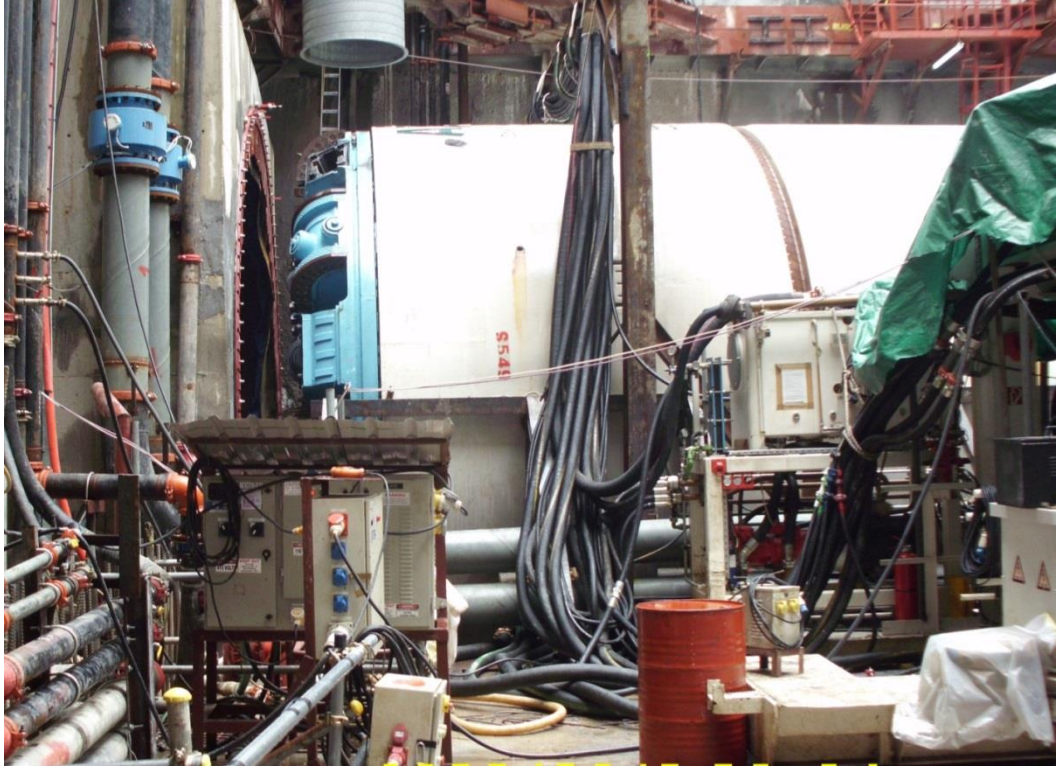


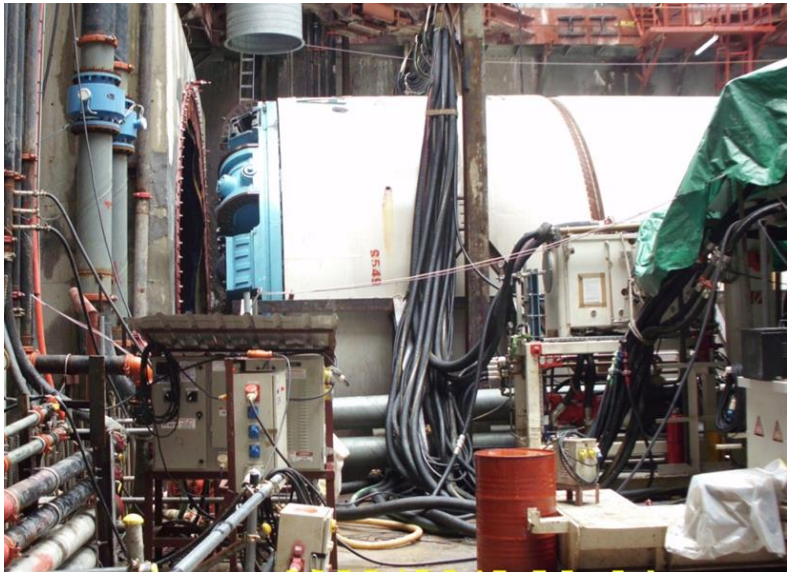
Pressurised TBMs and their interaction with weathered rock

Nick Shirlaw

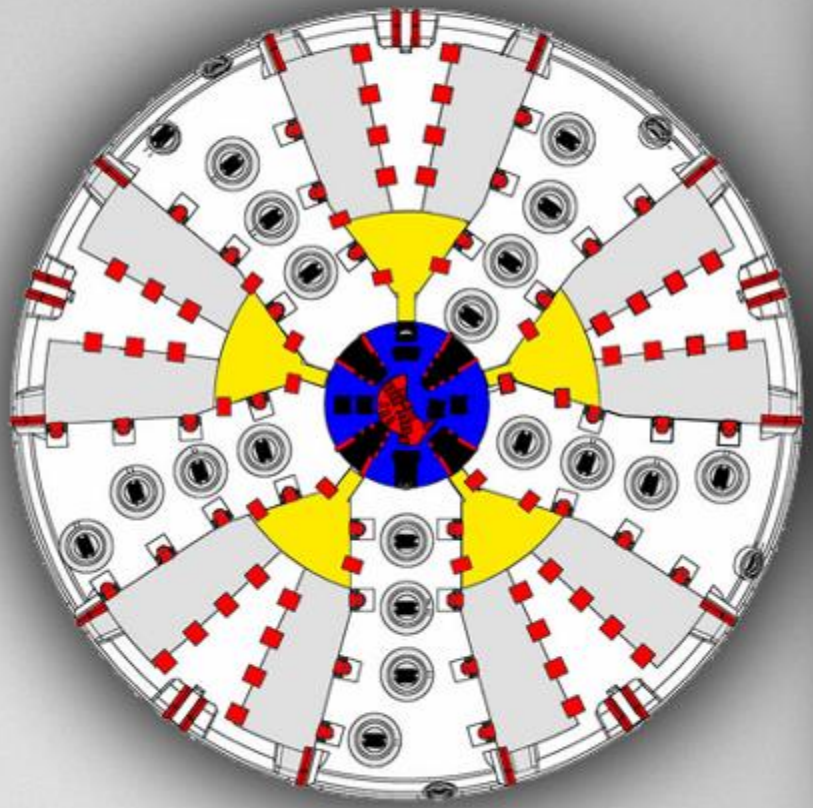
Golder Associates

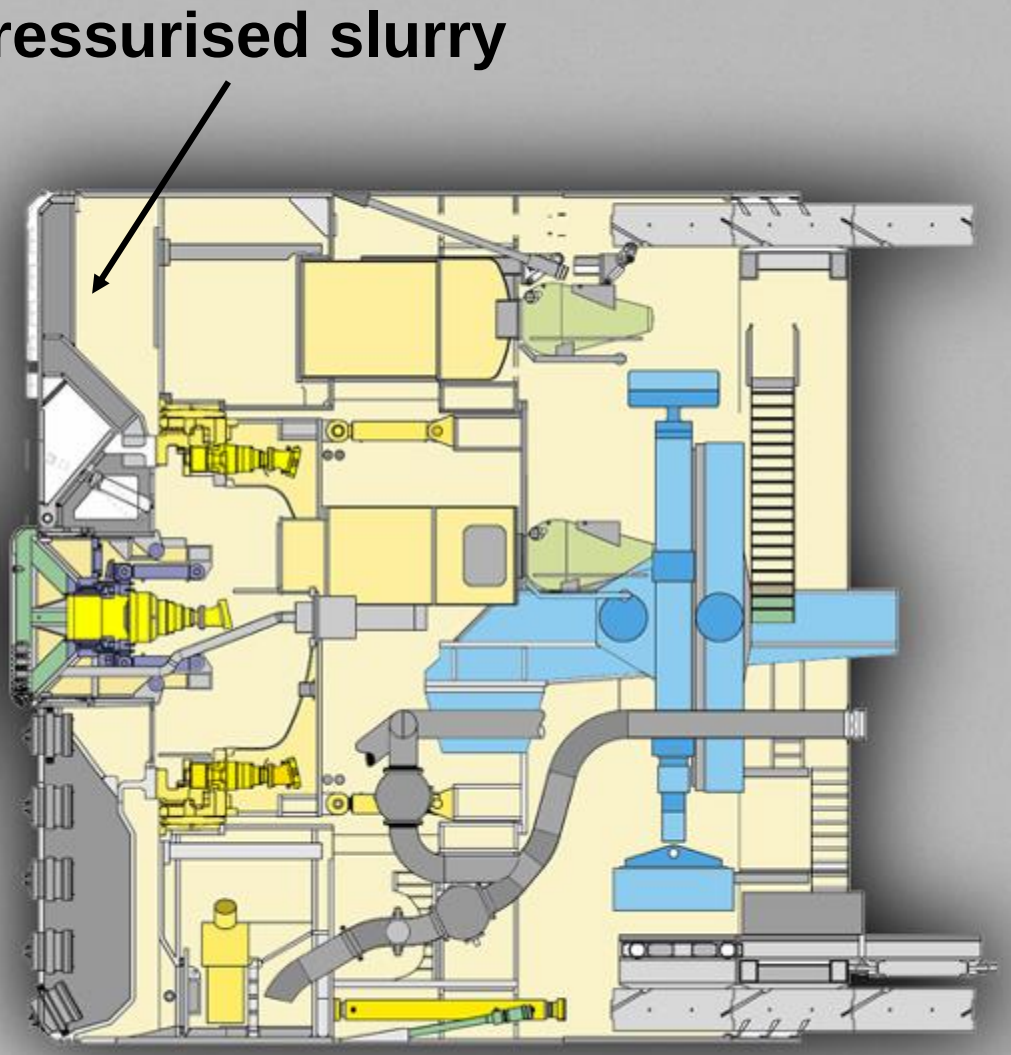
Pressurised TBMs

- Two basic types: slurry or Earth Pressure Balance (EPB)
- Fundamental differences in how they provide pressure to support the face
- Some modern TBMs can change from Slurry to EPB, including the ‘variable density’ TBM



