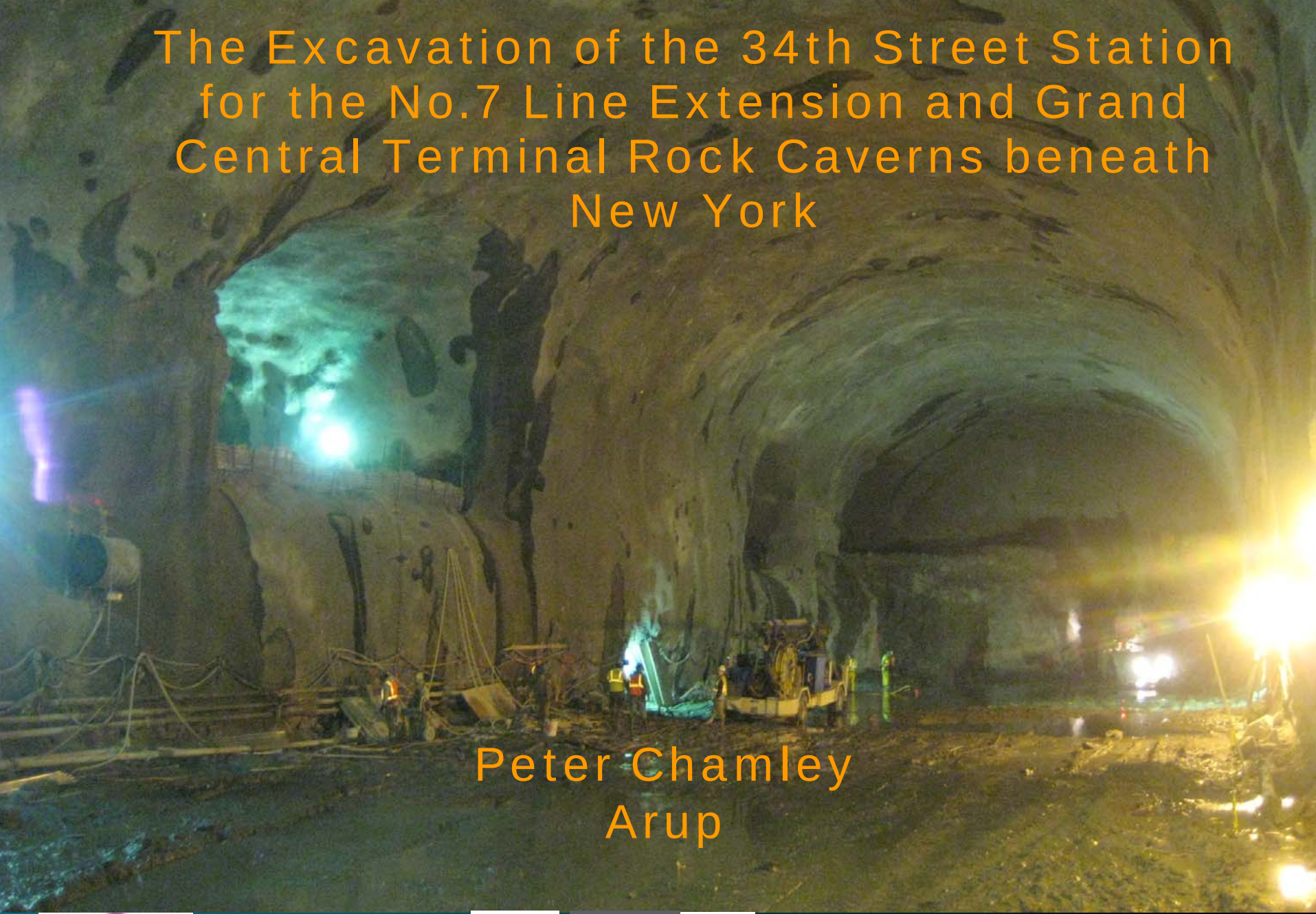
The Excavation of the 34th Street Station for the No.7 Line Extension and Grand Central Terminal Rock Caverns beneath New York



Peter Chamley
Arup

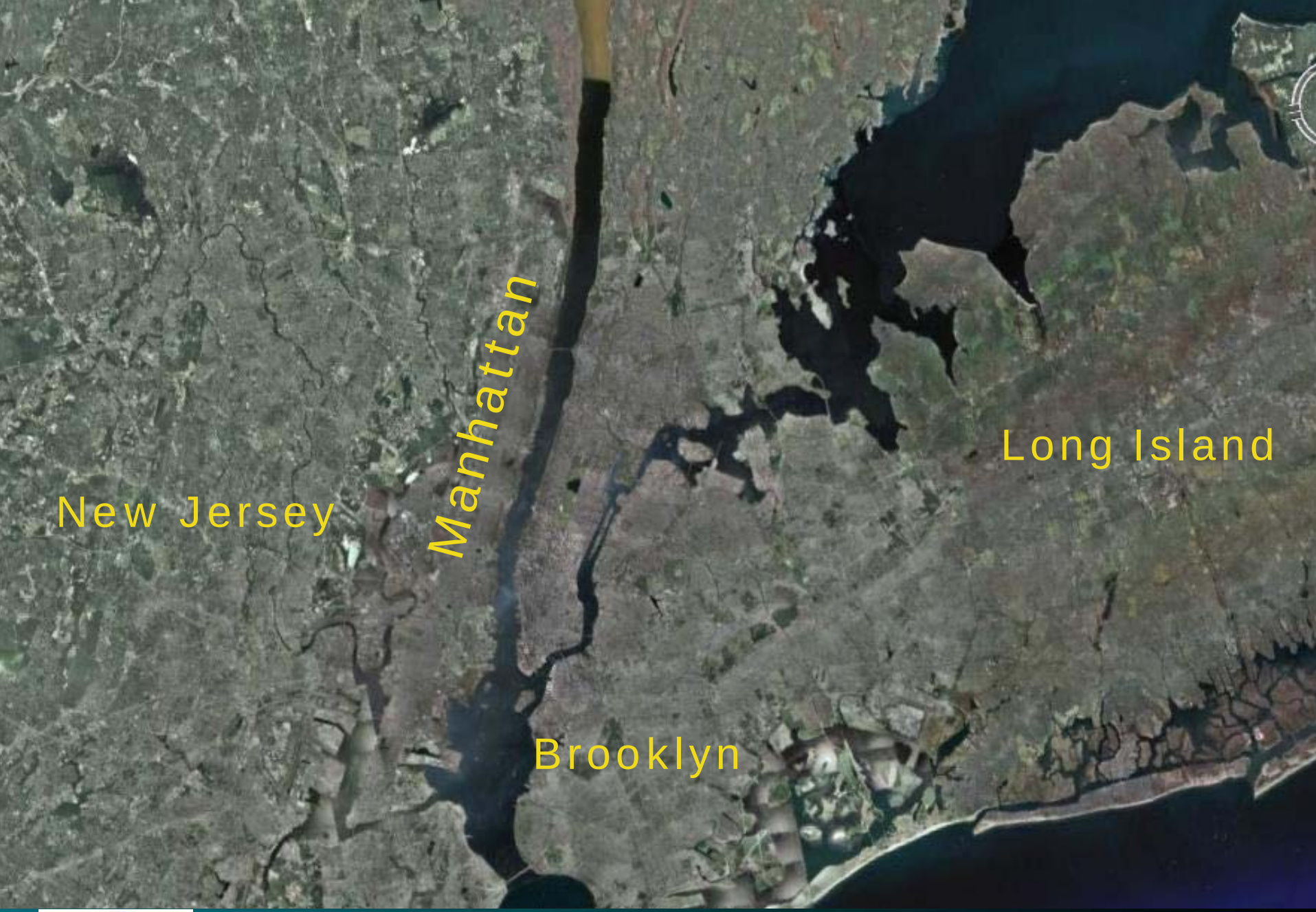
Introduction

Two recent Rock Cavern Case Studies from New York will be discussed

- **No. 7 Line Project (34th Street Station)**
- **East Side Access Project (Grand Central Station)**

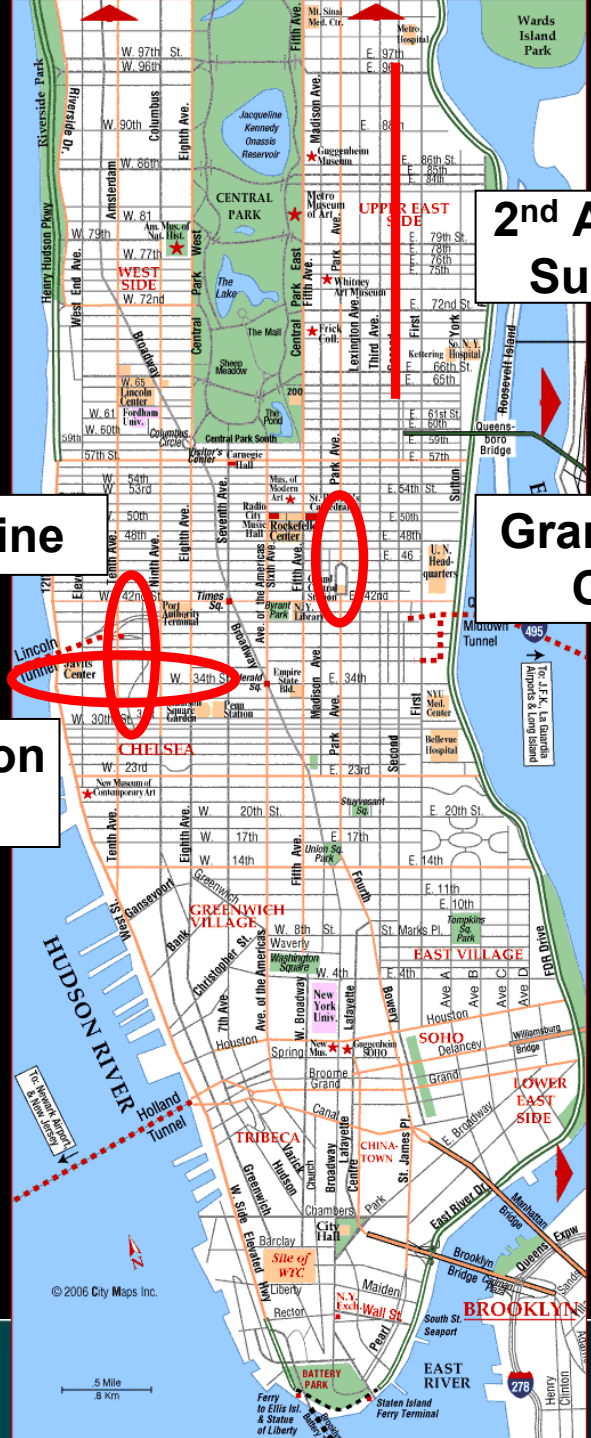
The presentation will focus on the site investigation, design and construction of the caverns on these projects

- **Geological Interpretation**
- **Empirical / Numerical Design**
- **Construction observations (movement, vibration etc)**



ARUP

Manhattan Projects



ARUP

No. 7 Line Project Overview

- **1st Design / Build Underground Project in NYC**
- **1st Cavern excavated in NYC in 40 years – cavern complete on time**
- **6+ months ahead of schedule (after 18 months)**
- **Arup scope:**
  - Initial support design for station caverns and 26th Street TBM Launch cavern
  - Site Presence, providing technical support and redesign work as required during construction

Project Team

Owner: New York City Transit

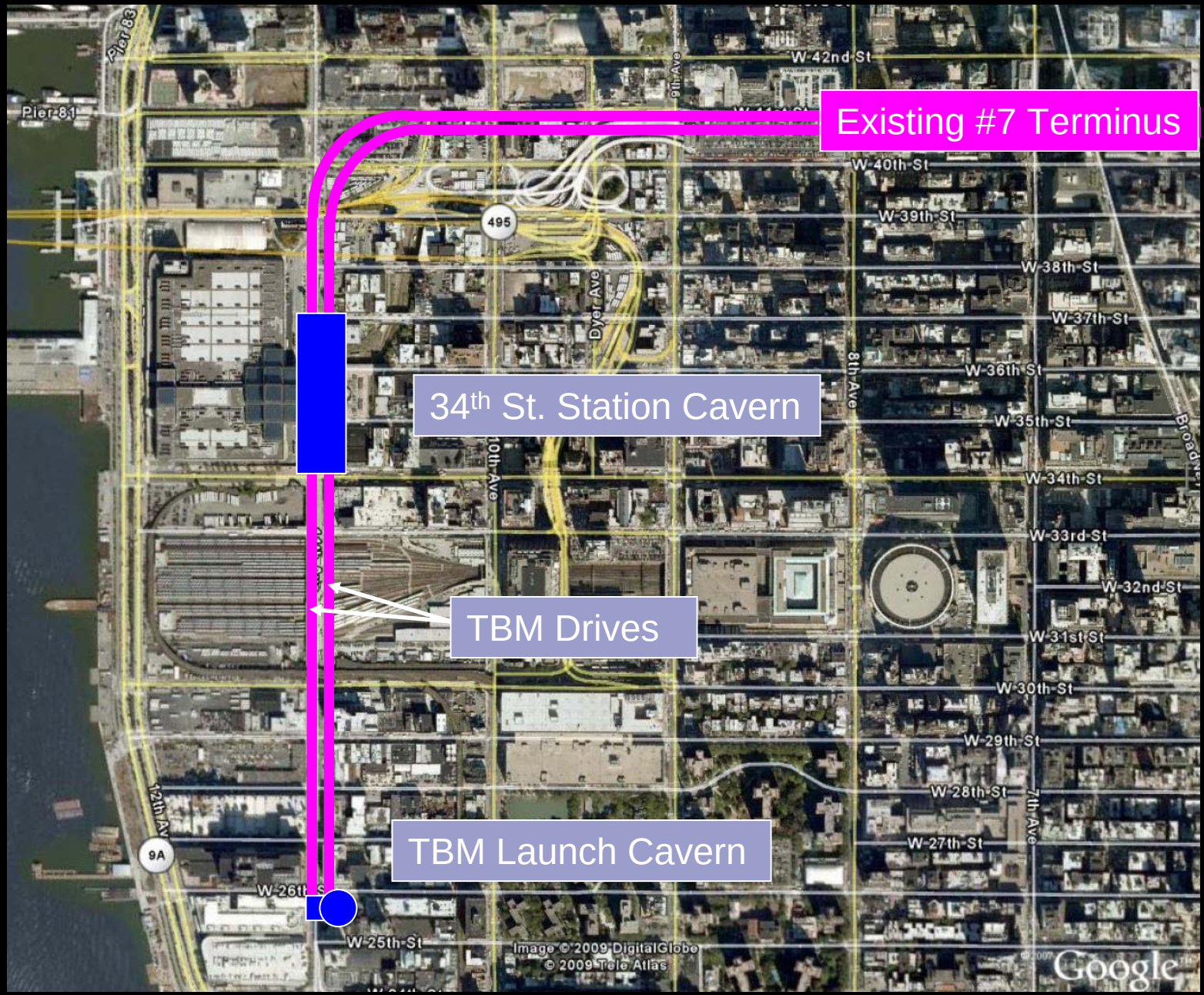
Contractor: S3II Tunnel Constructors

Owner's Engineer: Parsons Brinkerhoff

Construction Manager: Hill Intl/Liro/Lemley/HDR

Contractor's Designer: Arup

- Subconsultants: GZA, Snee Geoconsult


Existing #7 Terminus
34th St. Station Cavern
TBM Drives
TBM Launch Cavern
Pier 83
Pier 81
W-42nd St
W-40th St
W-39th St
W-38th St
W-37th St
W-36th St
W-35th St
W-34th St
W-33rd St
W-32nd St
W-31st St
W-30th St
W-29th St
W-28th St
W-27th St
W-26th St
W-25th St
9th Ave
Dyer Ave
8th Ave
10th Ave
12th Ave
7th Ave
Broadway
495
9A
Image © 2009 DigitalGlobe
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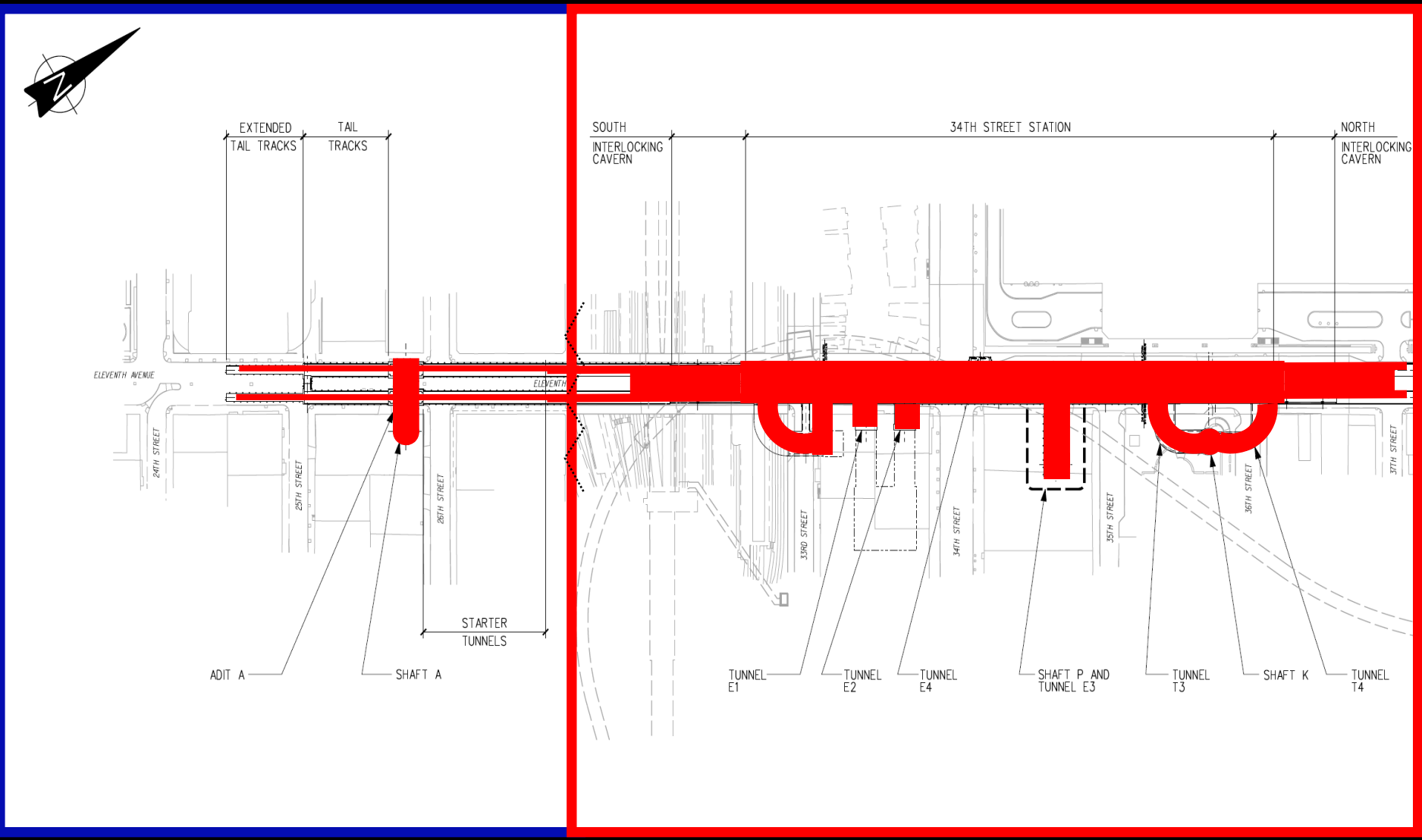
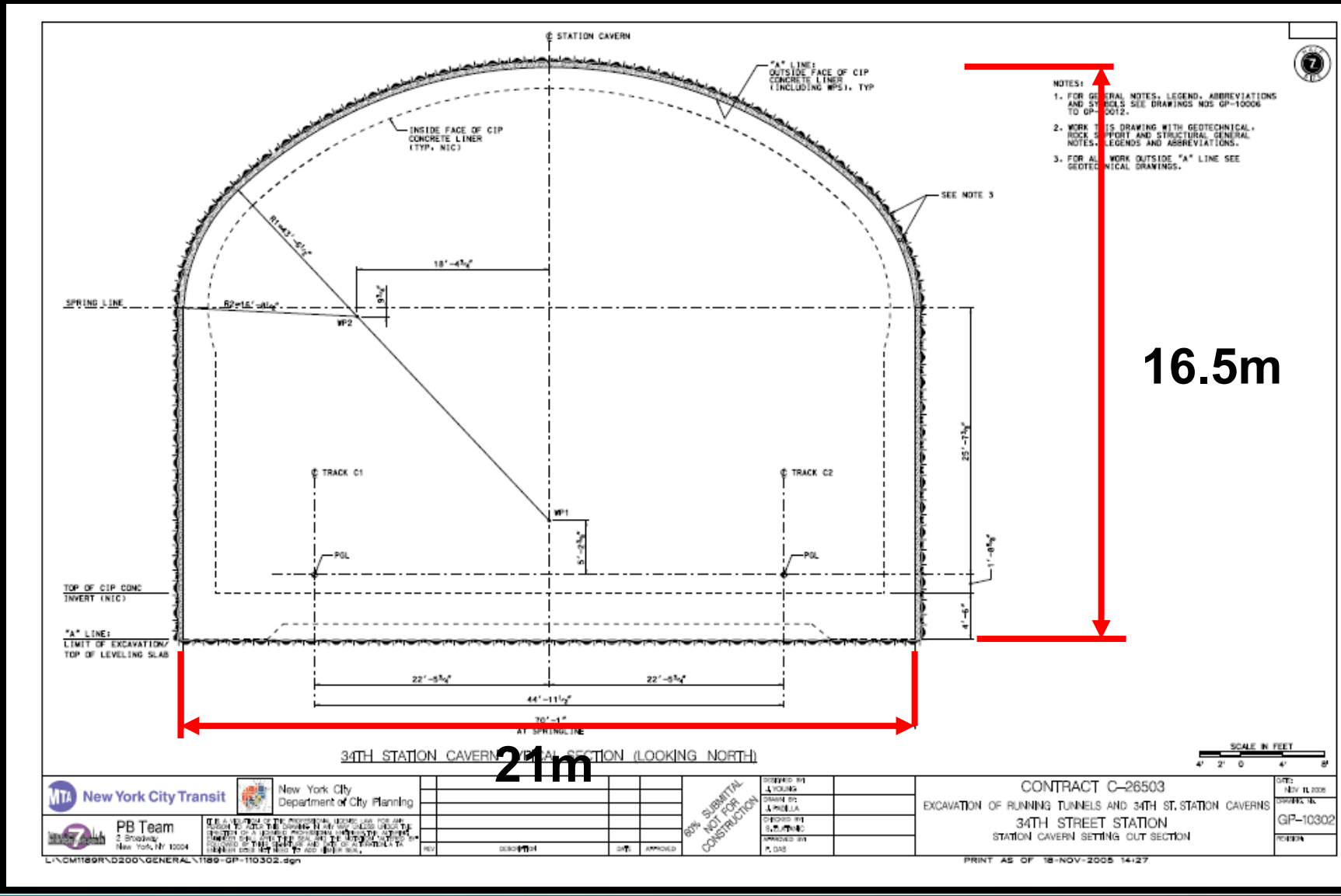
Google

