FINAL DRAFT Technical Memorandum #08

Assessment of Minimum Rock Cover Over Crown – Rev A

GPC6, C-2012668-02, Task Order #39 Dallas CBD Second Light Rail Alignment (D2 Subway)

FINAL DRAFT

Dallas, TX
July 22, 2019

This Report was Prepared for DART
General Planning Consultant Six Managed by HDR

Document Revision Record

FINAL DRAFT Technical Memorandum #08 Assessment of Minimum Rock Cover Over Crown	**HDR Report Number:** Click here to enter text.
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Revision Number: A	**Date:** July 22, 2019
Version 1	*Date: Click here to enter text.*

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Contents

1 EXECUTIVE SUMMARY 3

2 INTRODUCTION 5

2.1 Purpose 5

2.2 Assumptions 6

2.3 Good Engineering Practices in Cavern Design 6

3 CROWN PILLAR STABILITY ANALYSIS 7

3.1 Geomechanics System 10

3.2 Norwegian Geotechnical Institute System 10

3.3 Scaled Crown Span 10

3.4 Scaled Crown Span Equations (1992) 10

3.5 Generalized Logistical Model Probability of Failure (2014) 14

3.6 Guidelines for the Scaled Crown Span Method 14

4 CROWN ARCH DESIGN 15

4.1 Rock Characteristics 15

4.1.1 AUSTIN CHALK CHARACTERISTICS 15

4.1.2 JOINTING CONDITIONS 15

4.1.3 RELEVANT BOREHOLES 16

4.2 Groundwater and Stress Characteristics 17

4.3 Austin Chalk NGI-Q Parameters 17

5 SCALED CROWN SPAN CALCULATIONS 17

5.1 Metro Center Station 17

5.2 Commerce Station 18

5.3 CBD East Station 18

5.4 Scaled Crown Span Calculation Spreadsheet 18

5.5 Minimum Rock Cover Calculations 19

5.6 Actual Condition of Crown Arch (Commerce Station) 22

6 CONCLUSION 24

7 RECOMMENDATIONS FOR PE 20% DESIGN 25

7.1 Design Recommendation #1 25

7.1.1 DESIGN RECOMMENDATION 25

7.1.2 BASIS OF RECOMMENDATION 25

7.1.3 SOURCES OF UNCERTAINTY 25

7.2 Design Recommendation #2 25

7.2.1 DESIGN RECOMMENDATION 25

7.2.2 BASIS OF RECOMMENDATION 25

7.2.3 SOURCES OF UNCERTAINTY 25

7.2.4 RISK, COST, AND SCHEDULE COMPARISON 26

7.3 Design Recommendation #3 26

7.3.1 DESIGN RECOMMENDATION 26

7.3.2 BASIS OF RECOMMENDATION 27

7.3.3 SOURCES OF UNCERTAINTY 27

8 REFERENCES 28
9 ATTACHMENT 1: TABLE A-1: ASSUMED NGI – Q PARAMETERS FOR DART D2 CAVERN STATIONS 29
10 ATTACHMENT 2: TABLE A-2: CROWN PILLAR STABILITY ANALYSIS 30
11 ATTACHMENT 3: FIGURE A-1: CROWN PILLAR PROBABILITY OF FAILURE CHART 31

Tables

TABLE 5-1. MINIMUM REQUIRED ROCK COVER ABOVE STATION CROWN 21

Figures

FIGURE 2-1. MINED ROCK CAVERN TERMINOLOGY 7
FIGURE 3-1. ARCHED AND BINOCULAR CAVERN CONFIGURATIONS 9
FIGURE 3-2. SUMMARY OF CROWN PILLAR CASE RECORDS PLOTTED AS THICKNESS TO SPAN RATIOS VERSUS ROCK MASS QUALITY OF WEAKEST ZONE OF CROWN GEOMETRY 12
FIGURE 3-3. SUMMARY OF CROWN PILLAR CASE RECORDS PLOTTED AS SCALED CROWN SPANS VERSUS ROCK MASS QUALITY 13
FIGURE 5-1. SURFACE CROWN PILLAR EMPIRICAL DESIGN CHART FOR SIZING CROWNS OF LONG STRIKE LENGTH - (STRIKE LENGTH I SPAN RATIO > 10) AND ROCK MASS UNIT WEIGHT, y = 2.7 T/m3 (CARTER, 1992, P. 81) 20
FIGURE 5-2. CROSS SECTION OF COMMERCE STATION AT 72+00 FEET 23

1 EXECUTIVE SUMMARY

The minimum rock cover over the crown of the excavation can be determined with a stability analysis of the “crown pillar” or “crown arch.” This technical memorandum summarizes the results of a crown arch stability analysis for three mined station caverns along the proposed DART D2 subway project; it was originally carried out for the Locally Preferred Alternative (LPA) alignment and has been updated for the 10% South of Swiss Alignment, March 8, 2019. This analysis has been implemented using the scaled crown span method developed by T. G. Carter from 1992 to 2014. The primary purpose of the analysis was to evaluate the current alignment profile with respect to the anticipated application of mined methods of construction of both arched center platform stations and binocular stations, to minimize impacts of cut and cover construction on dense urban environment of downtown Dallas, including communities, businesses, streets, utilities, traffic, and overlying and adjacent structures and facilities.

Considering the relatively shallow profile resulting from the limited rock cover condition of the original LPA alignment, the station cavern concept analysis was based on binocular cavern configuration. Arched station configurations with a mezzanine over train room and platform area was not considered feasible. Even for a more compact binocular station configuration, the CBD East station cavern and the Metro Center station cavern crown would extend above the anticipated top of rock elevations, requiring extensive application of ground improvement and pre-support measures with unacceptable risk of excavation instability during mining construction.

For CBD East station, an additional risk issue of the original LPA alignment is the presence of the existing pile foundation under the Elm Street Parking Structure, which extends into the top of rock surface and encroaches into the planned station limits requiring extensive underpinning. Constructing such a shallow station cavern of a relatively wider span (over 65-foot wide) under the existing structure, encroaching into the structure's foundation, would carry significant risks and would possibly be prohibitively more expensive than construction of a deeper cavern (with industry-standard application of a required rock cover over the cavern arch that would carry the overlying foundation surcharge without a need for structural underpinning).

The Commerce station cavern would be constructed in rock, however maintaining the stable crown arch conditions would carry increased risks because the anticipated rock cover above the cavern crown would be substantially less than the required minimum cover. Additional risk factor is the presence of a seven-foot diameter horseshoe-shaped storm sewer tunnel, located near the previous LPA invert. For these reasons, it is strongly recommended that the alignment for the Commerce Street Station be lowered if the mined tunnel methodology is to be used.

This situation with the insufficiency of the crown arch and the obstructions at Commerce and CBD East station caverns could be rectified by lowering the tunnel alignment and relocating the alignment out from under the CBD East Station. The recommended values related to lowering the track alignment are based on the cover depths necessary for underground mined cavern construction techniques in rock and are as follows:

- Metro Center Station Lower by 26 Feet
- Commerce Station Lower by 20 Feet
- Crossover Cavern Lower by 24 Feet
- CBD East Station Lower by 32 Feet

The insufficiency of the crown arch thickness at the original LPA profile elevation presented a significant risk to the construction of the mined station caverns; if possible from overall operations standpoint lowering the alignment would achieve the following beneficial objectives:

- Provide a stable mining environment in rock mining conditions

- Avoid obstructions of a 7-foot diameter storm sewer at Commerce station
- Avoid obstructions of pile foundations at CBD East station

Alternatives to lowering the alignment include application of shallower cut and cover stations that would allow removal and/or relocation and support of the present underground obstructions and utilities, respectively, including major storm sewer line.

As a result of these considerations, the 10% South of Swiss Alignment of March 8, 2019 incorporated a lower Commerce Station, elimination of the double crossover cavern, designation of Metro Center and CBD East Stations as cut and cover construction, and relocation of the alignment to stay beyond the footprint of the parking garage structure. These changes were implemented to improve the constructability of the DART D2 alignment. This analysis indicates that the 10% South of Swiss Alignment of March 8, 2019 can incorporate high arched, low profile arched, and binocular station configurations at Commerce Station.

2 INTRODUCTION

This technical memorandum summarizes the results of a crown arch stability analysis performed for the locations of three station caverns and one crossover cavern along the proposed DART D2 subway project for LPA alignment and subsequently for the 10% South of Swiss Alignment of March 8, 2019. The terminology for crown pillar and crown arch stability analysis is provided in **Figure 2-1**.

This crown arch stability analysis has been performed to evaluate whether the crown arch for potential caverns at three station cavern locations can be expected to remain stable while the final lining is being installed. Of particular concern is the stability of the crown arch during the following activities: cavern excavation, initial lining installation, and final lining placement.

2.1 Purpose

This analysis identifies the minimum rock cover thickness for the crown arch of rock to be left in place above the station cavern and adjacent to the cavern for support of the cavern structures. This allows selection of the most economical means and methods for constructing the underground mined caverns. For the Commerce Station underground cavern excavation, a recommendation to lower the current LPA alignment by 16 to 29 feet was recommended and implemented in the 10% South of Swiss Alignment, March 8, 2019.

2.2 Assumptions

This memorandum has been prepared using the following assumptions and inputs:

- The project alignment is as provided on March 8, 2019 (an updated alignment will be issued by the end of July 2019)
- The project alignment includes consideration of 9 existing adjacent buildings and their foundations (as of July 2019 the effort to identify affected subsurface structures and foundations along the alignment corridor is still undergoing)
- Ground conditions are based on data presented in the February 28, 2019 Draft Geotechnical Data Report prepared by Alliance Geotechnical Group (as of July 15, 2019, the Final Geotechnical Data Report is still pending)
- Commerce Station location is between STA 71+13.15 and STA 77+38.15 (in July 2019 it is expected that the station location will be adjusted to the west by approximately 350 feet as part of an updated alignment that would be issued by the end of July 2019).

