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SIG SESSION: INSPECTION, INVESTIGATION AND MONITORING DURING SERVICE LIFE

Damages on lining induced by the construction of a new tunnel and the design of refurbishment: a case history

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Friday November 27th 2020 – fully digital

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Introduction

- ✓ The refurbishment design of old tunnels is a very peculiar topic
- ✓ Beyond the traditional approach, a relevant role is played by the calibration of the employed models based on measurement of the stress state acting on the linings
- ✓ This calibration is crucial because allow to overcame a lot of uncertainty: geotechnical operational values of mechanical parameters, initial state of stress in the ground, stress release percentage associated to the excavation techniques adopted …..
- ✓ The presentation deals with inspection, investigation, monitoring, provisional refurbishment design and related works of **Casal di Pari tunnel** on E78 Grosseto-Siena road, in the central of Italy
- ✓ During the construction of a new tunnel (doubling the roadways), the lining of the old tunnel was seriously damaged (tunnel axis distance about 3 diameters)

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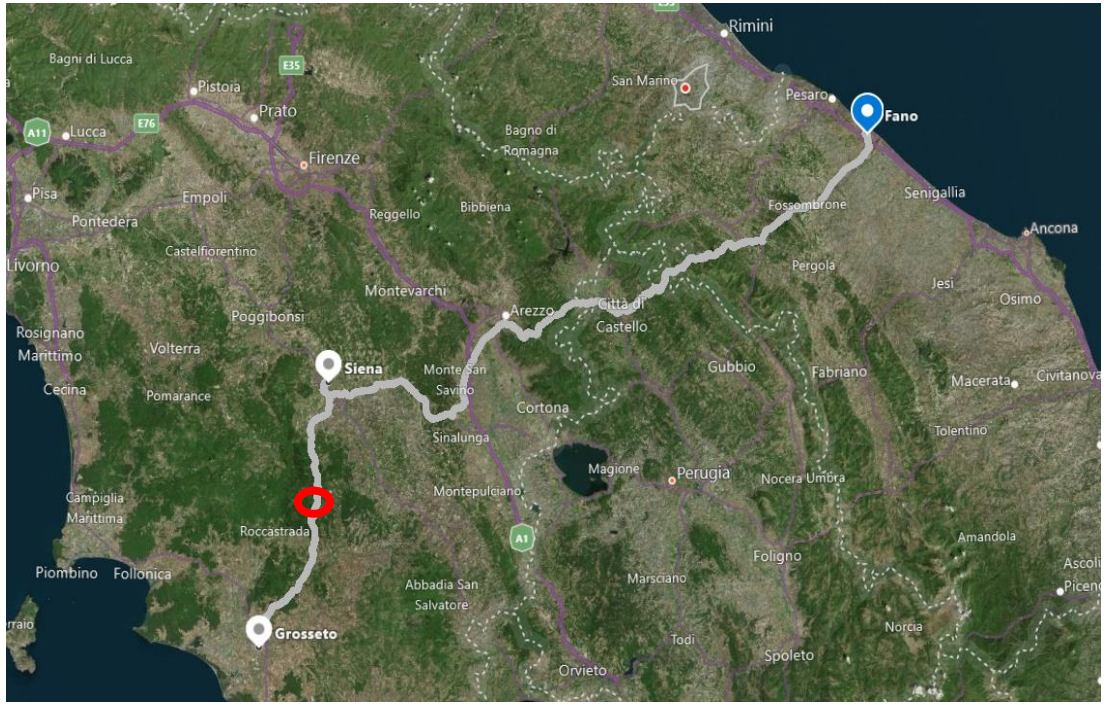
Summary

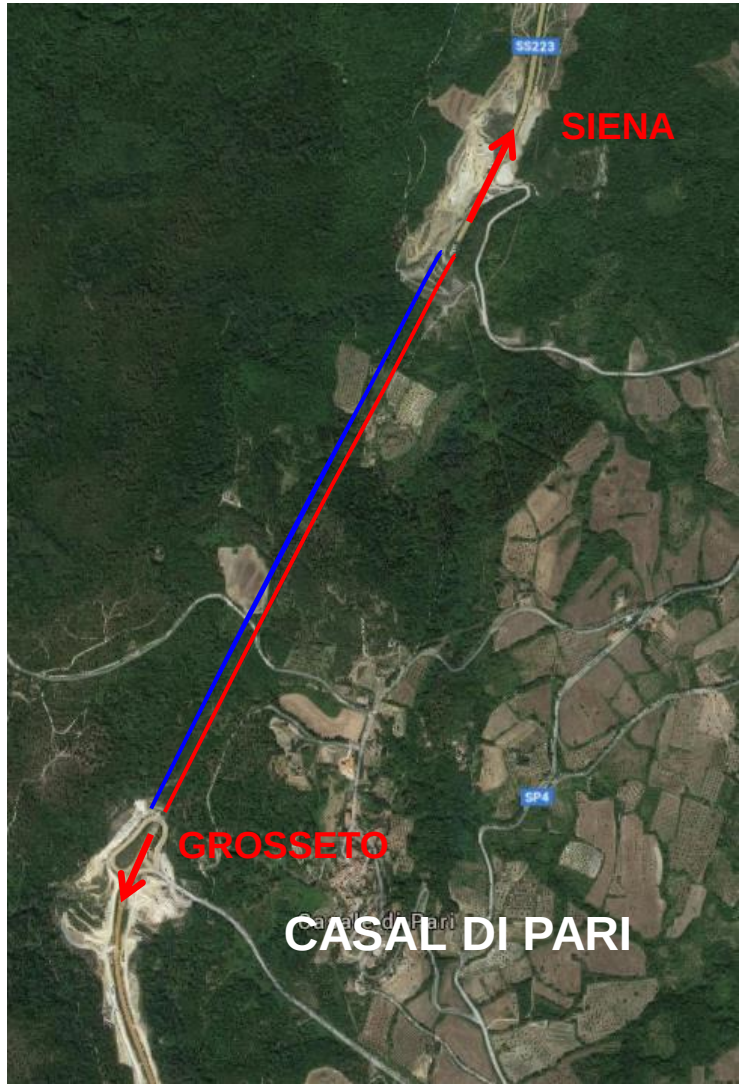
- ✓ The events
- ✓ Geology and geomechanics
- ✓ Surveys
- ✓ Model calibration
- ✓ Refurbishment design + monitoring
- ✓ Works description
- ✓ Measurements vs predictions
- ✓ Concluding remarks

Location



Motor way **E78 Grosseto-Siena** modernization works: construction of the new **Casal di Pari tunnel** close to the existing/old one

The two Casal di Pari tunnels



EXISTING TUNNEL

Gabarit 4.65 m (two tracks)

Excavation Technique: conventional partialized face

Pre-support: metallic ribs and spritz beton

Final lining: plane concrete and locally (masonry)

Lining thickness: 50-120 cm

NEW TUNNEL

Gabarit 5.05 m (two tracks + emergency)

Excavation Technique: conventional full face

Pre-support: metallic ribs and spritz beton

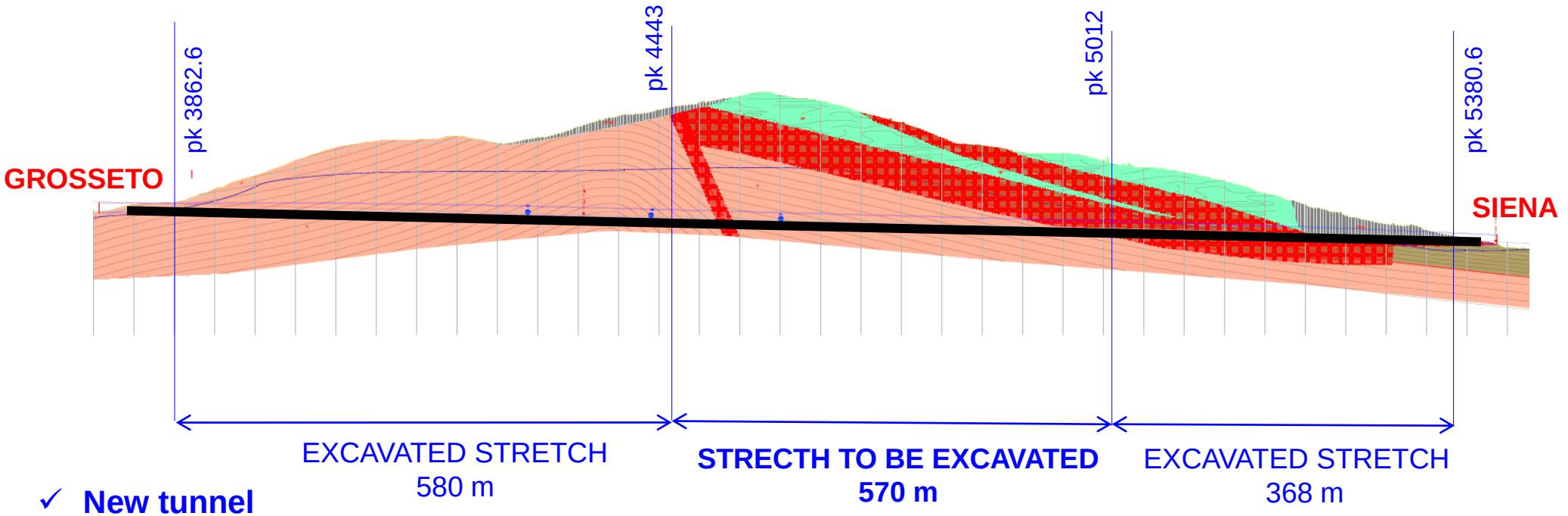
Final lining: reinforced concrete (60-120 cm)