Project Alignment

Anticipated Construction Sequence

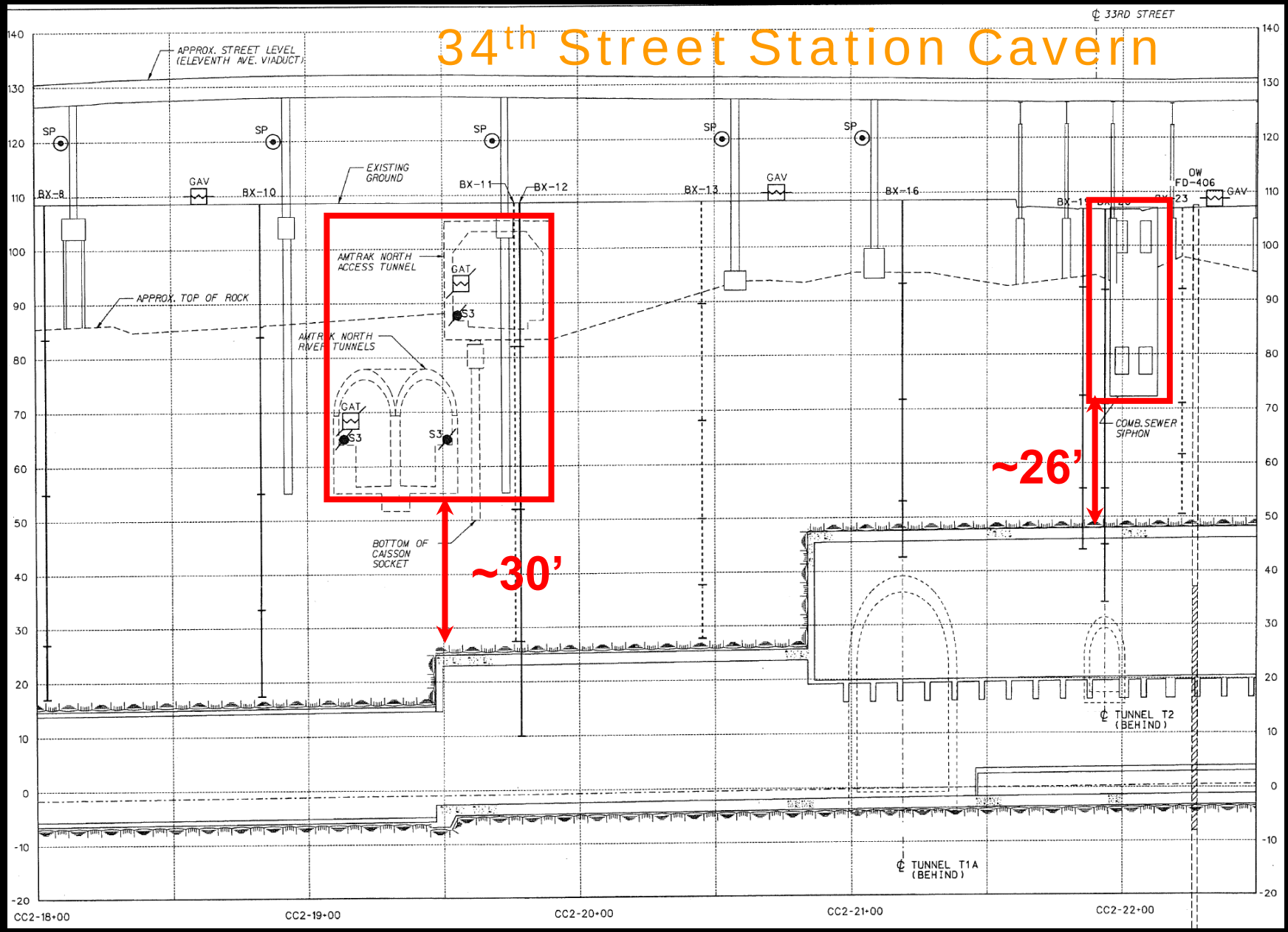


34th Street Cavern

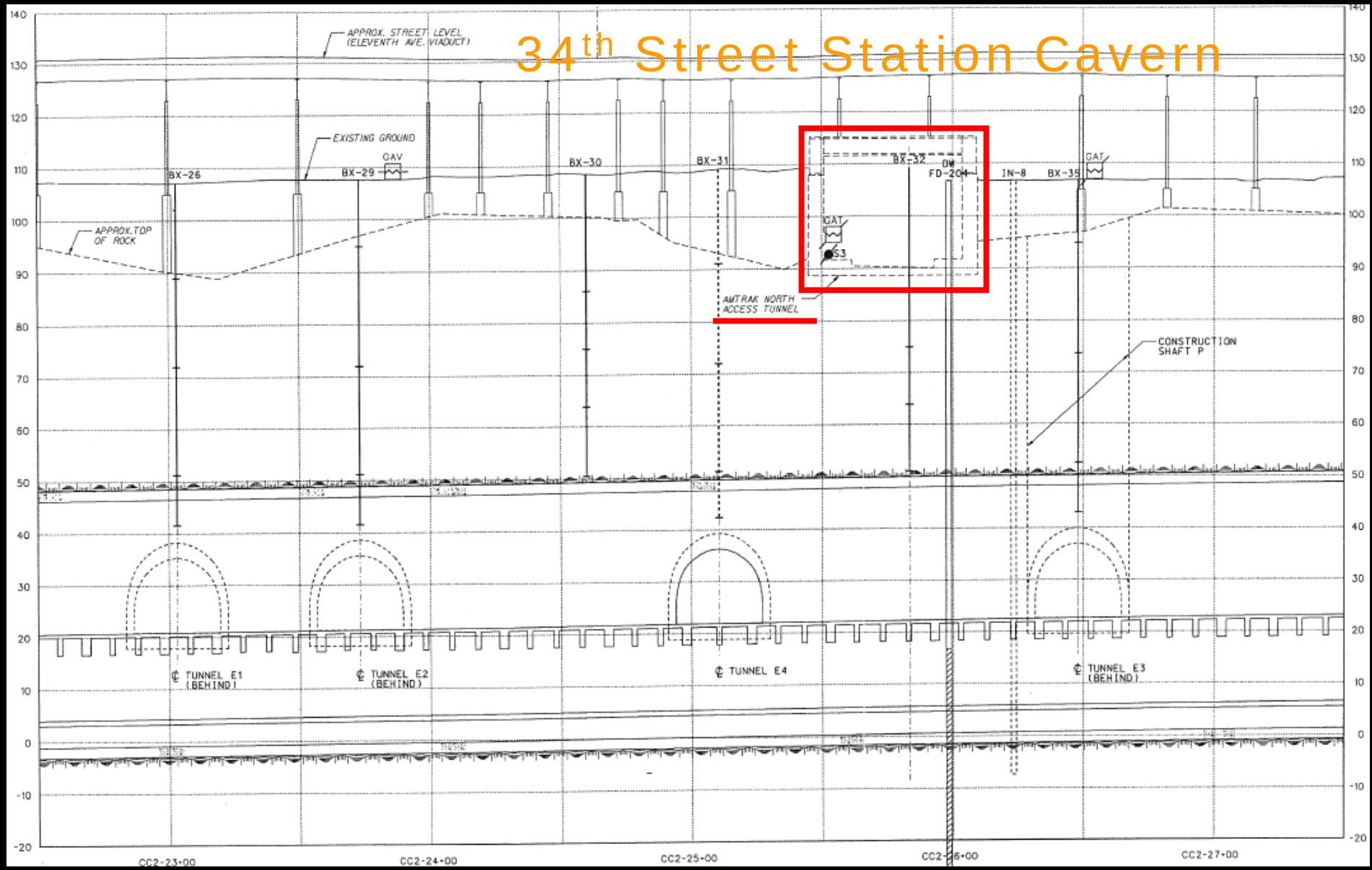


ARUP

34th Street Station Cavern



34th Street Station Cavern



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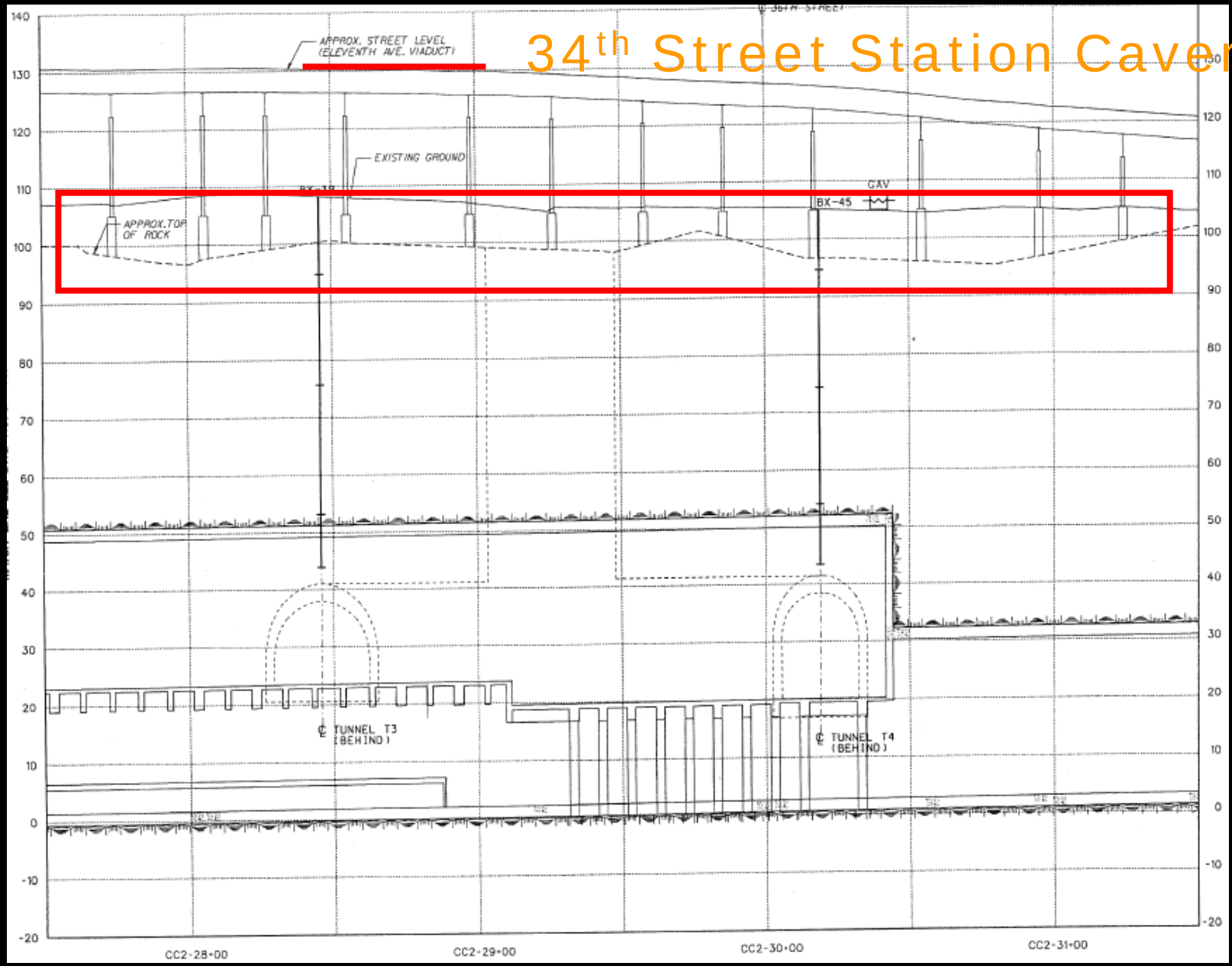
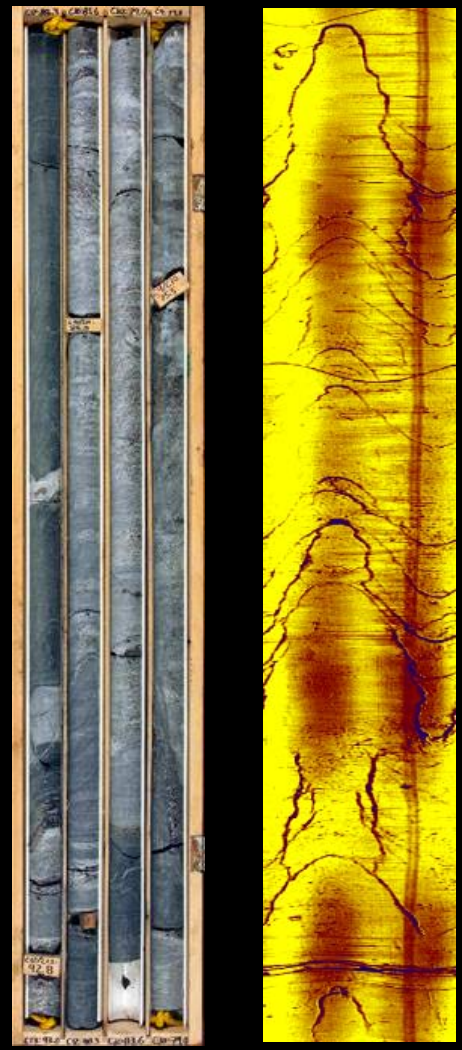
34th Street Station Cavern



Sources of Information

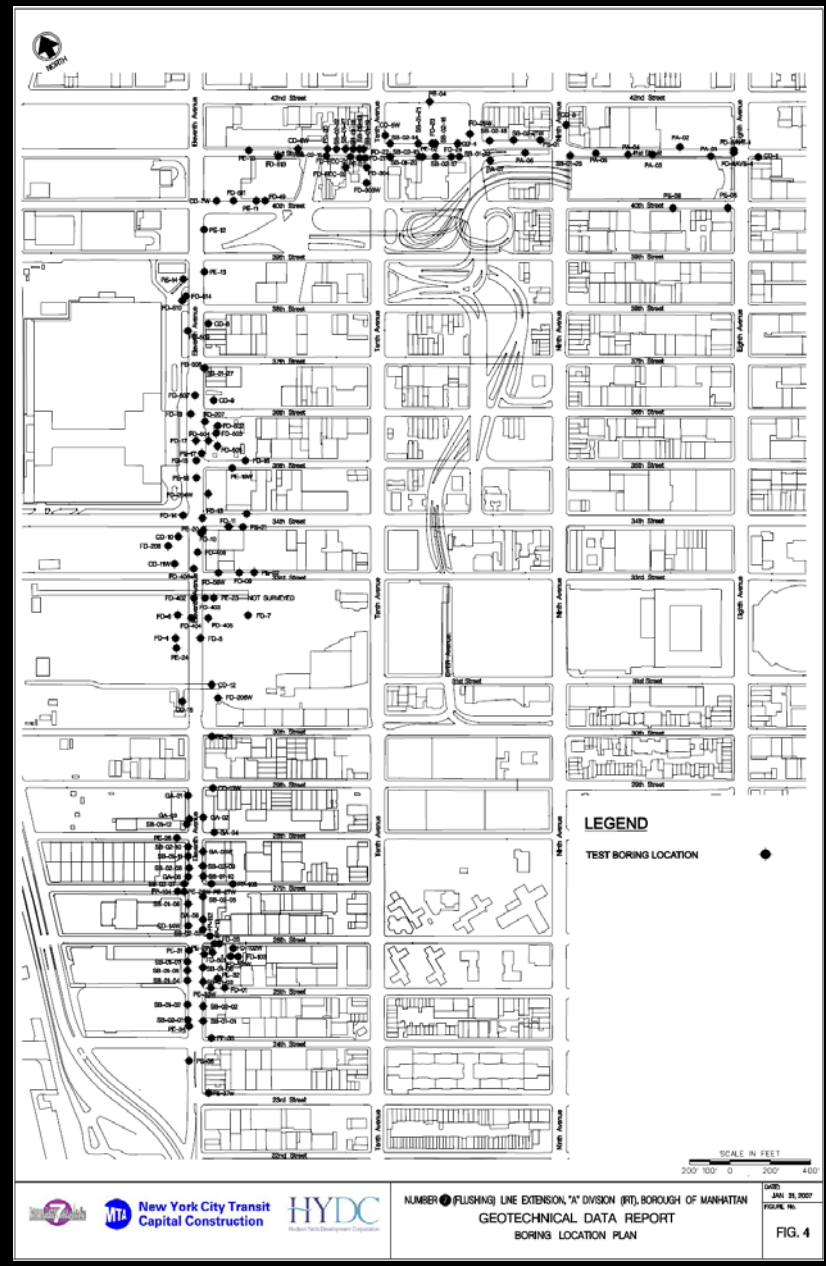
- **Geotechnical Baseline Report**
- **Geotechnical Data Report**
  - Subsurface Investigation
    - Soil and rock core logging, oriented core
    - Acoustic Televiewer corehole logging
    - Observation wells
    - Hydraulic fracturing tests
    - Rock core photographs
    - Laboratory testing of rock core
    - Geologic mapping



- **Information from TBM and Drill-and-Blast tunneling projects in NYC (historic, current i.e. THE Project)**

Subsurface Investigation

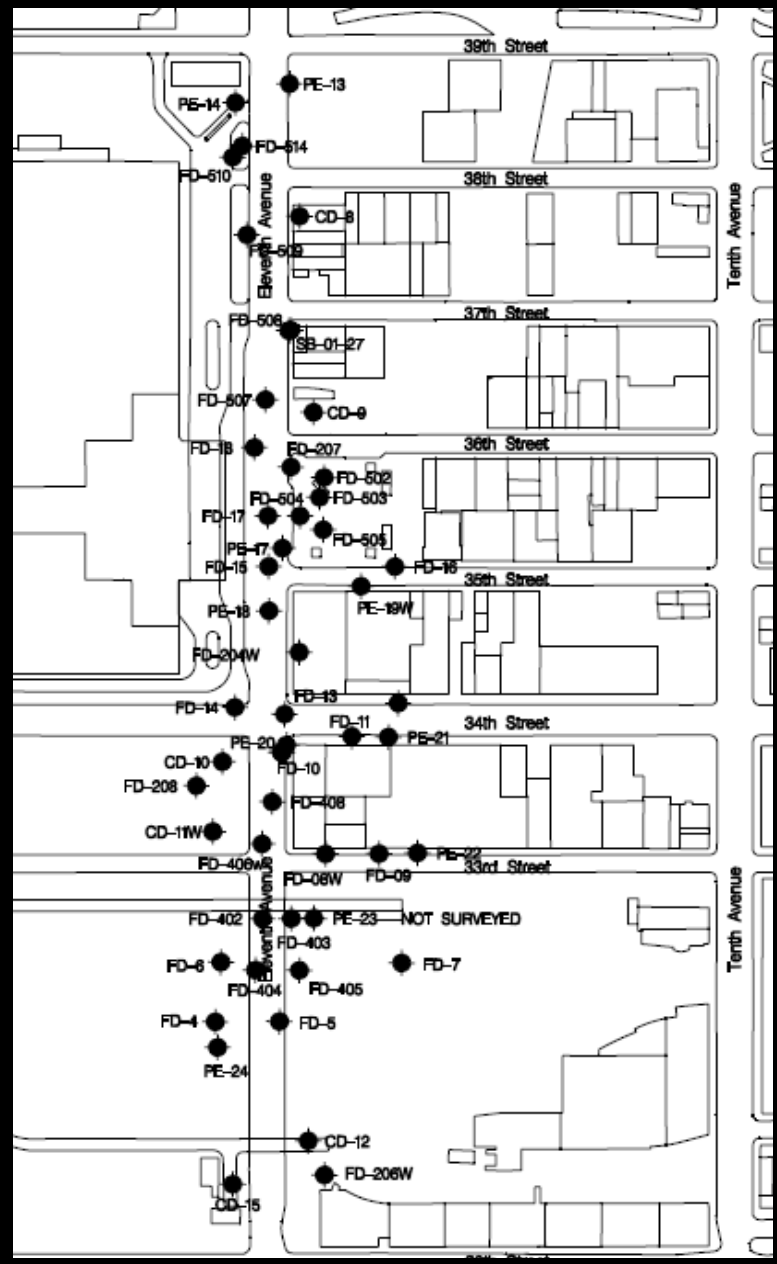
- **164 geotechnical borings, 5 oriented, several phases**
- **22 observation wells**
- **228 packer tests in 89 boreholes**
- **60 acoustic/optical televiewer logs**
- **7 hydraulic fracture tests in 2 boreholes**
- **Extensive laboratory testing**
  - UCS, triaxial
  - Tensile strength
  - Elastic constants
  - Petrography etc.



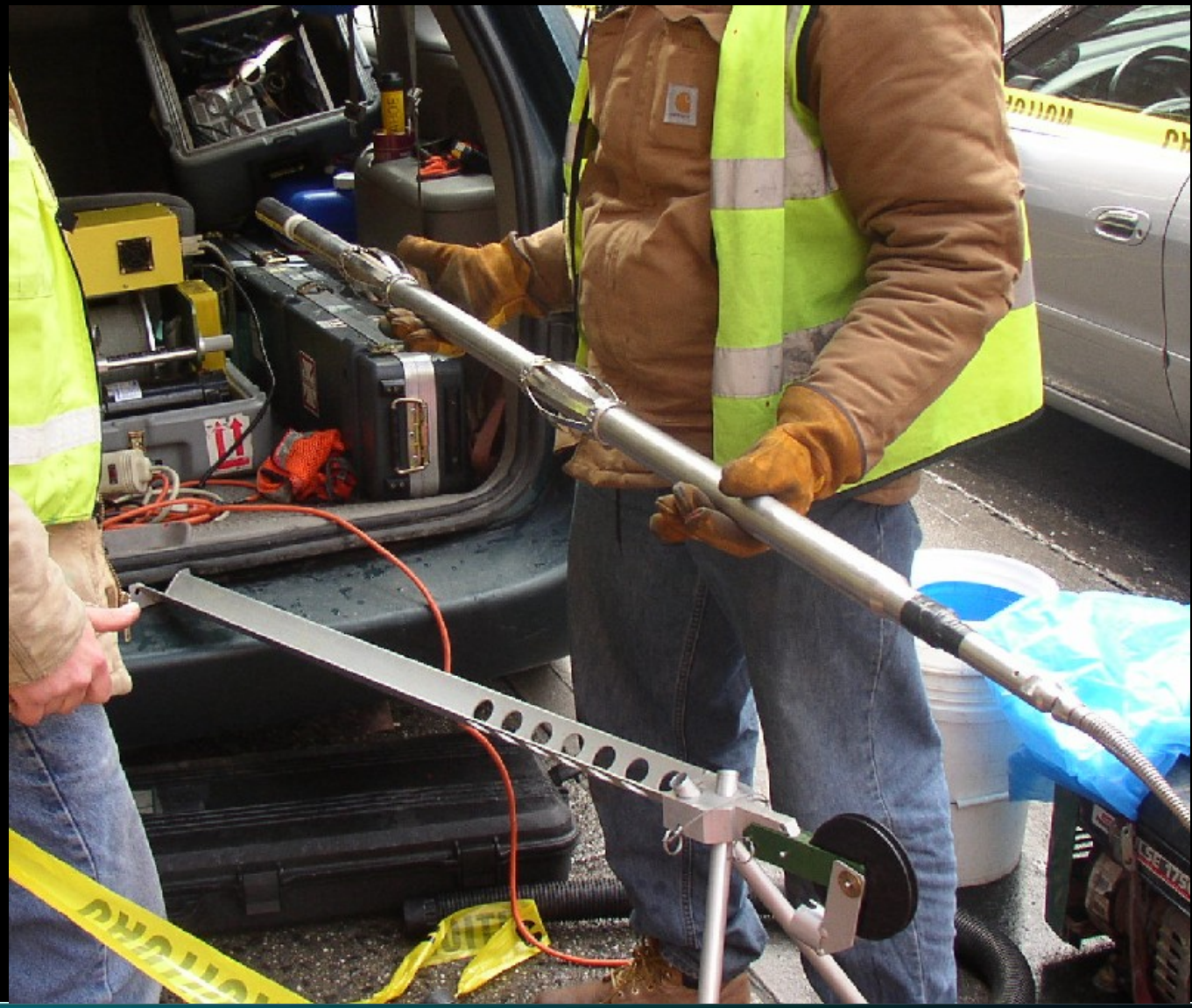
ARUP

Subsurface Investigation
34th Street Cavern

- **49 existing boreholes**
- **26 additional borings planned by Arup/GZA**
- **Surface mapping of outcrops**

