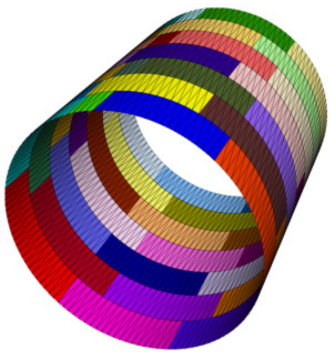
Recent Development in Modeling the Interaction of Segmental Tunnel Lining with surrounding Ground



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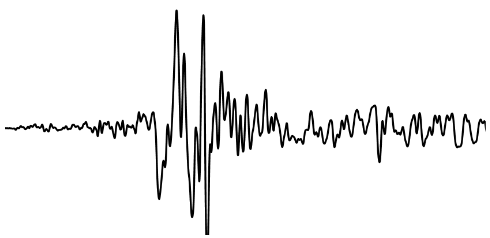
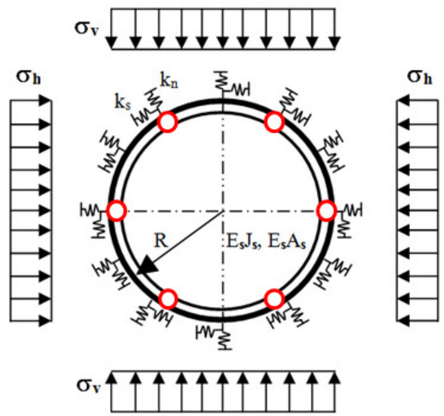




Background and Problematic

- What is segmental lining ?

Precast concrete segments

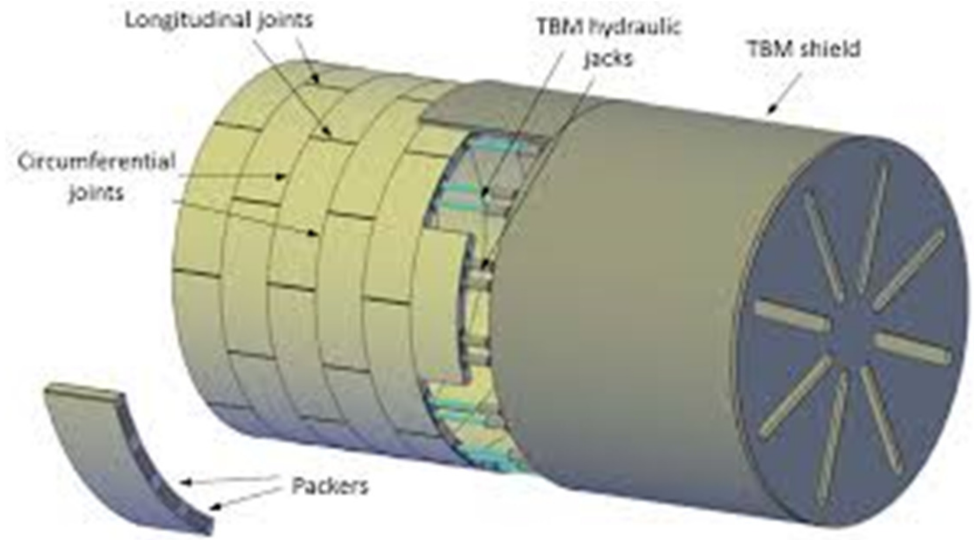
Connected each other by bolts

Use of a Tunneling Boring Machine

→ Setup of segmental lining

Background and Problematic

- What is segmental lining ?



Joints

3D process to create a circular annulus

Purposes and Methodology

Purposes:

✓Study the behaviour of segmental tunnel lining under static and dynamic loads, using 2D and 3D numerical models

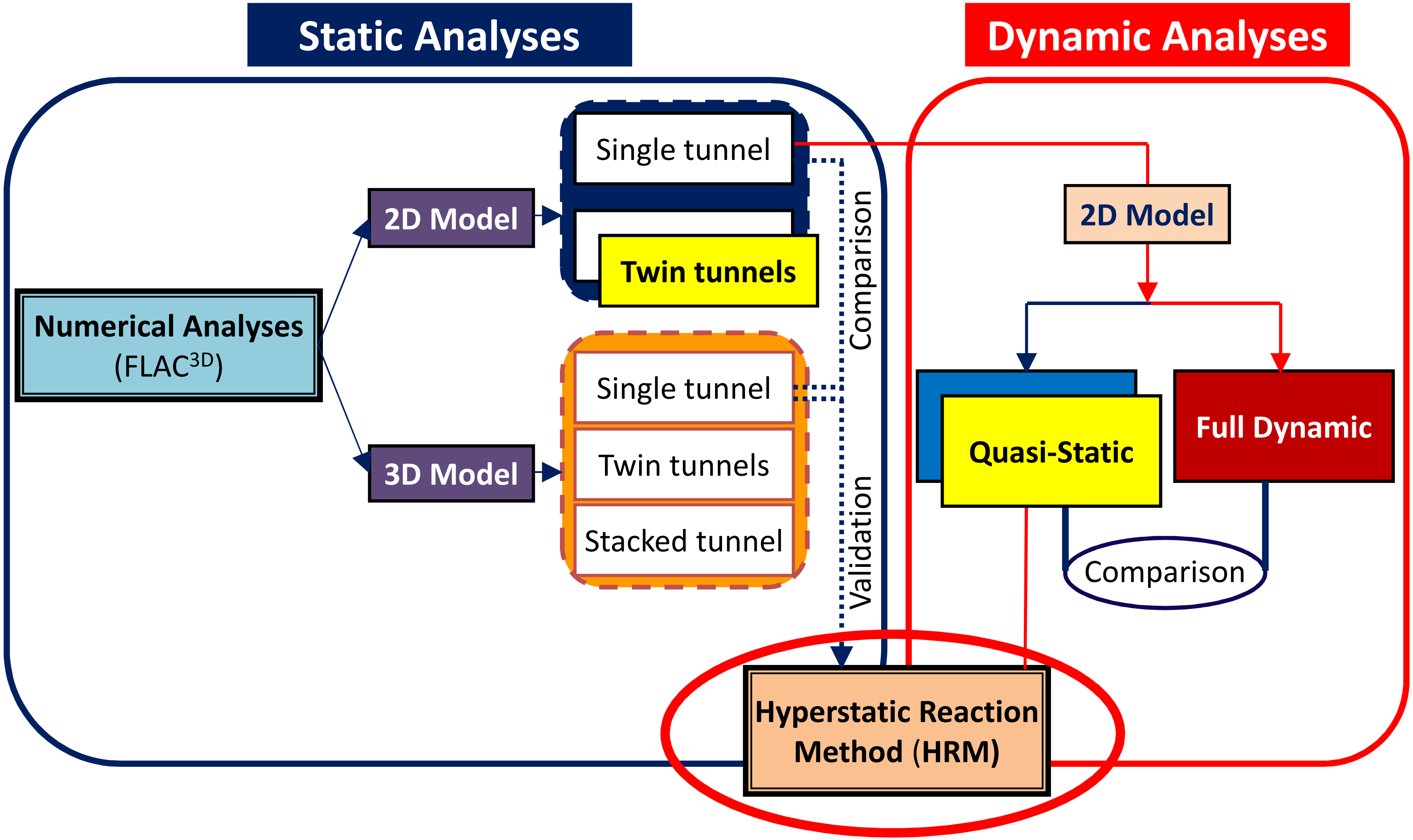
✓Develop a new numerical approach to the Hyperstatic Reaction Method for the design of segmental tunnel linings under static and dynamic loads

Methodology is:

✓Numerical simulations using a finite difference program (FLAC^{3D})

✓Classical deformation method in matrix format written in Matlab program

Scope - Objective

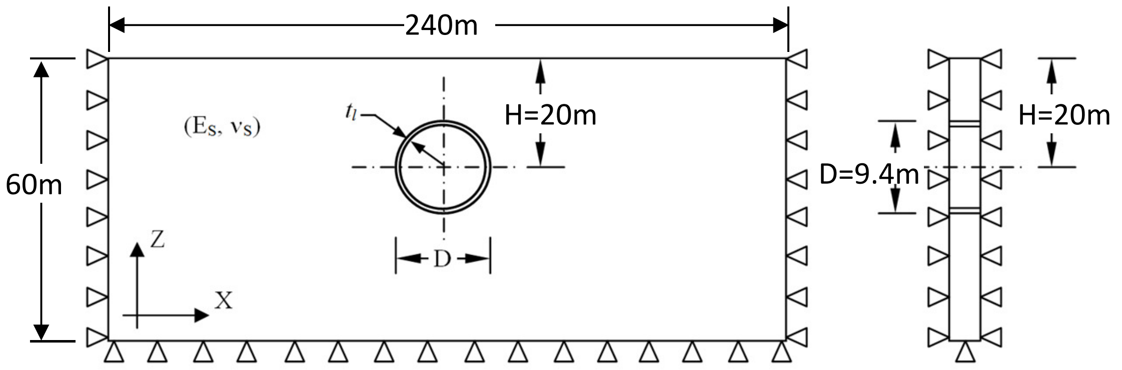


STATIC ANALYSES

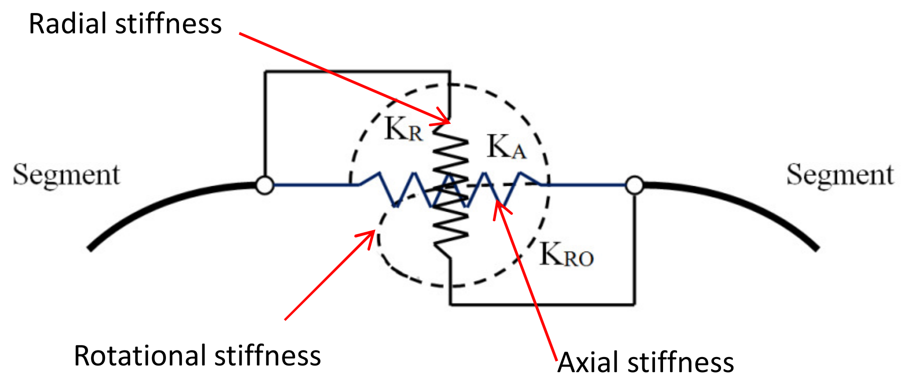
1) **2D investigations using FLAC^{3D}**
2) 3D investigations using FLAC^{3D}
3) New Hyperstatic Reaction Method (Matlab)

2D investigation of segmental tunnel linings

- **Objective**: highlight the effects of the joint stiffnesses, joint distribution, deformability of the ground



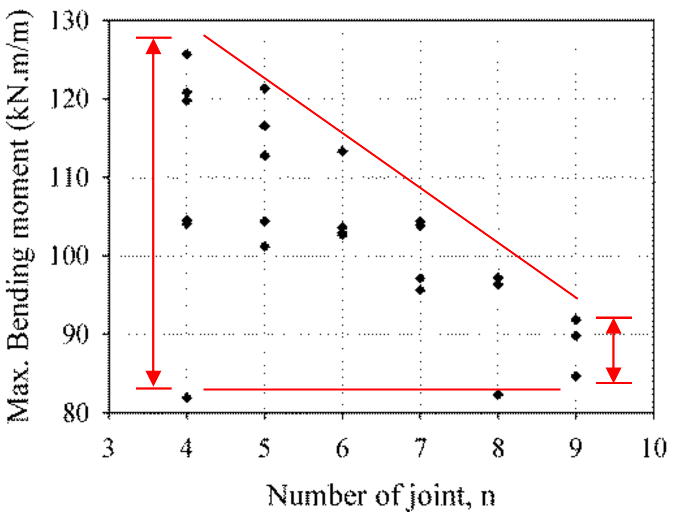
The plane-strain model (not scaled)

