

Three-Dimensional Interaction of Multiple Perpendicularly Crossing Tunnels with Circular and Horseshoe-shaped Cross-sections



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THE HONG KONG UNIVERSITY OF
SCIENCE AND TECHNOLOGY

Contents

- Brief introduction of Hong Kong University of Science and Technology (HKUST)
- Fundamental principles of geotechnical centrifuge modelling + two examples
- Research objectives, strategy, methodology
- Effects of construction sequences
- Effects of cover depth of tunnels (C/D)
- Effects of pillar distance between tunnels (P/D)
- Shielding effects
- Shape of an existing tunnel (circular vs horse-shoe)
- Summary and major conclusions

Shenzhen (the Mainland)



Airport

New Territories

HKUST

Kowloon

Victoria Harbour

Lantau Island

HK Island

Approx. 1,000 km²

Satellite Image of Hong Kong (Geotechnical Engineering Office, 1997)



H O N G K O N G

Along the Two Sides of the Victoria Harbour in Hong Kong

The Hong Kong University of Science & Technology (HKUST)

Established in 1991, 4 schools, 9,500 UGs, 2,300 TPGs, and 2,200 RPGs
(80 RPGs in Geotechnical)

East



NE



SW



The Hong Kong University of Science & Technology (HKUST)



Centrifuge



Exchange scholarships (PGs) = about
US\$ 1,300 per month
Scholarships for full-time research students = about
US\$ 2,000 – 2,500 per month





FINAL deadline for abstract submission: 15 April 2017

KEYNOTE and FEATURE SPEAKERS

(More to come)

- Eduardo Alonso, *UPC, Spain*
- Pierre Delage, *ENPC, France*
- Antonio Gens, *UPC, Spain*
- Lyesse Laloui, *EPFL, Switzerland*

GENERAL REPORTERS

(More to come)

- Fernando Marinho, *USP, Brazil*
- David Masin, *CU, Czech Rep.*
- John McCartney, *UCSD, USA*
- Marcelo Sanchez, *Texas AMU, USA*

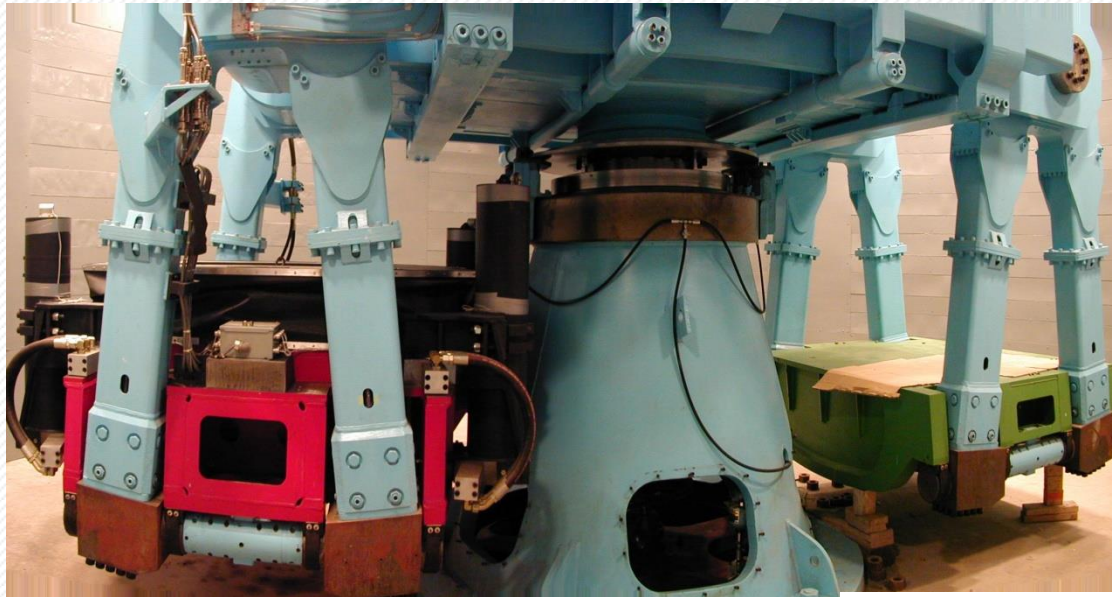
THE 2ND BLIGHT LECTURE: Prof. Delwyn Fredlund, *Golder Associates*

Will collaborate with *TC215 – Environmental Geotechnics*, *TC206 – Interactive Geotechnical Design* and *TC308 – Energy Geotechnics* for organizing mini-symposia

Autors of all papers will be invited to give a 5-min pitch oral presentations and poster displays

Fundamental Principles of Geotechnical Centrifuge Modelling

The Geotechnical Centrifuge Facility at Hong Kong University of Science and Technology



- Diameter: 8.4m
- Maximum g-level: 150g
- Maximum payload: 400g-ton (design)
- Real-time monitoring and viewing via internet
- Operated in 2001

The world first 2D Hydraulic In-flight Shaking Table

The world 2nd Four-Axis Robotic Manipulator

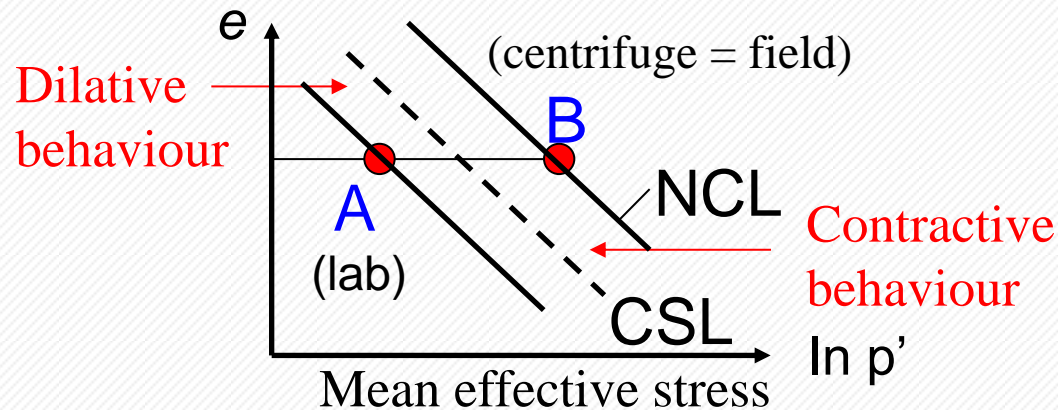


Fundamental Principle of Centrifuge Modelling

- The basic principle of centrifuge modelling is to **recreate the stress conditions** which would exist in a **full-scale situation** (prototype), using a model of greatly reduced scale.
- This is done by subjecting the model components to **an enhanced body force** which is provided by a centripetal acceleration ($r\omega^2=ng$).

$$\sigma_p = \rho g h_p = \rho (ng) \frac{h_p}{n} = \rho g h_p$$

- Thus, centrifuge is suitable for modelling **stress dependent problems** such as consolidation, slope instability, tunnelling effects and pile capacity.



Scaling laws

e.g., 1-day consolidation test
at 150 g = 150x150 days
or 62 years (prototype)

$$T_V = \frac{c_v t}{d^2}$$

$$\frac{t_p}{t_m} = \frac{d^2}{(d/n)^2} = n^2$$

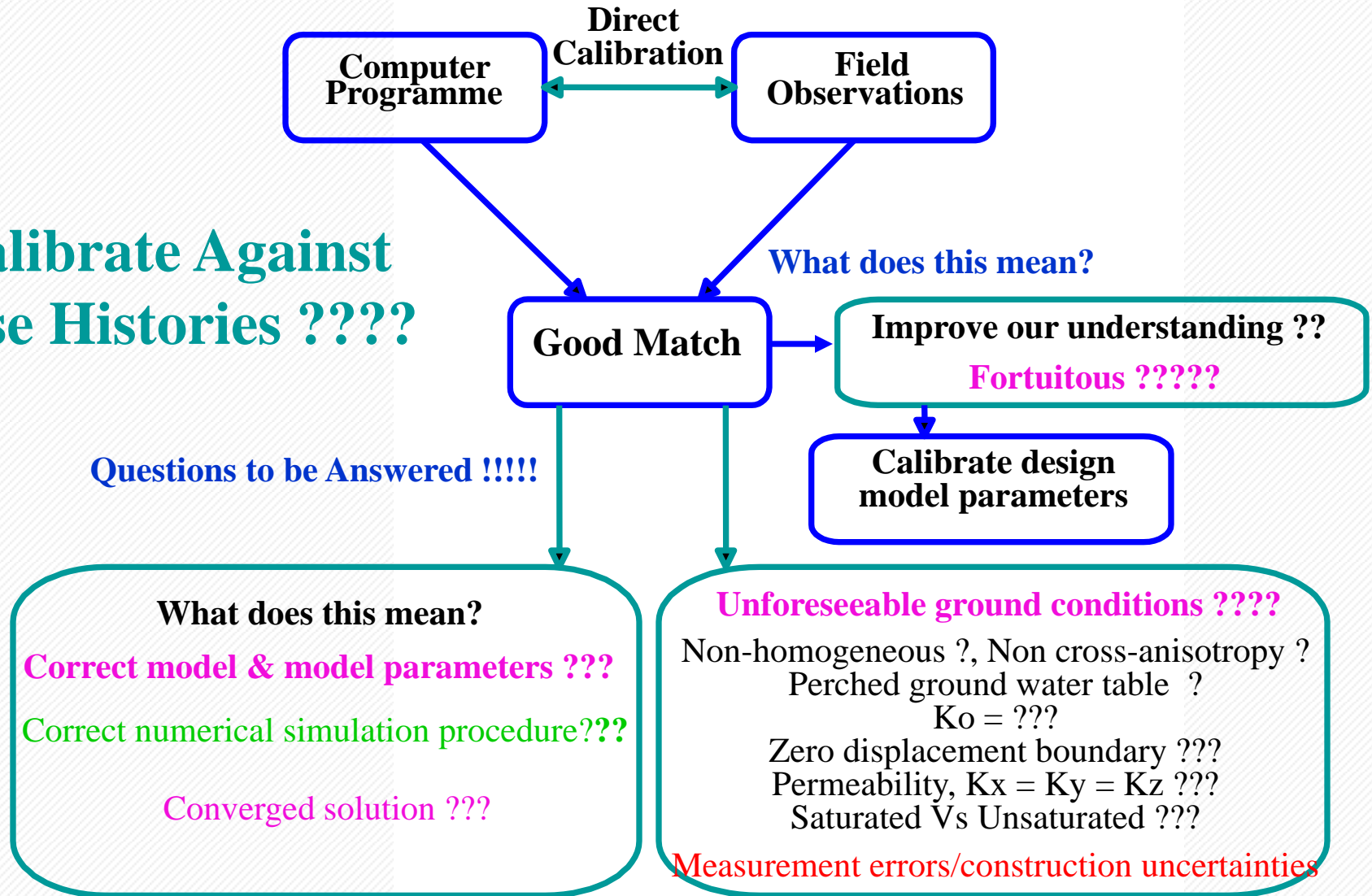
Parameter	Scale (model/prototype)
Acceleration	n
Linear dimension	1/n
Area dimension	1/n ²
Volume dimension	1/n ³
Stress	1
Strain	1
Mass	1/n ³
Density	1
Unit weight	n
Force	1/n ²
Bending Moment	1/n ³
Bending Moment / unit width	1/n ²
Flexural stiffness / unit width	1/n ³
Time (dynamic)	1/n
Time (consolidation/ diffusion)	1/n ²
Time (creep)	1
Pore fluid velocity / rainfall	n
Concentration	1
Velocity (dynamic)	1
Frequency	n

Principal Applications of Geotechnical Centrifuge Technology (Ko, 1988)

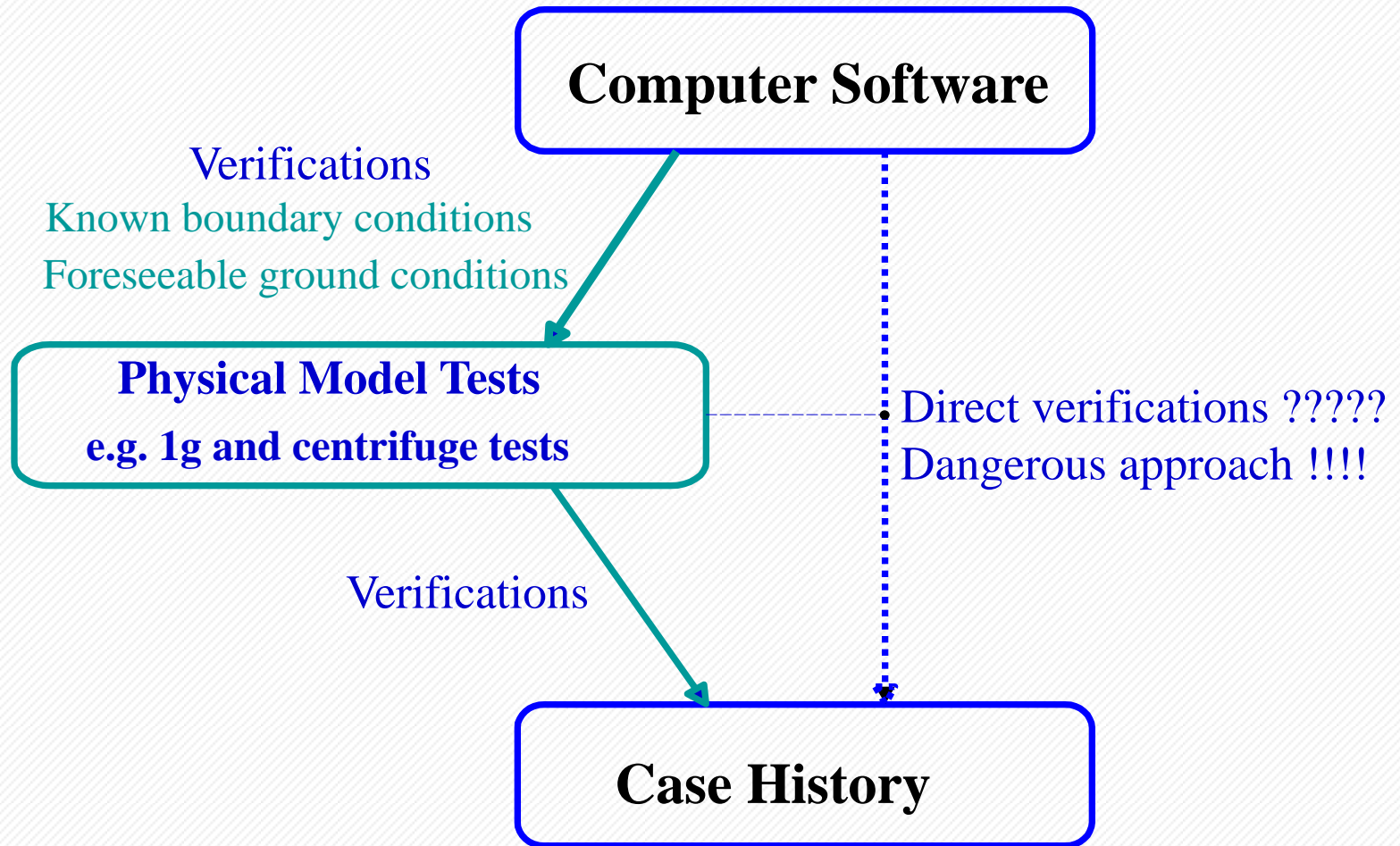
1. **Modelling of Prototypes** such as tunnels, piles, excavations, slopes, geo-environmental & earthquake-induced problems, consolidation settlements
2. **Investigation of New Phenomena and Mechanisms** such as explosions, plate tectonics, liquefaction problems, contaminant transports
3. **Parametric Studies** such as bearing capacity of footings on slopes, laterally loaded pile groups
4. **Calibrations of Numerical Models and Methods** - how do you know your computed results are correct ? **Calibrate against case histories ?**

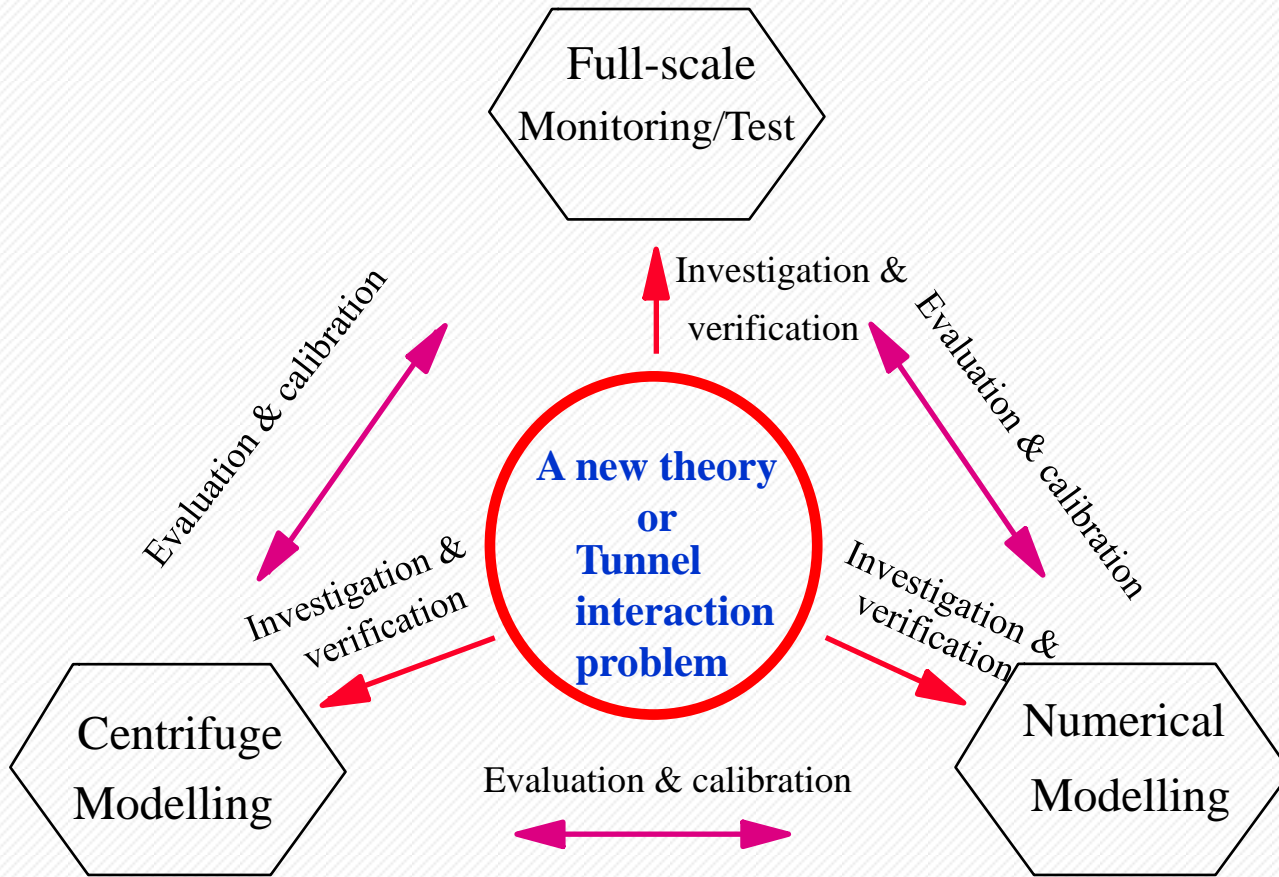
Concept of Compensating Errors

Calibrate Against Case Histories ????



The Missing Link





Fools with tools are still.....fools

(i) Forensic Engineering: Collapse of Building in Shanghai

Client: 华东建筑设计研究院

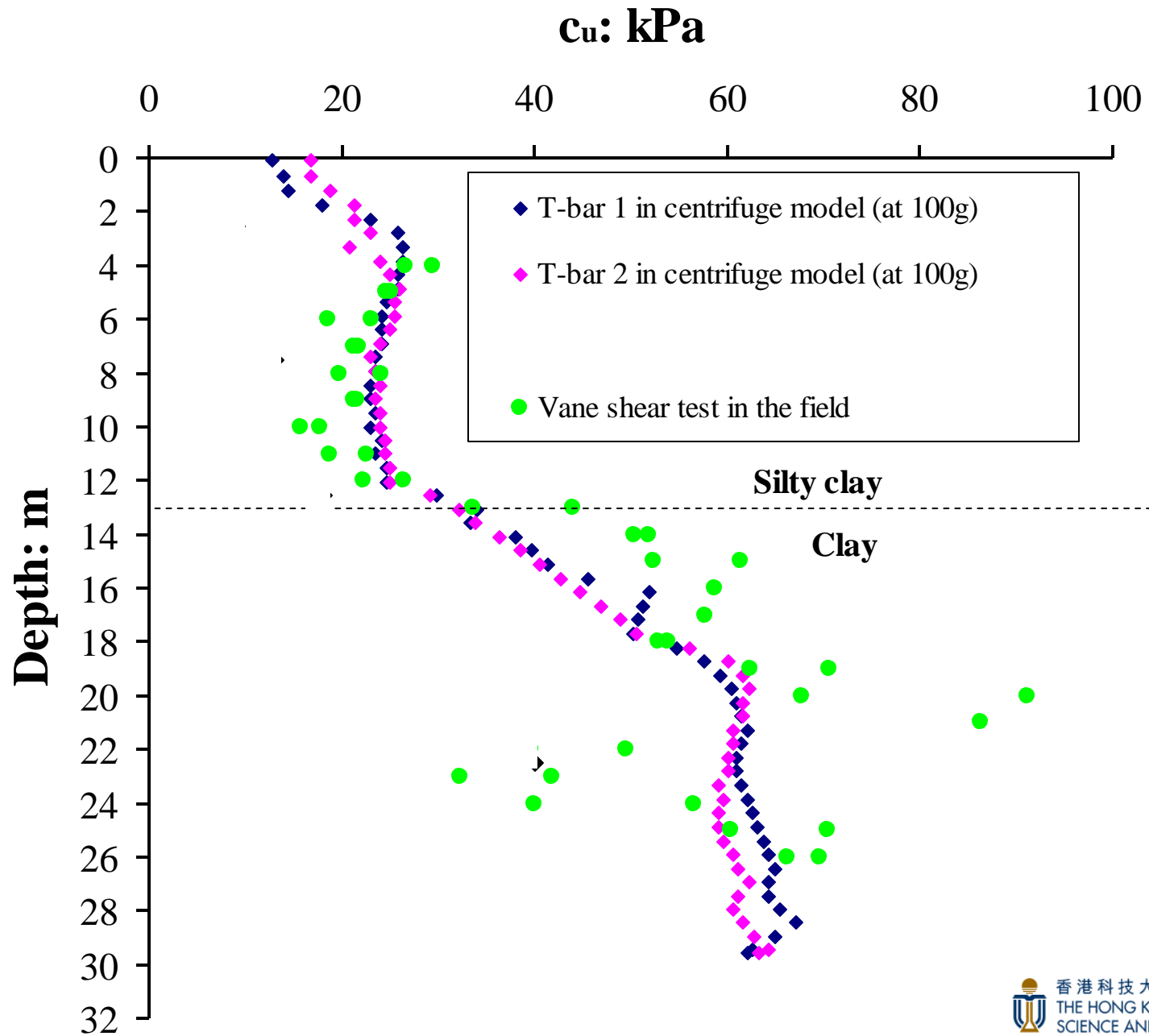
East China Architectural Design & Research Institute Co. Ltd



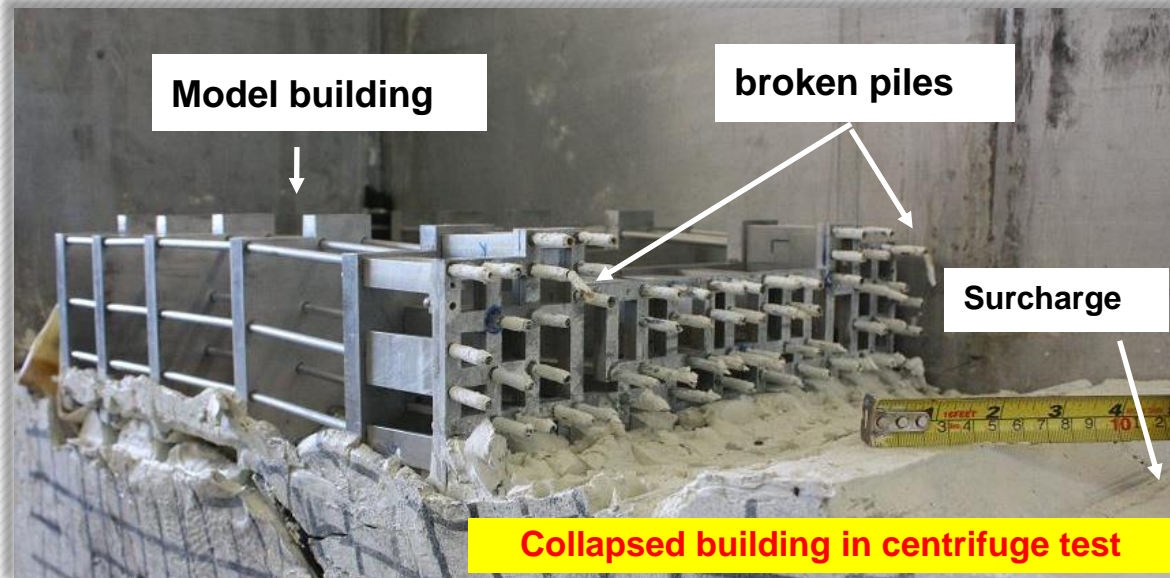
A new 13-storey building collapse
on 27th June 2009 in Shanghai



