IV

MTiG International Workshop

Modern Trends in Geomechanics — Assisi, 16-18 May 2016

Seismic behaviour of tunnels in sand

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Seismic Behaviour of Tunnels and Underground Structures

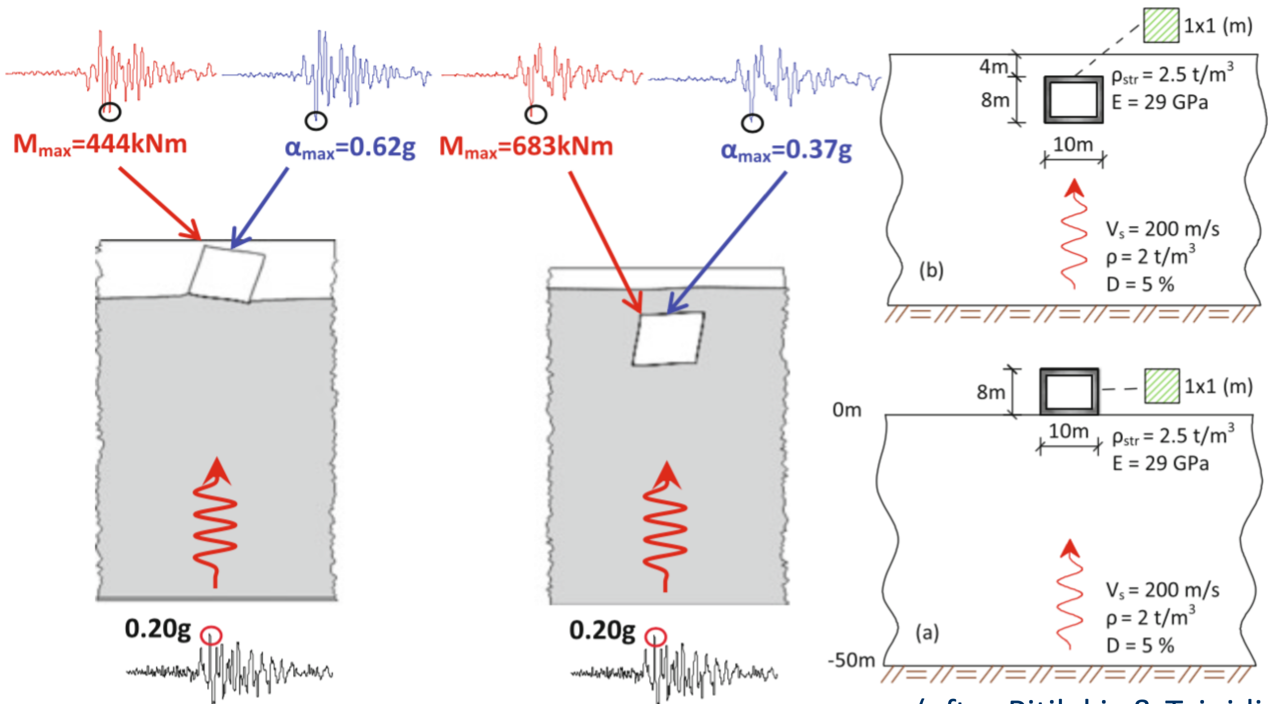
General statements

Ground shaking due to wave propagation and permanent ground displacements due to lateral spreading, landslides and fault rupture are affecting underground structures during a strong earthquake.

- these structures include **tunnels** and **pipelines**;
- the failure patterns of underground structures are attributed both to **transient** and **permanent seismic ground displacements**;
- a common feature of these structures is their **high flexibility** and **small mass**, compared to surrounding soil.

General statements

Seismic behaviour of tunnels is very different from above-ground structures.

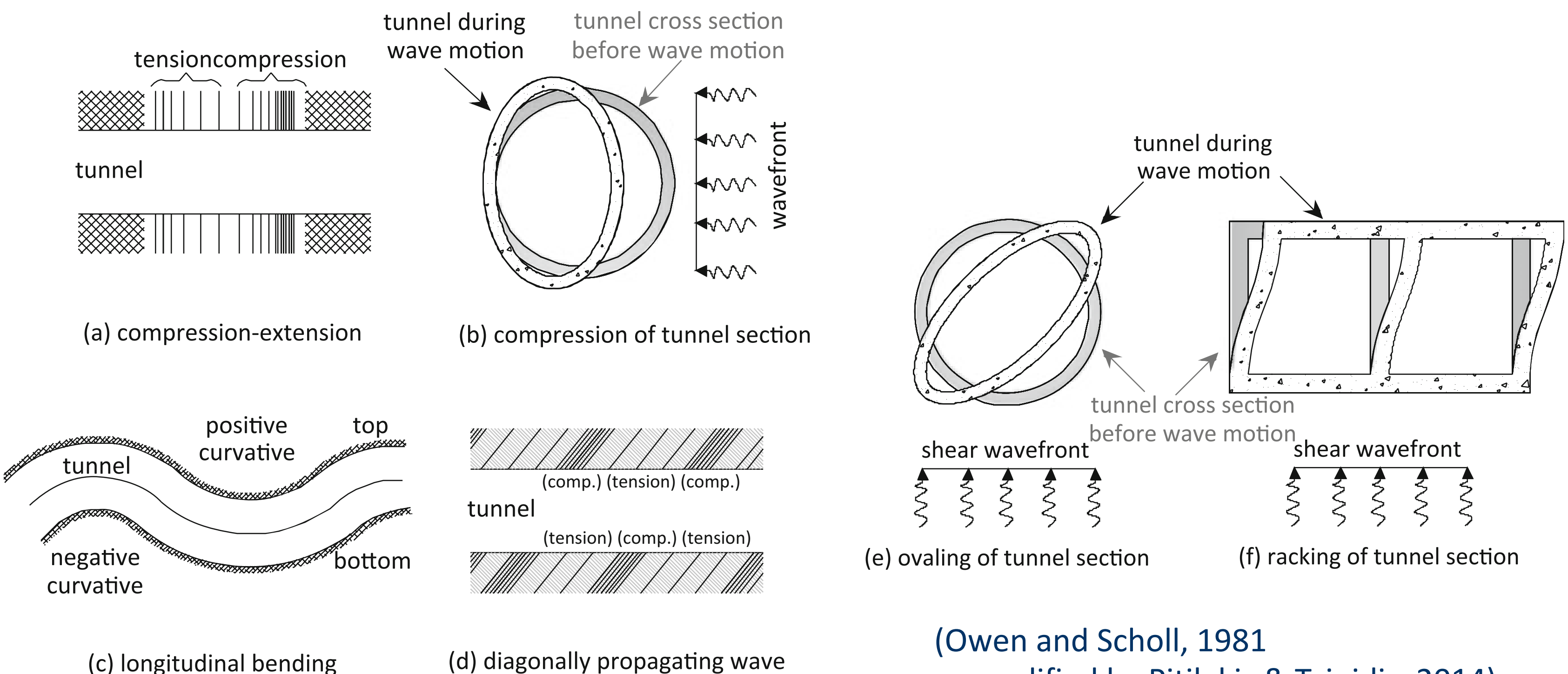


(after Pitilakis & Tsinidis, 2014)

The response of the embedded structure is dominated by the response of the surrounding soil

Deformation patterns

When travelling seismic waves hit an underground structure, they force it to deform in various modes

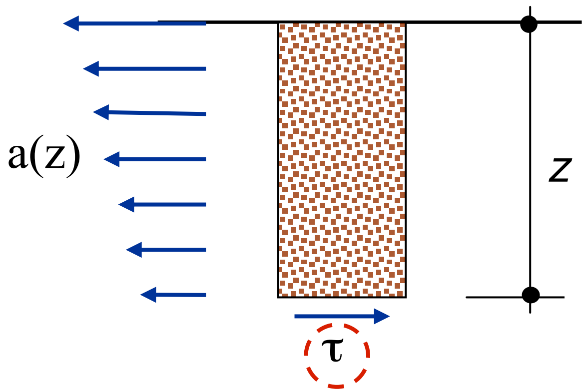


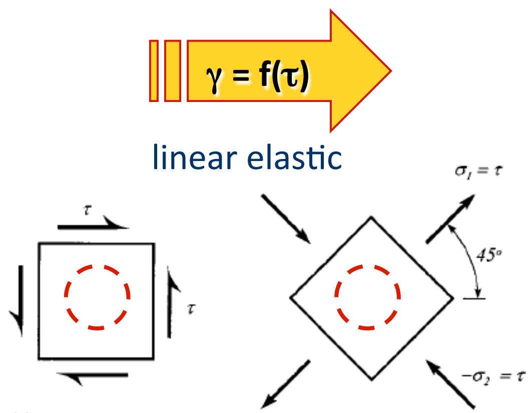
(Owen and Scholl, 1981
as modified by Pitilakis & Tsinidis, 2014)

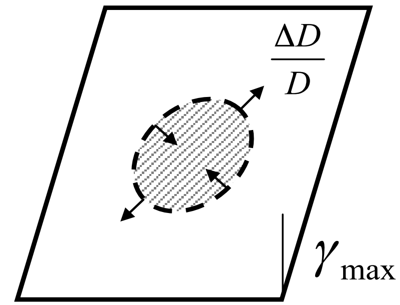
Increments of internal forces in transverse section

Closed-form solutions accounting for ovalisation

(Wang, 1993; Penzien & Wu, 1998; Penzien, 2000)



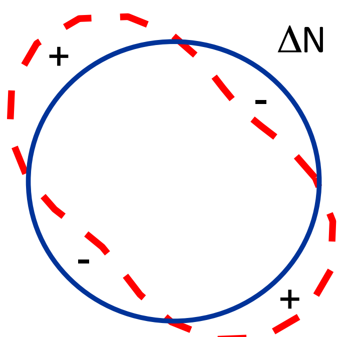




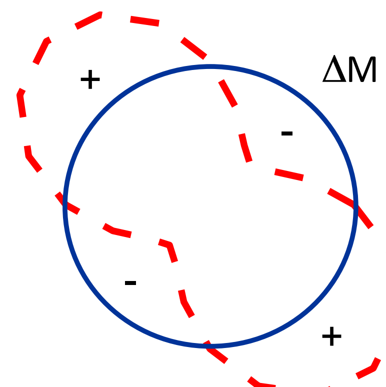
$$F = \frac{E_s\left(1 - \nu_l^2\right)R^3}{6E_l I_l\left(1 + \nu_s\right)}$$

'full slip' *vs.* 'no slip'

$$\frac{\Delta N_{max}}{\tau_{max} \cdot D} = K_N\left(F, \nu_s\right)$$



$$\frac{\Delta M_{max}}{\tau_{max} \cdot D^2} = K_M\left(F, \nu_s\right)$$



Seismic Behaviour of Tunnels

Soil-structure interaction

It is regulated by two crucial factors:

- the soil-lining relative flexibility;
- the interface at the contact between the lining and the ground.

during seismic shaking both factors may change due to the

non-linear behaviour of soil

(shear stiffness and strength)

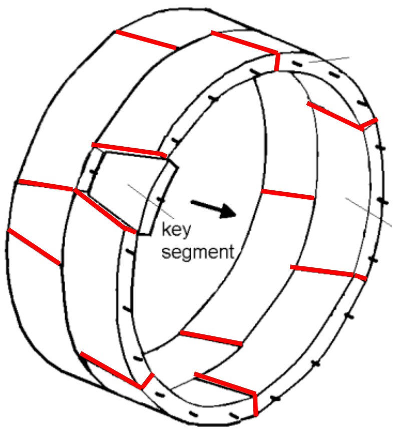
Is an ‘equivalent linear approach’ enough to predict the increase of structural demand in the lining?