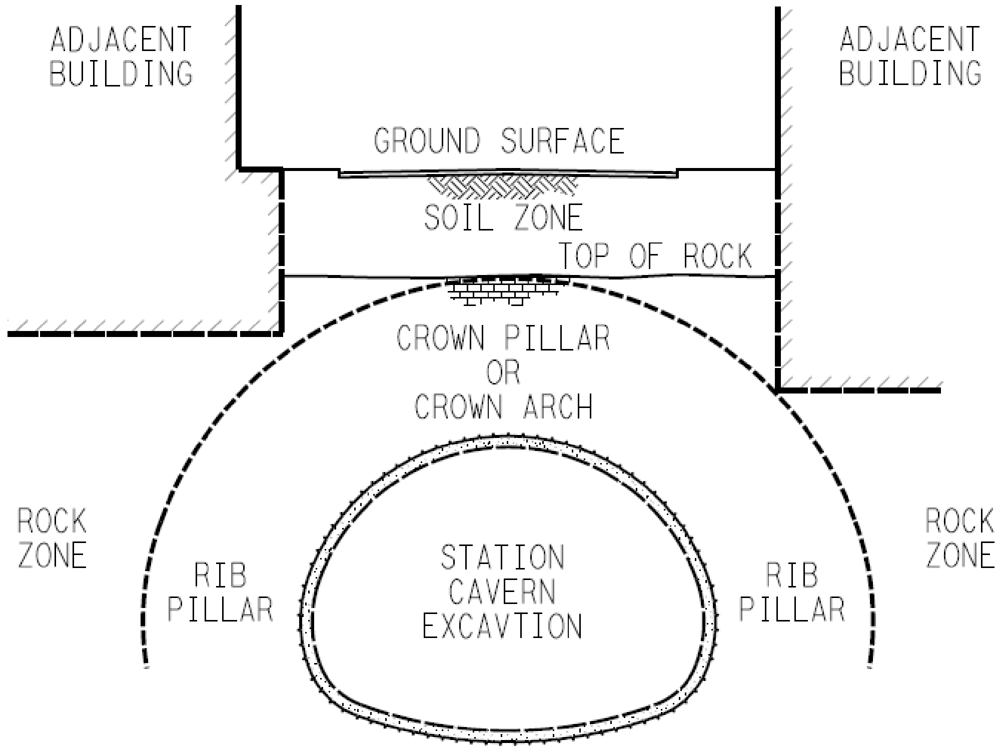
2.3 Good Engineering Practices in Cavern Design

There are certain key parameters that must be determined in advance of a design of a mined subway station cavern in rock. These key parameters include, but are not limited to the following;

- Reasonable estimate of the competency of the rock mass surrounding the cavern
- Stable cavern configuration geometry
- Compatible ground support strategy for the prevailing geotechnical conditions
- A minimum rock cover thickness over the cavern
- A minimum pillar adjacent to the cavern.

Good engineering practice requires that a comprehensive geotechnical investigation be conducted at the planned cavern location. After determining the prevailing geotechnical conditions and establishing representative geotechnical design parameters, the key parameters must be evaluated, and determined to be compatible with the contemplated cavern design. Specifically, there must be a sufficient rock cover over the cavern to allow for safe rock mining methods to be carried out. This single parameter will lower the risk and cost of mining the cavern and prevent adverse impacts to overlying and adjacent existing structures if the crown arch does not perform in a manner to control settlement above the cavern.

FIGURE 2-1. MINED ROCK CAVERN TERMINOLOGY



(a) The terms Crown Pillar and Crown Arch are synonyms.

3 CROWN PILLAR STABILITY ANALYSIS

A crown pillar is the zone of rock directly above the limits of a mining, tunnel, or cavern excavation. The stability of a crown pillar can be analyzed by various empirical and numerical methods.

The crown pillar thickness is the rock cover, excluding the soil zone over the cavern, that forms the crown pillar to the outside edge of the cavern excavation. This information can generally be obtained only from borehole data.

In general, when left unsupported the rock mass in a crown arch can be either stable, subject to failure over time unsupported, or subject to immediate collapse upon excavation. The resulting condition of the crown arch is determined by four factors;

- Rock mass quality
- Cavern excavation width

- Proximity to the surface
- Method of excavation.

The rock mass quality can be expressed by qualitative descriptions or numerical indices such as the Geomechanics (RMR) and the Norwegian (Q) systems. With respect to both of these systems, as well as other rock mechanics indices, the stability of the excavation decreases as the rock quality decreases.

The cavern excavation width, expressed in feet or meters to the outside of the final excavation surface, typically affects the excavation by trending away from stability as the cavern excavation width increases.

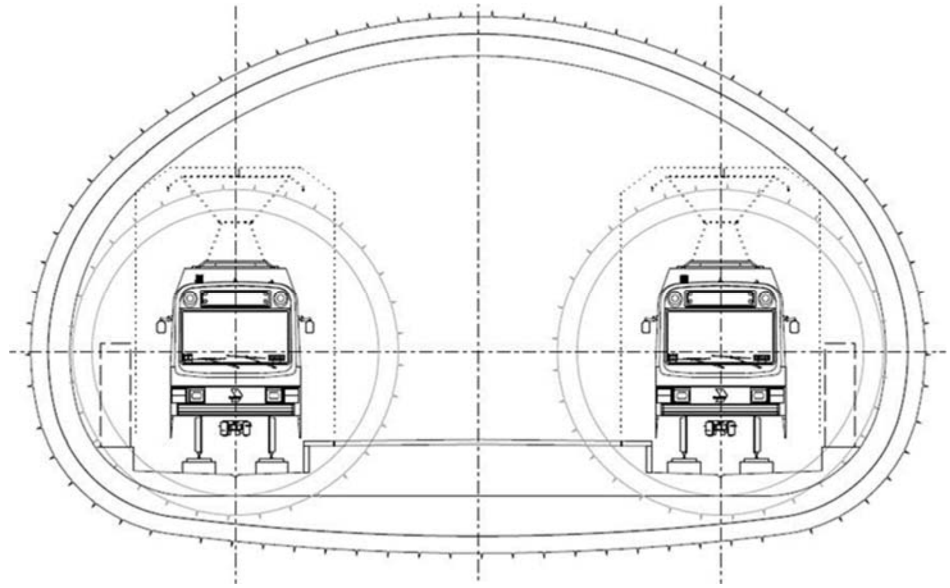
The proximity of the excavation to the ground surface adversely affects the cavern stability. This is due to the fact that as the cavern approaches the surface, the ability to employ arching action diminishes, and the support is required to develop beam action. Effects of this phenomena are considered by the scaled crown span equation. There are two basic cavern configurations available, which are suited to construction under shallow cover, as shown in the following **Figure 3-1**. An arched cavern is typically constructed where there is sufficient crown arch thickness to allow for the development of arching action in the rock mass. A binocular cavern should be used where the cavern excavation would otherwise protrude above the top of rock surface.

The method of excavation is also a factor affecting stability of the crown pillar during excavation. Blasting will tend to loosen up rock blocks around and cause blast damage to the periphery of the excavation to a greater extent as compared to excavation by roadheaders. Drill and blast excavations will tend to be less stable and require more support for a given cavern width, rock quality and proximity to the surface. This effect is expressed in some systems used in rock mechanics today. However, it is not currently expressed in a practical system for evaluating the crown arch stability. It must, however, be considered during the construction phase. Although blasting is currently precluded on the DART D2 project, it should also be recognized that due to the extremely thin crown arches on the present alignment, it is not recommended to allow drilling and blasting as a means and methods of construction for these caverns due to the following unfavorable site conditions;

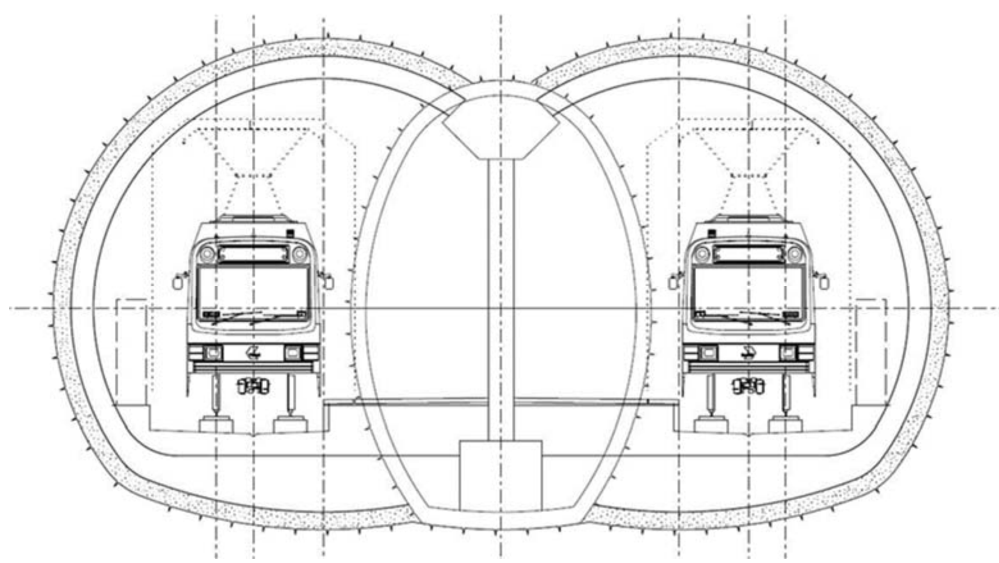
- Extremely soft rock with clay seams
- Shallow rock cover
- Closely located obstructions in proximity to the crown arch
- Densely populated urban areas with adjacent and nearby structures, sensitive to vibrations.

The effects of these four factors are difficult to determine quantitatively because the complexities of the geometry and geology of the typical rock masses comprising such crown pillars are difficult to categorize and simplify for analytical calculation or modelling purposes.

