slopes
- Multiple geometries.

08-2023



NOTES:
1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.
2. "Other" refers to entries where geographical location is unknown, or generic (i.e., a single survey response covered many locations).
3. Figure adapted from http://pngimg.com/image/34474

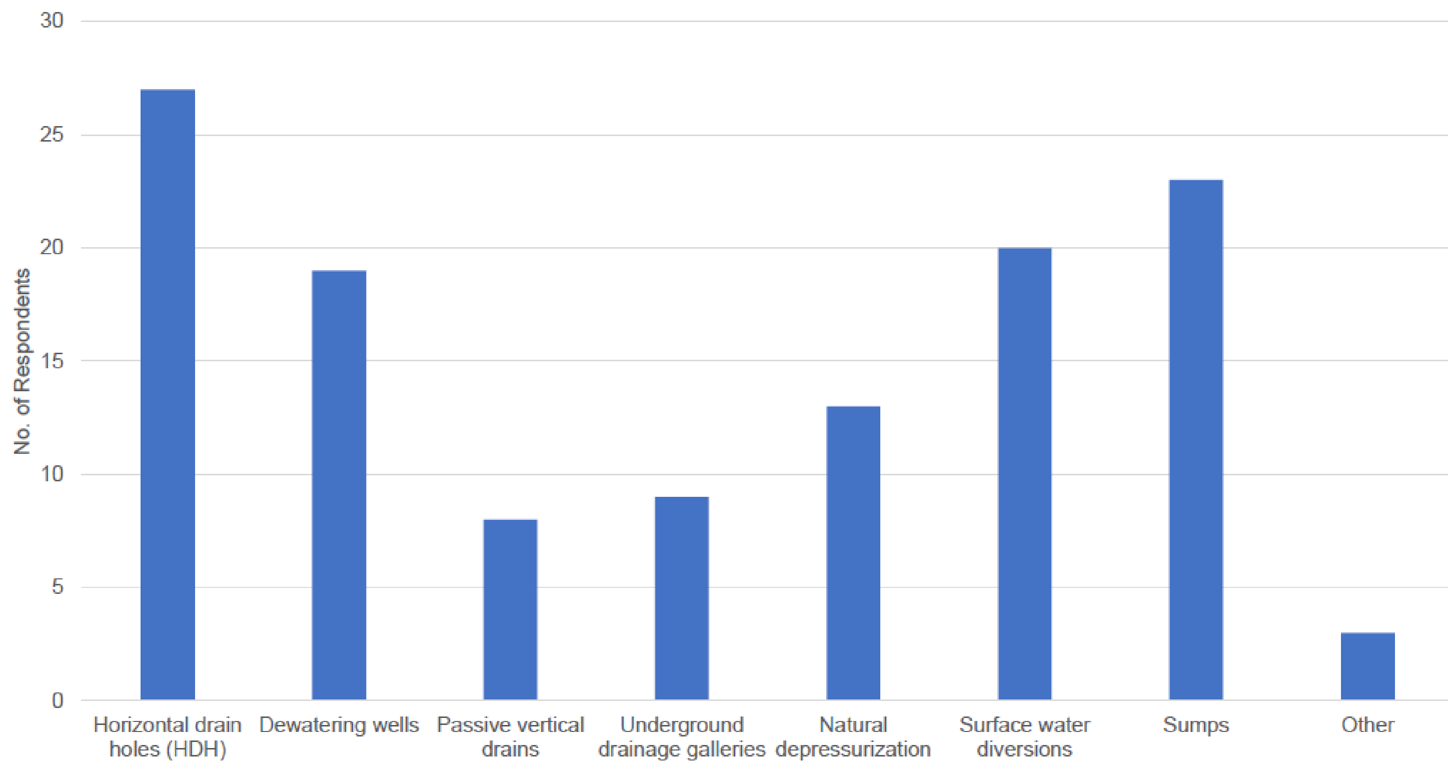
PREPARED BY: SP	FIGURE TITLE: REGIONAL DISTRIBUTION OF HDH SURVEY RESULTS			
CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT			
APPROVED BY: TC	SCALE: NTS	PROJECT NO: 2236001	FIGURE NO: 1	

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 1. Regional distribution of HDH survey results.

08-2023



NOTES:
1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.
2. Data is from survey results, including response from operations and literature review case studies.
3. Based on the results of 31 responses.
4. "Other" includes steam release wells, drainage galleries and directional trenches

PREPARED BY: SP
CHECKED BY: HWN
APPROVED BY: TC

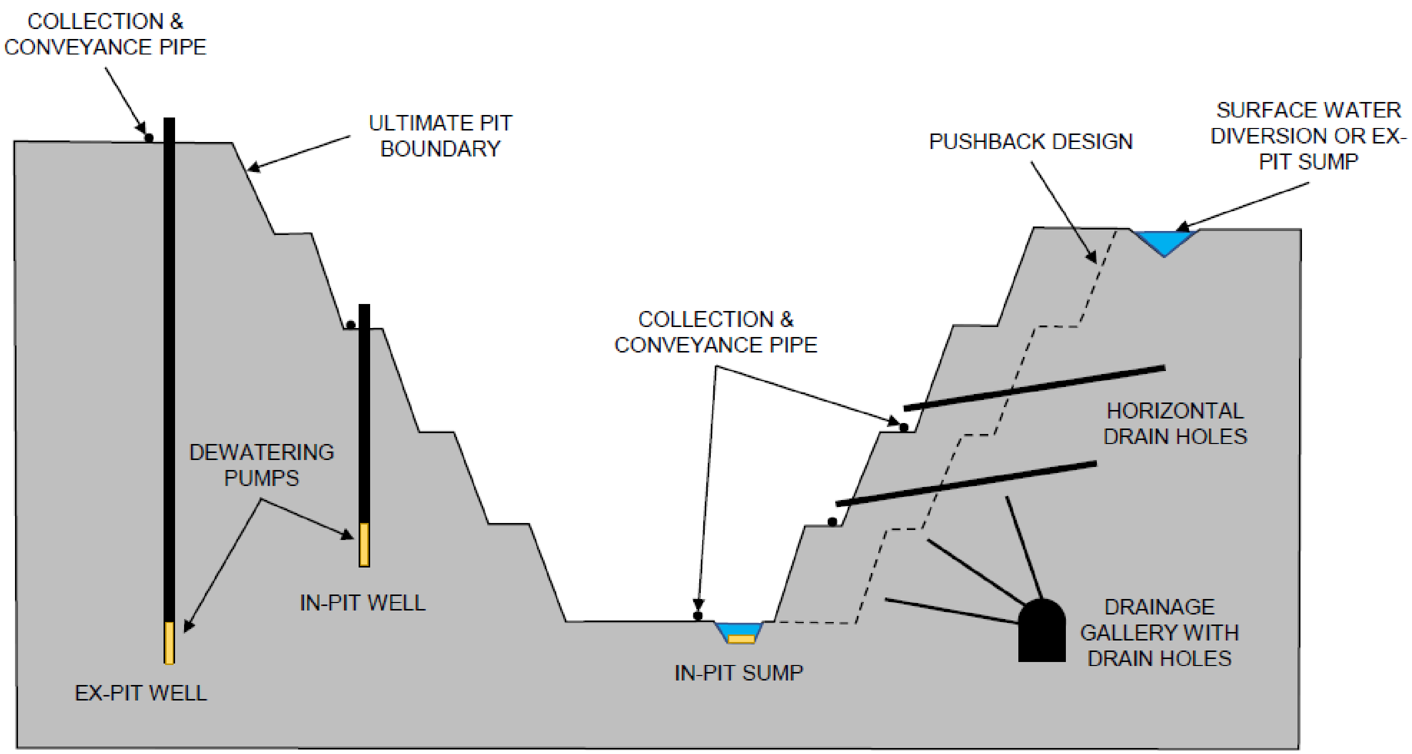
FIGURE TITLE: SURVEY RESULTS – GROUNDWATER MANAGEMENT COMPONENTS
CLIENT: LARGE OPEN PIT PROJECT
SCALE: N/A
PROJECT NO: 2236001
FIGURE NO: 2

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 2. Survey results – groundwater management components.

08-2023



NOTES:

1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.
2. Figure adapted from Hanna (2016).

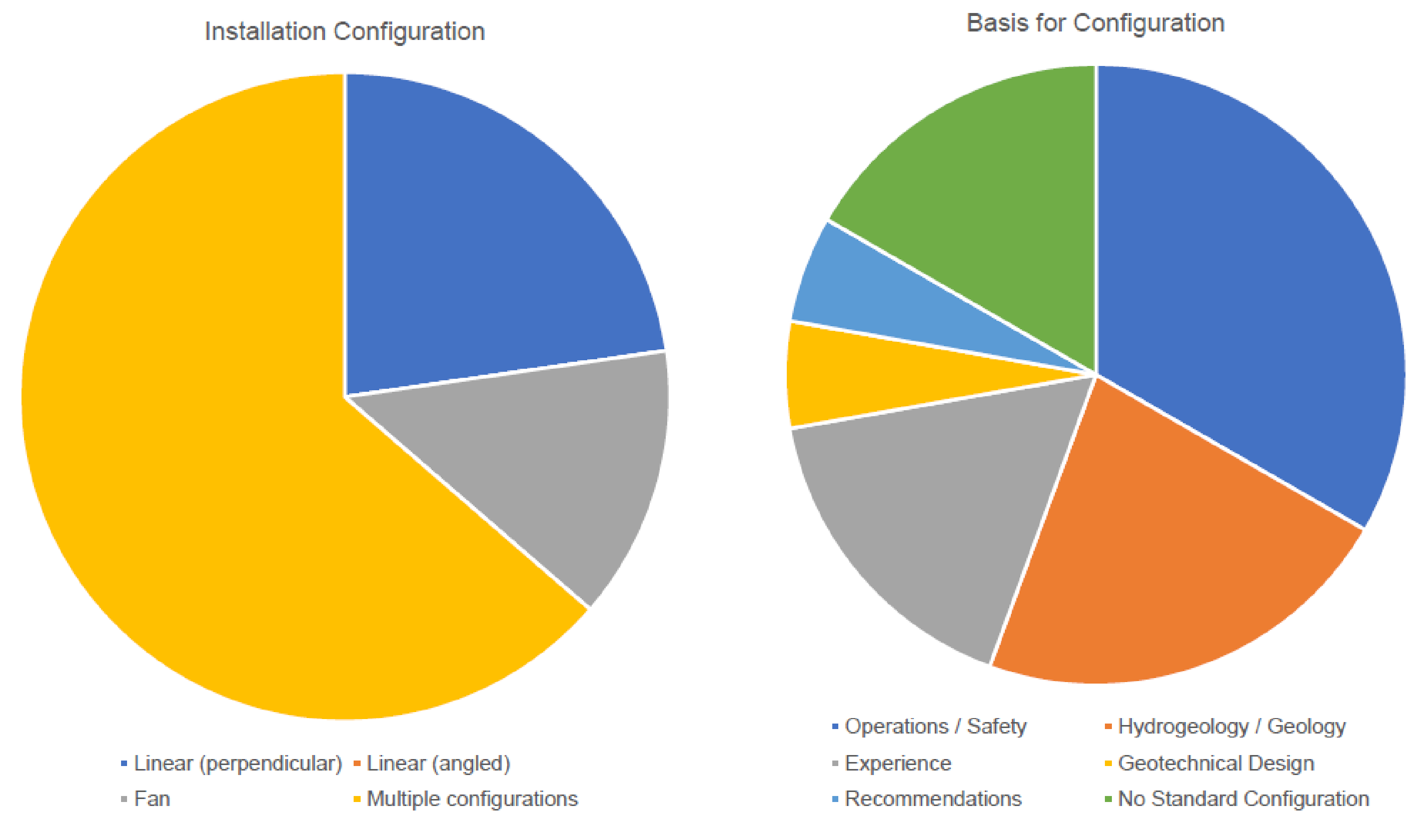
PREPARED BY: SP	FIGURE TITLE: DEWATERING AND DEPRESSURIZATION TERMINOLOGY			
CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT			
APPROVED BY: TC	SCALE: NTS	PROJECT NO: 2236001	FIGURE NO: 3	

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 3. Dewatering and depressurization terminology.

08-2023



NOTES:

1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.
2. Data are from survey results, including response from operations and literature review case studies.
3. Based on the results of 24 responses for Installation Configuration, and 17 responses for the Reason for Configuration.

PREPARED BY: SP	FIGURE TITLE: SURVEY RESULTS – HDH CONFIGURATION AND BASIS		
CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT		
APPROVED BY: TC	SCALE: N/A	PROJECT NO: 2236001	FIGURE NO: 4

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 4. Survey results – HDH configuration and basis.

Nearly two thirds of the respondents use multiple configurations to achieve their depressurization goals based on site-specific hydrogeology and geotechnics, or to adapt to operational constraints. HDHs are generally installed in targeted locations/orientations to liberate water from specific geologic features or hydrostratigraphic units, indicating the importance of understanding the hydrogeologic conditions in the pit. However, the primary basis for the chosen configuration(s) indicated was for Operations/Safety (Figure 4) which confirms the need to integrate HDH installations with the mining operation.

Responsibility for the slope depressurization systems varied widely across the operations surveyed, and included on-site hydrogeologists, mine geologists or geotechnical staff, and off-site corporate teams or consultants. Installation details varied depending on region, site requirements and available equipment (discussed further in Sections 6.6 and 6.7).

The impacts and effectiveness of HDHs are typically measured by pore pressure response and groundwater discharge from the HDHs. The survey results (Figure 5) indicate that the success of HDH installations at the various operations who responded is measured by the following parameters, in increasing order:

- Installation meterage
- Improved slope performance
- Water flows/strike/interception
- Decrease in head/pore pressure.

Baseline pore pressures are collected before mining and prior to the next pushback by approximately three quarters of the respondents. Pore pressures are most commonly measured using nested VWPs. Nearly half of the respondents indicated a major water source was nearby; however, it was unclear from the responses if the presence of this feature influenced the decision to install the HDHs or had an impact on the magnitude and continuity of the HDH outflows.

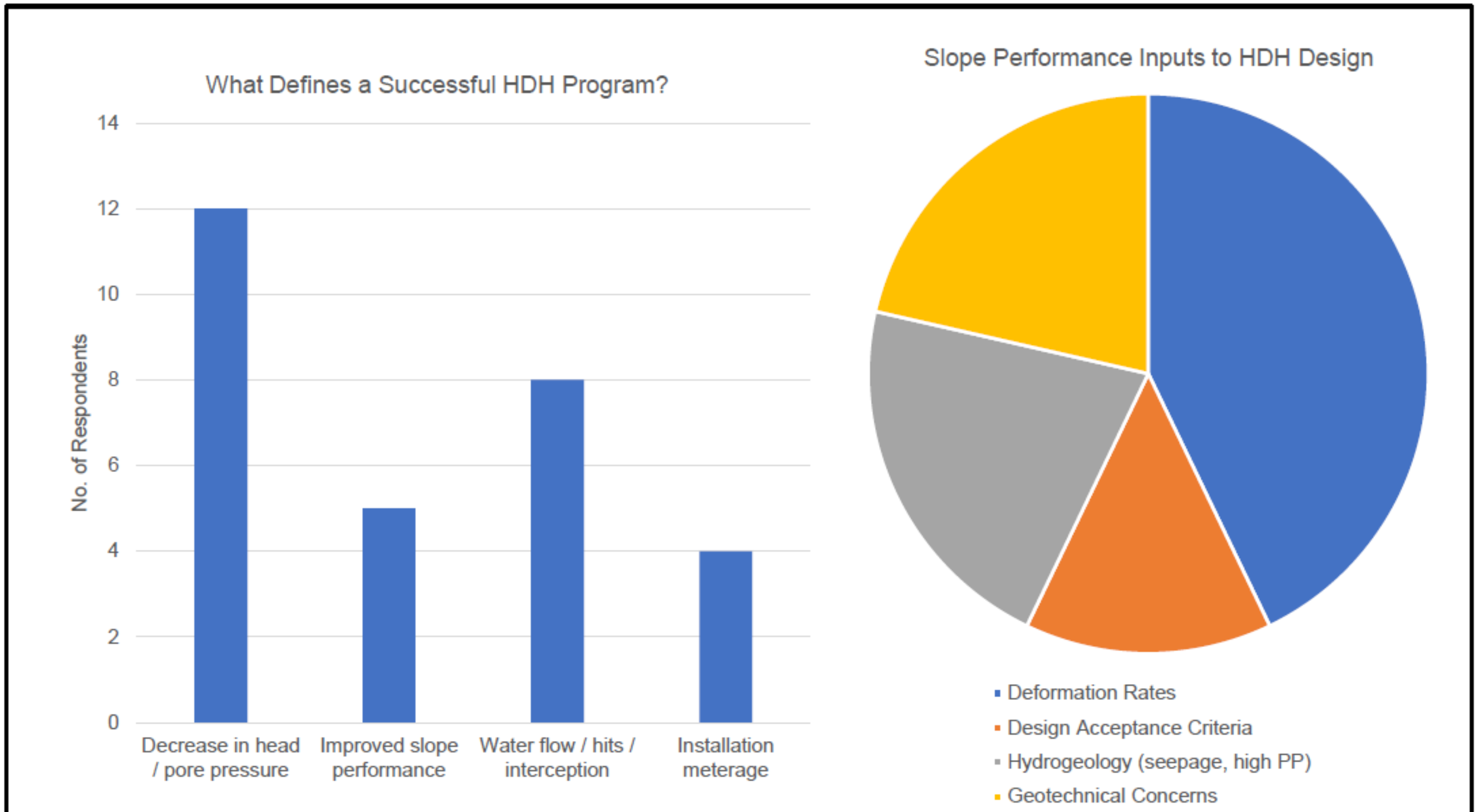
Industry practice generally ranges from regular (i.e., annual or quarterly) HDH installation during mining, to targeted or “as needed” installations. The flexibility of HDH installations often makes them a more useful tool than wells when localized, elevated or anomalous groundwater pressures within the open pit require mitigation. Almost all the operations who responded make efficient use of HDHs locally; however, one mining operation relies solely on them to depressurize their pit slopes, without installing any vertical wells.

The responses provided indicate that longer drains are generally installed in deeper pits. The inference is that deeper pits would be farther below the water table, requiring more drains and thus greater total lengths of drains (Figure 6).

Additional state of practice information from the survey respondents regarding the various considerations when implementing an HDH program include:

- HDHs are rarely terminated based on outflow criteria
- Structural geologic data is used to provide guidance in the orientation of most HDHs
- Slope performance (i.e., stability) is typically the driving rationale for installing HDHs
- HDHs are typically terminated at specific target depths.

08-2023



NOTES:
1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.
2. Data is from survey results, including response from operations and literature review case studies.
3. Based on the results of 19 responses for what defines a successful HDH program, and 14 responses for slope performance inputs to HDH design.

