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A case study in borrow source characterisation

N Cristi *BHP, USA*

Abstract

Early material characterisation is regarded as an important step in the mine closure planning process; however, the extents of what can be required in advancing the understanding of engineering properties from a scoping-level evaluation to construction is often underestimated. This case study seeks to scrutinise the engineering requirements in characterising a borrow source that was completed to progress the design of a stabilisation buttress into execution. By examining the granularity of the materials' design requirements and the nuances of the constructability implications sufficiently early in the design process, we can provide insight into how a host of individual studies contributed to advancing the team's understanding of the expected range in engineering parameters and improved the confidence level in developing tender documents.

Desktop studies, subsurface investigations, and laboratory testing were completed early in the project design to gain a preliminary understanding of the material's site-specific and long-term properties. Through a detailed evaluation of the remaining unknown parameters at each stage, it became necessary to augment this 'limited' sample size with testing at a scale more representative of the actual construction endeavour. Geophysical assessments, (more) site characterisations, and additional laboratory testing were completed to address remaining unknowns and increase confidence of the construction estimate and schedule. To test engineering assumptions and prepare for construction readiness, the team had to bridge the gap associated with translating the engineering designs into construction drawings, technical specifications, and material take-offs. To this end, large-scale pilot excavations were conducted to develop the borrow sources and examine variations in material processing and screening requirements. The large-scale testing shed new light on trade-offs that would be required in execution, and valuable insights were utilised to inform constructability reviews and improve the overall design.

The project is currently preparing for execution readiness and the goal of the thorough characterisation described herein was to de-risk the design as it transitions from the engineering phase into construction. The borrow source characterisation is intended to provide an improved understanding of the material properties while reducing the inherent uncertainty in order to minimise construction disputes and interruptions while allowing for delivery within the assumed allowances and contingencies.

Keywords: *material characterisation, buttress design, closure planning*

1 Introduction

A stabilisation buttress with a geomorphic landform and an engineered cover system across the face of the embankment has been extensively evaluated and advanced as one key design element of the long-term closure strategy for a legacy tailing's storage facility located in the southwestern United States. The site's overall closure strategy included a thorough characterisation of the tailings themselves in addition to the proposed buttress foundation, along with several additional components that aim to address a range of multidisciplinary domains in a holistic manner; however, these studies lie outside the purview of this paper.

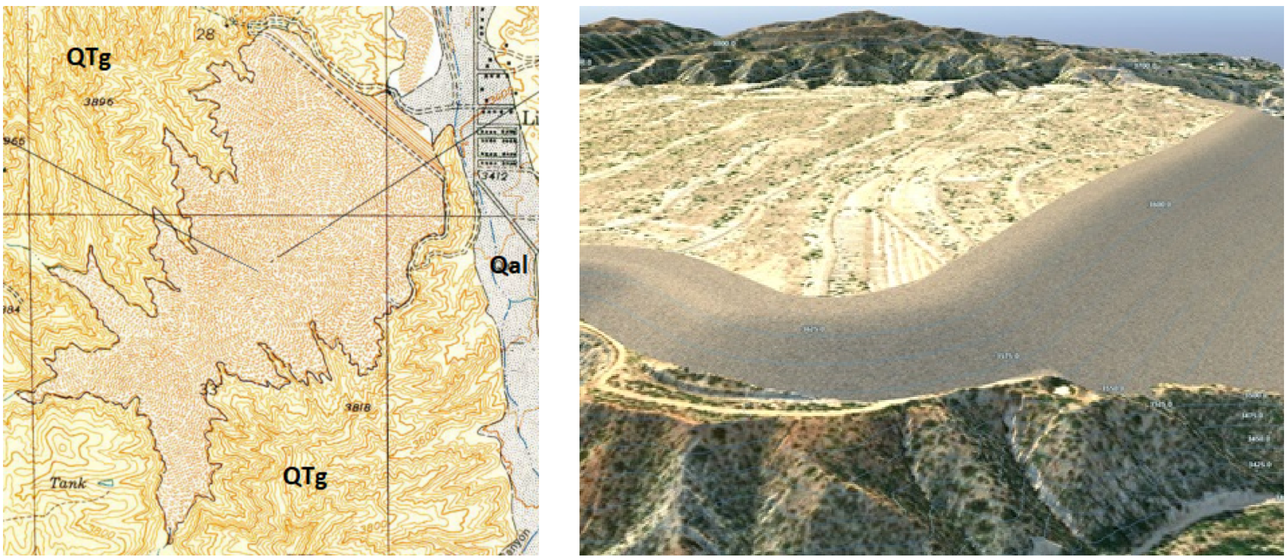
The buttressing project is anticipated to require upwards of 122,400 cubic metres (m^3) of granular underdrainage material, 2.2 M m^3 of compacted earthen fill and 104,000 m^3 of rock armouring on the outer slope. As a result of these anticipated volumes, sourcing and defining the optimal construction material/s have been a key focus of the study since its inception. Equally important from a risk management perspective and intertwined with these endeavours was understanding downstream material procurement strategy ramifications, such as possible impacts to local traffic patterns, increased carbon emissions with additional haulage, and the inherent risks associated with quality assurance of third-party suppliers (for imported materials). It is envisaged that as a result of thorough characterisations, a majority of the construction materials can be locally sourced from the native ridges adjacent to the site. Other material needs will be imported from local quarries (where required) to make up any specific material imbalances. Furthermore, the range of third-party suppliers available near the site is thought to be sufficiently well understood to support the project needs.

