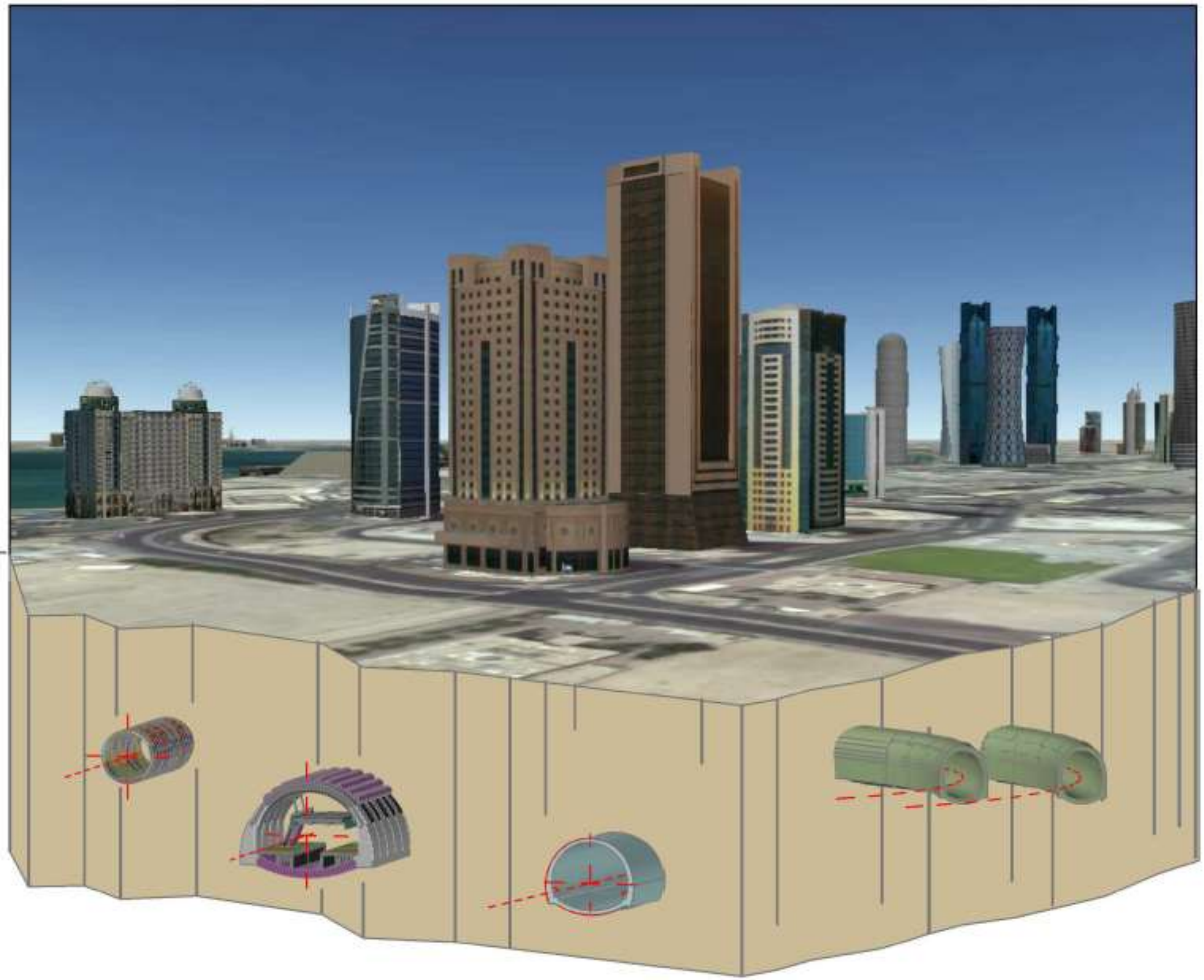
Pietro Lunardi

Evolution of design and construction approaches in the field of underground works: from NATM and derived methods to ADECO-RS

Surface and underground works

Difference between costructing on surface and constructing underground

Construction by addition of material



Construction by subtraction of material

The ingredients for:

On surface works

Underground works

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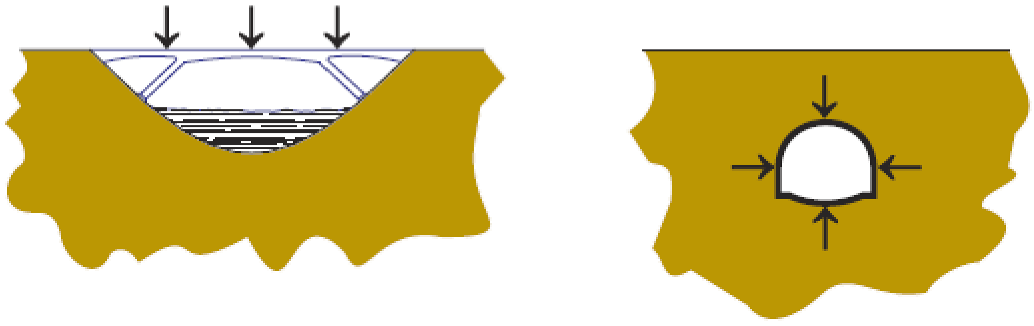
DIFFERENCES BETWEEN THE DESIGN OF SURFACE AND UNDERGROUND WORKS

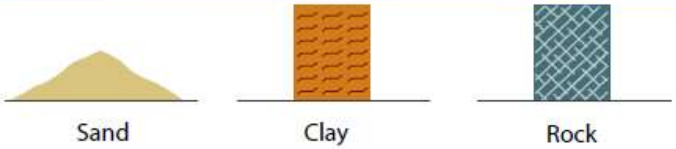


INGREDIENTS	SURFACE WORKS	UNDERGROUND WORKS
MEDIUM (construction material)	●	○
ACTION (loads on structures)	●	○
REACTION (response in term of stress and strain)	●	○

● Determined *a priori* ○ Not predetermined

INGREDENTS
IN THE UNDERGROUND WORKS

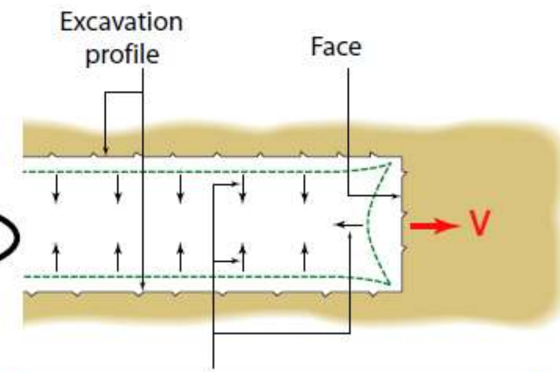
KNOWLWDGE



- Ground as construction material subject to stress fields of lithostatic and tectonic origin
- Geological and geomechanical characterization

Medium

Reaction



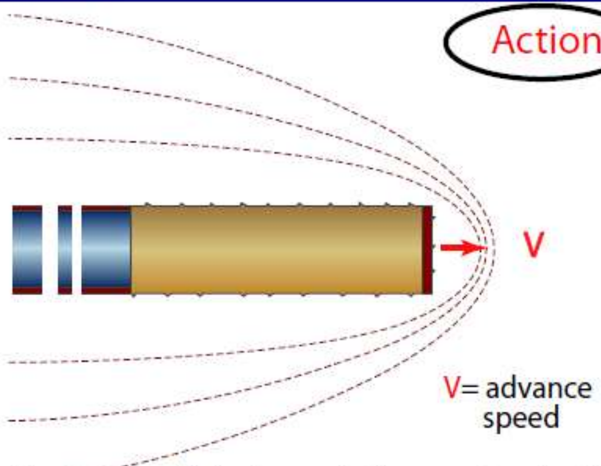
Deformation Response

D.R. depends on:

- mechanical and structural characteristics of the ground
- stress fields
- excavation method (advance speed V)

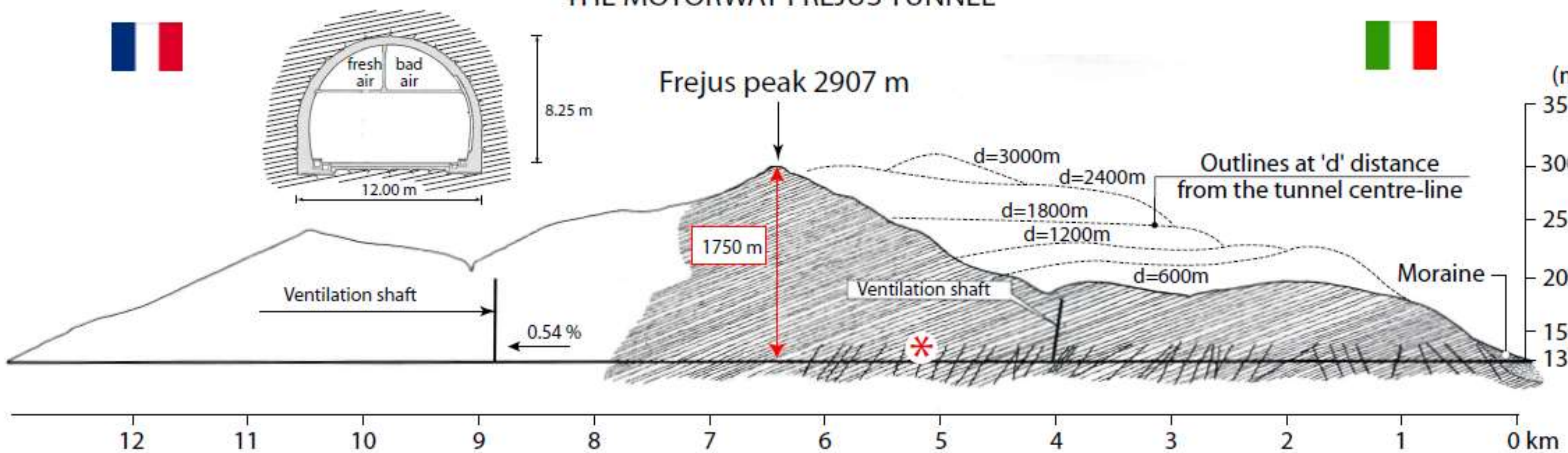
CHOICE

Action



- It produces disturbance in the medium in 3D
- The importance of the disturbance depends on V
- V is a function of the excavation system (mechanized or conventional)