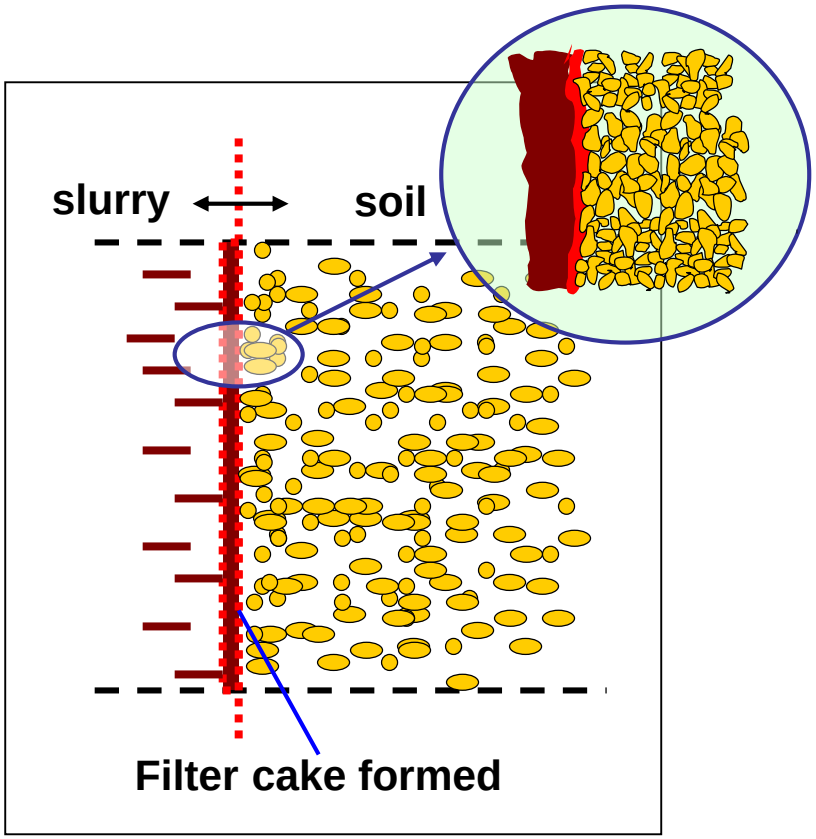
Slurry TBM





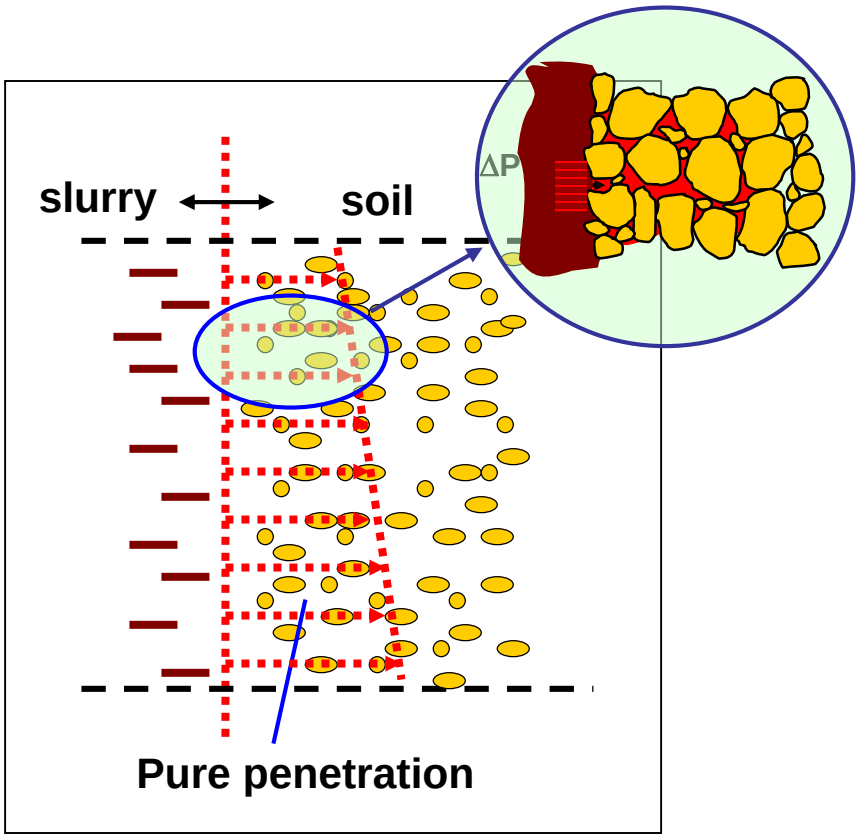
Application of slurry pressure

Membrane model



Fine sand
Medium sand

Penetration model



Coarse sand
Gravel

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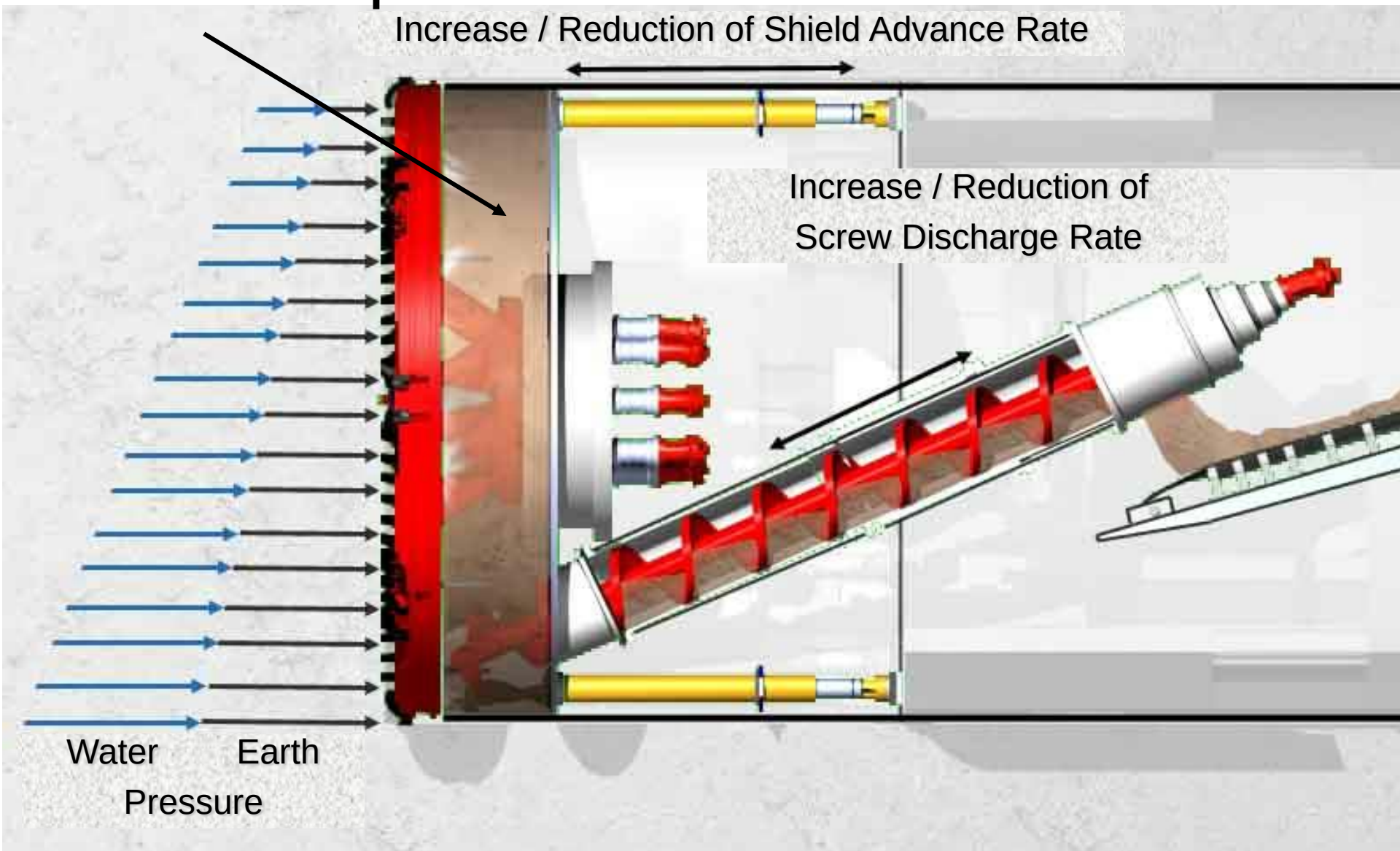
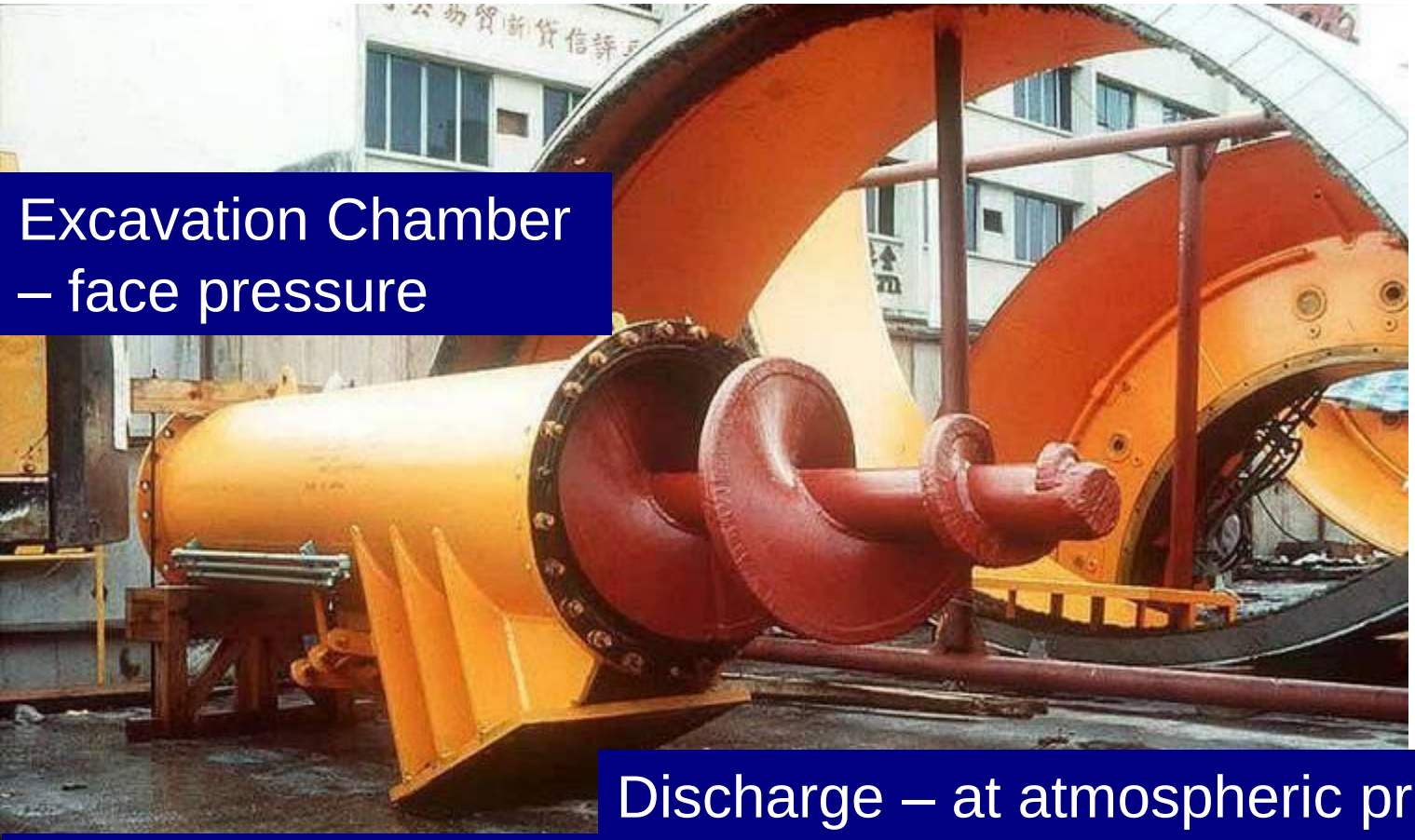
Earth Pressure Balance

Pressurised spoil



Screw Conveyor



Excavation Chamber – face pressure

Discharge – at atmospheric pressure

Pressure drop along screw conveyor = difference between face pressure and atmospheric

EBP-Shield Taipai (Ø 6.26 m) , belt conveyor outlet

Ideal soil for EPB operation – low permeability & plastic, to support pressure drop along screw conveyor

Typical mixed ground cutterhead

Discs for rock and scrapers for soil

Opening ratio 25% to 35% (example is 33%)

Interventions

Confined space to:

- Inspect and change cutting tools
- Tighten bolts
- Repair grizzly bars, mixing and crusher arms
- Remove blockages, lost steel

Interventions

Typically under compressed air in soil & mixed ground

Damage in mixed faces of rock and soil

Impact damage to discs

Abrasion

Damage to mixing and rock crusher arms, cutterhead

Blockage

Blockage

Heat generated during EPB tunnelling. Muck temperature can be 60 + degrees C

Some issues with mixed faces of rock and soil






Major risk factor for large settlement and sinkholes

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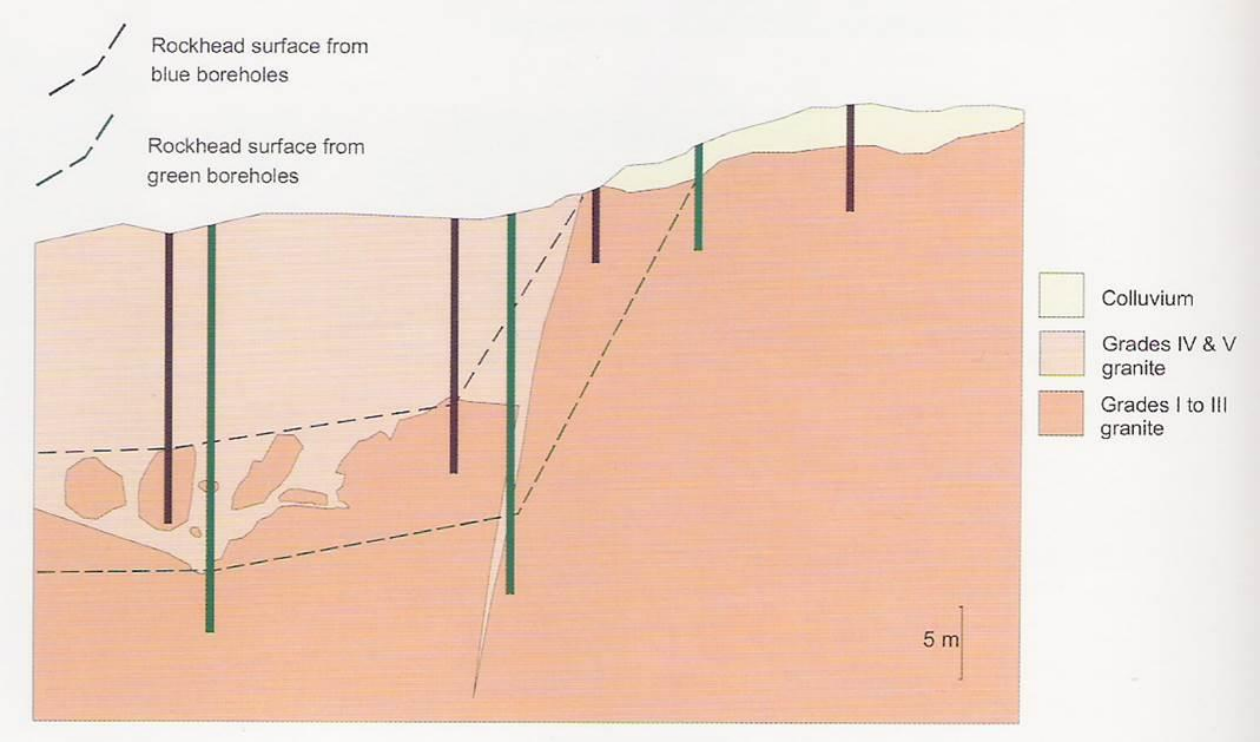
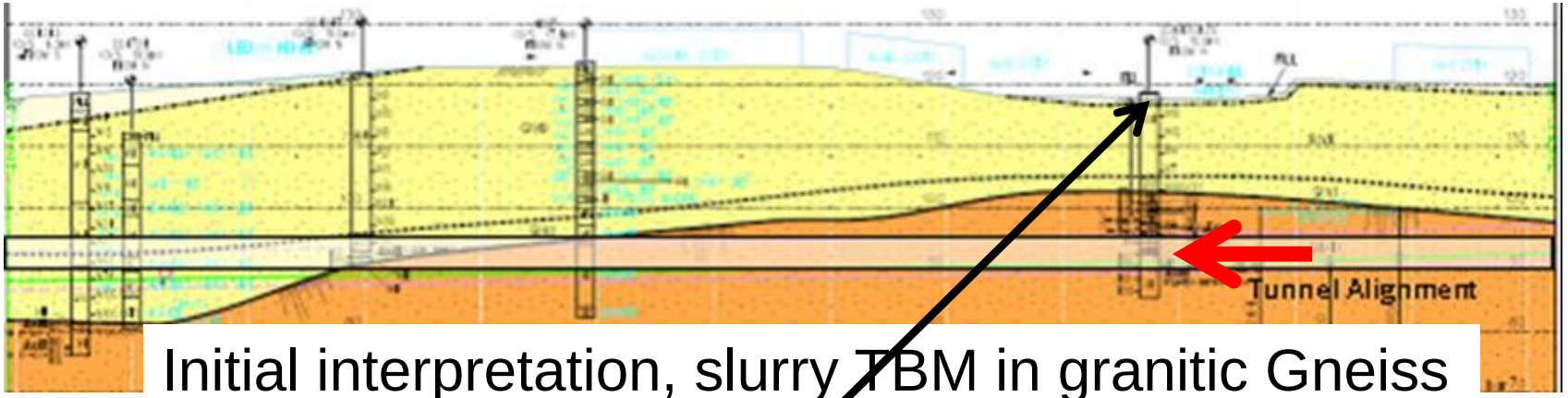
Correlating problems with geology

- If we want to relate problems to geological conditions, the first thing we need to know is what the geological conditions are
- This is a problem in weathered rock
- Extrapolations from borehole information often inaccurate (Fletcher)

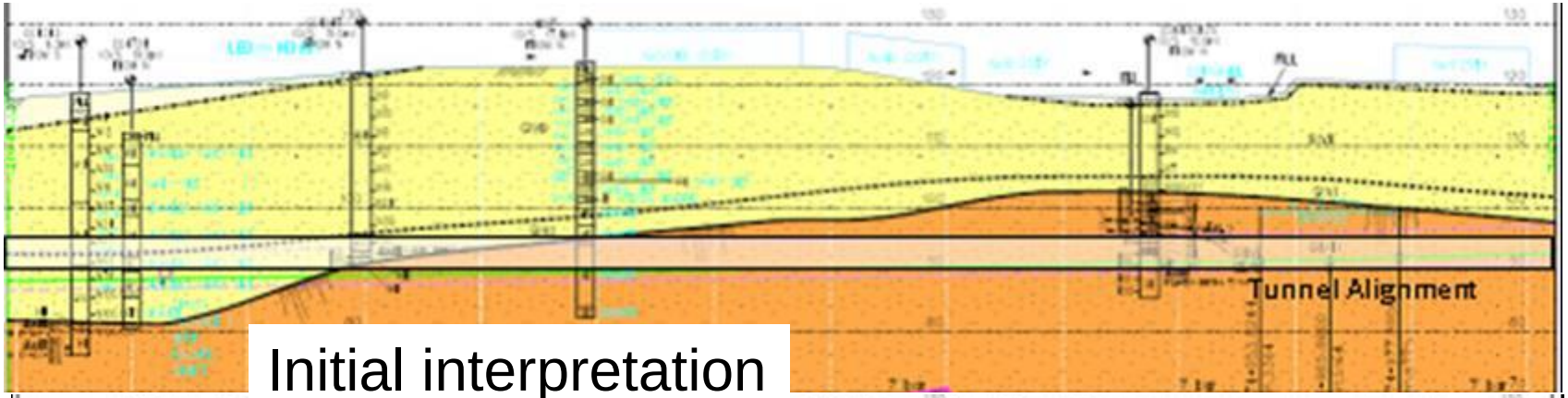


Establishing rockhead level from boreholes

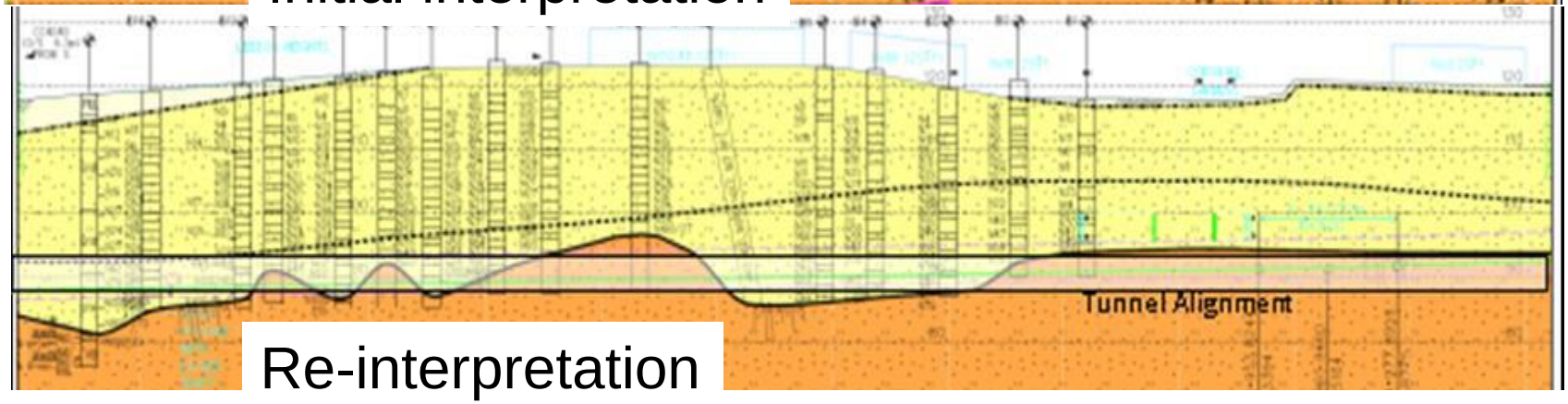


Initial interpretation, slurry TBM in granitic Gneiss

Establishing rockhead level from boreholes



Initial interpretation



Re-interpretation

Actual ground conditions observed in tunnel different from re-interpretation

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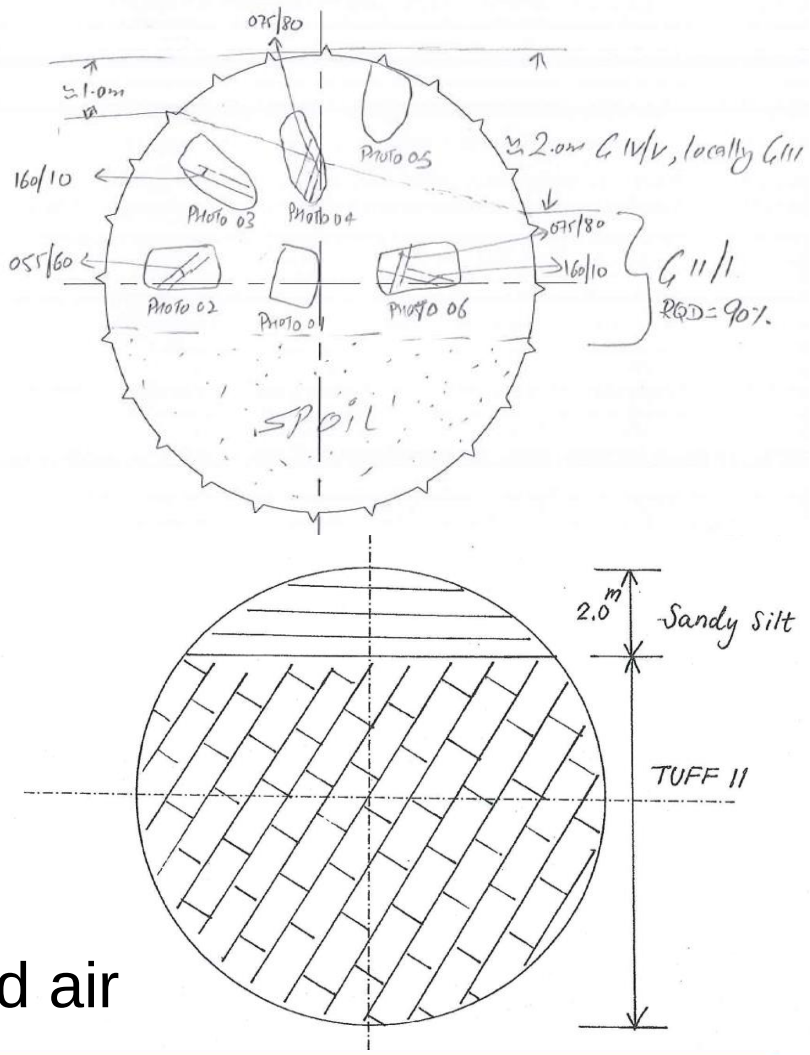
What we see during TBM advance

