Appendix C

Geotechnical Analysis Report

Geotechnical Analysis for Sio Silica Extraction Project

Project # 129500426

January 14, 2022

Prepared for:

Sio Silica Corporation

Prepared by:

Stantec Consulting Ltd.

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Executive Summary

Sio Silica Corporation (Sio Silica) formerly CanWhite Sands Corp. retained Stantec Consulting Ltd. (Stantec) to complete geotechnical analyses for caprock stability following sand extraction at the BRU property located 52 km east of the city of Winnipeg, Manitoba (the Project Site). The Project Site includes Sio Silicas operating area for the first 5 years. This report presents the information sources, site conditions, design basis, and methodologies used to complete the analyses as well as the analyses results, conclusions, and recommendations.

Sand extraction will utilize an airlift extraction technique that involves drilling through the quaternary till, carbonate limestone and shale, into the underlying Carman Sand. Boreholes will be cased and grouted, isolating overlying aquifers from the Winnipeg Formation. Air will then be circulated in the casing to extract Carman Sand.

Stantec previously analyzed the caprock and extraction cavity shear failure mode stability. Sio Silica has since gathered additional information to close gaps and support analyses of other failure modes identified by Stantec. As the additional information and subsequent analyses impacts results, this report presents the combined and updated geotechnical analyses design basis, results and recommendations.

The site geology includes a Quaternary overburden on a carbonate Limestone and a shale layer under the Limestone on top of the target Carman Sand. The groundwater in the area includes upper and lower aquifers with an upper to lower gradient between 0 and 0.072 (AECOM 2021). The short-term horizontal gradient toward the extraction location in the lower aquifer is estimated to be less than 0.1. The Project site is located in a low seismicity area.

The caprock intact strength and deformation parameters are estimated based on the laboratory, field and borehole logging data. Review of the site investigation and laboratory data concluded that the competent limestone caprock has an average estimated Geological Strength Index (GSI) of 60.8 with a lower quartile GSI of 60. Laboratory testing on rock from boreholes provided average tensile strength and Unconfined Compressive Strength (UCS) values of 5.3 MPa and 68.1 MPa, respectively. The laboratory strength data was downsized to consider long-term stress effects (creep) on strength as well as the size effect of laboratory test samples versus the in-situ rock. The Carman Sand properties were back-calculated using the cavity size and shape result from the Side Scan Sonar survey data. The analysis showed that the in-situ sand has cohesion which contributes to short-term vertical extraction cavity walls.

Acoustic and optical borehole imaging shows that the competent limestone has no cross-joints and is sub horizontally layered. The Side Scan Sonar data shows that extraction cavities are partially in-filled by fines and loose sand following extraction. The extraction cavity was approximately axisymmetric in one borehole while it had a preferential expansion from the SW to NE direction in another. Surface subsidence monitoring around three of the extraction wells detected at or near zero deformation after extraction.

Stantec developed the basis of geotechnical design to meet the short- and long-term stability requirements for the extraction cavity and caprock. The analysis is completed to identify stable allowable extraction cavity sizes as well as distances between extraction boreholes and multi-borehole patterns that will not generate surface subsidence and to eliminate potential for connection to occur between the upper and lower aquifers as a result of caprock subsidence. The target design stability factor of safety (FoS) of 2.0 was selected based on the long-term stability requirement.

A review of the failure modes based on the updated information concluded that the potential failure modes for the extraction cavity and caprock stability are Shear (caprock shearing into the cavity) and Bending (separation of the limestone bedding (beams) and failure into the cavity).

The Shear Failure mode analysis concluded that the allowable long-term unsupported span (cavity size) varies between 35 m and 60 m for the expected range of caprock and overburden thickness. The Bending Failure mode controls stability and analysis concluded that the allowable long-term unsupported span varies between 24 m and 50 m. The minimum required distance between boreholes or multi-hole patterns was identified as 60 m for the long-term scenario.

Based upon the results of geotechnical assessment and with the understanding that Sio Silica will follow guidance provided by Stantec including continuing to assess the geotechnical characteristics and performance of the sand deposit and overlying materials during the project life and to adjust design accordingly, no large scale surface subsidence is expected to occur as a result of sand extraction.

Based upon the geotechnical analysis, the following recommendations are provided:

- Design the borehole arrangement and depth to limit the extraction disturbance geometry to the design extraction geometry presented in Table 9 in this document.
- Limit extraction to areas with competent limestone thicker than 15 m.
- Locate extraction group wells with at least 60 m edge to edge distance between their expected long-term cavity disturbance zone (approximately 70 m for short-term cavity disturbance zones)
- Complete a full-scale extraction test to confirm conditions with pre-extraction measurement and monitoring requirements listed in this report.
- Update the FLAC model as more data becomes available for the extraction boreholes and surface settlement data.
- Measure the overburden, caprock, competent limestone, and sand thickness at each extraction location before the start of extraction. Apply the relevant extraction design based on the recommendations in Section 3.9 or the refined design as needed based upon full-scale extraction testing results.
- Follow the monitoring guidance provided in this report, including development and use of a Trigger Action Response Plan (TARP) for extraction locations. This includes surface, caprock and piezometric monitoring and review during and after extraction.

1.0 INTRODUCTION

1.1 TERMS OF REFERENCE

Sio Silica Corporation (Sio Silica) formerly CanWhite Sands Corp. plans to extract silica sand from the Carman Sand Member of the Winnipeg Formation at the BRU Property (Project Site). The Project Site includes Sio Silica's operating area for the first 5 years of operations. The center of the site is located approximately 52 km east of the city of Winnipeg, Manitoba, within the Rural Municipality of Springfield.

Stantec Consulting Ltd. (Stantec) was retained by Sio Silica to complete geotechnical analyses and design to assess the potential for surface subsidence to occur in response to sand extraction and to identify maximum unsupported cavity spans and minimum distances between boreholes and extraction areas. Stantec previously completed preliminary geotechnical analyses which focused on the shear failure mode with simplified assumptions for the subsurface cone of depression to be generated in the Carman Sand Member by the sand extraction process and the caprock thicknesses greater than 15 m. Stantec identified other potential failure modes including bending during the preliminary review. Stantec also identified uncertainties related to the long-term stability of the extraction cavity and reliance on the caprock for seepage controls between upper and lower aquifers. Sio Silica gathered additional information to address uncertainties and allow for analyses of additional failure modes. This report presents the geotechnical analyses results for the Project Site which includes:

- Review of site conditions
- Review and update of the basis of design and design criteria
- Review of failure modes
- Failure mode analyses
- Results and Recommendations

1.2 INFORMATION SOURCES

The information sources used to complete this geotechnical assessment are as follows:

- Borehole logs and point load testing (PLT) results (for drilling carried out by Sio Silica and borehole logging and PLT completed by Stantec)
- Laboratory testing results
- Acoustic Borehole Imaging (ABI) and Optical Borehole Imaging (OBI) survey results
- Side Scan Sonar survey results
- Previous FLAC (Fast Lagrangian Analysis of Continua) shear failure mode modeling

2.0 BACKGROUND INFORMATION

2.1 MINING METHOD DESCRIPTION

The BRU extraction process will utilize an airlift extraction technique that involves vertical drilling through the quaternary sediments, carbonate unit and shale, into the underlying sand. The extraction boreholes will be cased to the top of the sand and extraction casing will be lowered into the sand. The boreholes will be grouted, isolating overlying aquifers from the Winnipeg Formation. Air will then be circulated in the extraction casing, approximately 10 m to 15 m above the bottom of the casing. By circulating compressed air into the bottom of boreholes through unconsolidated and consolidated geological formations, drill cuttings (sand) can be extracted (AECOM, 2021). An injection process will return the majority of the groundwater that is withdrawn with the sand during the extraction process. This will occur underground through the borehole without the use of high pressure. Finally, boreholes will be progressively decommissioned to comply with the Manitoba *Groundwater and Water Well Act* and its supporting regulations.

2.2 GEOLOGY

The stratigraphy of the Project Site consists of Quaternary sediments, carbonate and shale intervals of the Red River Formation, unconsolidated sand, sandstone, and shale of the Winnipeg Formation, and Archean-age granitoid basement rock (Table 1). The upper unconsolidated sand interval of the Winnipeg Formation, which is known as the Carman Sand Member, is the target interval for extraction. This unit is dominantly an unconsolidated laterally extensive unit across the property, as confirmed through previous drilling campaigns.

Table 1: Project Site Lithology

Eon	Era	Period	Geologic Unit	Member	Lithology	Role/Impact on Stability
Phanerozoic	Cenozoic	Quaternary			Diamicton (Till)	Overburden Load
	Paleozoic	Ordovician	Red River Formation	Selkirk, Cat Head, Dog Head Members	Carbonate (Limestone)	Supporting Caprock
					Shale	Not Supporting
			Winnipeg Formation	Carman Sand Member	Sand	Target Extraction Zone
				Equiv. Ice Box Member	Shale	Not Drilled
				Black Island Member	Sand	Not Drilled
Archean					Granitoid	Not Drilled

Quaternary

The Pleistocene-aged diamicton (till) is heterolithic, varies in material size distribution from silty to rocky, and typically has a calcareous component. In the Project Site area, the diamicton ranges from 5 m to 43 m in thickness.

This member imparts load on the underlying rock units and is not considered to be a supporting member for stability analysis.

Red River Formation

Carbonate

The carbonate member, which is upper Ordovician in age, is in the lower Red River Formation. In Southern Manitoba, this member includes the Dog Head, Cat Head, and Selkirk members (Natural Resources Canada, 2015). The member varies in composition from limestone to dolostone, contains bedding-parallel fractures, and is vuggy in areas. Commonly, the bottom 1 m to 5 m interval contains shale interbeds with an argillaceous carbonate which occurs directly above the shale interval. Based on reliable drill holes, the carbonate total thickness ranges from 0 m to 48 m at the Project Site.

The uppermost and lowermost portions of this member may be fractured at the contact with overlying and underlying members, respectively. For the stability analysis, only the massive intact (middle) portion of the carbonate/Limestone member was considered as supporting overburden and resisting settlement.

Shale

A shale member occurs directly beneath the carbonate. This shale forms the base of the Red River Formation and is proposed to be part of the Dog Head Member. This shale is highly fractured and friable. The colour of the shale varies through the interval, including brick red, greyish green, and bluish grey colourations. This shale interval, based on reliable historic boreholes as well as the 2017 and 2018 drill campaigns, varies in thickness from 0 m to 11 m.

This is a weak member and is not considered to be providing support to resist failure for stability analysis.

Winnipeg Formation

Sand

The sand encountered directly beneath the base of the Red River Formation is the Carman Sand Member (Natural Resources Canada, 2009a,b). The Carman Sand Member is in the upper section of the Winnipeg Formation. The Winnipeg Formation, which in southwestern Manitoba is at the base of the Williston Basin strata, is composed of interbedded sands and shales (Lapenskie, 2016). These sediments were deposited during the Middle Ordovician, in shallow marine seas. The Carman Sand Member is typically uncemented, well sorted, well-rounded, and typically has a fine to medium grain size. The Carman Sand Member in the Property was measured to have thicknesses varying between 20 m and 23 m. A basal cemented sandstone that typically ranges in thickness from 0.3 m to 0.5 m, was encountered in boreholes BH-02-17, BH-10-17, and BH-14-17.

This is the target member for sand extraction where cavities will form during extraction.

Shale

A shale occurs directly beneath the Carman Sand Member. This shale is proposed to be equivalent to the Ice Box Member, which occurs as the middle member in the Winnipeg Formation in North Dakota and Saskatchewan (Natural Resources Canada, 2004). The colouration of this shale varies significantly, including emerald green and dark brown colouration. The test drilling of this shale was slow, supporting that the material is more competent than previously encountered members. The thickness of this shale interval in the Project area, based on reliable drill holes that penetrated the entire member, varies from 1 m to 24 m in thickness.

This member will not be drilled during extraction and is not expected to play a role in stability.

Sand

An unconsolidated sand member below the shale interval is proposed to be equivalent to the Black Island Member (Natural Resources Canada, 2009c). On the Property, it is approximately 1 m thick, and is fine-grained, well sorted, and well-rounded. Commonly a cemented sandstone occurs either above or below this unconsolidated sand. This sandstone interval, where encountered, typically ranges in thickness from 0.3 m to 0.6 m.

This sand layer is not the target of the sand extraction. This member will not be drilled during extraction and will not play a role in stability.

Granitoid

Granitoid basement, which is Archean in age, is altered and in areas contains disseminated pyrite.

This member will not be drilled during extraction and will not play a role in stability.

2.3 GROUNDWATER

Currently, there are two aquifers in the Project Site , the Red River Carbonate aquifer and the Winnipeg Sandstone aquifer. These aquifers will be isolated from drilling and extraction by casing and grouting each borehole. Modeling results from the hydrogeological study (AECOM, 2021) using existing data supplemented by on-site pump test data obtained in 2020 and 2021 determined that effects on groundwater quantity are anticipated to be relatively small, local, temporary and reversible, with groundwater levels simulated to recover shortly (20 to 80 days) with approximately 80% recovery approximately two days after operations end each year.