Comparisons of field and simulated shear strength c_u profiles



Comparison of model and prototype

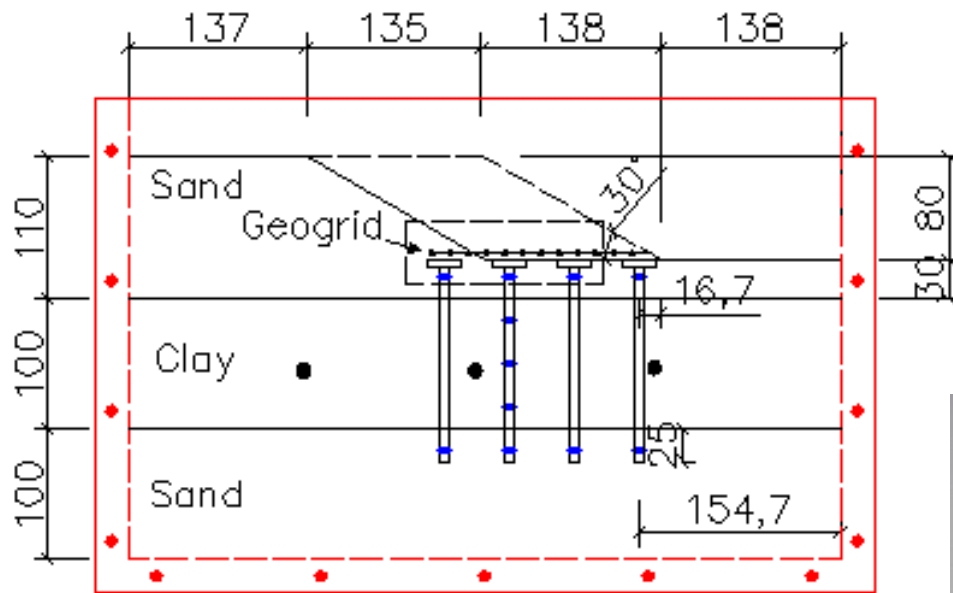


(ii) Embankment widening in soft clay

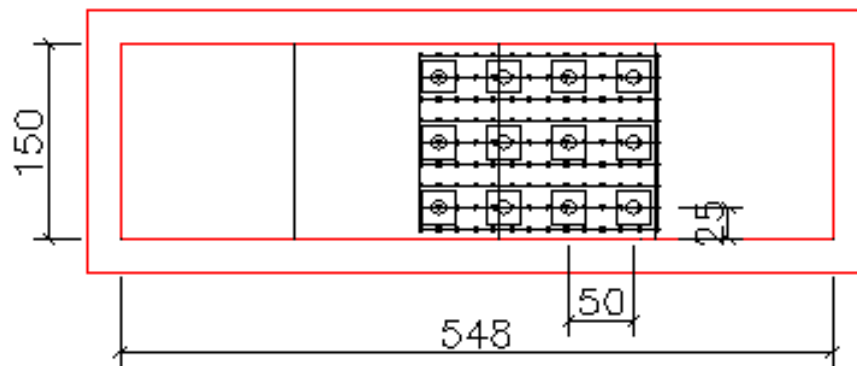
In-flight construction of an embankment at 60g

Two clients from Mainland China

Test setup and instrumentation of a typical test

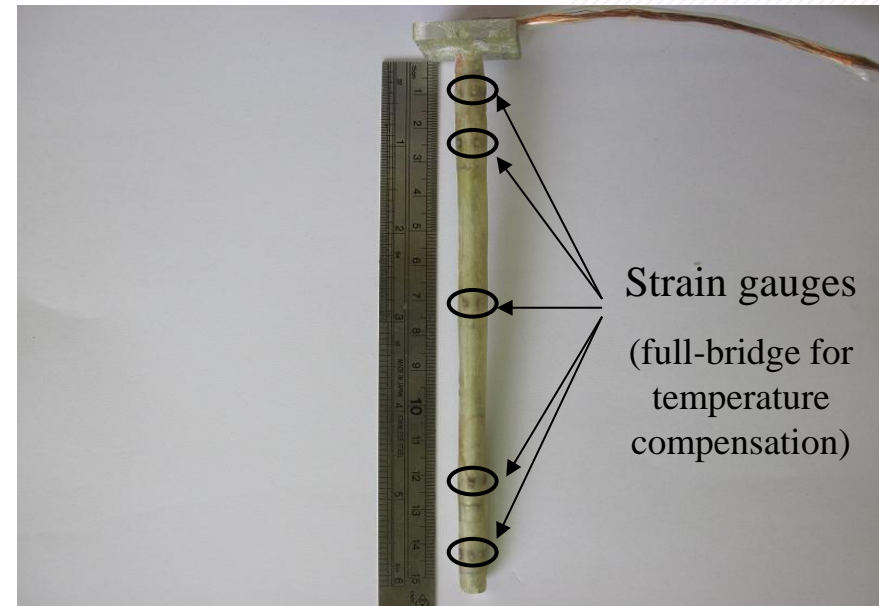


Elevation view (unit: mm)



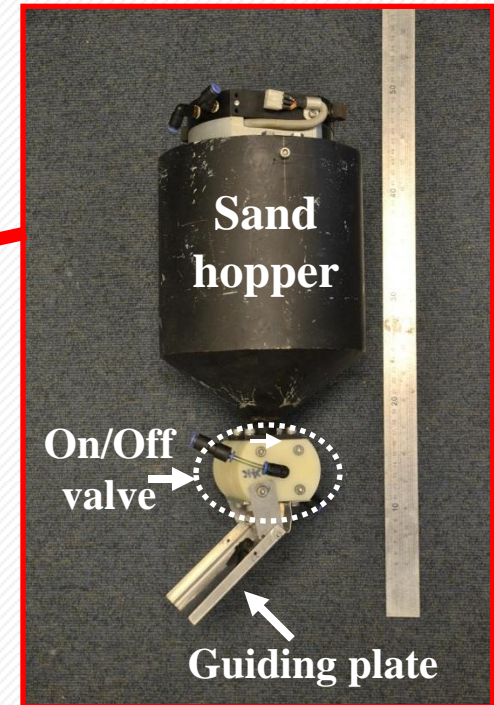
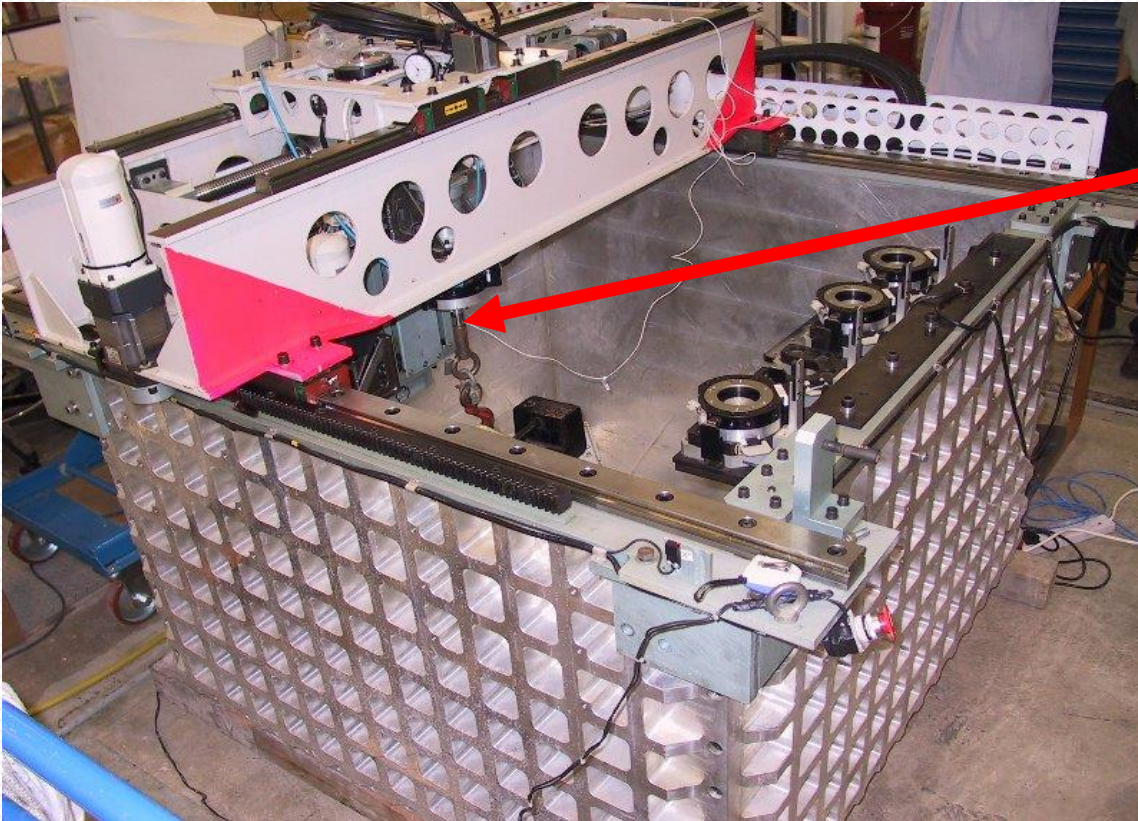
Plan view (unit: mm)

- Pore pressure transducer
- Strain gauge

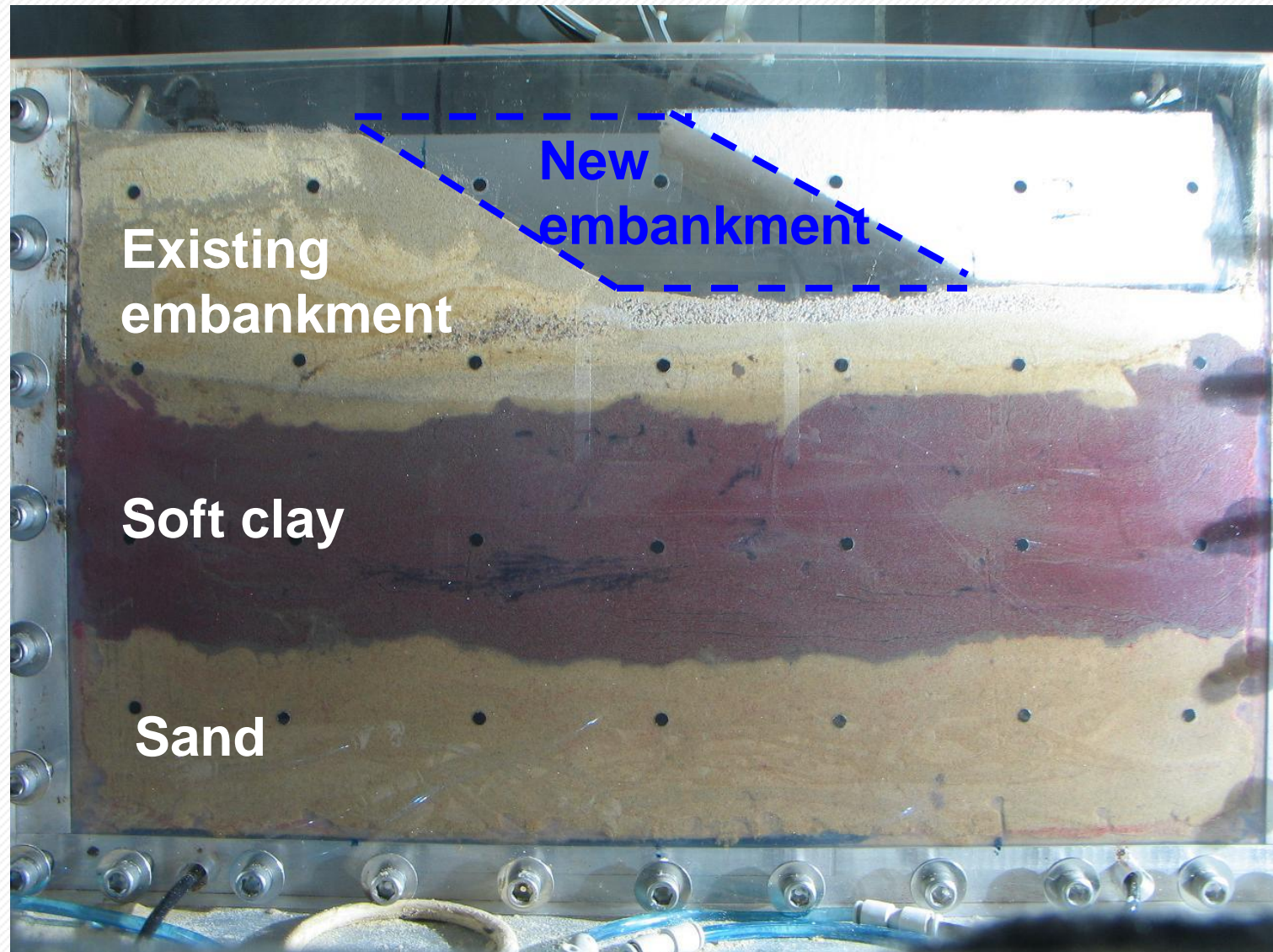


an instrumented model pile

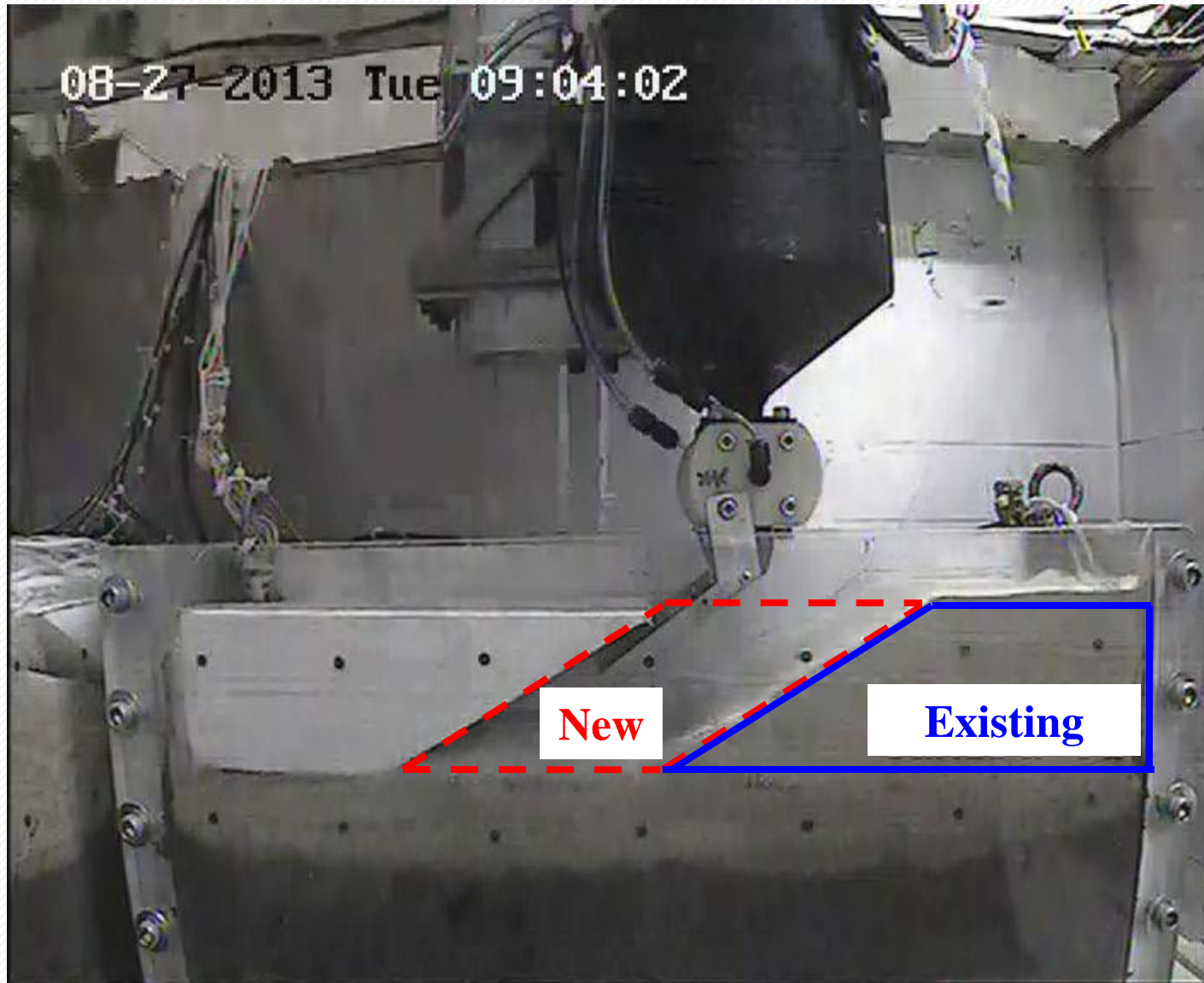
4-axis robotic manipulator and sand hopper



In-flight simulation of embankment construction



Before constructing embankment



After constructing the 1st layer of embankment



After constructing the 2nd layer of embankment



After constructing the 3rd layer of embankment



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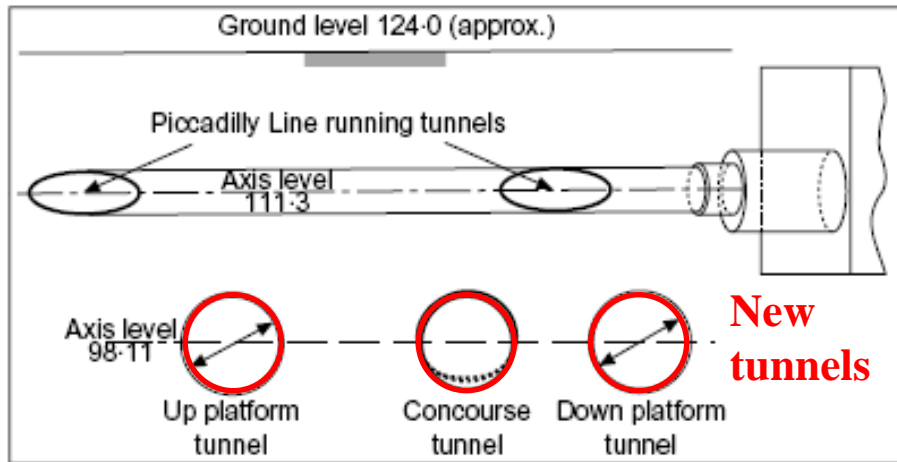


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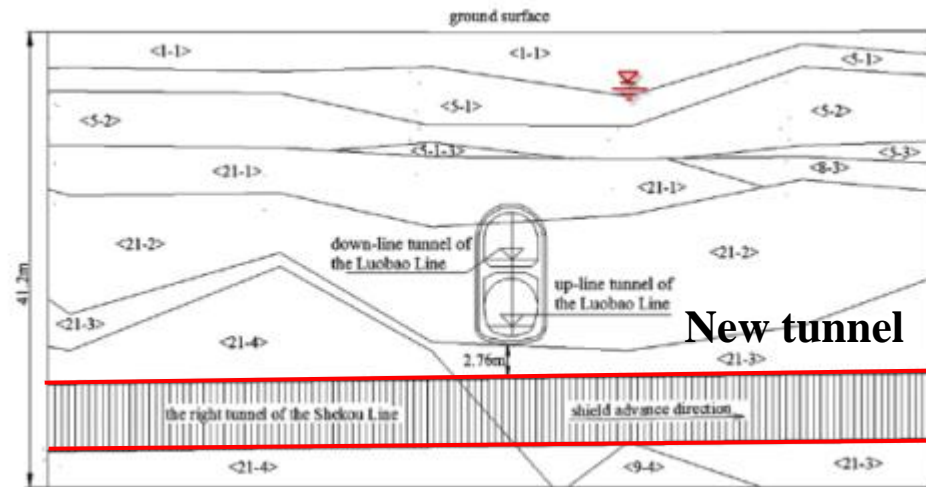
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Background

- **Case histories** (Cooper et al., 2002; Mohamad et al., 2010; Liu et al., 2011; Li and Yuan, 2012)
 - **Large tunnel settlements** [38 mm > 20 mm (BD, 2009)]
 - **Large tunnel gradient** [1: 400 > 1:1000 (LTA, 2000)]
 - **Cracks on tunnel linings and tunnel distortion**



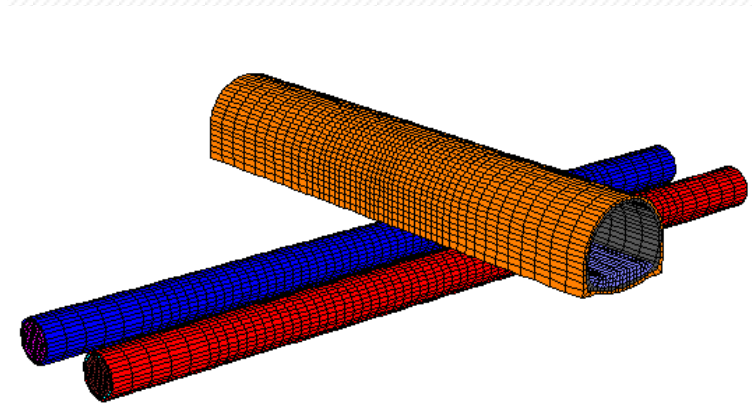
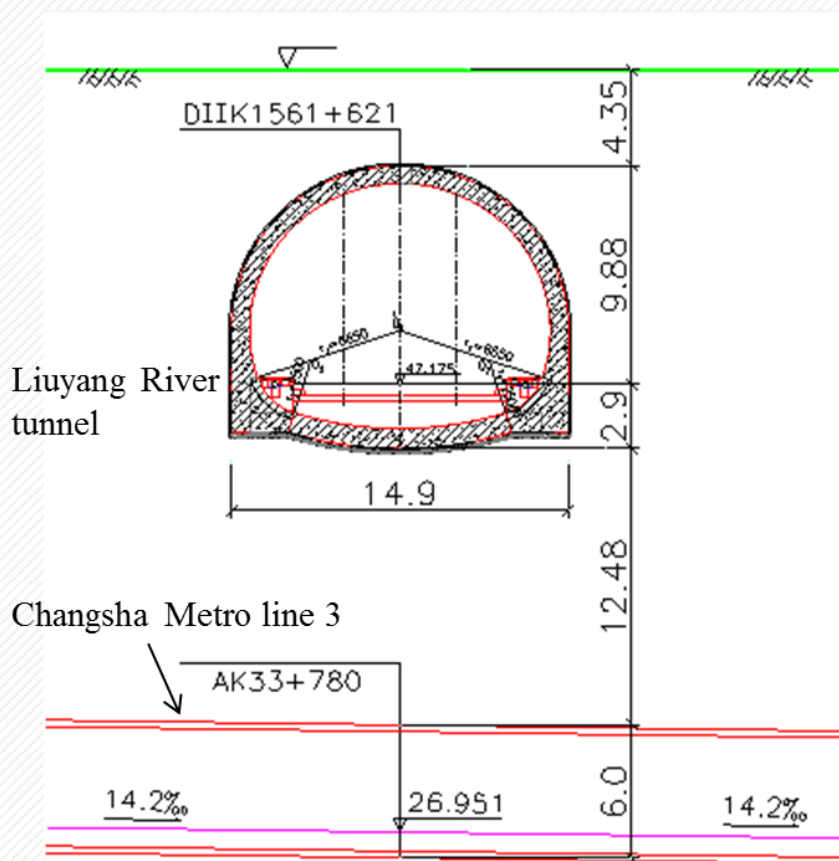
(Cooper et al., 2002)



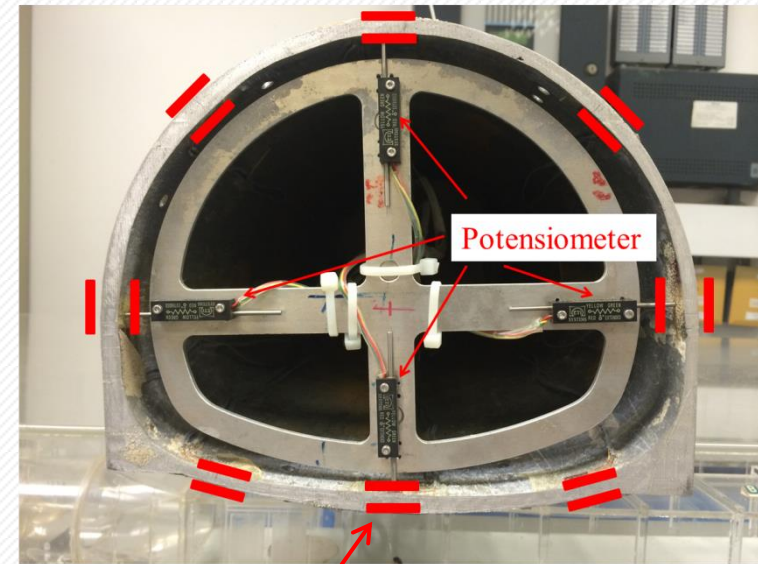
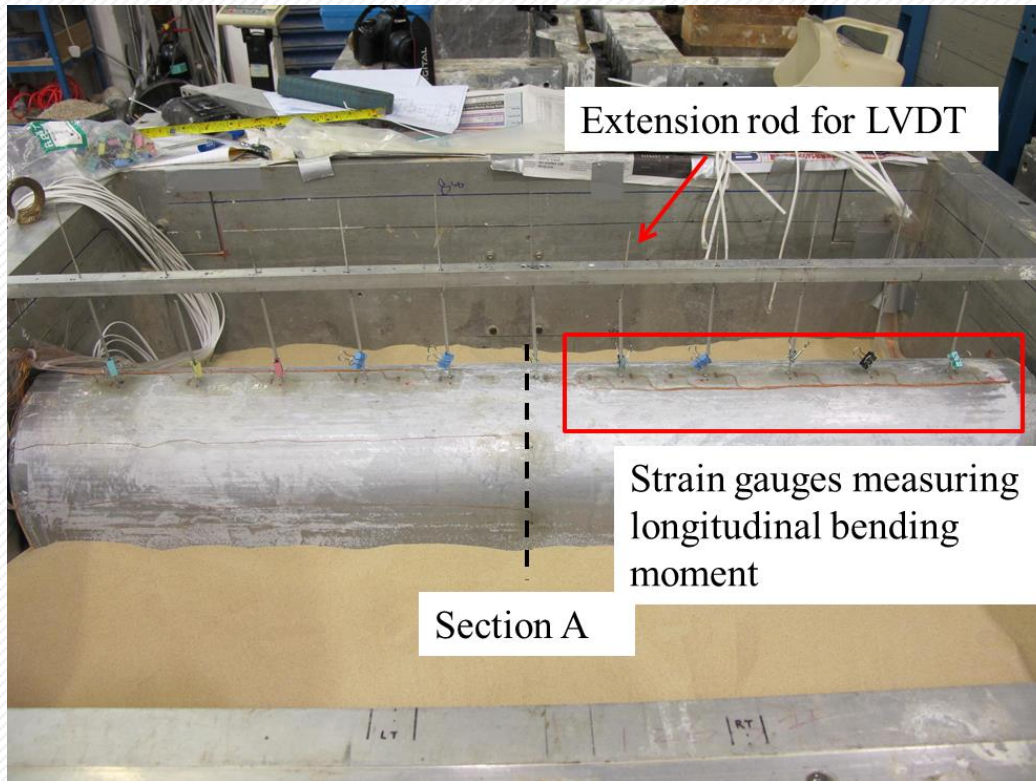
(Li and Yuan, 2012)

Wuhan-Guangzhou high speed railway - Changsha Metro Line 3

- New Changsha Metro Line 3 (twin tunnels) is being constructed undercrossing the existing Liuyang River tunnel.
- Deformation and stress control is vital to ensure the safety and serviceability of Wuhan-Guangzhou high speed railway that inside the Liuyang River tunnel.



