ITACET Foundation
Foundation for Education and Training on Tunnelling and Underground Space Use

Società Italiana Gallerie
Italian Tunnelling Society

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Mechanized Tunnelling: challenging case histories

1st December 2016 - Rome

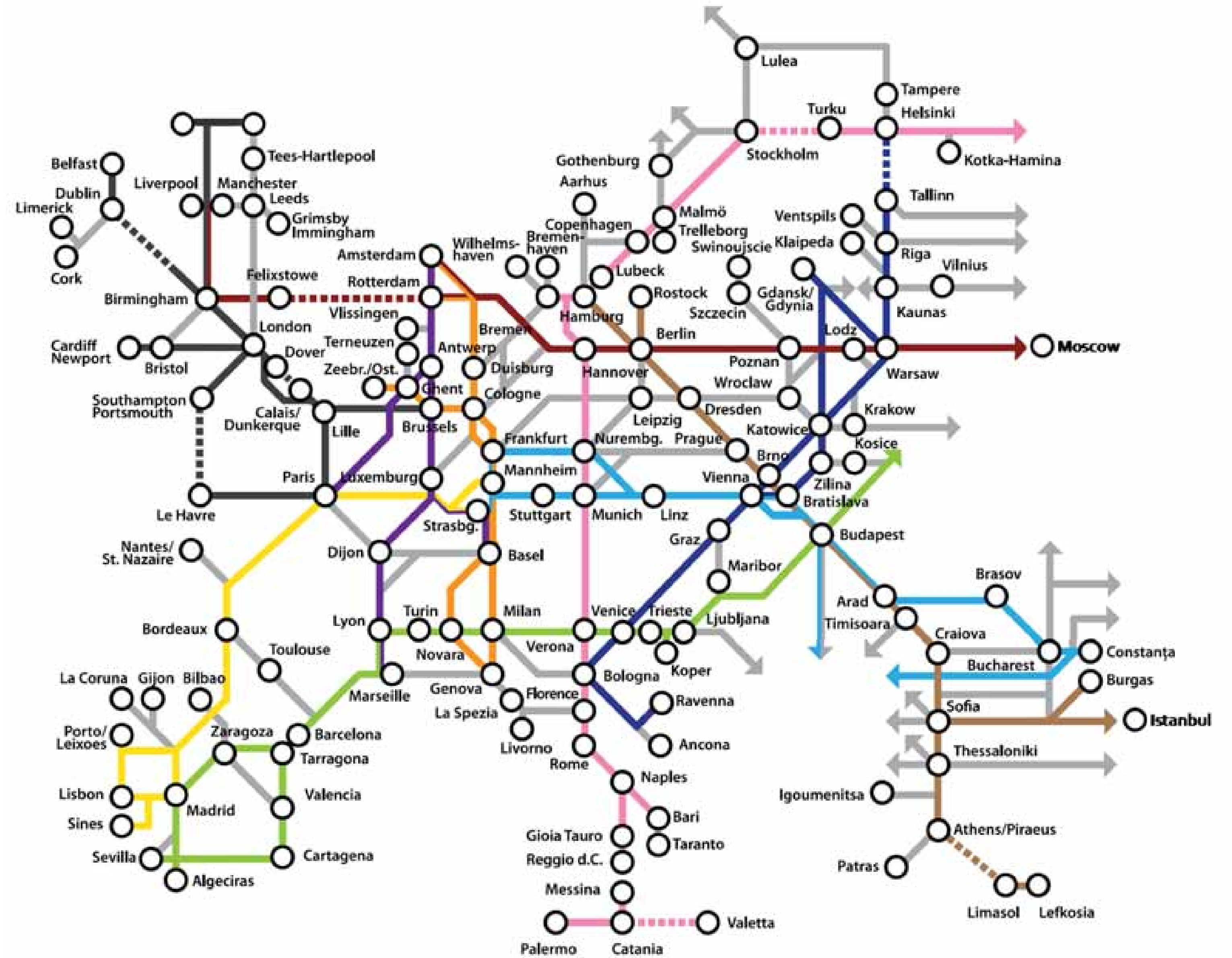
Case history of hard rock TBM

La Maddalena exploratory adit for the Turin-Lyon high speed railway base tunnel

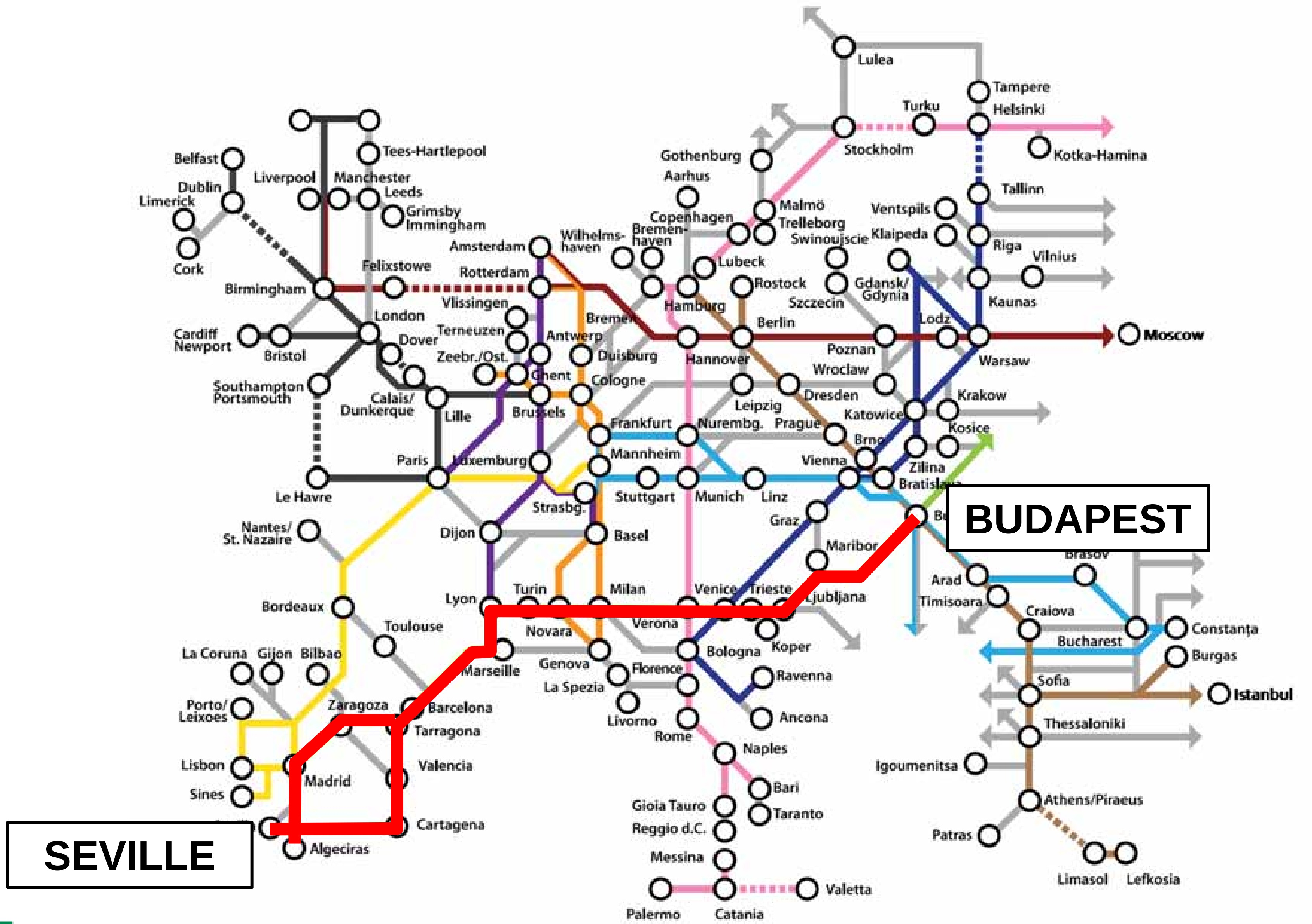
E. Fornari, G. Russo, L. Ferrero

GEODATA ENGINEERING

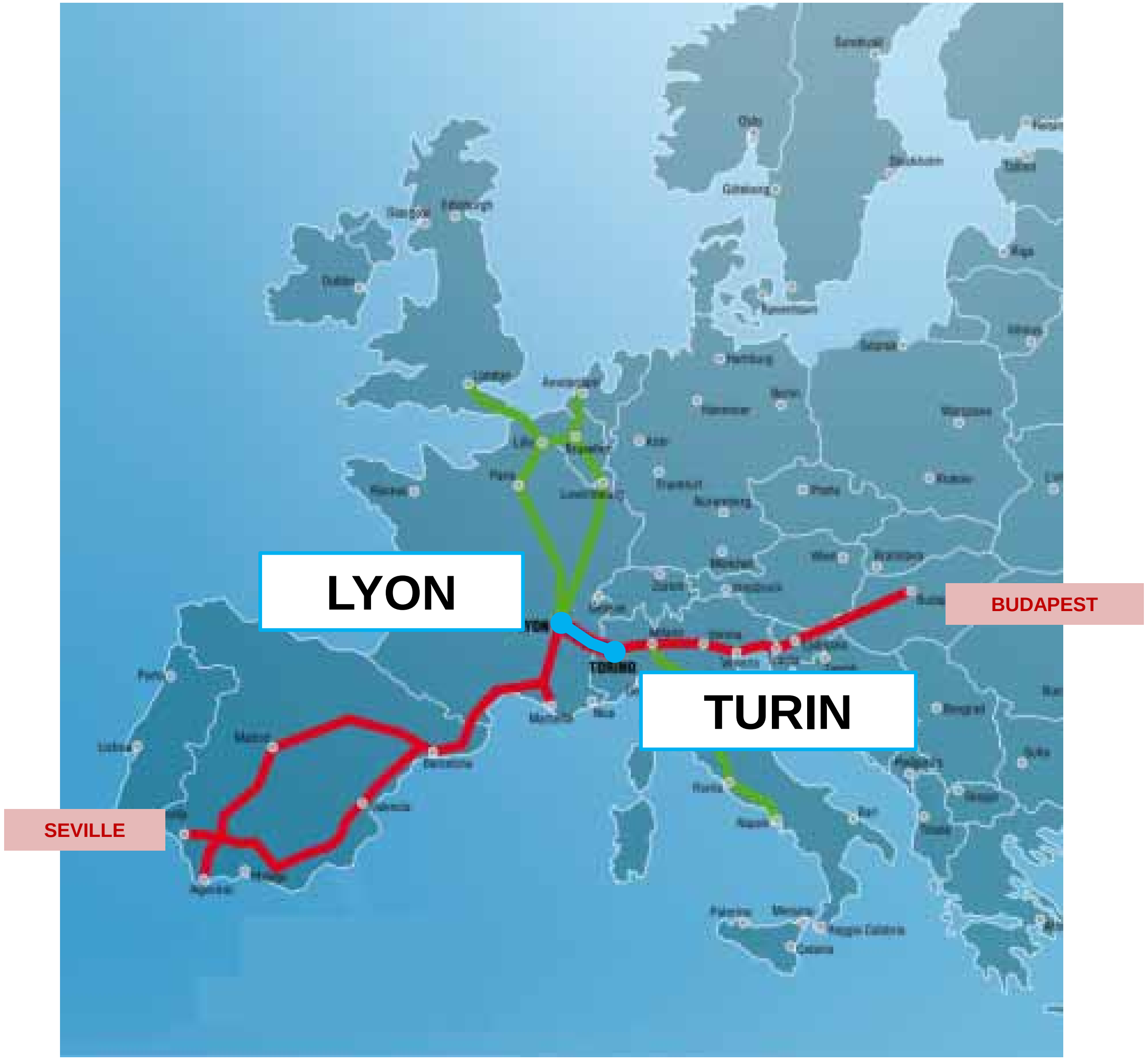
The HSR network in Europe: like a giant Metro-System connecting main cities



The “Mediterranean Corridor” will connect Seville (Spain) to Budapest (Hungary).