THE MOTORWAY FREJUS TUNNEL

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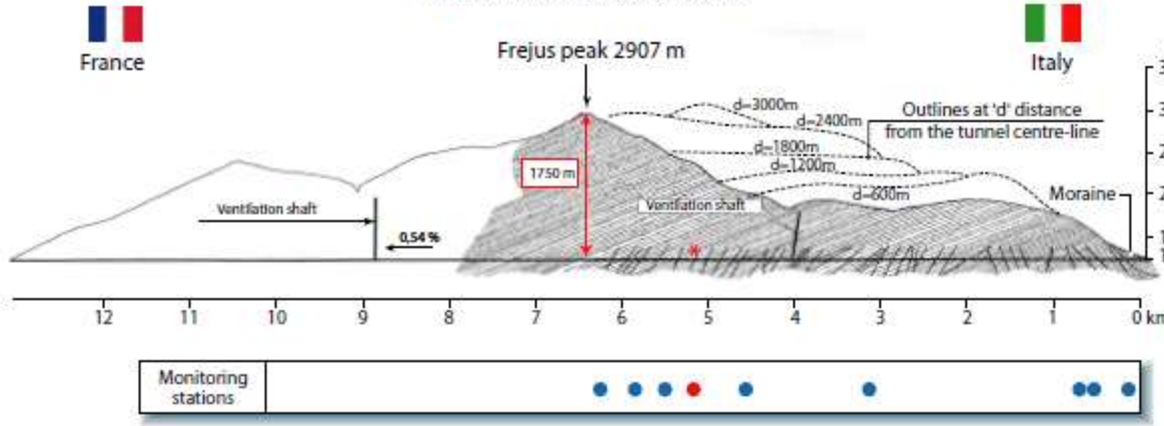
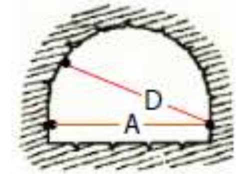
LITHOTYPE: CALC-SCHIST
EXCAVATION DIAMETER: ~ 12 m
MAIN GEOMECHANICAL PARAMETERS
- σ_{gd} = strength of the rockmass = 20 MPa (≅ 200 Kg/cm^2)
- σ_f = unconfined compression strength = 86 ÷ 108 MPa (≅ 860 ÷ 1080 Kg/cm^2)
- E = elastic modulus = 10000 MPa (≅ 100000 Kg/cm^2).

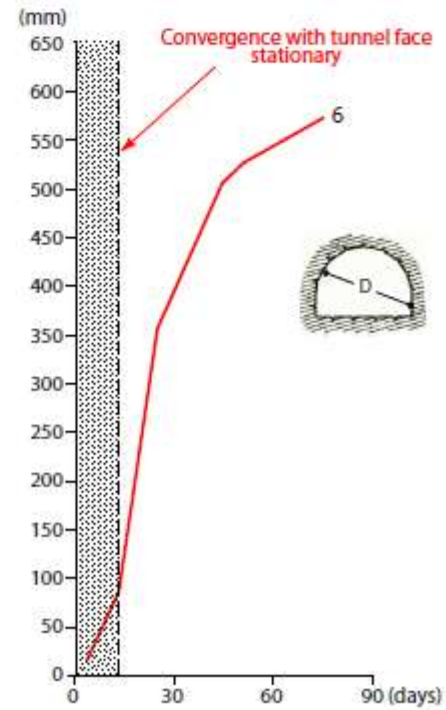
THE MOTORWAY FREJUS TUNNEL



MEASUREMENTS OF CONVERGENCE

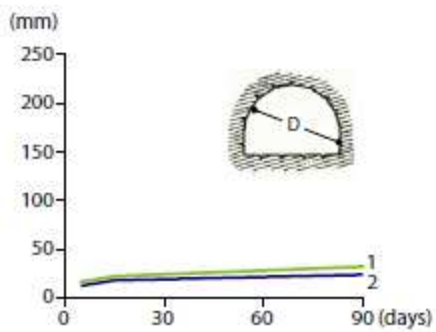


No. 6 monitoring stations
(overburden H = 1,200 m)



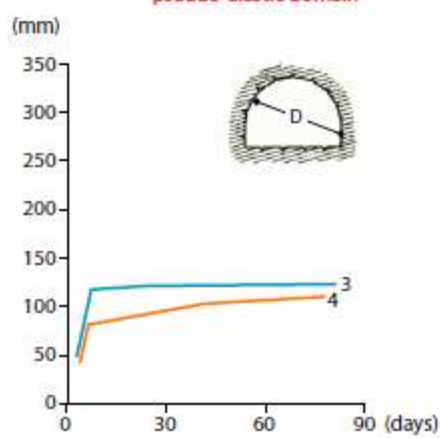
No. 1÷2 monitoring stations
(overburden H = 490÷500 m)

elastic domain



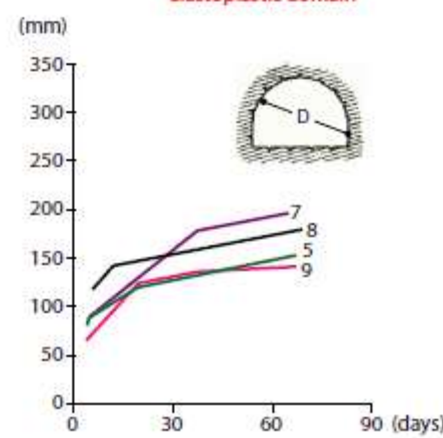
No. 3÷4 monitoring stations
(overburden H = 580÷590 m)

pseudo-elastic domain



No. 5÷9 monitoring stations
(overburden H = 740÷1640 m)

elastoplastic domain



Monitoring stations	1	2	3	4	5	7	8	9	6
Chainage (m)	845	861	2772	3954	4507	5533	5915	6066	5172
Overburden (m)	490	500	580	590	740	1400	1530	1640	1200

It must always be remembered that we build for subtraction of material and the Earth’s crust is made up of material that is subject to stress fields of gravitative, lithostatic and tectonic nature and which must therefore be considered a “living thing”, that tends to deform as a reaction to excavation and therefore generate a Deformation Response which must always be the focus of any designer of underground works.

P. Lunardi – Muir Wood Lecture 2015

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PREROGATIVE
od the
Deformation
Response

1 Spy for the arch effect/stability

2 Evolution as a function of the boundary conditions

3 Central role in the design

Reaction = Deformation Response

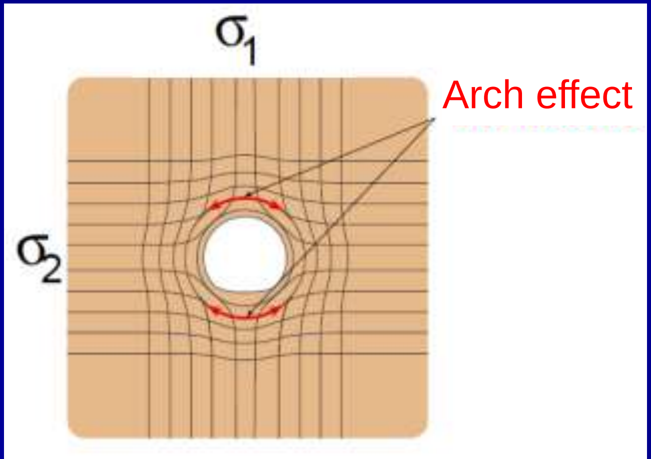
FUNDAMENTAL PREROGATIVE OF THE DEFORMATION RESPONSE

① **Spy of the ARCH EFFECT mobilization around the cavity**

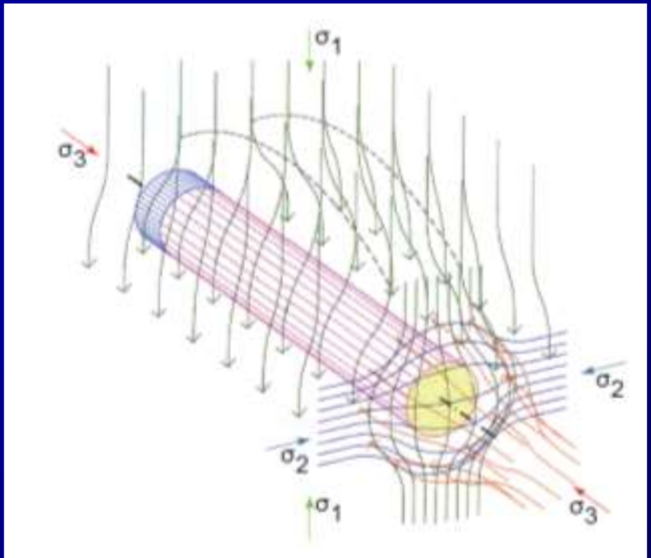
ARCH EFFECT = CHANNELLING OF THE STRESSES

Stress field in the ground around a tunnel in progress

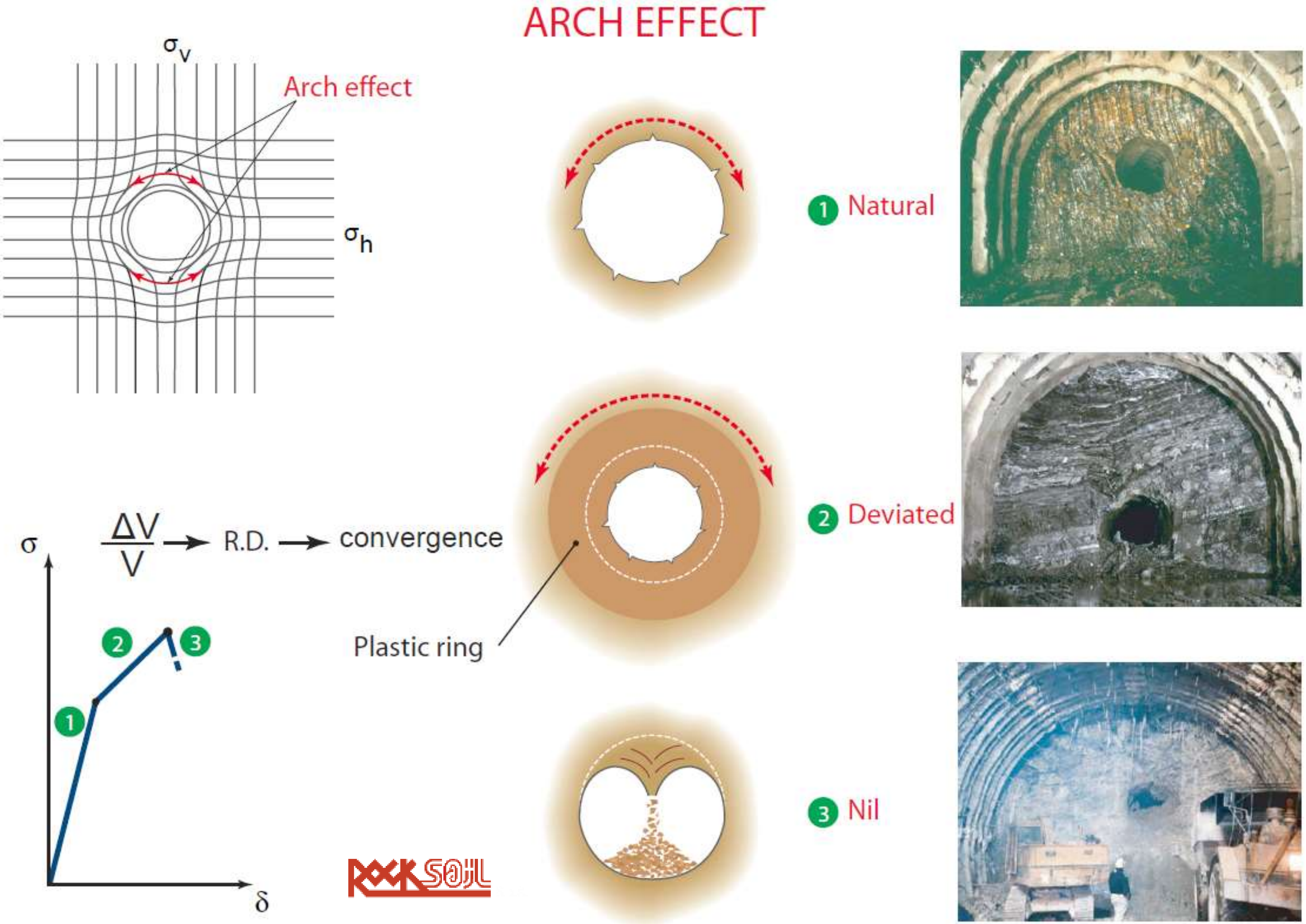
Bi-dimensional model



Three-dimensional model



The position of the channeling of stresses around the cavity is conditioned by the strength of the ground



The Deformation Response is the SPY of the ARCH EFFECT mobilization

What is the ARCH EFFECT ?