The estimated vertical gradients from upper to the lower aquifer varies between 0 and 0.072 at the Project Site. Assuming the drawdown of 10 m at the extraction location, the short-term horizontal gradient toward the extraction location in the lower aquifer is estimated to be less than 0.1.

2.4 SEISMICITY

The Project Site has a low seismic hazard level (2015 Seismic Hazard Map, Geological Survey of Canada, Appendix A).

Seismic hazard values from the 2015 National Building Code Seismic Hazard Calculation were used for the seismic hazard calculation (NRC, 2021). A summary of the NRC 2021 calculation output is included in Appendix A. Peak horizontal ground accelerations and corresponding return periods are shown in Table 2.

Table 2: Seismic Hazard Summary

Return Period (Years)	Probability of Exceedance (%) (1)	Peak Ground Acceleration (PGA) (g) (2)
100	40	0.002
475	10	0.009
1000	5	0.016

Notes:
1. For Design Life of 50 Years.
2. PGA obtained from 2015 seismic hazard calculator from the Natural Resources Canada website.

Due to the low seismic hazard level for the area, seismicity is estimated to have a low probability for impacting stability of the Project Site.

2.5 SITE INVESTIGATIONS

Sio Silica previously completed site investigation programs including borehole drilling within the BRU and directly adjacent DEN properties. Sio Silica exploration drilling programs included 6 boreholes drilled in 2017, 18 boreholes drilled in 2018 - 2019 and 15 boreholes drilled in 2020 – 2021 (see location of geotechnical and other boreholes in Appendix B, Figure B-1).

The 2017 drilling campaign was used to recover and collect samples of the Carman Sand Member. All holes were drilled vertically, and therefore the sample length is the true thickness of the Carman Sand Member. The 2018 to 2019 drill campaigns included boreholes to identify formation tops and constrain sand samples and others for extraction tests and aquifer monitoring. Twelve holes were drilled vertically in the BRU property in 2020 to 2021 to develop extraction design, collect geotechnical and hydrological data and to complete sand, limestone and shale monitoring wells. The final three boreholes drilled in 2021 were completed in the DEN property to further assess the integrity of the caprock.

The 2018 and 2021 drilling programs provided the majority of geotechnical data to support the analysis. These programs included geotechnical core logging, core photography, Point Load Testing, core sampling for later laboratory testing, and borehole data quality assurance and quality control. Many additional geological boreholes were completed and logged by Sio Silica and others (Friesen Drillers and AECOM) and results were used to confirm continuity of site geologic conditions (see Figure B-1).

2.5.1 Borehole Drilling Results

Drilling and laboratory testing data was reviewed to assess the Geological Strength Index (GSI), based on Rock Mass Ratings (RMR). The analysis incorporated results from geotechnical tests conducted on the overlying carbonate unit (Limestone) as the performance of this unit is considered to be the governing factor in the analysis. Table 3 presents results which demonstrate that the carbonate unit has an average GSI of 60.8. The most recent RMR values from the 2021 DEN drilling campaign were not included in the GSI calculation, as competent limestone depths were not tested for these sampling intervals.

Table 3: Borehole Information used to Calculate Design GSI

Borehole ID	Total Limestone Thickness (m)	Competent Limestone Depth Range (m)	Competent Limestone Thickness (m)	Most Likely Estimated GSI
BH 10-17	19.81	35.18 - 54.21	19.03	65.0
BRU 121-1	12.80	22.25 - 35.05	12.80	57.5
BRU 146-1	14.33	34.73 - 48.77	14.04	60.0
BRU 95-8	16.47	35.94 - 48.13	12.19	60.3
DEN 216-1	21.34	41.57 - 62.79	21.22	61.3
		Average	**15.90**	**60.8**
		Standard Deviation	**4.00**	**2.70**
		Lower Quartile	**12.80**	**60.0**
Note: Average GSI values for Limestone in three additional boreholes drilled in the DEN property (DEN 117-1, DEN 120-1, and DEN 204-1) is estimated to be 70 for dry conditions and 65 for wet conditions				

2.5.2 Laboratory Test Results

Core samples were collected from boreholes in the site investigation programs to quantify material strength parameters. The testing carried out for the caprock analyses included the following:

- Brazilian Tensile Strength Tests following ASTM D3967
  - 6 samples tested from 2018 drilling
  - 28 samples tested from 2020 drilling (BRU 95-8)
  - 37 samples tested from 2021 DEN drilling
- Uniaxial Compression Tests following ASTM D7012 (Method C)
  - 6 Tests from 2018 drilling
  - 4 Tests from 2020 drilling (BRU 95-8)
  - 2 Tests from 2021 DEN drilling (Den 117-1, Den 120-1)
- Triaxial Compression Tests
  - 4 Tests from 2018 drilling

Table 4 and Table 5 below show averaged tensile and unconfined compressive strength values for the carbonate (limestone) used for analyses. Test results conclude that the carbonate unit has an average tensile strength of 5.3 MPa and an average unconfined compressive strength of 68.1 MPa.

Table 4: Brazilian Tensile Test Results Limestone

Borehole	Sample ID	Tensile Strength (Avg. of tested specimens in the sample) (MPa)	Tensile Strength (Individual Specimen Range) (MPa)
BH-10-17	B1	6.9	6.9
BH-10-17	B2	10.1	10.1
BH-10-17	B3	7.7	7.7
BH-10-17	B4	8.3	8.3
BH-10-17	B5	6.8	6.8
BH-10-17	B6	8.3	8.3
BRU 95-8	BT1	5.2	3.9 to 6.3
BRU 95-8	BT2	4.7	3.2 to 5.6
BRU 95-8	BT3	5.4	4.7 to 6.0
BRU 95-8	BT4	2.5	1.5 to 3.2
BRU 95-8	BT5	5.1	4.5 to 6.0
Den 117-1	CW-6000	3.5	2.3 to 5.0
Den 117-1	CW-6002	5.9	4.2 to 7.8
Den 117-1	CW-6003	6.4	4.4 to 8.4
Den 120-1	CW-6007	5.6	3.6 to 6.7
Den 120-1	CW-6008	7.1	5.7 to 8.1
Den 120-1	CW-6010	4.8	4.0 to 5.6
Den 120-1	CW-6011	3.8	3.5 to 4.6
Den 204-1	CW-6013	6.7	5.1 to 8.3
# of Tests			**71**
Average			**5.3**
Minimum			**1.5**
Maximum			**10.1**
80% Data Larger that this Value (MPa)			**3.8**

Table 5: Unconfined Compressive Strength (UCS) Test Results Limestone

Borehole	Sample ID	USC (Avg.) (MPa)
BH-10-17	U1	48.4
BH-10-17	U2	34.0
BH-10-17	U3	34.4
BH-10-17	U4	44.8
BH-10-17	U5	90.3
BH-10-17	U6	43.8
BRU 95-8	UCS 1	96.0
BRU 95-8	UCS 2	112.0
BRU 95-8	UCS 3	56.0
BRU 95-8	UCS 4	84.0
Den 117-1	CW-6001	74.3
Den 120-1	CW-6009	99.7
	# of Tests	**12**
	Average	**68.1**

2.5.3 ABI/OBI Survey Results

Acoustic borehole imaging and optical borehole imaging was completed for borehole BRU 92-1 and was reviewed for the design of bedding separation thickness. ABI provides a continuous high-resolution oriented ultrasound image of the borehole wall, and with the application of the ABI probe, fracture location and orientation is identified. When combined with the visual representation of the OBI results, detailed structural and geological information was obtained.

Based on the imaging results, the BRU 92-1 borehole was divided into three bedding zones as seen in Table 6. Zone 1 is deemed as unreliable for the basis of caprock stability analysis due to the occurrence of cross-joints and was not used for this analysis. However, Zones 2 and 3 are primarily composed of horizontal bedding and are estimated to be stable. To identify an average bedding separation value for design, a weighted average bed thickness was calculated as 0.76 m for Zones 2 and 3. The weighted average thickness of beds including Zone 1 is 0.70 m.

Table 6: Borehole BRU 92-1 Average Bedding Separation Competent Limestone

Zone	Depth Range (m)	Joint Description	Average Bedding Separation (m)
1	33.80 to 36.13	Horizontal bedding with cross-joints	0.4
2	36.13 to 45.40	Open horizontal bedding with some joints in other directions	0.8
3	45.40 to 47.60	Similar to Zone 2 but with increased open bedding joints	0.6
Note: Cross jointed Shale and Shale/Limestone zones below Zone 3 are not relied upon for the caprock strength			

2.5.4 Side Scan Sonar Survey Results

Side scan sonar surveys were conducted on two boreholes BRU 92-2 and BRU 92-8 for the purpose of borehole mapping and imaging. Side scan sonar transmits an acoustic beam down a survey track. As the acoustic beam travels outward, obstructions reflect portions of the sound back in the direction of the sonar. Travel time and amplitude of these reflections are analyzed to create borehole images.

The first well, BRU 92-2 was surveyed with a total extraction depth of 228 feet. Based on sonar data, BRU 92-2 had an open void volume of 2, 218 m^3. A portion of the original extraction cavity was infilled by disturbed sand and fines shortly after extraction. The volume of the disturbed sand and fines is not measured in the sonar survey. Figure 1 highlights the expansion of the cavity in various directions. Changes in the cavity size with different direction is relatively minimal and the cavity is close to axisymmetric.

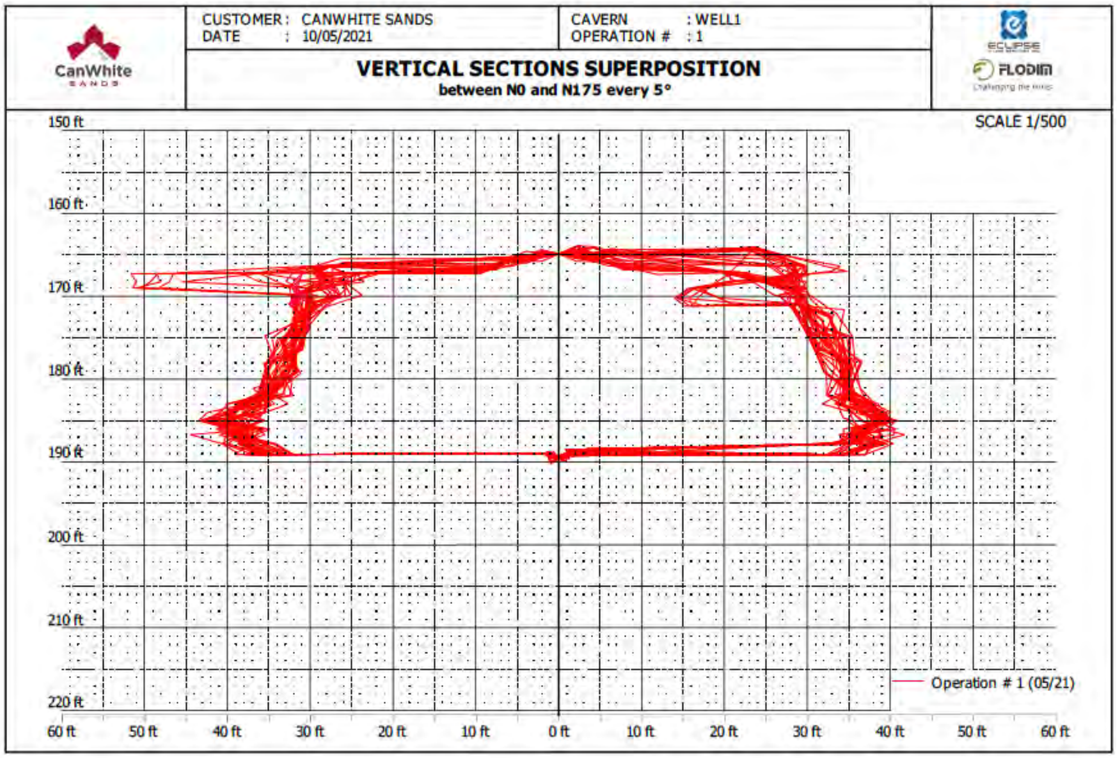

Figure 1: Vertical Superposition of 1st Survey on Borehole BRU 92-2

Two sonar surveys were completed on borehole BRU 92-8, with the first survey completed after 3,500 tonnes of sand were extracted and the second after 4200 tonnes were extracted. The surveys were completed once an extraction depth of 229 feet was reached. To allow for fines to settle between surveys, survey one was carried out 52 hours after extraction and survey two was carried out 60 hours after extraction. Figure 2 and Figure 3 show the gradual expansion of the cavity measured in the 2nd survey. The total cavity volumes for the two surveys were 2,333 m^3 and 2,800 m^3. A portion of the extraction cavity was infilled by disturbed sand and fines shortly after extraction. The volume of the disturbed sand and fines is not measured in the sonar survey.