Interventions – opportunity to map the face



Limitations:

- Limited openings
- Generally spoil up to axis level
- Training of staff fit for compressed air

Pressurised TBMs

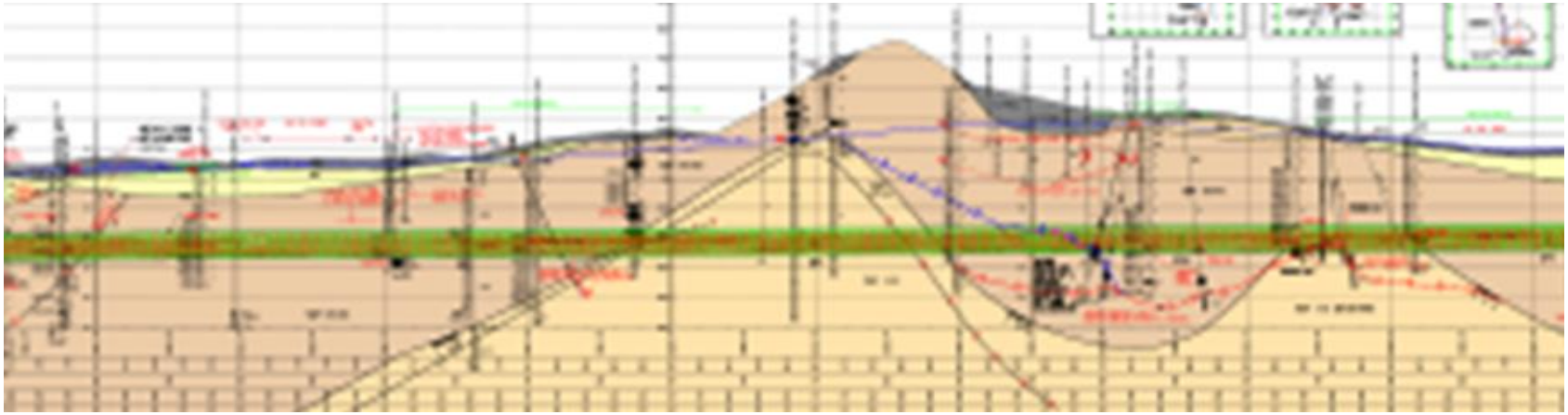
- Numerous parameters measured within the TBM during tunnelling
- Analysis of the data can be used to:
  - Aid in assessing whether the TBM is in soil, mixed ground or rock
  - The strength of the rock encountered
  - Choice of slurry, EPB or variable density TBMs
  - The effect of the various ground conditions on TBM advance rates, tool consumption
  - Suggest what improvements can be made to the TBM or tunnelling procedures to improve tunnelling performance

Method of assessment of ground conditions

- Boreholes and face logs (from interventions) give occasional fixed information
- TBM data – the only available information that is continuous
  - Express as Penetration Index (Contact Force per cutter/advance per revolution) or Specific Energy (Torque per sq.m of face/advance rate)
  - Calibrated against data from boreholes and face logs

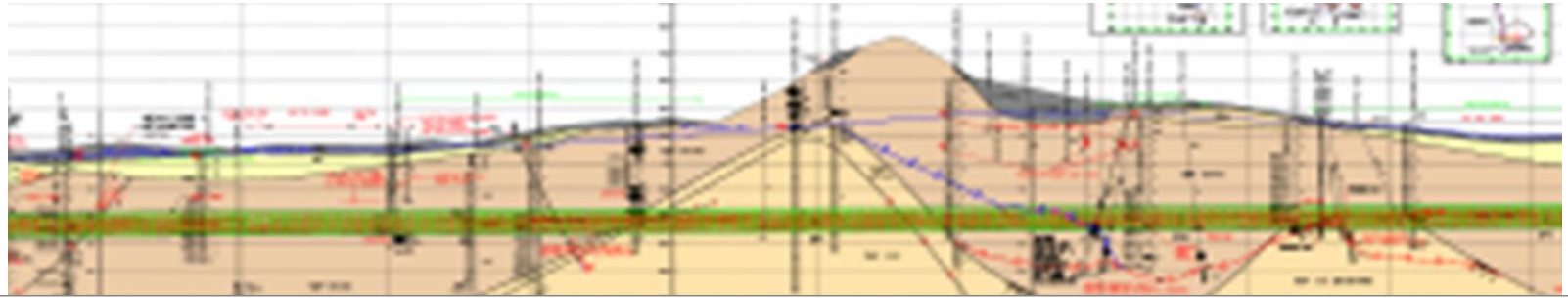
Tunnel A

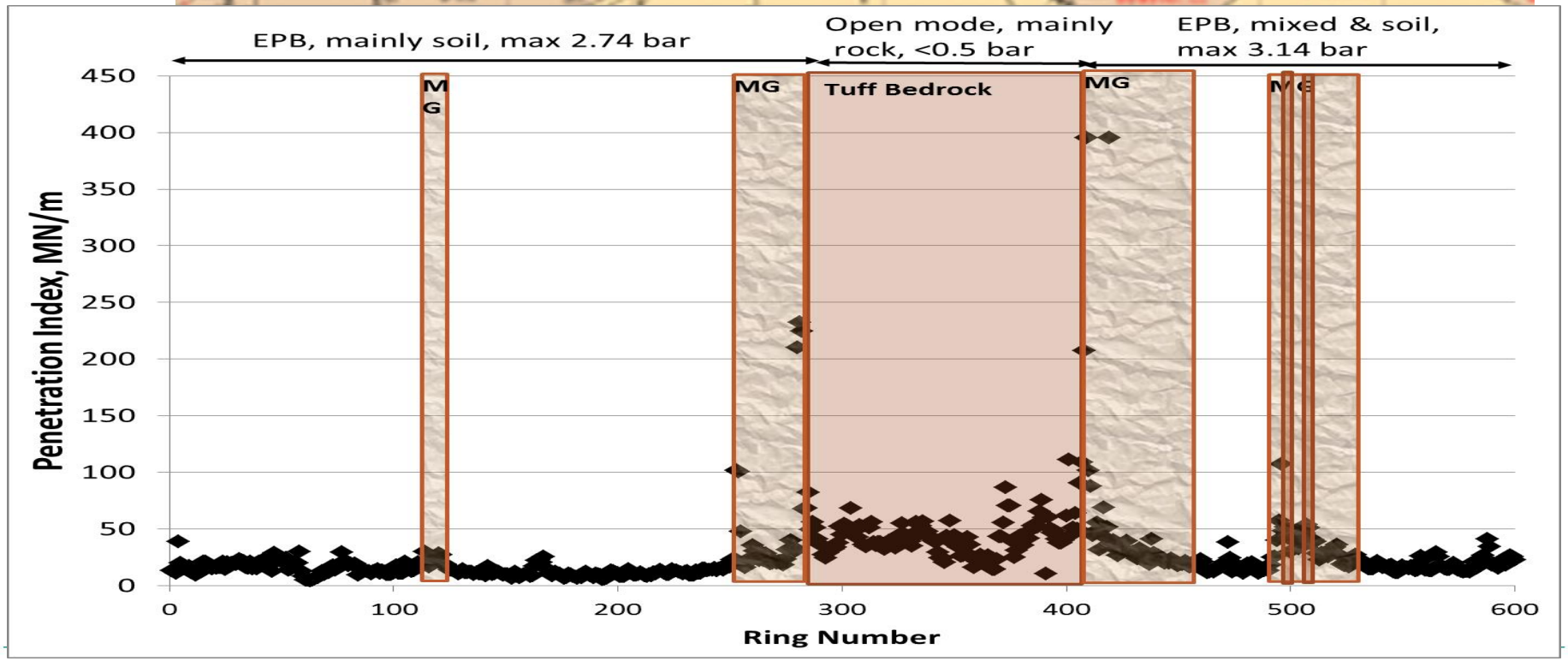
- 9.23m diameter EPB drive
- 53 No 17” discs
- 1.8m long rings
- Tuff rock and soil grades of weathered tuff
- Average CAI of rock: 3.5
- Geological section from boreholes that were mostly significantly offset



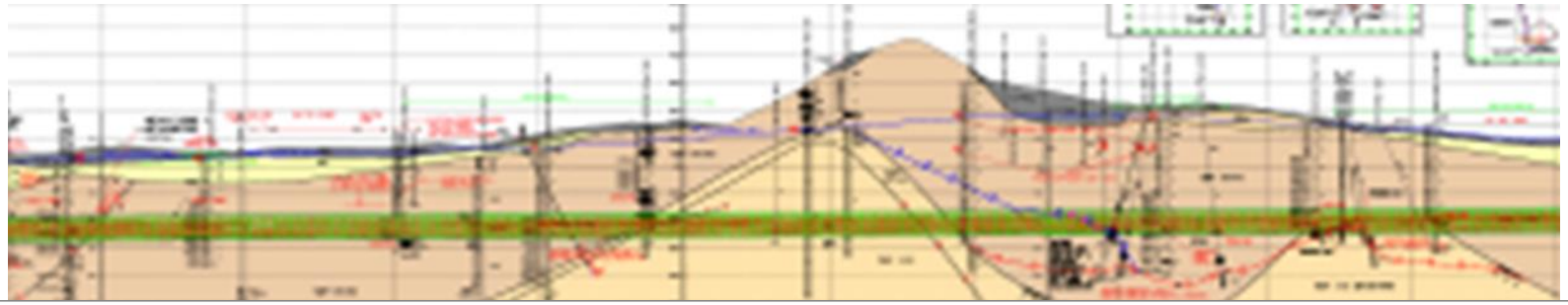
Direction of drive

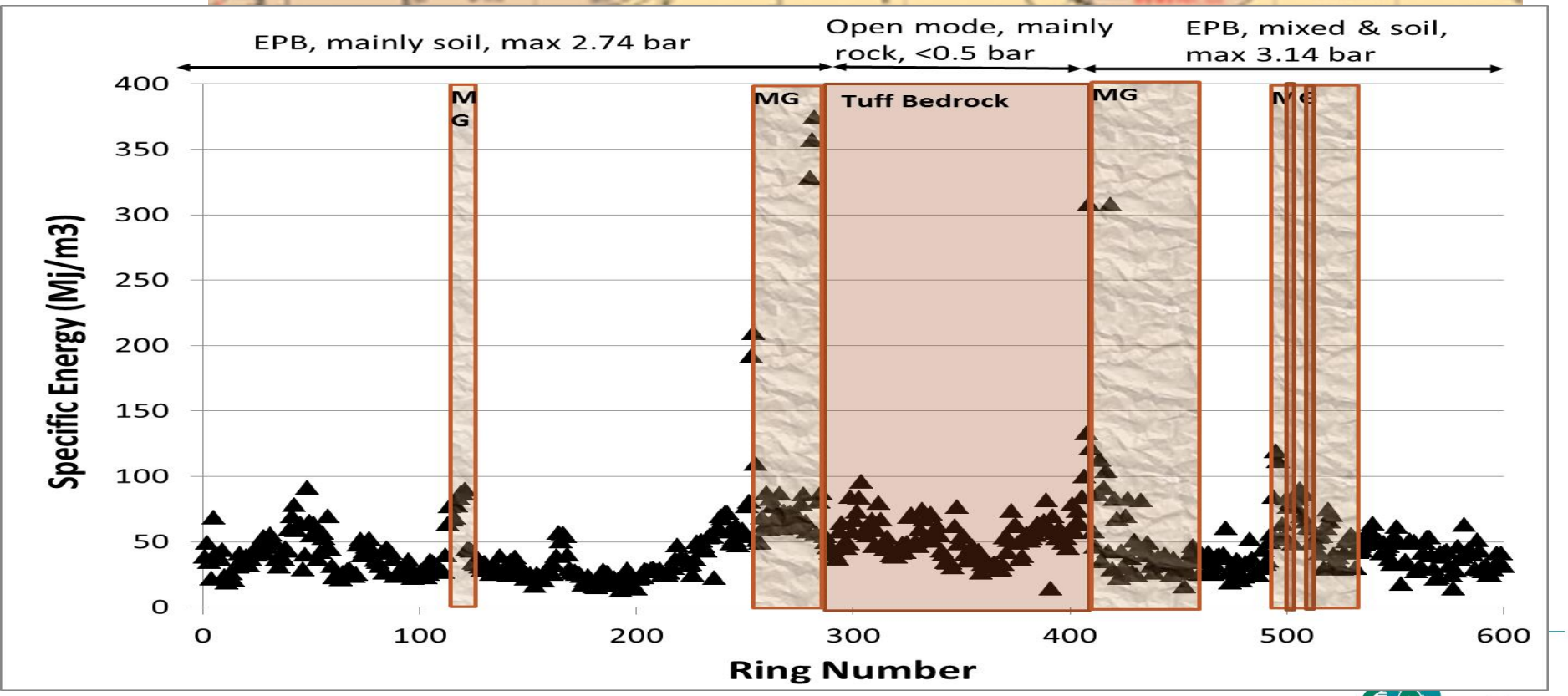
Tunnel A, Penetration Index





Tunnel A, Specific Energy





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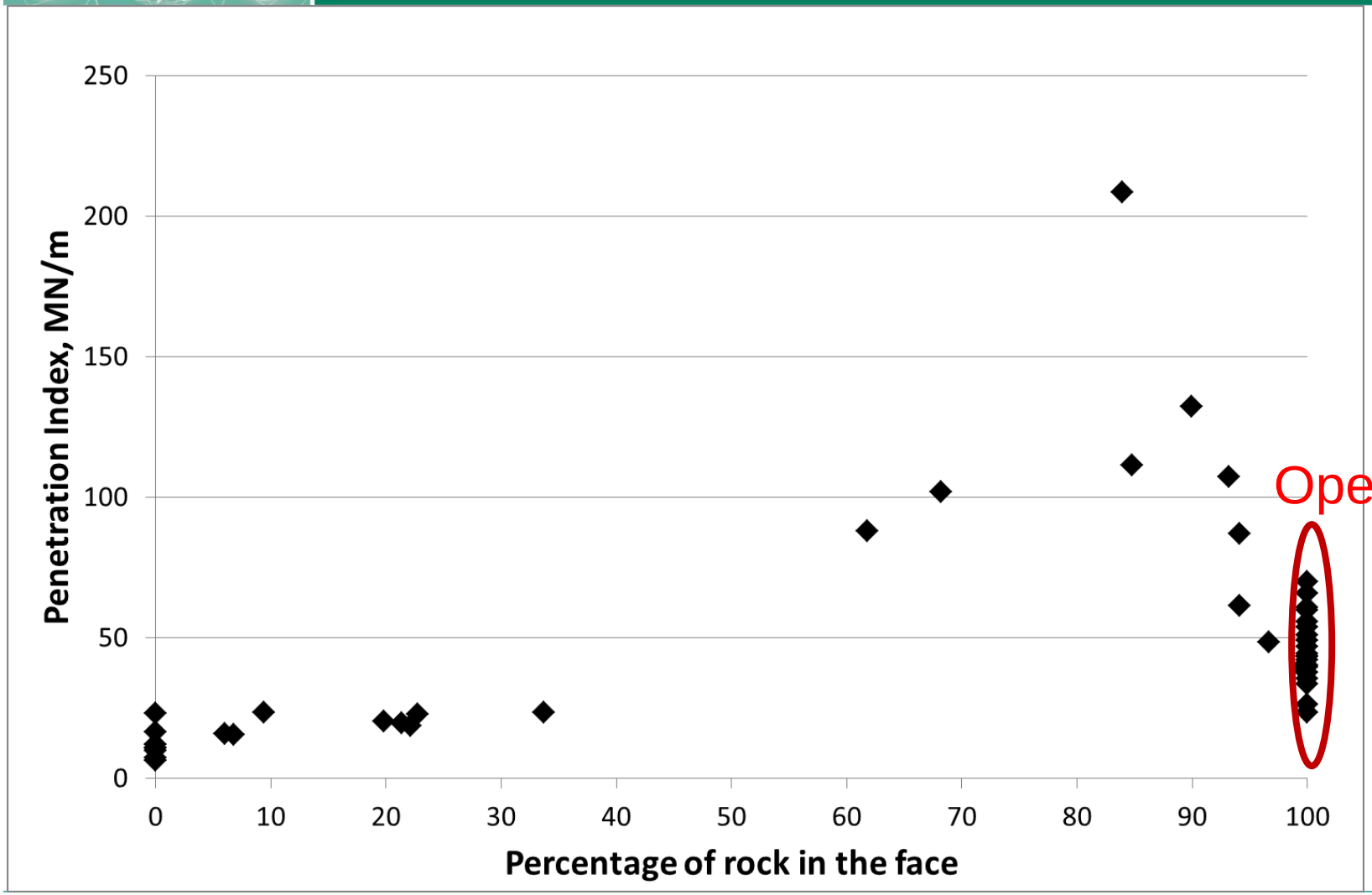
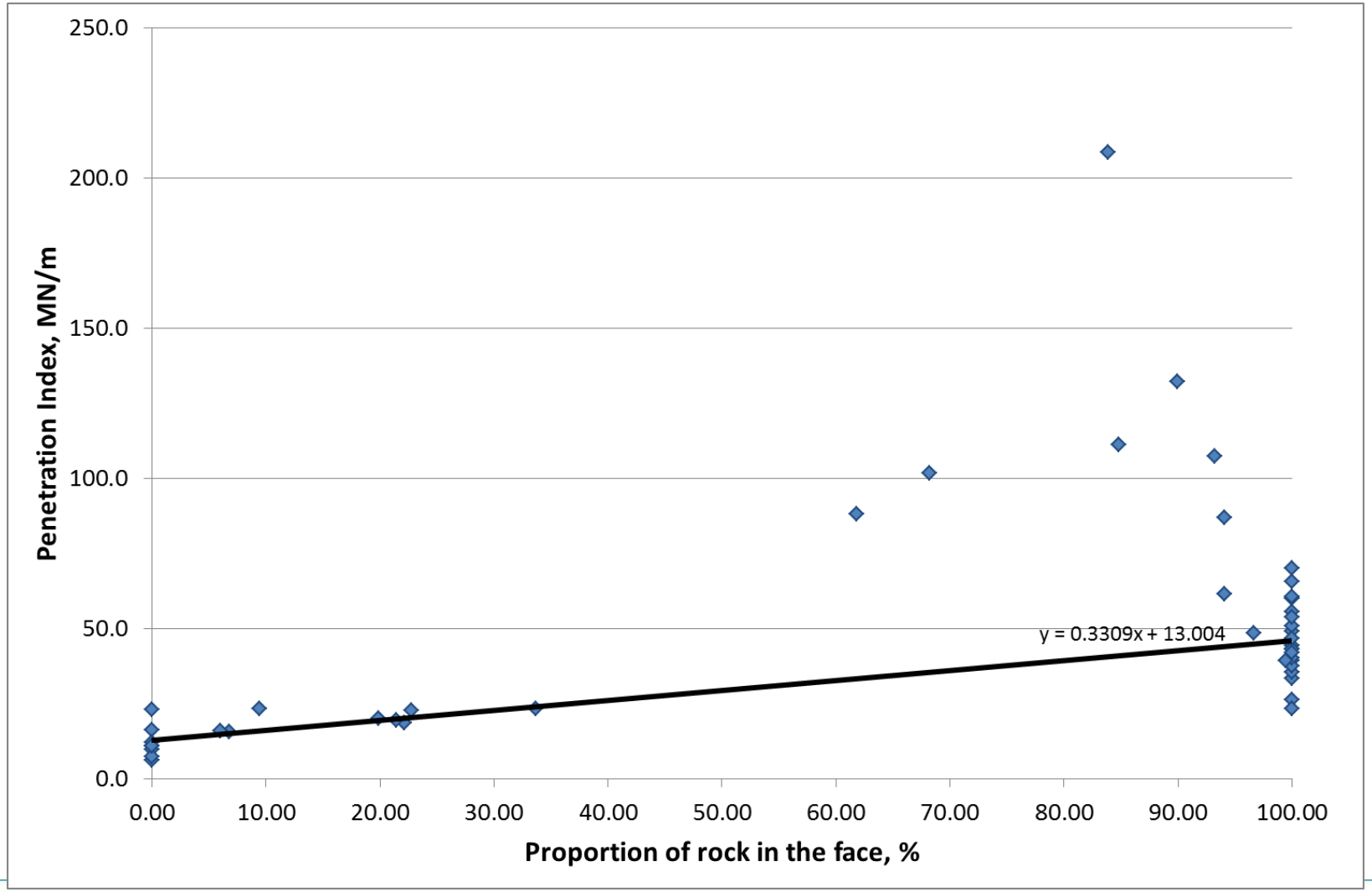
Tunnel A – Penetration Index