Instrumentation of existing horse-shoe shaped tunnel

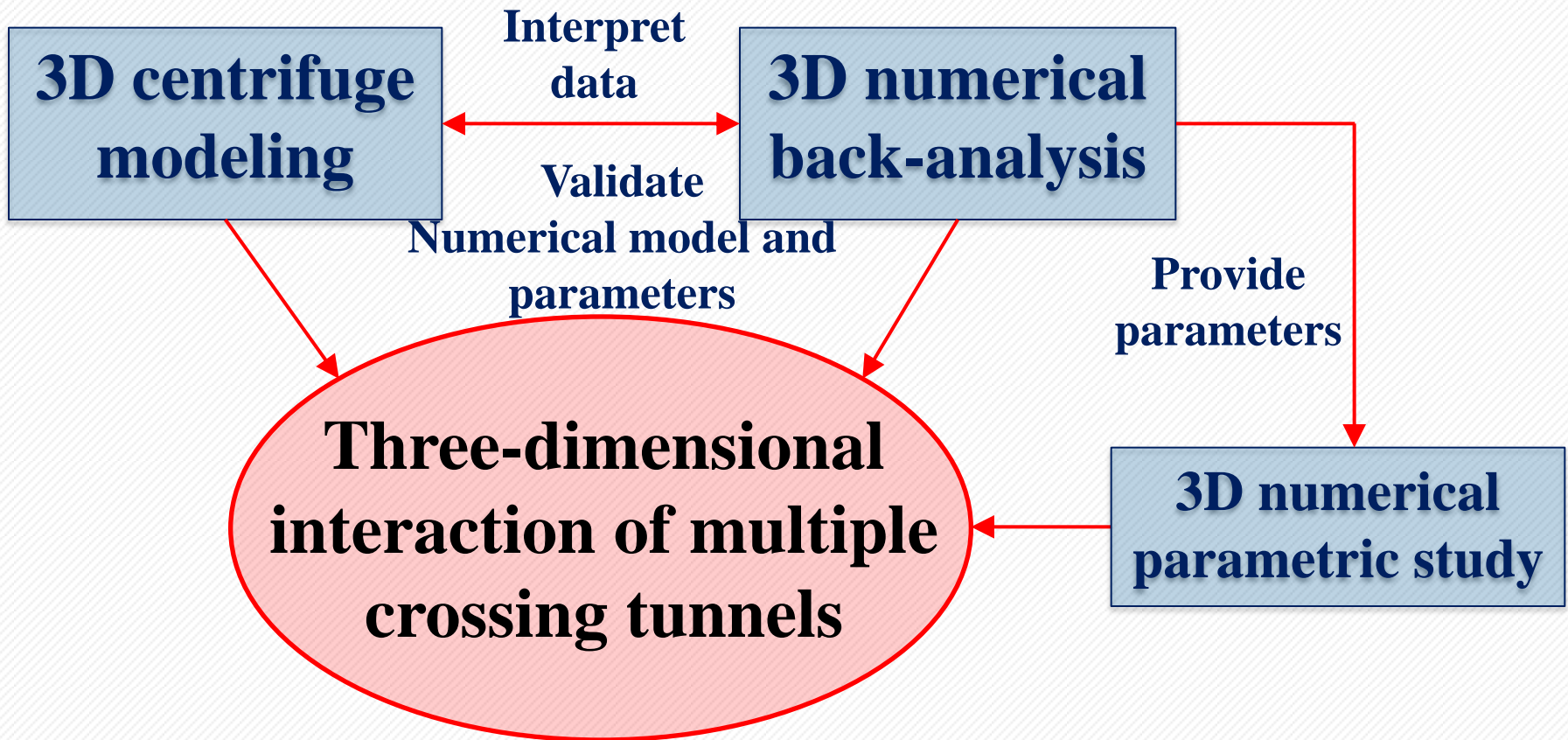


Strain gauges measuring transverse bending moment (every 45°)

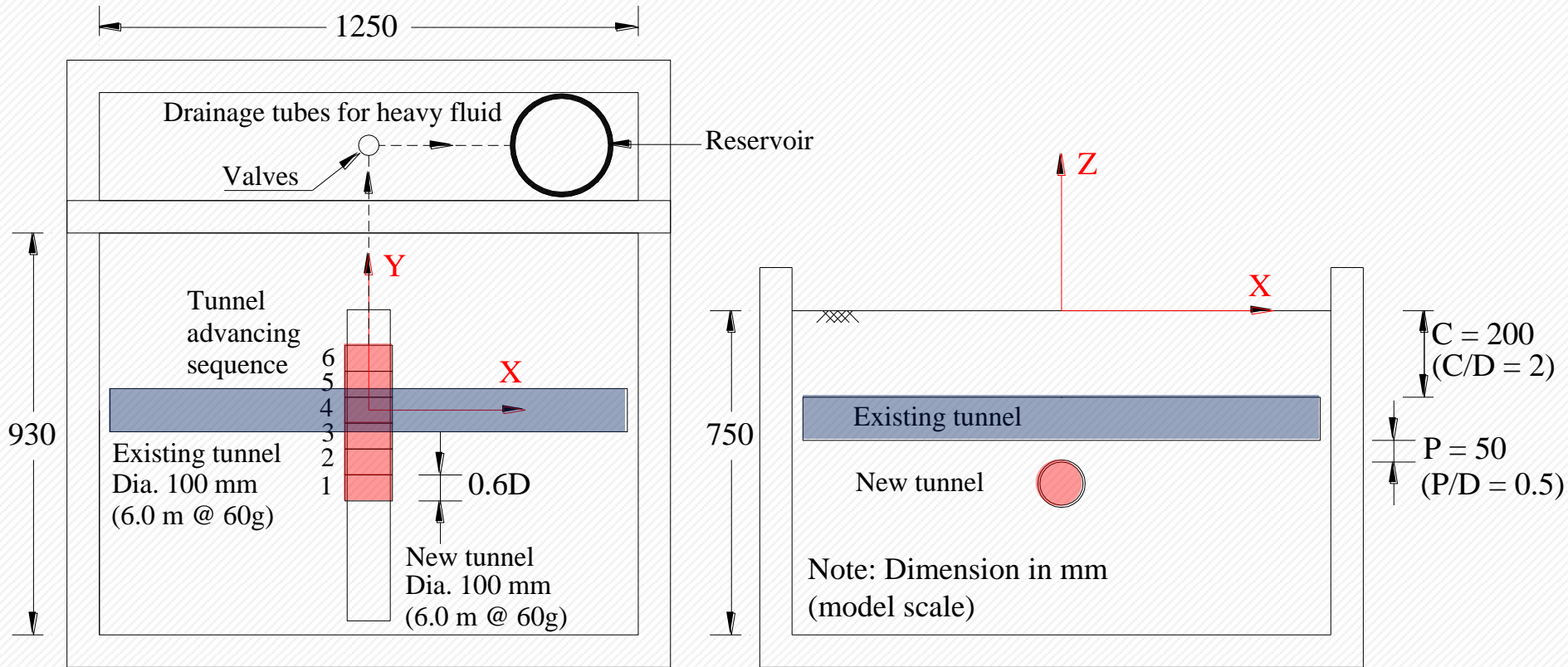
Objectives

- To investigate factors affect ground movements, existing tunnel and stress induced by **crossing-tunnel interactions**
- **Factors investigated**
 - Construction sequences
 - Cover depth of tunnels (C/D)
 - Pillar distance between tunnels (P/D)
 - Shielding effects
 - Shape of an existing tunnel

Research strategy



Typical centrifuge model package

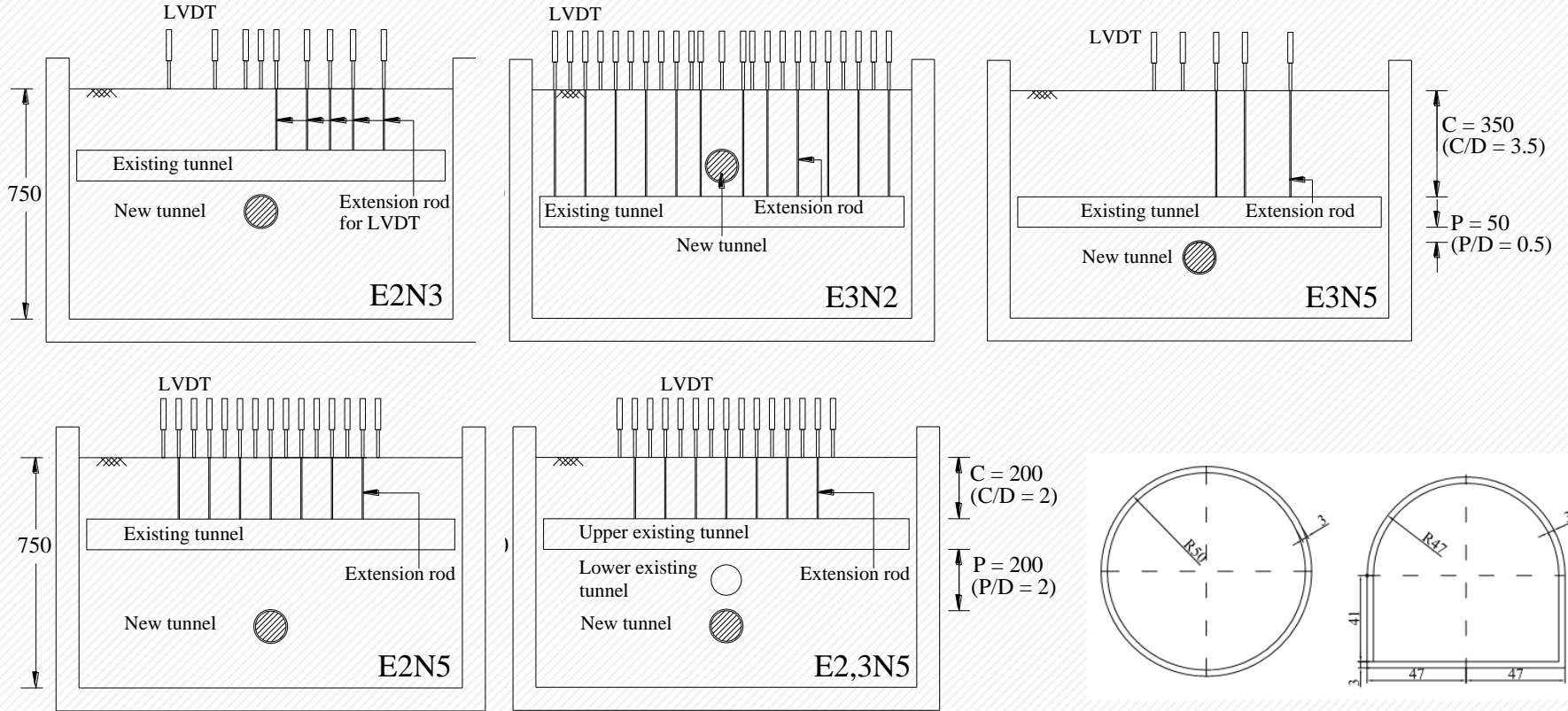


(a) Plan

(b) Elevation

- Tunnel diameter (D) = **6 m** in prototype (at 60g)
- Wished-in-place existing tunnel
- **Three-dimensional in-flight tunnel advancement in six stages**

Summary of centrifuge tests at 60g



Existing tunnel

E2N5

E2N5-H

Note: **E2N3** **E=Existing N=New**

└── C/D of new tunnel

└── C/D of existing tunnel

C/D denotes cover depth-to-diameter ratio

Modeling of tunnel excavation and advancing sequences

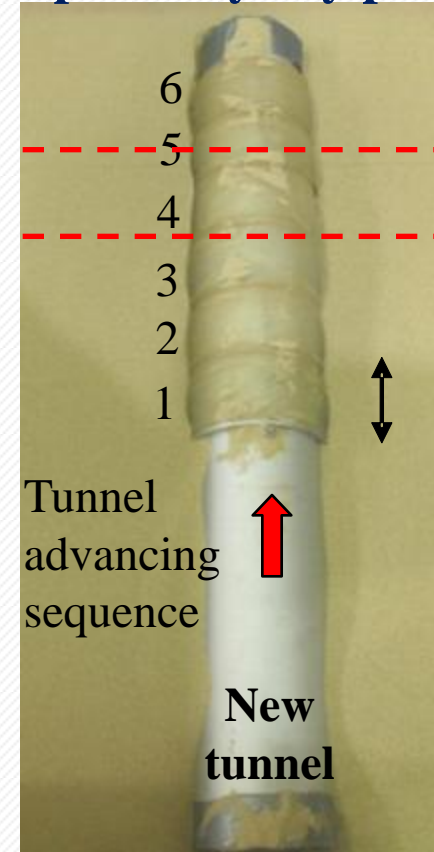
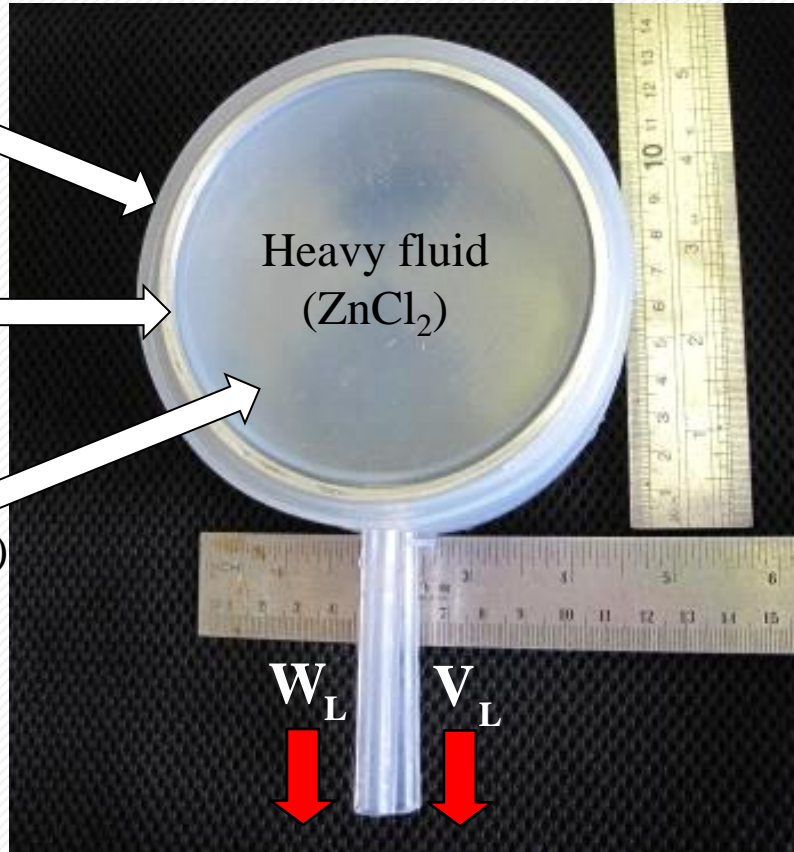
Dry Toyoura Sand, $D_r = 65-66\%$
Prepared by dry pluviation

Outer rubber
Membrane
(Volume loss)

$$V_L = 2\%$$

Tunnel lining

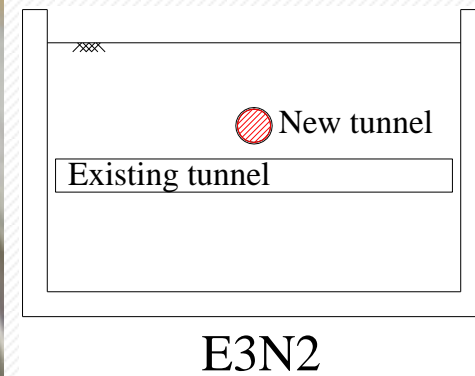
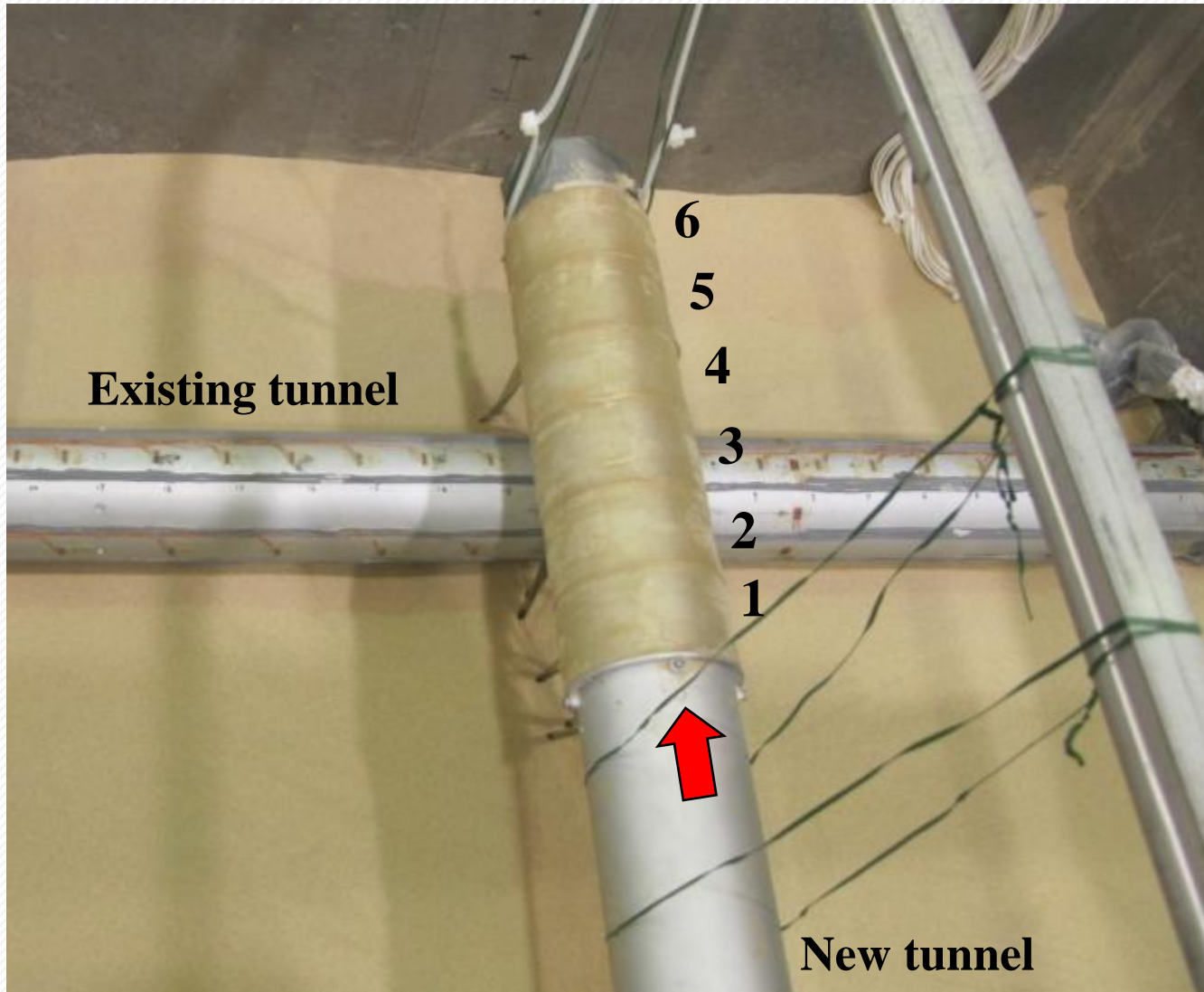
Inner rubber bag
(Weight loss, W_L)



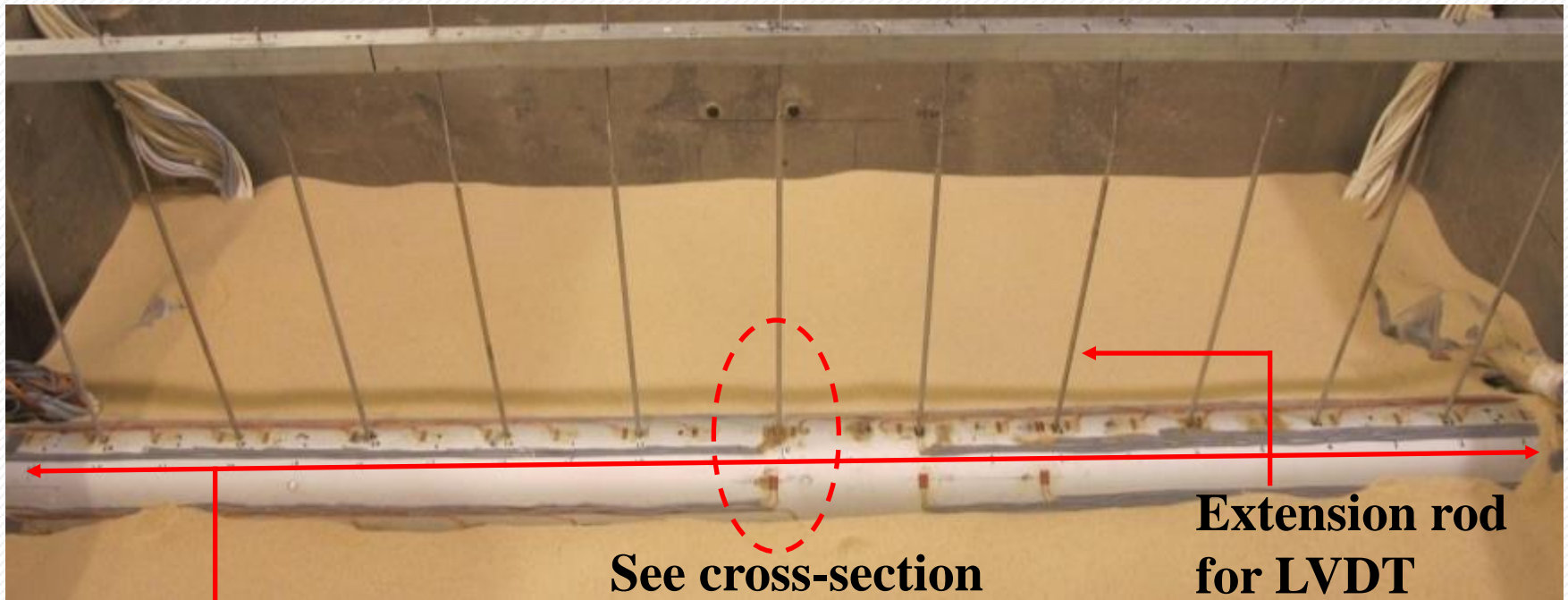
(a) “Donut” for simulating volume and weight losses in tunnel excavation

