FIRST DRAFT Technical Memorandum #07 - Anticipated TBM Performance

GPC6, C2012668-02 Task Order #39 Dallas CBD Second Light Rail Alignment (D2 Subway)

FIRST DRAFT – REV A

Dallas, Texas
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DRAFT DOCUMENT

This DRAFT TECHNICAL MEMORANDUM IS PROVIDED AS IN-PROGRESS CONDITION BASED ON CURRENT CONCEPTUAL STATUS OF DESIGN AND INCOMPLETE STATUS OF THE GEOTECHNICAL DATA INTERPRETATION. THE SITE-SPECIFIC INFORMATION HAS BEEN LIMITED AND IS INCOMPLETE.

This DRAFT document has been provided under an assumption that the tunnel excavation will be provided by Tunnel Boring Machine (TBM). Presently, the project is likely advancing anticipating implementation of Sequential Excavation Method (SEM) techniques instead of TBM due to the limited length of the tunnel to be excavated

1 Introduction

This Geotechnical Design Memorandum (GDM) has been prepared for HNTB as part of the DART CBD Second Light Rail (D2 Subway) project in Dallas, Texas to offer an overview of the anticipated performance of the tunnel boring machine (TBM) if selected for excavation of the running tunnel portion of the project. The 2.3-mile Locally Preferred Alternative (LPA) extends generally east-west from Victory Park to Deep Ellum via Commerce Street and downtown Dallas. The underground portion of the LPA, including tunnel portals, is 6,005 feet long. Depth from the ground surface to proposed top of rail ranges from 10 feet to 78 feet, typically on the order of 50 to 60 feet. The mined portion of the tunnel is estimated to be 3,207.19 ft (from station 54+22.42 to 86+29.61) [8][1]. The memo includes a brief overview of the documents reviewed and used for developing the report, the geological and geotechnical settings at the site, most likely machine type and specifications, expected rate of penetration and daily advance rate, and the list of potential risks.

2 Available Documents

Some of the documents produced by the design team and other project consultants have been reviewed and used in developing the current memo. A list of the documents used for preparation of this memo is offered in Appendix A.

3 Geology and Geotechnical Settings

This section includes a brief overview of the information used for preparation of the TBM performance estimates. The intent is not to reproduce the available information, but rather to state the assumptions used in the calculation of the TBM performance rates and related risks.

3.1 Regional Geology and Hydrology

The project area is in the sedimentary basin in Dallas County, in north-central Texas. Thick layers of sediment accumulated during progressive Tertiary-age downwarping of the Gulf of Mexico. The rock formations from older to younger (bottom to top) include Eagle Ford, Austin Chalk, and Ozan Formation, with a unconformity (1-12 ft) at the contact between the Eagle Ford Shale and the overlying Austin Chalk. While there are some outcrops of Austin Chalk spotted, the area is covered with a layer of brown to black silty clay to clay residual soil 20 to 80 inches thick. There is not much seismic activity in the area and several faults are reported in the general area, none to be encountered within the mined tunnel part of the project. The regional aquifer is at relative deeper depth but shallower aquifers are

[1] [#] refers to the documents used for development of GDM and listed in Appendix A.

connected to surface water and in Austin Chalk and yield 100-1000 gpm in water wells. Extensive tunneling activities in Austin Chalk were completed for the US Department of Energy's Superconducting Super Collider project in early 1990's. This project was located around 30 miles south of Dallas. Table 3-1 is a summary of anticipated rock types for the tunnel sections in the DART D2 project.

TABLE 3-1. SUMMARY OF FORMATIONS ALONG THE TUNNEL PART OF D2 PROJECT [4]

Rock Type	Ground Class Group	Percent Volume for Reach			
		2	4	6	8
Limestone	I	100%	61%	61%	100%
Limestone	II	0%	0%	39%	0%
Shale	I	0%	0%	0%	0%
Shale	II	0%	39%	0%	0%

"Hydraulic conductivity for the Eagle Ford Shale to be 2.2 x 10-7 cm/sec, based on a single field packer test performed for another Dallas-area project. Lachel Felice, 2006 also reports hydraulic conductivity of the Austin Chalk ranging from zero to 2.6 x 10-5 cm/sec, averaging 1.8 x 10-6 cm/sec, based on 17 field packer tests" [6]

"Construction of the DART 3.5-mile long twin tunnels under North Central Expressway encountered fuel-contaminated soil and pockets of methane gas. The methane source is believed to be an oil or natural gas deposit nearly 2 miles below the expressway, which at time could exceed LEL" [6][2]. So, the new DART D2 tunnel being discussed in this memo may potentially be classified as gassy.