Figure 2 and Figure 3 show the expansion of the cavity in various directions. Unlike survey results from BRU-92-2, the side sonar survey data from BRU 92-8 shows that the cavity expansion is mostly in the SW/NE direction.

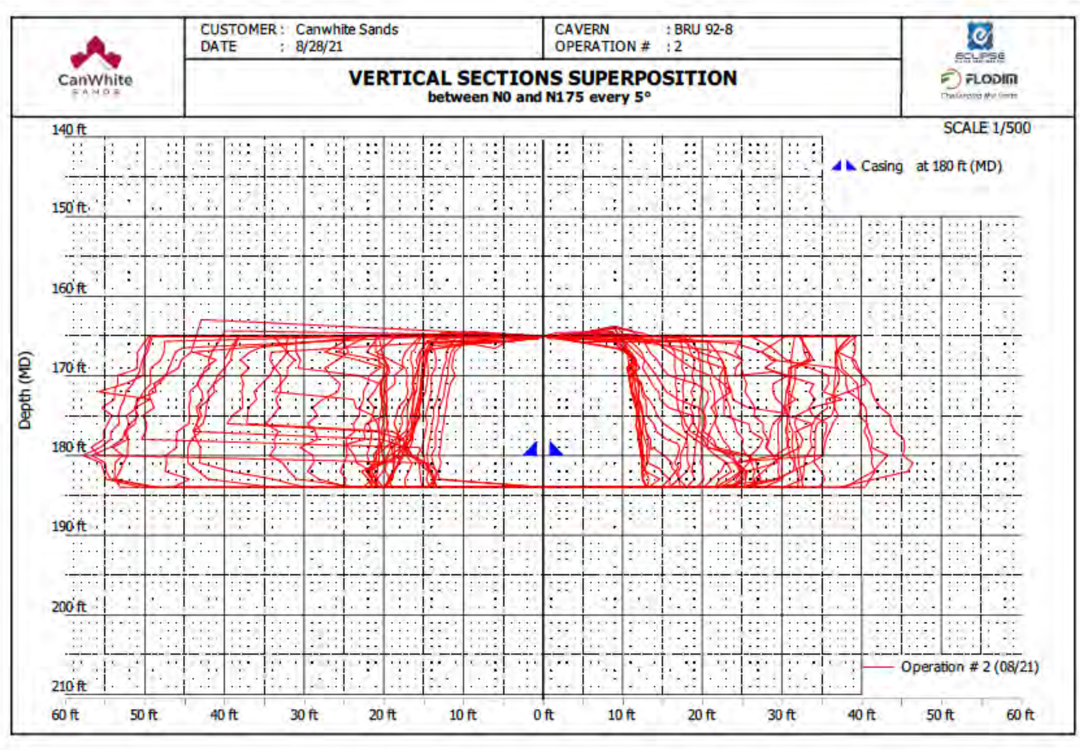

Figure 2: Vertical Superposition of 2nd Survey on Borehole BRU 92-8

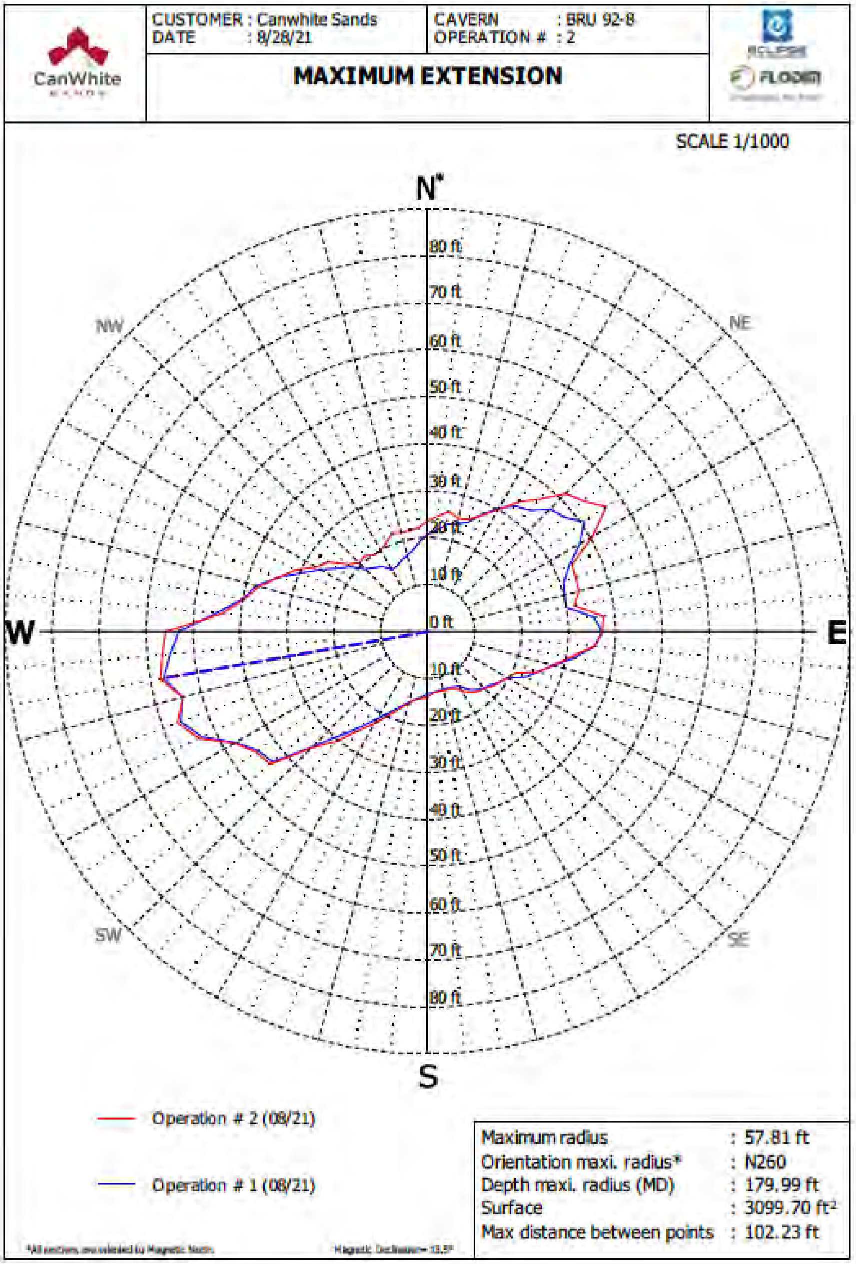

Figure 3: Maximum Extension of Cavity on Borehole BRU 92-8

2.6 SURFACE SETTLEMENT MONITORING RESULTS

Surface deformation was surveyed at points around boreholes BRU 92-3, BRU 92-2 and BRU 92-8 to identify potential changes as a result of stress changes within the earth after completion of sand extraction. Figure 4 shows the surface settlement results in 2021. Differences between initial and post extraction ground elevation show very limited deformation, ranging from 0.000m to -0.002m. The accuracy of the monitoring survey method is 1 mm and the very small deformation measured may be the result of monitoring error or local ground movement unrelated to sand extraction. Stantec deems that at or near zero deformation has been measured to date.

TABLE 1: MONITORING DATA

INITIAL DATA

POINT ID NO.	NORTH.	EAST.	GEODETIC ELEV.	DESCRIPTION
DATE: APR. 28, 2021				
30	5526452.24	681563.61	274.920	P-10 FOOT BERNSTEIN
33	5526465.63	681575.43	274.912	P-10 FOOT BERNSTEIN
34	5526480.05	681585.94	274.941	P-7 FOOT BERNSTEIN
DATE: AUG.10, 2021				
40	5526392.53	681632.45	274.548	P-12 FOOT BERNSTEIN
41	5526394.85	681653.45	274.427	P-16 FOOT BERNSTEIN
DATE: DEC. 22, 2021				
42	5526375.19	681615.95	274.628	FROST FREE BERNSTEIN
43	5526388.40	681634.17	274.828	BRU 92-8

NOTE: COORDINATES DATUM (NAD 83 - UTM Zone 14)

	ROUND 6 DATA	DIFFERENCES BETWEEN INTIAL AND 6TH ROUND
	DATE: DEC. 22, 2021	
POINT ID NO.	GEODETIC ELEV.	Δ ELEV.
30	274.919	-0.001
33	274.910	-0.002
34	274.940	-0.001
40	274.547	-0.001
41	274.427	0.000

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Our File: 21-0518
Acad dwg: 21-0518 SKETCH MW UTMGRID_2021-12-22-DEC
Field Book: 1420-92-93&112; 1448/21-24; 120-121
Drafter: AS/HT

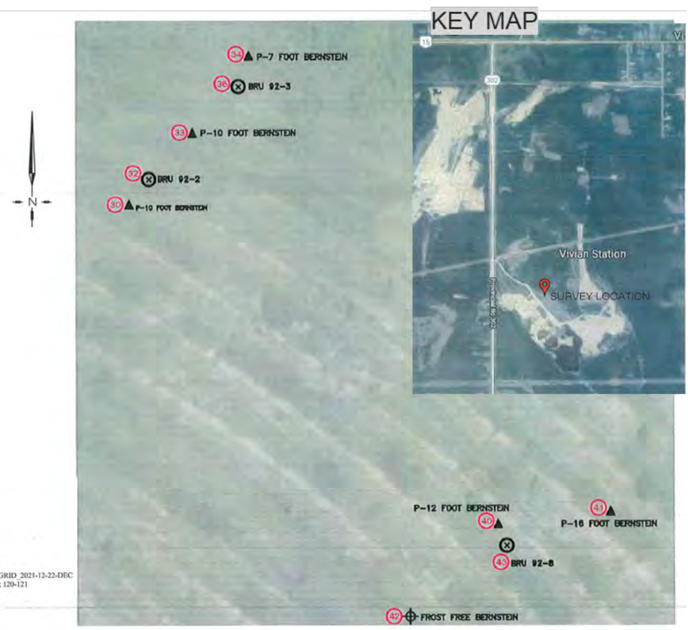


Figure 4: Surface Settlement Monitoring Data

3.0 ANALYSES

This section provides the basis of the design, failure modes considered in the design, design criteria and the summary of analyses methods and findings.

3.1 BASIS OF GEOTECHNICAL DESIGN

This Basis of Design (BoD) documents the principles, assumptions, criteria, and considerations used for the geotechnical assessment of sand extraction in the BRU property. The geotechnical design is based on the following:

1. **Selection of controlling failure scenarios:** The geotechnical assessments consider the potential failure scenarios (modes) relevant to the stability of the underground cavity as a result of the sand extraction at the BRU property.
2. **Stability Factors of Safety:** A factor of safety of 2.0 is deemed to be reasonably conservative for stability analysis to verify that subsidence will not occur.
3. **Lifetime of the project:** For geotechnical stability design, the lifetime of the project includes operational lifetime (duration of extraction) as well as the post operational lifetime that cavities shall not cause a significant surface settlement or sinkholes risk to the public. It is assumed that the extraction holes will be developed in the areas that public structures are not within the range of influence of possible collapse of a post extraction cavity. The design life expectancy for post extraction stability is set as long-term (quasi-permanent) with a lifetime of 50 to 100 years. It is assumed that if the adverse stability effect is not observed during this time frame, there is minimal risk for development of adverse effects in a longer-term.
4. **Use of Site data to develop design parameters for BRU property:** Stantec assumed that the results of geotechnical borehole logging, point load testing, laboratory testing and ABI/OBI as well as supporting information from other borehole geological logging are representative of the site wide rock mass characteristics, with the exception that the thickness of lithologic units varies. Although borehole logging indicates that conditions are relatively consistent, there remains some potential for local variability of rock strength and structure to occur which may contribute to local settlement.
5. **Use of monitoring data to develop design parameters:** Stantec assumes that the results of settlement monitoring to date, which indicates no apparent early term settlement, is representative of probable settlement during full scale mining and the long-term. There remains some potential for changes in local support conditions to generate settlement in the short or long term.
6. **Use of downhole side scan sonar data to develop design parameters:** Stantec assumes that the results of downhole side scan sonar of the cavity (void) after mining is representative of the probable behaviour of the void during full scale mining. There is some potential that additional changes to the cavity and the area of influence of sand extraction may change over the long term.
7. **Development of operational level monitoring systems:** The geotechnical design includes recommendations for operational monitoring systems to confirm the design assumptions and performance during extraction process.
8. **Development of operational level mitigation options:** The design includes operations level recommendations for mitigation options should monitoring data show changes in design assumptions or if less favorable conditions are observed during operation.

A summary of Basis of Design is presented in Table 7.