(b) Tunnel advancing sequence in centrifuge

A new tunnel excavation above an existing tunnel

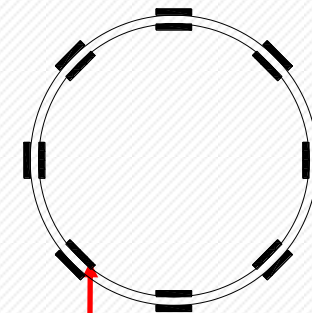
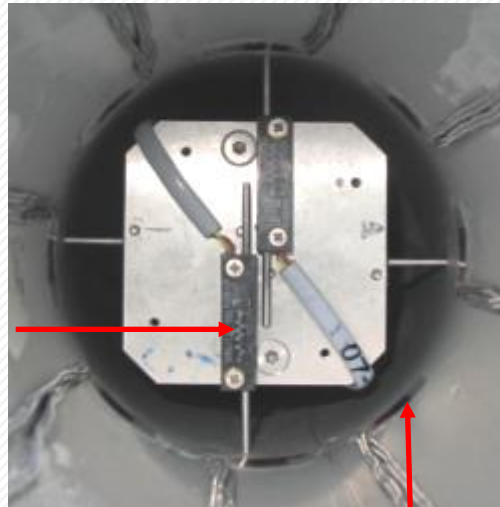


Instrumentation on existing tunnel



Strain gage in the longitudinal direction

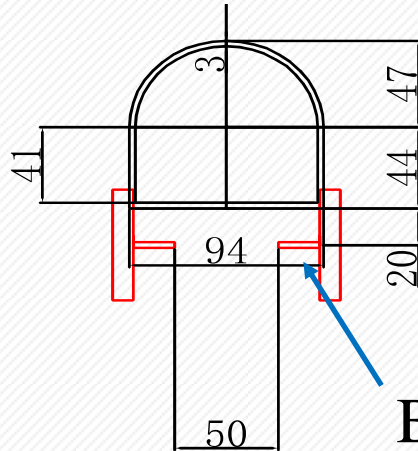
Potentiometer



Cross-section

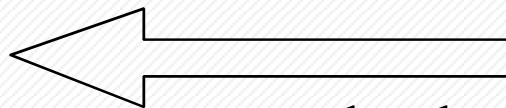
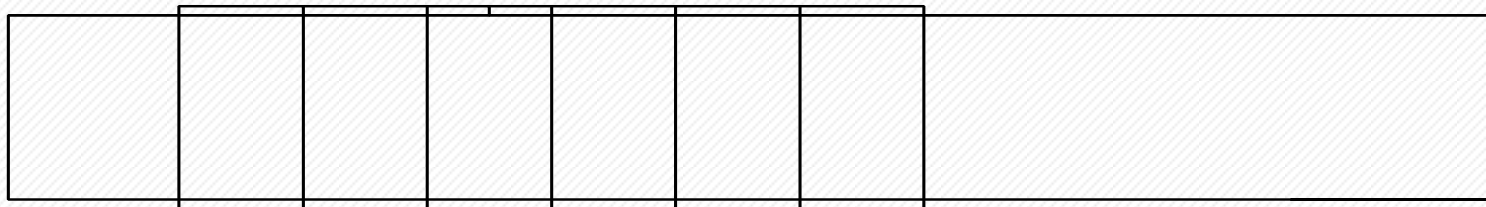
Strain gage in the transverse direction

Bender elements



existing
tunnel

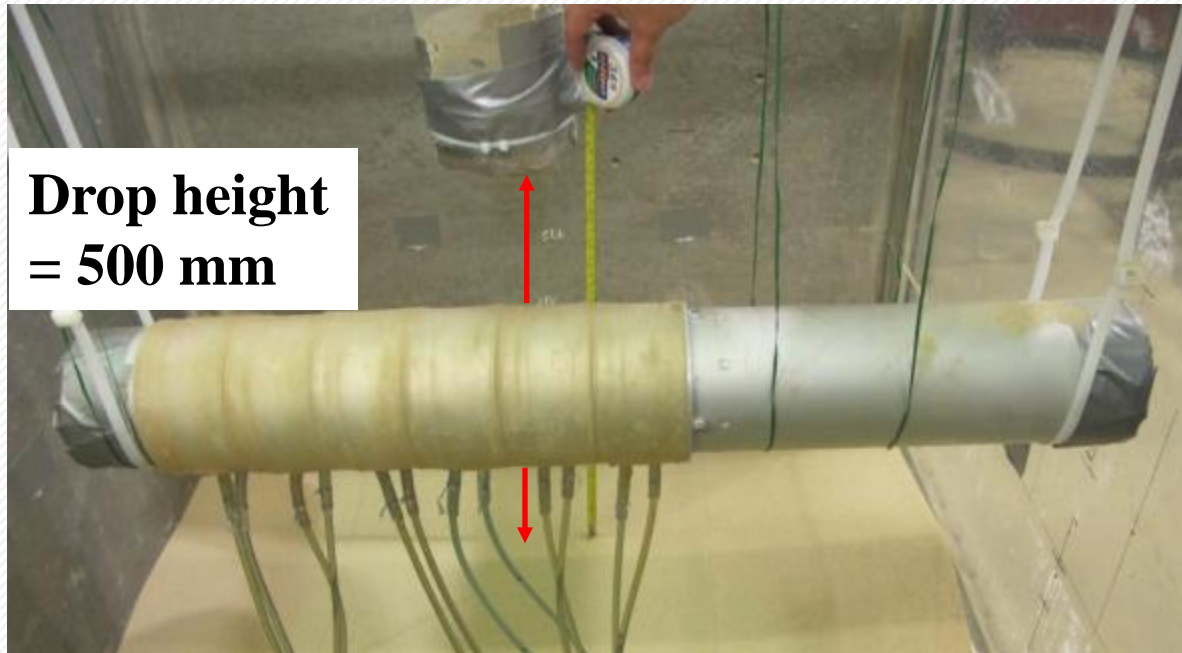
Bender element



tunnel advancing
direction

(first time used in tunnelling centrifuge tests)

Model preparation



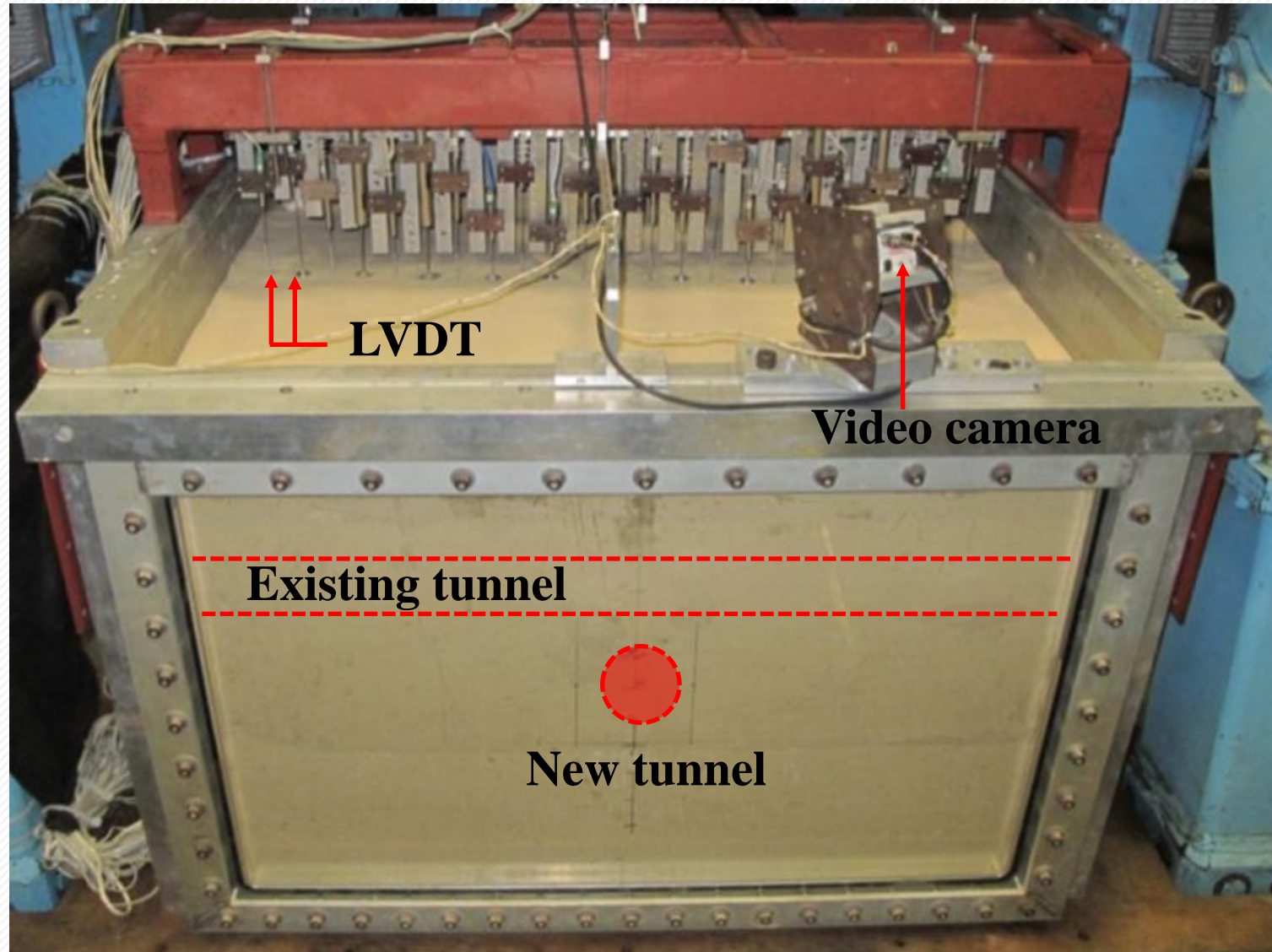
- Dry Toyoura sand
- Pluviation method or “sand raining”
- Density (ρ_d) = 1529 - 1535 kg/m³ (D_r = 64-66%)

Grain size effect:
not significant

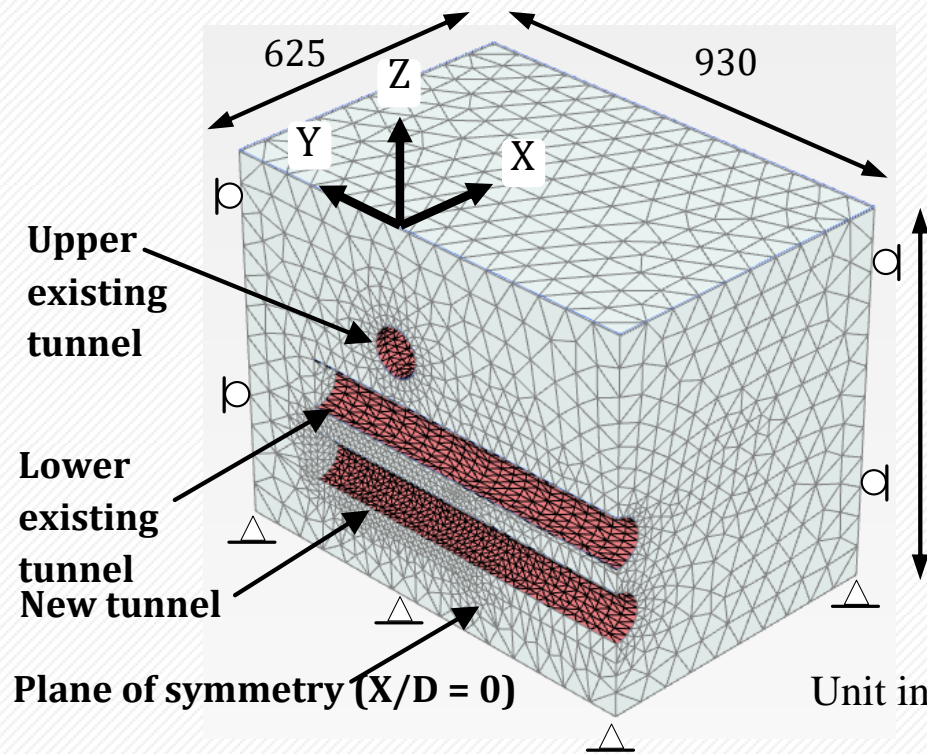
$D_{\text{tunnel}} / D_{50, \text{sand}} = 588 > 175$
(Garnier et al., 2007)

Variation in dry density:
 $\Delta\rho_d \leq 8 \text{ kg/m}^3$ (Garnier, 2001)

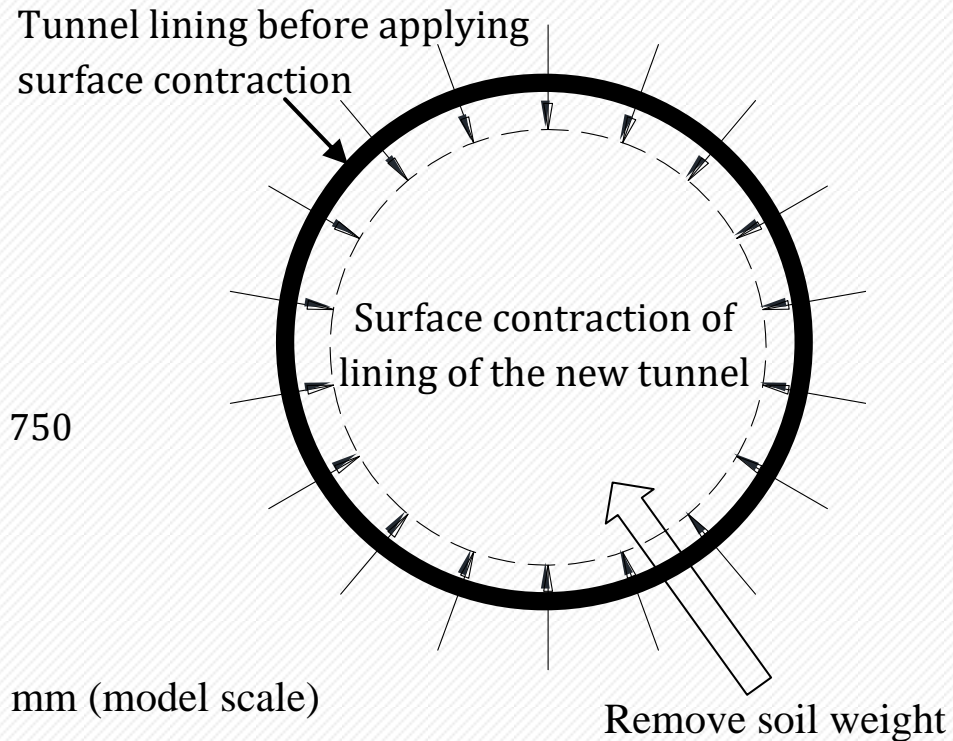
Overview of a centrifuge model package



3D Numerical back-analysis & parametric study



(a) Finite element mesh

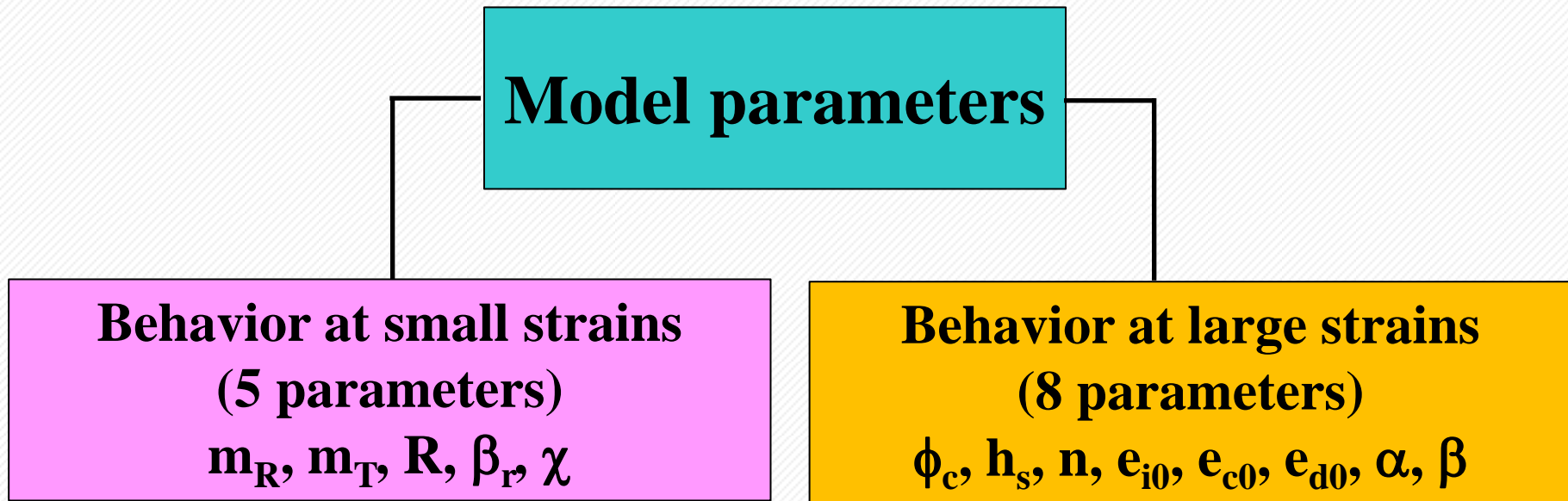


(b) Tunnel excavation simulation

- **Finite element software:** PLAXIS 3D
- **Geometry:** Identical to that in each centrifuge test
- **Constitutive model:** Hypoplasticity constitutive model with small strain stiffness (von Wolffersdorff, 1996; Niemunis and Herle, 1997; Mašín, 2012)

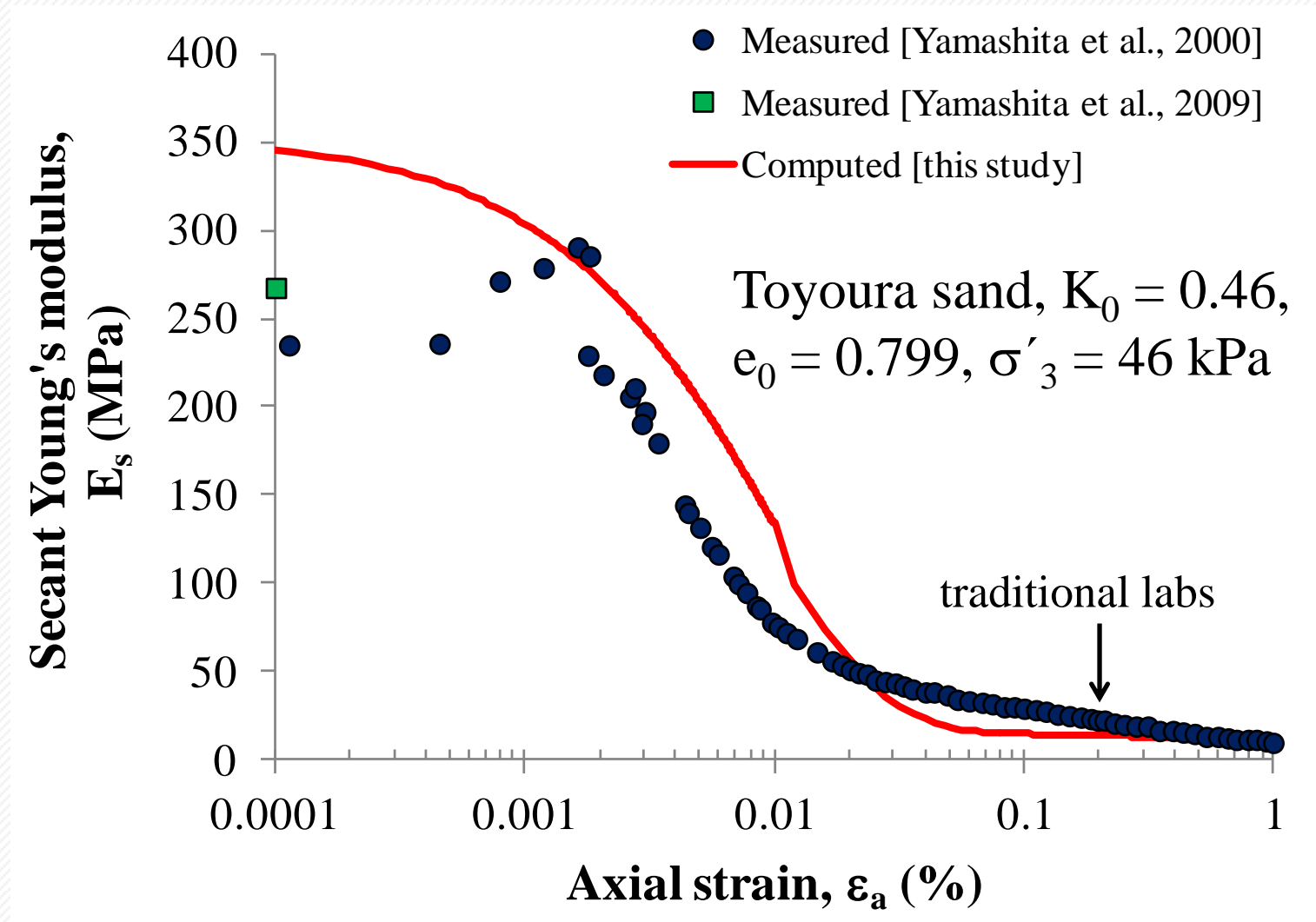
General description of hypoplasticity constitutive model

- **Key strength:** capability of simulating **path-dependent, strain dependent soil stiffness** of soil at small strains (less than 0.01%)



Model parameters: Herle and Gudehus (1999); Yamashita et al. (2000, 2009)

Calibration of small strain stiffness parameters



Centrifuge and numerical modeling procedures

Centrifuge test procedures

Model preparation in 1g



Increase centrifugal acceleration to 60g



Tunnel excavation:
Remove heavy fluid from each
“Donut” one after another



Spin down to 1g

Numerical analysis procedures

Initialize the numerical model in 1g



Increase g-level to 60



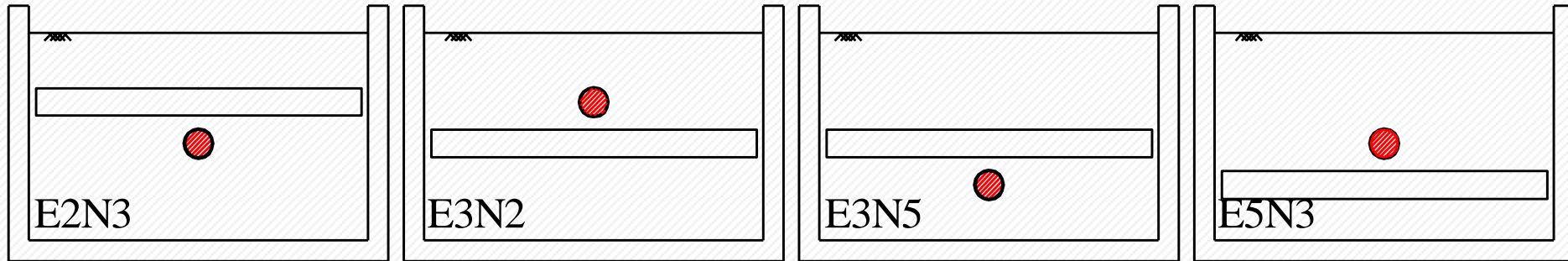
Tunnel excavation:
Volume loss:
Surface contraction ($V_L = 2\%$)
Weight loss:
Remove soil inside the new tunnel

Interpretation of results

- **All results are in prototype scale unless stated otherwise**

Influence of **construction sequence** and **cover depth** on the interaction of crossing tunnels

Where will you excavate your new tunnel ? Why ?