Seismic Behaviour of Tunnels

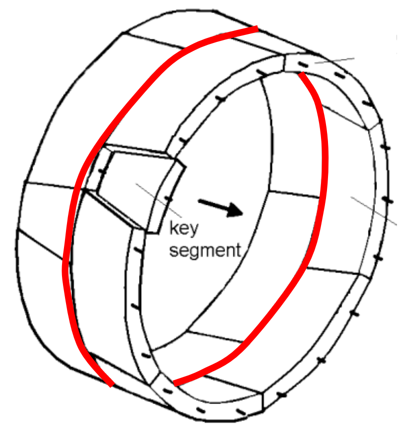
Segmental lining

Mechanised excavation → segmental lining

Longitudinal joints

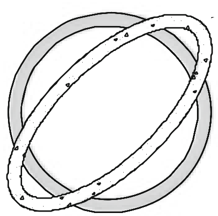


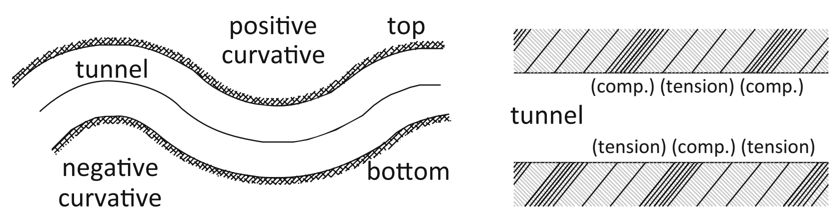
Transverse joints



Ovalization of transverse section → opening of longitudinal joints

Bending in longitudinal direction → opening of transverse joints





→ watertightness issues

Seismic Behaviour of Tunnels in Sand

Outline

- Non-linear and irreversible behaviour of soil
    - experimental and numerical evidences in plane strain
    - effects of tunnel excavation in 3D conditions
- Influence of the jointed pattern of a segmental lining
    - influence of longitudinal joints on the internal forces
    - fragility of a segmental lining

Experimental benchmark

(*Round Robin on Tunnel Test, cf. Bilotta et al., 2014)

Centrifuge tests (→ RRTT*)

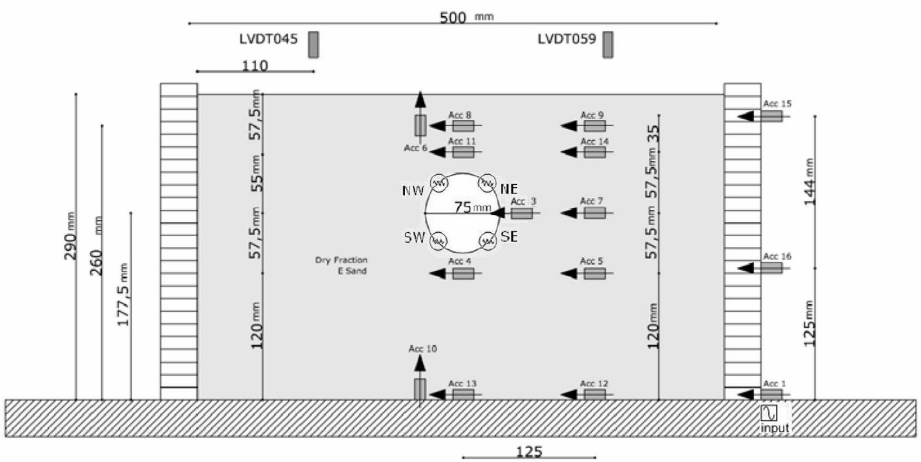
centrifuge spin N = 80

test	diameter, D P [M]	layer thickness, z P [M]	cover, C P [M]	relative density, Dr (%)
T1	6 m [75 mm]	23.2 m [290 mm]	6 [75]	75
T2	6 m [75 mm]	23.2 m [290 mm]	6 [75]	40
T3	6 m [75 mm]	23.2 m [290 mm]	12 [150]	75
T4	6 m [75 mm]	23.2 m [290 mm]	12 [150]	40

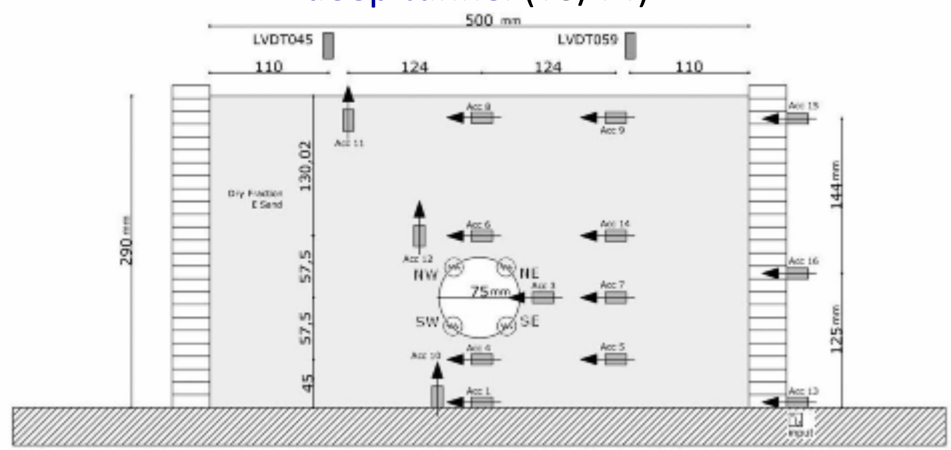
Tube thickness: 0.5 mm
(≈ 6 cm shotcrete lining)

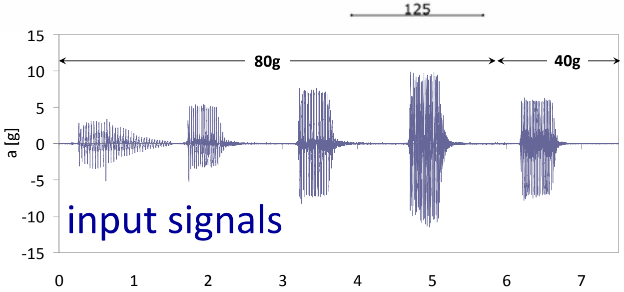
Soil:
dry Leighton Buzzard Sand
(fraction E)

shallow tunnel (T1/T2)



deep tunnel (T3/T4)





Accelerometer with a sensing direction towards left

LVDT

strain gauge

reference accelerometer recording input signal

input

(Lanzano et al., 2012)

Numerical modelling

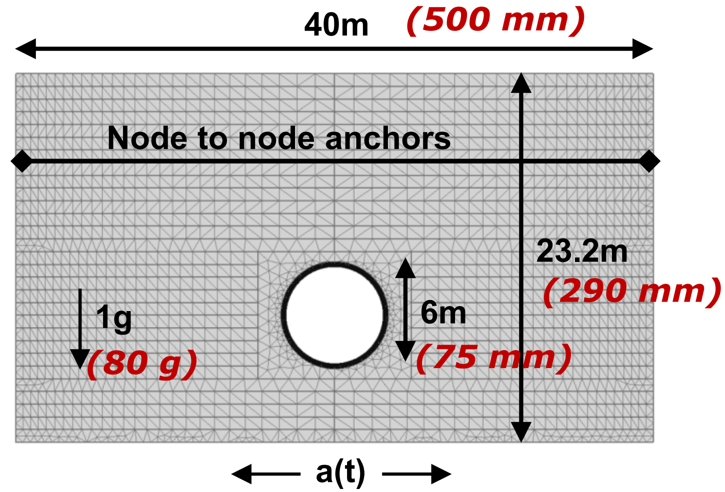
Plane strain models

Plaxis 2D (Brinkgreve et al. 2011).

elasto-plastic with strain hardening model
(Schanz et al, 1999)
+
small strain overlay (Benz et al. 2009)

Hardening Soil with small strain

- *model scale (80g)*
- prototype scale (1g)



3D models

Plaxis 3D (Brinkgreve et al. 2013).

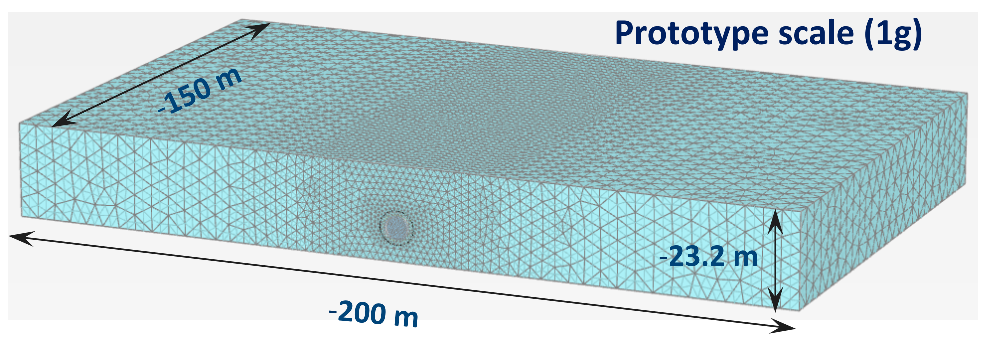
Initial static conditions:

- same initial stress as in centrifuge or
- modelling a typical excavation process.

Input signals:

- same input signals as in centrifuge;
- natural signals.

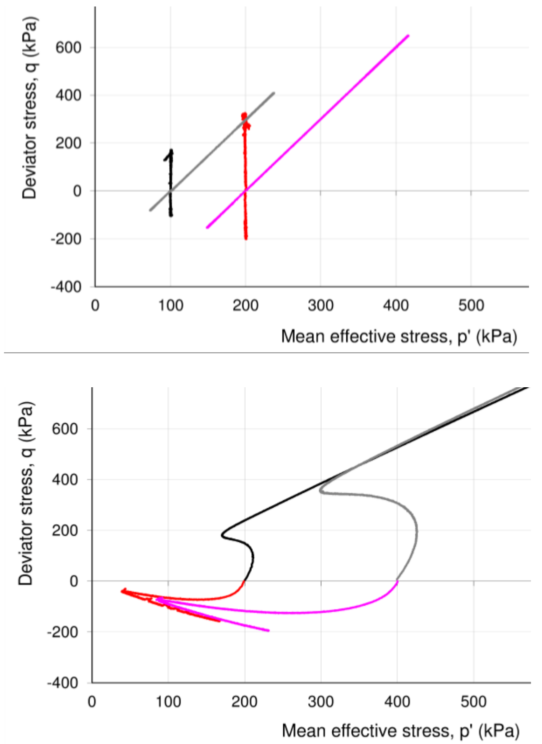
Segmental lining

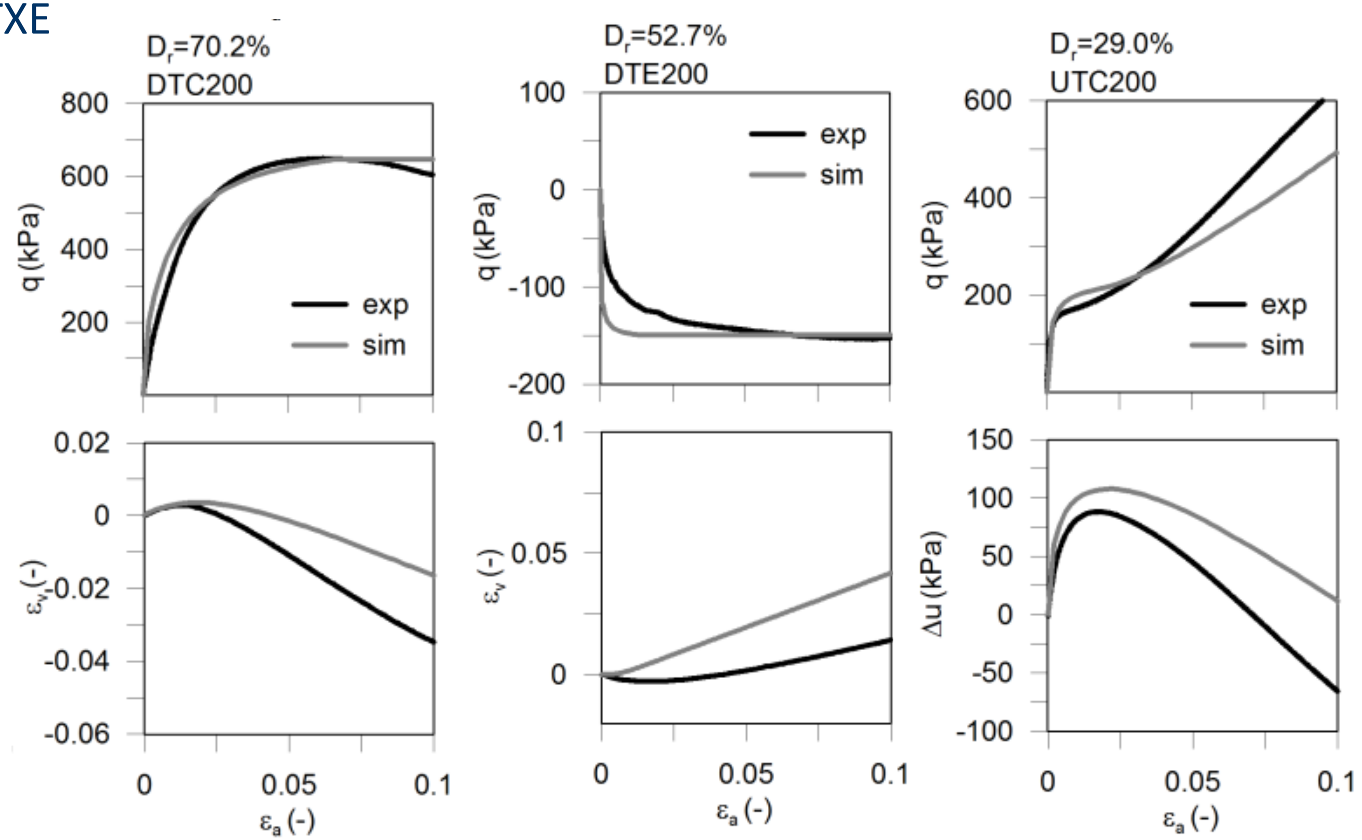


Numerical modelling

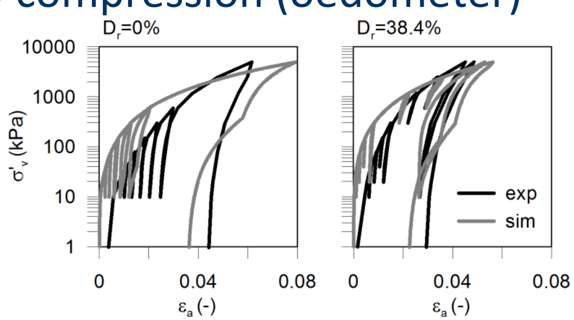
Model calibration

Drained & Undrained TXC/TXE

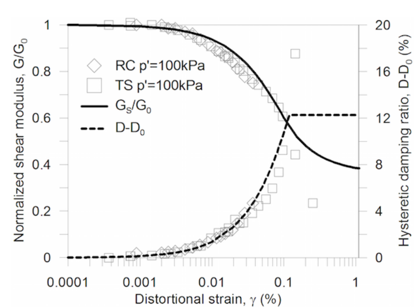




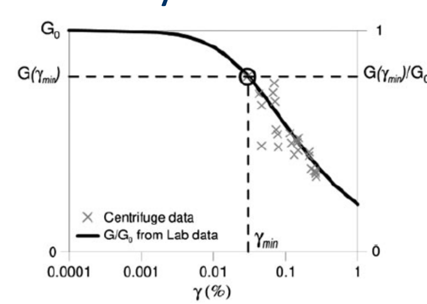
1D compression (oedometer)