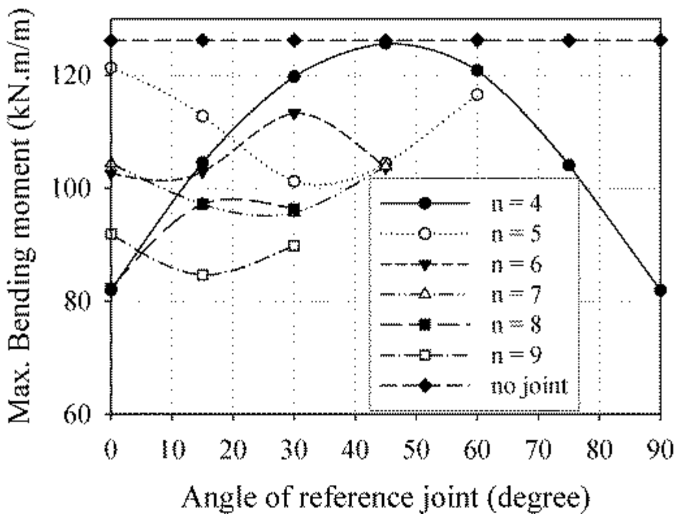


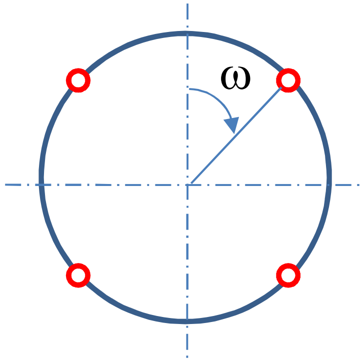
Joint stiffnesses of a joint

2D investigation of segmental tunnel linings

- **Variation of the maximum absolute bending moment with the joint number and joint orientation for cases K_0 = 0.5**







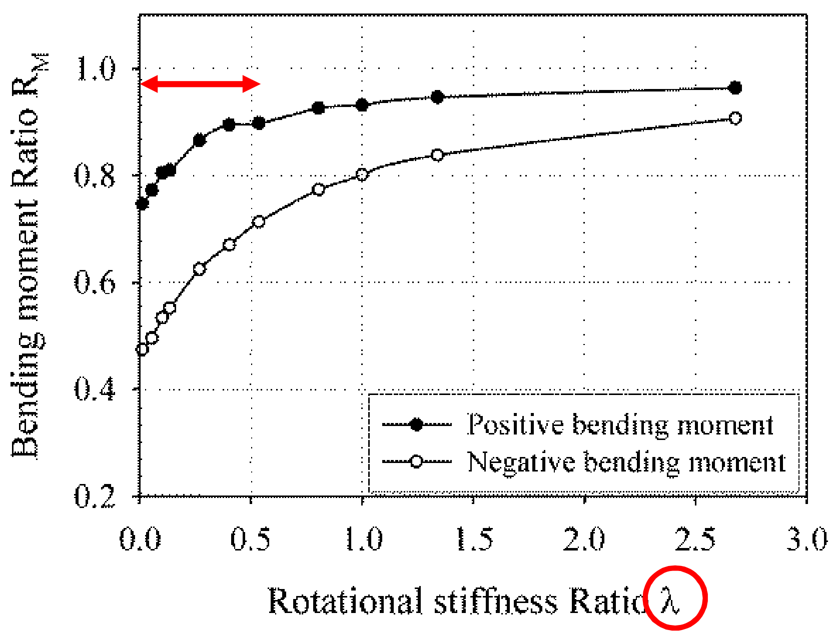
Definition of angle of reference joint

Influence of joint location on the maximum bending moment in the lining

The effects of the joint location around the tunnel when the joint number is even or odd are not the same

2D investigation of segmental tunnel linings

- **Influence of joint Rotational stiffness(K_{RO}), Axial stiffness K_A, Radial stiffness K_R**



$$R_M = M_{seg.} / M_{cont.}$$

Joint number = 6

$K_0 = 0.5$; $E_S = 150$ MPa

$\lambda = K_{RO} l / E_l I_l$

$l = 1$m;

E_l = Young's modulus of lining;

I_l = inertia moment of lining

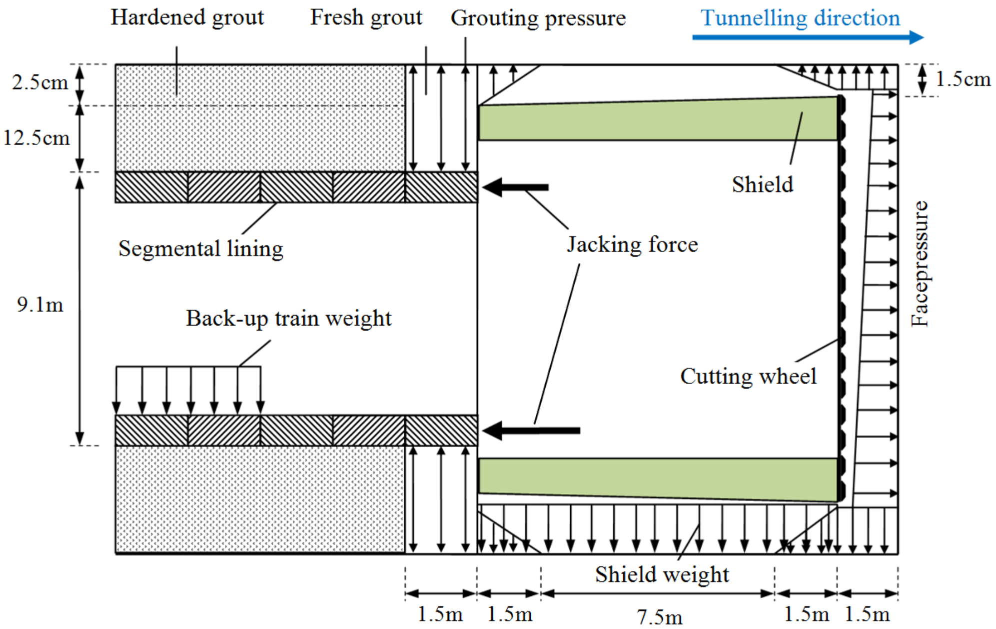
- The effect of rotational stiffness must be considered
- The effect of radial stiffness and axial stiffness can be neglected

STATIC ANALYSES

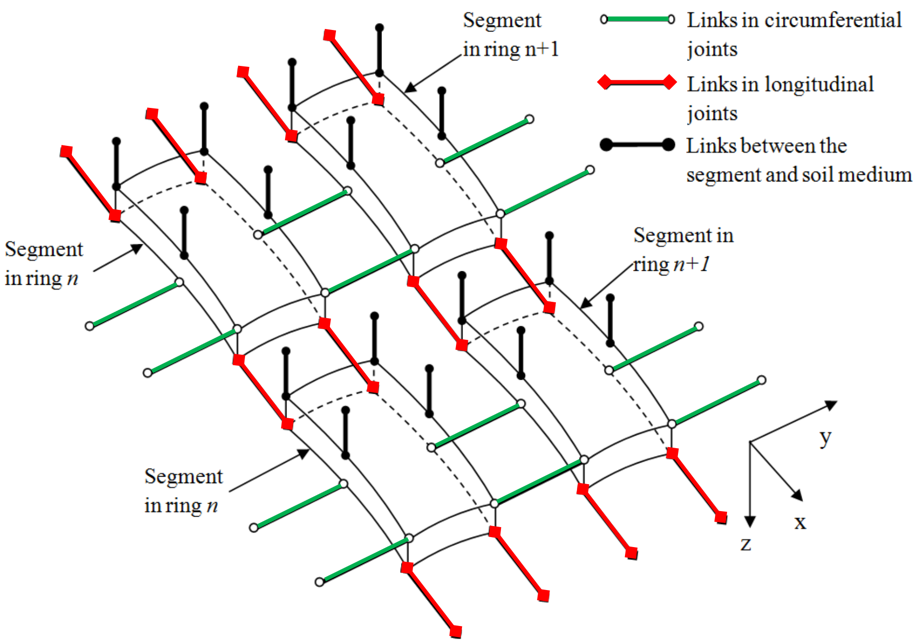
1) 2D investigations using FLAC^{3D}
2) **3D investigations using FLAC^{3D}**
3) New Hyperstatic Reaction Method (Matlab)

3D investigation of a single segmental tunnel lining

- **Objective**: highlight the effects of the joint pattern, soil constitutive model



Layout of the proposed TBM model (not scaled)

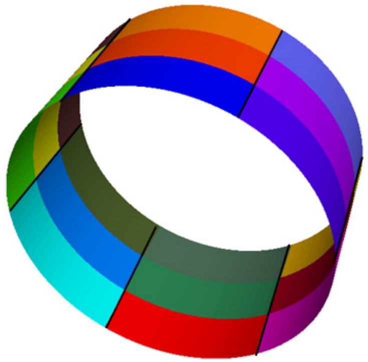


Joint scheme

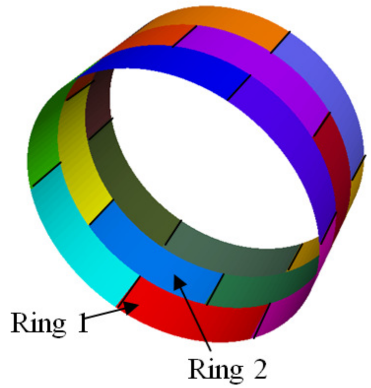
3D investigation of a single segmental tunnel lining

- **Considered lining models with different joint pattern**

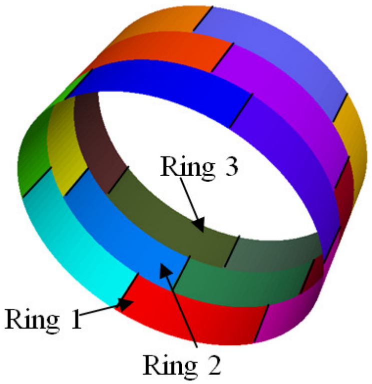
Model **M1** –
Continuous Lining



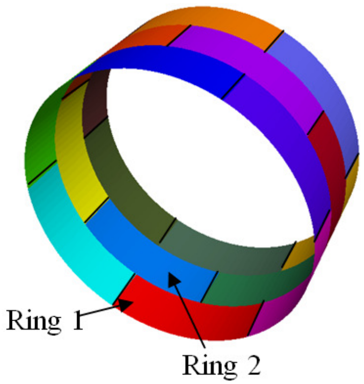
Model **M2** - Straight Rings –
1 ring type, True link



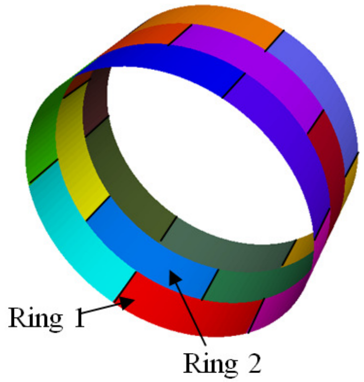
Model **M3** - Staggered Rings –
2 ring types, True link