The legacy tailings facility, which was inherited as part of a historic acquisition, is being closed several decades after receiving its final tailing's deposition, at which time a partial reclamation effort was undertaken. The historic nature of the facility has allowed the characterisation studies described herein to progress over the years, together with the engineering assessments needed to understand the construction history and develop the various elements of the closure design. Operating mines should view the closure-related material characterisations and borrow source assessments as an opportunity that they can potentially pursue, along with ongoing exploration and drilling campaigns, to avoid undue delays, which will allow them to plan for a progressive closure outcome. As we will see in this case study, early characterisation efforts that consider possible closure ramifications can present many opportunities for downstream cost optimisation and assist in coalescing the closure plan into a successful rehabilitation.

The work to date on the material characterisation of the borrow sources has included a detailed desktop review of the native geology, two subsurface investigations, geophysical studies, and development of a large-scale pilot excavation. In this paper, we peel back the layers of the material characterisation progressed throughout the various design phases and give a brief outline of the techniques employed in carrying out the full range of the studies, along with a summary of the key insights that were obtained.

1.1 Geologic site setting

The tailings facility is situated in the structural transition zone between the Sonoran section of the Basin and Range physiographic province to the south-southwest and the Colorado Plateau to the north. The terrain surrounding the site is generally mountainous with an adjoining ephemeral wash to the east and north (MWH 2007). The regional geology and stratigraphic rock units found in and around the project area have been well mapped and are thought to be comprehensively understood. Detailed descriptions are available elsewhere by Ransome (1903) and Peterson (1962). A geologic map of the area along with an isometric rendering of the proposed buttress is provided below in Figure 1.



(a) (b)

Figure 1 (a) Geologic map of the project area where QTg = Gila Conglomerate (Peterson 1962); (b) Isometric view of the project with the western borrow areas depicted in the background

The site is largely underlain by a thick sequence of consolidated gravels of the Tertiary Gila Group that are incised by a northeast-trending gulch. The northern (lowest) portion of the facility rests on unconsolidated alluvial silt and gravel material, near its confluence with an ephemeral wash. The borrow material characterisation, which is the focus of this case study, focuses on the native Gila Conglomerate (Gila) material contained in the western ridges of the site.

The Gila was deposited as a series of near-source, basin-fill sedimentary layers during the Miocene and Pliocene epochs ranging from 23 to 2.5 million years ago. Similar age basin-fill deposits are found from western Arizona through central and southern Arizona through to New Mexico. It is dominantly composed of overlapping alluvial fans of material derived from the rocks of the nearest mountain range (Jacobsen 1976). As such, its properties vary locally because of source rocks and local geometry in the basins where the conglomerate was deposited. Throughout the mining district, the Gila is a buff-coloured matrix-to-clast-supported sandy boulder conglomerate, interbedded with layers of slightly coherent sand, gravel, tuff, and sheets of basalt. The clast composition depends on the rocks exposed in upstream basins or ridges during its deposition and is therefore variable with depth and areal extent. Regionally, the formation has been studied to comprise a 'coarse'-grained variant, with boulders of up to 3.7 m in diameter, and a 'fine-grained' variant, with boulders up to 0.6 m in diameter (Kidd 1989). It is typically cemented with calcareous material and does provide a fair amount of acidic buffering capacity. Broadly speaking, around the facility, the lowest portion of the Gila is typically unsorted, angular fragments of Pinal Schist. Stratigraphically higher in the Gila, increasing amounts of Madera diorite are present. The uppermost portion of the formation is dominated by fragments of Schultze Granite (SRK Consulting 2019a).

Observations from small construction endeavours in the area support the rock clast variances described in the literature and highlight the local variability of the cementation. Neighbouring properties have reported the conglomerate required blasting methods for excavation, while others have encountered a much weaker cementation that would favourably present it as an ideal candidate for excavation in a borrow pit.

2 Desktop studies

The efforts to better understand the material properties of the Gila commenced by leveraging the existing regional data to provide a preliminary macro-level understanding of observed characteristics that had been studied throughout the mining district over the years. To this end, site documents and published literature were researched to compile available information on the geologic formations.

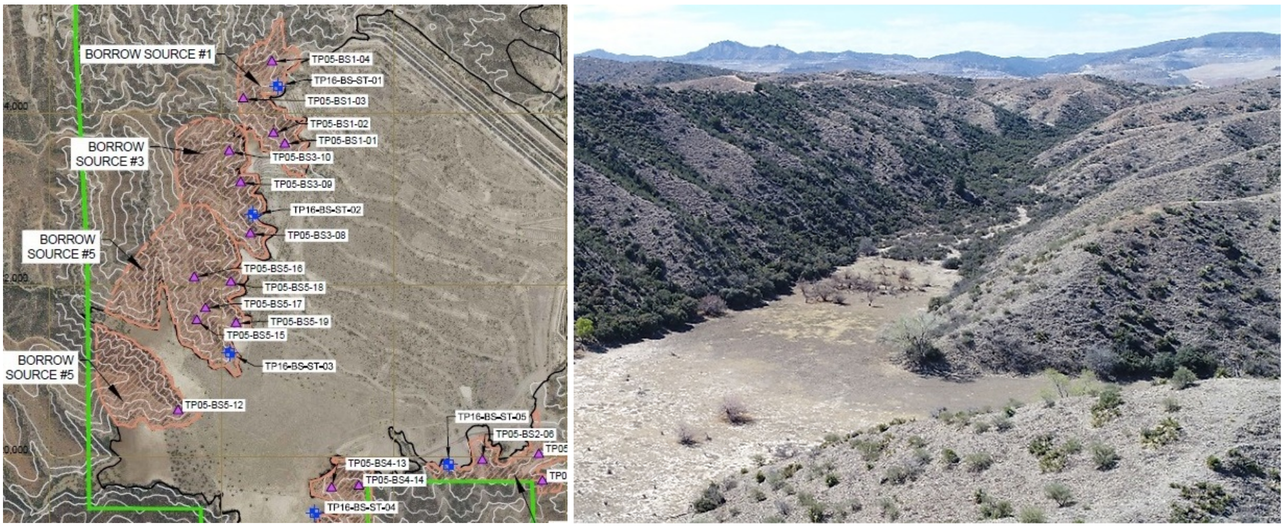
When closure planning initiated, the early characterisation objectives were focused on gaining a holistic understanding of the facility through a series of multidisciplinary investigations intended to align the intended closure strategy with the site-specific constraints, the envisioned land uses, and the emergent tailings safety paradigms that have been the attention of new international guidelines as governed by the Global Industry Standard on Tailings Management (Global Tailings Review 2020). Focused subsurface investigations and laboratory testing would be needed to obtain site-specific information on the physical, chemical, and agronomic properties of the soils and rock from the identified borrow sources in order to assess the suitability of the material for the design intents and allow for an accurate accounting of the earthworks. These earthwork volumes would drive construction costs and have implicit impacts to sustainability targets and commitments.