3.2 Rock Strength Properties

Some of the rock basic properties have been measured are listed in Table 3-2 A) and B) below. As shown by the intact rock properties presented in Table 14 of the TM#3 on Ground Characterization [6], the limestone is a weak rock (ISRM, 1981), with unconfined compressive strength ranging from 615 to 4,159 pounds per square inch (psi) and averaging 2,468 psi (from data by Lachel Felice, 2006). The review of the new data in GDR [1] shows the range of UCS measured by GTX and AGG to be 262 to 5754 psi with an average of ~3200 psi. The two averages are fairly close for operational and tunneling purposes. Mean dry unit weight is 129 pounds per cubic foot (pcf). Shale is a very weak rock (ISRM, 1981), with average unconfined compressive strength of ~1400 psi. Based on available DART D2 draft boring logs, limestone of the Austin Group will constitute about 65.8 percent of material to be excavated and shale of the Eagle Ford Group will constitute about 11.5 percent of material to be excavated along the new DART D2 underground alignment current as of December 20, 2018. A quick scanning of the data from point load index reported in Appendix F5 of the GDR also shows that the range of IS_{50} reported is from 22 to 284 with average of 175 psi and if a general adjustment factor of around 24 is used, the estimated

[2] This is a direct quote from a previous report and the current project is also called D2 and is referred to as New D2 in the rest of this memo.

UCS of the rock would be around ~4200 psi. Again, this is in line with other strength measurements of the formations. Thus, the available summary in Table 3-2 seem to be valid and applicable for the preliminary estimation of the TBM performance in the formations anticipated along the alignment.

3.3 Rock Abrasion and other Properties

Rock abrasion determines the rate of cutter wear and the pertinent properties of rock formations along the alignment have been measured and for the limestone, the Cerchar Abrasion index of the rock has been measured to range between 0.4-0.6 with a mean value of 0.53. This indicates that the rock is non-abrasive and that cutter life is going to be very long.

3.4 Rock Drillability/Boreability and Brittleness

To characterize rock boreability, two samples have been subject to Norwegian Drilllability/boreability tests as reported in the final GDR [1]. The results are consistent with the measured values in rock mechanics testing in that the yielded very high drillability (DRI>80) which is extremely high meaning easy to drill/bore, with low bit wear index (BWI) of typically less than 10 and cutter life index (CLI) ~ 80 which indicates low abrasivity and long cutter life. The results of punch penetration test show low brittleness of the 7 samples reported in GDR and the peak values indicating easy penetration.

TABLE 3-2. A) SUMMARY OF THE ROCK PROPERTIES MEASURED IN THE PRELIMINARY SITE INVESTIGATION CAMPAIGN [4]

			L-I, L-II, L-III / Limestone	S-I, S-II, S-III / Shale
Unconfined Compressive Strength	Min	psi	615	29
	Max	psi	4,159	700
	Mean (preliminary design)	psi	2,468	190
UU Compressive Strength	Min	psi	2,126	128
	Max	psi	6,048	321
	Mean (preliminary design)	psi	4,205	203
Modulus of Elasticity, E	Min	10^6 psi	0.03	0.01
	Max	10^6 psi	1.46	0.08
	Mean (preliminary design)	10^6 psi	0.47	0.04
Poisson's Ratio, v	Min	_	0.15	0.19
	Max	_	0.40	0.30
	Mean (preliminary design)	–	0.23	0.25
Point Load Strength, Axial	Min	psi	67	38
	Max	psi	780	64
	Mean (preliminary design)	psi	462	59
Point Load Srength, Diametral	Min	psi	26	_
	Max	psi	656	_
	Mean (preliminary design)	psi	274	_
Tensile Strength (Brazilian)	Min	psi	94	_
	Max	psi	350	_
	Mean (preliminary design)	psi	234	_