1

Elastic domain

Arch effect: natural

Deformation Response: almost nothing

The Deformation Response is the SPY of the ARCH EFFECT mobilization

What is the ARCH EFFECT ?

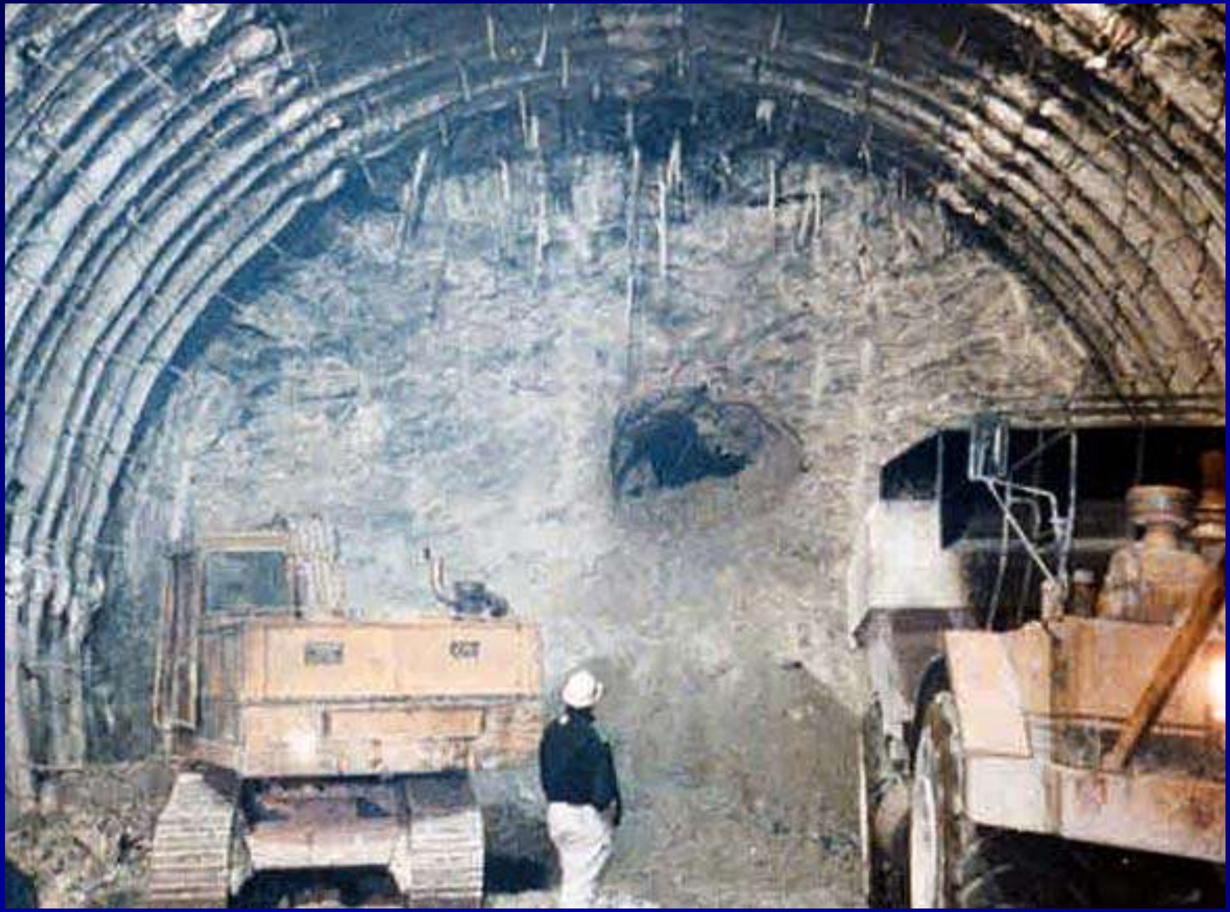
2 **Elastic-plastic domain**

Arch effect: deviated

Deformation Response: not negligible

The Deformation Response is the SPY of the ARCH EFFECT mobilization

What is the ARCH EFFECT ?



3

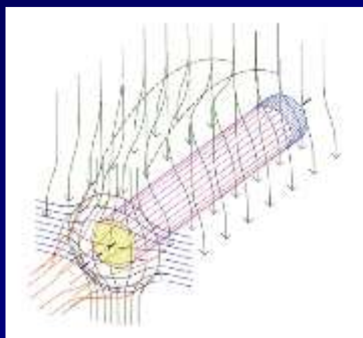
Failure domain

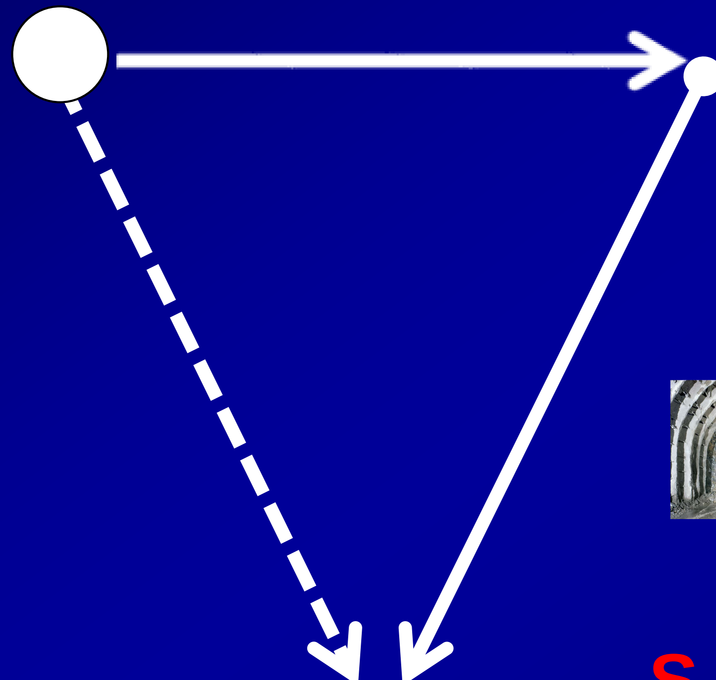
Arch effect: nil

Deformation Response: collapse

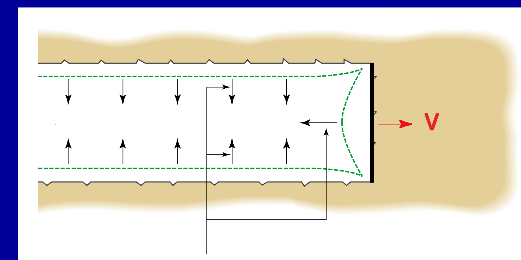
The Deformation Response is the SPY of the ARCH EFFECT mobilization

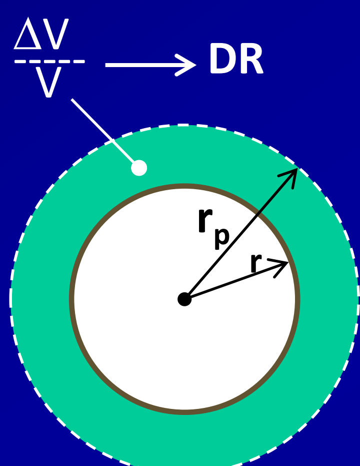
ARCH EFFECT (AE)





DEFORMATION RESPONSE (DR)





STABILITY (S)

$$S = \frac{\text{AE position}}{\text{DR}}$$

where: $\text{AE position} = \dfrac{r}{r_p}$

r_p = plasticisation radius

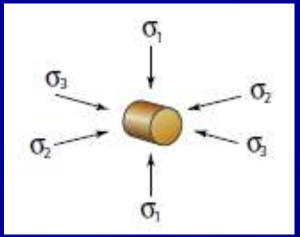
PREROGATIVE OF THE DEFORMATION RESPONSE

2

It evolves in function of the type of ground, the intensity of the stress field and the advance speed V

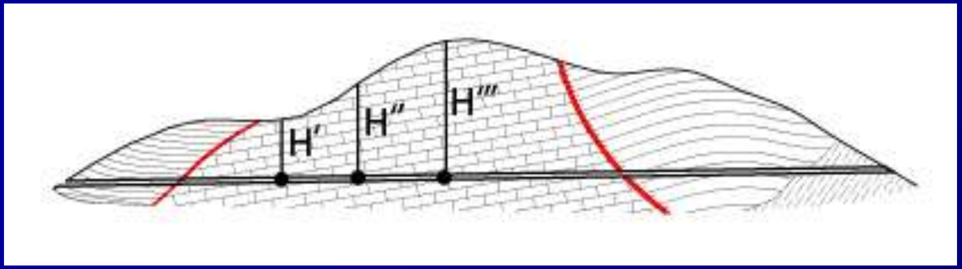
Evolution of the Deformation Response as a function of the stress field intensity

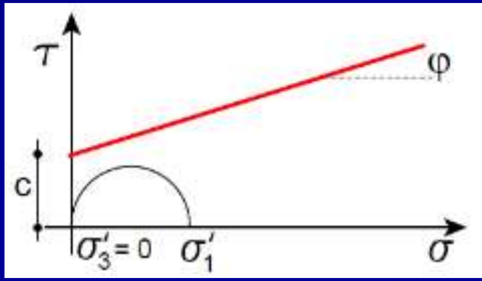
In case of homogeneous soil, when $\sigma_3 \longrightarrow 0$ due to the face advance, only varying the lythostatic overload or the stress field DR can develop in domain……



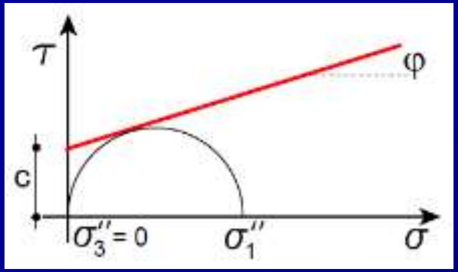
$$\sigma_{nat} = \gamma H$$

$$\sigma_1 = 2\gamma H$$

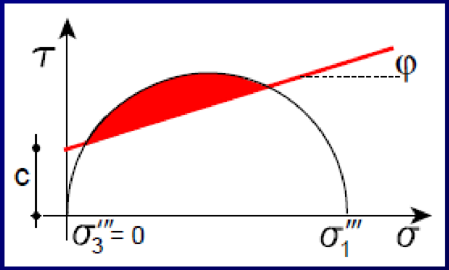




(Deformation Response in elastic domain)



(Deformation Response in elasto-plastic domain)



(Deformation Response in failure domain)

PREROGATIVE OF THE DEFORMATION RESPONSE

3 Central role in the design

DESIGN

- Analysis
- Control

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Central role of the Deformation Response in the design

DESIGN APPROACH

- ANALYSIS of the expected Deformation Response
  - selection of the 2D or 3D reference model
  - components of the Deformation Response
- CONTROL of the expected Deformation Response
  - selection of the excavation systems
  - selection of the stabilisation instruments

Therefore designing an underground work means to analyze and control the expected Deformation Response.

