

Independent Expert Engineering Investigation and Review Panel

**Report on Mount Polley
Tailings Storage Facility Breach**

Appendix D: Subsurface Investigation

January 30, 2015

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1.0 OVERVIEW

Appendix D presents a brief summary of the historical geotechnical site investigations completed for the Mount Polley Mine tailings storage facility (TSF). It also describes the program of work undertaken by the Panel and others, and provides the results of the post-breach geotechnical investigations. The purpose of the recent site investigations was to investigate the soil and groundwater conditions within both the breach and the surrounding area.

2.0 HISTORICAL SITE INVESTIGATIONS FOR TSF DESIGN

Historical subsurface investigations were carried out by Knight Piésold (KP) to obtain information about the soil and groundwater conditions within the area of the TSF including the footprint of the dams (Main, Perimeter and South Embankment). Details related to the historical site investigations are contained in the reference documents provided in Appendix B. Drawings showing summaries of historical subsurface investigation are at the end of Appendix D.

The first three drawings accompanying this appendix provide snapshots of subsurface investigations at different times, filtered according to depth and type of information collected.

Drawing D1 shows all subsurface investigation locations up to July 2014. It highlights subsurface investigation locations for three different sets of dates when the investigations took place. For each set of dates, there are four cases defining the depth of the holes and whether in situ and laboratory testing were included. The depths that are used in these cases are 8 m and 3 m. The deeper value indicates the general location of the top of the Upper GLU (discussed in section D.6.4.3). The 3 m depth includes only the shallow till and surficial fill materials.

Drawing D2 shows all boreholes and test pits completed up to 1996 prior to the start of TSF construction. It highlights subsurface investigation locations where in situ or lab testing data were collected more than 8 m and 3 m below the pre-construction ground surface.

Drawing D3 shows only subsurface investigation locations prior to July 2014 where in situ or lab testing data were collected more than 3 m below the pre-construction ground surface. Information that extended more than 8 m below pre-construction ground surface is highlighted.

The next two drawings focus on subsurface investigations in and around the breach area, including those subsequent and prior to the breach itself.

Drawing D4 shows post-breach subsurface investigation locations in the breach area but includes some historical investigation locations that extended more than 8 m below pre-construction ground surface and included in situ or lab testing data.

Drawing D5 shows the pre-breach subsurface investigation locations in the breach area in a similar format to D3.

3.0 RECENT (POST-BREACH) SITE INVESTIGATIONS

Two separate site investigations were commissioned following the breach of the TSF. Klohn Crippen Berger (KCB) was retained by the B.C. Ministry of Energy and Mines (MEM) to investigate the cause of the breach. Separately, the Government of British Columbia established an Independent Expert Engineering Investigation and Review Panel (the Panel) to complete its own investigation, of which this appendix is a part. These two investigations also coordinated with Golder Associates (Golder) who was contracted directly by the Mount Polley Mining Corporation (MPMC).

The subsurface and field-work portions of these separate investigations were completed concurrently at the mine site. MPMC worked with both parties to facilitate access such that both parties could make the necessary observations and obtain the required subsurface information. Factual information obtained during the investigations by KCB and the Panel was shared between the two parties. While the data was common to both parties, its interpretation remained exclusive to each one individually.

Drawing D4 generally shows the investigation locations completed by KCB and the Panel. Detailed borehole and cone penetration test (CPT) location plans for the subsurface investigations by both parties are included in Attachments D1 to D7.

About half of the locations for the KCB investigation were located in the failed section footprint as well as through the remaining embankment into the underlying foundation. The Panel developed a separate field program that allowed insitu testing and sampling in a larger number of locations in the area where foundation materials have not been preloaded by the embankment.

Table D3.1-1 provides a summary of the coding used to identify the hole locations and associated test designations. It also lists the Attachments where the information is located.

TABLE D3.1.1: SUBSURFACE INFORMATION CODING

TYPE OF INFORMATION	DESIGNATION	INVESTIGATION	EXAMPLE	DATA LOCATION
Sonic boreholes	SH14-1 series	KCB logged by Thurber	SH14-05	Attachment D1
Cone penetration soundings	CPT-100 series	Panel	CPT-101	Attachment D2
Resistivity Cone Penetration Test	RCPT14-100 series	Panel	RCPT-107	Attachment D2
Resistivity Cone Penetration Test	RSCPT14-1 series	KCB	RSCPT14-05	Attachment D2
Vane Shear Testing	VST14-100 series	Panel	VST14-111	Attachment D4
Vane Shear Testing	VST14-1 series	KCB	VST14-22	Attachment D4
Pressuremeter Testing	PMT14-100 series	Panel	PMT14-108	Attachment D5
Boreholes and Sampling	MR14-100 series RH14-100 series SC14-100 series	Panel	MR14-115 RH14-117 SC14-103	Attachment D6

4.0 PANEL PROGRAM OF WORK

4.1 FIELD MAPPING

Field mapping was completed by Thurber Engineering Ltd. (Thurber) under the direction of the Panel. The results of the field mapping are provided in Appendix C.