Model **M4** –Staggered Rings
– 3 ring types,
True link



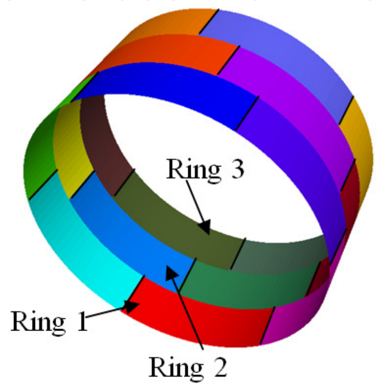
Model **M5** - Staggered Rings –
2 ring types,
Rigid link at the ring joint



Model **M6** - Staggered Rings –
2 ring types,
Free link at the ring joint

3D investigation of a single segmental tunnel lining - Conclusions

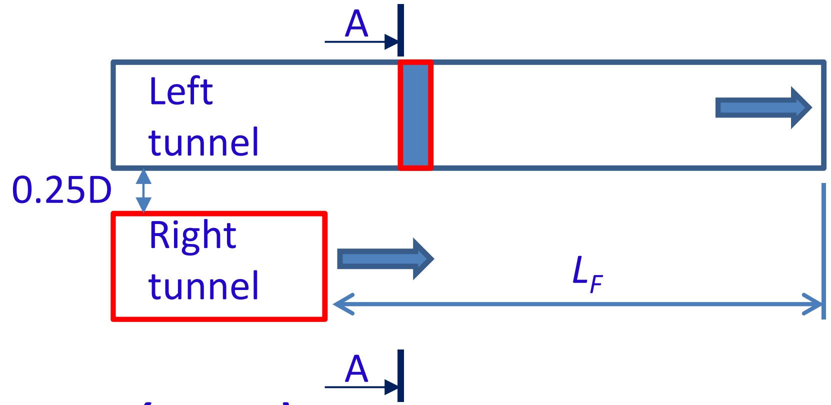
- Construction loads (jacking forces, grouting pressure) have great impacts on the internal forces induced in the tunnel lining; the largest values of normal force and longitudinal force are observed right after the installation of the lining ring behind the shield tail;
- Segment layout in successive rings and the attachment conditions of the joint (*coupling effect*) are two important factors that affect the internal forces and lining deformation;
- Internal forces induced in successive rings in a staggered segmental lining are not the same;
- Lining model M4 with more type of the rings is better to use than the other models, in terms of internal forces.



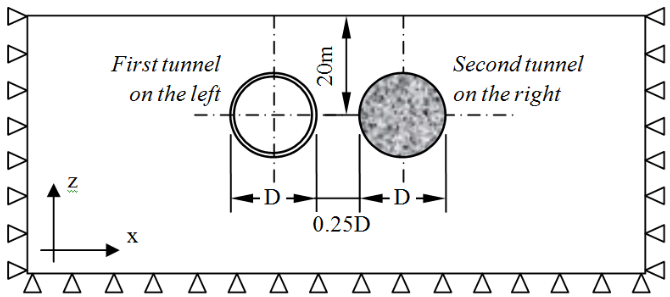
3D investigation of twin **horizontal** tunnels

- **Objective**: - the impact of the new tunnel excavation on the existing tunnel;
  - the influence of tunnelling procedure

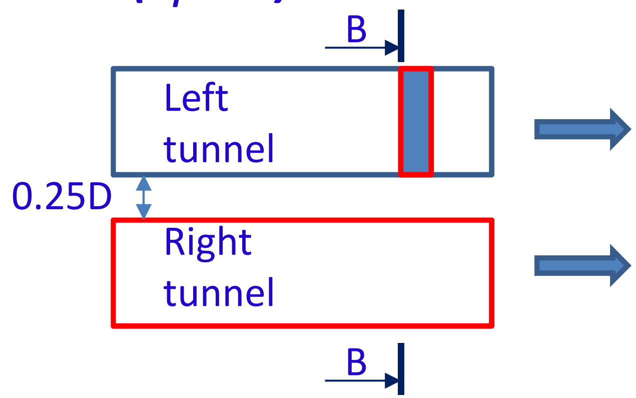
Case 1 (L_F=10D)



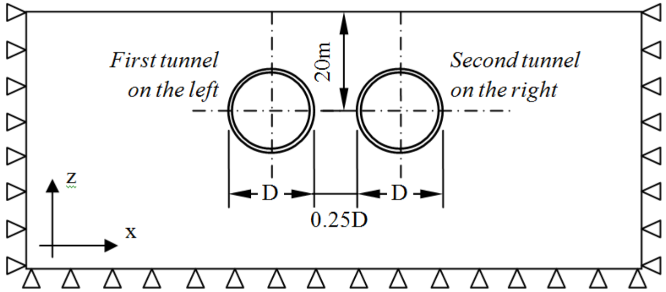
A-A



Case 2 (L_F=0D)



B-B

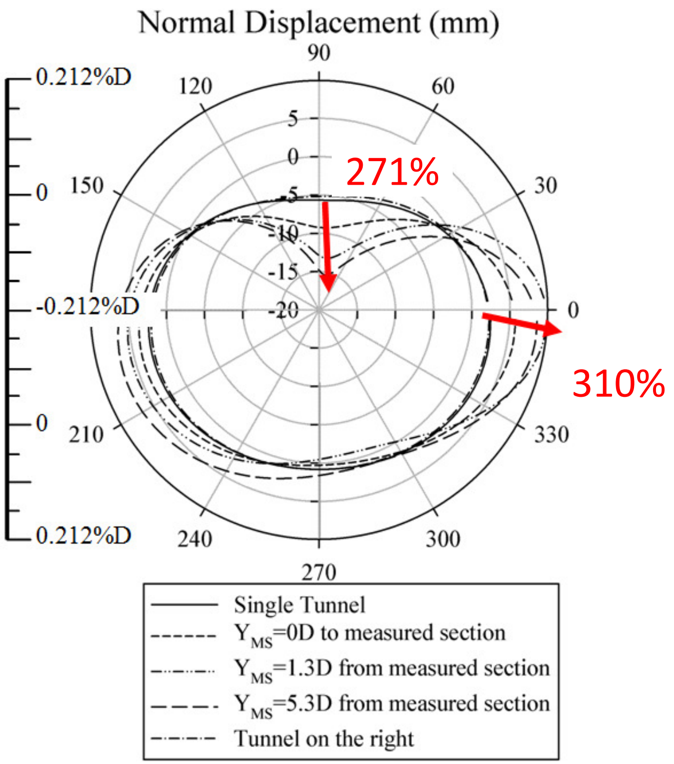


Measures lining ring

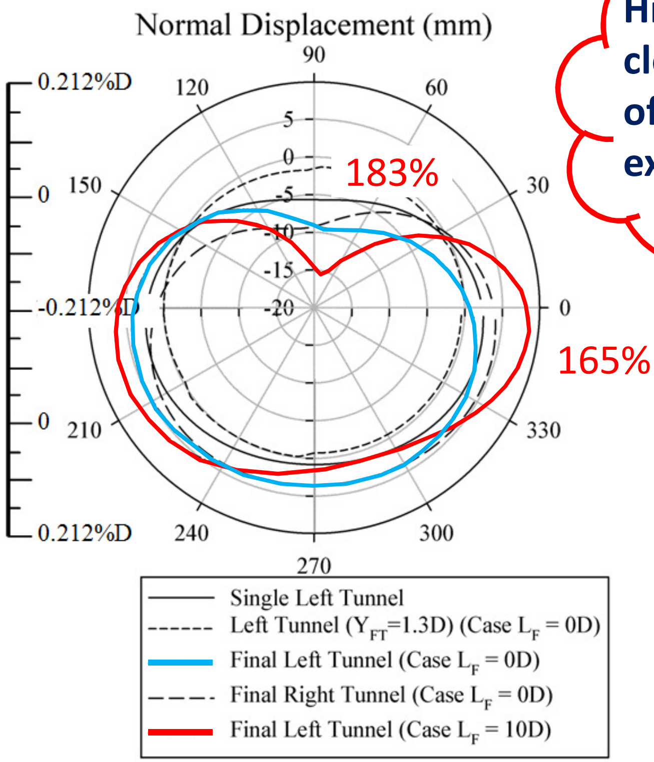
Excavation procedures

3D investigation of twin horizontal tunnels

Normal displacement in the tunnel linings



Normal displacement in the existing (left) tunnel lining, for the L_F = 10D case

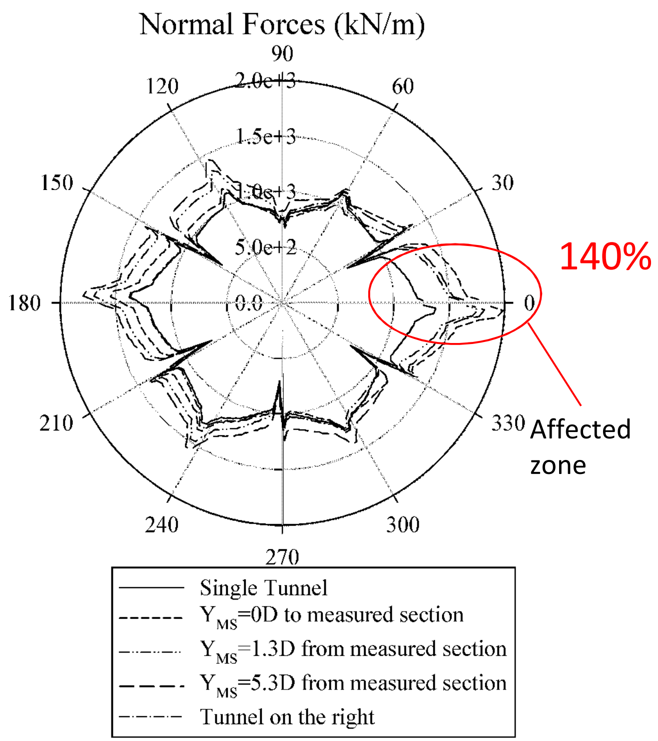


Comparison of normal displacement in the tunnel lining

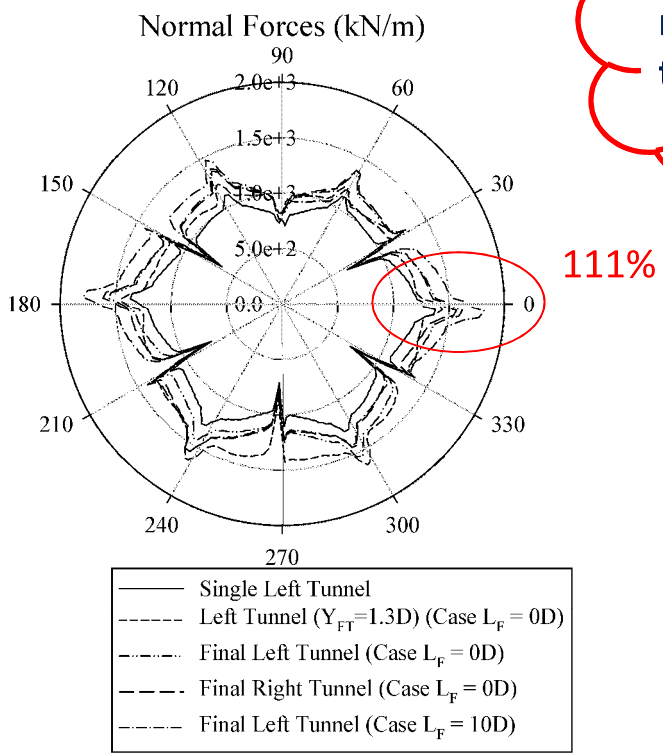
Higher impact of the close tunnels in case of successive excavation (L_F = 10D)