TABLE 3-2. B) SUMMARY OF ROCK PROPERTIES BASED ON ADDITIONAL MEASUREMENTS AS REPORTED IN GDM#3 AND GDM#11 [9,10]

LIMESTONE					
Property		Range		Median Value (Design)	75th/25th Percentile Value (Preliminary Baseline) [6][7]
		minimum	maximum		
Index Properties	Bulk Density, pcf [1]	121	137	129	132
Strength & Mechanical Properties	Unconfined Compressive Strength, psi				
	- from tests by ASTM D7012-C and D7012-D [2]	1,543	5,792	3,238	4,255
	- estimated from axial PLI tests [3]	3,270	5,410	4,650	4,840
	Dynamic Elastic Modulus, E, 10^6 psi [4][5][6]	0.25	2.94	0.43	-
	Dynamic Poisson's Ratio, v [4][5][6]	0.15	0.49	0.39	-
	Splitting Tensile Strength, psi	225	254	239	247
Abrasiveness & Hardness	CERCHAR Abrasiveness Index	0.50	0.64	0.53	0.59
	Rebound Hammer Hardness, H_R	17.1	23.3	20.7	21.6
Slaking Properties	Slake Durability Index, %	86.1	97.8	96.8	96.1
Drillability Indices [8]	Drilling Rate Index (DRI)	88	89	88.5 (extremely high)	88.8 (extremely high)
	Bit Wear Index (BWI)	8	8	8 (extremely low)	8 (extremely low)
	Cutter Life Index (CLI)	112.6	115.4	114.0 (extremely high)	114.7 (extremely high)

SHALE					
Property		Range		Median Value (Design)	75th/25th Percentile Value (Preliminary Baseline) [6][7]
		minimum	maximum		
Index Properties	Bulk Density, pcf [1]	128	137	136	137
Strength & Mechanical Properties	Unconfined Compressive Strength, psi				
	- from tests by ASTM D7012-C and D7012-D [2]	267	2,553	1,410	1,981
	- estimated from axial PLI tests [3]	1,690	1,690	1,690	1,690
	Dynamic Elastic Modulus, E, 10^6 psi [4][5][6]	0.12	0.12	0.12	-
	Dynamic Poisson's Ratio, v [4][5][6]	0.18	0.18	0.18	-
Abrasiveness & Hardness	Cerchar Abrasiveness Index	0.54	0.54	0.54	0.54
	Rebound Hammer Hardness, H_R	12.0	12.0	12.0	12.0
Slaking Properties	Slake Durability Index, %	40.6	44.2	42.4	41.5

3.5 Rock Mass Properties

Rock mass conditions and jointing can be expressed by rock mass classifications such as RMR, Q, or GSI. In this project, the rock mass along the tunnel is assessed using GSI system as summarized in the Table 3-3.

The limestone-chalk rock along the new DART D2 alignment generally presents a simple structure, and based on draft rock core data available to date, most bedding planes do not appear to be clearly defined discontinuity surfaces. For this reason, the GSI structure classifications for “blocky” or “massive” are applicable. However, the discontinuities are seldom better than a “good,” rating, and the relatively low intact rock strength assumed from data collected for other projects yields a GSI of about 50 to 65 for L-I, 40 to 50 for L-II, and 30 to 40 for L-III.