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DESIGN AND CONSTRUCTION APPROACHES OF THE PAST (NATM AND DERIVED METHODS)

Deformation Response

How the Deformation Response was analysed and controlled in the past and how it is analysed and controlled today ?

Approaches of the past (NATM and derived methods (1950 ÷ 1980)	Modern approaches Analysis of COntrolled DEformations In Rocks and Soils (ADECO-RS) since 1980

Approaches of the past
(NATM and derived methods

(1950 ÷ 1980)

Modern approaches
Analysis of COntrolled DEformations
In Rocks and Soils
(ADECO-RS)

since 1980

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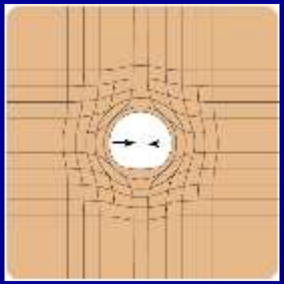
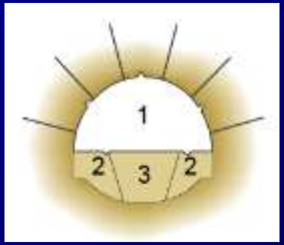
ACCORDIND TO THE APPROACHES OF THE PAST

- ANALYSIS (theoretical prediction of the expected deformation response): referred only to the geomechanical classifications



  - MODEL SELECTION : bidimensional models
  - DEFORMATION RESPONSE: 1 component (convergence of the cavity)

- CONTROL (selection of the excavation system and of the instruments to control the Deformation Response):



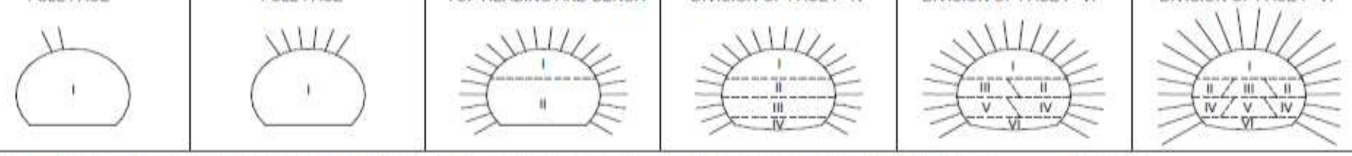
  - operations only downstream of the excavation face
  - advancement after partitioning the excavaton face)

ANALYSIS CONTROL

of the Deformation Response according to the approaches of the past based on geomechanical classifications

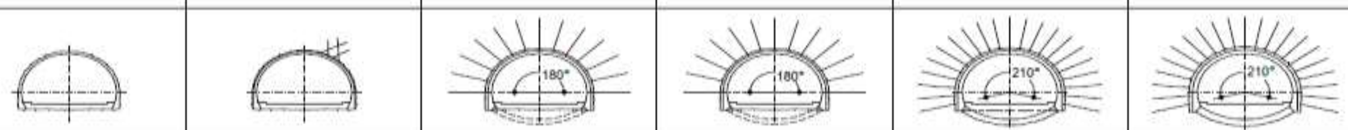
THE NEW AUSTRIAN TUNNELLING METHOD (NATM)
ROCK CLASSIFICATION ACCORDING TO RABCEWICZ-PACHER

ROCK CLASSES	I FROM STABLE TO SLIGHTLY BRITTLE	II VERY BRITTLE	III FROM UNSTABLE TO VERY UNSTABLE	IV SQUEEZING	Va VERY SQUEEZING	Vb LOOSE MATERIAL
CHARACTERISTICS	MATERIALE COMPATTO, FESSURAZIONE DA LEGGERA A MEDIA.	SUDDIVISIONE ACCENTUATA PER STRATIFICAZIONE E FRATTURAZIONE. LE SINGOLE FESSURE SONO PIENE DI MATERIALE ARGILLOSO; INTERCALAZIONI SCISTOSE.	ELEVATO GRADO DI SUDDIVISIONE PER STRATIFICAZIONE E FRATTURAZIONE IN PIU' PIANI; LE FESSURE RISULTANO PIENE DI MATERIALI ARGILLOSI.	ROCCIA MOLTO ALTERATA, RIPIEGATA E SCISTOSA; FASCI DI FAGLIE; MATERIALE SCIOLTO BEN CONSOLIDATO, COERENTE.	MATERIALE COMPLETAMENTE MILONITIZZATO ED ALTERATO RIDOTTO A GHIAIETTO, SCIOLTO NON CONSOLIDATO, LEGGERMENTE COERENTE.	MATERIALE SCIOLTO, INCOERENTE.
CHARACTERISTICS	LA RESISTENZA DELLA ROCCIA ALLA COMPRESSIONE UNIASSIALE σ_{gd} E' MAGGIORE DELLA TENSIONE TANGENZIALE σ_T; CONDIZIONI DI EQUILIBRIO PERMANENTE ESISTENTE O ASSICURATO DA: MISURE DI PROTEZIONE LOCALE	RINFORZO DELL'ANELLO DI ROCCIA PORTANTE IN CALOTTA	IL LIMITE DI RESISTENZA DELLA ROCCIA VIENE RAGGIUNTO E SUPERATO AL CONTORNO DELLA SEZIONE. SONO NECESSARI SOSTEGNI E LA CREAZIONE DI UN ANELLO DI ROCCIA PORTANTE	LE TENSIONI TANGENZIALI SUPERANO LA RESISTENZA DELLA ROCCIA. IL MATERIALE, A COMPORTAMENTO PLASTICO, TENDE VERSO LA CAVITA' RIDUCENDONE LA SEZIONE; FENOMENO DI INTENSITA': MEDIA	FORTE SPINTE LATERALI E SOLLEVAMENTO DELLA PLATEA. I MOVIMENTI VENGONO CONTRASTATI DALL'ANELLO PORTANTE COMPLETAMENTE CHIUSO.	VEDI CLASSE Va
INFLUENCE OF WATER	NESSUNA.	IRRILEVANTE.	PREVALENTE SUL CAVO. DELLE FESSURE.	DISCRETA.	ANCHE FORTE (IL MATERIALE TENDE AD IMBIBIRSI)	
EXCAVATION	FULL FACE	FULL FACE	TOP HEADING AND BENCH	DIVISION OF FACE I - IV	DIVISION OF FACE I - VI	DIVISION OF FACE I - VI

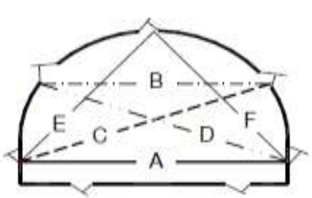


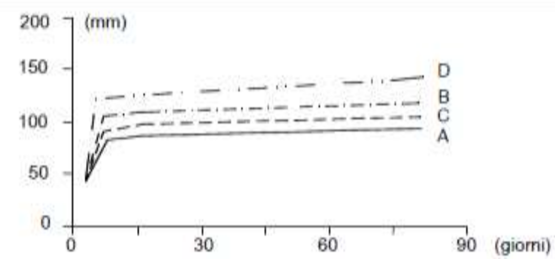
ACTIVE STABILIZATION CROSS SECTION TYPES FOR TUNNEL Ø = ~ 10.00 m

ROCK CLASSES	I	II	III	IV	V	VI
CROSS SECTION TYPES						
CHARACTERISTICS	PASSO 3.5/4.5m. RIVESTIMENTO Sp.=0+0+30=30cm.	PASSO 2.5/3.5m. BULLONI LOCALI L=4.00m. RETE ELETTROSALDATA RIVESTIMENTO Sp.=5+5+30=40cm.	PASSO 1.5/2.5m. BULLONI SISTEMATICI L=4.00m. RETE ELETTROSALDATA RIVESTIMENTO Sp.=10+10+35=55cm.	PASSO 1.0/1.6m. TIRANTI SISTEMATICI L=4.00m. CENTINE RETE ELETTROSALDATA RIVESTIMENTO Sp.=10+15+40=65cm. ARCO ROVESCIO	PASSO 0.8/1.2m. TIRANTI SISTEMATICI L=4.00m. CENTINE RETE ELETTROSALDATA RIVESTIMENTO Sp.=10+20+45=75cm. ARCO ROVESCIO Sp.=0.75m.	PASSO 0.5/1.0m. TIRANTI SISTEMATICI L=4.00m. CENTINE RETE ELETTROSALDATA RIVESTIMENTO Sp.=10+25+50=85cm. ARCO ROVESCIO Sp.=0.85m.



Geomechanical classification	Convergence / base %
I	Almost absent « 1
II	Negligible < 1
III	Low 2–5
IV	Medium 5–10
Va	Strong 10–15
Vb	Very strong >15





ANALYSIS CONTROL

of the Deformation Response according to the approaches of the past based on the convergence alone and the advancement after partitioning the excavation face and stabilisation operations only downstream of the face itself

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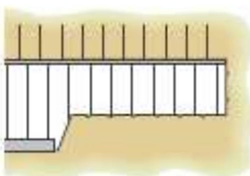
Expected Deformation Response in domain:	Approaches of the past NATM and derived methods

Elastic

They use
roof bolts
steel ribs
shotcrete

Elastoplastic



They partition
the excavation face

Stability of the face
Stability of the cavity

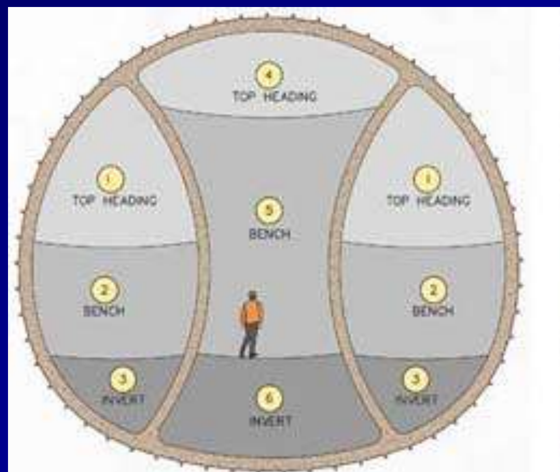
Failure

They use
roof bolts
steel ribs
shotcrete
provisional invert

ANALYSIS CONTROL

of the expected Deformation Response according to the approaches of the past

To stabilise the face they partitioned it



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ANALYSIS CONTROL

of the expected Deformation Response according to the approaches of the past

To stabilize the cavity they use only bolts, steel ribs and shotcrete

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MODERN DESIGN AND CONSTRUCTION APPROACHES
(ADECO-RS)

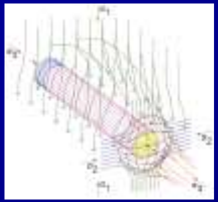
Deformation Response

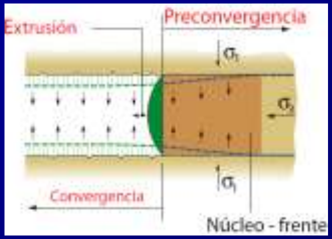
How the Deformation Response was analysed and controlled in the past and how it is analysed and controlled today ?