3D investigation of twin horizontal tunnels

Normal force in the tunnel linings



Normal force in the existing (left) tunnel lining, for the L_F = 10D case

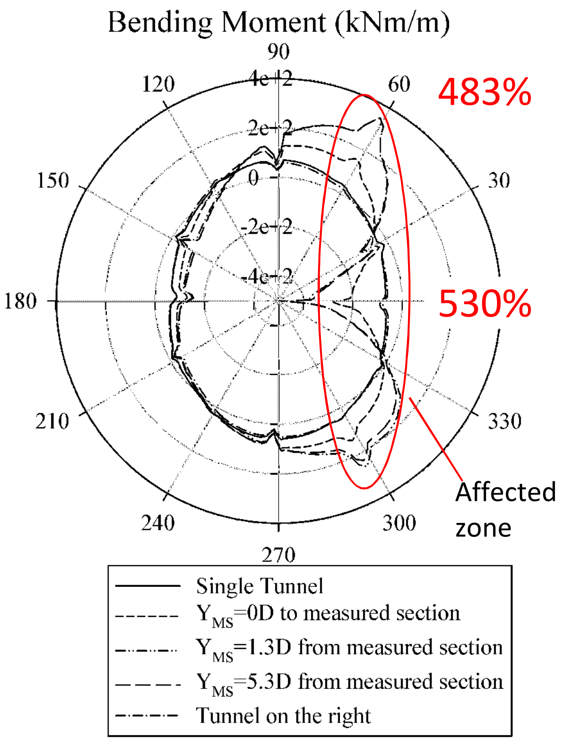


Comparison of normal forces in the tunnel lining

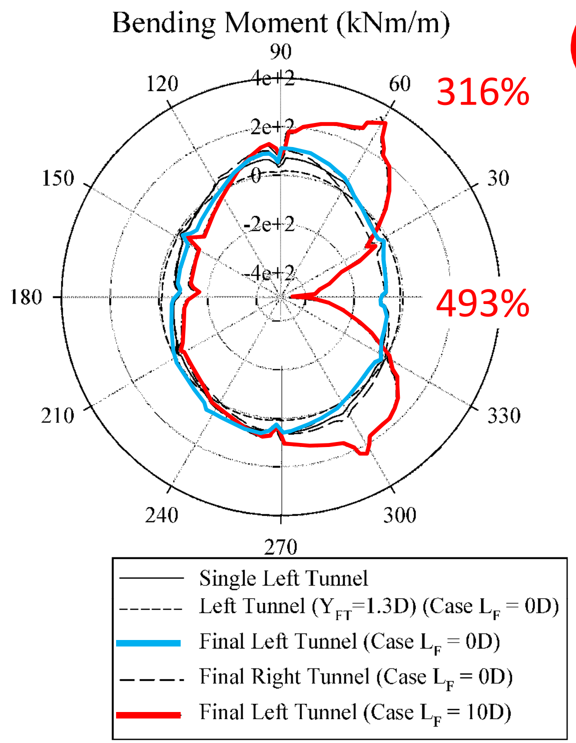
The existing tunnel bears more external loads than the new tunnel

3D investigation of twin **horizontal** tunnels

Bending Moment in the tunnel linings



Bending moment in the existing (left) tunnel lining, for the L_F = 10D case



Comparison of bending moment in the tunnel lining

The existing tunnel is more affected by tunnelling procedure than the new tunnel

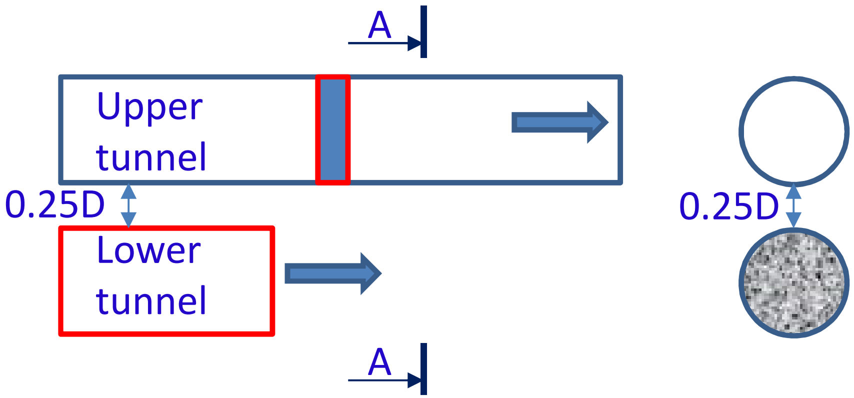
3D investigation of twin horizontal tunnels - Conclusions

- The excavation of the new tunnel has a high impact on the behaviour of the existing tunnel. The impact of excavation is important, in particular, on the tunnel side near the new tunnel. The maximum interaction between two tunnels occurs when the shield tail of the new tunnel passes over the measured section;
- Generally, the simultaneous excavation of twin tunnels (i.e. L_F = 0D) causes smaller structural forces and lining displacements than those induced in the case of twin tunnels excavated successively (i.e. L_F = 10D);
- The simultaneous excavation of twin tunnels could result in a higher settlement above the two tunnels than that in case of successive excavation;
- The behaviour of the new tunnel is similar to that of a single tunnel

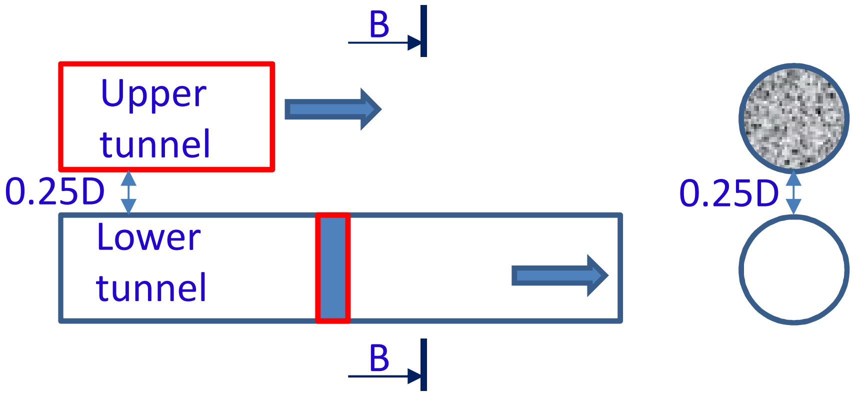
3D investigation of twin **stacked** tunnels

- **Objective**: - the impact of the new tunnel excavation on the existing tunnel;
  - the influence of tunnelling procedure