TABLE 3-3. SUMMARY OF ANTICIPATED ROCK MASS CONDITIONS [4]

	L-I	S-I	L-II	S-II
Rock Type	Limestone	Shale	Limestone	Shale
Preliminary GSI Range (1)(2)	50-65	Not applicable (3)	40-50	20-30

4 TBM Specifications

The planned excavated diameter of the tunnel is 23' 8" (7218 mm) including a 1-inch overcut, which means the diameter of the leading end of the front shield will be around 23', 6" diameter. Given the conicity of the shields (~1.5"), thickness of the shield (~1.5"), gap between the interior surface of the shield and the back of the segment (3") of around 6 inches, the OD of the segment will be around 22', 6". If the thickness of the segmental lining is 1 ft, the ID of the tunnel will be 20', 6" or ~ 6252 mm. The envelope allows for a 5 inch construction tolerance and 10' 9" of application envelope as indicated in drawings [8]. These dimensions are the most common dimensions for a double tube, single track metro tunnels around the world and by far the most dominant size of shielded TBMs.

Given the site geology and available geotechnical information, plus the final application of the tunnel being for public transportation, the TBM to be used in this project will be a shielded machine to allow for the concrete segmental lining to be installed through chalk and shale strata. These units allow for controlling of the ground and facilitating the control of the groundwater. A single shield TBM should be able to meet the requirements of the project but at this stage, there are two possible type of single shields that can be used in this project. This includes open mode and Earth Pressure Balance (EPB) machines.

The final selection of the machine will be based on the anticipated groundwater conditions. The recorded data from the local piezometers listed in the GDR shows that the water head at the invert could reach nearly two bar (60 ft or 20 m), around Commerce Street Station (Station ~70+00). If the final GBR anticipates the possibility of encountering shear zones or other features in the tunnel that can carry water to the face, the machine may have to operate under nearly two bar of pressure. However, if there is no shear zones anticipated, since Chalk is rather impermeable, it is less likely to have a full face of Chalk with significant water seepage into the tunnel. In this case, a single shield with open mode will be more efficient and can advance more rapidly. If the tunnel alignment passes through water bearing zones with shear or fault features and high permeability, the preferred choice for TBM will be the EPB machine to maintain face pressure and prevent water ingress into the tunnel. Water inflow into the tunnel can flood the tunnel and also can cause surface subsidence if it lowers the groundwater table by a substantial amount.

Typical machines for this size tunnel is fitted with around 2000 kW power to assure availability of sufficient torque to turn the head, for hard rock to offer the energy for rock breakage and in soft rock to allow for deeper penetration. Using an EPB means that substantial amount of power is used in rotating the head and to overcome the friction of the material in the cutting chamber. The cutterhead torque of around 10,000 kNm and thrust of around 40MN is not unusual for machines this size, although the operating torque is anticipated to be lower and typical operating thrust of around 10-15 MN (1000-1500 tons) are used during the advance cycle. The TBM cutterhead will feature disc cutters for cutting the soft rock, along with scrapers and face buckets or openings at the face to facilitate the efficient flow of material into the plenum.

5 Anticipated TBM Performance

The expected performance and advance rate of the tunnel boring machine will depend on the type of machine to be used, lithological formations along the tunnel, and finally the turns in the alignment. The available geotechnical information indicates that the majority of the alignment will be in Austin Chalk (or as referred to in Tables above, Limestone) and in such soft rocks, cutting of the material is relatively easy and discs can achieve high penetrations at low thrust levels. The chalk is also an easy medium to tunnel through because the ground is mostly self-supporting (at shallow depth), so there are less concerns with ground collapse around the shield and lower shield friction. Based on the properties of the material to be excavated, the cutter life will also be very high and low wear rate and limited number of cutter changes are expected. Following is the anticipated rate of advance for each type of machine.

5.1 Performance of Open Mode TBM

If further investigation and the GBR confirm that there is low likelihood of running into water bearing zones along the alignment or if the selected contractor chooses to use an open mode machine for its higher efficiency while performing ground modifications in small reaches of the tunnel, an open mode single shield TBM can be considered for this project. Ground improvement will include probe drilling and grouting ahead of the face to consolidate and reduce permeability of the ground in water bearing zones. This allows the machine to operate in open mode via mucking through buckets and face conveyor.