Table 7: Summary of Basis of Design

Items	Criteria	Reference
Extraction Area Offsets	• Extraction holes shall be offset from the right of way for (and/or the property limits whichever is closest to extraction locations) roads and buildings at least equal to the expected long-term zone of influence of the extraction – estimated to be 100 m from centre of the extraction location.	Stantec
Cavity Lifespan	• Extraction shall not result in adverse effects in the form of sinkholes and connection between upper and lower groundwater systems for the long-term after completion of the extraction (i.e., 100 years after extraction).	Carter 2014
Stability Factors of Safety	• A minimum factor of safety of 2 shall be adopted against allowable strength in sand and caprock.	Carter 2014
Cavity Geometry	• Side Scan Sonar survey data used to estimate the range of the short-term extraction cavity shape: data shows a possible cavity shape from close to vertical side walls symmetrical around the drillhole with a major portion of cavity filled with disturbed sand and fines.	Side Scan Sonar Data
Geology	• Based on geology studies. • The diamicton ranges from 5 m to 43 m in thickness. • Carbonate (Limestone) varies between 0 and 48 m. • Shale unit thickens varies in thickness from 0 m to 11 m. • The Carman Sand Member varies in thickness between 20 m and 23 m.	Results of Geotechnical Drilling
Hydrogeology	• Vertical and horizontal gradients are based on the Hydrotechnical Report.	AECOM 2021
Seismicity	• Seismic Hazard Calculation from the National Building Code of Canada	NBCC 2015
Material Strength	• Quaternary sediments strength is based on geological descriptions and previous experience. • Caprock (Carbonate/Limestone) Geological Strength Index (GSI) is based on geotechnically logged boreholes • Shale is not relied upon for stability. • Intact rock strength parameters for caprock (Carbonate/Limestone) derived from Tensile and UCS test results. • Undisturbed Carman Sand Member short-term strength is back calculated from cavity short-term shape from Side Scan Sonar survey data. • Disturbed Carman Sand Member strength is based on angle of repose of disturbed sand (31 degrees).	Results of Geotechnical Drilling and Laboratory Testing

3.2 FAILURE MODES ANALYSIS

Stantec reviewed the potential geotechnical failure modes for the post-extraction cavities. In general, the stability of the post-extraction cavity depends upon the unsupported span under the caprock, the sand behaviour over time, on the caprock thickness and competence, on original in-situ stress state, on overburden thickness and related overburden load, and on other factors (for example possible seepage gradient force vertically or horizontally). Each of these factors may contribute to failure modes. Raveling and slow upward migration of caving normally results in long-term instability while unfavorable caprock conditions may result in more rapidly occurring instability.

The risk of failure modes for an underground cavity were evaluated based on the categories presented by Carter (2014) to identify their potential as follows:

- **Shear Failure Mode:** This failure mode is equivalent to the Plug Failure mode presented by Carter for Crown Pillar failure mechanisms (Carter 2014). In this failure mode, the shear surface can develop in the caprock due to the load from the overburden material. As the shear surface develops in the caprock, the caprock shears into the cavity leaving the overburden material unsupported. The cavity then will develop into the overburden and may continue to move upward to the ground surface with time. Considering the load from the overburden material on the caprock this is considered to be a valid failure mode which is analyzed in the following sections.

- **Bending (Tensile) Failure Mode:** This failure mode is equivalent to the Delamination mode presented by Carter for Crown Pillar failure mechanisms. In this failure mode, horizontally bedded rock layers will separate from the roof of the cavity leaving the next layer of rock unsupported. Continued failure of these rock layers can eventually daylight at the caprock surface resulting in a failure of the overburden material into the cavity. The cavity then expands toward the surface in the overburden material. Considering that the site investigations to date have identified mainly horizontal bedding limestone layers in the caprock, this is considered to be a valid failure mode which is analyzed in the following sections.

- **Cross-joints Failure Mode:** This failure mode is equivalent to the Unravelling failure mode presented by Carter for Crown Pillar failure mechanisms. In this failure mode, blocks of rock separate from the cavity roof along the joint surfaces. Continued failure of these rock layers can eventually daylight at the caprock surface resulting in a failure of the overburden material into the cavity. The cavity then expands toward the surface in the overburden material. The site investigations to date show possible cross-bedding joints at the limestone contact with overburden soil and in the shale or lower zones of the limestone/shale contact. However, the majority of the limestone is observed to be massive without cross- joints. Therefore, this failure mode is not considered to be a controlling failure mode capable of developing to a full failure of the caprock and expansion of the cavity to the surface.

- **Other Failure Modes:** Other failure modes that may control the stability of cavities in the mining environment are Caving and Chimneying failures. Chimneying failure is common in weak rock while Caving is observed in heavily broken rock. The caprock is a massive limestone and is considered to be relatively strong rock. In addition, in this shallow rock in the Canadian interior region, large horizontal tectonic stress that could damage the limestone is not expected. Therefore, Caving and Chimneying failures are not considered as potential failure modes for the current extraction plan.

Figure 5 which follows presents a graphical representation of the failure modes discussed above.

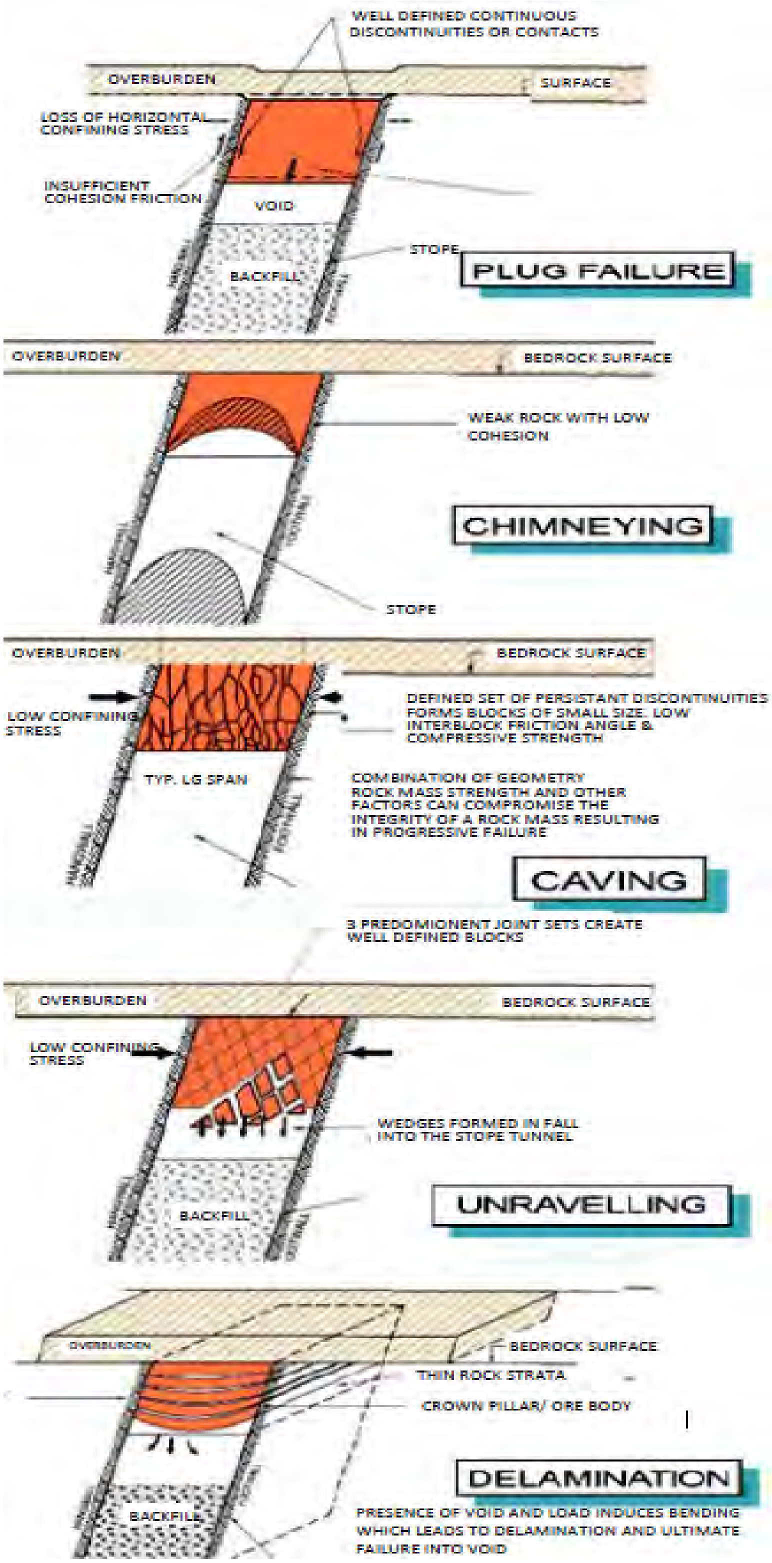


Figure 5: Typical Failure Mechanisms for Crown Pillars (Carter 2014)

3.3 DESIGN CRITERIA

The geotechnical design criteria are presented in Table 8 below.

Table 8: Geotechnical Design Criteria

Items	Criteria	Reference
Cavity Lifespan	• 100 years after extraction	Carter 2014
Stability Factors of Safety	• The minimum factor of safety against allowable strength versus long-term stress in sand and limestone caprock is 2	Carter 2014
Extraction Cavity	• Axisymmetric development of cavity • Depth of extraction in sand: 20 m maximum	Side Sonar Survey Data – 2021a
Stratification	• Overburden varies between 25 and 35 m in extraction area • Caprock strength based on limestone thickness between 10 and 25 m in the extraction area • Shale and limestone/shale rock excluded from the caprock strength (not relied on for caprock strength) • Cross-bedded limestone excluded from the caprock strength	Geological and Geotechnical Drilling and Laboratory Testing Results
Carbonate/ Limestone GSI	• Caprock Geological Strength Index (GSI) of 60	Geotechnical Drilling and Laboratory Testing Results
Hydrogeological Conditions	• Maximum vertical gradient between upper and lower aquifers is 0.1 in the long-term • Maximum horizontal gradients after extraction are 0.1 in the short-term after extraction	AECOM 2021
Seismicity	• Low seismic activity area	NBCC 2015

3.4 PARAMETERS

Strength parameters for short-term and long-term differ due to the effect of creep in caprock and sand in the long-term. This section provides background information on selection of strength and deformation parameters for various units in the analysis.

3.4.1 Quaternary Deposit

The Quaternary Deposit at the BRU project site is mainly Diamicton (Till). The strength parameter for this member is estimated based on the typical strength parameter for till from previous experience. Till is generally a mixture of gravel, sand and fines (i.e. silt and clay) in almost equal portions with some boulders and cobbles. Till is generally well-compacted due to past glaciation loads.

This mixture of gravel and sand with fines normally provides a friction angle between 28° to 33° when disturbed (in the critical state) (Budhu 2010). But effects of past loading (compactness) and boulders and cobles generally add strength to till greater than the critical state strength. For the range of stress in the till at the BRU site, the estimated additional strength from compactness is between 20 kPa and 40 kPa. Therefore, a cohesion component of 20 kPa is added to the frictional component of the till.

3.4.2 Carbonate/Limestone Caprock

Uniaxial Compression Strength (UCS) tests were completed on 12 samples from limestone (Table 5) which returned an average UCS value of 68.1 MPa. The UCS value of 50 MPa was used in the analyses to consider long-term effects on the intact rock strength.

Brazilian Indirect tensile strength tests were completed on 12 specimens from limestone (Table 4) which returned an average tensile strength of 5.3 MPa. Based on this data, 80% of the tested specimens had a minimum tensile strength of 3.8 MPa. To consider the effect of larger bedding size than the tested samples, a factor of 0.8 was applied to the 3.8 MPa to estimate the limestone tensile strength. In addition, to estimate the long-term (100 years) degradation of the tensile strength, a reduction factor of 0.5 was applied. Therefore, a limestone tensile strength of 1.5 MPa was used in the analysis.

The Carbonate/limestone caprock includes intact rocks and joint and bedding systems. No cross-bedding joints were observed in the majority of the limestone. Cross-bedding joints were observed in the surface layers of limestone in contact with Quaternary till and the lower layers in contact with Shale. Excluding those weaker cross-bedded limestone zones, the strength of the limestone rock mass was estimated using its Rock Mass Rating (RMR) parameters from geotechnical logging. Average weighted RMR values ranged from 65 to 70. The average Geological Strength Index (GSI) for the competent limestone rock mass is estimated to be 60.8 (Table 3) for the five boreholes in the BRU property and its vicinity. The design GSI value for competent limestone was selected as 60 which is equivalent to the lower quartile of the estimated GSI.

The density of the intact limestone was estimated based upon laboratory tests on 16 limestone samples. The average density of the intact limestone samples was calculated to be 2,570 kg/m^3 with values ranging from 2,510 kg/m^3 to 2,630 kg/m^3. Due to bedding and joints, the limestone rock mass is expected to have a lower density than intact rock. The design density for the limestone rock mass is then selected as 2435 kg/m^3.

Deformation properties of the limestone rock mass were estimated based on its GSI value of 60 and an intact limestone Young’s Modulus of 25 GPa. This resulted in a design limestone rock mass deformation Young’s Modulus of 13 GPa. Design Bulk Modulus and Shear Modulus for the limestone rock mass then are 10 GPA and 5 GPA, respectively assuming a Poisson’s ratio of 0.29.

