Physical modeling for the evaluation of the seismic behavior of underground structures TA- SERIES

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Underground structures

- Mountain tunnels
- Subways
- Highway tunnels
- Shallow and deep metro stations
- Underground parking stations, commercial centers
- Nuclear power plants ducts

- Their seismic design in seismically prone areas is of major importance
- Safety - economy

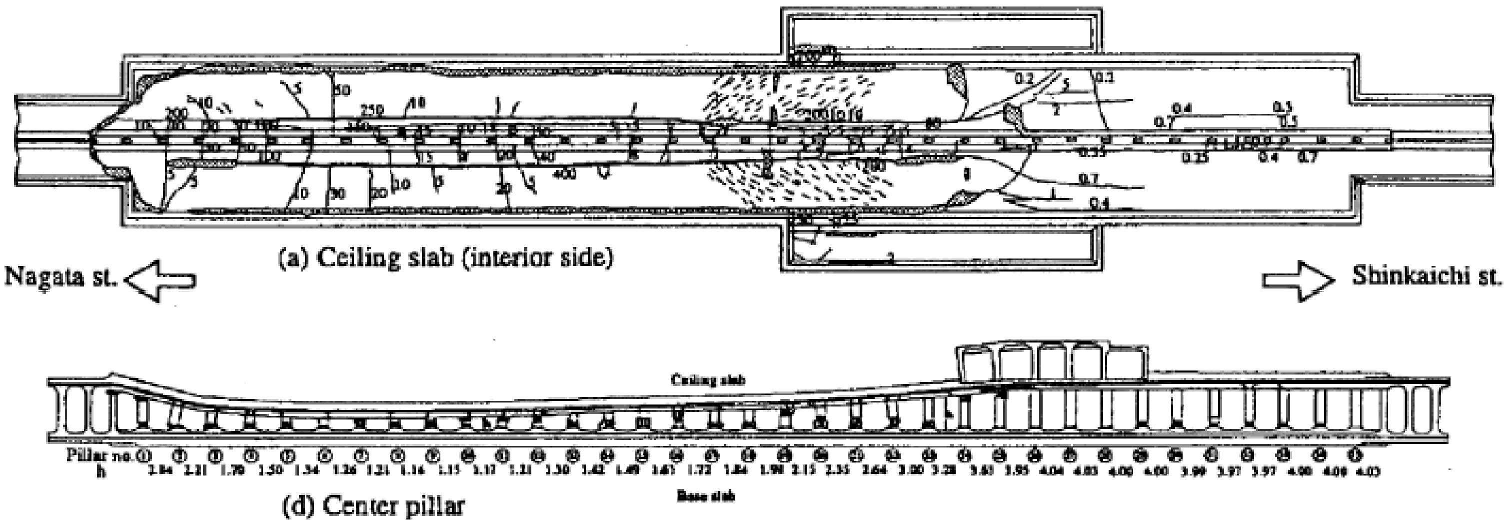
Observed damages in past earthquakes
Seismic performance

Observed damages in past earthquakes

Dakai subway, Kobe, 1995, Mw=6.9

- Collapse of the station
- Designed with poor seismic design considerations

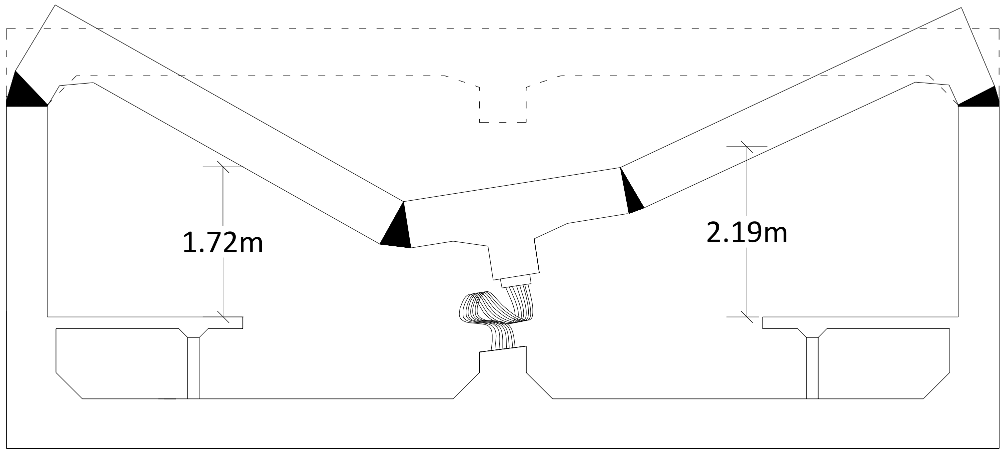
Dakai subway, Kobe, 1995, Mw=6.9



- **The main cause of collapse is due to the shear and buckling failure of the centre columns, which were designed and constructed with insufficient transverse shear reinforcement**

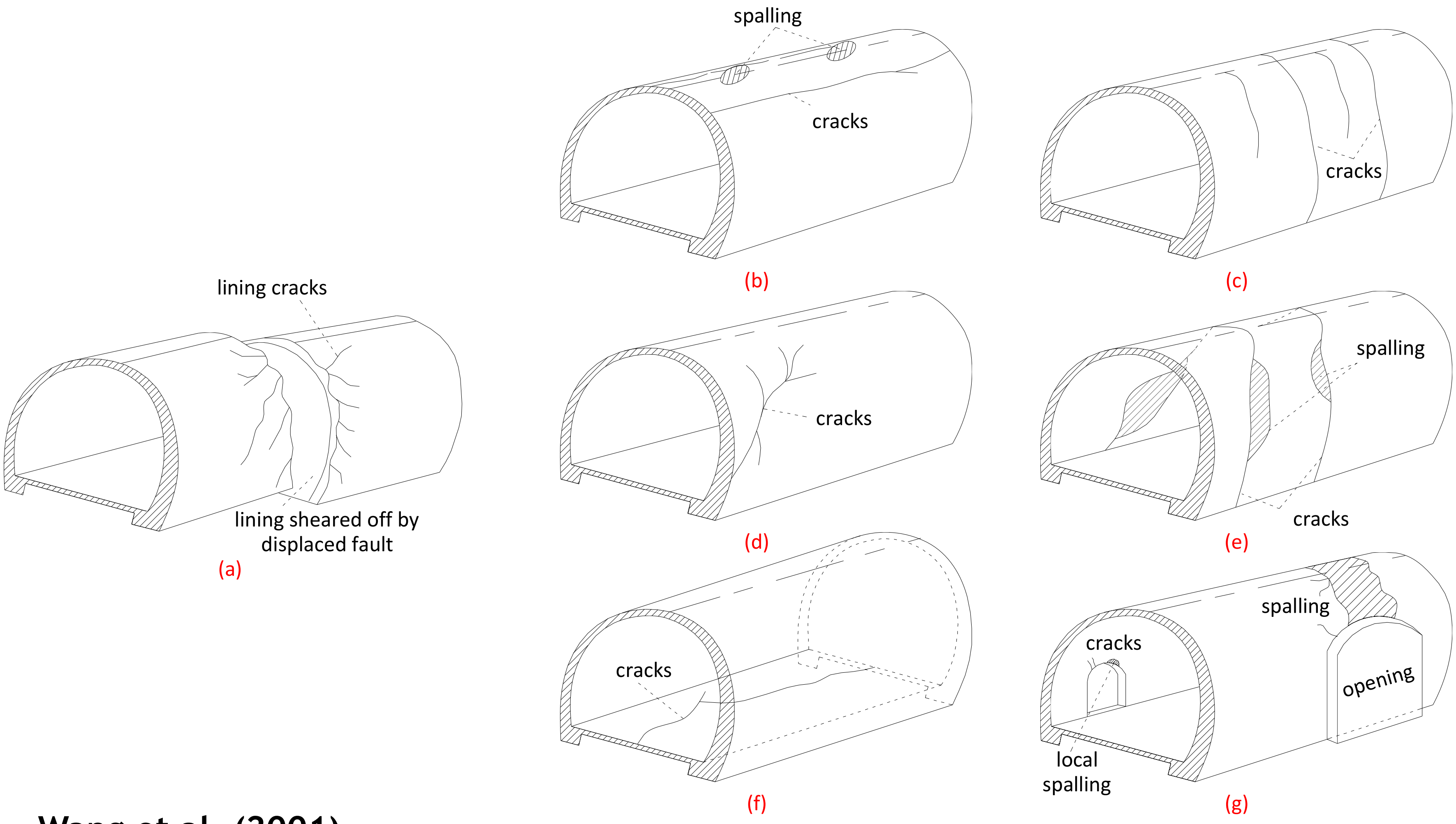
Iida et al., 1996, Kawashima, 2000, Hashash et al., 2001

Dakai subway, Kobe, 1995, Mw=6.9



Column 10

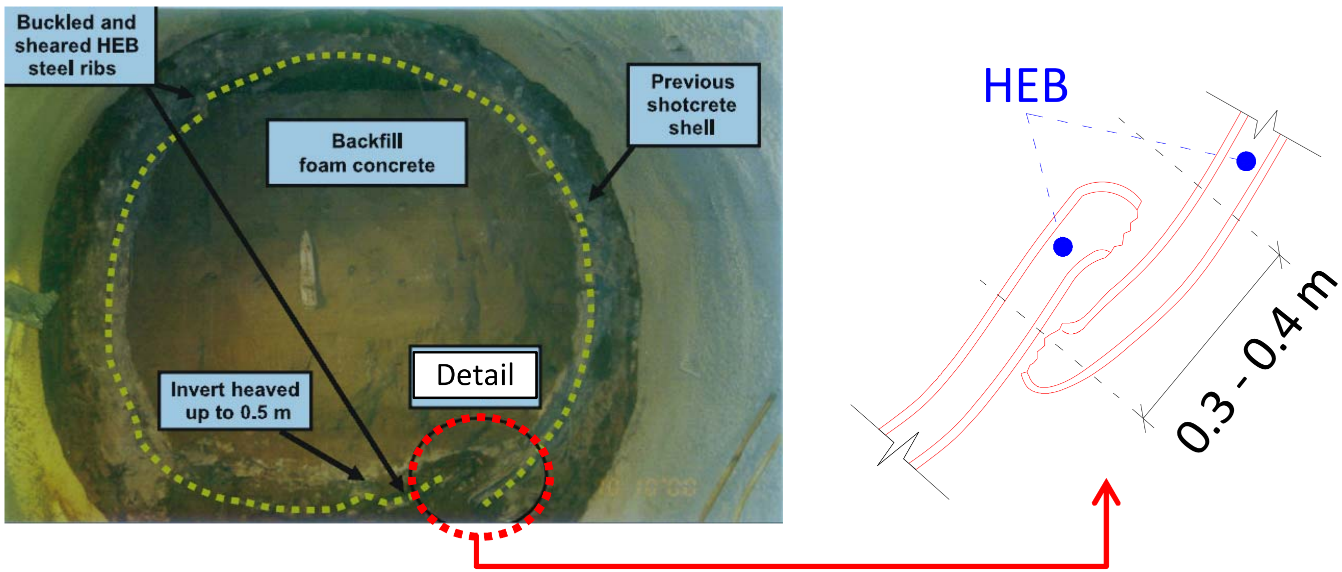
Chi Chi earthquake (1999)



Wang et al. (2001)

Kocaeli earthquake (1999)