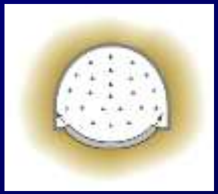
Approaches of the past (NATM and derived methods	Modern approaches Analysis of COntrolled DEformations In Rocks and Soils (ADECO-RS)
(1950 ÷ 1980)	since 1980

Approch according to ADECO-RS

- ANALYSIS (theoretical prediction of the expected deformation response): developed through 3D numerical calculation and triaxial extrusion tests in laboratory
    - MODEL SELECTION: three-dimensional models
    - DEFORMATION RESPONSE: 3 components, extrusion, preconcergence and convergence
- CONTROL (selection of the excavation system and of the instruments to control the expected Deformation Response):
    - operations upstream and downstream of the excavation face
    - full face advancement



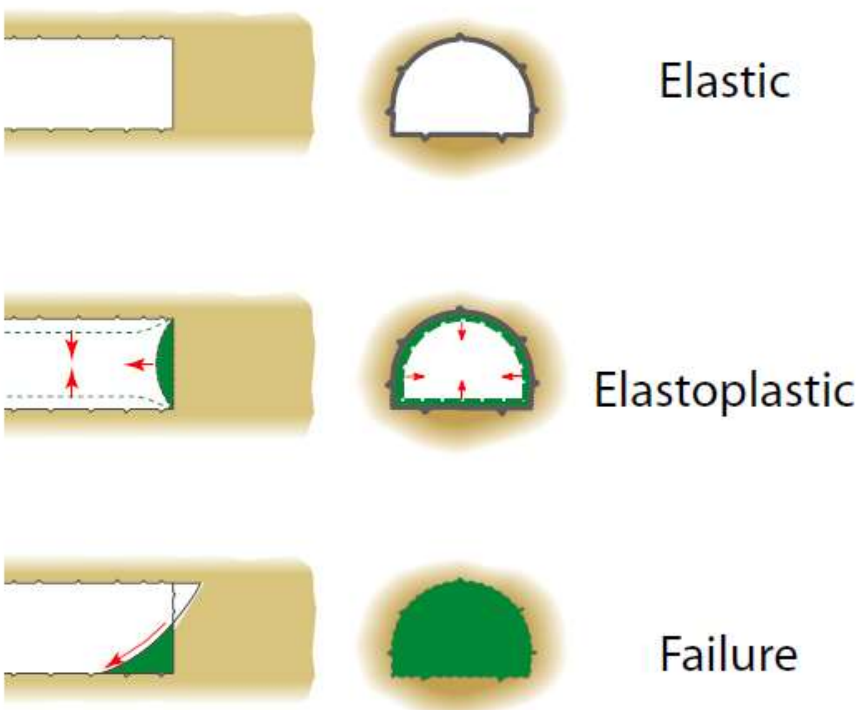




ANALYSIS of the expected Deformation Response according to ADECO-RS

Having chosen a three-dimensional model, ADECO-RS attaches priority to the expected Deformation Response of the excavation face

Expected Deformation Response in domain:



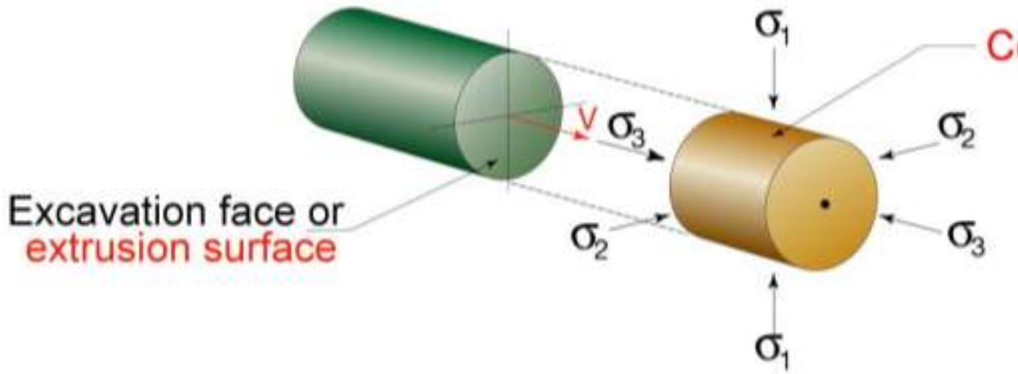
Modern approaches (ADECO-RS)

Working in three dimensions, it becomes essential to consider as deformation response that of the excavation face, therefore it is necessary to establish:

NEW FRAMEWORK OF REFERENCE

ANALYSIS of the expected Deformation Response according to ADECO-RS

ADECO-RS considers as fundamental Deformation Response that of the core-face, therefore has to consider NEW REFERENCES

