Evaluating the application limits of unreinforced concrete tunnel final linings

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Outline of the presentation

1. Recent tunnel cases in Europe where unreinforced concrete tunnel linings were successfully constructed – Is it a prohibitive design concept?
2. Existing Design Codes and Design Recommendations framework for the unreinforced concrete tunnel linings
3. Numerical parametric analyses of the unreinforced concrete tunnel linings, under static and seismic loading conditions. The cases of T1, T2 tunnels of Maliakos - Kleidi Motorway and T26 tunnel of Athens – Patras Motorway in Greece
4. Some critical thoughts about the appropriate value of the rockmass elastic modulus to be used in the design of unreinforced concrete tunnel linings
5. Conclusions

1. Is the concept of the unreinforced concrete tunnel lining a prohibitive one?

The existing design and construction experiences in tunnelling worldwide gives the answer:

NO

Recent tunnels with unreinforced concrete tunnel linings

Tunnel	Country	Type of tunnel	Completion time	Length (km)	Tunnel section (m2)	Final lining thickness (cm)	Brief geology
Tradenberg	Switzerland	Motorway	2009	2	126	40	Mudstones, Sandstones, Clay marls
Grouft Tunnel	Luxembourg	Motorway	2010	3	96		Marls, Sandstones
Gotthard – Base Tunnel	Switzerland	Railway	On going	25	65	30 - 40	Gneiss
Loetschberg	Switzerland	Railway	2008	35			
Schwarzer berg Tunnel	Germany	Motorway	2004	1	102	30 - 40	Gypsum
CTRL 104 North Downs tunnel	U.K.	Railway	2002	3	103	35 - 40	Chalk

Recent tunnels with unreinforced concrete tunnel linings

Tunnel	Country	Type of tunnel	Completion time	Length (km)	Tunnel section (m2)	Final lining thickness (cm)	Brief geology
Aesch Tunnel	Switzerland	Motorway		2.3	135	35 - 40	Molasse rocks
Rennsteigtunnel	Germany	Motorway	2001	8	80 – 120	30	Sandstones, Siltstones, Conglomerates
Tempi Tunnel T1	Greece	Motorway	Almost completed	1.8	120	45	Marbles and Amphobolites
Tempi Tunnel T2	Greece	Motorway	Almost completed	6	120	45	Amphibolites Marbles with phyllites intercalations
Panagopoula Tunnel T26	Greece	Motorway	On going	4	100	40	Limestones, Cherts and Conglomerates

- Unreinforced concrete tunnel linings were successfully constructed even in tunnels of large cross sections and in different ground conditions
- Rennsteigtunnel presently is the longest Motorway tunnel in Germany. Length ~ 8km
- Tempi Tunnel T2 presently is the longest Motorway tunnel in the Balkans region. Length ~ 6km
- In CTRL 104 North Downs Tunnel, the unreinforced lining is considered as a real “value engineering” solution resulted to £10m savings in the budget and completion time 5 months ahead of the Project’s schedule

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Major issues to be considered for the successful application of the concept

- **Application Limits** of the concept must be derived
- These **Application limits** are related to:
  i. The geotechnical environment
  ii. The seismic / tectonic regime
  iii. The topography

  of every tunnel location
- The **Application limits** are related to well determined safety and serviceability requirements of the unreinforced tunnel final lining behavior.
- The Design and Construction must fulfill these requirements

Major issues to be considered for the successful application of the concept

- The Safety and Serviceability Requirements of the unreinforced tunnel final lining behavior are described in existing Design Codes and Design Recommendations

- Realistic cost-effective in situ concrete construction solutions, which prevent from the formation of the initial cracking, caused during the temperature cycle: ***"Dissipation of the hydration heat and subsequent shrinkage***"

2. Existing Design Codes and Design Recommendations for the unreinforced concrete tunnel linings

I. **Eurocode 2 EN 1992 – 1 / Section 12**: Plain and lightly reinforced concrete structures

II. **AFTES Recommendations** in respect of the use of plain concrete in tunnels (e.g. crack depth and loads eccentricity limits)

III. **Rudolf Pottler publication**: “The unreinforced inner lining of rock tunnels – stability analysis and deformation of the crack area” (e.g. crack width estimation)

IV. **DAUB Recommendations** for executing and application of unreinforced tunnel inner linings

Eurocode 2 EN 1992 – 1 / Section 12: Plain (unreinforced) and lightly reinforced concrete structures

SECTION 12 PLAIN AND LIGHTLY REINFORCED CONCRETE STRUCTURES

12.1 General

(1)P This section provides additional rules for plain concrete structures or where the reinforcement provided is less than the minimum required for reinforced concrete.

Note: Headings are numbered 12 followed by the number of the corresponding main section. Headings of lower level are numbered consecutively, without reference to subheadings in previous sections.

(2) This section applies to members, for which the effect of dynamic actions may be ignored. It does not apply to the effects such as those from rotating machines and traffic loads. Examples of such members include:

- members mainly subjected to compression other than that due to prestressing, e.g. walls, columns, arches, vaults, and tunnels;
- strip and pad footings for foundations;
- retaining walls;
- piles whose diameter is $\geq$ 600 mm and where $N_{Ed}/A_c \leq 0{,}3f_{ck}$.

Eurocode 2 EN 1992 – 1 / Section 12: Plain (unreinforced) and lightly reinforced concrete structures

Concrete additional design assumptions (Clause 12.3.1):

1. Design compressive strength: $f_{cd} = a_{cc,pl} \left\{ \frac{f_{ck}}{\gamma_c} \right\}$

2. Design tensile strength: $f_{ctd} = a_{ct,pl} \left\{ \frac{f_{ctk,0.05}}{\gamma_c} \right\}$

where: $a_{cc,pl}$ & $a_{ct,pl}$ = 0.8, due to the less ductile properties of plain concrete