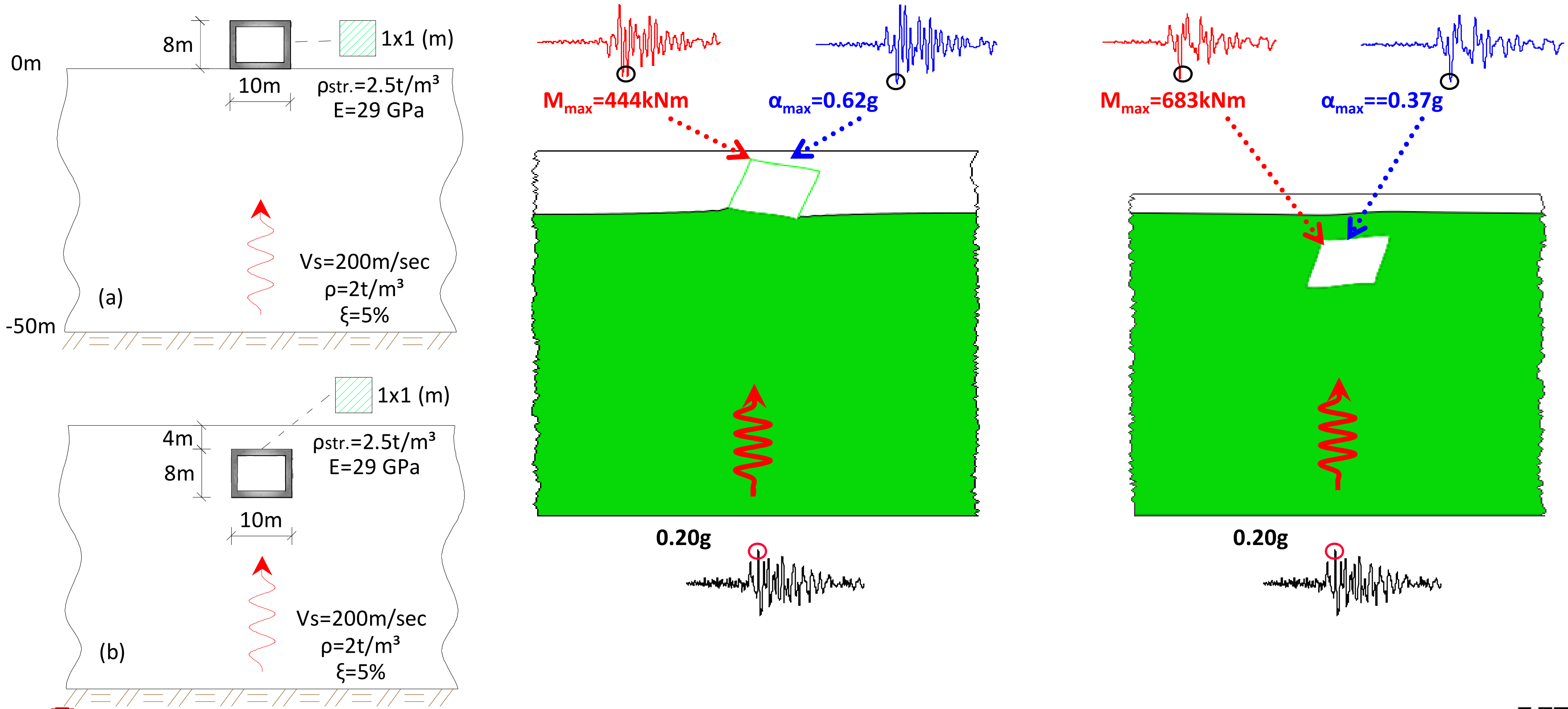
- **Circular tunnel – failure during construction**



Kontoe et al. (2008)

Seismic behavior

- **Seismic behavior of underground structures is substantially different from aboveground structures**
- **Imposed seismic ground deformations rather than inertial forces dominate the structure's seismic response**

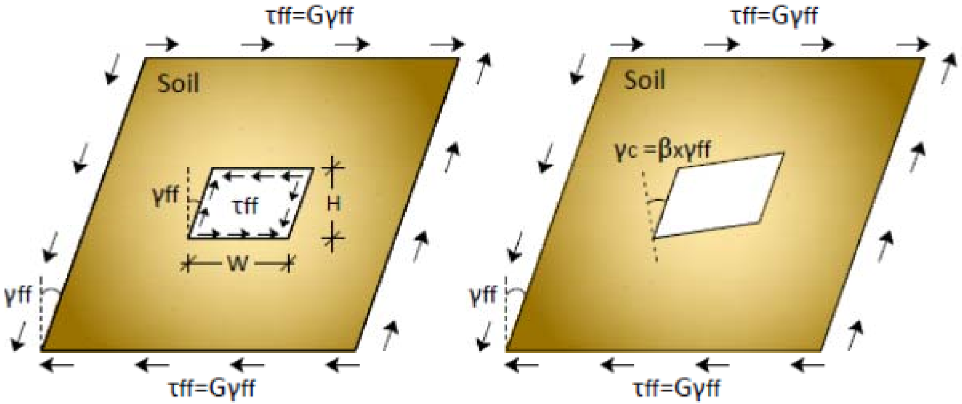


- Shaking
- Imposed seismic ground deformations and the relative stiffness or the stiffness contrast between the structure and surrounding soil, control the overall seismic behaviour of an underground structure
- Ground failure
- The response is also controlled by the imposed permanent ground deformations and displacements due to:
  - Liquefaction : Settlements, lateral spreading
  - Slope failure
  - Fault movements

- Crucial parameters controlling the soil - structure system behavior:
  - Soil to structure flexural stiffness (Flexibility ratio)
  - Soil – tunnel interface conditions (rough or smooth interface)

Flexibility ratio

- Penzien, 2000
- Deformations of rectangular cavity

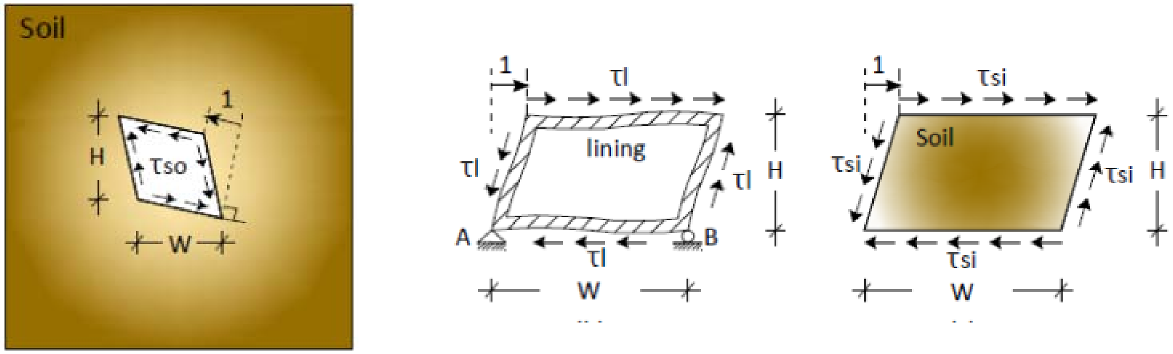


$$\tau_{ff} = G_s \gamma_{ff}$$

$$\gamma_c = \beta \gamma_{ff}$$

$$\beta = \gamma_c / \gamma_{ff} = 4(1 - \nu_s)$$

- Stiffness of outside soil, inside soil and lining
- Compatibility of deformations

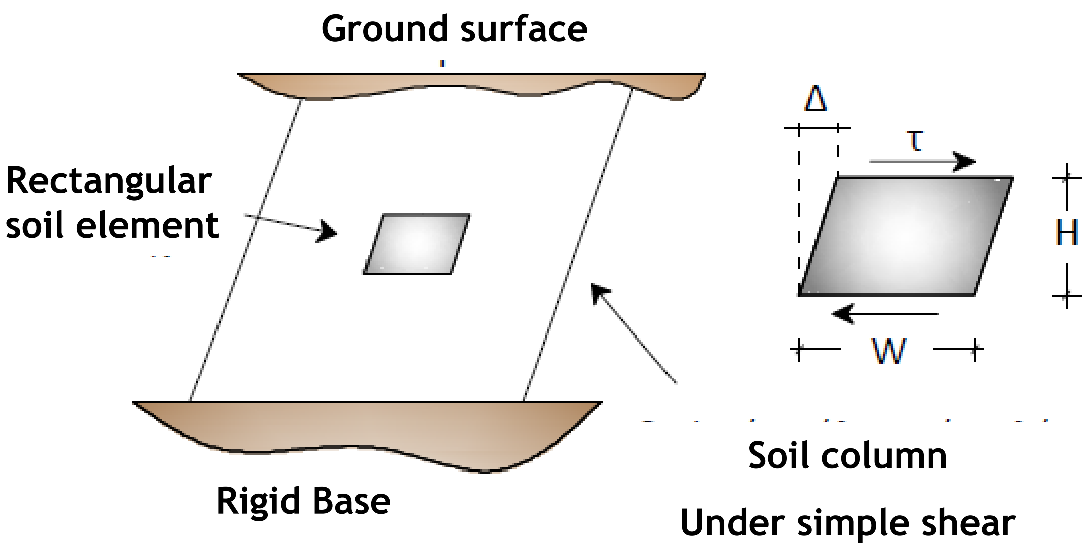


$$k_{soil} = \tau_{si} = G_s / H$$

$$k_{soilo} = k_{soil} / (3 - 4\nu_s)$$

$$\Delta d_{stru} + \Delta d_{is} = 4(1 - \nu_s)\gamma_{ff} H$$

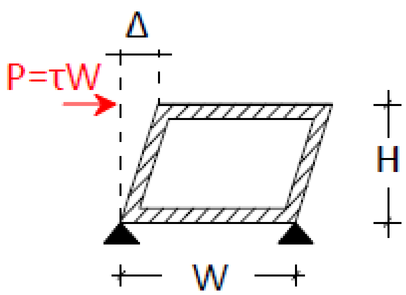
- **Wang, 1993**
- **Concentrated load P - Fixity of the invert slab**
- **S_1: force required to cause unit racking to structure - estimate from simple static analysis**



$$\gamma_s = \frac{\Delta}{H} = \frac{\tau}{G_m}$$

$$\frac{\tau}{\gamma_s} = \frac{\tau}{\Delta/H} = G_m$$

$$\gamma_s = \frac{\Delta}{H} = \frac{P}{HS_1} = \frac{\tau W}{HS_1} \rightarrow \frac{\tau}{\gamma_s} = \frac{\tau}{\Delta/H} = \frac{HS_1}{W}$$



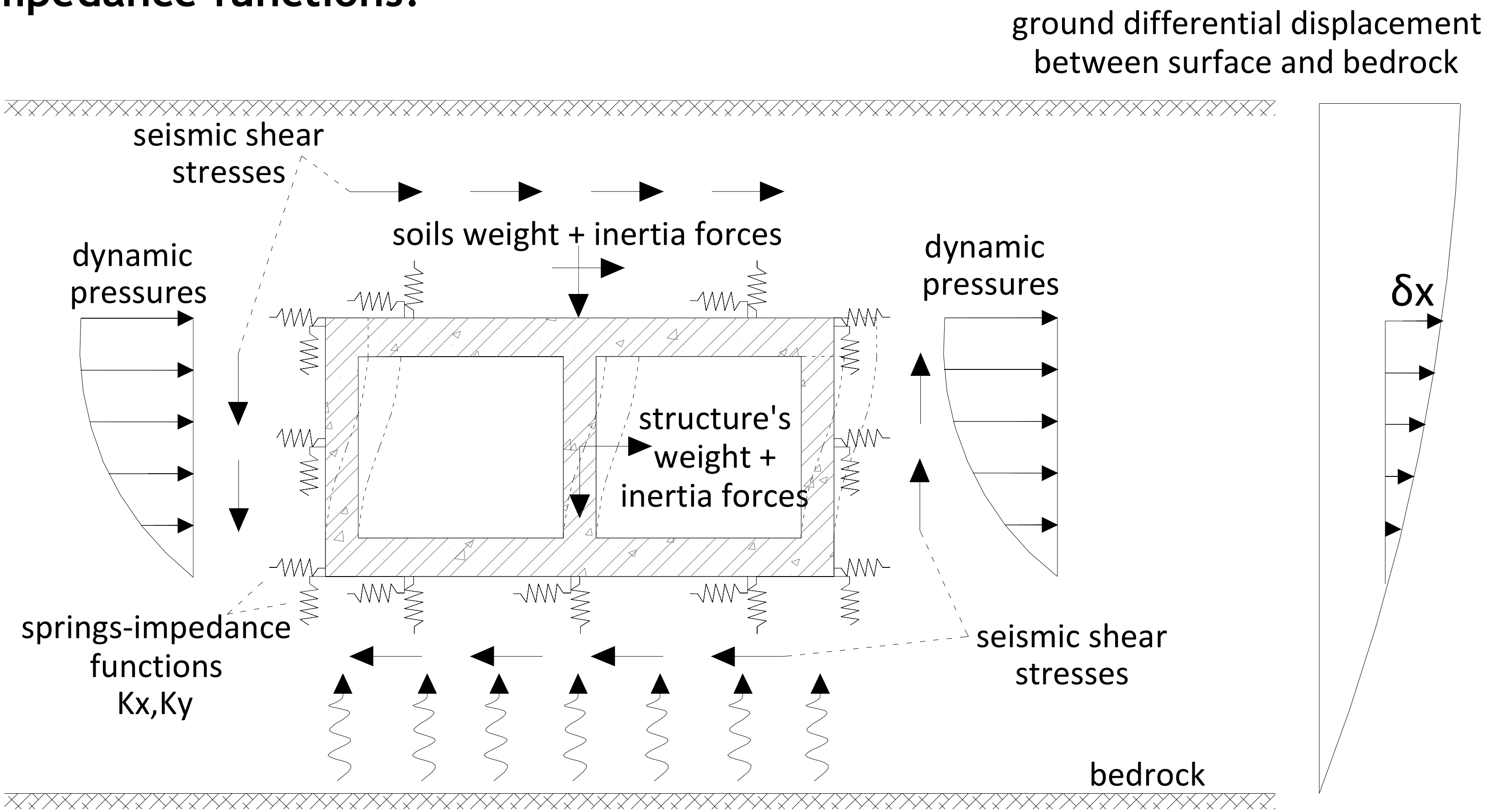
$$F = \frac{G_m W}{HS_1}$$

Important "open" issues

- Input motion intensity and characteristics and modeling issues
- Transversal seismic behavior and analysis
  - Estimation of seismic earth pressures
  - Estimation of seismic shear stresses along the perimeter
  - Deformation pattern
  - Estimation of impedance functions
  - Modeling features (i.e. equivalent static loads, boundaries etc.)
- Longitudinal seismic behavior and analysis
  - Estimation of the asynchronous seismic motion
  - Estimation of impedance functions
  - Deformation patterns and modelling
- Several other issues coming from the design and construction point of view
  - Joints performance, design and construction, in case of segmented underground structures (e.g. immersed tunnels)

