UNIVERSITÀ DEGLI STUDI FIRENZE

Dipartimento Scienze della Terra

Prof. Geol. Massimo Coli

HEC case studies

- Santa Lucia tunnel - motorway A1 Bologna-Firenze

  ASPI supervisor for Geology, Hydrogeology, Geomechanics

- Genoa by-pass - linking motorways A10/A7/A12/A26 and Genoa port

  Member of the Scientific-Technical Committee nominated by ASPI and MIT

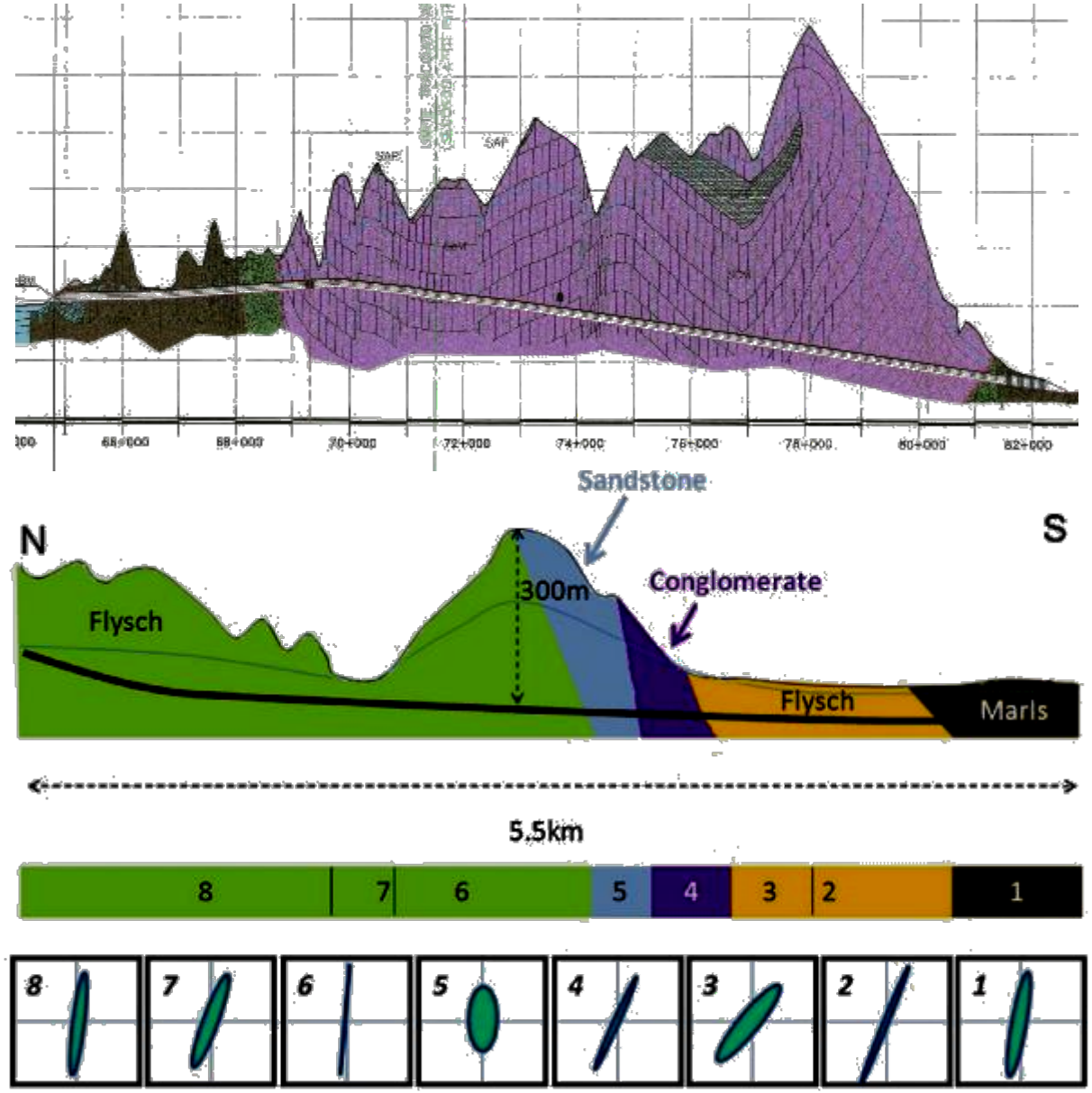
European Commission

Jaspers

European Investment Bank

HEC ROAD MAP

- Development of the hydrogeological profile in terms of ground water level, rock-mass permeability, fractures corridors and faults
- Prediction of water flows in terms of chainage, type and quantity
- Development of the HEC
- Definition of the mitigation measures in the design



TYPES OF WATER INFLOW

LEAKAGE ALONG THE UBIQUITOUS DISCONTINUITIES

- Low impact on local water resources
- Best possible project predictions
- Mitigations can be incorporated in the design
- Solution through water-proofing and lining
- Possible water recovery
- Mitigation costs can be estimated

WATER INRUSH ALONG FAULTS AND FRACTURE CORRIDORS

- Heavy and permanent impact on local water resources
- Well-defined design prediction
- Mitigation measures to be included in the design
- Pre-grouting of the high permeability zones
- Possible water recovery
- Mitigation costs can be estimated
- Very high costs for specific tunnel stretches

SANTA LUCIA TUNNEL

- The Santa Lucia tunnel is part of the upgrading of the Bologna-Florence section of the A1 Milan - Rome motorway
- Budget: 1 billion €
- Designed for > 100 vehicles/minutes
- Savings of 1.5 Mhrs/year by reducing travel time by 30%
- Minus 2,000 t/y of CO_2 emissions by reducing queues and stop-and-go

SANTA LUCIA TUNNEL

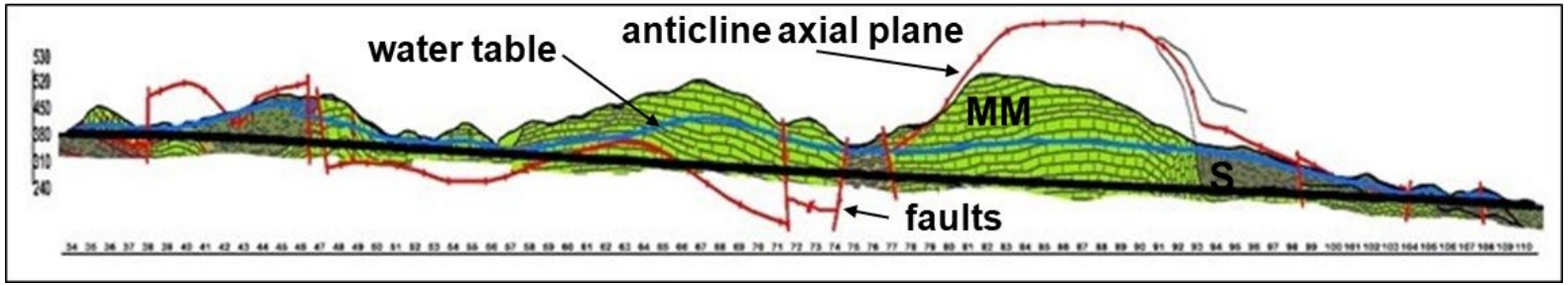
- Tunnel length: 7,528 m
- Excavated by EPB-TBM 15.87 m in diameter
- TBM cost 72 M€
- Single tube, three lanes plus emergency lane
- Under high pressure water head
- In presence of methane and swelling rock masses

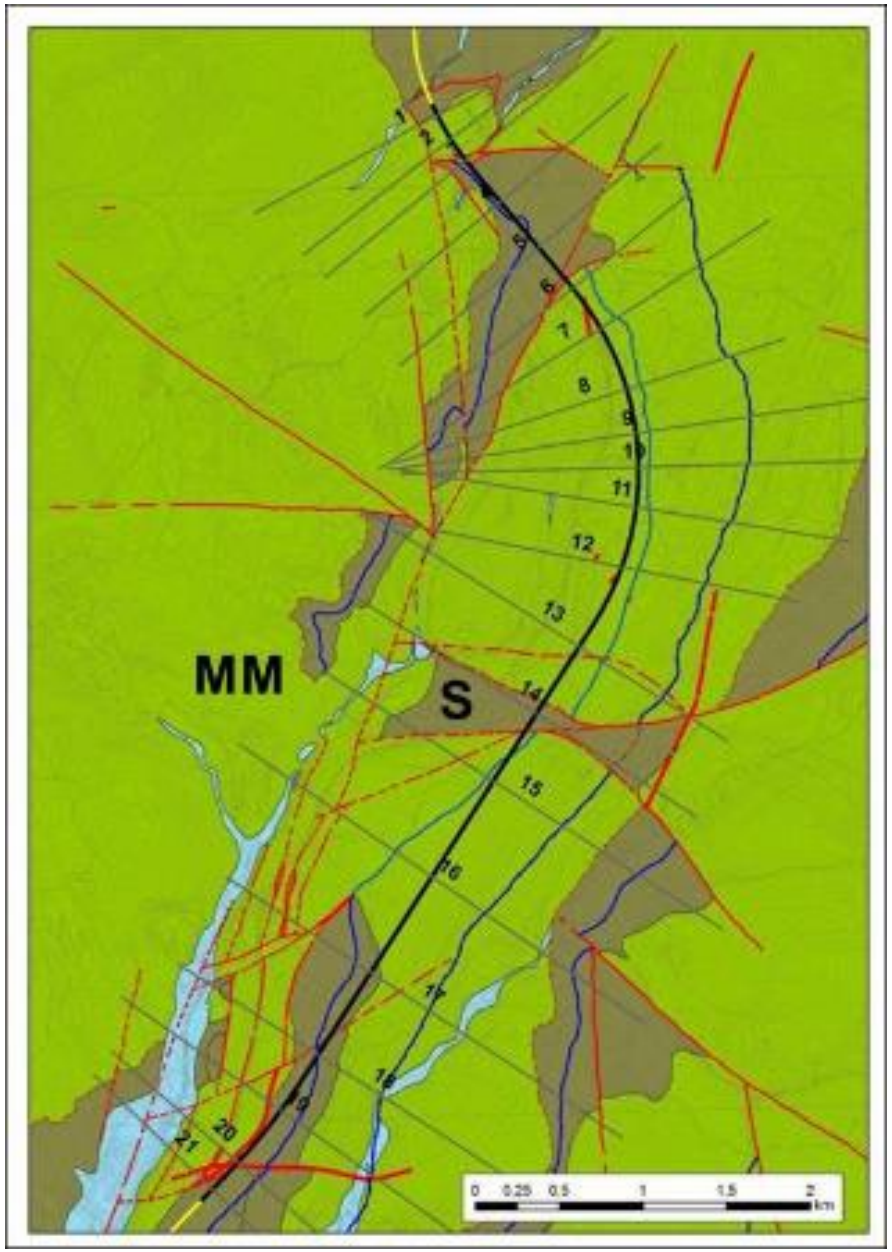
GEOSTRUCTURAL SETTING

- The tunnel runs parallel to a main anticlinal fold composed by tectonised shales and limestones in the core of the anticline
- Limestones present “ubiquitous” discontinuities due to bedding and two sets of joints regularly spaced
- Water-flow occurs along the network of discontinuities

MM = regular bedded limestone

S = highly tectonised shales





KARST

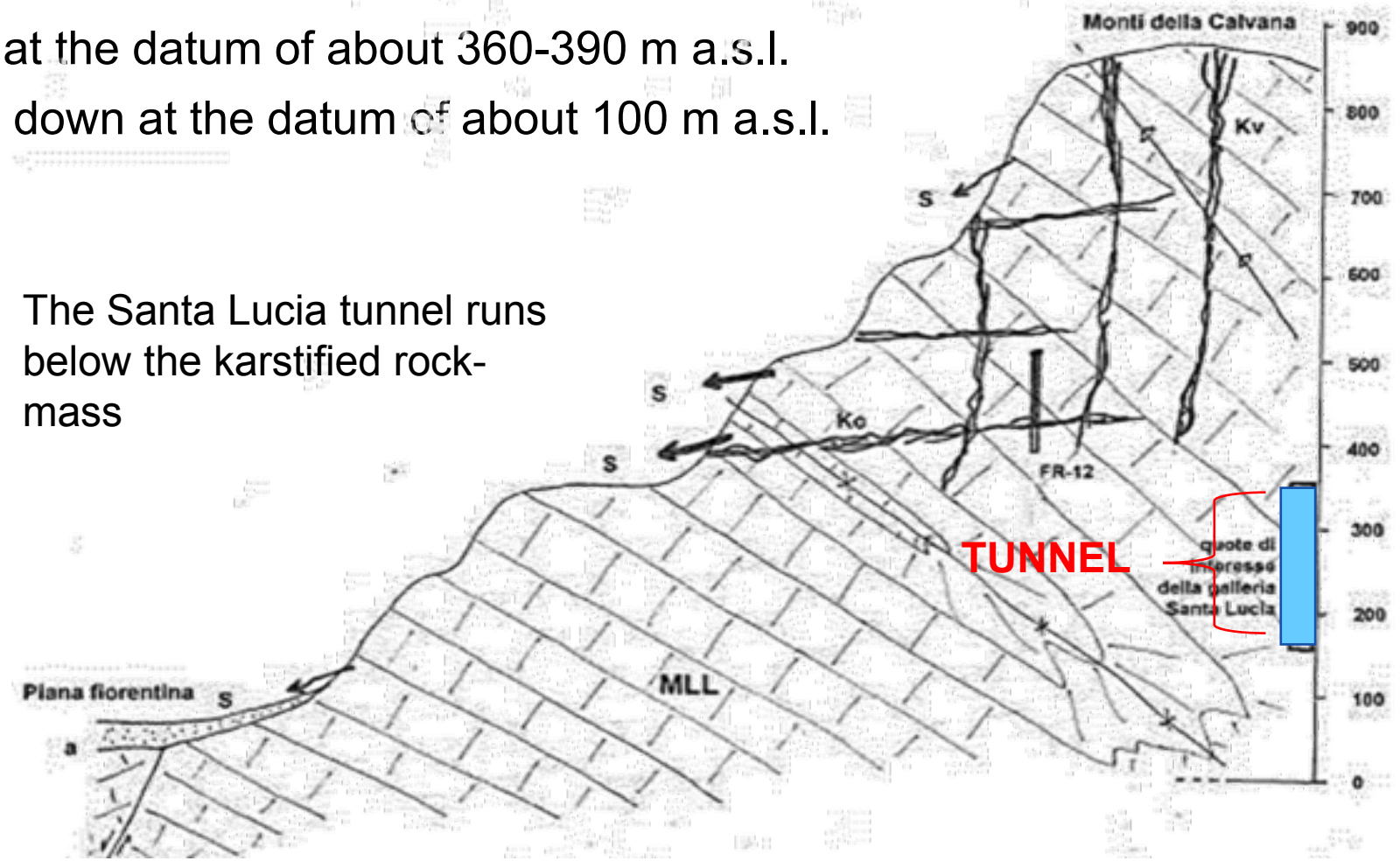
The Karst phenomenon developed after a subsequent lowering of the water-base level:

- 20 Myears - low acclivity surfaces (<10°) at the datum of 850-930 m a.s.l.
- 11 Myears - low acclivity surfaces at the datum of about 700 m a.s.l.
- 6 Myears - low acclivity surfaces at the datum of about 360-390 m a.s.l.
- Post 2 Myears - water-base level down at the datum of about 100 m a.s.l.