3.4.3 Carman Sand

Previous analysis of the cavity stability used the angle of repose of the disturbed sand (31°). The recent Sonar Survey data showed that the extraction of the sand leaves a cavity that has side walls close to vertical in the short-term. Therefore, it is estimated that the internal friction angle of the sand deposit is greater than the angle of repose. This higher strength may be the result of weak cementation, short-term suction after extraction, or a combination of these factors. Considering that the extraction cavity will be full of water shortly after extraction, the suction induced apparent cohesion may not be the main source of additional strength in this sand deposit.

The deposition environment of Carman Members in a shallow marine sea can create weak cementation. In addition, Standard Penetration Testing (SPT) in the sand deposit was not successful due to its very high strength. All of these indicate cementation of some form in the sand deposit.

Most shallow sea cemented sand deposits have a peak friction angle in the range of 38° to 43°. Based upon Sonar Survey data and understanding that sand will be disturbed by the extraction process, the peak friction angle of sand was assumed to be 35°. The residual friction angle of sand was assumed to be angle of repose. The sand friction angle changes from its peak to residual gradually with strain. The analysis assumes that the sand friction angle will be at its residual value wherever it is strained to 5% (0.05).

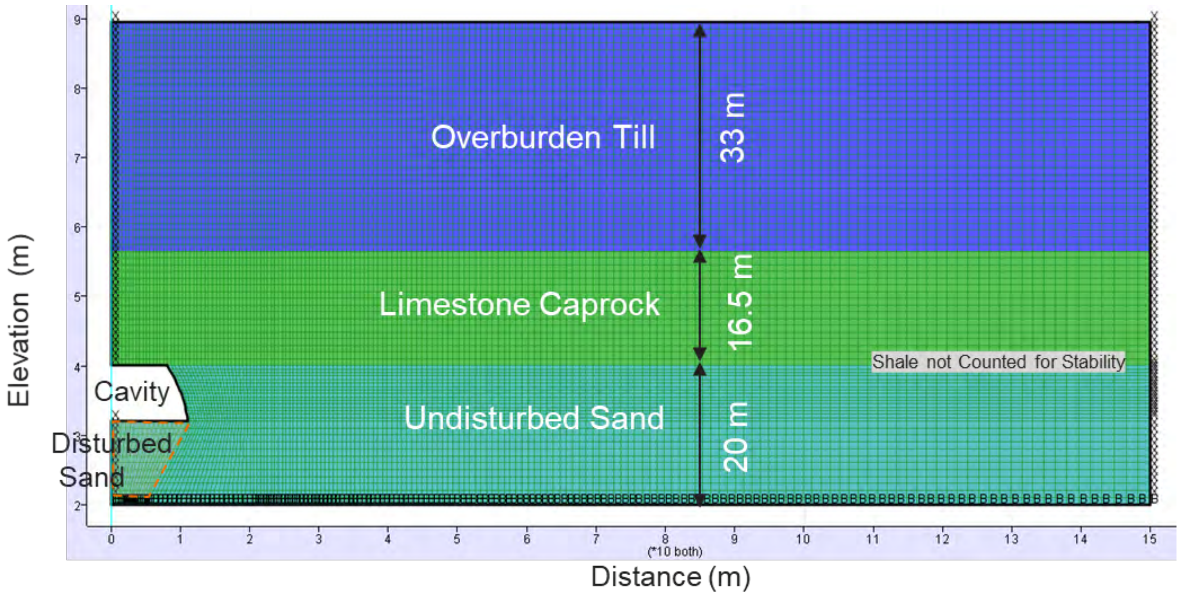
To estimate the possible cohesion component of the sand strain, the sand deposit strength was back-calculated using the Sonar Survey data on the post-extraction cavity. The sand extraction left a cavity with sidewalls with vertical side slopes. These side slopes will not be stable without cohesion and cohesion will be lost with a very small strain. It is assumed that the cohesion will be zero wherever the sand is strained to 0.5% (strain 0.005).).

Using these parameters, a FLAC analysis was completed with the cavity geometry for Borehole Bru 92-2 (Figure 6). The sand cohesion was varied until a stable cavity wall was predicted. The analysis showed that the cavity will be stable with a peak cohesion value of 220 kPa (Figure 7). It is important to note that the Shale below the Limestone is excluded from the model because of its cross-bedded joints and therefore low GSI. The Shale is not relied upon for caprock stability.

Undisturbed sand deformation parameters were selected based on weakly cemented deformation parameters. The normal range of shear modulus (G) of cemented sand is between 150 GPa and 300 GPA for the void ratio similar to the Carman Sand in-situ void ratio (estimated at 0.8) and range of stress (500 to 1000 kPa). For the analysis, a shear modulus (G) of 200 GPA was used with Poisson's ratio of 0.35. Bulk Modulus of 600 GPA was used in the analysis.

The deformation parameters for disturbed sand and fines were selected as a Shear Modulus of 120 GPA, a Bulk Modulus of 300 GPA and Poisson's ratio of 0.35.

There are shale (Equiv. Ice Box Member) and sand (Black Island Member) members below the Carman Sand member, but extraction is limited to the Carman Sand and will not disturb these lower members.



Notes:
1) Red River Formation Shale has not been relied upon for the stability of cavity
2) Ice Box Member Shale and Black Island Member Sand Below the Carman Sand Member are not included in the model because they are not disturbed by the extraction

Figure 6: FLAC Model Geometry to Back-Calculate Sand Cohesion – BRU 92-2 Trial Extraction Modeling

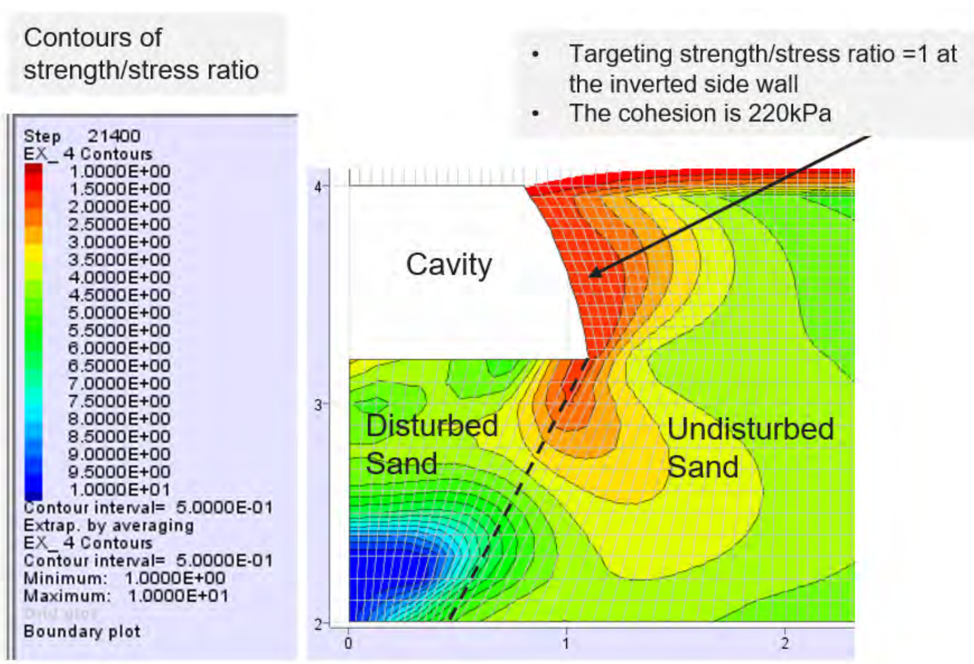


Figure 7: FLAC Model Results – Back-Calculation of Sand Cohesion – Strength Ratio of 1 using Sand Cohesion 220 kPa

3.4.4 Summary of Design Parameters

A summary of design parameters is presented in Table 8.

Table 8: Summary of Design Soil and Rock Parameters

Material	Material Model	Density (kg/m3)	Bulk Modulus (MPa)	Shear Modulus (MPa)	Young's Modulus (GPa)	Poisson's Ratio	Soil Strength Parameters	Rock Strength Parameters
Till (Quaternary)	Plastic - Mohr Coulomb	2,000	50	20	-		C= 20 kPa ϕ= 30 °	-
Limestone (Carbonate)	Plastic - Hoek Brown	2,435	10,000	5,000	13	0.29	-	Tensile Strength= 1.5 MPa Intact Rock UCS = 50 MPa GSI=60 Mi=10 D=0
Undisturbed Carman Sand	Strain Softening	2,000	600	200	0.54	0.35	C=220 to 0 (kPa) ϕ= 35° to 31°	-
Disturbed Carman Sand	Plastic - Mohr Coulomb	2,000	300	120	0.54	0.35	C=0 ϕ= 31°	-

3.5 EMPIRICAL ESTIMATION OF LONG-TERM STABLE SPAN

There are both analytical and empirical methods to estimate the maximum unsupported span before instability occurs as a result of failure of the first beam.

Carter 2014 provided an empirical method for estimation of the maximum crown pillar stable span (S) based on the Maximum Scaled Span (Cs) for design classes and Q system rock quality (Barton, Lien, and Lunde,1974). The Scaled Spans relation to the stable span is presented in the formula:

$$C_s = S\left(\frac{\gamma}{t(1+S_R)(1-0.4\cos\theta)}\right)^{0.5}$$

In this formula:

S=crown pillar span (m)
γ = specific gravity of crown pillar
t = thickness of crown pillar (m)
SR= span ratio=S/L (crown pillar span/crown pillar strike length)
θ = dip of the orebody or foliation (degree)

A table which presents probability of failure and minimum factor of safety as they relate to the Scaled Span and other criteria is presented in Figure 8 below.

Class	Probability of Failure %	Minimum Factor of Safety	Maximum Scaled Span, Cs (= Sc)	ESR (Barton et al. 1974)	Design Guidelines for Pillar Acceptability/Serviceable Life of Crown Pillar				
					Expectancy	Years	Public Access	Regulatory position on closure	Operating Surveillance Required
A	50 – 100	<1	$11.31Q^{0.44}$	>5	Effectively zero	< 0.5	Forbidden	Totally unacceptable	Ineffective
B	20 – 50	1.0	$3.58Q^{0.44}$	3	Very, very short-term (temporary mining purposes only ; unacceptable risk of failure for temporary civil tunnel portals	1.0	Forcibly Prevented	Not acceptable	Continuous sophisticated monitoring
C	10 – 20	1.2	$2.74Q^{0.44}$	1.6	Very short-term (quasi-temporary stope crowns ; undesirable risk of failure for temporary civil works)	2 – 5	Actively prevented	High level of concern	Continuous monitoring with instruments
D	5 – 10	1.5	$2.33Q^{0.44}$	1.4	Short-term (semi-temporary crowns, e.g.under non-sensitive mine infrastructure)	5 – 10	Prevented	Moderate level of concern	Continuous simple monitoring
E	1.5 – 5	1.8	$1.84Q^{0.44}$	1.3	Medium-term (semi-permanent crowns, possibly under structures)	15–20	Discouraged	Low to moderate level of concern	Conscious superficial monitoring
F	0.5 – 1.5	2	$1.12Q^{0.44}$	1	Long-term (quasi-permanent crowns, civil portals, near-surface sewer tunnels)	50–100	Allowed	Of limited concern	Incidental superficial monitoring
G	<0.5	>>2	$0.69\,Q^{0.44}$	0.8	Very long-term (permanent crowns over civil tunnels)	>100	Free	Of no concern	None required

Figure 8: Acceptable Risk Exposure Guidelines – Comparative Significance of Crown Pillar Failure (Carter 2014)

The limestone has a GSI of 60 approximately equivalent to a Q value of 6. The project is located in an area with public access. Therefore, the cavity should be stable for 50 to 100 years based on the factors in Figure 8. The Maximum Scaled Span (Cs) then is calculated to be 6.72 m. Other parameters related to the estimation are:

T= 10 to 25 m

γ = 2.4

θ = 90 (degree)

Sr=1 (symmetric cavity)

The estimated maximum span (S) is calculated to be between 19 m and 31 m for caprock thickness 10 m and 25 m, respectively. Note that while these values are within the results from the analytical approach, there are differences between these empirical results and the analytical results. These differences are related to assumptions for a typical mining Crown Pillar and the special case of BRU sand extraction which include:

- The cavity from sand extraction at BRU has sand walls while a typical Crown Pillar is rock.
- The caprock has sub-horizontal bedding. While it may have the same GSI as the Crown Pillar based on the empirical graphs, it lacks the cross-bedding joints used in calibration of the empirical graphs.

3.6 SHEAR FAILURE MODE ANALYSIS

The shear stress in the limestone caprock is a function of overburden thickness and parameters, competent limestone caprock thickness and parameters, sand extraction cavity size and shape as well as the sand parameters. Any surcharge on the ground surface due to drilling and pumping equipment at the well or other infrastructures are assumed to be negligible in comparison to the overburden and caprock load.