Important “open” issues - example

- **Input motion? Shear stresses**
- **Equivalent static forces?**
- **Impedance functions?**



Physical modeling of seismic behavior of underground structures

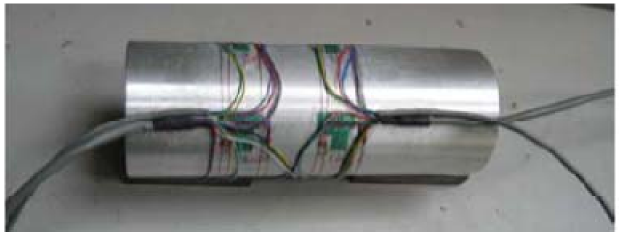
Short literature review

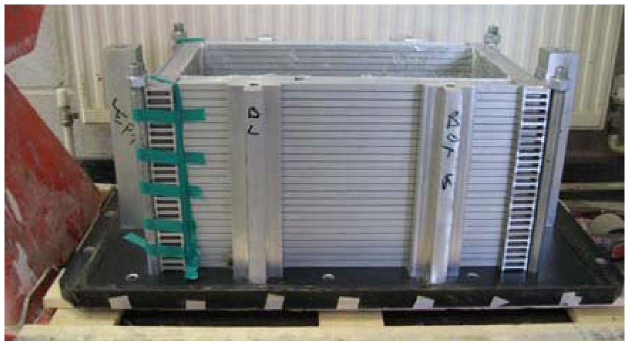
Physical modeling of seismic behavior of underground structures

- Few well-documented case histories, lack of comprehensive methodologies specific guidelines and seismic code regulations for the seismic design of underground structures with the exception maybe of gas and oil pipelines
- Physical modeling and numerical analysis are used to better understand the physical problem and in particular the soil-structure interaction phenomenon
- Physical modeling provide quality data under perfectly controlled conditions for the validation of the numerical procedures and codes
- Indicative examples (a list of references is presented at the end)

Case 1

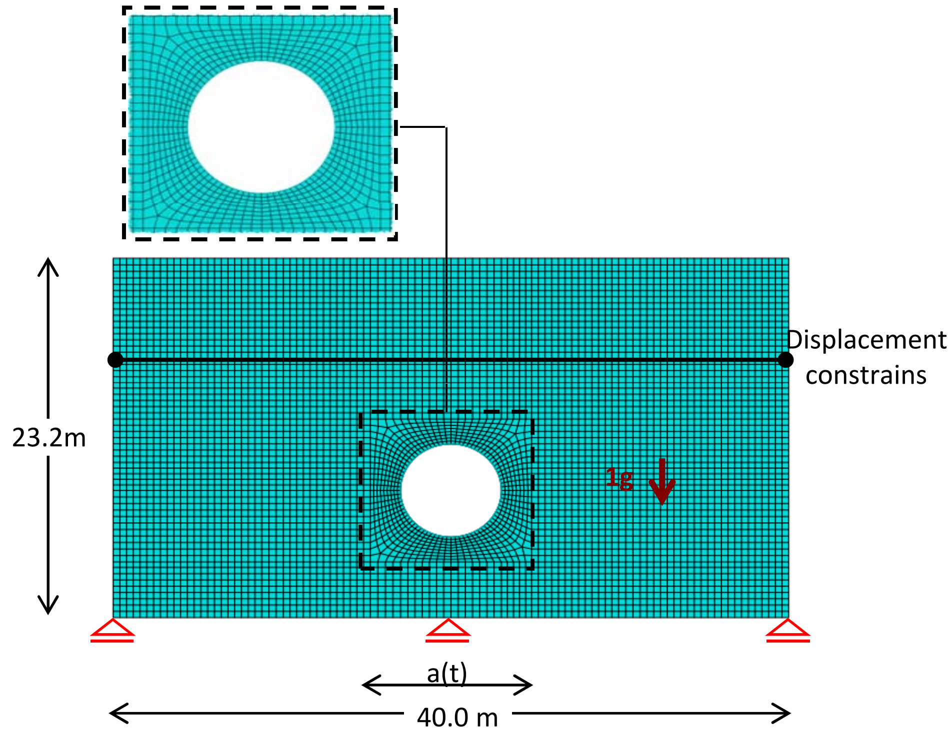
- **Researchers:** Bilotta et al., 2009, Lanzano et al., 2010 (ReLUIS project)
- **Type of structure:** Circular tunnels
- **Type of experiments:** dynamic centrifuge tests performed on aluminum tunnel models embedded in dry sand under 80g, to study the affection of burial depth on the seismic behavior and mainly to produce data for the validation of the design methods (uncoupled and coupled methods)
- Tests conducted at the Centrifuge facility of the Schofield Center in a laminar box

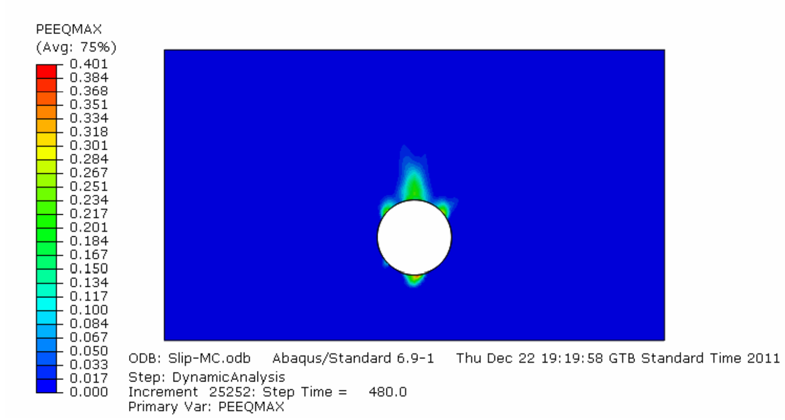


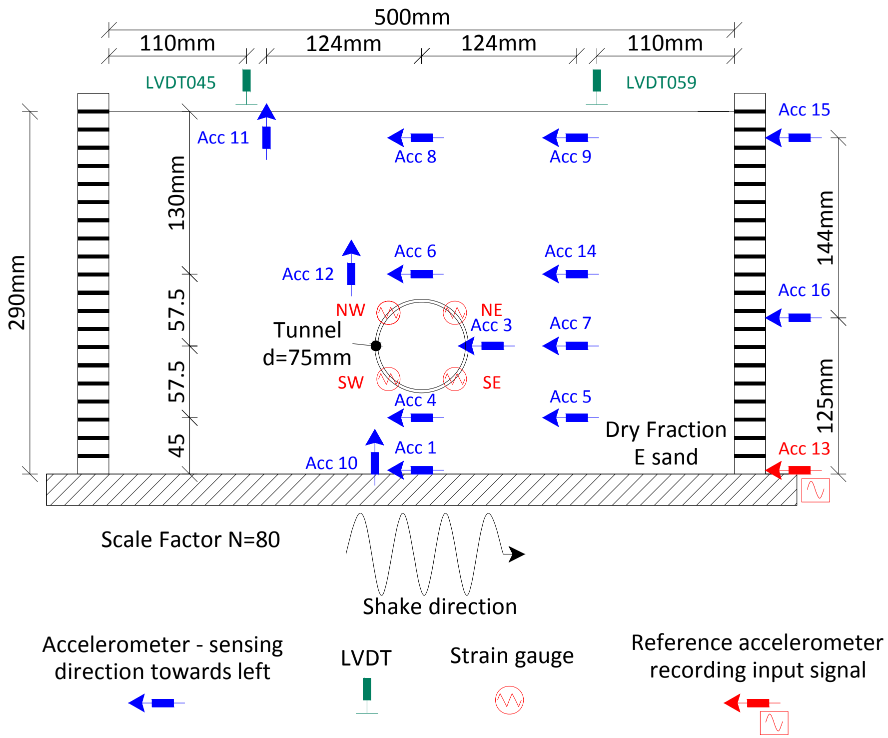


Case 1

- **Round Robin numerical Test on Tunnels under seismic loading (TC104, TC203 and TC204)**
- **Blind prediction numerical test**
- **AUTH participation**







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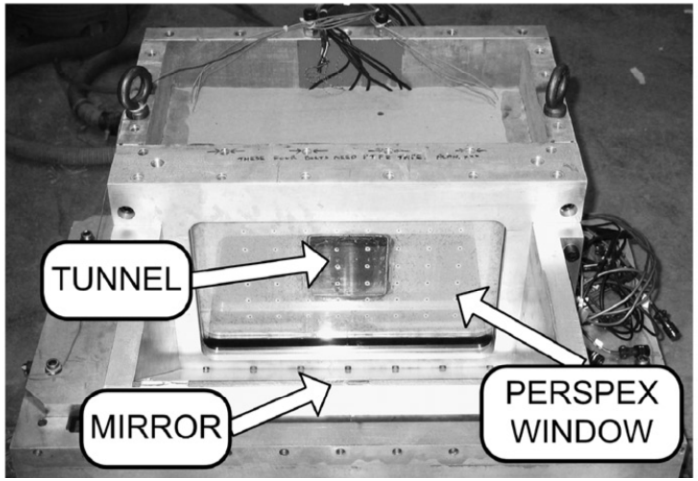
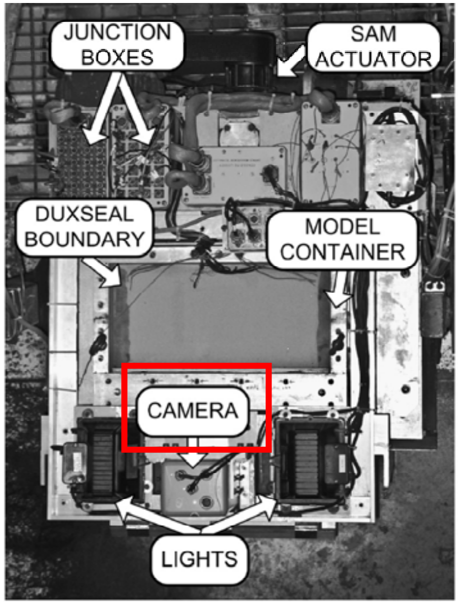
Case 2

- Researchers: Cilingir & Madabhushi (2010a, 2010b, 2011)
- Type of structure: Square, Circular tunnels
- Type of experiments: dynamic centrifuge tests performed on aluminum tunnel models embedded in dry sand under 50g, to study the affection of the input motion characteristics and of the burial depth of the tunnels on the seismic behavior
- Tests conducted at the Centrifuge facility of the Schofield Center at the University of Cambridge UK using a Rigid box with a window