Length 1530 m

Maximum Depth 150 m

Distance between axis 37.5 m (about 3 diameters)

Problems during new tunnel construction



- ✓ **New tunnel**
  - **Instabilities at the face (front collapse at pk 5087)**
  - **High values of convergence at pk 5045 - pk 5019 (6 – 21 cm)**
- ✓ **Existing tunnel**
  - **Cracking and concrete detachment of the lining**
  - **Uplift and deformation of the road platform**

Problems during new tunnel construction

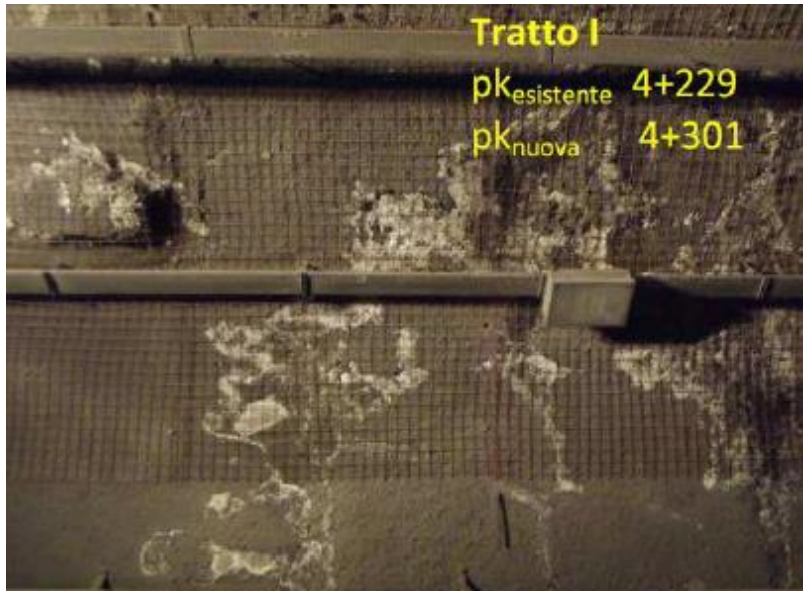
New cracks appearance

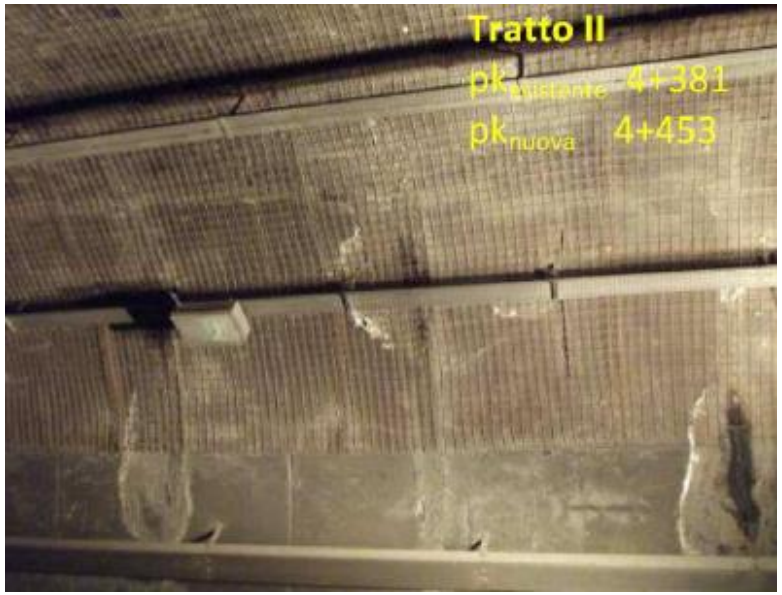
Vault concrete detachments

Uplift and deformation of the road platform

Problems during new tunnel construction

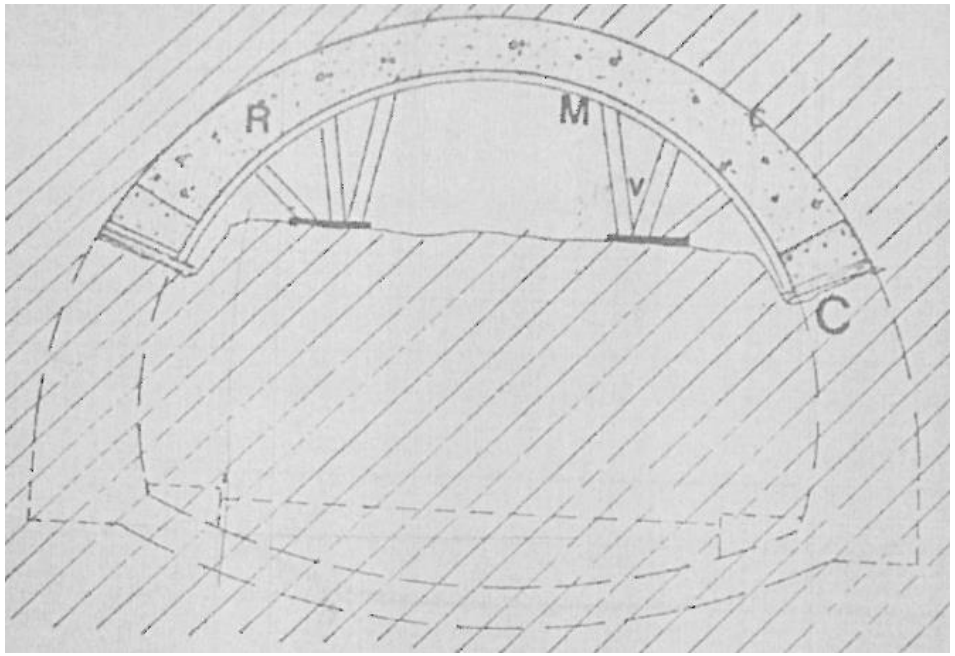
- ✓ Some detachments were also observed far away from the excavation faces of the new tunnel
- ✓ Phenomena probably associated to an earthquake of relatively low magnitude occurred in the area (end of **August 2015**)

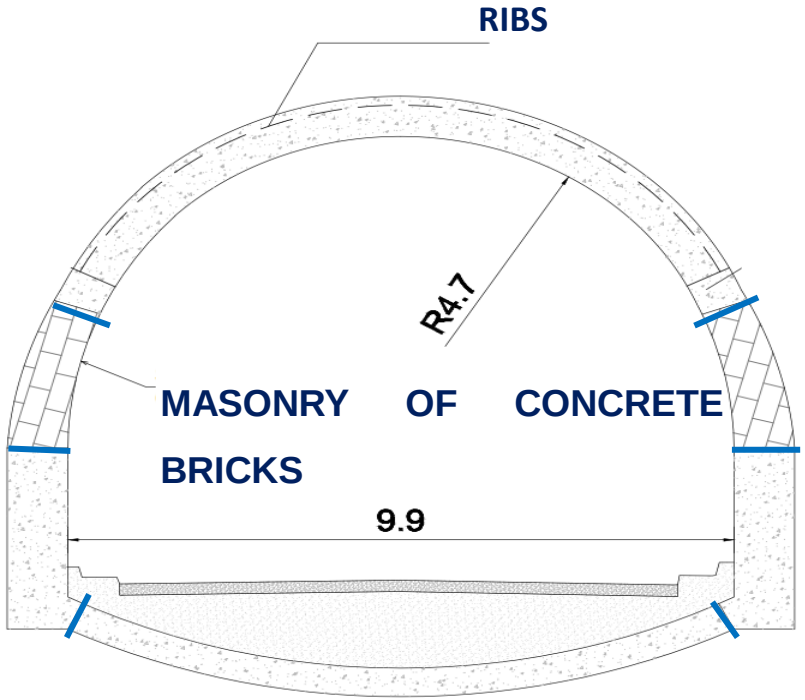




- ✓ Old tunnel was closed (**August 2015**), traffic diverted to a secondary road
- ✓ Works for the construction of the new tunnel were suspend