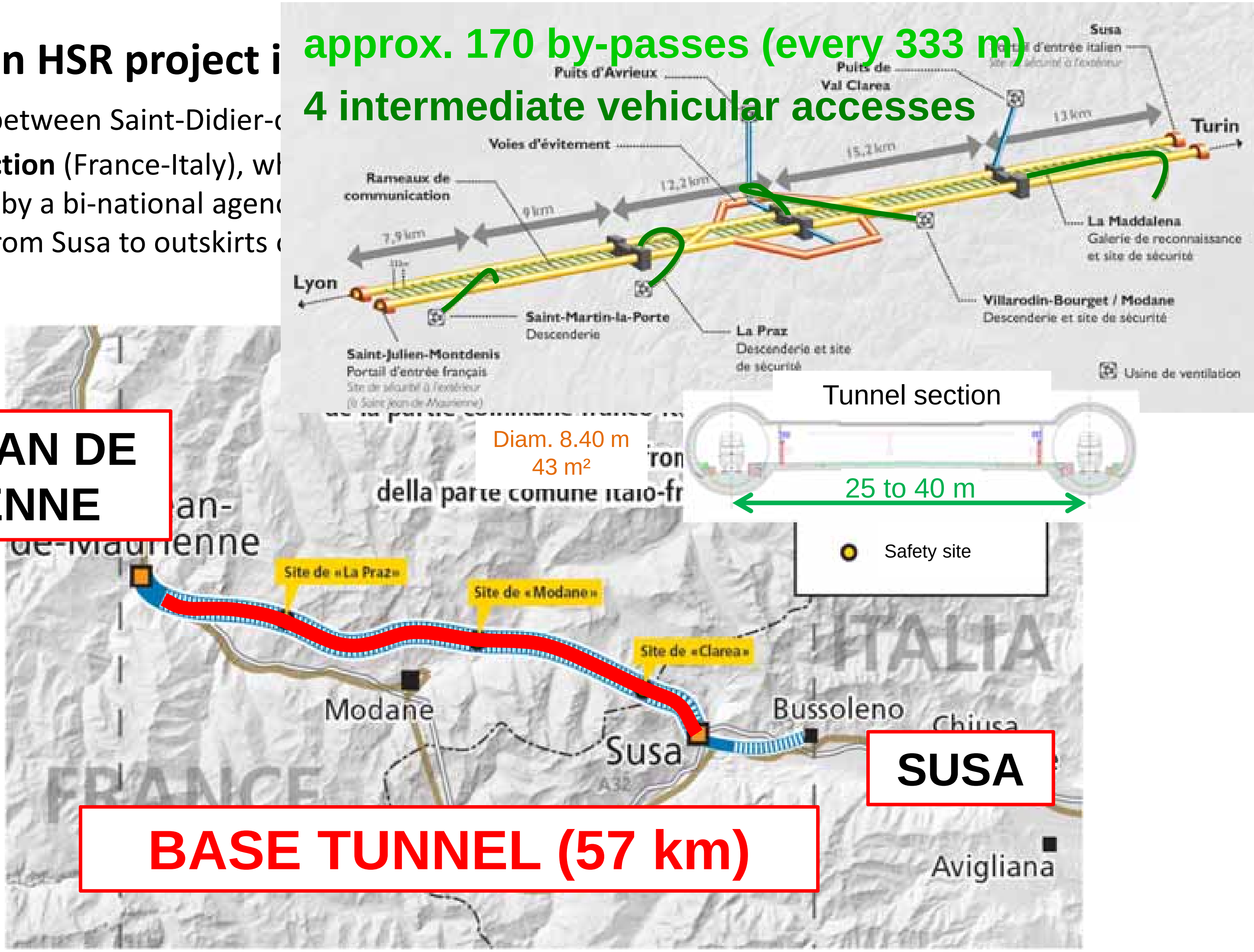


The Turin-Lyon high-speed rail project is halfway along the future "Mediterranean Corridor" from Seville (Spain) to Budapest (Hungary).



The Turin-Lyon HSR project i

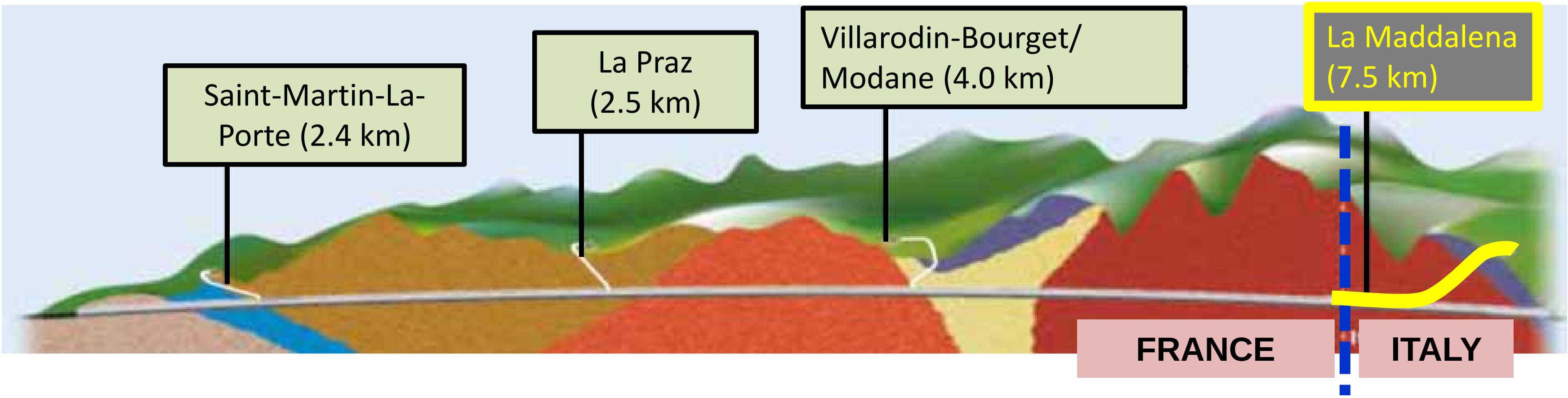
- **French section**, between Saint-Didier-c
- **International section** (France-Italy), wh (Italy), managed by a bi-national agenc
- **Italian section**, from Susa to outskirts c

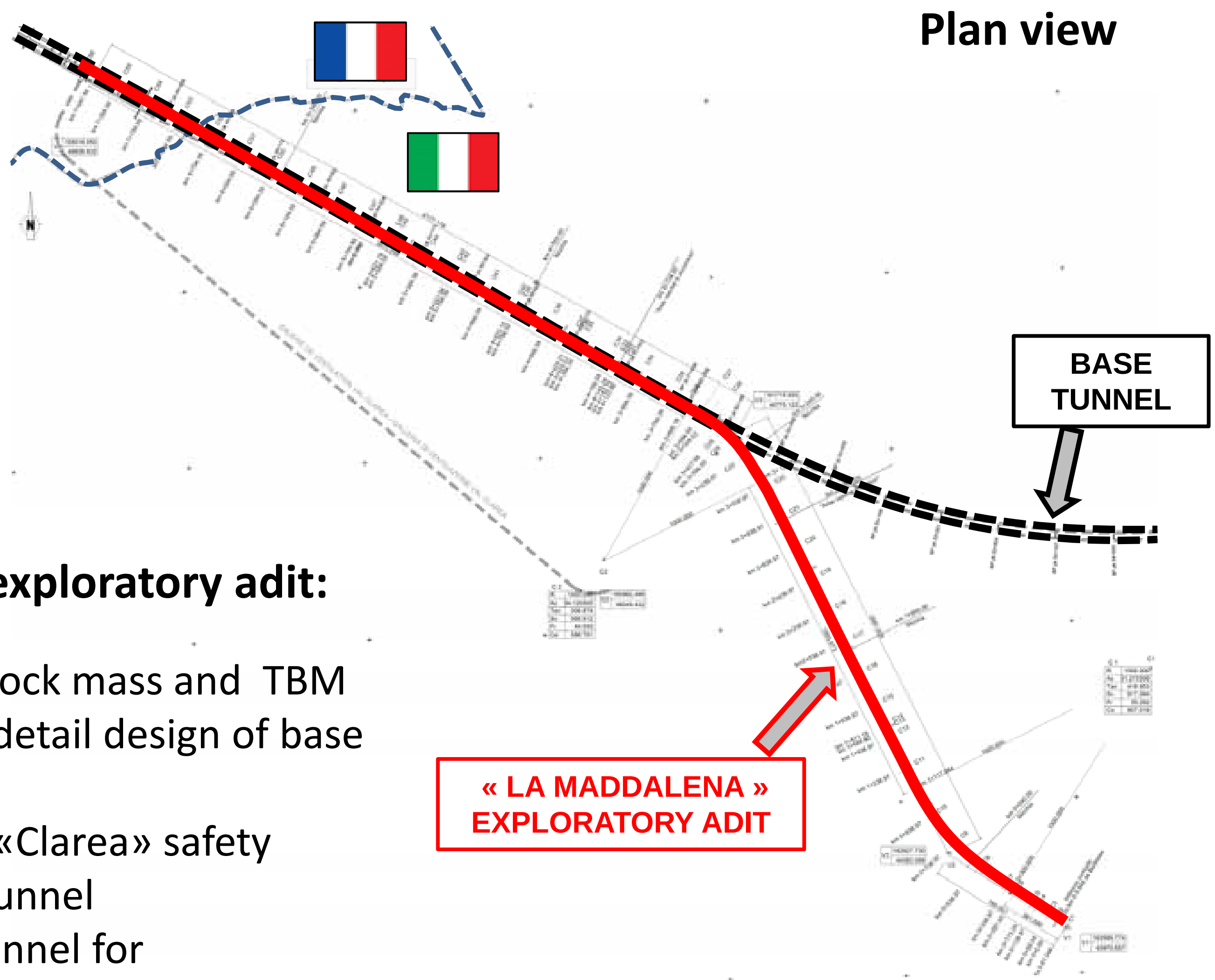


The project includes a 57 km-long Alpine base tunnel, whose construction will be starting soon.

The base tunnel has four adits:

- three in France (all completed)
- one in Italy (under completion) – **La Maddalena**.