3 Subsurface investigations

A series of site reconnaissance visits facilitated the planning and execution of two early borrow source investigations for examining the geotechnical, hydraulic, geochemical, and agronomic characteristics of the Gila material. These characterisation programs included drilling of select boreholes and excavation of test pits to assist in collection of 'representative' subsurface samples for visual classification and laboratory testing required to ascertain the materials' overall suitability as a future construction material.

Due to the steep native ridges where these investigations would occur, the site presented some complications and logistical constraints to the investigative teams with regard to safely accessing ideal sampling locations. With these access constraints, only four air-rotary boreholes were completed to confirm the thickness and vertical extent of the potential borrow source areas and to collect samples for possible analysis in the future (MWH 2007). Within the drilling investigation, disturbed samples of the potential borrow sources were taken from the air returns of the rotary drill hammer for logging by visual classification and subsequently stored for testing purposes at a later date, although the highly disturbed nature of the drilling method limited the future laboratory uses of these samples. Alternative drilling methods, such as roto-sonic, which could have returned sample material of higher quality at depth, were contemplated for future phases but proved problematic due to the space constraints associated with the auxiliary supports that a larger rig set-up would have required.

In order to infill collection points between the boreholes and to assist with improvements to the overall understanding of the near-surface spatial viability inherent in the Gila, a series of 23 test pits were excavated in two separate field campaigns. These excavations were limited in their vertical extents either by the reach of the excavator or by refusal but allowed for the collection of bulk samples that would be characterised in the laboratory to understand the makeup of the material as required to satisfy a multitude of multidisciplinary objectives (MWH 2007; SRK Consulting 2019b). Samples in these campaigns were collected either directly from the stockpiled spoils or from the excavator bucket using a stainless-steel trowel. Figure 2 presents the location of the early test pit locations, along with a site picture of the difficult terrain.



(a) (b)

Figure 2 (a) Locations of early subsurface (test pit) characterisation programs (SRK Consulting 2019c); (b) Overview of one of the borrow areas where the steepness constrained site access

These two earlier field investigations examined similar characterisation objectives with the material and sought to better understand various parameters that would be important for realising the closure vision (soil covers and/or fill material). A complete list of the laboratory testing suites conducted during both aforementioned subsurface investigations is provided in Table 1.

Table 1 Laboratory testing from early characterisation programs

Characterisation goal	Laboratory tests performed
Geotechnical	Particle size distribution, Atterberg limits, moisture content, standard Proctor, and one-dimensional consolidation
Geochemical	Acid base accounting, trace elements, rinse/paste pH, total metals, and electrical conductivity (EC)
Soil compositional analysis (agronomic characteristics)	pH, EC, lime, % organic matter, soil texture, NO_{3}-N, P, K, Zn, Fe, Mn, and Cu
Hydraulic characteristics	Saturated hydraulic conductivity

Results from the analytical laboratory programs that were conducted for these characterisations served as the foundation of the knowledge basis for the present-day understanding of the borrow source parameters.

3.1 Sampling methodologies

A standard operating procedure for these early field investigations could not be found together with the archived reports, but obtaining unbiased samples from stockpiles can be notoriously difficult due to the segregation that occurs when the material is amassed with the coarser particles typically rolling to the outside base of the pile. Proper sampling of stockpiles can be performed with the correct methods as well as through care and attention to detail in attaining a representative sample that has minimised the individual's bias and material's variance.

When sampling stockpiles, methods such as splitting and quartering known volumes of material are common practice; but alternative methods exist, such as drawing material from various levels (top, middle, and bottom third) as well as from multiple sides or locations of the pile, ensuring sufficient material is collected from the centre of the mass to capture proper uniformity. The separate portions of material taken from the different areas must then be proportionally combined to form a composite sample. As noted by Schultze (1957), a true representative sample should be at least five to 10 times the size of the largest constituent particle diameter, so the Gila adds an additional layer of complexity with its sandy-rocky conglomerated composition and prohibitively large clasts and rocks. It is common to observe larger rocks being discarded from sampling bags and buckets where the focus is the soil matrix that will be analysed in the laboratory; however, this can lead to erroneous size distribution results if care is not taken to visually account for material not collected in the sample. Furthermore, when sampling Gila, the presence of cemented clasts should be clearly communicated to the lab ahead of time to decide and plan for how these will be treated in the sieve analysis to ensure results are accurate and the samples are representative of material actually encountered during excavation.