Caves type and features

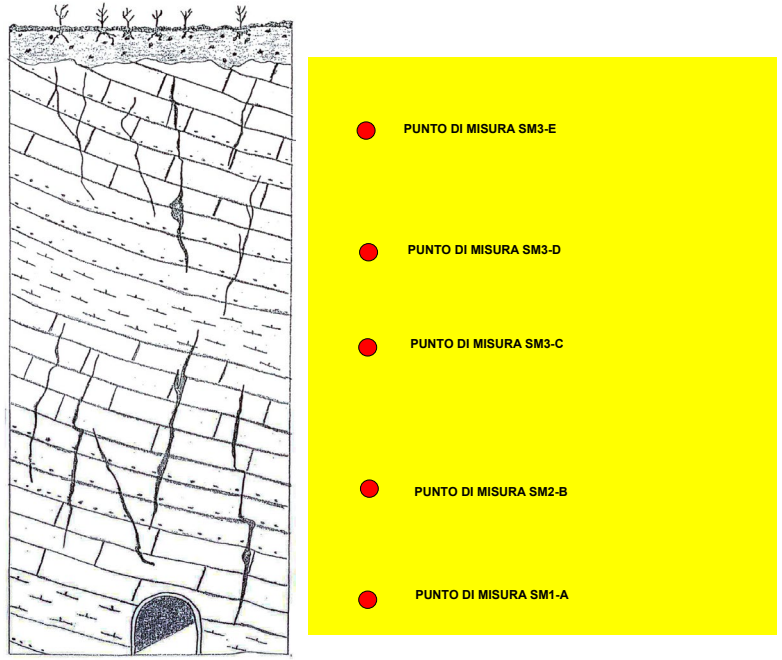
Nome	Sviluppo prevalente	Quota ingresso m s.l.m.	Profondo m	Sviluppo m
La Spilunchina	Verticale	910		
Spelonca delle Capanne di Savignano	Verticale	820	18	
Spelonca delle Pille	Verticale	760	12	40
Buca del Ciuco	Verticale	740	23	40
Speloncaccia	Verticale	725	25	35
Spelonca di Colle Fiesoli	Verticale	715	10	14
Grotta dei Massi	Verticale	670	10	
Buca del Castello	Verticale	650	35	35
Grotta Battista	Verticale	630		
Buca del Buccia	Verticale	625		
Grotta del Castagno	Verticale	590	18	44
Buca del Cane	Verticale	570	15	17
Grotta del Tasso	Orizzontale	490		70
Buca del Ragno	Verticale	410		
Fonte Buia	Orizzontale	395	16	381
Tana dei Buti	Orizzontale	390	19	170
Grotta di S. Anna Vecchia	Vert./Orizz.	375	212	658
Grotta del Drago	Verticale	370	70	106
Grotta della Civetta	Verticale	360	106	301
Sifone della Biscia	Orizzontale	355	7	14
Grotta Ulivello	Verticale	350	15	35
Forra Lucia	Orizzontale	335	31	262
Grotta dei Muri	Orizzontale	325	10	35
Fonte Buia Inferiore	Orizzontale	300	48	10
Grotta dei Torri	Orizzontale	235	16	78

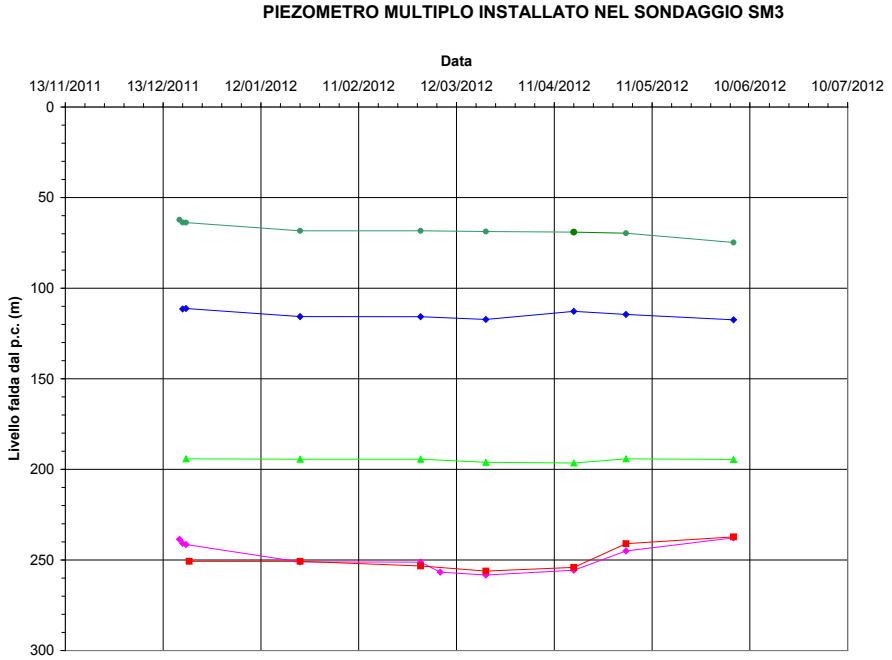
- The Santa Lucia tunnel runs below the karstified rock-mass



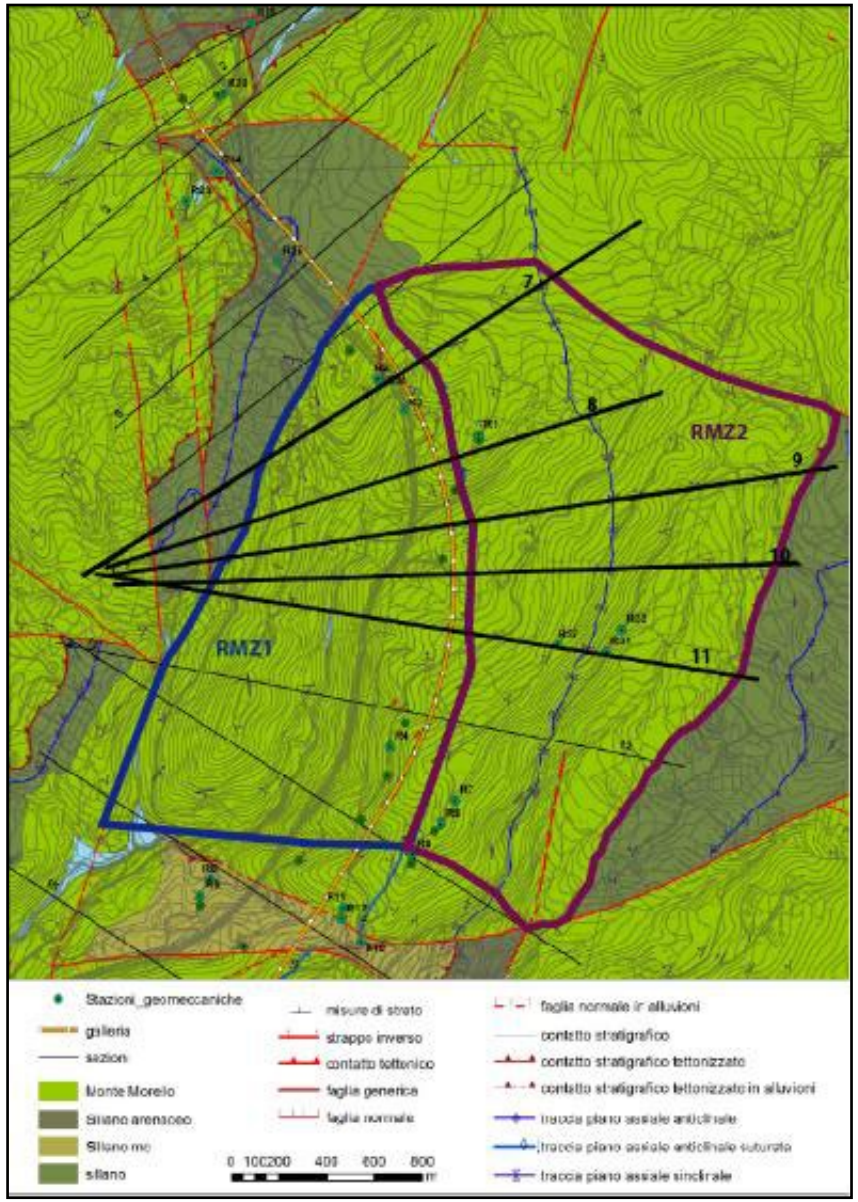
MULTISTRATA ACQUIFER

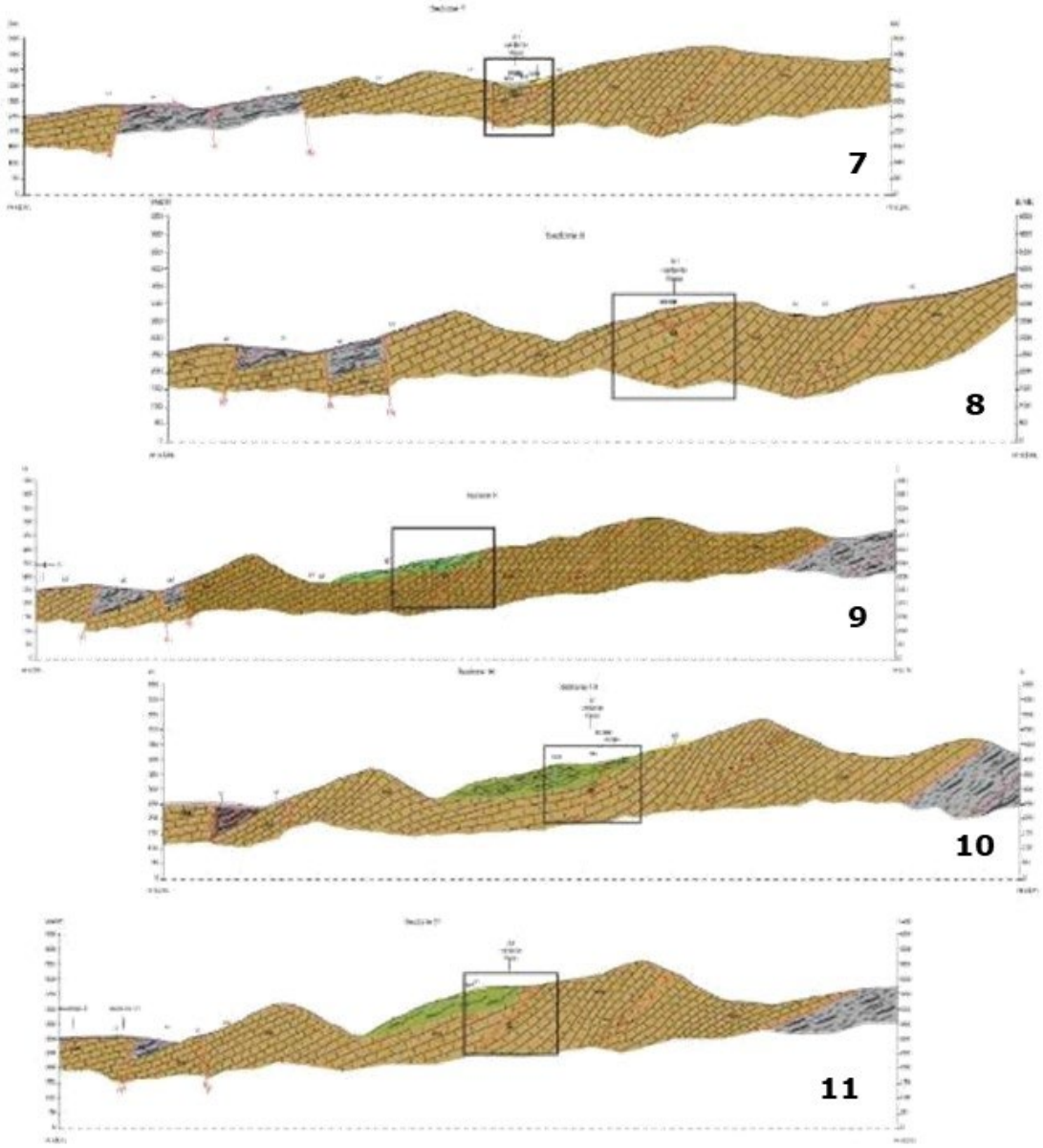
- Composite multilayer, with compacted strata with permeability due to discontinuities alternating with less permeable shaley levels
- Multiple water table levels
- The real water overburden on the TBM is no more than 100 m = 10 atm (like a submarine at a depth of 100 m b.s.l.)
- TBM can faces up to 12 → 16 atm