FIGURE 3-1. ARCHED AND BINOCULAR CAVERN CONFIGURATIONS



(a) Arched Mined Station Cavern Configuration



(b) Binocular Mined Station Cavern Configuration

3.1 Geomechanics System

The Geomechanics classification system, or Rock Mass Rating (RMR) was developed by Bieniawski in 1972 and was updated in 1976 to clarify the significance of some of the input parameters. This system is explained in Technical Memorandum #06 – Cavern Final Lining Loads.

3.2 Norwegian Geotechnical Institute System

The Norwegian Geotechnical Institute's Rock Tunneling Quality index, (Q) system, is a rock mass classification system used worldwide for the design of rock support for civil and mining construction projects. It was first used in hydropower projects in Norway and in a water transfer project in Peru in 1974. (Barton and Grimstad, 2014). The system was developed based on application in Norwegian road tunnels during which hundreds of case studies were examined. This system provides a simple means of communication for geologists, rock engineers, mining engineers and lawyers. The Q system is used, often in combination with the geomechanics system, in thousands of tunneling projects around the world and in all principal mining countries. It provides an evaluation in terms of both rock quality and cavern width. The Q index has been employed to provide a first indication of initial ground support, as well as final support for tunnels and caverns to put these designs correspondingly within the acceptable range based on other tunneling projects worldwide.

The Q system is described in detail in Technical Memorandum #06 – Cavern Final Lining Loads.

3.3 Scaled Crown Span

The Scaled Crown Span empirical method has been developed by T. G. Carter over a period of two decades. Relevant publications on this method are provided in (Carter, 1992; Carter and Miller, 1995; Carter, 2000, Carter, 2014). This method uses case studies of both stable and unstable crown pillars for various known crown pillar conditions and normalizes these cases with respect to the scaled span of the crown pillars. This method, although general in nature, provides a realistic assessment of the stability of a crown pillar.

3.4 Scaled Crown Span Equations (1992)

Carter (1992) develop a method of stability analysis in which crown pillar instability occurs when the scaled crown pillar span (Cs) is greater than the critical span (Sc). These parameters are defined as follows:

Scaled crown pillar span (m): $C_s = S \times [\, \gamma / (T\,(1+S/L)\,(1-0.4 \cos\theta)\,)\,]^{0.5}$

Critical span (m): $S_c = 3.3 \times Q^{0.43}$

Minimum crown pillar thickness (m): $T_{min} = 5.11 \times Q^{-0.19} \times [\, \sinh^{0.0016} (Q)\,]$

Where:

S = actual crown pillar span (m)

L = actual crown pillar strike length (m)

T = actual crown pillar thickness (m)

γ = rock specific gravity (S.G.)

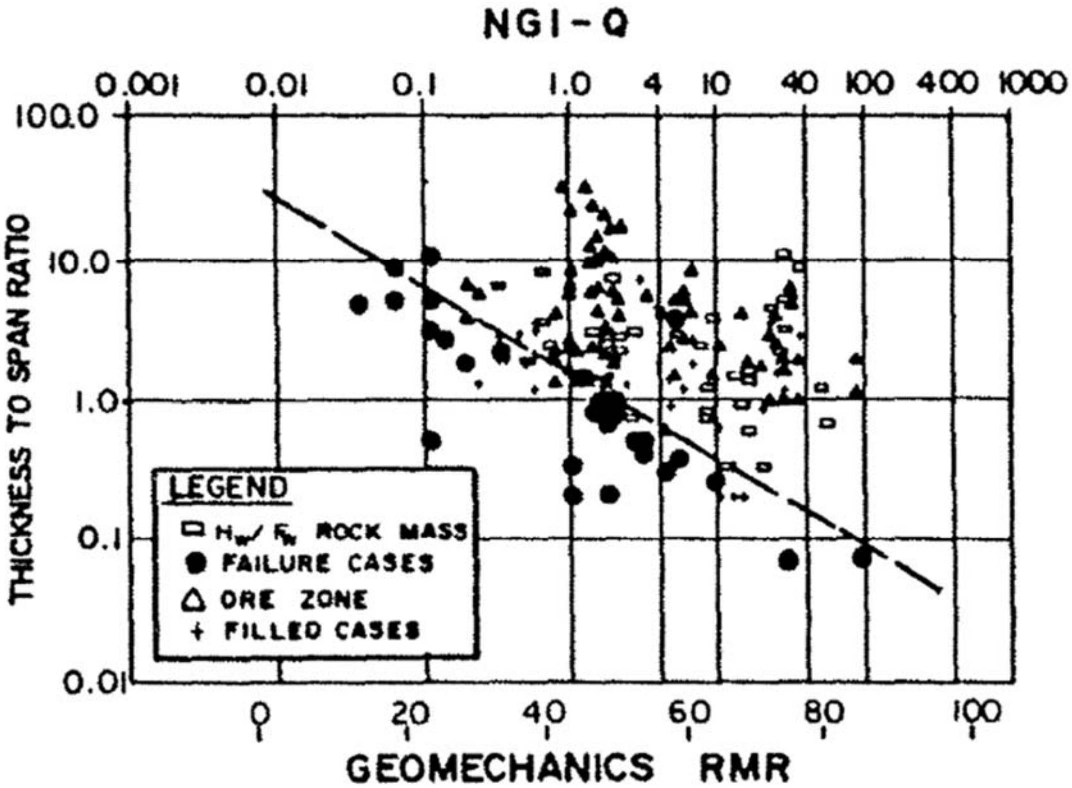
θ = foliation dip (degrees)

Q = Norwegian Method of Tunneling (NMT) rock tunneling quality index.

The critical span represents the cavern span in the given geotechnical and geometrical conditions at which the span over the cavern has a 50% probability of failure if left unsupported. The critical span dimension can be considered the minimum acceptable rock cover over the crown of the cavern at which the cavern is considered stable. If less rock cover is provided than the critical span, ultimate failure of the crown span is likely, and these rock loads will necessarily need to be carried by initial lining support and final lining structure. Likewise, an equivalent thickness of rock should be provided in each rib on the two sides of the cavern. This situation can be inferred by referring **Figure 5-2** in a later section. If one of the ribs has been removed for some other reason, such as excavation for a nearby building foundation, instability of the crown pillar becomes a definite construction risk.

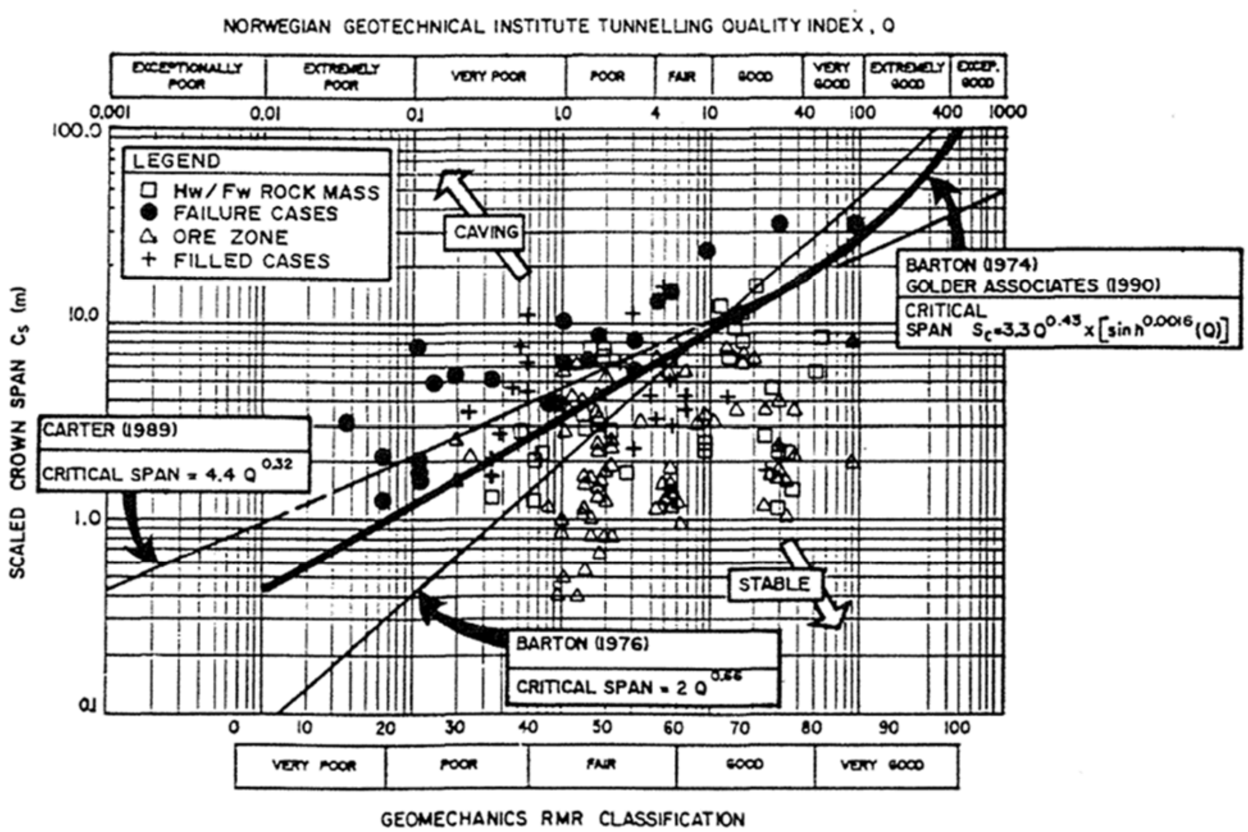
The scaled crown span approach was developed by seriously considering the back calculated thickness to span ratio for crown pillars in Canada which had failed and comparing those to crown pillars which remained stable given the prevailing geotechnical conditions. The graph resulting from Carter's analysis is shown in **Figure 3-2**. Note that the failed crown span ratios fall to one side of a line which can be drawn as a function of rock quality. This data, from the case records of over 200 crown pillars with 30 failed cases, can be used to predict the stability of future crown pillars based on rock quality and cavern geometry.