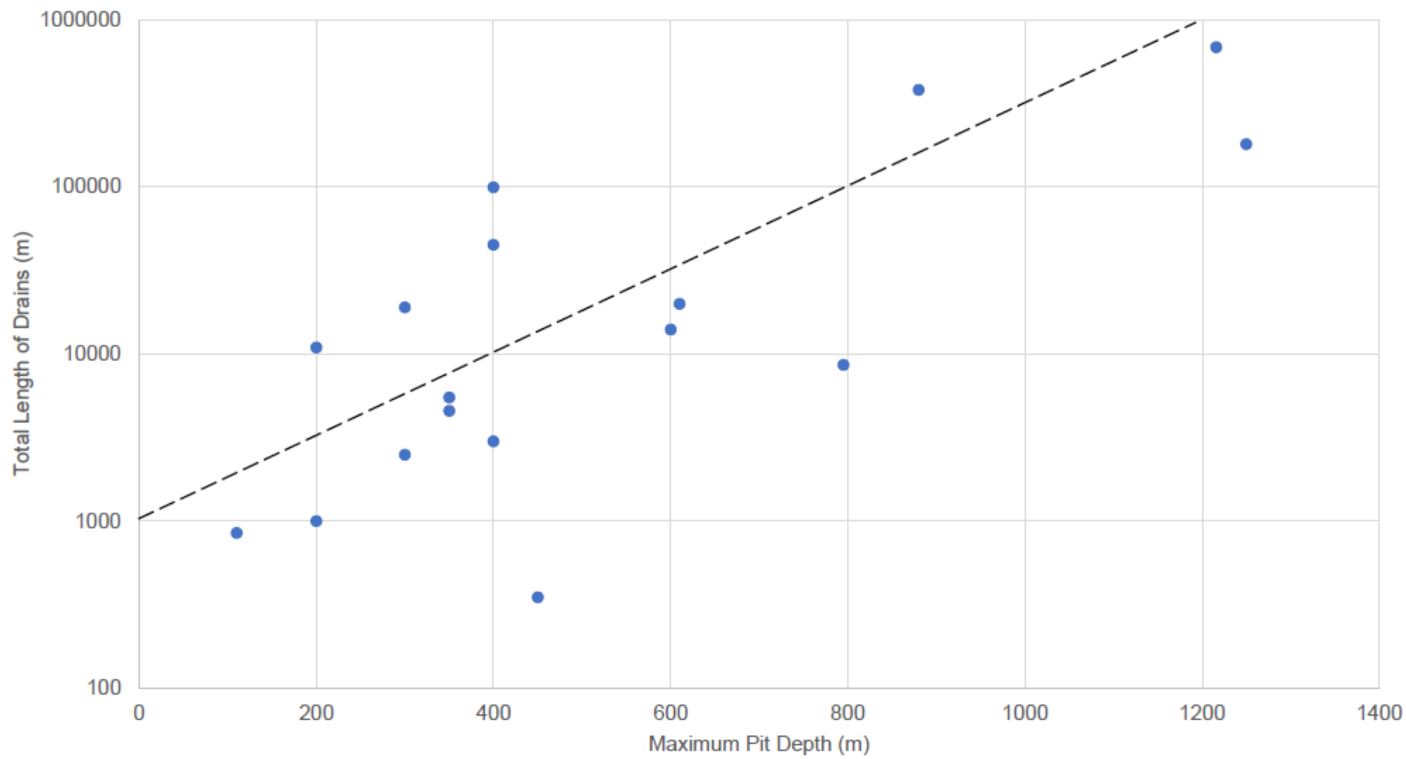
PREPARED BY: SP	FIGURE TITLE: SURVEY RESULTS – HDH PROGRAM SUCCESS AND SLOPE PERFORMANCE		
CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT		
APPROVED BY: TC	SCALE: N/A	PROJECT NO: 2236001	FIGURE NO: 5

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 5. Survey results – HDH program success and slope performance.

08-2023



NOTES:
1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.
2. Data is from survey results, including response from operations and literature review case studies.

PREPARED BY: SP	FIGURE TITLE: SURVEY RESULTS – MAXIMUM PIT DEPTH BY TOTAL LENGTH OF DRAINS		
CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT		
APPROVED BY: TC	SCALE: AS SHOWN	PROJECT NO: 2236001	FIGURE NO: 6

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 6. Survey results – maximum pit depth by total length of drains.

The HDHs are usually installed at the following locations:

- Along ramps and at specific elevations
- Along every bench
- Along geotechnical berms
- Opportunistically as mining allows access to the walls.

A consistent theme in the survey responses was that HDHs were used primarily to address site specific requirements and hydrogeological complexity. While not unexpected, this finding suggests that developing prescriptive or “one-size-fits-all” HDH solutions is impractical.

3.4. Lessons Learned

Survey respondents were encouraged, with the use of open-ended questions, to elaborate on their experience and discuss the advantages of HDHs over pumping wells, where the biggest challenges lie in developing and implementing a HDH program, and what the lessons learned were from their HDH programs.

The respondents indicated that HDHs are effective at controlling pore pressures, although few provided details to support this conclusion. HDHs are generally considered an essential slope design optimization tool, and approvals and budgets for their implementation were not generally an impediment, suggesting they are a key component of typical multi-faceted slope depressurization systems at most operations.

Some highlights from the Lessons Learned category of the survey include:

- HDHs installed from the open pit face are not generally useful in very cold or far northern regions due to the length of the winter and problems associated with freezing. They are useful in moderate climates even if they freeze up in the winter as long as they are functioning during freshet when groundwater is typically recharged from snowmelt, runoff and rainfall events increasing pore pressures locally and temporally.
- Planning and scheduling of the HDH installations around the mining schedules and mining activities is paramount and can be challenging. The timing and duration of the program and the ease of access are crucial planning pieces and learnings from each campaign must be used to design the next one.
- Surface water management systems play a large role in preventing recharge to the pit scale groundwater flow system and, when effective, can reduce the amount of HDHs required to lower pore pressures. Groundwater flows to the open pit, including natural seepage and discharge from HDHs, needs to be collected and conveyed through pipelines to sumps and pumped out of the pit to prevent recharge to the slopes below.
- Advance design and integration of instrumentation to monitor slope depressurization (i.e., VWPs, weirs, flow meters, etc.) into the overall slope monitoring system is crucial to understanding the performance and effectiveness of a HDH program, and the data collected can be used to optimize the design of future HDH programs.

4.0 APPLICATIONS AND CONSIDERATIONS

4.1. Applications

The results of the literature review and survey of operating mines indicate that HDHs are an integral component of open pit slope depressurization systems. HDHs are typically employed as a supplementary tool, primarily in conjunction with vertical wells installed in advance of mining, to depressurize the slopes. Surface water sumps and ditches are usually already in place to limit recharge to the groundwater table in open pit slopes. HDHs are effective in moderately low to high permeability rock masses where groundwater may be compartmentalized by low permeability materials associated with steeply dipping faults.

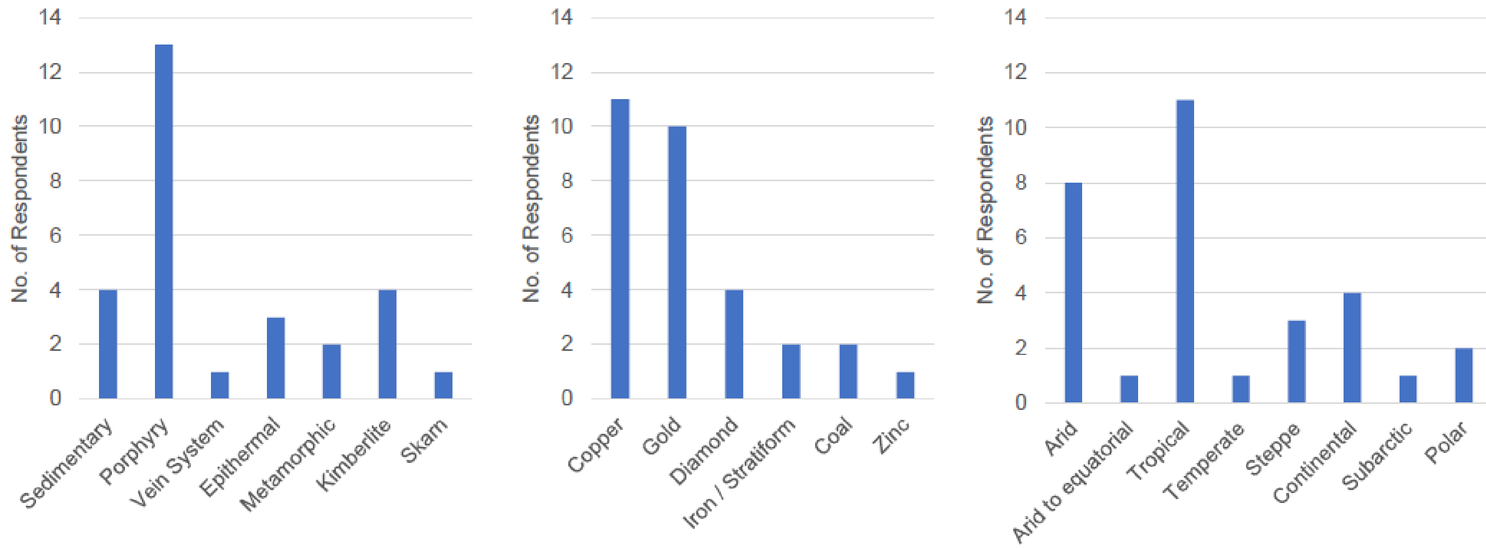
The survey results were heavily influenced by mines located in porphyry deposits and weighted towards copper and gold commodities in tropical and arid climates (Figure 7). Nonetheless, HDHs are generally accepted as an in-pit depressurization tool in most operating mines regardless of ore body genesis, commodity or climate. An exemption to this generalization is in northern climates where HDH discharge pipes are exposed to prolonged freezing temperatures which often result in cessation of flows out of the HDHs. In cold climates where HDHs are required they are often drilled from drainage adits or underground workings to avoid freezing. An example of an underground HDH layout from a mine in northern Canada is shown in Figure 8.

4.2. Geologic Considerations

The geologic environment and the hydrogeologic regime in which HDHs are to be installed must be well understood and taken into consideration when planning a HDH program. Due to the sub-horizontal inclination of the HDHs they tend to be most effective at depressurizing slopes impeded from draining due to steep, low hydraulic conductivity geologic structures (e.g., faults and shears). Before planning a HDH program, however, a good understanding of where the pore pressures are highest and most critical to the stability of a pit slope is required. This information should be obtained from piezometers and well (monitoring and pumping) networks installed throughout the pit area, seepage observations, water levels in production boreholes and potential groundwater recharge sources (Figure 9; Newcomen et al., 2002).

In some situations, the source of the seepage water may not initially be obvious or the hydrogeologic model may still be under development. Many operating mines measure water levels in production blast holes to estimate the extent of the areas that need to be drained (Brawner, 1982). Often these observations yield information about the potential barriers and conduits in the rock mass that may be at a scale much smaller than that at which the hydrogeologic model has been developed.

08-2023



NOTES:
1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.
2. Data is from survey results, including response from operations and literature review case studies.
3. Based on the results of 31 responses.

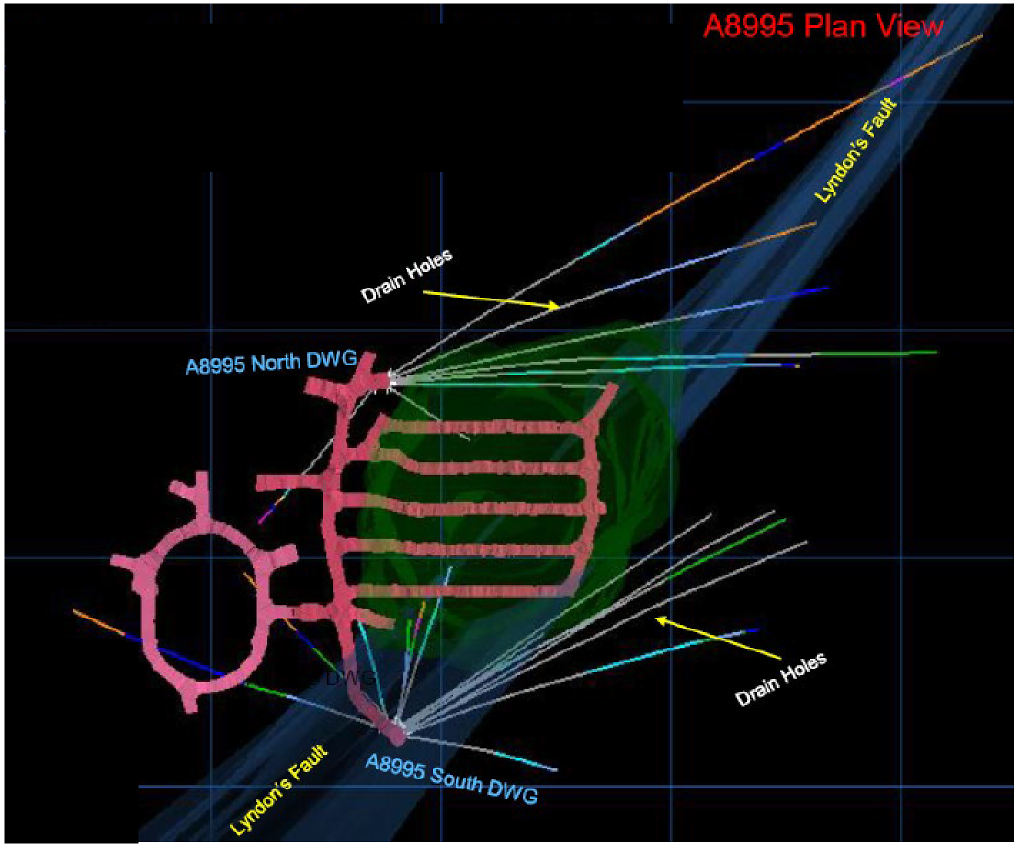
PREPARED BY: SP	FIGURE TITLE: SURVEY RESULTS – GEOLOGIC SETTING, COMMODITY AND CLIMATE		
CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT		
APPROVED BY: TC	SCALE: N/A	PROJECT NO: 2236001	FIGURE NO: 7

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 7. Survey results – geologic setting, commodity and climate.

08-2023



NOTES:
1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.

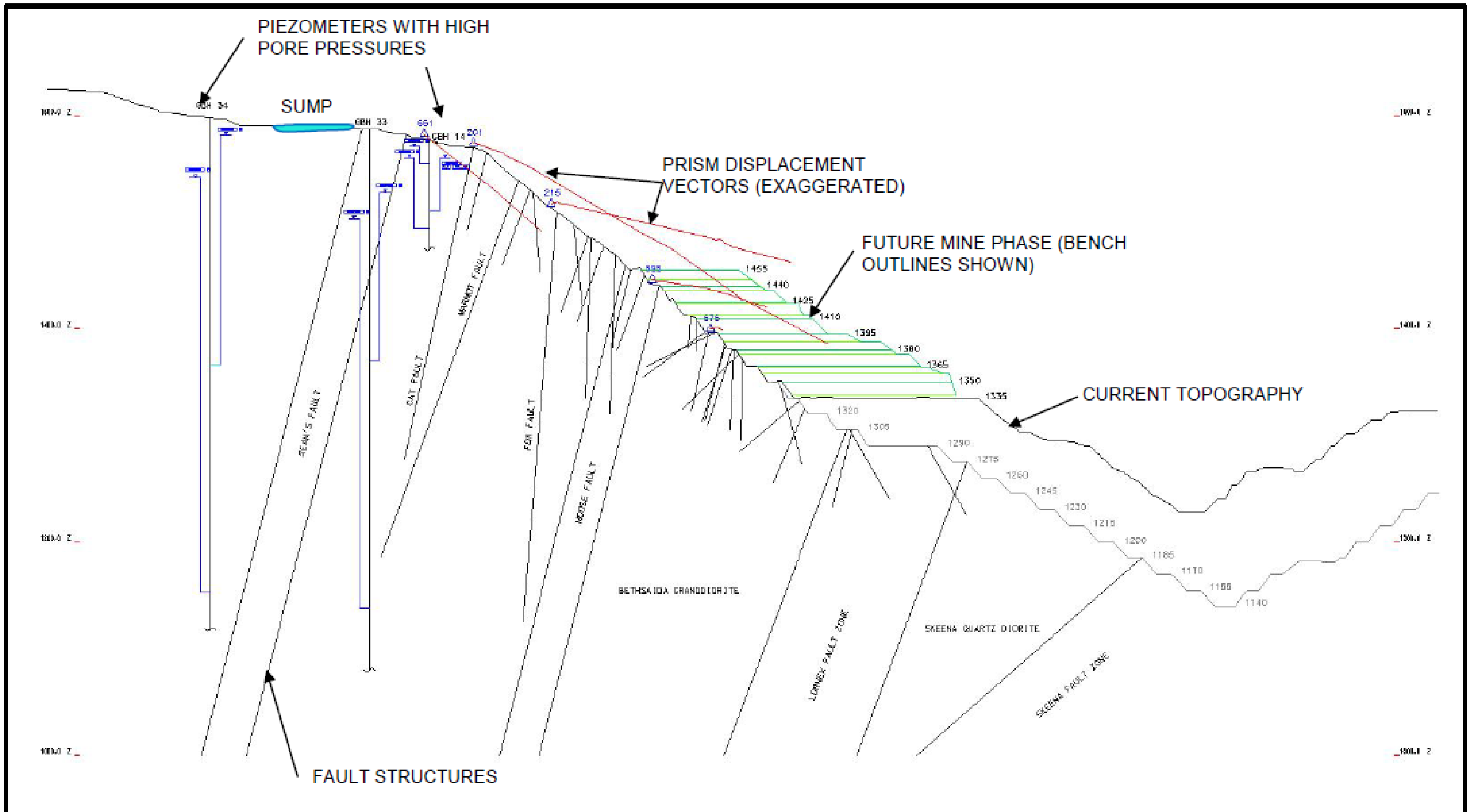
PREPARED BY: SP	FIGURE TITLE: EXAMPLE LAYOUT OF HDH UNDERGROUND		
CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT		
APPROVED BY: TC	SCALE: AS SHOWN	PROJECT NO: 2236001	FIGURE NO: 8

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 8. Example layout of HDH underground.

08-2023



NOTES:
1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.
2. Figure modified from Newcomen et al. (2002).

PREPARED BY: SP	FIGURE TITLE: EXAMPLE OF HIGH PORE PRESSURES IN SLOPE DUE TO STEEPLY DIPPLING FAULT STRUCTURES			
CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT			
APPROVED BY: TC	SCALE: AS SHOWN	PROJECT NO: 2236001	FIGURE NO: 9	

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 9. Example of high pore pressures in slope due to steeply dipping fault structures.

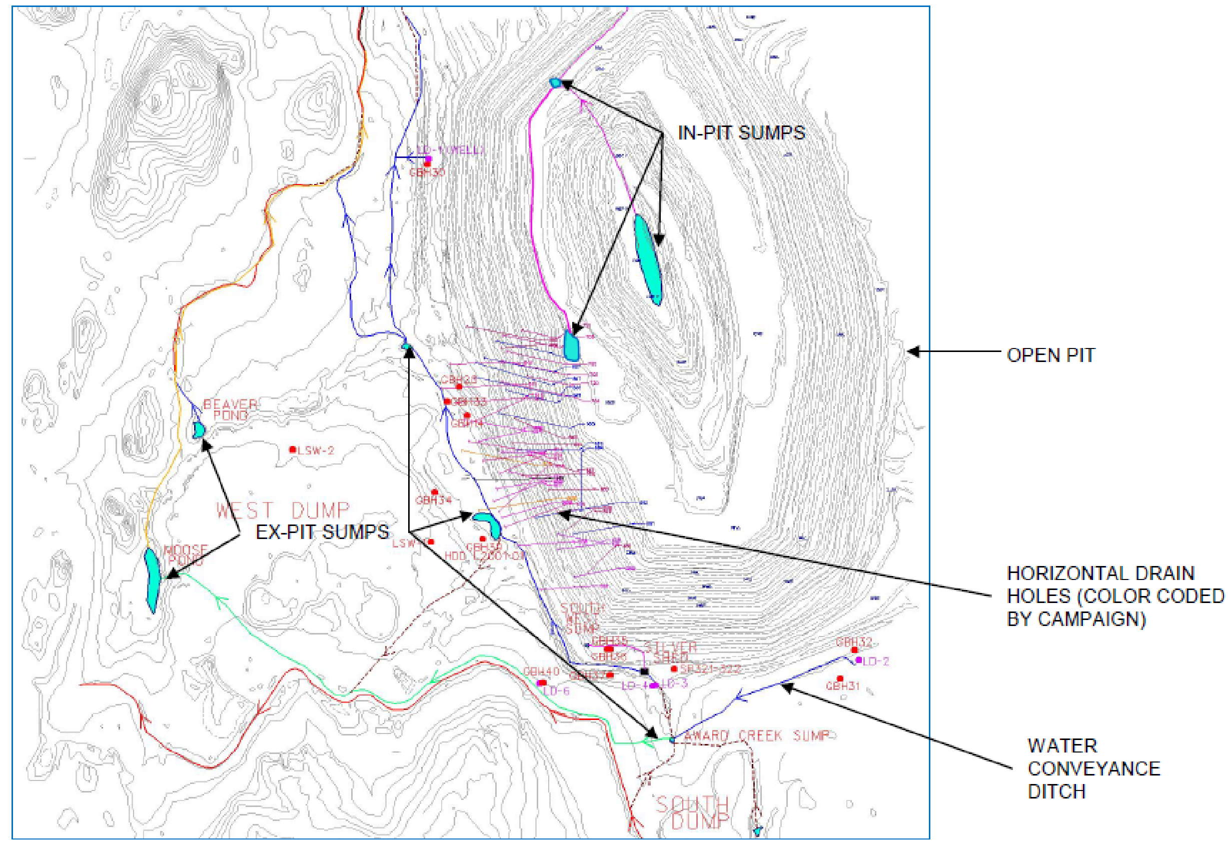
The above considerations require a three-dimensional understanding of the various hydrogeologic units present in the pit slopes, with the current and proposed pit slopes superimposed on them. Once the location(s) of the undrained areas of the rock mass are determined and their need for dewatering and depressurization are prioritized, areas where the pit slope can be accessed need to be identified in close cooperation with the mine planning team to determine if the HDHs are going to be effective and whether the required lengths are practical. Accessible areas, present and future, can then be determined from the mine plan and used to plan and refine the HDH program.