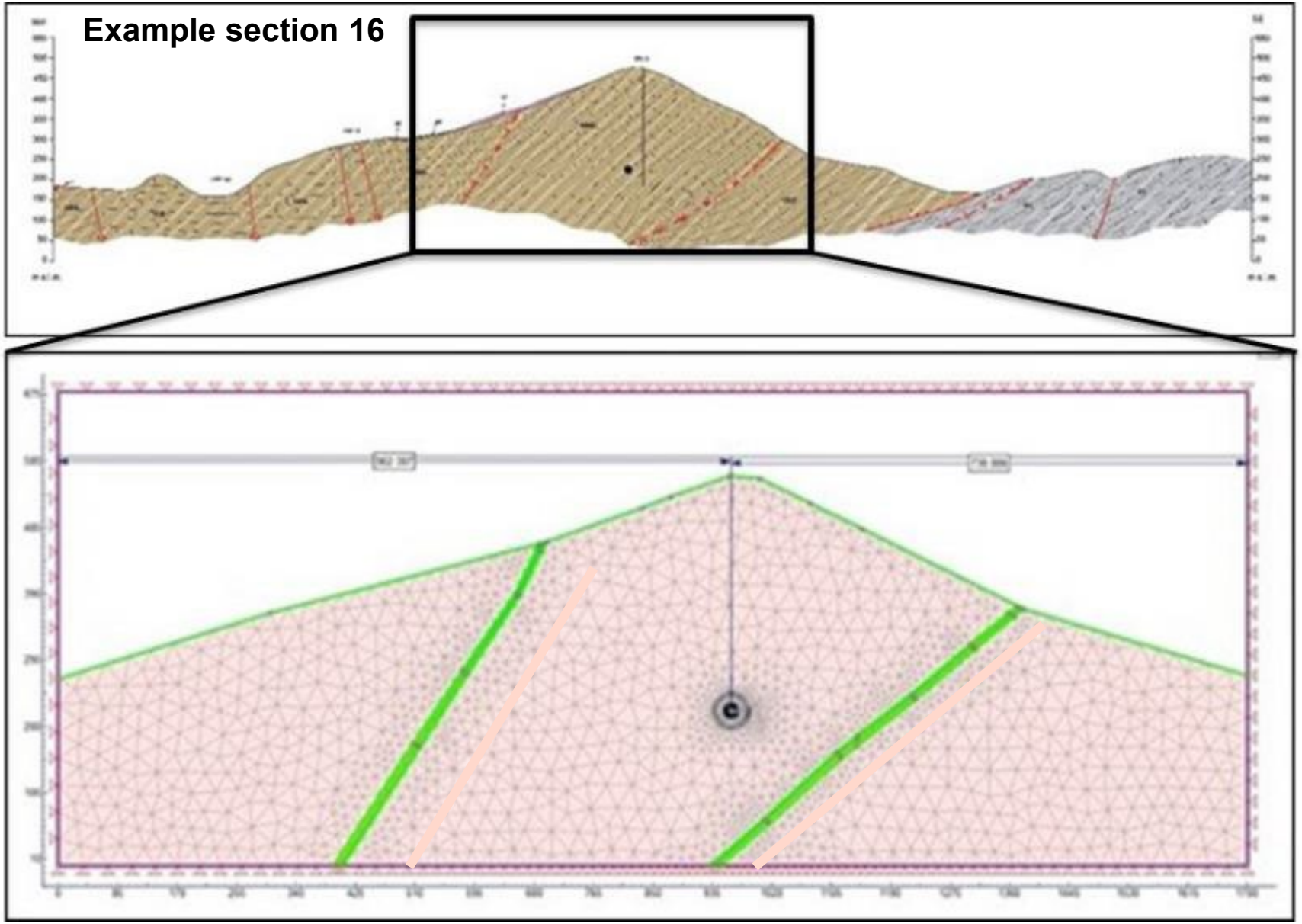


WATER FLOW ANALYSIS FOR TUNNEL IN 33 STRETCHES



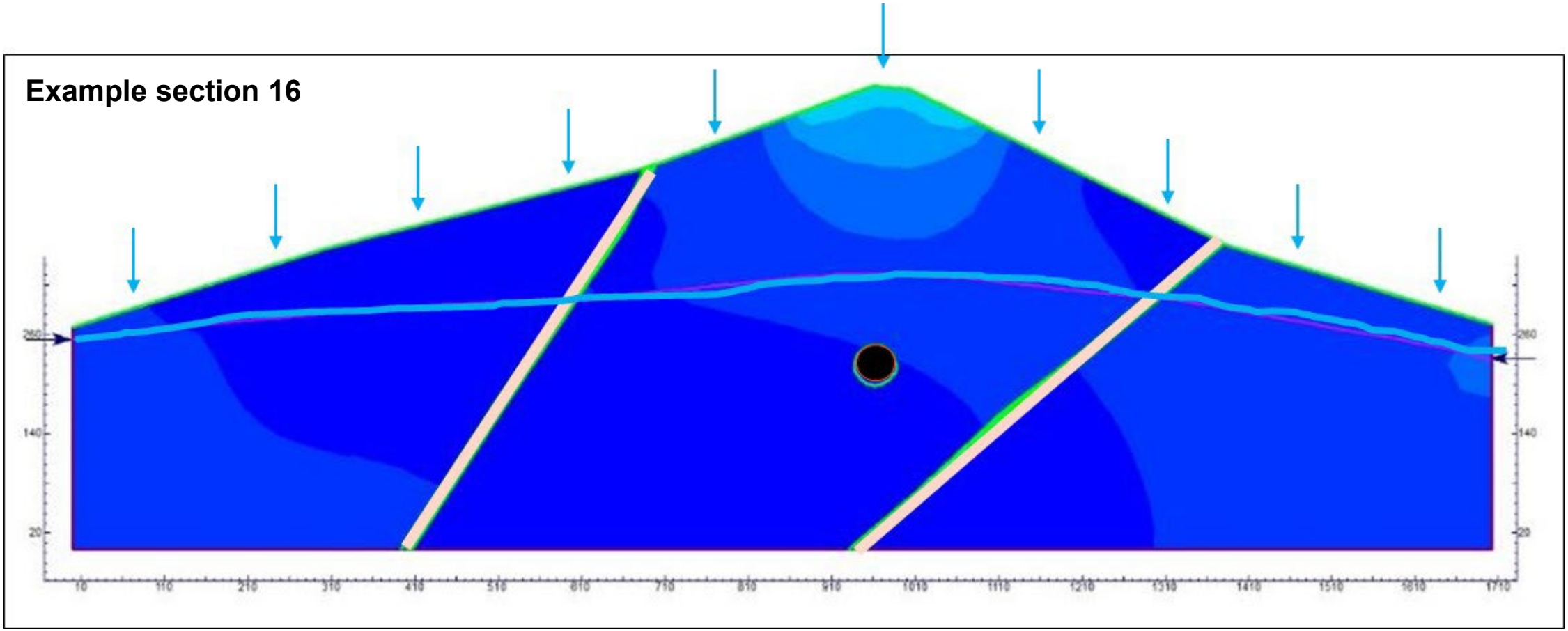


FEM MODEL FOR WATER FILTRATION



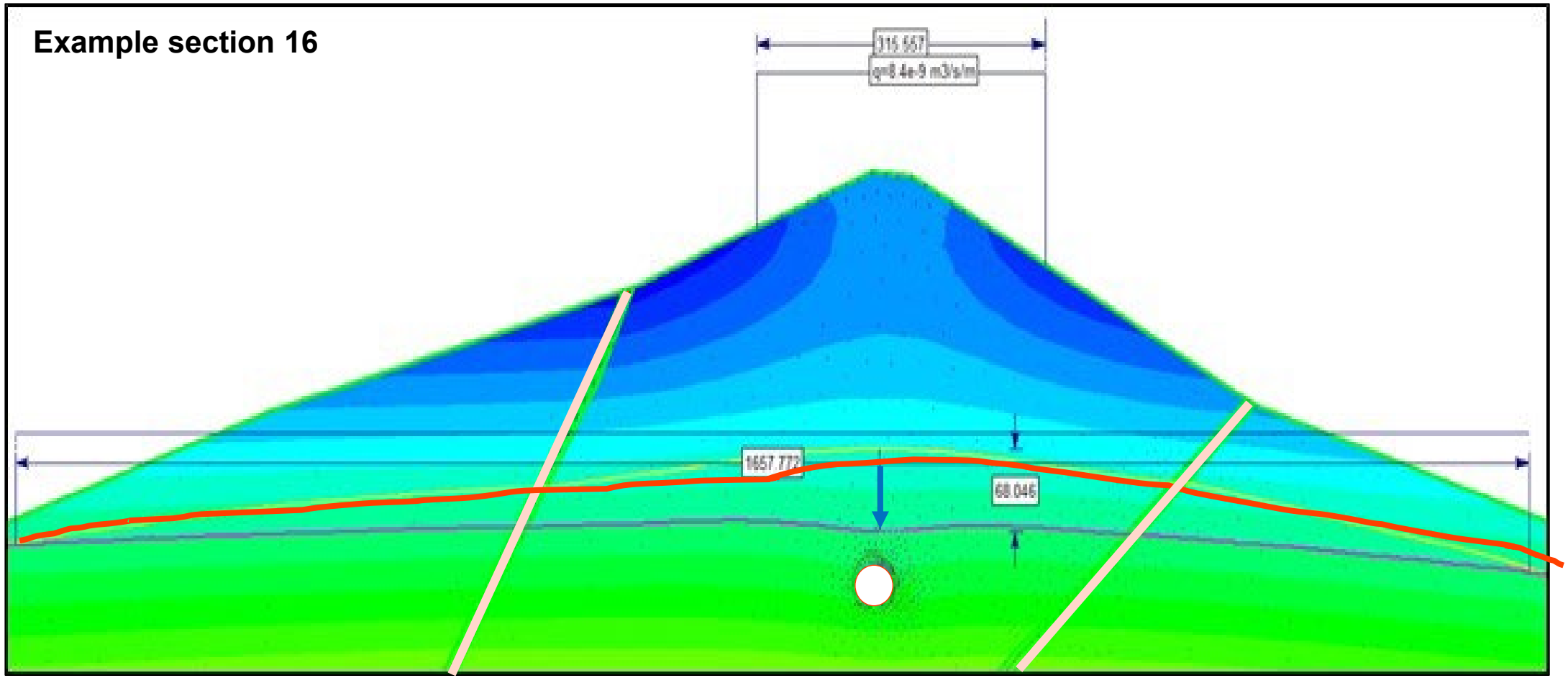
FEM FILTRATION ANALYSIS OF THE NATURAL WATER TABLE SETTING BEFORE TUNNELLING

Water recharge has been modeled using historical meteo data of rain precipitations = Max 10 l/s