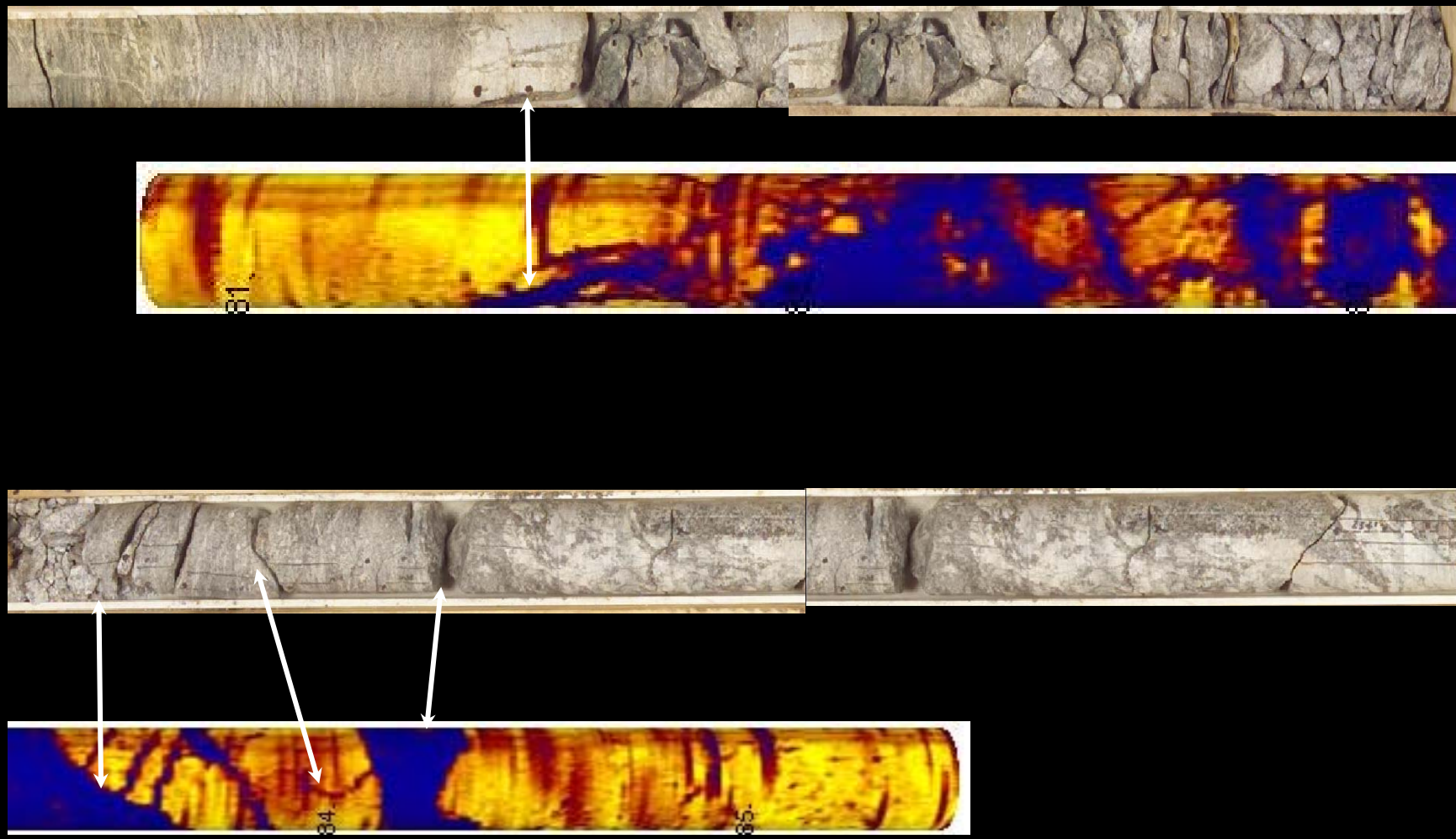


Acoustic televiewer



Correlation of ATV and Core

Core

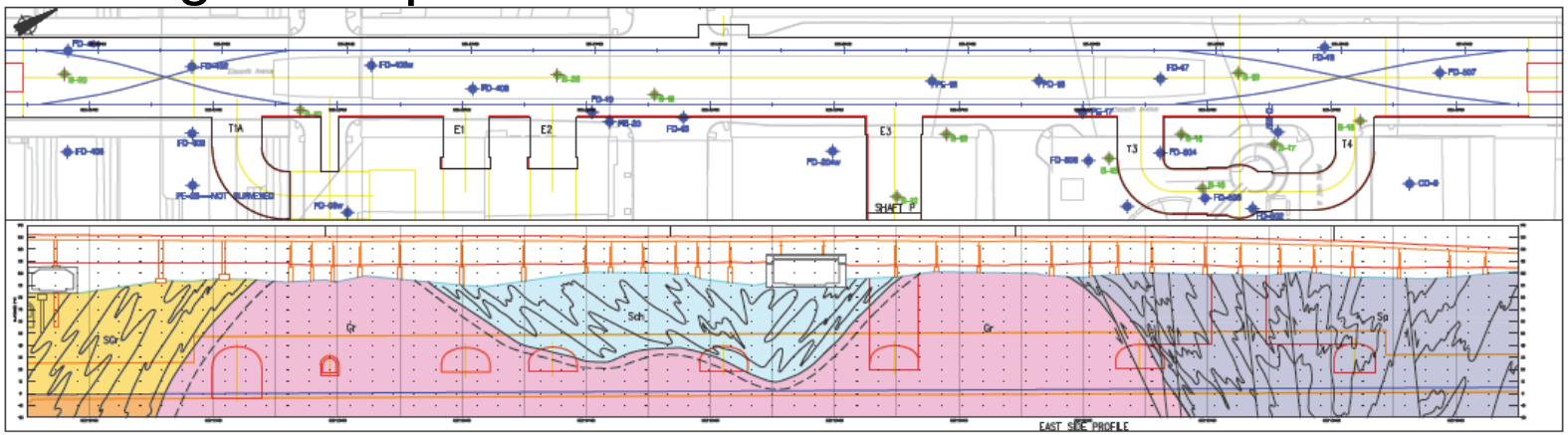


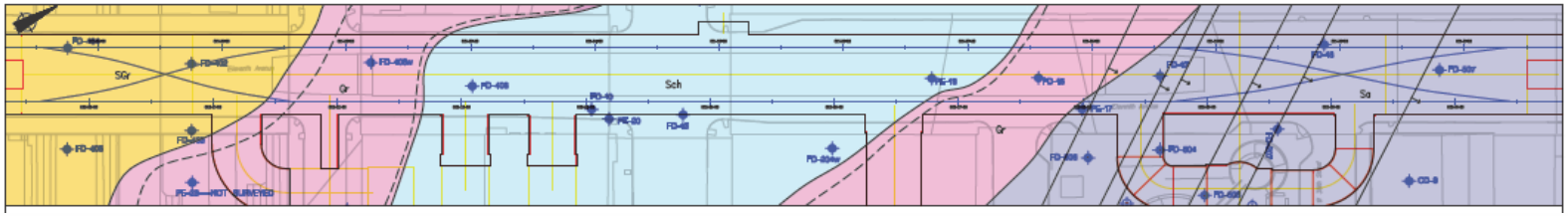

Styrofoam

Surface Mapping

Geologic Interpretation

Geologic Interpretation – 34th Street Cavern area





Sch	Gneissic schist with subordinate pegmatite, highly convoluted foliation
Sa	Gneissic to amphibolitic schist
Gr	Granofels with subordinate pegmatite
SGr	Intercalated schist, pegmatite and granofels

Geological Interpretation

- **Geotechnical interpretations on plan / section**
- **Three rock classes:**
  - A – Q > 3.5; RMR > 55
  - B – Q range 1.5 to 3.5; RMR range 45 to 55
  - C – Q < 1.5; RMR < 45
- **Particular concern with character of rock mass in north end of 34th Street Cavern**
- **Contact zones**

Schist / Granite Contact

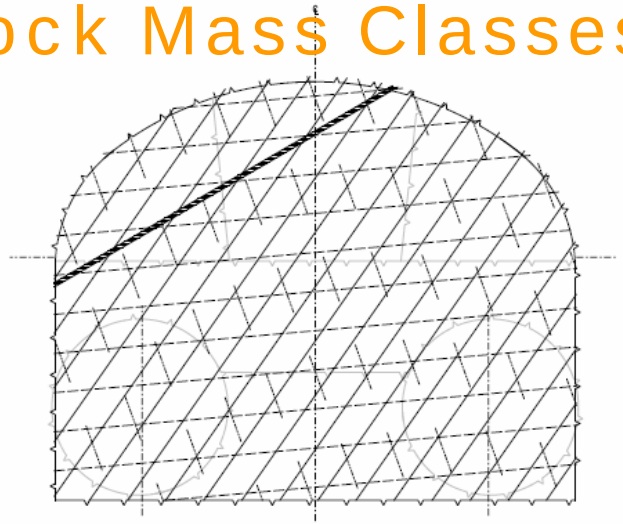
Contact at Site A

Contact at 34th Street Cavern

Design Philosophy

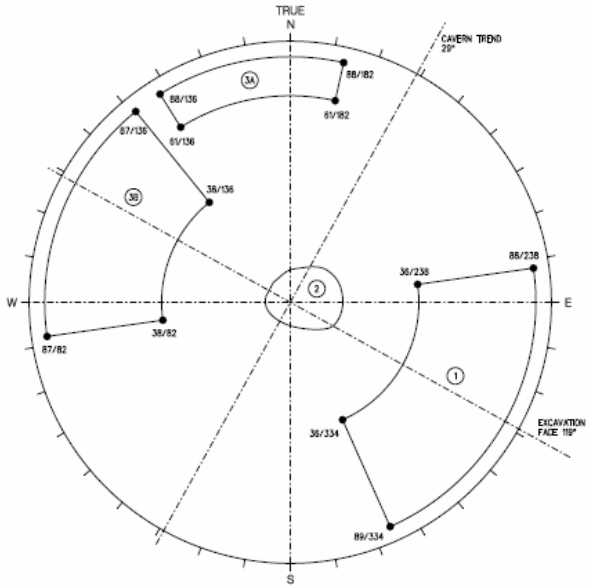
- **Shallow Cavern, in hard competent rock**
- **Cavern / Tunnel Stability is controlled by structural discontinuities within a competent rock (i.e. problem is not one of stress, but stabilizing wedges)**
- **Provide support to ensure interlocking of these blocks and limit block movement along joints**

Rock Mass Classes



ROCK MASS CLASS TYPE B

1/8"=1'-0"



EXPECTED JOINT SET ORIENTATIONS

LOWER HEMISPHERE EQUAL ANGLE

1/8"=1'-0"

TABLE 1: EXPECTED ROCK TYPE AND STRENGTH

PARAMETER	DISCUSSION	TO BE VERIFIED DURING CONSTRUCTION BY	EXPECTED RANGE
ROCK MASS DESCRIPTION	AS CHARACTERIZED BY TERZAGHI	OBSERVATION	MASSIVE TO MODERATELY JOINTED
MINERALOGY	SCHIST: MED DARK GRAY TO BLACK, PRINCIPALLY COMPOSED OF BIOTITE, QUARTZ, PLAGIOCLASE FELDSPAR, SOME HORNBLENDS. GRANITE/GRANOFELS: PINK TO GRAY f-m GRAINED, COMPOSED OF QUARTZ, K-SPAR, MUSCOVITE, SOME MINERAL ALIGNMENT.	OBSERVATION	-
ROCK STRENGTH	RESULT OF THE UNIAXIL COMPRESSION STRENGTH TEST GIVES THE RANGE FROM 5,800 TO 39,000 (PSI), AVERAGE 21,000 (PSI)	GEOLOGICAL HAMMER MORE THAN 1 FRM BLOW TO BREAK	SCHIST: 5,700 - 13,900 (PSI) GRANITE: 9,700 - 31,300 (PSI)
WEATHERING GRADE	SLIGHT RUST DISCOLORATION ON SURFACES, SOME OR ALL MATERIAL MAY BE SOMEWHAT WEAKER EXTERNALLY THAN IN ITS FRESH CONDITION.	OBSERVATION	UNWEATHERED TO SLIGHTLY WEATHERED (W1 - W2)

TABLE 2: STRUCTURAL GEOLOGY

PARAMETER	DISCUSSION	TO BE VERIFIED DURING CONSTRUCTION BY	EXPECTED RANGE
JOINT SYSTEM	THREE TO FOUR JOINT SETS	COMPASS MEASUREMENT	-
TYPICAL BLOCK SIZE	EQUIDIMENSIONAL OR CUBICAL BLOCK	JOINT VOLUME	2 (CU.FT.) TO > 100 (CU.FT.)
FAULTS/SHEAR ZONES	OBSERVED SHEAR PLANES TYPICALLY OCCURING AT SCHIST - GRANOFELS CONTACT, CONTAIN CLAY OR DISINTEGRATED ROCK BETWEEN ROCK SURFACES, WITH A THICKNESS OF ALTERATION PRODUCTS NOT TO EXCEED 6 INCHES	OBSERVATION	1 PER FACE
IN SITU STRESS	NO POPPING ROCK EXPECTED, POPPING ROCK MATERIAL INDICATES HIGHER IN SITU STRESS THAN ANTICIPATED	OBSERVATION	1 - 2

TABLE 3: JOINT INFORMATION

EXPECTED JOINT TYPES	SET 1	SET 2	SET 3	TO BE VERIFIED DURING CONSTRUCTION BY
	FOLIATION SET	SUBHORIZONTAL	CROSS FOLIATION	
AVERAGE ORIENTATION (DIP ANGLE/DIRECTION)	54 / 287	12 / 270	3A: 77 / 156, 3B: 60 /107	COMPASS MEASUREMENT
APERTURE	CLOSED	0.5 - 1.0 IN (OPEN)	CLOSED	MEASURING TAPE
SPACING	FROM 2 FT TO 5 FT	FROM 2 FT TO 5 FT	FROM 2 FT TO 5 FT	MEASURING TAPE, SCANLINE
PERSISTENCE	HIGH PERSISTENCE	HIGH PERSISTENCE	LOW PERSISTENCE (GENERALLY LESS THAN 6 FT)	MEASURING TAPE
ROUGHNESS	SMOOTH UNDULATING TO SLICKENSIDED (AVERAGE Jr - 2)	SMOOTH UNDULATING TO SLICKENSIDED (AVERAGE Jr - 2)	SMOOTH UNDULATING TO SLICKENSIDED (AVERAGE Jr - 2)	JRC TABLE / LINEAR PROFILING / PROFILE GAUGE
ALTERATION	UNALTERED TO NON-SOFTENING MINERAL COATING (AVERAGE Ja - 2)	UNALTERED TO NON-SOFTENING MINERAL COATING (AVERAGE Ja - 2)	UNALTERED TO NON-SOFTENING MINERAL COATING (AVERAGE Ja - 2)	Ja (Q SYSTEM)

TABLE 4: GROUNDWATER CONDITIONS

PARAMETER	TO BE VERIFIED DURING CONSTRUCTION BY	EXPECTED RANGE
GENERAL CONDITIONS	OBSERVATION	DRY OR MINOR INFLOW (< 5 L MIN) DEPPING DISCONTINUITIES, ALSO SHORT TERM MODERATE INFLOW FROM SET 2 JOINTS
EXPECTED INFLOW	OBSERVATION	5 - 20 L / MIN / 10 FT OF DRIFT

TABLE 5: ROCK MASS CHARACTERIZATION

SYSTEM	DISCUSSION	TO BE VERIFIED DURING CONSTRUCTION BY	EXPECTED RANGE
TYPICAL ROCK CORE QUALITY (RQD)	GENERAL RQD VALUES RECORDED FROM BOREHOLE DATA IS IN THE RANGE FROM 80 TO 100, DISCRETE ZONES OF RQD VALUES OF 50 MAY BE ENCOUNTERED OVER LIMITED DISTANCE/EXTENT.	JOINT VOLUME ESTIMATION ON UNIT VOLUME OF ROCK	80 - 100 (2)
GSI	-	GEOLOGICAL MAPPING	55 - 70
Q'	Q' = RQD / Jn x Jr x Ja	GEOLOGICAL MAPPING	5 - 20 (AVERAGE 10)
RMR	-	GEOLOGICAL MAPPING	37 - 72 (AVERAGE 58)
TERZAGHI	-	GEOLOGICAL MAPPING	MODERATELY JOINTED - MODERATELY BLOCKY OR SEAMY
STANDUP TIME	-	OBSERVATION	10 HOURS - 2 YEARS (AVERAGE 1 MONTH)

Rock Mass Classification – Q System

- **Joint number (Jn)**

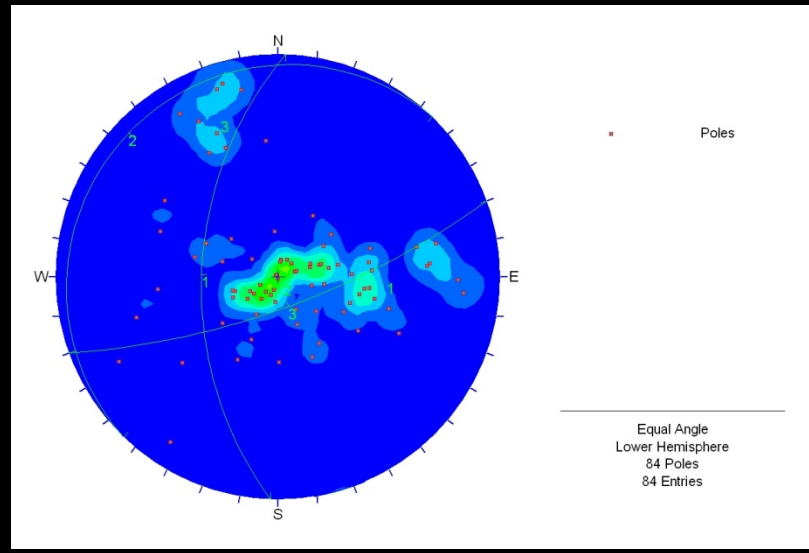
  ATV data along cavern alignment;

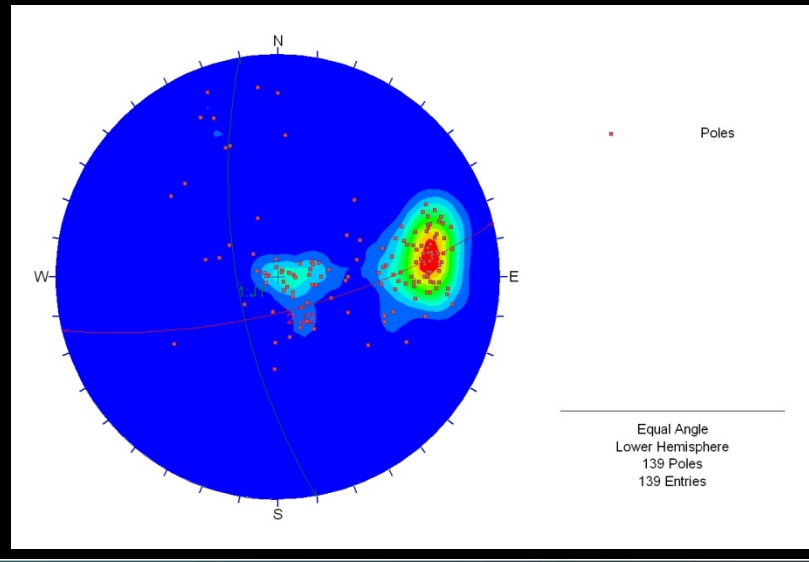
  Consistent joint orientations (3 sets) for Jn=9 rating

  (exception is tail/starter tunnels and Shaft/Adit A where Jn=6)

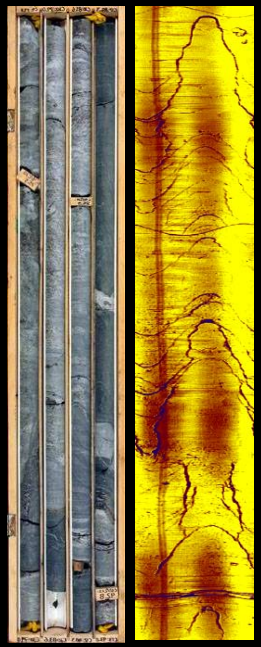
- **RQD, Jr, Ja**

  Obtained directly from boring logs, verified by field logging and additional boreholes





Simplified Cavern Design Methodology



A) Empirical Design

Q-system Barton (1993)
- Rock bolt length / spacing
- Shotcrete type and thickness

R/B length check
-Empirical Recommendations (USACE)

Input
- ∅ peak
- Joint Orientation

B) Verification wedge stability check (UNWEDGE)

Increase
Rock Bolt Length / Support pressure

- Is bolt length sufficient for wedge size?
- Is sufficient supporting pressure to satisfy SF > 2.0?

No

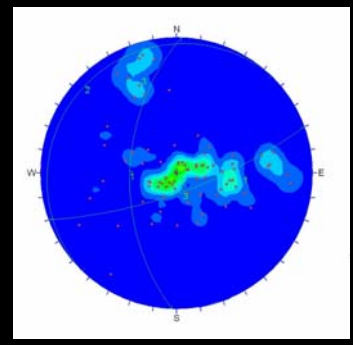
Input
-Rock mass parameters
-Construction sequence
-Material properties

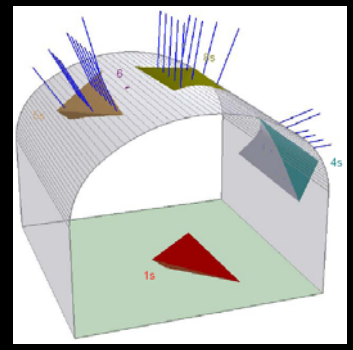
C) Verification through numerical modeling (Ie UDEC)
-check bolt forces
-check M-N diagram

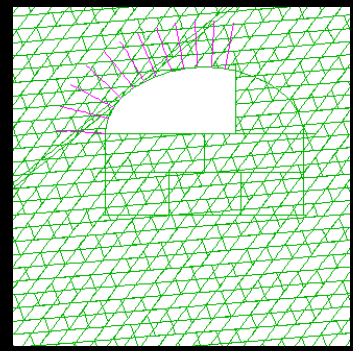
Revise

Ok?

Accept



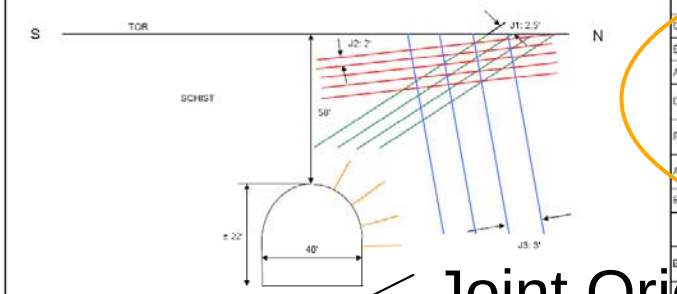




Summary Sheet

NO. 7 LINE PROJECT	KINEMATIC BLOCK STABILITY PARAMETERS	ARUP GZA	SHEET: 13 OF 14	REV.: 0
JOB TITLE:			DATE: 1/4/2007	CHKD.: PJH
			ORIGINATOR: SEP	REVIEW: CS

TUNNEL T3 ADIT

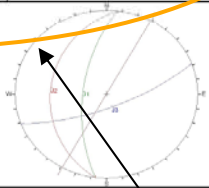


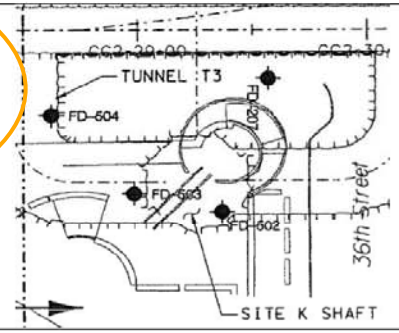
GENERAL INFORMATION

GROUND SURFACE ELEVATION	±108 FT
EXCAVATION SPAN	40 FT
ANTICIPATED JOINT WATER PRESSURE	0 KSF
DESIGN FACTOR OF SAFETY	1.5
ROCK LEVEL	EL 98 FT
ADIT INVERT LEVEL	EL 20 FT
EXCAVATION TREND	209-299

ACOUSTIC TELEVIEWER DATA

BOREHOLES	FD-504	
BOREHOLE USED	FD-504	-
CORRECTED FOR DECLINATION?	YES	
ROCK DENSITY	175 PCF	
ROCK MASS COMPOSITION	JOINTED SCHISTOSE ROCK W/ CRUSHED CONTACT ZONES	





BOREHOLE LOCATION PLAN

GEOLOGIC INTERPRETIVE SECTION TUNNEL T3

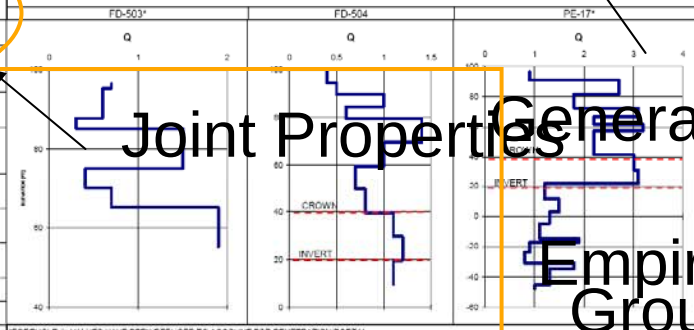
JOINT ORIENTATIONS

SET	DIP	DD	TRUE SPACING
J1 FOL	61	277	2.5'
J2 FORZ	27	277	2'
J3 CONS	71	159	3'

JOINT PROPERTIES

φ°	c' [KSF]	i°	PERSISTANCE [FT]	TENSILE STRENGTH [KSF]
30	0	5	30	0
30	0	3	50	0
30	0	7	30	0

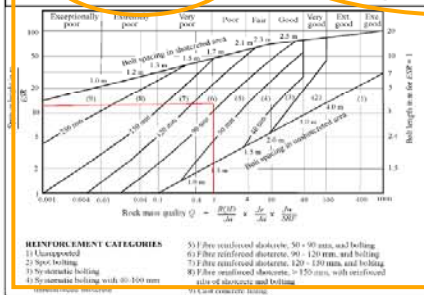
ROCK MASS CLASSIFICATION



*BOREHOLE Jn VALUES HAVE BEEN REDUCED TO ACCOUNT FOR PENETRATION/PORTAL

Q VALUE VS ELEVATION [FT] FOR RELEVENT BOREHOLES

EMPIRICAL SUPPORT DESIGN USING Q SYSTEM [AFTER BARTON ET AL., 1993]



REINFORCEMENT CATEGORIES
1) Unsupported
2) Spot bolting
3) Systematic bolting
4) Systematic bolting with 40-100 mm
5) Fibre reinforced shotcrete, 50 - 90 mm, and bolting
6) Fibre reinforced shotcrete, 90 - 120 mm, and bolting
7) Fibre reinforced shotcrete, 120 - 130 mm, and bolting
8) Fibre reinforced shotcrete, > 150 mm, with reinforced ribs of shotcrete and bolting
9) Cast concrete lining

GLOBAL Q PARAMETER VALUES

J_n	9
JW	1
SRF	2.5
ESR	1

Q VALUES

TUNNEL T3	Q_{CROWN}	1
	Q_{WALL}	2
MAIN CAVERN	Q_{CROWN}	

GROUND SUPPORT PROPERTIES

GROUTED DOWEL					SWELLEX MN24C FRICTION BOLT				FIBER REINFORCED SHOTCRETE	
DIAMETER [IN]	TENSILE CAPACITY [KIPS]	PLATE CAPACITY [KIPS]	BOND STRENGTH [KIPS/FT]	BOND LENGTH [%]	TENSILE CAPACITY [KIPS]	PLATE CAPACITY [KIPS]	BOND STRENGTH [KIPS/FT]	BOND LENGTH [%]	SHEAR STRENGTH [KSF]	UNIT WEIGHT [PCF]
1	59	36	32	100	35	20	22	100	25	150