4.2 LOGGING OF KCB SONIC BOREHOLES

Sonic boreholes were completed by KCB between September 25 and October 27, 2014 using a track-mounted sonic drilling rig operated by Mud Bay Drilling Ltd. Boreholes were completed at 22 locations (SH14-01 to SH14-22). At locations SH14-01, 02, 05, 08, and 22 an additional borehole, labeled A, was completed adjacent to the initial hole. At location SH14-11, two additional boreholes, labelled A and B, were completed adjacent to the initial hole. These additional boreholes were completed for various reasons such as poor or no recovery in the initial hole, high disturbance of a particular sample zone and drilling equipment issues. Additional boreholes labelled A were also completed adjacent to SH14-03 and SH14-10 for the purposes of bulk sampling zones of particular interest. KCB site representatives logged and sampled each borehole. Boreholes were terminated by KCB upon reaching KCB's required depth.

An experienced geotechnical engineer from Thurber independently logged all of the KCB sonic holes in the field. These borehole logs are presented in Attachment D1. The soil profile shown on the logs is based on visual observations during drilling. Density and/or consistency descriptions in the logs were based on field observations of the highly disturbed sonic core sample. The consistency measured using vane shear test (VST) and/or cone penetration test (CPT) data can be higher than the consistency noted on the logs, which is another indicator of material sensitivity. At the direction of the Panel, no samples were obtained by Thurber for confirmatory laboratory testing. Instead, KCB took samples and performed lab testing. The Panel's photos of sonic core are in Appendix B.

Instrumentation, including piezometers and inclinometers, were installed in several sonic boreholes upon completion of drilling. Further discussion related to the instrumentation is provided in KCB's report to the MEM entitled "*Mount Polley Dam Failure, Site Investigation, Progress Report No. 1*" dated December 2014.¹

4.3 CONE PENETRATION TESTING

CPTs and resistivity cone penetration tests (RCPTs) were carried out by the Panel between October 15 and October 24, 2014 at 15 locations (CPT14-101 and 102 and RCPT14-103 to 115). Pore pressure dissipation tests were completed at select locations. The testing was completed by ConeTec Investigations Ltd. using a track-mounted cone pushing rig.

The Panel's CPT and RCPT profiling logs and pore pressure dissipation test results are respectively presented in Attachments D2 and D3 along with summary tables and location plans.

¹ KCB00001

4.4 ELECTRONIC FIELD VANE SHEAR TESTING

The Panel conducted in situ electronic field VST in select boreholes. The testing was carried out in general accordance with ASTM D2573, Standard Method for Field Vane Shear Test in Cohesive Soil and according to the manufacturer's instructions. The instrument used for the tests was manufactured by ConeTec Investigations Ltd. of Richmond, British Columbia.

A summary table, location plan and the vane shear test results are presented in Attachment D4. The vane shear test results were significantly impacted by the presence of gravel, which is interpreted to manifest as results that do not show a smooth curve. See section D6.7 for discussion related to comparing VST data with CPT data.

4.5 PRESSUREMETER TESTING

The Panel drilled mud rotary holes PMT14-105, 105A, 106 and 108 primarily to perform pressuremeter testing. Pressuremeter testing was carried out by In Situ Engineering in a pre-bored hole or "test pocket" using a mono-cell electronic pressuremeter equipped with a pressure sensor and three electronic displacement sensors spaced 120 degrees apart at the center of the instrument.

A summary table of the pressuremeter testing results, a location plan and a pressuremeter testing report by In Situ Engineering is presented in Attachment D5.

4.6 BOREHOLES

The Panel's boreholes were completed between October 16 and November 10, 2014 using a track-mounted drill rig operated by Geotech Drilling. Air rotary, mud rotary and core drilling techniques were used during the drilling program to set casing, obtain thin-walled tube samples and carry out vane shear and pressuremeter testing. All boreholes were grouted to the surface or to the base of the rockfill fill upon completion. The top portions of the holes drilled through rockfill were filled with drill cuttings and bentonite chips.

A total of 36 mud rotary holes were completed at 16 separate locations (MR14-101 to MR14-116). The MR-series borings, whose sole purpose was to obtain samples for testing, were typically not continuously logged. At many locations more than one mud rotary hole was completed to conduct additional undisturbed soil sampling, electric VST and pressuremeter testing within a zone of interest. Vane shear and pressuremeter testing results are respectively presented in Attachments D5 and D6 and discussed in further detail below. Continuous large penetration testing (LPT) was completed in MR14-116 and the recorded blow counts are presented on the logs.

Rotary holes were drilled using the odex drilling method to obtain undisturbed soil samples from specific zones at 2 separate locations (RH14-117 and RH14-118).

Undisturbed sampling with the Upper Till, described as firm to stiff, sandy silt with some gravel, proved challenging with thin walled samplers, particularly with respect to tip damage. Soil coring was completed at SC14-103 and C14-103A in an effort to obtain undisturbed samples of the upper firm to stiff, sandy silt. PQ and HQ sized triple tube core barrels were utilized, lined with acrylic liners. PQ soil coring, which creates a hole about 122 mm in diameter and provides a soil core of about 85 mm in diameter, was attempted using both air and fluid circulation methods. HQ soil coring, which creates a hole about 96 mm in diameter and provides a soil core of about 61 mm in diameter, was only attempted using fluid circulation methods. Recovery of samples using soil coring was poor and the sampling method was abandoned.

A summary of the completed mud rotary holes, rotary holes, soil coring holes, location plans and the mud rotary and soil core logs are presented in Attachment D6.

4.6.1 Thin-walled Tube Sampling

Various tube sampling methods/techniques were used to obtain samples during the borehole drilling with varying degrees of success. Methods employed included direct push of thin-walled tubes, piston tube sampling and the Pitcher Sampler. Pocket penetrometer and torvane testing was conducted in accordance with the manufacturer's instructions on the soil at the end of the tubes after retrieval of a relatively undisturbed sample. Results from this testing are shown on the logs as shear strength. The samples were sealed with hot wax, the ends filled with packing material to confine the sample, and purpose-built, plastic caps attached to the ends and fixed with duct tape or electrical tape.