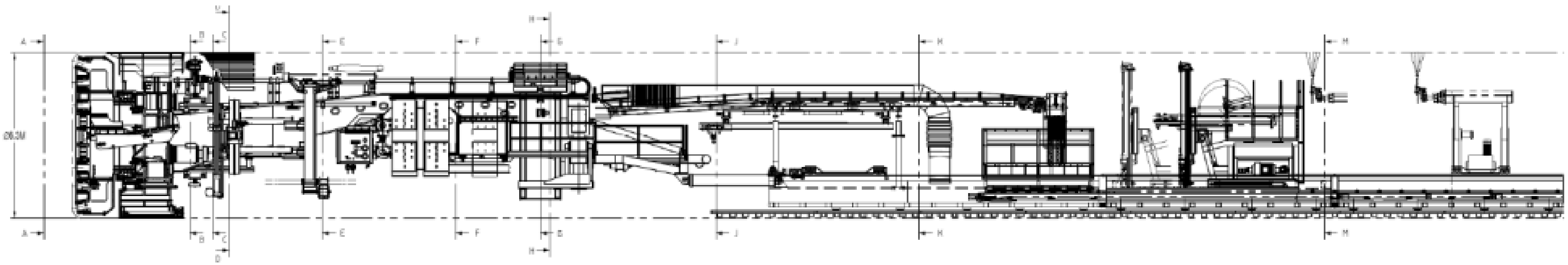




Scope of «La Maddalena» exploratory adit:

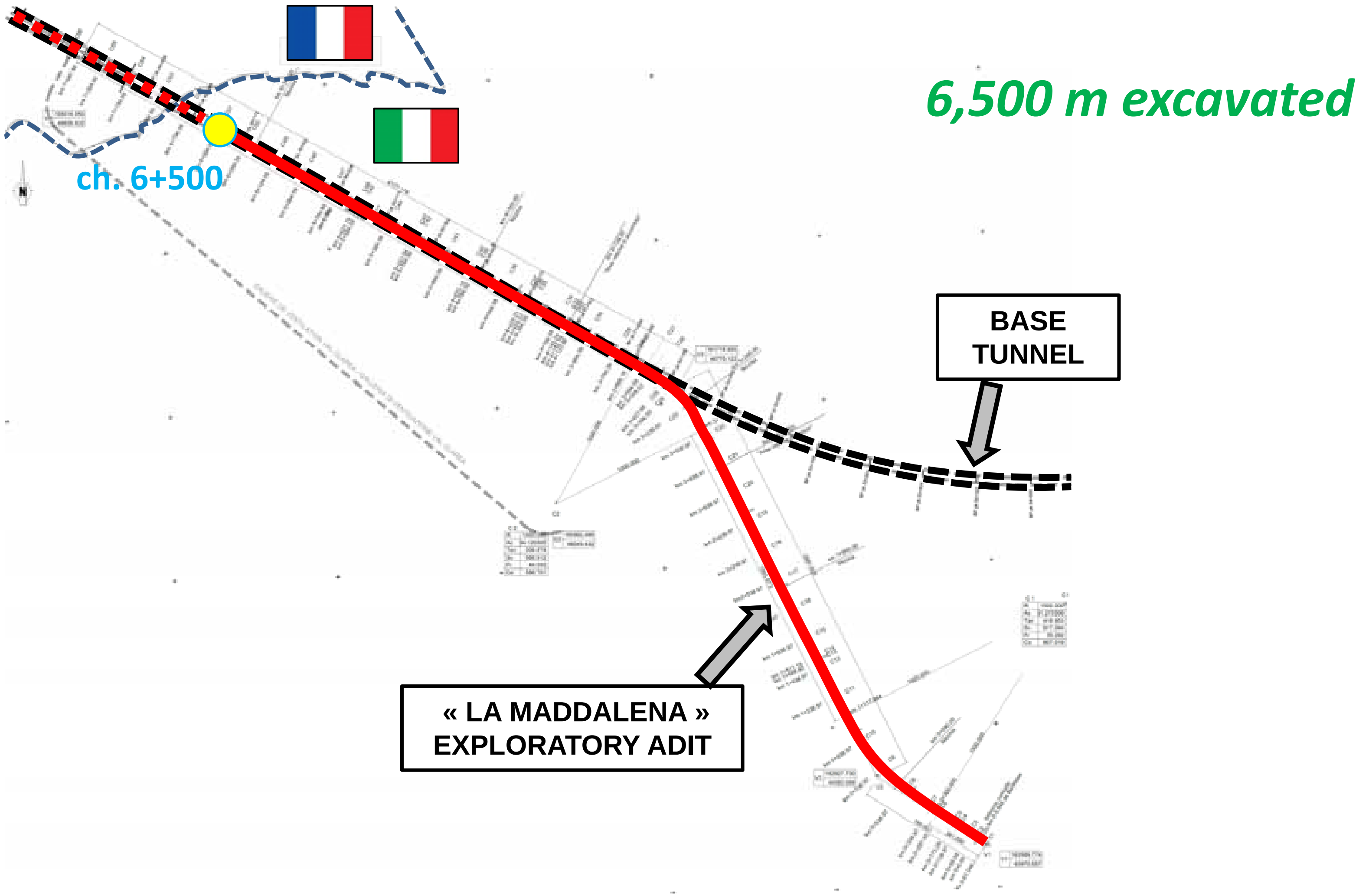
- **Investigation** of rock mass and TBM performance for detail design of base tunnel
- **Construction** of «Clarea» safety cavern on base tunnel
- **Access** to base tunnel for maintenance or emergency

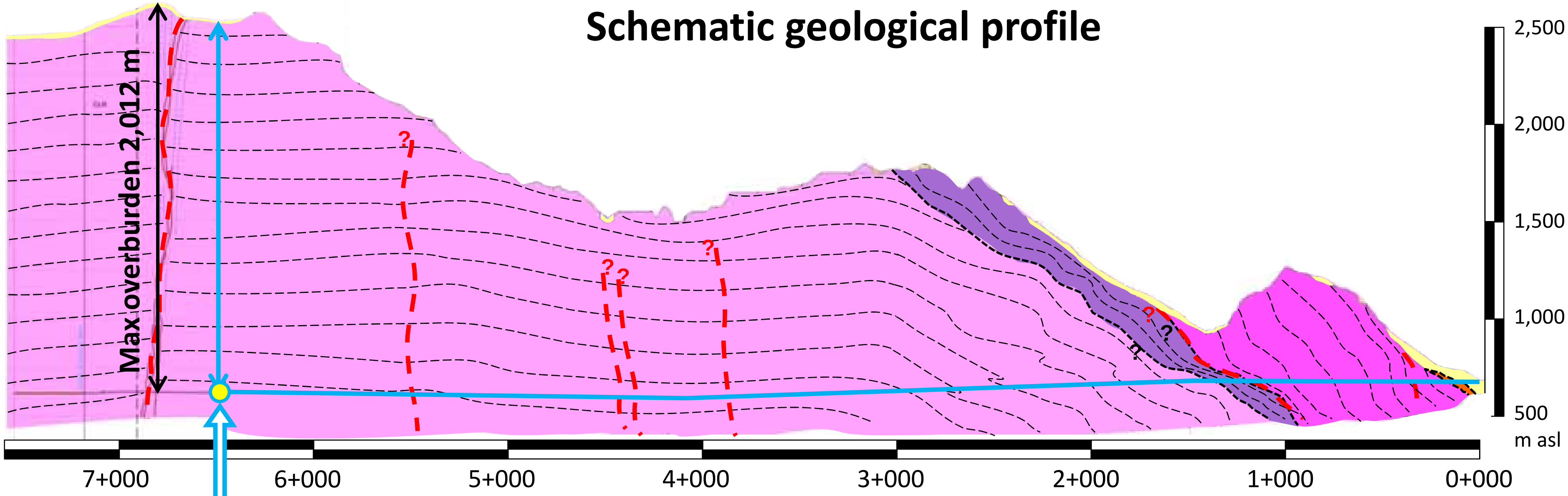
«GEA» Main Beam TBM (Robbins MB1812-299-2)	
Machine Diameter	6.30m
Overboring	0.1- 0.2m
Number of disc cutters	43 (17’’)
Maximum Recommended Individual Cutter Load	311kN
Normal Operating Cutterhead Thrust @4200PSI	12,756kN
Periodic Maximum Cutterhead Thrust @4500PSI	13,667kN
Cutterhead Drive	7 electric motors, gear reducers and brake
Cutterhead Power	2,954HP
Cutterhead Speed	0-10.8rpm
Cutterhead Torque @ 10.8 rpm	2,083kNm
Stroke	1.83m
Number of Main Thrust Cylinders	4
TBM weight (approx.)	250 ton



Main beam TBM assembly under telescopic shed at tunnel entrance

Present state of “La Maddalena” construction





chainage 6+500
Overburden approx. 1,910 m

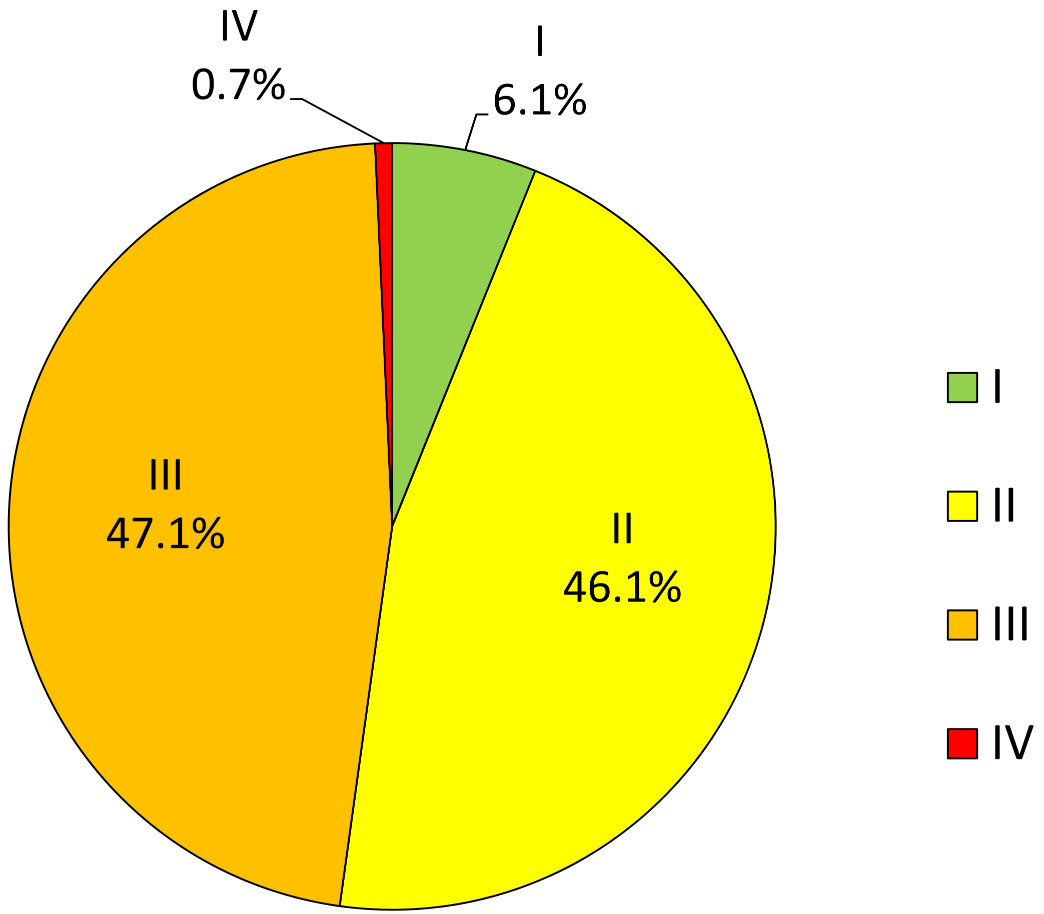
- Quaternary deposits
- Tectonic carbonatic rocks
- Ambin Rock complex (Aplitic Gneiss)
- Ambin Rock complex (Quartzitic Micaschists)
- Clarea Rock complex (Micaschists)

MAX RMR: **98**

MAX GSI: **98**

MAX σc: **236MPa** (lab test)