RC-TS tests



Back-analysis of centrifuge tests

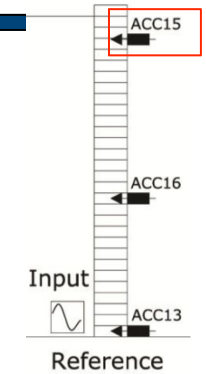


(Lanzano et al., 2016)

Outline

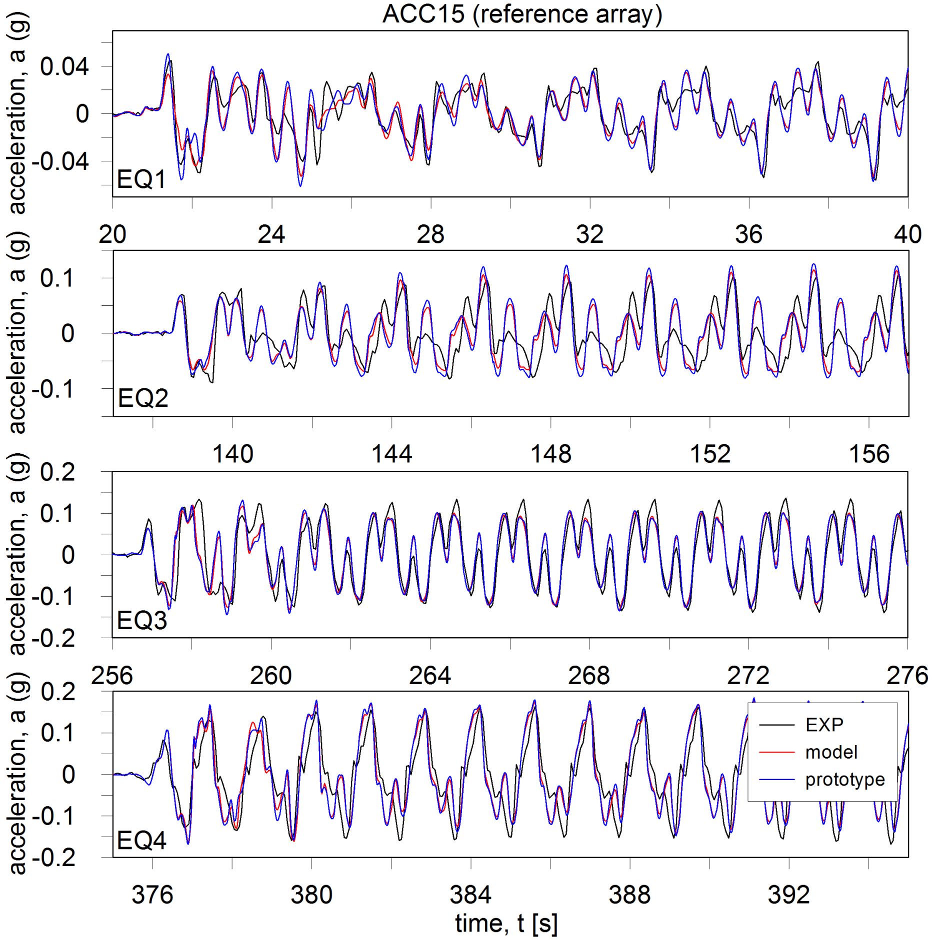
- Non-linear and irreversible behaviour of soil
    - **experimental and numerical evidences in plane strain**
    - effects of tunnel excavation in 3D conditions
- Influence of the jointed pattern of a segmental lining
    - influence of longitudinal joints on the internal forces
    - fragility of a segmental lining

Experimental and numerical evidences in plane strain

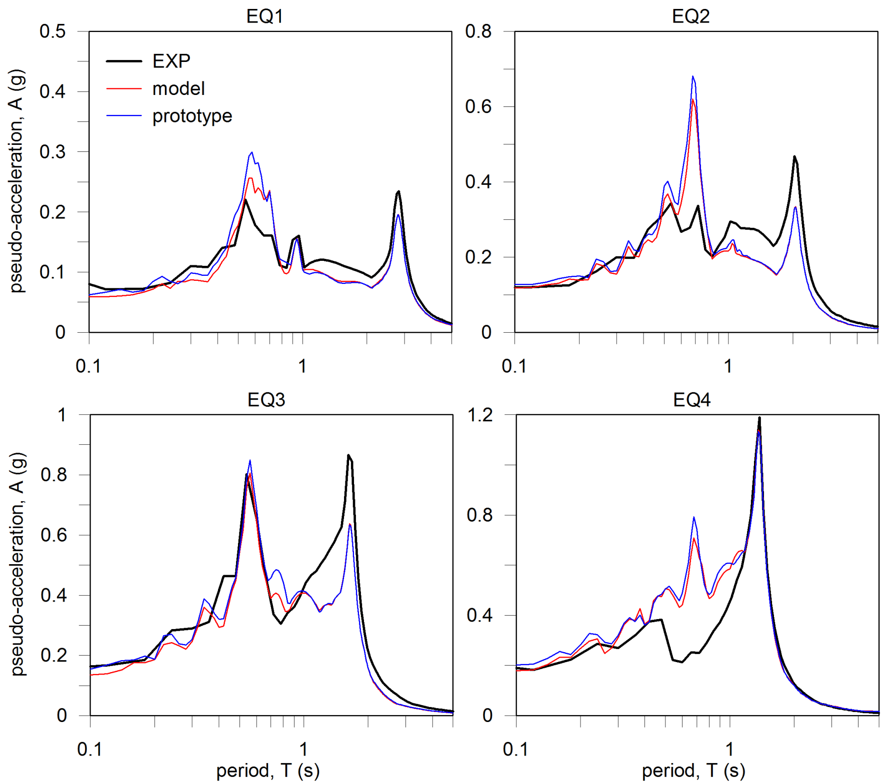


Dynamic amplification

Time histories of acceleration at surface



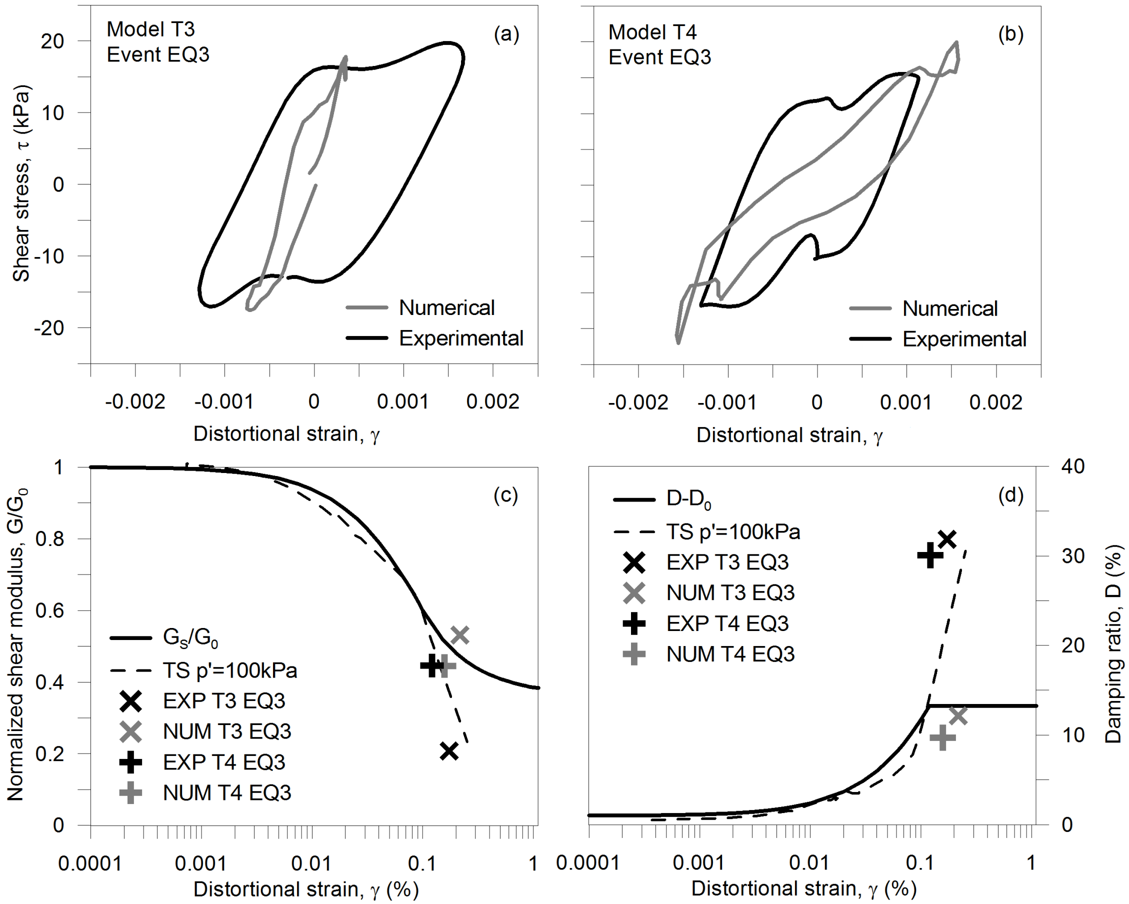
Response spectra



→ the amplification of ground layer is relatively well matched

Experimental and numerical evidences in plane strain

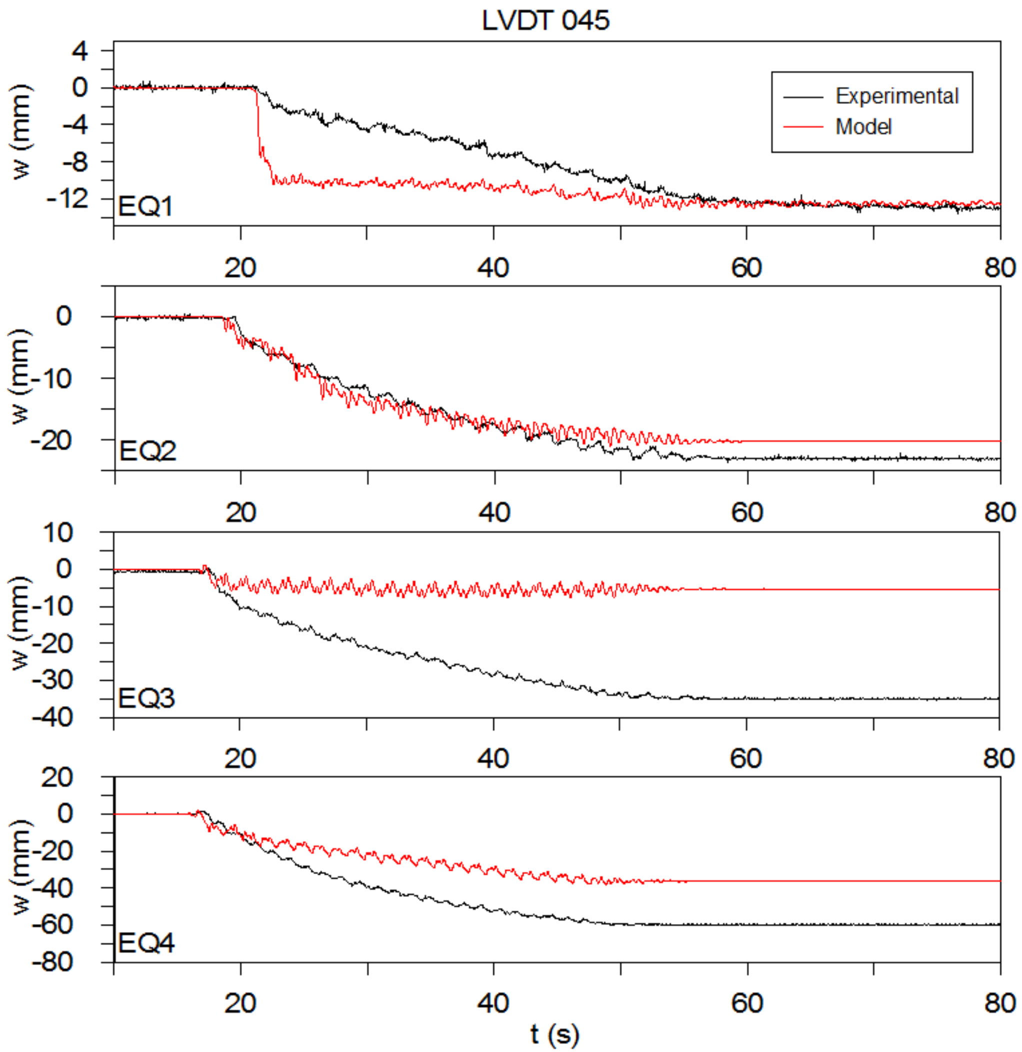
Stress-strain cycle and associated damping and shear stiffness