f_{ck} is the characteristic compressive strength of concrete

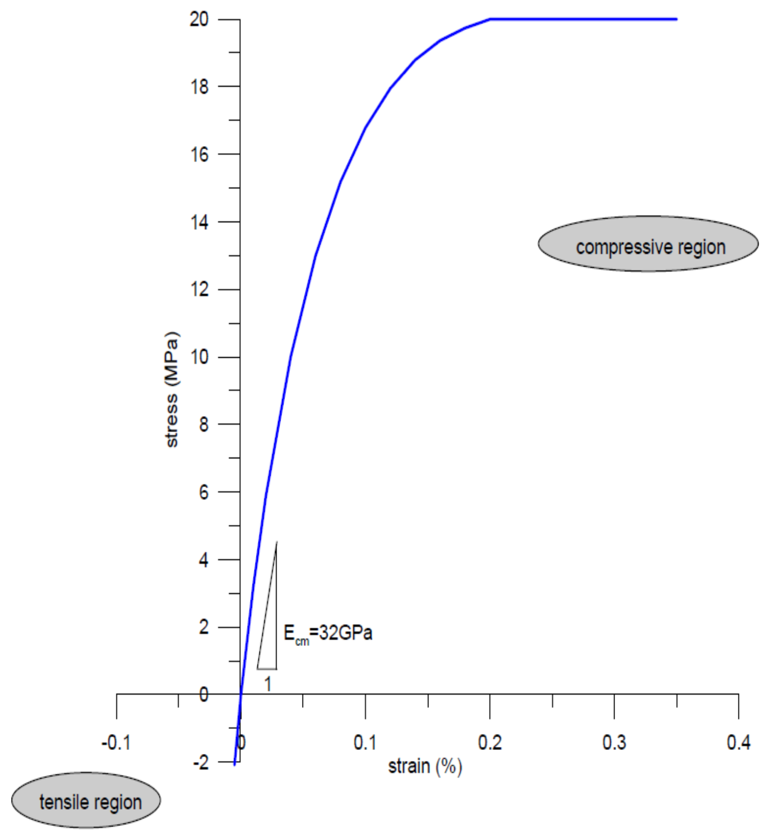
$f_{ctk,0.05}$ is the characteristic axial tensile strength of concrete and

γ_c =1.50 for persistent and transient actions, 1.20 for accidental actions

Eurocode 2 EN 1992 – 1 / Section 12: Plain (unreinforced) and lightly reinforced concrete structures

Concrete additional design assumptions (Clause 12.3.1):

3. Tensile stresses can be considered in the design, by extending linearly the stress- strain diagram of concrete into the tensile region, up to the design tensile strength f_{ctd}



Eurocode 2 EN 1992 – 1 / Section 12: Plain (unreinforced) and lightly reinforced concrete structures

Verification Criteria at the Ultimate Limit States are described in Clause 12.6

1. **Clause 12.6.1** describes the design resistance to **bending and axial force** :

   Computed axial force N<

   f_{cd} is the concrete design compressive strength

   N_{Rd} is the ultimate axial force, $N_{Rd} = f_{cd} x b x h_w x \left(1 - \frac{2e}{h_w}\right)$

   b is the overall width of the lining section, h_w is the overall thickness of the lining section and

   e is the load eccentricity

   No limit to acceptable crack depth

2. **Clause 12.6.3** describes the design resistance to **shear**:

   For a tunnel lining section subjected to a shear force V and an axial force N, acting over a compressive area A_{cc}, then:

   the shear component of design stress $\tau_{cp} = 1.5 \frac{V}{A_{cc}} \leq f_{cvd,}$

   where f_{cvd} is the concrete design strength in shear and compression

AFTES Recommendations in respect of the use of plain concrete in tunnels

Verification criteria at the Ultimate Limit State (based on Eurocode 2 concepts):

1. ***Design resistance to bending and axial force***.

   i. If the computed axial forces $N < N_{Rd0} = 0.027(f_{ck} x b x h_w)$, **NO particular check is needed**

   f_{ck} is the characteristic compressive strength of concrete, b is the overall width of the lining section and h_w is the overall thickness of the tunnel lining section

   ii. If the computed axial forces $N > N_{Rd}$ (ultimate axial force), **then Reinforcement <u>MUST</u> be provided or Redesign of the section is <u>NECESSARY</u>**

$$N_{Rd} = 0.57 x f_{ck} x b x h_w x \left\{1 - \frac{2e}{h_w}\right\} \ (basic\ ULS)$$

$$N_{Rd} = 0.74 x f_{ck} x b x h_w x \left\{1 - \frac{2e}{h_w}\right\} \ (accidental\ ULS)$$

$$load\ eccentricity\ e = \frac{M}{N}, M\ is\ the\ computed\ bending\ moment$$

AFTES Recommendations in respect of the use of plain (unreinforced) concrete in tunnels

Verification criteria at the Ultimate Limit State (based on Eurocode 2 concepts):

1. ***Design resistance to bending and axial force***

   iii. If the computed axial forces $N_{Rd0}<N<N_{Rd}$ then:

   Load eccentricity $e=M/N > 0.3xh_w$ → Unreinforced tunnel lining section is **UNACCEPTABLE**

   Load eccentricity $e=M/N < 0.3xh_w$ → Unreinforced tunnel lining section is **ACCEPTABLE**

AFTES recommends the limitation of the load eccentricity: $e< 0.3xh_w$ and imposes the crack depth limitation to the ½ of the unreinforced tunnel lining thickness (***major serviceability criterion for the unreinforced concrete tunnel final linings***)

Serviceability criterion of the unreinforced concrete tunnel final linings related to the maximum accepted crack width (Pottler's publication)

- For unreinforced concrete tunnel final linings, accepted crack width w can be $\leq$ 0.25mm
- The estimation of the crack width w can be done according to Pottler's publication, by employing the following mathematical relationship:

$$w = \frac{N}{E} \times \left\{\frac{2}{a^2} - \frac{6}{{h_w}^2} - \frac{4 \times a}{h_w^3}\right\} x(\, h_w - a)^2$$

where: N is the computed axial force

h_w is the overall thickness of the tunnel lining section

a is the height of the remaining concrete compression zone after cracking

E is the Young modulus of concrete

DAUB – German Recommendations for executing and application of unreinforced Tunnel final (inner) linings

- **DAUB** attempts to restrict the application fields of unreinforced tunnel final linings, due to high possibility of cracking, as an effect of their low tensile strength
- According to **DAUB**, unreinforced tunnel final linings are suitable for blocks of standard geometry in road tunnels, provided that these are located in solid rocks and not in excessive depths

DAUB – German Recommendations for executing and application of unreinforced Tunnel final (inner) linings

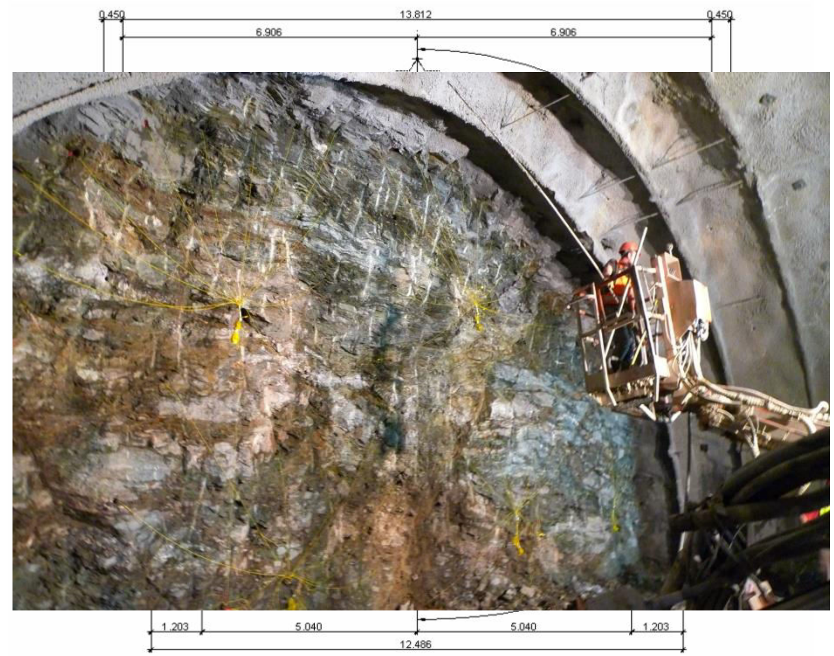
DAUB proposes:

1. Unreinforced tunnel linings can be executed at maximum block lengths of 12m to 12.5m
2. For road and railway tunnels, the minimum thickness of unreinforced tunnel linings is 30cm . Smaller thicknesses are possible for relative smaller tunnel sections
3. Suitable concrete mixes, which restrict the maximum temperature during the setting process, but result to short stripping periods.
   - Cement / fly ash combinations are advantageous
   - The addition of hard coal fly ash reduces the hydration heat effect, improves processability, diminishes the danger of demixing and caters for a denser concrete texture

3a.Numerical parametric analyses under static loading conditions. The case <u>T2 Tempi tunnel </u>of Maliakos - Kleidi Motorway

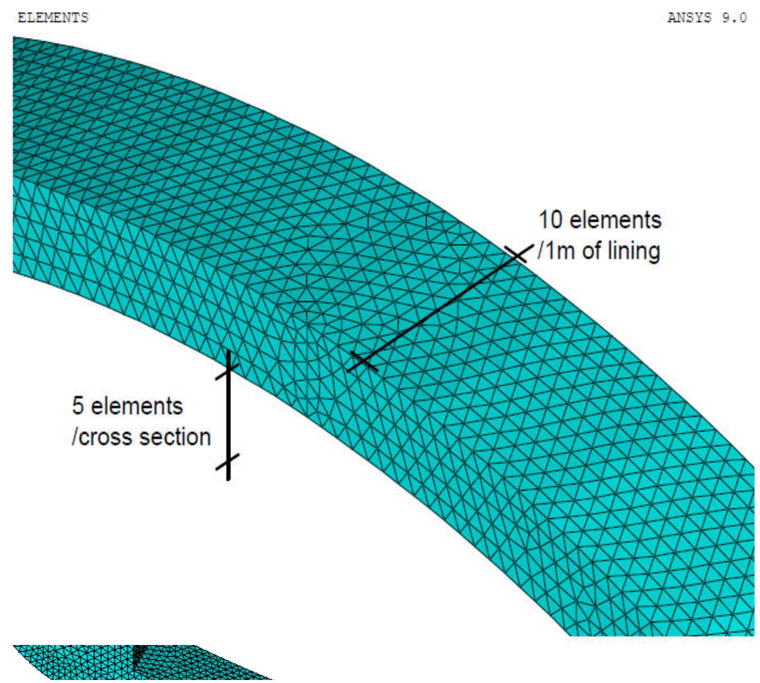
T2 Tempi Tunnel Maliakos – Kleidi Motorway in Greece

- Located in North Greece
- Two bore NATM tunnel with cross section 120m^2. Length = 6km
- Geological conditions: Marbles and Amphibolites (mostly competent rock mass conditions)

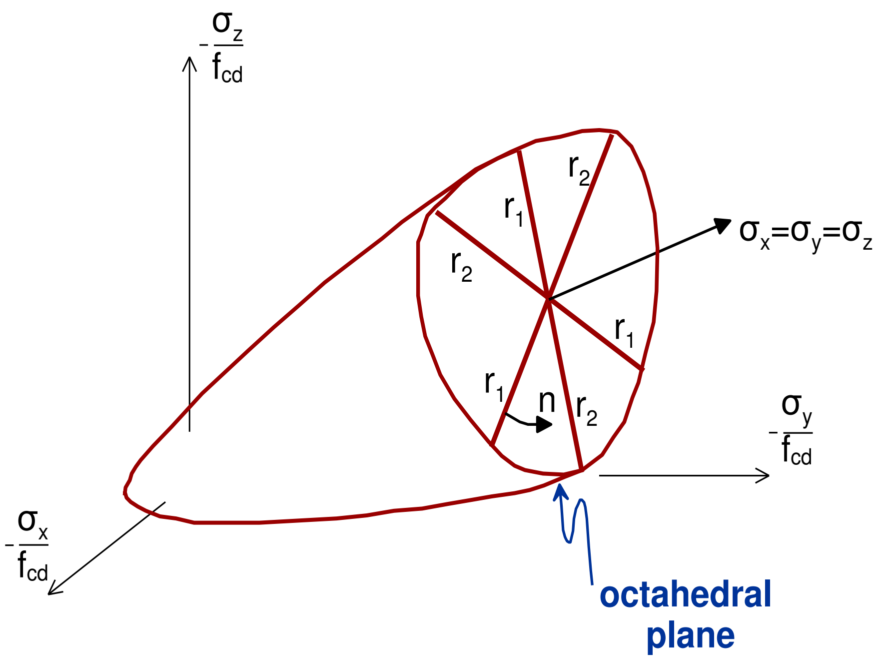


Numerical parametric analyses – Static conditions

1. Eurocode Part1-1/Section 12 and AFTES recommendations for plain concrete were adopted
2. 3-D non-linear Finite Element code was used
3. Willam & Warnke constitutive model to simulate concrete response (cracking and crushing) was adopted
4. Basic Ultimate Limit States (for different load cases and lining types) were calculated
5. The numerical parametric analyses examined the effect of the in-situ rockmass properties on to the linings response



Willam & Warnke Unreinforced concrete constitutive model (1975)



Major advantages of the model:

1. Simulate concrete non-linear stress-strain response, as well as concrete cracking/crushing in three-dimensions
2. Adopts different strength values in compression and in tension
3. Accounts directly lining stiffness degradation due to cracking