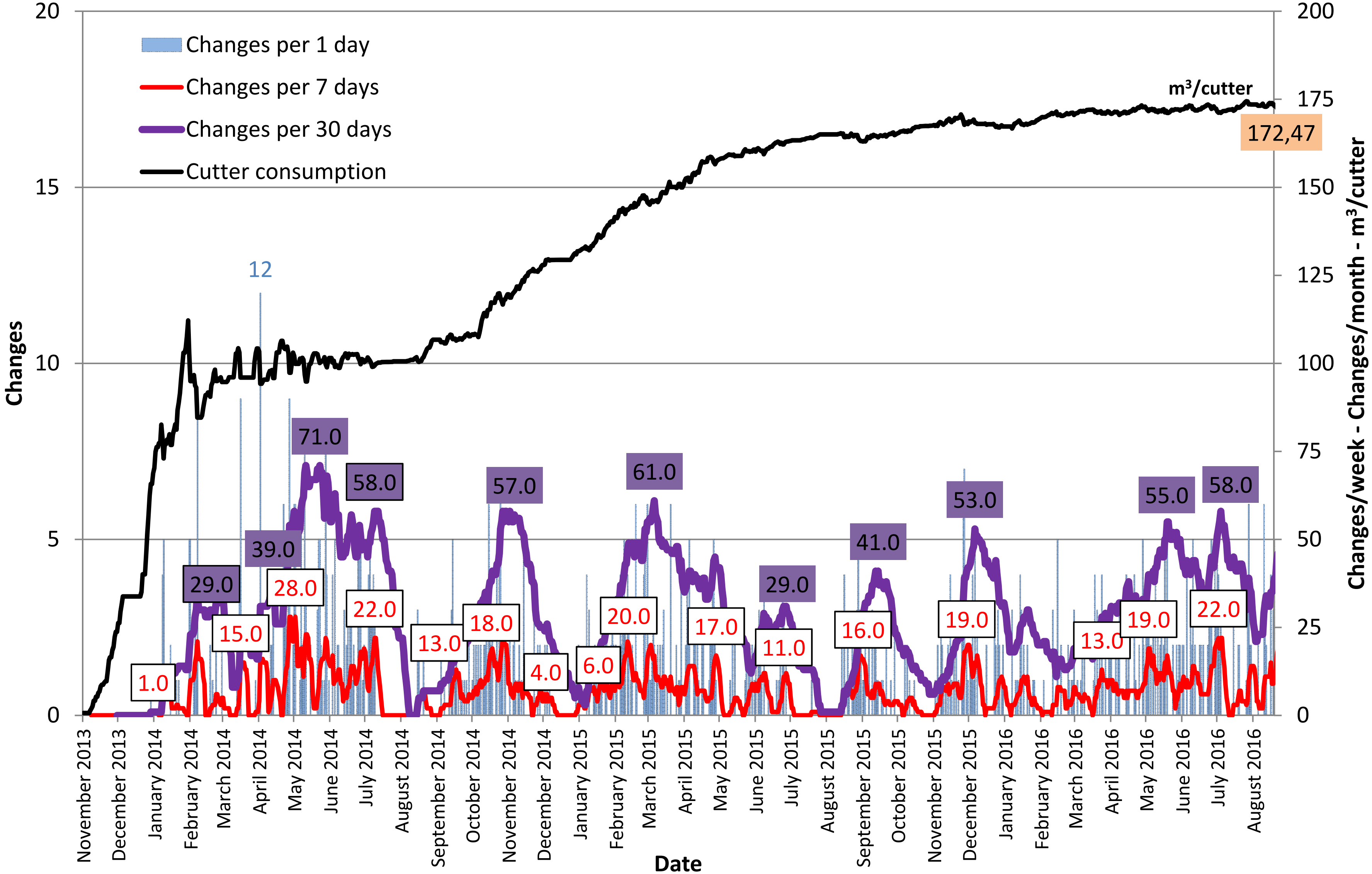
AS-BUILT – RMR



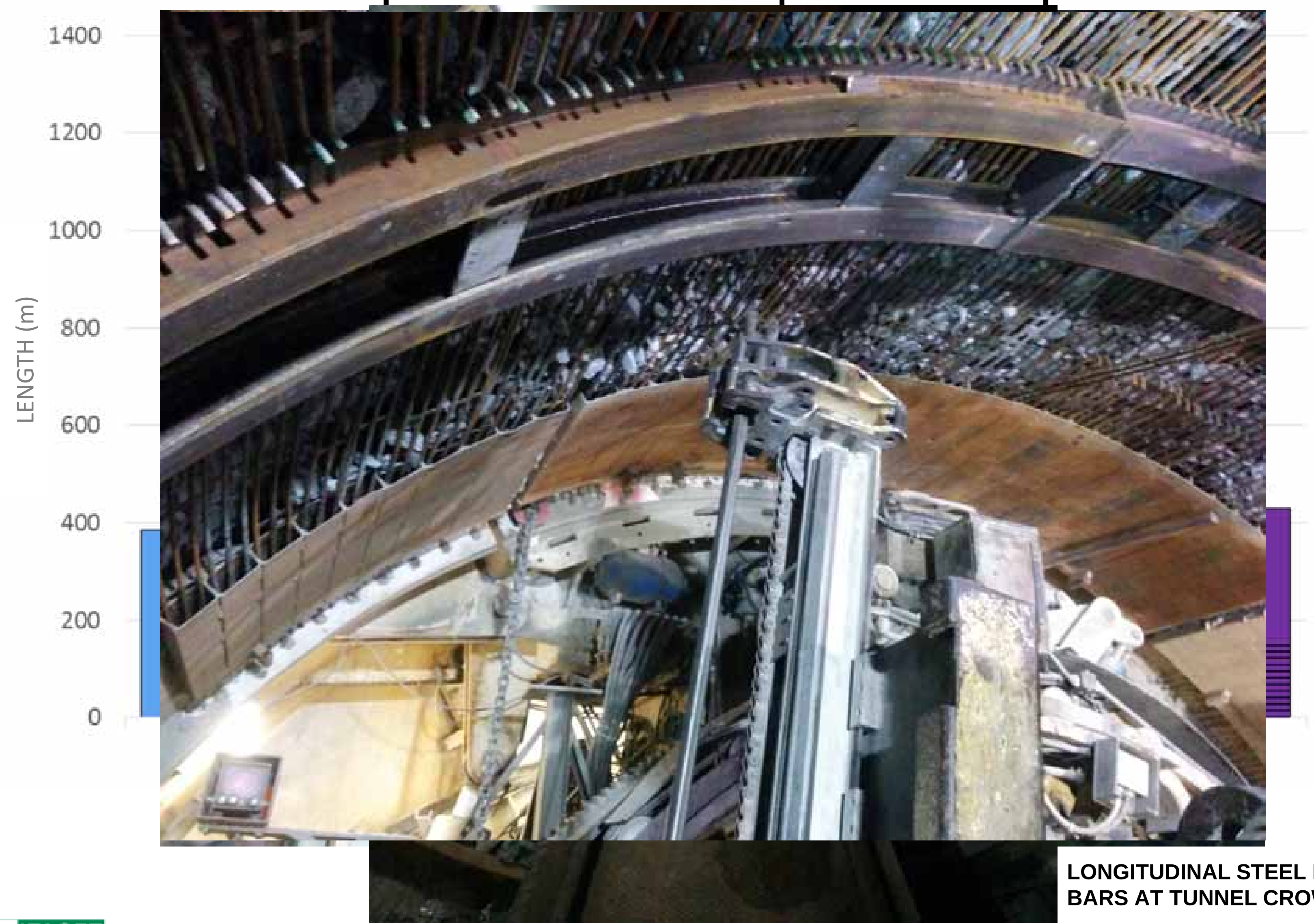
Extremely hard and abrasive rock mass

Rock mass rated fair (III) to good (II)

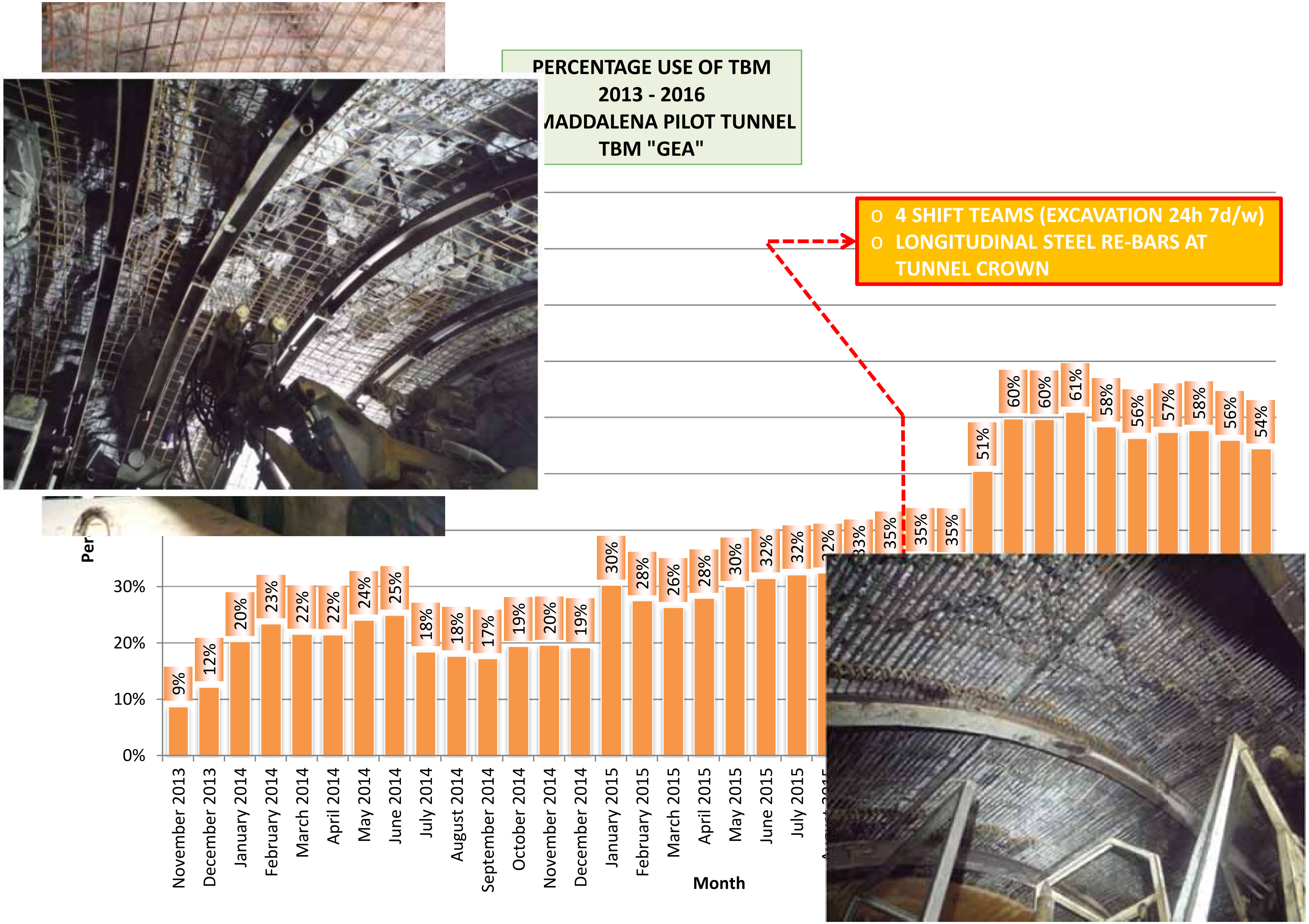
CUTTER CONSUMPTION
LA MADDALENA PILOT TUNNEL
TBM *"GEA"*



19,1% OCCASIONAL BOLTING | **21,6% SYSTEMATIC BOLTING** | **38,5% LIGHT STEEL RIBS** | **20,8% HEAVY STEEL RIBS**



LONGITUDINAL STEEL RE-BARS AT TUNNEL CROWN


PERCENTAGE USE OF TBM
2013 - 2016
MADDALENA PILOT TUNNEL
TBM "GEA"
o 4 SHIFT TEAMS (EXCAVATION 24h 7d/w)
o LONGITUDINAL STEEL RE-BARS AT TUNNEL CROWN
30%
20%
10%
0%
9%
12%
20%
23%
22%
22%
24%
25%
18%
18%
17%
19%
20%
19%
30%
28%
26%
28%
30%
32%
32%
33%
35%
35%
35%
51%
60%
60%
61%
58%
56%
57%
58%
56%
54%
November 2013
December 2013
January 2014
February 2014
March 2014
April 2014
May 2014
June 2014
July 2014
August 2014
September 2014
October 2014
November 2014
December 2014
January 2015
February 2015
March 2015
April 2015
May 2015
June 2015
July 2015
Month