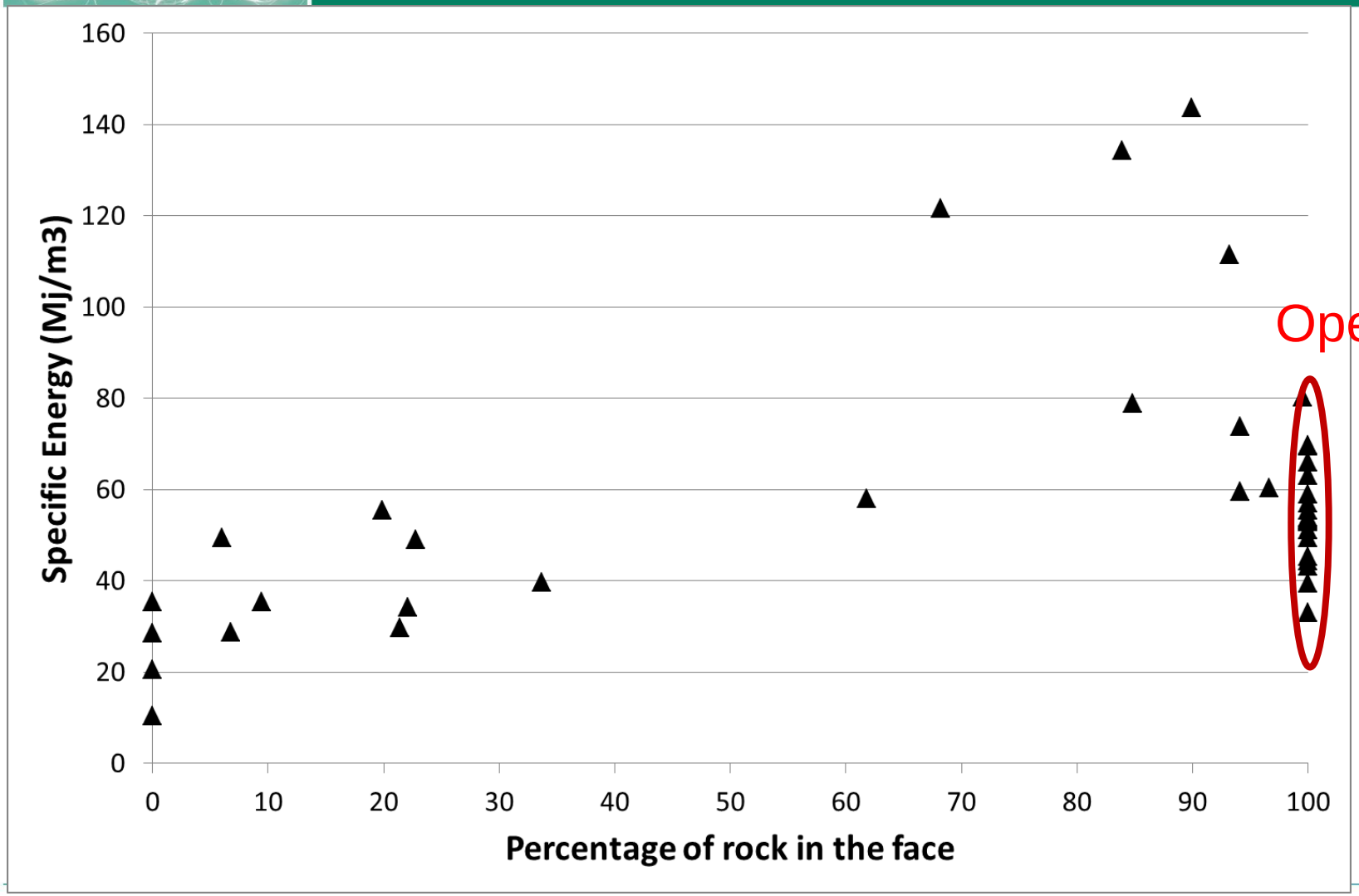


Based on known ground conditions at interventions, on line boreholes

Deviation in Penetration Index from trend >50% rock



EPB in Mixed Ground – Specific Energy



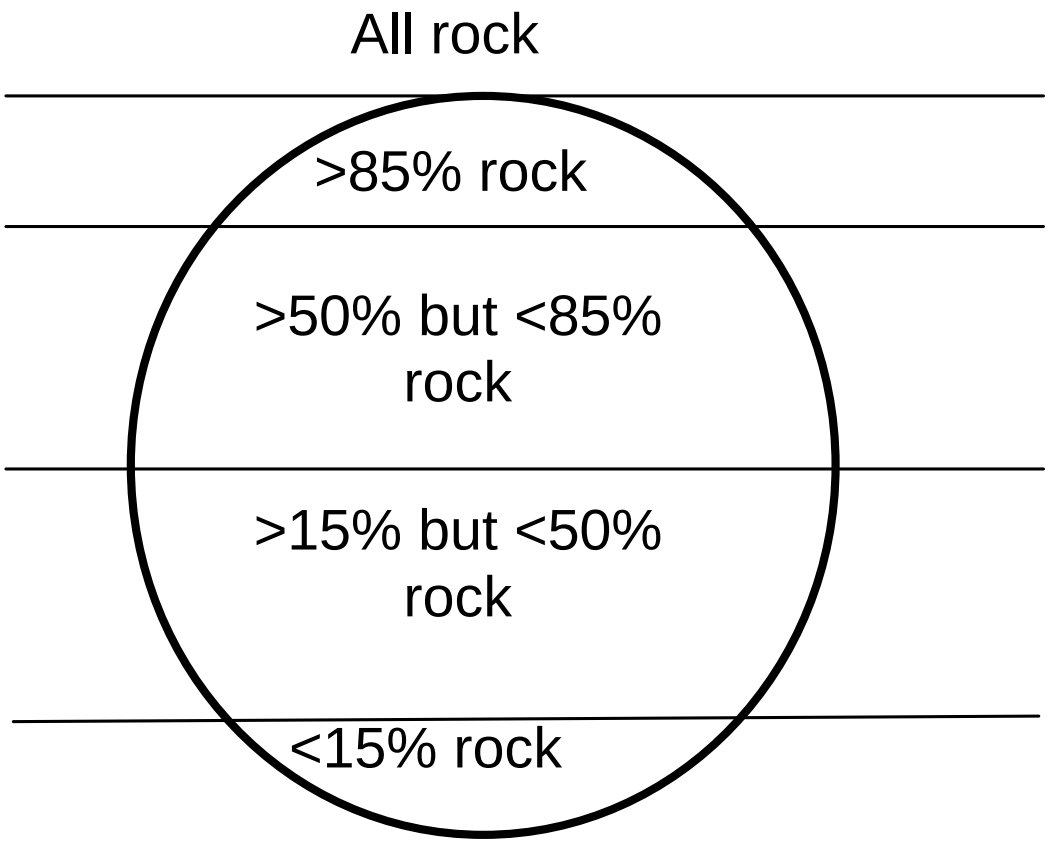
Max value 376 Mj/m^3, at known rock / soil interface, but not mapped

Mixed Ground categories – Tunnel A

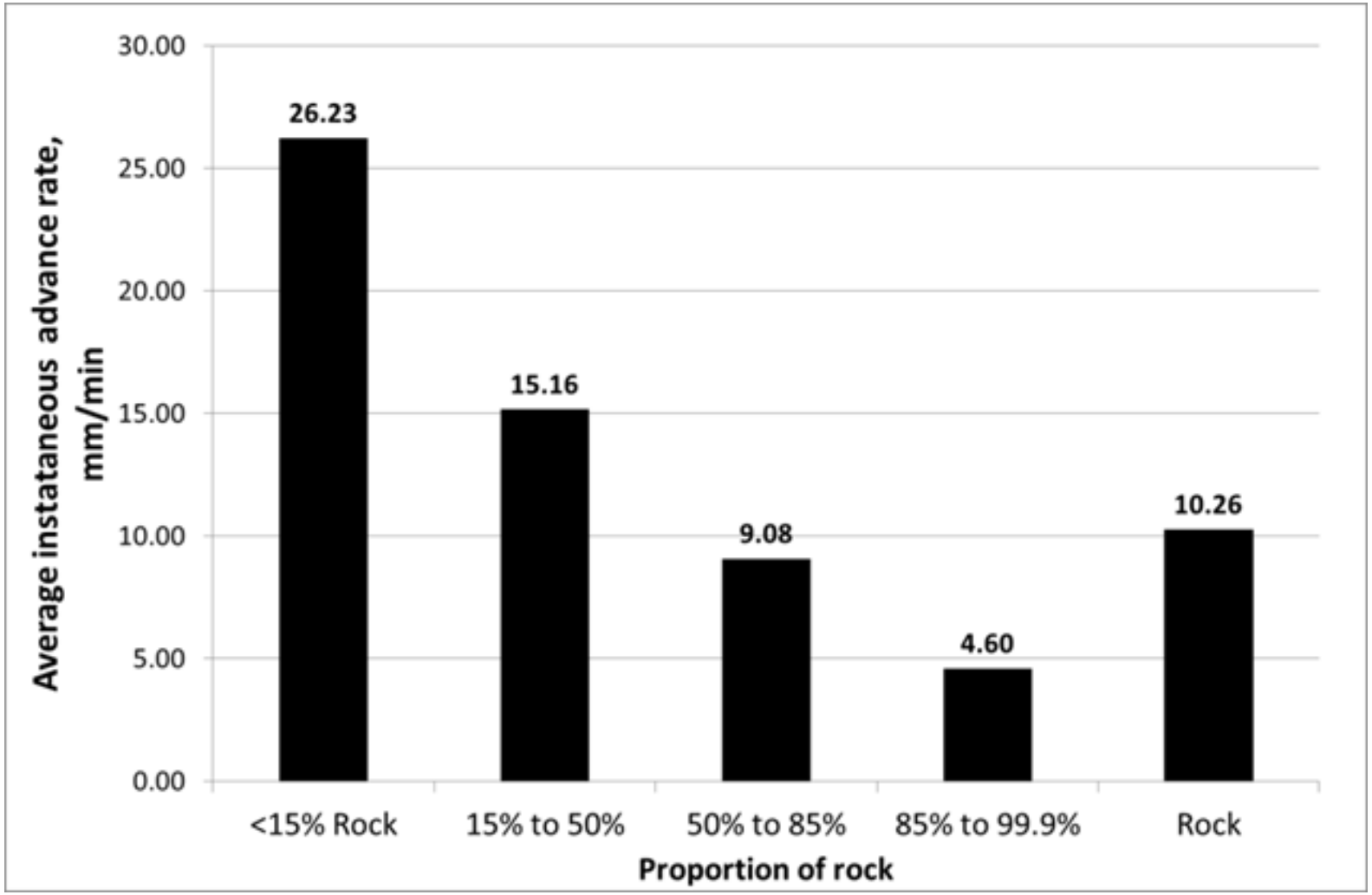
Use all of the data:

- Boreholes (within 3m)
- Face logs
- TBM data

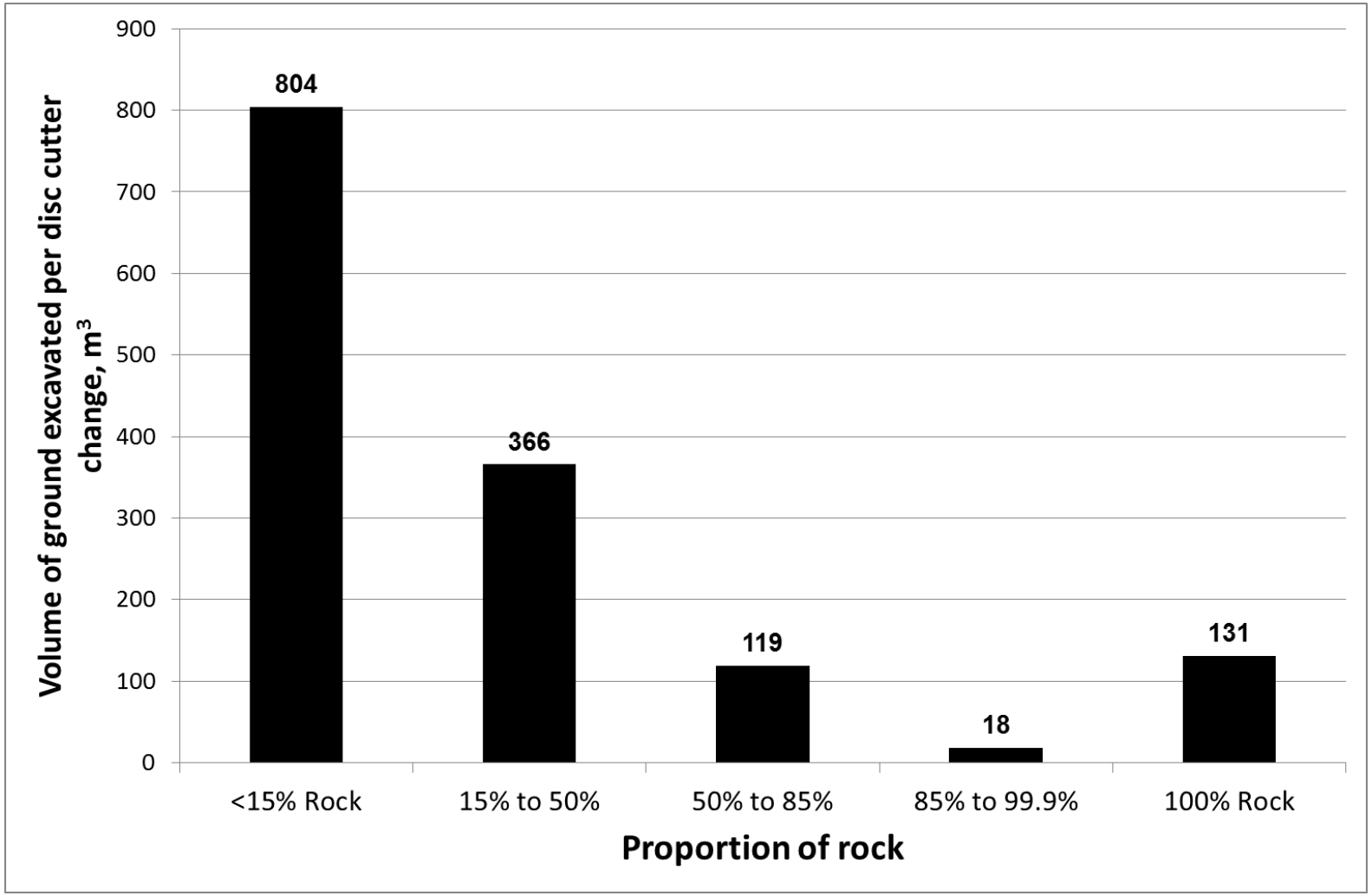
To reassess geology along the drive



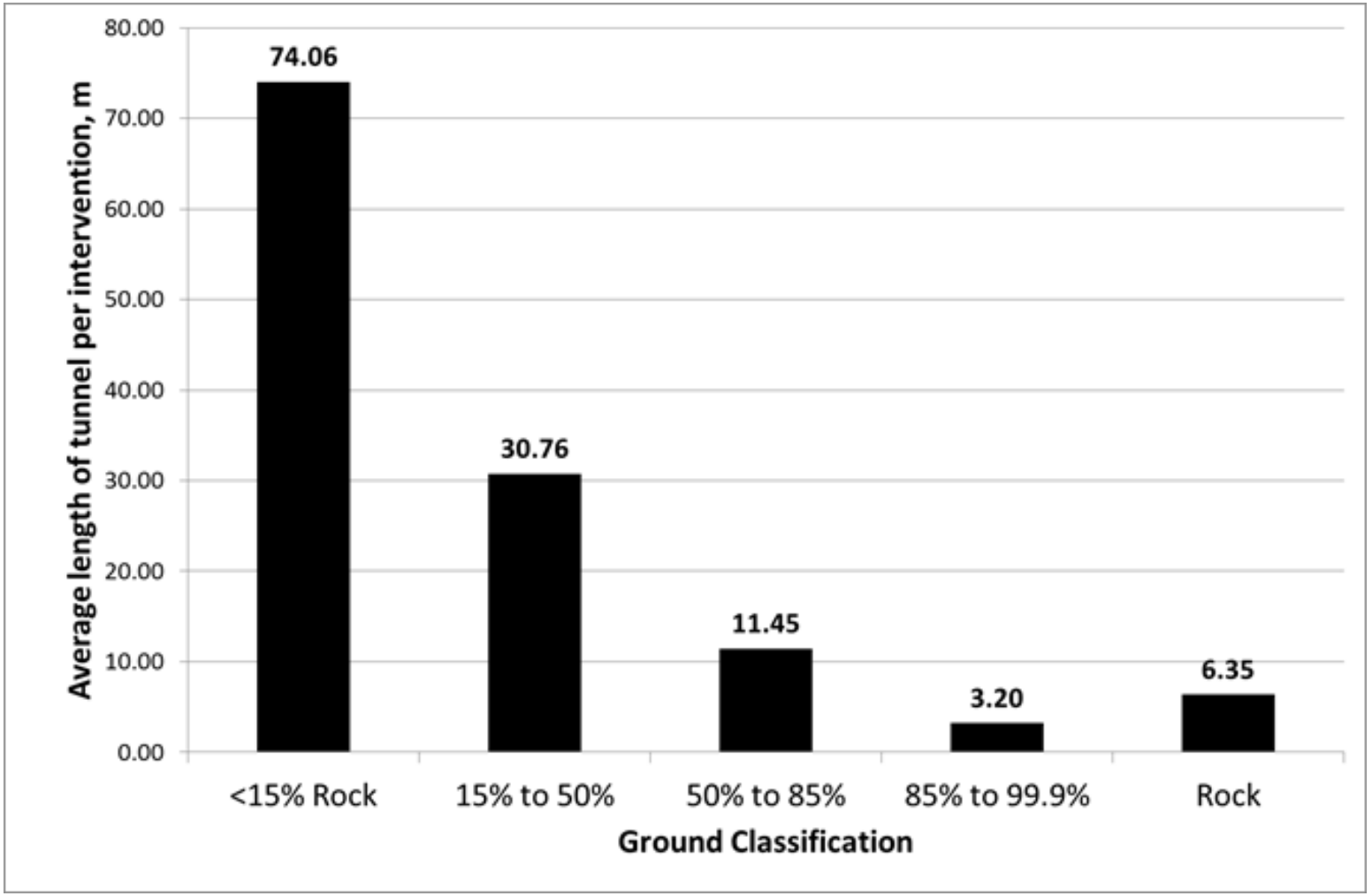
Tunnel A - Average instantaneous advance rate



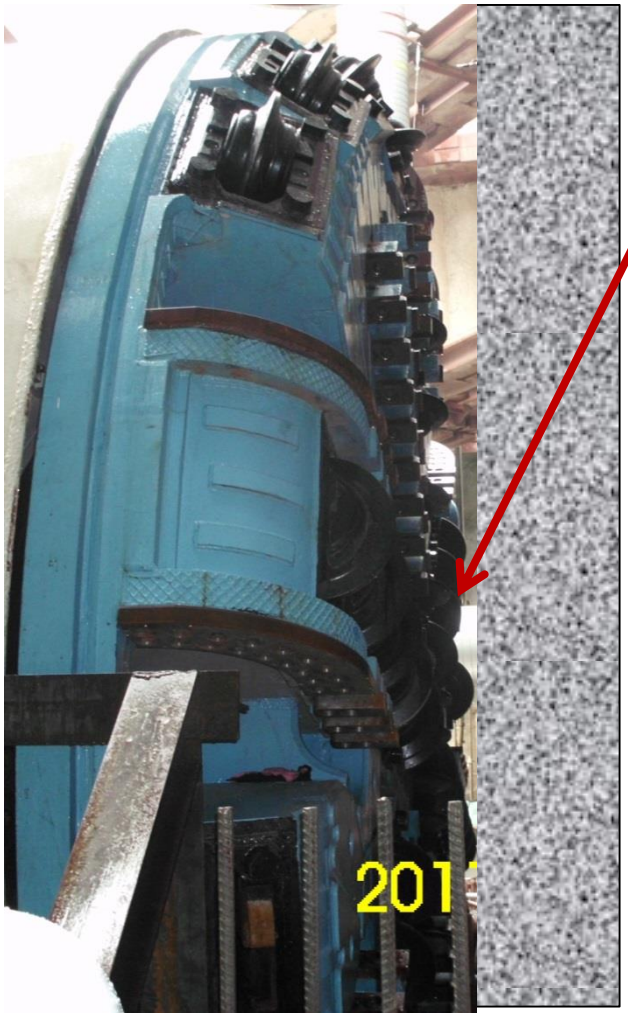
Tunnel A – m^3 per 17” disc



Tunnel A - Length of tunnel per intervention



Coarse particle clogging



‘Tool gap’. Typically 150mm to 200mm

Material we are trying to get to flow, when cutting rock – mostly 50mm to 75mm rock fragments. In EPB mode under high contact forces.

Components of time for TBM tunnelling

- Ground related
  - TBM advancing
  - Intervention time
- Not ground related
  - Ring build
  - Other maintenance
  - Extension of cables, pipework, rails
  - Other delays

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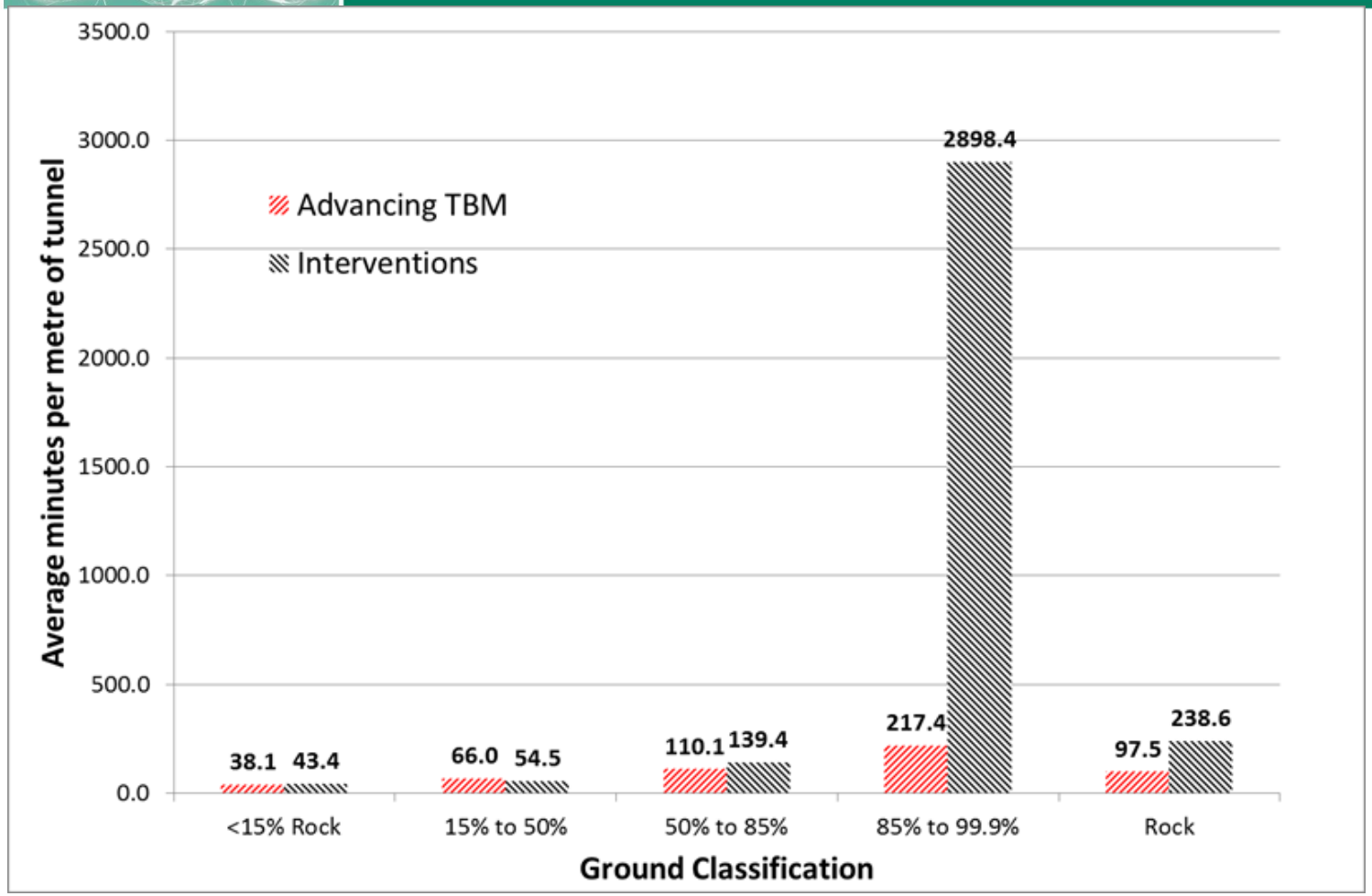
Tunnel A - Time per m of tunnel for advance, interventions



1.65% of the tunnel drive in 85% to 99.9% rock

Required 33% of the total time for TBM advance + interventions

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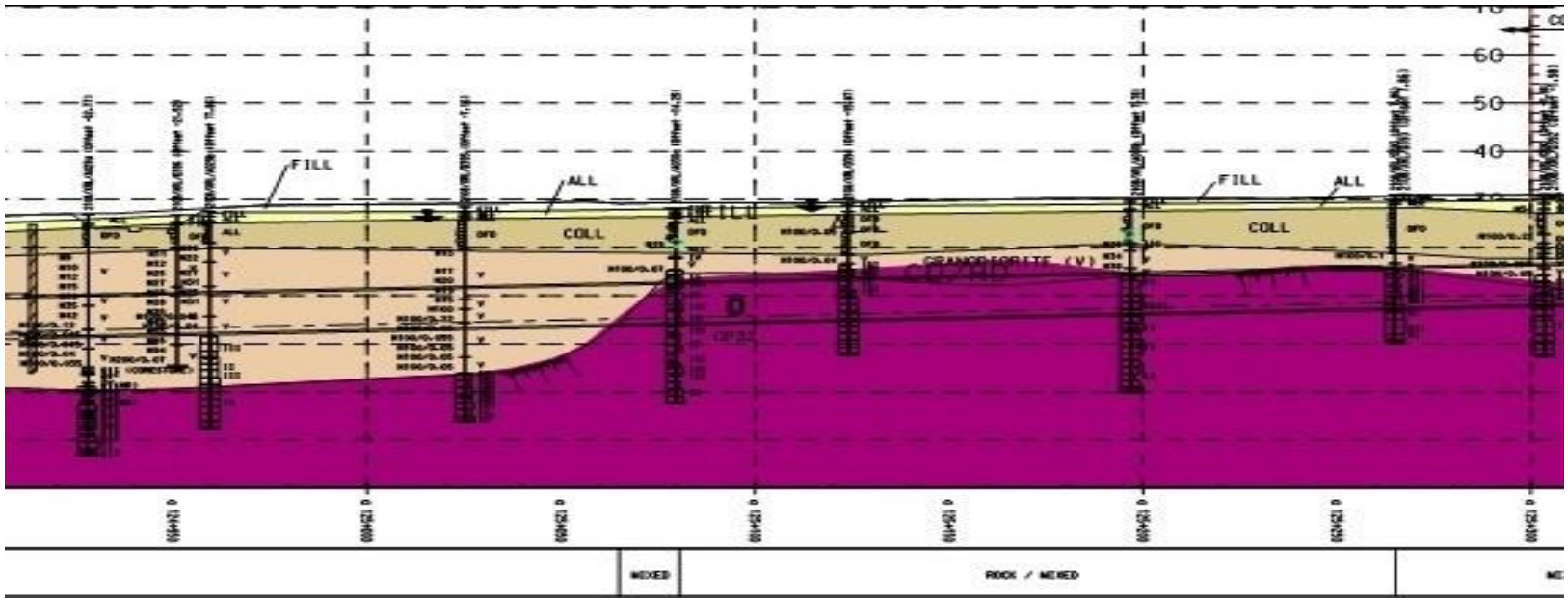
EPB in mixed ground

- In mixed ground of soil and strong rock, with >50% rock:
  - Very slow advance speed
  - Very rapid tool wear & damage
  - Very frequent interventions
  - Very long interventions
  - High heat, with extended flushing required to make safe for intervention
- Extended flushing, long & frequent interventions increase risk of instability/sinkhole formation

Tunnel B – EPB drive in mixed ground of mainly Granodiorite rock



Compared with Tunnel A:

- Different rock
- Different contractor
- Different TBM manufacturer
- A lot more tunnelling in mixed ground, high % rock

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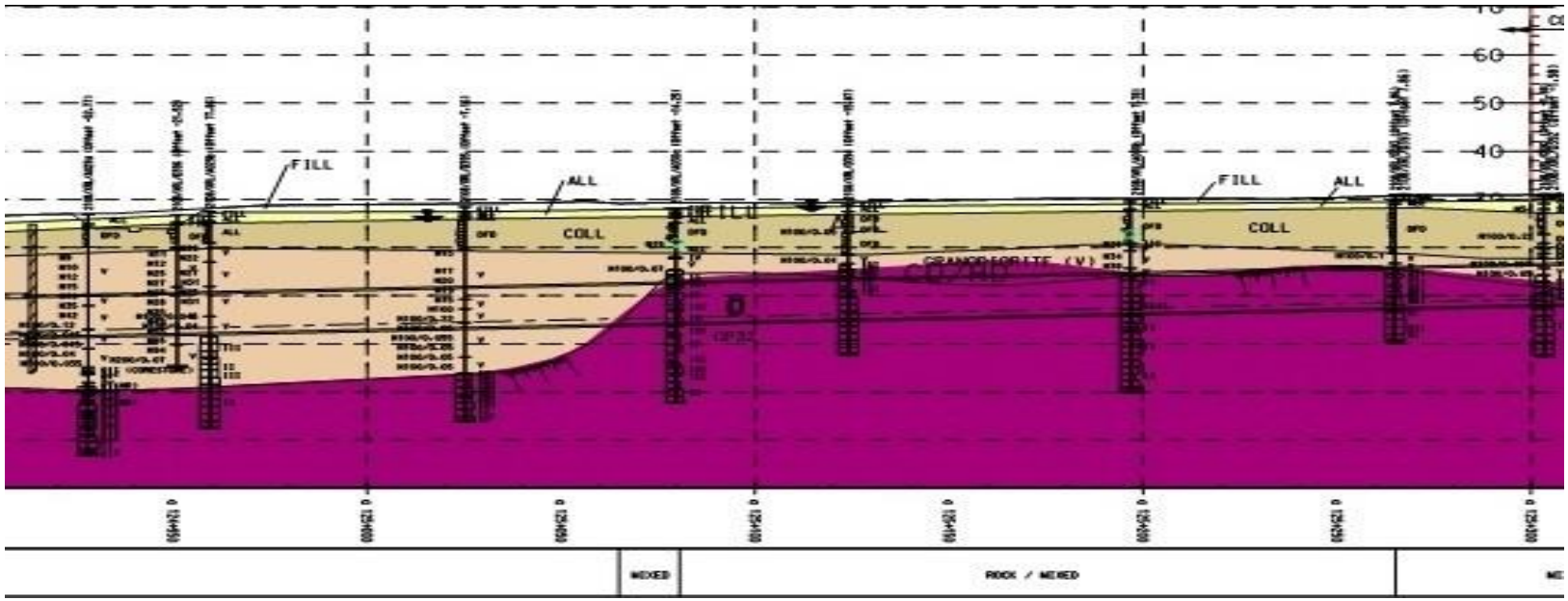
Tunnel B – EPB drive in mixed ground of mainly Granodiorite rock