FIGURE 3-2. SUMMARY OF CROWN PILLAR CASE RECORDS PLOTTED AS THICKNESS TO SPAN RATIOS VERSUS ROCK MASS QUALITY OF WEAKEST ZONE OF CROWN GEOMETRY



The same crown pillar case data can be plotted on a graph with the scaled crown span versus the rock quality as shown in **Figure 3-3**. This stability graph can be used for the design of future crown pillars. With use of the Scaled Crown Span, Cs, concept to scale different crown geometries for comparison with the Critical Span, Sc, expression, a significant improvement can be made to the previously used conventional Rule of Thumb approaches for determining safe spans and crown thicknesses. (Carter, 1992)

FIGURE 3-3. SUMMARY OF CROWN PILLAR CASE RECORDS PLOTTED AS SCALED CROWN SPANS VERSUS ROCK MASS QUALITY



3.5 Generalized Logistical Model Probability of Failure (2014)

In 2008 the scaled crown span method was updated to include a generalized logistic model for the probability of failure of a crown pillar based on empirical methods. The general probability of failure was explained by Carter (2014). The resulting equation is as follows;

Crown pillar probability of failure (%): $Pf = 100/[1+440 \times \exp(-1.7*Cs/Q^{0.44})]$

Critical Span Line (50% Failure) (m): $Sc = 3.58\ Q^{0.44}$

Where:

Cs = Scaled crown pillar span (m)

Q = NMT rock tunneling quality index.

Since the introduction of the original Scaled Span chart in 1989, further updates have included up to 500 case studies including 70 analyzed failures. (Carter, 2014) The resulting failure probability chart based on these logistic regression relationships, as a consequence of the development of the scaled crown span method over two decades, now allows very rapid assessment of possible risk for any known crown geometry and rock mass quality. However, the stability analysis and design of a crown pillar must preclude consideration of insufficient data for the individual caverns. To better estimate the relative probability of failure (Pf) for the crown pillars in this investigation, the crown and opening geometry and rock mass quality are estimated from several boreholes in addition to consideration of the available geotechnical data in the Geotechnical Memorandum of Design. The spread of data is indicated in the subsequent section below.

3.6 Guidelines for the Scaled Crown Span Method

The basis for the design acceptability of new cavern excavations for civil engineering structures is achieving a very low degree of risk. In particular, subway station caverns typically feature public access over the structure and buildings directly over near-surface underground excavations. Tolerance to risk in such cases is limited and the acceptable degree of risk must be essentially zero. To the extent possible, and where economically feasible, the crown pillar geometry and rock quality should provide for a cavern crown pillar probability of failure for an unsupported cavern excavation in categories E, F, and G, or less than 5%. To the extent that any probability exists, the crown pillar requires rock reinforcement and structural support.

4 CROWN ARCH DESIGN

4.1 Rock Characteristics

The geotechnical characteristics of the Austin Chalk are described in other geotechnical reports associated with the present DART D2 project development. Specifically, characteristics of the Austin Chalk will be described in the following reports being developed during preliminary engineering;

- Geotechnical Data Report - DART D2 Subway Project – 10% Design
- Geotechnical Memorandum of Design - DART D2 Subway Project – 10% Design

4.1.1 AUSTIN CHALK CHARACTERISTICS

The Austin Group, frequently called "Austin Chalk," is primarily light to medium gray chalk with interbedded calcareous claystone. The Austin Chalk is a relatively competent soft rock. Unconfined compressive strength is typically about 2,468 psi., varying from about 615 to 4,159 psi. (Ciancia, 2019) Rock strength generally increases with decreasing water content and increasing carbonate purity.

4.1.2 JOINTING CONDITIONS

Joints with smooth fracture surfaces are common in the chalky beds of the Austin Chalk and less common in the shales and marls. (Ciancia, 2019) They are nearly vertical and occur in sets with consistent trends over small areas. Mapped strike directions are:

- N65E and due north at Chalk Hill
- N30E and N80W near White Rock Lake, with minor sets striking N63E, N58W, and N5W
- N15E and N85W in the marly beds of the middle member of the Austin Chalk at White Rock Lake

For preliminary baseline purposes, it is assumed that two near-vertical joint sets are present along the DART D2 alignment, one of which strikes about N65E.

Bedding planes are assumed to have planar joint surfaces. Rock Jointing is common throughout the region, although generally infrequent, with high joint frequencies usually limited to the areas of faulting. The geologic conditions that contribute to the observed jointing include regional uplift, faulting, erosional stress relief, and seismic activity. These joint sets are related to the local stress regime. Therefore, the joint set developed along bedding planes should be considered, and is the primary joint set affecting the stability of the excavations. Consider also two additional high angle joint sets affect stability in localized areas. Therefore, at this preliminary stage consider a joint set number, Jn, ranging from 9 for three joint sets to 15 for four joint sets plus random joints.

The joint roughness number, Jr, ranges from 2 for smooth and undulating joints to 3 for irregular and undulating.

The joint alteration number, Ja, ranges from 1 for unaltered joint walls to 6 for strongly over-consolidated, non-softening clay mineral fillings.

These preliminary discontinuity values are subject to change and will be updated as needed during later phases of the project based on project-specific rock core data.

4.1.3 RELEVANT BOREHOLES

The boreholes relevant to the design of the three station caverns are as follows;

Metro Center Station

• B-1	N. Griffin Str.	Alignment Station Approximately	51+00
		Surface Elevation	428.37 Feet
		Top of Rock Depth	25 Ft bgs
		RQD	73% to 100%
		Joint Roughness	Planar/(rough-smooth)
		Joint Aperture	Tight to open
		Joint Infilling	None described
		Joints in Austin Chalk with shears in shale at 83 to 98 feet bgs	
• TS-104	N. Griffin Str.	Alignment Station Approximately	54+00
		Surface Elevation	427.71 Feet
		Top of Rock Depth	25 Ft bgs
		RQD	90% to 100%
		Joint Roughness	Planar to Stepped
		Joint Aperture	Tight to Open
		Joint Infilling	1 calcite filled

Commerce Station

• TS-202	Commerce Str.	Alignment Station Approximately	71+50
		Top of Rock Depth	16 Ft bgs
		RQD	93% to 100%
		Joint Roughness	Planar/(rough-slick.)

		Joint Aperture	Tight
		Joint Infilling	1 calcite filled

CBD East Station

• TS-209	Elm Str.	Alignment Station Approximately	97+10
		Top of Rock Depth	38 Ft bgs
		RQD	98% to 100%
		Joint Roughness	Planar
		Joint Aperture	Tight
		Joint Infilling	Calcite stringers

Refer to the Geotechnical Data Report for further information on these boreholes.

4.2 Groundwater and Stress Characteristics

The ground water parameter, Jw, for the NGI-Q calculations is taken as 1 for minor inflow.

The stress reduction factor, SRF, will typically range from 2.5 for low stress, near surface, open joints to 5 for Single weakness zones containing clay or chemically disintegrated rock less than 164 feet depth.

4.3 Austin Chalk NGI-Q Parameters

The NGI–Q parameters for the expected, best, and worst cases for use in the crown pillar stability analysis are provided in **Table A-1**, which is included as **Attachment 1** to this memorandum.

5 SCALED CROWN SPAN CALCULATIONS

The scaled crown span calculations for the crown arch analysis are based on the site-specific geotechnical characteristics of the underground cavern locations as described in the Geotechnical Memorandum of Design – 10% Design which will be subject to revision based on project specific geotechnical data. These characteristics are described as follows;

5.1 Metro Center Station

The Metro Center Station is located in the vicinity of the Crowne Plaza, between Elm Street and Pacific Avenue, on North Griffin Street.

The rock characteristics at the Metro Center Station are described in the FIRST DRAFT Technical Memorandum #3, Preliminary Ground Characterization, Rev A, January 24, 2019.

5.2 Commerce Station

The Commerce Station is located in the vicinity of the AT & T campus on Commerce Street, between South Field Street and Lane Street.

The rock characteristics at the Commerce Station are described in the FIRST DRAFT Technical Memorandum #3, Preliminary Ground Characterization, Rev A, January 24, 2019.

5.3 CBD East Station

The CBD East Station is located in the Central Business District under the Elm Street Parking Garage structure between Main Street and Elm Street and also between North Harwood Street and South Pearl Street.

The rock characteristics at the CBD East Station are described in the FIRST DRAFT Technical Memorandum #3, Preliminary Ground Characterization, Rev A, January 24, 2019.

5.4 Scaled Crown Span Calculation Spreadsheet

The preliminary calculations for the crown pillar stability analysis for each underground station cavern have been performed in an excel spreadsheet. Calculations are based on the relevant publications as shown in the spreadsheet notes. Assumptions concerning geotechnical parameters were based on logs of boreholes listed above and on characteristics of the Austin Chalk described in Moore and Teetes. (Moore and Teetes, 2006) Cavern geometry data is derived from typical tunnel cross sections being developed and included in the AMCR report. The resulting calculations are summarized in **Table A-2**: DART D2 Crown Arch Stability Analysis, which is included as **Attachment 2**. These preliminary calculations may be subject to revisions based on project specific geotechnical data.

The results in **Table A-2** are shown graphically in **Figure A-1**: Crown Pillar Failure Classes Chart, which has been included as **Attachment 3**. This graph shows the rock quality expressed in terms of the NGI Q value on the x-axis and the scaled crown span on the y-axis.

Several sets of data are plotted on this chart.

Three configurations of the Commerce Station are represented on the graph for three rock qualities in terms of the NGI Q value. The worst case, expected case, and best-case rock quality are plotted at Q=0.2, Q=2.4, and Q=8.9, respectively;

- High Arch – Scaled Span = 52 ft, Rock Cover = 15 ft, Probability of Failure = 98-100%
- Low Profile Arch – Scaled Span = 46 ft, Rock Cover = 19 ft, Probability of Failure = 95-100%
- Binocular – Scaled Span = 42 ft, Rock Cover = 23 ft, Probability of Failure = 90-100%.