4.3. Operational Considerations

A successful HDH program requires that it be synchronized with the mining operation, i.e., that there is sufficient time for the drains to be installed when mining a particular bench or pushback, that enough drains are installed to achieve the objective of the program (e.g., routine pore pressure mitigation or stabilization of a specific slope, etc.) and that the water produced from the drains can be collected and conveyed to collection points where it can be removed from the pit. In this regard, it is important to understand the temporal component of the planning so that the area of interest remains accessible and the proposed drilling locations are not impeding mining operations while the HDH program is executed. At this point the mine planners have to determine whether or not there is enough time to install the number of HDHs required and construct the associated water collection infrastructure to manage the outflow from the drains. Groundwater discharging from the HDHs in the short term, prior to being collected in hoses or pipes and connected to headers, will have to be conveyed away from the working area. It is important to avoid pooling of the discharge water as this is a potential safety concern and can have detrimental effects on productivity and equipment longevity (e.g., increased tire wear, wet blast holes, etc.) over the longer term if left uncollected. Downslope areas that may be sensitive to water infiltration must also be considered when managing HDH outflows.

When planning the drain hole water collection measures, the locations of ditches and sumps must be considered. Sumps can often be conveniently located on haul roads, along geotechnical berms, at step-outs or in the bottom of the open pit (Figure 10; Newcomen et al., 2002). Depending on the depth of the pit, multiple pumping transfer stations may be required to convey the HDH outflows away from the pit. If sumps cannot be conveniently placed then a portable tank or water-tight shipping container to collect the water may be an alternative. The size of the tank will need to take into consideration the amount of water coming into it and the ability to contain that water until it can be pumped out of the pit.

08-2023



NOTES:

1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.
2. Figure modified from Newcomen et al. (2002).

PREPARED BY: SP	FIGURE TITLE: EXAMPLE OF HDH LAYOUT AND SURFACE WATER MANAGEMENT		
CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT		
APPROVED BY: TC	SCALE: AS SHOWN	PROJECT NO: 2236001	FIGURE NO: 10

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 10. Example of HDH layout and surface water management.

Another important consideration is the safety of the crew and protection of the HDH drill. In general, the slope above the drill must be safe to work under. The slope above the drill pad should be scaled and potential rock falls must be mitigated prior to moving the drill rig into the area. When drilling into or adjacent to unstable slopes equipment and personnel may have to be in close proximity to the instability to intersect the failure plane or hydrogeologic targets making this challenging. This can be addressed by remote operation of the drilling equipment. Alternatively, rockfall protection can be installed above the drill rig to protect the rig and personnel from rockfalls. Decommissioned haul truck boxes have been used at some mines by turning them over and mounting them on skids to serve as a robust steel canopy for the drill. Alternatively, the drill can be set up behind a rockfall mitigation measure such as an impact berm or mesh screen.

4.4. Integration of Hydrogeologic and Geotechnical Designs

Various authors cite the importance of integrating hydrogeologic designs for pit slope depressurization and slope designs. Broad assumptions are often made by geotechnical and pit slope engineers about the ability to depressurize pit slopes to meet depressurization “targets” required to achieve the slope stability Design Acceptance Criteria (DAC), without sufficient forethought or input from the hydrogeologists on whether those targets can be reasonably met.

Brawner (1982) states that “the most important effect of groundwater in open pit mine stability is its impact on the stability of the pit slopes”. Groundwater pressures can reduce the shear strength of discontinuities and the rock mass, increase seepage forces in discharge areas, decrease stability when present in tension cracks and increase the impacts of hydrodynamic shock from blasting. Groundwater discharging from the pit slopes is often responsible for increased haulage costs due to the increased unit weight of the blasted muck, with additional costs for drilling and blasting and increased equipment maintenance costs also typically incurred. However, the most disruptive aspect of high groundwater pressures is when it causes pit slope displacements that are unmanageable or unsafe to mine below, resulting in sterilization or deferred recovery of ore.

Considerations regarding pit water management in a mine planning cycle (Douglas et al., 2009) are discussed in a case study for the Olympic Dam Mine in Australia. A risk-based planning approach was incorporated into mine planning, scheduling and development of an operational strategy that took into consideration the locations and implementation of dewatering/depressurization infrastructure. Hydrogeological and geotechnical assessments were coupled to identify key geotechnical units requiring a reduction in pore pressures during a relatively rapid mining phase of the mine. In-pit HDHs and fan drain arrays installed from the existing underground workings were proposed as a means of reducing residual pore pressures in specific areas and hydrogeologic units. Pore pressures were estimated along sections of interest for stability assessments to enable fully coupled modeling. The modeling was initially carried out in 3D to generate estimates of groundwater inflows and dewatering requirements, then vertical slice models coincident with the geotechnical cross-sections were used to estimate pore pressures using different depressurization methods to mitigate pore pressures behind the pit slopes. The effects of mining and subsequent unloading from removal of rock were used to estimate joint opening and potential associated changes (increases) in hydraulic conductivity of specific geologic units, which were then subject to depressurization measures using HDHs and “intervention drains” drilled from the underground workings. Because the HDHs had to be drilled from surface, additional consideration of the mine plan was required to assess whether they could be drilled on every bench without compromising mining activities.

Dowling et al. (2020) outline an integrated workflow to allow reconciliation of pit slope pore pressures at the Morenci Mine in Arizona, USA. The groundwater management system is intended to reduce the impacts of groundwater seepage on mining and to attain specific groundwater pressure targets for slope management purposes, with the primary goal being to reconcile observed pit slope pressures against the predicted pressures and targets. The integrated workflow involved the participation of the Mine Hydrogeology and Dewatering Group, Geomechanics Team, Mine Operations and consultants. The main elements included using a predictive 3D groundwater flow model incorporating the initial layout and planned additions of dewatering wells, preparation of a FLAC3D model to evaluate slope stability and establish depressurization targets to meet the DAC, comparisons of pore pressure predictions from the groundwater model with the depressurization targets to determine where the targets are (or are not) being met, implementation of a tracking system to assess where and when the dewatering system will achieve compliance, and a reporting system. This process highlights the advancement of 3D numerical stability modeling and more routine use in slope designs. A “heat map analysis” was introduced to compare the predicted groundwater pressures, based on the current and anticipated future dewatering system layout and associated mine plan, with the targets required to comply with the DAC. The heat maps were transferred onto cross-sections for selected mining years to present visual evidence of the benefit of the planned dewatering program (when compliance is being achieved) and highlight where additional dewatering efforts will be required in future years (Figure 11; Dowling et al., 2020).

Golestanifar & Ahangari (2012) present guidance on how to choose and develop the optimal pore pressure mitigation program for open pit mines, noting that the scale of the program depends on three factors:

- The hydrogeologic characteristics of the rock mass
- The depth of the excavation below the groundwater table
- The strength of the materials making up the pit slopes.

They present a number of factors to consider when assessing the suitability of the dewatering systems such as:

- Response time
- Hydrological condition compatibility
- Experience with the system
- Flexibility
- Impact/interference with mining operations.

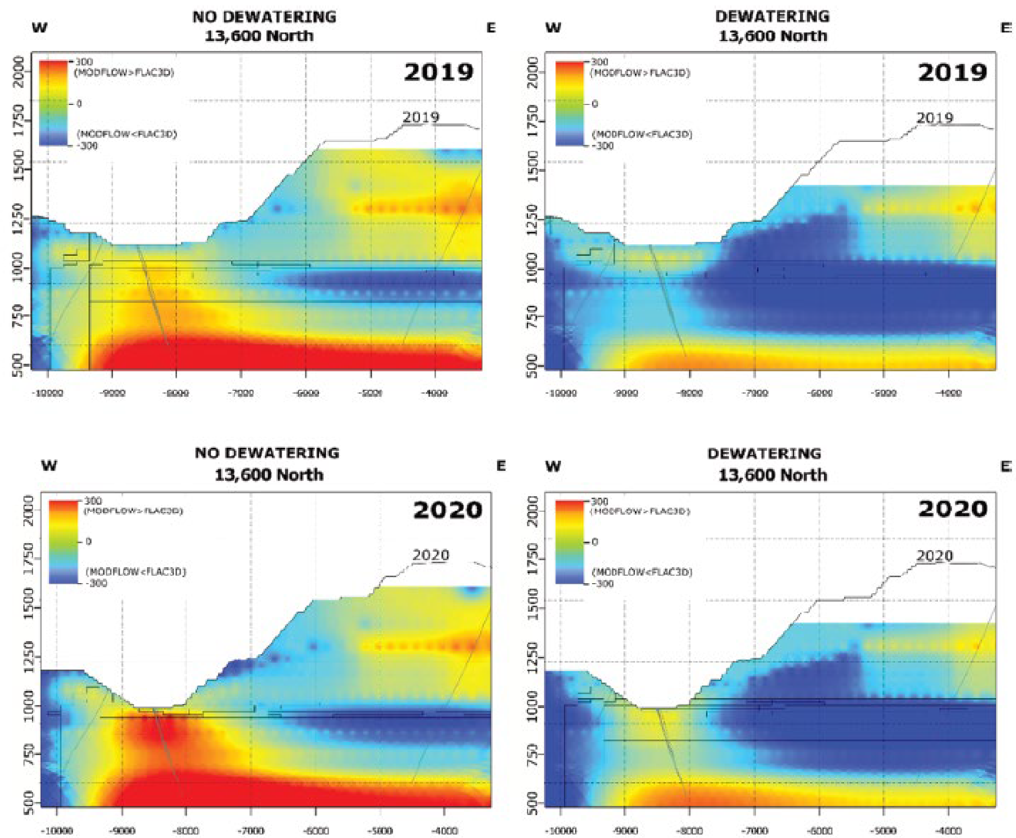
Regarding the hydrological condition compatibility, (i.e., the hydraulic conductivity), the minimum hydraulic conductivity for which horizontal drains are effective is generally assumed to be around 1×10^{-7} m/s. However, depressurizing rocks with lower permeabilities is possible if the drain holes are tightly spaced, the rate of mining is slow, or HDH flows can be enhanced (e.g., attached to a vacuum).

Differences between the data gathering philosophy and the domaining of the pit are mentioned by Campbell et al. (2013) and should be considered when integrating the hydrogeological and geotechnical considerations (Figure 12). Of primary importance is to avoid assuming that the geotechnical domains are the same as the hydrogeological domains. Although the mechanical properties of a rock mass can influence both the strength and the permeability of that rock mass, the discontinuities (both large and small) can have a significant impact on the propensity of the rock mass to stand up, with or without pore pressures present, as well as the ability of the rock mass to transmit water/drain. Alternative mitigation measures such as in-pit wells may be limited, expensive to install, costly to maintain or of limited life span due to compartmentalization of the groundwater and damage to wells due to slope movements and mining. This approach, however, requires good knowledge of the structural geology of the pit and sufficient piezometric data to understand where the high pore pressures are so the required depths of the HDHs can be determined. This was reflected in the survey responses which indicated the importance of the structural and hydrogeologic models (Figure 13).

Rock slopes that are prone to toppling are particularly sensitive to high pore pressures. Although the rock mass between the steeply dipping faults contributing to toppling failure may be competent, high pore pressures behind the faults due to heavy rainfall and runoff are often the main driving force of the movement. This was observed in the Lornex Pit at Highland Valley Copper (HVC) where low permeability faults dipping steeply into the slope, resulted in poor passive drainage of the slope and compartmentalized groundwater (Figure 9, Newcomen et al., 2002). To mitigate this, the mine plan considered the time of year when mining would most efficiently be carried out below this slope, and the HDHs were installed at specific elevations when certain geologic structures could be penetrated by the drains. The success of various drilling campaigns (i.e., groundwater strikes), piezometer locations, the location of surface water sumps (in-pit and ex-pit) and HDH discharge collection measures were also considered during the integration and planning process (Figure 10, Newcomen et al., 2002).

Lucas and de Graaf (2013) present a case history for the Tom Price mine where HDHs were planned in the bottom of the pit as a slope depressurization measure to reduce pore pressures behind sub-vertical faults and across shallow features dipping into the pit which comprised potential slope instabilities. The number and location of drains was determined by the vertical mining progression and corresponding access to the working areas of the pit. Groundwater strikes and outflows from HDHs for various campaigns, carried out at different elevations, can also be used to plan and optimize subsequent drilling and depressurization campaigns (Figure 14, McKelvey et al., 2002).

08-2023



NOTES:
1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.
2. Figure from Dowling et al. (2020).

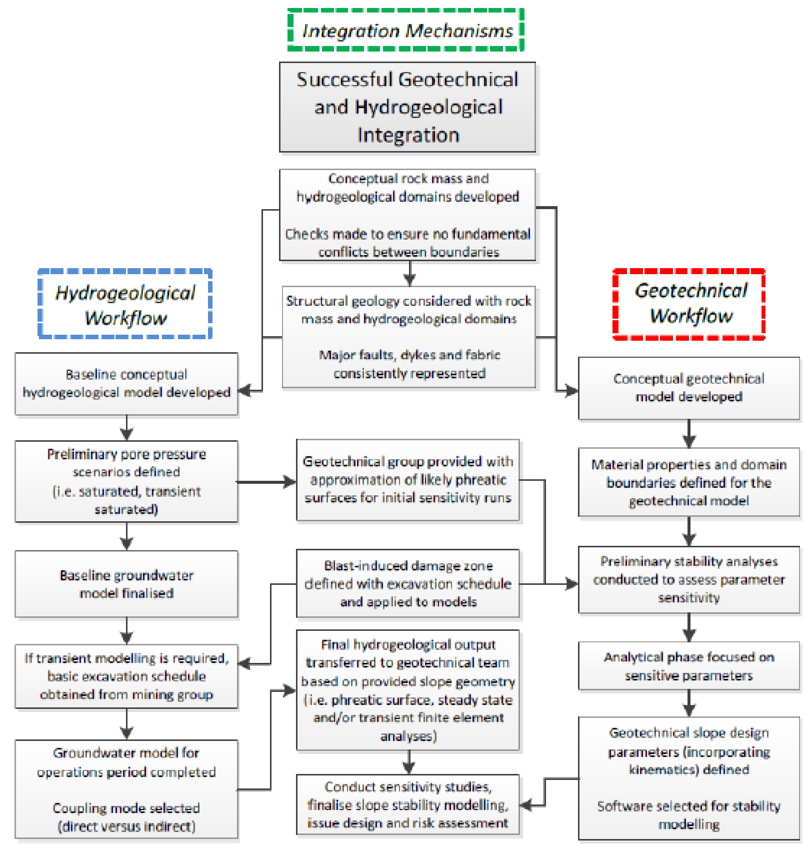
PREPARED BY: SP	FIGURE TITLE: HEAT MAP ANALYSIS FOR SELECTED MINING YEARS			
CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT			
APPROVED BY: TC	SCALE: AS SHOWN	PROJECT NO: 2236001	FIGURE NO: 11	

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 11. Heat map analysis for selected mining years.

08-2023



NOTES:
1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.
2. Figure from Campbell et al. (2013).

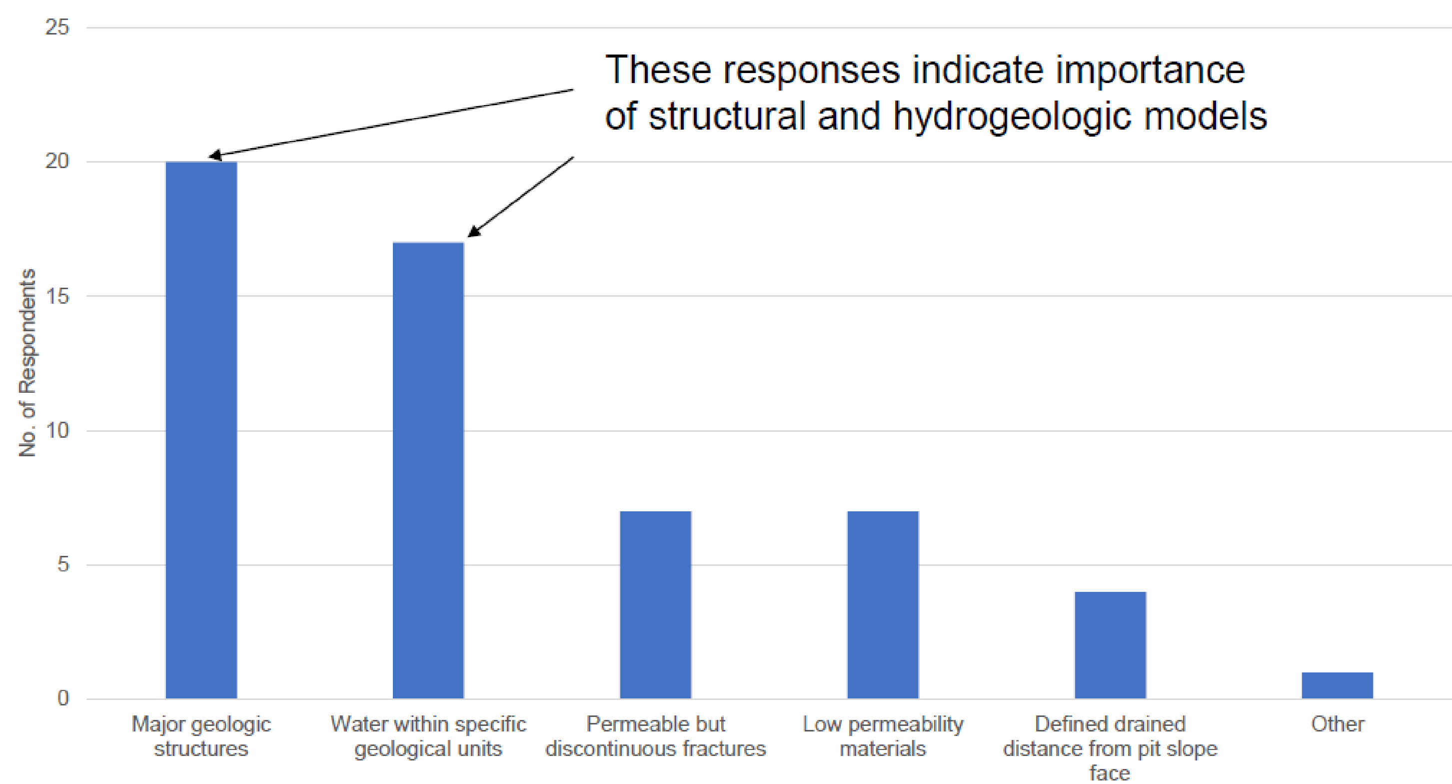
PREPARED BY:	FIGURE TITLE		
SP	GEOTECHNICAL-HYDROGEOLOGICAL INTEGRATION PROCESS		
CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT		
APPROVED BY: TC	SCALE: N/A	PROJECT NO: 2236001	FIGURE NO: 12

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 12. Geotechnical-hydrogeological integration process.

08-2023



NOTES:

1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.
2. Data is from survey results, including response from operations and literature review case studies.
3. Based on the results of 24 responses.
4. Major structures include but are not limited to faults, foliation parallel jointing, bedding planes.
5. Other = Not Applicable.