As discussed above, sampling of the upper firm to stiff, sandy silt with some gravel, by pushing thin-walled tubes proved to be very difficult. Many sample tubes were damaged resulting in samples that were highly disturbed. The Pitcher Sampler was also used in this material but resulted in very poor recovery.

Relatively undisturbed samples were collected in soft to stiff silt and clay using the direct push and piston tube methods. Sampling was carried out in general accordance with ASTM D1587, Standard Practice for Thin-Walled Tube Sampling of Soils. Sample storage and transport to the lab was completed in general accordance with ASTM D4220.

Thurber field photos of tube samples are provided in Attachment D6.

4.7 LABORATORY INDEX TESTING

Soil samples retrieved from soil coring and thin-walled samplers were subjected to typical laboratory index testing, including moisture content determination, visual classification, grain size analysis, Atterberg limit testing and specific gravity testing.

A summary of laboratory index testing is presented in Attachment D7. The results in Attachment D7 include those completed for the mapping and core excavation investigations and are also presented in Appendix C.

5.0 KCB PROGRAM OF WORK

5.1 DRILLING, SAMPLING AND LAB TESTING

KCB completed a site investigation program concurrently with the program of work described above. KCB's program of work included sonic boreholes, CPT, VST, soil sampling and geophysics surveys. Factual data including laboratory index test results on soil samples from the sonic boreholes, CPT, VST and results of the geophysics surveys were provided to the Panel. The information provided is summarized below and the detailed information is presented in the attachments as indicated.

- **Cone penetration testing** – A summary table, location plan and the CPT profiling logs and dissipation test results are contained in Attachments D2 and D3.
- **Vane shear testing** – A summary table, location plan and VST results are contained in Attachment D4.
- **Sonic boreholes** – Index testing completed by KCB are contained in Attachment D7 and summarized in a format consistent with the index testing completed by the Panel. Data related to grain size and Atterberg limits were provided by KCB. Data related to moisture content were taken from the KCB sonic logs presented in KCB's December 2014 report.² Index testing data from KCB up to December 31, 2014 are included in the Attachment D7.

5.2 GEOPHYSICS

Frontier Geosciences (Frontier), under the direction of KCB, completed a seismic refraction and resistivity surveys. Frontier's interpreted data along with the raw data was provided to the Panel. The Panel retained DMT Geosciences (DMT) to review the raw data and provide an independent interpretation. The results of DMT's assessment are provided in Attachment D8.

² KCB00001

6.0 INTERPRETATION OF SITE INVESTIGATION DATA

6.1 GEOLOGICAL MODEL

Development of a geological model for the breach area is required for interpretation and presentation of site investigation results and for use in consolidation, stability and seepage analyses.

A geological model was developed from the following information sources:

- Observations collected during the site investigation
- In situ testing data
- Available literature on the quaternary geology of the Williams Lake area
- Imperial Metals exploration surficial geology documents
- Bedrock maps in the Mount Polley area available on the website of the B.C. Ministry of Energy and Mines.

The interpreted stratigraphic units in the vicinity of the breach based on the geological model developed by the panel are summarized in **Table D6.1.1**. The origin and depositional sequence of each sub-unit is discussed below.

TABLE D6.1.1: INTERPRETED STRATIGRAPHIC UNITS IN THE BREACH AREA

INTERPRETED GEOLOGIC UNIT	UNIT #	INTERPRETED GEOLOGIC SUB-UNIT
Upper Till	1	Surficial Silt - Possible Glaciolacustrine
	2	Moraine/Ablation Till - Desiccated Crust
	3	Moraine/Ablation Till - Softer
Upper Glaciolacustrine (Upper GLU)	4	n/a
Lower Tills	5	Grey Basal Till
	6	Lower Glaciolacustrine (Lower GLU)
	7	Glaciofluvial
	8	Grey over 'Maroon' Basal Till
Bedrock	9	Possible Fine Ash Tuff
	10	Brecciated Volcanics & Intrusions

6.2 PROBABLE DEPOSITIONAL SEQUENCE

The depositional sequence within the breach area is likely underlain by Triassic age bedrock of volcanic and plutonic origin (Nicola Group Volcanics and Mount Polley Intrusive Complex), which has been heavily hydrothermally altered and extensively brecciated and deformed by hydrothermal, volcanoclastic and/or glacial processes (Unit 10). Shearing and faulting during accretion of the volcanic arc terrane may also have modified the bedrock. A localized thick unit of hard silt and clay overlies the bedrock in one area of the breach site, interpreted as possible fine volcanic ash tuff (Unit 9). Discontinuous zones of sedimentary bedrock including sandstone with coal fragments were also encountered as inclusions within the modified volcanic deposits. The resulting complex modified bedrock was typically poorly lithified and weak, often resembling very dense or hard soil. Rock coring in the bedrock was not attempted during the current investigation.

Glacial processes dominate the quaternary deposits overlying the bedrock in this region. Ice direction from the most recent glaciation has been identified at the Mount Polley site to be approximately 310 to 320 degrees based on glacial features on outcrops and large-scale features including the surrounding lakes (McAndless & Taylor, 2005). As is typical in glaciated environments, the interpreted quaternary units were found to vary significantly and rapidly in elevation, thickness and composition.