Joint Orientation

Joint Properties

General Info

Empirical Summary

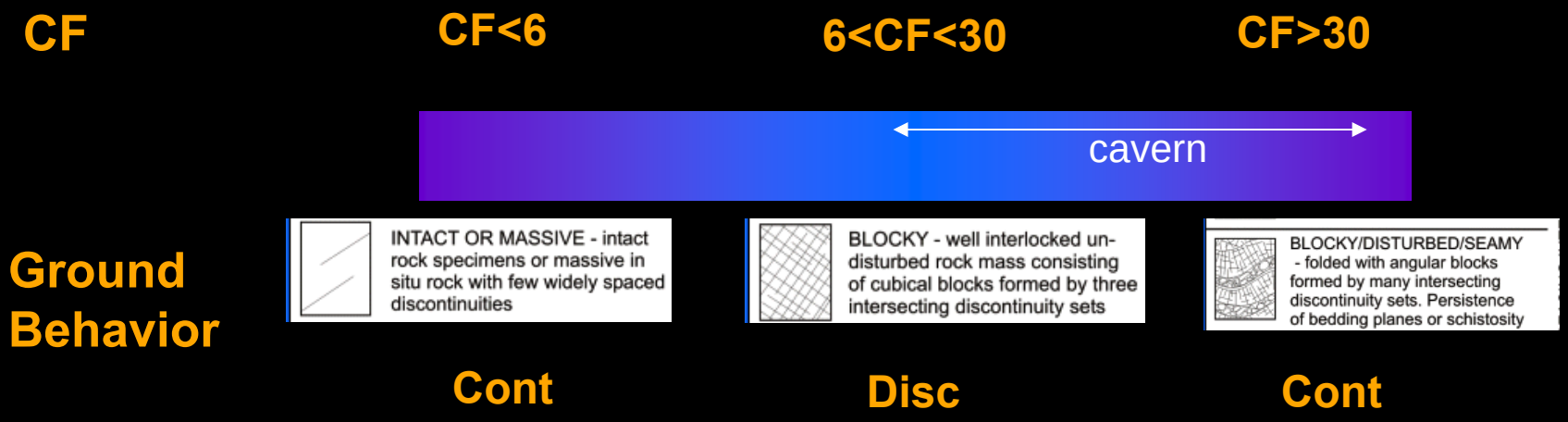
Ground Support

Key Block Analysis

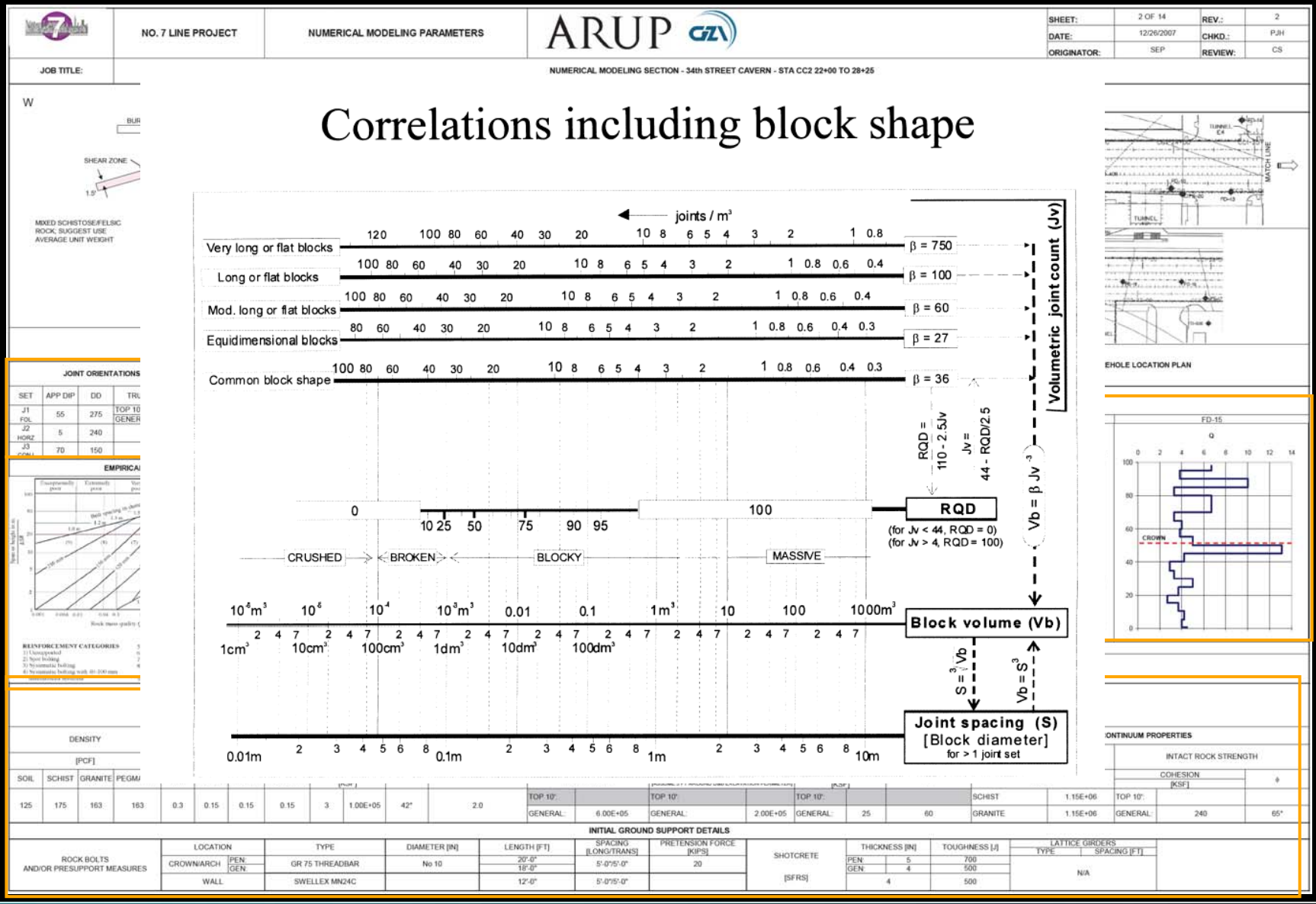
- Use of UNWEDGE software at sections through cavern and adits where ATV data was available (17+ sections completed to date)
- Support input was that determined by empirical method (Q, USACOE)
- Accounted for overbreak

Numerical Model Verification

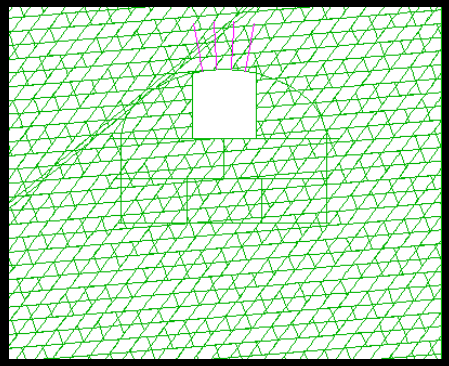
- **UDEC for discontinuum, FLAC for continuum**
- **Distinguished by ratio of cavern span/estimated block diameter (continuity factor); i.e. no. of blocks occurring along cavern roof (Palmstrom 2005,2008)**



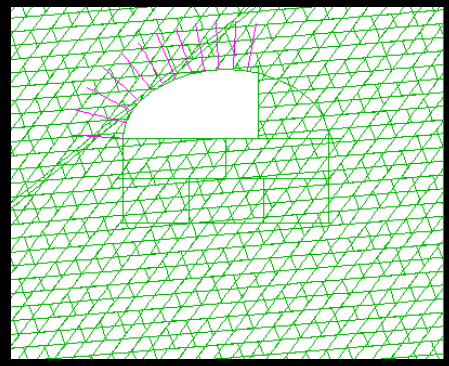
UDEC Input Properties



Typical UDEC Modeling Construction Sequence



Stage 1



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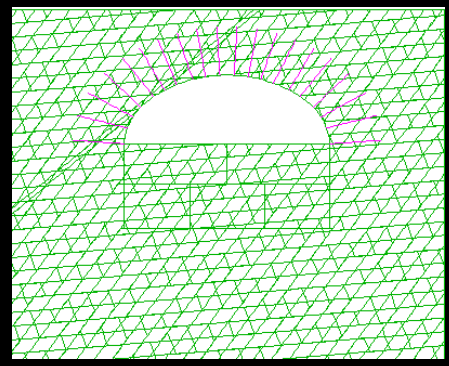

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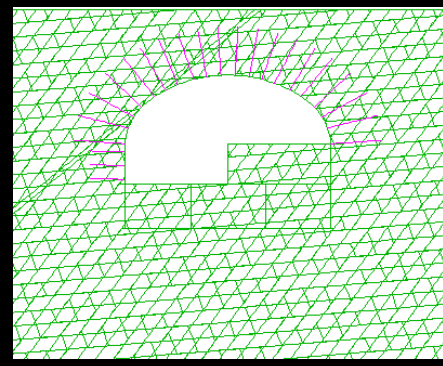

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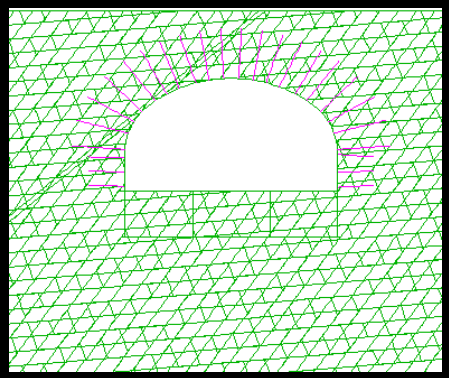

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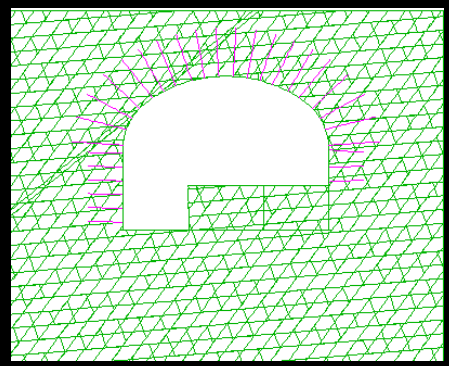

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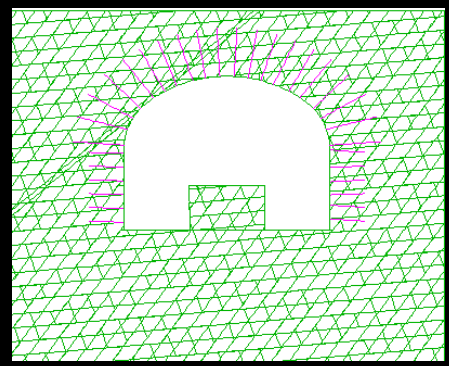

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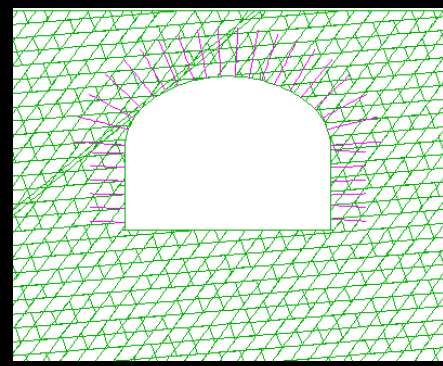
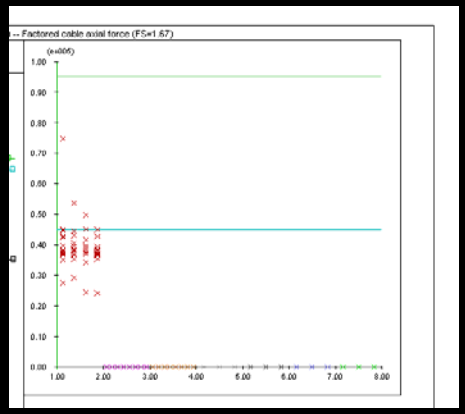


Stage 8

UDEC Results – Type B Support Rock Bolts



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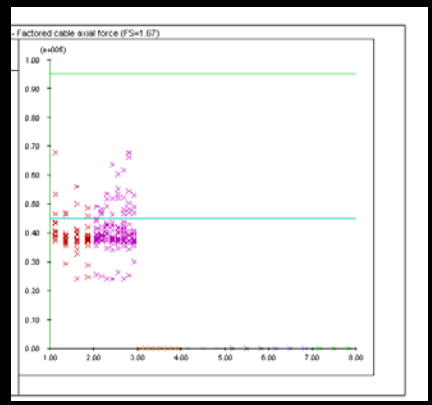

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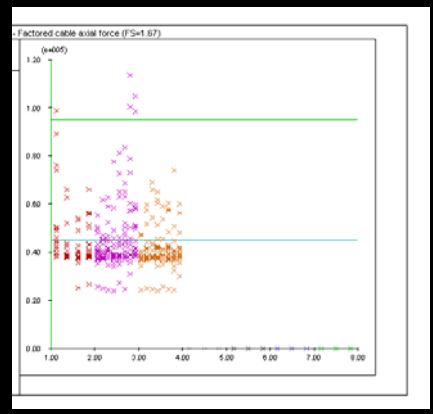

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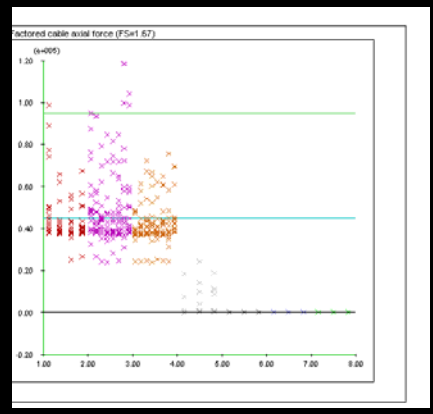

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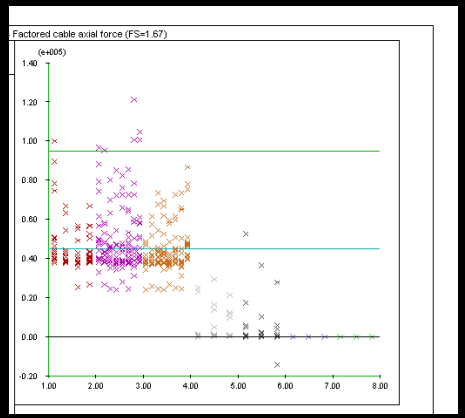
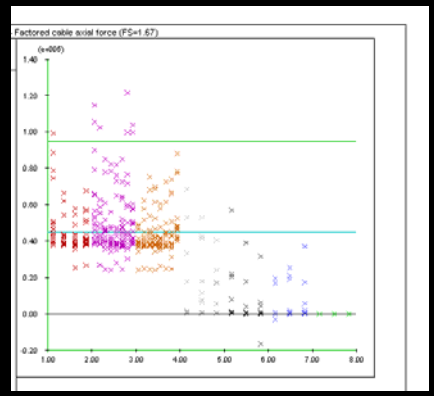
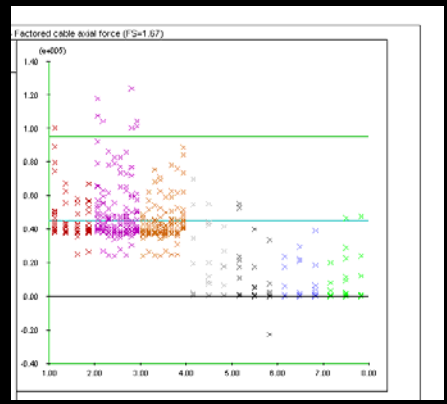


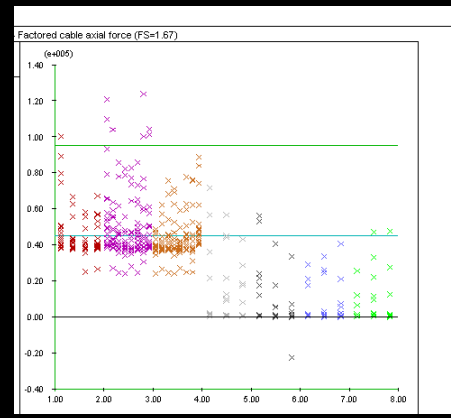
Stage 5



Stage 6

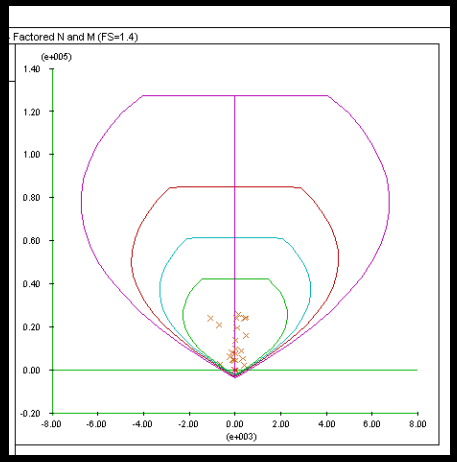


Stage 7

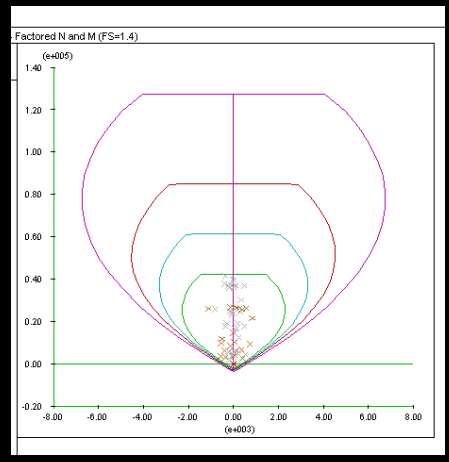


Stage 8

UDEC Results – Type B Support Shotcrete



Stage 1



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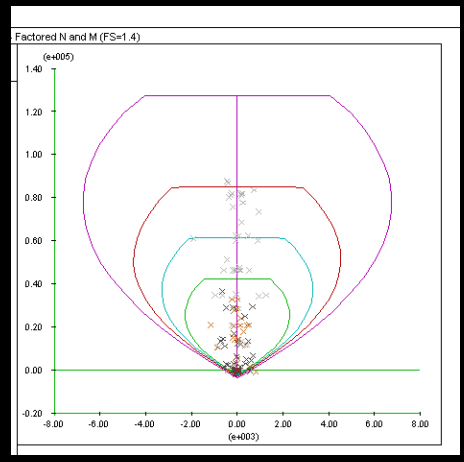

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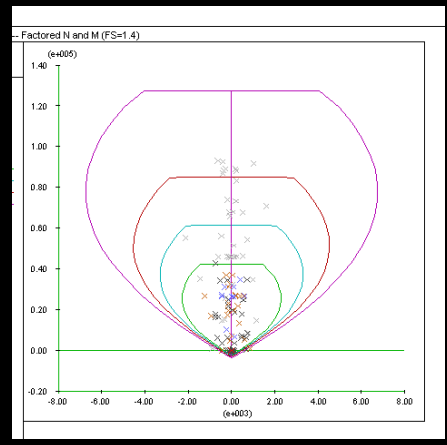

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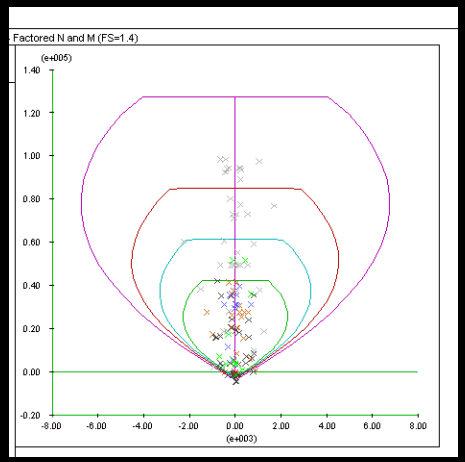

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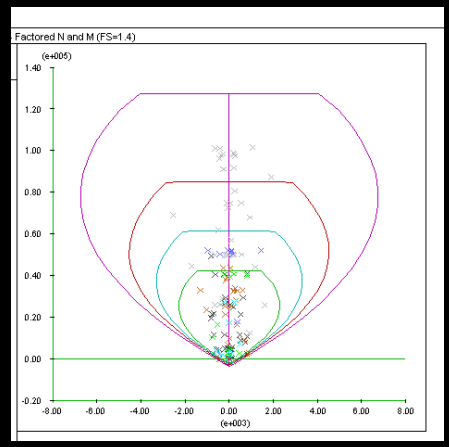
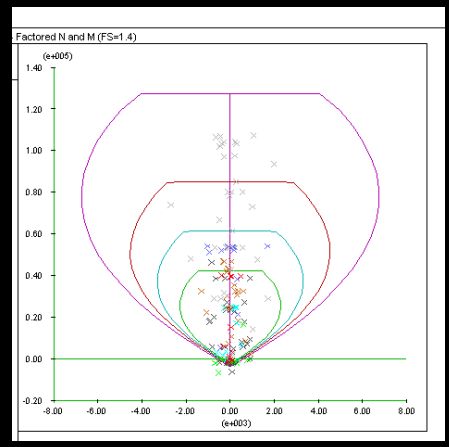
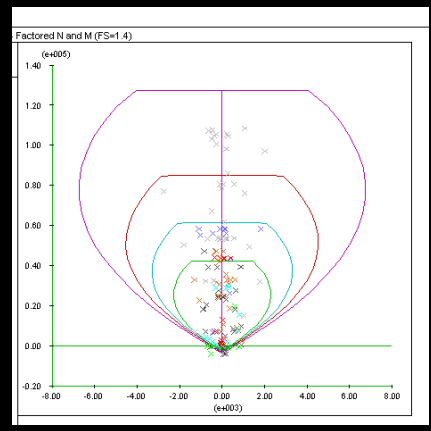