Existing tunnel, historical information



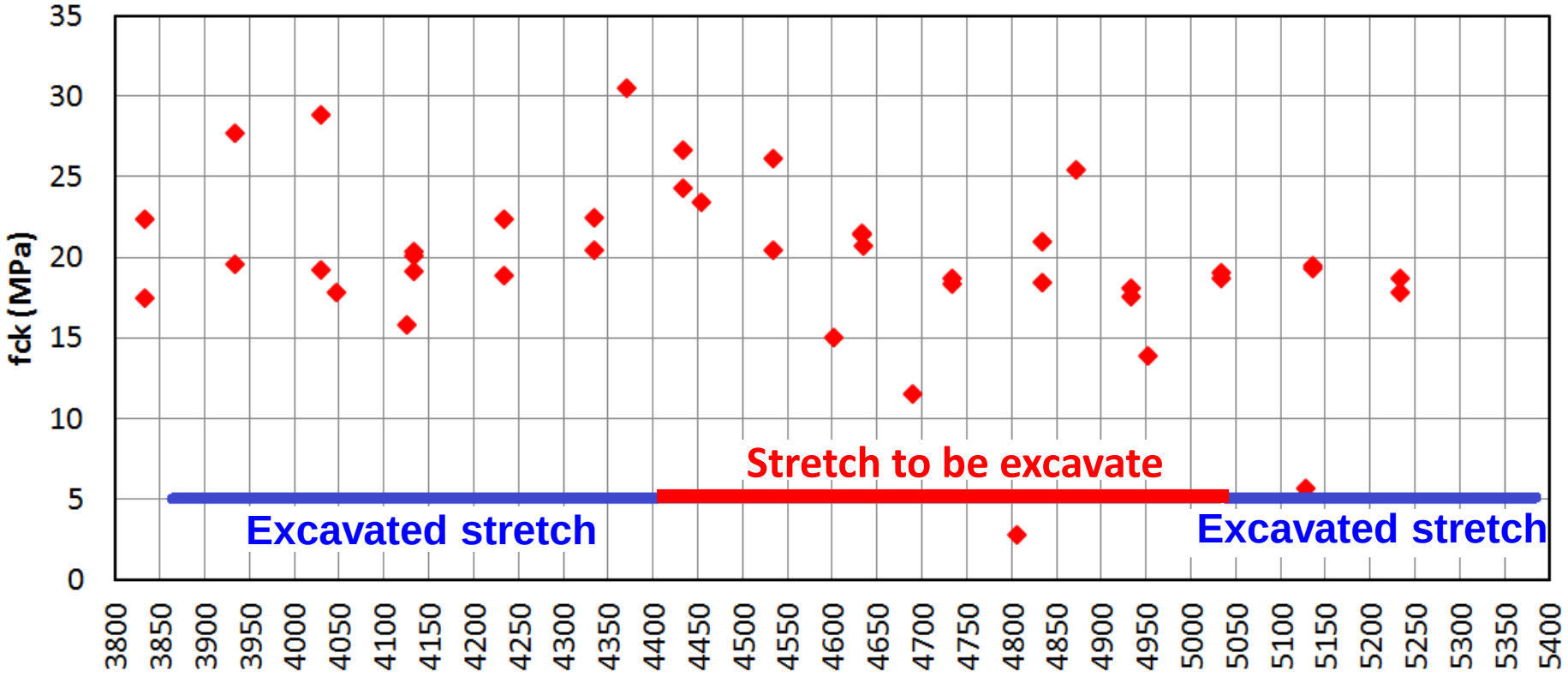


- ✓ Construction years 60's – partialized face
- ✓ Preliminary support at the crown: metallic ribs
- ✓ Final lining: 6 cast in place independent segments (plane concrete and locally masonry)
- ✓ Thickness: crown/vault 0.5÷0.9 m – benches 0.7÷1.2 m – invert 0.5÷1.0 m

Lining inspections and surveys

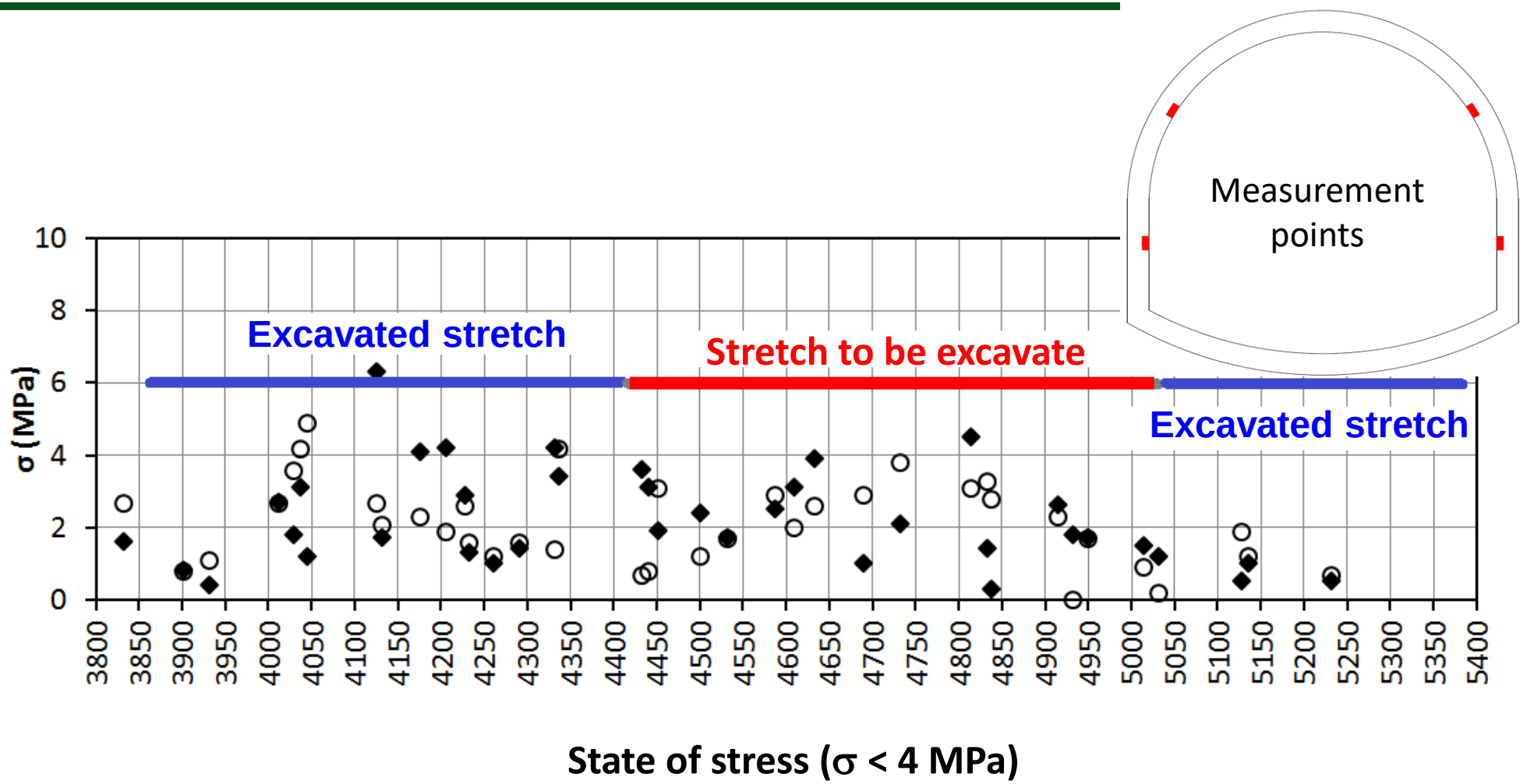
- ✓ Laser scanner reliefs (internal geometry)
- ✓ Visual and photographical reliefs (cracks), before and after hydro-demolition
- ✓ Continuous core bore-holes on the lining (lining thickness, concrete strength)
- ✓ Georadar surveys (lining thickness, ribs)
- ✓ Flat-Jack tests on concrete lining benches/springs (state of stress evaluation)

Lining inspections and surveys



UCS results – Specimens of the lining (fck=15-25 MPa)