FLAC analysis was completed assuming the various long-term size of the cavity for various combinations of caprock thickness and overburden thickness. To simplify analysis, the long-term cavity was modeled as a cone with side angles equal to the angle of repose of sand (31°). The analysis was completed with competent limestone thickness of 15 m to 100 m and Quaternary till overburden thickness of 25 and 35 m. The cavity diameter was increased in each case until a shear surface was predicted by the FLAC model in the limestone caprock. Figure 9 shows an example FLAC geometry for a 25 m thick Quaternary till overburden Deposit and a 15 m thick Limestone.

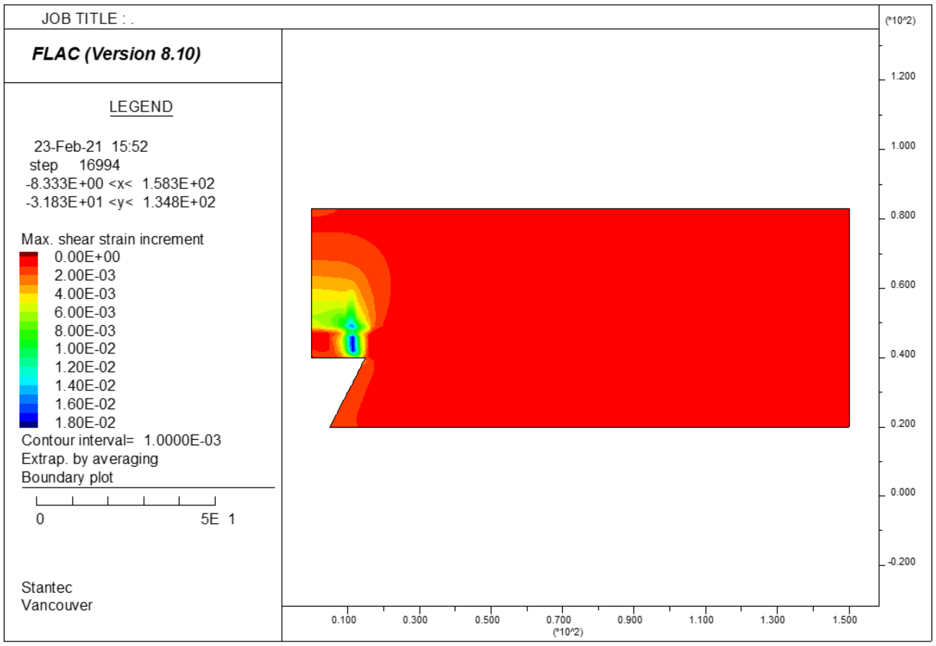


Figure 9: Example FLAC Analysis Shear Strain Prediction – Axisymmetric Model

The maximum long-term limestone caprock unsupported opening size for various limestone thickness and overburden thickness of 25 and 35 m is shown in Figure 10 for the Shear Failure mode.

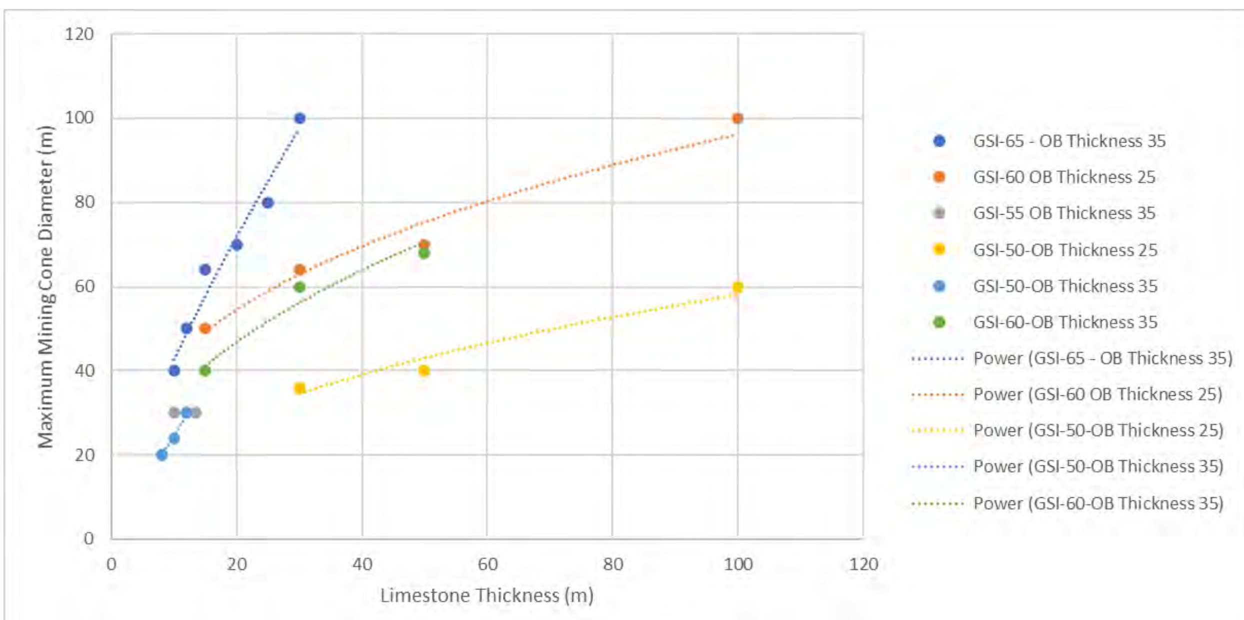


Figure 10: Maximum Long-term Unsupported Limestone Opening Size - FLAC Analysis Results – Shear Failure Mode

3.7 BENDING FAILURE MODE ANALYSIS

The limestone caprock in the BRU property includes sub-horizontal bedding layers. When horizontally bedded rock lies above the roof of the extraction cavity, the thinner strata near the opening will tend to detach from the main rock mass and form separated beams. With large stress and thin beds, the roof bed (beam) will flex downward, cracking will occur, and beams will fail over time. Continued failure and fall of beams eventually can produce a stable trapezoidal opening (Figure 11).

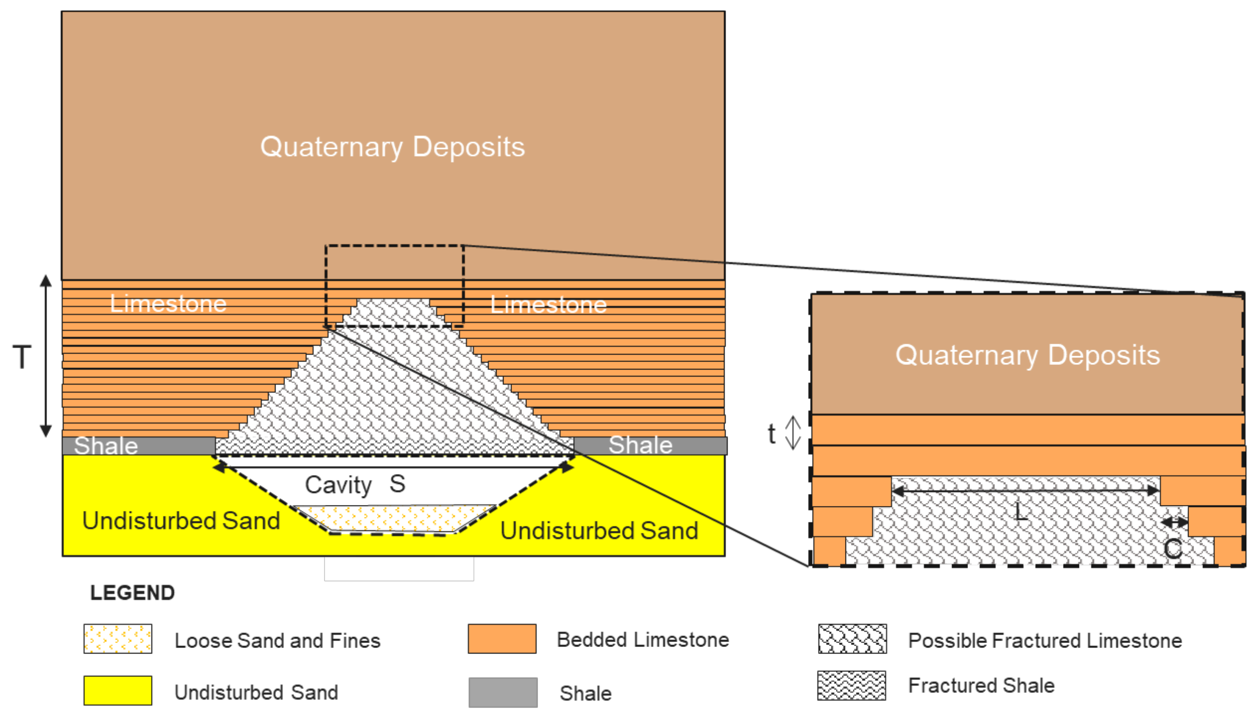


Figure 11: Bending Failure Mode in Bedded Limestone

The bending failure mode analysis is carried out to identify the extraction approach to ensure that any trapezoidal failure does not daylight to the limestone surface causing failure of the Quaternary overburden into the cavity that can progress to a sinkhole or cause a connection between upper and lower aquifers. Both analytical and empirical methods were used to estimate the maximum unsupported size of the roof before causing a failure beyond the caprock.

An analytical approach was used to estimate the stable beam span and also the cantilever spans which form the total stable span.

3.7.1 Stable Beam

Assuming fixed beams, the formula below presents the relationship between maximum stress (σ_{max}), span length (L), beam thickness (bedding thickness) (t, 0.7 m for this calculation), horizontal stress (σ_h), and the distributed load on the beam (W).

$$\sigma_{max} = \frac{WL^2}{2t} - \sigma_h$$

Assuming that the overburden load will be distributed onto the limestone beams and considering the unit weight of the limestone and average beam thickness of 0.7 m, the unit load on the individual beams is estimated to be between 55 kN/m and 60 kN/m. The formula above provides an estimated 6 m stable beam size without horizontal load and 7 m stable beam size with a horizontal load equal to the vertical load for a 2D analysis.

3.7.2 Stable Cantilever Span

Assuming that each cantilever will act as a fixed end beam and using the average load on each cantilever beam from its weight and the load from the Quaternary overburden soil, the maximum hangover length (C) of each cantilever is calculated using the formula:

$$C = \sqrt{\frac{t^2\sigma_{max}}{3W}}$$

In the hangover length calculation, the maximum allowable tensile stress is assumed to be 1.5 MPa (long-term allowable stress), beam thickness (t) of 0.7 m, average weight of beam and Quaternary overburden, and a downward seepage gradient of 0.1 (seepage force added to the vertical stress in the limestone). Using these assumptions, the cantilever hangover length (C) is calculated to be 0.6 m to 0.8 m for various overburden and limestone thickness.

The total long-term allowable span based on this failure mode is then the summation of maximum stable beam and sum of the hangover length of all cantilevers. The calculation predicts long-term stable spans between 24 m (for 10 m thick limestone with 35 m overburden load) and 50 m (for 25 m thick limestone and 25 m thick overburden soil).

3.8 ALLOWABLE LONG-TERM SPAN

The long-term opening size from the shear failure mode analysis was calculated to be between 35 m (for 10 m thick limestone caprock and 35 m thick overburden) and 60 m (for 25 m thick limestone and 25 m thick overburden).

For the bending failure mode, the total allowable long-term span includes a span that has at least one stable full beam and several stable cantilevers (depending on the limestone thickness) to prevent failure of overburden into the cavity in the long-term. The maximum allowable tensile strength is adopted with a reduction factor of the laboratory test data for size effect (a factor of 0.8) as well as long-term performance (factor of 0.5). The long-term allowable unsupported span of the circular unsupported span is then calculated to be between 24 m (for 10 m thick limestone rock and 35 m thick overburden) and 50 m (for 25 m thick limestone and 25 m thick overburden). The bending failure mode controls the long-term stability of the unsupported opening.

3.9 ALLOWABLE SHORT-TERM SPAN

The short-term cavity left after the extraction will expand with time due to sustained load and creep in the sand and caprock and due to possible underground water flow. The horizontal seepage gradient will cause a seepage pressure. The vertical seepage pressure is included in the beam failure mode as part of the vertical load on the beams and cantilevers. The horizontal seepage force is estimated to be too small in comparison to the load stress from overburden and caprock to change the stress regime and cause a failure due to change in stress, but long-term seepage may still cause erosion on the cavity surface.

The cavity wall change due to sustained stress is estimated using a FLAC analysis and strain-softening model that allows loss of strength (cohesion and friction components) with strain. The zones where stress level is more than 0.5 of the strength of the sand (a factor of safety of 2 against stress) are predicted to fail in the long-term.

3.9.1 Prediction of Expansion of Cavity with Time

A FLAC model was completed to evaluate the stress change at the cavity walls with distance from the short-term cavity wall. The assumed geometry for the FLAC model is presented in Figure 12.