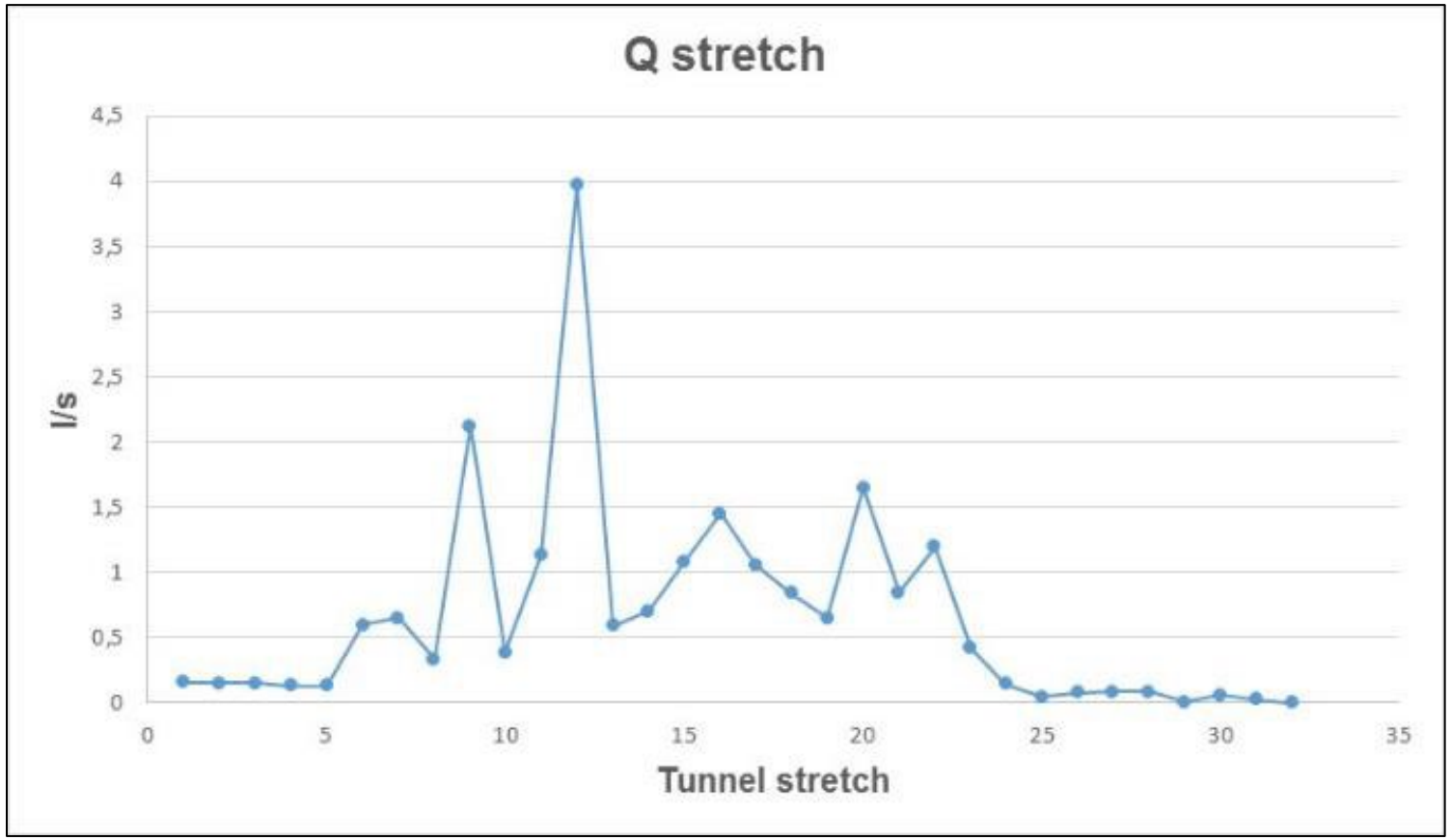
FEM FILTRATION ANALYSIS AFTER TUNNELLING WITHOUT MITIGATION

Lowering of the water table up to 30 m



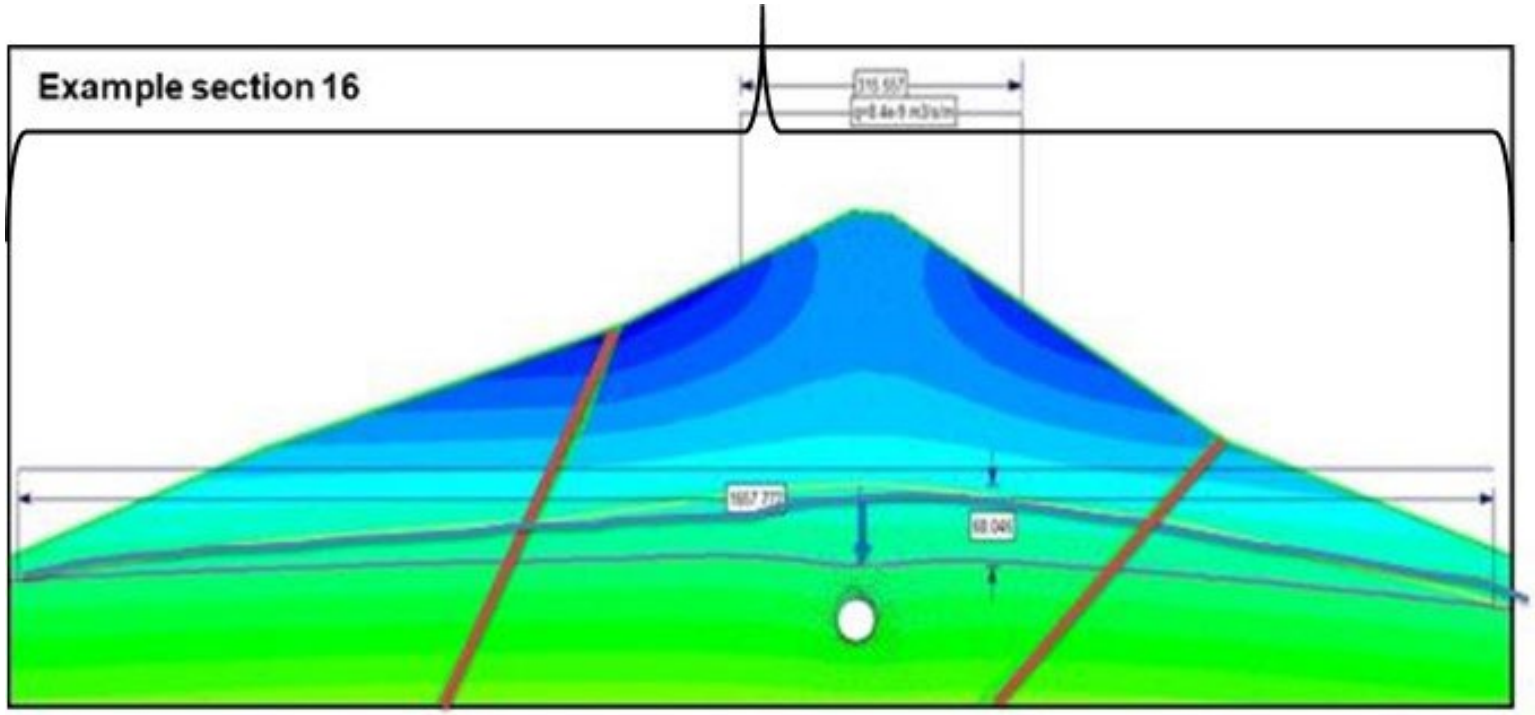
EXPECTED WATER INFLOW WITHOUT MITIGATION

- Total potential water inflow for the whole tunnel would be Q_T = 21 l/s
- Maximum available recharge by rain is Q = 10 l/s
- There would be a deficit; therefore, mitigation measures are needed