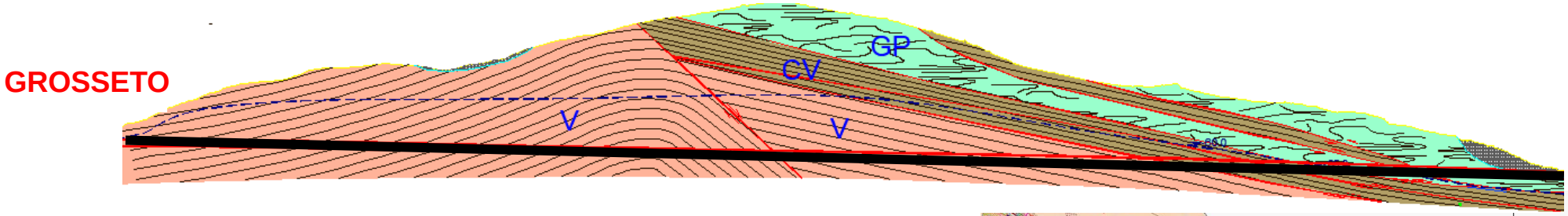
Lining inspections and surveys



State of stress (σ < 4 MPa)

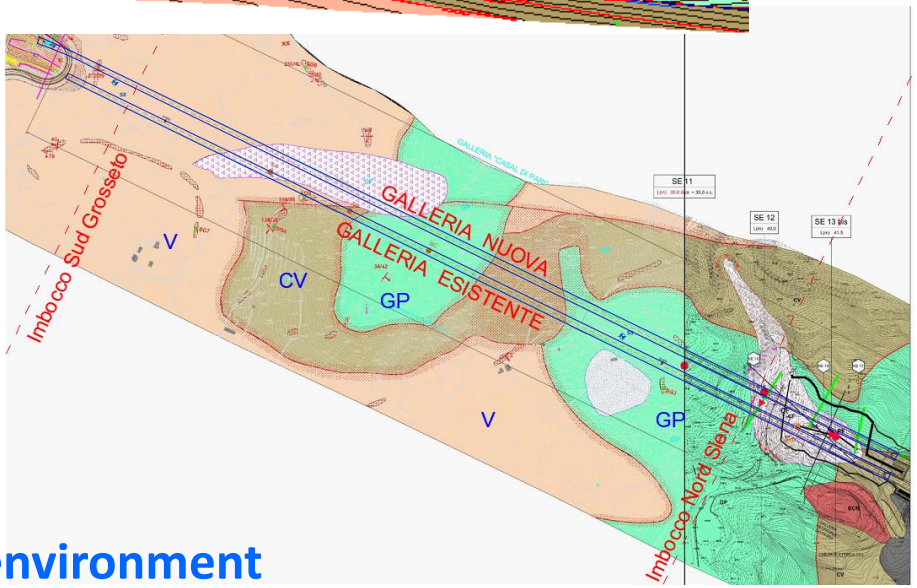
Geology

GP **Galestri e Palombini:** strata of clayey shales varicoloured (galestri) and siliceous/calcareous rocks (palombini)



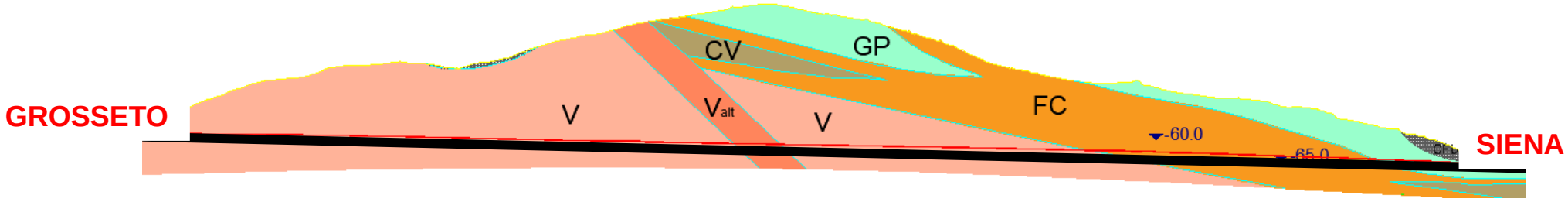
CV **Calcare cavernoso:** calcareous and siliceous sands (very disturbed)

V **Verrucano:** silty-sand shales with inter-bedded quartzarenitic and calcarenitic strata



Very tectonically disturbed geo-environment

Physical-mechanical soil/rock parameters



Geomechanics Units	γ (kN/m³)	c′ (kPa)	φ′ (°)	E′ (MPa)	c_u (kPa)
Galestri e Palombini (**GP**)	21	0 ÷ 14	15 ÷ 40	70 ÷ 600	50 ÷ 200
Calcare Cavernoso (**CV**)	23	20 ÷ 90	35 ÷ 40	500 ÷ 1000	-
Verrucano (**V**)	22	25 ÷ 235	20 ÷ 40	80 ÷ 1400	-
Cataclastic zones (**FC**)	21	15 ÷ 92	22 ÷ 35	100 ÷ 600	-

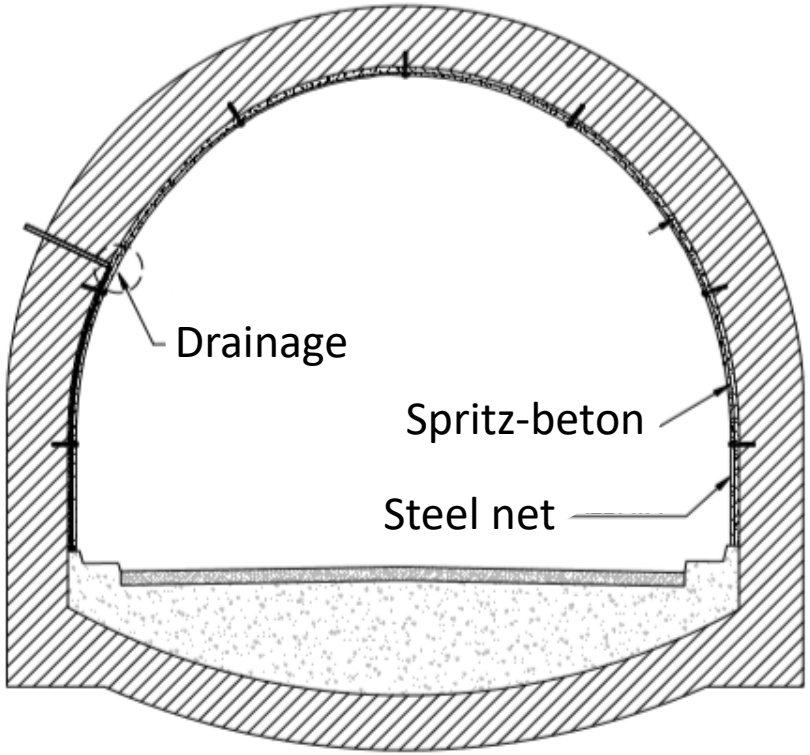
Design approach

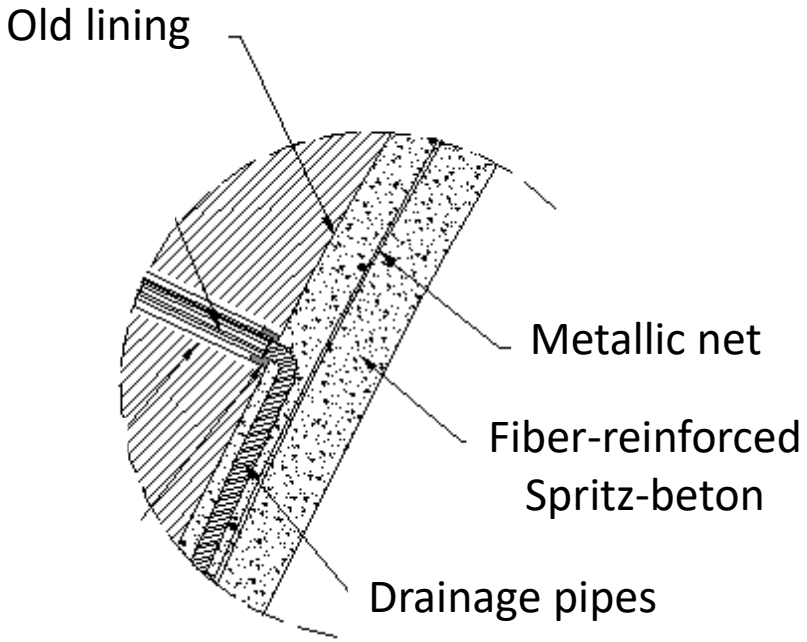
The design was developed pursuing the following goals:

- ✓ Works very fast to carried out (the old tunnel should be re-opened as soon as possible – minimizing inconvenient to the users)
- ✓ Provisional works (to guarantee temporary safety only) (The tunnel needed very important refurbishment works (expensive and long time) which cannot be realized at the time)
- ✓ Very cheap works and very easy to remove (costs limitation, to make easer the subsequent/final refurbishment works)
- ✓ Guarantee the safety of the operational (safety for the users) during the completion works of the new tunnel (taking in account further effect induced)
- ✓ Make the lining more ductile/increase the ductility of the lining (increasing the safety and make possible to control safely its behaviours by monitoring the displacements)