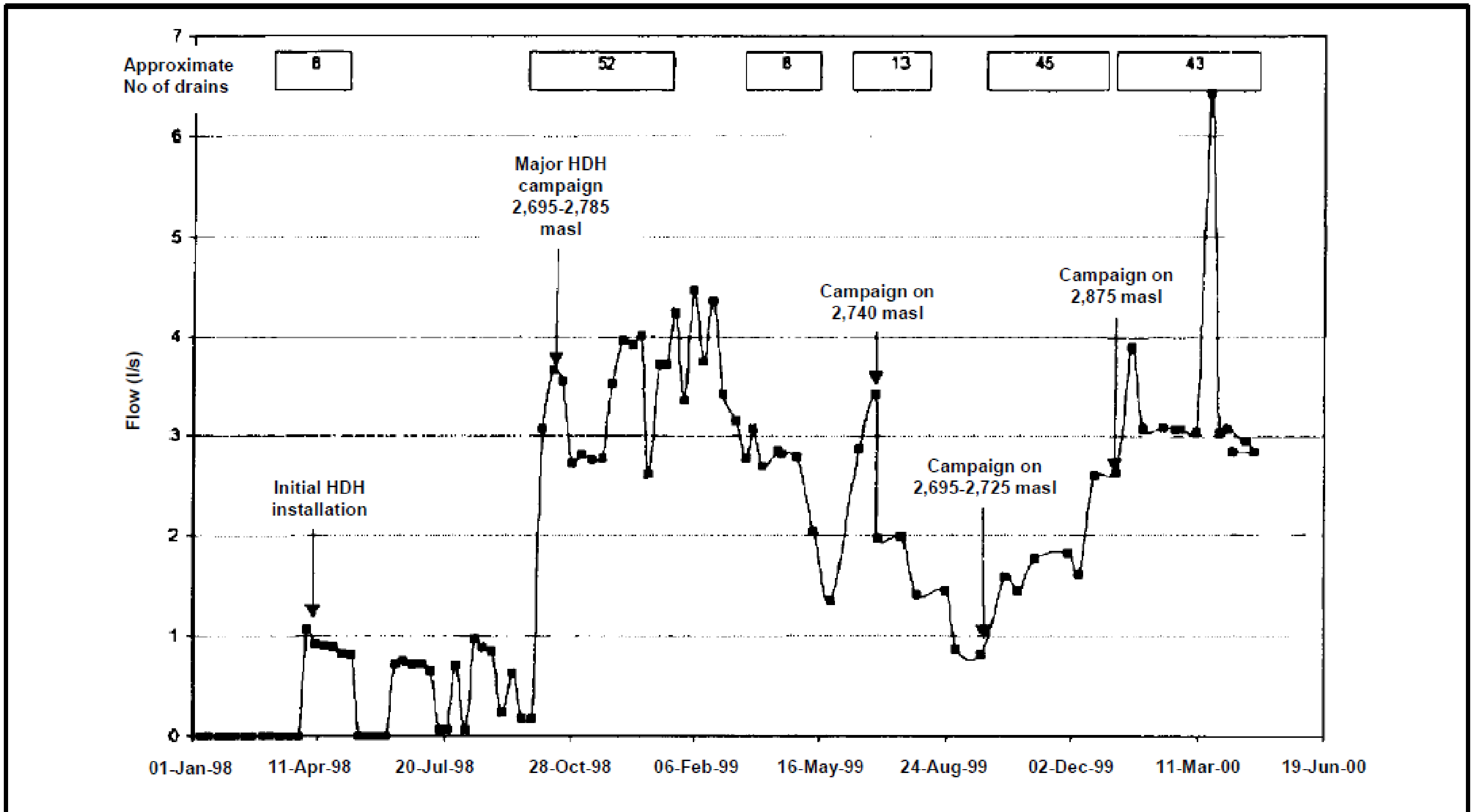
PREPARED BY: SP	FIGURE TITLE: SURVEY RESULTS – TYPICAL DEPRESSURIZATION TARGETS			
CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT			
APPROVED BY: TC	SCALE: N/A	PROJECT NO: 2236001	FIGURE NO: 13	

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 13. Survey results – typical depressurization targets.

08-2023



NOTES:
1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.
2. Figure from McKelvey et al. (2002).

PREPARED BY: SP	FIGURE TITLE: EXAMPLE OF DATA PRESENTATION – MONITORING OF DRAIN FLOW		
CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT		
APPROVED BY: TC	SCALE: AS SHOWN	PROJECT NO: 2236001	FIGURE NO: 14

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 14. Example of data presentation – monitoring of drain flow.

Cintolesi et al. (2020) discuss the importance of taking a consistent approach to the planning and implementation of dewatering/depressurization strategies that address pore pressure targets to meet slope design acceptance criteria, as well as a number of other factors including regulatory requirements, dewatering ahead of operations and the site wide water balance. Although it is important to integrate the hydrogeological and geotechnical design work, the impacts of inadequate dewatering/depressurization can be as costly as poor slope performance. This may require a risk-based decision-making approach involving the various disciplines with an interest in the project, utilizing analytical and/or numerical supporting analyses to quantify the risks in the final stages of the system design to determine which dewatering/depressurization system is most effective.

5.0 JUSTIFYING THE HDH PROGRAM

Justification of an HDH program can be accomplished in several ways. Methods typically used to justify an HDH program fall under one or more of the following categories; benchmarking, technical, operational or economic as discussed in the following sections.

5.1. Benchmarking

One approach to assessing the potential magnitude and associated cost of pit dewatering/depressurization effort is to undertake a benchmarking study. This involves looking at other open pit mines in similar deposits, climates and jurisdictions with comparable pit size and hydrogeologic conditions. Such a study would also inform mine planning/sequencing so that access, schedule and resources (technical staff, equipment and materials) are factored into mine operations and budgeting. Preliminary estimates of the slope depressurization efforts required are made to confirm that installing HDHs will have the desired outcome, i.e., achieving hydrogeological and geotechnical targets such as a reduction in the phreatic surface, maintaining or improving the stability of the pit slopes, and keeping the operating area free of water due to seepage out of the pit walls. The information from the benchmarking exercise will better inform the technical, operational and economic justifications, as discussed in more detail below.

5.2. Technical Justification

Technical justification of a HDH program is generally straightforward. The first step required is to demonstrate the need for the dewatering and depressurization efforts. This can be accomplished by presenting the impacts of the efforts to mine operations with and without the HDH program. Typical examples for the technical need to dewater or depressurize slopes are as follows:

- A geotechnical requirement to achieve a specified DAC, such as Factor of Safety (FOS) or Probability of Failure (POF), to maintain stability of the pit slopes
- A geotechnical requirement to limit slope displacements or prevent instabilities
- Intercepting recharge to lower portions of the slope
- A water management requirement to control seepage, along with a geotechnical requirement to reduce or mitigate surface erosion
- An operational requirement to prevent groundwater seepage entering blast holes or working areas
- A requirement to supplement water supply for processing or dust control.

With consideration of the above, it may become apparent that vertical pumping wells are impractical or insufficient to achieve the above requirements and HDHs are required to replace or supplement the wells because:

- The hydraulic conductivity is too low for wells to be efficient
- Compartmentalization of the groundwater flow regime favours HDHs over wells (e.g., sub-vertical, impermeable fault sets)
- Fracture networks are poorly inter-connected or adversely oriented, resulting in a low success rate of wells

- The ability to depressurize the area close to the slope face is often easier to accomplish with HDHs due to the myriad of constraints encountered when siting and maintaining wells (access, power, discharge lines, etc.)
- The lead time required to drill and commission a well and the projected life of the well may favour HDHs, which can be installed relatively quickly, begin to work immediately, and are considered more "disposable" than wells
- Water chemistry/quality (high acidity, high pH, high Iron content, high fines content, high temperatures) may make wells more expensive to maintain and operate than HDHs.

Technical justification to continue with future HDH drilling campaigns may be required after initial trials have been carried out. In this case the benefit of installing the HDHs could be demonstrated by illustrating the response to the HDHs installed during the trials by documenting:

- Changes in pore pressures in piezometers (provided such instrumentation and data collection was included in the trial program)
- Reductions in slope displacement rates
- Changes to the amount of seepage observed in the bench faces
- Working conditions on the pit floor with respect to ponded water
- The volume of water collected from the HDHs over time.

As indicated by the survey responses, HDHs are primarily installed in combination with other slope depressurization methods (Figure 2) to achieve pore pressure targets and address deformations or geotechnical concerns (Figure 5) above the mining area. These targets are initially characterized by a phreatic surface (estimated or modeled) which will result in the designed pit slope meeting the specified DAC. The phreatic surface is typically simplified for stability analyses and rarely captures the complexity of the pore pressures in the pit walls; however, it must be measured (early, often and for as long as possible) with piezometers to determine if those targets are being met to confirm that they are realistic and appropriate for interim or final pit slopes.

A significant disadvantage is that HDHs cannot be installed until the open pit operating level is below the water table and the benches are accessible; this does not facilitate advance depressurization of the pit slopes on that layback. If advance depressurization is required to achieve the geotechnical or hydrogeologic goals, vertical wells or vertical passive drains will also be required. It must also be kept in mind that passive drainage may not be as effective as pumping due to limitations regarding the amount of drawdown that can be achieved. Thus, a methodology for comparing cost and effort versus zone of influence in both the vertical and horizontal direction is required when conducting the technical justification.

Input on the practicality of achieving the target pore pressures should be solicited from the mine hydrogeologists early in the design stage to confirm that the target pore pressures and the location and timing of the various depressurization methods are reasonable, fit for purpose and can be achieved in sufficient time. In situations where the depressurization efforts are implemented to reduce slope displacements, movement rates in areas where the drains were installed should be compared prior to and following the HDH program and referenced to piezometric pressures or drain outflows in those areas to see if the program has had a measurable influence on the slope movements. An example of this type of technical justification, is illustrated in Figure 15 (Reano et al., 2020) where the water level in piezometers (decreasing) are plotted against the cumulative flow (increasing) out of the HDHs, resulting in reduced slope displacement rates.

5.3. Operational Justification

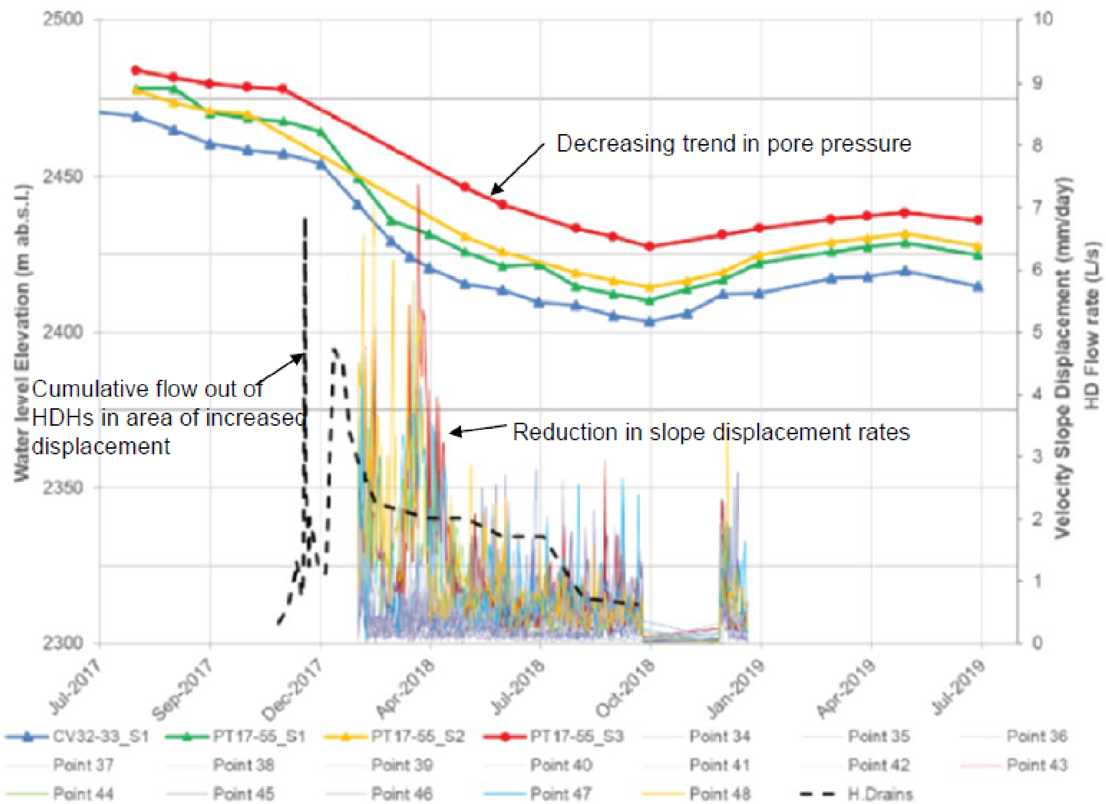
The HDH slope depressurization program must consider the implications of the program on the mine plan (and vice versa) and the resources required from mine operations. The geotechnical engineer or hydrogeologist recommending the depressurization measures will garner more support from mine operations if they can illustrate improvements to safety and productivity. Specifically, if the HDHs are effective in minimizing pit slope displacements and the potential for moving or shutting down equipment while the stability of the slope is being assessed, the program will be favourably received by operations. The following should be considered when justifying an HDH program on the basis of mine operations:

- Improved safety will be achieved if slopes are stable or moving at lower velocities
- The mine is more likely to reach production targets if offload cuts and step-ins to manage instability can be avoided
- Less frequent disruptions will occur due to geotechnical alarms and associated zone evacuations if the pit walls are stable
- Dry blasting patterns will result in fewer hole collapses, less emulsion use and better working conditions
- A dry pit floor will result in better trafficability, requiring less frequent grading, reduced maintenance, and reduced wear and tear on equipment tires
- Drier muck piles will result in less water being moved by haul trucks and shovels.

If slope depressurization and dewatering can be accomplished with a smaller team by installing HDHs instead of wells, which operations may not have the expertise or sufficient staff to maintain, this may also be a strong incentive to j use HDHs.

Following the justification, mine operations must still be made aware, however, that access to the HDHs and piezometers will be required to carry out routine monitoring of outflows and pore pressures, and/or maintenance of the discharge lines. Oftentimes this is a challenge within the pit where geotechnical berms, jump ramps and other means of access to the HDHs are eliminated due pit slope movements or operational requirements. It is important to anticipate ongoing maintenance of discharge hoses or water collection headers installed to convey the outflows away from the slope into portable or permanent sumps so that the water is managed and pumped out of the pit in a controlled manner. As the pit is deepened, the collection measures will likely need to be extended and/or moved to be effective. The above tasks may require additional manpower and this must be accounted for in both the operational and economic justification processes.

08-2023



NOTES:
1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.
2. Figure adapted from Reano et al. (2020).

PREPARED BY: SP	FIGURE TITLE: EXAMPLE OF DATA PRESENTATION - SLOPE MOVEMENT AND GROUNDWATER LEVEL			
CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT			
APPROVED BY: TC	SCALE: AS SHOWN	PROJECT NO: 2236001	FIGURE NO: 15	

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 15. Example of data presentation – slope movement and groundwater level.

5.4. Economic Justification

Economic justification for a HDH program involves putting costs to the technical and operational justifications and comparing the outcomes. To accurately justify the use of HDHs economically, the program planners must have cost information for other means of slope depressurization to compare with the cost of installing HDHs. Drilling, installation of pumps (for wells) and water conveyance costs are relatively straightforward to estimate for slope depressurization measures; however, long-term maintenance and power costs for pumping wells must also be considered. These costs could vary considerably depending on the well construction, pump type, frequency of pump cycling and the groundwater quality. The longevity of wells versus HDHs is also an important consideration when undertaking the economic justification. Mines that have previously employed various slope depressurization methods should have a good understanding of the costs to install and maintain the HDHs and wells.

Economic justification may be as simple as demonstrating the costs or savings for one aspect of drains versus wells (e.g., based on unit cost per length of hole), or it can be more complicated and involve a cost benefit analysis with the following considerations:

- What are comparative costs for various water management configuration options (i.e., surface water controls, wells and HDHs)?
- What is the cost of instability if depressurization targets are not achieved (i.e., cost of alternative mitigation measures such as step-outs or unloading, cost of mining delays, cost of ore sterilization or deferral to later mining phases, etc.)?
- What is the economic benefit if slopes can be steepened, if depressurization targets can be achieved or exceeded?
- What are the savings if emulsion requirements are reduced?
- What are the potential savings if the size of the road maintenance fleet can be reduced?
- How does equipment tire life compare between wet and dry conditions and how does that impact the overall cost of mining?
- What is the added expense for hauling water in trucks compared with pumping it out of the pit?

Consideration also needs to be given to the benefits of preventing surface water from entering the rock mass behind the pit wall by implementing runoff controls (e.g., ditches and pipelines) and strategic placement of sumps to collect and remove surface water. By reducing the infiltration of surface water in the upper elevations of the pit wall, the need for HDHs could potentially be reduced if surface water is the primary source of recharge to the groundwater regime.

It has been suggested that for every $1 million invested in slope depressurization activities a reduction in mining costs of between $5 and 10 M USD can be realized (Beale et al., 2013; Kolpakov et al., 2019) This is equivalent to a return on investment of 5 to 10 times, if slope depressurization and pit dewatering can be effectively carried out. Further details on the range of costs for HDHs, based on the survey information collected, are provided in Section 6.8.

6.0 PLANNING AND IMPLEMENTATION

6.1. Hydrogeologic Environments

Planning and implementing a successful HDH program requires a good understanding of the hydrogeologic system that the drains are to be installed in. On the assumption that the survey results received to develop these guidelines are representative of industry, approximately 85% of the mines using HDHs consider the groundwater system at their operation to be "moderately to well understood". Similarly, 80% of the respondents indicated that they have a groundwater model which is primarily used for dewatering and/or water balance purposes, drawdown prediction and environmental compliance. This is not surprising as a groundwater model is generally necessary to complete the feasibility study for a mining project and the model is generally refined during detailed design when dewatering and slope depressurization options need to be better understood so they can be incorporated into capital and operating cost estimates.

More granularity on the pore pressures in the vicinity of the open pit is required if stability analysis modeling of specific pit slopes is to be carried out. Approximately half of the survey respondents indicated that they have groundwater models that are typically updated every one to five years and are used to predict drawdown in the pit area. This is a good starting point to assess whether the planned pit slope depressurization schemes, in conjunction with passive drainage of the slopes in response to mining, are going to be sufficient to achieve phreatic surface targets. However, given that HDHs are often used to target hydraulically conductive discrete faults and fracture zones, or compartmentalized pockets of groundwater between these features, more detailed structural and hydrogeologic models may be required in specific areas of the pit. Several mines that responded to the survey indicated that "discrete fractures" are included in their groundwater models but this was not typical of most operations. Presumably the mines that have identified such features recognize that they play a key role in the hydrogeologic environment and must be taken into consideration if groundwater pressures and seepage into the pit are to be effectively managed or mitigated.

6.2. Identifying Targets

Major geologic structures, faults and permeable fracture zones are often the target of HDH installations and thus a good understanding of the structural geologic model is required. Potential depressurization targets can be confirmed by plotting high hydraulic conductivity structures or hydrogeologic units on cross-sections and plans to estimate the number of HDHs required and the range of depths which need to be drilled. This is relatively straightforward in operating mines where depressurization efforts have been previously carried out but may be impractical and/or poorly informed prior to mining the open pit. Where groundwater and stability modeling results from the feasibility study and detailed design stages indicate that HDHs are going to be needed to supplement ex-pit or pre-mining depressurization measures such as wells, a uniform distribution of drains is likely a reasonable starting point for planning and resource evaluations until the "pit-scale" hydrogeology is better defined.