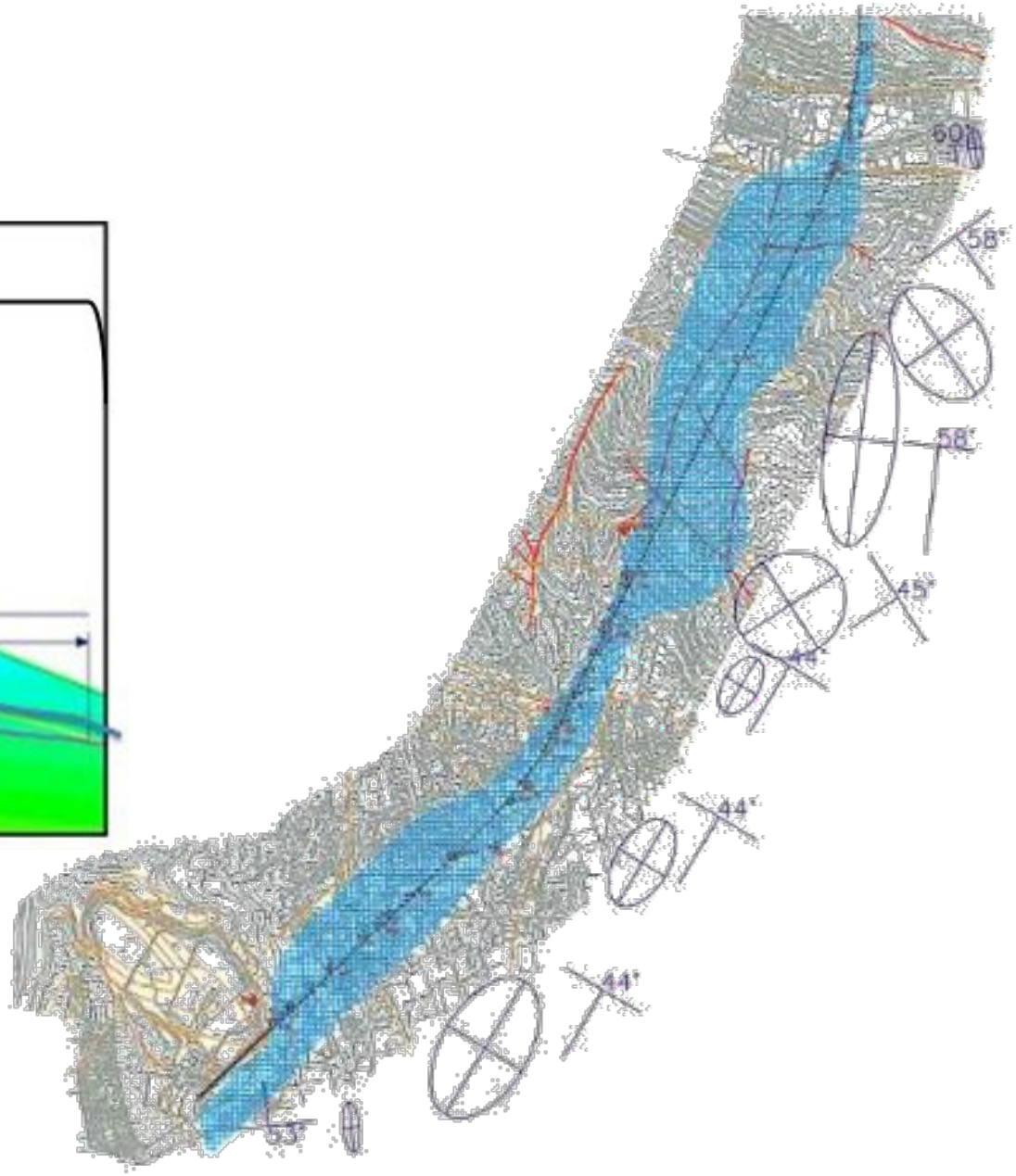


ANALYSIS OF INFLUENCE WITHOUT MITIGATION

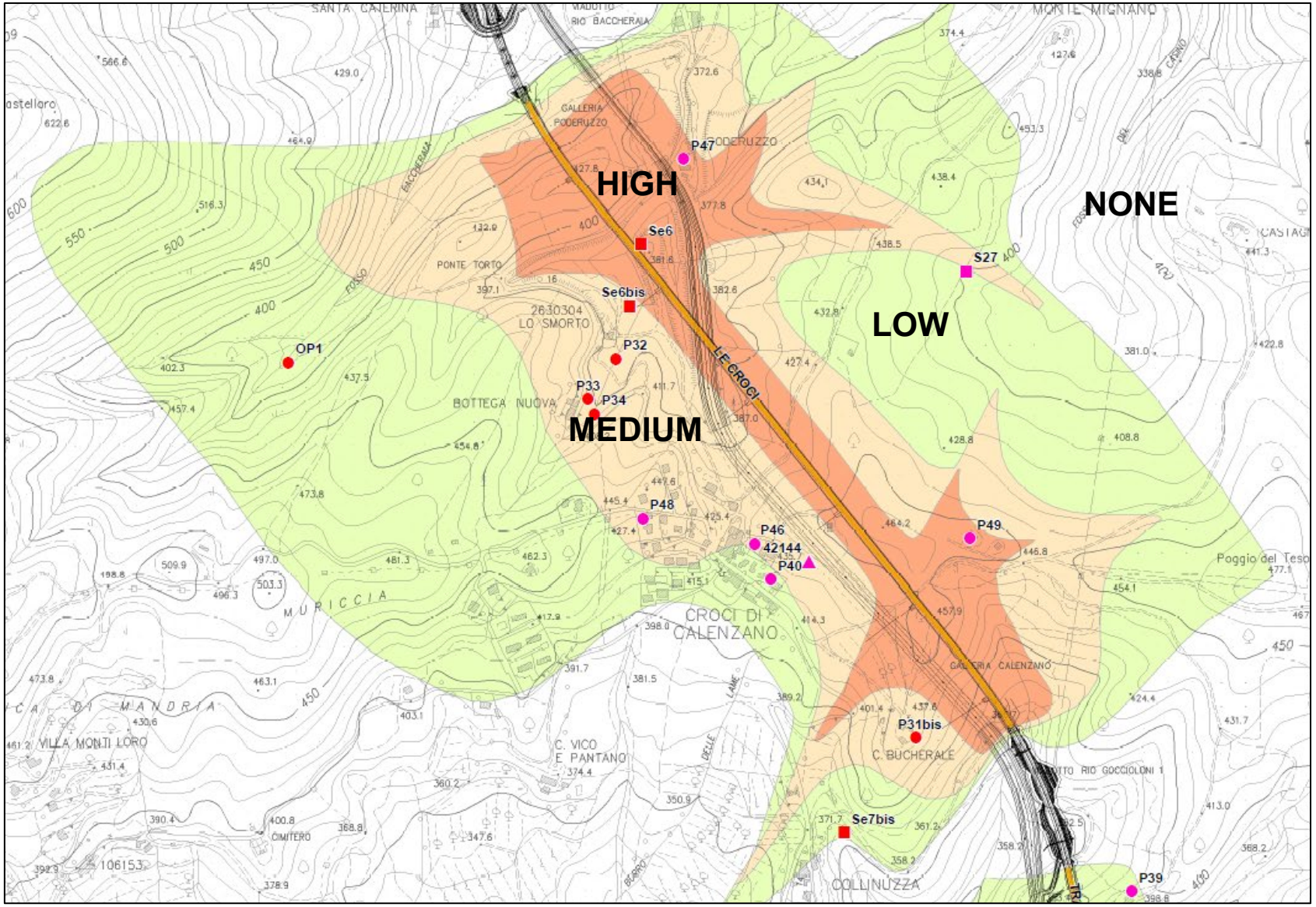
Area of Influence



Directions of the water flows



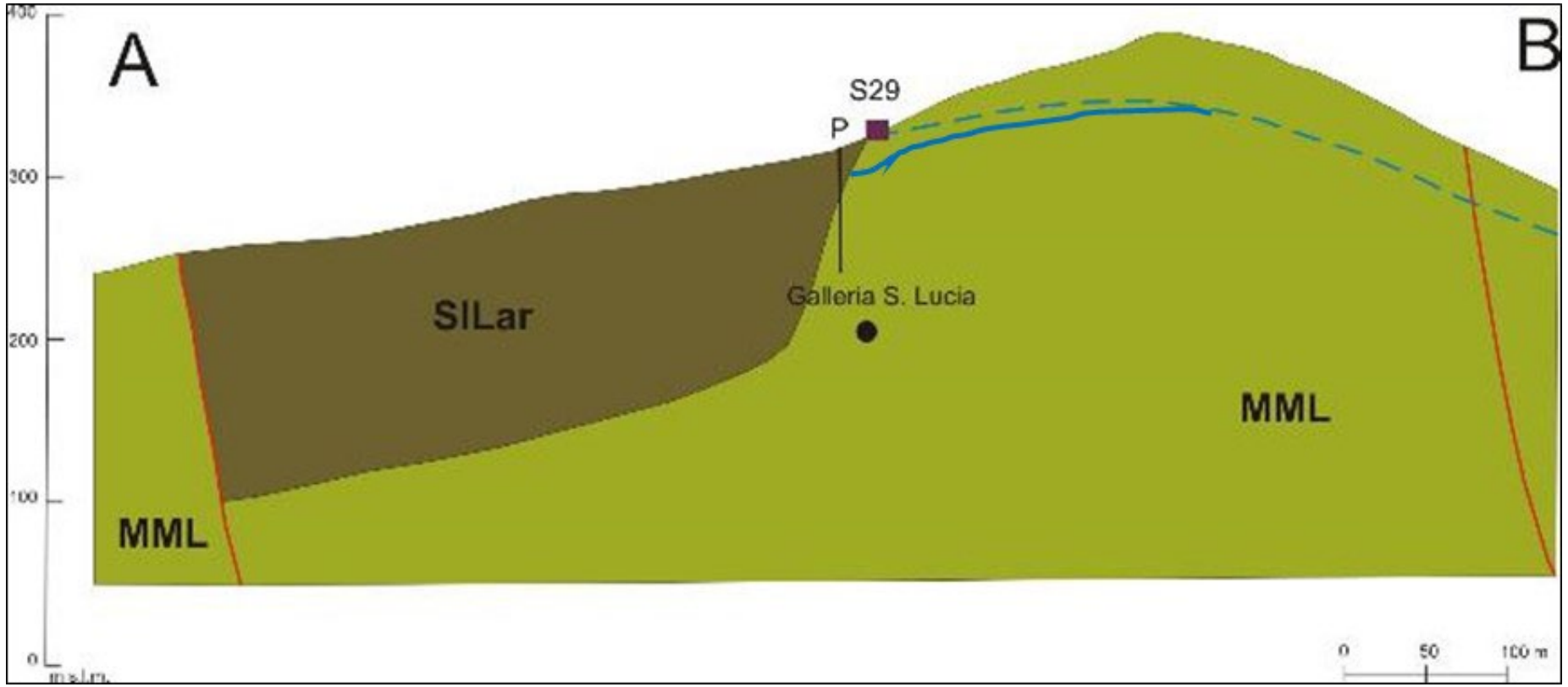
ANALYSIS OF IMPACT WITHOUT MITIGATION



MITIGATION AND COMPENSATION

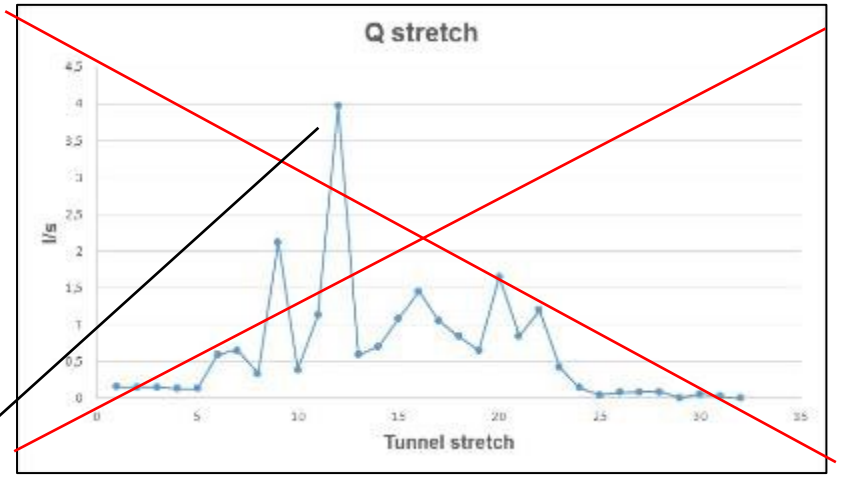
- THE TBM IS DESIGNED TO BE SEALED TO PREVENT METHANE AND WATER INFLOWS
- WHERE NEEDED EXECUTION OF PRE-GROUTING UP TO 50 m AHEAD THE FRONT

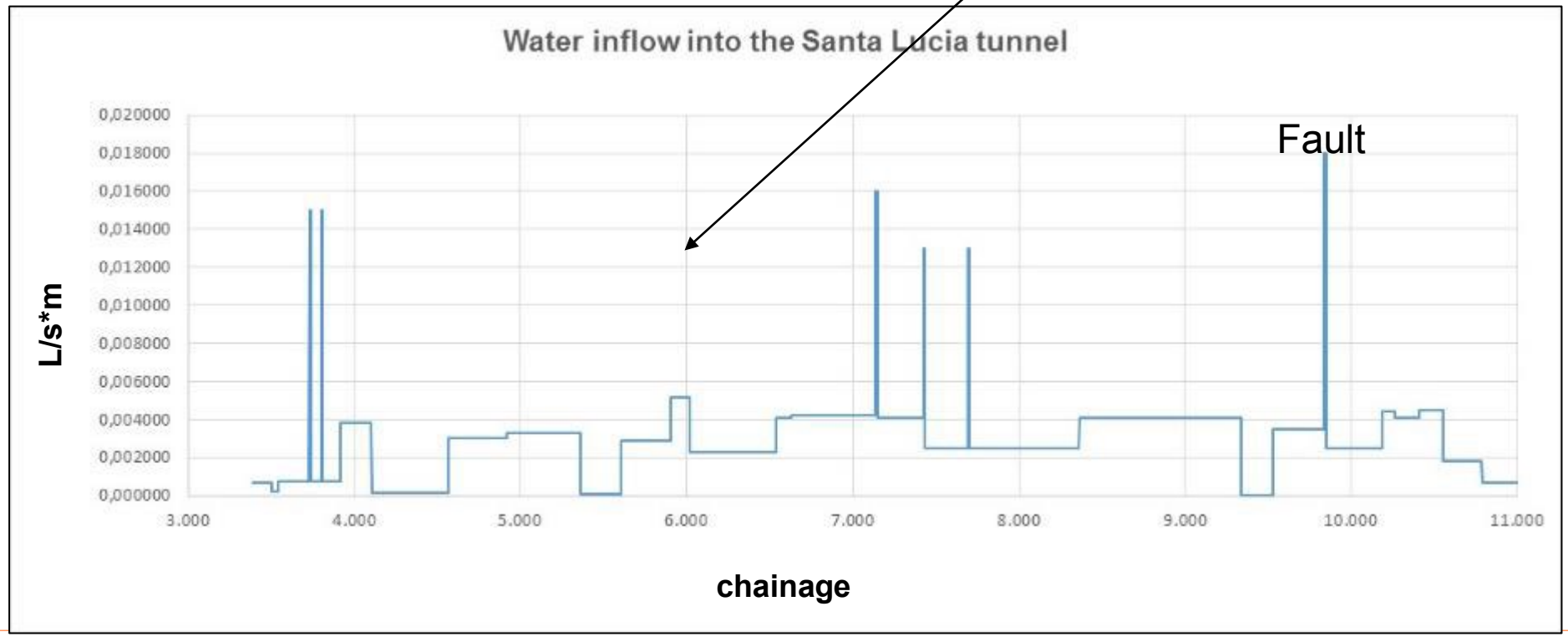
In the event of lowering of the water table impacting a spring or a well, execution of a dedicated new well



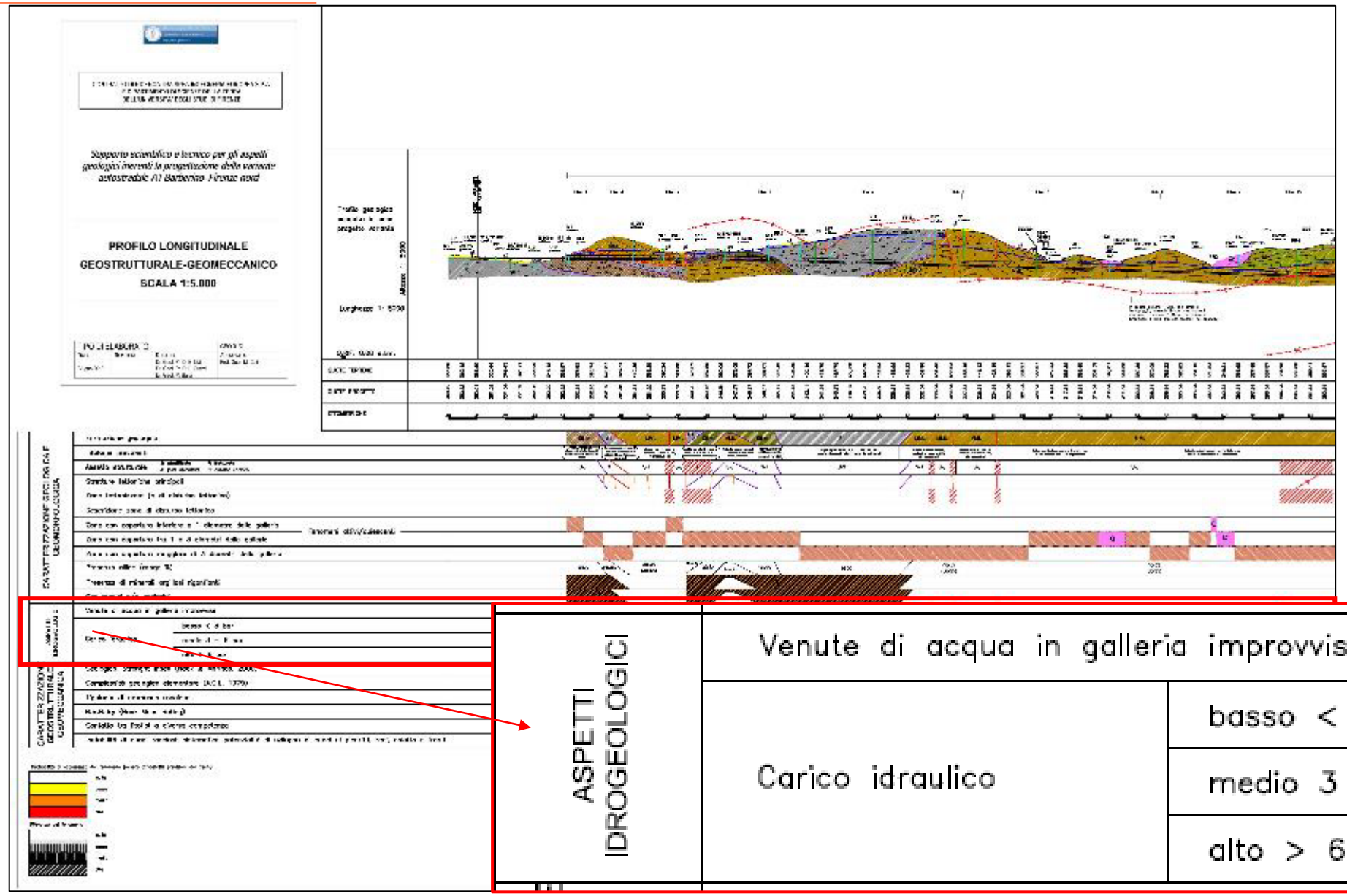
FINAL FLOW RATES

- With mitigation the residual Q values range from Q ≈ $1.1*10^{-3}$ l/s to Q = $2*10^{-2}$ l/s
- The expected flow rate decreases from a maximum of Q = 4 l/s down to a residual Q ≈ 0.02 l/s, in correspondence of faults





GEOMECHANICAL PROFILE



Genoa by-pass

The By-pass is intended to solve the node of Genoa (TEN-T corridor)

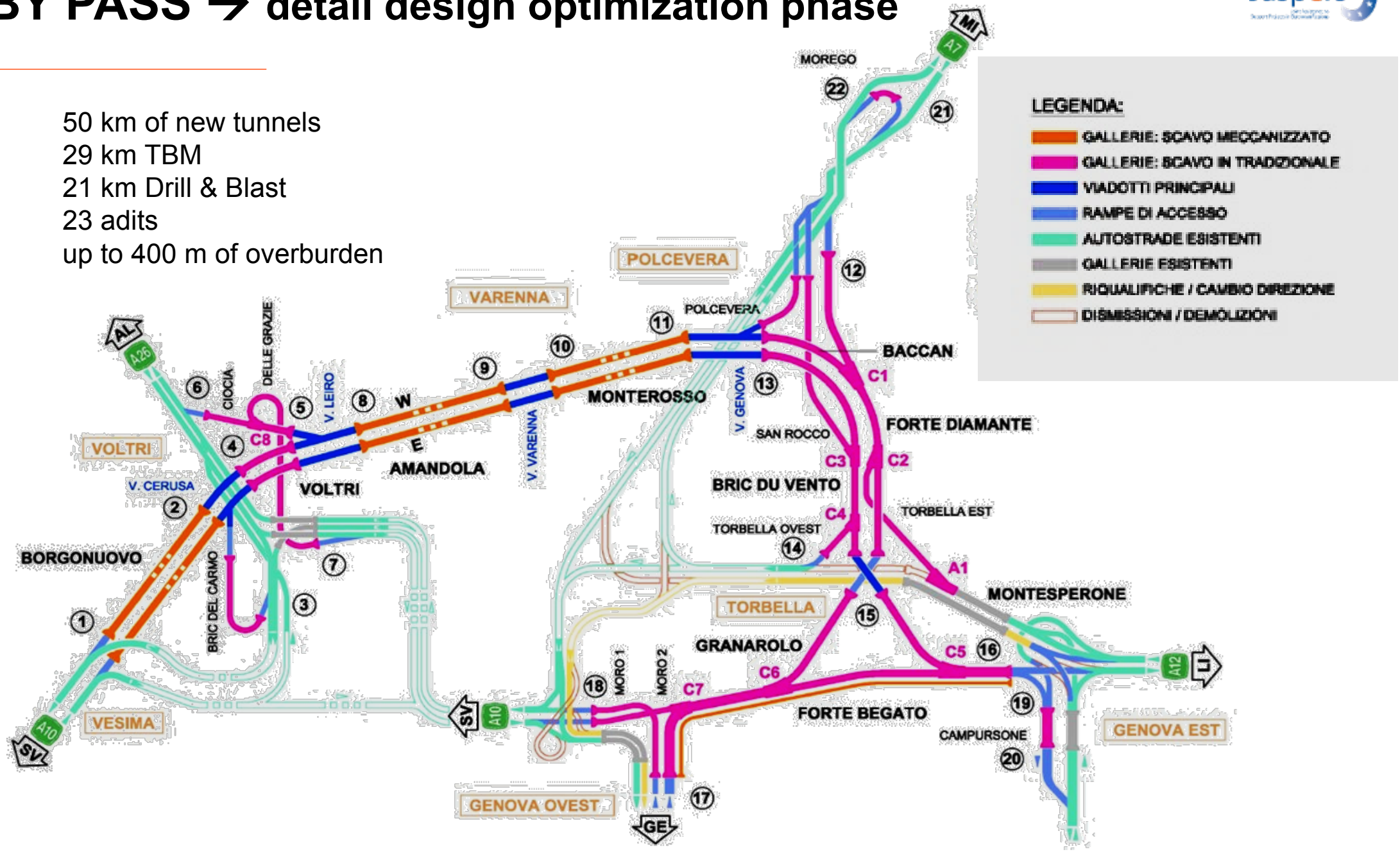
Currently:

- Traffic: 280.000 vehicle/day
- Delays: 2 up to 5 hours
- Queues: up to 15 → 25 km
- Need to replace the existing motorway, with long closure pending collapse

- Budget: 6 B€
- 10 years of works

GENOA BY PASS → detail design optimization phase

50 km of new tunnels
29 km TBM
21 km Drill & Blast
23 adits
up to 400 m of overburden