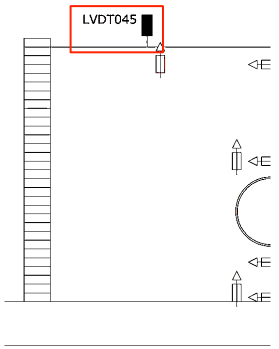


- → shear stiffness is properly modelled overall
- → hysteretic damping is underestimated (cf. Brinkgreve et al., 2007)

Experimental and numerical evidences in plane strain

Surface settlement



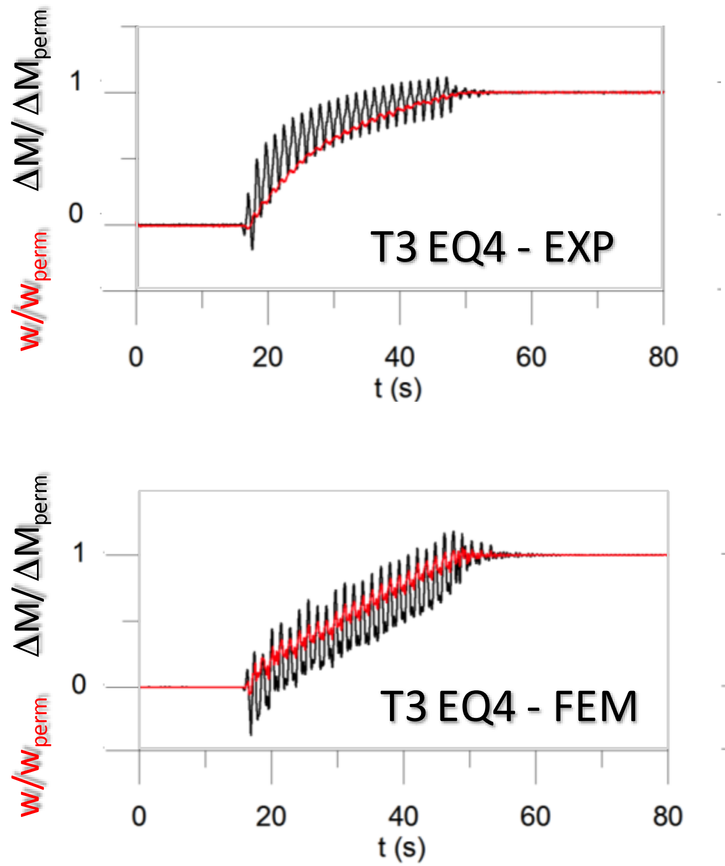


→ permanent volumetric changes (sand densification) are observed

Experimental and numerical evidences in plane strain

Influence of sand densification on internal forces in the lining

$w(t)/w_{perm}$ represents the evolution of densification of the sand layer



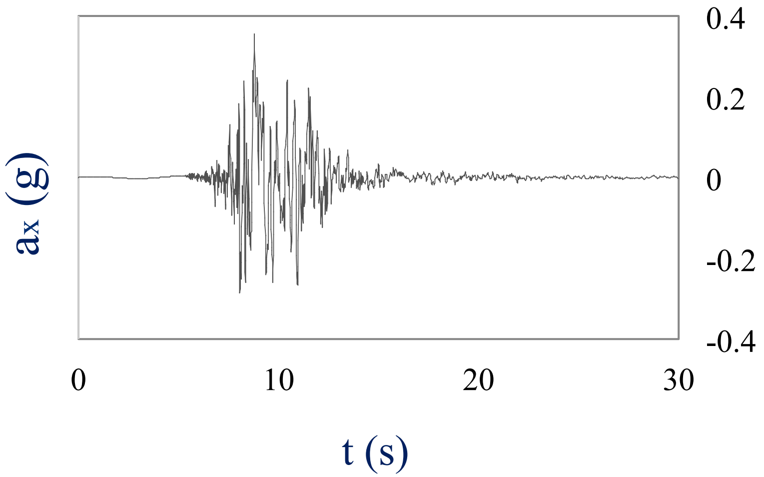
→ permanent changes of internal forces are associated to densification