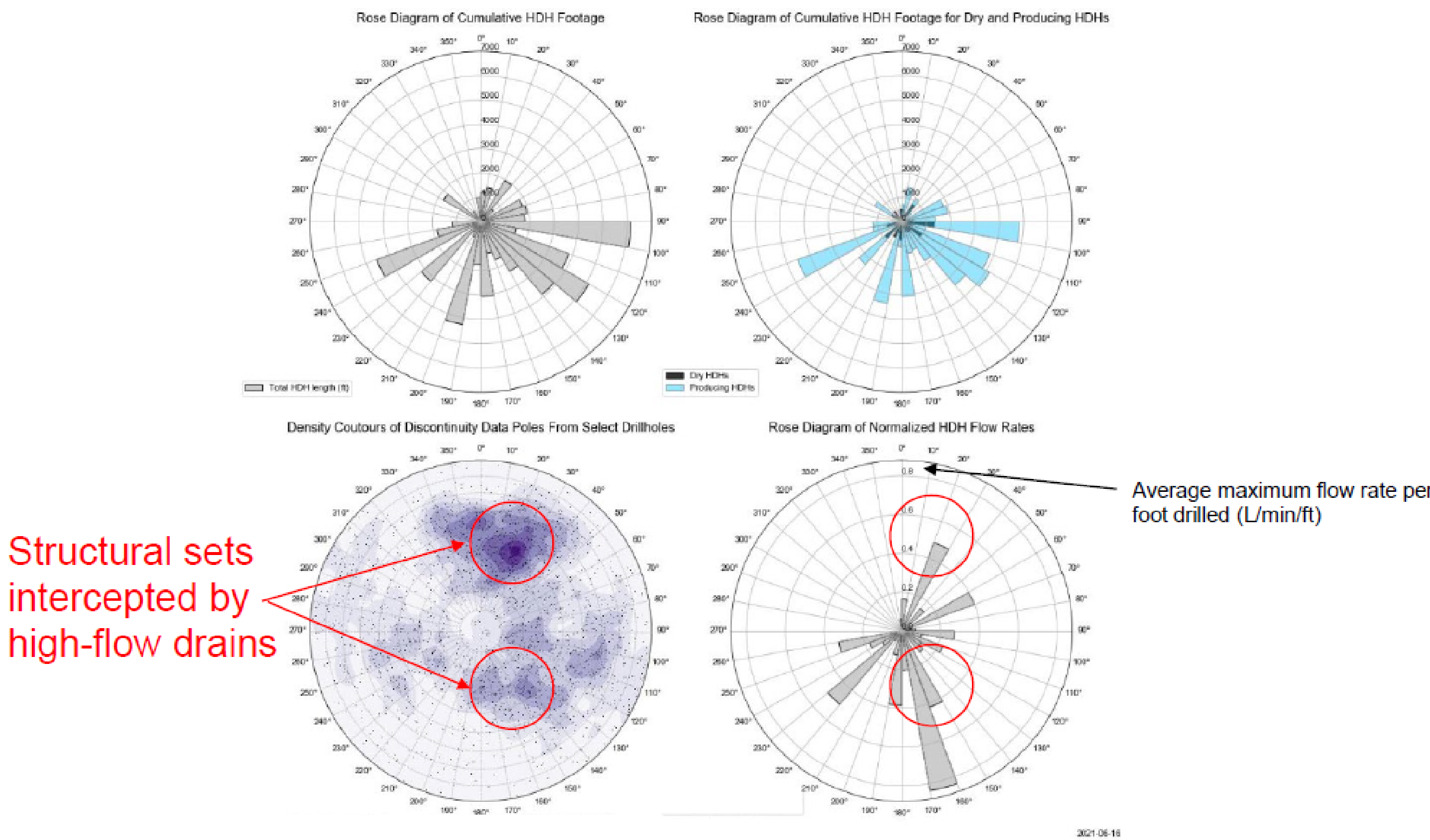
Groundwater within specific geologic units was identified as a primary target for HDH installations at many mines. This may be easier to define in stratiform deposits where there is a notable contrast between the hydraulic conductivity of more coarse-grained units daylighting in the pit walls than the fine-grained ones. Similar contrasts in conductivity might be found in crystalline or porphyry deposits albeit with potential greater complexity depending on the genesis of the deposit; however, they may be less evident and require more hydrogeologic testing (i.e., packer and pumping tests) to define the various units. Approximately three-quarters of the survey respondents indicated that they had completed some type of hydrogeological testing, including upset testing in standpipe piezometers, packer testing in drillholes, and pumping tests in wells, and were routinely monitoring pit inflows and seepage. An awareness of the conductivity of the targets is needed to confirm that the depressurization efforts are adequate to meet the pit development schedule.

One-quarter of the respondents had completed downhole televiewer surveys to identify potential high conductivity geological structures (based on aperture) and measure their orientations. One of the mining operations that responded to the survey compares the yield of the HDHs, normalized by drain hole length, to the orientation of the holes and the orientations of the structural discontinuities to determine if there is a preferential direction for drilling relative to the fabric in the rock (Figure 16). These efforts speak to the importance of understanding both the hydrogeology and the structural geology, as well as tracking groundwater strikes on previous and current pushbacks (Figure 17) so that appropriate targets can be exploited as part of the mine’s slope depressurization efforts.

The geotechnical engineer must also understand the potential pit slope failure mechanisms to fully appreciate which hydrogeologic units or specific geologic structures need to be depressurized. Another challenge is defining the pore pressure thresholds for those potential instabilities. At the feasibility level stage of design this may be as simple as requiring “dry” or “partially saturated” slopes if “saturated” slopes do not achieve the DAC. As a starting point, the pore pressures can be estimated in terms of B-bar or r_u coefficients as opposed to a specific phreatic surface. In operating mines with well-defined failure mechanisms involving discrete faults or hydrogeologic units the depressurization targets will likely be more specific.

The disturbance zone (sometimes referred to as the overbreak zone) in the near surface of a pit wall due to blasting and ground relaxation, which generally has higher hydraulic conductivity than the rock mass at greater depth, is a primary source of recharge in the pit wall and may limit the depth of instability. Understanding the depth of this zone and the depth of the more conductive rocks in the disturbance zone will reduce the amount of drilling. Open pit slopes with steeply dipping wedge or planar instabilities parallel to the bench faces or inter-ramp slopes may not require long HDHs, in which case they would play an important role in managing single to multi-bench scale instability as opposed to inter-ramp or overall slopes.

08-2023



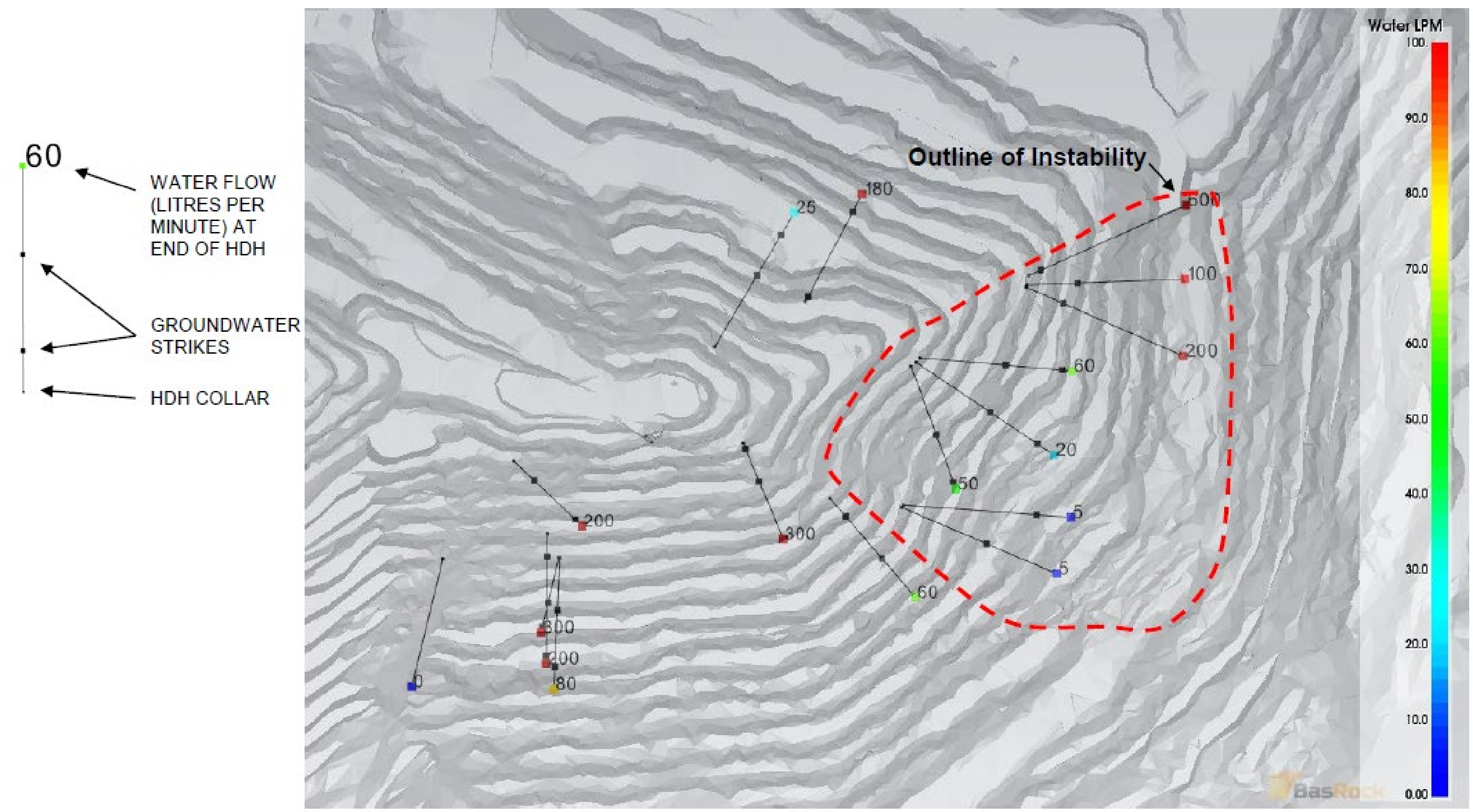
NOTES:	PREPARED BY:	FIGURE TITLE		
1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.	SP	EXAMPLE OF PRESENTATION – HDH FLOWS RELATIVE TO STRUCTURAL TRENDS		
	CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT		
	APPROVED BY: TC	SCALE: AS SHOWN	PROJECT NO: 2236001	FIGURE NO: 16

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 16. Example of data presentation – HDH flows relative to structural trends.

08-2023



NOTES: 1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.	PREPARED BY: SP	FIGURE TITLE EXAMPLE OF AN HDH LAYOUT SHOWING GROUNDWATER STRIKES		
	CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT		
	APPROVED BY: TC	SCALE: N/A	PROJECT NO: 2236001	FIGURE NO: 17

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 17. Example of an HDH layout showing water strikes.

6.3. The Role of Hydrogeological Modeling

Large scale mining projects and mining operations usually rely on site-wide groundwater flow models to forecast hydrogeological conditions at various stages of mining, including changes in groundwater fluxes to mine facilities, expansion of the drawdown cones associated with mine dewatering, and evaluation of groundwater pathways. Model development often begins during pre-feasibility/feasibility studies, and the model is gradually refined to provide input for permitting work, detailed engineering design and eventually to support operations. Large mines commonly treat the site-wide groundwater models as a “living tool”, with regular model updates completed when additional hydrogeological data become available during advancement of the open pit/underground workings, expansion of mine storage facilities, and implementation of groundwater mitigation measures (dewatering/depressurization wells, drainage galleries, etc.). In some jurisdictions, mining permits require updates to models at regular intervals as part of ongoing submissions with mining and closure plans.

If regularly updated, the site-wide groundwater models integrate hydrogeological data across the property and provide the best tool for forecasting hydrogeological response to mining at the site scale. However, at the pit-wall scale, or in specific sectors of the pit where high hydraulic heads may be anticipated, their level of detail may not be sufficient to assess the effectiveness of HDHs. In that case, pit-wall scale analysis supported by additional field programs may be warranted (Zawadzki et al., 2008). Such analysis commonly relies on a range of modelling tools (Section 6.4) that build on the hydrogeological knowledge embedded in the site-wide model. Alternatively, the site-wide groundwater model may be locally refined to a sufficient detail required for the HDH designs (Lawrence et al., 2010).

An important aspect of hydrogeological modelling to support HDH designs in fractured rock is the applicability of the equivalent porous medium (EPM) assumption commonly invoked in the site-wide models. Depending on the degree of fracturing and fracture connectivity, an EPM approach may be appropriate at the site scale (100s – 1000s of meters) but may fail at the pit wall or bench scale (10s – 100s of meters). This is particularly true in situations where the pit wall is located in close proximity to a source of groundwater recharge, like a lake or perennial stream, leading to the development of high pore pressures behind the pit wall along discontinuities that are in direct hydraulic connection with this source of recharge. In these situations, the pit-wall scale analysis needs to incorporate such discontinuities by either adopting a hybrid-EPM approach or by relying on a discrete fracture network (DFN) model for selected pit-wall sectors (Reinson et al., 2006; Bieber et al., 2007; Chorley et al., 2009). In the former, the bulk rock mass is represented using the EPM approach while the known discrete features are explicitly included. In the latter, the rock mass behind the pit wall is represented as a fracture network using statistical distributions derived from the drilling programs and pit wall mapping. DFN type models are data intensive hence they can only be deployed following extensive rock mass characterization that at some locations may be difficult to implement.

Independent of the approach chosen, the pit-wall scale model or the site-wide model that was refined along the pit wall, is used to evaluate hydraulic head reductions resulting from the HDH installations relative to the conditions that could be expected without any mitigation. For HDHs that are planned to be relatively long (100s of metres) and sparse, each HDH can be represented in the model individually using specialized boundary conditions or discrete 1D elements with high permeability. This assumes that the underlying model has sufficiently high horizontal and vertical resolution to adequately represent the flow field that develops around each HDH (Lawrence at al., 2010). Alternatively, shorter and more densely spaced HDHs can be simulated as a zone of enhanced hydraulic conductivity behind the pit wall that extends over the planned depth of HDH installations. In the latter approach, care is needed in establishing the appropriate value for the enhanced hydraulic conductivity such that the effects of the densely spaced HDHs are not overestimated. The limitation of this approach is that the spacing between individual HDHs cannot be estimated directly.

Analytical and numerical modelling tools also aid in the design of the monitoring system, that can be used to assess the performance of the HDH system and help to establish thresholds for pit wall Trigger Action Response Plans (TARPs). These triggers may include specific reductions in hydraulic heads recorded at the VWPs installed behind the pit wall, reductions in groundwater flow rates reporting to the portion of the pit wall where the HDHs are installed, and reductions in the extent of the seepage face observed near the HDHs. The example shown in Figure 15, where slope displacement rates are inversely proportional to pore pressures in the pit wall which are in turn reduced by the cumulative flow out of the HDHs in the area of instability, could be used as a guide to develop a TARP.

6.4. Design Tools

Several tools commonly applied in hydrogeological engineering can be used to aid the design of a successful HDH system. These tools range from simple analytical models for well hydraulics, across a spectrum of 2D and quasi-3D saturated or variably-saturated models, up to complex 3D models on pit wall or site-wide scales, with the latter not used directly for HDH system design but instead providing input for the local-scale analyses. Depending on the amount of available data, previous hydrogeological analyses, and stage of HDH implementation, it is prudent to select the tool that is most appropriate to advance the HDH system design without oversimplifying or excessively complicating the analysis.

It is also advisable to advance the analysis supporting the HDH system design gradually and introduce additional complexity once further site data are collected and only if such data warrants deployment of more sophisticated models (NGWA 2017a, 2017b). Lastly, a phased approach to HDH implementation combined with progressively more complex analysis that benefits from data collected during each phase of HDHs installation often results in the most robust HDH system.

The following is brief overview of hydrogeological analysis tools available to support the HDH system design, and their advantages and limitations:

- Analytical Models
    - Commonly based on the adaptation of analytical solutions for well hydraulics for steady state (Thiem, 1906) or transient (Theis, 1935) conditions, or for inflow to a tunnel (Goodman, 1965). The well hydraulics solutions can be used for predictions of HDH discharge given a known head reduction target or, by rearrangement, the head reduction target given a known discharge.
    - Most applicable to settings where the EPM assumption is valid, where the rock mass properties are relatively homogeneous and where the rock mass can be treated as a confined system.
    - Also applicable in settings where a distinct higher-permeability and tabular structure (e.g., a permeable fault) behind the pit wall requires depressurization.
    - Limited to the assessment of a single HDH or a small group of HDHs (via principle of superposition), with the analysis results later upscaled for the entire system.
    - Limited in representation of hydrogeological boundaries that may affect HDH performance, including surface water features located near the pit wall crest, proximal water table, and zones of relatively low hydraulic conductivity in the rock mass.
    - Limited ability to calibrate the model to site-wide hydrogeological observations.
    - Relatively easy to implement but requires significant experience and good judgment when used. Well suited for fast, scoping level analysis.
- 2D Cross-sectional Models
    - Often developed along cross sections used for slope stability analyses using SeepW (GeoSlope, 2021), FEFLOW (Diersch, 2015), or MODFLOW (Harbaugh, 2005; Panday et al., 2013)
    - Applicable in settings where an EPM or hybrid-EPM approach is valid, where the rock mass is heterogenous along the section but heterogeneity remains similar along nearby sections, and where hydrogeological boundaries are linear and generally parallel to the pit wall crest
    - Capable of simulating HDH lines installed from individual benches, but not individual HDHs or their spacing, and not capable to forecast hydraulic heads between HDHs installed on the same bench (i.e., no ability to simulate radial flow)
    - Model calibration possible but limited to hydraulic head and seepage data collected along the cross-section
    - Easy to moderate effort to implement, well suited for initial phases of HDH program implementation.
- Quasi-3D Models
    - Often developed by expanding the existing 2D cross-sectional model in the third-dimension perpendicular to the cross-section line, a process that is streamlined in FEFLOW but can also be accomplished in other groundwater modelling codes such as MODFLOW

  - Similar advantages and limitations as the 2D cross-section models but can account for radial flow between individual HDHs thus allowing estimates of their spacing along each bench
  - Moderate effort to implement, well suited for initial phases of HDH program implementation.

- 3D Pit Wall Scale Models
  - Commonly developed for the area immediately around the pit or, if hydrogeological conditions allow, for the sector(s) of the pit wall that requires depressurization
  - A variety of numerical codes available for model development including, among others, MODFLOW (Harbaugh, 2005; Panday et al., 2013), FEFLOW (Diersch, 2015), HydroGeoSphere (Aquanty, 2021) if the EPM or hybrid-EPM modelling approach can be adopted, or FRACMAN (Dershowitz, 2014) or HydroGeoSphere if a DFN approach is required
  - Can adequately represent rock mass heterogeneity and hydrogeological boundaries that are close to the pit wall crest
  - Can be calibrated to hydrogeological observations collected in the vicinity of the pit walls
  - Limited ability to account for hydrogeological inputs/stresses originating at greater distances away from the pit wall crest
  - Requires application of specialized boundary conditions (e.g., discrete feature elements available in FEFLOW) to adequately represent HDHs
  - Moderate to high effort to implement, well suited for advanced phases of HDH program implementation.

- 3D Site-Wide Models with Refinement
  - Commonly developed for the mine site and the surrounding areas as part of earlier studies, with numerical grid/mesh refined along the pit walls of interest to support HDH analyses
  - Typically adopt EPM or hybrid-EPM approach and are developed using MODFLOW (Harbaugh, 2005; Panday et al., 2013), FEFLOW (Diersch, 2015), or HydroGeoSphere (Aquanty, 2021) among others
  - Have similar capabilities as the pit-scale models, but benefit from hydrogeological data and calibration targets collected both near and away from the pit walls
  - Can account for changes in hydrogeological conditions behind the pit wall due to expansion of other mine facilities (e.g., tailings storage facility, water storage ponds, other pits, diversions) throughout the mine life, at mine sites where these effects are significant
  - Benefit from the effort previously expanded on constructing and calibrating the model
  - Requires application of specialized boundary conditions (e.g., discrete feature elements available in FEFLOW) to adequately represent HDHs
  - High effort to implement, at times numerically cumbersome. Well suited for advanced phases of HDH program implementation.