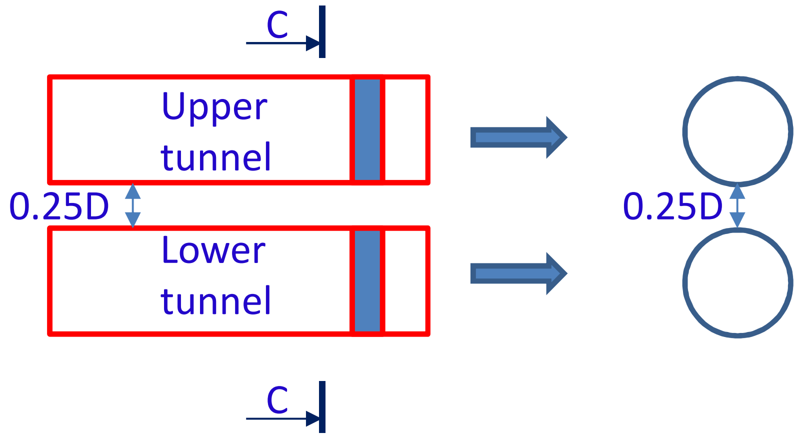
Case 1 (upper tunnel first) **A-A**



Case 2 (lower tunnel first) **B-B**



Case 3 (simultaneously) **C-C**

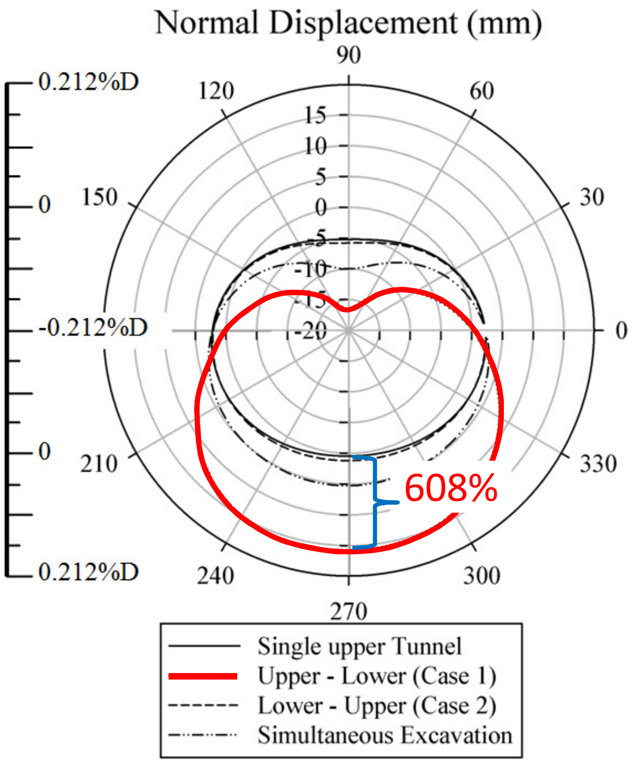



Measures lining ring

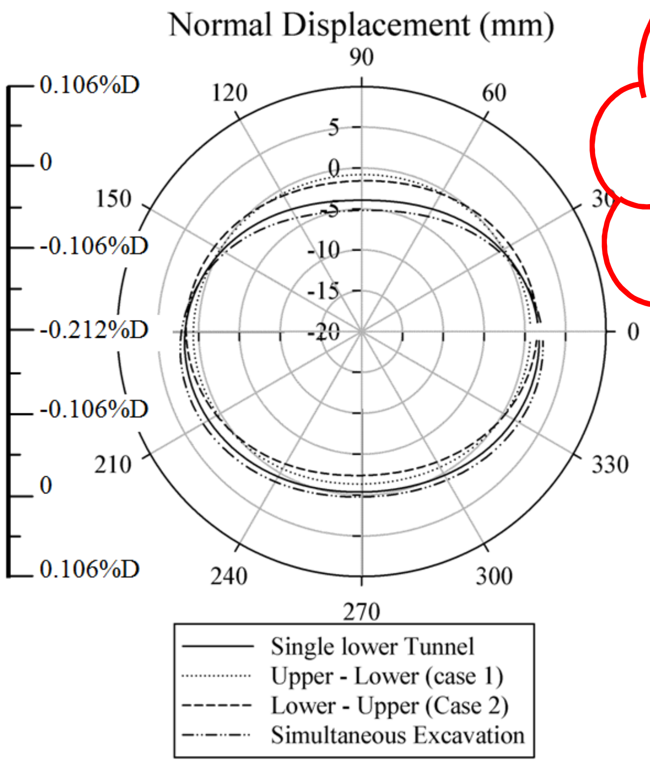
Excavation procedures

3D investigation of twin stacked tunnels

- **Normal displacement in the tunnel lining**



Comparison of the normal displacement in the upper tunnel lining

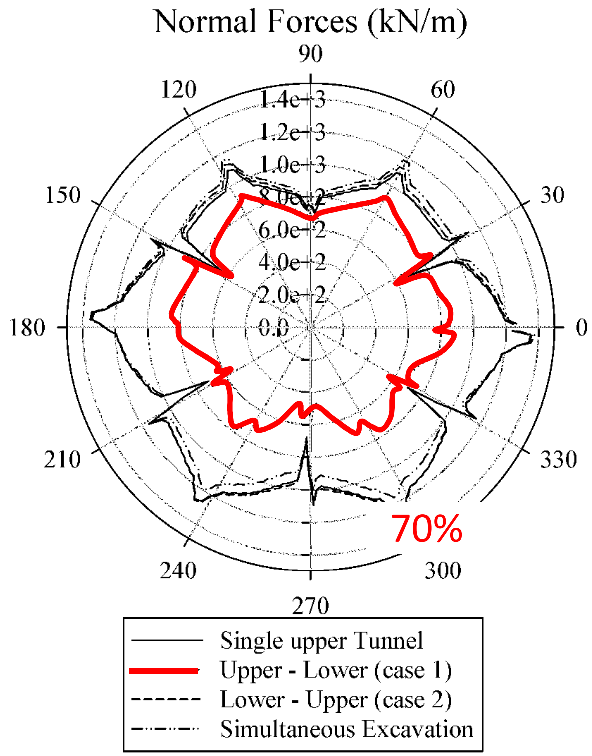


Comparison of the normal displacement in the lower tunnel lining

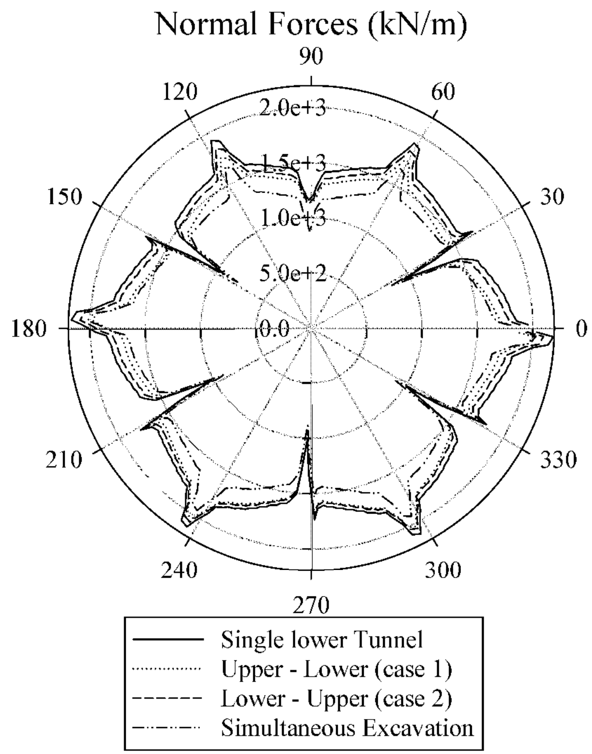
Normal displacement in the upper tunnel is affected more by the tunnelling procedure than the lower tunnel, particular in case 1

3D investigation of twin **stacked** tunnels

Normal forces in the tunnel lining



Comparison of the normal forces in the upper tunnel lining

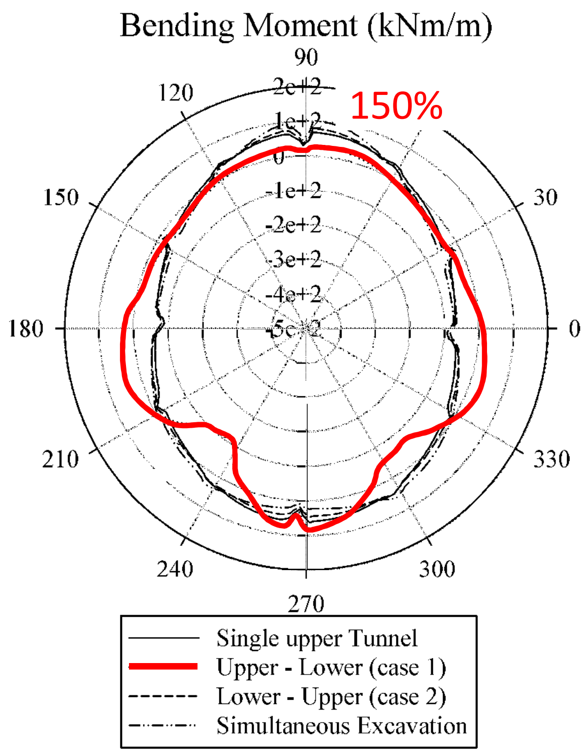


Comparison of the normal forces in the lower tunnel lining

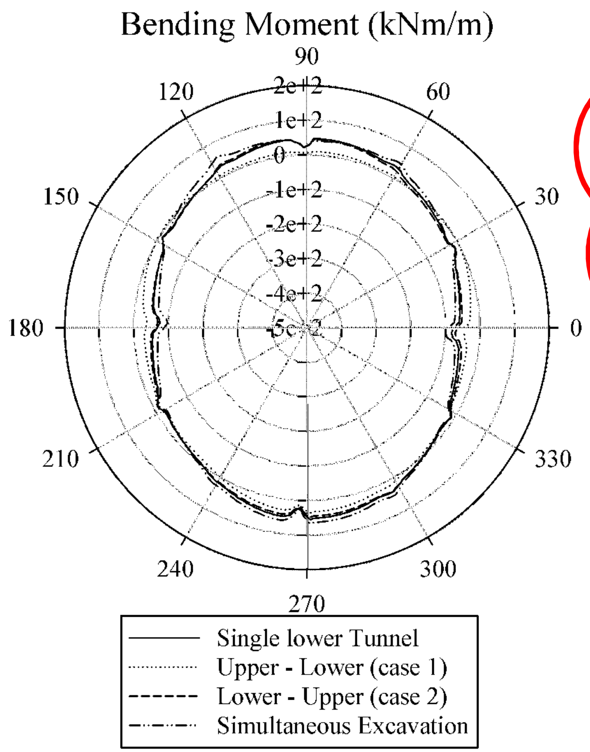
Normal forces in the upper tunnel is affected more by the tunnelling procedure than the lower tunnel, particular in case 1

3D investigation of twin **stacked** tunnels

Bending moment in the tunnel lining



Comparison of the bending moment in the upper tunnel lining



Comparison of the bending moment in the lower tunnel lining

Bending moment in the upper tunnel is affected more by the tunnelling procedure than the lower tunnel, particular in case 1

3D investigation of twin stacked tunnels - Conclusions

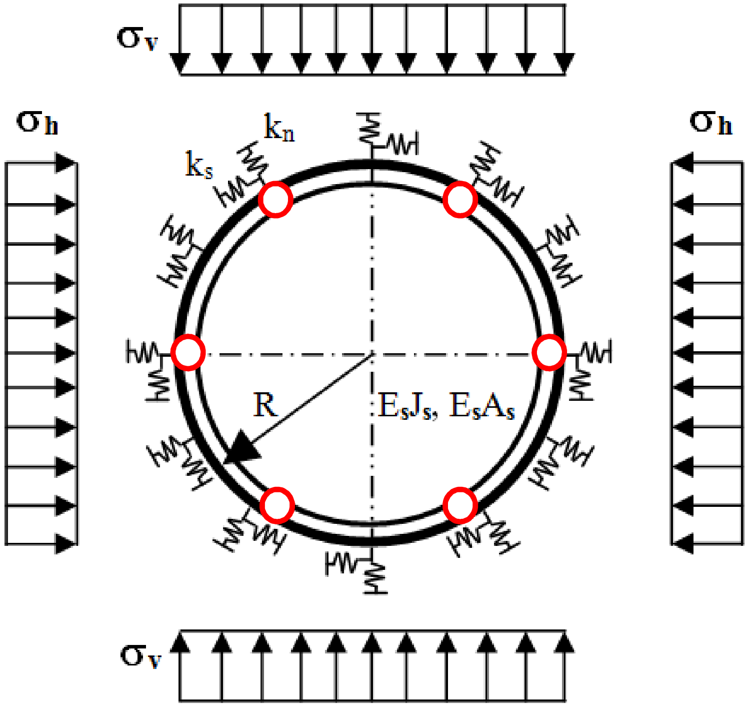
- The greatest impacts have been observed for case 1 in which the upper tunnel is excavated first.
- Case 1, in which the upper tunnel is excavated first, leads to smaller normal forces than in case 2.
- Generally, the internal forces induced in both stacked tunnels for simultaneous excavation case (case 3) are greater than those obtained for successive excavation cases (case 1 and case 2);
- The successive excavation of stacked tunnels cause an increase in the maximum bending moment in the upper tunnel and a decrease in the bending moment in the lower tunnel at the final state;
- The upper tunnel is affected to a greater extent by the excavation procedure for all cases.

STATIC ANALYSES

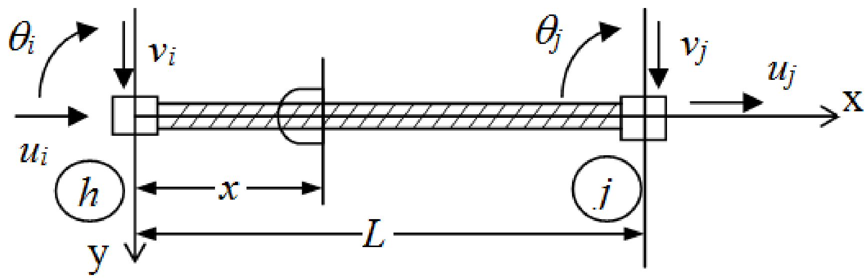
1) 2D investigations using FLAC^{3D}
2) 3D investigations using FLAC^{3D}
3) **New Hyperstatic Reaction Method (Matlab)**

A New Hyperstatic Reaction Method (HRM) applied to segmental lining

- **Classical displacement method applied to a rigid frame – continuous lining**



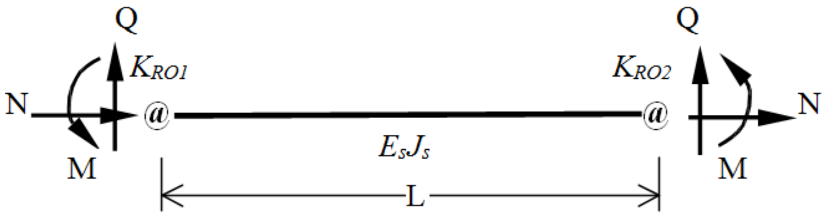
Calculation scheme of rigid frame - continuous lining



Rigid beam element

A New Hyperstatic Reaction Method (HRM) applied to segmental lining

- **Semi-rigid joint using a lengthless rotational spring – segmental lining**



Semi-rigid member (Burns et al. [2002])