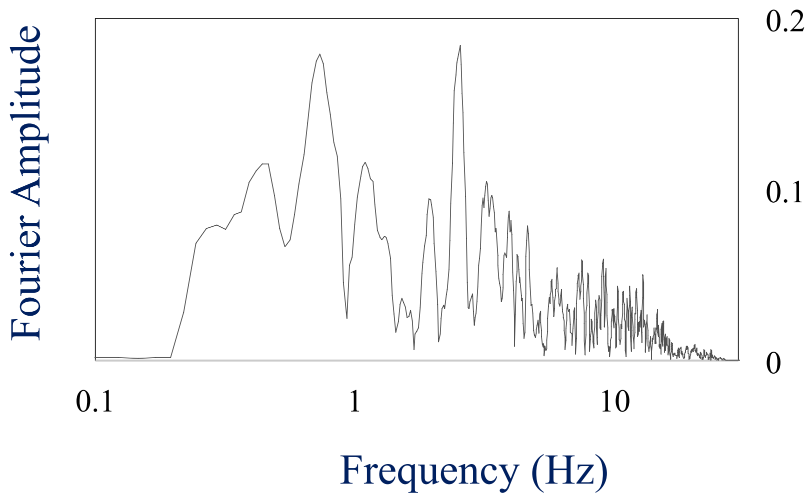
Numerical evidences in plane strain

Input signal

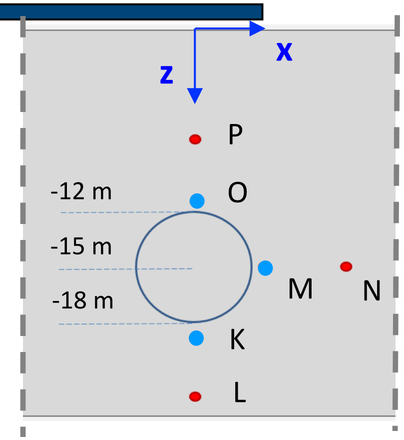
South Iceland (2000), M_w=6.6 from ESD

Scaled to a_{max}=0.35g; f_p =4.2 Hz



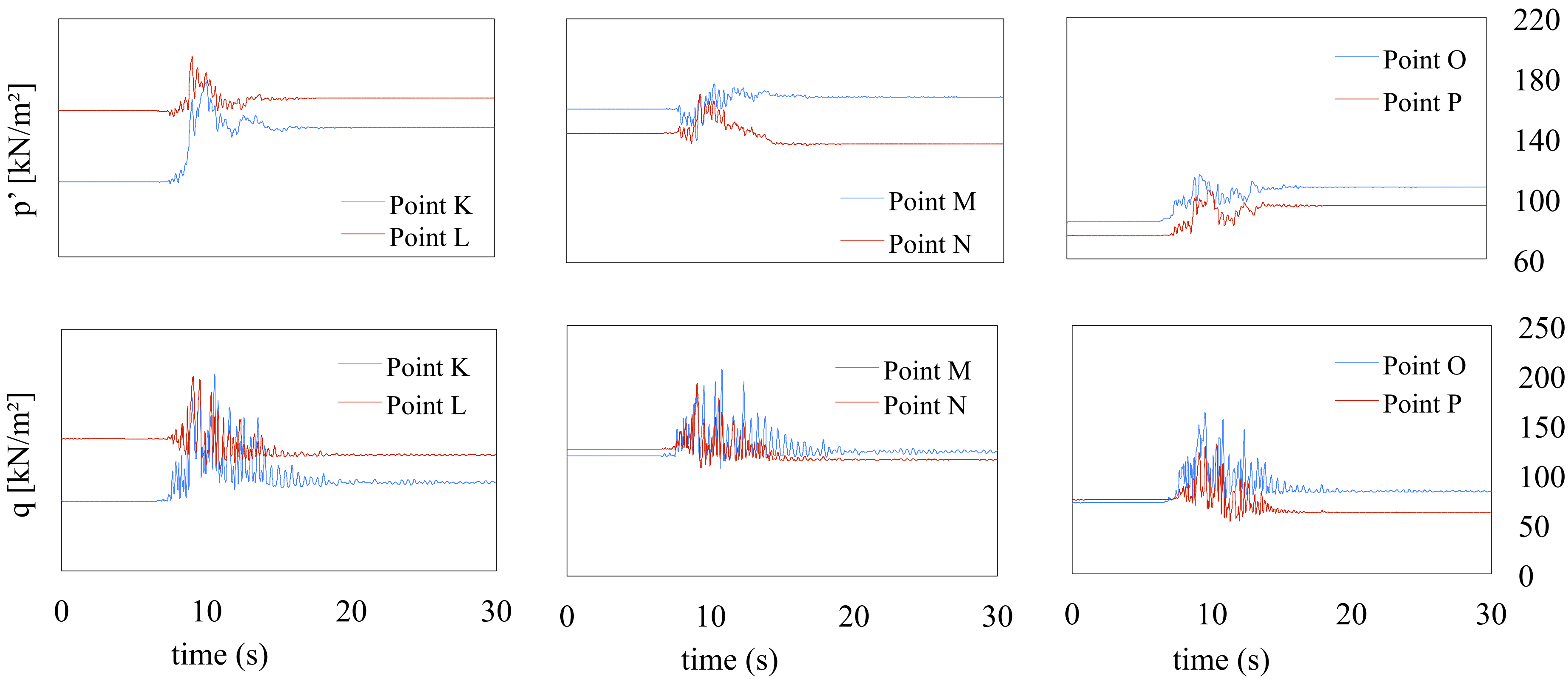


Numerical evidences in plane strain



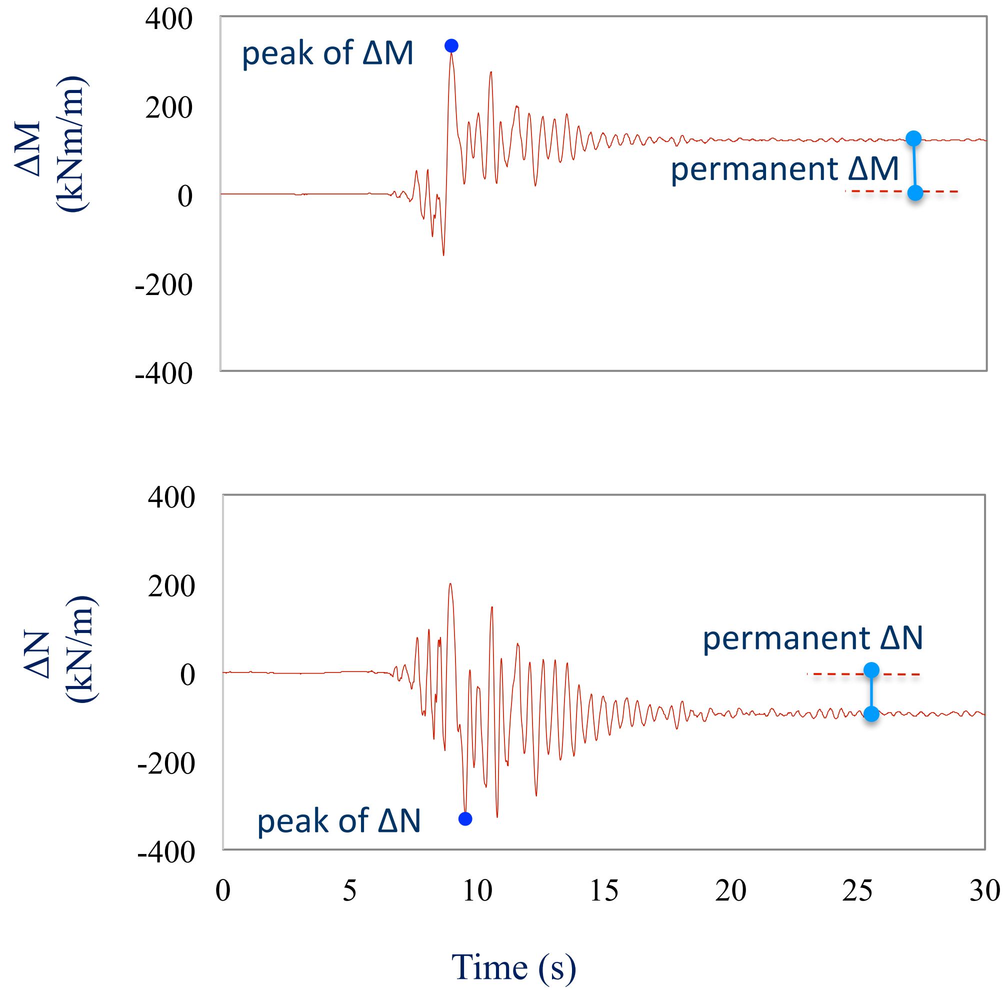
Evolution of stress around the tunnel

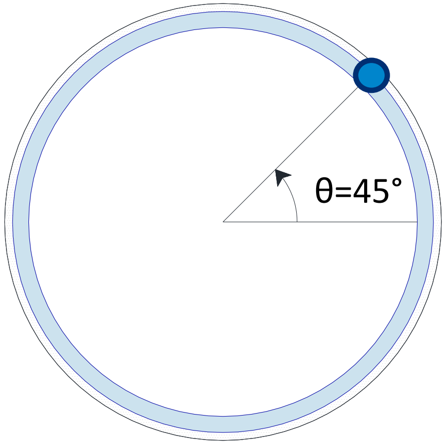
During seismic excitation → redistribution of stresses



Numerical evidences in plane strain

Time histories of changes of internal forces





after seismic excitation → residual changes

Seismic behaviour of tunnels in sand

Experimental and numerical evidences in plane strain

- Permanent changes of internal forces are locked into the tunnel lining
- They are associated to plastic volumetric deformation of soil
- Typical simplified calculations (i.e. Wang, 1993; Penzien & Wu, 1998) are unable to predict permanent changes

Outline

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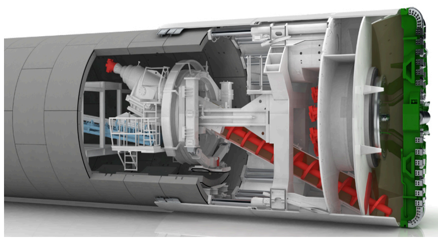
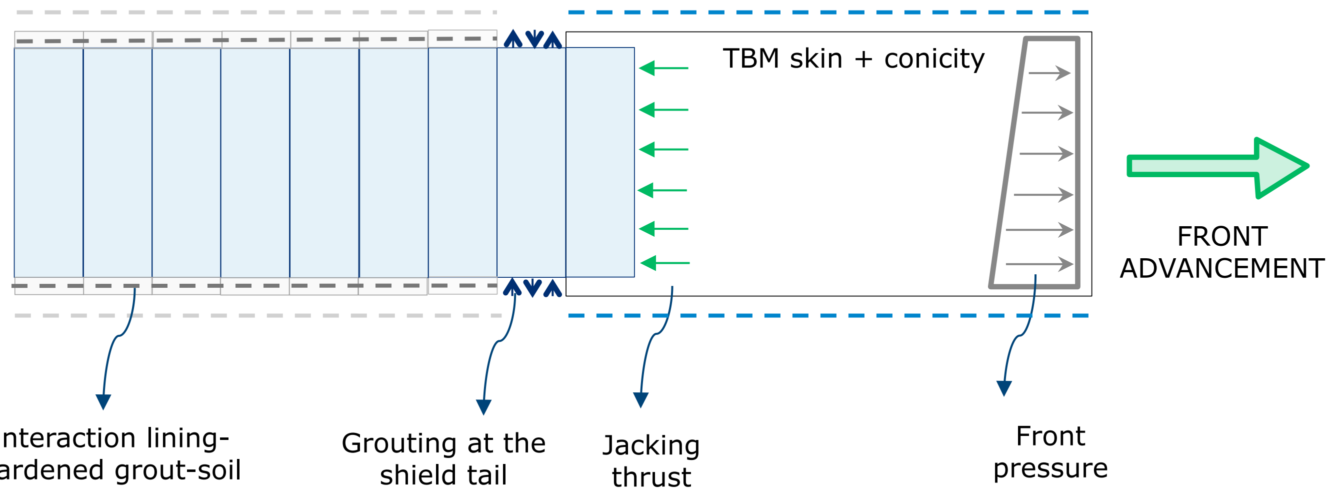
Modelling tunnel excavation in 3D conditions

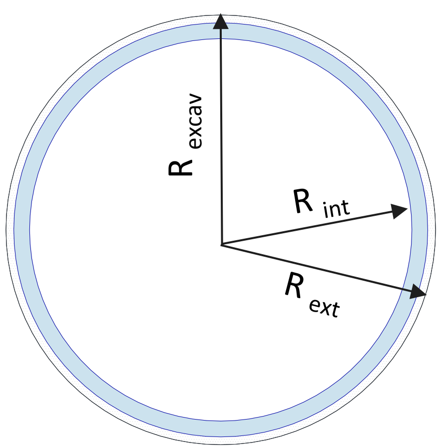
Process of construction of a EPB Tunnel Boring Machine

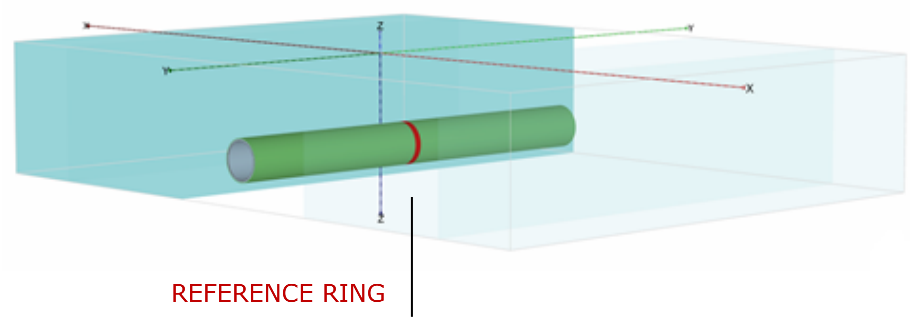




Transverse section

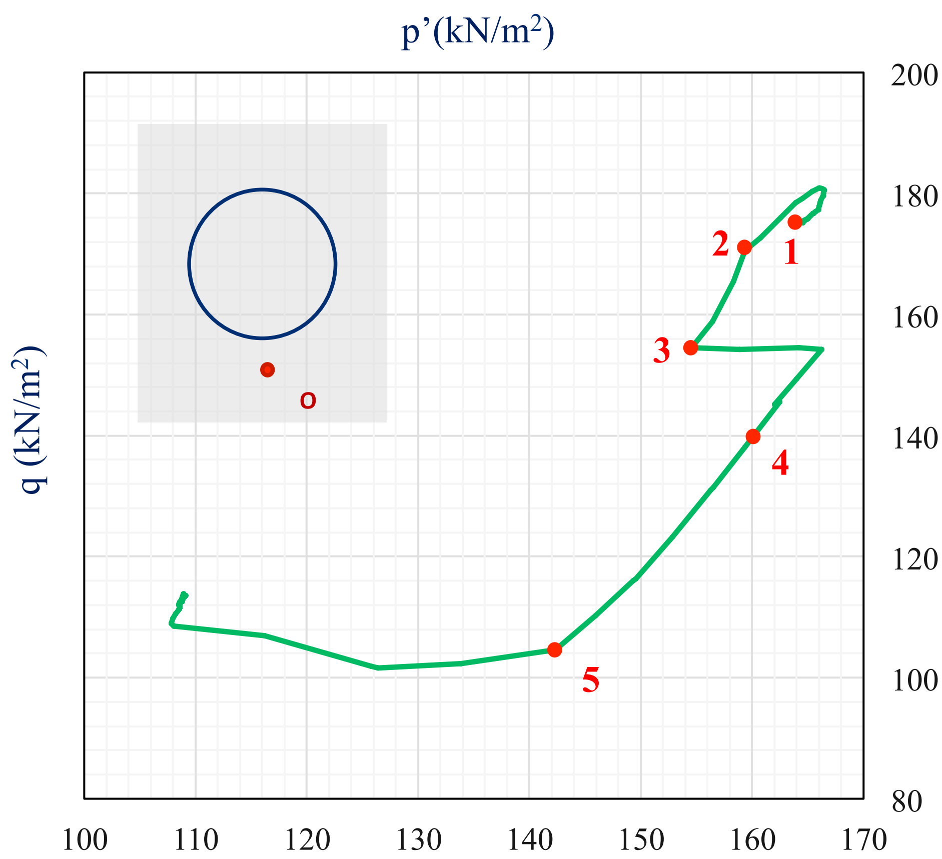
- R_{int} = 3.00 m
- R_{ext} = 3.30 m
- R_{exc} 3.45 m
- t_{lining} = 0.30 m
- t_{grout}= 0.15 m
- E_{cls} = 35 GPa
- E_{grout} = 10 GPa



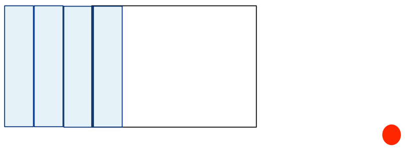


Modelling tunnel excavation

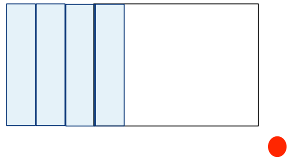
Stress-paths around the tunnel



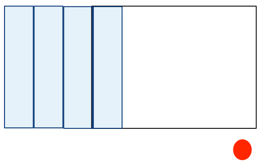
Condition 1 : reference section far from the front



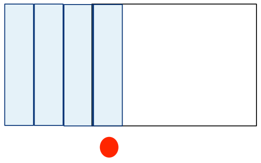
Condition 2 : TBM approaching



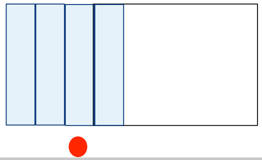
Condition 3 : TBM passing



Condition 4 : ring installation within shield

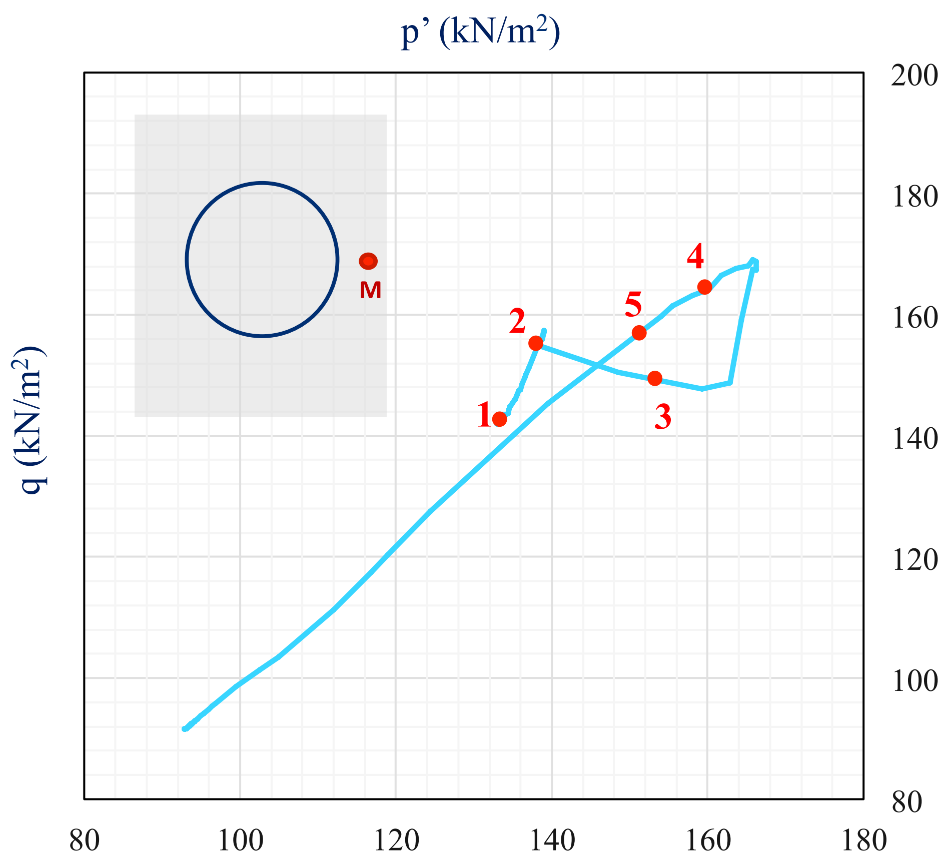


Condition 5 : grout pressure at the shield tail



Modelling tunnel excavation

Stress-paths around the tunnel



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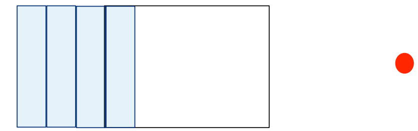