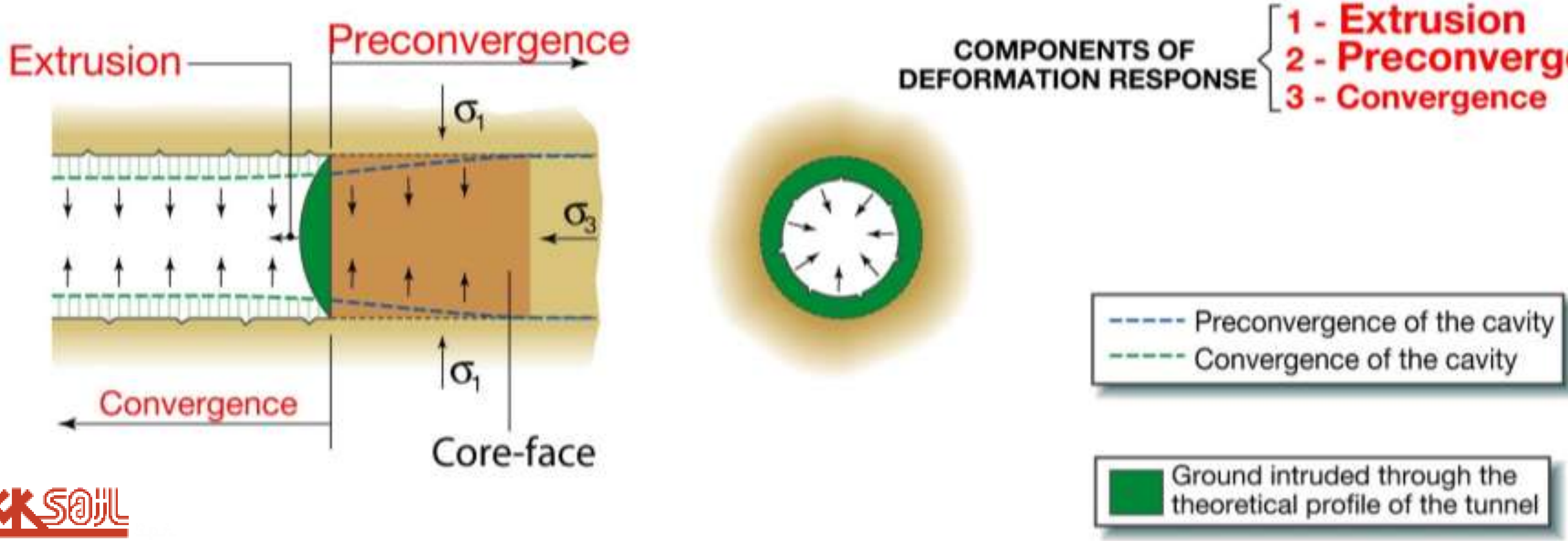


fundamental

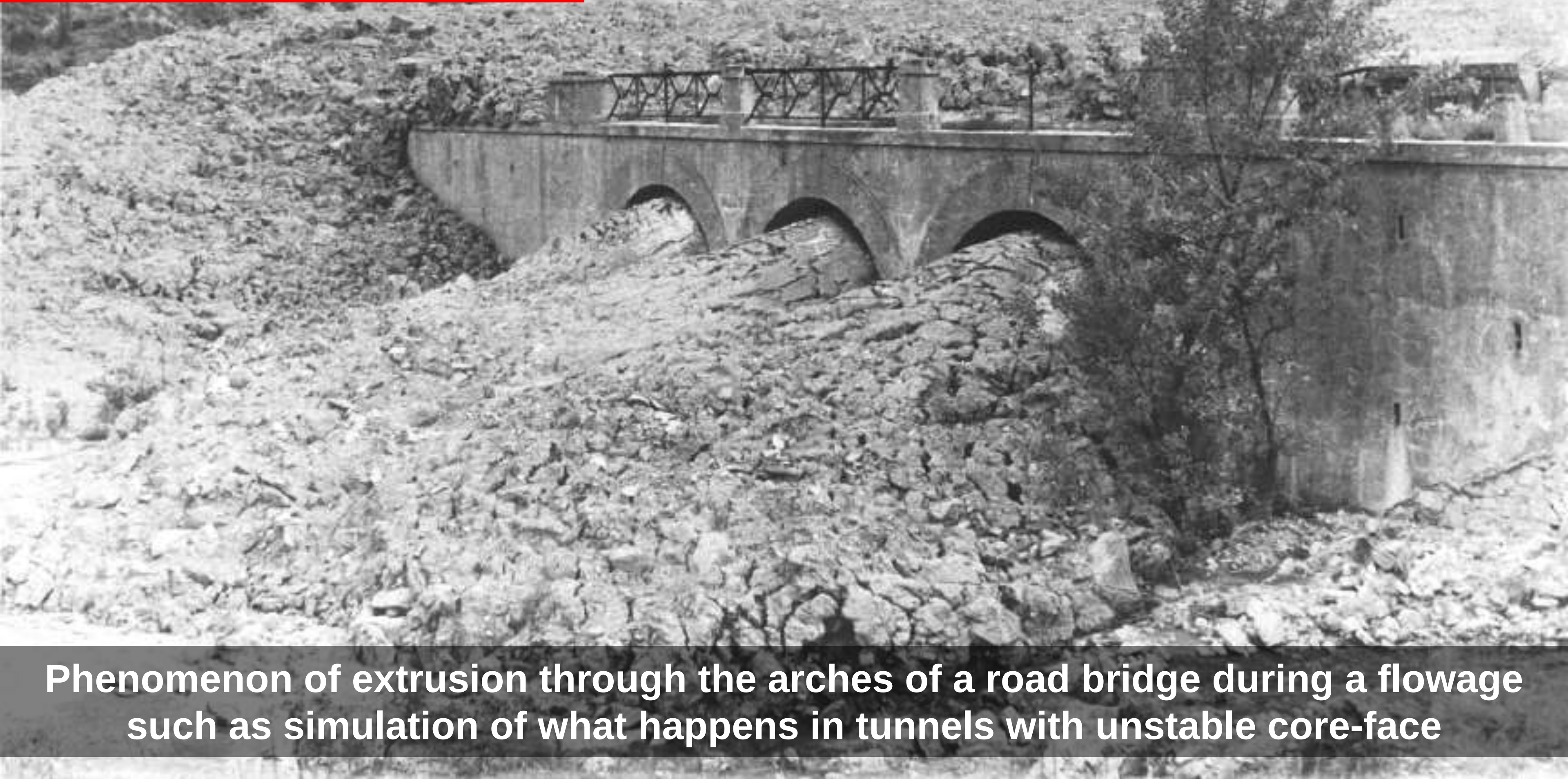
$\sigma_1 = \gamma H$

being: H = overburben
γ = unit weight of the ground

COMPONENTS OF DEFORMATION RESPONSE
1 - **Extrusion**
2 - **Preconvergence**
3 - **Convergence**



Vasto tunnel



Phenomenon of extrusion through the arches of a road bridge during a flowage such as simulation of what happens in tunnels with unstable core-face

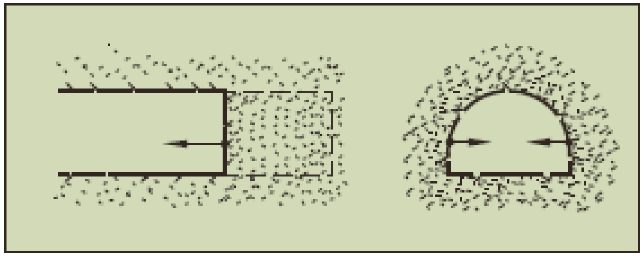
RESEARCH ON THE DEFORMATION RESPONSE DEVELOPED THROUGH THREE STAGES

(it lasted more than 30 years, on over 1,000 km of tunnels constructed and tens of thousands of excavation faces)

1

1st stage: in terms of analysis

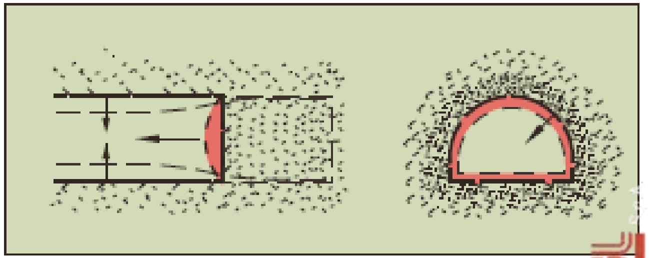
SYSTEMATIC OBSERVATION OF THE DEFORMATION BEHAVIOUR OF THE CORE-FACE AND NOT JUST OF THE CAVITY



2

2nd stage: in terms of analysis

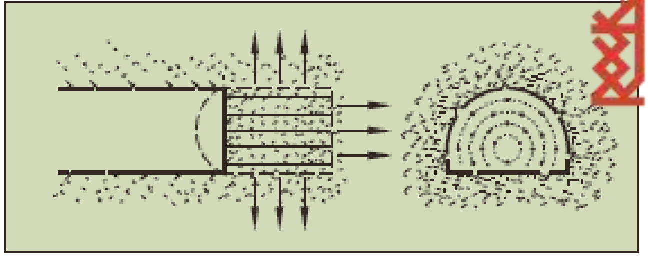
VERIFICATION OF THE EXISTENCE OF CONNECTIONS BETWEEN THE DEFORMATION BEHAVIOUR OF THE CORE-FACE AND OF THE CAVITY



3

3rd stage: in terms of control

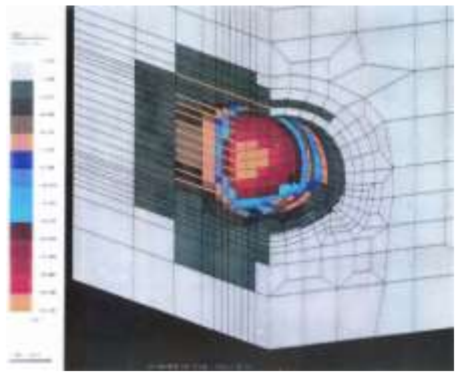
VERIFICATION OF HOW THE DEFORMATION RESPONSE OF THE CAVITY CAN BE CONTROLLED BY ADJUSTING THE RIGIDITY OF THE CORE-FACE



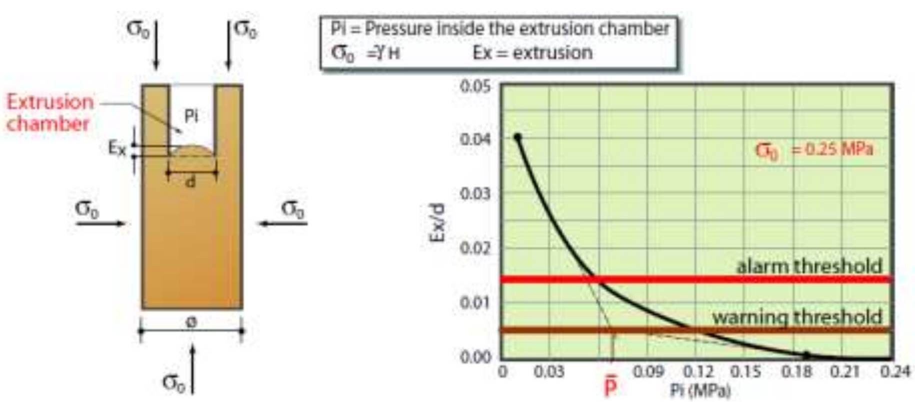
ANALYSIS of the Deformation Response according to ADECO-RS

EXPECTED DEFORMATION RESPONSE → How to study it during the design stage?

3D Finite Elements



Numerical calculation

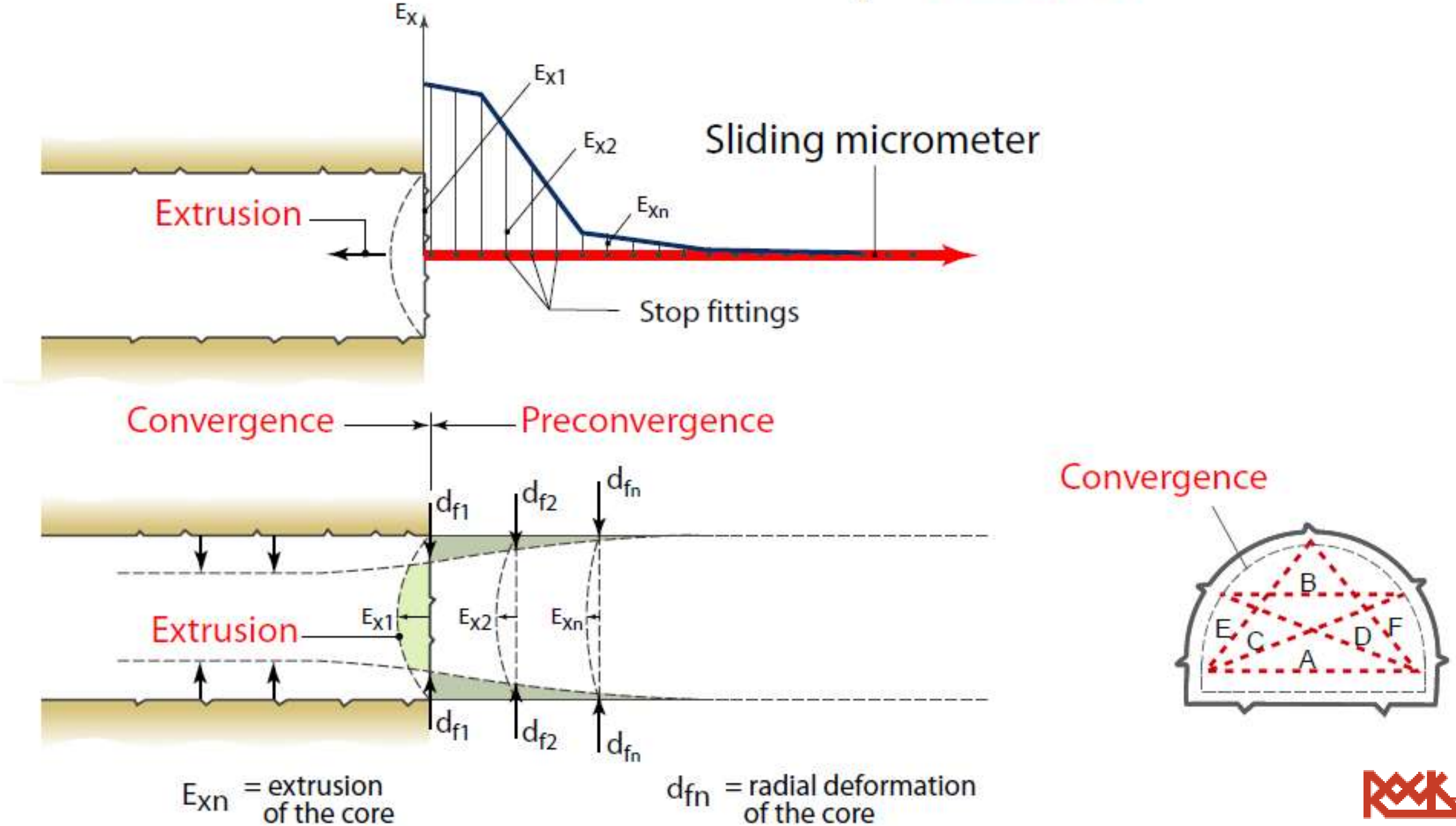


Experimentation on a reduced scale in the laboratory

ANALYSIS of the Deformation Response according to ADECO-RS

REAL DEFORMATION RESPONSE → How to assess it during the construction stage?