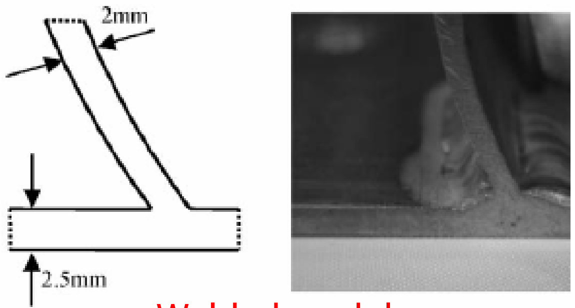
a



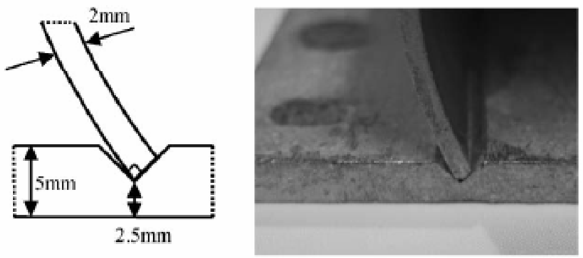


Case 3

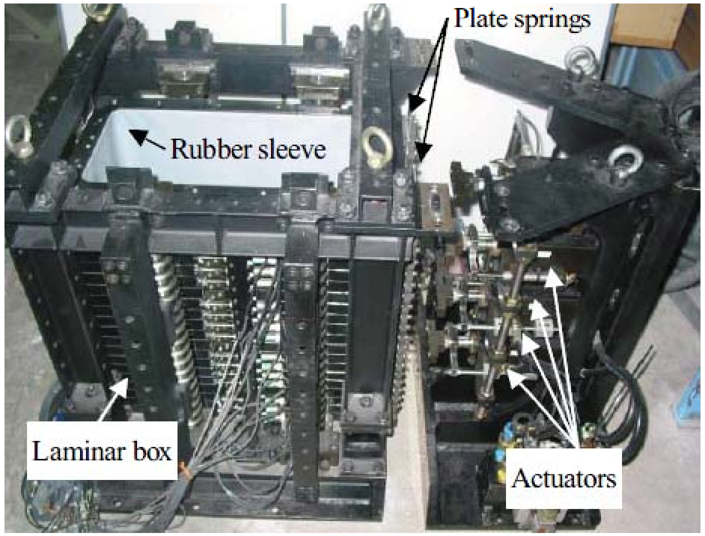
- **Researchers:** Shibayama et al., 2010
- **Type of structure:** Urban mountain type tunnels
- **Type of experiments:** pseudo-static centrifuge tests performed on aluminum tunnel models embedded in dry sand, to study the effect of burial depth and the connection of the invert slab with the tunnel lining

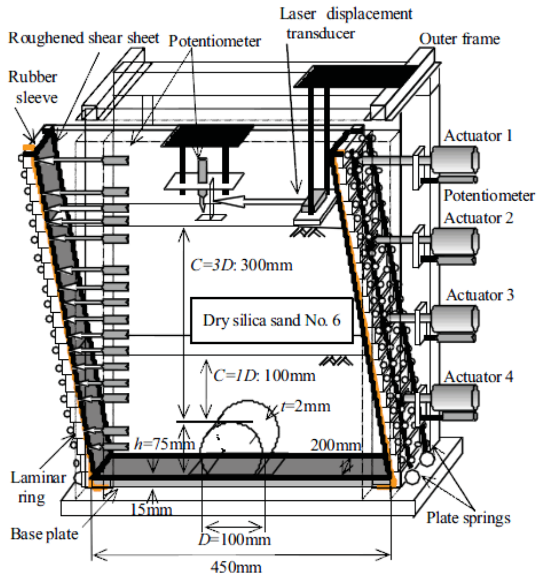


Welded model



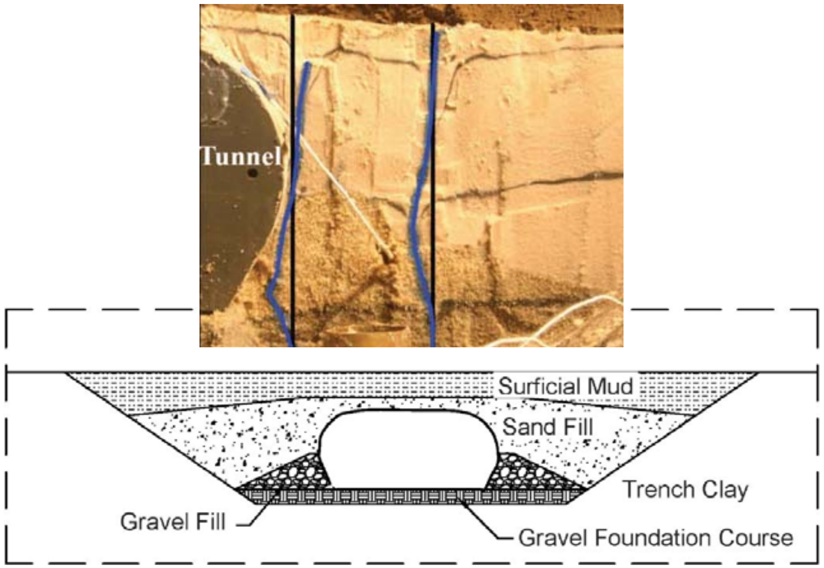
Non-welded model





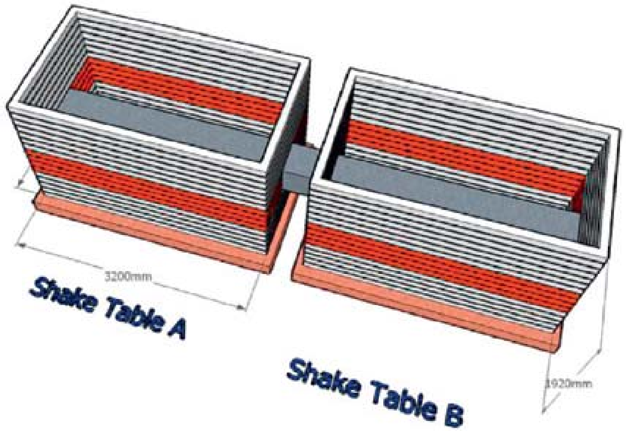
Case 4

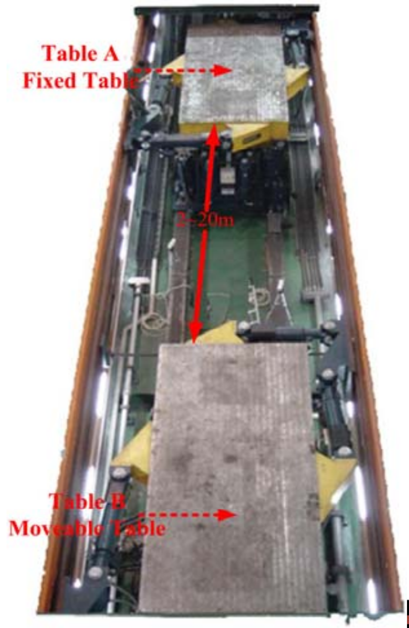
- **Researchers:** Chou et al., 2010, Kutter et al., 2008, Travasarou & Chacko, 2008, Travasarou, 2010
- **Type of structure:** immersed tunnel, retrofit check of the existing BART system
- **Type of experiments:** 2 dynamic centrifuge tests performed on PVC tunnel models, under 40g, to evaluate the potentially uplift of the BART tube caused by liquefaction (UC Davis USA)



Case 5

- **Researchers:** Chen et al., 2010
- **Type of structure:** Rectangular utility tunnel
- **Type of experiments:** 46 shaking table tests performed on RC models (one jointless and one with 2 construction joints) embedded in unsaturated sand to study the effect of the non-uniform ground motion along the alignment of a utility tunnel
- Sensors to measure slippage at the interface, displacement and rotation at the joints





Main remarks

- For horizontal shaking appearance of vertical acceleration components (i.e. Yukio et al., 2001)
- Physical modeling can help to understand the uplift behavior of immersed tunnels during liquefaction, validate the efficiency of the countermeasure retrofit techniques and validate the numerical models (i.e. Adalier et al., 2003, Chou et al., 2010 etc.)
- Kinematic loads (ground strains) are more important than inertial forces (i.e. Iwaga et al., 2006)
- Internal forces, in case of flexible embedded structures; Three distinctive stages are observed namely a transient stage following by steady state circles and finally a post-earthquake residual stage, (i.e. Bilotta et al, 2010, Lanzano, 2009, Cilingir & Madabhushi, 2010a, 2010b, 2011)

- Shear stresses around the perimeter of an underground structure: It is very difficult to be measured accurately. Their values depend on several factors (intensity of the input motion, rugosity of the soil lining interface, measuring equipment etc) (Tohda et al, 2010).
- Flexible tunnels (square or circular) tend to deform inward (i.e. Cilingir & Madabhushi, 2010a, 2010b, 2011). Except for racking or ovaling deformations
- Non-uniform earthquake excitations produce higher intensities compared to uniform ones (i.e. Chen et al., 2010)
- Non-uniform earthquake excitations can lead to important differential displacements and rotation of the joints in case of segmented structures (i.e. Chen et al., 2010)

- Questions on crucial "open" issues are not fully answered, namely:

  - Input motion (characteristics, asynchronous motion)?
  - Seismic earth pressures on the side walls?
  - Seismic shear stresses around the embedded structure perimeter?
  - Deformation patterns
  - Impedance functions for underground structures?
  - Effect of backfill material on the seismic behavior of underground structures?
  - Joints performance and appropriate design?

AUTH ongoing research projects on the seismic behavior of rectangular embedded structures with reference to physical modelling in the framework of SERIES

Introduction

- Further experimental and numerical study deemed to be necessary, especially in case of rectangular embedded structures, to answer the "open" questions and improve the seismic design

- Two relevant research projects are running within the Transnational Access task of SERIES, titled:

  - *"Investigation of the seismic behavior of shallow rectangular underground structures in soft soils using centrifuge experiments"*
  - *"Investigation of several aspects affecting the seismic behavior of shallow rectangular underground structures in soft soils"*

- The first program is running at the centrifuge facility of IFSTTAR in Nantes, France, whereas the second program is running at the centrifuge facility of the Schofield Center at the University of Cambridge, UK

- Centrifuge testing of rectangular embedded structures in dry or saturated sands submitted to simple sine waves or real recordings

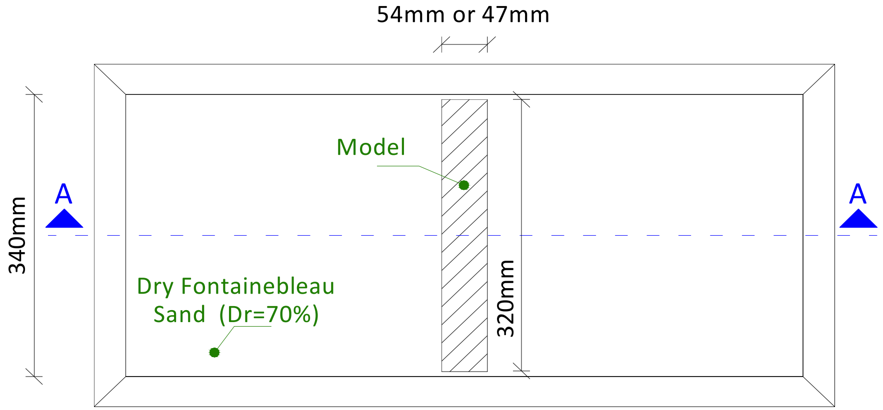
- **Main objectives:**
  - **Study the influence of the relative flexibility ratios on the drift displacement**
  - **Study the seismic earth pressures distribution along the side-walls**
  - **Study the seismic shear stresses distribution and magnitude along the perimeter of underground structures**
  - **Estimate proper impedance functions for underground structures to model kinematic and inertial soil structure interaction effects**
  - **Study the effect of backfill material (e.g. gravel), on the seismic behavior of an underground structure**

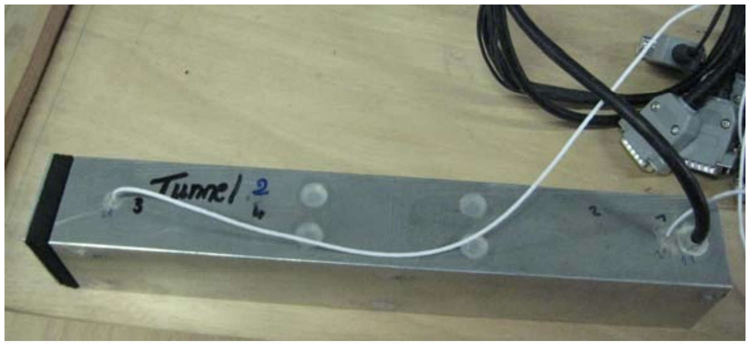
“Investigation of the seismic behavior of shallow rectangular underground structures in soft soils using centrifuge experiments”