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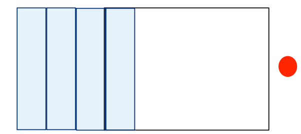

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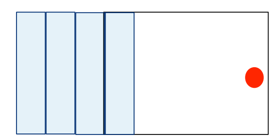

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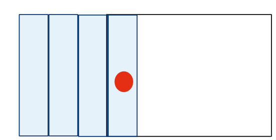

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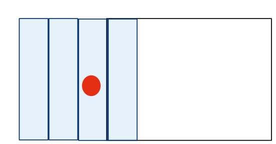
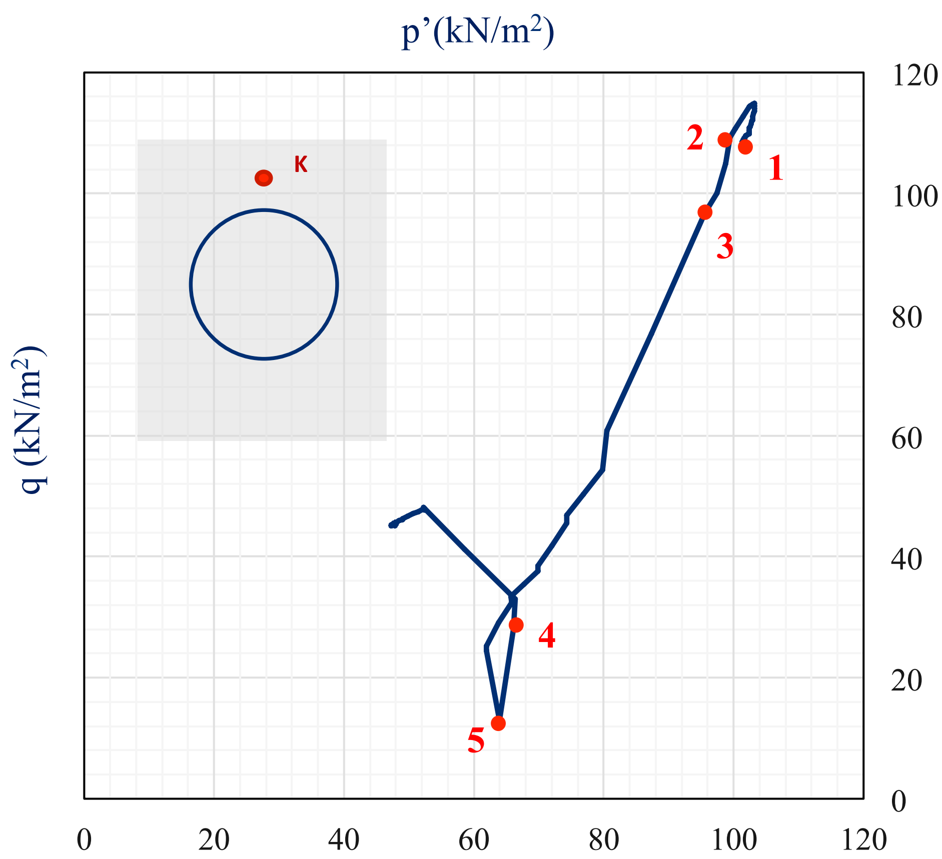
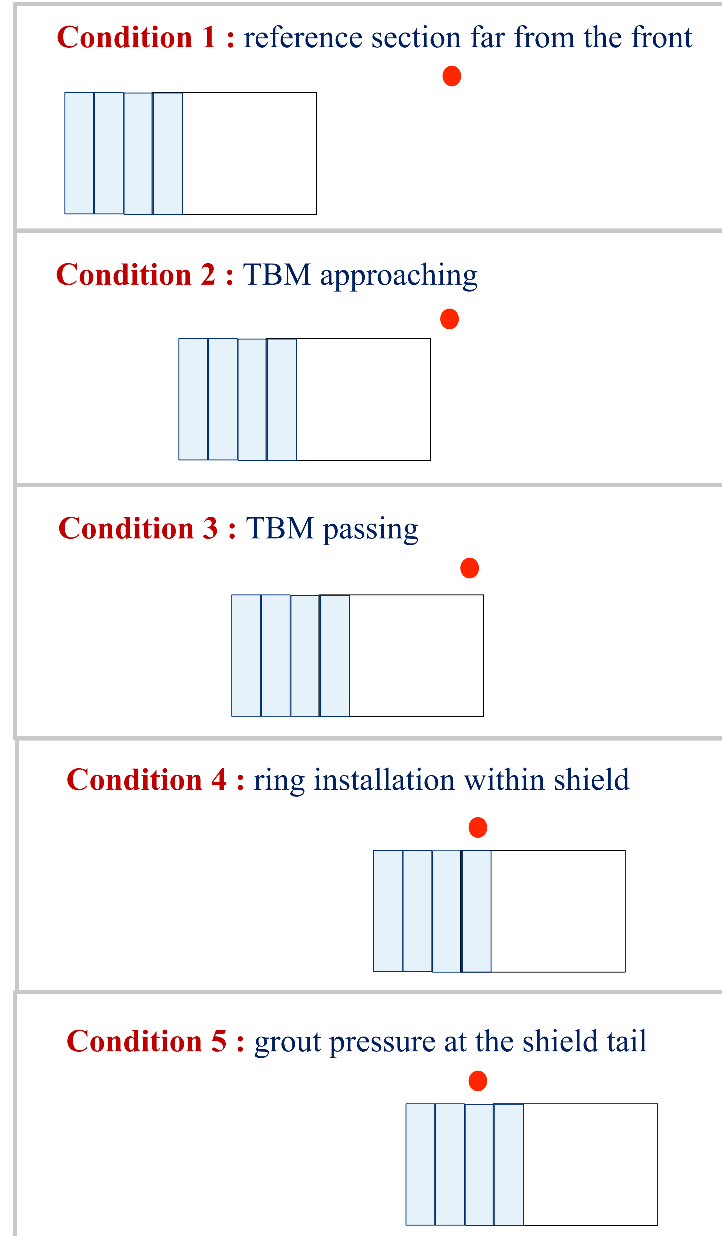


Modelling tunnel excavation

Stress-paths around the tunnel

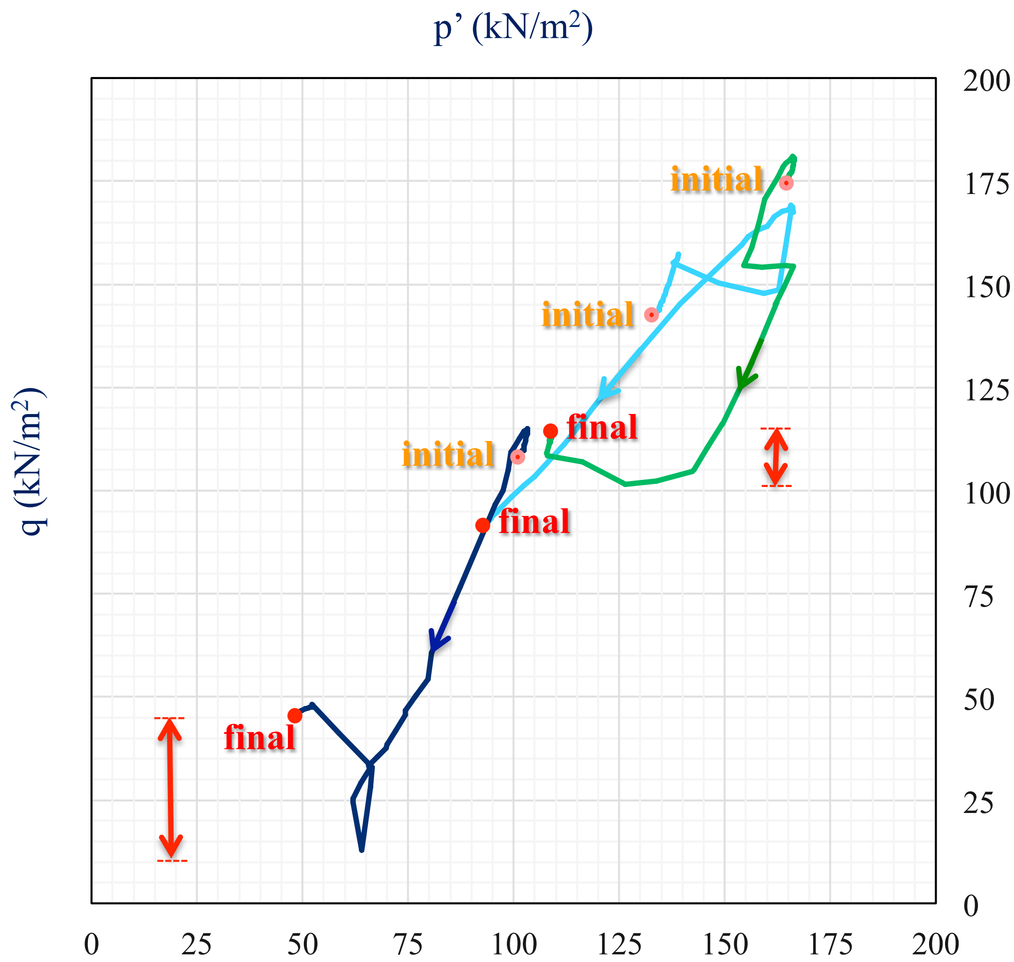


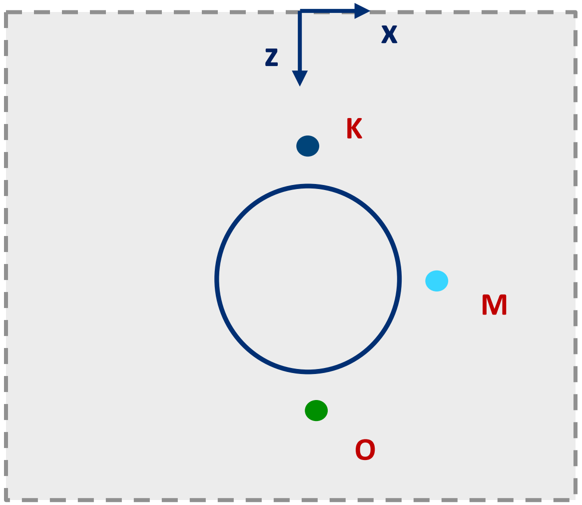


Modelling tunnel excavation

Stress-paths around the tunnel

Before the seismic excitation

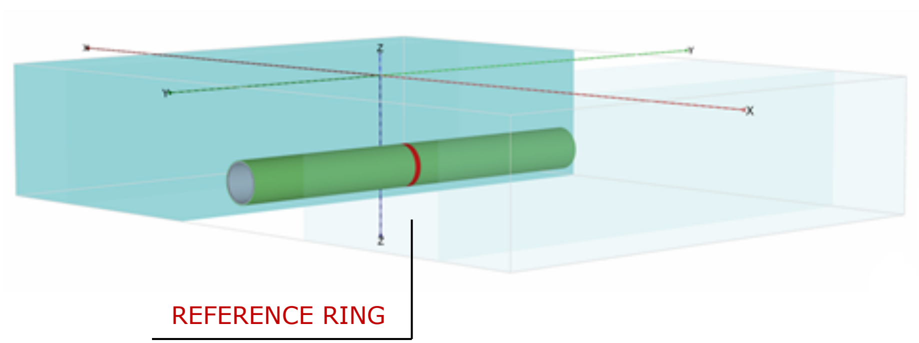


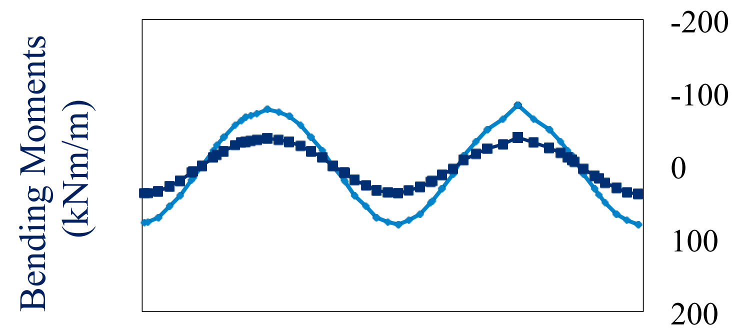


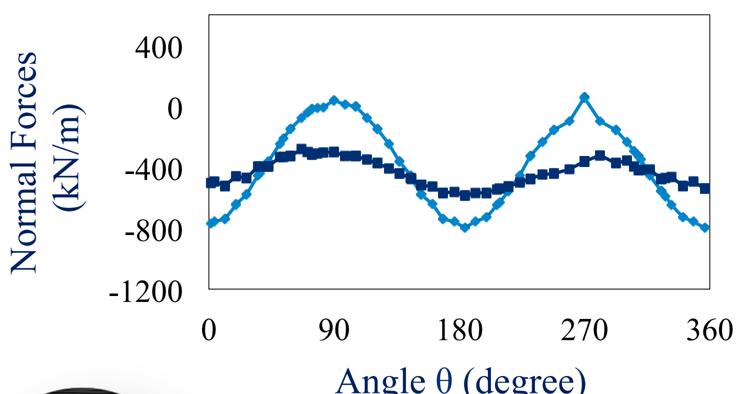
A smaller amount of deviatoric stress is loading the lining ring