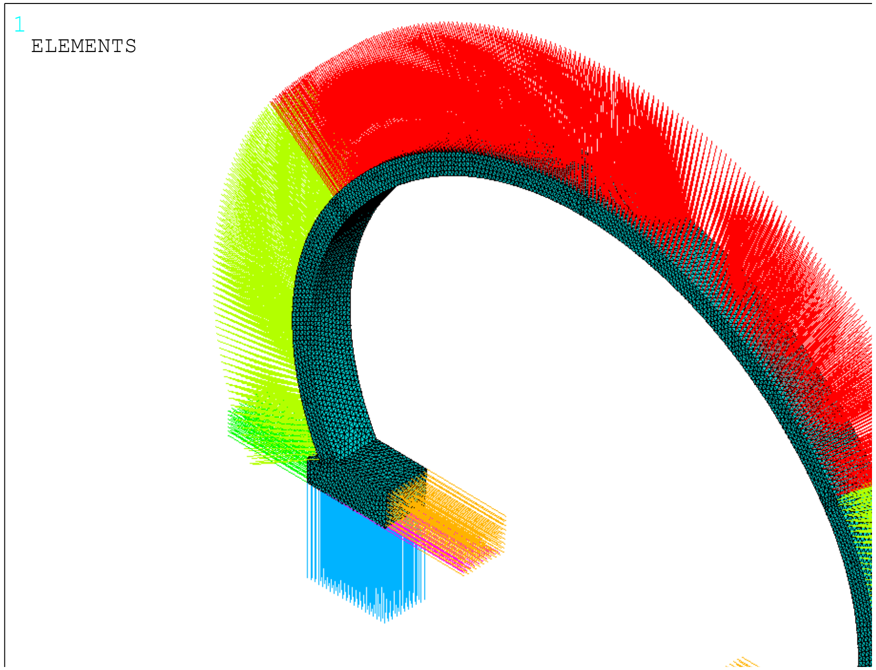
However it requires very fine 3-D finite element mesh (element size ≈0.05m)

Properties of the Unreinforced Concrete used in Willam & Warnke constitutive model

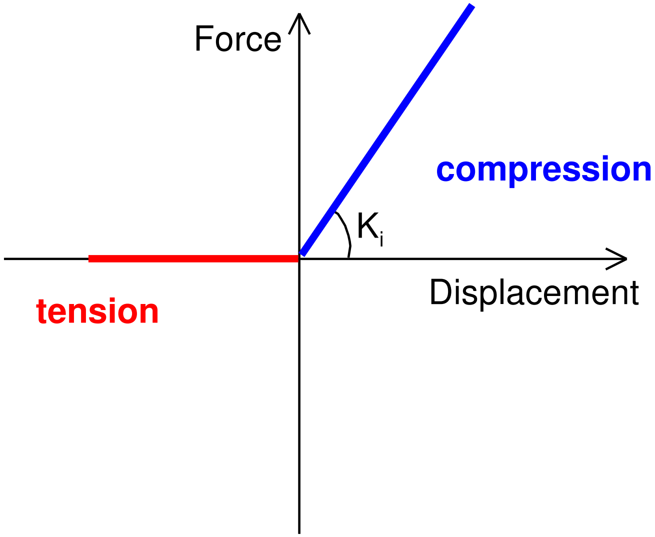
Summary of C30/37 properties according to Eurocode 2

Characteristic compressive cylinder strength at 28 days, f_{ck} (MPa)	30
Mean value of compressive cylinder strength, f_{cm} (MPa)	38
Mean value of axial tensile strength of concrete, f_{ctm} (MPa)	2.9
Characteristic axial tensile strength of concrete, $f_{ctk,0.05}$ (MPa)	2.0
Secant modulus of elasticity of concrete, E_{cm} (GPa)	32
Poisson's ratio of concrete, v (uncracked)	0.2
Compressive strain in the concrete at the peak stress, ε_c (%)	2.2
Compressive strain in the concrete at the peak stress, ε_{cu} (%)	3.5
Coefficient of thermal expansion, α (1/C°)	10^{-5}

Numerical simulation of concrete tunnel lining – geomaterials interaction

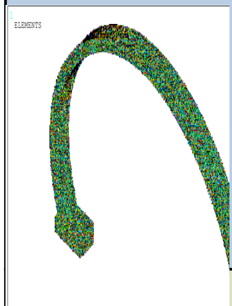
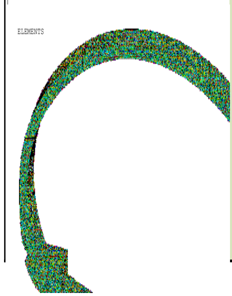


"Stick-slip" elastic springs



K_i values = f(rockmass, lining geometry)

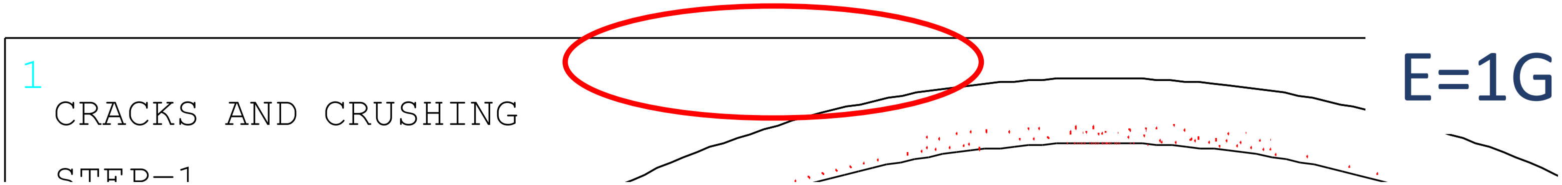
Examined ULS cases

final lining type	load case	description	rockmass modulus of deformation	maximum rockmass load
	LC11	temperature	1000MPa	0
	LC13	rockmass+temperature		180KPa
	LC100	de-moulding stage		0
	LC31	explosion		0
	LC11	temperature	300MPa	0
	LC13	rockmass+temperature		220KPa
	LC100	de-moulding stage		0
	LC31	explosion		0

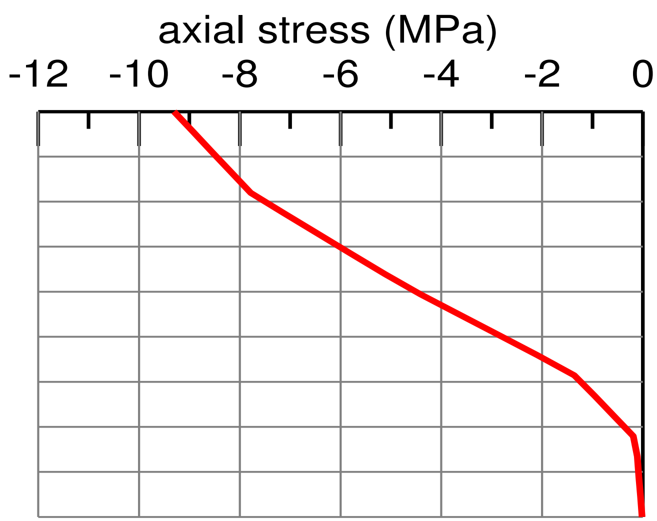
Additional parametric analyses for closed tunnel section:

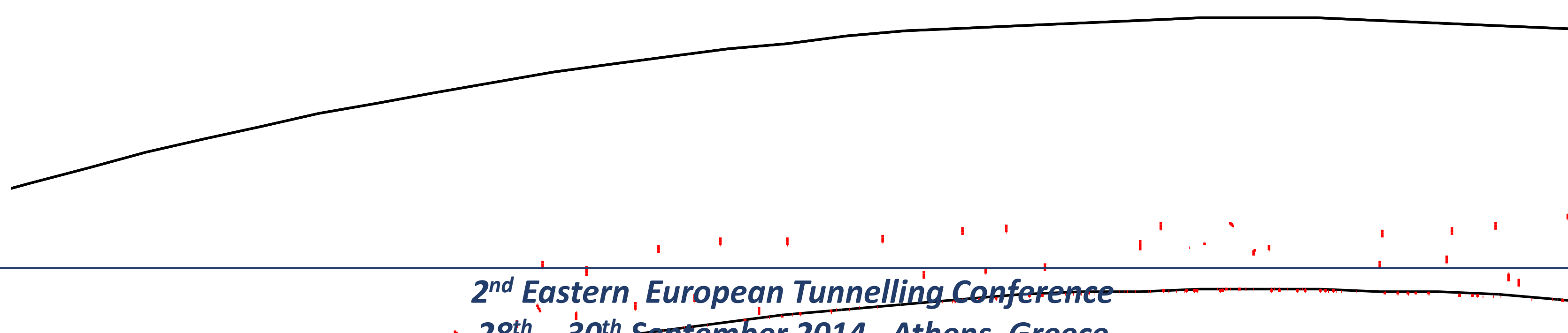
- Uniform face conditions: Erockmass = 150MPa, 800MPa
- Mixed face conditions: Erockmass, vault / invert = 150 MPa / 800MPa,
  800MPa / 150MPa
- Maximum rockmass load 220KPa

Estimation of cracking development in competent rockmass conditions E=1GPa – Rockmass load case



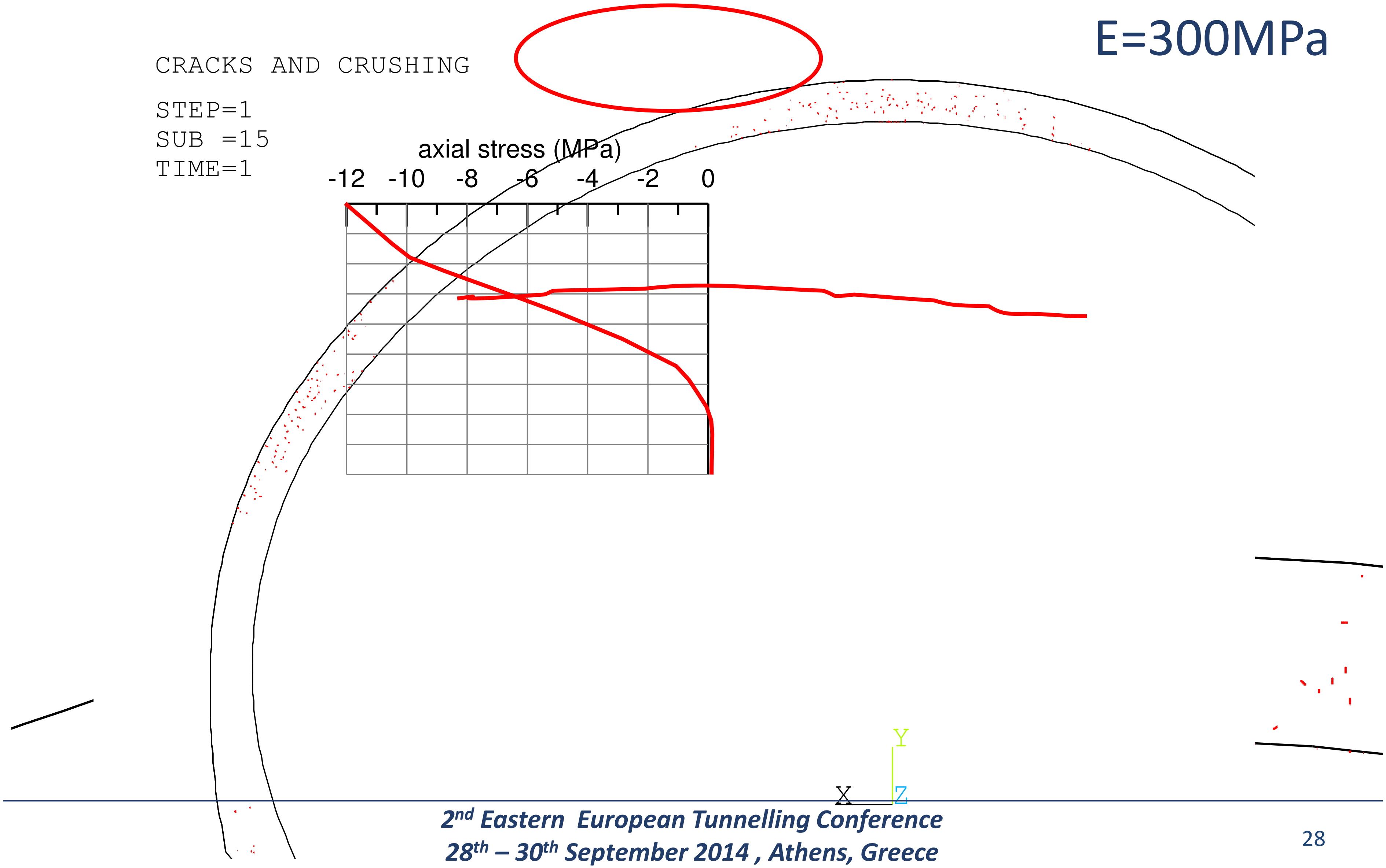
E=1GPa





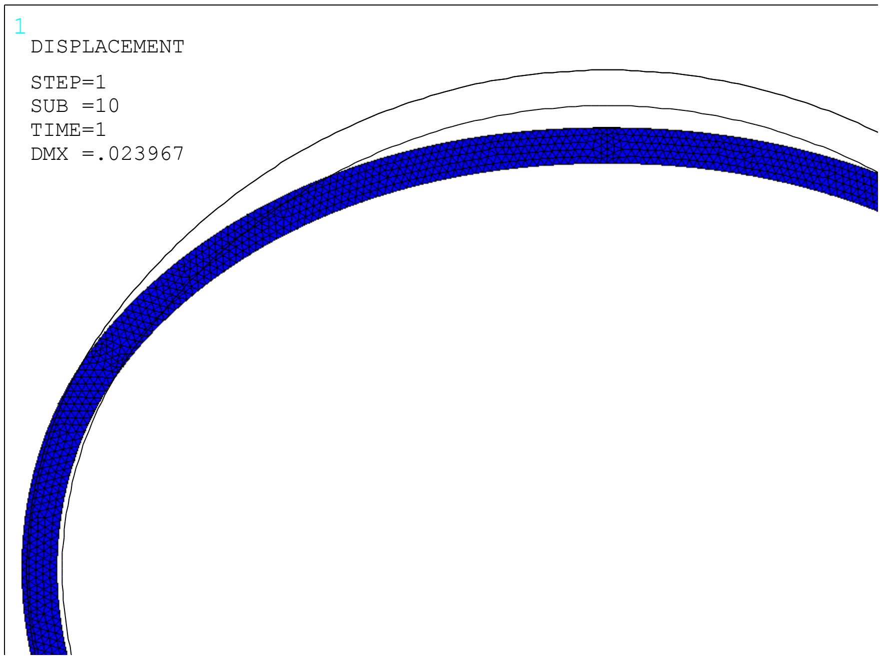
Estimation of cracking development in "poor" rockmass conditions E=300 MPa – Rock mass load case