Centrifuge facility of IFSTTAR, Nantes, France

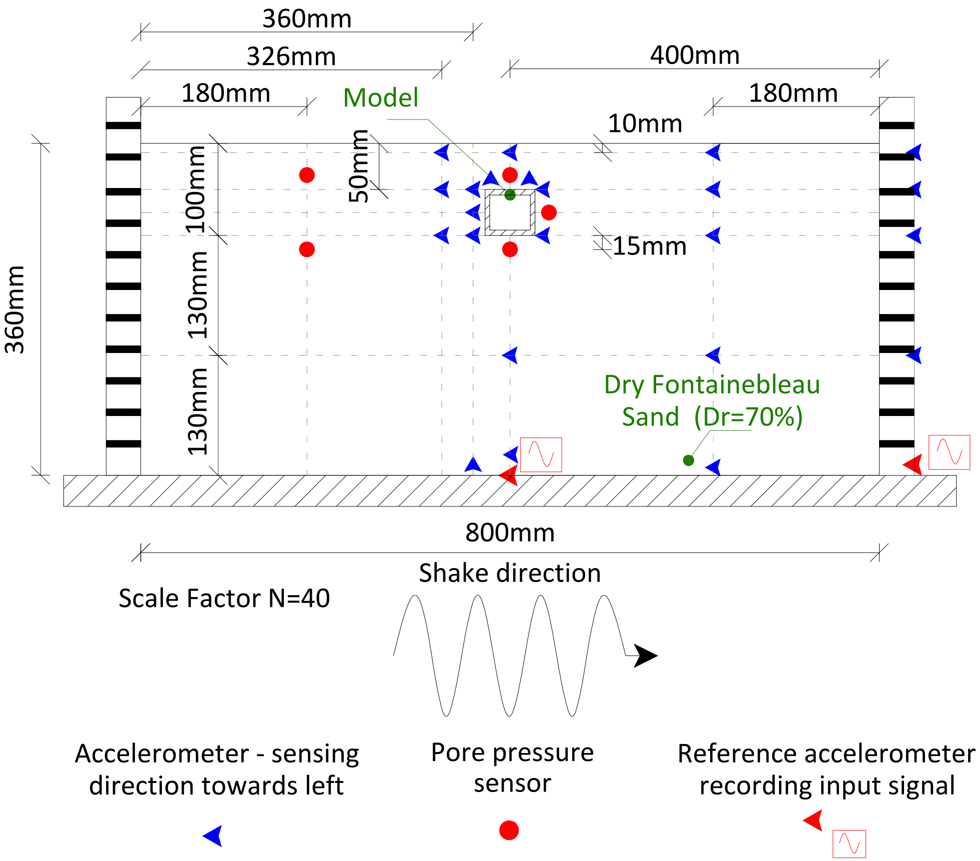
General description

- Centrifuge tests on rectangular tunnel models, embedded in saturated or dry sand under a centrifugal acceleration of 40g will be carried out at the centrifuge facility of IFSTTAR in Nantes, France





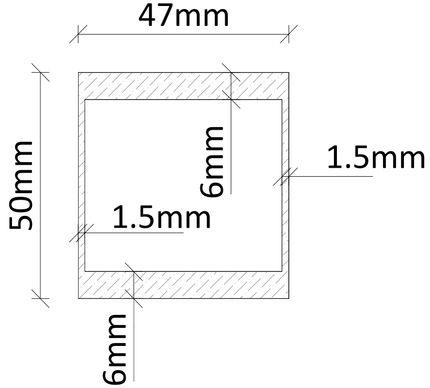
Section A-A - Soil instrumentation



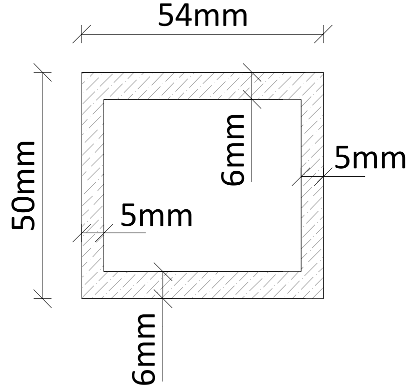
- Objectives:
  - Seismic earth pressures distribution along the side-walls
  - Seismic shear stresses distribution along the perimeter
  - Impedance functions

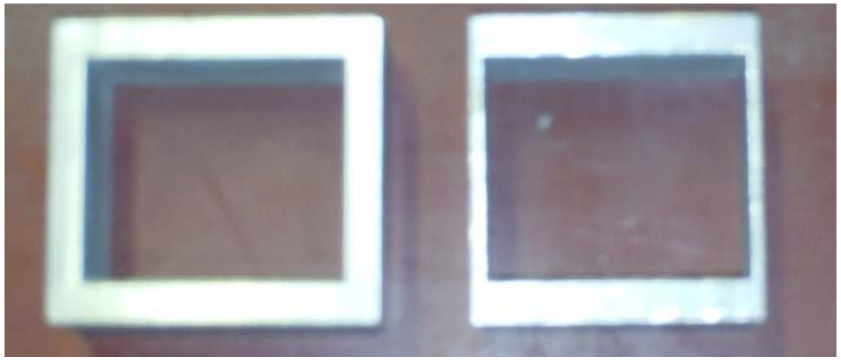
- Reduction factor N=40
- 2 models: flexible model, rigid model (2017 A aluminium alloy)
- 2 levels of rugosity (smooth interface: $\delta = \delta_{aluminium}$, rough interface: $\delta = \varphi$)
- Dry / saturated Fontainebleau sand NE34 (Dr=70%)
- Real recordings of increasing amplitude (+ sine wavelets)
- 7 tests + 1 free field test

Model 1

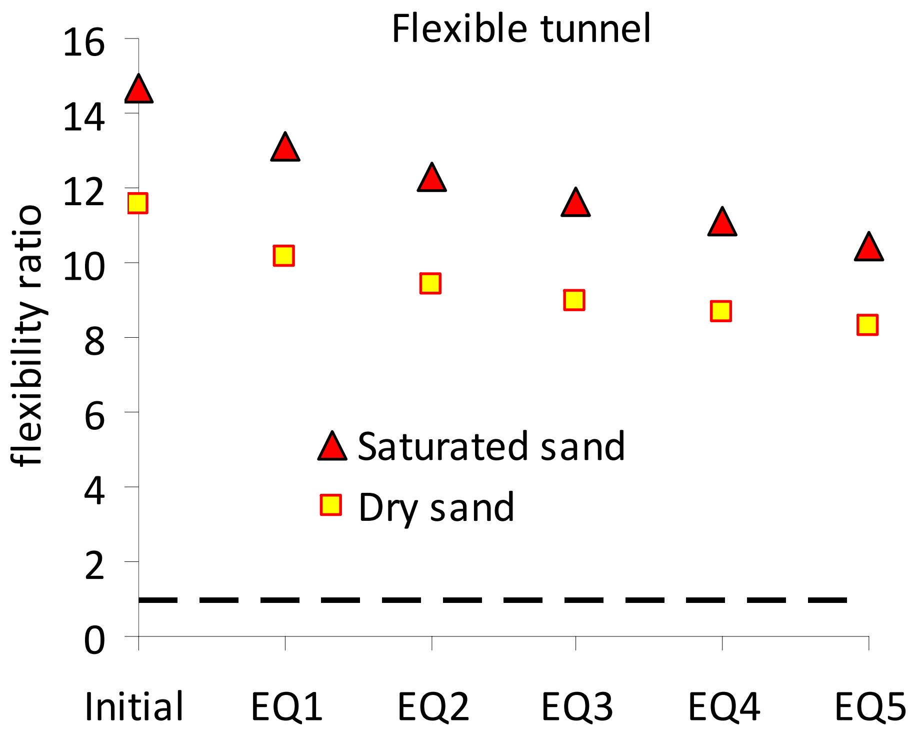


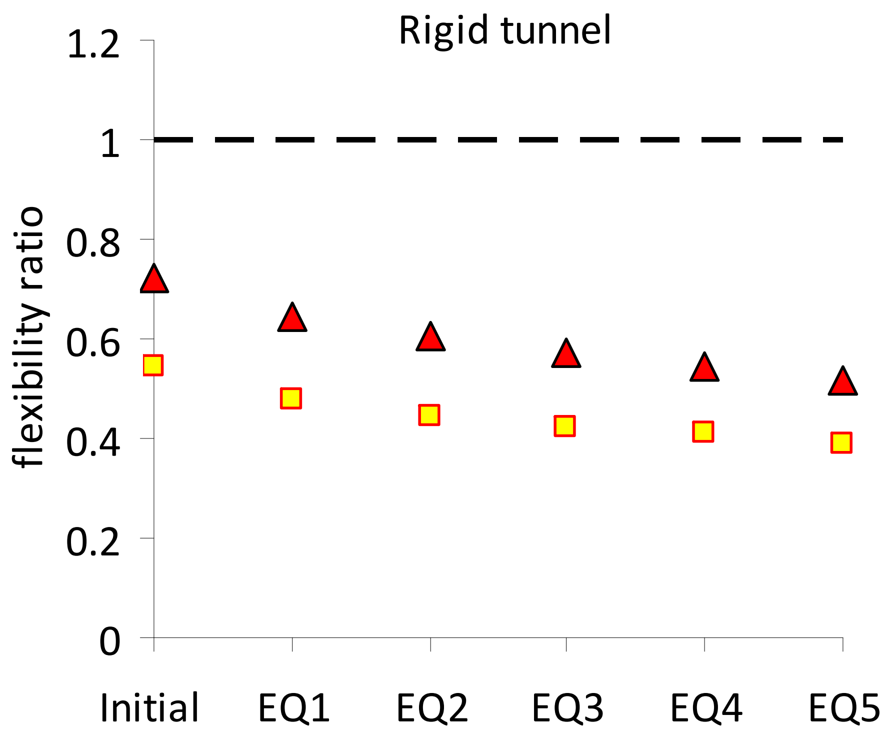
Model 2

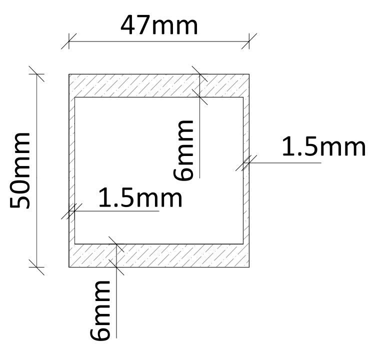




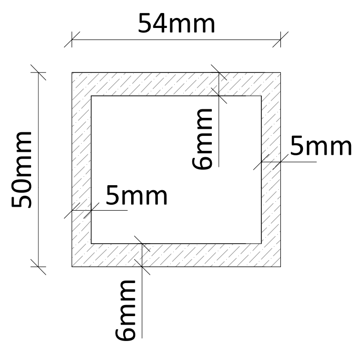
- **Estimation of the flexibility ratio for the proposed model sections**
- **Takatori, 1995 (scaled to 0.05g (EQ1), 0.10g (EQ2), 0.15g (EQ3), 0.20g (EQ4), 0.30g (EQ5))**