ENVIRONMENTAL SUSTAINABILITY

- The "Guidelines for the technical-economic feasibility project", approved by the Superior Council of Public Works in 2021 (LLGG), contemplates the development of an *ex-ante* analysis of the works through a "Report of Sustainability"

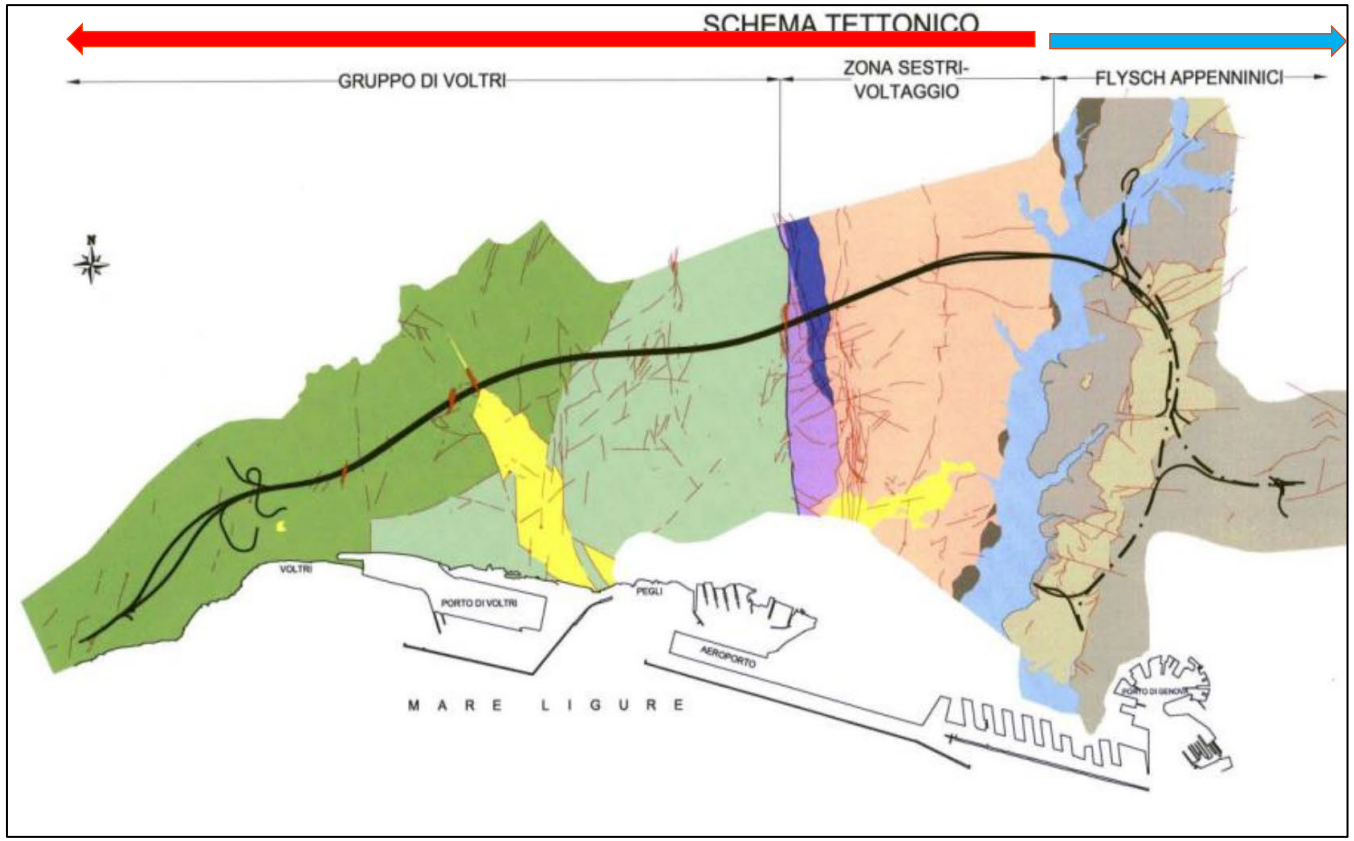
- The report for the sustainability assessment of the Genoa by-pass, which responds to the elements and evaluation parameters referred to chapter 3.2.4 of the LLGG and to the 6 priority environmental objectives indicated in Regulation 2020/852 of the European Parliament and of the Council of 18 June 2020, had been presented in June 2023

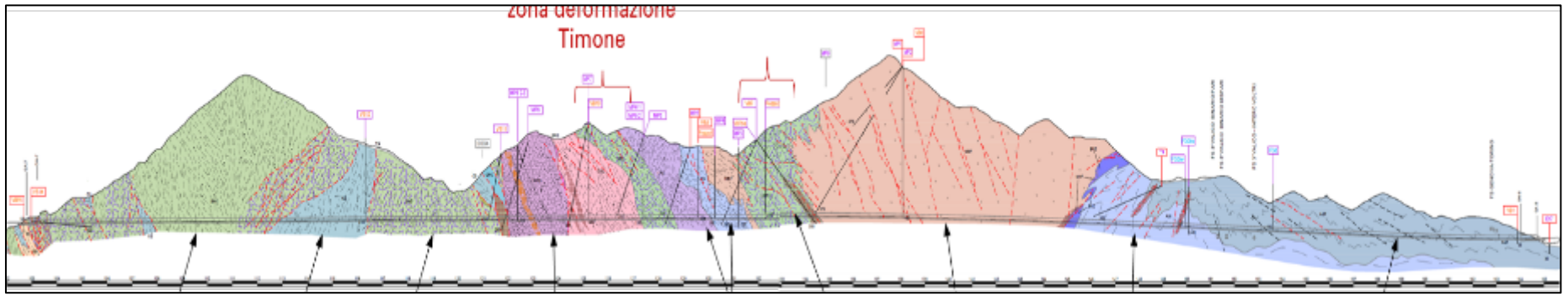
Table 2: Modifications according to Article 4(7), quality elements and possible effects

Modification / alteration / sustainable human development activity according to Article 4(7)	Surface water bodies				Groundwater bodies	
	Ecological status / potential			Chemical status	Quantitative status	Chemical status
	Biological quality elements	Supporting elements: Hydro-morphological quality elements	Supporting elements: Chemical and physico-chemical quality elements			
1) Modification to the physical characteristics of a body of surface water	Possible direct and/or indirect effects	Possible direct and/or indirect effects	Possible direct and/or indirect effects	Possible indirect effects	Possible indirect effects	Possible indirect effects
2) Alterations to the level of bodies of groundwater	Possible indirect effects	Possible indirect effects	Possible indirect effects	Possible indirect effects	Possible direct effects	Possible indirect effects
3) New sustainable human development activities*	Possible direct and/or indirect effects	Possible direct and/or indirect effects	Possible direct and/or indirect effects	Not applicable (because no definition of high status)	Not applicable (because not addressed in this specific context)	

GEOLOGY

- High structural complexity, in the Alps - Apennine contact area
- Alps = metamorphic
- Apennine = sedimentary
- For design numerous Rock Mass Zones had been defined





HEC

For each tunnel we have a Hydrogeological Excavation Code

autostrade per l'italia

NODO STRADALE E AUTOSTRADALE DI GENOVA

Adeguamento del sistema
A7 - A10 - A12

Lotto 4 - Ambito Genova Est - Genova Ovest

PROGETTO ESECUTIVO

DG - DOCUMENTAZIONE GENERALI

OPERE IN SOTTERRANEO

Parte generale

Codice di scavo ai fini idrologici - Scavo in Tradizionale

IL PROGETTISTA SPECIALISTICO
Ing. Simona Comi
Ord. Ingg. Milano n.A18014
RESPONSABILE PROGETTAZIONE OPERE IN SOTTERRANEO

IL RESPONSABILE INTEGRAZIONE PRESTAZIONI SPECIALISTICHE
Ing. Pietro Mele
Ord. Ingg. Milano N. A30141

IL DIRETTORE TECNICO
Ing. Orlando Mazza
Ord. Ingg. Pavia N. 1496
PROGETTAZIONE NUOVE OPERE AUTOSTRADALI

CODICE IDENTIFICATIVO											ORDINATORE
RIFERIMENTO PROGETTO			RIFERIMENTO DIRETTORIO				RIFERIMENTO ELABORATO				--
Codice Commessa	Lotto, Sub-Prog. Cod. Appalto	Fase	Capitolo	Paragrafo	W B S	Parte d'opera	Tip.	Disciplina	Progressivo	Rev.	SCALA
110722	LL04	PE	DG	OST	GE000	00000	R	T U N	0024	-1	-

spea ENGINEERING
Atlantia

PROJECT MANAGER: Ing. Sara Frisiani, Ord. Ingg. Genova N. 9810A
SUPPORTO SPECIALISTICO:
REDATTO:
VERIFICATO:

REVISIONE	
n.	data
0	LUGLIO 2018
1	FEBBRAIO 2019
2	-
3	-
4	-

VISTO DEL COMMITTENTE
autostrade per l'Italia
IL RESPONSABILE UNICO DEL PROCEDIMENTO
Ing. Alberto Selleri

VISTO DEL CONCEDENTE
Ministero delle Infrastrutture e dei Trasporti

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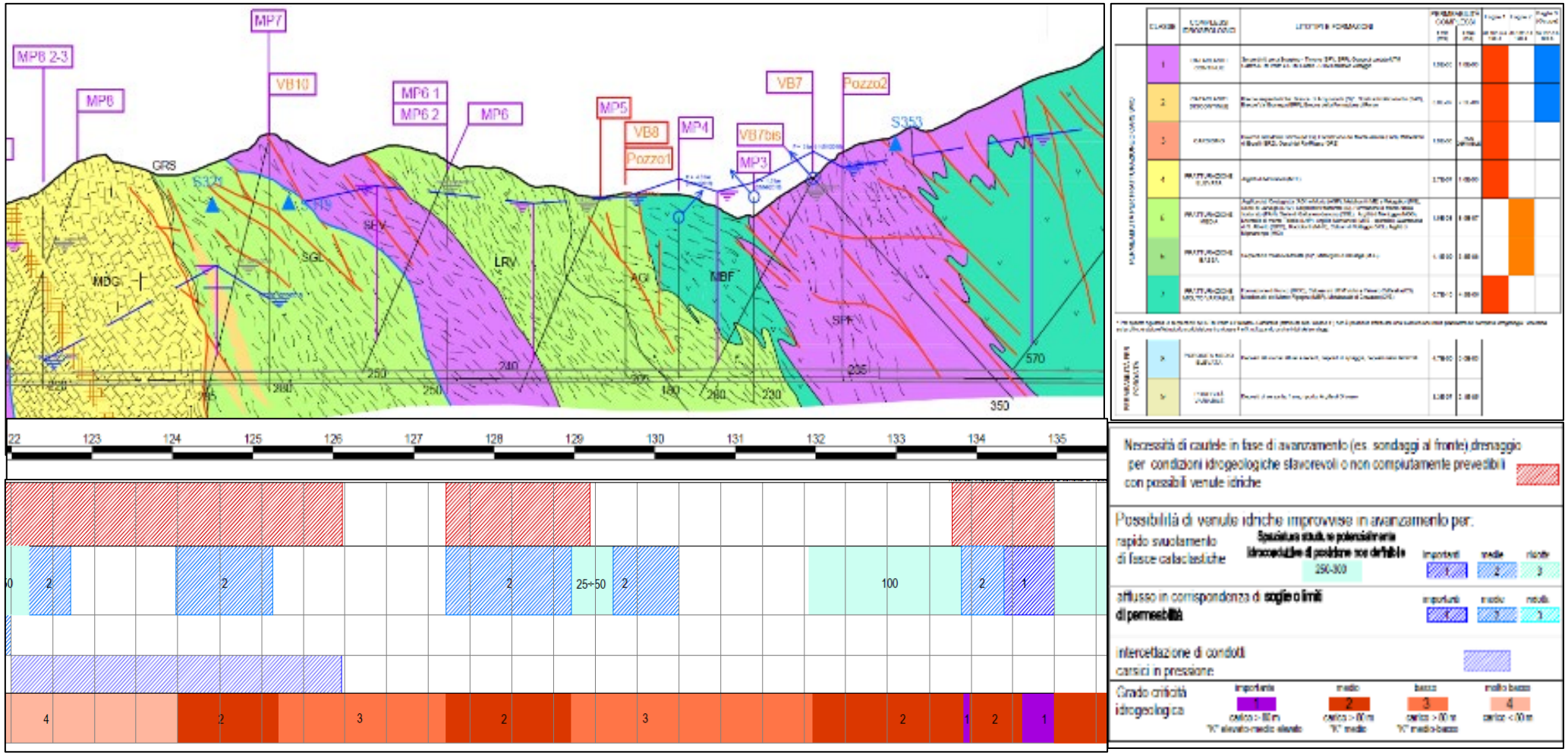
Codice Elaborato	Titolo Elaborato	Gallerie analizzate	Lotto Operativo
110721-LL1A-PE-S3-G22-GN22U-00000-R-TUN3070-0	Galleria Morego - Codice di scavo ai fini idrogeologici	Galleria Morego	1A
110721-LL1A-PE-S6-G21-GN21U-00000-R-TUN4176-0	Galleria Campursone - Codice di scavo ai fini idrogeologici	Galleria Campursone	1A
110721-LL1B-PE-A1-G03-GN03E-00000-R-TUN0802-0	Galleria Voltri Est - Codice di scavo ai fini idrogeologici	Galleria Voltri Est	1B
110721-LL1B-PE-A1-G03-GN03W-00000-R-TUN0848-1	Galleria Voltri Ovest - Codice di scavo ai fini idrogeologici	Galleria Voltri Ovest	1B
110721-LL1B-PE-S2-G02-GN02U-00000-R-TUN5542-1	Galleria Bric del Carmo - Codice di scavo ai fini idrogeologici	Galleria Bric del Carmo	1B
110721-LL1B-PE-S2-G04-GN04U-00000-R-TUN6050-1	Galleria Ciocia - Codice di scavo ai fini idrogeologici	Galleria Ciocia	1B
110721-LL1B-PE-S2-G04-GN04C-00000-R-TUN6131-1	Galleria Ciocia – Camerone 8 - Codice di scavo idrogeologico	Galleria Ciocia	1B
110721-LL1B-PE-S2-G05-GN05U-00000-R-TUN6602-1	Galleria delle Grazie - Codice di scavo ai fini idrogeologici	Galleria delle Grazie	1B
110722-LL02-PE-DG-OST-GE000-00000-R-TUN0494-0	Opere in sotterraneo - Codice di scavo idrologico	Galleria Forte Diamante (Tratto Nord fino al Camerone 1) Galleria San Rocco Galleria Polcevera Galleria Baccan (fino al Camerone 1) Galleria Bric du Vento (Tratto Nord fino al Camerone 3)	2
110722-LL03-PE-DG-OST-GE000-00000-R-TUN0498-0	Opere in sotterraneo - Codice di scavo ai fini idrologici	Galleria Granarolo (Tratto Nord fino al Camerone 6) Galleria Forte Diamante (Tratto a Sud del Camerone 1 incluso + Camerone 2) Galleria Torbella Est (con Alesaggio Montesperone) Galleria Torbella Est (con Alesaggio Montesperone) Galleria Bric du Vento (Tratto a Sud del Camerone 3 incluso + Camerone 4) Galleria Monte Sperone (Tratto Nord fino al Camerone 5) Galleria Torbella Ovest	3
110722-LL03-PE-A2-G11-GN11F-00000-R-TUN8501-1	Gall. Forte Diamante (Camerone 8) - Codice di scavo idrogeologico	Galleria Forte Diamante	3
110722-LL03-PE-A2-G11-GN11D-00000-R-TUN8601-1	Gall. Forte Diamante (Camerone 2) - Codice di scavo idrogeologico	Galleria Forte Diamante	3
110722-LL03-PE-A3-G12-GN12F-00000-R-TUN8701-1	Galleria Bric Du Vento (Camerone 3) - Codice di scavo idrogeologico	Galleria Bric Du Vento	3
110722-LL03-PE-A3-G12-GN12F-00000-R-	Galleria Bric Du Vento	Galleria Bric Du Vento	3
TUN8801-1	(Camerone 4) - Codice di scavo idrogeologico		
110722-LL04-PE-DG-OST-GE000-00000-R-TUN0024-1	Codice di scavo ai fini idrologici - Scavo in Tradizionale	Galleria Moro 1 – Moro 2 Galleria Granarolo (Tratto Sud fino al Camerone 6 incluso) Galleria Forte Begato Galleria Monte Sperone (Tratto Est fino al Camerone 5 incluso)	4
110722-LL04-PE-DG-OST-GE000-00000-R-TUN0211-0	Codice di scavo ai fini idrologici - Scavo in Meccanizzato	Cunicolo di sicurezza	4
110728-LL08-PE-A1-G01-GN01U-00000-R-TUN0653-2	Galleria Borgonuovo - Codice di scavo ai fini idrogeologici e Linee Guida	Galleria Borgonuovo	8
110728-LL08-PE-A1-G06-GN06U-00000-R-TUN2082-2	Galleria Amandola - Codice di scavo ai fini idrogeologici e Linee Guida	Galleria Amandola	8
110728-LL08-PE-A1-G07-GN07U-00000-R-TUN3053-2	Galleria Monterosso - Codice di scavo ai fini idrogeologici e Linee Guida	Galleria Monterosso	8