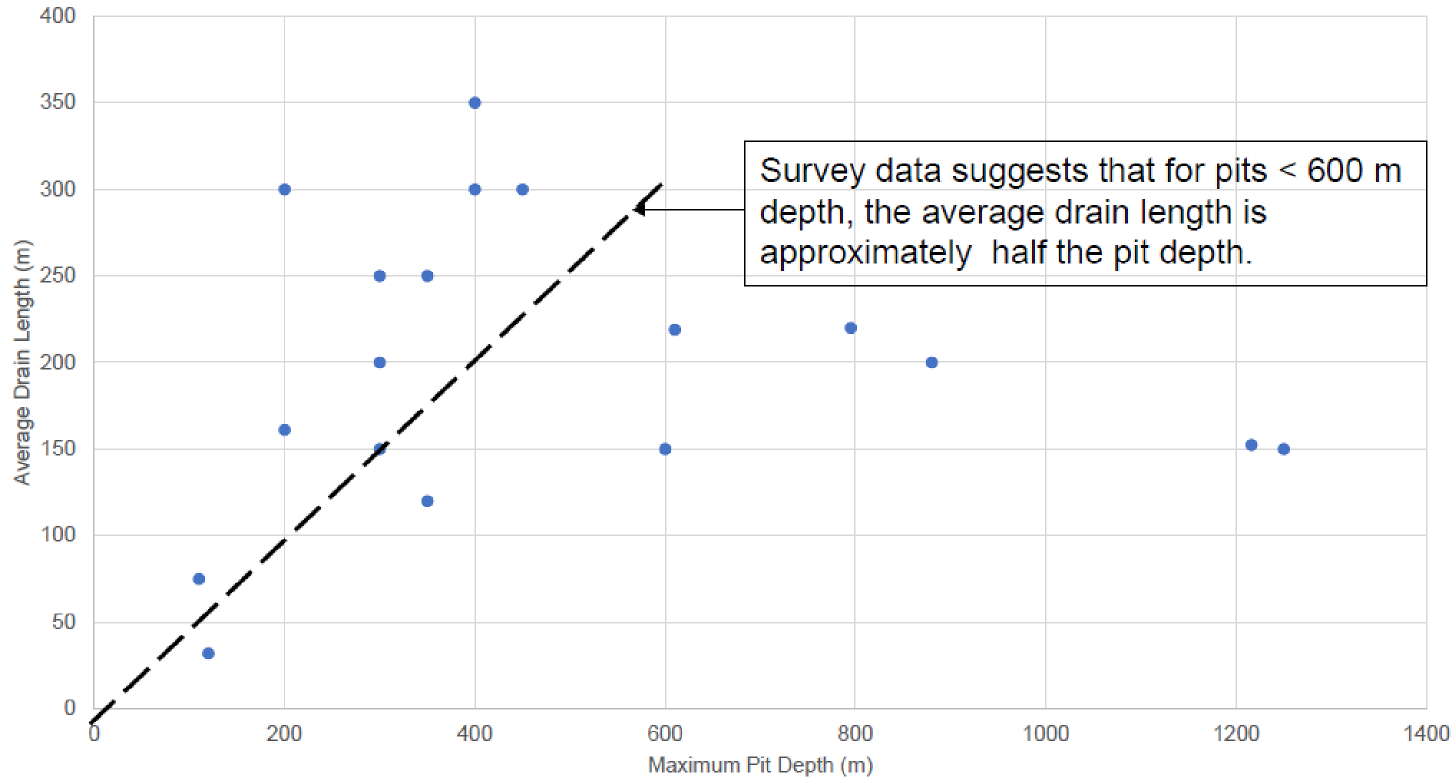
6.5. Implementation Considerations

Designing an HDH program prior to mining an open pit is generally more challenging than designing one for a pushback or pit expansion that has the benefit of previous experience regarding the controls of groundwater distribution and how efficiently it was withdrawn from the pit slopes. In spite of these limitations for greenfield or early-stage mining projects, it is prudent in the early stages of design to assume that some level of additional localized slope depressurization, in conjunction with well installations outside of the open pit, will be required. Survey respondents indicated that implementation of an HDH program is rarely guided by numerical modeling. However, the survey results did suggest that, as a rule of thumb, the average length of HDHs installed could reasonably be assumed to be approximately half the depth of the proposed pit for pits less than about 600 m deep (Figure 18). Another rule of thumb, based on unpublished modeling studies by BGC, is that the HDHs should be twice as long as the desired degree of depressurization behind the pit slope face. This is primarily applicable to pre-feasibility and feasibility level studies where saturated pit slope conditions are typically initially assumed. If the DAC for the stability of the slope cannot be achieved then anticipated phreatic surfaces from an HDH drilling program are projected various distances behind the pit wall (up to about 150 m) until the DAC are met.

Required lateral and vertical spacings of the drain holes, however, are not as easily assumed and are better defined by modeling. Most mining projects will have had at least one and possibly several pumping tests carried out as part of feasibility level and detailed designs. These tests can be used to assist with dewatering and depressurization requirements, to estimate how many wells need to be installed in each hydrogeologic unit to keep the pit slopes depressurized and the mining area dry, as well as the time required to achieve this target. The pumping test results (or in low-permeability settings where flow-recession and packer tests results are available) can also be used to estimate the number of horizontal drains required to “mop up” groundwater that the ex-pit or in-pit wells may not be able to capture. To support the dewatering and depressurization strategy and refine the number and location of wells and HDHs in the pit footprint, it is of vital importance to install piezometers in advance of installing the wells and HDHs to monitor changes to the phreatic surface due to pumping, mining and seasonal effects. The piezometer responses will also be needed to ascertain the hydrogeological properties of the depressurization targets.

Pore pressure monitoring data are generally most efficiently carried out with either dataloggers or telemetry systems and are more likely to provide confidence regarding the performance and efficiency of the HDHs if the decrease in pressure head can be shown to correspond with the installation of the HDHs. Piezometer data can also be used to confirm pore pressures which may have been assumed in slope stability models and compared with targets set out to confirm the DAC required for the pit slopes at selected phases of the open pit development.

08-2023



NOTES:
1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.
2. Data is from survey results, including response from operations and literature review case studies.

PREPARED BY: SP	FIGURE TITLE: SURVEY RESULTS – MAXIMUM PIT DEPTH BY AVERAGE DRAIN LENGTH			
CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT			
APPROVED BY: TC	SCALE: AS SHOWN	PROJECT NO: 2236001	FIGURE NO: 18	

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 18. Survey results – maximum pit depth by average drain length.

As discussed in Section 4.3, sequencing the HDHs with operations and integrating the drain hole installations with mine planning is critical to the success of a program, and is often identified as the biggest impediment to using HDHs. Successful implementation of HDHs requires that areas where they could be installed with minimal disruption to operations, periods where mining may be paused and/or equipment is moved to other areas, and areas where sufficient working platforms exist to collect the outflows need to be identified and worked into the slope depressurization planning process.

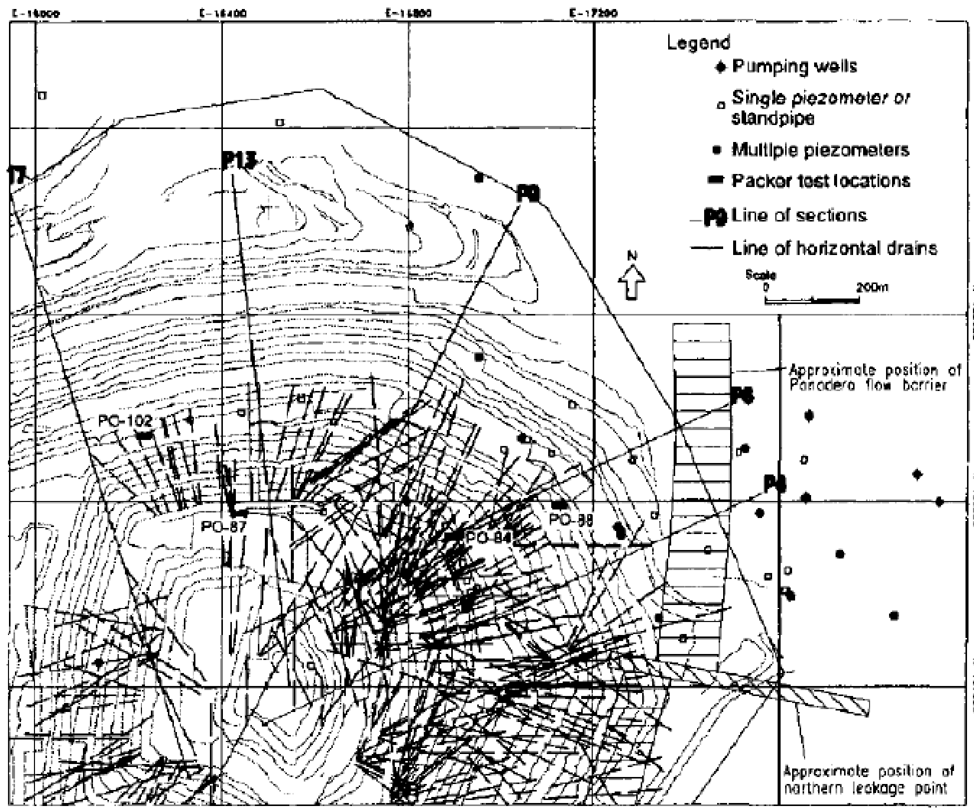
There are relatively few options available for the layout of HDHs; essentially consisting of linear or fan configurations, or a combination of both (Figure 4). Most operations use a combination of linear and fan configurations, with the linear holes generally drilled perpendicular to the bench face and the fanned holes drilled at a range of angles depending on the extent of the area to be depressurized, the depth of the holes and the conditions of the rock face (Figure 19; McKelvey et al., 2002). Fan configurations have the advantage of being able to drill several HDHs from the same location, thus reducing the amount of drill pad preparation work. They are also useful when trying to intercept numerous geologic structures or focusing on high permeability rock units daylighting in the pit slope. Fan configurations are efficient when collecting the water into a header, as less discharge pipe is required to bring the flows into the groundwater collection system (Figure 20; Leech & McGann, 2008). HDH fans typically average three holes (with a range of two to five) but up to 15 holes have reportedly been drilled from one pad.

In situations where an adit or drainage gallery behind the open pit slope is available to drill HDHs from, a high degree of flexibility is provided as the drain holes can be drilled at an even greater number of angles (into the slope and towards the pit face) as well as into the roof of the adit (Figure 21; Dowling et al., 2011). The adit can also serve as a water collector, if it is inclined, allowing access during mining and greater flexibility if additional drain holes are required later in the mine life. Another advantage of drilling HDHs from an adit is that they remain accessible year-round, as the drain hole collars are not generally affected by freezing temperatures.

6.6. Installation Details

Hole diameters for HDHs can range from 7.5 cm to 20 cm, with the most commonly reported diameters between 10 and 14 cm (Figure 22). Most installations are lined with perforated PVC pipe and attached to a solid discharge pipe at the pit face to reduce the amount of leakage. Hole liners are not used at some operations; however, this practice is only appropriate in competent rock where the potential to lose groundwater collected deeper in the holes is less likely to occur. Casing at the pit face is typically grouted in at the collar although packers are occasionally installed in lieu of grout. Depth of casing installations range from 1.5 m to 12 m; however, the depth of fracturing/disturbance due to blasting should be considered when choosing the casing depth. Greater casing depths generally allow HDH lengths to be maximized, prevent collapse in blast damaged zone closest to the bench face, and prevent introduction of water draining from deeper in the slope to the more permeable overbreak zone near the face. Shallower casing depths would be appropriate for pit walls where controlled blasting is being carried out.

08-2023



NOTES:				
1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023. 2. Figure from McKelvey et al. (2002).	PREPARED BY: SP	FIGURE TITLE: EXAMPLE OF AN HDH LAYOUT		
	CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT		
	APPROVED BY: TC	SCALE: AS SHOWN	PROJECT NO: 2236001	FIGURE NO: 19

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 19. Example of an HDH layout.

08-2023

NOTES:
1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.
2. Image from Leech & McGann (2008).

PREPARED BY: SP	FIGURE TITLE: EXAMPLE OF HIGH FLOWS OUT OF A FAN CONFIGURATION		
CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT		
APPROVED BY: TC	SCALE: N/A	PROJECT NO: 2236001	FIGURE NO: 20

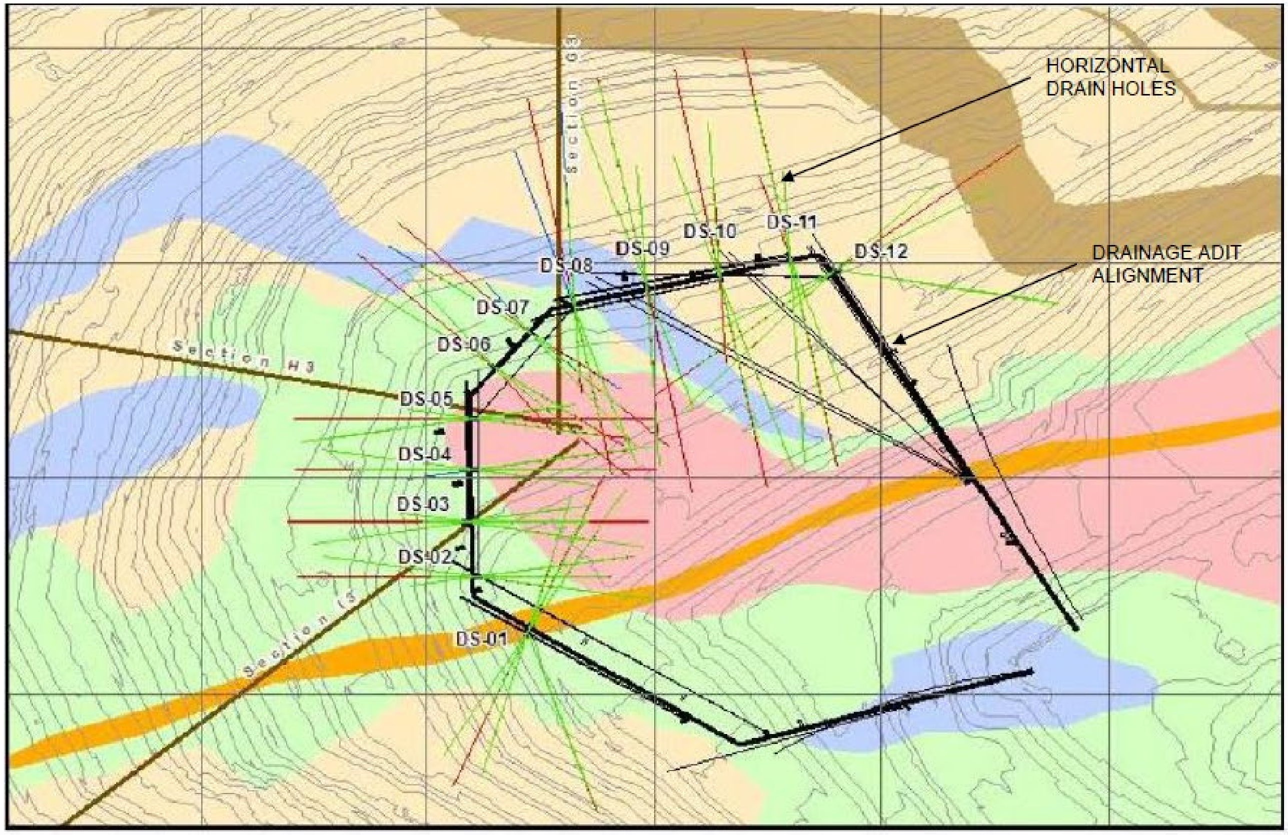
0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 20. Example of high flows out of a fan configuration.

BGC ENGINEERING INC.

08-2023



NOTES:
1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.
2. Figure from Dowling et al. (2011).

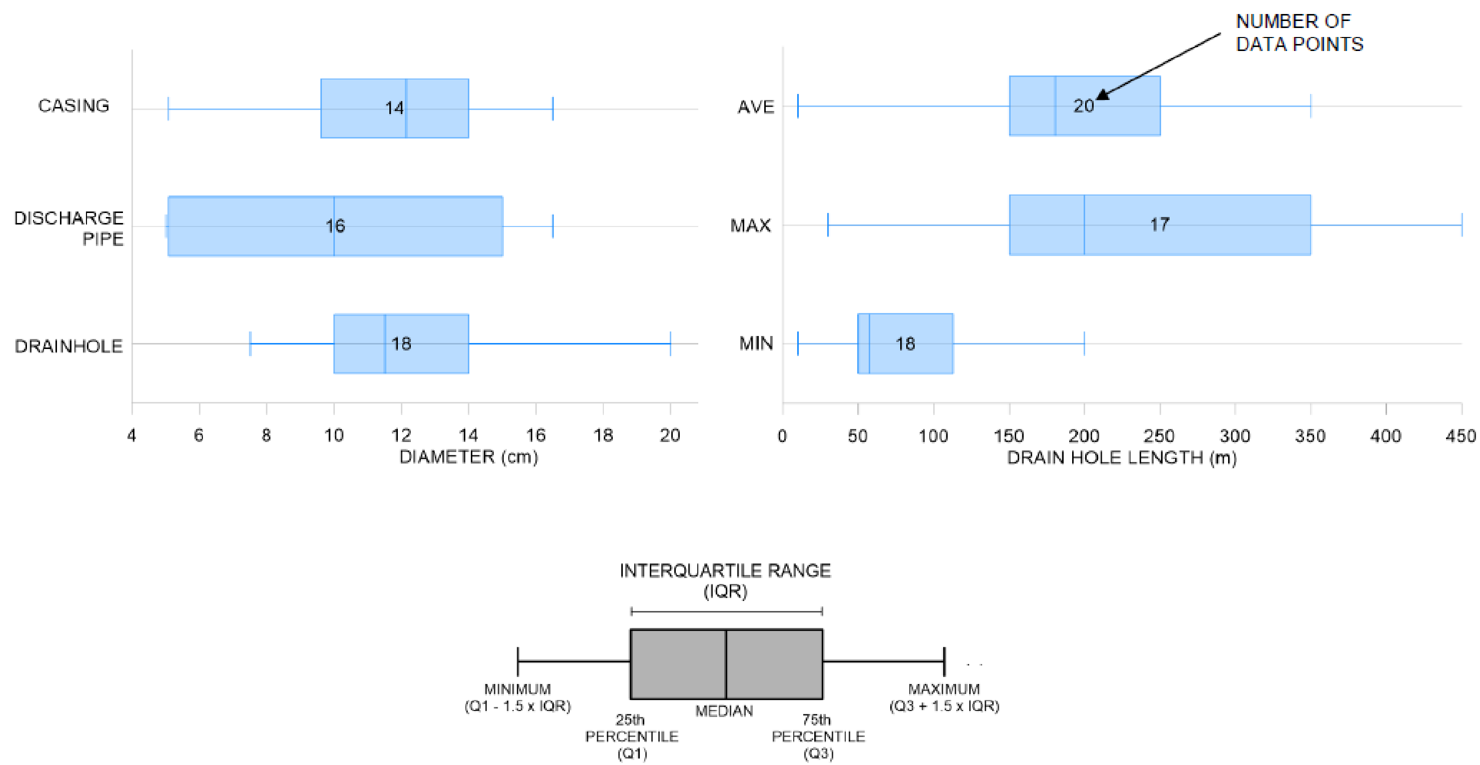
PREPARED BY: SP	FIGURE TITLE: EXAMPLE LAYOUT OF HDH FROM AN ADIT OR DRAINAGE GALLERY			
CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT			
APPROVED BY: TC	SCALE: AS SHOWN	PROJECT NO: 2236001	FIGURE NO: 21	

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 21. Example layout of HDH from an adit or drainage gallery

08-2023



NOTES:
1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.
2. Data is from survey results, including response from operations and literature review case studies.

PREPARED BY: SP	FIGURE TITLE: SURVEY RESULTS – HDH INSTALLATION SPECIFICATIONS			
CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT			
APPROVED BY: TC	SCALE: AS SHOWN	PROJECT NO: 2236001	FIGURE NO: 22	

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 22. Survey results – HDH installation specifications.

HDH lengths of up to 450 m have been reported; however, maximum lengths for the operations which responded to the survey ranged from 150 to 350 m (Figure 22). Average drain hole lengths of the survey respondents ranged from 150 – 250 m and minimum drain hole lengths ranged from 50 to 120 m. The length of hole will be affected by the targets, the depth of the pit, and historical HDH yields. Drain hole yields are generally prone to decline with depth and increasing confining stress.

HDH inclination angles can range from between -10° to +15° but were most commonly reported in the +5° range. Upward dips are advantageous to assist the hole in "self-cleaning" but downward dips are occasionally used to intersect specific targets and have the advantage of being easier to grout if the HDHs exhibit low yields and are subsequently converted into piezometers, a common practice at some mining operations.

The survey responses indicated that hole deviation surveys are not typically conducted; however, periodic surveys should be considered as they are useful for more accurate location in 3D and thus provide greater confidence when trying to define water bearing units and/or geologic structure intersections and can be used to more accurately update the geotechnical and hydrogeologic model. Depending on the type of drill used, HDHs that start out with a positive (upward) inclination may end up with a negative inclination and completely miss intended targets at greater distances behind the pit slope.