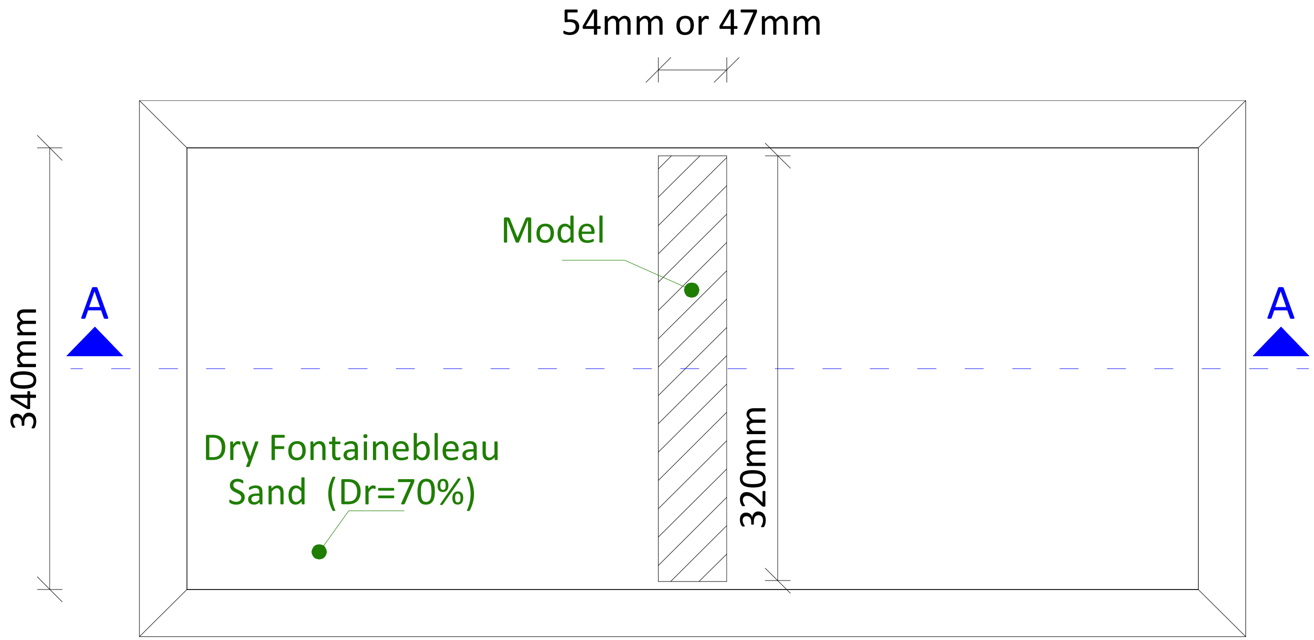


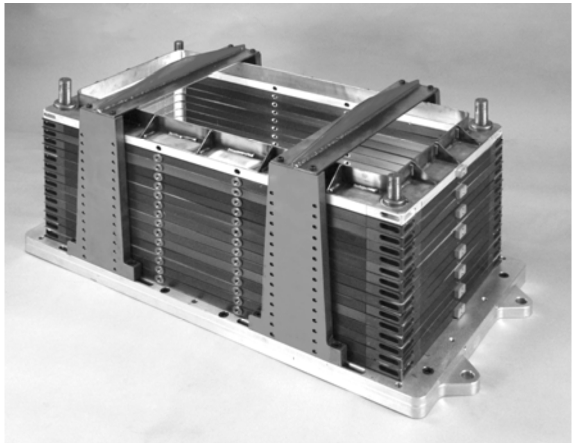


$$F = \frac{G_m}{12}\left(\frac{HW^2}{EI_R}\psi\right)$$



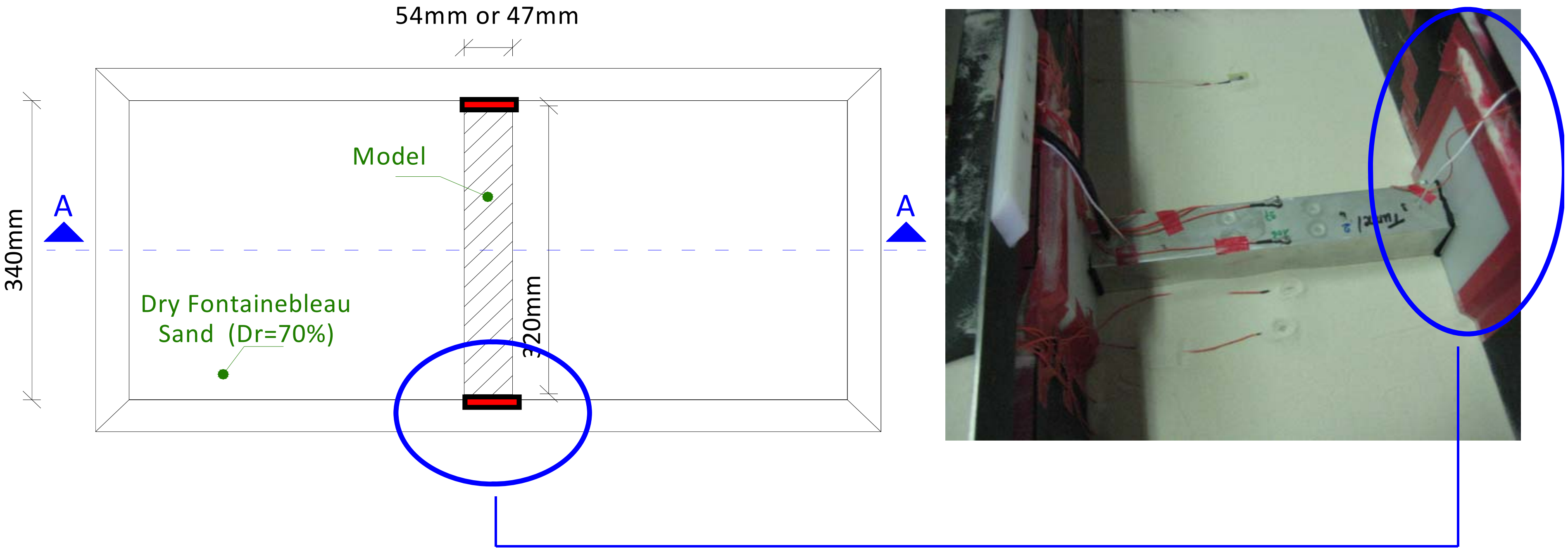
- **Large ESB box is utilized to minimize the boundary effects**
- **ESB dimensions: 800x350x410 (mm)**



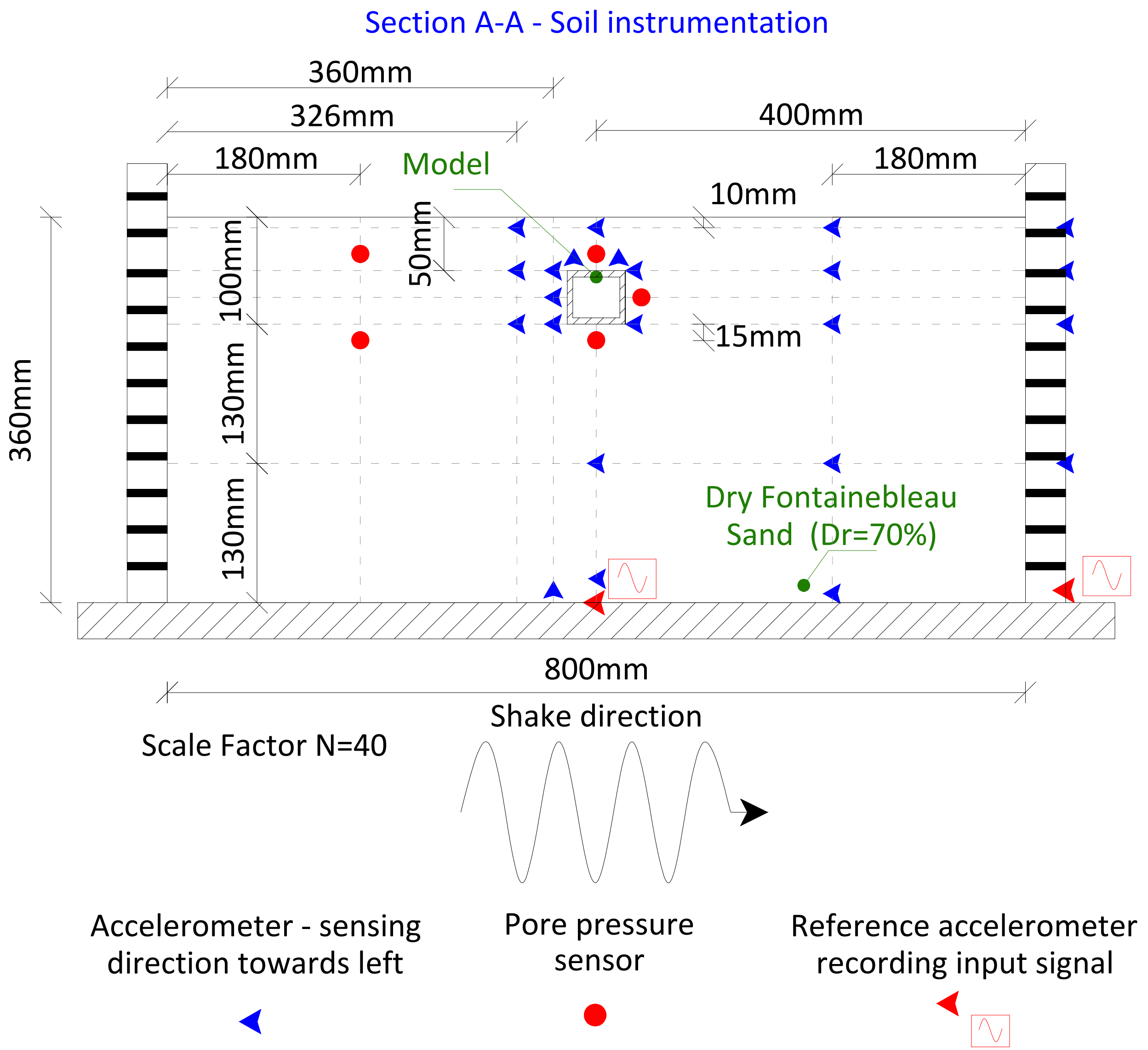


- **Special connection of the tunnel models ends to the laminar box to avoid any limitation of the models deformation that can affect the plane strain behavior**

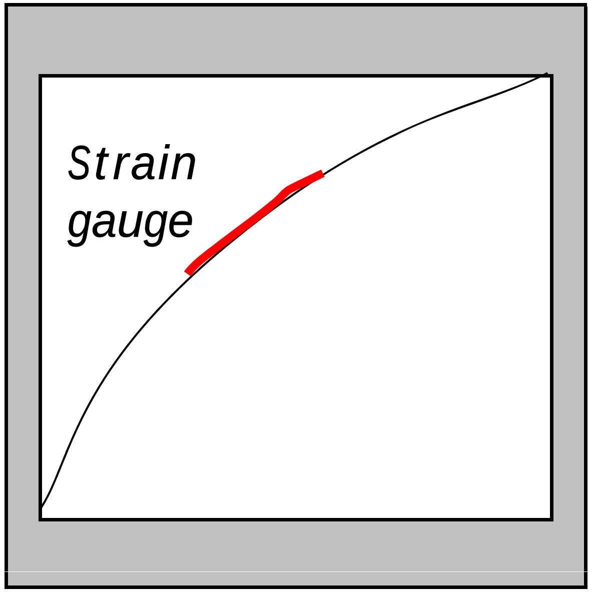
- **10mm thick Teflon plate + waterproof knob + aluminium plate glued on the knob**



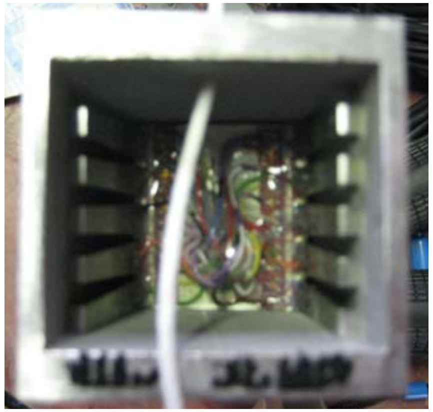
- **Model configuration - instrumentation scheme**

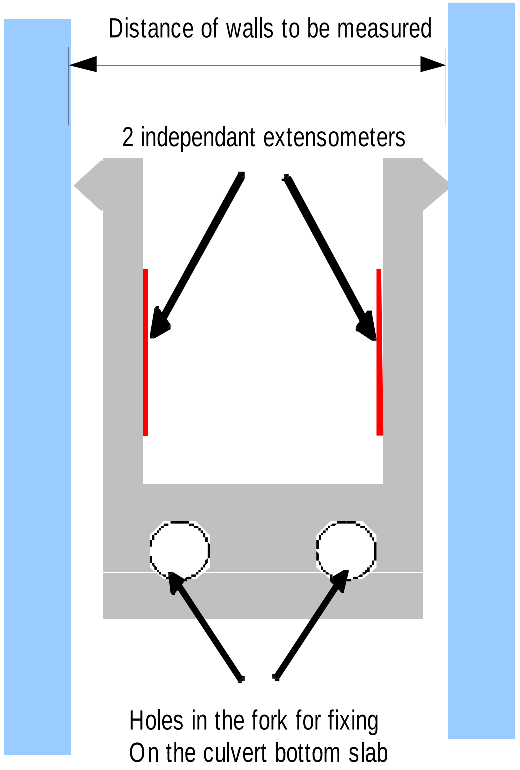


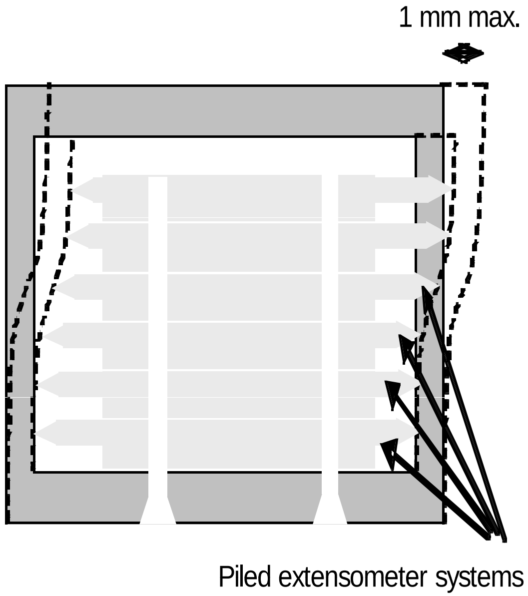
- **Check of the plane strain conditions with diagonal extensonmeters at three sections of the model (2 ends, middle)**