As noted in various studies during the literature review, the collection and preparation of undisturbed or even slightly disturbed samples of a rocky conglomerate (i.e. Gila) has presented difficulties to geotechnical practitioners in the past. Kidd (1989) noted that due to its interbedded rocks (ranging in size from gravels to boulders) and inherently hard and cemented in situ nature, the material is not conducive to collection via either thin-walled tubes or driven penetration samplers. Additionally, even if a suitably sized specimen could be obtained by bulk excavation or some other means, trimming of the sample in the laboratory has in the past destroyed the matrix of the material, even when being confined in the preparation process. This inability to prepare specimens for relatively simple (but important) laboratory tests reinforces the need for either in situ testing of this type of material and/or remoulding these samples under the correct reconstitution parameters (Kidd 1989).

4 Geophysical mapping

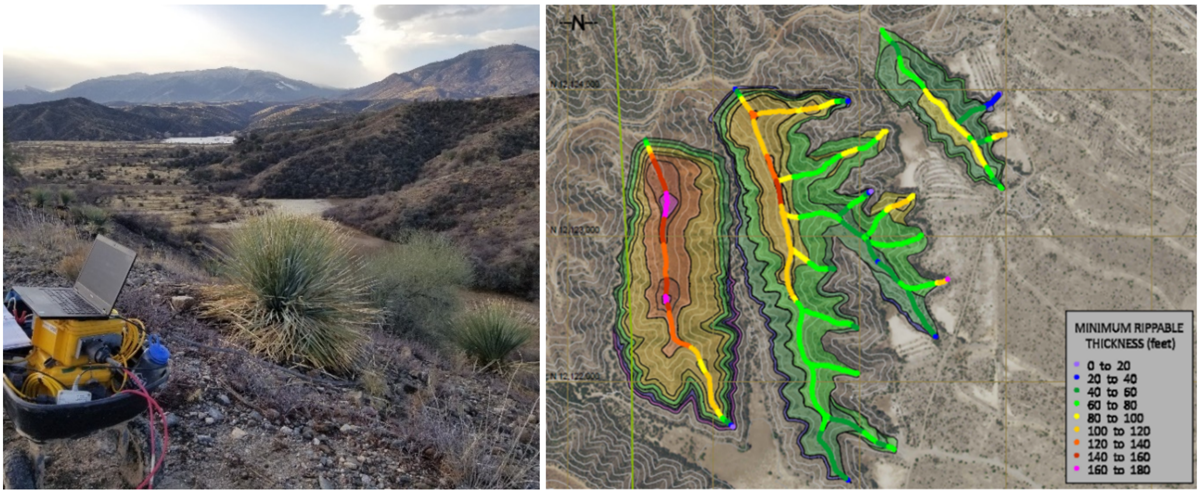
The literature review of regional rock mass strengths suggests a relatively wide range in material hardness may be encountered with the Gila by virtue of its deposited location, major fractures, and conglomerated nature (Jacobsen 1976). Understanding the in situ parameters of the hardness was a key objective of the subsequent investigations due to the associated trade-off that would be required in confirming the excavation methodology for the material (i.e. ripping or blasting). Caterpillar® Inc (CAT) has conducted extensive testing of its manufactured track-type tractors (i.e. dozers) to correlate the seismic velocity of the material to its degree of rippability (performance and efficiency) under mechanical shearing. This assessment of production ripping is provided in the *Handbook of Ripping* as well as a qualitative measure of the consolidation in the rock formation to its seismic velocity (Caterpillar 2000), which can serve as a starting point for the equipment selection and configuration to be utilised in the excavation operation.

A seismic refraction survey would allow the design team to leverage these correlations and determine if production ripping would be an economical strategy for excavation during the construction stage as it would streamline logistical hurdles. In consultation with a retained geophysics contractor, a rippability assessment was conducted through a series of P-wave refraction surveys on the ridgelines. It was determined that due to the dependence of the seismic velocity on the elasticity and density of the material through which the energy would be passing, seismic refraction surveys would provide a suitable measure of material hardness that could be used to assess rippability and rock quality.

The P-wave refraction method is based on the measurement of the travel time of seismic waves refracted at the interfaces between subsurface layers of different velocity and would be limited by the length of the active line that could be rolled out ahead of the energy source. Observation of the travel times of the direct and refracted signals along a linear array of geophones would provide information on layer velocity, which could in turn calculate the depth profile of the refractor. Data processing for the seismic refraction method consisted of accounting for the energy source and geophone locations, making adjustments for topographic changes along the geophone array profiles and determining the first arrival times at the geophones. Subsequently, the subsurface acoustic properties were determined using two different processing methods: refraction analysis and tomographic inversion (hydroGeophysics [HGI] 2022).

In total, 16 lines of P-wave seismic refraction measurements were performed in the geophysical investigation, with individual line lengths varying from 70 m to 908 m. The depth of investigation varied along each line depending on the length of the array, the amount of energy imparted into the ground at each ‘shot’ point, the ground coupling of individual geophones, and the amount of noise present at the time of each individual reading. In general, the measured depths correlated well with the expected approximation of 25% of line length, which represented a suitable profile of the seismic energy ray path and ultimately the investigation depth. The geophysics results showed the seismic velocities were all within the traditionally rippable range of a CAT D10 track-type tractor, so the dozer size was downgraded to a CAT D8 for the qualitative rippability classification and assessment.

A site photograph of the terrain traversed with the geophysics contractor is presented in Figure 3, along with a map overlaying the geophysical lines and the inferred rippability results for a CAT D8 track-type tractor.



(a) (b)

Figure 3 (a) Site photograph during completion of the geophysics program; (b) Geophysical investigation line location(s) on the ridges and inferred CAT D8 rippability results (HGI 2022)

According to the CAT D8 ripper performance chart in the *Caterpillar Handbook of Ripping*, P-wave velocities for conglomerate rocks below 1,951 m/s are defined as rippable, P-wave velocities between 1,951 and 2,438 m/s are defined as marginally rippable, and P-wave velocities above 2,438 m/s are non-rippable. In general, the in situ materials from our borrow source investigation (to the imaging depth limits) were within the rippable range of a D8 track-type tractor for approximate depths that varied from 3 to 59 m below ground surface.