E=300MPa



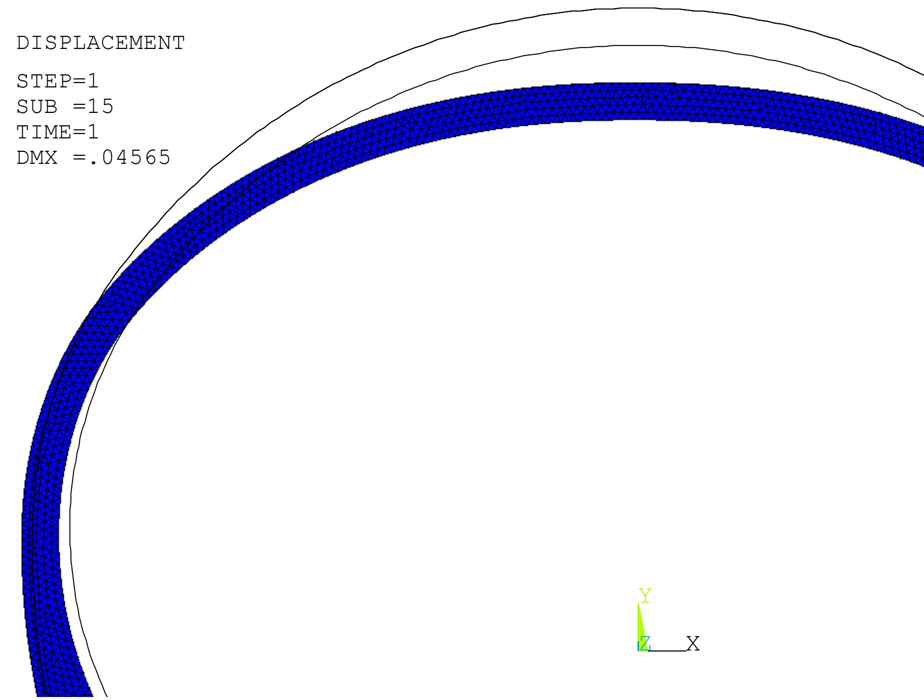
Tunnel linings – Calculated deformed shape under rockmass loadings

Open tunnel section
Erockmass=1 GPa



δ_{max}=2.39cm

Tunnel section with closed invert
Erockmass=300MPa



δ_{max}=4.56cm

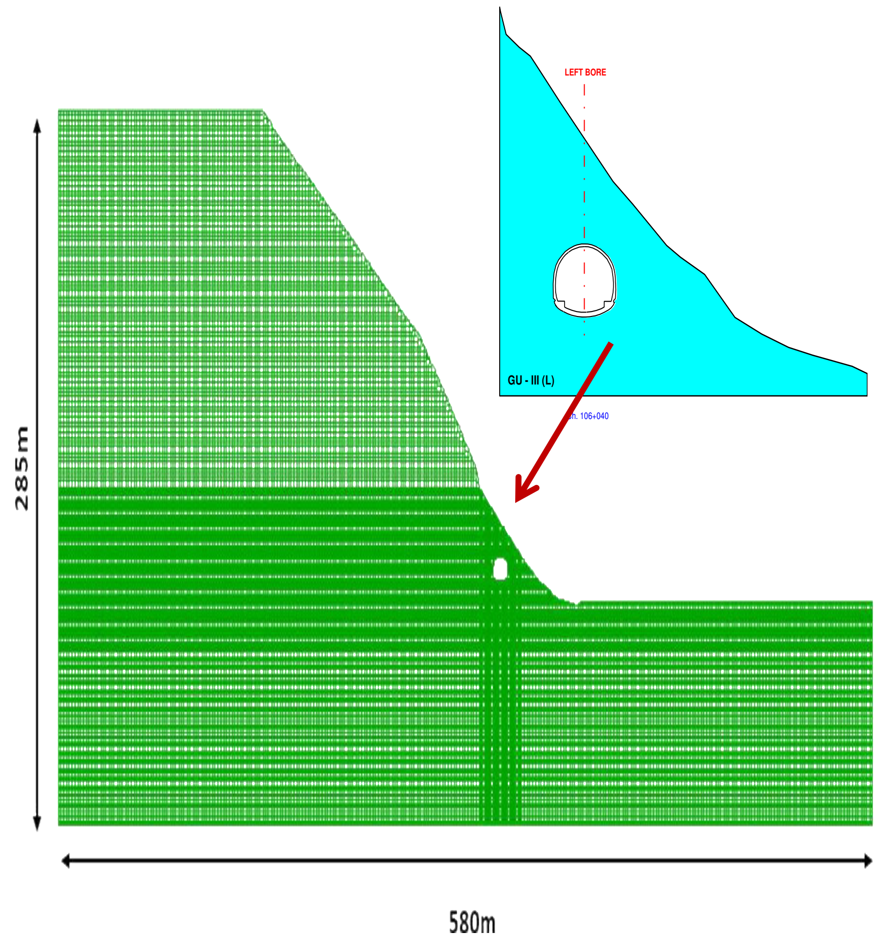
3b.Numerical parametric analyses under seismic loading conditions. The case T26 Panagopoula tunnel of Athens – Patras Motorway