A veneer of basal till of local origin overlies the bedrock (Unit 8), characterized by highly chemically altered sediments and relatively rounded particles, identified by McAndless & Taylor (2005) as "Maroon Basal Till" although the color varies significantly with alteration facies. Overlying this local origin till in some areas is a common grey basal till of mixed particle origin.

Overlying this basal till is a unit of grey glaciofluvial sands often with a distinctive odour of organic decomposition (Unit 7). This unit locally exhibits a gradual transition and interbedding with the Lower GLU deposit above including layers with higher organic content. This unit was interpreted by McAndless & Taylor (2005) to have been deposited at the ice front, possibly as a braided deposit including back channels with fines and organics.

The Lower GLU unit (Unit 6) is typically very stiff to hard and exhibits significant deformation of bedding where apparent (note that consistency referenced herein is as determined from CPT and VST data not from visual observations of disturbed core). Reworking of the deposit is likely to have occurred during glacier advance and deposition of the overlying till. Its occurrence and thickness appear to be controlled by the elevation of the bedrock and intermediate quaternary units which form a basin that was filled by the Lower GLU unit. Together the glaciofluvial (7) and Lower GLU (6) deposits may represent an interglacial period or ice recession.

Overlying the Lower GLU unit is a very stiff to hard basal till of mixed particle origin, identified by McAndless & Taylor (2005) as "Grey Basal Till" (Unit 5). CPTs typically met refusal or significant increases in tip resistance at the upper surface of this unit.

The Upper GLU deposit (Unit 4) is typically stiff to very stiff and contains zones of deformed bedding. It generally separates the Upper and Lower Tills but also occurs as a second zone within the Upper Till. Its structure ranges from thinly laminated to massive and is often interbedded with thin partings of sand. The variation in gradation is consistent with fluctuations in melt water inflow rates that occur in glaciated regions. This unit was notably free of organic material. It is possible this unit was deposited during an interglacial period, near an ice margin or in contact with ice. It may have been partly or wholly frozen during periods of glacial advance. The occurrence and thickness of the Upper GLU deposit appear to be controlled by the elevation of the upper surface of the Lower Tills which forms a basin or low point within the breach area.

The Upper Till layer is characterized by a weathered surface including organics and a stiff, likely desiccated crust (Unit 2), with a softening downward trend (Unit 3) and mixing with underlying soils. This till was identified as "Moraine Till" by McAndless & Taylor (2005) and is interpreted to be ablation or moraine till.

In several locations a surficial unit of silt exists overlying or included near the top of the ablation till (Unit 1), typically weathered and with organics - this deposit is possibly another glaciolacustrine unit. It was generally sub-excavated during foundation preparation in the breach area but was encountered in several holes where sub-excavation was incomplete or beyond the dam footprint.

At the time of the drilling investigation the native surface was typically obscured by anthropogenic deposits including in situ dam fill, slide debris (dam fill and tailings), stripping berms and road fills.

6.3 INTERPRETED GEOLOGICAL CROSS-SECTIONS

Interpreted geological cross-sections within the breach area are shown in Drawings D6 through D15. Drawings D6, D8, D10, D12 and D14 are cross-sections developed using a simplified soil profile. Drawings D7, D9, D11, D13 and D15 utilize a more complex soil profile with sub-units within the Lower Tills. Contours of Upper GLU thickness are presented in Drawings D16 and D17 and demonstrate the localized nature of the Upper GLU unit within the breach area.

The longitudinal cross-sections in Drawing D6 and Drawing D7 and thickness contours of Upper GLU on Drawing D16 and Drawing D17 illustrate the presence of the Upper GLU between about El. 919 m and El. 922 m localized within the breach area. The Upper GLU pinches out both longitudinally along the dam alignment on both sides of the breach and transversely to the dam alignment below the dam core and beyond the dam toe.

The more complex soil profile within the Lower Tills shows the complex glacially controlled depositional sequence at depth. The presence of the glaciofluvial layer is important with respect to consolidation and seepage analyses.

6.4 GEOTECHNICAL SOIL DESCRIPTIONS

6.4.1 General

For the purposes of the geotechnical interpretation the geologic model was simplified to the major and minor stratigraphic units shown in **Figure D6.4.1**.

FIGURE D6.4.1: INTERPRETED GEOTECHNICAL STRATIGRAPHIC UNITS

Major Stratigraphic Unit	Stratigraphic Sub-Unit
Upper Till	Upper Till
	Upper Glaciolacustrine (Upper GLU)
Lower Tills	Lower Basal Till
	Lower Glaciolacustrine (Lower GLU)
	Glaciofluvial
	Lower Basal Till
Weak Bedrock	Weak Bedrock

Additional discussion related to each soil unit is provided below and summarized in a table on Drawing D18. The borehole logs in Attachment D1 and laboratory testing results in Attachment D7 should be referred to for detailed information.

6.4.2 Upper Till

The Upper Till unit is present throughout the breach area and extends to the limits of the current investigation area. Thickness ranges from 2 m to 13 m and within the breach area is typically 6 m to 8 m. Along the post-breach whaleback feature it is apparently thickened by up to 5 m, even above the pre-breach ground surface.

This unit typically exhibits a desiccated very stiff to hard crust and is generally 4 m to 6 m thick within the breach area but as thin as 1 m locally. Below the crust the till typically softens downward to firm to stiff. This softening downward trend is generally less pronounced or absent beyond the lateral extents of the Upper GLU unit. The transition from the crust to the relatively softer till often occurs just below a colour change from grey-brown in the crust to grey below which may mark the desiccation/weathering boundary (refer to Figures D6.4.2A and D6.4.2B).