Although the material shows to be rippable with a CAT D8 track-type tractor, the reader should note that the seismic waves encountered were on the upper limits of the selected equipment's capabilities for distinguishing zones of hardness, and consideration should be given to undue wear of the equipment. The benefits from a larger and heavier track-type tractor should be examined to understand trade-offs with efficiency and reliability, which may lead to increased productivity, a lower operational cost, and overall benefits to the economic viability. Aside from the optimal equipment size, the selected track-type tractor for a production ripping application would also be influenced by a host of factors the team would next optimise, from shank configuration to tip style and length, which are holistically intertwined with achieving an optimised efficiency and yielding a maximised production (i.e. lowest cost/m^3).

With the qualitative interpretation afforded by the results of the geophysics investigation, attention turned to developing the specifics of a pilot-scale excavation of the borrow areas and to conducting placement trials for the material to confirm remaining data gaps. The pilot excavation coupled with the placement trials would examine the scalability of the project for construction, with a particular focus on confirming the assumptions underpinning the methods and procedures associated with material handling and equipment configuration. Additional aims would include gathering sufficient detail on material variability to define a tendering package representative of the in situ parameters and would aim to minimise future contractor disputes.

5 Borrow development and pilot excavations

The early characterisation studies formed a solid foundation of knowledge to advance the design, but comparison of the available results showed some notable differences with material properties, primarily related to the expected amount of rock that could be sourced directly from site as opposed to the local quarries. Additionally, some important unknowns remained with how the material properties might be changing at depths beyond the excavated samples as well as other remaining data gaps with still untested parameters that would be important for construction, such as shrink–swell factors (among others). While the geophysics results suggested rippability would likely be feasible, the design team still needed to confirm design assumptions with the processing/screening of the material once it had been excavated and select the most efficient equipment for construction.

For the project to stand up to the technical rigour and scrutiny of the internal reviews required as part of the capital allocation framework, the design team felt it would be necessary to augment the more historical data and improve the understanding of the material properties that would pose the greatest risk to execution from a cost and schedule standpoint. A pilot excavation and trial placement program was designed and conducted on the native ridges in order to examine how, under controlled conditions, the Gila may behave under dozing and compaction operations. The first component of the study was understanding the material availability, composition, and suitability in determining the level of effort required to produce the fill, which would consist of a rippability, screening, and crushing assessment. After producing the material, the level of effort necessary to achieve design specifications was evaluated (i.e. material characteristics versus design specifications via compaction field trials).

The objective of this scope included confirming the rippability conclusions of the geophysics study as well as examining the heterogeneity and the changing characteristics of the Gila with depth through the use of additional laboratory analysis (Stantec 2022). The scale of the work would provide additional clarity on the multifaceted nature of the Gila's engineering parameters due to the variations in cementation and the presence of oversize material. Additionally, it would also allow for a formulation of the comprehensive understanding of the intertwined relationships with the soil phases and behaviour under compaction. Note that the placement trials that evaluated compactive simulation runs to assist in specifying moisture requirements, placement thickness, and compactive energy requirements for construction are the subject of a separate paper, currently under development and therefore not discussed herein.

The pilot excavation program was focused on four ridges along the western boundary of the facility to evaluate possible spatial variability in the material between ridges with different seismic wave inferences. Disturbances were limited in areal extents due to operational constraints with local reclamation permits and the mandate to stay in compliance with all applicable regulatory requirements. These four test locations were fully developed to depths of roughly 15 m according to their grading plans within the delineated boundaries and produced approximately 38,000 m^3 (total) of material to evaluate by means of visual inspection and laboratory testing. Generated fill material not utilised in the compaction portion of the placement study was stockpiled for future use in early construction activities, such as road construction and lay-down yard preparations.

The four test areas for the borrow development are presented in Figure 4, along with a site photograph of the excavation being progressed during execution of the pilot program.

(a) (b)

Figure 4 (a) Test areas for the pilot-scale borrow development and compaction trials (Stantec 2022); (b) Borrow development area no. 1 being excavated as part of the pilot-scale excavation program

Samples were collected along the excavation profile to augment the sample database at depth and arrive at a more discrete understanding of material properties that could shed light on the spatial variability over the area of interest. In this effort, laboratory results at each borrow area were plotted and analysed for discernible patterns that may give an indication of layered changes within the depth profile. Additionally, results were holistically compared across the borrow ridges to examine spatial trends across the area. The project is currently scoping the undertaking of a more detailed analysis using geostatistical techniques (Usowicz 2002) to understand if semivariograms can be used to give a more robust statistical description of the distribution and its spatial dependence.

5.1 Level of effort for material production

During rippability testing, a CAT D8N track-type tractor was utilised to rip and excavate the ground within the delineated regions, although it is understood that a larger piece of equipment with more energy may have produced greater efficiencies as the amount of material that can be excavated in a given time is interrelated with both the hardness of the material and how much work must be done by the machine. There was a general consensus among the general contractors consulted that a track-style tractor should utilise an adjustable parallelogram ripper with a multi-shank arrangement to optimise ripping productivity and efficiency. In the borrow development trials, straight ripper shanks with shank protectors and intermediate tips were utilised and resulted in reasonably good penetration of the material while balancing impact and abrasion on the equipment.

The dozer performed several passes to free material from the slope, pushing it down to the toe for evaluation and processing until it reached its final grade at a slope inclination of approximately 2H:1V. A qualitative judgement on the material strength can be made by engineers when they watch equipment work on a job site or in a mine and assess the machine’s performance (Savely 1990). An accurate estimate of ripping production rate would be needed to inform unit ripping costs and support development of construction schedule and associated productivities.