T26 Panagopouls Tunnel
Athens – Patras Motorway in Greece

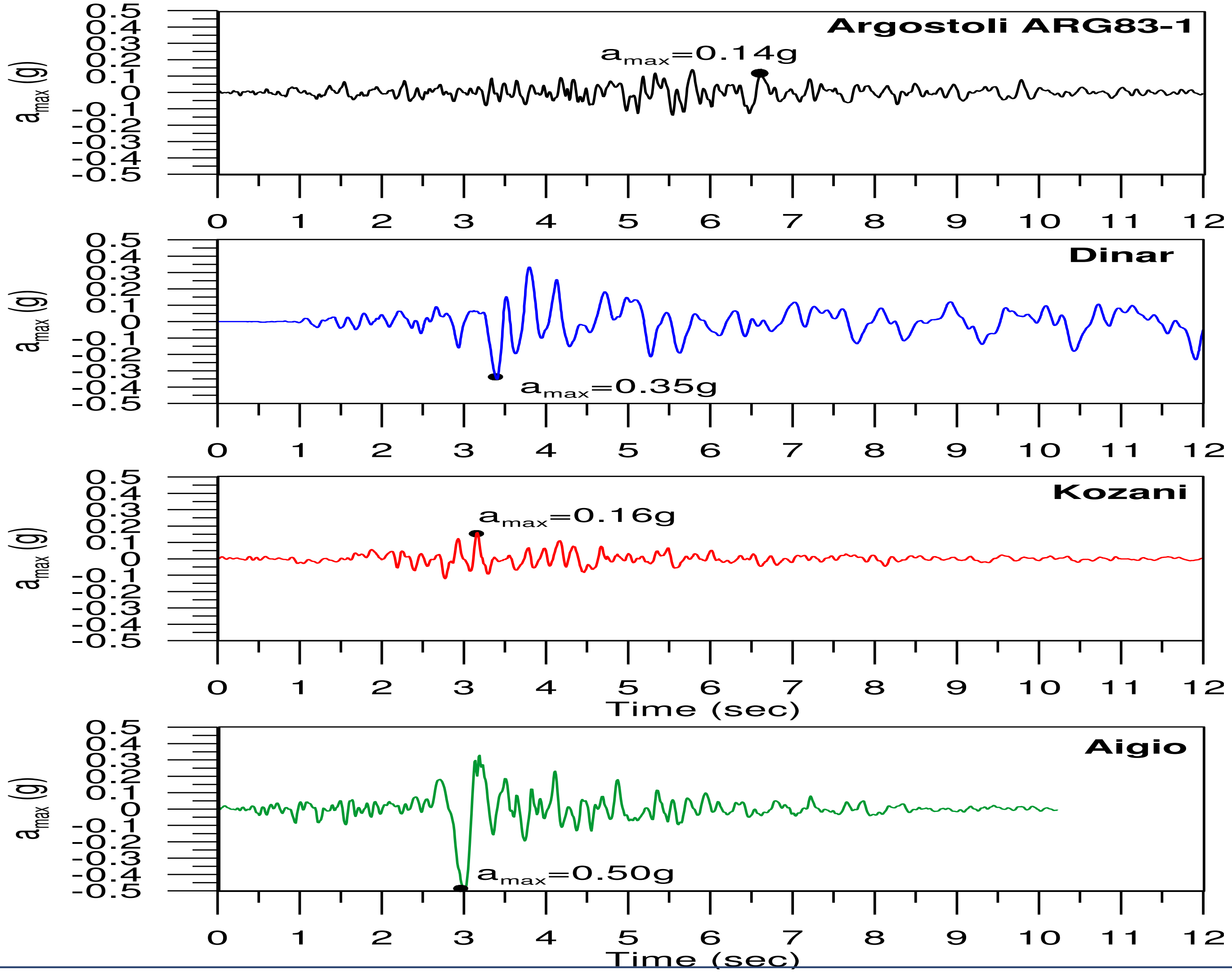
- Located in Peloponnese close to Patras
- Two bore NATM tunnel with cross section $100m^2$. Length = 4km
- Geological conditions: Limestones, Conglomerate and Cherts (competent rock mass conditions along significant stretches)
- High seismicity area. Design acceleration, <u>a=0.36g</u>

2-D Dynamic numerical analyses

- Eurocode Part1-1/Section 12 and AFTES recommendations for plain concrete were adopted. Seismic actions resulting in low axial forces did not require an eccentricity check (no restrictions in crack depth)
- Eurocode 8 EN-1998 was used to determine seismic actions, concrete properties, factors of safety for the accidental load case etc
- Competent limestone conditions E = 1GPa and irregular topography were examined