As shown, the worst-case rock quality plot in the red area of the graph for which there is a 100 percent probability of crown arch failure if the cavern is opened up without support. The expected and best-case rock qualities plot in the Class A area of graph. The classification for a Class A crown arch is 50% to 100% probability that the crown arch will experience a failure within 6 months if heavy support is not provided. (Carter and Miller, p. A46, 2008) It is therefore likely that these ground conditions will experience immediate collapse if heavy ground support is not provided. Heavy support will be provided and is the subject of further investigations during preliminary and final design.

The Crossover Cavern was deleted in the 10% South of Swiss Alignment of March 8, 2019. However, for illustration the conditions at that location are described here. Due to the arched double crossover cavern height there remains only 4 feet of crown arch above the cavern. This adverse situation causes the scaled value of the cavern span to scale equivalent with caverns of a larger span, specifically 101 feet, and require design for full overburden loads equivalent to 33 feet of cover. This higher rock load is required because the 4-foot rock span overhead represents an adverse geotechnical condition.

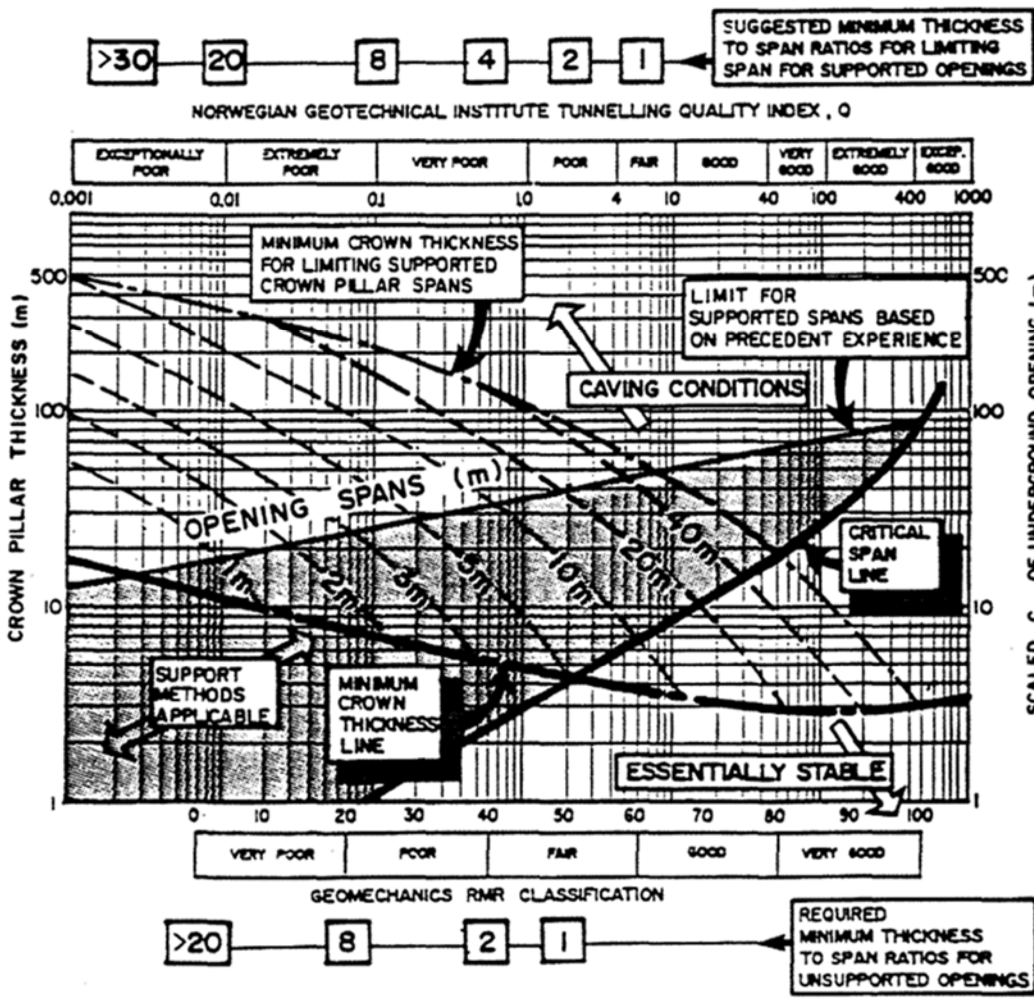
The Metro Center Station has been revised to cut and cover excavation in the 10% South of Swiss Alignment. Had it been considered as a mined cavern with a binocular configuration there would have been a crown arch thickness of 8 feet. This would have scaled equivalent to a cavern with a span of 67 feet and required a rock loading of 26 to 33 feet (full overburden). Alternatively, an arched cavern configuration would have a scaled crown span of 93 feet and required a rock loading of 29 feet (full overburden). Based on these extremely high rock loads, this station was not considered suitable for an underground mined cavern solution. Due to a requirement for a large mezzanine, it was considered a better alternative to raise the track elevation and excavate by cut and cover.

The CBD East Station is not in a location conducive to mined cavern excavation.

5.5 Minimum Rock Cover Calculations

The minimum required crown arch thickness equation is shown in the spreadsheet in the appropriate column. This equation gives the minimum required rock cover in terms of the rock quality as expressed by the Q index as explained above. The explanation for the equation comes from the 1992 paper by Carter. (Carter, p. 81, 1992) **Figure 5-1** presents a graphic representation for the minimum required crown arch thickness in terms of the rock tunneling quality index, Q and the geomechanics system, Rock Mass Rating (RMR).

FIGURE 5-1. SURFACE CROWN PILLAR EMPIRICAL DESIGN CHART FOR SIZING CROWNS OF LONG STRIKE LENGTH - (STRIKE LENGTH I SPAN RATIO > 10) AND ROCK MASS UNIT WEIGHT, y = 2.7 T/m3 (CARTER, 1992, P. 81)



The results of these equations are as indicated in **Table 5-1** below. In this table, the actual rock cover is compared to the rock cover required for the worst, expected, and best cases. Where the actual rock cover over the cavern is less than the required minimum, based on rock quality, attempting to construct caverns under these circumstances is not recommended unless substantial provisions are made to support large ground loads with initial and final lining systems. Estimation of ground loads for subway station caverns is explained in TM #06 Cavern Final Lining Loads. Based on this comparison, a recommendation for lowering the alignment is reasonable. If the alignment can be lowered, mined rock cavern stations can be constructed with traditional underground rock mining techniques employing rock reinforcement of the crown arch. If the alignment cannot be lowered, more expensive SEM mining for soil conditions will be required. Alternatively, shallower stations might be provided with cut and cover construction schemes.

Note that an arched cavern configuration is not shown for the CBD East Station cavern. This is because the cavern crown excavation encroached up to 23 feet into the soil zone. This was complicated by the fact that there was a sensitive parking garage structure located above this cavern. Therefore, an arched cavern configuration was not recommended because of the impracticality and inherent risk of attempting to construct an arched cavern below a sensitive existing structure without causing damage. This conflict with the existing parking facility was addressed in the 10% South of Swiss Alignment dated March 8, 2019.

TABLE 5-1. MINIMUM REQUIRED ROCK COVER ABOVE STATION CROWN

Equivalent Feet of Rock

Station	Config-uration	Borehole	Prob-ability of Failure	Anticipated Rock Cover	Minimum Required Rock Cover Thickness			Recommend-ed Alignment Lowering
				Estimated from Borehole	Worst Case	Expected Case	Best Case	
				(Feet)	(Feet)	(Feet)	(Feet)	(Feet)
Metro Center	Binocular	B-1	NA	-2	24	15	12	26
Metro Center	Arched	B-1	NA	-15	24	15	12	39
Commerce	Binocular	TS-202	100	3	23	14	12	20
Commerce	Arched	TS-202	NA	-10	23	14	12	33
Crossover	Low Arch	TS-202	100	-1	23	14	12	24
CBD East	Binocular	B-2	NA	-10	22	14	12	32
CBD East	Arched	B-2	NA	-24	22	14	12	46

Note 1: The recommended extent of track lowering corresponding to the minimum depths for more economical rock cavern construction techniques rather than SEM techniques in soil, given the present LPA alignment.

Note 2: The Commerce Station and Crossover Cavern on the LPA have a seven-foot diameter horseshoe shaped storm sewer tunnel located as an obstruction in the vicinity of the present LPA invert, further requiring lowering of the present LPA alignment.