To this end, the team first surveyed the three-dimensional area before work began and then recorded the time spent ripping, taking note throughout the work shift of the number of hours worked per shift, less any stoppages due to breaks, weather delays, or equipment breakdowns. After the material was removed, the area was cross-sectioned by surveying to determine the volume of material moved. This volume of ripped material divided by the time spent ripping gave an estimated ripping rate in terms of bank cubic metres per hour. It is important to also mention that there is an inherent trade-off associated between equipment productivity in ripping material and various variables, such as variations in ripping depth, spacing, and direction of passes, which can usually be tailored in combination to produce desired material sizes. These field estimates will be a helpful comparison for scaling the project as well as for breaking down the constituent parts into first principles when evaluating productivity, utilisation, and efficiencies in the estimating process.

5.2 Screening and crushing assessment

At each borrow area, a known volume of 7,500 m^3 of pit-run material was fed through a Finlay 883+ track-mounted scalping screen to produce stockpiles of 7.62 cm (3-inch) minus material, 7.62 cm to 15.24 cm material, and 15.24 cm (6-inch) plus material. The individual stockpiles of material were surveyed and logged via photo-sieve gradation to determine the percentages of particle ranges present in each stockpile and to have a point of reference to compare against the manual samples collected by splitting and quartering the pit-run material as it was being generated. The 15.24 cm plus material was subsequently crushed via a MB-BF 90.3 crushing and screening bucket, then rescreened and the stockpiles resurveyed to determine yield volumes of additional 7.62 cm minus and 7.62 cm to 15.24 cm material produced.

Particle size distribution analysis would be used primarily for soil classification purposes and would also allow the team to define material imbalances with rock importation for the rock armour specified in the cover design. Being able to source both soil and rock materials onsite would have several benefits to costs and sustainability – from reduced haulage costs and climate emissions to decreased reliance of outside infrastructure and traffic impacts to local roadways. Structural fill material would account for a significant proportion of construction cost and its particle size distribution would have a direct correlation with the achieved dry density, shear strength, and other physical and compactive properties and therefore directly influence the quality and safety of the final structure (Jiejie 2019). Due to the importance of this engineering parameter, the material composition and sizing was the focus of increased attention in the planning stage.

The ripped onsite material would also give an indication of the amount of cemented clasts that were present in the Gila and assist in defining whether processing of the material would need to be accounted for in the construction estimates and schedule. In addition to being undesirable from a material handling perspective, the presence of clasts can also be problematic to proper compactive fill placement as the cemented pieces need to be broken down in order to absorb water and bond to the surrounding soil matrix. As discussed previously, conglomerates have presented difficulties for in situ characterisation in the area because of the wide ranges in particle sizes, the unknown behaviour of large clasts, and the inherent stiffness of the material; all of which contribute to make the material not amenable to standard testing and can additionally present difficulties for construction. As noted by Savely (1990), representative undisturbed samples of cemented conglomerates (i.e. Gila) for laboratory strength testing are nearly impossible to obtain. Samples are generally selected to eliminate large clasts, cemented clasts are broken down through mechanical means, or the sample is scalped of large sizes, graded to a size distribution that is smaller but proportional to the in-place material, and remoulded. In these processes of scalping, proportional grading, and remoulding, one can significantly change the cohesion. There is a tendency for fine-grained granular material to have a lower friction angle than coarse-grained material, although this depends on the exact nature of the grading. The result is usually a low estimate for the shear strength, which may lead to a conservative design (Savely 1990).

5.3 Field characterisation and laboratory testing

During the borrow development study, samples of the Gila material were collected from the dozed slopes at defined intervals along the depth profile of the excavation to understand the discrete variability of changing engineering parameters with depth as well as the spatial changes in the lateral extents between excavation sites. To minimise sampling bias when selecting samples for laboratory testing, a standardised amount of pit-run Gila was split and quartered when reducing the material volumes. This initial discrete understanding of the index properties informed more advanced soil tests for understanding the material behaviour, which were performed on samples of the screened material, although these latter composites were representative of much larger intervals. Screened material was sampled directly from the stockpile, albeit with the due diligence of the recommended sampling measures described previously having been incorporated into the standard operating procedures.

As part of the laboratory preparation instructions, cemented clasts were broken down with a rubber mallet prior to testing. Due in part to the compacted state of the material to be placed in the buttress construction, the study was limited to laboratory analyses of remoulded samples for strength testing; however, the value of information that can be gleaned from large-scale in situ tests should not be discounted for future endeavours. An understanding of the intact properties of the Gila and back-analysis of the results would be needed to support the final borrow excavation design and inform the long-term slopes of the maximum cut wall heights and any intermediate bench requirements.

The laboratory analysis and testing program for the material was tailored to address remaining unknowns with the engineering properties, inform predications of future behaviours, and to address remaining data gaps that may affect the construction tendering package. A complete list of the laboratory testing summary conducted for the pilot borrow area investigations is provided in Table 2. A separate laboratory testing stream was also included for samples collected during the compaction trials.