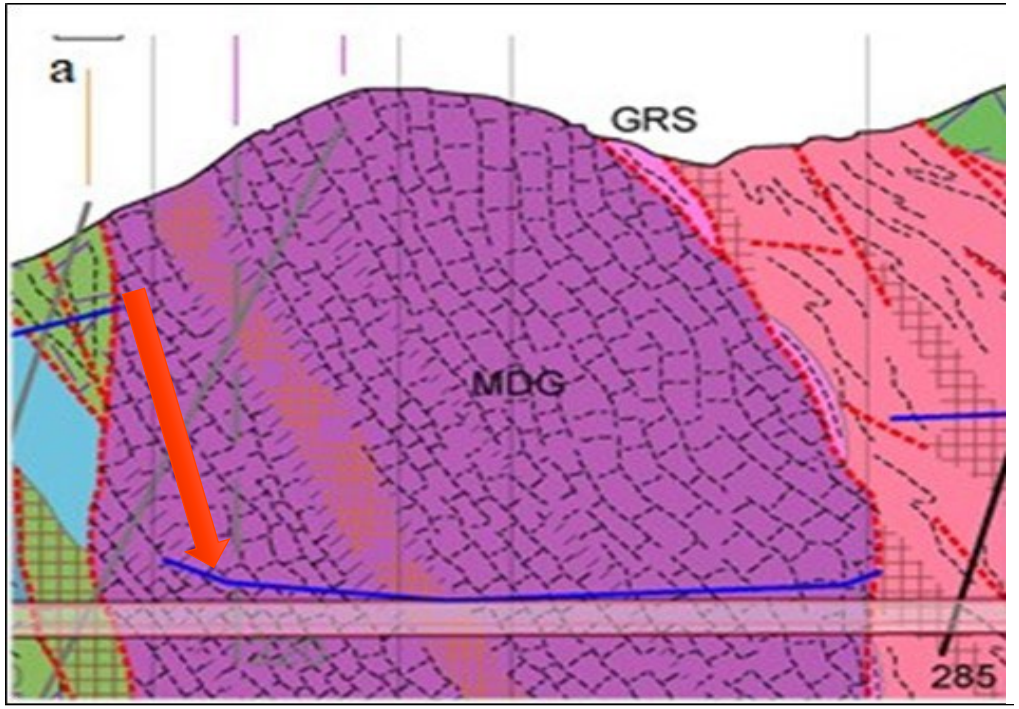
HYDROGEOLOGICAL MODEL

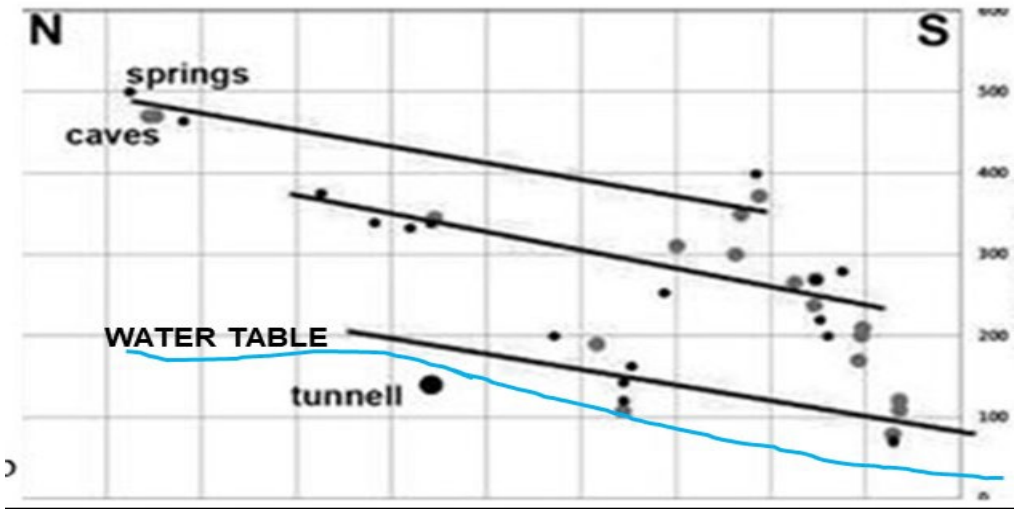
Hydrogeological basins, karst, permeability, water table, water head, meteoric supply, natural and anthropic discharge, hydrogeological balance



KARST

- A segment of about 300 m will cross a dolomite with numbered of karst conduits and small caves. A drastic drop of the water table of about 300 m has been found
- Springs and known caves have different elevations going from the coast (south) to the Apennine ridge (north) and does not seem interfering with the tunnel
- 20 kyears ago, the sea level was -110 m below, the potential occurrence of paleo-karst features at the tunnel axis is highly probable

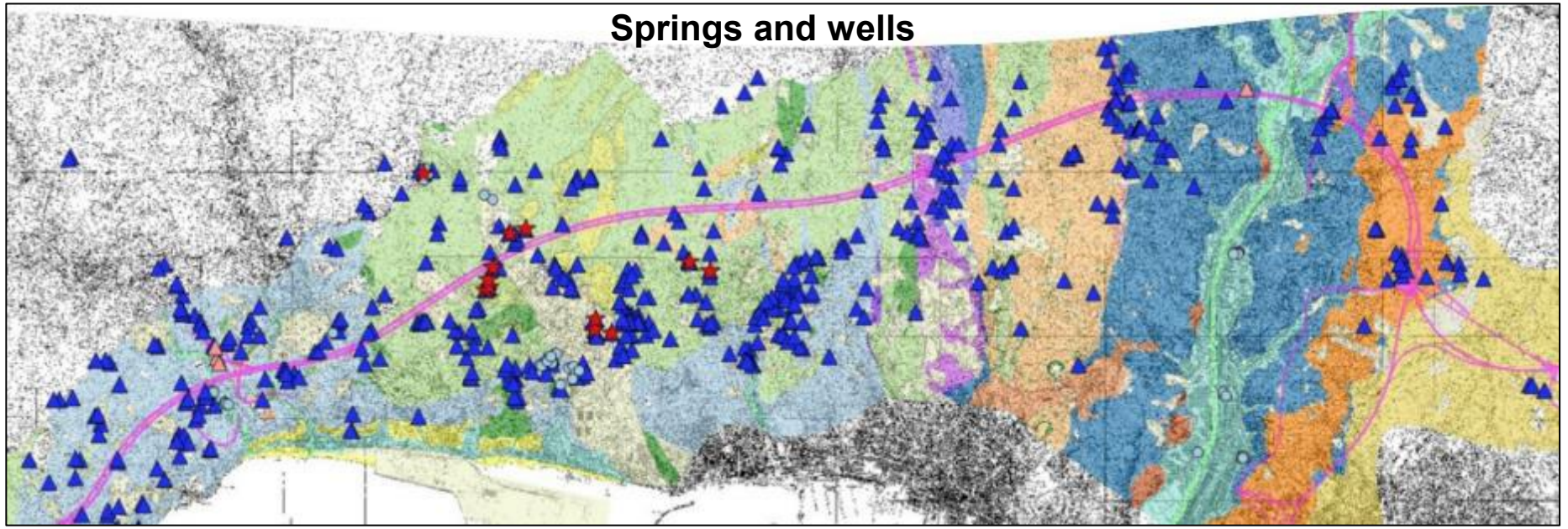




WATER MONITORING - WIP

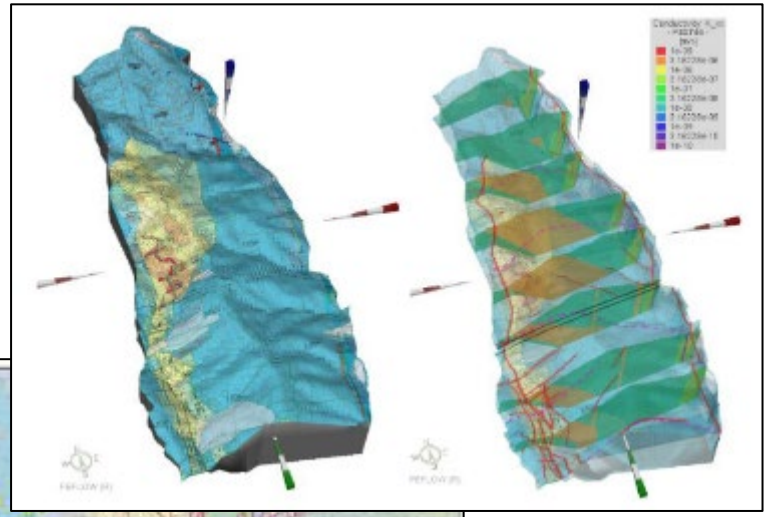
- Map of the water features: springs, wells, creeks
- 20 years of hydrogeological data acquisition to go on in execution and operation

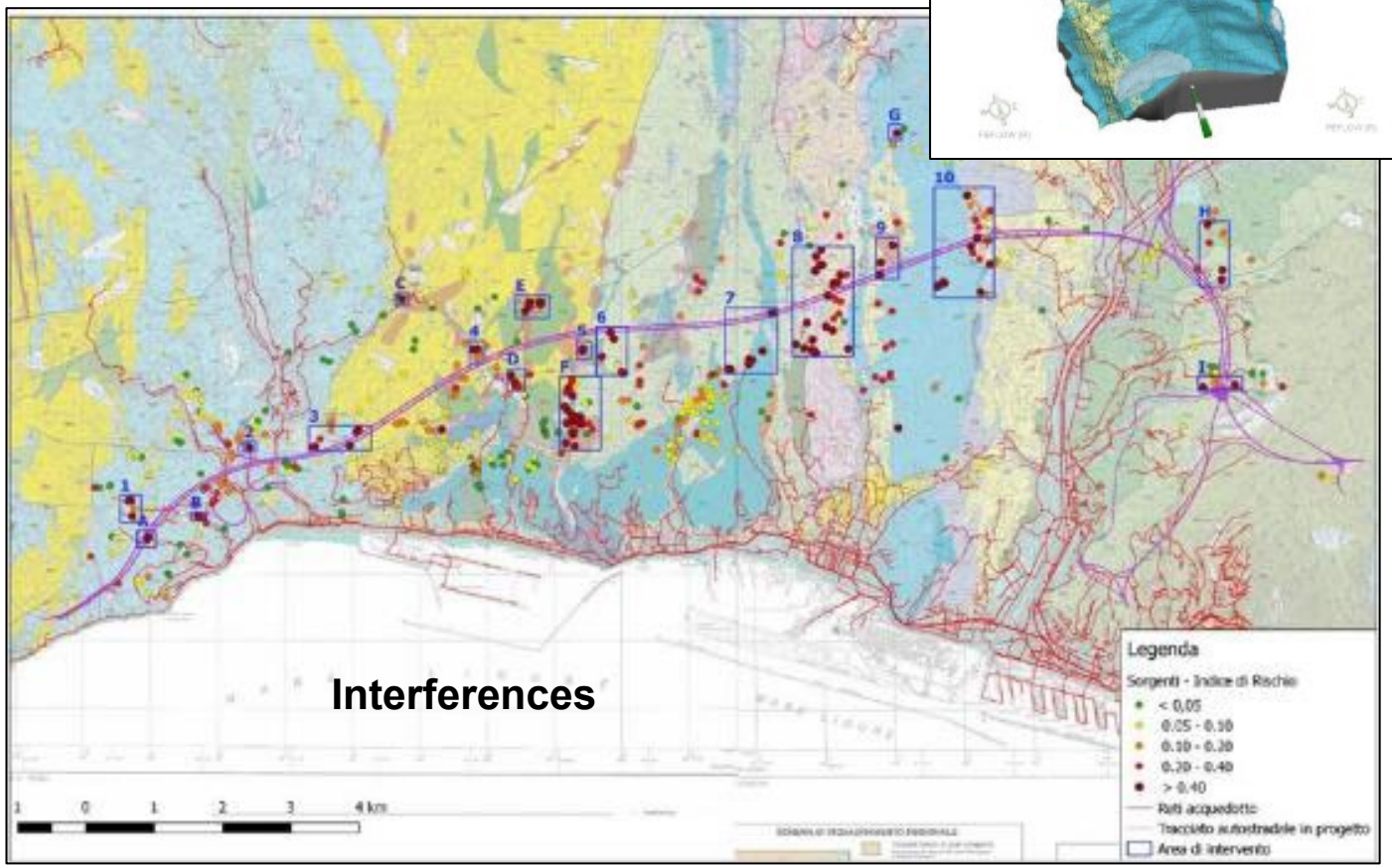
- 550 springs and wells monitored
- 45 points measures in creeks
- 6 continuous measurement stations aimed at evaluating the annual balances
- 4 long-term pumping tests
- 3 instrumented piezometers with pressure gauges
- more than 100 permeability tests
- 100 hydro-chemical characterisation