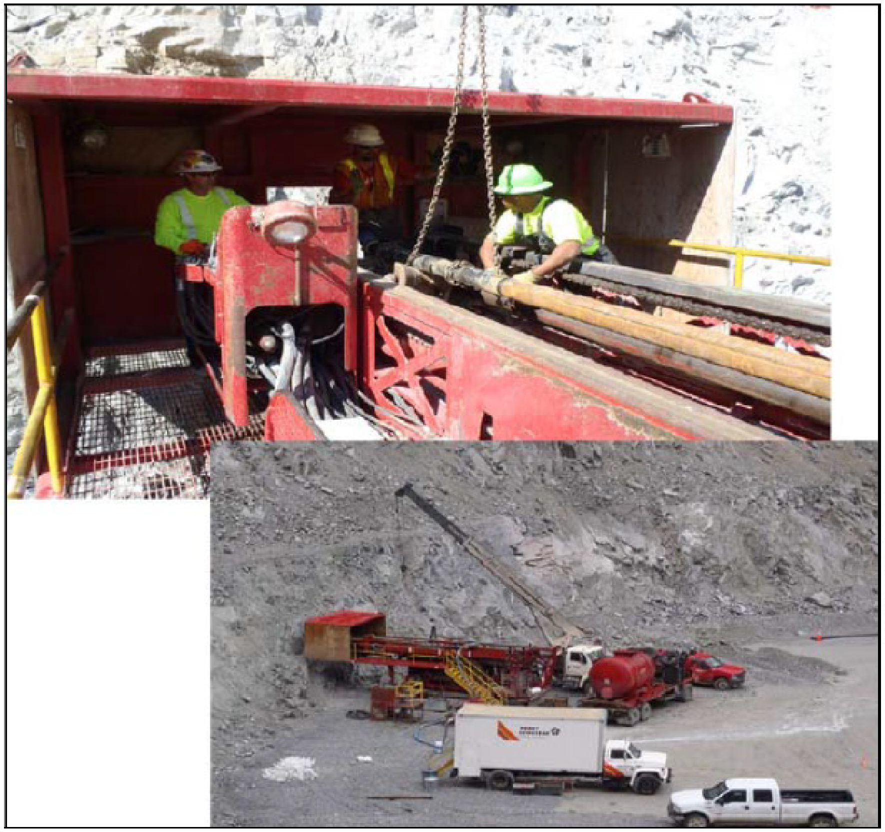
6.7. Equipment Considerations

Survey respondents indicated that the preferred drilling methods were predominantly: percussion-style drilling (7), mud rotary (6) and reverse circulation (4). Some operations indicated that they have adapted their underground drill rigs to install HDHs, while others responded that they use "horizontal drill rigs" (no further specifications provided); however, there are numerous specialized drill rigs developed by rock slope stabilization contractors to respond to the needs of mines in North America and likely similar rigs in other jurisdictions.

Rock fall protection is required where drill rigs are manually operated to shield personnel from upslope hazards (Figure 23). This potential hazard can be avoided by using remote control drills (Figure 24). Typically, remote drills work well for adding rods during drilling; however, cementing the surface casing and connecting the discharge hoses to headers still requires workers to be close to the bench face, in which case some form of rock fall protection will be required.

In addition to experienced drilling personnel and well-maintained equipment, a successful program requires that the cuttings generated during the drilling process are removed. This is generally dependent on the air compressor used; air flow rates of up to 1200 cubic feet per minute (cfm) are typically required, with air pressures reaching up to 1000 psi.

08-2023



NOTES:

1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.
2. Image from Dowling et al. (2011).

PREPARED BY: SP	FIGURE TITLE: TYPICAL CONFIGURATION OF HDH DRILLING EQUIPMENT		
CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT		
APPROVED BY: TC	SCALE: N/A	PROJECT NO: 2236001	FIGURE NO: 23

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 23. Typical configuration of HDH drilling equipment.

BGC ENGINEERING INC.

08-2023

NOTES:
1. This figure should be read in conjunction with BGC's report titled "Horizontal Drain Hole Guidelines – FINAL" and dated August 2023.
2. Image from Leech & McGann (2008).

PREPARED BY: SP	FIGURE TITLE: EXAMPLE OF REMOTE CONTROL HDH DRILLING EQUIPMENT			
CHECKED BY: HWN	CLIENT: LARGE OPEN PIT PROJECT			
APPROVED BY: TC	SCALE: N/A	PROJECT NO: 2236001	FIGURE NO: 24	

0 5 10 mm in ANSI A sized paper

BGC ENGINEERING INC.

Figure 24. Example of remote control HDH drilling equipment.

Room for support trucks should be considered when allocating space for the HDH drilling rig. If the working area below the bench face is wet the drill pad may need to be elevated to keep the area dry. Alternatively, culverts may be installed to convey water away from the working area.

A potential development in depressurization of slopes is the advancement of directional drilling technology. Directional drilling has the advantage of locating the collar of the drain hole outside of the area influenced by mining and developing multiple drainage conduits from one location. Although this drilling technique has not been extensively used in mining, it appears that the cost of directional drilling is becoming competitive with conventional HDH drilling methods.

6.8. Typical Costs

Estimating the cost to carry out a HDH program requires consideration of the location of the mine (i.e., mobilization costs), the types of drilling rigs and materials available in the region, the cost of labour and the average hole length which has an impact on the size and number of compressors required. The survey results (13 respondents) indicate that the total costs of an annual HDH program ranged from a minimum of $250,000 USD to a maximum of $4,000,000, averaging approximately $1,400,000. This works out to between about 40 and 50% of the total depressurization budget of the mines that responded. The approximate cost per meter of HDH installations (10 respondents) ranged from a minimum of $44/m to a maximum of $600/m, averaging approximately $220/m.

7.0 SELECTED CASE HISTORIES

7.1. Batu Hijau, Sumbawa, Indonesia

Batu Hijau is an open pit copper gold deposit located on the Indonesian island of Sumbawa. The deposit's country rock consists of andesite volcanics, volcaniclastic sediments and porphyritic andesite, intruded by quartz diorite in the northeastern region, the contacts of which were intruded by tonalite porphyries resulting in mineralization. Part of the mineralization process resulted in extensive hydrothermal alteration (Leech & McGann, 2008). Two major fault zones intersect three kilometers northwest of the deposit center, with discrete faults transecting the open pit at a spacing of 50 m, and a less persistent orthogonal fault set. Due to the low grade, high tonnage and a relatively short mine life of 27 years, maximizing open pit slope angles and minimizing costs have significant economic impact. The concentric shape of the orebody means that mine sequencing and pit access are relatively inflexible; instabilities in the pit cannot be left exposed, and any redesign must allow operations to continue.

The deposit itself is relatively low in geographical elevation (mining takes place below sea level); however, steep groundwater gradients in the area suggest that the formation permeability is low, and in the range of $1x10^{-6}$ to $1x10^{-8}$ m/s. The annual rainfall in the region can accumulate to approximately 2,500 mm over the wet season (May to September), typically occurring in intense short-duration events (Leech & McGann, 2008). Rainfall primarily drives recharge into the pit following preferential flow paths, however, the influence of transecting fault networks on groundwater flows is not well understood. Hydrogeological characterization of the area suggests the deposit porosity ranges between 0.1% and 0.5%, with lower permeability due to weathering in the upper 100 to 150 m of the deposit. Faults in the southern sector of the pit typically act as barriers to local groundwater, although the permeability along one of the major regional fault zones is enhanced.

Batu Hijau's dewatering program requires continuous maintenance of a large dewatering sump in the pit bottom to control and remove surface water runoff from rainfall and groundwater inflows. A system of floating sump pumps keeps the open pit dry by conveying water through HDPE pipelines along haul roads, with average pumping peaks of 40,000 m^3/day during the wet season. In-pit wells were trialed but were deemed impractical due to the high vertical mining advance rate. Sump pumping has been effective at controlling surface inflows, resulting in a reduction in near-pit groundwater levels of approximately 450 m; however, there has been little impact on regional groundwater levels.

The Batu Hijau open pit was designed using a criteria philosophy that encouraged a "more is better" approach to depressurization, as acceptable levels of slope depressurization were somewhat difficult to quantify (Leech & McGann, 2008). As a result, developing, updating and improving a reliable hydrogeological model has been a focus at Batu Hijau, to help with predictions in depressurization.

An initial small-scale trial of horizontal drains indicated that horizontal drains had little impact to improving the natural rate of depressurization due to the rapid advancement of the open pit. HDHs were trialed again in response to a slope failure that was driven by groundwater pressure; 1,500 m of drains were drilled into the slope, following the installation of three standpipe piezometers designed to monitor the effectiveness of the HDHs. The success of this trial resulted in the implementation of a HDH program totaling 98,000 m over the span of two years.

Drain holes were typically inclined at 5° above horizontal, drilled with a conventional open hole hammer at 200 mm diameter to a length of 5.5 m, set with 150 mm PVC surface casing, drilled at 150 mm diameter to a length of 350 m and lined with 40 mm Schedule 80 blank and machine slotted production liner. Configurations of HDHs included both single drains installed perpendicular to slope, and fan configurations of four to six drains at a single location to optimize the interaction and reduce interference with mine operations, as well as minimize contractor exposure to hazards. The average cost per meter of horizontal drain construction for the program was approximately $44 USD/m.

The HDH program focused on areas where historical slope instability was prevalent. In some instances, drains yielded little flow, which led to an initial interpretation of low rock mass permeability. As a result, additional drains were installed in closely-spaced configurations in an attempt to increase depressurization, with no improvement observed. This misinterpretation was caused by a lack of monitoring infrastructure and data to properly assess the effectiveness of the drains. To address this, a series of nested vibrating wire piezometers were installed across the pit using the grout tremie method, and VWP sensors were occasionally installed in horizontal drains.

With the introduction of VWP monitoring data, the hydrogeological model indicated that a portion of the HDHs that yielded little to no flow in the first trial program had, in fact, been collared above observed groundwater heads. The introduction of VWP data at the design stage allowed subsequent HDHs to be better targeted, in some cases ultimately yielding flows up to 20 liters per second (Leech & McGann, 2008).

Experience at Batu Hijau indicates that developing geotechnical and hydrogeological models in the pre-mining stages is critical in the development of a mining operation, however, maintaining, updating and re-integrating a model with new and more reliable data is of utmost importance as an open pit is developed. Batu Hijau's experience in depressurization not only highlights the effectiveness of HDHs in an economically driven and hydrogeologically complex deposit, but also emphasizes the positive benefits of installing monitoring infrastructure in advance to measure the effectiveness of a depressurization program.

7.2. Ok Tedi, Western Province, Papua New Guinea

The Ok Tedi Open Pit Mine is an open pit copper, gold and silver mine located in the Western Province of Papua New Guinea. The geology of the Ok Tedi deposit consists of siltstones and limestone with monzonite porphyry intrusions forming the ore body (de Bruyn et al., 2011). Skarns formed on the fringe of the intrusive bodies are the target for mining operations. The deposit is situated in a seismically active, mountainous region where the average annual rainfall ranges between 8,000 and 10,000 mm and is relatively evenly distributed throughout the year (Muller et al., 2011).

A pushback of the West Wall was being considered to deepen the pit. The West Wall is transected by two major thrust fault zones, which contain highly altered fault gouge and breccias typically surrounded by a 20 to 30 m thick fractured zone, and in some places reaching up to 80 m. A steeply dipping major fault also intersects the West Wall, with an associated fracture zone of brecciated siltstone and highly fractured limestone (de Bruyn et al., 2011). Sinkholes (karst voids) have periodically been uncovered during mining activity. These contrasting conditions with the host rock result in variable material permeabilities. Pore pressure distribution, the varying quality of materials and locations of major fault structures significantly impact the stability of the West Wall.

Over the course of 30 years, numerous exploration, geotechnical and dewatering boreholes were drilled, forming an extensive database; however, only a limited number were being used to monitor the hydrogeological environment in and around the open pit. To better understand the hydrogeological conditions within the pit and the impact of a proposed cutback of the West Wall, 15 additional boreholes were drilled for hydrogeological monitoring. This included fully cemented nested vibrating wire piezometers, and completion of more than 30 packer tests in numerous boreholes to estimate hydraulic conductivity (Muller et al., 2011).

A phased numerical modeling approach was devised to assess the stability of the West Wall design, and to investigate depressurization requirements for maintaining stability. Two initial slope stability analyses were run using small-strain finite element software Phase^2 to determine the approximate groundwater pressure distribution required to maintain an adequate FOS. The analyses indicated that the piezometric surface needed to be pushed back between 150 and 200 m behind the pit wall to achieve the desired FOS (Muller et al., 2011). Two-dimensional (2D) and three-dimensional (3D) modeling was then completed in FEFLOW to analyze various drain hole configurations which would achieve the target groundwater pressure distribution. This phase included consideration of mining constraints such as schedule and timing. The last phase of modeling re-introduced the results from FEFLOW to the initial slope stability modeling in Phase^2 to confirm results. Quasi-3D modeling in FEFLOW was used to assess the lateral spacing requirements for drain hole design (de Bruyn et al., 2011).

It was found through iterative modeling that a drain hole length of 300 m, horizontal spacing of 30 m and vertical spacing of 120 m (in model space) would achieve the desired piezometric surface pushback of 150 to 200 m. Results from the iterative process ultimately formed the most suitable inputs for the final distinct element modeling of the West Wall and helped inform the early understanding and feasibility of the potential pit slope depressurization requirements (de Bruyn et al., 2011).

Although there are no further details on this case study since it was published, this case history example from Ok Tedi is useful due to the approach that was taken. Iterative numerical modeling using geotechnical and hydrogeological data input was conducted during the design stage to develop a phased mining and depressurization sequence to maintain adequate stability of the West Wall pushback.

7.3. Confidential Project – North America

An open pit copper porphyry deposit is situated in Western Canada, where the average monthly temperature ranges from -30 to 25 degrees, and the average annual rainfall observed is approximately 200 mm. Water management practice includes the use of unlined ditches and sumps to collect surface water. Vertical dewatering wells and HDHs are installed as part of the mine's depressurization program for the two pits in operation. The site has a detailed site-wide water balance model and a numerical groundwater model to predict pore pressures within the walls of the two existing pits and a third proposed pit. The existing pits, which reach depths of up to 350 m, are subject to runoff inflows, and the site is located within a groundwater recharge zone. Sumps and surface water diversion measures are constructed in key areas to minimize infiltration.

HDHs are used at this mine in response to slope stability issues and to meet design slope depressurization targets. Approximately 60% of the slopes in the open pits are depressurized by HDHs. The hydraulic conductivity of bedrock is about $3x10^{-8}$ m/s and is controlled by discontinuities in the rock mass, fracture frequency, fracture aperture, and degree and type of infilling materials. Major geological structures are the main cause of slope deformations therefore groundwater behind major geological structures and within specific geological units are the primary target for HDHs.

Horizontal drains are generally drilled at angles of 4-5° upward from horizontal, with an average length of 120 m. Approximately 25 holes are drilled annually both in an individual linear configuration or in fans of three holes to minimize disruptions to mine operations. Depressurization work is completed quarterly, with multiple targeted areas depressurized by HDHs. Structural data are used to orient the HDHs. HDH drilling is stopped once the designed target depth is reached, rather than a target flow rate. A typical drain hole is 100 mm in diameter, completed with a 6 m long collar casing for hole stabilization. The hole is left open below the collar. The approximate annual cost of the HDH program each year is $465,000 USD, which works out to about $155/m.

The effectiveness of horizontal drains is assessed by the response from various VWPs installed around the pit area, a decrease of slope deformation rates, and the measured flow response from the drains themselves. Flow is typically measured manually during drilling of the drains, after the drain is completed and for several weeks following completion. However, since the target areas are instabilities they typically become ineffective when they become sheared off due to slope movements. Overall, the HDH program is considered successful with "the rate of slope displacements changing drastically immediately after HDH implementation".

7.4. Confidential Project – Asia

An open pit copper porphyry deposit is situated in the arid climate of the Indo-Pacific region, where average monthly temperature ranging from -30 to 40 degrees, and average annual rainfall of about 80 mm. An adjacent river acts as a source of seasonal recharge for the open pit operation. Water management practice includes the use of unlined ditches and sumps to collect surface water, and HDHs are installed as part of their depressurization program. Numerous data sources are used to inform and calibrate a 3D, pit-scale hydrogeologic model; hydrogeological testing within boreholes (i.e., slug tests, packer tests, pumping tests), seepage monitoring and groundwater monitoring well data. Pore pressure models have been developed in support of geotechnical assessments and the models are calibrated using the hydrogeological testing results. The hydrogeologic model is updated on an annual basis as new data become available, including observed flow data and VWP data, and it is maintained by an external consultant.

HDHs were introduced when other methods of depressurization were deemed unsuccessful. The HDHs help manage nuisance water and reduce the water content of mined material, resulting in an overall improvement of mining conditions. The biggest advantage of using HDHs at this operation is that they are a passive drainage method with no power requirement; however, mine plan constraints and operational interruptions occasionally still limit their use. The HDH program was also developed to reduce pore pressures in areas within the pits where historic instabilities have been identified. As a result, HDHs are typically installed on specific wall orientations and target pore pressures in major geologic and water bearing structures within specific rock mass units. The maximum planned pit depth is approximately 800 m.

Approximately 45 HDHs are drilled annually at an angle of 10 degrees upward from horizontal and between 75 and 350 m in length, with an average drain hole length of 220 m. The drains are installed at specific elevations, with a horizontal spacing of 175 m and vertical spacing of 45 m. They are drilled in a fan configuration to reduce disruptions to mine operations, with three drain holes and typically one VWP installed per fan. A typical drain hole is 115 mm in diameter, completed with collar casing for hole stabilization and slotted casing for the remainder of the hole. Groundwater collected by the HDHs is conveyed away in piping manifolds to lower levels.

The effectiveness of horizontal drains is assessed by the response from various VWPs installed around the pit area, as well as the measured flow response from the drains themselves. Flow is typically measured manually during and immediately after drilling of the drains, and for about 2 to 3 weeks following completion.

Despite using piezometric response data to check the effectiveness of horizontal drain installations, the site does not have specific criteria to validate the response. They use a feedback loop of performance indication criteria based on either the piezometer response or drain hole flow response to confirm the efficacy of a horizontal drain program.

8.0 VALIDATION

8.1. Monitoring

The efficacy of an HDH program to depressurize a pit slope can be assessed by reviewing piezometric data from the rock mass behind the pit face, flow data from the HDHs, and in some situations the performance of the pit slope (Figure 15). Upon initial completion of an HDH, instantaneous flow can be estimated using a rudimentary method (i.e., graduated bucket and stopwatch) to provide a baseline for initial flow and for comparison to transient changes in flow. Following completion of each HDH, shut-in pore pressures should also be monitored using a pressure transducer to assess the initial pore pressure conditions prior to depressurizing. Following initial manual flow and pressure monitoring, water produced from individual HDHs should be monitored and recorded using totalizing flow gauges to allow a better understanding of transient or seasonal changes to flow.

Horizontal drain holes that do not appear to produce initial flows should be recorded and used to guide the locations and orientations of future HDHs. Lack of flow from an HDH does not necessarily indicate lack of pore pressure along the length of the HDH, and so pore pressure monitoring should be considered with the use of piezometers. Piezometers could include vibrating wire piezometers (VWPs) and/or Casagrande standpipe piezometers and can be installed as nests of two or more to assess the variability in pore pressure along the length of the HDH. Nested piezometers allow for monitoring changes in pore pressure due to changes in elevation or across identified discontinuities. Data loggers should be used to record piezometer pore pressure readings to assess temporal changes and infer the impact of an HDH program on targeted pore pressure elevations, if specified.

8.2. Tools for Analysis, Interpretation and Presentation of Data

Pore pressure data from piezometers and flow data from HDHs and other dewatering and depressurization measures (if applicable) should be monitored to support the analysis and interpretation of the effectiveness of those measures. To appropriately analyze and project these data into the future, the geospatial distribution and temporal data trends need to be plotted up and understood.

The distribution of pore pressure and HDH flow data can be reviewed by developing plan maps and cross-sections that present the orientation (trend and plunge) of the HDHs, the location of adjacent monitoring piezometers and their completion zones (Figure 19), the distribution of the targeted geological and hydrostratigraphic units, and the orientation and the location of important discontinuities (i.e., faults, joints, fracture zones, and structural fabric). The relationship between HDH orientation, flow rate (Figure 14 and Figure 15), and the orientation of discontinuities can be presented on rose diagrams (Figure 16). Presenting data in this fashion can indicate which HDH orientations produce the greatest flow and how this relates to specific discontinuity sets or faults intercepted by HDHs.