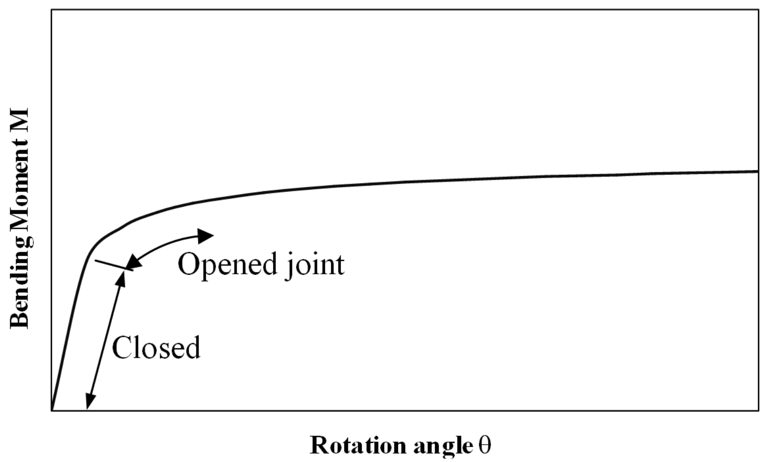
$$K_i^{SR} = Z_i . C_i$$

$$C_i = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & \dfrac{4r_2 - 2r_1 + r_1 r_2}{4 - r_1 r_2} & \dfrac{-2L_i r_1 (1 - r_2)}{4 - r_1 r_2} & 0 & 0 & 0 \\ 0 & \dfrac{6(r_1 - r_2)}{L_i (4 - r_1 r_2)} & \dfrac{3r_1 (2 - r_2)}{4 - r_1 r_2} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & \dfrac{4r_1 - 2r_2 + r_1 r_2}{4 - r_1 r_2} & \dfrac{2L_i r_2 (1 - r_1)}{4 - r_1 r_2} \\ 0 & 0 & 0 & 0 & \dfrac{6(r_1 - r_2)}{L_i (4 - r_1 r_2)} & \dfrac{3r_2 (2 - r_1)}{4 - r_1 r_2} \end{bmatrix}$$

"fixity factor" (Monforton and Wu [1963])

$$r_j = \frac{1}{1 + \dfrac{3E_S J_S}{K_{RO} L}}$$

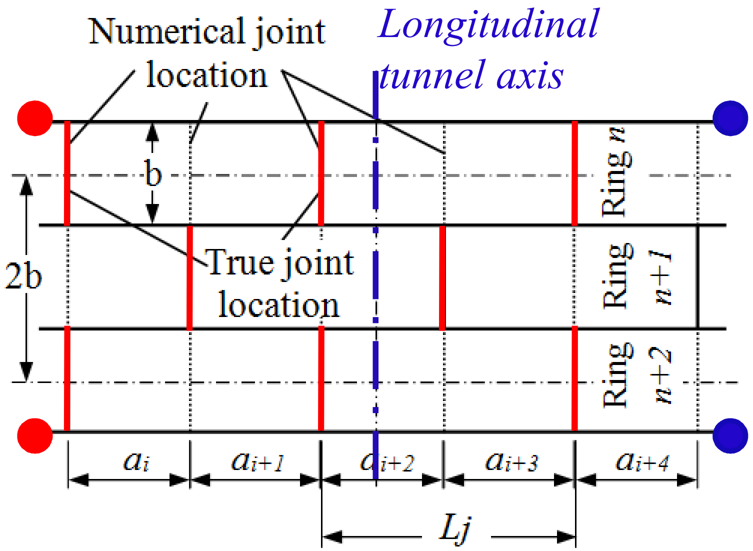
Relationship between the bending moments and rotations in a Janssen joint (K_{RO})



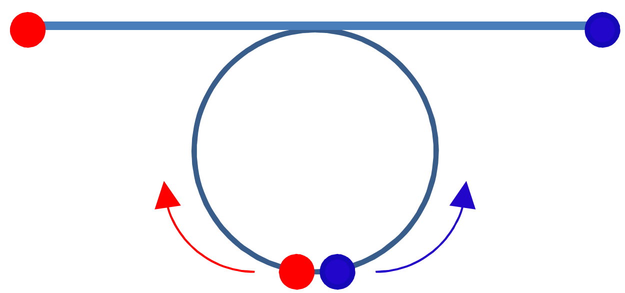
A New Hyperstatic Reaction Method (HRM) applied to segmental lining

Simplified model in the HRM

Unfold layout of true segmental tunnel lining



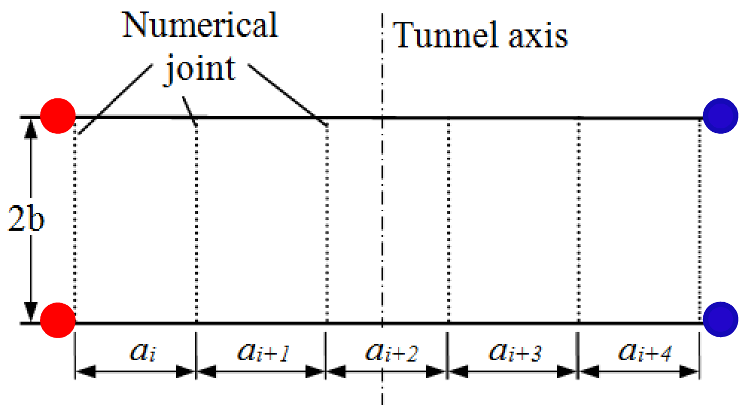
Circular tunnel



Unfolding

Simplification

Simplified model in the HRM



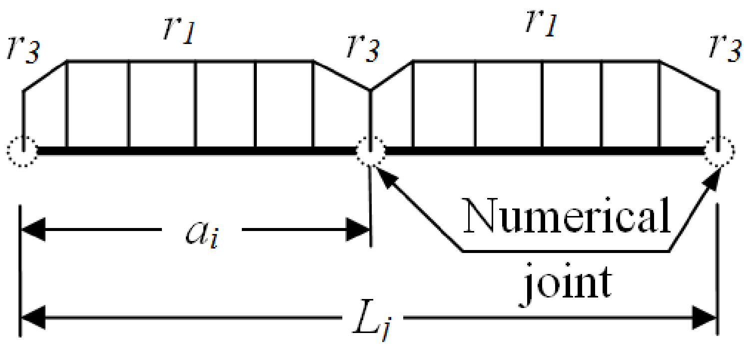
Joint location can be arbitrary

A New Hyperstatic Reaction Method (HRM) applied to segmental lining

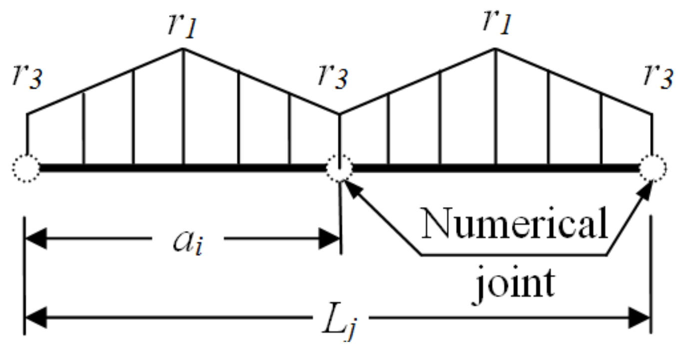
- Assumptions on the 3D effect between successive rings in the HRM method

Assumptions on the 3D effect simulation of a segmental tunnel lining

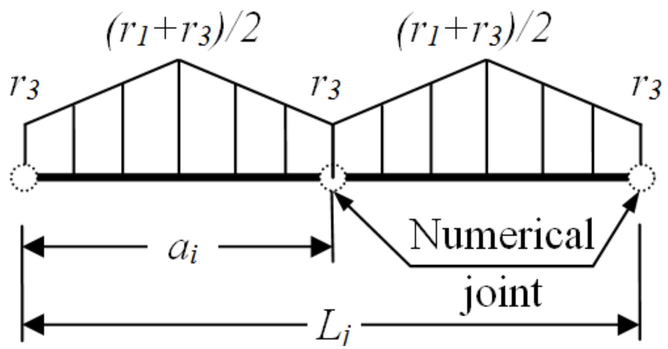
Assumption 1



Assumption 2



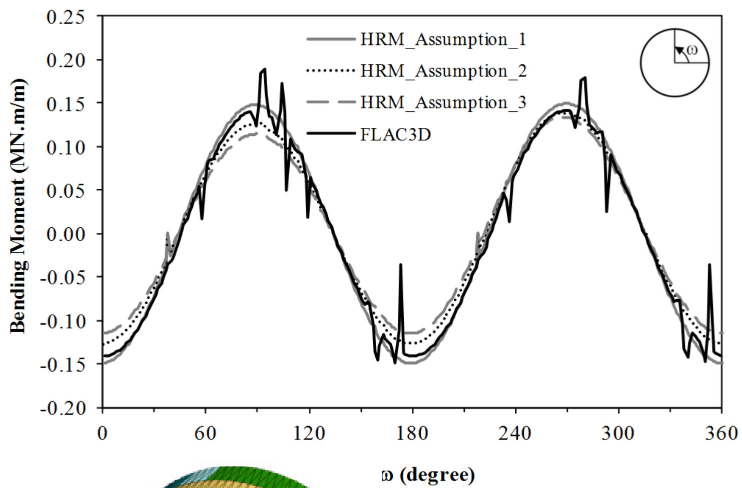
Assumption 3

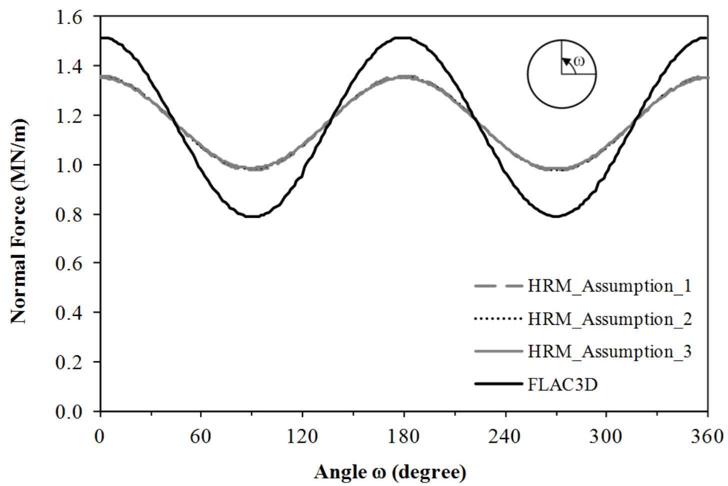


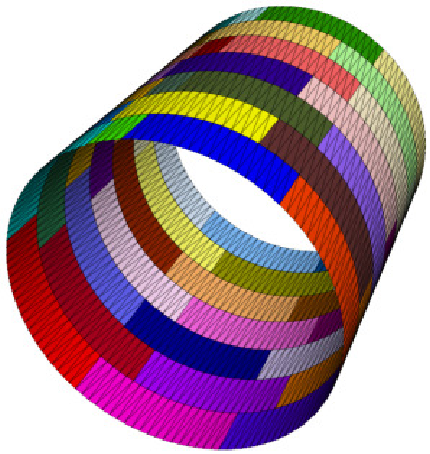
r_1 : fixity factor at concrete section;
r_2 : fixity factor at true joint;
$r_3 = 0.5(r_1+r_2)$

A New Hyperstatic Reaction Method (HRM) applied to segmental lining

- Comparison between the HRM and FLAC^{3D} numerical methods – **Case study Bologna-Florence tunnel**







- The structural force and (lining displacement) results obtained using the HRM method are basically in good agreement with the numerical FLAC^{3D} results;
- The influence of the joints between successive rings in segmental linings can be taken into consideration through numerical joints using one of above the three proposed assumptions in the HRM method. In this case study, **assumption 1** allows the numerical results to be in better agreement with the FLAC^{3D} results than the two others.