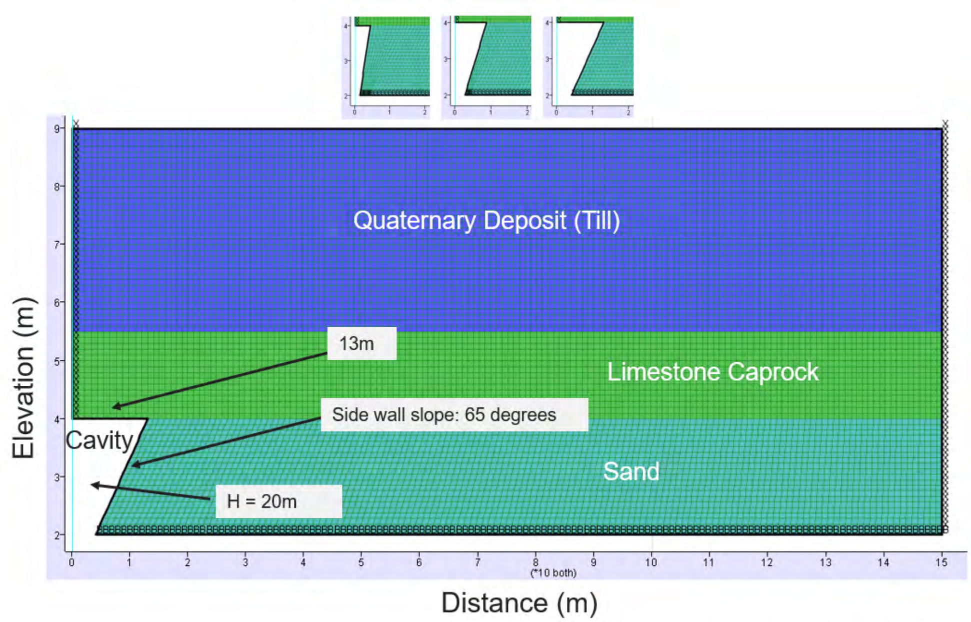


Figure 12: FLAC Model Geometry for Assessment of Stress Level Around Cavity

The FLAC model was completed in axisymmetric geometry (only half of the model is shown). The model assumes gradual expansion of the cavity to a post-extraction cavity with a final wall slope of 65°. The typical dimensions for such extraction in the short-term are modeled. The in-situ sand is modeled using a strain-softening soil model (Table 8). The base case model assumes a fully softened sand state will be reached after 0.005 and 0.05 strain against cohesion and friction angles respectively (change to C=0KPa and ϕ = 31° after this amount of strain).

The analysis results are presented with contours of the ratio between sand strength versus stress level (Figure 13). The limits of the strength to stress ratio of 2 (a factor of safety of 2) are presented in the figure. Based on this analysis the areas between 2 m and 5 m from the cavity surface have a strength to stress ratio (factor of safety) of 1 to 2. It is concluded that this area may fail in the long-term and increase the unsupported span of the caprock from the original cavity radius of 13 m radius to 18 m (a possible 5 m increase in radius after 100 years).

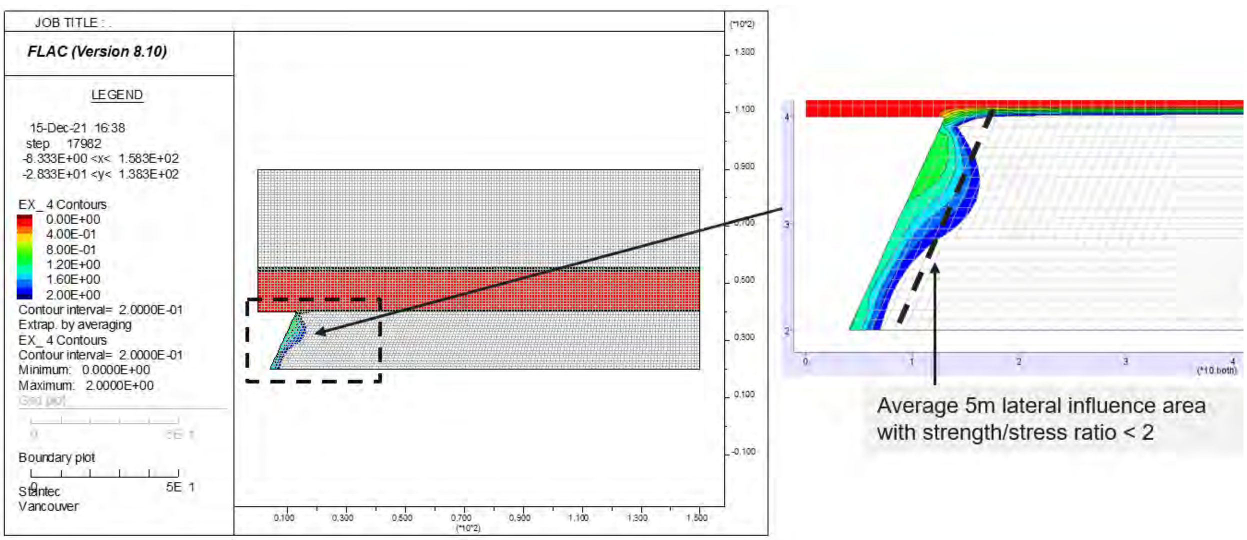


Figure 13: FLAC Analysis Results - Sand Strength to Stress Ratio Contours for an Example of Post Extraction Cavity

3.9.2 Allowable Extraction Zone

Based upon results of FLAC and other analysis, the allowable short-term extraction disturbance zone dimensions are presented in Table 9 below.

Table 9: Allowable Extraction Disturbance Zone Dimensions

Competent Limestone Thickness (m)	Overburden Thickness (m)	Long-term Allowable Limestone Unsupported Span (Diameter) (m) (Notes 1 and 2)	Extraction Disturbance Zone Dimensions (Notes 3 and 4)	
			Top Diameter (m)	Bottom Diameter (m)
10	25	26	16	0 (Note 5)
	35	24	14	0 (Note 5)
15	25	35	25	6
	35	32	22	3
20	25	43	33	14
	35	40	30	11
25	25	50	40	21
	35	47	37	18

Notes:

1) Bending (Tensile) is the controlling failure mechanism to determine the long-term allowable span.

2) Single beam maximum long-term allowable span is 7 m. Average competent limestone bedding thickness is 0.7 m.

3) Extraction zone side wall slope of 65°.

4) Extraction depth is 20 m.

5) The long-term diameter of the extraction cavity is expected to be 10 m larger than the short-term diameter.

6) Due to possible long-term cavity expansion, limit the extraction zone to the long-term allowable unsupported span.

7) Extraction in areas with only 10 m of competent limestone is discouraged due to competency uncertainties.

3.10 EFFECT OF ADJACENT EXTRACTION AREAS ON STABILITY

The stability analyses provided in this document assumes that the extraction plan will be managed at each extraction location to eliminate disturbance beyond the short-term extraction zones identified in Table 9 by using single or multi-hole extraction methods at each location. It is our understanding that the current extraction plan includes extraction using multiple boreholes at a series of extraction locations at the property. The extraction locations will be planned to allow for a suitable intact span between extraction areas .

FLAC analysis identified the possible radius of influence of a typical extraction location. Figure 14 shows the failed elements in the FLAC analysis model for the typical case of Quaternary thickness of 33.5 m, Limestone thickness of 13.5 m and depth of extraction of 20 m with cavity radius of 20 m and the initiation of shear failure. The analysis predicts limestone shearing at the edge of the cavity propagating to the limestone surface and continuing into the Quaternary overburden. The failed element contours are more scattered on the ground surface with failed elements in shearing and tension of up to 80 m from the center of the cavity (60 m beyond the edge of the cavity). Based on this analysis, it is concluded that in order to avoid the effects of one extraction location on another extraction location and to provide sufficient caprock support, extraction cavities shall be at least 60 m away from the next extraction zone.

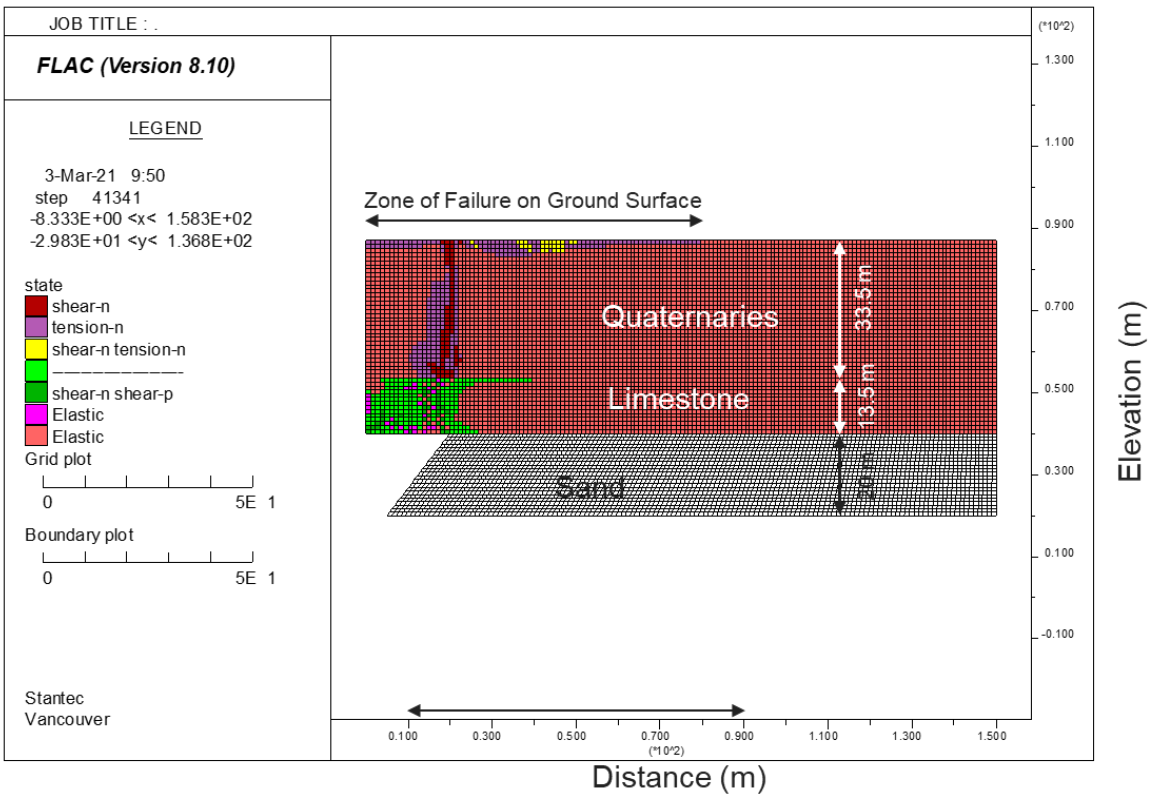


Figure 14: Failure Zones Predicted by FLAC Model for a Typical Site Condition

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

Based upon the geotechnical assessment of the proposed sand extraction in the BRU property, conclusions are as follows:

- Shear and Bending are the most probable failure modes with the potential to affect long-term stability. Unravelling, Caving, and Chimneying are not controlling failure modes for the BRU property due to the nature of the limestone caprock.
- The Bending failure mode is controlling the long-term stability of the post extraction cavity for the expected range of caprock and overburden thickness and material properties and the extraction depth in the sand. The stability analysis and extraction borehole spacing design were completed to achieve a factor of safety of 2.0, which is considered to be an acceptably conservative FOS for the project.
- The cavity after extraction is expected to further expand with time resulting in loose sand infilling the extracted void leaving a larger unsupported caprock span. Based on the assumption that the areas with factor of safety larger than 2 are stable in the long-term, approximately 5 m of additional raveling of the post extraction cavity walls is expected (by end of the design life of 100 years). Therefore, the unsupported caprock span will increase by 10 m with time after extraction.
- Based upon the results of geotechnical assessment and with the understanding that Sio Silica will follow guidance provided by Stantec including continuing to assess the geotechnical characteristics and performance of the sand deposit and overlying materials during the project life and to adjust design accordingly, no large scale surface subsidence is expected to occur as a result of sand extraction.

4.2 RECOMMENDATIONS

Based upon the geotechnical assessment of the proposed sand extraction at the BRU property, recommendations are as follows

- Design the borehole arrangement and depth at each extraction location to limit the Carman Sand disturbance zone to the short-term extraction geometry presented in Table 9 in this document.
- Limit the extraction to areas with competent limestone thickness greater than 15 m. Although extraction in areas with thinner competent limestone is theoretically possible, the extraction volume and depth are not supporting a full well extraction volume. In addition, the uncertainty in the progress of the weathered zone in the limestone can cause variable competent caprock in these thinner areas that can impact caprock strength and long-term stability.

- Locate extraction wells in each group to provide at least 60 m edge to edge distance between expected long-term cavity disturbance zones (approximately 70 m for short-term cavity disturbance zones).