Approaching the boundary of the Upper GLU unit below, the Upper Till often exhibits a transition zone with a fining downward trend.

The Upper Till is highly variable in composition, ranging from sandy clay to sand and silt, with gravel content ranging from trace to gravelly including cobbles up to 150 mm and trace to some organics near surface. Soil structure is typically massive within the Upper Till. Index testing on the relevant fractions suggest moisture content varies from approximately 5% to 30% and the plasticity index varies from approximately 5 to 20.

CPT tip resistances (q_t) ranged as high as 120 bar in the desiccated crust and as low as 10 bar below the crust. SPT N values ranged as high as 20 in the desiccated crust and as low as 5 below the crust. Peak values for the CPT and SPT are likely influenced by the presence of gravel.

FIGURE D6.4.2A: UPPER TILL DESICCATED CRUST



FIGURE D6.4.2B: UPPER TILL



6.4.3 Upper GLU

The Upper GLU unit is generally present throughout the breach area within the former footprint of the downstream shell and toe of the dam. It pinches out to the southwest below the dam crest and to the northwest below the left abutment of the breached dam. To the southeast, the unit extends below the right abutment and pinches out approximately 230 m from the centre of the breach. To the northeast its full extents were not encountered during the current investigation however the trend suggests the unit pinches out approximately 140 m downstream of the setting out line (S.O.L.).

The thickness of the unit is greatest (exceeding 2.5 m) near the centre of the breach below the toe of the former dam footprint and extending approximately 100 m to the southeast below the right abutment. Refer to Drawings D16 and D17 for schematic contours of interpreted Upper GLU thickness.

Where present, the Upper GLU unit typically separates the Upper Till from the Lower Tills at approximate El. 919 m to El. 922 m but it was also encountered separately as a bedded layer or lens within the upper till at approximate El. 924 m. This higher occurrence was generally only encountered at or downstream of the whaleback toe feature and also at SH14-08 below the right abutment.

The Upper GLU unit typically consists of a firm to stiff, grey silty clay with trace gravel and trace to some sand in separate bedded layers. Index testing on the relevant fractions suggest moisture content varies from approximately 15% to 40% and the plasticity index varies from approximately 20 to 50 indicating the behavior is medium to high plastic.

The clay is moderately sensitive with a peak undrained shear strength of 90 to 140 kPa, residual 40 to 65 kPa, and remolded 20 to 35 kPa, as measured by in situ vane shear test. This unit typically has CPT tip resistances (q_t) ranging from 10 to 35 bars. Refer to advanced testing results for additional strength and consolidation information.

The soil structure is strongly bedded, typically thinly laminated but with high variability, including zones with no apparent bedding. Often where thinly laminated, the clay is interbedded with fine sand in partings and occasional laminations (note that laminated fine grained soils are sometimes referred to as varved, which is customarily used to refer to laminations as a result of seasonal deposition). The bedding as observed in the sonic core was apparently deformed in several locations. Deformation was typically observed to be more common and severe within the breach area. Distal to the dam footprint, the soil structure was generally horizontal and deformations were generally not visible or were minor (refer to **Figures D6.4.3A** and **D6.4.3B**).

Some of the observed deformations may be a result of, or modified by, the sonic drilling and sample extrusion methods. However, due to the inconsistent and non-systematic nature of the observed deformations, and based on previous experience with the sonic drilling method, it is unlikely that all of the observed features are drill induced.

Folding deformation of inter-bedded lacustrine deposits has been previously identified under the side slopes and near the toe of large constructed embankments, with an associated reduction in peak shear stress (Burlingame et al., 2013).

At SH14-03 the bedding near the top of the Upper GLU unit was inclined (see **Figure D6.4.3B**), which is consistent with the observations reported by KCB at TP14-01. At SH14-06 the bedding within part of the Upper GLU unit was observed to be severely deformed with overturned folds and chaotic bedding orientations that may be indicative of the zone of shear that was involved in the failure (see **Figure D6.4.3C**). See section 6 of the main report for further discussion related to the failure mechanism.

FIGURE D6.4.3A: UPPER GLU OUTSIDE BREACH AREA



FIGURE D6.4.3B: UPPER GLU WITHIN BREACH AREA



FIGURE D6.4.3C: POSSIBLE SHEAR ZONE IN UPPER GLU



6.4.4 Grey Basal Till (Sub-unit of Lower Tills)

Two stratigraphically distinct basal tills exist within the Lower Tills suite, the uppermost of which is here described as grey basal till for clarity (refer to section 6.4.7 for the lowermost). The grey basal till is generally present throughout the investigated area and varies in thickness up to 7 m though it is indistinguishable from the Upper Till where the softening downward trend in the Upper Till and the Upper GLU unit are absent. Within the breach area, the grey basal till is often less than 1 m thick and is notably absent at SH14-07 below the dam crest and at SH14-15.

Similar to the Upper Till, the grey basal till is highly variable ranging from very stiff to hard sandy clay to very dense sand and silt, with gravel content ranging from trace to gravelly, including cobbles up to 150 mm. Soil structure is typically massive within the grey basal till as shown in **Figure D6.4.4**. Index testing on the relevant fractions suggest moisture content varies from approximately 5% to 20% and the plasticity index varies from approximately 5 to 20.