A machine with the specifications listed in the previous section can reach very high performance, almost at what is called the “pump limit”, meaning that there will be excess thrust and torque capacity. Consequently, the penetration rate will be limited to the limit of the hydraulic pumps in pushing the machine forward. This limit is often ~23-27 ft/hr (7 - 9m/hr) on TBMs of similar size. Using the lower range of 23ft/hr, and assuming a 24 hr operation (3@8 hour shifts for 5.5 day week operation) the daily advance rate will depend on the machine utilization rate and can be summarized in following table 5-1. It should be noted that higher utilization could be possible for longer tunnels but given the short length of this tunnel and thus short duration of tunneling in the project, about 3-4 weeks can be considered to be the learning curve for the TBM start up period. This will cover almost half of the tunnel. So the high overall average daily advance rates that has been experienced in some of the similar projects in recent years may not be realized in this project. The estimates in Table 5-1 are based on most likely scenarios and it is very possible that a record can be achieved in this project for daily advance on a few days, but the contractor will most likely plan the site set up and trailing gears to reach a reasonable rate, instead of heavy investment to reach a world record.

TABLE 5-1. ANTICIPATED DAILY ADVANCE RATE OF OPEN MODE SHIELD

Utilization Rate (%)	Daily Advance ft/day / (m/day)	Note
10%	55 / (16.8)	Very conservative, learning curve
15%	83 / (25.3)	Conservative
20%	110 / (33.7)	Likely Scenario
25%	138 / (42.1)	Optimistic

The choice of muck haulage and disposal system will have a bearing on the utilization rate and the most likely scenario is based on the use of conveyor belt to allow for the machine to reach its full production potential. However, the short length of the tunnel could warrant the use of rail haulage for mucking in a trade off with daily advance rate. This relates to the contractor’s choice of means and method and available equipment at their disposal to allow for lower bid prices. The most likely weekly advance will be in the range of 600 ft and therefore, the TBM tunneling will be done in around 6-7 weeks. This is based on the anticipated lower performance in the early stages of tunnel as part of the learning curve, followed by a tight radius curve on the alignment.

TABLE 5-2. ANTICIPATED PERFORMANCE OF OPEN MODE SHIELD TBM

Section	Start	End	Length (ft)	Utilization	AR (ft/day)	Work Days	weeks	Note
1	5422	5600	177.58	10%	55.2	2	0.64	Start up, Linear
2	5600	6200	600	15%	82.8	7	1.45	Curved alignment
3	6200	8629	2429.61	20%	110.4	22	4.40	Linear
Subtotal			3207.19				6.49	

5.2 Performance of EPB machine

If the site investigation confirms that there are water bearing zones along the alignment and the control of near surface aquifer becomes an issue, to reduce the possibility of excessive subsidence, the contract may specify the use of an EPB machine. This allows for better control of the face pressure while mucking is done by a screw conveyor.

A machine with specifications listed in the previous section can still reach very high performance, but slightly lower than the open mode machine, due to the slower pace of mucking by the screw conveyor and higher torque requirement of EPB machines. This limit is typically 12-16 ft/hr (4-5.3m/hr). Using the lower range of 12ft/hr, and assuming a 24 hr operation (3@8 hour shifts for 5.5 day week operation) the daily advance rate will depend on the machine utilization rate and can be summarized in Table 5-3.

TABLE 5-3. ANTICIPATED DAILY ADVANCE RATE OF EPB SHIELD

Utilization Rate (%)	Daily Advance ft/day / (m/day)	Note
10%	29 / (8.8)	Very conservative, learning curve
15%	43 / (13.2)	Conservative
20%	57 / (17.5)	Likely Scenario
25%	72 / (22)	Optimistic

As noted before, higher utilization could be possible for longer tunnels but given the short length of this tunnel and thus short duration of tunneling in the project, about 3-4 weeks can be considered to be the learning curve for the TBM start up and this will cover almost 1/4 of the tunnel. So the high overall average daily advance rates that have been experienced in some of the similar projects in recent years may not be realized in this project. The estimates in Table 5-3 are based on most likely scenarios and it is very possible that a new record can be achieved on a daily basis in this project for daily advance, but the contractor will most likely plan the site set up and trailing gear to reach a reasonable rate, instead of heavy investment to reach a very high daily advance rate.