Stage 6

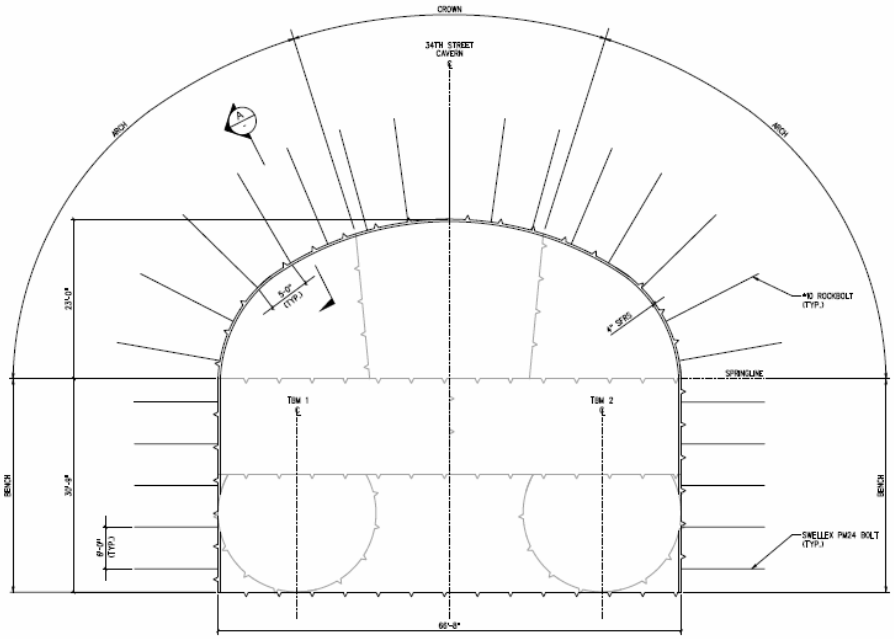


Stage 7

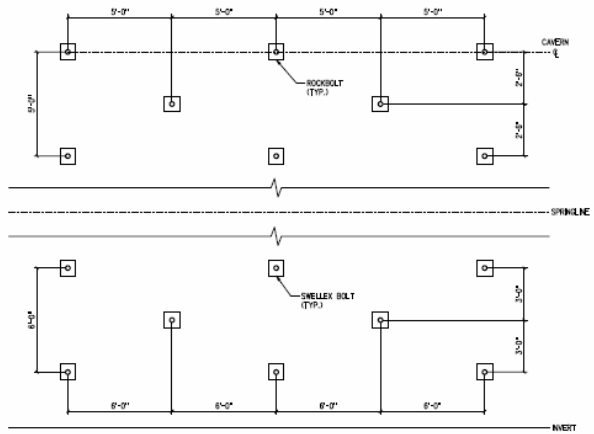


Stage 8

Support Type 1

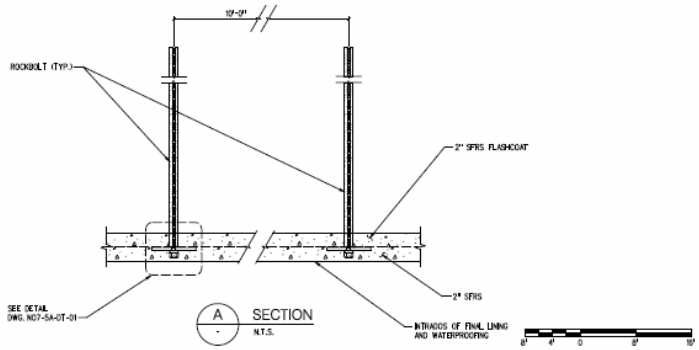


SECTION
CAVERN SUPPORT TYPE 1



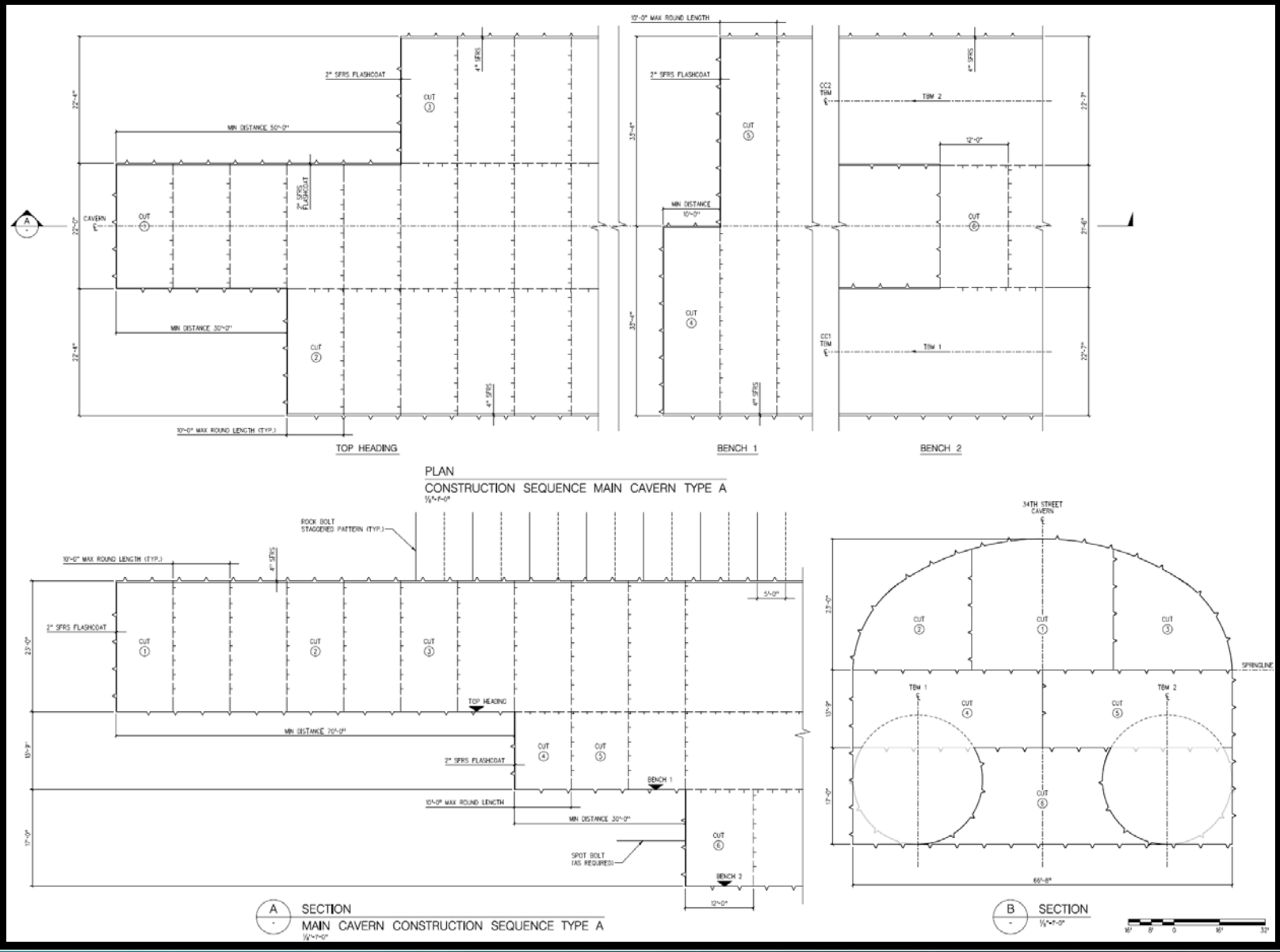
DETAIL
ROCKBOLT PATTERN
N.T.S.

ROCK BOLT SCHEDULE						
AREA	BOLT TYPE	DIAMETER	SPACING	PRE-STRESS	YIELD STRENGTH	LENGTH
CROWN	TENSION ROCKBOLT	1¼"	5'-0"/5'-0"	20 KIPS	95 KIPS	15'-0"
ARCH	TENSION ROCKBOLT	1¼"	5'-0"/5'-0"	20 KIPS	95 KIPS	15'-0"
BENCH	SWELLEX BOLT	1 ⅜"	6'-0"/6'-0"	-	45 KIPS	12'-0"



A
SECTION
N.T.S.

Proposed Construction Sequence

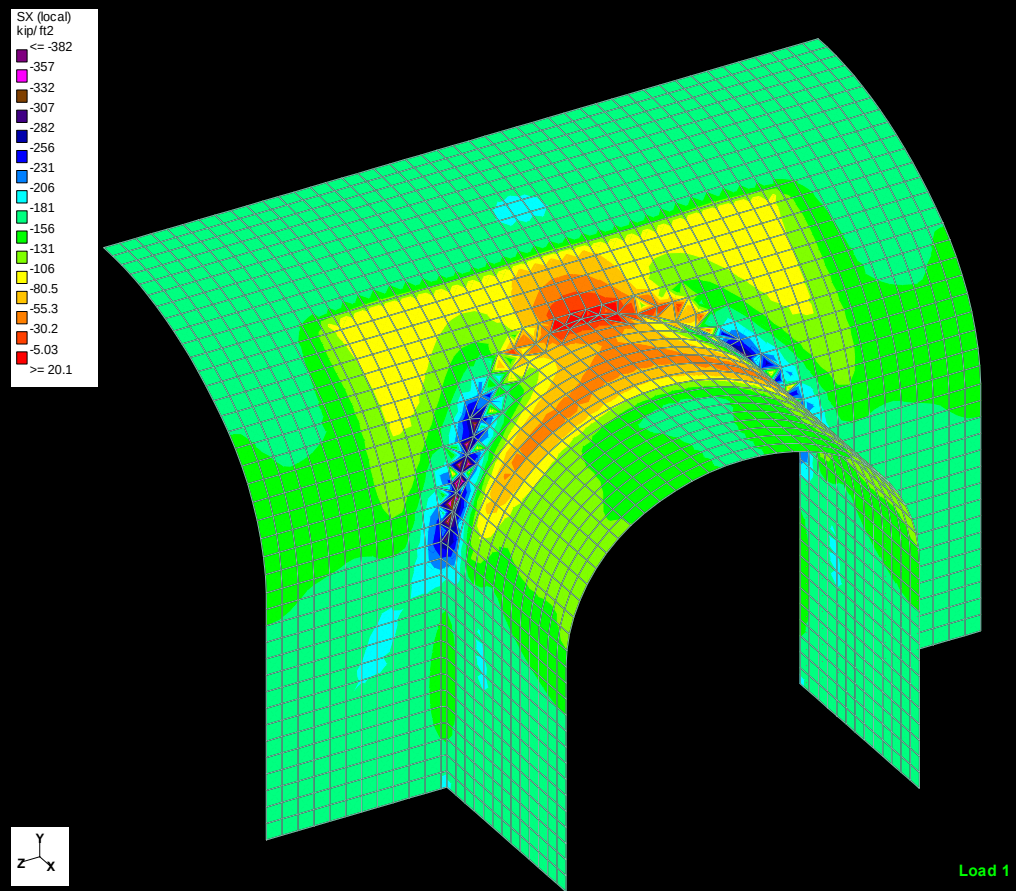


Support Types

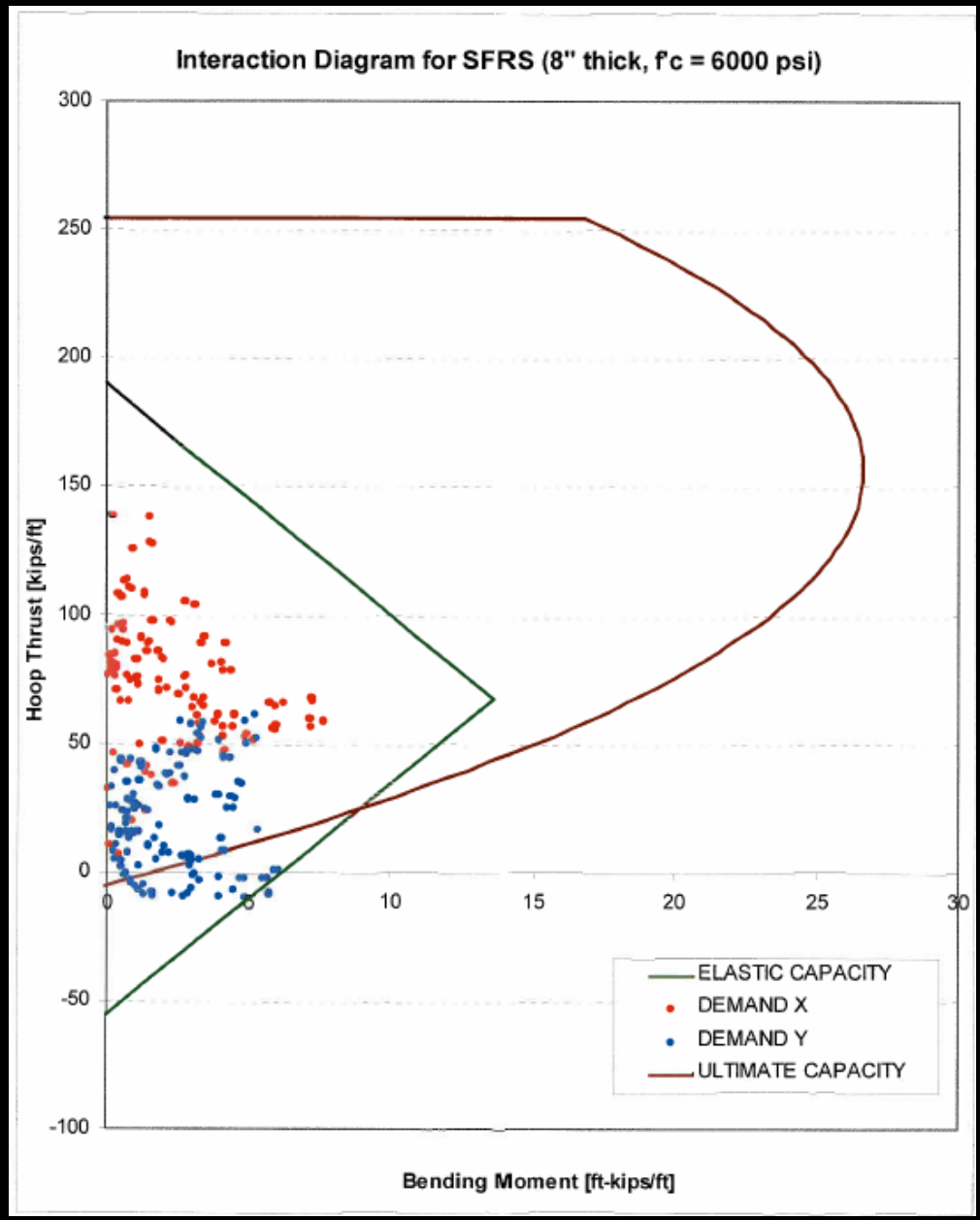
Support Class	Dywidag Bolt Length	Pattern (Crown & Arch)	Shotcrete (inches)
1	15	5 x 5	4
2	15	5 x 5	6
3	18	5 x 5	6

Support Class	Swellex Bolt Length	Pattern (Bench)	Shotcrete (inches)
1	12	6 x 6	4
2	12	6 x 6	6
3	12	6 x 6	6

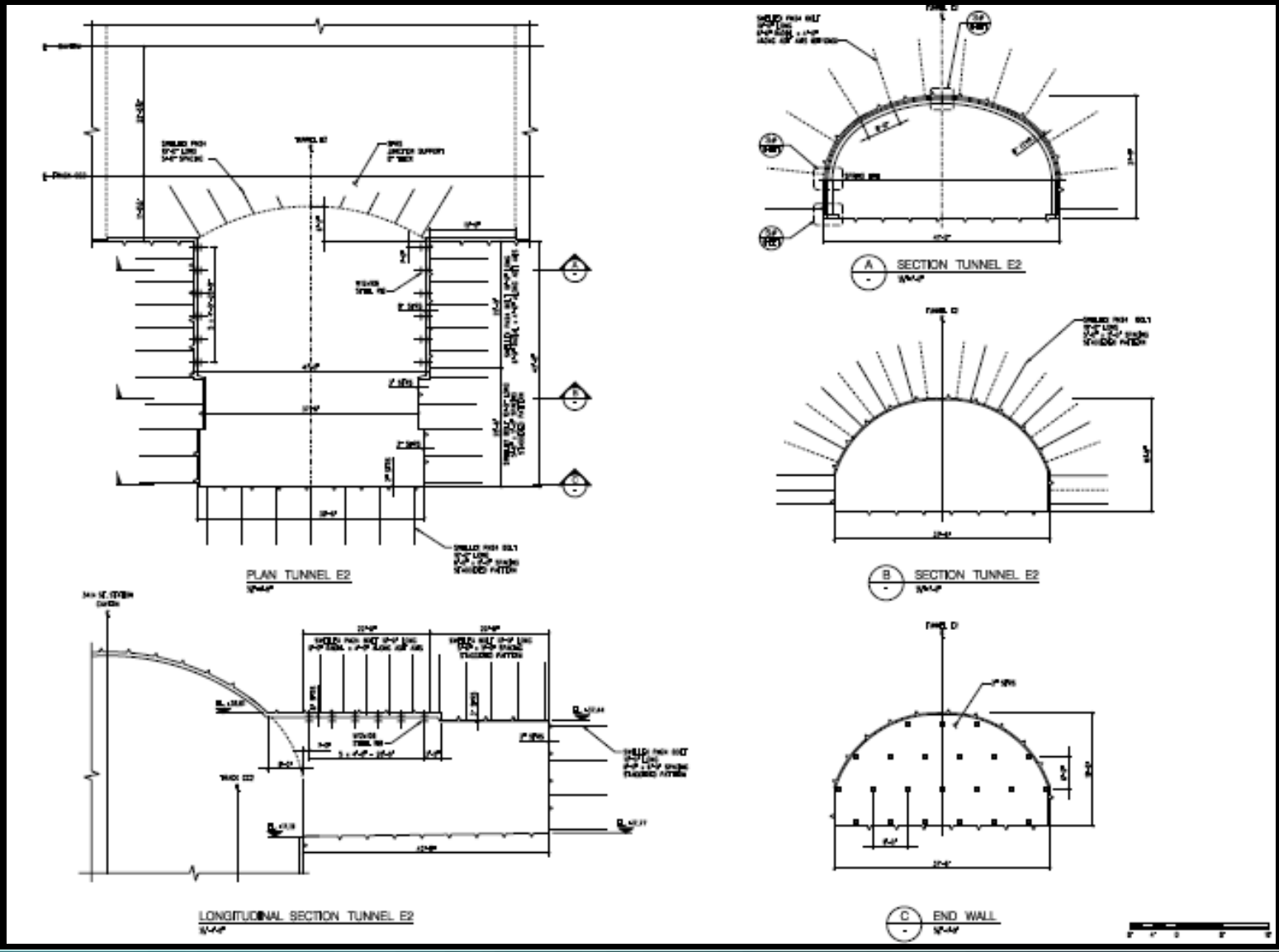
Shotcrete Junction Analysis – Axial Stress



- Typical interaction diagram at junction
- Points represent forces in FE plate elements in both directions (3D)
- All points within elastic capacity curve √ ok



Junction Design



Construction Photos

Shaft A –

TBM Assembly Cavern

Shaft P –

34th St. Station Cavern

TBM Assembly Chamber / Starter Tunnels


CRANE

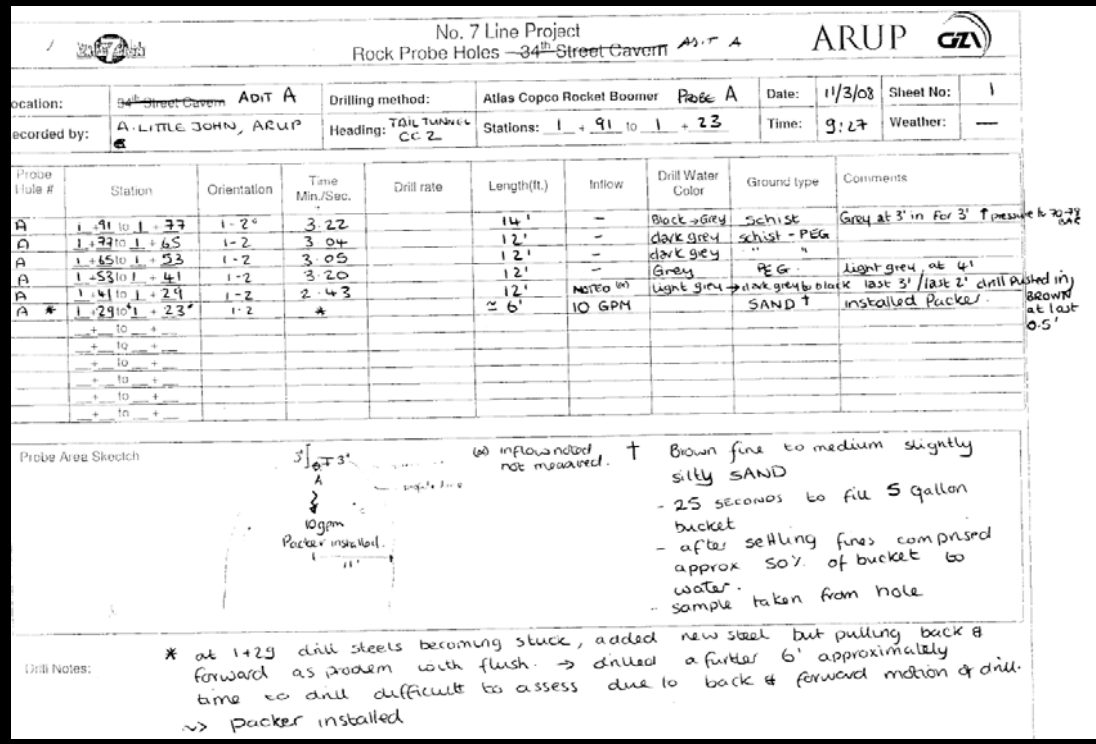
Bolt testing & probing

3% of all installed bolts tested

Tests to 1.3P for Dywidag bars to verify the design capacity achieved

Swellex tested to 74kips failure deamed as 12” displacement.

Pobing always maintained a minimum of 30ft (9.1m) ahead of tunnel face at all times, to verify cover and competent ground as construction advanced



No. 7 Line Project
Rock Probe Holes ~~34th Street Cavern~~ ADIT A

ARUP GZA

Location:	~~34th Street Cavern~~ ADIT A	Drilling method:	Atlas Copco Rocket Boomer Probe A	Date:	11/3/08	Sheet No:	1
Recorded by:	A. LITTLE JOHN, ARUP	Heading: TAIL TUNNEL CC 2	Stations: 1+91 to 1+23	Time:	9:27	Weather:	—

Probe Hole #	Station	Orientation	Time Min./Sec.	Drill rate	Length(ft.)	Inflow	Drill Water Color	Ground type	Comments
A	1+91 to 1+77	1-2°	3:22		14'	–	Black→Grey	Schist	Grey at 3' in for 3' ↑ pressure to 70-75 PSI
A	1+77 to 1+65	1-2	3:04		12'	–	dark grey	schist - PEG	
A	1+65 to 1+53	1-2	3:05		12'	–	dark grey	" "	
A	1+53 to 1+41	1-2	3:20		12'	–	Grey	PEG	light grey at 4'
A	1+41 to 1+29	1-2	2:43		12'	NOTED (a)	light grey→dark grey→black	last 3'/last 2' drill flushed in BROWN at last 0.5'	
A *	1+29 to 1+23'	1-2	*		≈ 6'	10 GPM		SAND †	installed Packer

Probe Area Sketch

(a) inflow noted not measured.

† Brown fine to medium slightly silty SAND
- 25 seconds to fill 5 gallon bucket
- after settling fines comprised approx 50% of bucket to water.
- sample taken from hole

Drill Notes:

* at 1+29 drill steels becoming stuck, added new steel but pulling back & forward as problem with flush → drilled a further 6' approximately time to drill difficult to assess due to back & forward motion of drill.
→ Packer installed

34th St Station Cavern Break-in

Cavern Top Heading Excavation

Cavern / Ancillary Tunnel Junction

Staggered Headings


CAT
JLG LIFT

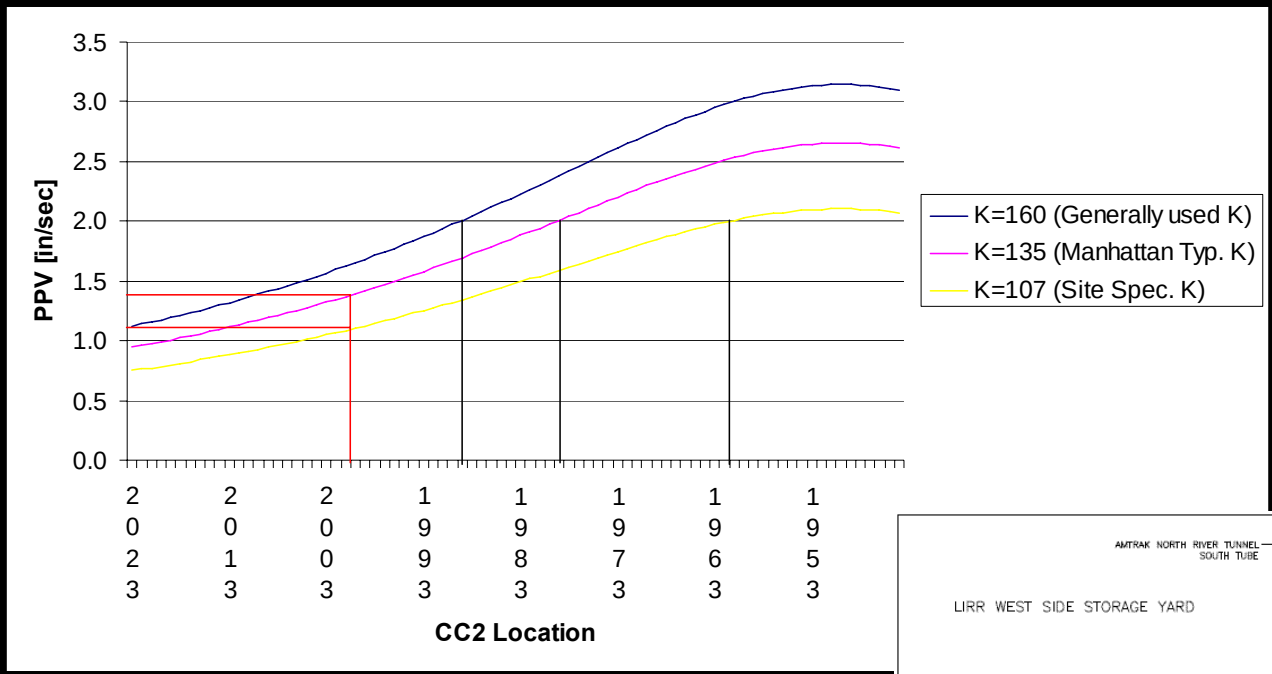
Ramp Down to Start Benching

Complex Geometries

Benching

Fully Developed Cavern Excavation

Blast Vibration Monitoring & Analysis



Controls:

Amtrack Vibration sensitive tunnels (stations 17+50 & 17+25)

Controlled limit of PPV=2”/sec

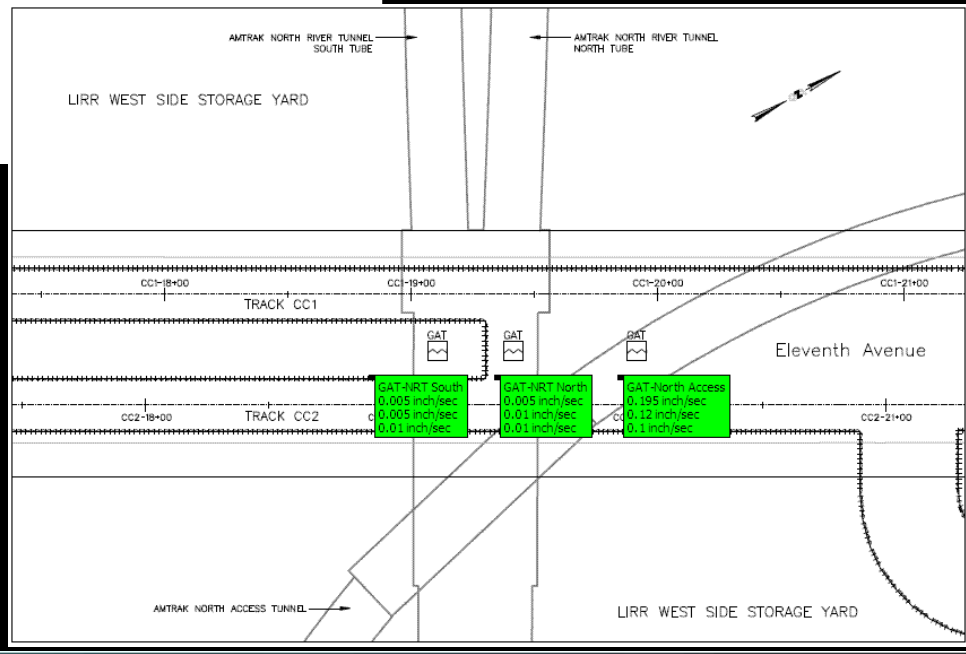
Live monitoring system with trigger values

Back analysis:

From Monitoring data established site specific K (ground constant value) of 107.