- **System of extensometers to measure the lateral displacement profile of the walls of the culvert due to the soil pressure**
- **At each level of the cross section a 2 tooth fork equipped with strain gauges will give the lateral displacement of the culvert wall at this level**

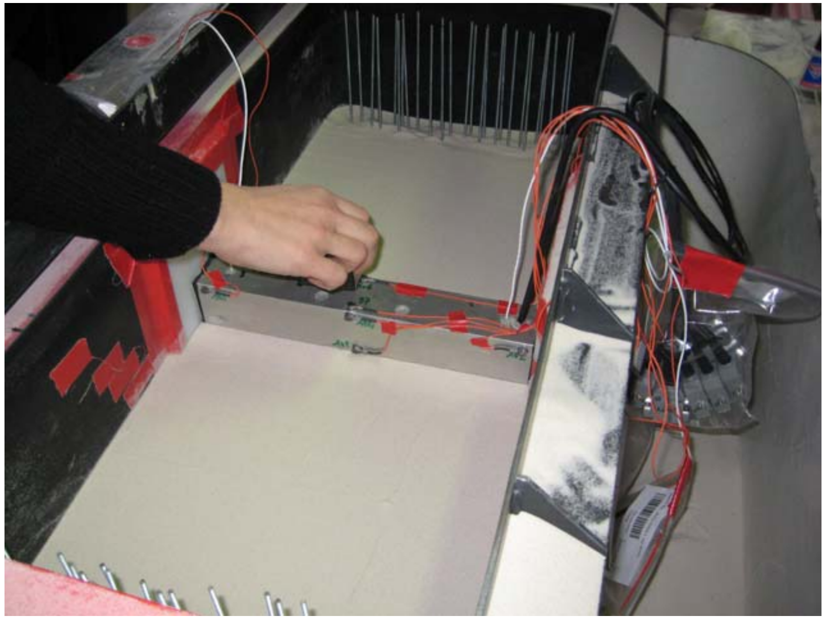


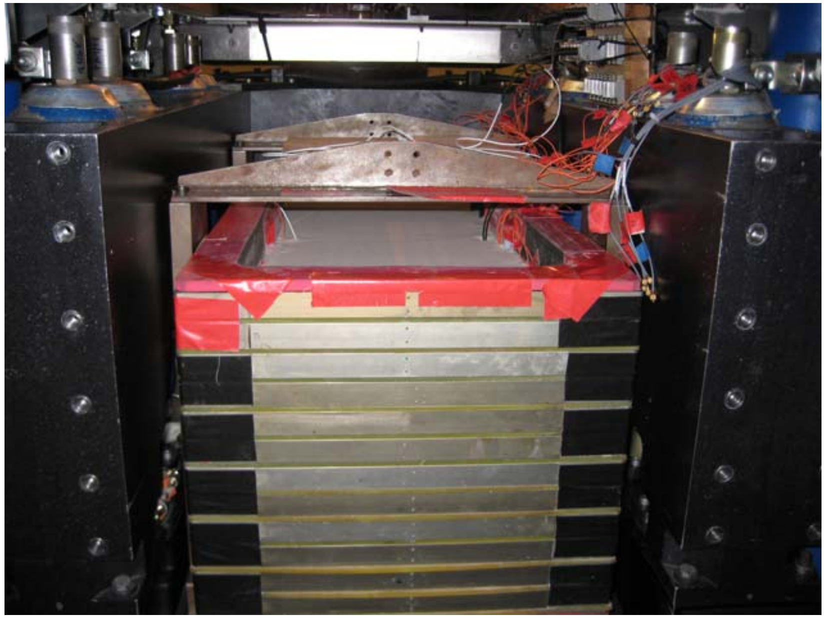




Preliminary test (December 2011)

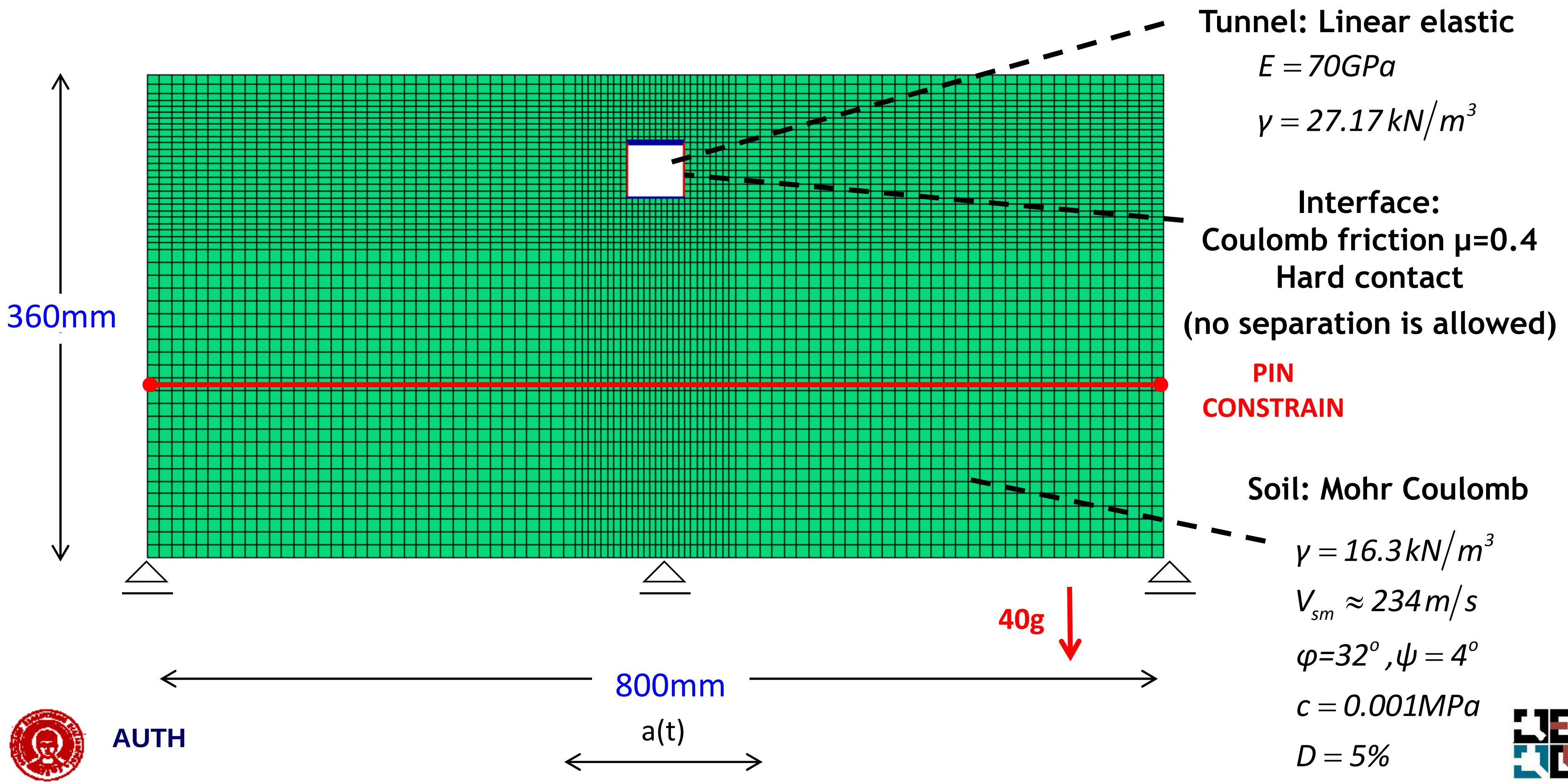
- Flexible model in dry sand excited with a real record from the Northridge earthquake
- 3 "earthquakes" of increasing amplitude were fired





Preliminary numerical analysis

- **Preliminary numerical analysis can be used to optimize the experimental set up giving a general idea of the expected performance**
- **Numerical simulation of the flexible tunnel model in dry sand in model scale using the ABAQUS**



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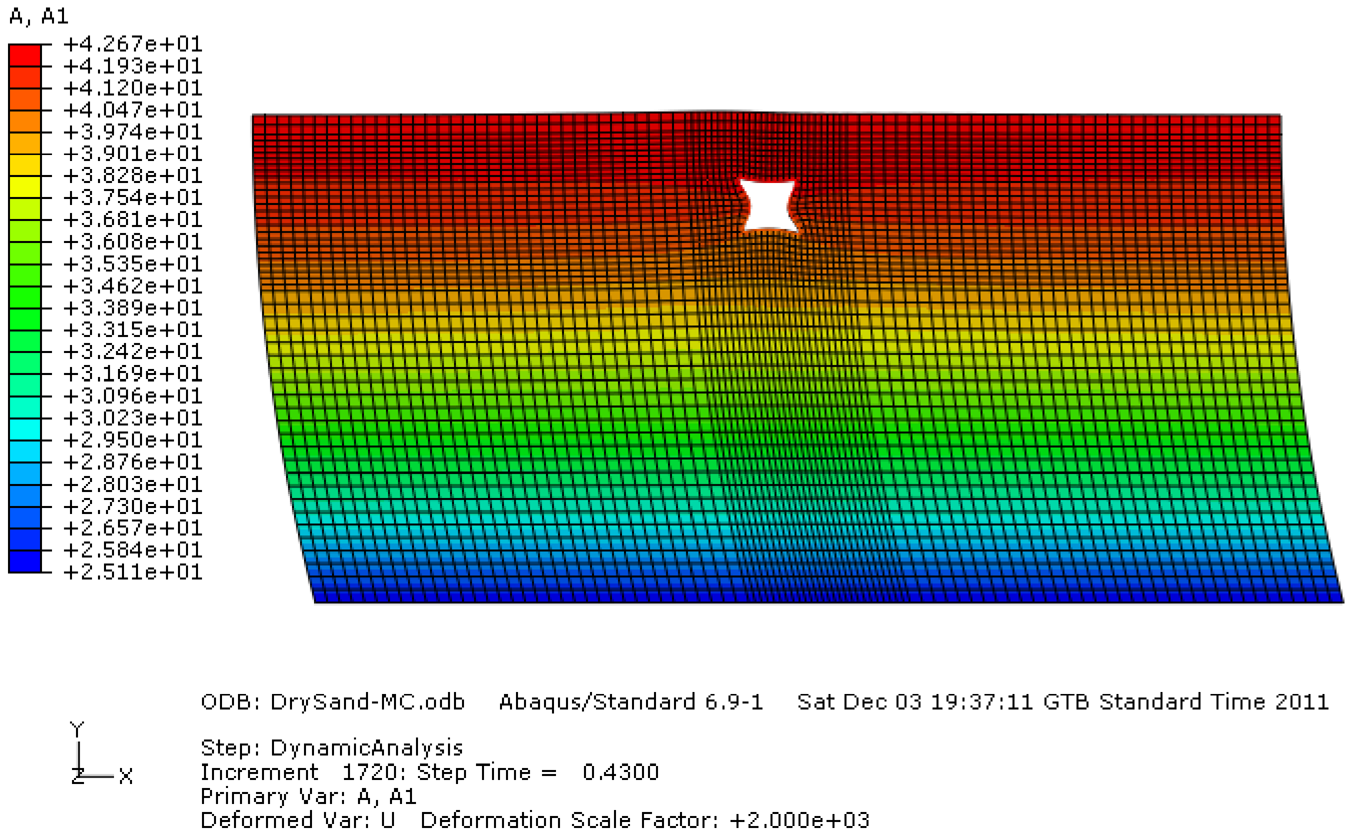
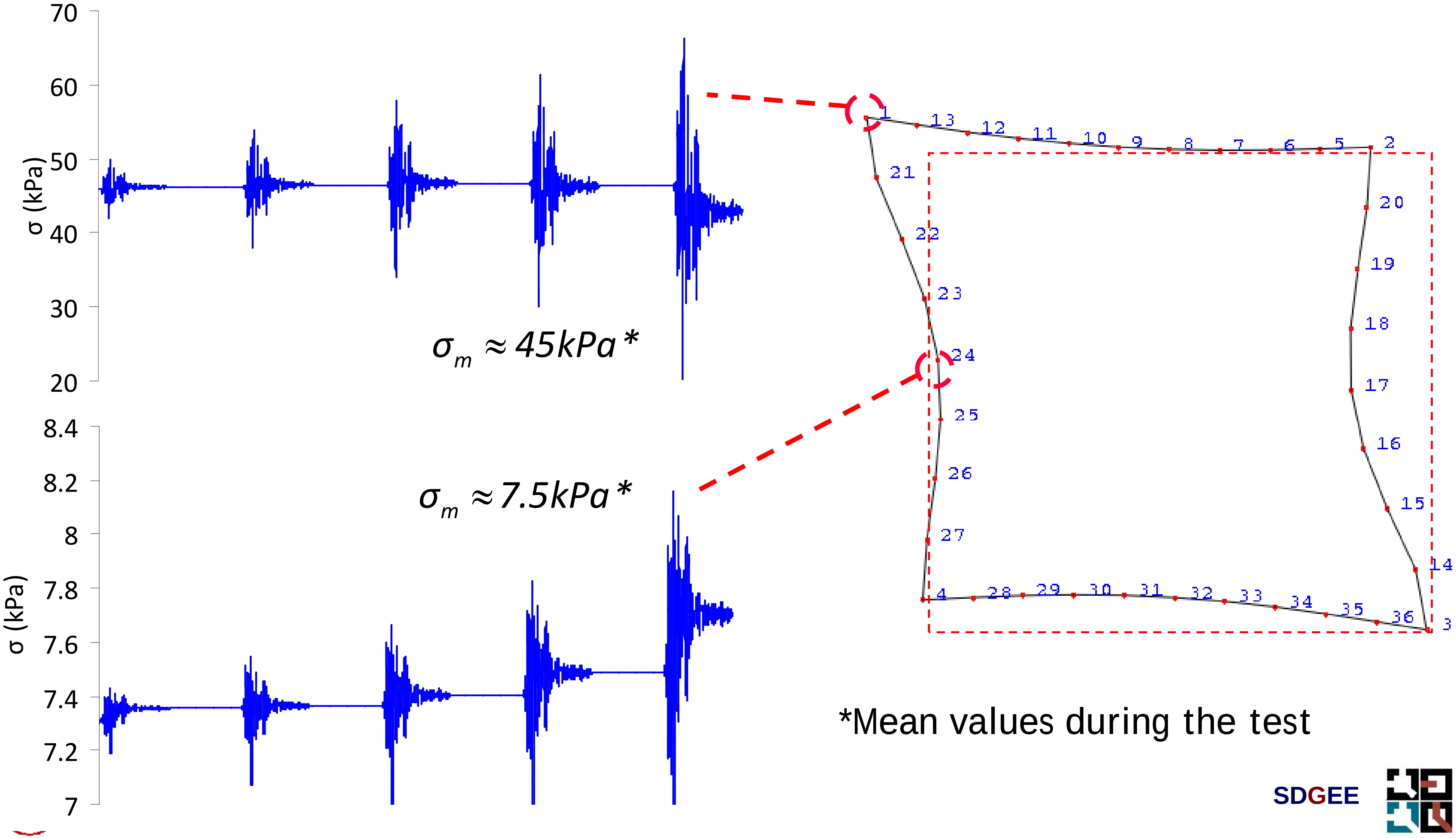
- **Dynamic Step**
- **Horizontal acceleration – EQ2 (t=0.43s)**