The choice of muck haulage will have a bearing on the utilization rate. The most likely scenario in normal tunneling operation is based on the use of conveyor belt to accommodate relatively continuous mining, allowing the machine to reach its full potential. However, the short length of the tunnel warrants the use of rail haulage for mucking in a trade off with daily advance rate. This relates to the contractor's choice of means and method and available equipment at their disposal to allow for lower bid. The most likely weekly advance will be in the range of 350 ft and therefore, the TBM tunneling will be done in about 11 to 12 weeks. This is based on the anticipated low performance in the early stages of tunnel as part of the learning curve and negotiating a tight curve along the way.

TABLE 5-4. ANTICIPATED PERFORMANCE OF EPB TBM

Section	Start	End	Length (ft)	Utilization	AR (ft/day)	Days	weeks	Note
1	5422	5600	177.58	10%	28.8	6	1.23	Start up, straight
2	5600	6200	600	15%	43.2	14	2.78	Curve
3	6200	8629	2429.61	23%	66.2	37	7.34	Straight
Subtotal			3207.19				11.4	

5.3 Expected Cutter Life

Expected cutter life in this project will be extremely high, and given low strength and abrasivity of the rock, it could reach nearly 2000 m^3/cutter, for a typical 17 inch (432 mm) diameter disc cutter. Given the diameter of the cutterhead of around 23.75 ft (7.2 m) and face area of 443 sqft (~41.2 m^2), total volume of rock excavated will be in the order of 52,600 cyd (40,300 m^3). This means that there might be a need for 20 cutter changes but most likely the first dressing of the cutterhead could potentially finish the job. The cutter changes could be due to bearing overheating at the gage area and occasional bearing failures or if the mucking is inefficient and by packing of the cutter housing with muck and preventing the discs from rotation at the center, there is relatively minimal possibility of wear flats.

6 Case Histories

As noted earlier and also indicated in the geotechnical reports of the project, there is substantial amount of experience in TBM tunneling in Limestone, or so called Austin Chalk. Construction of the tunnels for superconducting super collider projects in early 1990's south of Dallas in similar formations is the best example of TBM application in this rock. The available reports indicate that *"strength of both the Austin Chalk and Taylor Marl is low enough to promote efficient mechanical excavation but high enough that initial support requirements will be minimal. The rock is nonabrasive, which will reduce the number of cutter changes required; maintenance of the equipment will be facilitated by the dry conditions. Potential problems that may arise in tunneling through different geological units include the impact of mixed face conditions occurring at the transition between two materials. Nonetheless, the material strengths are not expected to be so different as to cause extreme problems for excavation by either soft-ground or hard-rock equipment." (Frobenius, P., 1989)*

The available records show that the best Shift 81.7 m (268 if.), best Day 143.9 m (472 if.), best Week 632.1 m (2074 If.), and best Month 2418.2 m (7934 if.) could be achieved in the SSC project (Cory 1995). This shows the potential for open mode machines to achieve very high rates. However, readers should be cautioned that the SSC TBMs were smaller diameter with higher RPM, and the length of the tunnel sections being several miles, allowed the contractor to mobilize for higher efficiency and advance rates. For the Dallas CBD Second Light Rail with the shorter length of tunnel section of only ~3500 ft, it is likely the contractor will select system of equipment that may not reach such high daily rates.

Another example of mining through chalk by TBM is the Channel Tunnel between UK and France which used a total of 11 TBMs. The project started in late 1980's and completed in Mid 1990's.

Example of some of the recent TBM application in Chalk includes parts of the Channel Tunnel Rail Link (CTRL) and Cross rail tunnels in London, UK. While a total of about 8 TBM were used in this project, parts of the tunnel were mined by a slurry shield. One section that was mined by a slurry machine was the Thames Tunnel section of the project and this machine was selected due to passage through some sandy layers along the alignment but the performance of the slurry machine and EPB unit in the DART D2 project are comparable. In this section, "*tunneling commenced for down-line construction on 10 July 2002, with continuous 7 day working average progress rates for the first 2 km of tunnel have so far exceeded the planned progress rate of 84.5m/week with peak production currently in excess of 130m/week*" (Woods et. Al. 2003). Cross Rail records show an EPB machine named "Ellie", managed a distance of 72 meters in 24 hours (Herrenknecht 2019).