CAI av. = 3.6

256m of tunnelling
116 interventions under compressed air
513 No. 17” discs changed
9.5 months to tunnel (av. 6.2m/week)

Mostly driven in semi-EPB mode,
using compressed air above axis level

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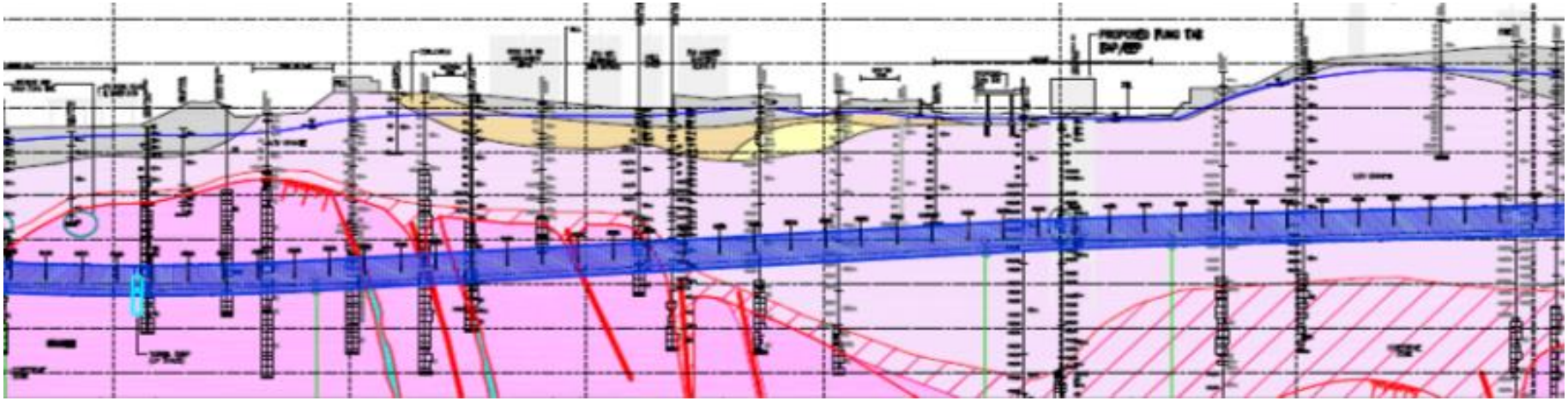
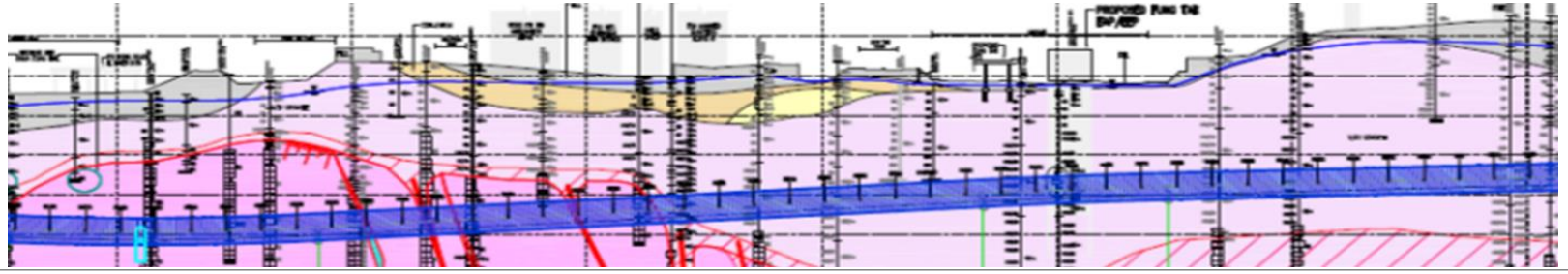
Tunnel C – Slurry drive in mixed ground

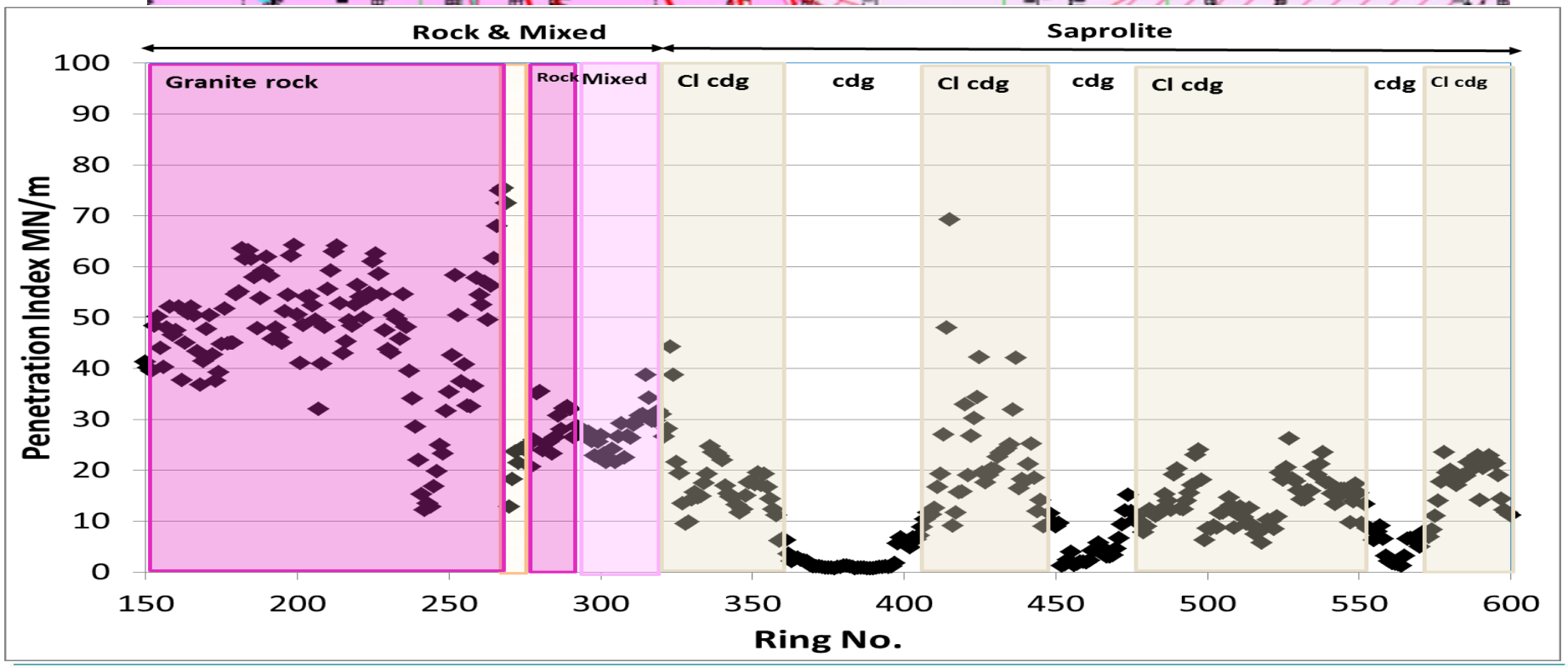
- 7.46m diameter slurry TBM drive
- 44 No 19” discs
- 1.5m long rings
- Granite rock and soil grades of weathered granite. Numerous intrusive dykes of rhyolite and basalt
- Average Cherchar Abrasion Index (CAI) of rock: 4.6, quartz content 30%



→ Direction of drive

Tunnel C – Penetration Index





Face pressure > water pressure in all conditions

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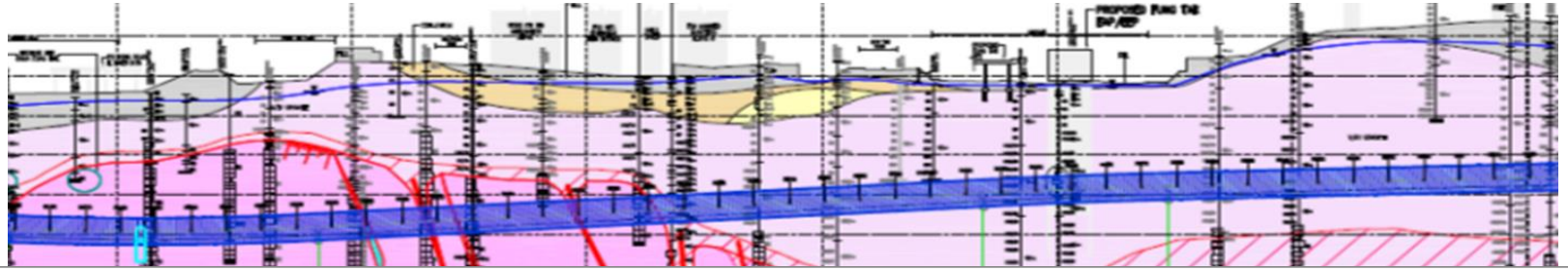
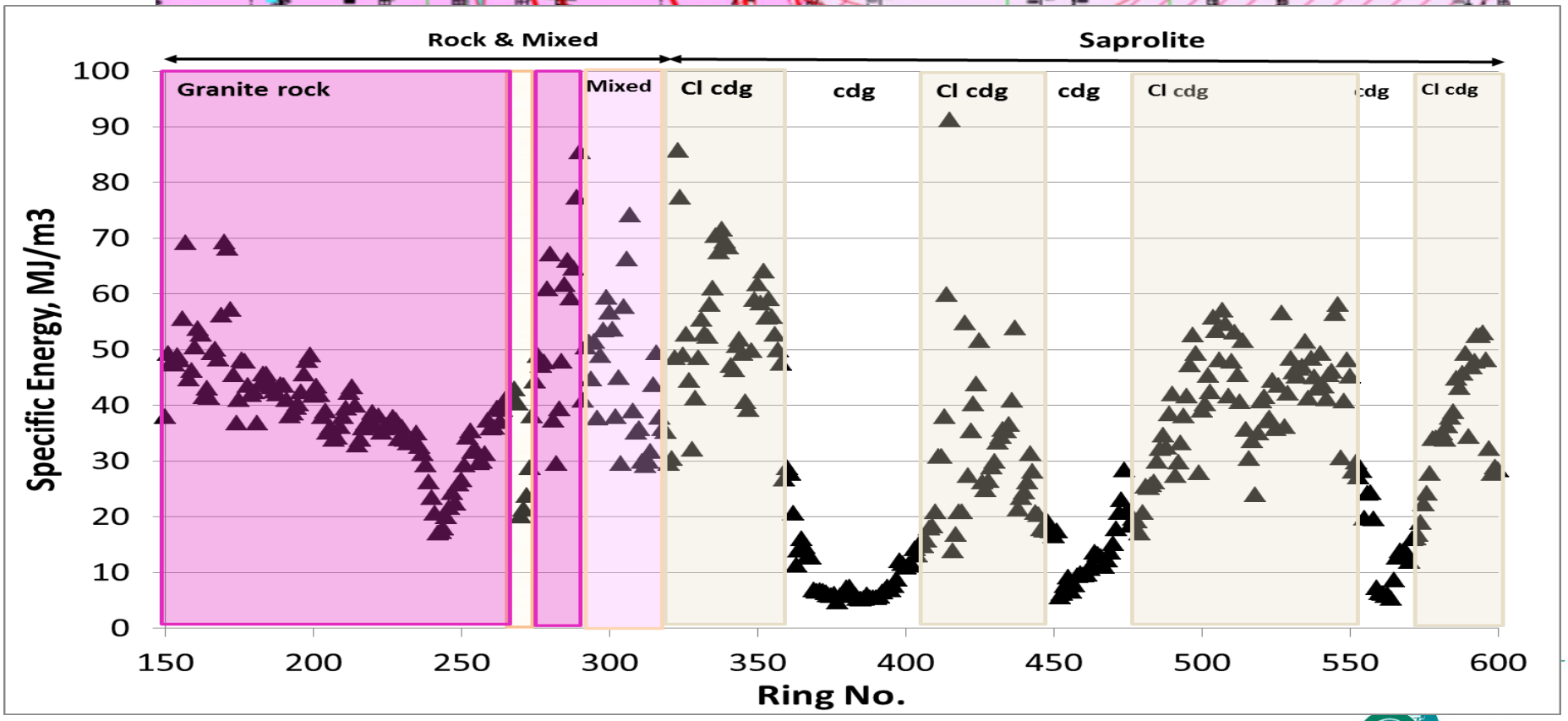
Tunnel C Fine particle clogging

- Zones of Completely Decomposed Granite were unusually sticky
- Smectites (swelling clay minerals) present

Tunnel C – Specific Energy





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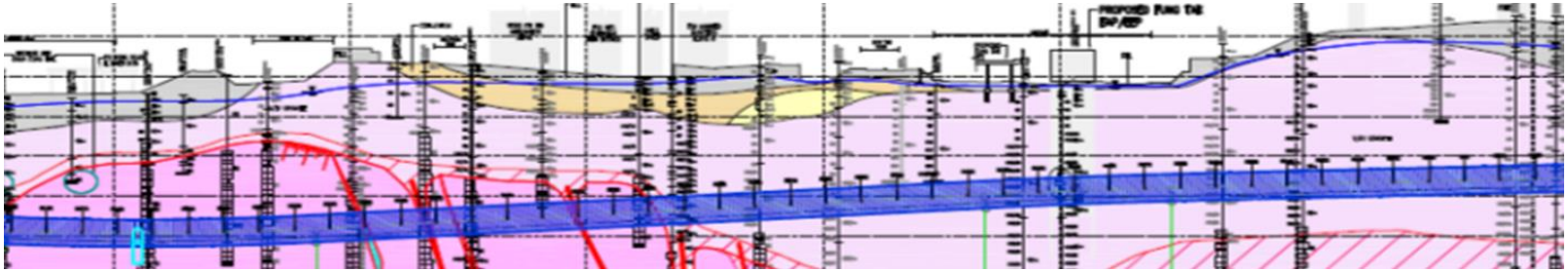
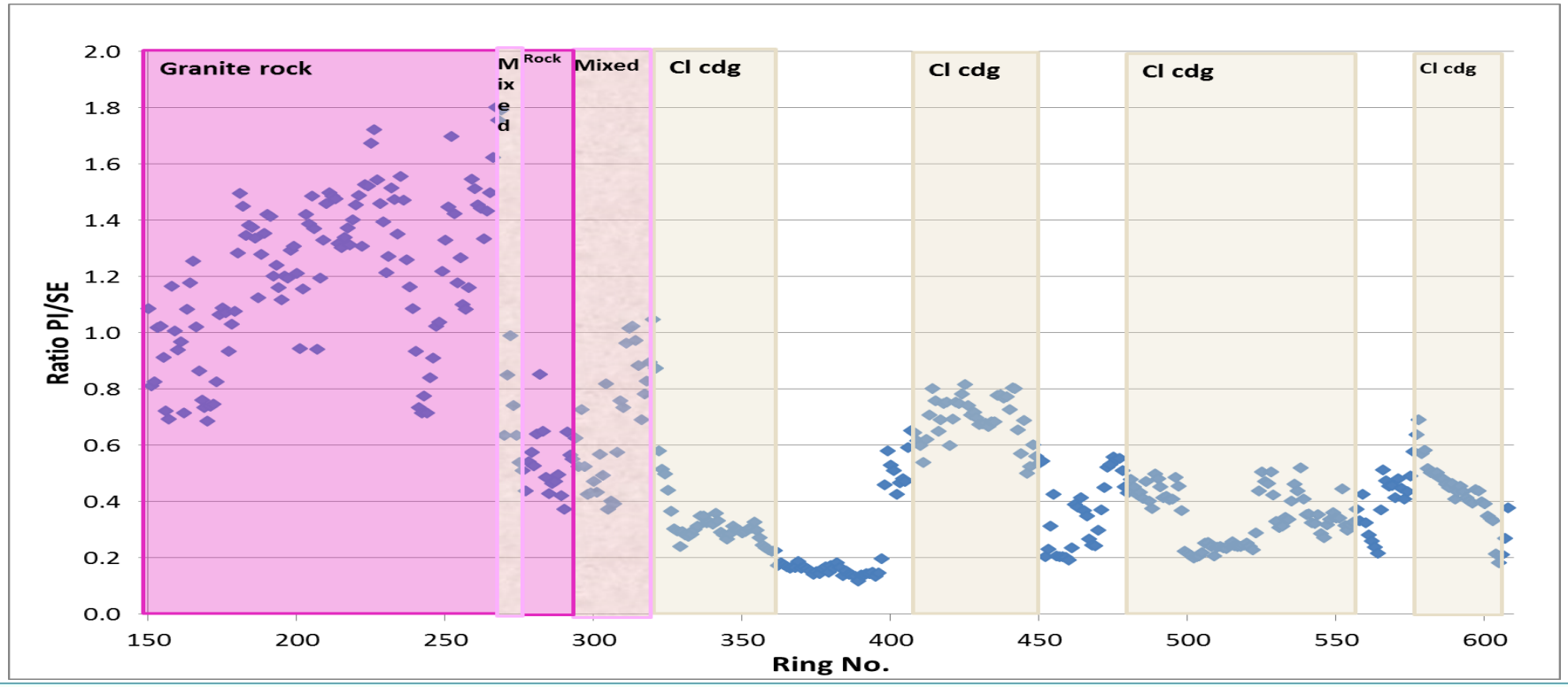
Tunnel C – PI/SE