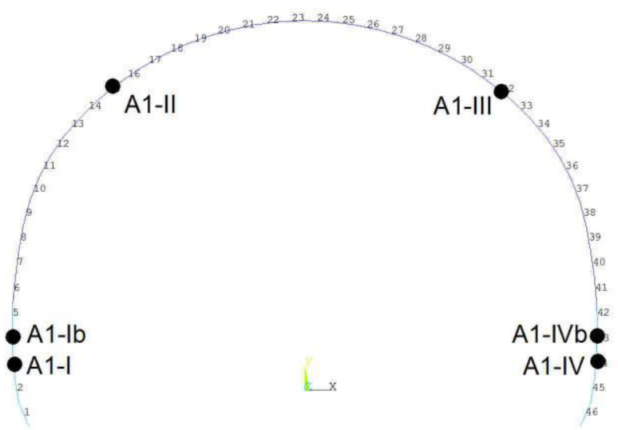


2-D Dynamic numerical analyses

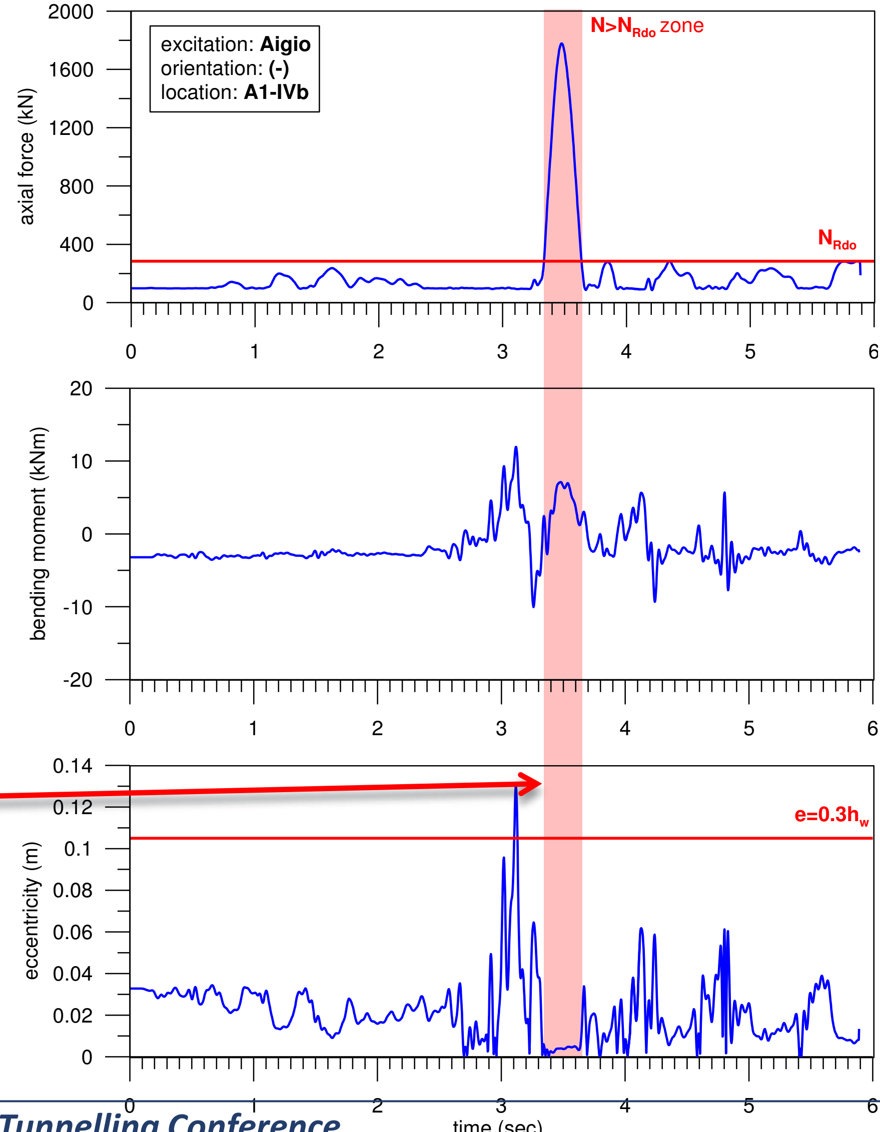


2-D Dynamic numerical analyses-Eccenticity check according to AFTES in competent rock mass conditions E = 1GPA

Results in critical points along the tunnel cross-section



Time-domain verification according to AFTES



zone of high axial force requirement for low eccentricity (crack control)

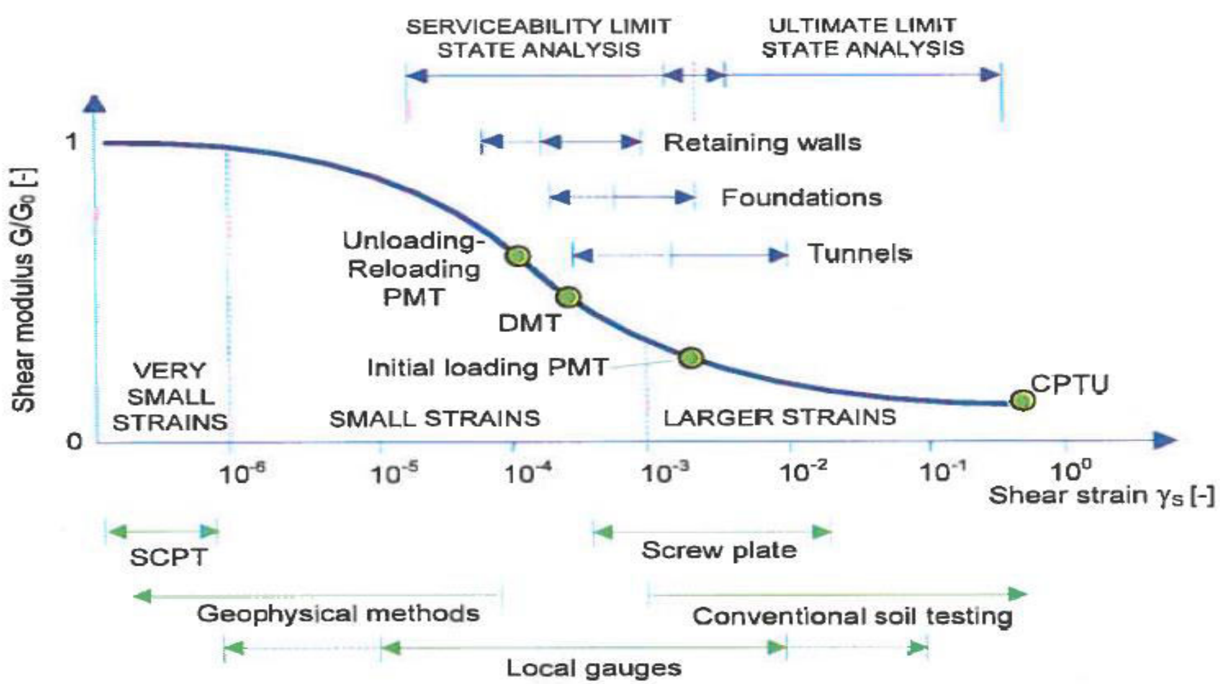
Conclusion: *In competent rock mass conditions (E=1GPa), an unreinforced lining may be sufficient, even in areas of high seismicity*

4. Some critical thoughts about the appropriate value of the rockmass stiffness modulus to be used in the design of unreinforced concrete tunnel linings

- The use of F.E. analysis has become widespread and popular in tunnelling, as means of controlling and optimizing design tasks
- F.E method is extremely powerful in stress – strain predictions
- The quality of any stress – strain prediction (with F.E methods) depends on the adequate model being adopted (rockmass constitutive model)
- More realistic prediction of rockmass movements requires the adoption of a non-linear stress – strain relation, before reaching the ultimate state
- Non-linear elasticity, characterized by strong variations of rockmass stiffness, which depend on the magnitude of strain levels occurring during construction stages

- In tunnelling design, pre-failure rockmass stiffness plays a crucial role in predicting the complete behavior of tunnels and their surrounding rockmass in Serviceability Conditions
- Characteristic Rockmass stiffness (G) vs shear strain curves must be derived
- These curves can be determined on the basis of reliable and accurate in-situ testing and conventional laboratory testing
- In situ testing methods: Seismic & Geophysical methods, Dilatometer tests(DMT), Pressuremeter tests (PMT)
- Conventional laboratory testing: UCS with stiffness measurement

Typical representation of rockmass stiffness variation as a function of the shear strain amplitudes



Rock mass stiffness for tunnel design in Serviceability conditions

- Proposed Rock mass stiffness value measured in dilatometer tests and in the initial loading cycles of pressuremeter tests
- Proposed Rock mass stiffness value at the range of shear strain: 0.5×10^{-3} to 10^{-3}

Conclusions

- The concept of the “unreinforced concrete tunnel final lining” is not a prohibitive one
- During the recent years, a significant number of motorway and railway tunnels with unreinforced concrete final linings have been constructed successfully
- Eurocode 2 EN 1992 – 1 / Section 12 and AFTES Recommendations, provide the necessary design code framework for the design of unreinforced concrete tunnel final linings
- The structural integrity of the unreinforced concrete tunnel linings has been verified for the case of competent rock masses with Em > 800MPa – 1000MPa, even in areas of high seismicity and irregular topography

Conclusions

- Unreinforced concrete tunnel linings in rock masses with 300MPa < Em ≤ 800MPa may exhibit significant cracking, in combination with spalling
- Unreinforced concrete tunnel linings of typical thickness 30cm to 40cm in rock masses with Em≤ 300 MPa are characterized by high risk of concrete crushing. **Must be avoided**.
- At tunnel portals, as well as in areas of nearby or crossing active faults, the unreinforced concrete tunnel linings **must be avoided**
- Proposed Rock mass stiffness value at the range of shear strain: $0.5x10^{-3}$ to 10^{-3} (from in-situ dilatometer and pressuremeter testing results)

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