Compared data with respect to distance from source and Maximum Instaneous Charge (MIC) for SS K value and referenced data in Schist.

Used to predict vibrations and control shot lengths during construction using the lifetime monitoring (right).



ARUP

Instrumentation data - settlements

- **All movements were less than predicted**
- **Typically around 25% of that predicted by UDEC**
  - Why ? –
    - Joint Persistence
    - Joint Waviness
    - Joint Condition

Grand Central Caverns – East Side Access

- **MTA Contract CM-019 Arup Scope**
  - Initial Ground Support Design

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RAIL: EAST SIDE ACCESS PROJECT

NY CONNECTION

A series of massive tunnelling projects is at the heart of a major new rail project for Manhattan. **Adrian Greeman** reports from NYC.

tions will run north of Grand Central and then east to link with an existing rail tunnel under the Hudson. The new tunnels run under Park Avenue from 42nd Street to 63rd street before heading east to the river.

The tunnels will end 25m below Grand Central, where an enormous underground extension to the famous railway station is to be carved from hard schist rock. Here, two giant

which run from the westernmost cavern to the surface. They pass through rock and between the foundations of buildings up to 30 storeys high.

"Mostly the escalators are built beneath street locations to avoid buildings, but there will be a need for underpinning and re-framing around some spread footing foundations," says Barratt.

The 30m long inclined escala-

side and one on the Queen's side of the river.

First is the new twin bore hard rock tunnel that runs from 42nd Street below Park Avenue and then turns to head towards the East River at 63rd Street, a distance of 1.2km.

At the river the tunnels connect with a double deck tunnel under the East River. The 2.6km long immersed tube is a four level structure, the upper levels

CIVIL ENGINEERING NEWS

RAIL INFRASTRUCTURE

East Side Story: Authority Will Construct New Facility beneath Grand Central Terminal

A new commuter terminal for the Long Island Rail Road (LIRR) is being constructed 140 ft (43 m) beneath the streets surrounding Manhattan's Grand Central Terminal. The East Side Access project—so named by its owner, New York State's Metropolitan Transportation Authority (MTA)—is designed to provide LIRR commuters with a faster and more direct connection to destinations on Manhattan's east side.

At present the LIRR brings approximately 240,000 passengers each workday into Pennsylvania Station (Penn Station), in midtown Manhattan. But more than half of these Penn Station passengers actually work on the east side of the city, which means "these commuters have to spend another thirty to forty minutes each way to go from Penn Station to their actual desti-

East Side Access – Grand Central Terminal Caverns

Grand Central Terminal

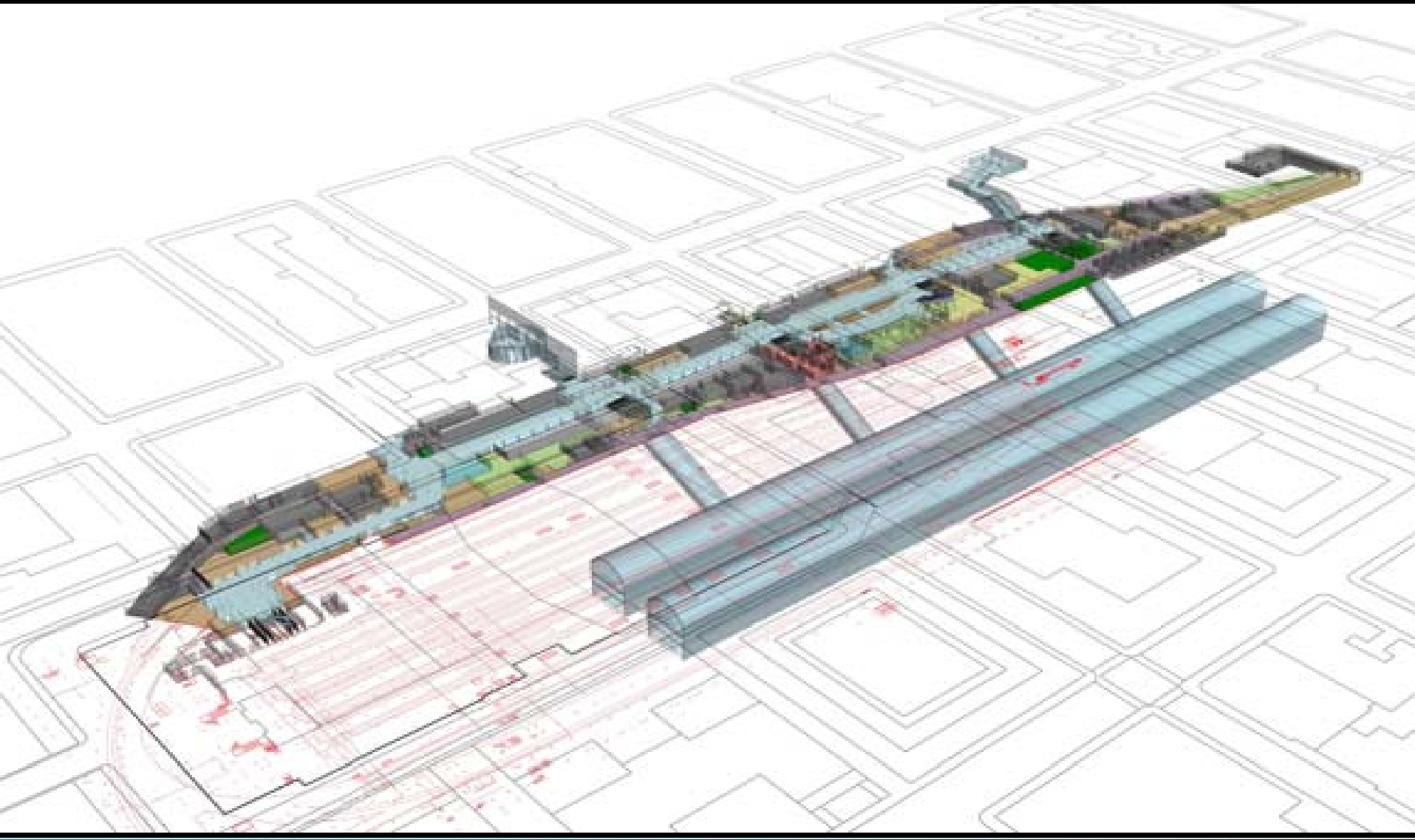
East Side Access - Grand Central Caverns

Grand Central Caverns - Project Team

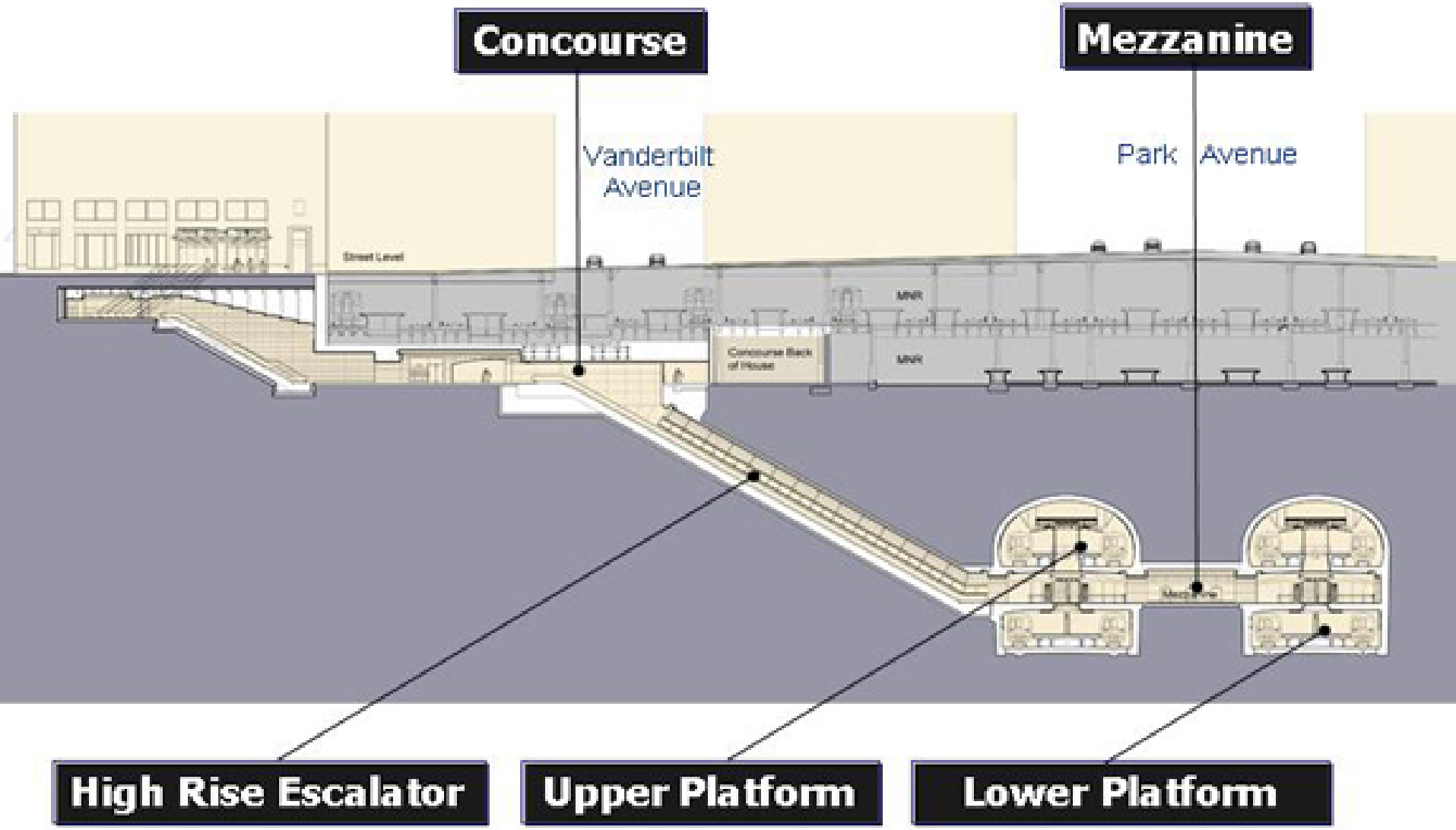
- **Owner: Long Island Rail Road**
- **Owner's Engineer: GEC (Parsons Brinkerhoff/ STV /PTG)**
- **Construction Manager: URS/ Hatch Mott MacDonald**
- **Contractor: Dragados Judlau JV**
- **Contractor's Designer: Arup**

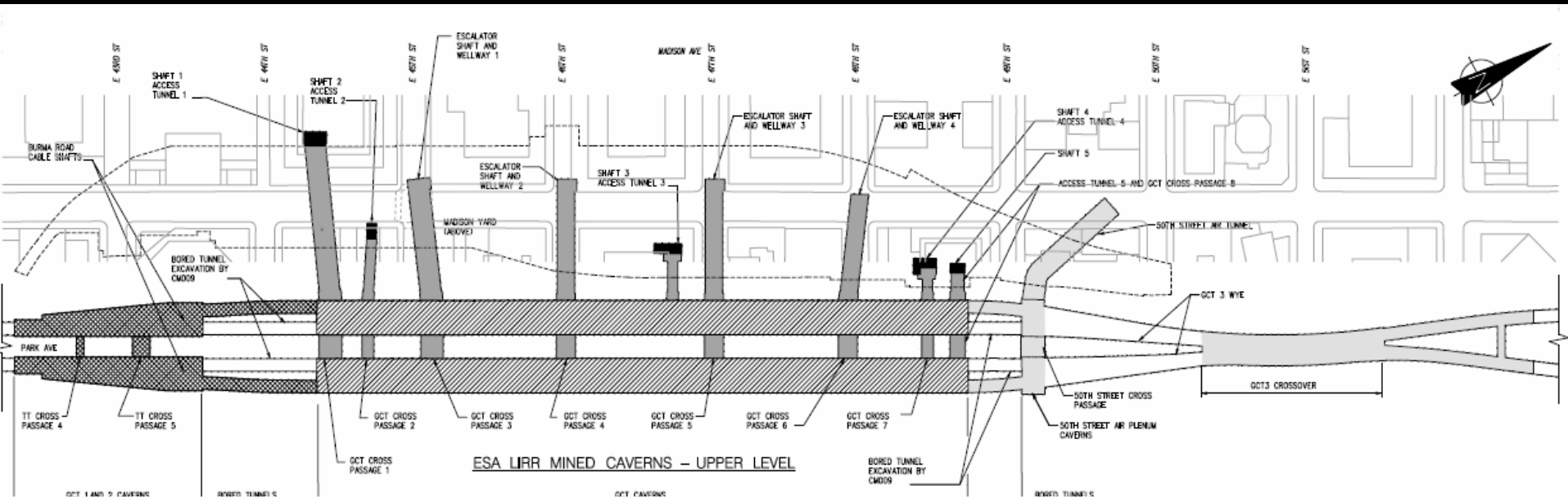
Grand Central Caverns

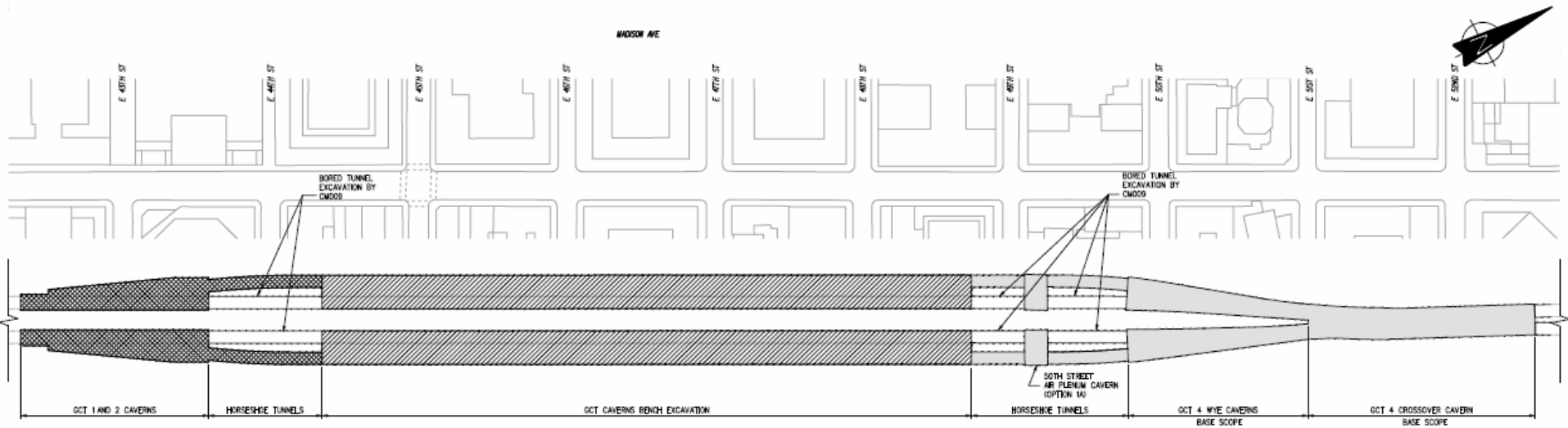
Grand Central Caverns

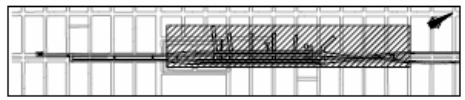


Grand Central Caverns

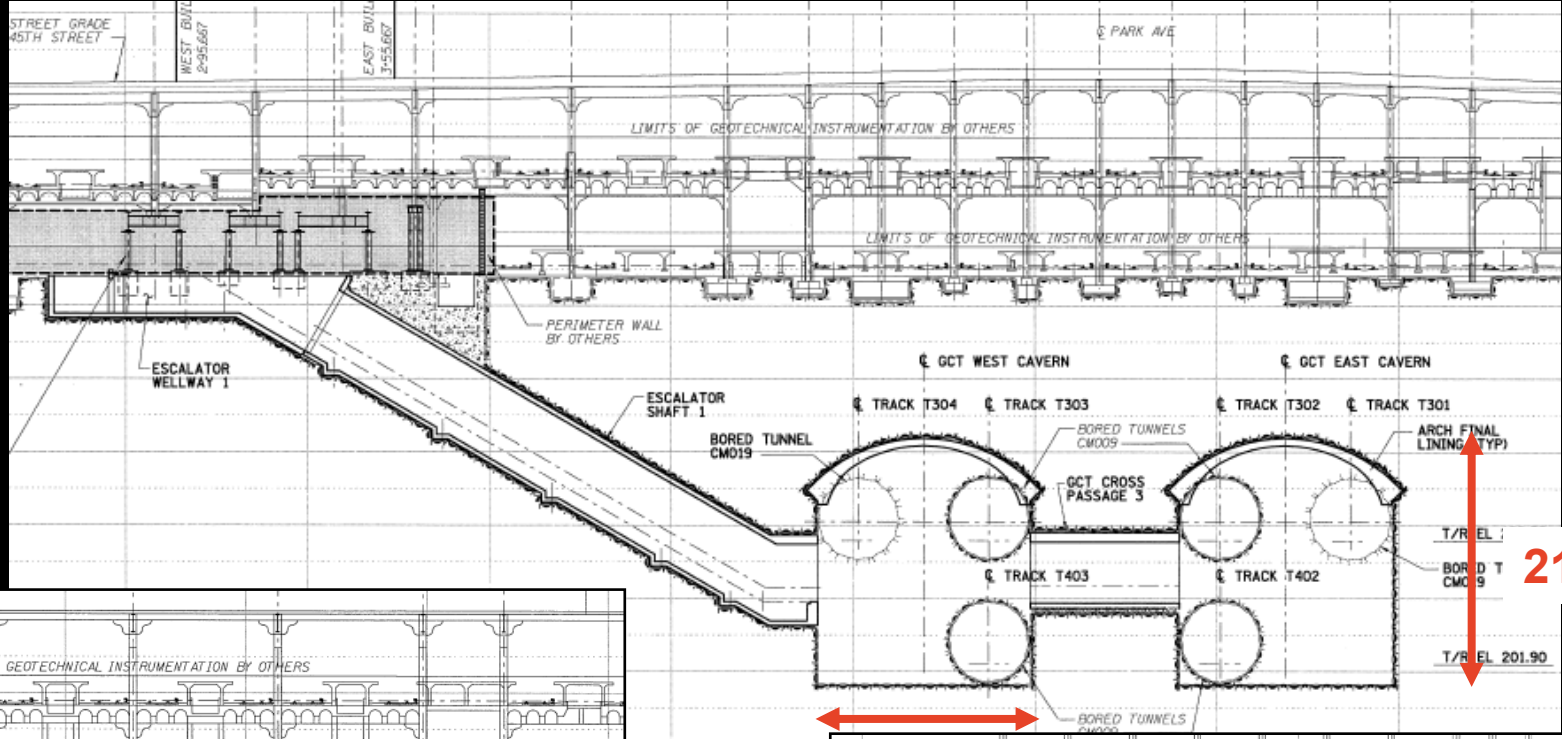


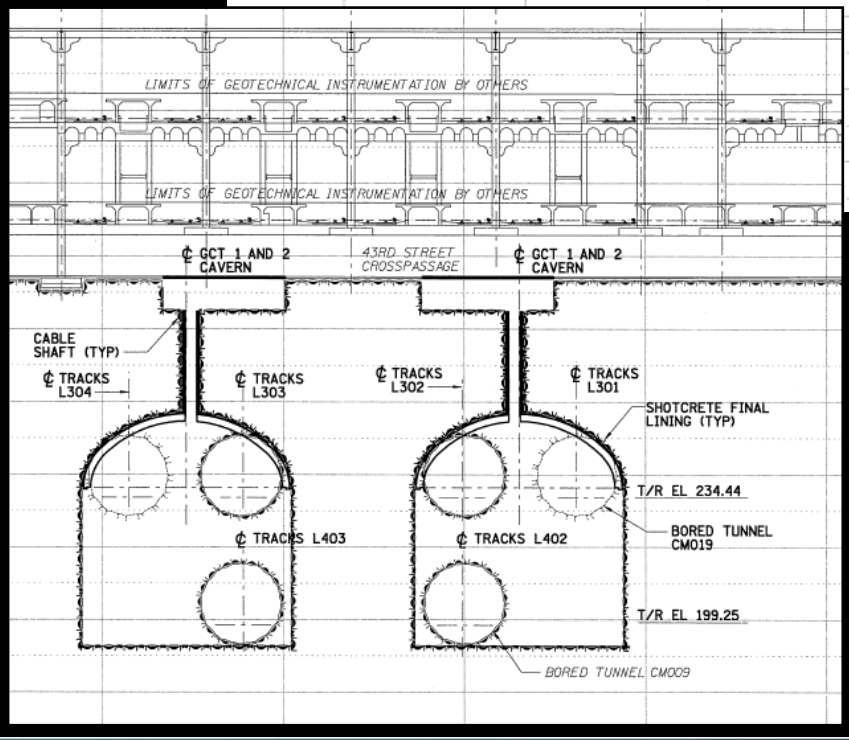


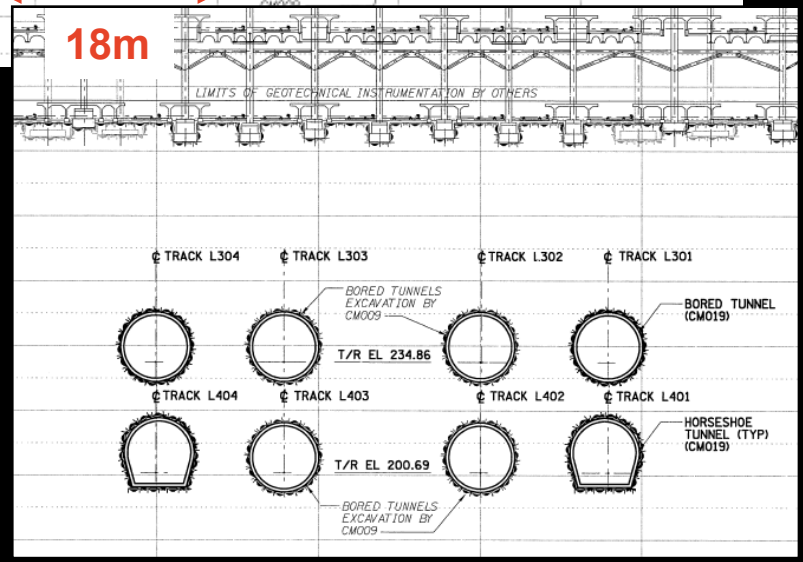




PARK AVENUE KEY PLAN


STREET GRADE
45TH STREET
WEST BUILDING
2-95.667
EAST BUILDING
3-55.667
℄ PARK AVE
LIMITS OF GEOTECHNICAL INSTRUMENTATION BY OTHERS
LIMITS OF GEOTECHNICAL INSTRUMENTATION BY OTHERS
PERIMETER WALL BY OTHERS
ESCALATOR WELLWAY 1
ESCALATOR SHAFT 1
℄ GCT WEST CAVERN
℄ GCT EAST CAVERN
℄ TRACK T304
℄ TRACK T303
℄ TRACK T302
℄ TRACK T301
BORED TUNNEL CM019
BORED TUNNELS CM009
ARCH FINAL LINING (TYP)
GCT CROSS PASSAGE 3
T/R EL
BORED T
CM 9
℄ TRACK T403
℄ TRACK T402
T/R EL 201.90
21m
BORED TUNNELS
18m


LIMITS OF GEOTECHNICAL INSTRUMENTATION BY OTHERS
LIMITS OF GEOTECHNICAL INSTRUMENTATION BY OTHERS
℄ GCT 1 AND 2 CAVERN
43RD STREET CROSSPASSAGE
℄ GCT 1 AND 2 CAVERN
CABLE SHAFT (TYP)
℄ TRACKS L304
℄ TRACKS L303
℄ TRACKS L302
℄ TRACKS L301
SHOTCRETE FINAL LINING (TYP)
T/R EL 234.44
℄ TRACKS L403
℄ TRACKS L402
BORED TUNNEL CM019
T/R EL 199.25
BORED TUNNEL CM009


LIMITS OF GEOTECHNICAL INSTRUMENTATION BY OTHERS
℄ TRACK L304
℄ TRACK L303
℄ TRACK L302
℄ TRACK L301
BORED TUNNELS EXCAVATION BY CM009
BORED TUNNEL (CM019)
T/R EL 234.86
℄ TRACK L404
℄ TRACK L403
℄ TRACK L402
℄ TRACK L401
HORSESHOE TUNNEL (TYP) (CM019)
T/R EL 200.69
BORED TUNNELS EXCAVATION BY CM009

Scope of Work – East Side Access Project

- **Following completion and logging of the initial running tunnels, design of the cavern initial support.**
- **Initial work included geological mapping**
- **Design of Initial Ground Support**
- **Design completed, cavern construction has recently started.**

GCT – TBM Drive


0
19+50
24/2/2009 3:49pm


24/2/2009 3:40pm

Rock Mass Zones

ARUP

Job No.	Sheet No.	Rev.
207975		

Member/Location

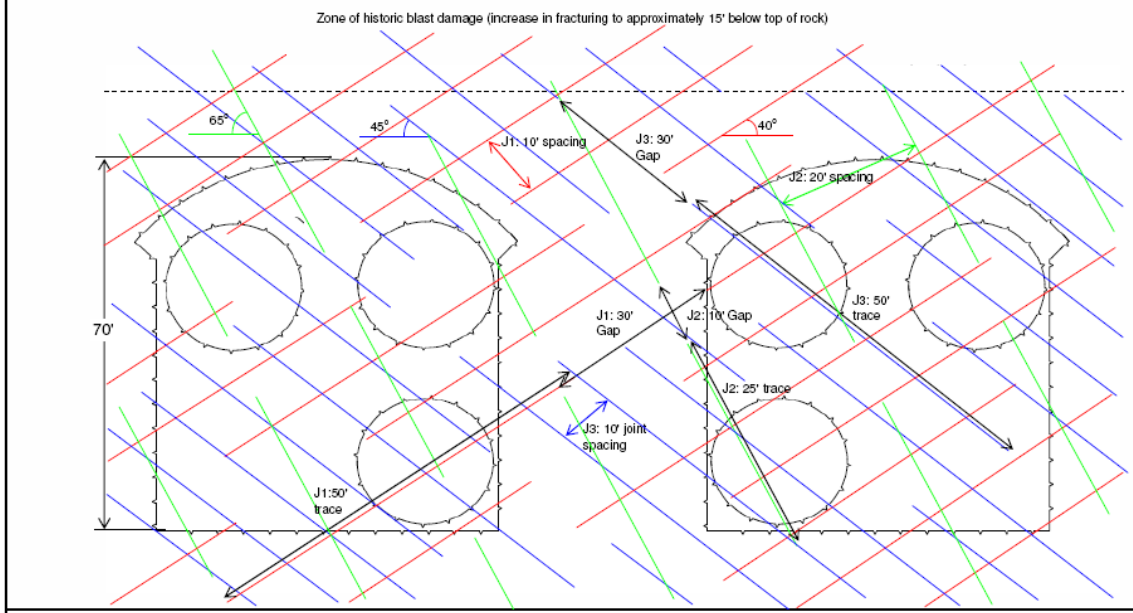
Job Title: CM019 - Grand Central Caverns

Drg. Ref.