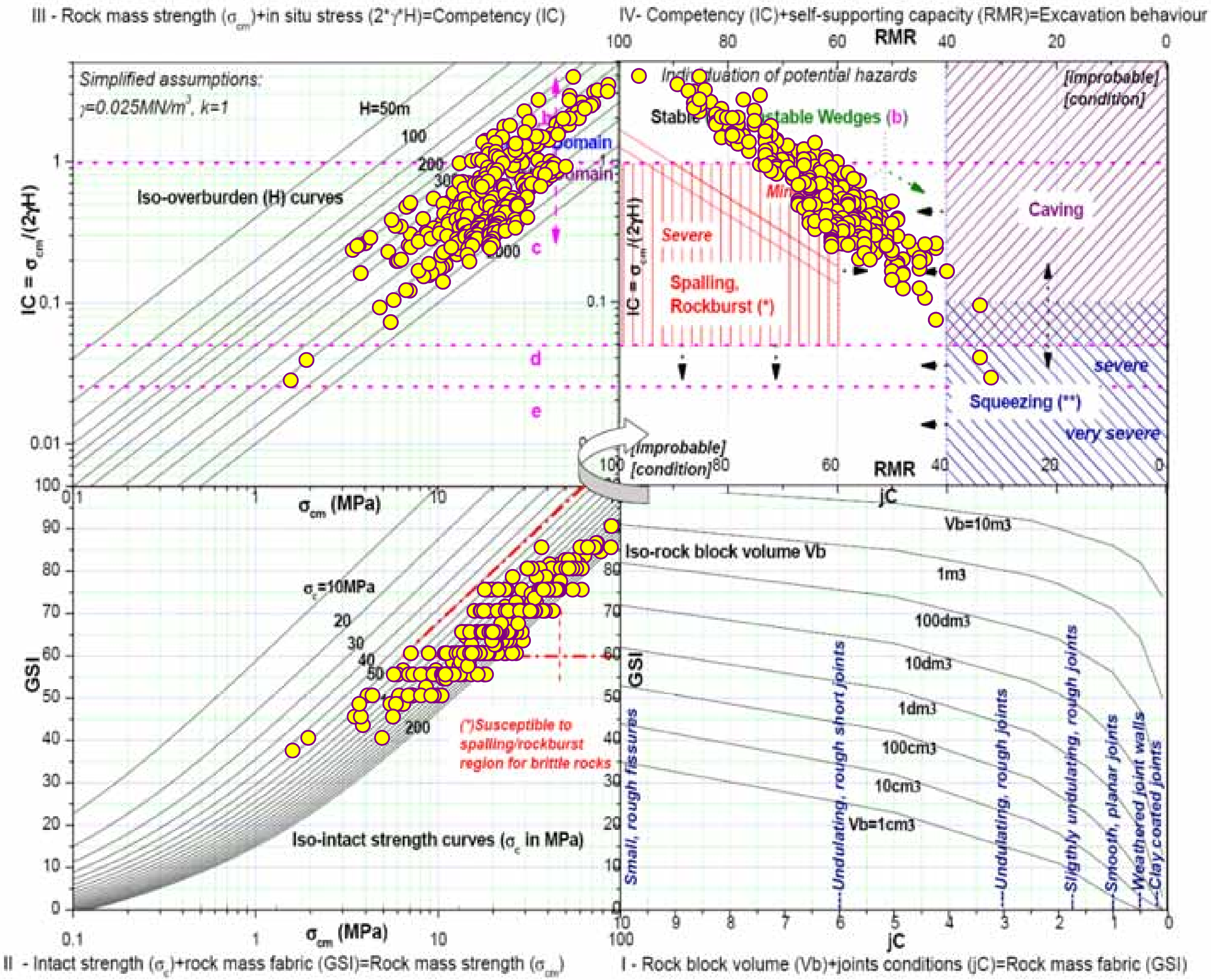
	WEEKLY HOURS AVAILABLE FOR EXCAVATION	HOURS WORKED PER WEEK	LABOUR AVAILABILITY
3 SHIFT TEAMS (exc. 24h/d 6d/w)	168	124	73.8%
4 SHIFT TEAMS (exc. 24h/d 7d/w)		168	100%

4 SHIFT TEAMS vs. 3 SHIFT TEAMS:

HOURS AVAILABLE FOR EXCAVATION

+35,5%

Observed behaviour of rock mass



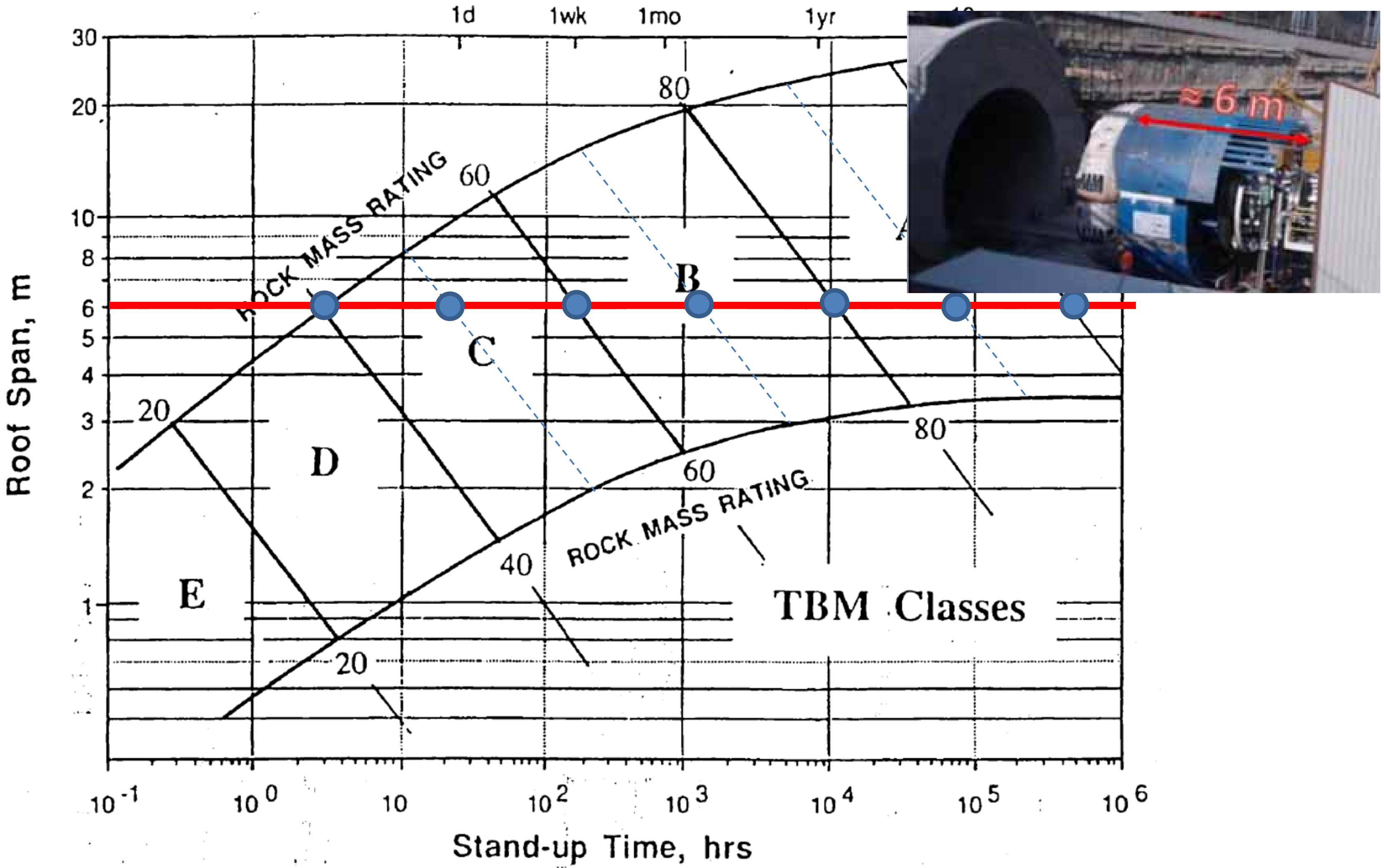
(*) only for the susceptible region, otherwise the development of plastic region and moderate radial convergences are more probable

(**) depending also from the length of the potential proned zone: given a possible "silo effect", for short zones included in good quality rocks, a caving behaviour it is most likely