Provisional works

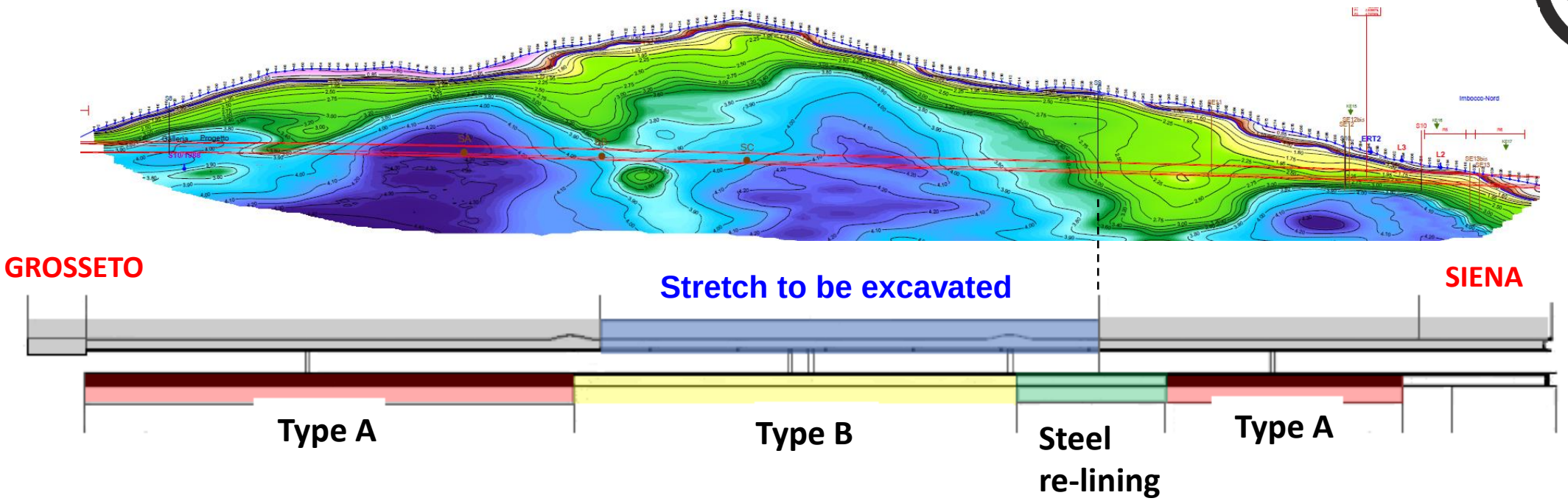
- ✓ “Section type A”, steel net ∅6/20x20 + *spritz beton* fiber-reinforced - t=12 cm
- ✓ “Section type B”, steel net ∅10/15x15 + s*pritz beton* fiber-reinforced - t=20 cm





Local drainage pipes: surface dry during spritzing

Stretch of application of the selected sections



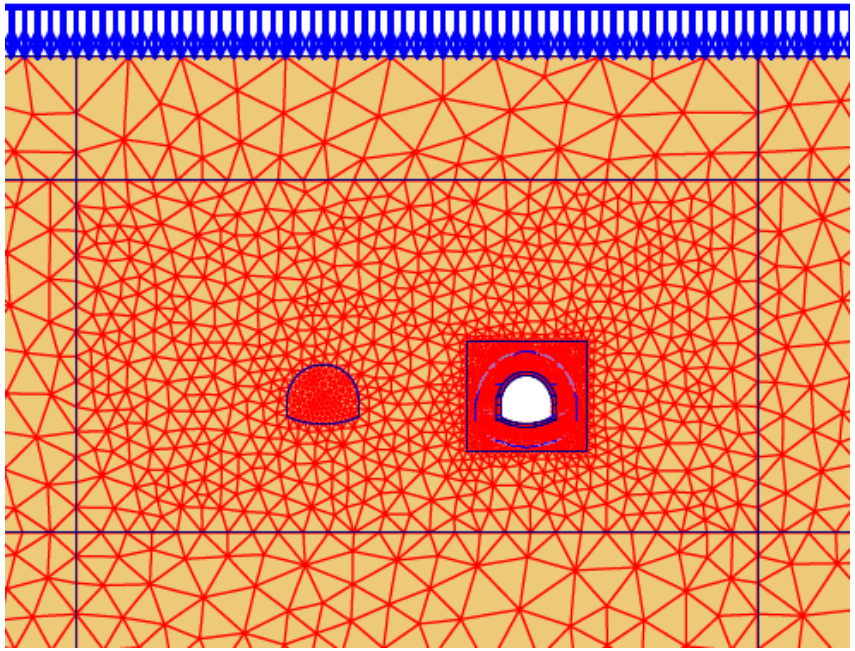
Section **type A** (light), stretch already excavated

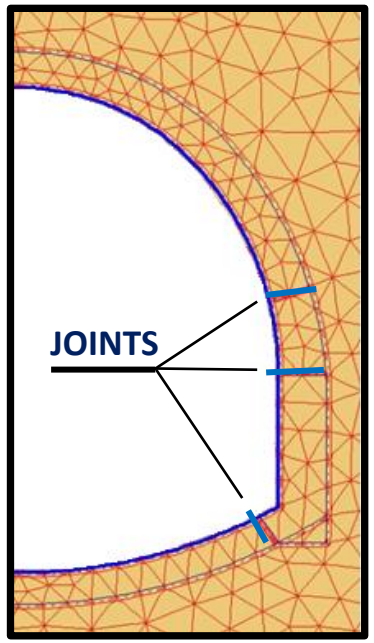
Section **type B** (medium), stretch to be excavated but in presence of **good rocks**

Full steel metallic re-lining, corresponding to the stretch to be excavated whit **poor soil/rock**

Model: 2D numerical analyses

- ✓ Constitutive model: elastic perfectly plastic (for ground and lining)
- ✓ Mohr-Coulomb failure envelop
- ✓ Lining modelled by continuous elements (no tensile strength)
- ✓ Joints between lining segments simulated via purely frictional interfaces





$S_{calotta}$ (m)	$S_{piedritti}$ (m)	S_{AR} (m)
0,7	1,0	0,6

c' (kPa)	Φ' (°)	E' (Mpa)
3000	28	26200

Geometry and mechanical behaviour of the lining

Model calibration

- ✓ Aim: reproducing in the model the state of stresses measured on the internal portion of the lining (flat-jacket)

- ✓ Calculation steps:

  - Geostatic state of stress in the ground before excavation (k_0 =1)
  - Application of geostatic stresses to the excavation profile after removal of inside continuous elements
  - Progressive stress release (factor λ)
  - Lining installation and complete stress release (λ = 1)

Model calibration

Calibration results

$$\lambda = 0.9 \rightarrow \sigma_n = 2.0 \div 2.5 \text{ MPa}$$

Formazione	γ (kN/m3)	c' (kPa)	Φ' (°)	E' (Mpa)
VERRUCANO	22	100	25	600

Geomechanics Units	γ (kN/m³)	c′ (kPa)	φ′ (°)	E′ (MPa)	c_u (kPa)
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Modelling the excavation of the new tunnel

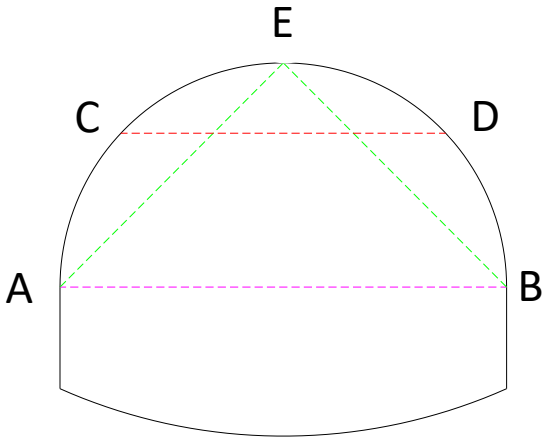
- ✓ Aim: calculate displacements and stresses induced to the reinforced lining of the old tunnel by the excavation of the new one