CPT tip resistances (q_t) ranged from as low as 20 bar to over 200 bar. Peak values for the CPT are likely influenced by the presence of gravel.



6.4.5 Lower GLU (Sub-unit of Lower Tills)

The Lower GLU unit (Lower GLU) is generally more laterally extensive than the Upper GLU unit extending, throughout the breach area from the upstream to the downstream limits of the investigation area. It pinches out to the northwest below the left abutment and to the southeast below the right abutment though it returns at the far southeast limit of the investigation area near design Section D. The thickness of the unit varies significantly to a maximum of 6 m, which occurs near the centre of the breach below the former dam toe footprint.

The Lower GLU generally consists of very stiff to hard, grey (occasionally brown), clayey silt to silty clay with trace to some fine sand and a trace of gravel (possibly drop stones). This unit occasionally includes thin fine sand laminations and fine organics where it grades into the glaciofluvial unit below (see **Figure D6.4.5B**). Index testing on the relevant fractions suggest moisture content varies from approximately 10% to 30% and the plasticity index varies from approximately 10 to 30, indicating the behavior ranges from low to high plastic. CPT tip resistances (q_t) ranged from as low as 30 bar to more than 200 bar.

Soil structure in the recovered soil core was typically bedding that was highly variable and deformed in all locations where it was encountered (see **Figure D6.4.5A** and **D6.4.5B**). This contrasts with the Upper GLU that typically did not exhibit deformation distal to the breach. Occasional slickensides in random orientations are typical of this deposit. After careful review of the logs and sections, it was concluded that the slickensides are not continuous.

FIGURE D6.4.5A:
LOWER TILLS – LOWER GLU



FIGURE D6.4.5B:
LOWER TILLS – LOWER GLU



6.4.6 Glaciofluvial (Sub-unit of Lower Tills)

The glaciofluvial unit is generally present throughout the investigated area except at SH14-05, SH14-07 and SH14-16. The thickness of this unit ranges significantly but within the breach area is generally between 2 m and 4 m.

Compositionally, the glaciofluvial unit ranged from relatively clean sand and gravel mixtures, to fine sand and silt with fine organics. Typical particle size and grading varied significantly between and within beds (see **Figures D6.4.6A** and **D6.6.6B**). Colour ranged from dark grey (especially where organics present) to brown. Index testing on the relevant fractions suggest moisture content varies from approximately 10% to 25%, and the plasticity index (where measured) was 4 or less, indicating the behavior is generally non-plastic. CPT tip resistances (q_t) ranged from 80 bar to more than 200 bar, indicating this unit is compact to very dense. In several locations within the breach area this unit exhibited minor artesian pore water pressures especially at SH14-18.

Glaciofluvial deposits typically consisted of beds of highly variable thickness with some thick laminations in silty zones where depositional energy was apparently reduced especially approaching the lower surface of the overlying Lower GLU unit.

FIGURE D6.4.6A: LOWER TILLS – GLACIOFLUVIAL



FIGURE D6.4.6B: LOWER TILLS – GLACIOFLUVIAL



6.4.7 Maroon Basal Till (Sub-unit of Lower Tills)

Two stratigraphically distinct basal tills exist within the Lower Tills suite, the lowermost of which is here described as maroon basal till for clarity (refer to section 6.4.4 for the uppermost). The maroon basal till is present throughout the investigated area (where it was within the depth investigated), except at SH14-03 and SH14-22. It varies significantly and rapidly in thickness, reaching a maximum of 9 m, but is typically less than 3 m thick within the breach area.

The maroon basal till varies significantly in colour across the investigated area, and within a given test hole, from red to green to grey to yellow in hue. Its varied colours reflect the alteration of the parent materials, which are likely derived from the surrounding meta-volcanic bedrock. The bedrock itself exhibits variable grades of alteration consistent with the proximity to an ore body. The maroon basal till often grades upward into a common grey basal till.

Similarly to the other tills, this till consists of variable mixtures of sand and silt with clay and gravel fractions varying from trace to clayey/gravelly, typically massive in structure with occasional shear banding infilled with very stiff clay. In many cases, the transition from this lowermost till to the interpreted bedrock below was gradual and marked only by the change from typically rounded coarse particles to typically angular coarse particles.

The basal till was very stiff to hard in consistency within the sonic core sample with CPT tip resistances ranging from 100 to 300 bars in the few locations where it was measured. Index testing within this unit was less frequent, but where available the moisture content varies from about 5% to 30%.

FIGURE D6.4.7: LOWER TILLS – MAROON BASAL TILL



6.4.8 Bedrock

The apparent bedrock surface was reached in all but one of the sonic drill locations (SH14-13) ranging from El. 925 m to El. 891 m across the investigation area. The bedrock elevation within the breach area is relatively consistent, varying from about 909 m to 915 m forming an apparent bench-like feature. The bedrock surface rises gradually upstream and downstream of the breach area and rises relatively quickly towards the left abutment consistent with pre-construction surface topography. To the south and southeast, below the right abutment, the bedrock surface drops relatively quickly.

The bedrock within the investigation area varies significantly and rapidly between and within test holes. Intact competent bedrock was not encountered during the current investigation. The interpreted bedrock was identified by a transition to angular particles though the composition and consistency was often similar to the overlying till. Bedrock in the area has apparently been heavily modified and disturbed by tectonic deformation, hydrothermal alteration, intrusion and multiple glaciations. As a result the bedrock was observed to be substantially brecciated, altered, sheared, veined, and deformed.