Table 2 Laboratory testing completed for the pilot borrow area excavations

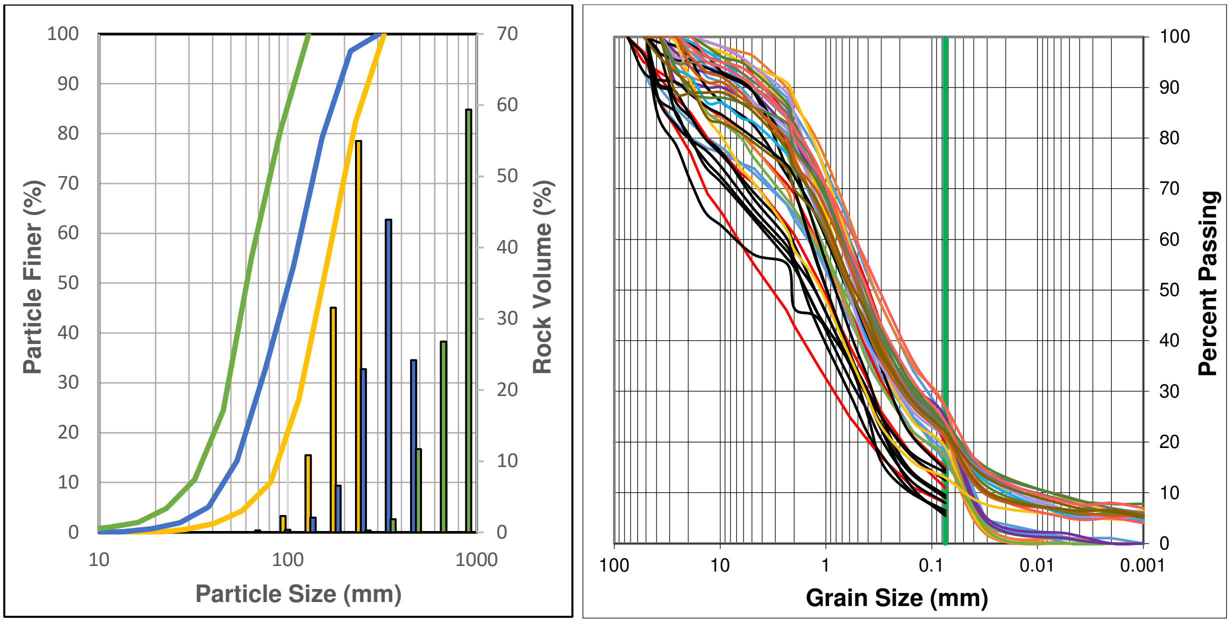
Material category	Laboratory tests performed
Topsoil and pit-run (agronomic characteristics)	pH, EC, Ca, Mg, Na, K, Zn, Fe, Mn, Cu, B, Ni, NO_3-N, PO_4-P, SO_4-S, free lime, ESP (calculated), and CEC (calculated)
Pit-run	Particle size distribution (w/sieve and hydrometer), Atterberg limits, moisture content, standard Proctor, calcium carbonate content, slake durability index, acid base accounting, ICP-AES (metals), and CVAA (mercury)
Soil matrix (7.62 cm minus [screened])	Particle size distribution (w/sieve and hydrometer), moisture content, standard Proctor, direct shear (scalped), CU triaxial compression (scalped), and shrink–swell testing
Rock armour and rip-rap (7.62 cm to 15.24 cm [screened and crushed])	Photo-gradation, sieve analysis of aggregates, specific gravity/absorption, Los Angeles abrasion, sodium sulfate soundness, acid base accounting, elemental analysis, meteoric water mobility procedure, and particle characterisation (Microtrac™)

Results from the laboratory program were added to the database and compared against the earlier characterisation efforts to round out the present-day understanding of the borrow source parameters.

6 Results

Analytical laboratory results obtained from the various phases of subsurface investigation described in this case study were assessed to arrive at a robust understanding of the borrow source characterisation and the range in engineering parameters that could be expected for the Gila Conglomerate. While the statistical description of the distribution and its spatial dependence hasn't yet been analysed, the various investigations do show that there is considerable spatial viability with the rock content that may be encountered between individual ridges during excavation of the fill material for construction. These investigations are also consistent with the anecdotal information available from other investigations and projects done by the team (in the broader mining district) and other parties.

This was particularly evident during the screening assessment of the pilot excavation study where the content of rocks greater than 7.62 cm (3-inch) was observed to vary from a low of 2.70% in Borrow Area 2 to a high of 13.24% in Borrow Area 3; and were separated by a linear distance of only 215 m. Figure 5 presents differences in rock content between borrow areas from the screening operation and also highlights the range of particle size distributions from the laboratory sieve analysis of all the Gila samples.