DYNAMIC ANALYSES

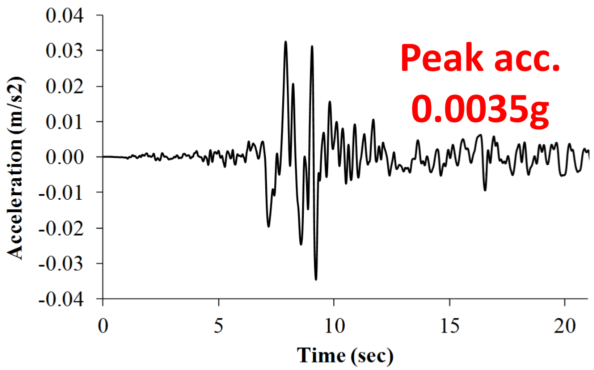
1) **Full dynamic analysis: FLAC^{3D}**
2) New Hyperstatic Reaction Method (Matlab)

Numerical analysis under dynamic loads: **Full dynamic analysis**

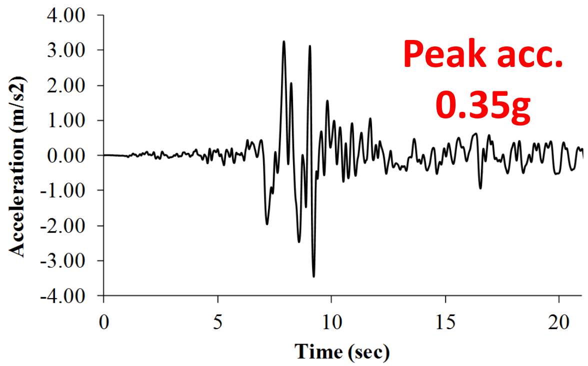
- **Objective**:

- Highlight the differences in tunnel behaviour under seismic excitation due to the effect of the segmental joints and of the soil constitutive model;

- Highlight the differences in structural lining forces when quasi-static analysis and a full dynamic analysis are performed



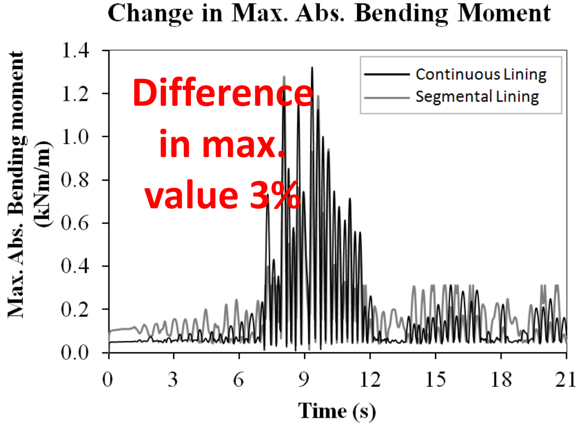
Low acceleration time history



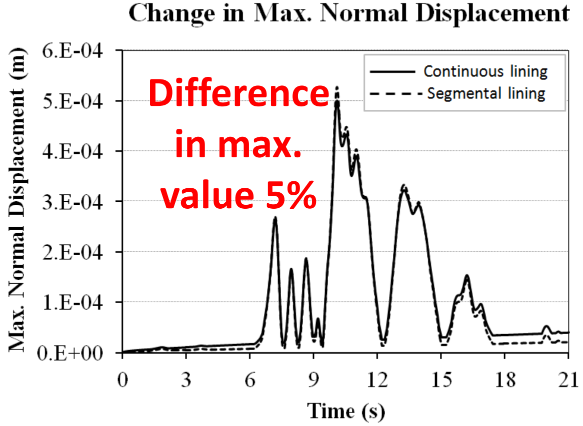
High acceleration time history

Numerical analysis under dynamic loads: Full dynamic analysis

- Behaviour of a tunnel under a **low** seismic load



Change in maximum absolute bending moment - Influence of segmental joints when an elastic constitutive model is used

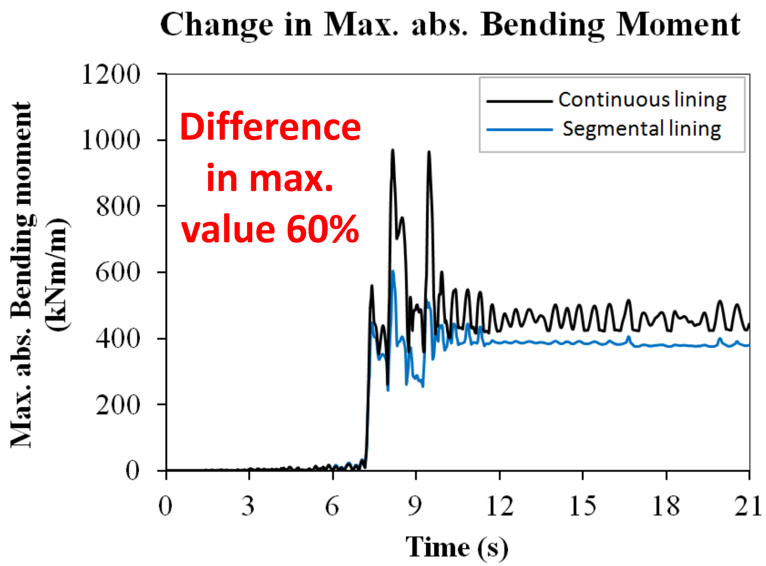


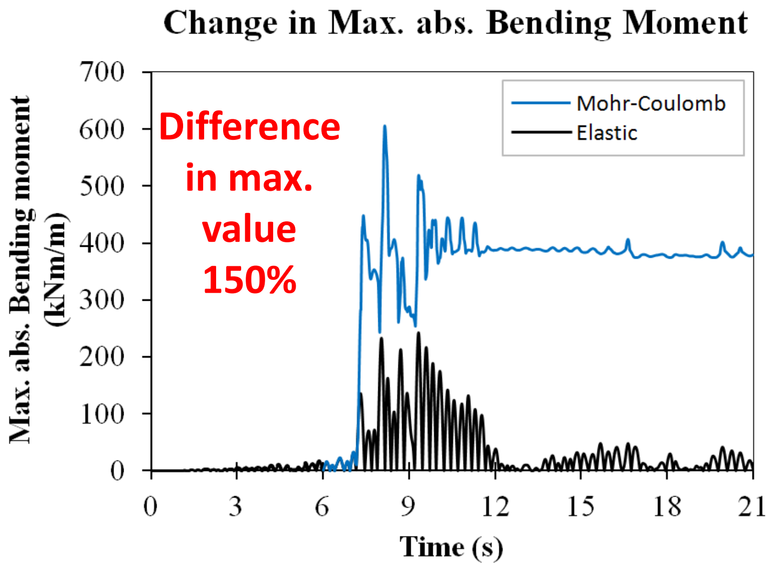
Change in normal displacement - Influence of segmental joints when an elastic soil constitutive model is used

insignificant influence of the soil constitutive model and segmental joints on tunnel behaviour under low seismic loads

Numerical analysis under dynamic loads: **Full dynamic analysis**

- Behaviour of a tunnel under a **high** seismic load





Residual value = 58% of the max. value

(a) Influence of segmental joints when the Mohr-Coulomb constitutive model is used

(b) Influence of the soil constitutive model when a segmental lining is used

Change in the maximum absolute bending moment

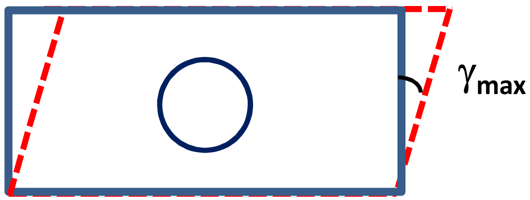
significant influence of the soil constitutive model and segmental joints on the bending moment under high seismic loads

Elastic constitutive model is not sufficient to reproduce the behaviour of the soil under dynamic loads

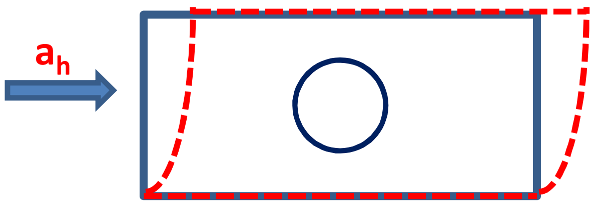
Numerical analysis under dynamic loads: **Full dynamic analysis**

- Validation of the quasi-static models

Prescribed shear strain method



Horizontal acceleration method



Tunnel lining:

Young's modulus: 24.8 GPa

Poisson's ratio: 0.2

Thickness: 0.3m

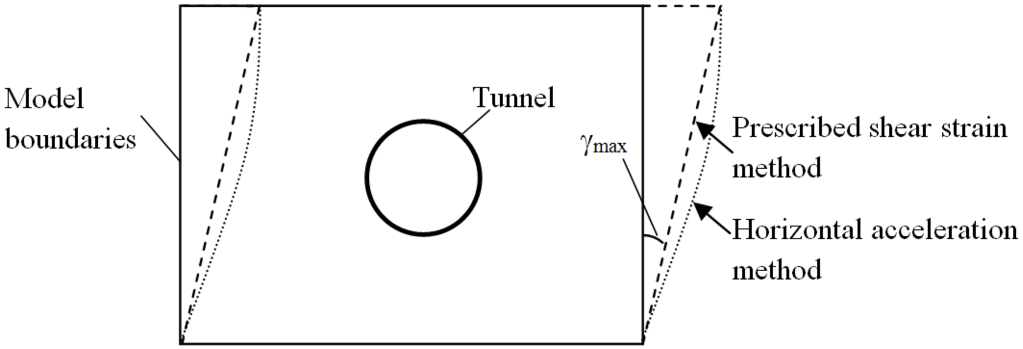
Soil:

Young's modulus: 312 MPa

Poisson's ratio: 0.3

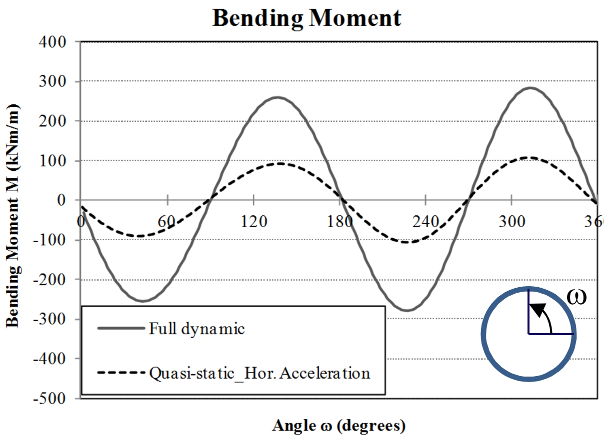
γ_{max} ***= 0.252%;*** a_h ***= 1.0381g***

Comparison of shear displacements

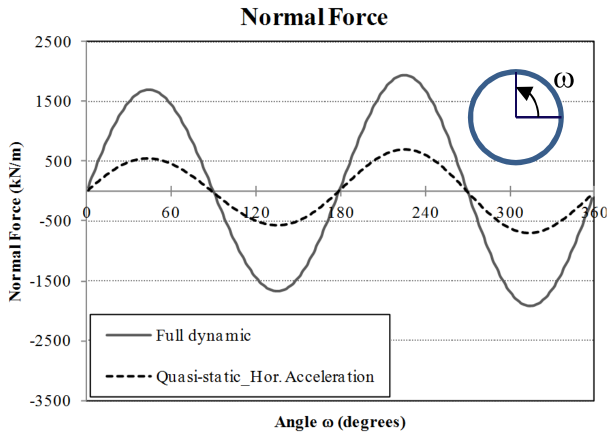


Numerical analysis under dynamic loads: Full dynamic analysis

- Comparison between quasi-static analysis and full dynamic analysis



Difference in max. Value 161%



Difference in max. Value 157%

Comparison between quasi-static analysis and full dynamic analysis (**high seismic signal case**)

DYNAMIC ANALYSES

1) Full dynamic analysis: FLAC^{3D}
2) **New Hyperstatic Reaction Method (Matlab)**

as follows
l. [2008]):