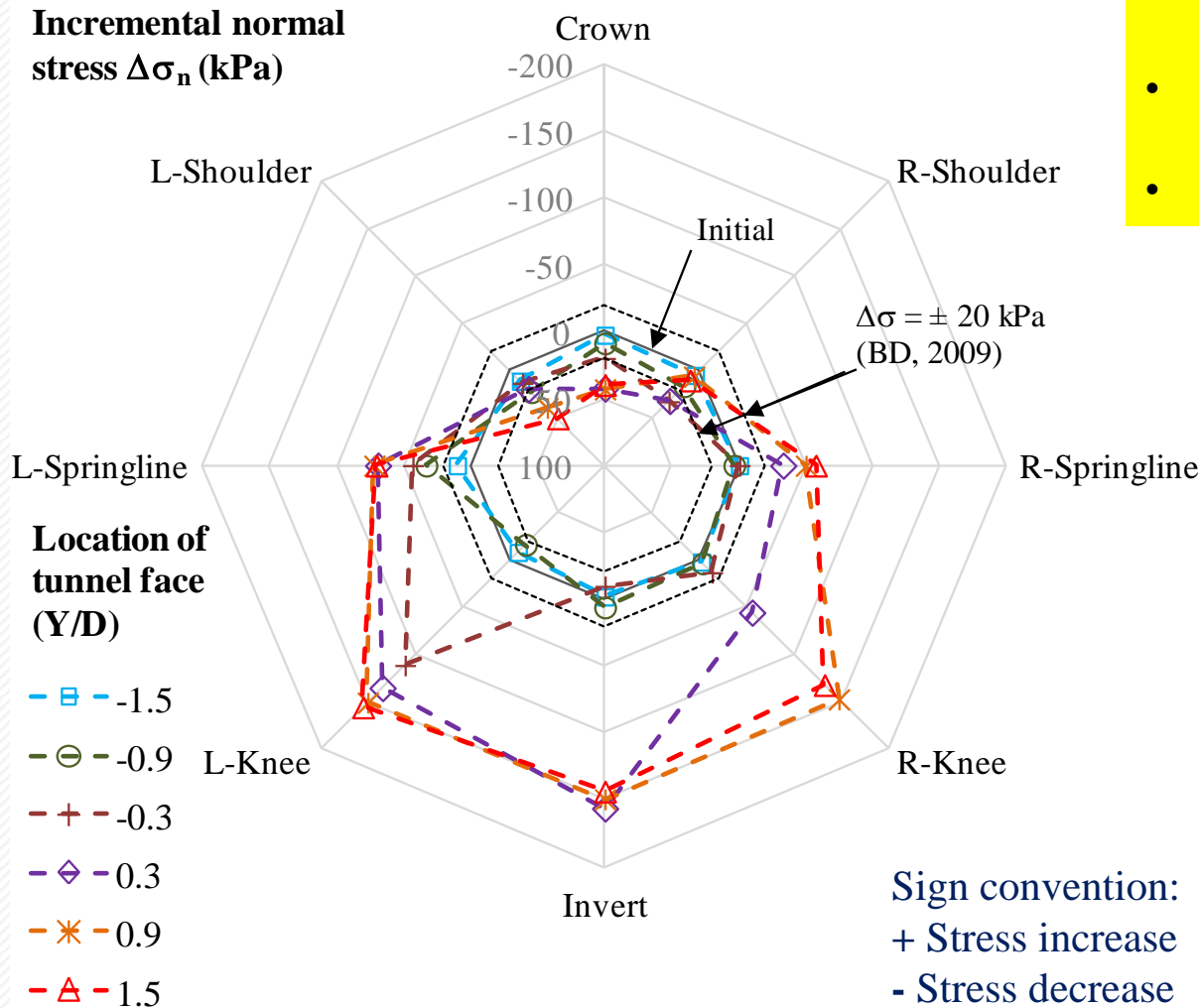
Note: **E2N3** **E=Existing N=New**



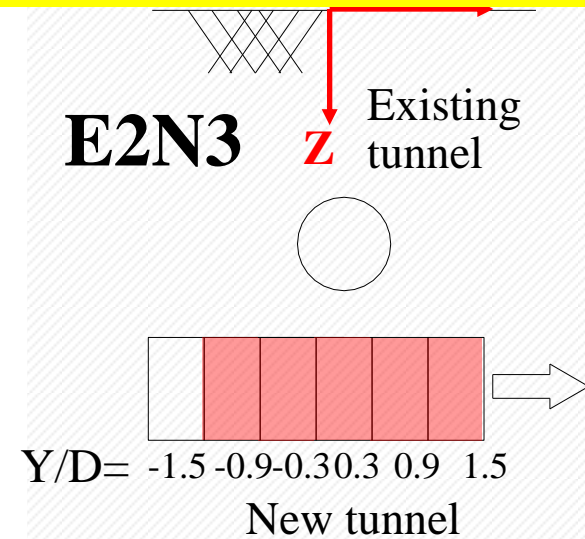
C/D of existing tunnel

C/D denotes cover depth-to-diameter ratio

3D stress transfer mechanism during new tunnel advancement



- Non-symmetric stress transfer and influence
- Stress relief below shoulders but increase above
- Exceed BD criterion



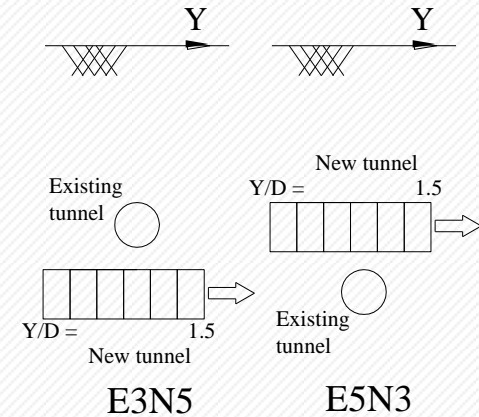
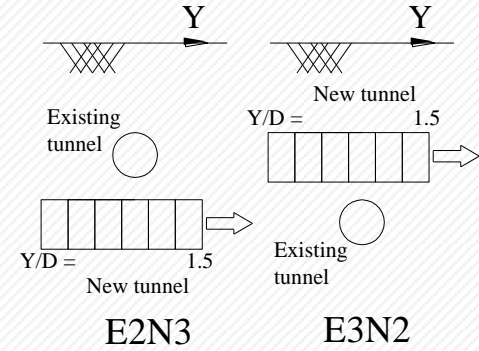
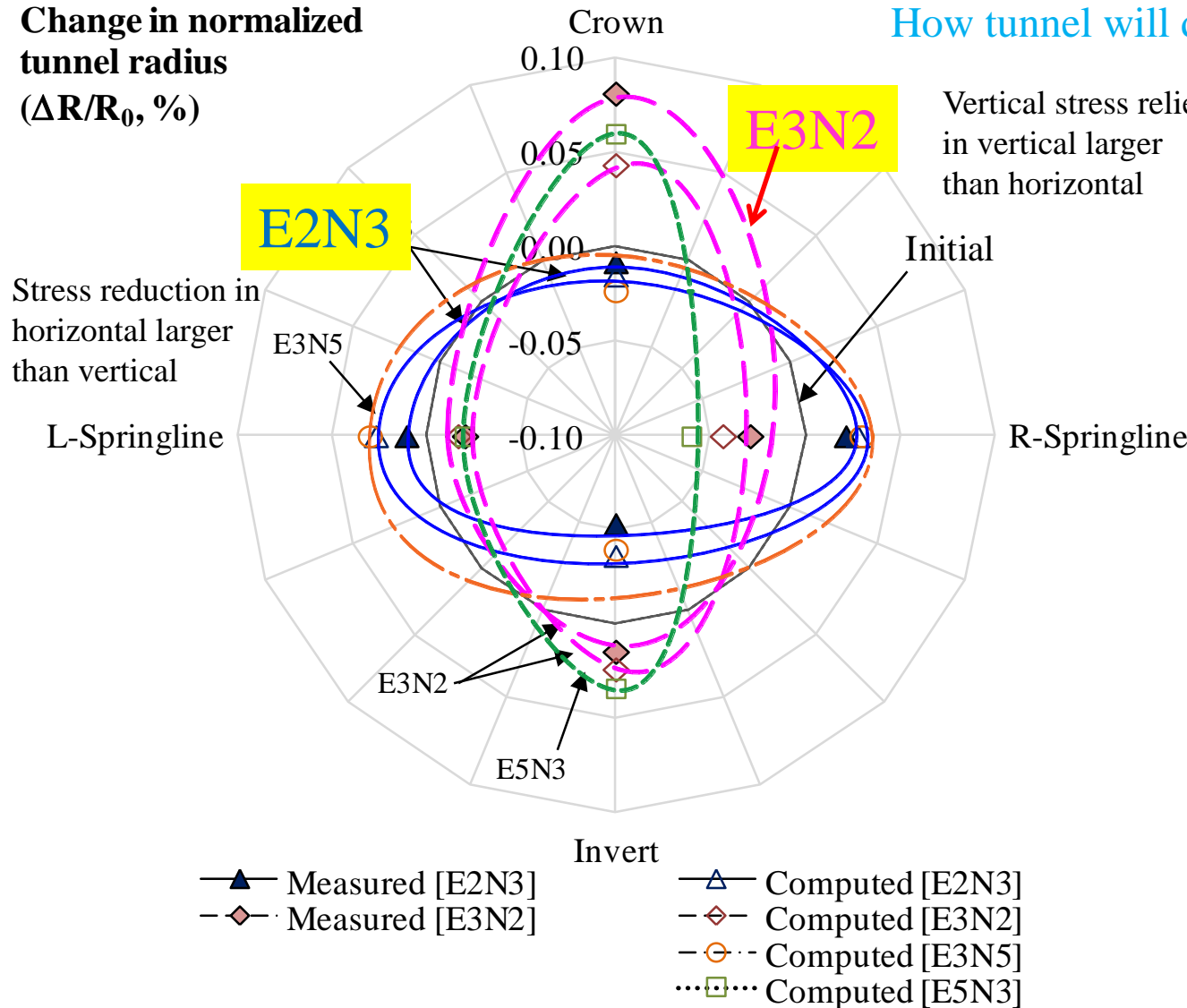
Influence of tunnel excavation = 1.5D

Result at different locations of tunnel face (Y/Ds)

Deformation of existing tunnel

Change in normalized tunnel radius ($\Delta R/R_0, \%$)

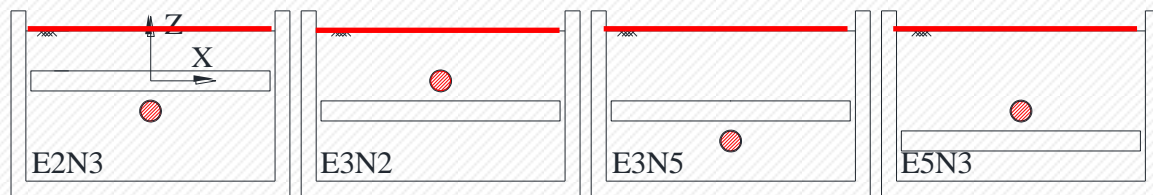
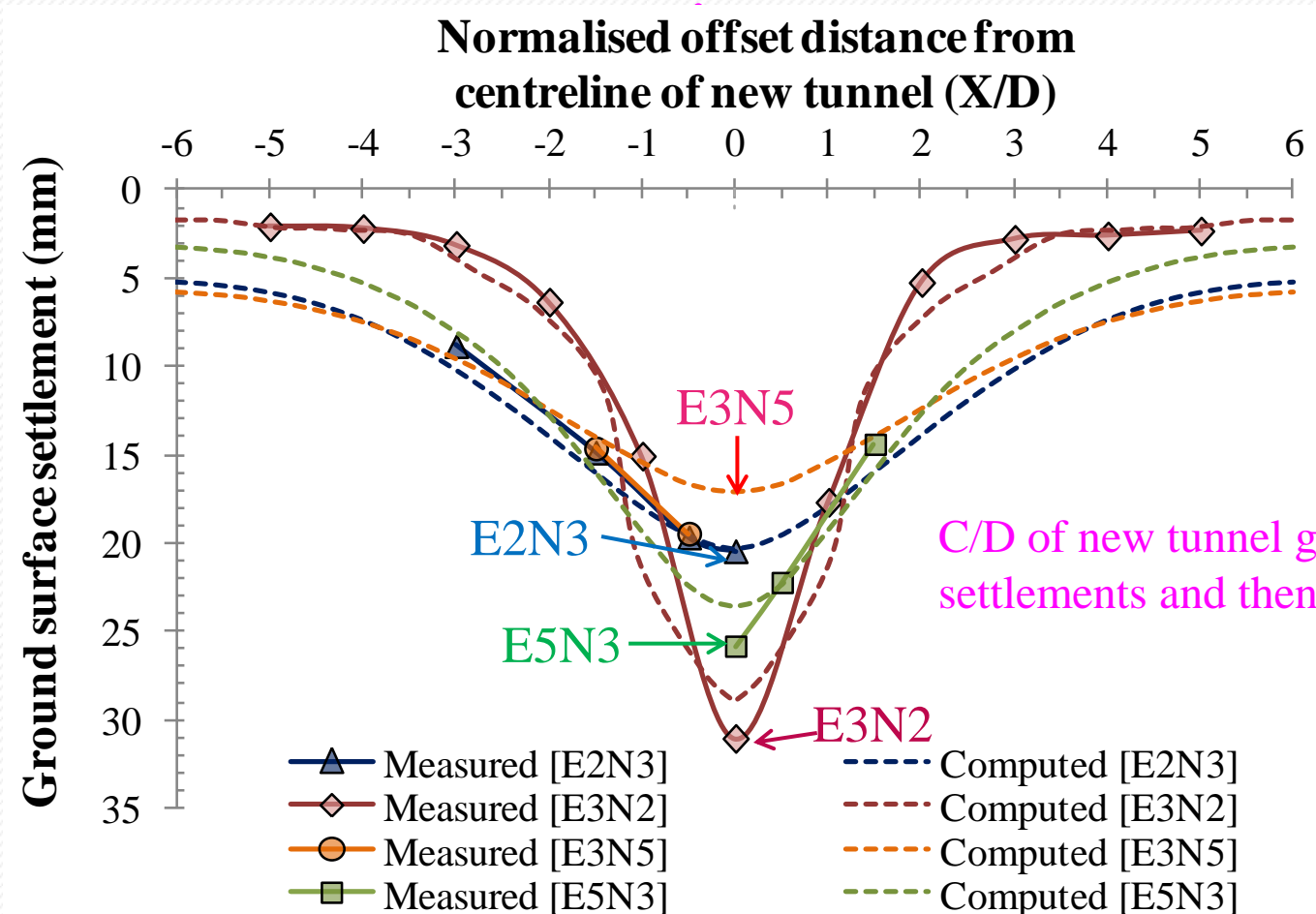
How tunnel will deform (E2N3 vs E3N2) ?



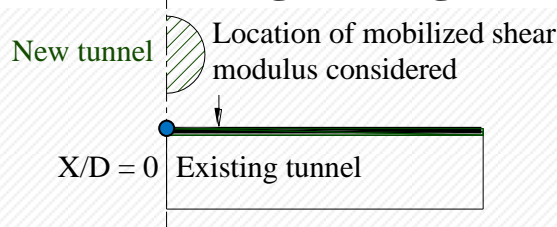
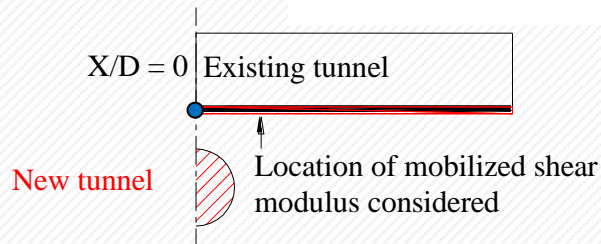
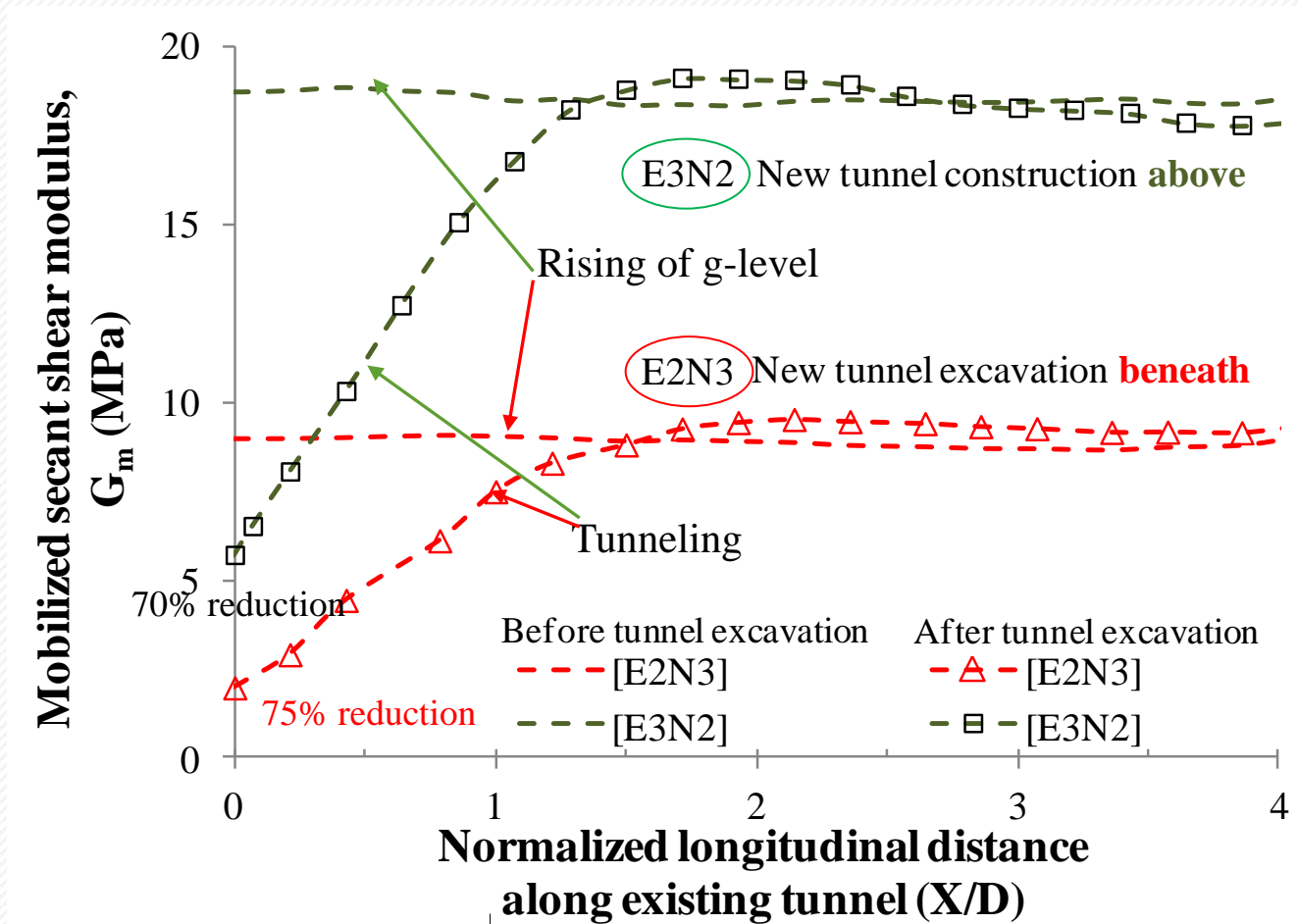
Sign convention of $\Delta R/R_0$
 + Tunnel radius increase
 - Tunnel radius decrease

$$(D_{\max} - D_{\min})/D_0 \leq 2\% \text{ (BTS, 2000)}$$

Ground surface settlements at the end of tunnelling



Mobilized shear modulus of soil along the existing tunnel

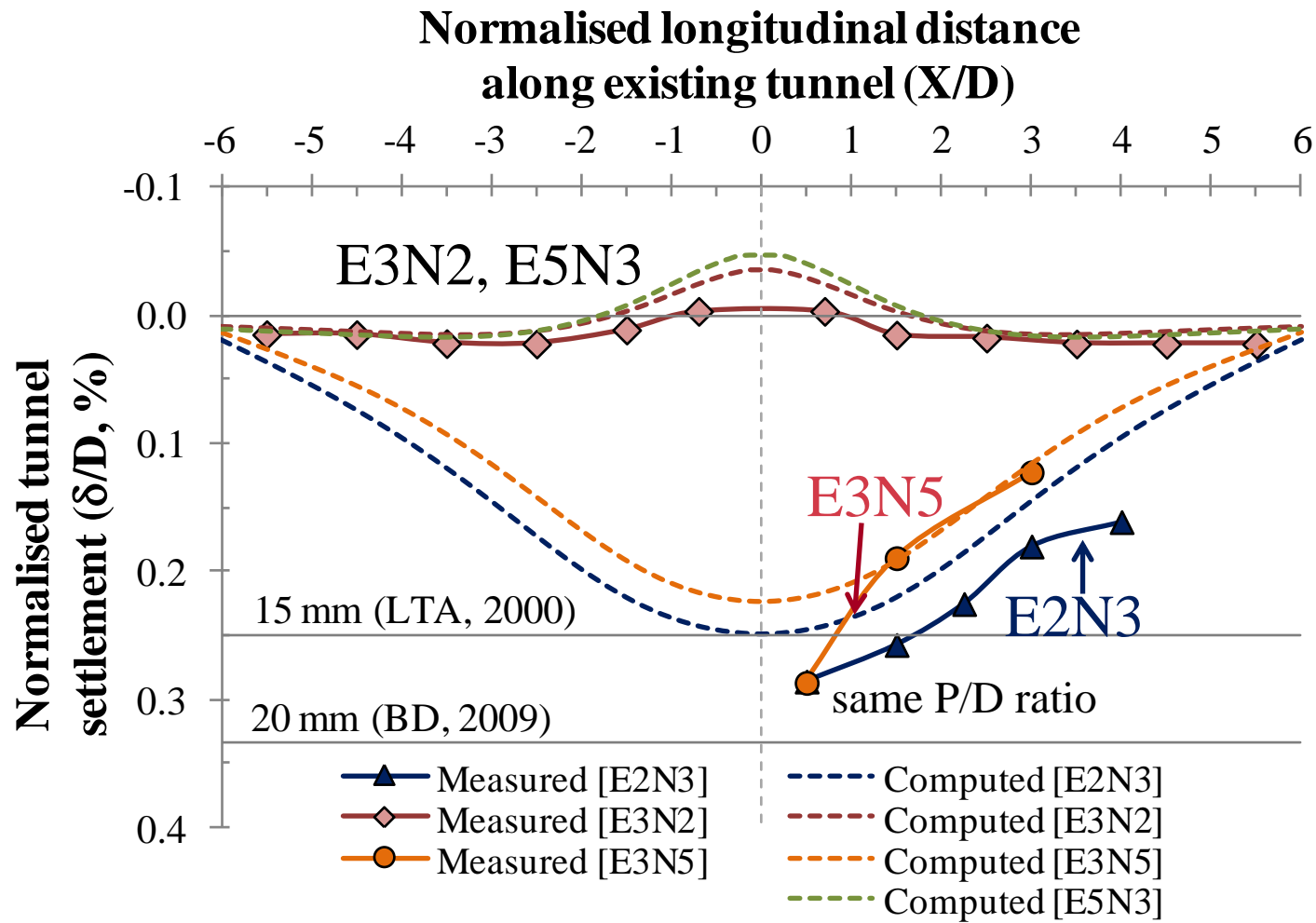


Influence zone = 1.5D

For Tests E2N3

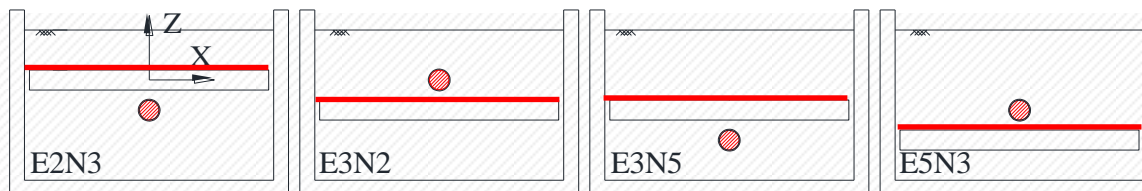
For Tests E3N2

Crown displacement existing tunnel at the end of tunnelling



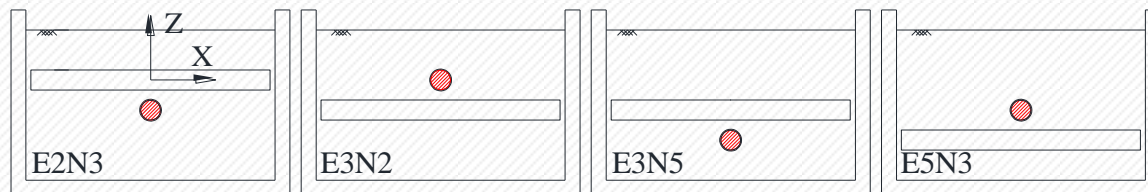
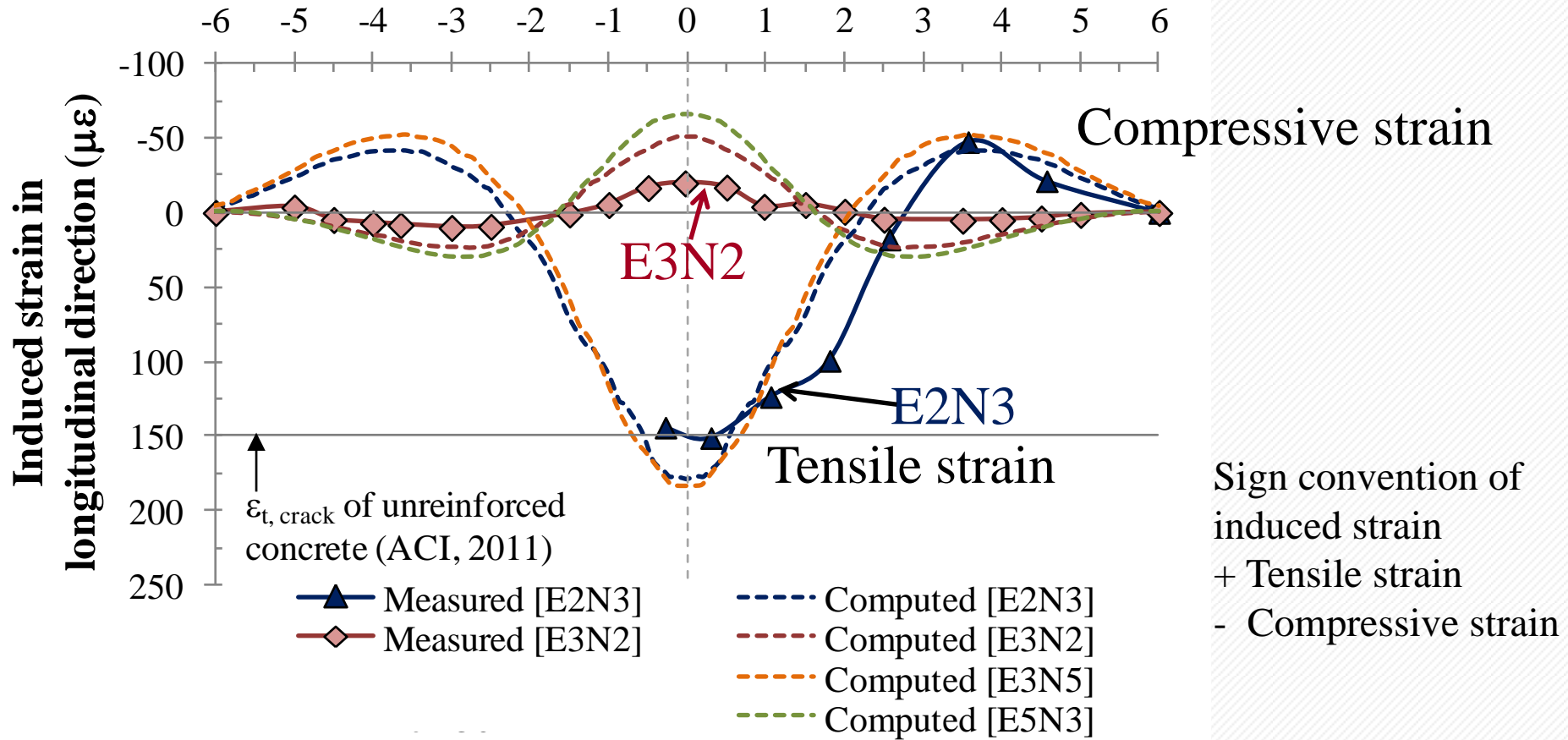
Heave
E3N2, E5N3