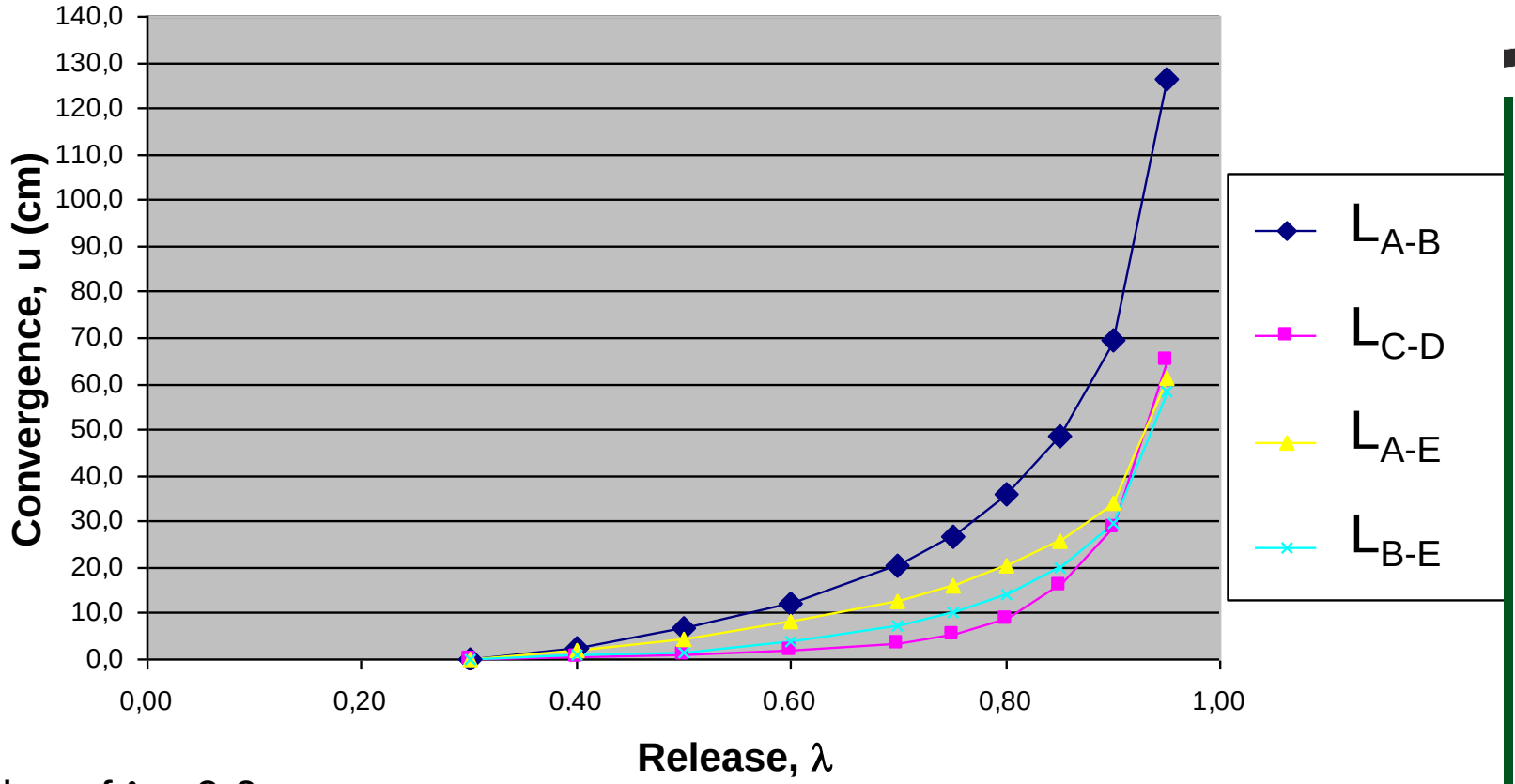
- ✓ Further calculation steps:

  - Re-profiling simulation (some element of the lining removed)
  - Installation of the fiber reinforced *spritz beton* (simulated as beam elements)
  - Simulation of the excavation of the new tunnel, progressive stresses release

Modelling the excavation of the new tunnel

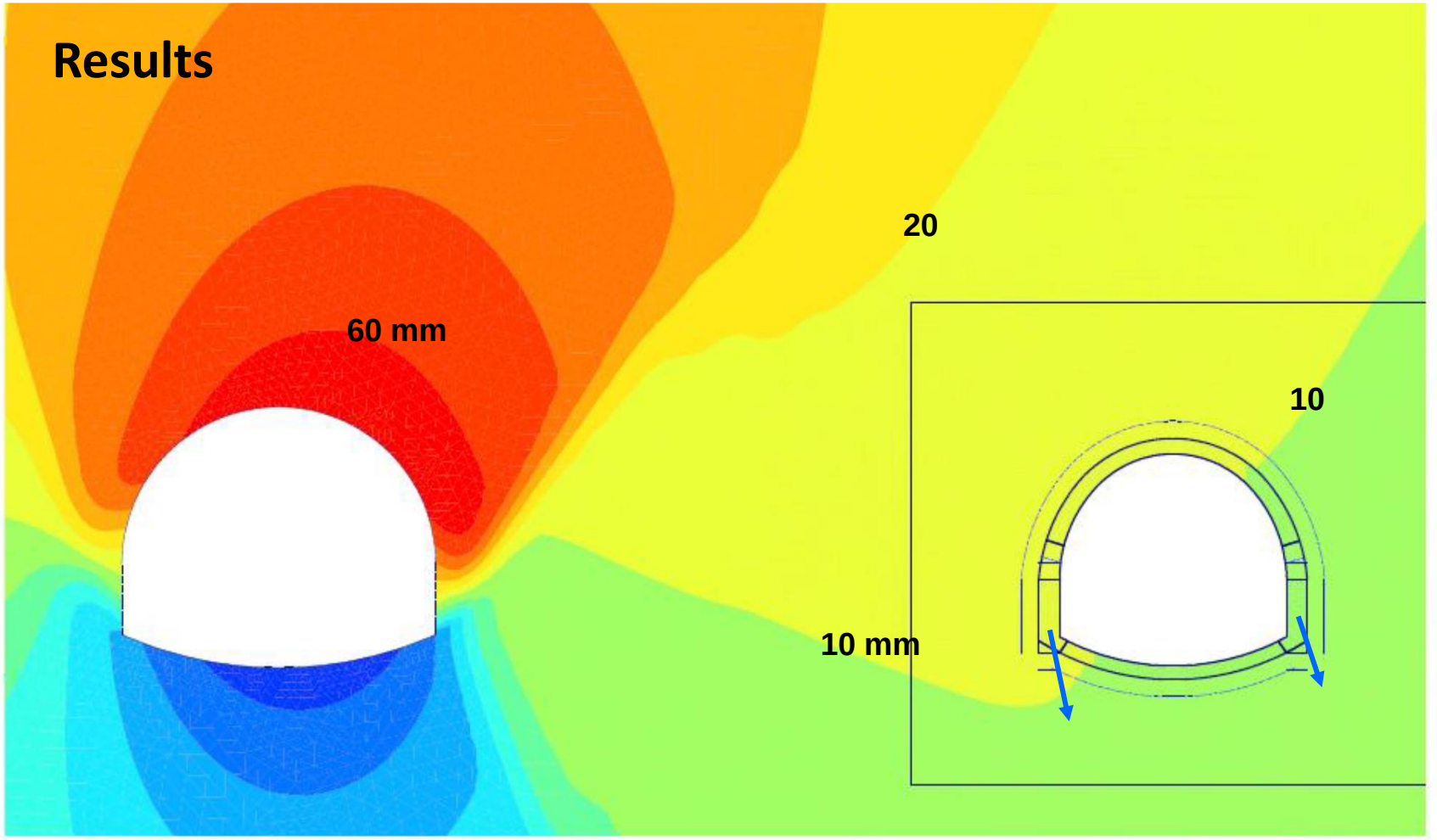
Results





- ✓ Linear behaviour until value of $\lambda = 0.6$
- ✓ Values of λ in the range 0.5-0.6 are assumed to be easily obtainable (consolidating adequately the nucleus and, eventually, realizing the invert close to the face)