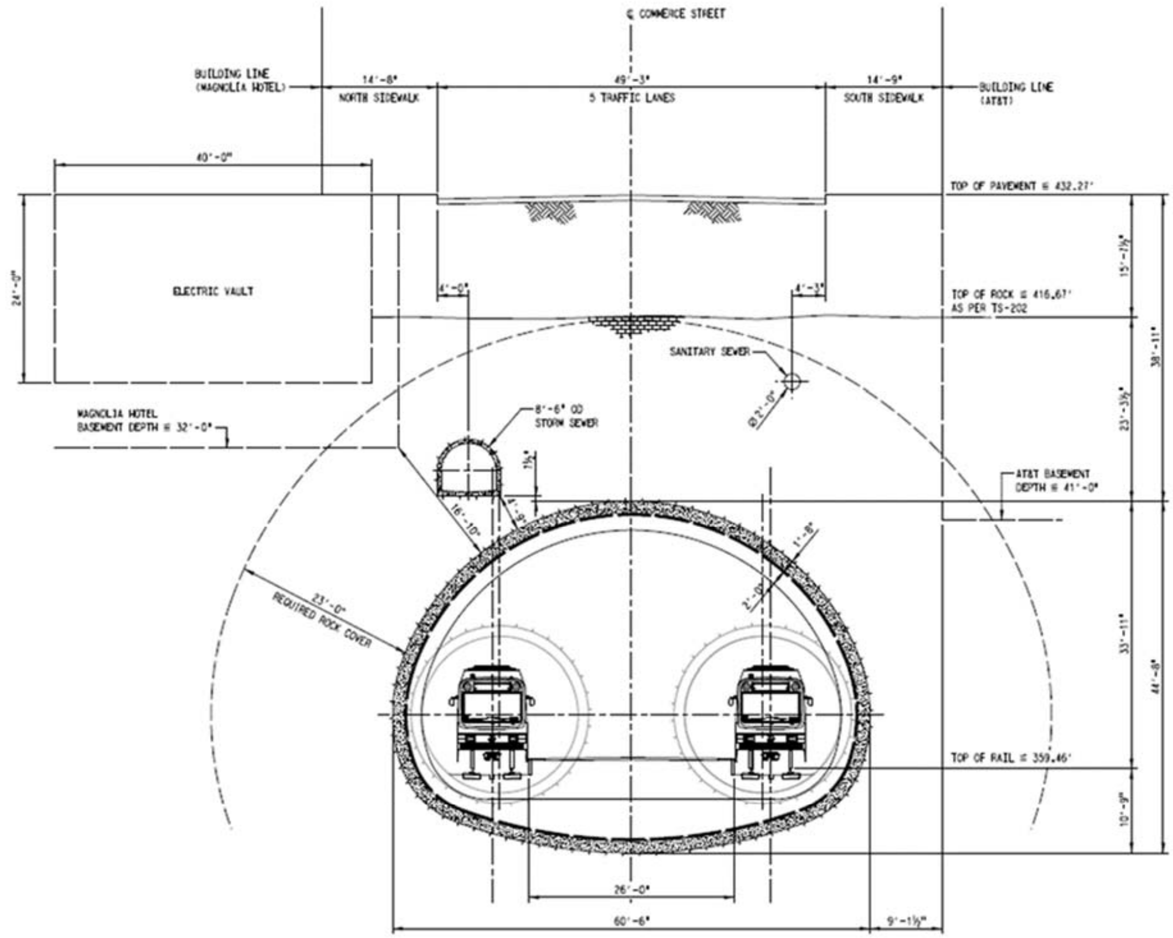
Note 3: The CBD East Station has a system of existing pile foundations under the Elm Street Parking Structure which extends into the top of rock surface. It may not be feasible or may be prohibitively expensive to construct this shallow 65-foot-wide station cavern under the present circumstances.

5.6 Actual Condition of Crown Arch (Commerce Station)

The analysis above indicates that best quality and worst quality rock in the vicinity of Commerce Station requires a minimum required crown arch thickness of 12 feet and 23 feet respectively. The poorer conditions account for areas of the Commerce Station with potential shear zones, which are expected to occur in some locations. Consequently, a minimum crown arch thickness of 23 feet is recommended.

The actual condition of the crown arch at Station 72+00 feet is shown in Figure 5-2. As indicated, the 10% South of Swiss Alignment of March 8, 2019 has been lowered to an elevation where the 23-foot minimum required crown arch can be accommodated.

FIGURE 5-2. CROSS SECTION OF COMMERCE STATION AT 72+00 FEET



CROSS-SECTION AT COMMERCE ST
(STA 72+00) LOOKING EAST
SCALE: ⅛" = 1'-0"

6 CONCLUSION

A crown pillar stability analysis has been performed for three station configurations, binocular, low profile arched, and high arched, for Commerce Station; two configurations for the location at Metro Center Station, and a high arched configuration for the location of the crossover cavern on the DART D2 alignment. The details of these calculations are shown in **Table A-2**: Crown Pillar Stability Analysis included as **Attachment 2**. The results of this set of calculations indicate that in terms of the stability of the crown arch, the binocular cavern station types would typically be recommended for stations in shallow rock cover. Furthermore, sufficient rock cover has been provided with the lowered 10% South of Swiss Alignment, March 8, 2019. Critical parameters from this analysis are summarized in **Table 5-1**, which shows the currently anticipated crown pillar thickness, required crown pillar thickness, and crown pillar probabilities of failure when unsupported.

As shown, the actual crown arch thickness for the binocular stations meet the required crown arch thickness of 23-feet for the lowered alignment. Binocular cavern configurations typically yield lower probabilities of failure in shallow cover.

The lack of sufficient crown arch thickness considering the original LPA profile elevation presented a risk to the construction of the station caverns. The resulting high probability of crown arch failure required that the LPA alignment be lowered. Lowering the alignment at the 10% submission achieved four positive results for the project as follows;

- Provided a stable mining environment in rock mining conditions
- Avoided obstructions of a seven-foot diameter storm sewer at Commerce Station
- Provided sufficient rock cover for a high arched cavern at Commerce Station
- Avoided obstructions of pile foundations at CBD East station.

Alternatives to lowering the alignment included mining with the more expensive Sequential Excavation Method (SEM) mining techniques for soil conditions. These techniques carry greater mining risks and higher costs—they usually require ground improvement and significant pre-support application and have great impacts on the project cost and schedule. Another alternative to lowering the alignment is to construct cut and cover stations from the surface to a shallower track alignment depth. This alternative will add high costs of utility conflicts and will cause a significant disturbance impact to the local community, businesses, streets and traffic. A lower alignment profile was therefore recommended and implemented in the 10% South of Swiss Alignment, March 8, 2019.

7 RECOMMENDATIONS FOR PE 20% DESIGN

7.1 Design Recommendation #1

7.1.1 DESIGN RECOMMENDATION

Minimum rock cover thicknesses for 20% design are provided in Table 5-1.

7.1.2 BASIS OF RECOMMENDATION

10% South of Swiss Alignment, March 8, 2019.

Historical empirical design methodologies as discussed above.

7.1.3 SOURCES OF UNCERTAINTY

Additional boring data could indicate less or more severe geotechnical conditions than those presently available. Changes in geotechnical conditions would alter the recommended minimum rock covers.

7.2 Design Recommendation #2

7.2.1 DESIGN RECOMMENDATION

Commerce Station should be a mined cavern excavation. Metro Center and CBD East Station should be excavated by the cut and cover method.

7.2.2 BASIS OF RECOMMENDATION

10% South of Swiss Alignment, March 8, 2019.

Historical empirical design methodologies as discussed above.

Design Recommendation #1 for minimum rock cover as discussed above.

7.2.3 SOURCES OF UNCERTAINTY

Additional boring data could indicate less or more severe geotechnical conditions than those presently available. Changes in geotechnical conditions may alter the recommended minimum rock covers.

Changes in the vertical profile track elevation due to further design development and driven by other issues may cause alternate excavation methods to be required.

7.2.4 RISK, COST, AND SCHEDULE COMPARISON

The design decisions leading to a mined cavern excavation for Commerce Station and cut and cover excavation for Metro Center and CBD East Stations is complicated and based on many variables. Of primary concern was the initial goal of putting the three stations in underground cavern excavations to accommodate the public's perception of the adverse impacts of cut and cover construction to the local community. Because the Commerce Station was located in the middle of the alignment, it was able to be lowered to an elevation where a mined cavern excavation was considered feasible. (See **Figure 5-2**). This feasibility is based on;

- Sufficient rock cover over the cavern to allow for safe rock mining methods
- Lower risk and cost of mining the cavern
- Mitigate adverse impacts to overlying and adjacent existing structures
- Controlling settlement above the cavern.

In the 10% South of Swiss Alignment, March 8, 2019, these objectives have been improved.

Lowering the track elevations of Metro Center and CBD East Stations to achieve a less risky mined cavern excavation would require increasing the lengths of the underground mined tunnels to accommodate operational requirements such as maximum track grades which are not considered desirable, infeasible due to other alignment constraints, and uneconomical. An additional consideration for the Metro Center Station is the large mezzanine requirement. This requirement can be accomplished with less expense by incurring the large volume of excavation in close proximity to the surface via cut and cover excavation. The CBD East Station is in proximity to the I-345 Highway, and the alignment tie in location at Good Latimer. These alignment constraints preclude the station from being lowered to a track elevation conducive to mined cavern excavation.

While a cost and schedule comparison incorporating the effects of all of these variables is beyond the scope of this memorandum, an overall cost estimate and schedule are being developed for the 20% design submittal.

7.3 Design Recommendation #3

7.3.1 DESIGN RECOMMENDATION

Additional geotechnical boreholes (with ATV logging and associated laboratory testing) should be drilled at the Commerce Station Cavern, covering the four corners of the mined cavern excavation, entrance structures, and shaft structures. This additional information is important. It should be scheduled in a subsequent boring program.

7.3.2 BASIS OF RECOMMENDATION

10% South of Swiss Alignment, March 8, 2019.

GDR Dallas CBD LRA DART D2, 10% Submittal, February 28, 2019.

7.3.3 SOURCES OF UNCERTAINTY

Additional boring data could indicate less or more severe geotechnical conditions than those presently available. Changes in geotechnical conditions would alter the recommended minimum rock covers.