Settlement
E2N3, E3N5

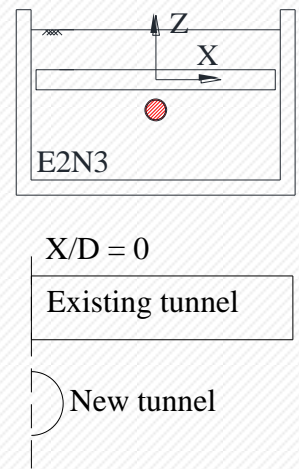
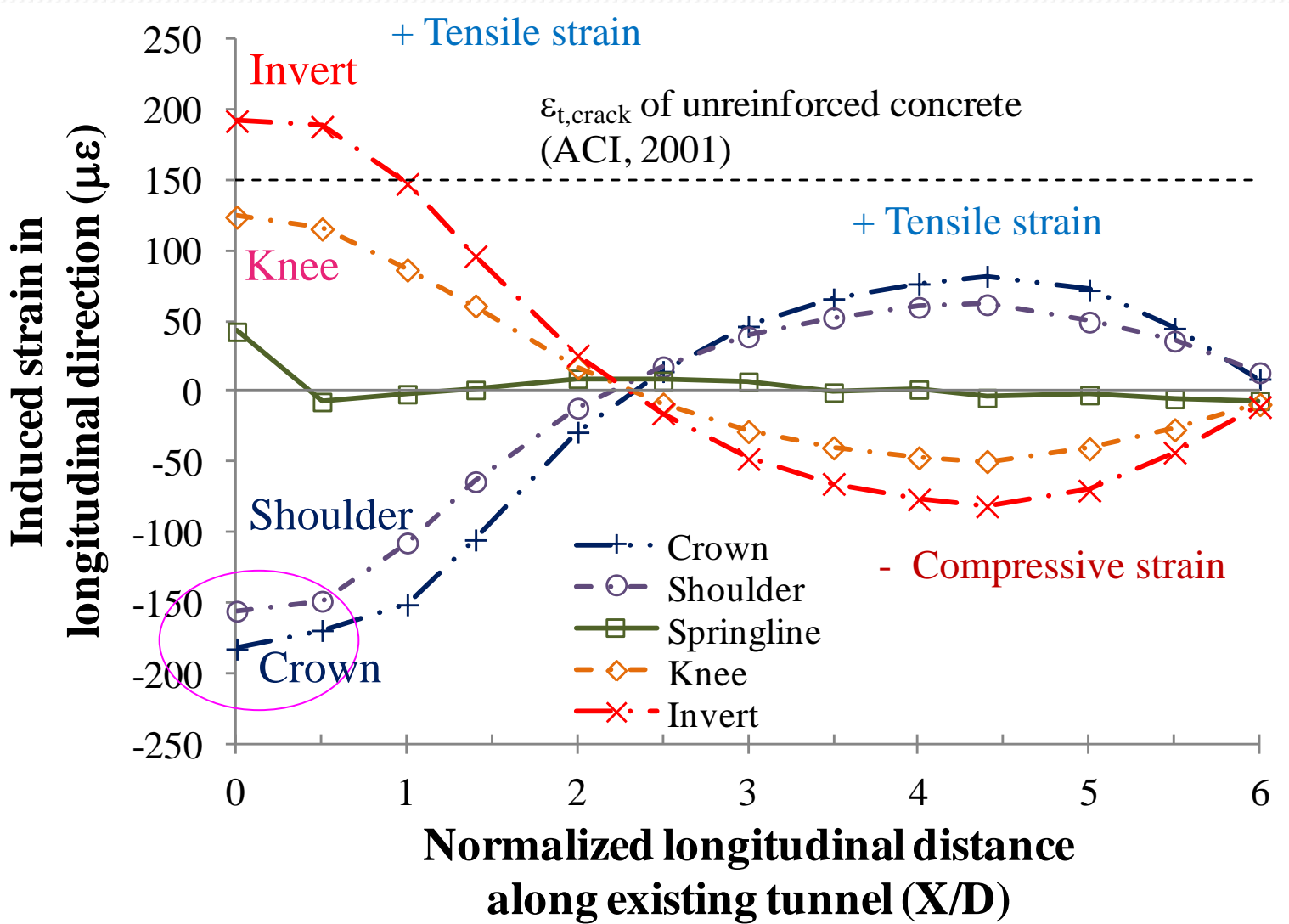


Induced strain along the invert of the existing tunnel

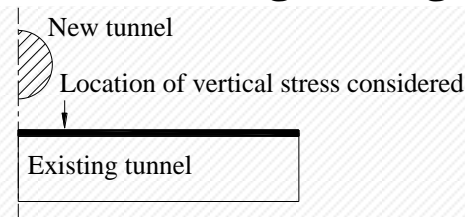
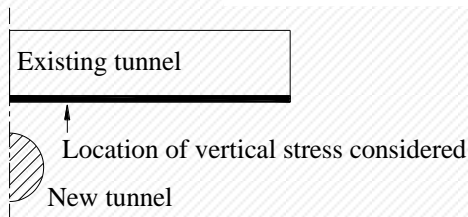
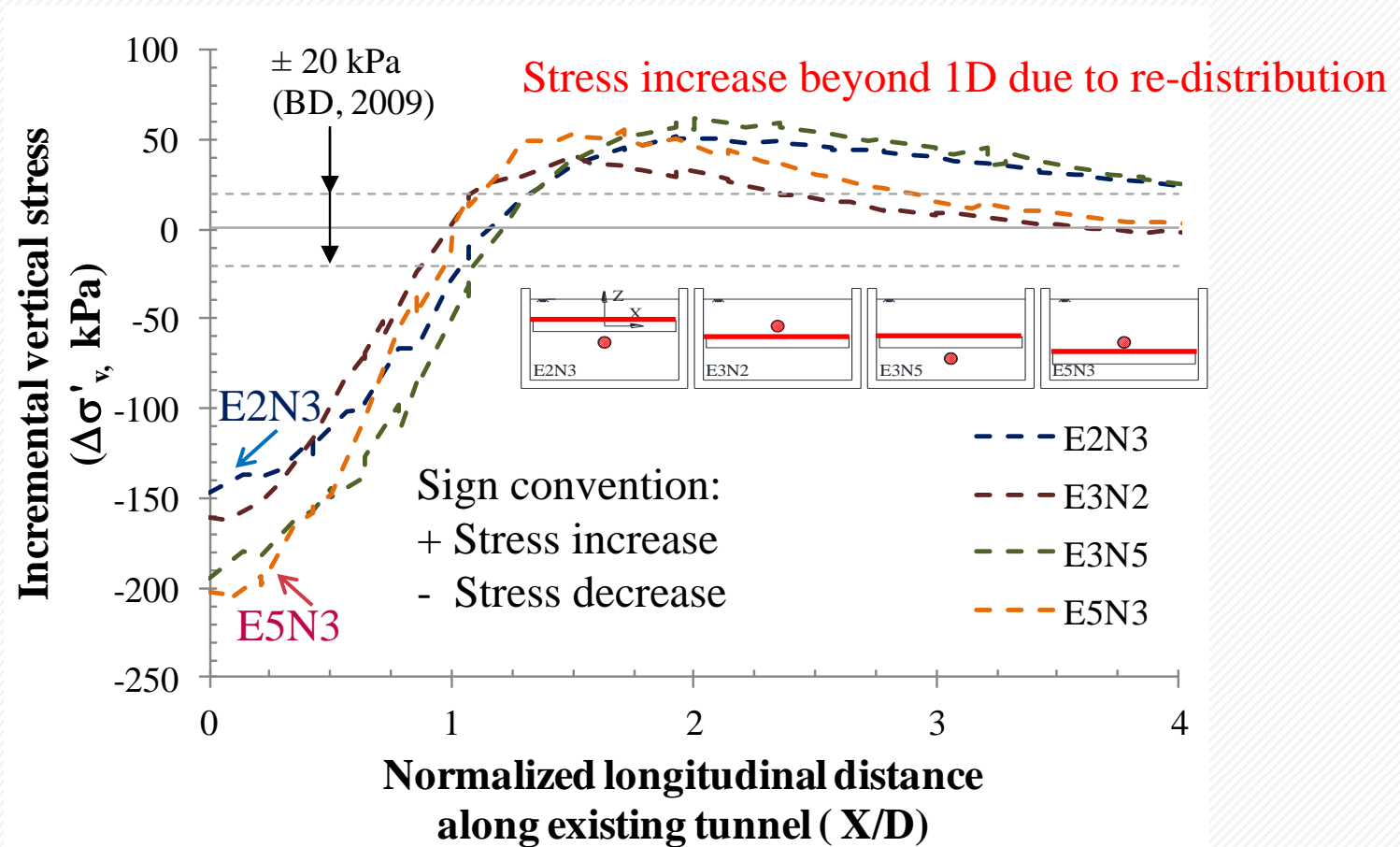
Normalised longitudinal distance
along existing tunnel (X/D)



Computed strains induced at different locations in longitudinal direction of the existing tunnel (Test E2N3)



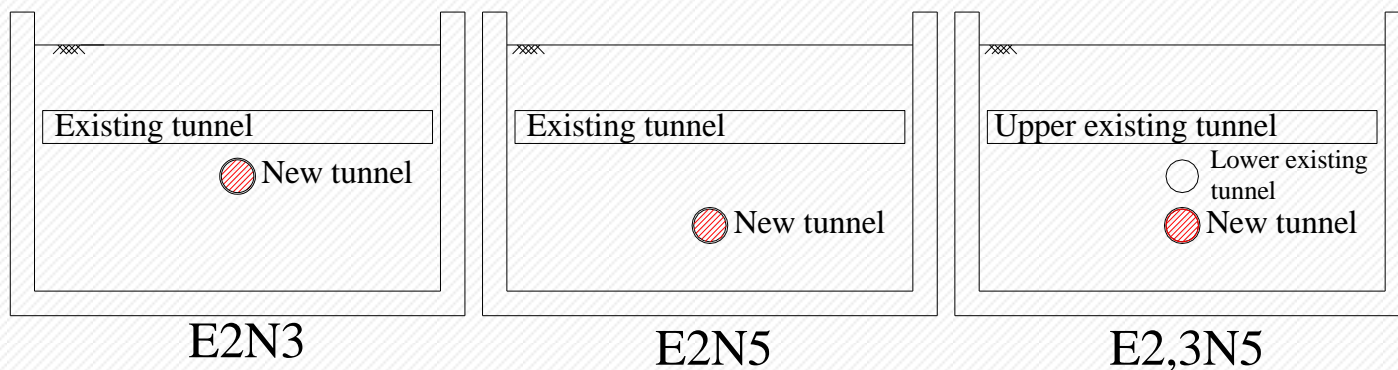
Incremental vertical stress acting on existing tunnel



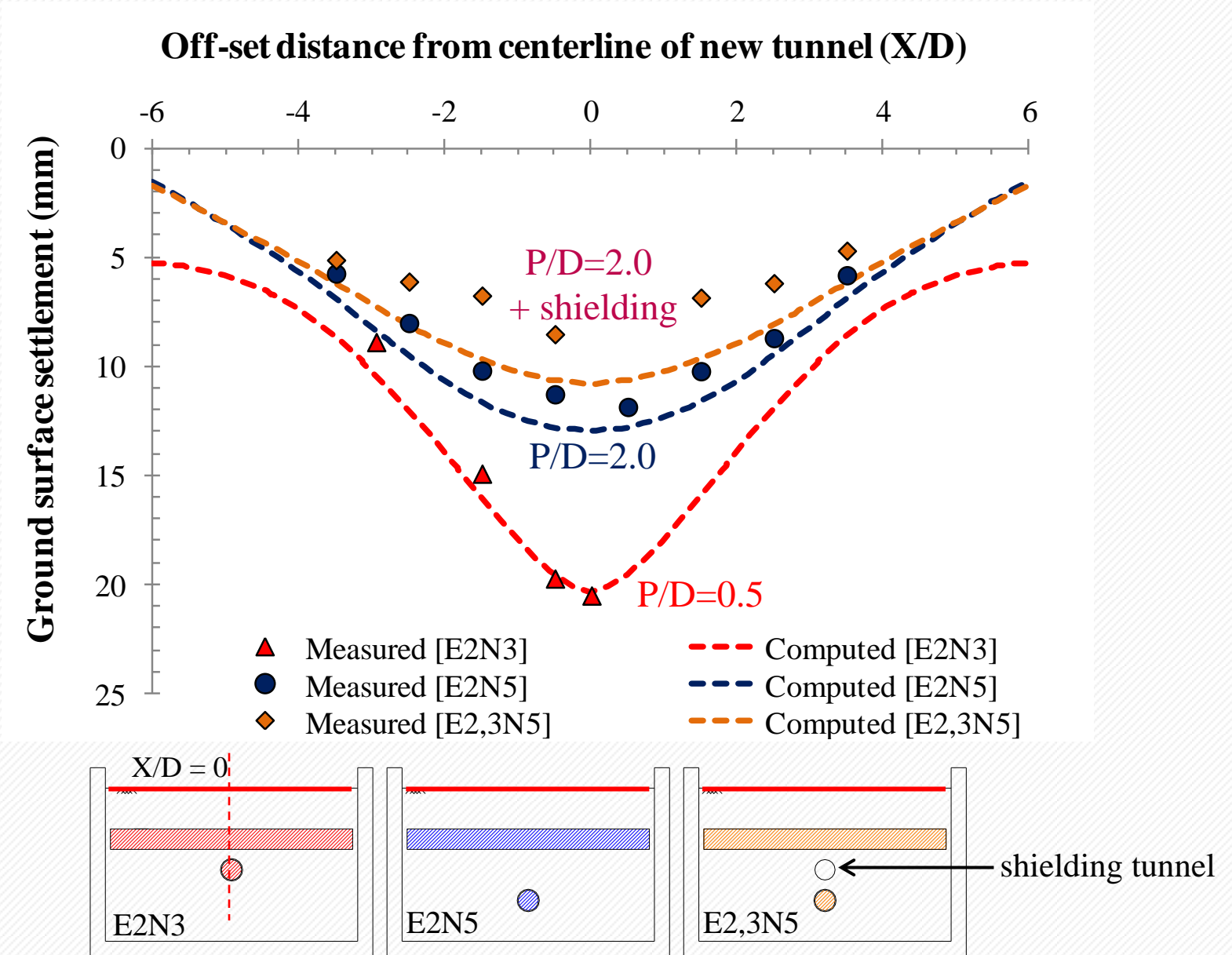
For Tests E2N3 and E3N5

For Tests E3N2 and E5N3

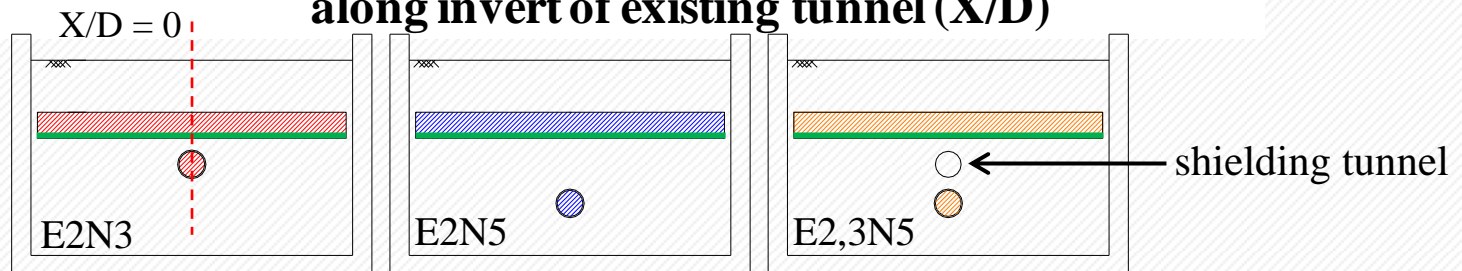
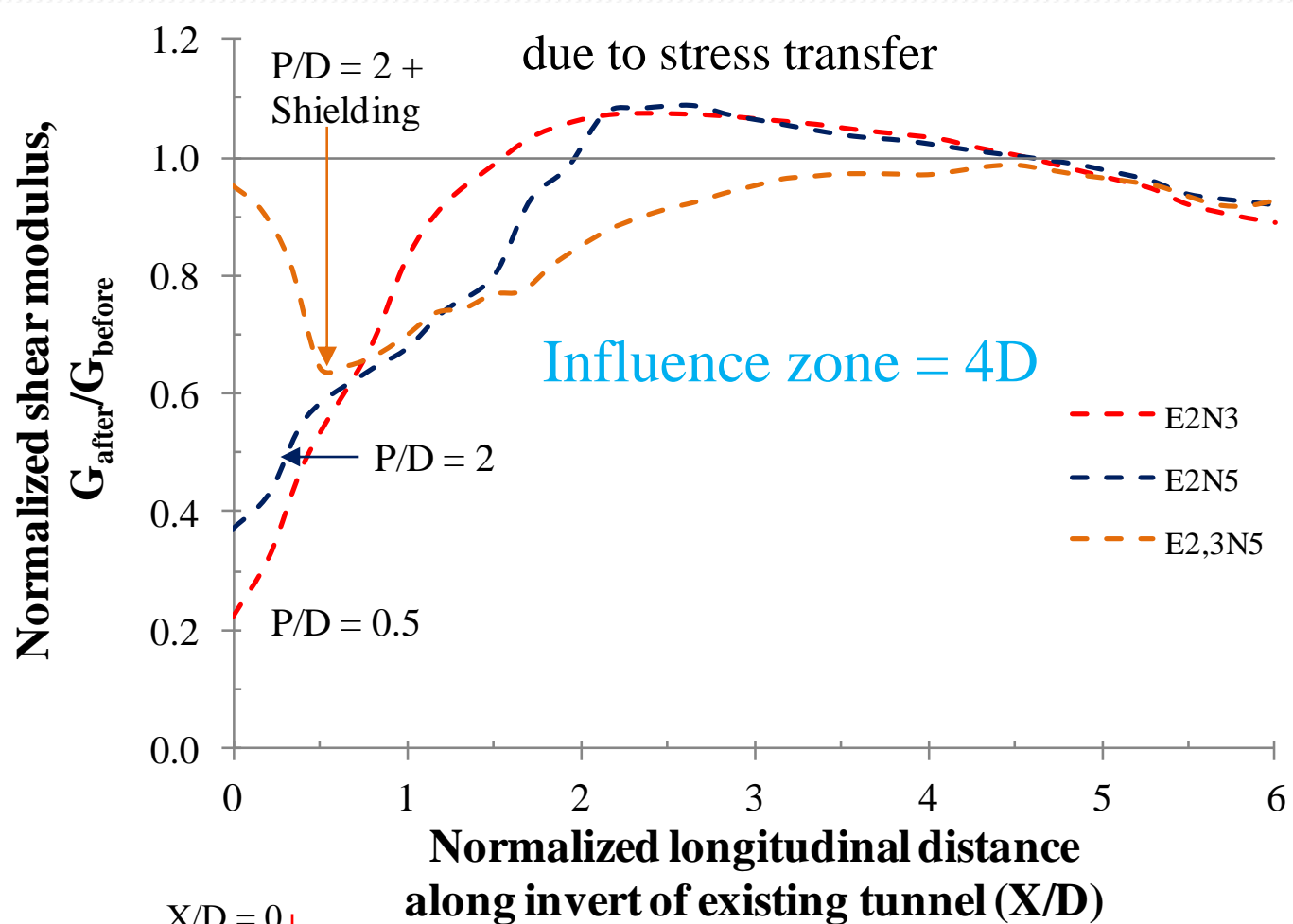
Effects of pillar distance (depth) and shielding on multi-tunnel interaction



Ground surface settlement at the end of tunnelling

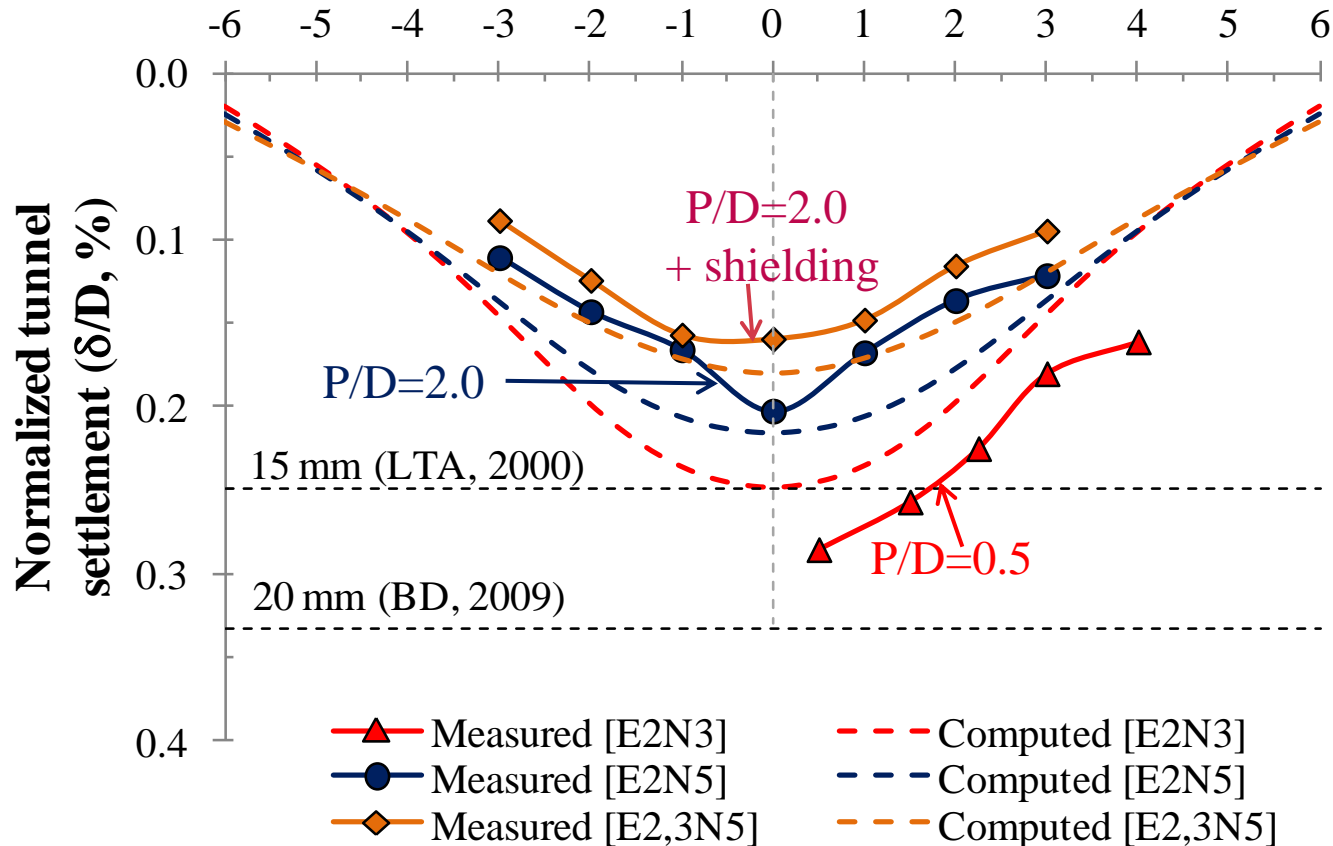


Mobilized shear modulus of soil along the invert of the existing tunnel



Settlement along the crown of existing tunnel

Normalized longitudinal distance
along existing tunnel (X/D)