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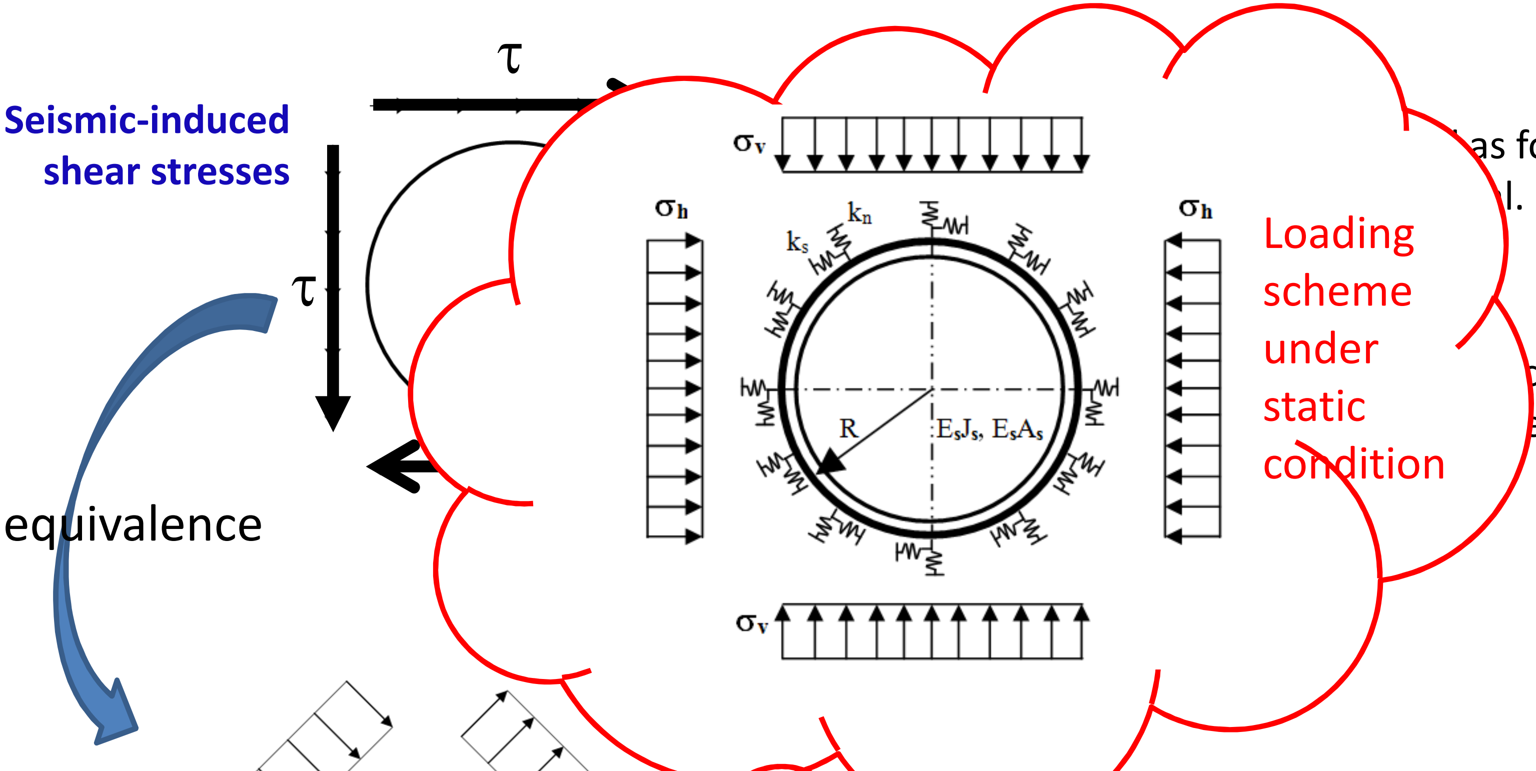
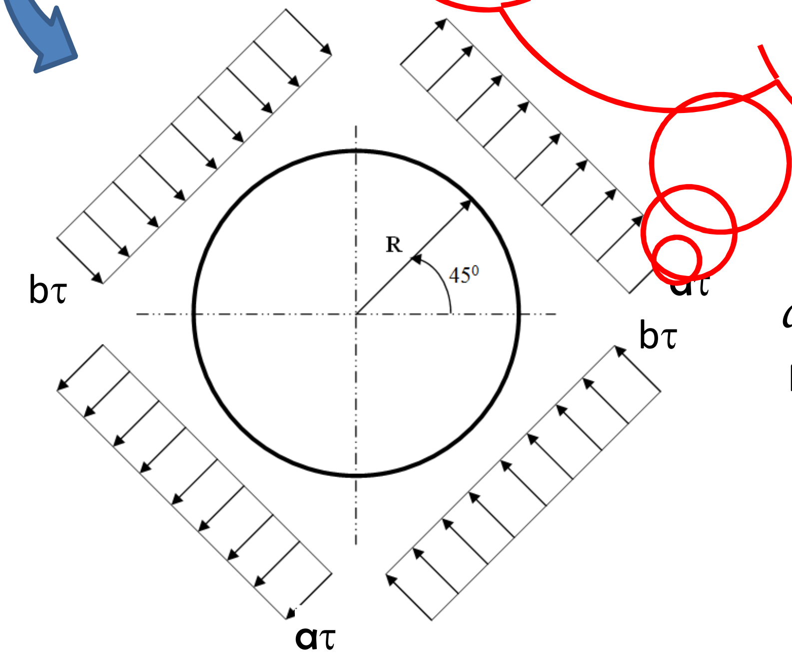
ear modulus of



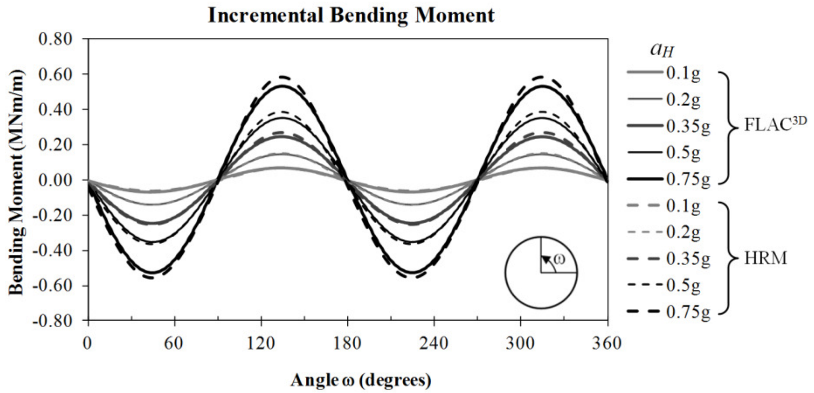


$$a = -0.7\ln(R) + 0.885 \qquad b = 1.25$$

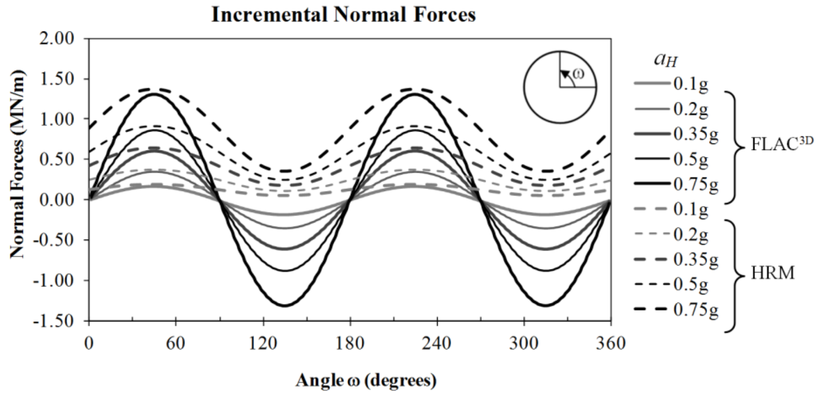
Proposed equivalent loading scheme under a seismic event in the HRM method

New Hyperstatic Reaction Method

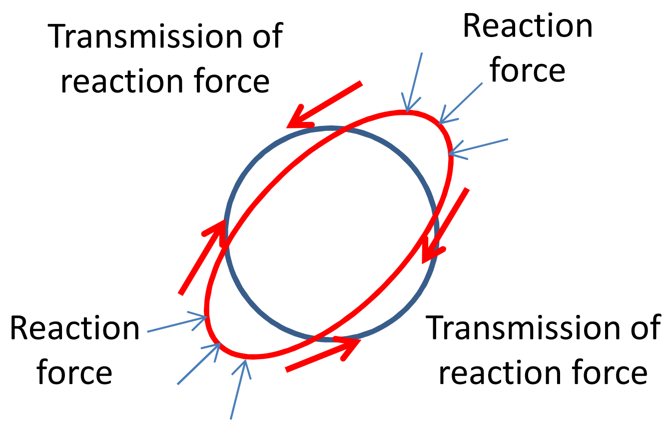
- Evaluation of the HRM under seismic loads applied to a continuous lining



Comparison of the incremental bending moment for *R* = 2.5m (only seismic-induced loads)



Comparison of the incremental normal forces for *R* = 2.5m (only seismic-induced loads)



GENERAL CONCLUSIONS

Static Part

- It is necessary to consider the effects of segmental joints, coupling forces between successive rings, excavation procedure of twin horizontal tunnels and twin stacked tunnels during the tunnel lining design;
- A new approach applied to the Hyperstatic Reaction Method has been developed, which is able to consider the effect of segmental joints in successive rings on the tunnel lining.
- The present HRM method allows the arbitrary distribution of segmental joints along the tunnel boundary to be taken into consideration. In addition, the rotational stiffness of the segmental joints has been simulated using nonlinear behaviour, which is closer to the true behaviour of a joint than linear or bilinear behaviour.
- FEM code of the HRM is free and the time consumption for a calculation using the HRM is reduced drastically (0.28 %) compared to a FLAC^{3D} calculation (5s with HRM and 30 minutes with FLAC^{3D} + dongle key).

Dynamic Part

- The effect of segmental joints under a low seismic excitation (peak acceleration of about 0.0035g) could be neglected;
- The effect of the soil constitutive model on the tunnel behaviour depends to a great extent on the amplitude of the seismic excitation and it could be neglected under low seismic excitation. However, this effect must be taken into consideration under a high seismic excitation;
- An elastic analysis is not sufficient to determine the seismic induced response of a soil-tunnel system and an equivalent static solution would yield smaller structural lining forces than those of a true dynamic solution
- A new solution applied to the Hyperstatic Reaction Method to consider the effect of dynamic loads on the segmental tunnel lining has been developed; Parametric results indicated that the effect of the joints on the internal forces should be considered to achieve an economical design of segmental lining exposed to seismic loads

Perspectives

For the short-term stage

- Validate all numerical models using experimental data collected at tunnel site or performed in laboratory;
- Develop 3D model for mechanized tunnelling process considering the effect of water on the tunnel lining behaviour in undrained analyses;
- Perform further investigations focusing on investigating the influence of other elements of the construction process, such as the tunnel distance, shield weight, back-up train, face pressure, grouting pressure, using the available numerical models;
- Perform dynamic calculations using more complicated constitutive model of the soil and apply to the case of twin tunnels.

Perspectives

For the long-term stage

- Perform 3D numerical analyses for mechanized tunnelling process at high depth;
- Develop a new approach to the HRM under seismic loads, in which true seismic signal is applied directly on the HRM model but not by using quasi-static loads.

Thanks for your attention !