8 REFERENCES

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9 ATTACHMENT 1: TABLE A-1: ASSUMED NGI – Q PARAMETERS FOR DART D2 CAVERN STATIONS

TABLE A-1: ASSUMED NGI – Q PARAMETERS FOR DART D2 CAVERN STATIONS

		Assumed NGI – Q Parameters for DART D2 Station Caverns		
		Worst Case	Expected Case	Best Case
Metro Center Station				
(See Borehole B-1)	RQD	73	90	100
	Jn	15	12	9
	Jr	1	1.5	2
	Ja	6	2	1
	Jw	1	1	1
	SRF	5	2.5	2.5
	Q	0.162	2.25	8.889
Commerce Station				
(See Borehole TS-202)	RQD	93	97	100
	Jn	15	12	9
	Jr	0.5	1.5	2
	Ja	3	2	1
	Jw	1	1	1
	SRF	5	2.5	2.5
	Q	0.207	2.425	8.889
CBD East Station				
(See Borehole B-2)	RQD	74	97	100
	Jn	15	12	9
	Jr	1.5	1.5	2
	Ja	6	2	1
	Jw	1	1	1
	SRF	5	2.5	2.5
	Q	0.247	2.425	8.889

10 ATTACHMENT 2: TABLE A-2: CROWN PILLAR STABILITY ANALYSIS

DART D2 - Subway Station Cavern Crown Pillar Analysis (Compared to WMATA Cavern Data)

Station Cavern Name	Station Cavern Configuration	Borehole Number (#)	Ground Elevation (Feet)	Top of Rock Elevation (Feet)	Track TOR Elevation (Feet)	Cavern Height above TOR (Feet)	Cavern Width S Note 1 (Feet)	Cavern Length L (Feet)	Crown Lining Thickness (Feet)	Rock Type	Rock Quality Expectation	Rock Specific Gravity S.G.	Bedding or Foliation Dip Angle θ (Degrees)	Rock Quality Desig-nation RQD	Joint Set Number Jn
Metro Center Station (DART D2)															
Metro Center Station	Binocular	B-1	428.37	403.37	367	25.75	61.3	400	2	Austin Chalk	Best	2.14	5	100	9
Metro Center Station	Binocular	B-1	428.37	403.37	367	25.75	61.3	400	2	Austin Chalk	Expected	2.14	5	90	12
Metro Center 367.1 to 360.1	Binocular	B-1	428.37	403.37	367	25.75	61.3	400	2	Austin Chalk	Worst	2.14	5	73	15
Metro Center Station	Binocular	TS-104	427.71	402.71	367	25.75	61.3	400	2	Austin Chalk	Best	2.14	5	100	9
Metro Center Station	Binocular	TS-104	427.71	402.71	367	25.75	61.3	400	2	Austin Chalk	Expected	2.14	5	95	12
Metro Center Station	Binocular	TS-104	427.71	402.71	367	25.75	61.3	400	2	Austin Chalk	Worst	2.14	5	90	15
Metro Center Station	Low Profile Arch	B-1	428.37	403.37	367	29.75	61.3	400	2	Austin Chalk	Best	2.14	5	100	9
Metro Center Station	Low Profile Arch	B-1	428.37	403.37	367	29.75	61.3	400	2	Austin Chalk	Expected	2.14	5	90	12
Metro Center Station	Low Profile Arch	B-1	428.37	403.37	367	29.75	61.3	400	2	Austin Chalk	Worst	2.14	5	73	15
Commerce Street Station (DART D2)															
Commerce Street Station	Binocular	TS-202	427	411	360	25.75	61.3	650	2	Austin Chalk	Best	2.14	5	100	9
Commerce Street Station	Binocular	TS-202	427	411	360	25.75	61.3	650	2	Austin Chalk	Expected	2.14	5	97	12
Commerce Street Station	Binocular	TS-202	427	411	360	25.75	61.3	650	2	Austin Chalk	Worst	2.14	5	93	15
Commerce Street Station	Low Profile Arch	TS-202	427	411	360	29.75	61.3	650	2	Austin Chalk	Best	2.14	5	100	9
Commerce Street Station	Low Profile Arch	TS-202	427	411	360	29.75	61.3	650	2	Austin Chalk	Expected	2.14	5	97	12
Commerce Street Station	Low Profile Arch	TS-202	427	411	360	29.75	61.3	650	2	Austin Chalk	Worst	2.14	5	93	15
Commerce Street Station	High Arch	TS-202	427	411	360	33.92	61.3	650	2	Austin Chalk	Best	2.14	5	100	9
Commerce Street Station	High Arch	TS-202	427	411	360	33.92	61.3	650	2	Austin Chalk	Expected	2.14	5	97	12
Commerce Street Station	High Arch	TS-202	427	411	360	33.92	61.3	650	2	Austin Chalk	Worst	2.14	5	93	15
Crossover Cavern (Optional East of Commerce Station) (DART D2)															
Crossover Cavern	Low Arch	TS-202	440	411	378	27	61	900	2	Austin Chalk	Best	2.14	5	100	9
Crossover Cavern	Low Arch	TS-202	440	411	378	27	61	900	2	Austin Chalk	Expected	2.14	5	97	12
Crossover Cavern	Low Arch	TS-202	440	411	378	27	61	900	2	Austin Chalk	Worst	2.14	5	93	15
CBD East Station (DART D2)															
CBD East Station	Binocular	TS-209	465	427	428	25.75	61.3	400	2	Austin Chalk	Best	2.14	5	100	9
CBD East Station	Binocular	TS-209	465	427	428	25.75	61.3	400	2	Austin Chalk	Expected	2.14	5	99	12
CBD East Station	Binocular	TS-209	465	427	428	25.75	61.3	400	2	Austin Chalk	Worst	2.14	5	98	15
CBD East Station	Low Profile Arch	TS-209	465	427	428	29.75	61.3	400	2	Austin Chalk	Best	2.14	5	100	9
CBD East Station	Low Profile Arch	TS-209	465	427	428	29.75	61.3	400	2	Austin Chalk	Expected	2.14	5	99	12
CBD East Station	Low Profile Arch	TS-209	465	427	428	29.75	61.3	400	2	Austin Chalk	Worst	2.14	5	98	15

Station Cavern Configuration	Joint Rough-ness Number Jr	Joint Alter-ation Number Ja	Joint Water Factor Jw	Stress Reduction Factor SRF	Rock Tunneling Quality Index Q	Station Crown Elevation (Feet)	Actual Depth of Overhead Soil and Rock H (Feet)	Actual Crown Pillar Thickness T (Feet)	Scaled Crown Span Cs Note 2 (1992) (Meters)	Scaled Crown Span Cs Note 2 (1992) (Feet)	Recommend-ed Minimum Crown Pillar Thickness Tmin Note 3 (1992) (Meters)	Recommend-ed Minimum Crown Pillar Thickness Tmin Note 3 (1992) (Feet)	Critical Span Sc Note 4 (2008) (Meters)	Critical Span Sc Note 4 (2008) (Feet)	Crown Pillar Probability of Failure Pf Note 5 (2014) (%)	Measured Cavern Rock Loads Note 6 (1983) (Feet)	Estimated Cavern Rock Loads A= 0.1 cs exp= 1.63 q exp= -0.79 Pcs,q Note 7 (2007) (Feet)	Estimated Cavern Rock Loads 3.297758099 0.969083869 -0.39259 Pcs,q Note 8 (2018) (Feet)
Metro Center Station																		
Binocular	2	1	1	2.5	8.89	395	33	8.37	20.5	67	3.4	12	9.4	31	99.9	-----------	2.4	26.1
Binocular	1.5	2	1	2.5	2.25	395	33	8.37	20.5	67	4.4	15	5.1	17	100	-----------	7.2	33.0
Binocular	1	6	1	5	0.16	395	33	8.37	20.5	67	7.2	24	1.6	6	100	-----------	33.0	33.0
Binocular	2	1	1	2.5	8.89	395	33	7.71	21.4	70	3.4	12	9.4	31	100	-----------	2.6	27.2
Binocular	1.5	2	1	2.5	2.38	395	33	7.71	21.4	70	4.3	14	5.2	18	100	-----------	7.4	33.0
Binocular	1	6	1	5	0.2	395	33	7.71	21.4	70	6.9	23	1.8	6	100	-----------	33.0	33.0
Low Profile Arch	2	1	1	2.5	8.89	399	29	4.37	28.4	93	3.4	12	9.4	31	100	-----------	4.2	29.0
Low Profile Arch	1.5	2	1	2.5	2.25	399	29	4.37	28.4	93	4.4	15	5.1	17	100	-----------	12.3	29.0
Low Profile Arch	1	6	1	5	0.16	399	29	4.37	28.4	93	7.2	24	1.6	6	100	-----------	29.0	29.0
Commerce Station																		
Binocular	2	1	1	2.5	8.89	388	39	23	12.7	42	3.4	12	9.4	31	89.7	-----------	1.1	16.4
Binocular	1.5	2	1	2.5	2.43	388	39	23	12.7	42	4.3	14	5.3	18	100	-----------	3.1	27.3
Binocular	0.5	3	1	5	0.21	388	39	23	12.7	42	6.9	23	1.8	6	100	-----------	21.6	39.0
Low Profile Arch	2	1	1	2.5	8.89	392	35	19	14	46	3.4	12	9.4	31	95.3	-----------	1.3	18.0
Low Profile Arch	1.5	2	1	2.5	2.43	392	35	19	14	46	4.3	14	5.3	18	100	-----------	3.7	30.0
Low Profile Arch	0.5	3	1	5	0.21	392	35	19	14	46	6.9	23	1.8	6	100	-----------	25.3	35.0
High Arch	2	1	1	2.5	8.89	396	31	15	15.8	52	3.4	12	9.4	31	98.5	-----------	1.6	20.3
High Arch	1.5	2	1	2.5	2.43	396	31	15	15.8	52	4.3	14	5.3	18	100	-----------	4.5	31.0
High Arch	0.5	3	1	5	0.21	396	31	15	15.8	52	6.9	23	1.8	6	100	-----------	30.9	31.0
Crossover Cavern (Commerce Street)																		
Low Arch	2	1	1	2.5	8.89	407	33	4	30.7	101	3.4	12	9.4	31	100	-----------	4.7	33.0
Low Arch	1.5	2	1	2.5	2.43	407	33	4	30.7	101	4.3	14	5.3	18	100	-----------	13.2	33.0
Low Arch	0.5	3	1	5	0.21	407	33	4	30.7	101	6.9	23	1.8	6	100	-----------	33.0	33.0
CBD East Station																		
Binocular	2	1	1	2.5	8.89	456	9	-29	NA	NA	3.4	12	9.4	31	NA	-----------	NA	NA
Binocular	1.5	2	1	2.5	2.48	456	9	-29	NA	NA	4.3	14	5.3	18	NA	-----------	NA	NA
Binocular	1.5	6	1	5	0.33	456	9	-29	NA	NA	6.3	21	2.2	8	NA	-----------	NA	NA
Low Profile Arch	2	1	1	2.5	8.89	460	5	-33	NA	NA	3.4	12	9.4	31	NA	-----------	NA	NA
Low Profile Arch	1.5	2	1	2.5	2.48	460	5	-33	NA	NA	4.3	14	5.3	18	NA	-----------	NA	NA
Low Profile Arch	1.5	6	1	5	0.33	460	5	-33	NA	NA	6.3	21	2.2	8	NA	-----------	NA	NA