RISK ANALYSIS - WIP

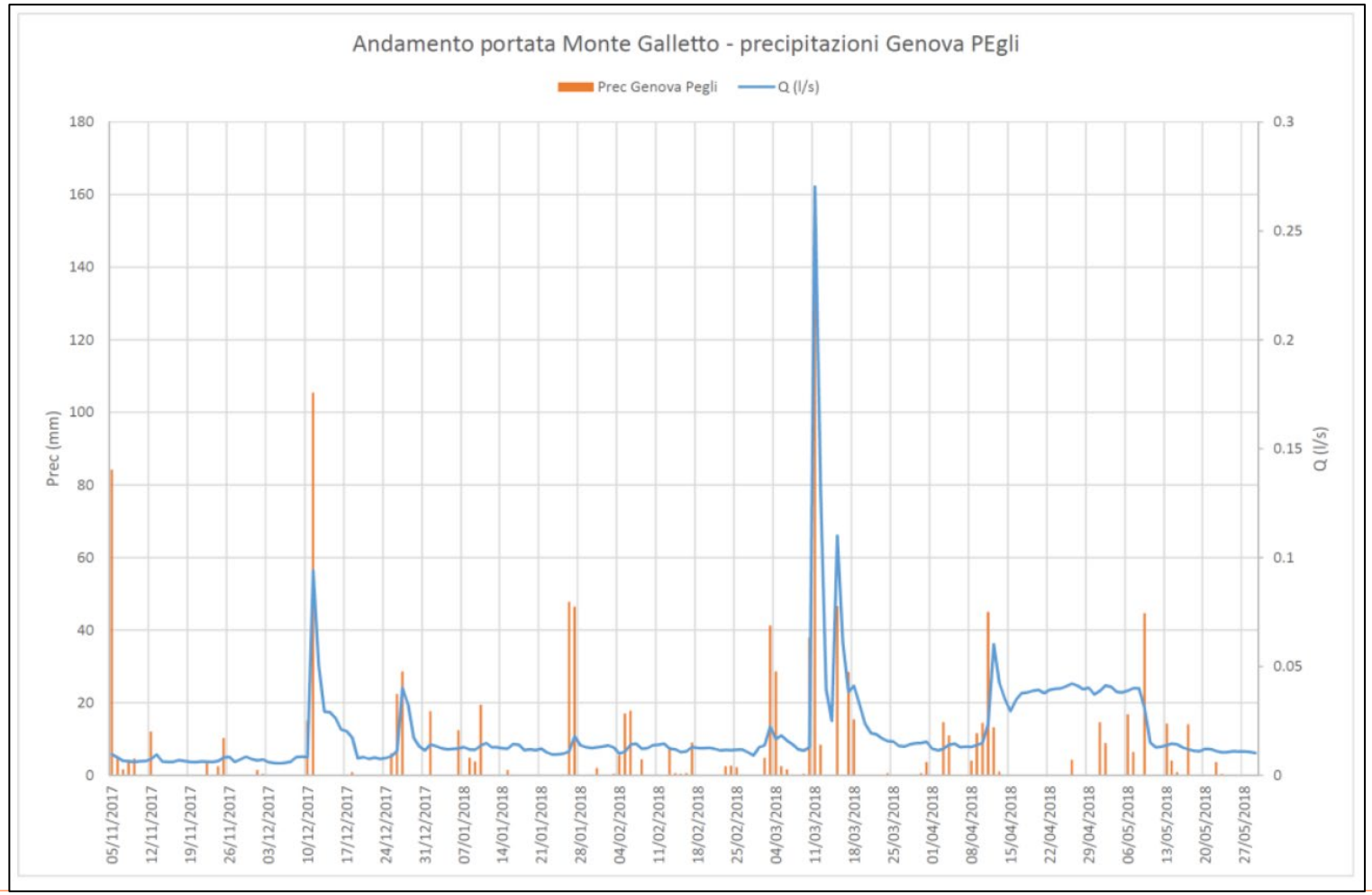
- Numerical analysis *before construction*
- Verification for impact on springs, wells and creeks *after construction*, with and without mitigation interventions
- Assessment of long-term equilibrium between rains and residual water drains by the tunnel
- Risks analysis for each tunnel/tunnel stretch related to:
  - rock mass features
  - permeability
  - flow rates
  - hydraulic loads
  - uses





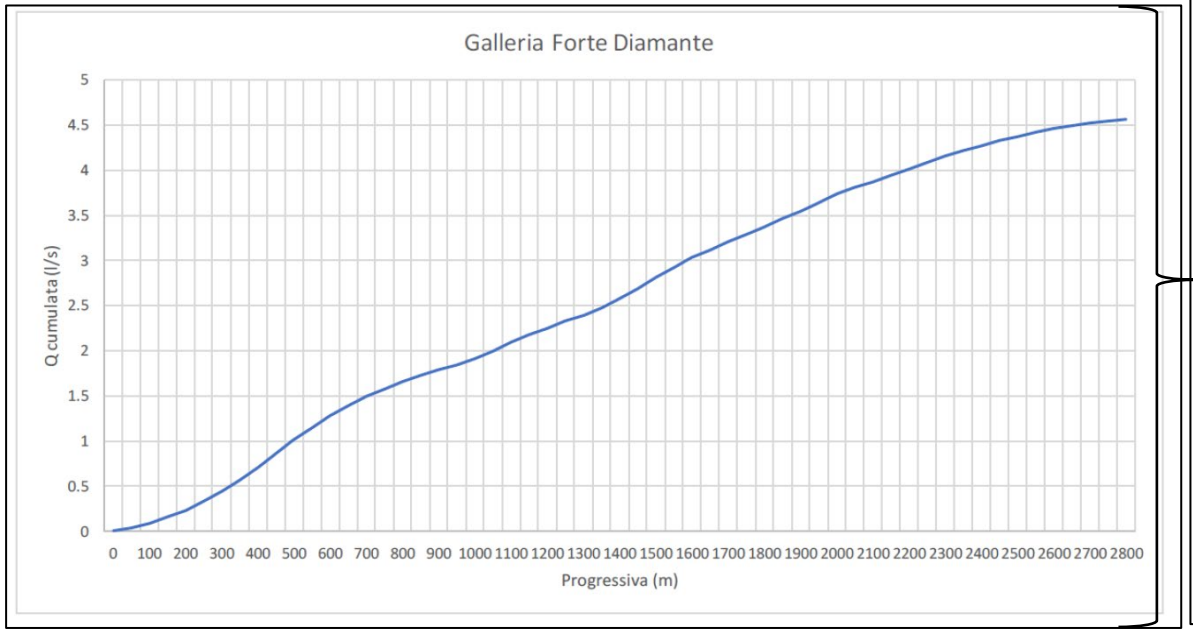
EXISTING IMPACTS

- In the existing tunnels, built in early 1960s without any mitigations, the cumulative water inflows vary between 12 and 25 l/s



IMPACTS WITHOUT MITIGATION - WIP

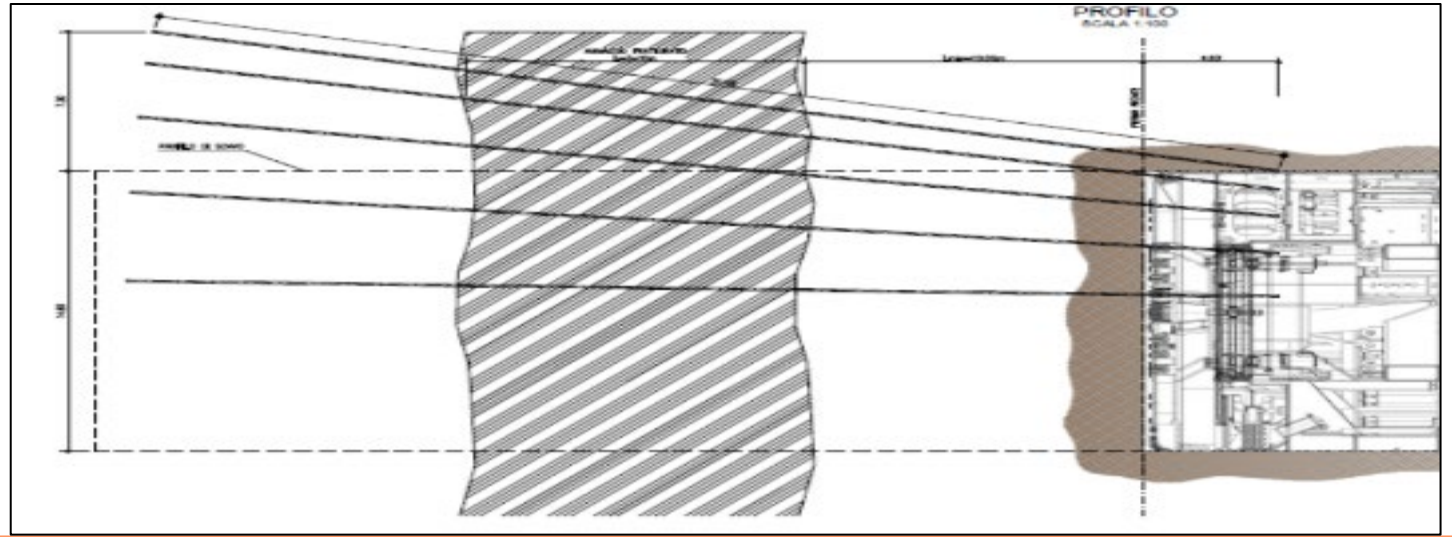
- Impact on the water resources linked to the Genoa aqueduct is excluded
- Springs, wells and creeks located higher then the tunnel level are at risk
- The range of the cumulative water inflow is between 1 → 142 l/s

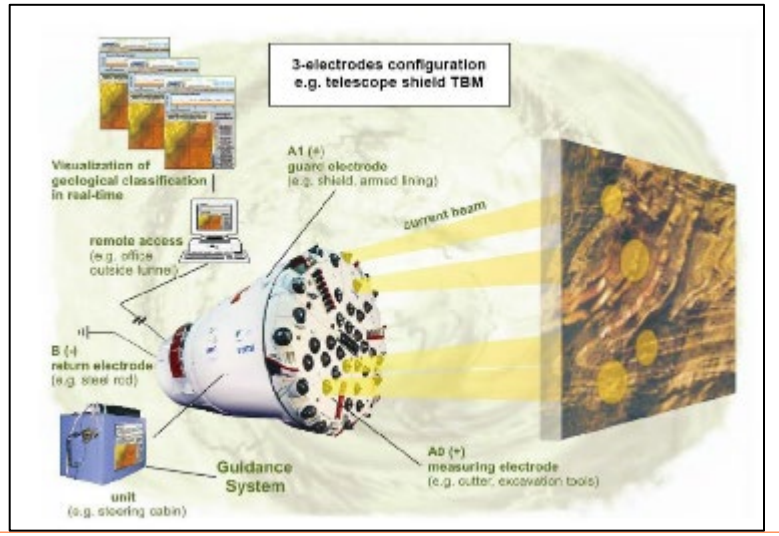


Galleria	Lunghezza (m)	Stima portata da Heuer (l/s)
Borgonuovo	2850	9.5 - 11.8
Voltri	200	0.3
Amandola	6000	62 - 91
Monterosso	6150	88 - 142
Bric del Carmo	1150	2.2
Delle Grazie	1300	3.9
Ciocia	600	1.0
Granarolo	3500	7.7
Forte Diamante	2800	4.6
Bric du Vento	2500	3.5
Montesperone	2130	8.0
Moro 1	1000	0.8
Moro 2	900	1.3
Torbella E	1530	4.0
Torbella W	400	0.6
Forte Begato	1300	7.7
San Rocco	1300	1.3
Baccan	1100	1.5
Polcevera	600	0.4

MITIGATION MEASURES - WIP

- D&B tunnels will be sealed waterproofed where necessary
- TBMs are designed to be sealed to prevent methane and water inflows
- Systematic geophysical investigations and exploratory drill holes up to 200 m ahead the front
- Where needed pre-grouting up to tens of meters ahead the front





POTENTIAL COMPENSATIONS - WIP

- Water reservoirs and supplied by water tanks
- New aqueduct connections, strengthening and integration the existing network, and drill of dedicated wells
- Flows drained in the tunnel taken for treatment to feed the aqueduct structures
- Reuse for specific interventions of public interest: firefighting storage basins, agriculture…

THE PERFECT SOLUTION !!!

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