Changes in the phreatic surface in response to the installation of HDHs, and projection of future head elevations with respect to pore pressure targets, if applicable, can be viewed and understood with the use of time-series plots. Additional information that can aid in the interpretation of trends in piezometric head elevation data include:

- Total flow from HDHs within a particular structural domain or hydrostratigraphic unit
- Pumping records from nearby dewatering wells
- Temperature and precipitation data from local or regional climate stations
- Pit bottom and/or active bench elevation(s)
- Dates of blasting activities and associated bench elevations
- Other mine site activities that could have an impact on pore pressure conditions.

At sites that adopt a phased approach for the implementation of the HDHs, additional insight can be gained by assessing approximate Specific Capacity (SC) of individual HDHs that were installed in the initial phases of the depressurization program. The approximate value of SC is calculated for each HDH using its long-term flow rate and the drawdown necessary to support this flow. In the absence of piezometric data, the drawdown can be approximated by the length of each HDH under the assumption that a seepage face was initially present near the HDH collar and the majority of inflow reports to each HDH near its terminus. Alternativity, drawdown can be approximated by the distance from the collar to any water-conductive feature intercepted by the HDH. Calculated values of approximate SC are then plotted on the corresponding pit face and can be contoured to reveal areas where SC is high. In the latter phases of HDH implementation, these high SC zones are targeted with infill HDHs to maximize groundwater interception and associated depressurization.

9.0 CLOSURE

We trust the above satisfies your requirements at this time. Should you have any questions or comments, please do not hesitate to contact us.

Yours sincerely,

BGC ENGINEERING INC.
per:

H. Warren Newcomen, P. Eng., PE
Principal Geotechnical Engineer

Willy Zawadzki, P.Geo.
Principal Hydrogeologist

Reviewed by:

Ian Stilwell, P.Eng.
Principal Geotechnical Engineer

Trevor Crozier, P.Eng.
Principal Hydrogeologist

WN/IS/TC/mm

REFERENCES

Abrao, P.C. (1978). Open Pit Mine Slopes Drainage through horizontal boreholes. Water in Mining and Underground Works, National Association of Mining Engineers, Vol. 1, pp. 573-583. Grenada, Spain.

Aquanty. (2021). HydroGeoSphere, User's Manual. Version 2223, 209 p.

Beale, G. & Read, J. (2013). Guidelines for Evaluating Water in Pit Slope Stability. CSIRO Publishing. Australia.

Bieber, C., K. Moffitt, D.W. Chorley, W. Zawadzki, and S. Greer. 2007. Detailed evaluation of pit slope stability in fractured rock and kimberlite slope – Diavik Diamond Mine, NWT. In Proceedings of 60th Canadian Geotechnical Conference and 8th Joint CGS/IAH Groundwater Conference, Ottawa, ON.

Brawner, C.O. (1982). Control of groundwater in surface mining. Proceedings of the First International Mine Water Association. Pp. 1-16. Grenada, Spain.

Brawner, C.O., Pakalnis, R. & Balmer, J. (1982). Vacuum drainage to stabilize rock slopes on mining projects. Proceedings of the First International Mine Water Association. Pp. 372-410. Budapest, Hungary.

Brawner, C.O., & Pakalnis, R. (1984). Slope stabilization by vacuum drainage. Presented at the SME-AIME Annual Meeting Los Angeles, California, February 26-March 1, 1984. Preprint Number 84-116.

Campbell, R., Mackie, D. & Anderson, W.S. (2013). Integrated slope stability assessment in a complex geotechnical and hydrogeological setting. Australian Center for Geomechanics. Slope Stability. Pp. 555-568.

Cashman, P.M. & Preene, M. (2020). Groundwater Lowering in Construction: A Practical Guide to Dewatering.3rd Edition, CRC Press, Taylor & Francis Group. Boca Raton, Florida, USA.

Chorley, D.W., Pesendorfer, M., Zawadzki, W., Rogers, S., Beddoes, R., Greer, S. 2009. Northwest Wall – Hydrogeological Characterization – Diavik Diamond Mine, Northwest Territories, Canada. In Proceedings of the International Conference SLOPE STABILITY 2009, Santiago, Chile.

Cintolesi, C., Beale, G., Dowling, J., Kotze, J., Rowland, A. & Mansell, S. (2020). Anglo American framework for strategic dewatering plans. Australian Center for Geomechanics. Slope Stability. Pp. 1290-1304.

de Bruyn, I.A., Mylvaganam, J. & Baczynski, N.R.P. (2011). A Phased Modelling Approach to Identify Passive Drainage Requirements for Ensuring Stability of the Proposed West Wall Cutback at Ok Tedi Mine, Papua New Guinea. Proceedings of the Slope Stability Conference, International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering.

Dershowitz, W., Lee, G., Geier, J., Foxford, T., LaPointe, P., Thomas, A. (2014). FracMan version 7.4—interactive discrete feature data analysis, geometric modeling, and exploration simulation: user documentation. Golder Associates, Redmond, Wash

Diersch, H.G. (2015). FEFLOW v. 6.2 Finite Element Subsurface Flow and Transport Simulation System. DHI-WASY Institute for Water Resources Planning and System Research Ltd., Berlin, Germany.

Douglas, B., Mercer, S., Wright, S. & Barclay, D. (2009). Pit water management in a mine planning cycle, Olympic Dam case study. Australian Institute of Mining and Metallurgy. Vol. 118. Pp. 115-130.

Dowling, J., Reidel, J. & Beale, G. (2011). A review of key factors affecting mine dewatering and slope depressurization. Proceedings of the Slope Stability Conference, International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering.

Dowling, J., Beale, G., Haas, P., Kaya, B., Mak, S., Tejada, L.C., Kramer, K., Johnson, J., Zea, R.E. & Palmer, C. (2020). Development of an integrated workflow for pit slope pore pressure reconciliation. Australian Center for Geomechanics. Slope Stability. Pp. 1267-1280.

Fortin, S., Rose, N.D. and Holmes, A.T. (2011) Investigation, Design and Development of the Valley Pit Big Bear Pushback at the Teck Highland Valley Copper Mine. International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering 18-21 September 2011 Vancouver, Canada

Geo-Slope. (2021). SEEP/W for Finite Element Seepage Analysis. Geo-Slope International Ltd. Calgary, Alberta.

Golestanifar, M. & Ahangari, K. (2012). Choosing an Optimal Groundwater Lowering Technique for Open Pit Mines. International Mine Water Association. Mine Water and the Environment. Vol. 31. Pp. 192-198.

Goodman, R.E., Moye, D.G., van Schalkwyk., A., and Javandel, I. (1965). Ground water inflows during tunnel driving. Eng. Geol., 2:39-56.

Hanna, B. (2016). Groundwater Component In Mining Operation-Mining Hydrology. Presentation from Itasca International, 24 October 2016.

Harbaugh, A.W. (2005). *MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model – the Groundwater-Water Flow Process*. U.S. Geological Survey Techniques and Methods 6-A16, 253 p.

Kolpakov, V.B. & Zhdanov, S.V. (2019). Implementation of slope drainage system for optimal slope design at Anfisa open pit, Khabarovsk Territory, Russian Federation. International Mine Water Association. Mine Water: Technological and Ecological Challenges. Pp. 570-576.

Lawrence, K.P., Zawadzxki, W., Mathai, A., Randall, J., McLaren, R. (2013). Simulation of horizontal well depressurization – MODFLOW versus FEFLOW. Proceedings of GeoMontreal 2013.

Leech, S. & McGann, M. (2008). Open pit slope depressurization using horizontal drains – a case study. Proceedings of the 10th International Mine Water Association. Mine Water and the Environment. Pp. 73-76.

Lucas, D.S. & de Graaf, P.J.H. (2013). Iterative geotechnical pit slope design in a structurally complex setting: a case study from Tom Price, Western Australia. Australian Center for Geomechanics. Slope Stability. Pp. 513-526.

McKelvey, P., Beale, G., Taylor, A., Mansell, S., Mira, B., Valdivia, C. & Hitchcock, W. (2002). Depressurization of the north wall at the Escondida Copper Mine, Chile. Mine Water Hydrogeology and Geochemistry, Geological Society of London. Vol. 198. Pp. 107-119.

Muller, S., Mylvaganam, J., de Bruyn, I. & Price, J. (2011). Mine groundwater control and slope depressurization methods at Ok Tedi in one of the highest annual rainfall areas in the world. Proceedings of the International Mine Water Association. Mine Water – Managing the Challenges. Aachen, Germany. Pp. 47-52.

Newcomen, H.W., Maggs, C.S. and Shwydiuk, L. (2002). Managing pit slope displacements: Highland Valley Copper's Lornex Pit Southwest Wall. CIM Bulletin 96(1071). Pp. 43-48.

NGWA (2017a). A Decision Framework for Minimum Levels of Model Complexity, NGWA White Paper

NGWA (2017b). A Stepwise Approach to Groundwater Modeling, NGWA White Paper

Pakalnis, R. (1982). Rock slope stability and design of Granite Lake Open Pit with the application of vacuum drainage, Gibraltar Mines, McLeese Lake, BC (Master's Thesis). University of British Columbia, Vancouver, BC.

Panday, S., Langevin, C.D., Niswonger, R.G., Ibaraki, M., and Hughes, J.D. (2013). *MODFLOW-USG version 1: An unstructured grid version of MODFLOW for simulating groundwater flow and tightly coupled processes using a control volume finite-difference formulation*. U.S. Geological Survey Techniques and Methods, book 6, Chap. A45, 66 p.

Pohll, G.M., Carroll, R.W.H., Reeves., D.M., Parashar, R., Muhunthan, B., Thiyagarjah, S., Badger, T., Lowell, S. & Willoughby, K.A. (2013). Design Guidelines for Horizontal Drains used for Slope Stabilization. Washington State Department of Transportation. Washington, USA.

Reano, E., Beale, G., Dowling, J., Tejada, L.C., Lacey, M. & Hazwezwe, H. (2020). Development of a mine dewatering and pit slope depressurization review process. Australian Center for Geomechanics. Slope Stability. Pp. 1253-1266.

Reinson, J.R., D.W. Chorley, S.F. Rogers, J.V. Wozniewicz, and W. Zawadzki. 2006. Influence of highly permeable geologic structure on inflows to A154 N/S Open Pit, Diavik Diamond Mines Inc., Lac de Gras, NWT. In Proceedings of May 2006 CIM Conference and Exhibition, Vancouver, BC.Thiem, G. (1906). Hydrologishe Methode. Leipzig, Gebhardt.

Theis, C.V. (1935). The relation between the lowering of the piezometric surface and rate and duration of discharge of a well using groundwater storage. Trans. Amer. Geophys. Union 2: 519-524.

Zawadzki, W., Chorley, D., Chance, A., Scholte, J., Warnock, G. (2008). Design of Pit Wall Depressurization System – Highland Valley Copper, Logan Lake, BC. GeoEdmonton '08.

APPENDIX A
SELECTED HORIZONTAL DRAIN HOLE REFERENCES

Table A-1. Selected horizontal drain hole references

Reference	Case Study	Numerical Modeling	Novel Applications	Design Guidance / Specifications	Decision Making Process / Integration	Cost Benefit / Optimization
Abrao, P.C. (1978). Open Pit Mine Slopes Drainage through horizontal boreholes. Water in Mining and Underground Works, National Association of Mining Engineers, Vol. 1, pp. 573-583.	x					
Straskraba, V. (1979). Some Technical Aspects of Open Pit Mine Dewatering. Mine Drainage – Proceedings of the First International Mine Drainage Symposium. Pp. 481-491. San Francisco, California, USA				x		x
Brawner, C.O., Pakalnis, R. & Balmer, J. (1982). Vacuum drainage to stabilize rock slopes on mining projects. Proceedings of the First International Mine Water Association. Pp. 372-410. Budapest, Hungary.	x		x			
Brawner, C.O. (1982). Control of groundwater in surface mining. Proceedings of the First International Mine Water Association. Pp. 1-16. Grenada, Spain.				x	x	
Pakalnis, R. (1982). Rock slope stability and design of Granite Lake Open Pit with the application of vacuum drainage, Gibraltar Mines, McLeese Lake, BC (Master's Thesis). University of British Columbia, Vancouver, BC.			x			
Brawner, C.O. & Pakalnis, R. (1984). Slope stabilization by vacuum drainage. Presented at the SME-AIME Annual Meeting Los Angeles, California, Gebruary 26 - March 1, 1984. Preprint Number 84-116.			x			
Tesarik, D.R. & Kealy, C.D. (1984). Estimating Horizontal Drain Design by the Finite-Element and Finite-Difference Methods. United States Department of the Interior, Bureau of Mines.				x		
Mckelvey, P., Beale, G., Taylor, A., Mansell, S., Mira, B., Valdivia, C. & Hitchcock, W. (2002). Depressurization of the north wall at the Escondida Copper Mine, Chile. Mine Water Hydrogeology and Geochemistry, Geological Society of London. Vol. 198. Pp. 107-119.	x			x		
Rahardjo, H., Hritzuk, K.J., Leong, E.C. & Rezaur, R.B. (2003). Effectiveness of horizontal drains for slope stability. Engineering Geology. Vol. 69. Pp. 295-308.	x				x	
Price, J., Haines, A., Baidoo, I. & Varaud, O. (2006). Design considerations for the Damang Open Pit. International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering. The Southern African Institute of Mining and Metallurgy. Pp. 239-264.	x	x		x		
Cook, D.I., Santi, P.M. & Higgins, J.D. (2007). Horizontal Landslide Drain Design: State of the Art and Suggested Improvements. Environmental & Engineering Geoscience, The Geological Society of America. Vol. 14. No. 4. Pp. 241-250.				x		

Reference	Case Study	Numerical Modeling	Novel Applications	Design Guidance / Specifications	Decision Making Process / Integration	Cost Benefit / Optimization
Leech, S. & McGann, M. (2008). Open pit slope depressurization using horizontal drains – a case study. Proceedings of the 10th International Mine Water Association. Mine Water and the Environment. Pp. 73-76.	x			x		
Dadzie, E., Abdulai, M. & Baku, A. (2008). Sustainability of innovative management practices of geotechnical risk at Damang Pit cut back (DPCB) - a case study at Gold Fields Ghana, Damang Mine. The Southern African Institute of Mining and Metallurgy, Surface Mining. Pp. 203-216.	x					x
Douglas, B., Mercer, S., Wright, S. & Barclay, D. (2009). Pit water management in a mine planning cycle, Olympic Dam case study. Australian Institute of Mining and Metallurgy. Vol. 118. Pp. 115-130.	x	x			x	
Morton, K.L. (2009). Comparison of designs for the dewatering of Coal, Gold and Diamond mines in Southern Africa. International Mine Water Conference. Pp. 277-288.				x		
Dowling, J., Reidel, J., Beale, G. (2011). A review of key factors affecting mine dewatering and slope depressurization. Proceedings of the Slope Stability Conference, International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering.					x	x
de Bruyn, I.A., Mylvaganam, J., Baczynski, N.R.P (2011). A Phased Modelling Approach to Identify Passive Drainage Requirements for Ensuring Stability of the Proposed West Wall Cutback at Ok Tedi Mine, Papua New Guinea. Proceedings of the Slope Stability Conference, International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering.	x	x				
Mayer, J.M. (2011). Applications of Uncertainty Theory to Rock Mechanics and Geotechnical Mine Design. Master's Thesis, Department of Earth Sciences, Faculty of Science, Simon Fraser University. Burnaby, BC, Canada.	x	x				
Muller, S., Mylvaganam, J., de Bruyn, I. & Price, J. (2011). Mine groundwater control and slope depressurization methods at Ok Tedi in one of the highest annual rainfall areas in the world. Proceedings of the International Mine Water Association. Mine Water – Managing the Challenges. Aachen, Germany. Pp. 47-52.	x	x		x		
Mansel, H., Drebenstedt, C., Jolas, P. & Blankenburg, R. (2012). Dewatering of Opencast Mines using Horizontal Wells. Proceedings of the International Mine Water Association. Pp. 574 A-574 I.				x		
Golestanifar, M. & Ahangari, K. (2012). Choosing an Optimal Groundwater Lowering Technique for Open Pit Mines. International Mine Water Association. Mine Water and the Environment. Vol. 31. Pp. 192-198.	x				x	
Campbell, R., Mackie, D. & Anderson, W.S. (2013). Integrated slope stability assessment in a complex geotechnical and hydrogeological setting. Australian Center for Geomechanics. Slope Stability. Pp. 555-568.	x				x	

Reference	Case Study	Numerical Modeling	Novel Applications	Design Guidance / Specifications	Decision Making Process / Integration	Cost Benefit / Optimization
Lucas, D.S. & de Graaf, P.J.H. (2013). Iterative geotechnical pit slope design in a structurally complex setting: a case study from Tom Price, Western Australia. Australian Center for Geomechanics. Slope Stability. Pp. 513-526.	x			x	x	
Rougier, M., Castro, L.M. & Birchall, D. (2013). A case study on actual water pressure measurements at an open pit excavated in strong, tight rock and the implications for slope design. Australian Center for Geomechanics. Slope Stability. Pp. 445-454.				x	x	
Evin, G., Henriquez, F. & Ugorets, V. (2015). Pie Slope Optimization Based on Hydrogeologic Inputs. International Mining Congress and Exhibition of Turkey.		x			x	
Preene, M. (2015). Techniques and Developments in Quarry and Surface Mine Dewatering. Proceedings of the 18th Extractive Industry Geology Conference. Pp. 194-206.				x		
Hanna, B. (2016). Groundwater Component in Mining Operation-Mining Hydrology. Presentation by Itasca.				x		
Widodo, L.E., Cahyadi, T.A., Syihab, Z., Notosiswoyo, S., Iskandar, I. & Rustamaji, H.C. (2018). Development of drain hole design optimization: a conceptual model for open pit mine slope drainage system with fractured media using a multi-stage genetic algorithm. Environmental Earth Sciences, Vol. 77. Pp. 721.		x				
Carroll, M. & Negroni, R. (2018). Geophysical investigation to support characterization of structurally controlled groundwater flow into an open pit mine. Australian Exploration Geoscience Conference.			x			
Kolpakov, V.B. & Zhdanov, S.V. (2019). Implementation of slope drainage system for optimal slope design at Anfisa open pit, Khabarovsk Territory, Russian Federation. International Mine Water Association. Mine Water: Technological and Ecological Challenges. Pp. 570-576.	x					x
Lloyd-Mills, F. & Dowling, J. (2019). Mine Plan Optimization with Effective Use of Pit Slope Horizontal Drains. Proceedings of the 53rd American Rock Mechanics Association. Pp. 41.	x					
Cintolesi, C., Beale, G., Dowling, J., Kotze, J., Rowland, A. & Mansell, S. (2020). Anglo American framework for strategic dewatering plans. Australian Center for Geomechanics. Slope Stability. Pp. 1290-1304.					x	
Dowling, J., Beale, G., Haas, P., Kaya, B., Mak, S., Tejada, L.C., Kramer, K., Johnson, J., Zea, R.E. & Palmer, C. (2020). Development of an integrated workflow for pit slope pore pressure reconciliation. Australian Center for Geomechanics. Slope Stability. Pp. 1267-1280.	x		x			

Reference	Case Study	Numerical Modeling	Novel Applications	Design Guidance / Specifications	Decision Making Process / Integration	Cost Benefit / Optimization
Duenas, J., Becerra, G., Ordonez, R. & Andrews, P.G. (2020). Geotechnical evaluation of the east wall of the Cerro Corona Pit. Australian Center for Geomechanics. Slope Stability. Pp. 473-486.	x					
Reano, E., Beale, G., Dowling, J., Tejada, L.C., Lacey, M. & Hazwezwe, H. (2020). Development of a mine dewatering and pit slope depressurization review process. Australian Center for Geomechanics. Slope Stability. Pp. 1253-1266.		x				
White, T., Bester, M. & Carey, R. (2020). Slope depressurization at Shishen Mine, Northern Cape, South Africa. International Mine Water Association. Mine Water Solutions. Pp. 212-217.	x			x		x
McQuillan, A., Yacoub, T., Bar, N., Coli, N., Leoni, L., Rea, S. & Bu, J. (2020). Three-dimensional slope stability modelling and its interoperability with interferometric radar data to improve geotechnical design. Australian Center for Geomechanics. Slope Stability. Pp. 1349-1358.	x			x	x	
Zhou, W. & Maerz, N.H. (2002). Identifying the Optimum Drilling Direction for Characterization of Discontinuous Rock. The Geological Society of America. Environmental & Engineering Geoscience. Vol. 8. Pp. 295-307.				x		