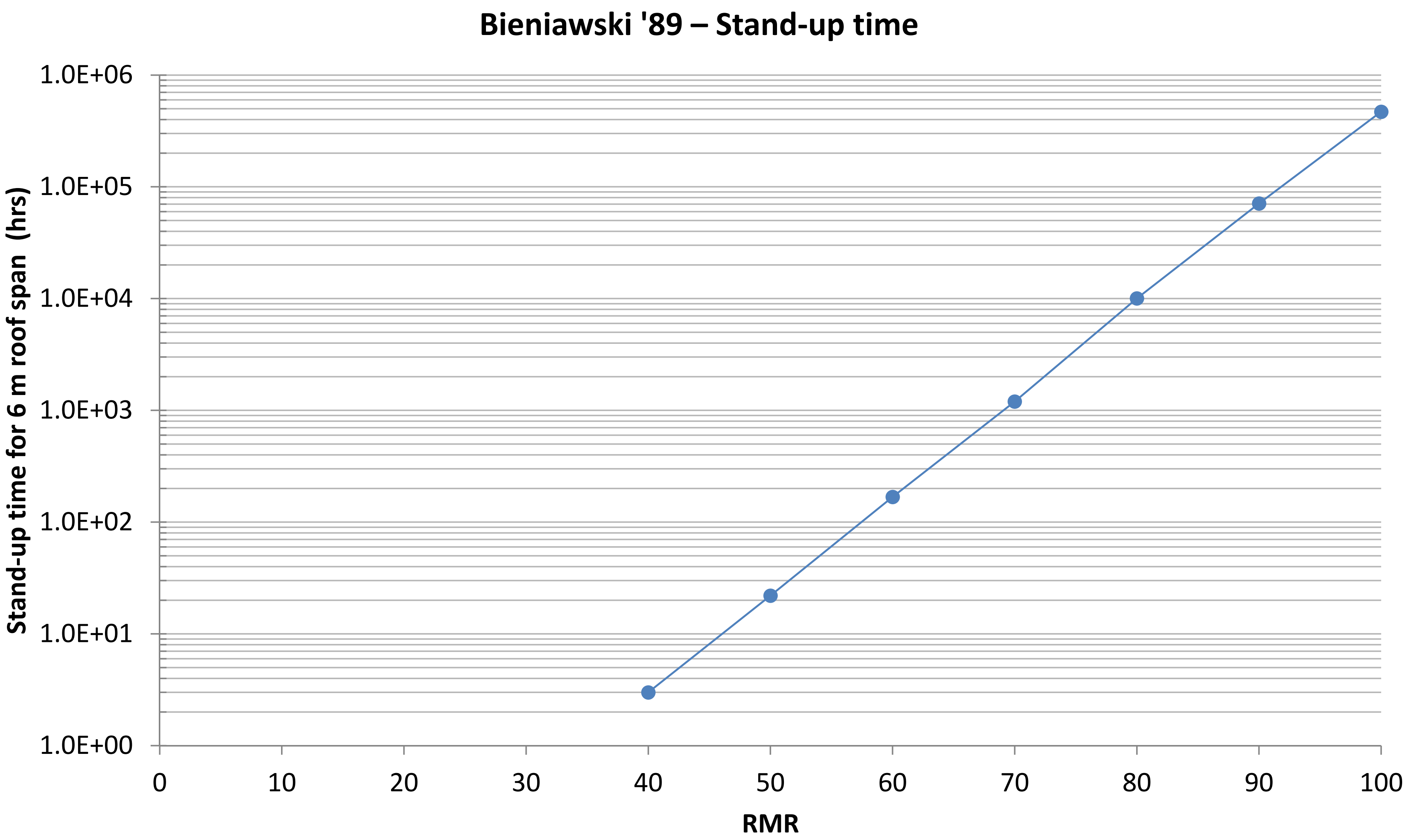
G. Russo, 2014

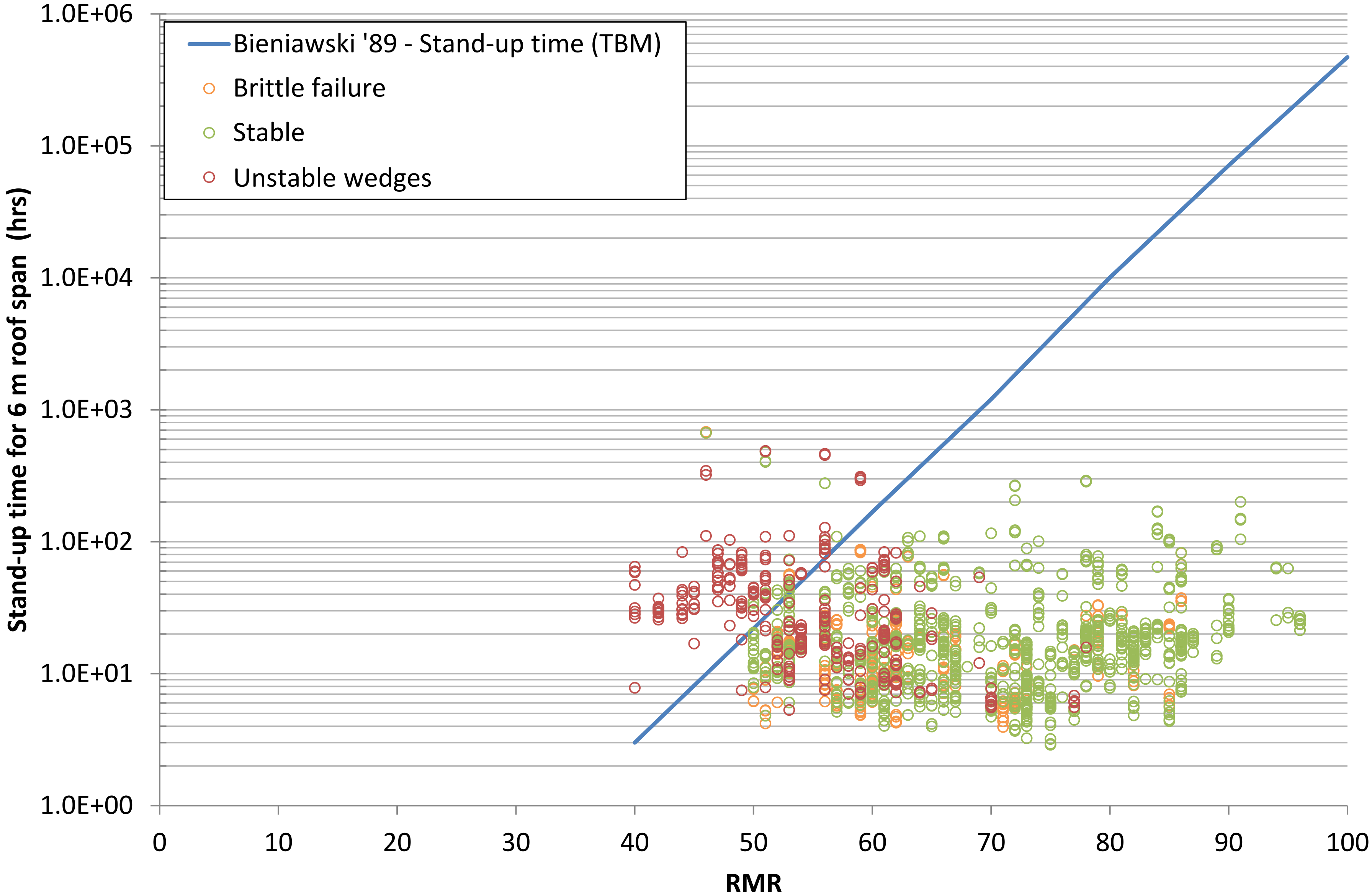
Effects from stress release were evident even with relatively low overburden (less than 400m).

Stand-up time in unsupported rock began to be systematically shorter than usually experienced (Bieniawski, 1989). Excavation often proceeded with relatively low TBM thrust on the face, leaving broken rock at tunnel crown.



Z.T. Bieniawski, 1989


Bieniawski '89 – Stand-up time
1.0E+06
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
Stand-up time for 6 m roof span (hrs)
0
10
20
30
40
50
60
70
80
90
100
RMR

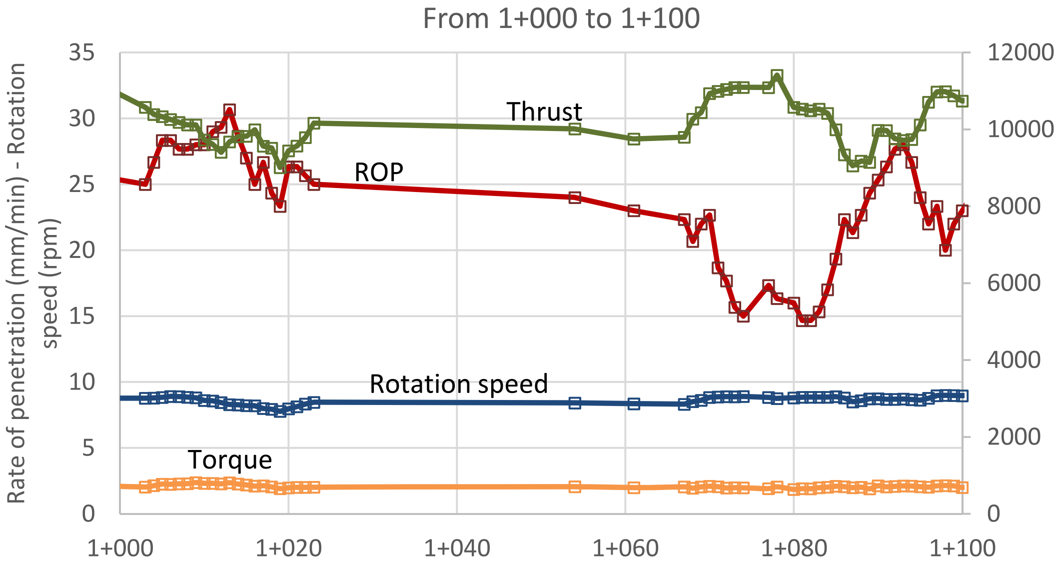


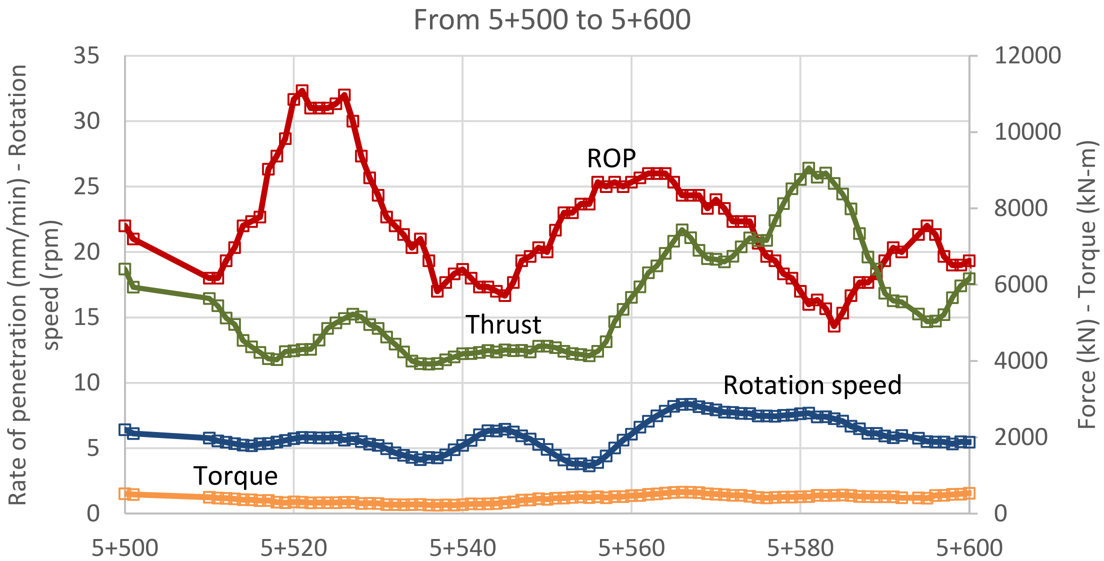
1.0E+06
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
Stand-up time for 6 m roof span (hrs)
0
10
20
30
40
50
60
70
80
90
100
RMR
Bieniawski '89 - Stand-up time (TBM)
Brittle failure
Stable
Unstable wedges

Lesson learnt: new type of support with circumferential steel ribs and longitudinal steel re-bars

Production now safely proceeds with installation of circumferential steel ribs connected with 120°arch of longitudinal steel re-bars