PI/SE – Tunnel C

- Effectively advance force/torque
- High (>1) in intact rock – need a lot of force on the tools, compared with torque
- Moderate (0.4 to 1), could be:
  - Highly fractured rock
  - Mixed Ground
  - Clogging clayey cdg
- Low (<0.4) in Granular soil (cdg): cutting action of the scrapers is based on torque, rather than force
- Values probably depend on TBM design and operation, and need to be customised for each tunnel

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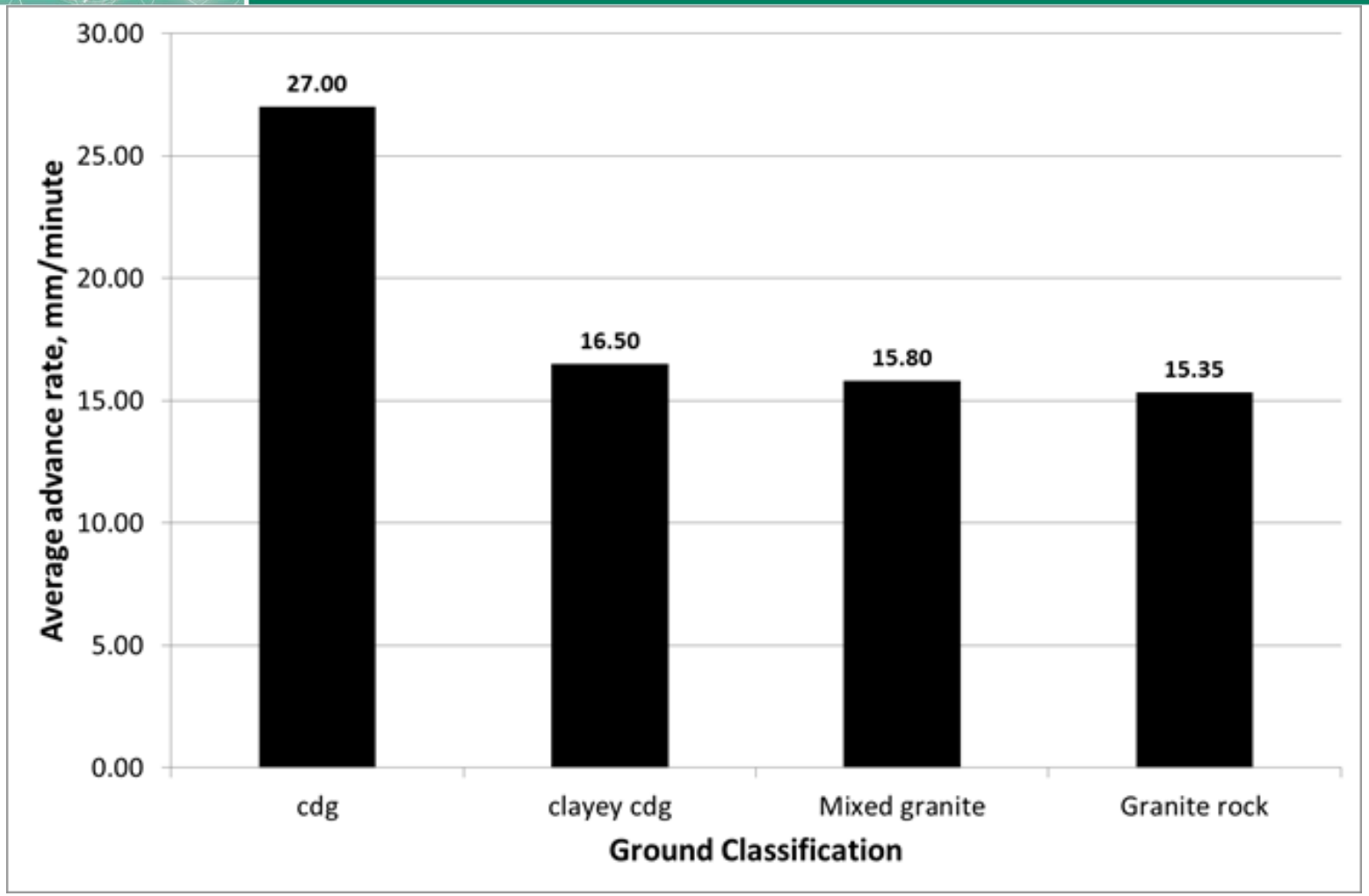
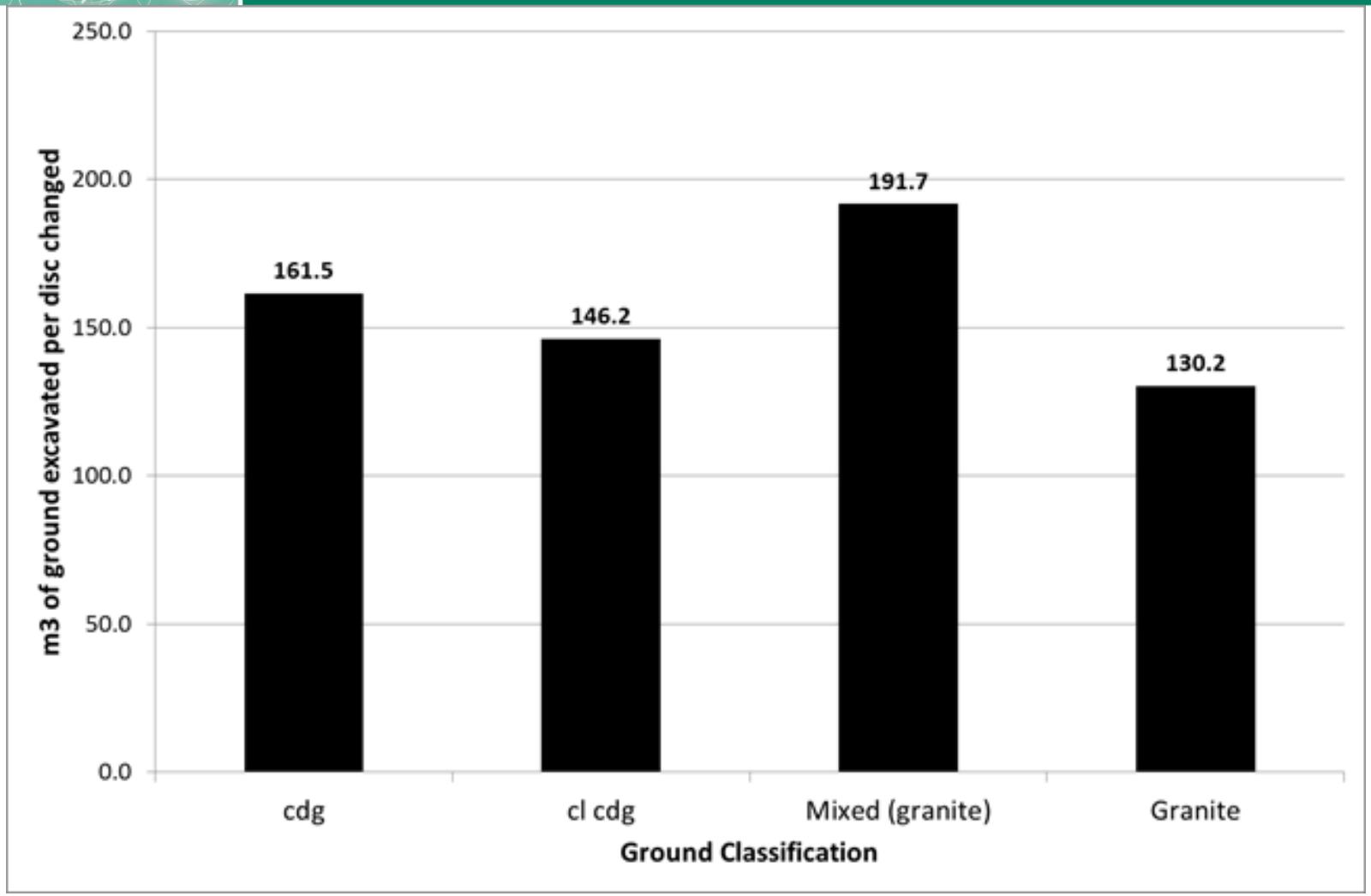
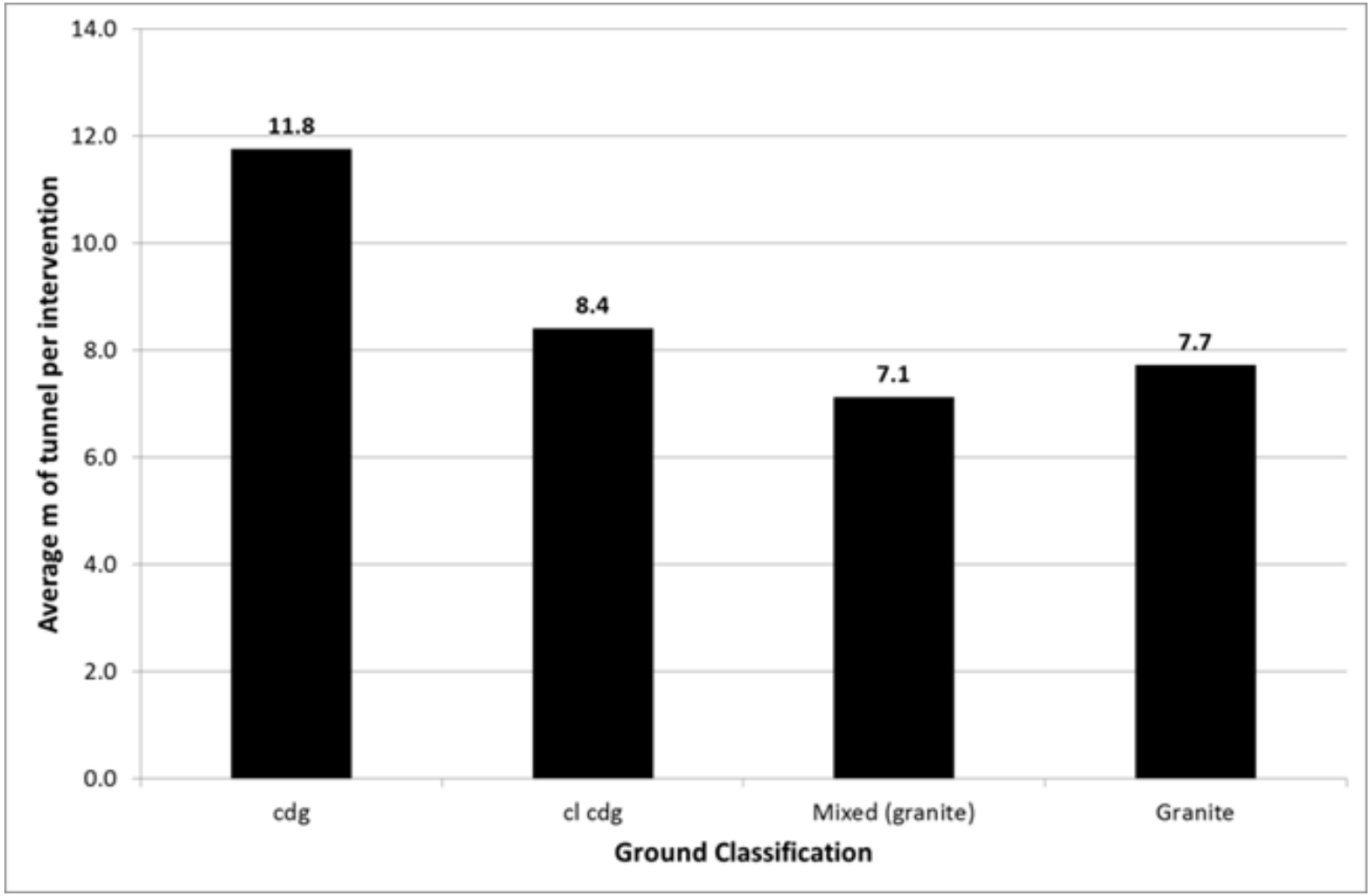
Tunnel C - Average instantaneous advance rate