Another project is Katzenbergtunnel in germany where a 11.2m diameter machine was used in marl/limestone/sandstone formations at 2 bar of pressure, and the recorded penetration using an EPBM machine was in the range of around 30-35 mm/revolution. (Rehm 2019). The ground type and range of anticipated face pressure is similar to the DART new D2 project in this study.

These records show that the estimated TBM tunneling rates for this project are within the bounds of what is achieved in this formation and with the type of machine that was indicated in Section 5 of this memo.

7 Potential Risks in TBM Tunneling

As with any tunneling and construction operations, there are some risks that are involved in the execution of the plans. While there are some general risks that are associated with the project relative to geology, operation, labor issues, unanticipated events such as flooding and severe weather, the following is a brief list of possible risks involved with TBM operation at this project rather than the general risks of the project.

- Ground subsidence due to water ingress into the tunnel in case open mode machine is used and a water bearing zone with high permeability is encountered that can: i) flood the heading, and ii) cause ground subsidence due to lowering of the shallow level aquifers that could cause differential settlement in the ground and perhaps, damages to the buildings along the alignment.

- Packing of the disc cutter housing due to the stickiness of the ground and inefficient mucking. This can cause wear flats on the disc cutters and need for more frequent replacement of the cutters beyond the anticipated rates. In case such conditions occur with EPB machine the intervention could be more complex and costly. However, the likelihood of running into packing of housing is low and the mitigation plans are relatively simple to implement and involve more efficient clearing of the muck in open machine and more efficient conditioning of the muck in EBP machines. Also, careful monitoring of the face pressure is essential to avoid compaction of the muck at the face.
- Clogging of the cutterhead and packing in the plenum, this is due to the sticky behavior and nature of the material, especially after mining and introduction of some moisture in the EPB operation. This could cause clogging of the openings and prevent mucking, could lead to consolidation of the material on the side walls and interior of the plenum and places with slow movement of materials and thus gradually reducing the area for passage of the muck. To remedy this phenomenon and to prevent clogging, the machine has to be operated at lower pressure to avoid compressing the muck and also proper conditioning to improve the fluidity of the muck and to prevent stickiness of the muck. This is similar to the issue that was mentioned relative to packing of the disc cutter housing but slightly different results.
- Face collapse if shear zones or erosional channels are encountered. The impact should be minimal due to the ability of the machine to overcome such conditions. High breakout torques on the drive units should allow the machine to restart if such situations are encountered.

8 References

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2019 Rehm, Ulrich, Private communications on Katzenbergtunnel project.

Appendix A.

Following is the list of documents reviewed for development of this memo.

#	Title	Issued by	Date
1	Geotechnical Data Report, Dallas CBD Second Light Rail Alignment - DART D-2	GPC6	August 27, 2019
2	Light Rail Transit System, Line Section CBD-2 Sta 70+00 to 115+11.59 (20% design) File: CBD2-SCH-LPA-001 20% compressed.PDF	GPC6	NA
3	Light Rail Transit System, Line Section CBD-2 Sta 10+00 to 70+00 o (20% design) File: CBD2-SCH-LPA-002 20% compressed.PDF	GPC6	NA
4	Geotechnical Baseline Report, @10% design	GPC6	February 14, 2019
5	Architectural Drawings, 10% submission	GPC6	March, 8, 2019
6	FIRST DRAFT Technical Memorandum #3, Preliminary Ground Characterization, Rev. A	GPC6	January 24, 2019
7	FIRST DRAFT Technical Memorandum #11, Interim Geotechnical Memorandum for Critical Structures and Summary of Criteria	GPC6	February 15, 2019
8	Light Rail Transit System Line Section CBD-2 Drawings	GPC6	December 20, 2019
9	GDM #3 – In-Progress Draft – Ground Characterization February 2020		NA
10	GDM #11 – In-Progress Draft – Geotechnical Design Recommendations for Critical Structures and Summary of Criteria February 2020		NA