DART D2 - Subway Station Cavern Crown Pillar Analysis (Compared to WMATA Cavern Data)

Station Cavern Name	Station Cavern Configuration	Borehole Number	Ground Elevation	Top of Rock Elevation	Track TOR Elevation	Cavern Height above TOR	Cavern Width	Cavern Length	Crown Lining Thickness	Rock Type	Rock Quality Expectation	Rock Specific Gravity	Bedding or Foliation Dip Angle	Rock Quality Desig-nation	Joint Set Number
							S Note 1	L				S.G.	θ	RQD	Jn
		(#)	(Feet)	(Feet)	(Feet)	(Feet)	(Feet)	(Feet)	(Feet)				(Degrees)		
Washington D. C. Caverns (WMATA)															
Medical Center Station	Arched						62	900		Gneiss		2.6	70	75	9
Rosslyn Station	Arched						80	722		Gneiss		3.2	78	85	12
Bathesda Station	Arched						62	800		Gneiss		2.6	60	75	12
Cleveland Park Station	Arched						58	900		Gneiss		2.8	60	75	12
Van Ness Station	Arched						58	900		Gneiss		2.8	55	75	15
Zoological Park Station	Arched						58	800		Gneiss		2.7	60	75	12
Dupont Circle Station	Arched						76	724		Schist		2.7	55	75	15
Tenley Circle Station	Arched						60	800		Gneiss		2.6	75	75	15
Tenley Circle Station	Intersection						60	800		Gneiss		2.6	75	75	45
Friendship Heights Station	Arched						67	950		Gneiss		2.6	70	75	15
Friendship Heights Station	Intersection						67	950		Gneiss		2.6	70	75	45

Notes

Note 1 - Equations are taken from references cited.

Note 2 - Scaled Crown Span (1992) is given by Cs = S x [S.G. / (T (1+S/L) (1-0.4 cos θ))] 0.5.

Note 3 - Minimum Crown Pillar Thickness (1992) is given by Tmin = 5.11 x Q -0.19 x [sinh 0.0016 (Q)].

Note 4a - Critical Span (2008) is given by Sc = 3.58 Q^.44.

Note 4b - This critical span is the span at which 50% of crown pillars are expected to fail if unsupported during excavation.

Note 5 - The crown pillar probability of failure is given by Pf = 100/[1+440 x exp(-1.7*Cs/Q 0.44)] .

Note 6 - Source of measured rock load data: (Cording, et. al, Vol. 1, Oct. 1983).

Note 7 - The original equation (2007) was in the form P(Cs,Q) = 0.1 $Cs^{1.6}$ x $Q^{-0.79}$.

Note 8 - The current equation (2018) is in the form P(Cs,Q) = 3.29776 Cs0.96908 x Q -0.39259.

Note 9 - If the calculated rock load exceeds the overburden depth, the overburden depth is used.

Note 10 - Metro Center Station and CBD East Station have been raised at 10% to allow cut and cover station excavation.

Note 11 - Metro Center and CBD East data is included to indicate required depth of lowering to allow rock cavern excavation.

Station Cavern Configuration	Joint Rough-ness Number Jr	Joint Alter-ation Number Ja	Joint Water Factor Jw	Stress Reduction Factor SRF	Rock Tunneling Quality Index Q	Station Crown Elevation (Feet)	Actual Depth of Overhead Soil and Rock H (Feet)	Actual Crown Pillar Thickness T (Feet)	Scaled Crown Span Cs Note 2 (1992) (Meters)	Scaled Crown Span Cs Note 2 (1992) (Feet)	Recommend-ed Minimum Crown Pillar Thickness Tmin Note 3 (1992) (Meters)	Recommend-ed Minimum Crown Pillar Thickness Tmin Note 3 (1992) (Feet)	Critical Span Sc Note 4 (2008) (Meters)	Critical Span Sc Note 4 (2008) (Feet)	Crown Pillar Probability of Failure Pf Note 5 (2014) (%)	Measured Cavern Rock Loads Note 6 (1983) (Feet)	Estimated Cavern Rock Loads A= 0.1, cs exp= 1.63, q exp= -0.79 Pcs,q Note 7 (2007) (Feet)	Estimated Cavern Rock Loads 3.297758099, 0.969083869, -0.39259 Pcs,q Note 8 (2018) (Feet)
Washington D.C. Caverns																		
Arched	5	3	0.5	2.5	2.78		80	40	9.1	30	4.2	14	5.6	19	97.8	12	1.6	18.8
Arched	1	4	0.66	5	0.23		65	50	11.1	36	6.7	22	1.9	7	100	16	16.1	60.5
Arched	1	6	0.5	5	0.1		90	20	13.3	44	7.9	26	1.3	5	100	20	41.9	90.0
Arched	3	2	1	7.5	1.25		60	12	16.8	55	4.9	16	3.9	13	100	23	8.3	46.5
Arched	2	3	0.66	5	0.44		65	38	9.6	31	6	20	2.5	9	100	23	7.6	40.7
Arched	3	3	0.66	5	0.83		100	60	7.3	24	5.3	18	3.3	11	99.9	30	3.0	24.4
Arched	1.5	5	0.66	7.5	0.13		60	30	13.6	45	7.5	25	1.5	5	100	30	35.3	60.0
Arched	2.5	2	0.66	7.5	0.55		85	65	6.7	22	5.7	19	2.8	10	100	28	3.6	26.3
Intersection	2.5	2	0.66	7.5	0.18		85	65	6.7	22	7.1	24	1.7	6	100	41	8.6	40.8
Arched	1.5	6	0.66	10	0.08		70	50	8.8	29	8.2	27	1.2	4	100	42	25.5	70.0
Intersection	1.5	6	0.66	10	0.03		70	50	8.8	29	9.9	33	0.8	3	100	49	55.3	70.0

11 ATTACHMENT 3: FIGURE A-1: CROWN PILLAR PROBABILITY OF FAILURE CHART

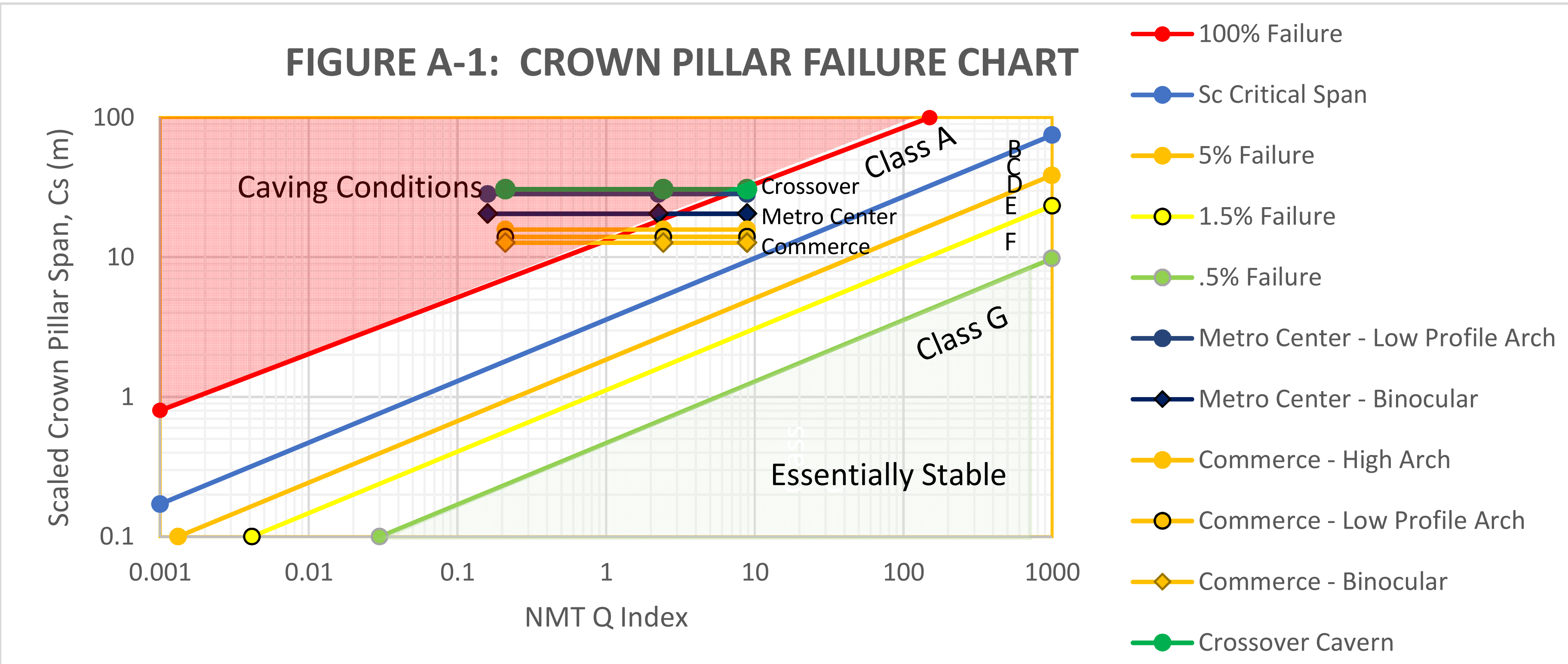
FIGURE A-1: CROWN PILLAR FAILURE CHART
Scaled Crown Pillar Span, Cs (m)
100
10
1
0.1
0.001
0.01
0.1
1
10
100
1000
NMT Q Index
Caving Conditions
Crossover
Metro Center
Commerce
Class A
B
C
D
E
F
Class G
Essentially Stable
100% Failure
Sc Critical Span
5% Failure
1.5% Failure
.5% Failure
Metro Center - Low Profile Arch
Metro Center - Binocular
Commerce - High Arch
Commerce - Low Profile Arch
Commerce - Binocular
Crossover Cavern