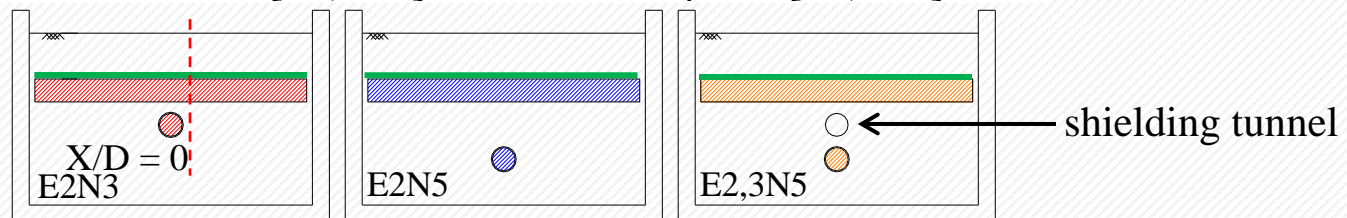
Maximum induced tunnel gradient

E2N3 = 1: 1600

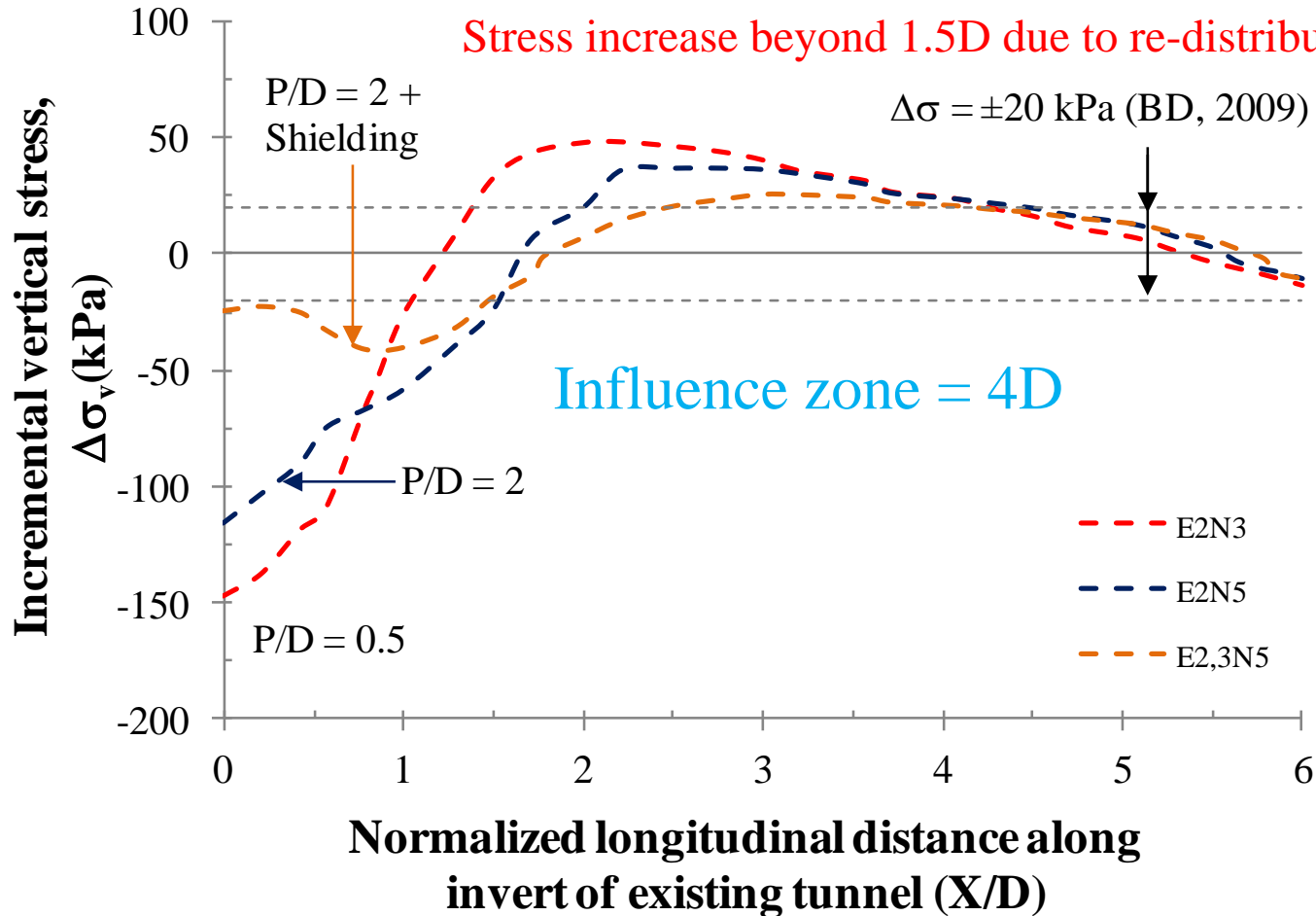
E2N5 = 1: 2700

E2,3N5 = 1: 2800

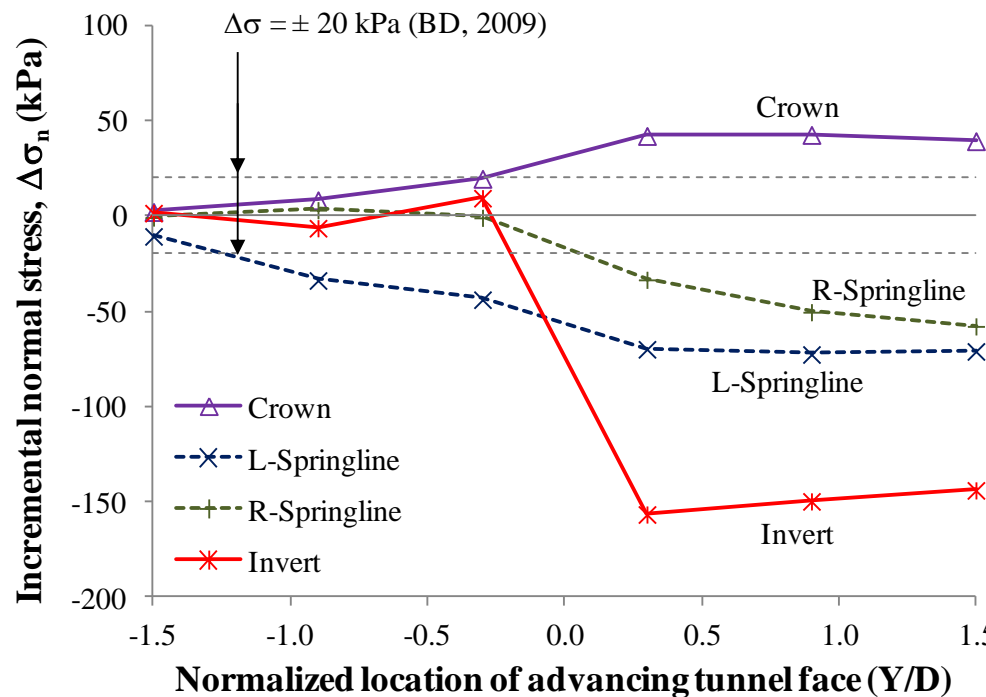
Allowable gradient
1: 1000 (LTA, 2000)



Incremental vertical stress acting on the invert of existing tunnel

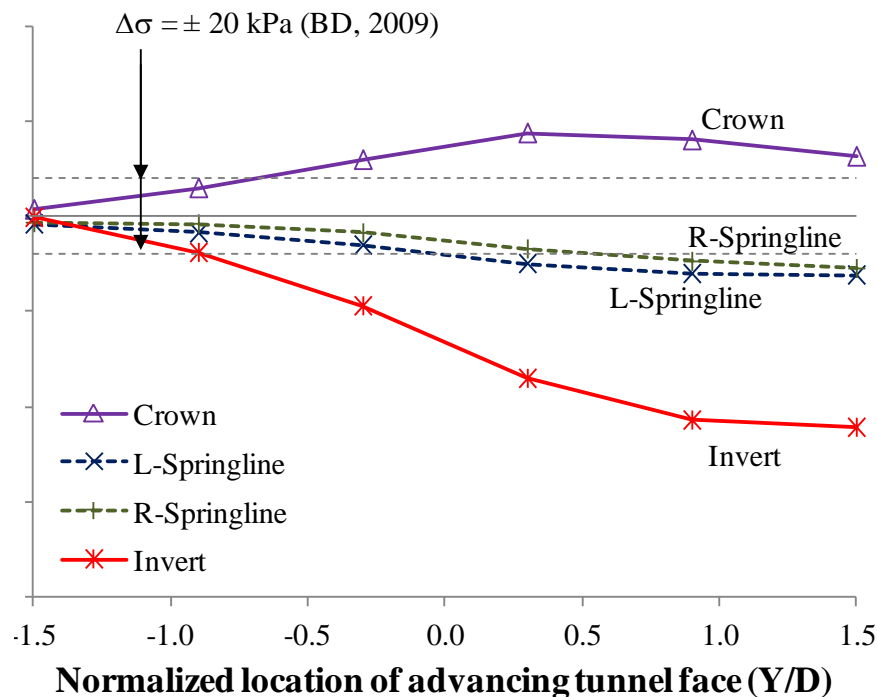


3D stress transfer on the existing tunnel at different P/Ds



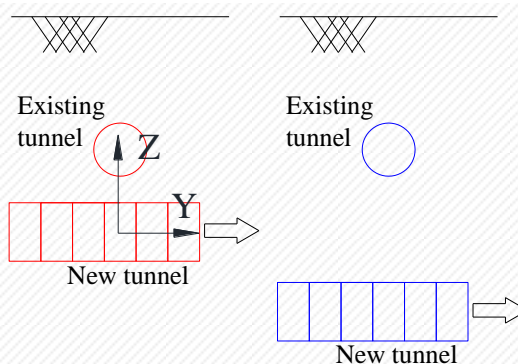
(a) Test E2N3

P/D = 0.5



(b) Test E2N5

P/D = 2

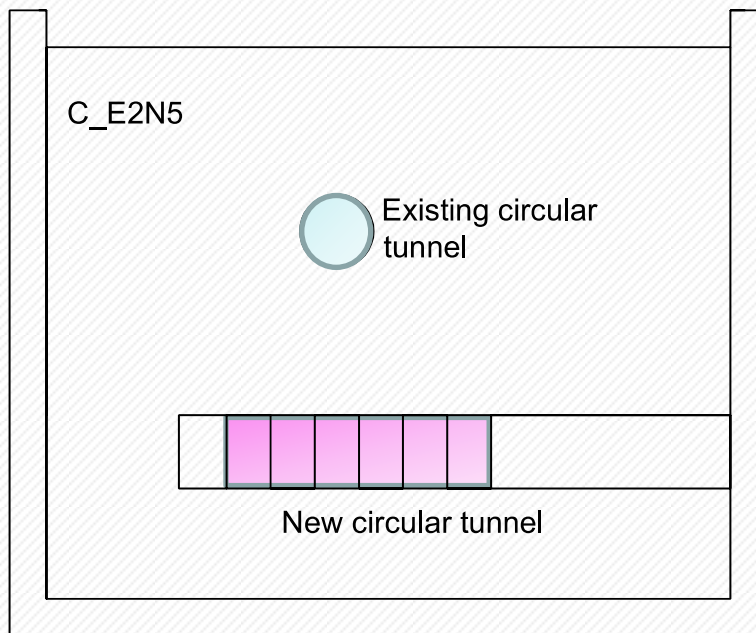


E2N3

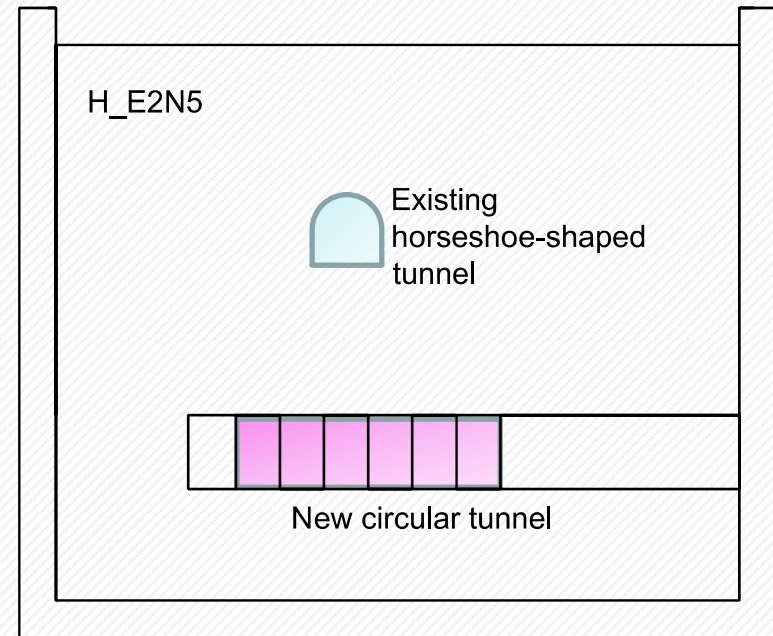
E2N5

Result at different locations of tunnel face (Y/Ds)

Effects of **shape of the existing tunnel** due to a new tunnel excavation underneath



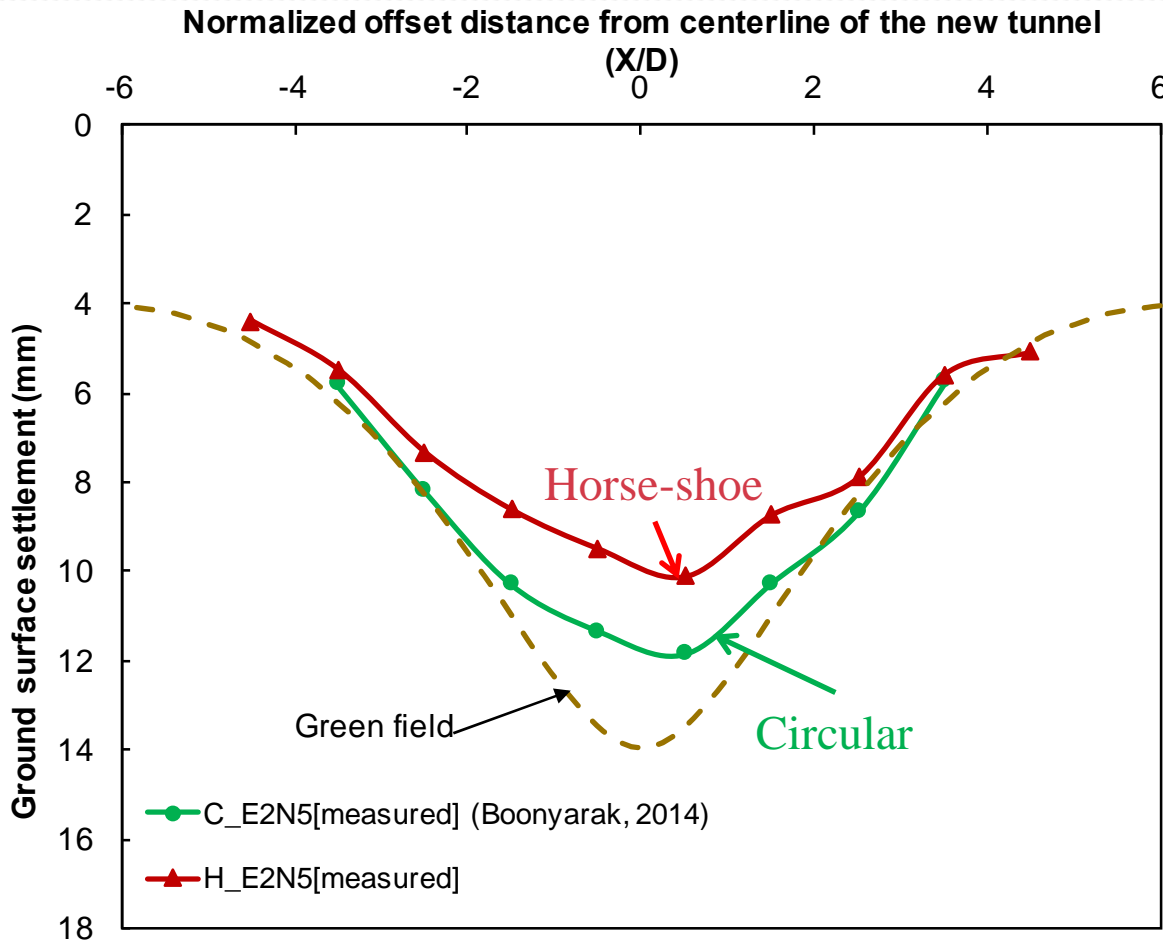
C_E2N5



H_E2N5

$E_c I_c = E_H I_H$ (same cross-section moment of inertia in the longitudinal and transverse direction)

Comparisons of ground surface settlement due to circular and horseshoe-shaped tunnels

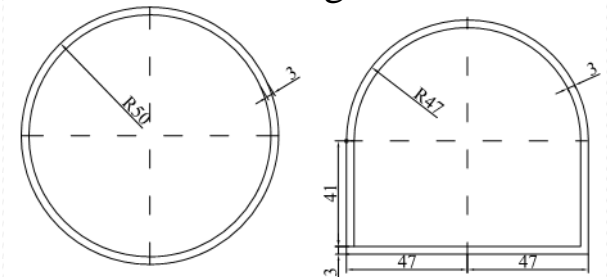


Maximum settlement:

C_E2N5: 12 mm

H_E2N5: 10 mm (20% smaller)
due to smaller reduction in soil stiffness

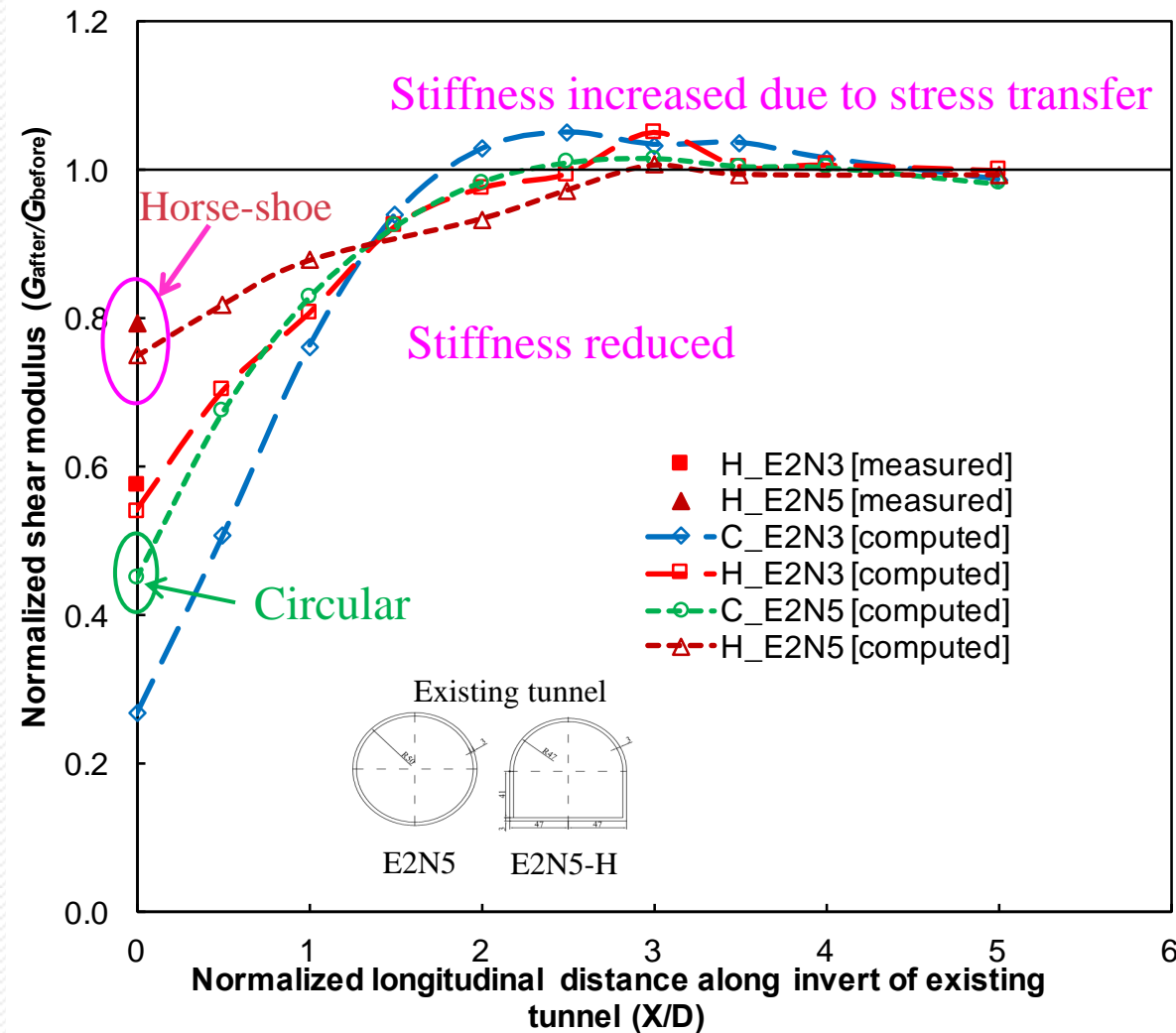
Existing tunnel



E2N5

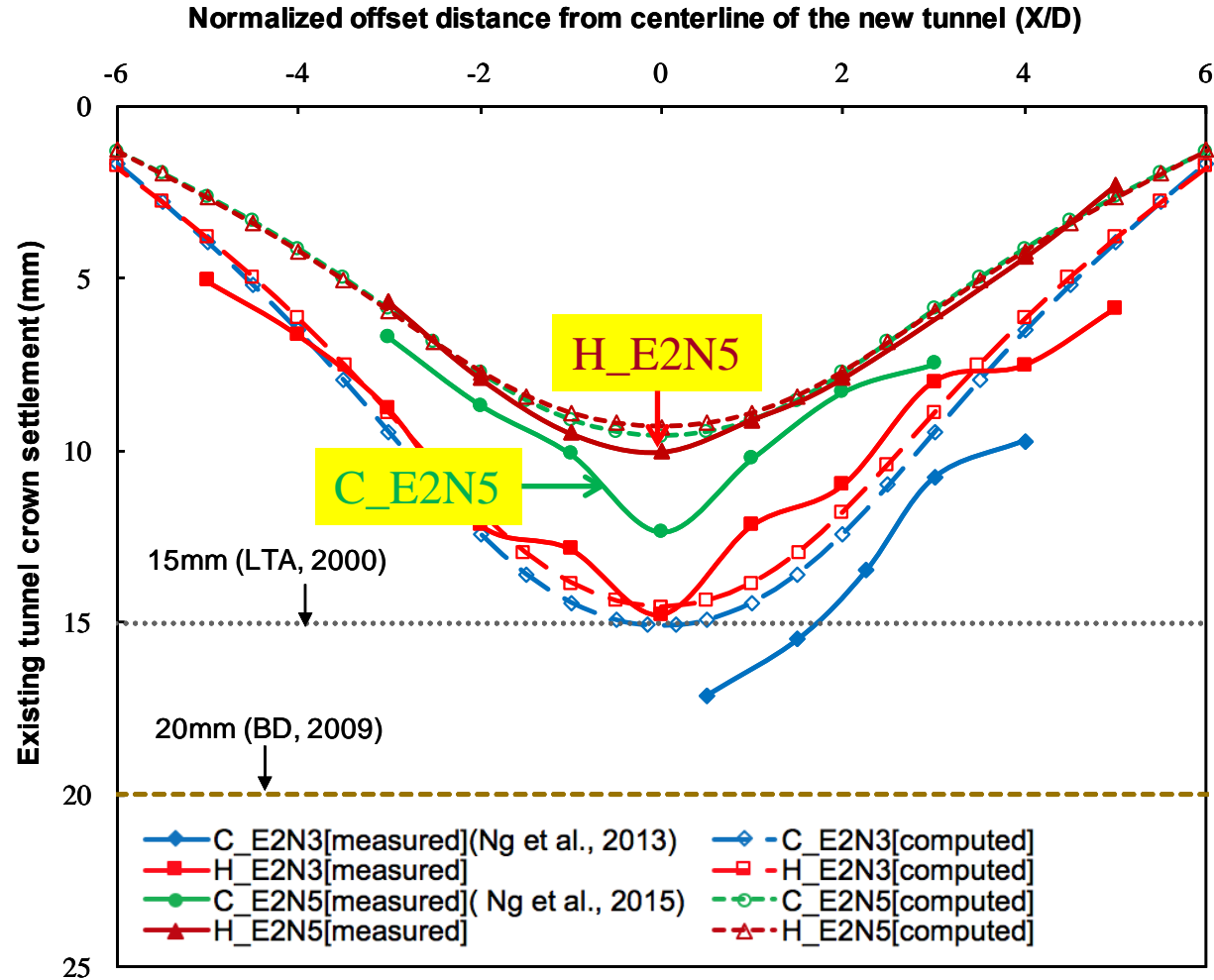
E2N5-H

Reduction of mobilized soil shear stiffness along the invert of the existing tunnel