Assessment of
- extrusion by experimental way
- preconvergence by analytical way
- convergence by experimental way

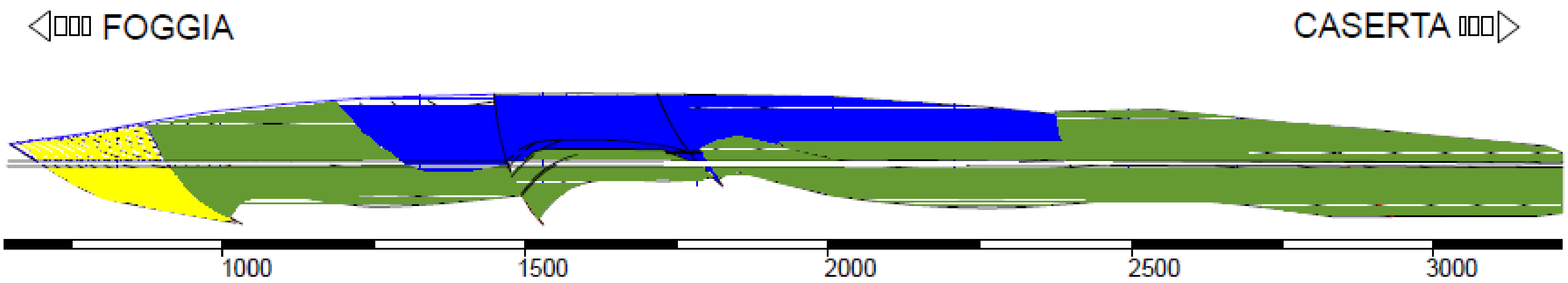


3rd research stage

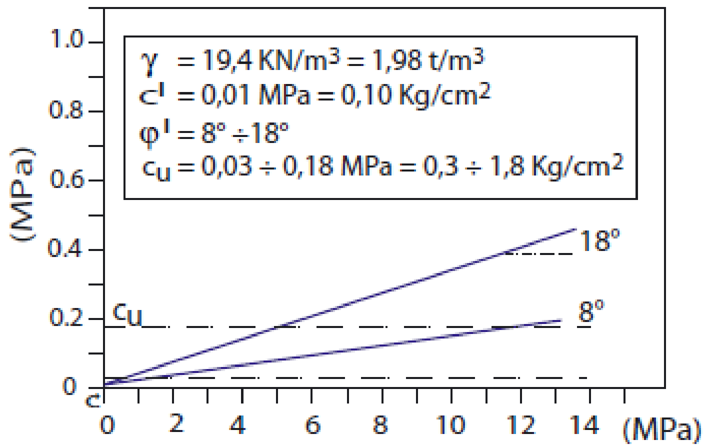
Sample tunnel

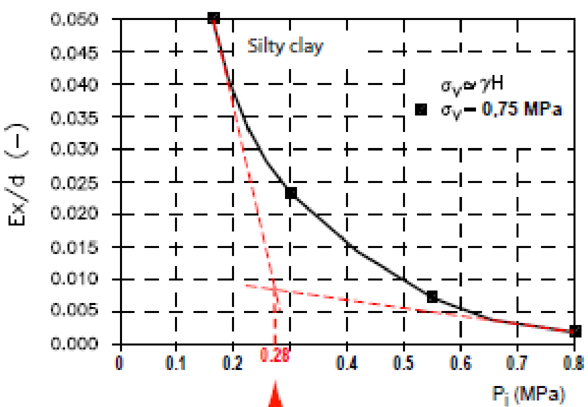
CASERTA - FOGGIA RAILWAY LINE - “S. VITALE” TUNNEL (year 1990)

Geological profile



SCALY CLAY: geotechnical characteristics and stability factor

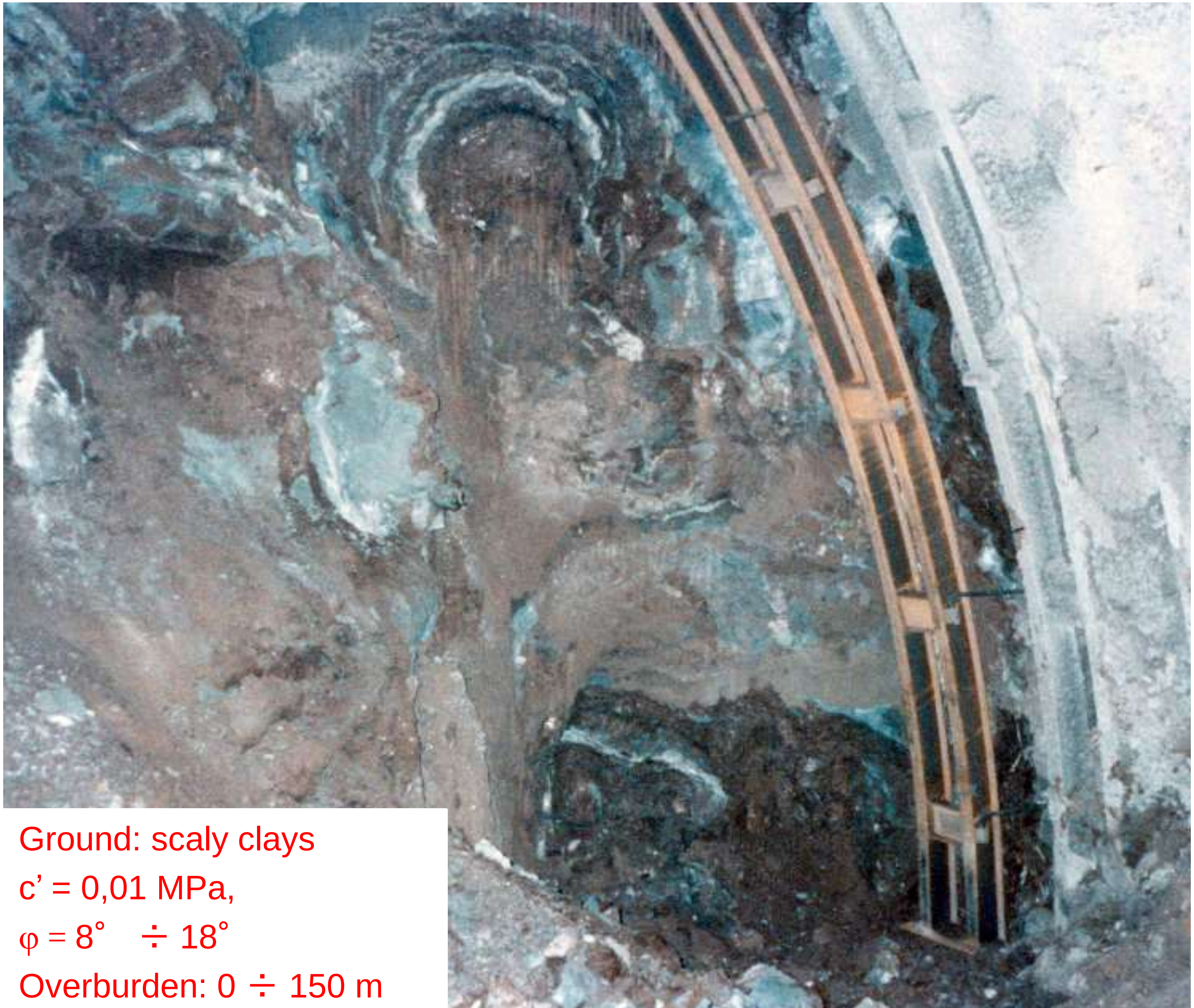




$\overline{P}_{cr}$ = min. confinement pressure

3rd research stage

CASERTA-FOGGIA RAILWAY LINE – SAN VITALE TUNNEL (1990)



Ground: scaly clays

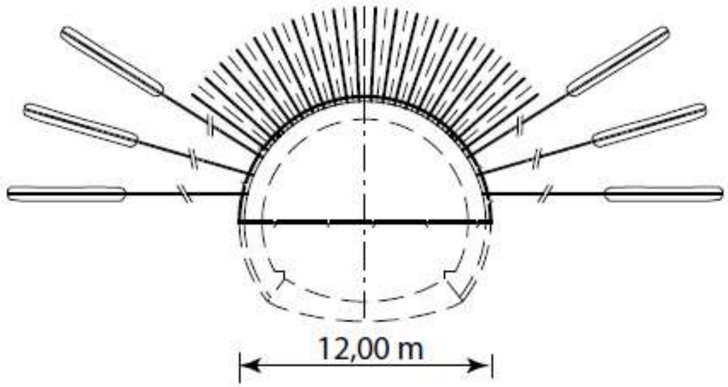
c' = 0,01 MPa,

$\varphi = 8° \div 18°$

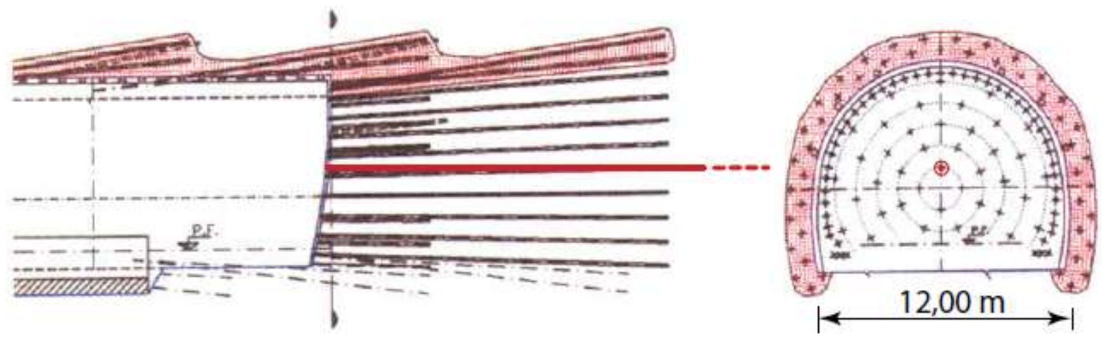
Overburden: 0 ÷ 150 m

CASERTA-FOGGIA RAILWAY LINE – SAN VITALE TUNNEL (1990)