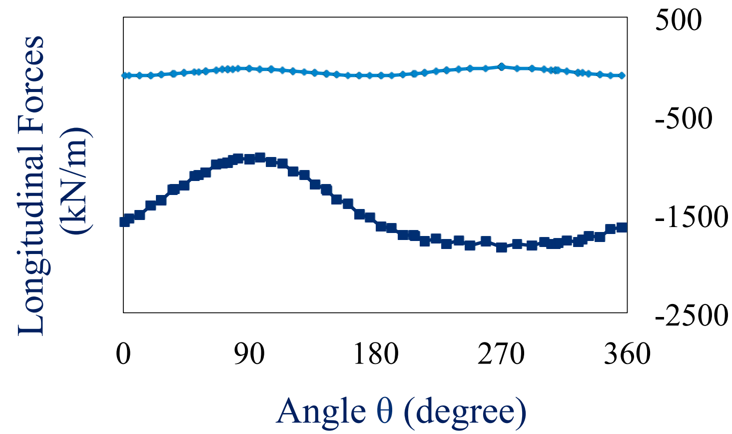
Influence of tunnel excavation

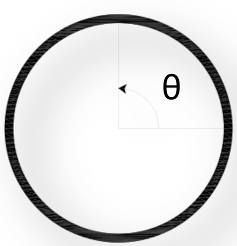
Initial static conditions







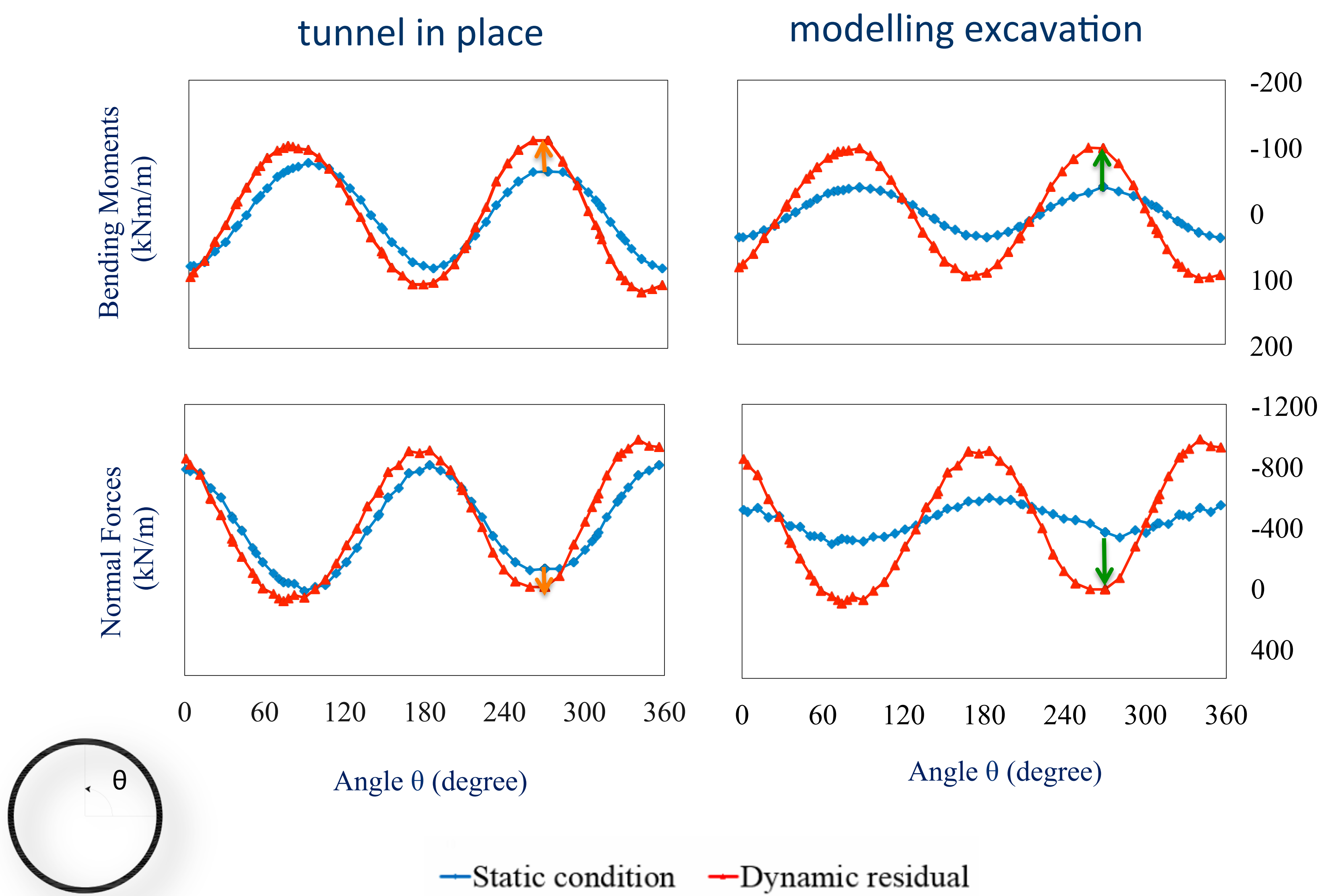




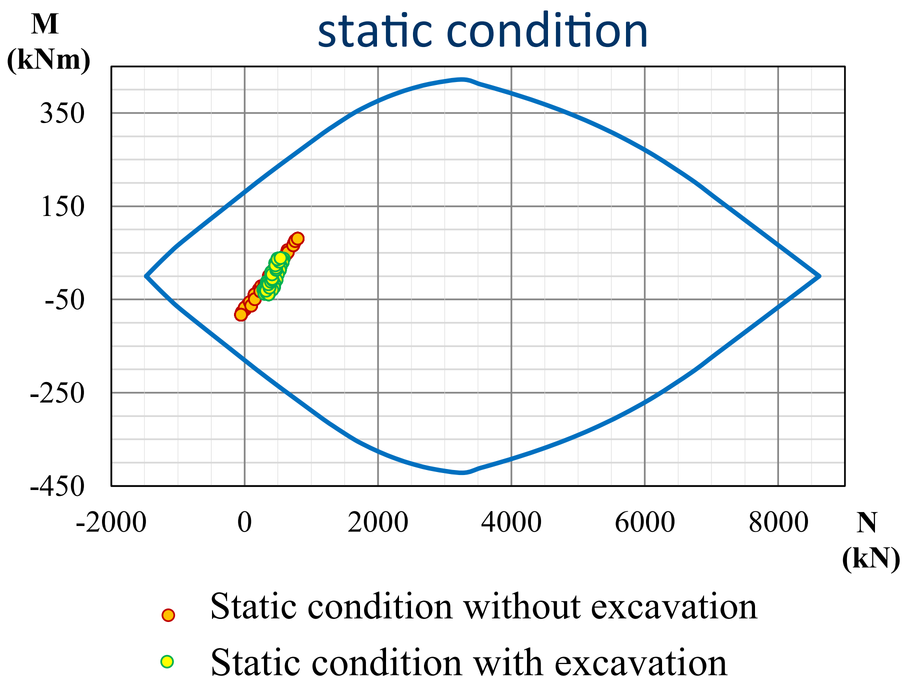
— tunnel in place — modelling excavation

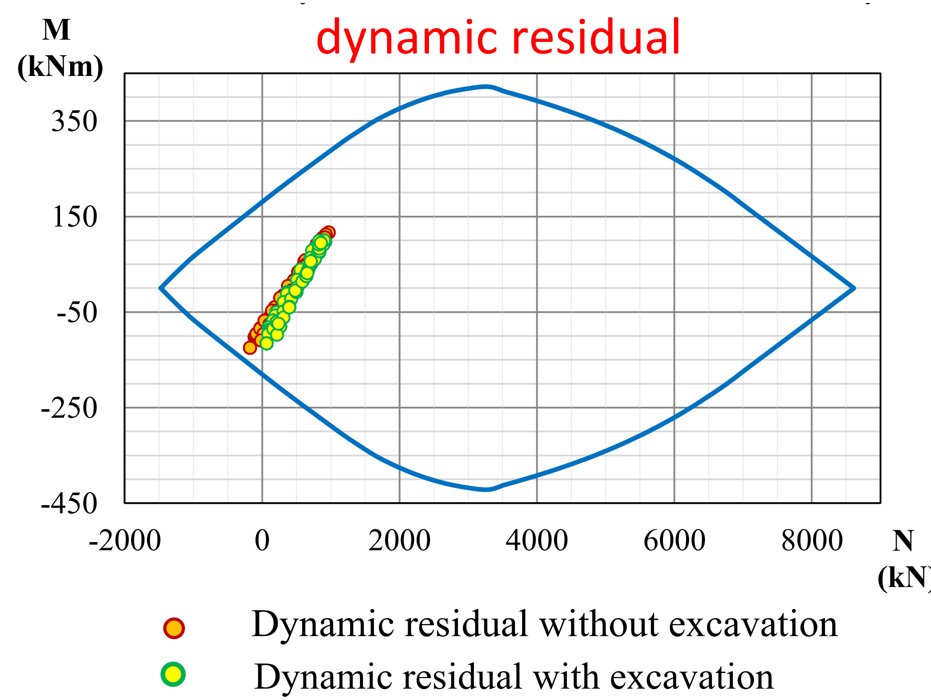
Influence of tunnel excavation

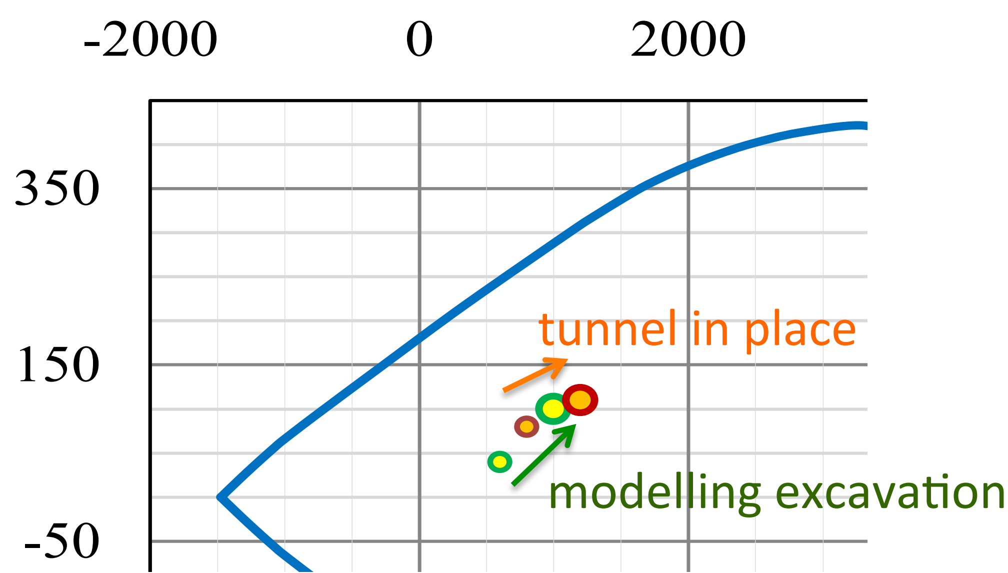
Distribution of internal forces



Influence of tunnel excavation







Section 1500mm x 30mm
Concrete C 35/45
Steel B 450 C

Seismic behaviour of tunnels in sand

Influence of tunnel excavation

- The state of stress around the tunnel lining changes during excavation
- Due to the reduction of deviatoric stress around the lining ring, the static internal forces are less severe
- The changes of internal forces during and after shaking depend on the strain level around the tunnel at the end of the excavation, which affect the relative stiffness.