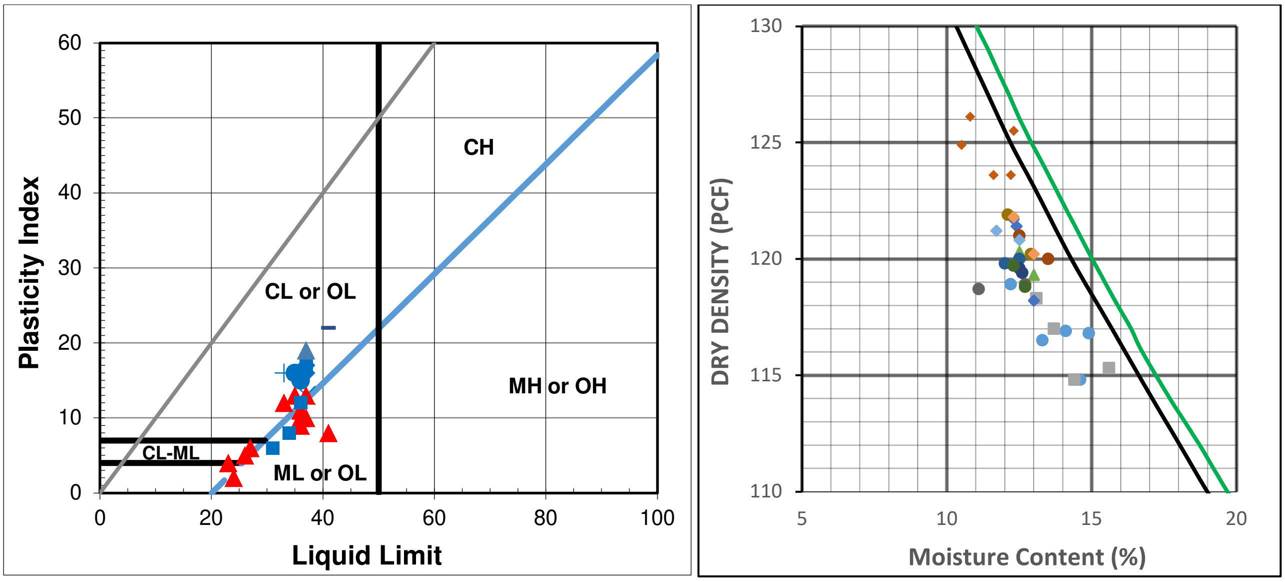


(a) (b)

Figure 5 (a) Photo-sieves were conducted on the surveyed stockpile volumes after screening; (b) Particle size analysis on the finer material shows a narrow band in the expected granulometric envelope

The noted difference in rock content between borrow areas was one of the drivers meriting a more rigorous statistical understanding of the spatial distribution be undertaken in a future study. At the high end of rock content encountered, the project may be able to successfully screen a majority of its rock material requirements onsite; however, a rigorous trade-off analysis of the construction-level implications from adding a processing and screening circuit to the material handling operations is still needed. In terms of rippability, all areas were rippable with a CAT D8N track-type tractor, lending confidence to the geophysical interpretations of the P-wave seismic velocities and to the larger implications in not requiring blasting during development of the excavations in construction.

Aside from the more substantial variations in the rock content encountered, particle gradations of the soil matrix were more consistent between areas and depths, with the majority of the Gila classifying from a silty sand to sandy silt with low to no plasticity, according to the Unified Soil Classification System (ASTM 2020). With respect to the maximum dry density achieved from the standard Proctors, the moisture-density relationships showed good alignment in maximum dry density values ranging from approximately 115 to 126 pounds per cubic foot (pcf) and optimum moisture contents ranging from 10.5 to 15.6%. Figure 6 presents the Atterberg limit plots showing differences in plasticity between samples of the Gila and also presents the range of Proctor values achieved in laboratory and field tests of the material.



(a) (b)

Figure 6 (a) Atterberg limits were consistent with field plasticity observation from the visual-manual tests; (b) Standard Proctors show the material will compact to a target density with moderate effort

Geochemical testing of the Gila concluded that the borrow areas show significant neutralization potential (NP), indicating a negligible potential for acid rock drainage. Additionally, correlations between modified NP and total inorganic carbon suggest that the NP occurs primarily as carbonate minerals. Total metal analyses indicate the material to be within residential soil remediation standards set by the state regulator for soils used in reclamation purposes. Furthermore, soil pH values are circumneutral, ranging from approximately 6.8 to 8.0, presenting a consistently near neutral or slightly alkaline pH. Collectively these results indicate there is a negligible potential for metal leaching and that the materials are inert and thus suitable for construction purposes.

Although herein we have broken down and examined the individual material properties of the borrow source, it should be noted that from the viewpoint of engineering behaviour, the individual parts represent an interconnected system that will be influenced by the broad combination of properties that must be integrated together for a comprehensive understanding of the site characterisation.

7 Conclusion

A thorough borrow source characterisation will be a necessary endeavour for understanding site-specific material properties and informing the engineering parameters of various aspects associated with the closure design. As a project advances from the early planning stages and construction of the design becomes more likely, additional characterisation can help to reduce inherent uncertainties and increase the confidence level associated with execution costs and schedules by defining remaining unknowns and de-risking both the tendering package and the forthcoming field execution. The case study presented herein has demonstrated that as the design of our stabilisation buttress and landform progressed in its objectives so too did our understanding of the material properties as a direct result of the subsurface investigations carried out during the planning and design stages. As with any geotechnical investigation, a reliable site characterisation that provides a thorough knowledge of the subsurface properties and their lateral variations is important for a comprehensive site understanding and should not be underestimated.

Broadly speaking, if robustly characterised ahead of time for physical and geochemical objectives, the material placement and stockpiling of fill material(s) and rock armour adjacent to any mining facility can start progressing concurrently with the mine life, thereby greatly reducing future excavation, procurement, and haulage costs for the mine rehabilitation phase. Active operations with modern facilities that are 'built for closure' with stabilised slopes, future-facing design criteria, and progressive reclamation present opportunities to avoid for themselves the costs and complexities associated with re-sloping facilities and/or placing a buttress later in the mine life to achieve their long-term closure obligations. To minimise the danger of reaching an incorrect conclusion from incomplete data, the design teams should continually challenge themselves through assumption checks to understand sensitivities to key parameters as well as to stress test the impacts of different design elements. In our case study, the contingencies associated with the assumptions on our material properties were consistently being flagged as a key risk in the cost forecasting models and internal reviews suggested the project was carrying large assumptions that needed to be thoroughly understood ahead of construction.

To overcome this danger of reaching a biased conclusion from incomplete data, the team carried out additional studies, including a geophysical investigation and a large-scale pilot excavation of the borrow source(s). This large-scale testing shed new light on trade-offs that would be required in construction with processing, screening, and crushing implications and allowed us to infill our internal understanding of the site-specific material properties. These thorough borrow source characterisations have increased the confidence of the engineering parameters needed to develop the construction tendering packages. The project is currently preparing for execution readiness as it completes analysis and transitions from the engineering design phase into construction where we hope to have minimised disputes and interruptions while allowing for delivery within the assumed allowances and contingencies.

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