Partitioned face



Full face



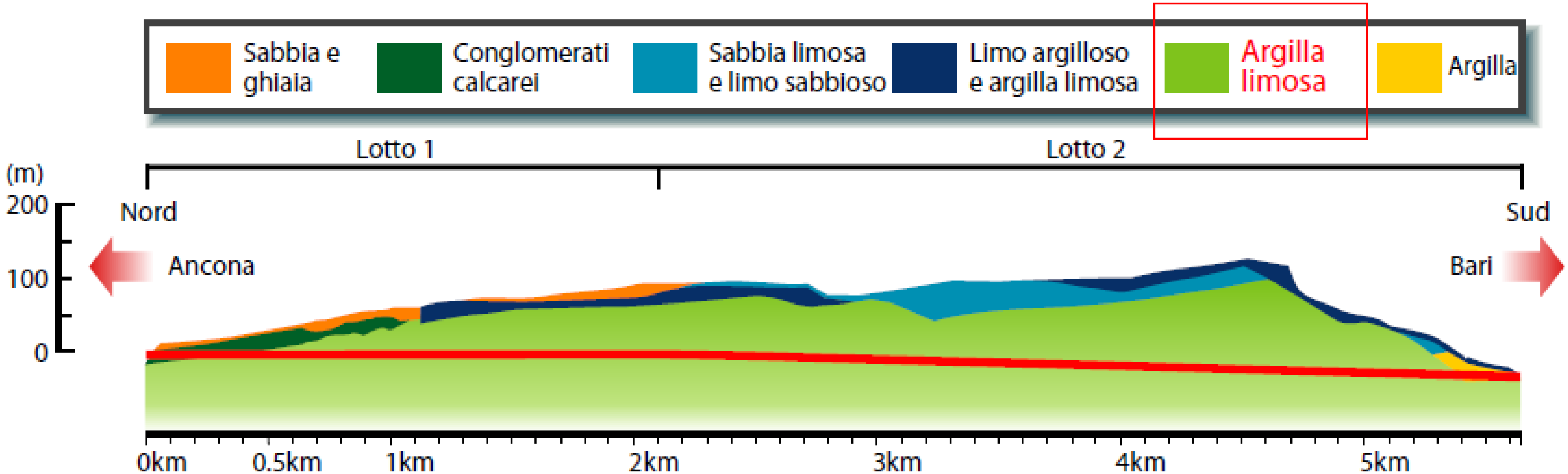
Result:
face stopped for four years

Result:
advance rate= 1.5 m/day of completed tunnel

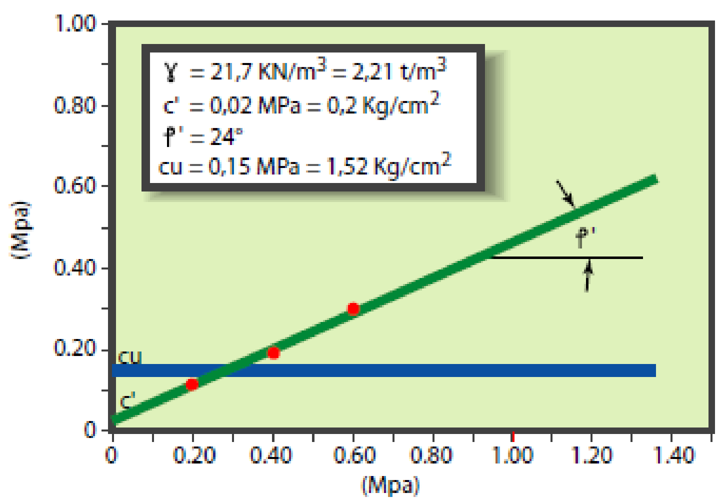
3rd research stage

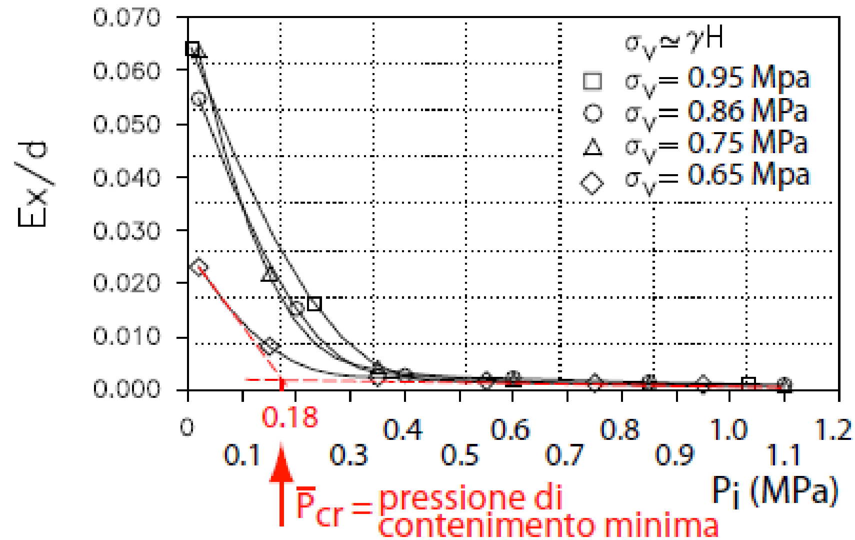
Sample tunnel

LINEA FERROVIARIA ANCONA - BARI - GALLERIA 'VASTO' (anno 1991)



ARGILLE LIMOSE: caratteristiche geotecniche e risultati prove di estrusione in cella triassiale





3rd research stage

ANCONA-BARI RAILWAY LINE – VASTO TUNNEL (1991)

Ground: silty clay

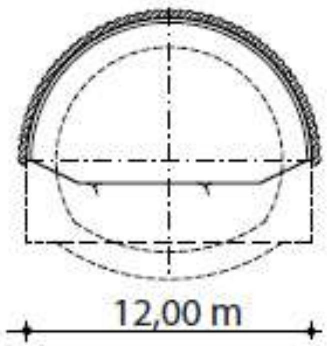
$c' = 0{,}02$ MPa,

$\varphi = 24°$

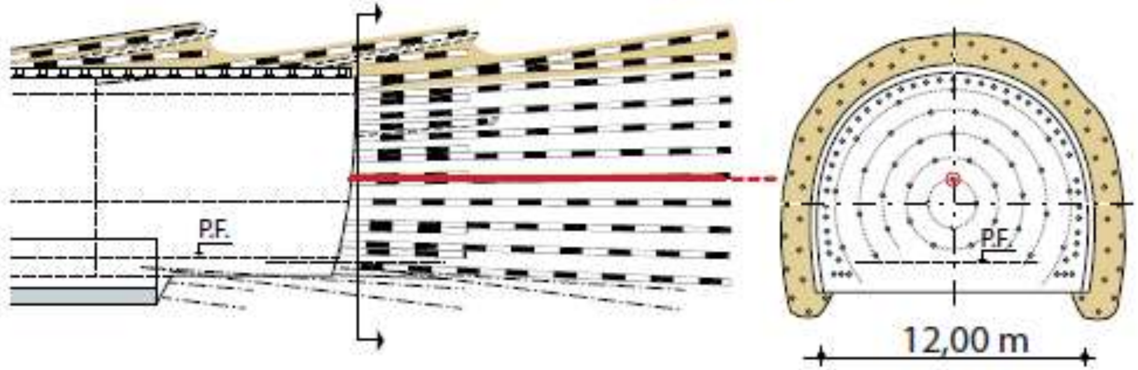
Overburden: $0 \div 150$ m

ANCONA-BARI RAILWAY LINE – VASTO TUNNEL (1991)

Partitioned face



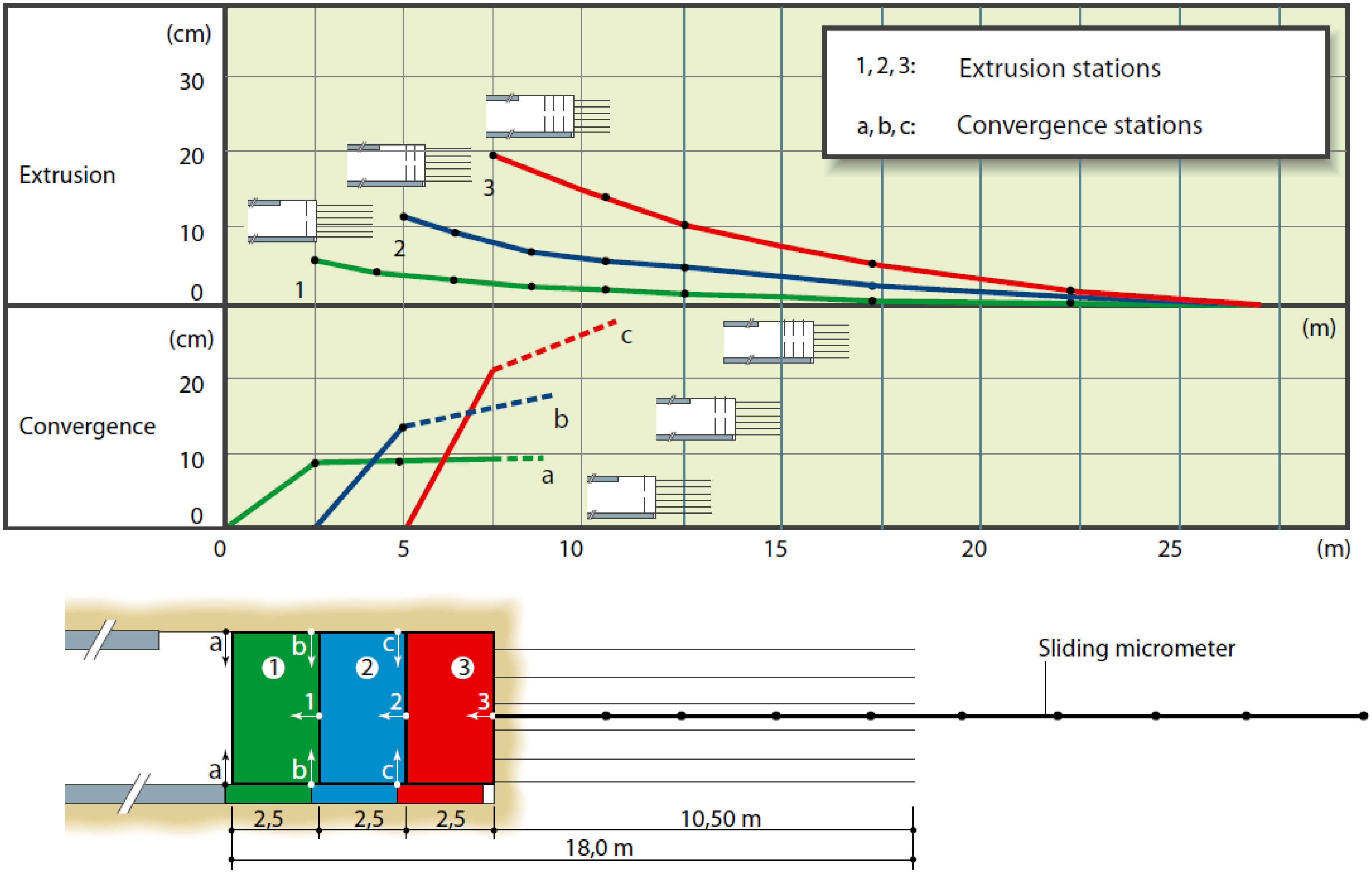
Full face



Result:
the unstoppable extrusion of the core-face makes it impossibilie to continue advancement

Result:
advance rate= 1.5 m/day of completed tunnel

CASERTA-FOGGIA RAILWAY LINE – SAN VITALE TUNNEL (1990)



ANALYSIS of the Deformation Response according to ADECO-RS

RESEARCH FINDINGS

- there is a strict correlation between the extrusive behaviour of the tunnel's core-face and what occurs downstream the same, in the cavity;
- the extrusive behaviour of the core-face always and inevitably influences the behaviour of the cavity;
- controlling the extrusive behaviour of the core-face also controls the deformation behaviour of the cavity;
- The role of convergence results therefore reduced as the last stage of Deformation Response under excavation action, which begins upstream the excavation face from the extrusive behaviour of the core-face.