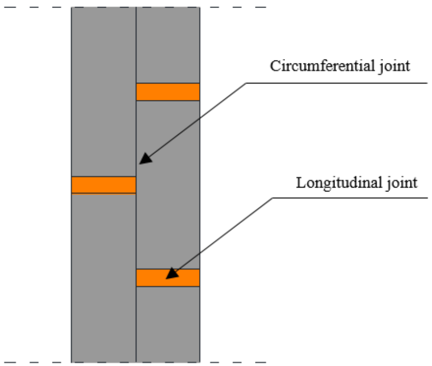
Outline

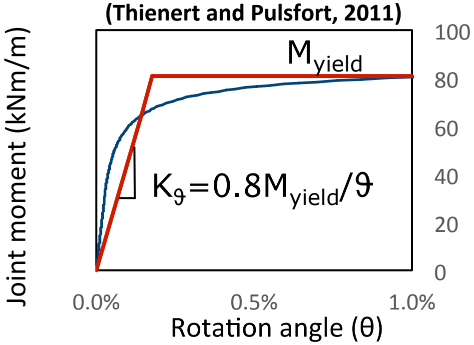
- Non-linear and irreversible behaviour of soil
  - experimental and numerical evidences in plane strain
  - effects of tunnel excavation in 3D conditions

- Influence of the jointed pattern of a segmental lining
  - **influence of longitudinal joints on the internal forces**
  - fragility of a segmental lining

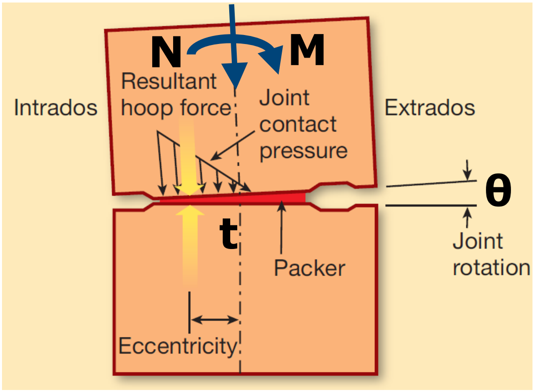
Influence of longitudinal joints on the internal forces

Effects of segmental lining





$$M_{yield} = M\left(\theta = 0.01rad\right) \cong M_{\lim} = \frac{1}{2}N \cdot t$$



(Janssen, 1983)

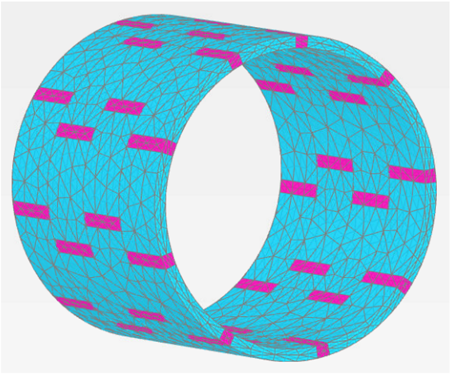
for $e = \frac{M}{N} \leq \frac{t}{6}$

$$\theta = \frac{M \cdot t}{E_c I} = 12\frac{M}{E_c t^2}$$

for $e > \frac{t}{6}$

$$\theta = \frac{8N}{9t \cdot E_c \left(\frac{2M}{N \cdot t} - 1\right)^2}$$

Numerical 3D model



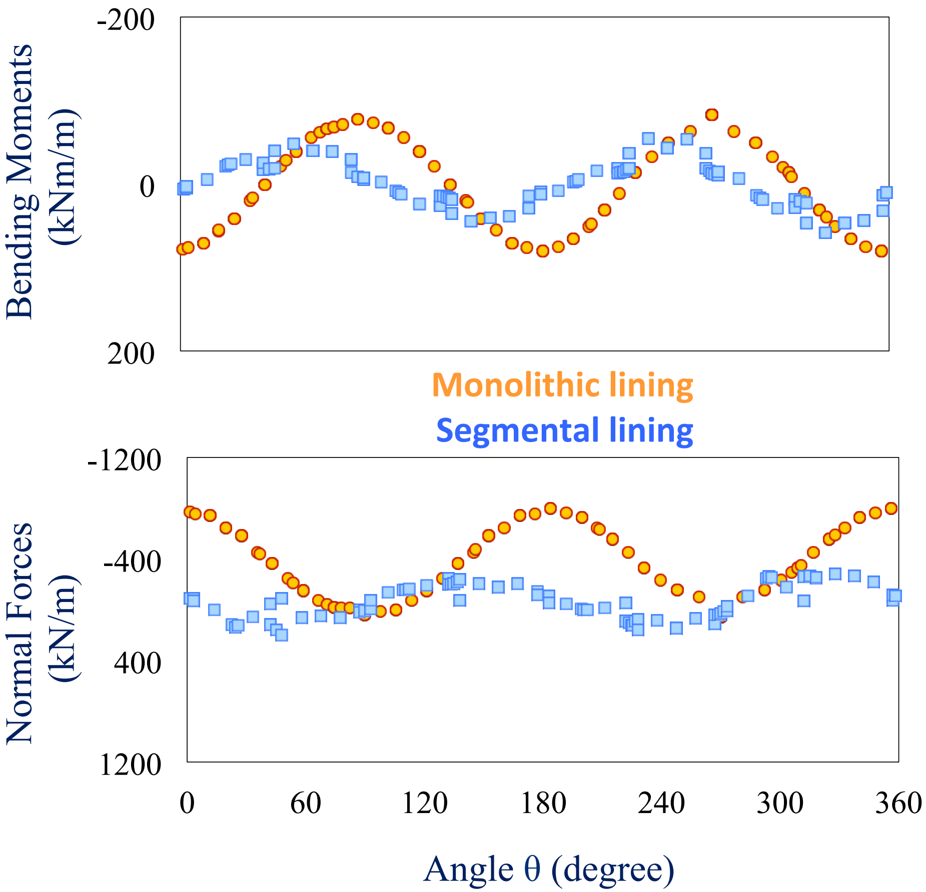
$$E = \frac{K_{\theta} \cdot t}{I}$$

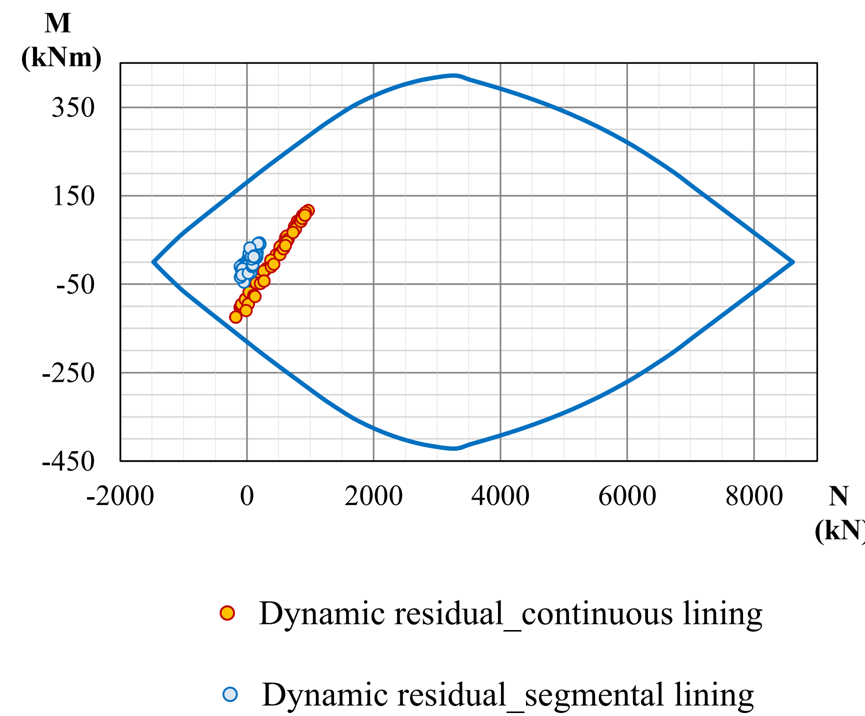
Influence of longitudinal joints on the internal forces

Effects of segmental lining

distribution of internal forces

(residual)





Seismic behaviour of tunnels in sand

Influence of tunnel excavation

- Due to the larger flexibility an compressibility of the assembled ring of lining, the static internal forces are less severe

BUT

- Is the safety level of the structural section (M,N) the only issue of concern?

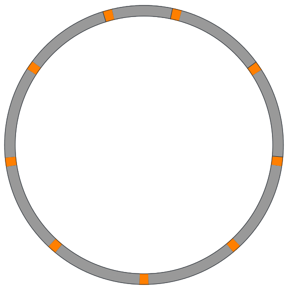
Outline

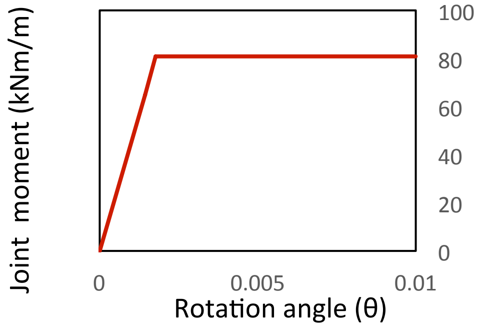
- Non-linear and irreversible behaviour of soil
    - experimental and numerical evidences in plane strain
    - effects of tunnel excavation in 3D conditions

- Influence of the jointed pattern of a segmental lining
    - influence of longitudinal joints on the internal forces
    - **fragility of a segmental lining**

Fragility of a segmental lining

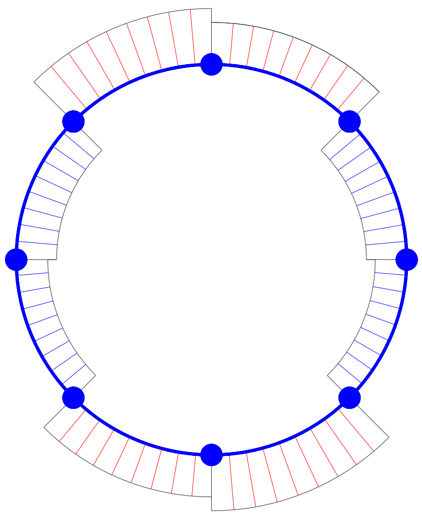
Relative rotation of the joint (2D)

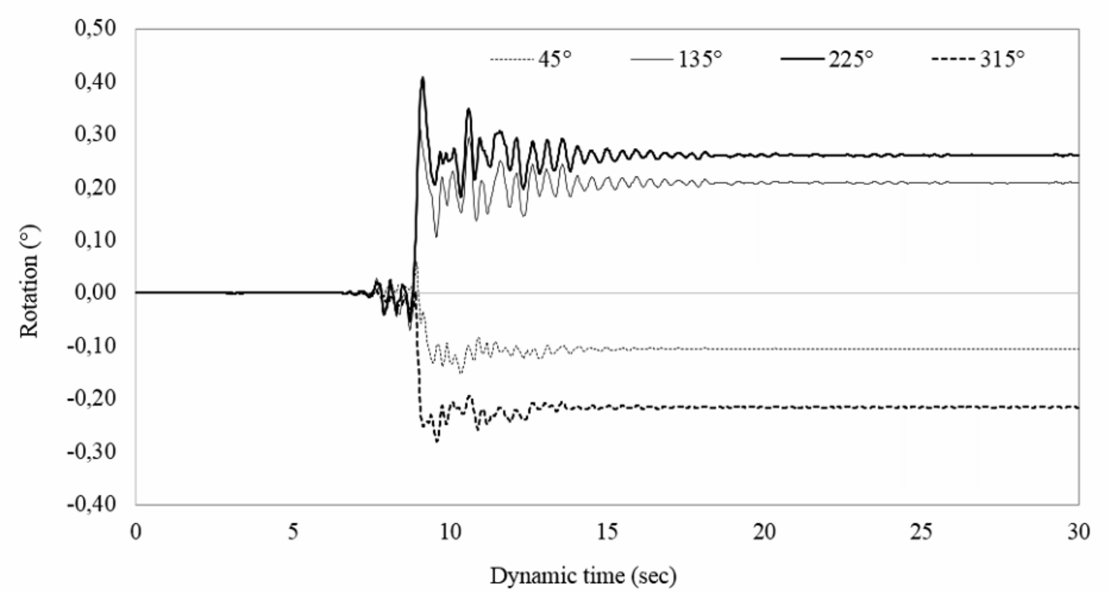




elasto-plastic hinges

distribution of rotation at a generic time during shaking





Time history of rotation at different joints

Summary and Conclusions

Seismic behaviour of tunnels in sand

- The behaviour of tunnel linings under seismic loading is not only an issue of structural mechanics
- The non-linear and irreversible behaviour of soil plays an important role in the interaction problem
- A suitable constitutive model for soil is needed to capture the effect of soil-lining interaction at different stages of the tunnel life (construction and pre-earthquake, during seismic excitation, and post-earthquake), even in rather simple ground conditions

Current trends of research

- 3D layouts of segmental lining
- Seismic wave propagation in different planes
- Ground failure (i.e. liquefaction, fault conditions, slope instability…)

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