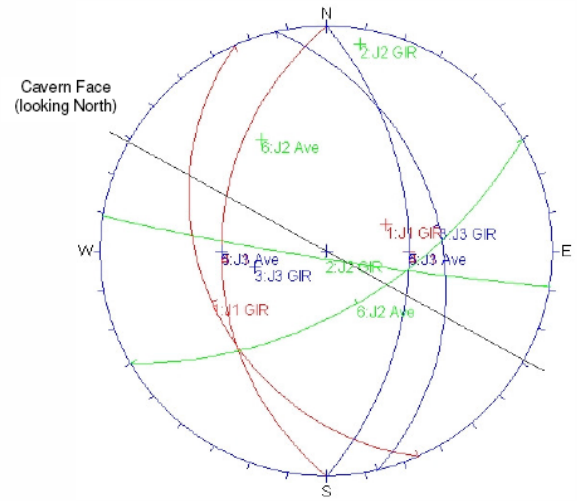
Calculation: Figure B.1 Geological Interpretation - Ground Type I, Package III, Central Cavern, Station 20+00 to 24+50.

Made by: ACL Date: March 2009 Chd.: PJH

A. Geological Section looking North along the cavern axis



C. Structural Geology



Note. In this context the Standard deviation and Variance refer to the +/- range from the mean value

	1 (Foliation)	2 (Cross - Foliation)	3(conjugate to J1)
True/ Apparent Dip S.D.	40/ 40 20	60/ 65 20	50/ 45 35
Dip Direction (S.D.)	270 (30)	150 (40)	90 (30)
Baseline Dip (GIR)	35	85	35
Baseline DD (GIR)	250	190	75

Referenced Boreholes for no. of fractures per core run: MG115, MG204, MG118, MG203, MD11, MG54, MG122, MG120, MG202, MD10

TBM Mapping used for orientations: TBM Mapping T304 16+80 to 28+60 (24th July to 22nd August 2008) and TBM Mapping T30117+20 to 28+40 (27th May to 8th July 2008)

B. Geological Zone Description (from *GIR June 2008, Section 5.0 and Figures 3 sheets 1 - 4*)
Refers to GIR Geological Zone reference T402 18+50 to 31+00
Dominant geology: Garnetiferous Schistose Gneiss and Gneiss
50% of rock mass moderately to widely spaced foliation fractures, 50% closely to moderately spaced
50% of rock mass widely spaced joints, 50% closely to moderately spaced
Few infilled joints, Quartz, Feldspar and Pegmatite veins in clusters
Joint set 1 - typically planar to undulating and rough
Joint set 2 - undulating rough to very rough with occasional infill of sand and clay and surface staining with iron oxide, particularly near shear zones and in areas of intense Pegmatite formation.
Joint set 3 - fresh, closed set, typically undulating and rough to very rough with no infill.
RQD 75-90%/ Q 1.5-10/ RMR 53-79
Groundwater anticipated 5' below GCT track level/ Range of Coeff. of Permeability 10^{-5} to 10^{-7} cm/sec
Note groundwater is currently pumped. The water level at the invert of GCT suburban level is EL 310, the water level at the East River is at EL 300.
Stream Channels (zones of anticipated weakness/shear zones and higher hydraulic conductivity in rock mass) from Viele 1874: approximate stations where streams are anticipated to intersect with cavern, trending SE to NW East Cavern 18+00 to 19+00 and 26+50 and 27+80; West Cavern 19+25 to 20+00.

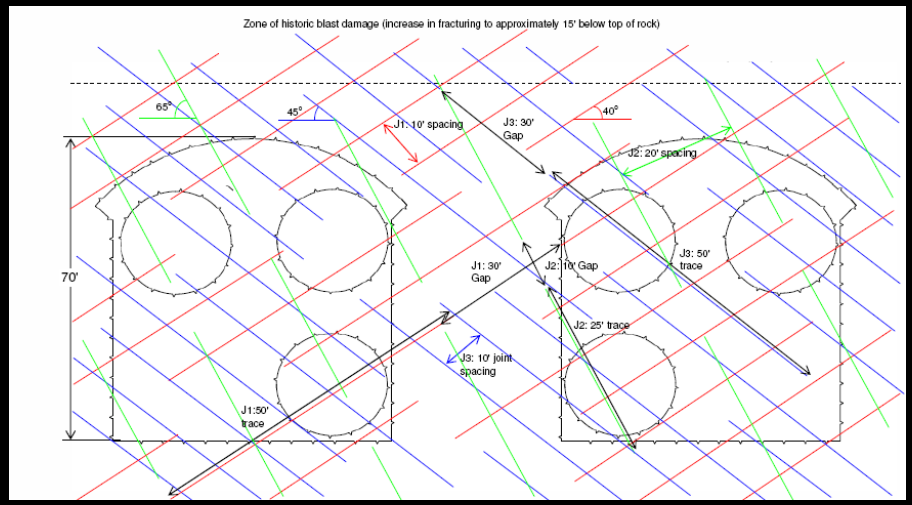
D. Joint Properties

Set No.	1 (Foliation)	2 (Cross-Foliation)	3 (Conjugate to J1)
Joint Trace (ft)	50' (Mean) 20' (Variance)	25' (Mean) 10' (Variance)	50' (Mean) 20' (Variance)
Joint Gap (ft)	30' (Mean) 15' (Variance)	10' (Mean) 5' (Variance)	30' (Mean) 15' (Variance)
Joint Seperation (ft)	10' (Mean) 2.5' (Variance)	20' (Mean) 5' (Variance)	10' (Mean) 2.5' (Variance)
Friction Angle (°) øb	30-40 (35)	30-40(35)	40-50 (45)
Dilation Angle (°)øi	3-10 (5)	3-10 (5)	3-10 (5)
Cohesion (lbf/ft²)	0	0	0
Alteration (J_a)	1	1	1
Roughness (J_r)	1.5	1.5	1.5
JRC Ave (Range)	10 - 12 (2-20)	14 - 16 (12-18)	12-14 (2-20)

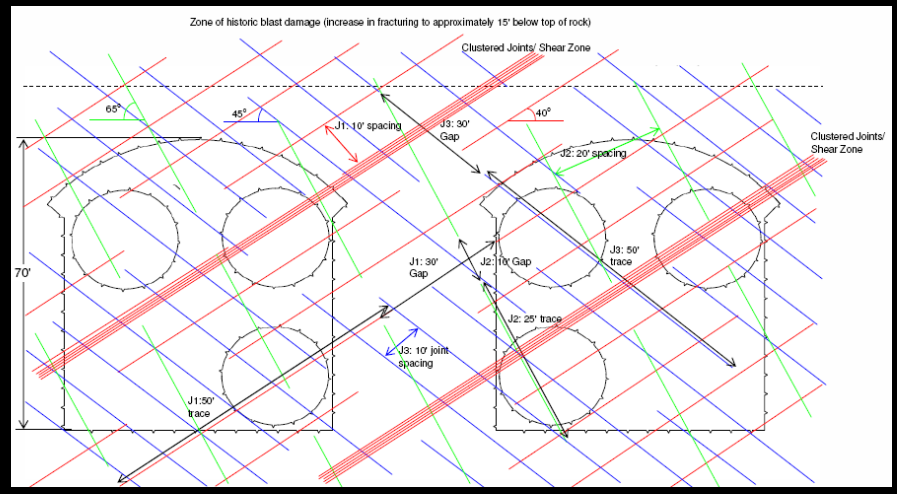
G. Structures/ Shear Zones

Notes:
The rock properties in the blast damaged zone (15' below top of rock) are currently being reviewed and revised rock properties may be provided for the final calculation submission.

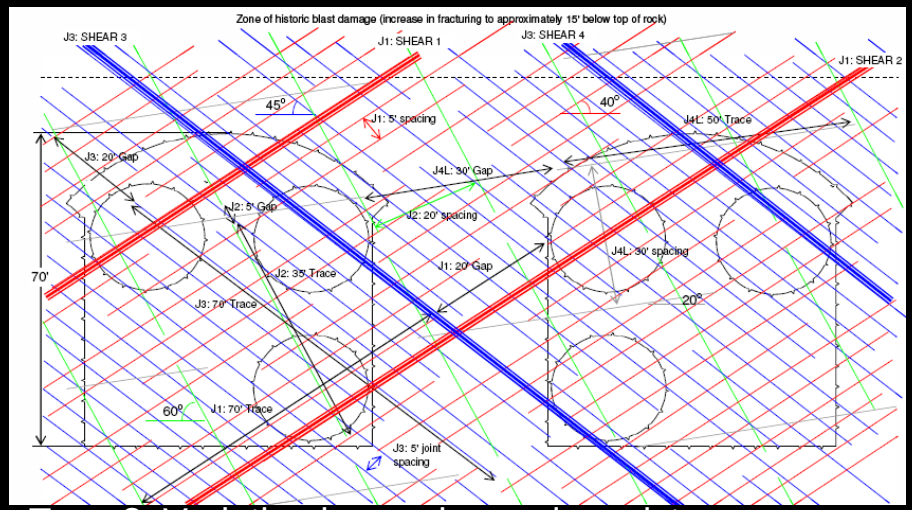
Rock Mass Zones – Idealised Models



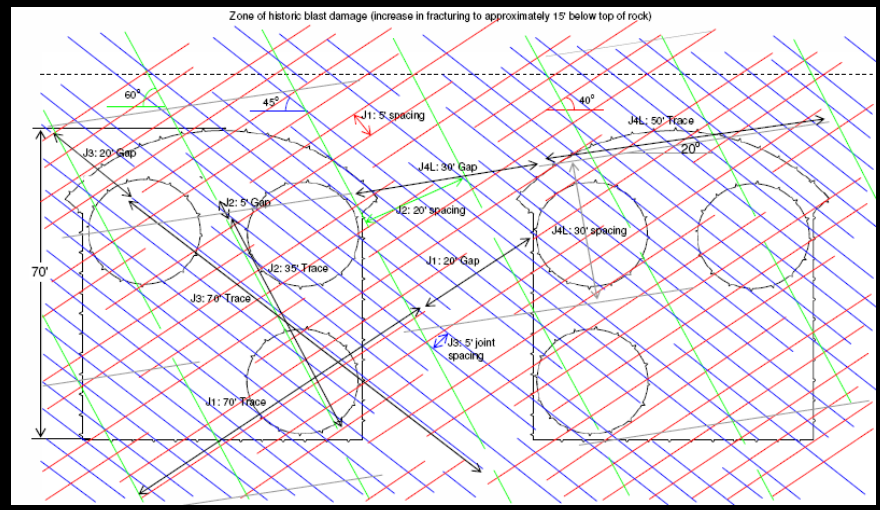
Type 1: Typical, 3 Joint sets J1 parallel to Foliation, J2 Sub-vertical set, J3 conjugate to J1



Type 2: Anticipated, as for type 1 with inclusion of zone of very closely jointed rock



Type 3: Variation in spacing and persistence modeling presence of 2 shear zones on J1 and J3



Type 4: Worst case model, including a 4th Joint set, this is a modeled worst case condition NOT anticipated

ARUP

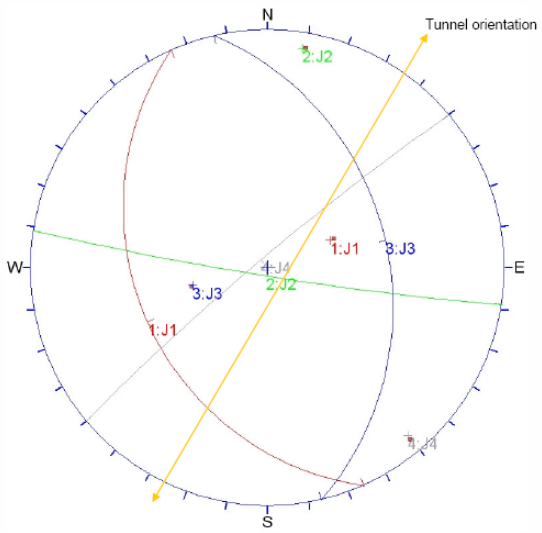
Key Joint Sets

ARUP

Job Title: Geological Interpretation Cavern Structures Package 3 | Job No. 207975

Figure: Figure C.1 - Typical joint orientations from GIR

DIPS Major Plane Stereoplot (Major planes line colour is represaentative of the joint set)
Analysed using DIPS Rocscience software V 5.1
Cavern alignment is orientated approximately NE to SW



Typical orientations:

Joint Set (plot colour)	GIR (18+50 to 31+00)	
	Dip Direction	Dip
J1	250 (195-300)	35 (15-55)
J2	190 (155-250)	85 (75-90)
J3	075 (035-140)	35 (25-50)
J4 Low	-	-
J4 High	320	85

where J1 is the dominant Foliation joint set and J3 is the cross-foliation joint set

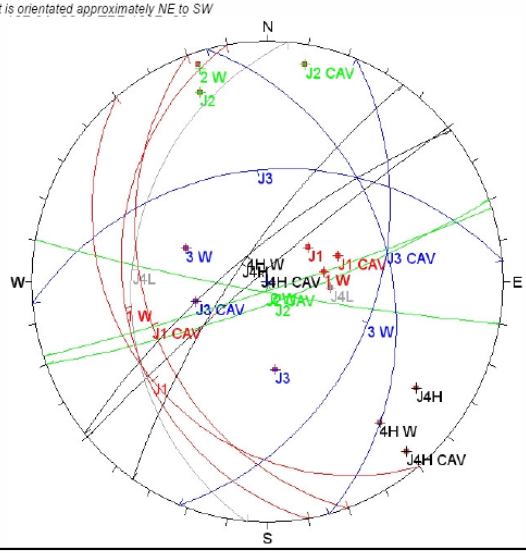
Source References:
GIR CM0019, Book 5 of 5 (June 2008) T402 18+30 to 31+00, Ref. (Table 5-1)

ARUP

Job Title: Geological Interpretation Cavern Structures Package 6 | Job No. 207975

Figure: Figure C.15 - Joint orientation comparison for GIR, Main Cavern average and west wall mapping

DIPS Major Plane Stereoplot (Major planes line colour is represaentative of the joint set)
Analysed using DIPS Rocscience software V 5.1
Cavern alignment is orientated approximately NE to SW



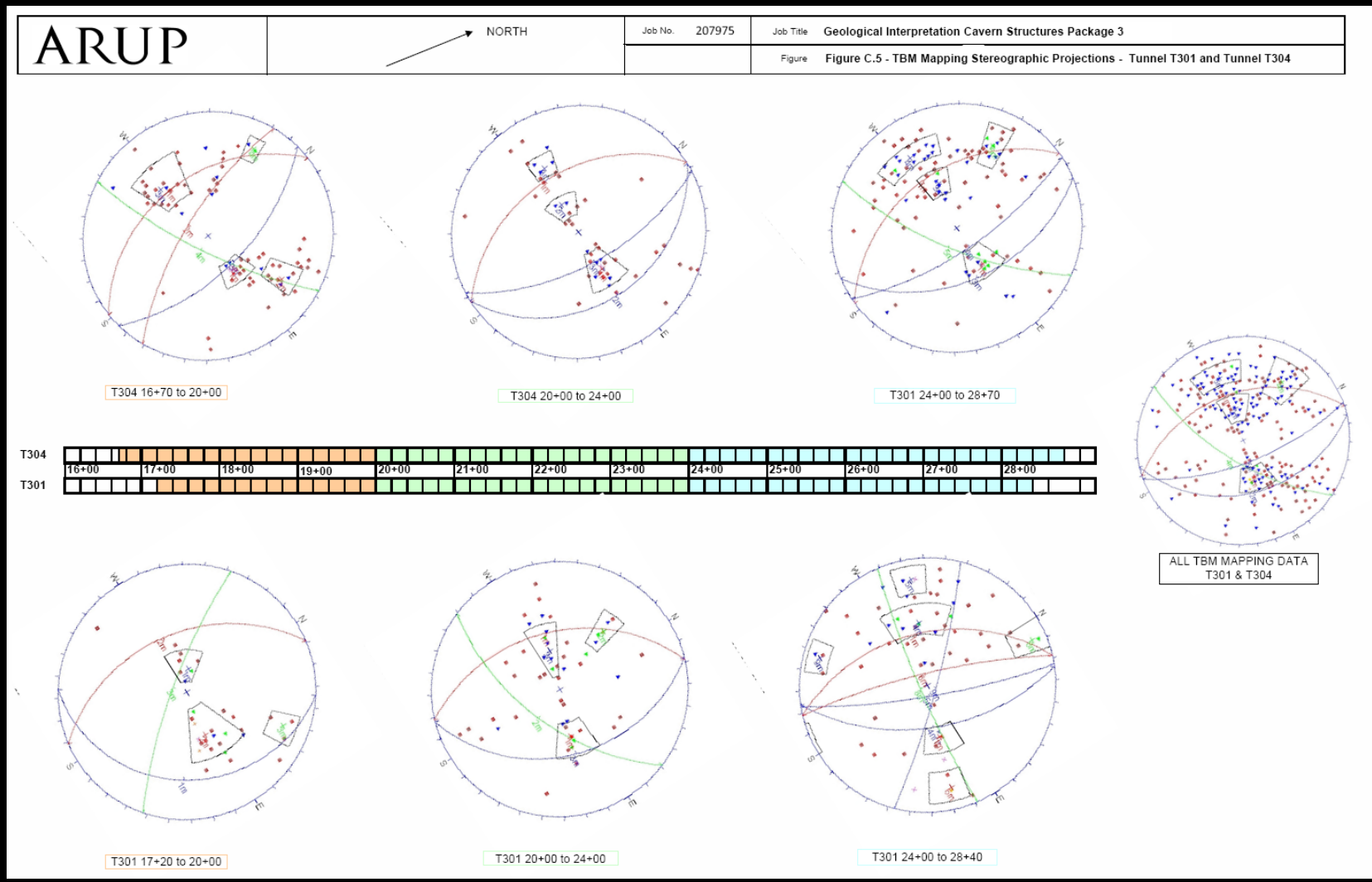
Typical orientations:

Joint Set (plot colour)	T402 31+00 to EB2 1052+00, Ref. (Table 5-1)		Mian Cavern Average (17+00 to 28+75)		West Wall Mapping	
	Dip Direction	Dip	Dip Direction	Dip	Dip Direction	Dip
J1	230 (110-340)	20 (5-55)	250	35	260 (200-300)	27 (5-55)
J2	160 (095 - 225)	80 (65-90)	190	85	-	-
J3	355 (335-010)	40 (15-60)	75	35	112 (90-140)	41 (15-50)
J4 Low	275 (265-285)	40 (10-30)	-	-	-	-
J4 High	305 (250-320)	75 (65-85)	320	80	321 (315-340) 162 (155-180)	74 (65-90) 87 (65-90)

where J1 is the dominant Foliation joint set and J3 is the cross-foliation joint set

Source References:
GIR CM0019, Book 5 of 5 (June 2008) T402 31+00 to EB2 1052+00, Ref. (Table 5-1)
GIR CM0019, Book 5 of 5 (June 2008) T402 18+30 to 31+00, Ref. (Table 5-1)
GDR (date) Volume 6, Appendix E - Manhattan Segment Field exploration program phase 1 & 1A (August 2001), Rock Wall Mapping along the West Wall of GCT

TBM Stereoplots with station T301



Emperical & Kinematic Assessment

ARUP

Job No.	Sheet No.	Rev.
207975		

Member/Location

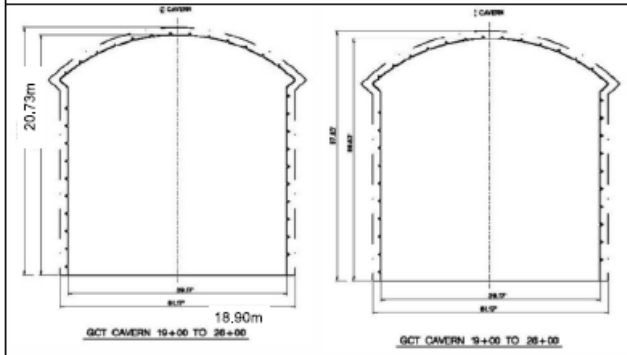
Drg. Ref.