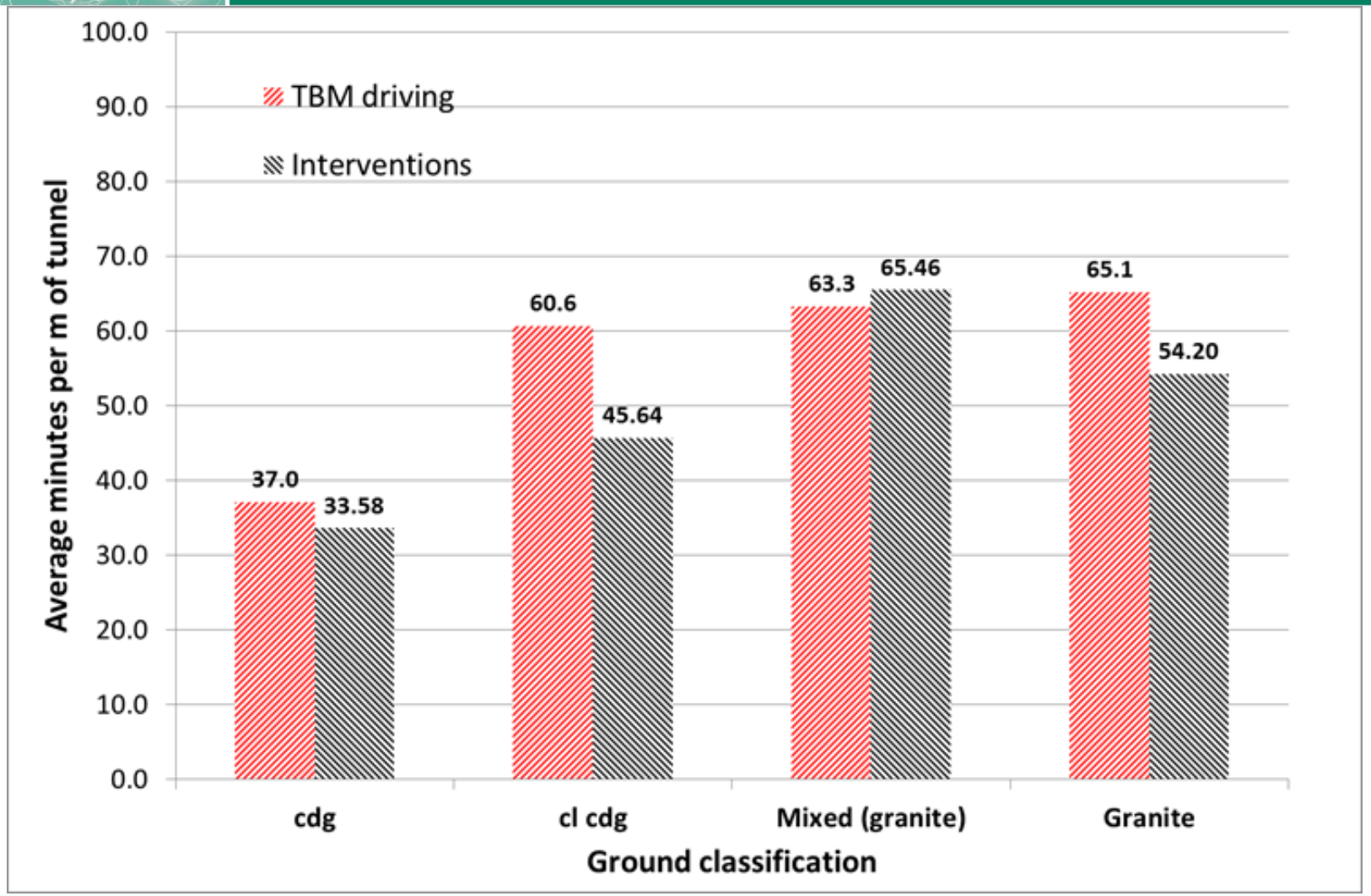
Tunnel C – m^3 per 19” disc



Tunnel C - Length of tunnel per intervention



Tunnel C - Time per m of tunnel for advance, interventions



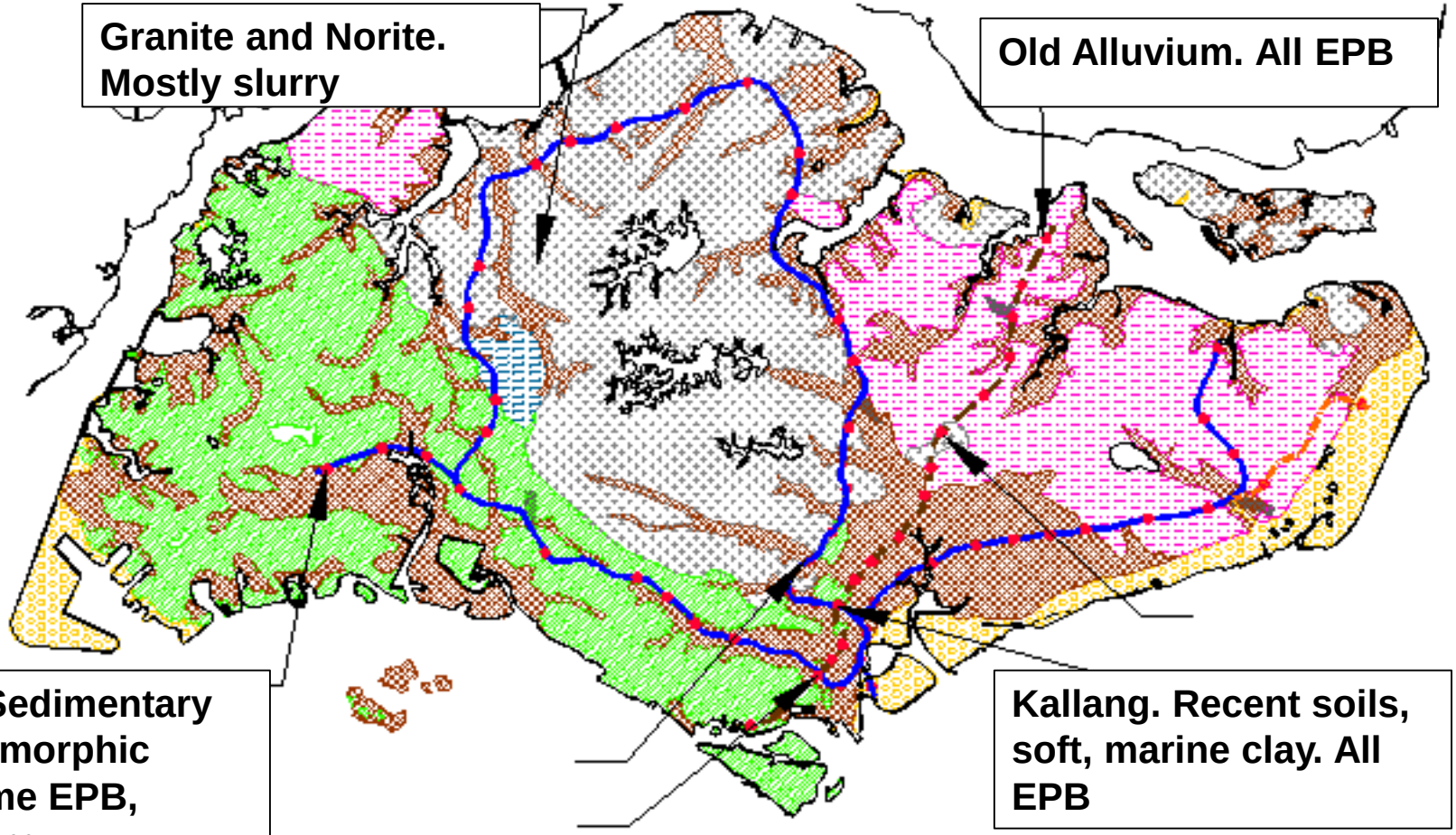
Tunnel C

- Graphs part of assessment of first tunnel drive
- Assessment used to justify:
  - Reduced rotation speed in clayey cdg
  - TBM for second, parallel drive altered, in particular to incorporate flushing at cutterhead
  - Slurry treatment plant upgraded to better deal with increased fines
  - Second drive had improved performance, compared with first, in clayey cdg
  - Comparison with Tunnels A and B shows how slurry shield operated in mixed ground with high % of strong rock without the problems experienced with the EPB TBMs at Tunnels A and B
  - Time for interventions is a major factor in TBM tunnelling in weathered rock

30 years of PTBMs in Singapore (>5m diameter)

Major Projects		TBMs: Numbers used	
Name	Tunnelling complete	EPB	Slurry
East-West Line	1987	2	-
North East Line (NEL)	2001	14	-
Deep Sewer Tunnels (1)	2005	8	-
Circle line (CCL)	2009	19	8
Downtown Line (DTL)	2014	42	9
Deep Cable Tunnels	In progress	3	11
Thomson – East Coast	In progress	28	23
Cross-Island Line	Planning	?	?
	Total	116+	51+

Singapore – current practice

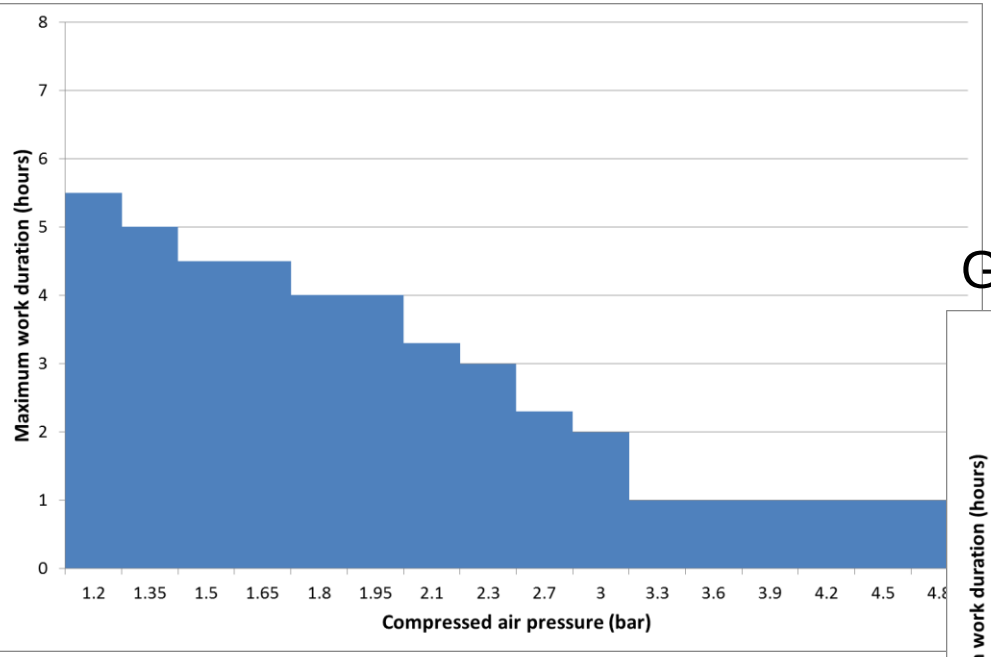


Mixed face tunnelling

- In Singapore and Hong Kong owners now commonly specify use of slurry TBMs in the most adverse mixed ground conditions. If owners don't specify, they will almost always get, in a competitive tender, an EPB, and, in adverse mixed ground conditions, the potential of long delays and large claims

Compressed air interventions – weathered rock

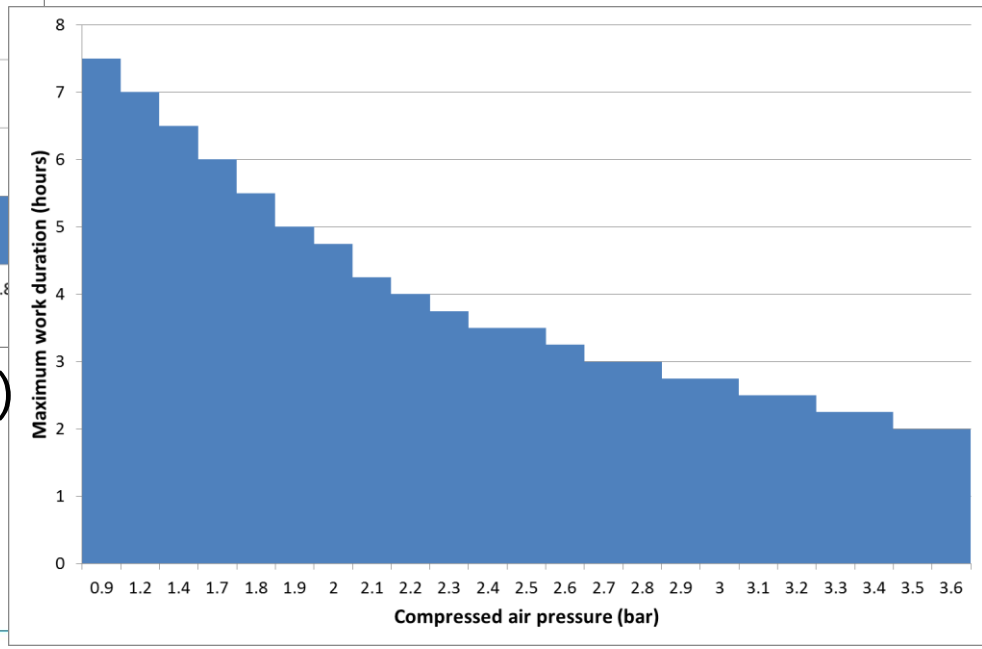
- Spending as long or longer on interventions as advancing the TBM



French tables (oxygen decompression)

Small reduction in pressure can significantly increase working time per shift for interventions, if safe to do so

German tables (oxygen decompression)



Deriving strength of rock from TBM parameters

Equations developed by Colorado School of Mines
For massive or widely jointed rock
Cubic relationship between UCS and advance speed, for given force on cutter
For typical mixed ground machines, only applicable to strong or stronger rock – below a UCS of 100MPa other factors control

For Strong or stronger rock, increase in UCS of 20% results in:

- 42% reduction in penetration/revolution
- 73% increase in disc consumption per m^3 excavated

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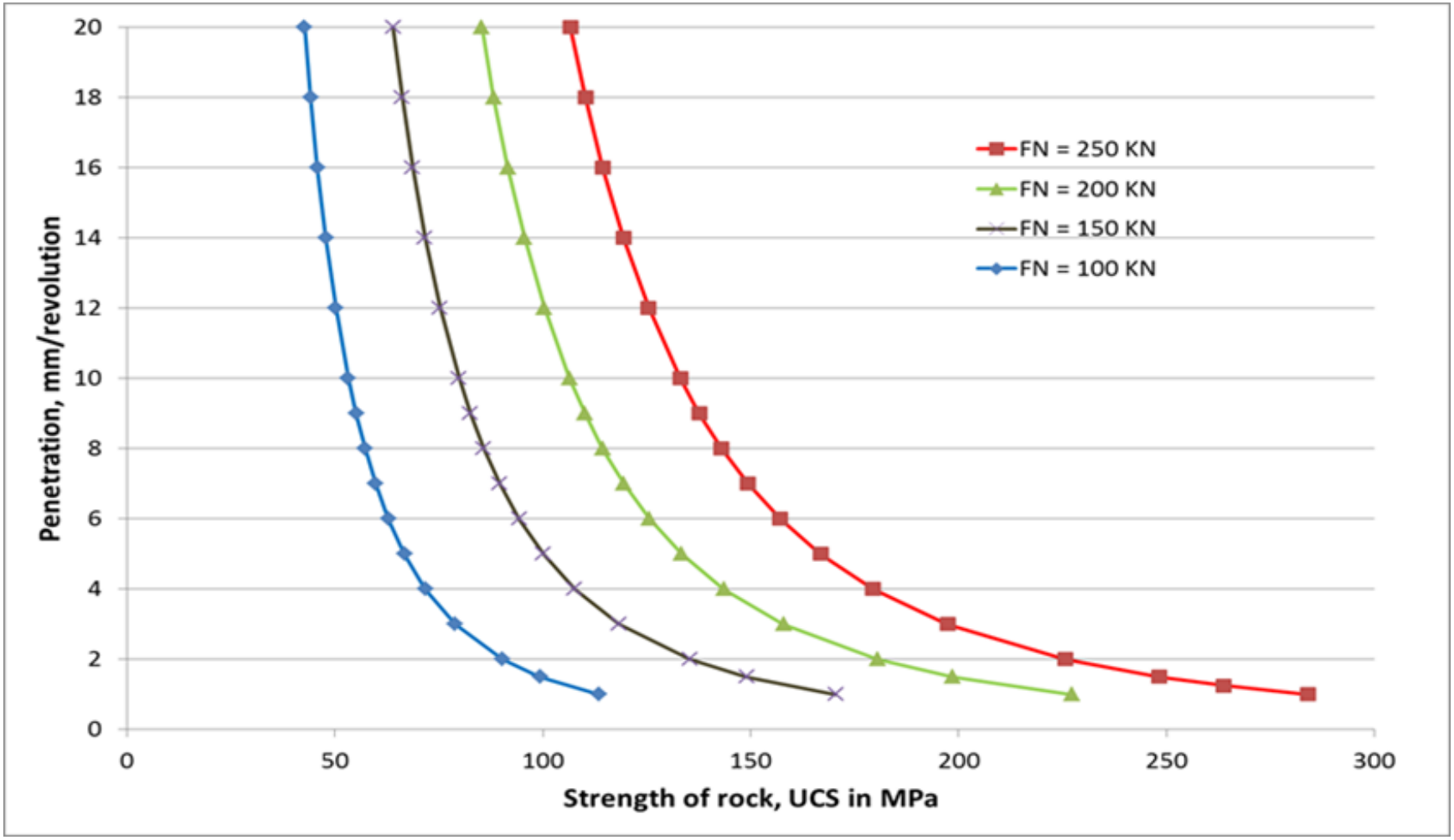
Penetration of 17” disc



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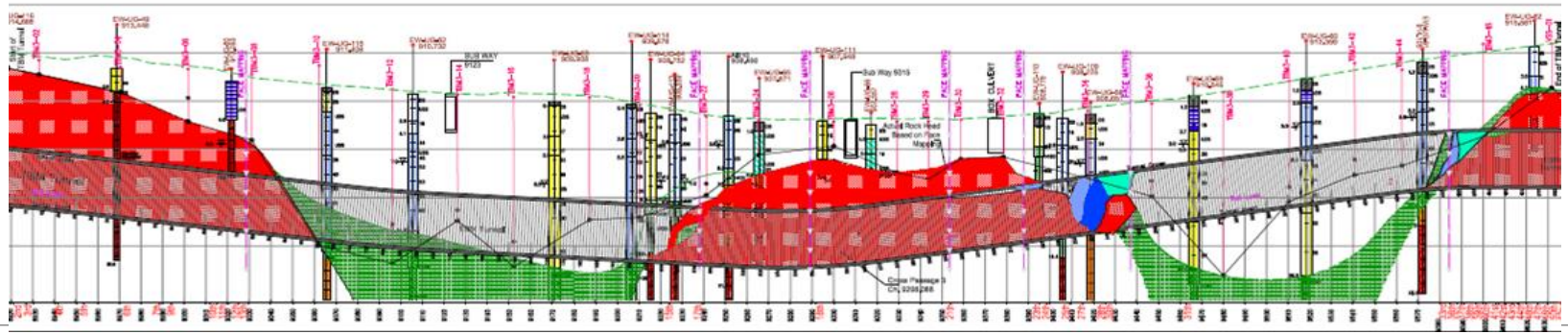
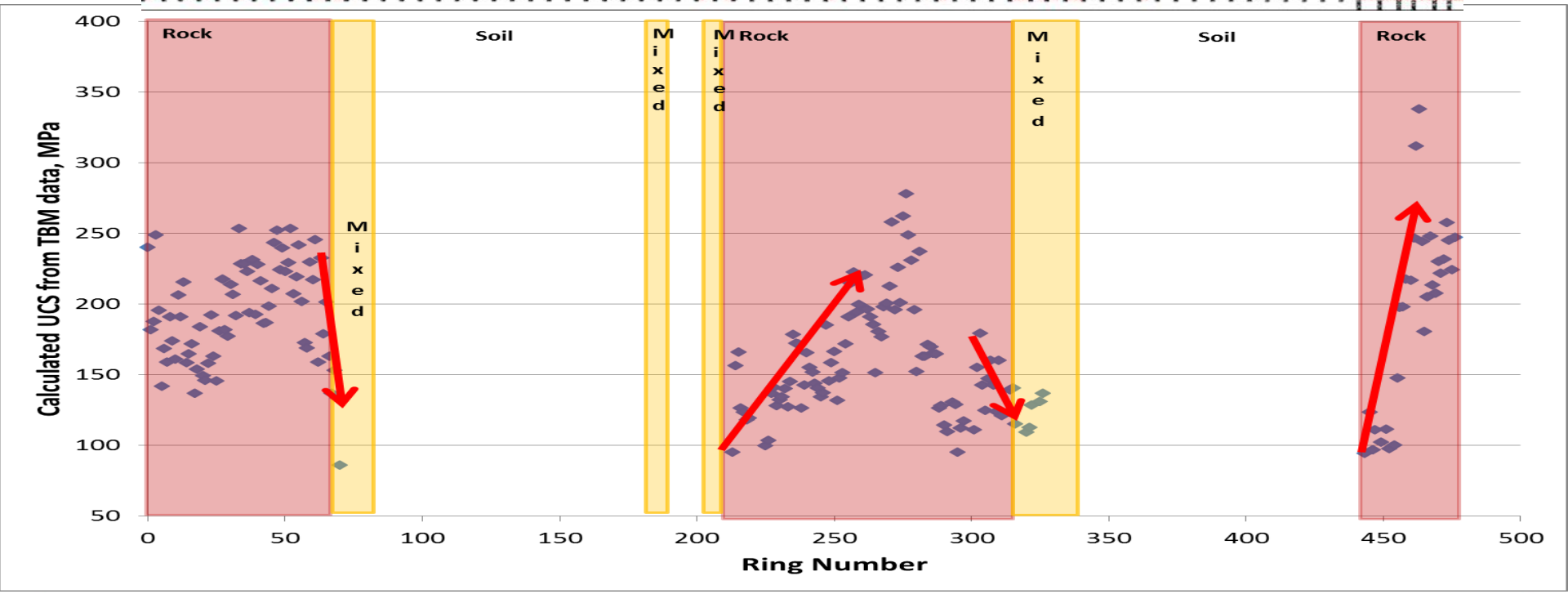
Derived strength of granitic Gneiss, Tunnel D





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Questions