Less work required to excavate with brittle failure at face



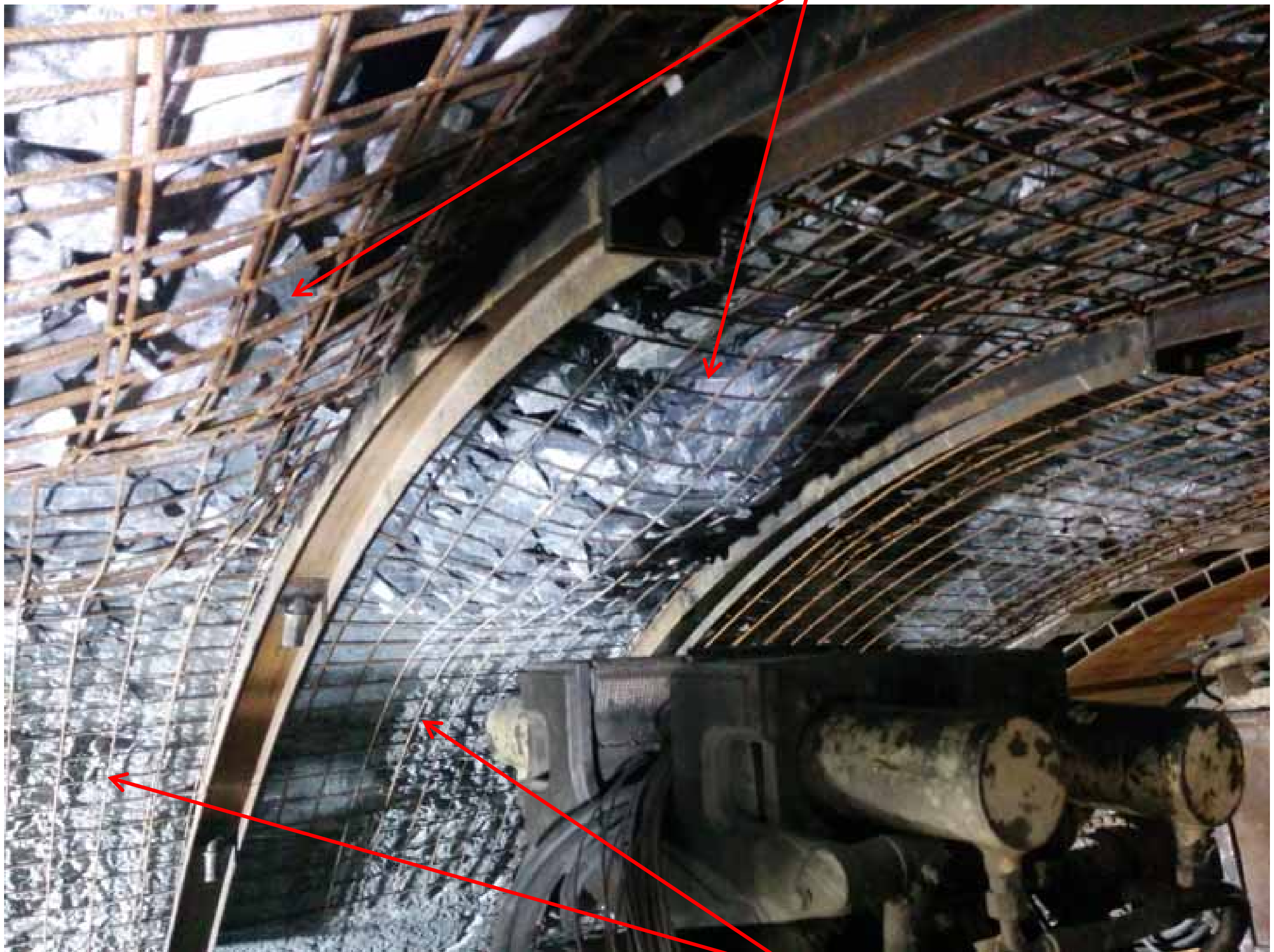


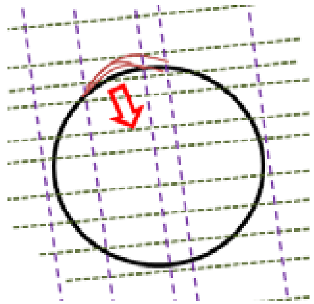
The most important brittle failure event occurred at 11 p.m. of 21/12/2015 around ch. 4+200 having a visible effect on support for a length of 10-12m of excavated tunnel

The rock mass, classified RMR = 61-72 and GSI = 62-75, presented subhorizontal schistosity and open discontinuities often with carbonate fill. Overburden was of about 1,000m

Workers heard a sudden smash. This was accompanied by large deformation of supports

Significant rock fragmentation at crown (result of failure between new/existing discontinuities and schistosities)





Lesser disturbed conditions with generally stable sidewalls

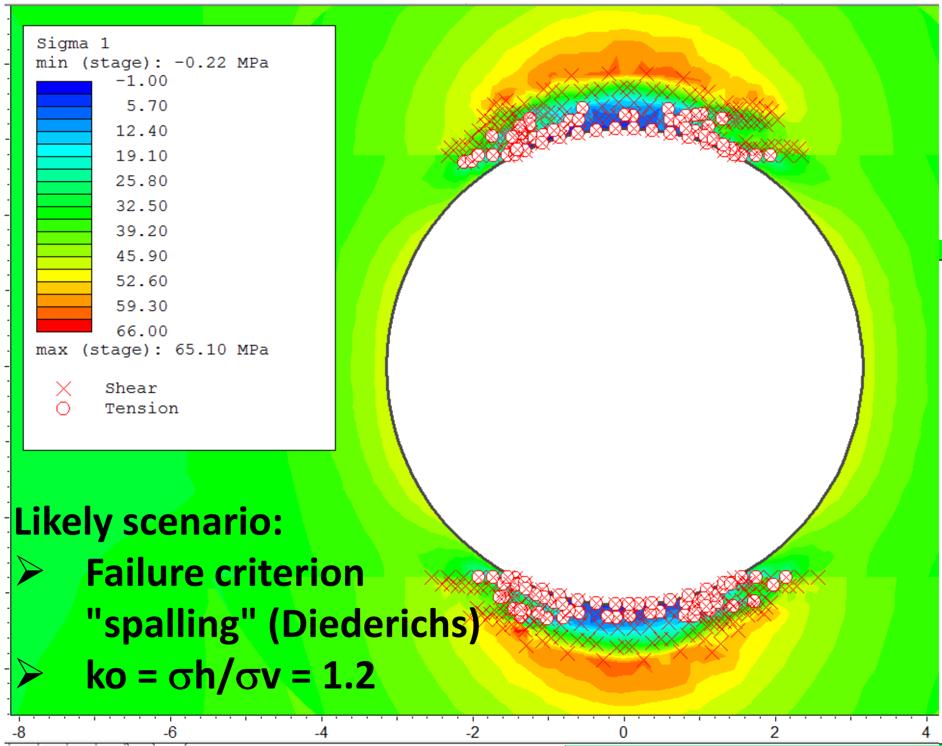
Rock fragmentation and observed behaviour correspond to a ***Bulking without ejection*** event (CRRP, 1996): the stored strain energy was consumed in the fracturing process, with significant increase of volume due to dilatancy.
There was no significant release of kinetic energy (rock ejection at high velocity).

Rockburst damage mechanisms and nature of the anticipated damage

Damage mechanism	Damage severity	Cause of rockburst damage	Thickness [m]	Weight [kN/m²]	Closure* [mm]	v_e [m/s]	Energy [kJ/m²]
Bulking without ejection	Minor Moderate Major	highly stressed rock with little excess stored strain energy	< 0.25 < 0.75 < 1.5	< 7 < 20 < 50	15 30 60	< 1.5 < 1.5 < 1.5	not critical not critical not critical
Bulking causing ejection	Minor Moderate Major	highly stressed rock with significant excess strain energy	< 0.25 < 0.75 < 1.5	< 7 < 20 < 50	50 150 300	1.5 to 3 1.5 to 3 1.5 to 3	not critical 2 to 10 5 to 25
Ejection by remote seismic event	Minor Moderate Major	seismic energy transfer to jointed or broken rock	< 0.25 < 0.75 < 1.5	< 7 < 20 < 50	< 150 < 300 > 300	> 3 > 3 > 3	3 to 10 10 to 20 20 to 50
Rockfall	Minor Moderate Major	inadequate strength, forces increased by seismic acceleration	< 0.25 < 0.75 < 1.5	$< 7g/(a+g)$ $<20g/(a+g)$ $<50g/(a+g)$	na na na	na na na	na na na

Numerical modelling

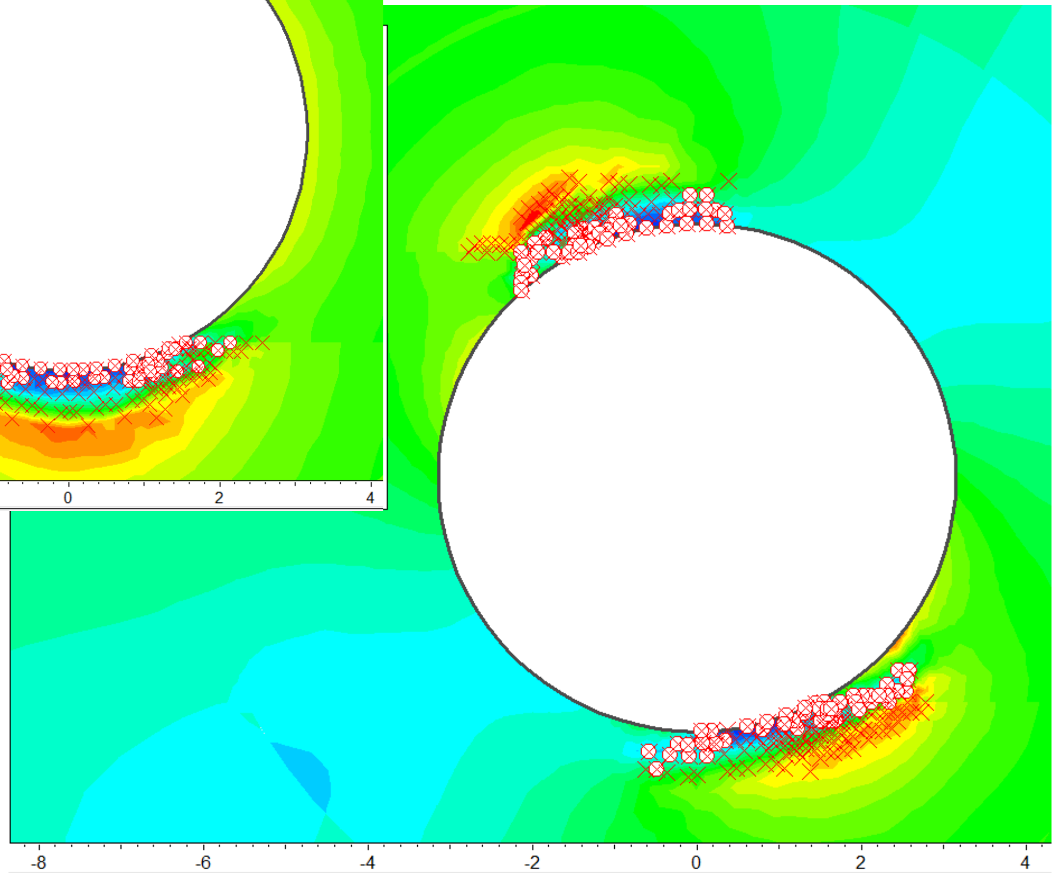
← Step 1: parametric analysis (ko=0.3-0.8-1-1.2; ...)



Likely scenario:

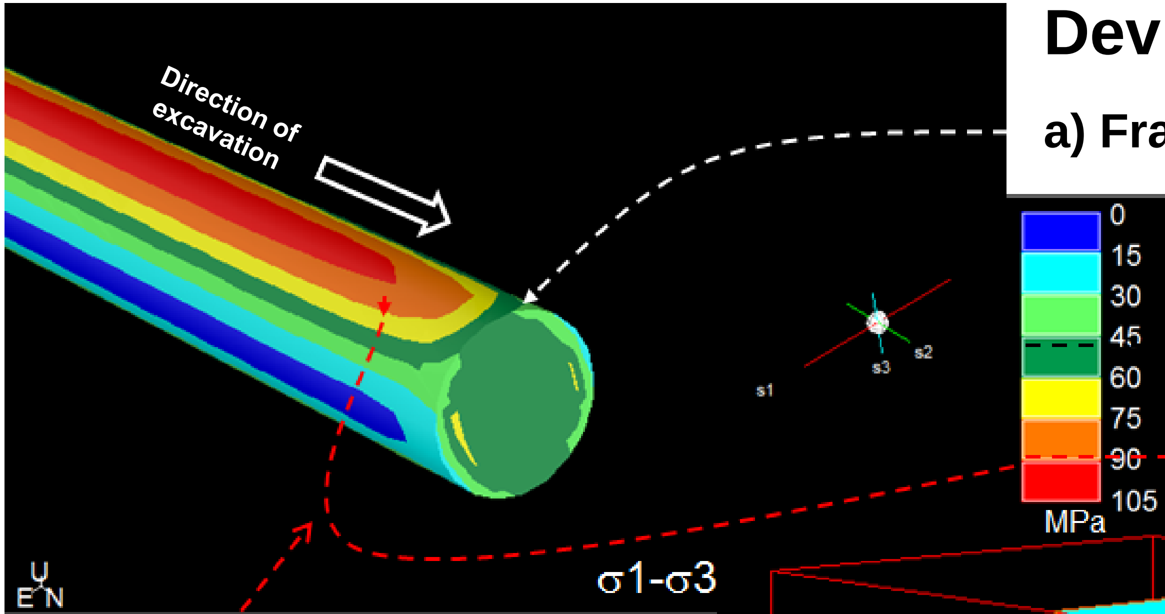
- **Failure criterion "spalling" (Diederichs)**
- **ko = σh/σv = 1.2**

Step 2: based on CSIRO tests results (niche 3) →



Deviatoric stress ($\sigma1-\sigma3$)