Job Title: CM019 - Grand Central Caverns

Calculation: Empirical Support – Location GCT Cavern 19+00 to 26+00 (East and West)

Made by | Date | Chd. PJH

Design Section – GCT Cavern 19+00 to 26+00



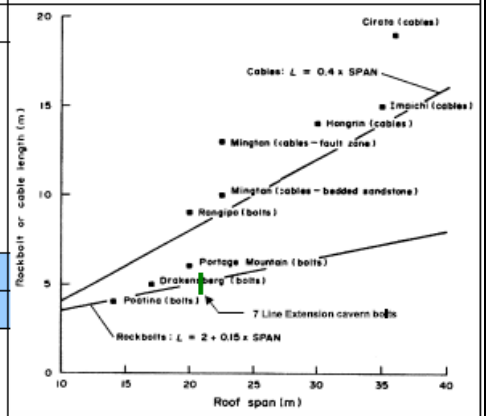
Rock Mass Classification

Based on boreholes: MG 9, MG 203, MD 19w, MD 11, MG202, MG312, MD 10, MG 120

Input	Value	Assumptions
Joint Set Number (Jn)	4-9	Two to three joints sets
Joint Roughness (Jr)	1.5	Rough and irregular, planar
Joint Alteration (Ja)	1 - 3	Predominatly unaltered joint walls, some thin clay coat
Joint Water Reduction (Jw)	1	Dry excavation or minor inflow
SRF	2.5	Low stress, less than one span rock cover
RQD	90%-100%	Excellent
ESR	1	Underground rail station - temp. support
Q Value	2-50	Average: 8 — 8 — FAIR
RMR Value (RMR=6.6lnQ+43)	47 - 69	Average: 57 — 57 — FAIR
Maximum span	62	ft
Crown deformation	0.1 in	From empirical data including 7 Line Extension cavern

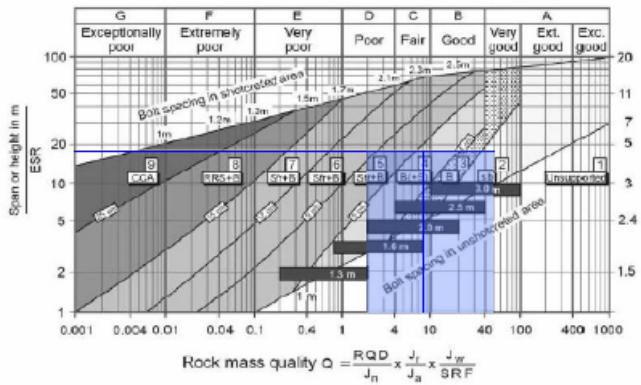
After Barton et al, 1974; Bieniawski, 1989; and Pollak, 2008

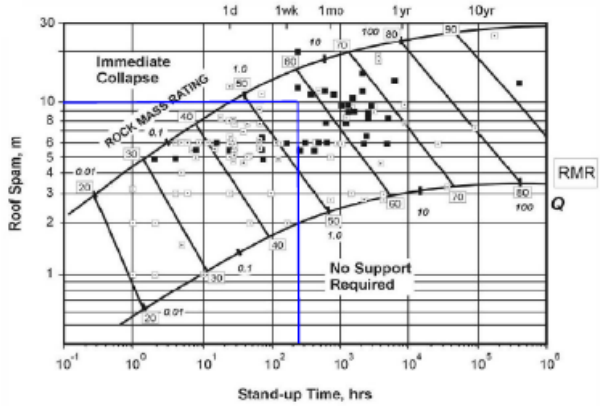
Empirical Rock Bolt Length



Recommended Bolt Length: 16 ft (After Barton, 1989) or 2 x Spacing (After USACOE, 1981)

Empirical Design Charts for Support and Stand-up Time





Proposed Initial Ground Support

Recommended Support

Arch rock bolt type: Resin grouted #10 bar

Arch/Sidewall rock bolt spacing: 6 ft x 6 ft

Arch rock bolt length: 16 ft

Sidewall rock bolt type: Swellex PM24

Sidewall rock bolt length: 12 ft

Shotcrete: 2 in steel fiber reinforced (general)
4 in steel fiber reinforced 10 ft around penetrations

Construction Considerations

Top heading to be excavated split headings with span no greater than 31 ft. Full support to be installed in drift prior to breaking out cavern to full span. Thickend shotcrete around penetrations to be in place prior to break out/in.

Maximum advance length limited to 12 ft before support installation. Bolts to be installed within 48 hrs of excavation.

ARUP

ARUP

Job No.	Sheet No.	Rev.
207975	9	

Member/Location

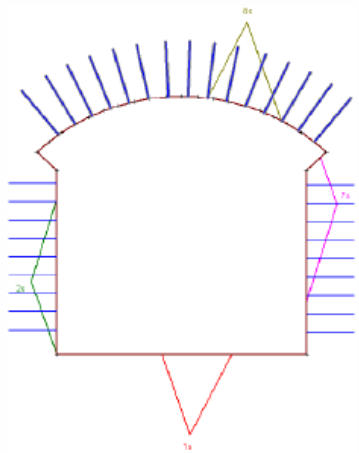
Job Title: CM019 - Grand Central Caverns

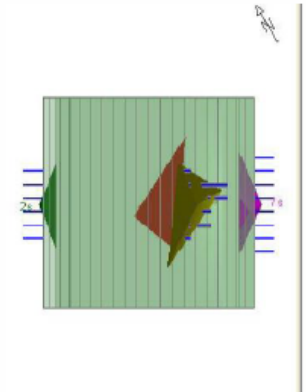
Calculation: Main Cavern STA 17+00 to 28+75 UNWEDGE Summary – Crown Critical Case (input & results) Rock Mass Type IV

Org. Ref. | Chd.

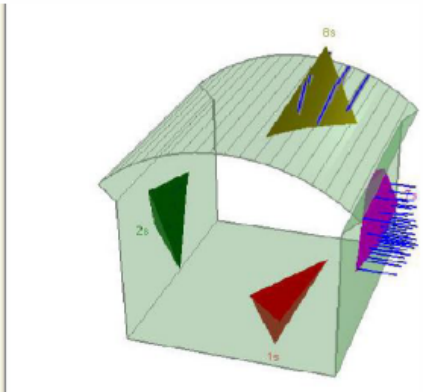
Made by: SP | Date: 03/02/2009 | PJH

Design Section model schematic including all loadings

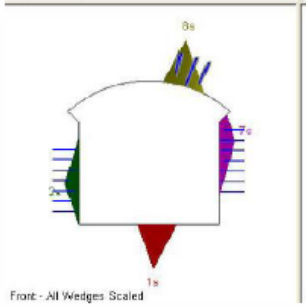




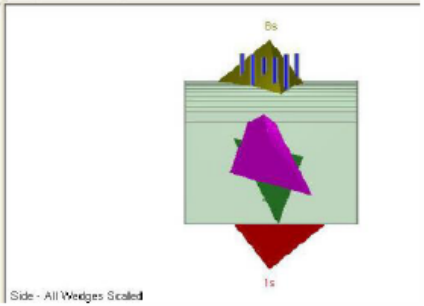
Top - All Wedges Scaled



Perspective - All Wedges Scaled *



Front - All Wedges Scaled



Side - All Wedges Scaled

UNWEDGE Input Properties

***General Project Conditions*:**
Tunnel Axis Orientation: 029°, 0° plunge
Unit Weight of Rock: 175 pcf
Seismic Force: Not considered
In-situ Stress: Using the measured in-situ stress values of about 2 will only lead to less conservative results, as such, they are not considered in the kinematic analysis.

Joint Properties:

Shear Strength Model: Mohr-Coulomb
Phi: 35° (Joint Sets 1 & 4) , 45° (Joint Sets 2 & 3)
Tensile Strength: 0 ksf
Cohesion: 0 ksf
Water Pressure: 0 ksf
Structure / Waviness: 0° (assumed planar, conservative)
Wedges Scaled to: 35,70, 50 ft trace length (respectively)

Ground Support Properties: ***Ground Support Pattern:***

Arch: 15-ft long, 5-ft x 5-ft stagger FS = 1.57
Rock Bolts: Dywidag #10
Tensile Capacity: 72 kips (60% GUTS)
Plate Capacity: 14 kips (washer circumference x plate thickness x fu = 58 ksi)
Bond Strength: 32 kips / ft

Wall: 12-ft long, 5-ft x 5-ft stagger FS = 1.35
Friction Bolts: Swellex PM24
Tensile Capacity: 45 kips
Plate Capacity: 20 kips
Bond Strength: 8 kips / ft

Shear Strength: Not considered
Bolt Orientation Efficiency: Cosine tension/shear

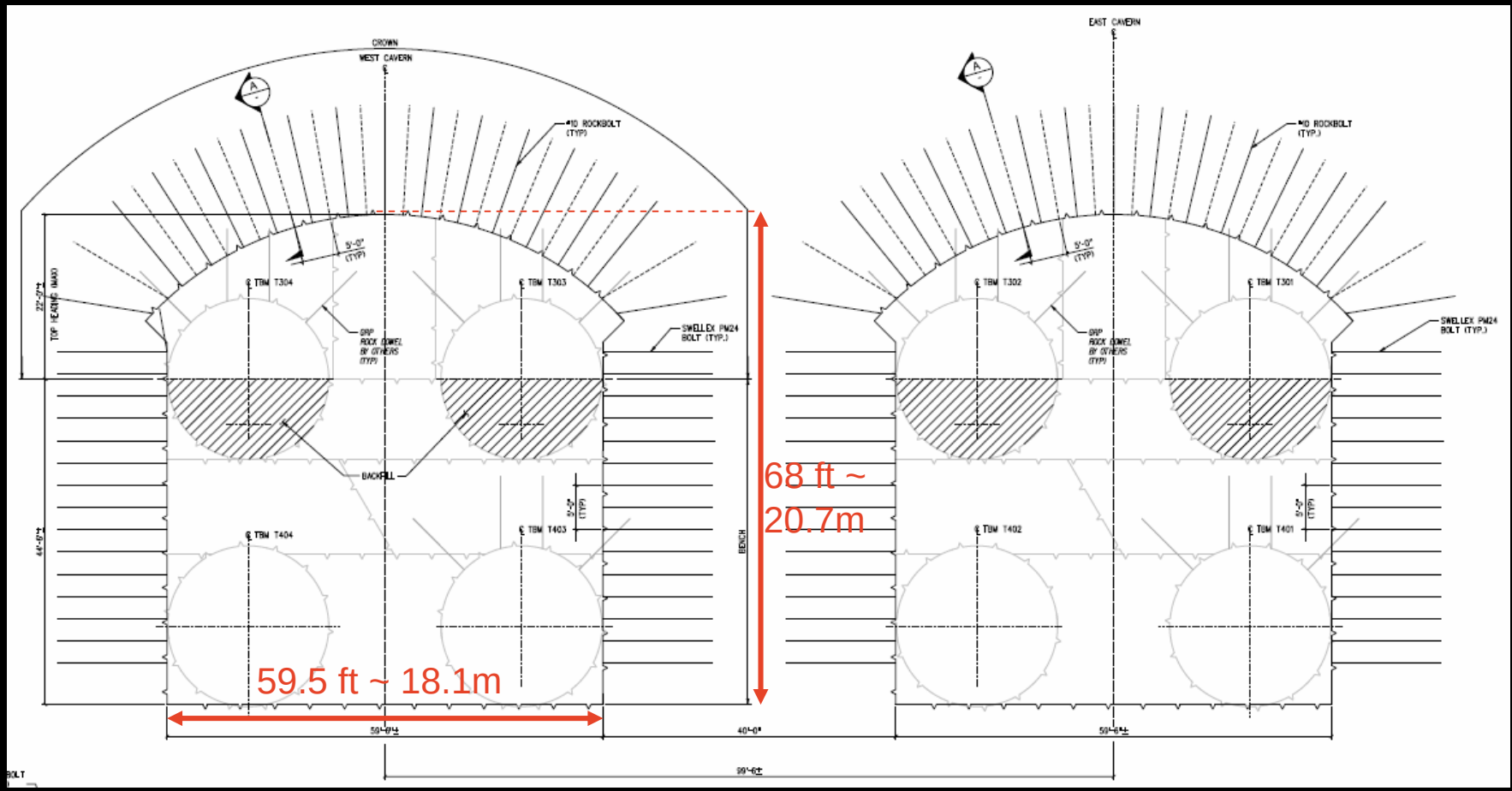
Joint Orientations:

Joint Set	1 (Foliation)	2 (Cross - Foliation)	3 (conjugate)	4 (Low)	4 (High)
True Dip	40	80	70	20	70
Dip Direction	270	150	70	320	305
Baseline Dip (GIR)	35	85	35	20	70
Baseline DD (GIR)	250	190	75	320	305

Critical

Wedge Scaling: Crown wedges scaled to approximately 2/3 maximum excavation height, or 40 feet.

Grand Central Caverns



Selection of Rock parameters

- **GDR/GBR baseline properties; used for continuum and discontinuum models**

Table 1: Discontinuum Input Parameters for Ground Types A, B, and C

Property	Value	Notes
Rock Density (γ)	175 pcf	Derived from laboratory testing results presented in the GDR
Poisson's Ratio (ν)	0.23	Derived from laboratory testing results presented in the GDR
Failure Envelope Range (σ_{3max})	12 ksf	Calculated at cavern crown level from in situ stress and surcharge loads
Intact Rock Cohesion (ci)	210 ksf	Output from RocLab based on input of above parameters; within accepted range for Manhattan Schist
Intact Rock Friction Angle (ϕi)	55°	Output from RocLab based on input of above parameters; within accepted range for Manhattan Schist
Young's Modulus (Ei)	8.65E+05 ksf	Derived from laboratory testing results presented in the GDR
Tensile Strength (σt)	150 ksf	Calculated by tension cutoff: c/tanϕ
In situ Stress Ratio (K)	2	From hydrofracture testing in Manhattan from various tunnelling projects

Table 2: Continuum Input Parameters for Ground Type D

Property	Value		Notes
	Ground Type D	Disturbed (Blasting) Zone	
Unconfined Compressive Strength (UCS)	1008 ksf		Derived from laboratory testing results presented in the GDR
Geological Strength Index (GSI)	50		Based on rock core photographs and logs; a qualitative assessment of the rock mass as "very blocky" with "fair" to "good" surface quality condition; as per Hoek et al. 1995
Poisson's Ratio (ν)	0.25		Derived from laboratory testing results presented in the GDR
Disturbance Factor (D)	0.0	0.8	Rock mass considered undisturbed for general analysis but severely impacted for 5 ft zone beyond drill and blast excavation perimeter; as per Hoek et al., 2002
Failure Envelope Range (σ_{3max})	12 ksf		Calculated at cavern crown level from in situ stress and surcharge loads
Deformation Modulus (Em)	2.2E+05 ksf	1.1E+05 ksf	Output from rock mass modulus reduction, values verified using RocLab
Rock Mass Cohesion (c)	10 ksf	7.5 ksf	Output from RocLab based on input of above parameters; within accepted range for Manhattan Schist
Rock Mass Friction Angle (ϕ)	55	50	Output from RocLab based on input of above parameters; within accepted range for Manhattan Schist
In situ Stress Ratio (K)	2.0		From hydrofracture testing in Manhattan for various tunneling projects

ARUP

Job No.	Sheet No.	Rev.
207975		

Member/Location

Drg. Ref. Chd.

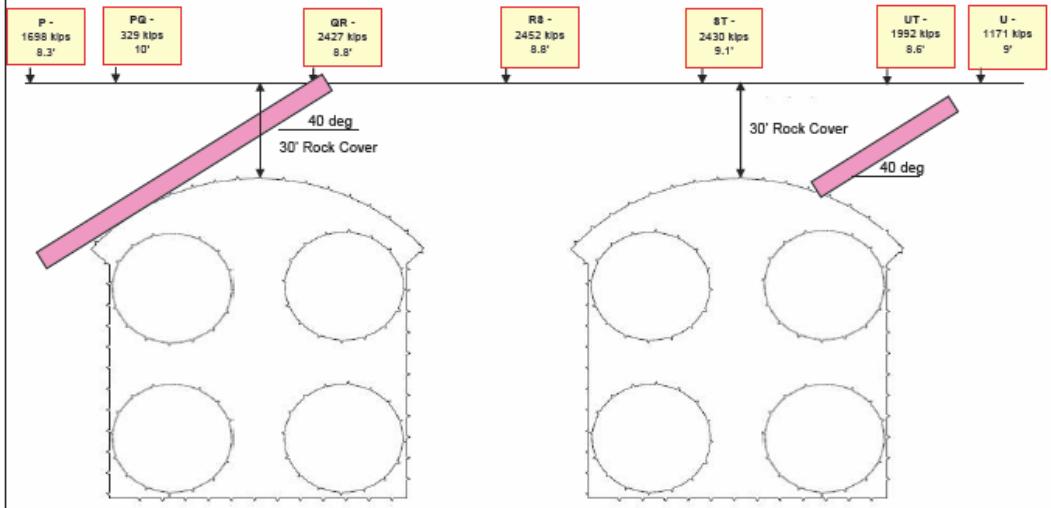
Made by PJH Date PJH

Job Title: CM019 - Grand Central Caverns

Calculation: UDEC Summary (input & results) **Rock Mass Type II (South and North Cavern) - Model B.0**

DESIGN SECTION

SURCHARGE LOADING B



UDEC INPUT PROPERTIES

INTACT ROCK PROPERTIES (Mohr-Coulmb Model):

Density = 5.4390e (slug/ft^3)
Youngs Modulus = 8.6400e+008 (lbf/ft^2)
Poissons Ratio = 2.5000e-001
Cohesion =2.0880e+005 (lbf/ft^2)
Angle of friction = 55°
Tensile Strength =1.462e+005 (lbf/ft^2)
Dilation Angle = 0°

SHEAR ZONE PROPERTIES (Mohr-Coulmb Model):

Young's Modulus = 3.0e+008 (lbf/ft2)
Cohesion = 6.0e+003 (lbf/ft2)
Angle of friction = 50°
Tensile Strength =5.03e+003 (lbf/ft2)
Poissons Ratio = 2.5000e-001

IN-SITU STRESS

K_o = 2
Surcharge = See Column Loads on Design Section

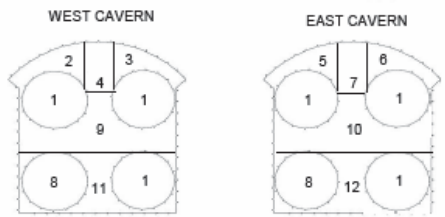
GROUNDWATER

No water loads considered

JOINT PROPERTIERS (Mohr-Coulomb Model): Joint Pattern A

Joint Set	1 (Foliation)	2 (Cross - Foliation)	3(Conjugate)	4 (Random Low)	4 High
True/ Apparent Dip (S.D)	40/ 40 (5)	60/ 65 (5)	50/ 45 (5)	NA	NA
Dip Direction (S.D.)	270 (5)	150 (5)	90 (5)	NA	NA
Baseline Dip (GIR)	35	85	35	NA	NA
Baseline DD (GIR)	250	190	75	NA	NA
Mean Angle (S.D.) degrees					
Mean Trace (S.D.) feet	50 (5)	25 (5)	50 (5)	NA	NA
Mean Gap (S.D.) feet	30 (5)	10 (2.5)	30 (5)	NA	NA
Mean Spacing (S.D.) feet	10 (2.5)	20 (2.5)	10 (2.5)	NA	NA
Normal Stiffness (lbf/ft^2/ft)	160000000	160000000	160000000	NA	NA
Shear Stiffness (lbf/ft^2/ft)	8300000	8300000	8300000	NA	NA
Tensile Strength (lbf/ft^2)	0	0	0	NA	NA
Friction Angle (degrees) ϕ_b	35	35	45	NA	NA
Dilation Angle (degrees) ϕ_i	5	5	5	NA	NA
Cohesion (lbf/ft^2)	0	0	0	NA	NA

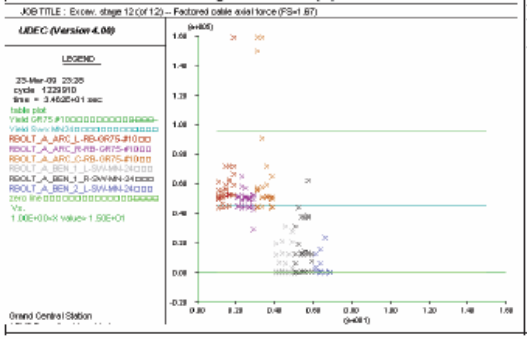
CONSTRUCTION SEQUENCE : 3 TOP HEADINGS



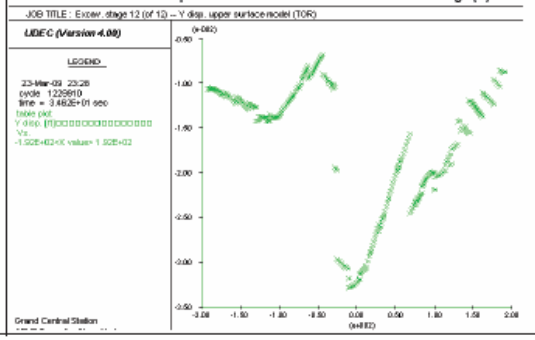
Stage	Description
1	TBM Tunnels excavated under contract CM009
2	Excavate West Cavern top heading - Install bolts
3	Excavate West Cavern top heading - Install bolts
4	Excavate West Cavern pillar - Install bolts
5	Excavate East Cavern top heading - Install bolts
6	Excavate East Cavern top heading - Install bolts
7	Excavate East Cavern pillar - Install bolts
8	Excavate final two TBM tunnels
9	Excavate two bench levels - Install bolts
10	Excavate two bench levels - Install bolts
11	Excavate lower bench - Install bolts
12	Excavate lower bench - Install bolts

NB. Top heading excavation in West Cavern to be kept 60' ahead of East Cavern top heading excavation

ROCKBOLT SUMMARY - Final Stage West Cavern (lb)



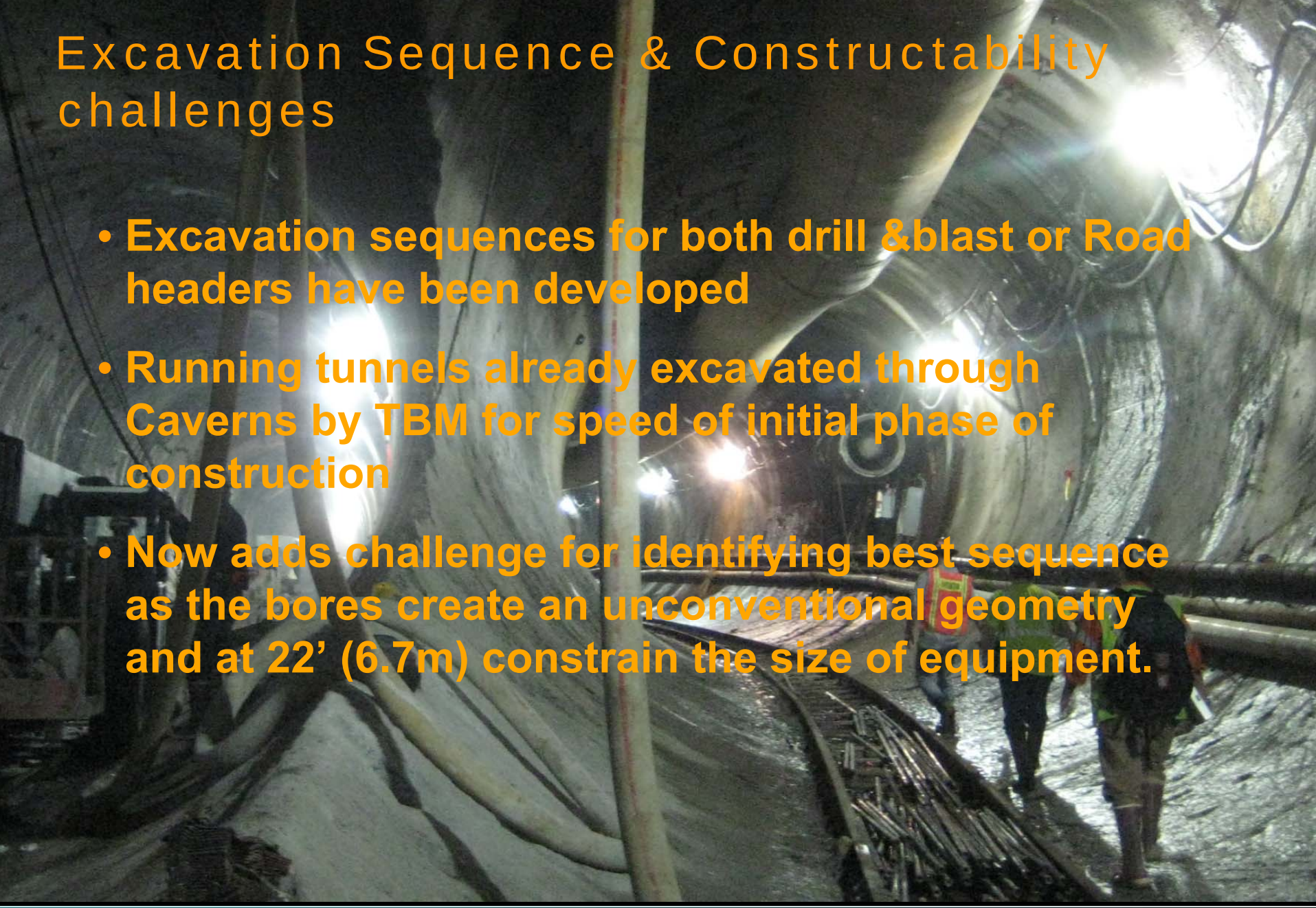
MOVEMENT SUMMARY - Top of Rock Subsidence at Final Excavation Stage (ft)



SUPPORT PROPERTIES

	Crown/ Arch	Sidewall		Crown/ Arch	Sidewall
Bolt Type	RB-GR75 no.10	SW-PM-24	Max compressive force (lbf)	9.50E+04	4.50E+04
Bolt Length (ft)	15'	15'	Max tensile force (lbf)	9.50E+04	4.50E+04
Spacing (ft) Radial / Longitudinal	5' x 5'	5' x 5'	Youngs modulus (lbf/ft2)	4.18E+09	4.18E+09
Cross sect. area (ft2)	8.82E-03	5.18E-03	Grout Stiffness (lbf/ft2)	1.11E+08	1.60E+09
Diameter (ft)	1.1E-01	8.1E-02	Grouth Bond strength(lbf/ft)	4.00E+04	7.00E+03
Pre-tension force (lbf)	3.00E+04	0			
Density (slug/ft3)	1.51E+01	1.51E+01			

Excavation Sequence & Constructability challenges



- **Excavation sequences for both drill &blast or Road headers have been developed**
- **Running tunnels already excavated through Caverns by TBM for speed of initial phase of construction**
- **Now adds challenge for identifying best sequence as the bores create an unconventional geometry and at 22’ (6.7m) constrain the size of equipment.**

Questions ?