- Larger reduction in shear modulus (measured by bender elements) in C_E2N5 than H_E2N5 (45% vs 78% remaining)
- Much larger stiffness due to the presence of horse-shoe shaped than circular one
- Stiffness increase beyond 2D due to stress transfer (redistribution)
- Influence zone about 4D

Settlement of existing tunnel



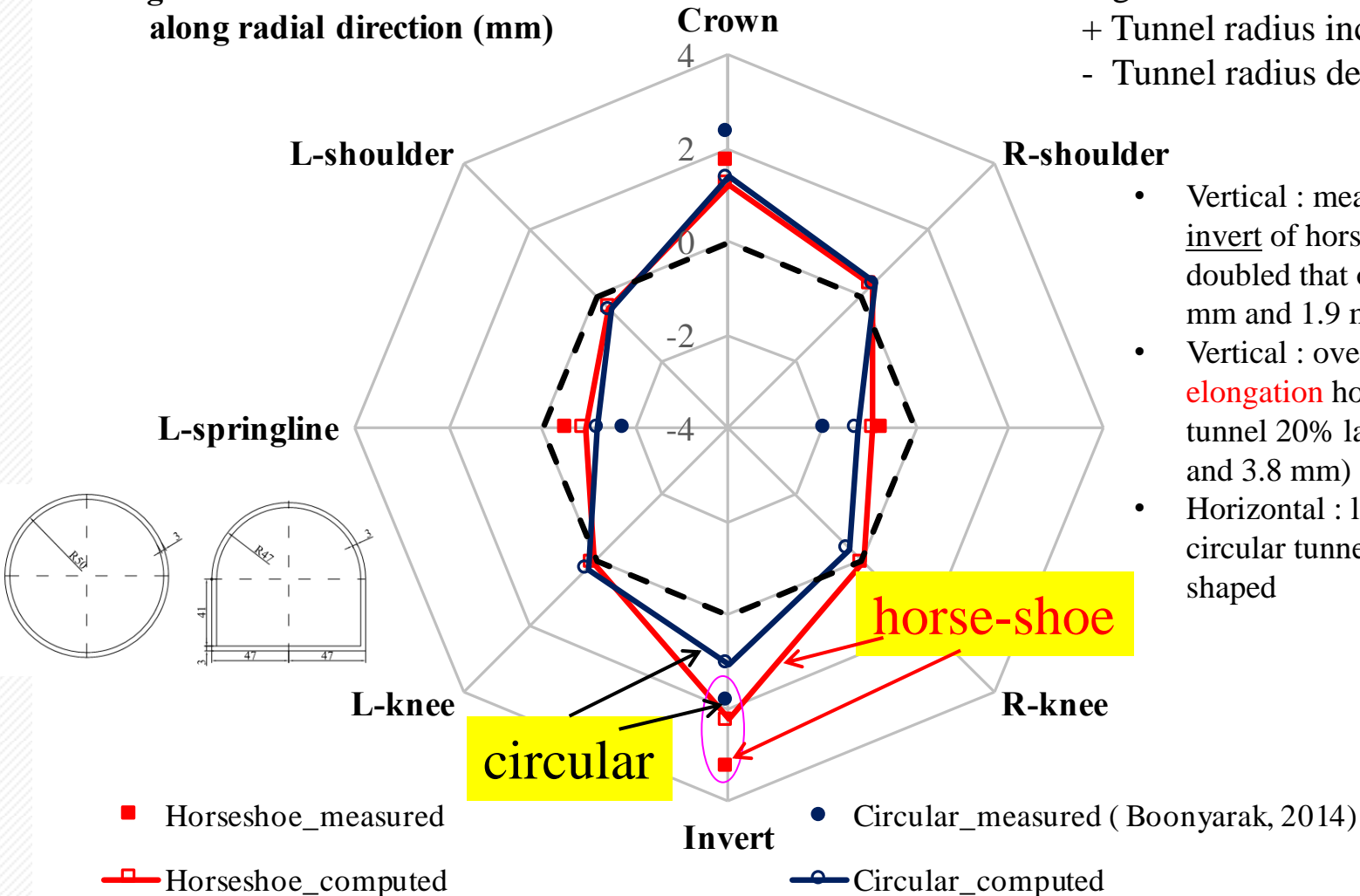
For larger pillar depth
 H_E2N5, max. : 9 mm
 C_E2N5, max. : 12 mm (33% larger)

Larger for circular, stress path closer to CSL, stiffness smaller

Cross-sectional deformations of existing tunnel

Existing tunnel cross-section deformation along radial direction (mm)

Note: Result at mid-plane, $X/D = 0$
 Sign convention of $\Delta R/R_0$
 + Tunnel radius increase
 - Tunnel radius decrease

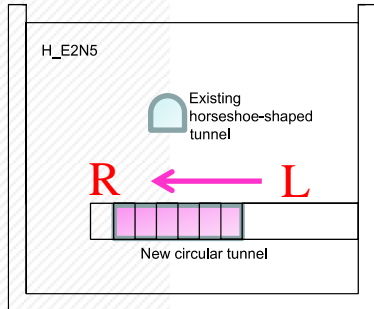


- Vertical : measured **elongation** at invert of horseshoe-shaped tunnel doubled that of the circular (3.8 mm and 1.9 mm)
- Vertical : overall measured **elongation** horseshoe-shaped tunnel 20% larger circular (5 mm and 3.8 mm)
- Horizontal : larger **compression** in circular tunnel than horse-shoe shaped

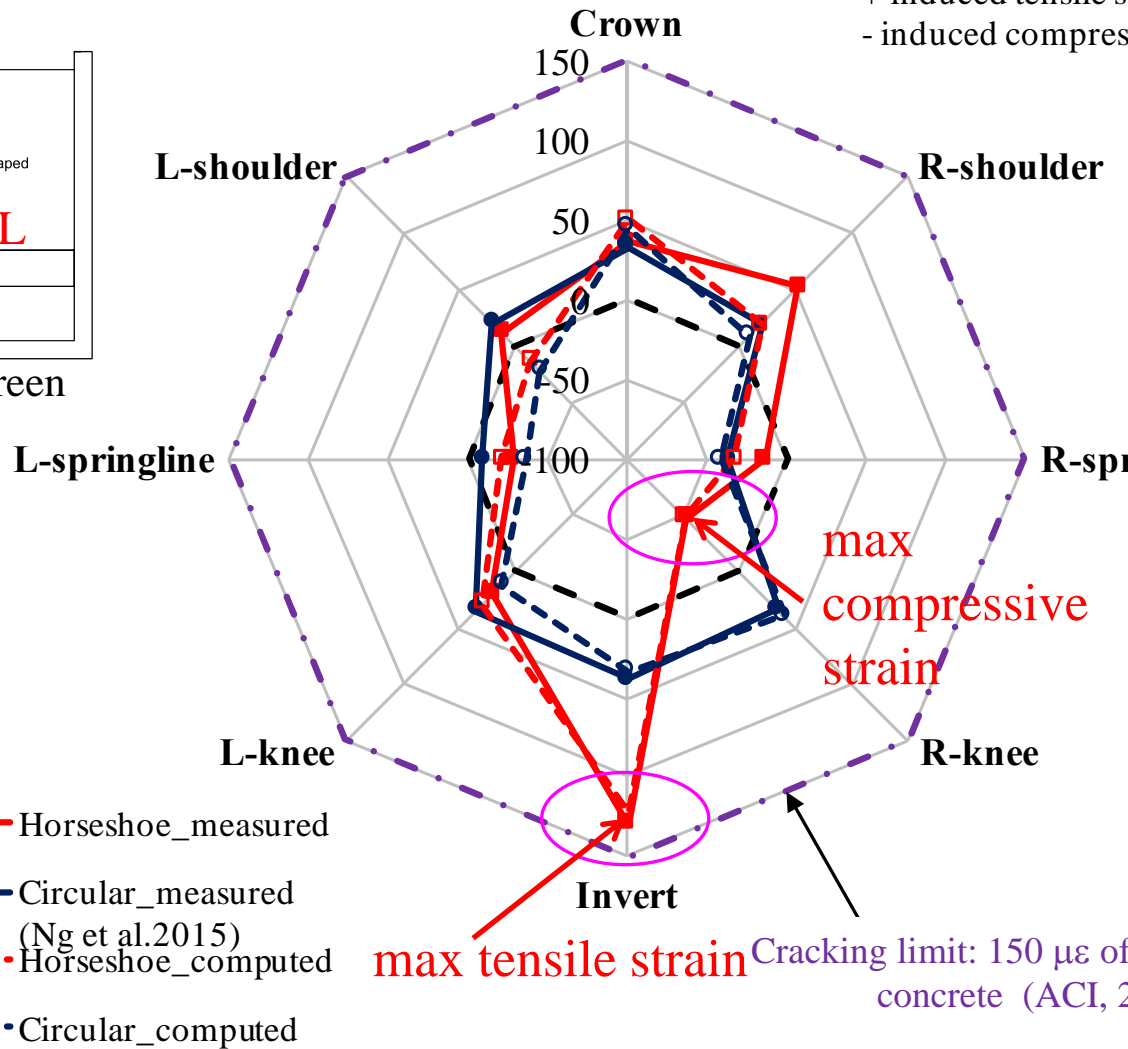
Transverse bending strain induced on the existing tunnel

Induced bending strain ($\mu\epsilon$)

Sign convention:
 + induced tensile strain
 - induced compressive strain



Look out of screen



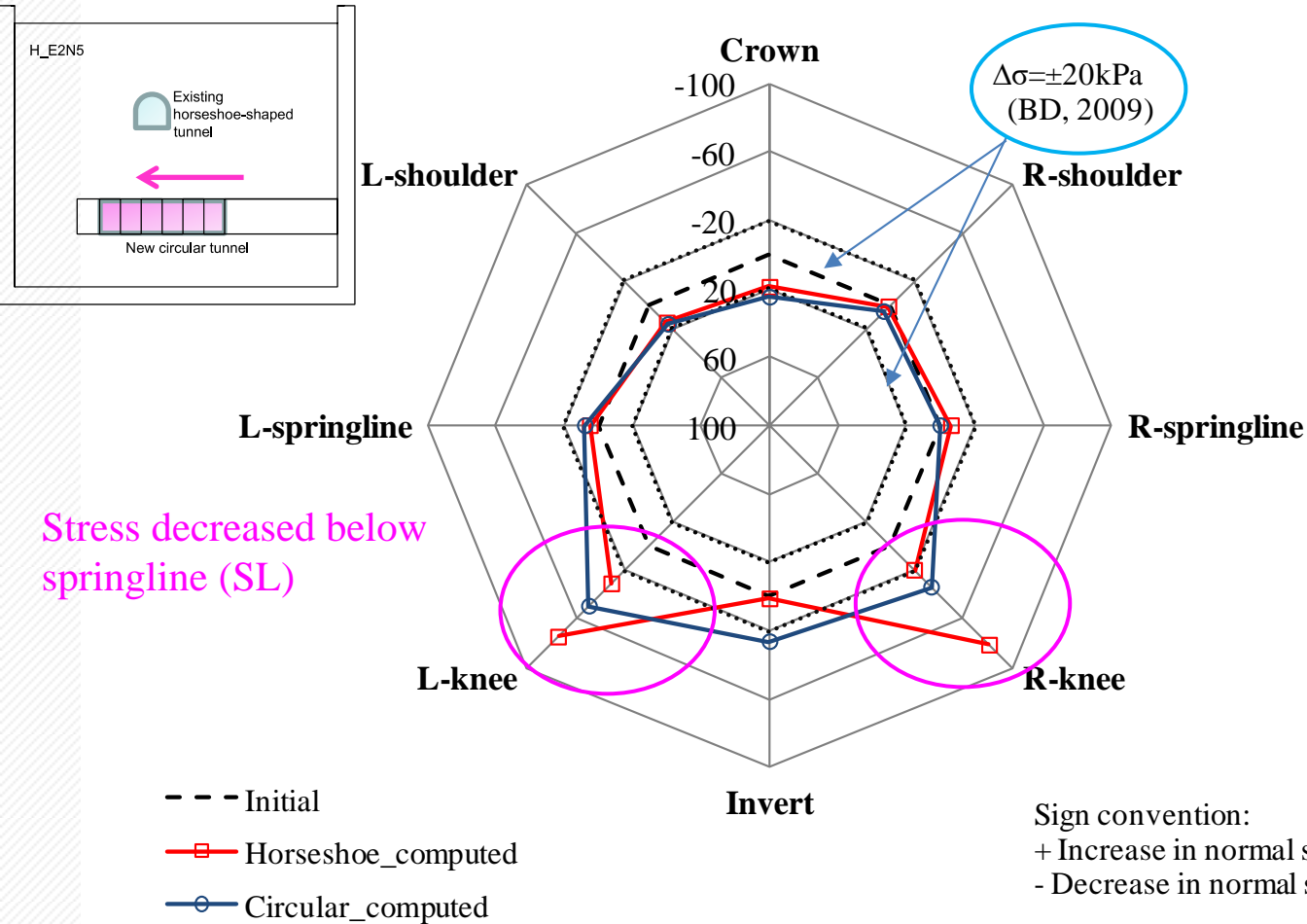
Horse-shoe

- Asymmetric strain distribution due to 3D tunnelling process and stress transfer
- Only compressive strains at R-springline and R-knee, but others tensile

Cracking limit: $150 \mu\epsilon$ of unreinforced concrete (ACI, 2001)

Computed incremental normal stress acting on existing tunnel

Incremental normal stress (kPa)



Stress decreased below springline (SL)

Horse-shoe

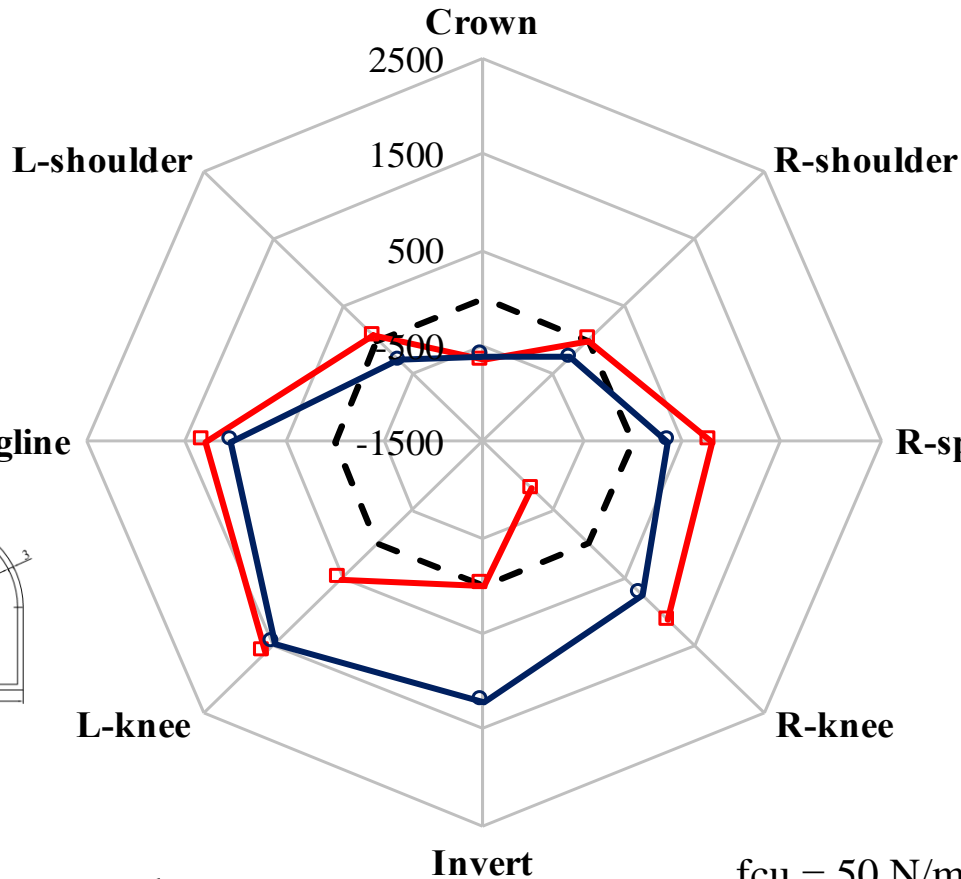
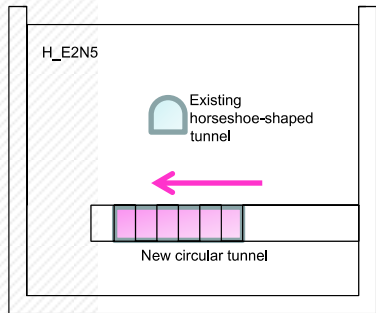
- Asymmetric stress distribution
- Stress reduction below the springline (SL) but increase above SL
- Exceed BD requirement
- Max reduction at knees
- Min reduction at invert

Circular

- Stress reduction below the springline (SL) but increase above SL
- Exceed BD criterion

Computed incremental hoop stress of the existing tunnel

Incremental hoop stress (kPa)

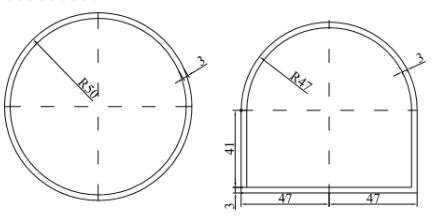


Horse-shoe

- Asymmetric distribution of hoop stress
- Hoop stress increased except at invert and R-knee
- Discontinuous at two knees

Circular

- Asymmetric distribution
- Hoop stress increased everywhere



- - Initial
- Horseshoe_computed
- Circular_computed

$f_{cu} = 50 \text{ N/mm}^2$
or 50,000 kPa

Summary and Key conclusions

Summary

- **Interaction of crossing-tunnel investigated using a novel technique modelling effects of “volume loss” and “weight loss” for tunnel excavation in three-dimensional centrifuge tests**
- **Three-dimensional back analysis of tunnel-tunnel interaction carried out using an advanced Hypoplasticity constitutive model. The model has a capability of simulating stiffness dependency on state, strain and path**
- **Factors influenced interaction of crossing tunnel considered:**
 - **Construction sequence and tunnel cover depth**
 - **Pillar depth and shielding**
 - **Shape of the existing tunnel**

Key conclusions

- **Influence of construction sequence on crossing-tunnel interaction**
 - **Tensile strain induced at the invert** in the longitudinal direction is significantly larger when the new tunnel is excavated beneath than above
 - **Vertical displacement of existing tunnel**
 - **Settlement** due to new tunnel excavation **beneath** was significantly **larger than** heave caused by new tunnel construction **above**
 - **Reason:** larger vertical stress reduction and smaller mobilized shear modulus around the existing tunnel in the former than the latter
 - **Deformation of existing tunnel**
 - **New tunnel underneath** ⇒ existing tunnel elongated **horizontally**
 - **New tunnel above** ⇒ **vertical** elongation of existing tunnel
 - **Reason:** Arch length above the new tunnel extended **further** than below the new tunnel ⇒ reduction in stress in the horizontal direction > vertical direction in the former case

Key conclusions

- **Effects of P/D and shielding on the interaction of multiple tunnels**
 - **Settlement of existing tunnel**
 - **Two-tunnel interaction: 50% smaller settlement at P/D of 2 than at P/D of 0.5**
 - **Three-tunnel interaction: Shielding effects → 25% smaller settlement (for both tests at P/D of 2)**
 - **Reason: Decrease in mobilized shear modulus and vertical stress acting on the existing tunnel reduced with increasing P/D and shielding effects**
 - **Deformation mechanisms of existing tunnel**
 - **Elongated horizontally at P/D of 0.5 but elongated in the vertical direction at P/D of 2**
 - **Reason: Arch length of new tunnel extended to the side of the existing tunnel at P/D of 0.5 → stress reduction in the horizontal direction > vertical direction**

Key conclusions

- **Effects of horse-shoe (HS) shaped tunnel**
 - **Settlement of ground surface**
 - **20% smaller induced ground settlement than circular tunnel**
 - **Reason: smaller reduction in soil stiffness in HS-shaped tunnel**
 - **Deformation of the existing tunnel**
 - **Larger elongation in the vertical direction than circular tunnel**
 - **Reasons: larger vertical stress reduction, smaller hoop stress below the springline**
 - **Larger bending moment (BM) induced in HS-shaped tunnel below the springline than circular tunnel.**
 - **The max. BM induced at invert of HS was three times larger**

Journal publications

1. Ng, C. W. W., Wang, R. & Boonyarak, T. (2016). A comparative study of different responses of circular and horseshoe-shaped tunnels to an advancing tunnel underneath. *Geotechnique Letters*, Vol. 6, 168–175.
2. Ng, C. W. W.; Boonyarak, T. & Mašin, D. (2015). Effects of pillar depth and shielding on crossing multi-tunnel interaction. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*. Vol. 141, No. 6.
3. Boonyarak, T. & Ng, C. W. W. (2015). Effects of construction sequence and cover depth on crossing-tunnel interaction. *Canadian Geotechnical Journal*. Vol. 52, No. 7, 851-867.
4. Boonyarak, T., Phisitkul, K., Ng, C. W. W., Teeparaksa, W. & Aye, Z.Z. (2014). Observed ground and pile group responses due to tunneling in Bangkok stiff clay. *Canadian Geotechnical Journal*. Vol. 51, No.5, 479-495.
5. Ng, C.W.W., Boonyarak, T. & Mašin, D. (2013). Three-dimensional centrifuge and numerical modeling of the interaction between perpendicularly crossing tunnels. *Canadian Geotechnical Journal*. Vol. 50, No. 9, 935-946

Conference papers

1. Boonyarak, T., Ng, C.W.W. & Mašin, D. (2016). Influences of shielding of multi-crossing tunnels on ground displacement. *Proc. 13th Int. Conf. Underground Construction*, Prague 23-25 May, **Czech Republic**.
2. Boonyarak, T. & Ng, C. W. W. (2015). Three-dimensional influence zone of new tunnel excavation crossing underneath existing tunnel. *Proc. 15th Asian Regional Conf. on SMGE*, 9-13 Nov. Fukuoka, **Japan**.
3. Boonyarak, T., Ng, C.W.W. & Mašin, D. (2014). An investigation of perpendicularly across twin-tunnel interaction. *Proc. of 8th Int. Conf. Physical Modelling in Geotechnics (TC2)*, 14-17 Jan., Perth, **Australia**. Vol. 2, 951-957.
4. Boonyarak, T, Lim, K. S.G. & Ng, C. W. W. (2012). Three-dimensional Centrifuge and Numerical Modeling of Perpendicularly Crossing Tunnel Interaction. *World Tunnelling Congress, 18-23 May, Bangkok*. 904-905. Full paper in CD.
5. Lim, K.S.G., Boonyarak T. & Ng, C.W.W. (2012). Significance of simulating weight loss in numerical investigation of perpendicularly crossing tunnel interaction. *World Tunnelling Congress, 18-23 May, Bangkok*. 928-929. Full paper in CD.
6. Boonyarak, T. & Ng, C. W. W. (2012). Tunneling effect on pile group response in Bangkok. *Geocongress - State of the Art and Practice in Geotechnical Engineering, ASCE*, March 25-29. Oakland, California USA. Geotechnical Special Publication no. 225, 3119-3128.

Thank You