Diamond coring was not part of the current investigation. Nevertheless, the sonic core recovery suggests that the Rock Quality Designation (RQD) of the bedrock encountered was typically zero, though disturbance from the sonic drill action is likely significant. Typically the bedrock encountered was weak to very weak, disintegrating when handled or easily cut with an edge, often strongly resembling hard or very dense soil.

The primary type of bedrock encountered was a form of volcanic basalt breccia, typically matrix supported and heavily sheared and altered (see **Figure D6.4.8A**). Coarse angular basalt fragments were often friable but intact particles were moderately strong. Intrusions of highly weathered igneous rock were apparent in several test holes. The igneous zones had generally disintegrated into angular sand composed of phenocrysts (see **Figure D6.4.8B**). Sandstone inclusions were encountered within the volcanic breccia, often with coal fragments (see **Figure D6.4.8C**). In SH14-03, SH14-06, SH14-08, SH14-09 and SH14-14 a zone of hard clay to soft claystone was encountered that was interpreted as a volcanic fine ash tuff (see **Figure D6.4.8D**). The tuff ranged in thickness from 2 m to more than 30 m where encountered. The tuff was typically fine grained, with occasional inclusions of volcanic breccia, and often with a greenish hue consistent with chloritic alteration. Veining and discontinuous random slickensides were also typical of the volcanic tuff along with higher moisture contents of 30 to 55% (see Attachment D9). These higher moisture contents reflect alteration of the bedrock that is nevertheless stronger than the overlying deposits.

Index testing and CPT were generally not completed within the bedrock. Where results exist the CPT tip resistance (q_t) ranged from 100 to 300 bars until refusal. CPT was not attempted within the volcanic fine ash tuff zones.

FIGURE D6.4.8A: WEAK BEDROCK – VOLCANIC BRECCIA



FIGURE D6.4.8B: WEAK BEDROCK – VOLCANIC FINE ASH TUFF



FIGURE D6.4.8C: WEAK BEDROCK – IGNEOUS TEXTURE



FIGURE D6.4.8D: WEAK BEDROCK – SANDSTONE INCLUSION



6.5 DISCUSSION

6.5.1 Slickensides

All observations of slickensides noted in the post-breach sonic holes were compiled in **Table D6.5-1** to examine spatial distribution and potential continuity. Slickensides noted within the Lower GLU occurred as localized features at random orientations. Slickenside features noted within the weathered bedrock were typically within volcanic tuff. No slickenside features were observed within the LPT or extruded thin-walled tube samples.

TABLE D6.5.1: SUMMARY OF OBSERVED SLICKENSIDES

LOCATION	HOLE NO.	ELEVATION (m)	SOIL UNIT
Within Breach	SH14-08/08A	926.5	Upper Till
	SH14-08/08A	921.0	Upper GLU
	SH14-16	919.5	Lower GLU
	SH14-09	916.0	
	SH14-08	906.5	Basal Till
	SH14-08	900	Weathered Bedrock
	SH14-09	899.5	
	SH14-09	877.5	
Outside Breach	SH14-17	922.5	Basal Till
	SH14-18	918.5	Weathered Rock

After careful review of the logs and sections, it was concluded that slickensides within the area investigated are not continuous.

6.5.2 Comparison of CPT Tip Resistance and Moisture Content

CPT tip resistance values (q_t) from SH14-01 to SH14-16 were plotted versus elevation with the results of moisture contents completed by KCB on samples obtained from adjacent sonic holes.

The results of the comparisons are provided in Attachment D9, along with the inferred soil units. Note that SH14-01, 08 and 13 include moisture content results to a greater depth than other holes and the comparison at these locations are repeated showing test results for the full depth.

Results of the comparisons show that high moisture contents are found in a majority of the sonic holes between about El. 919 m to El. 922 m. Sonic hole log descriptions generally indicate laminated glaciolacustrine unit generally between about El. 919 m and El. 922 m.

Higher moisture contents are also present in the volcanic tuff as discussed above.

6.5.3 Review of Field Sensitivity Using CPT Tip Resistance

Field sensitivity was examined by comparing CPT tip resistances measured within and outside the breach area, based on the assumption that CPTs completed outside the breach area are representative of peak strength conditions and CPTs completed inside the breach area are representative of remolded strength conditions induced as a result of the failure. Summary plots are contained in Drawing D19 and indicate the Upper GLU between El. 920 m and El. 922 m has a sensitivity between about 1.0 and 3.0.

6.5.4 Correlations to Undrained Strength and Stress History

The CPT profiling data was subjected to advanced interpretation and is presented on plots that include CPT tip resistance (q_t), peak undrained shear strength (s_u), preconsolidation pressure (σ'_p), overconsolidation ratio (OCR) and interpreted geological unit versus elevation. The advanced interpretation for both the Panel and KCB CPT data are included Attachment D10.

Peak undrained shear strength estimated using CPT data was calculated using an average N_{kt} value of 15. The average N_{kt} value was determined by reviewing specific CPT-vane shear test correlations at VST14-105, -106 and -107 and then taking an overall average. A comparison of the actual versus computed vane shear strengths is also presented in Attachment D10.

Preconsolidation pressure (σ'_p) was determined using Figure 3-13 of the Electric Power Research Institute's (EPRI) *"Manual on Estimating Soil Properties for Foundation Design"* (Kulhawy and Mayne, 1990). This correlation uses excess pore water pressure induced during cone penetration to calculate a preconsolidation pressure. Where the excess pore pressures are low or negative, a preconsolidation pressure less than the vertical effective stress can be calculated. Where the preconsolidation pressure was estimated to be less than the vertical effective stress, it was not plotted.