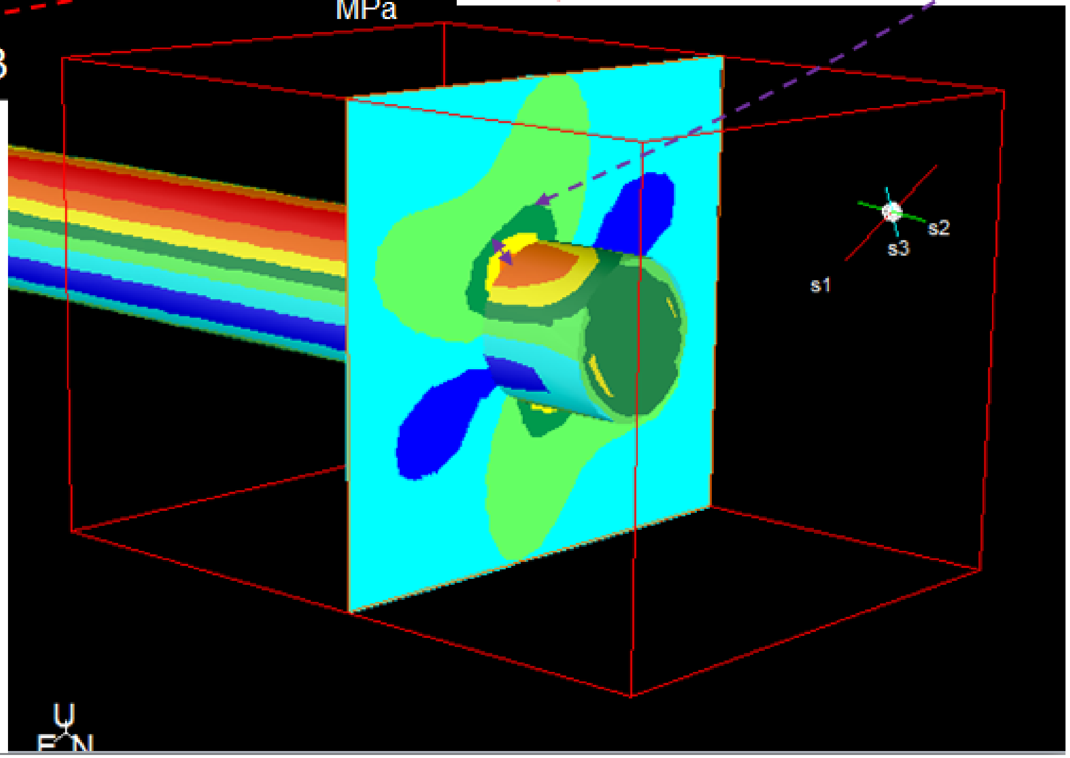
a) Fracturing starts («damage»)



a) $\sigma1-\sigma3 \approx 0.4$ UCS

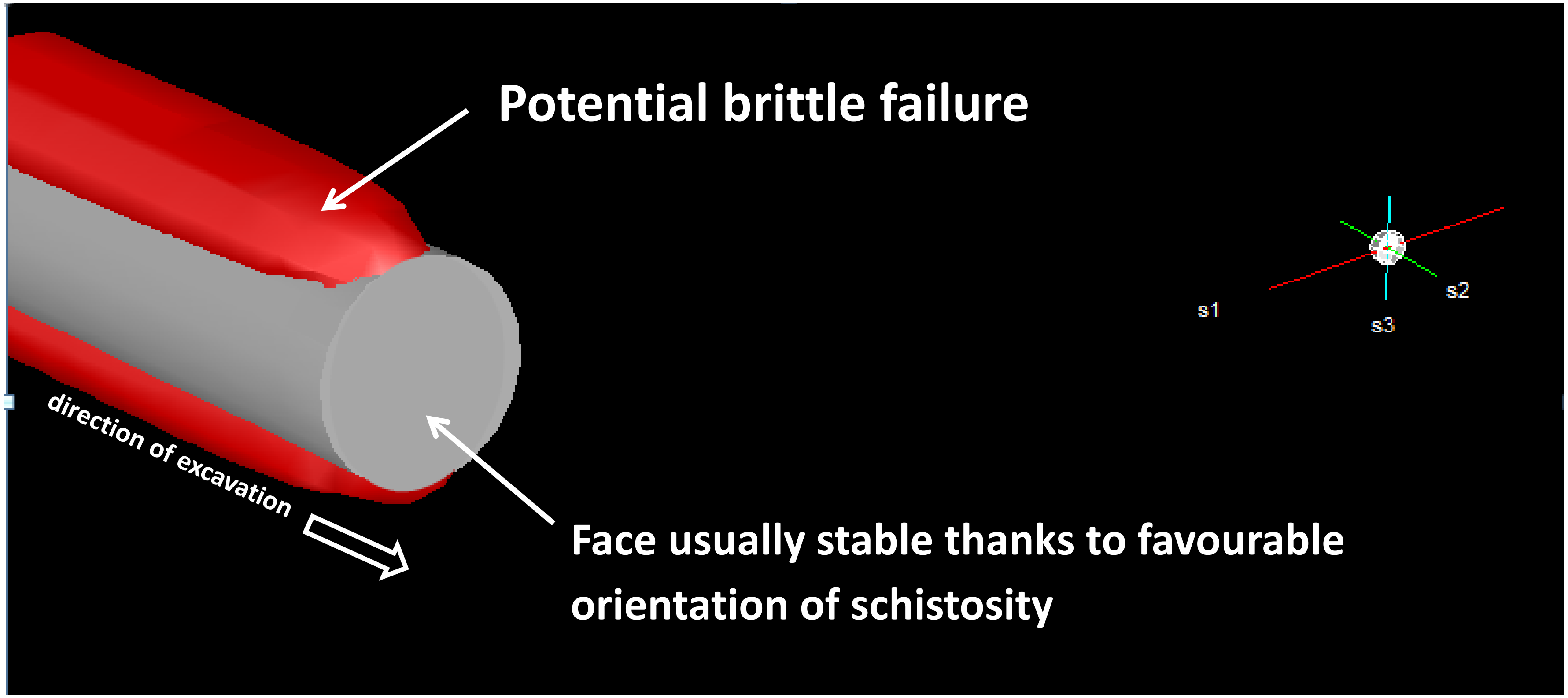
b) $\sigma1-\sigma3 \approx 0.7$ UCS (*)

b) potential rockburst conditions



3D NUMERICAL ANALYSIS

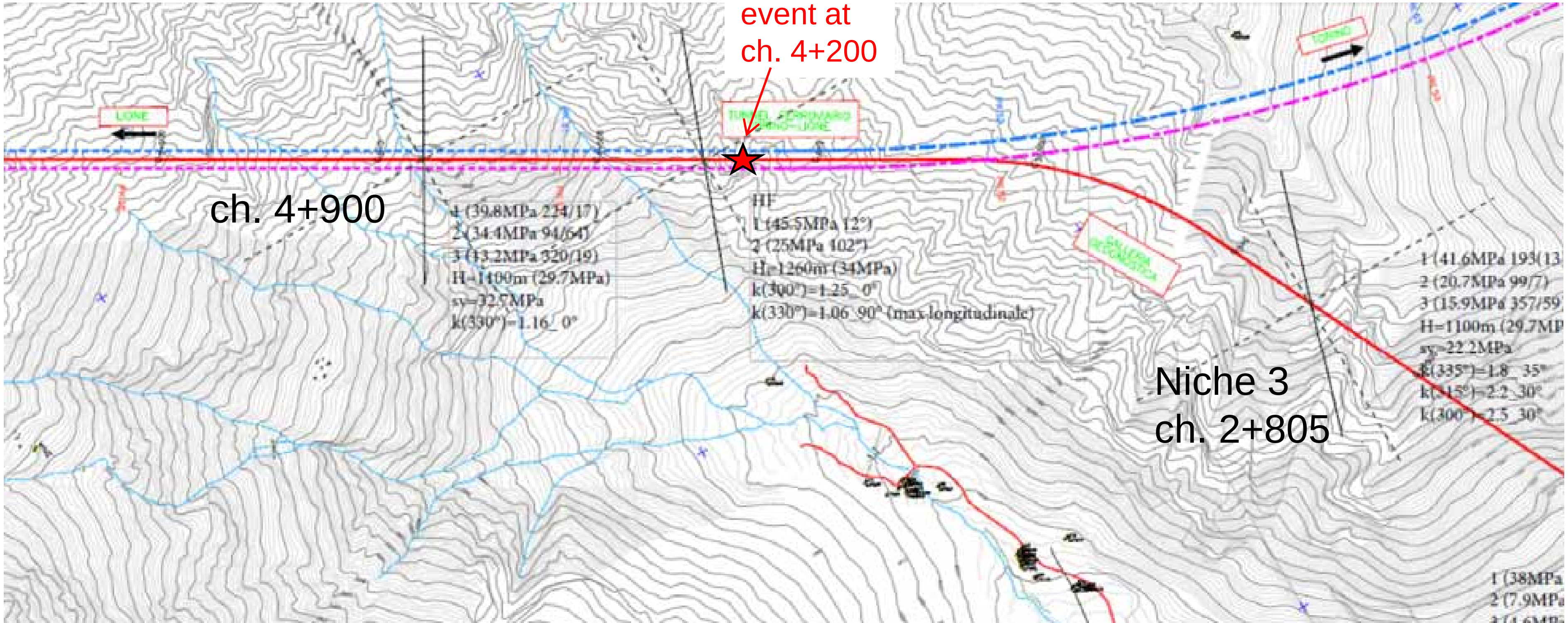
(*) Castro, McCreath e Kaiser (1995)

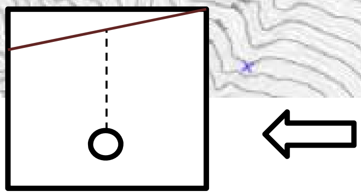


OBSERVED MECHANISM

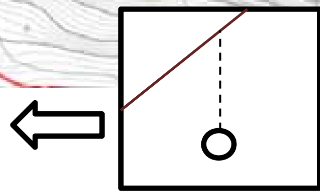
- Fracturing (damage) starts near excavation face at crown and invert
- Potential rockburst conditions from about one diameter behind face
- Depth of damage is at max 1-1.5m from excavated profile

Brittle failure events, from ch. 4+200 onwards, were less intense





Change in morphology/stress



SUMMARY AND CONCLUSIONS

- The **main beam hard rock TBM** used for La Maddalena exploratory adit has excavated **6.5km** in a rock mass (gneiss and micaschists) rated from fair to good and has reached the exceptionally high **overburden of 2,000m** under Mount Ambin.
- **Stress release effects**, with **fracturing and failures especially at tunnel crown**, have accompanied excavation since overburden exceeded about 400m, when it was observed that **stand-up times in unsupported rock began to be systematically shorter than usually experienced** (Bieniawski, 1989).
- Another side effect from stress release, with fracturing at tunnel face rather than at tunnel crown, was the **reduction of TBM thrust, torque and head rotation velocity** required for excavation.
- The type of brittle failure observed is of **dilatant fracturing** (or “bulking without ejection”), a rockburst mechanism **without significant release of kinetic energy**.

SUMMARY AND CONCLUSIONS

- Only on one occasion, at the end of 2015 when overburden was of the order of 1,000m, **rock mass bulking provoked large deformations of tunnel steel rib supports**.
- Even now, with 2,000m overburden, **minor brittle failure continues to take place**, always without violent rock ejections.
- Tunnel profile supports have since been adapted, by using **systematic protection with a 120°arch of longitudinal steel re-bars supported by circumferential steel ribs**, a solution which allows to continue excavation even when the rock mass at crown has broken into fragments.
- The new supports brought to an immediate sustained increase of percentage of use of TBM (**efficiency**), from under 35% to over 55%, allowing productions of about **12m/day** as opposed to about **4m/day** in unstable crown conditions.

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1st December 2016 - Rome

Disclaimer

a) The speakers are presenting their own personal views and are not expressing the view of the Foundation.