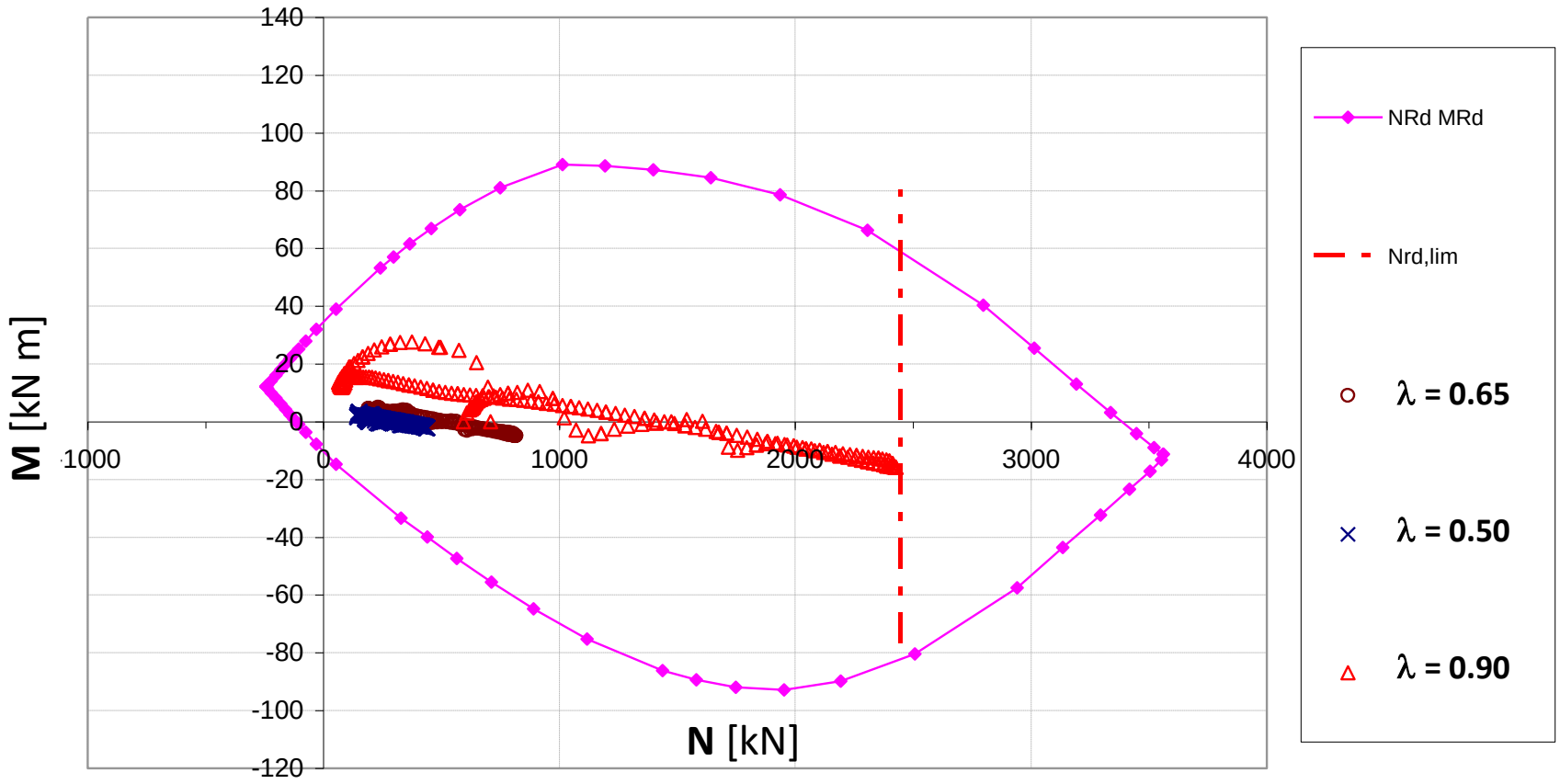
Modelling the excavation of the new tunnel



Vertical displacements induced by the excavation of the new tunnel (λ = 0.6)

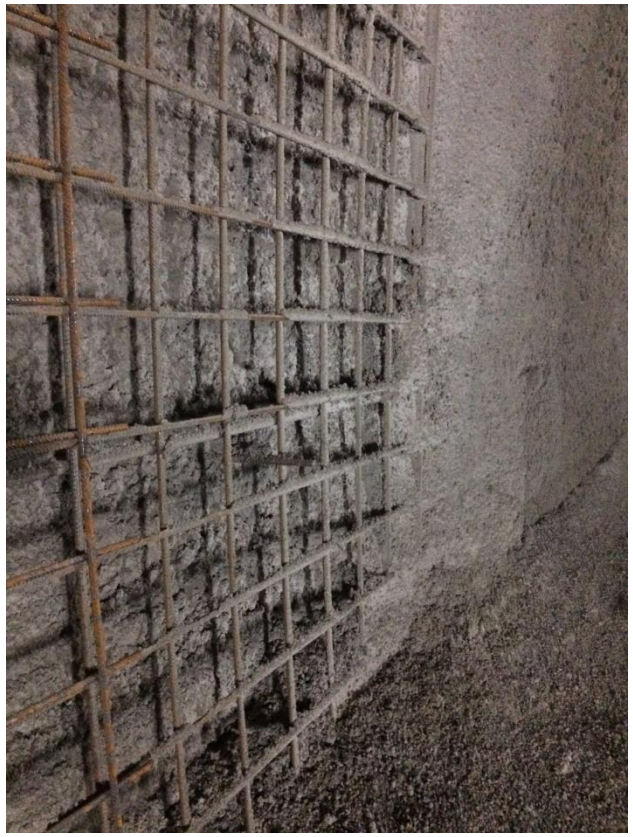
Modelling the excavation of the new tunnel

Results



- ✓ The internal lining is structurally adequate until a value of $\lambda = 0.65$
- ✓ For exceptional values of $\lambda = 0.90$ (unrealistic), the internal lining is also verified

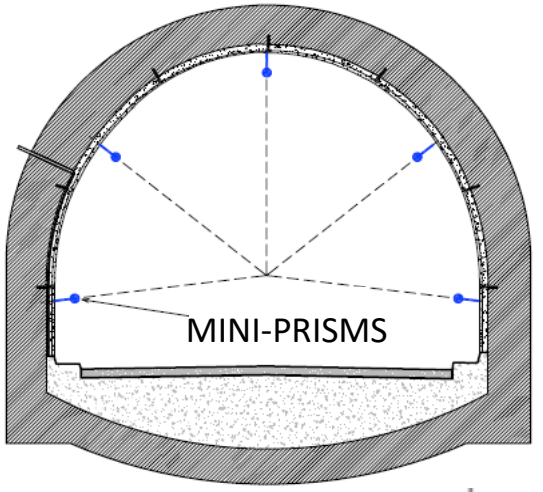
Works

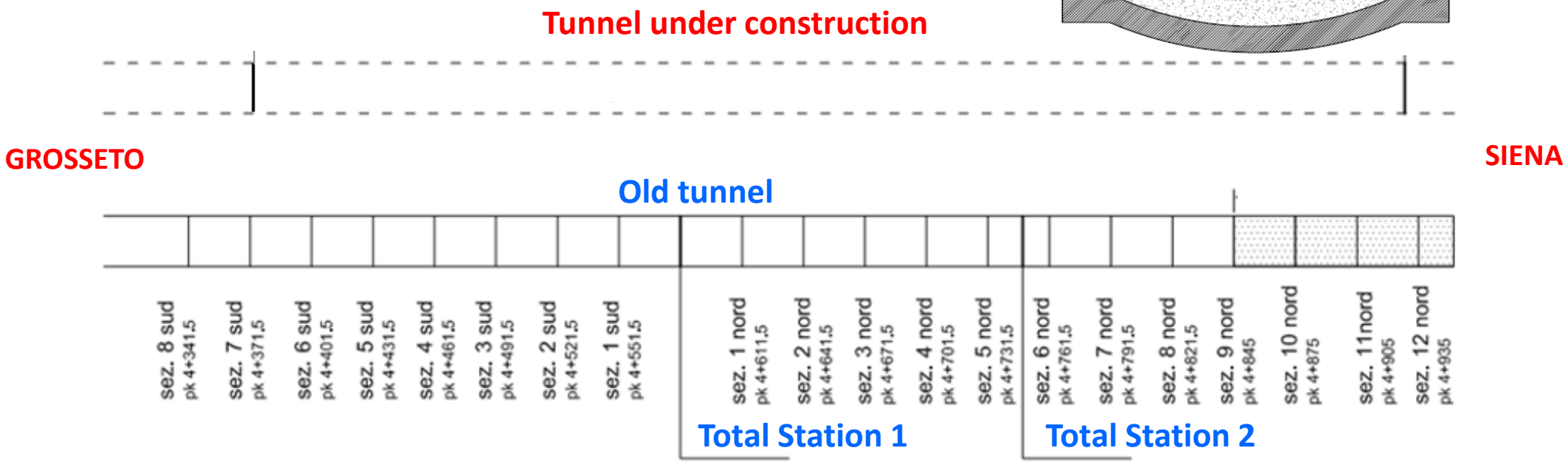


- ✓ Provisional works completed on **January 2016**
- ✓ Old road re-opened and works for the construction of new tunnel re-started on **February 2016**
- ✓ New tunnel completed on **April 2016** **(9 months after the closure)**

Monitoring plan

- ✓ Displacements measurements (5 mini-prisms/20 sezioni)
- ✓ 2 automatic Total Station
- ✓ High measurements frequency (4 measures/day)
- ✓ Real time elaboration and data transmission