Overconsolidation ratio (OCR) was determined using the calculated σ'_p and the vertical effective stress (σ'_v). Vertical effective stress (σ'_v) was determined based on available existing surveyed ground elevation assuming an in situ unit weight (γ) of 21 kN/m³. The ground water table was assumed to be at El. 932 for RCPT14-101 and -102, El. 930 for RCPT14 103 to -105 and at ground surface for RCPT14-106 to -112. The ground water table for RCPT14 101 to -105 was based on KCB's piezometer data.

Preconsolidation pressures estimated from Panel oedometer testing are also presented on the plots for MR14-105, MR14-106, MR14-107, MR14-110, MR14-111 and MR14-113 and show reasonable agreement with the interpreted CPT data for the Upper Till and Upper GLU. The comparison between the interpreted CPT data and the oedometer data for the Upper GLU is shown on Drawing D20.

A comparison of the longitudinal variation in CPT tip resistance within the upper and Lower GLU units is also presented on Drawing D21. The tip resistance is lowest within the Upper GLU in the breach area.

6.5.5 Stratigraphic Variation of Upper and Lower GLU Units

Drawing 22 was prepared to obtain a broader perspective of the stratigraphic variations on a larger scale. The historical boreholes logs (GW96-1A/B and VW11-10) used on Drawing D22 are included on Drawings D23 and D24.

The Upper GLU at the breach shows apparent similarities to glaciolacustrine soils at similar elevation in GW96-1A that would be characterized as soft to medium according to their SPT blowcount of 6 (Kulhawy and Mayne, 1990). On the other hand, the uppermost GLU layer encountered in VW11-10 has an average water content of 23%, which corresponds closely to that of the Lower GLU shown in the table on Drawing D18.

These illustrations of both small-scale and large-scale variation in stratigraphy and properties of the GLU materials serve to highlight the complexity that their depositional environment produced. This degree of geologic complexity discourages attempts at broader generalization beyond the immediate areas where subsurface data have been obtained.

- **Table D.2-1:** Summary Of Available Boreholes (BH), Test Pits (TP) and Cone Penetration Test (CPT) Information

Appendix D: Drawings

- **Drawing D1:** Pre-breach Subsurface Investigation Summary
- **Drawing D2:** Subsurface Investigation 1996 and Prior
- **Drawing D3:** Locations Greater Than 3M Depth Pre-Breach Subsurface Investigation With In Situ or Lab Testing Data
- **Drawing D4:** Post-Breach Subsurface Investigation Summary
- **Drawing D5:** Pre-Breach Subsurface Investigation In Breach Area
- **Drawing D6:** Geological Section 6 - Simple
- **Drawing D7:** Geological Section 6 - Complex
- **Drawing D8:** Geological Section 4 - Simple
- **Drawing D9:** Geological Section 4 - Complex
- **Drawing D10:** Geological Section 5 - Simple
- **Drawing D11:** Geological Section 5 - Complex
- **Drawing D12:** Geological Section 3 - Simple
- **Drawing D13:** Geological Section 3 - Complex
- **Drawing D14:** Geological Section 7 - Simple
- **Drawing D15:** Geological Section 7 - Complex
- **Drawing D16:** Upper Glaciolacustrine Thickness Contours With Post-breach Ortho Photo
- **Drawing D17:** Upper Glaciolacustrine Thickness Contours With Post-breach Topography
- **Drawing D18:** Geotechnical Properties Summary Table
- **Drawing D19:** Review of Field Sensitivity Using CPT Tip Resistance
- **Drawing D20:** Comparison of Interpreted CPT Data To Oedometer Data In Upper GLU
- **Drawing D21:** Longitudinal Variation in CPT Tip Resistance
- **Drawing D22:** Upper GLU And Lower GLU
- **Drawing D23:** GW96-1A / 1B Bore Hole Log
- **Drawing D24:** VW11-10 Bore Hole Log

List of Attachments

- **Attachment D1:** Thurber Logs of KCB Sonic Holes
- **Attachment D2:** Panel And KCB CPT Profiling Data
 - *Panel CPT Profiling Data*
 - *Panel CPT Profiling Standard Plots*
 - *Panel CPT Profiling Resistivity Plots*
 - *KCB CPT Profiling Data*
 - *KCB CPT Profiling Standard Plots*
 - *KCB CPT Profiling Resistivity Plots*
 - *KCB CPT Profiling Seismic Plots*
- **Attachment D3:** Panel and KCB CPT Dissipation Data
 - *Panel CPT Dissipation Data*
 - *KCB CPT Dissipation Data*
- **Attachment D4:** Panel And KCB Vane Shear Testing Data
 - *Panel Vane Shear Testing Data*
 - *KCB Vane Shear Testing Data*
- **Attachment D5:** Panel Pressuremeter Testing Data
- **Attachment D6:** Panel Boreholes and Sampling
 - *Panel Borehole Logs*
 - *Field Photos of Tube Samples*
- **Attachment D7:** Panel and KCB Laboratory Index Testing
 - *Panel Laboratory Index Testing*
 - *KCB Laboratory Index Testing*
- **Attachment D8:** DMT Geophysics Interpretation
- **Attachment D9:** CPT Tip Resistance and Moisture Content Comparison
- **Attachment D10:** CPT Correlations to Undrained Strength and Stress History)