- Complete a full-scale extraction test to confirm expected conditions. Assess the stratigraphy and caprock conditions before start of the full-scale extraction test and use the recommended extraction design in this document. Monitor the surface and caprock settlement during extraction as well as the piezometric head change at the upper aquifer. Complete side scan sonar survey after each borehole completion and assess results against cavity extraction assumptions. Complete in-situ strength testing of the sand deposit strength prior to extraction and at adjacent boreholes after extraction. Update the FLAC model with additional data from full-scale extraction monitoring results. Use results to refine the extraction method for the remainder of full-scale extraction.

- Gather and confirm the overburden, competent limestone, shale and Carman Sand thickness at each location before the start of extraction. Apply the relevant extraction design based on the guidance provided in Section 3.8.2 or the refined design if refinement was needed as a result of test extraction.

- Install an underground extensometer anchored to the caprock top surface, in the vicinity of the central extraction borehole (within 5 m), monitor daily and compare with the surface settlement data to detect subsidence/settlement.

- Install piezometers before extraction at extraction locations within the overburden and at the top of the caprock surface within 5 m of the center of extraction. Monitor daily during and for a period after extraction. Assess and adjust design if changes occur.

- Monitor surface settlement using securely anchored monuments. Review data daily during extraction and if settlement/subsidence is measured, clear and close the area and reassess before returning.

- Continue surface monument deformation monitoring with monthly data analysis for the first 3 months after extraction. Reduce data analysis to quarterly after 3 months from the extraction with annual data review to detect possible long-term surface settlement/subsidence.

- Continue caprock settlement (extensometer) monitoring and review with the same frequency as the surface settlement monitoring. Compare extensometer data against the surface settlement data to detect any differential settlement in the caprock surface.

- Continue daily piezometric monitoring and monthly data review for 3 months after completion of extraction.

- Develop a Trigger Action Response Plan (TARP) with defined proper series of protocols to respond to an issue such as extraction roof failure.

5.0 REFERENCES

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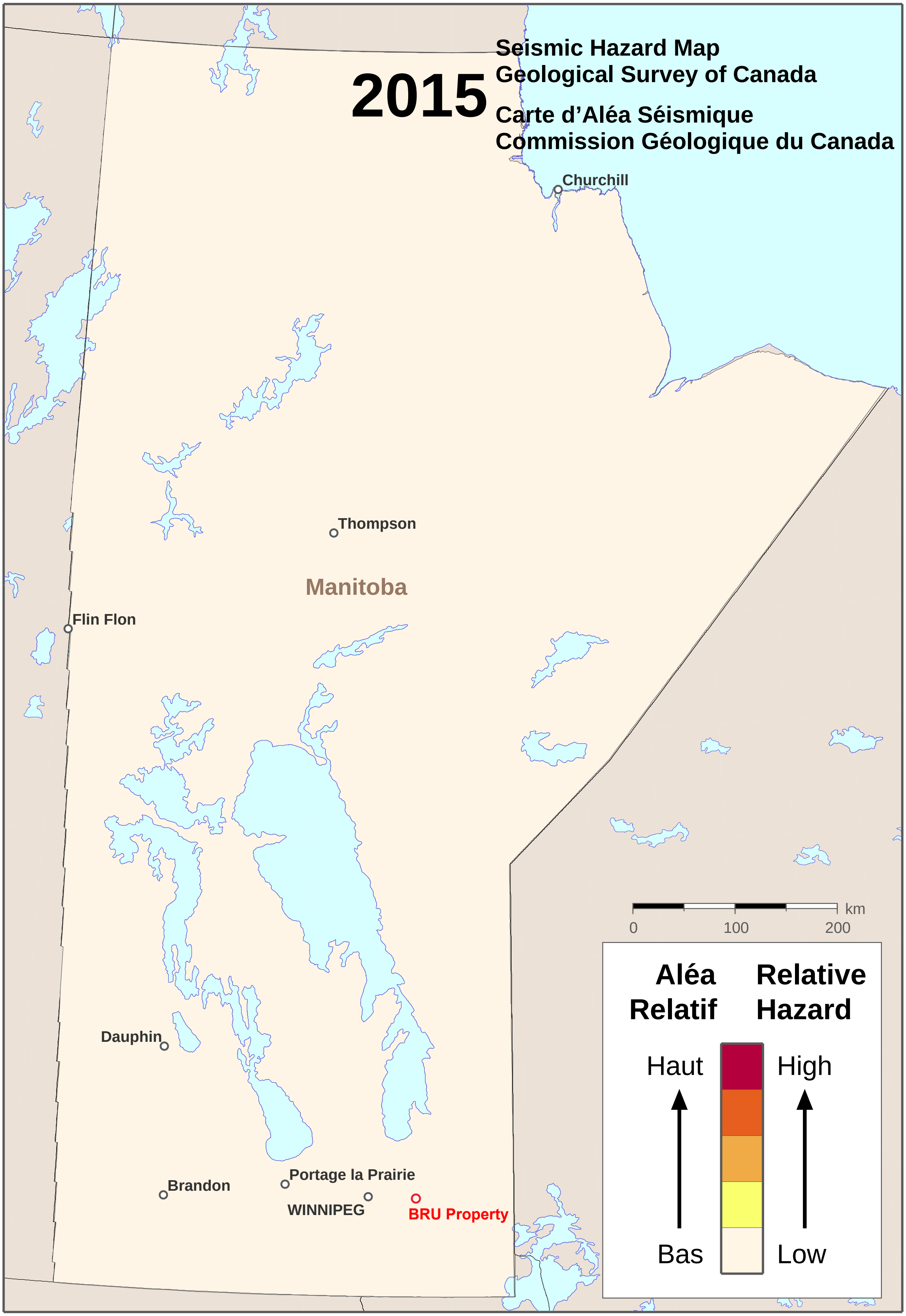
APPENDIX A

Seismic Hazard Calculations

Natural Resources Canada   Ressources naturelles Canada



2015 National Building Code Seismic Hazard Calculation

INFORMATION: Eastern Canada English (613) 995-5548 français (613) 995-0600 Facsimile (613) 992-8836
Western Canada English (250) 363-6500 Facsimile (250) 363-6565

Site: 49.842N 96.498W

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Probability of exceedance per annum	0.000404	0.001	0.0021	0.01
Probability of exceedance in 50 years	2 %	5 %	10 %	40 %
Sa (0.05)	0.043	0.020	0.011	0.002
Sa (0.1)	0.060	0.030	0.017	0.003
Sa (0.2)	0.056	0.030	0.017	0.004
Sa (0.3)	0.045	0.025	0.015	0.003
Sa (0.5)	0.033	0.019	0.011	0.002
Sa (1.0)	0.017	0.009	0.005	0.001
Sa (2.0)	0.007	0.004	0.002	0.000
Sa (5.0)	0.001	0.001	0.001	0.000
Sa (10.0)	0.001	0.001	0.000	0.000
PGA (g)	0.032	0.016	0.009	0.002
PGV (m/s)	0.022	0.012	0.006	0.001

Notes: Spectral (Sa(T), where T is the period in seconds) and peak ground acceleration (PGA) values are given in units of g (9.81 m/s^2). Peak ground velocity is given in m/s. Values are for "firm ground" (NBCC2015 Site Class C, average shear wave velocity 450 m/s). NBCC2015 and CSAS6-14 values are highlighted in yellow. Three additional periods are provided - their use is discussed in the NBCC2015 Commentary. Only 2 significant figures are to be used. **These values have been interpolated from a 10-km-spaced grid of points. Depending on the gradient of the nearby points, values at this location calculated directly from the hazard program may vary. More than 95 percent of interpolated values are within 2 percent of the directly calculated values.**

References

National Building Code of Canada 2015 NRCC no. 56190; Appendix C: Table C-3, Seismic Design Data for Selected Locations in Canada

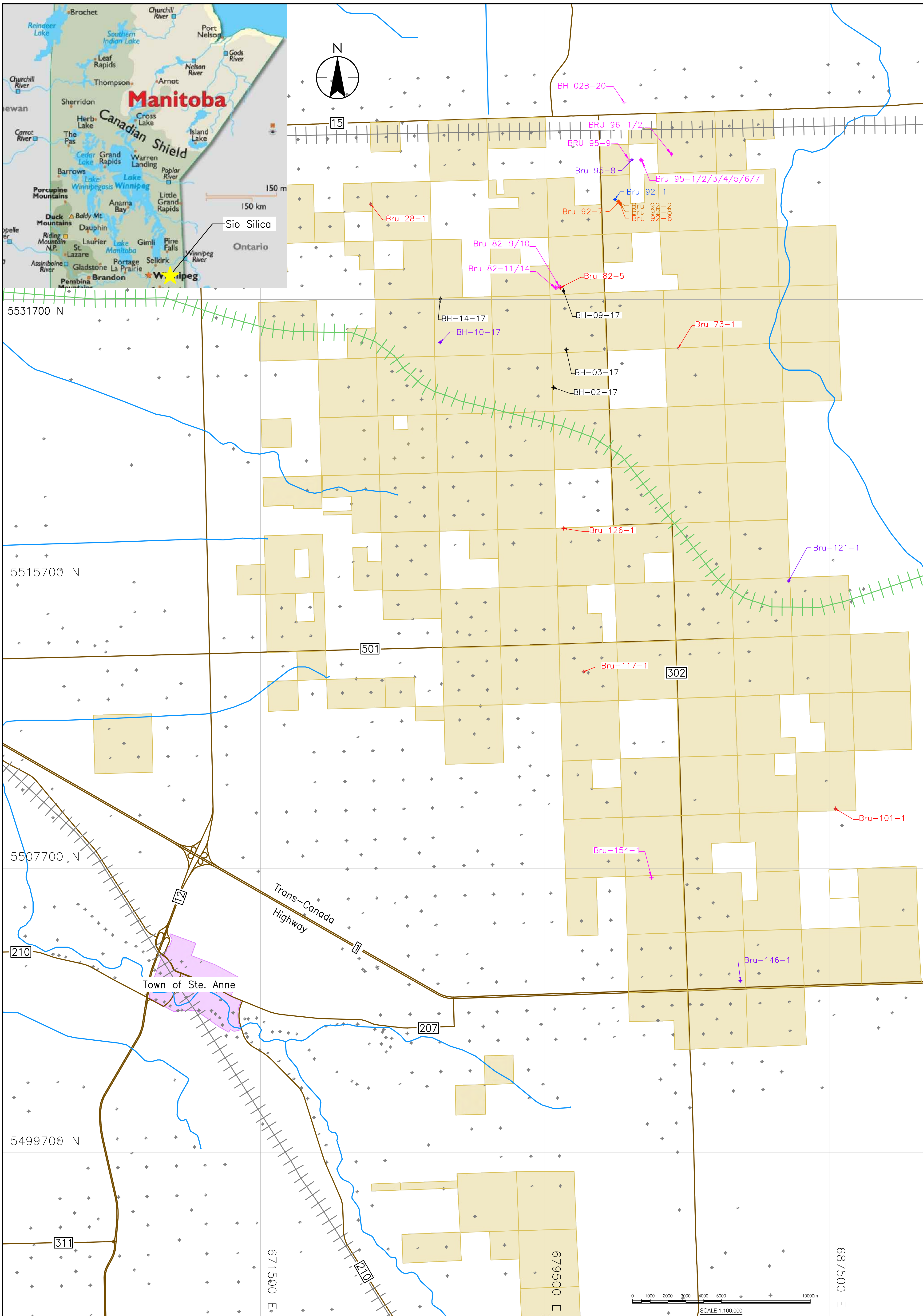
Structural Commentaries (User's Guide - NBC 2015: Part 4 of Division B)
Commentary J: Design for Seismic Effects

Geological Survey of Canada Open File 7893 Fifth Generation Seismic Hazard Model for Canada: Grid values of mean hazard to be used with the 2015 National Building Code of Canada

See the websites www.EarthquakesCanada.ca and www.nationalcodes.ca for more information

APPENDIX B

BRU Property Site Investigation Plan View



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Stantec

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Tel:+1(403) 716-8000
www.stantec.com

Notes
1. COORDINATES IN UTM ZONE 14N NAD83.

Legend
- 2021 Sio Silica Side Scan Sonar
- 2021 Sio Silica SPT
- 2021 Sio Silica ATV/OTV
- Sio Silica Drill Hole with Detailed Logged (for GSI)
- Non Sio Silica Drill Hole (GWDrill Provincial Database)
- 2019-2021 Sio Silica Drill Hole
- 2018 Sio Silica Drill Hole
- 2017 Sio Silica Drill Hole
- Mining Claim
- City/Town
- River
- Road
- GWWD Rail Line
- CN Rail Line

Client/Project Logo

Sio SILICA

Client/Project
SIO SILICA CORPORATION

BRU PROPERTY SAND EXTRACT.
- GEOTECHINCAL ANALYSIS

Title
BRU PROPERTY SITE INVESTIGATION
PLAN VIEW

Scale: 1:100000			Figure No.	B-1
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Dwn.	Dsgn.	Chkd.	YYYY.MM.DD	Revision: A

Project No.: 129500426

File Name: FIGURE 1 PLAN VIEW_REV A

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