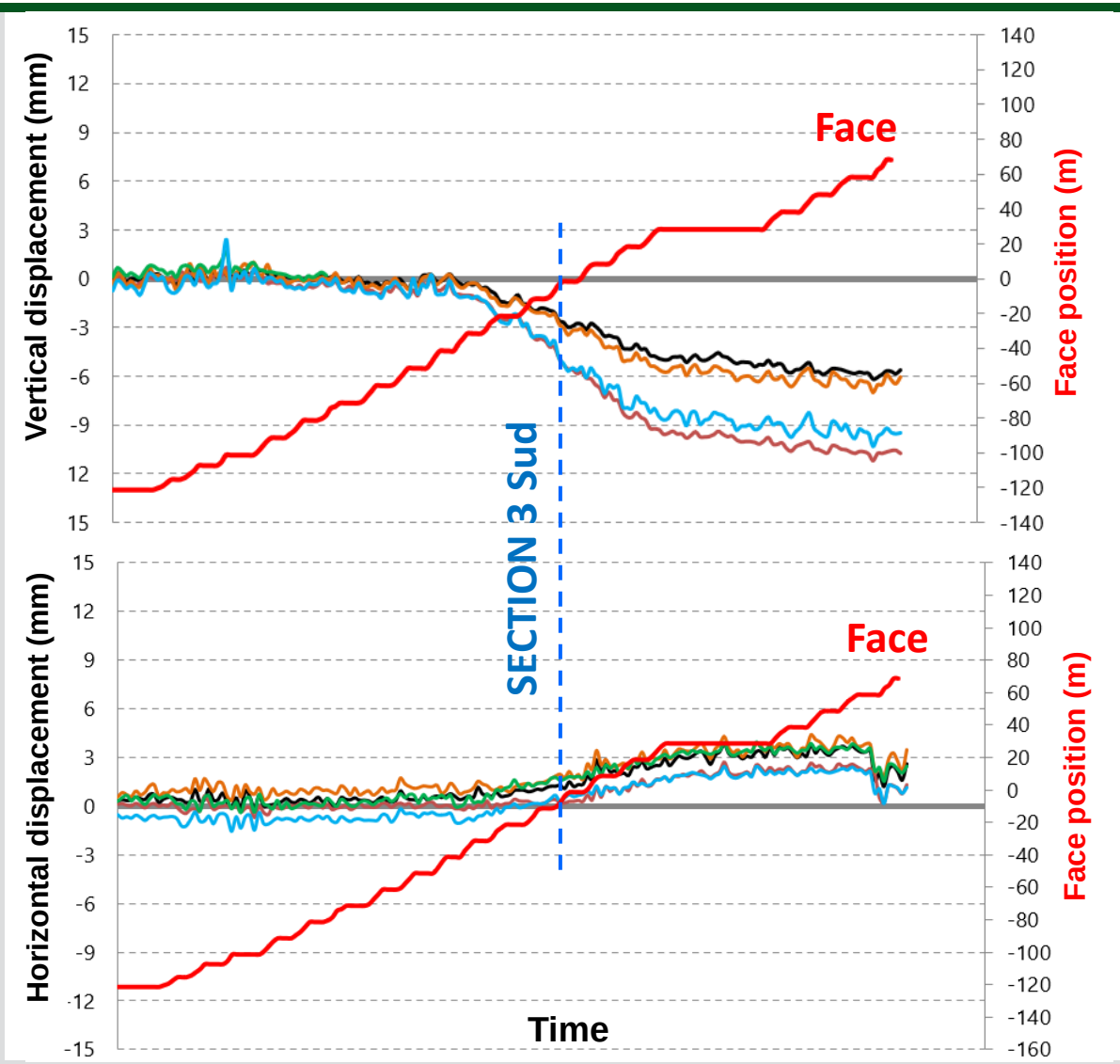


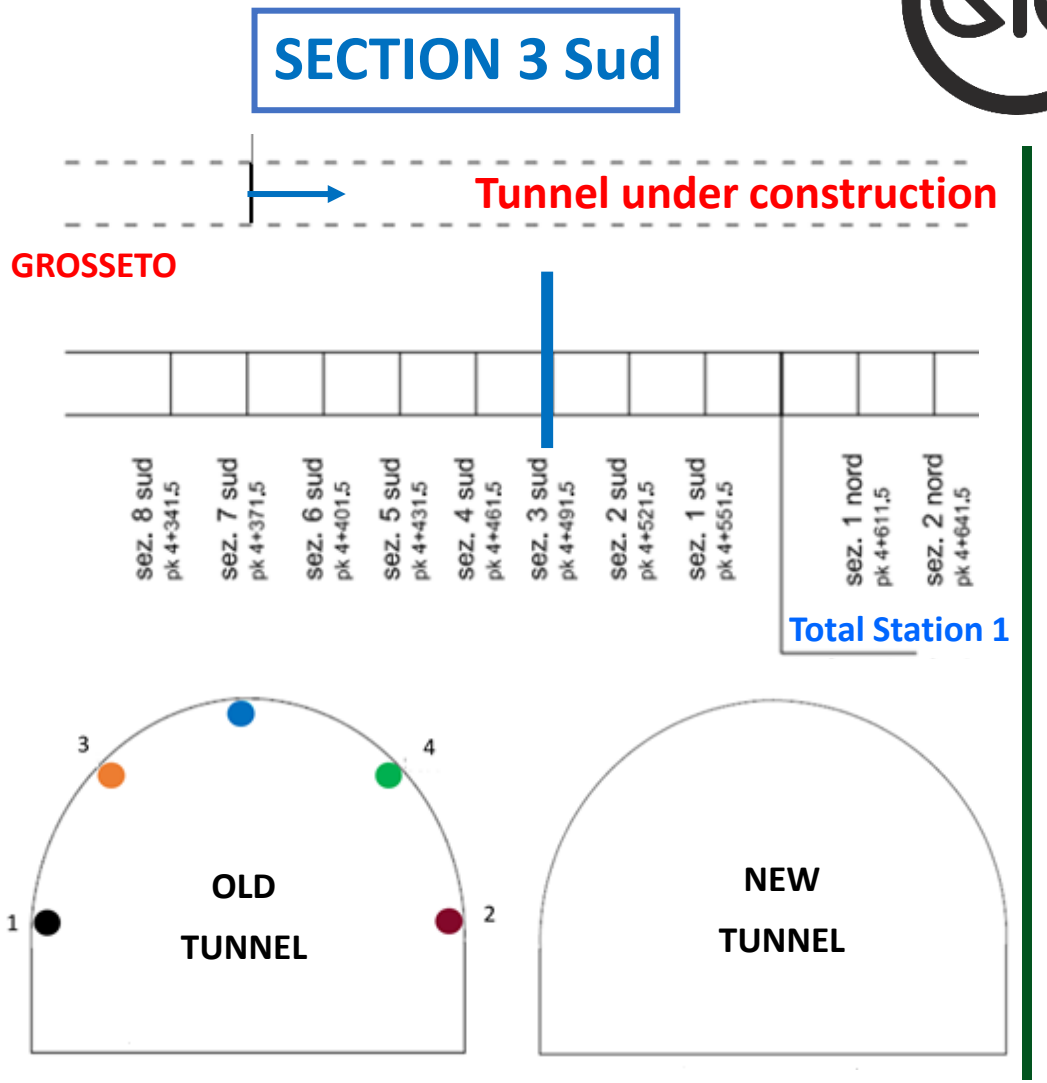


Behaviour during the excavation of the new tunnel

Siena side - face immediately after the excavation restart (formation: **GP**/**CV**)

Behaviour during the excavation of the new tunnel





Today/current situation

- ✓ Construction works of the new tunnel completed on March 2018
- ✓ The traffic was diverter in the new tunnel (in both directions), old tunnel was closed and today is yet closed waiting for final refurbishment works
- ✓ Final refurbishment project was completed (August 2020) and it is now following the process for obtain the approvals

Concluding remarks

Referring to the case history presented:

- ✓ 2D analyses were adequate (stress release techniques)
- ✓ Very simple constitutive was adequate (linear elastic plastic perfect both for ground and plane concrete)
- ✓ Simulation of the lining as continuous was necessary to properly take in account the joints (structural joints) (also in order to make easy the simulation of the milling of the lining)
- ✓ The calibration of the numerical model employed based on measured stresses is a very relevant/peculiar point (allow to overcame a lot of uncertainty: geotechnical operational values of mechanical parameters, initial state of stress in the ground, stress release percentage associated to the excavation techniques adopted, …..)
- ✓ A distance between tunnel axis of about 3 diameters was not enough to avoid induced effects (damages)

Concluding remarks

- ✓ The refurbishment works should be designed to obtain a more ductile lining (to increase the safety, large deformations must occur before collapse)
- ✓ Make the lining more ductile make possible to control safely its behaviours by monitoring the displacements
- ✓ Many of these remarks, are expected to be valid also in general

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