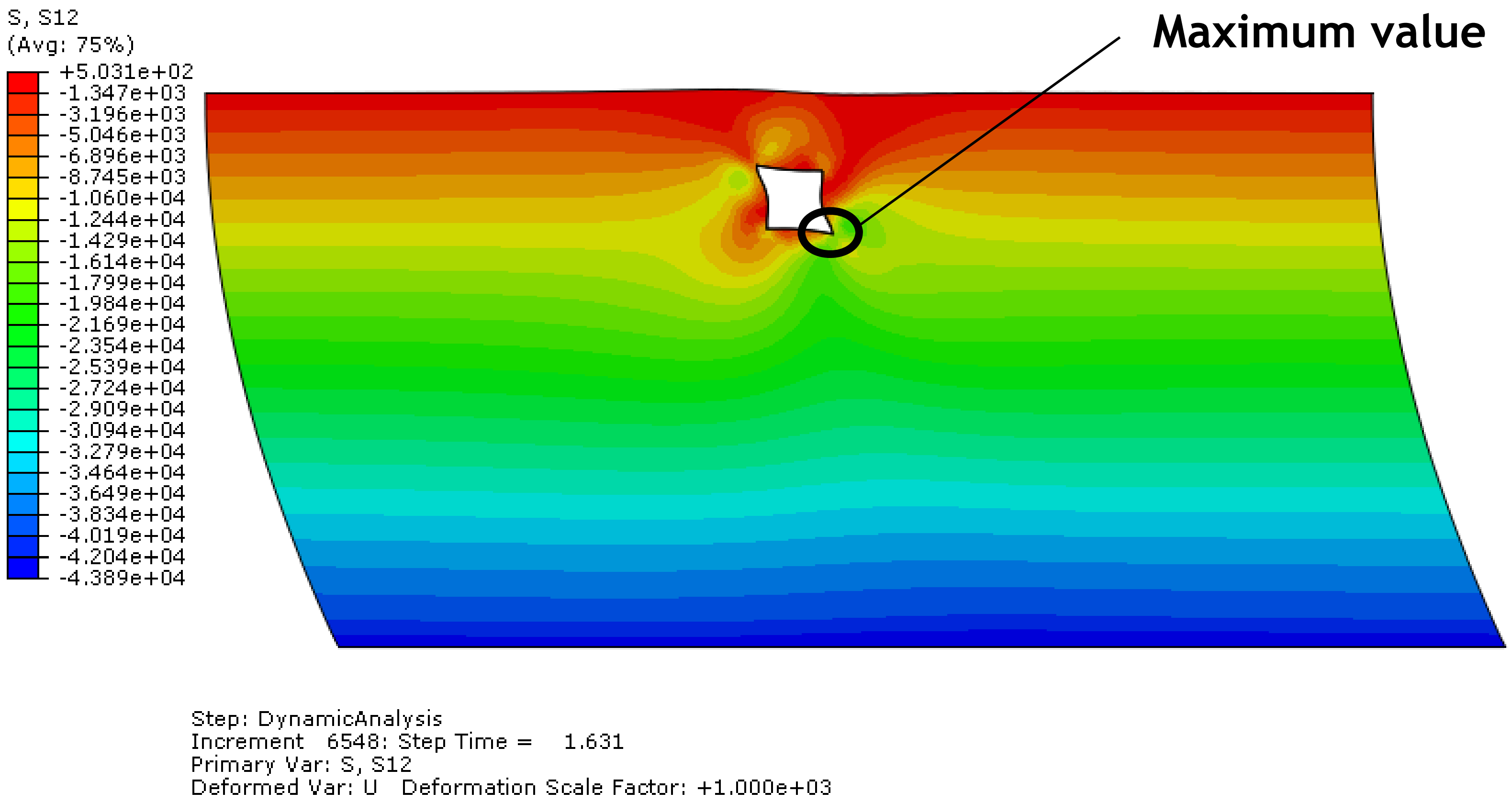


- **Dynamic Step**
- **Residual pressures after strong excitations**
- **Larger pressures at joints (corners)**

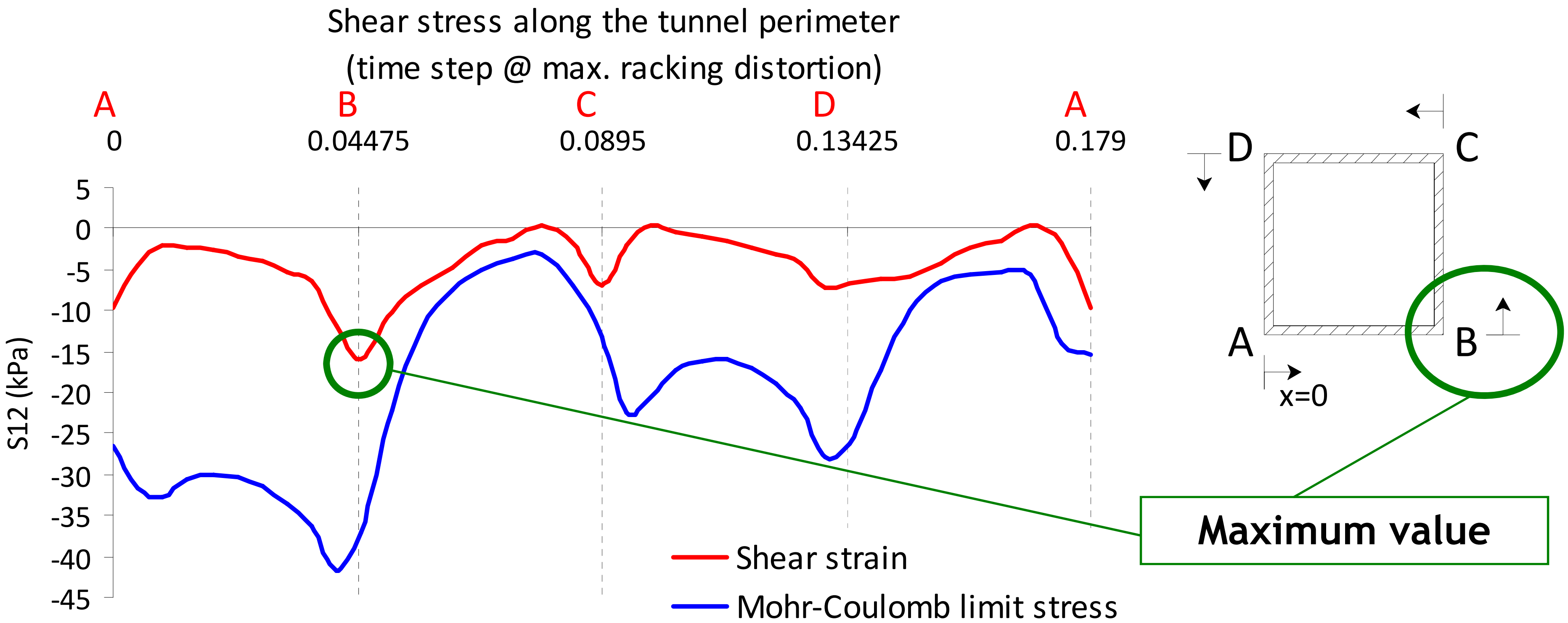


*Mean values during the test

- **Dynamic Step**
- **Shear stresses at maximum racking distortion**



- **Dynamic Step**
- **Shear stresses at maximum racking distortion vs. Mohr Coulomb limit stress**



$$Slabs: \sigma_{max} = \left\{ \sigma_{stat.,yy} + \sigma_{dyn.,yy} \right\} \times tan\varphi$$

$$Side\ walls,\ \sigma_{max} = \left\{ \sigma_{stat.,xx} + \sigma_{dyn.,xx} \right\} \times tan\varphi$$

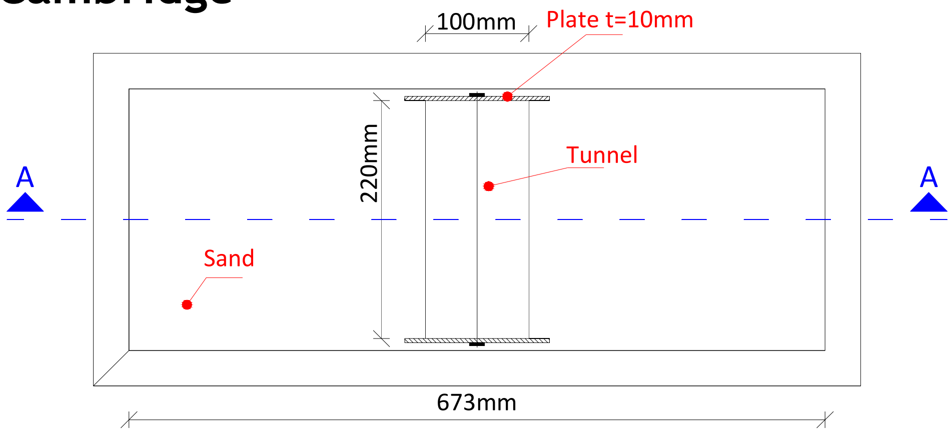
$$\varphi = 32^o$$

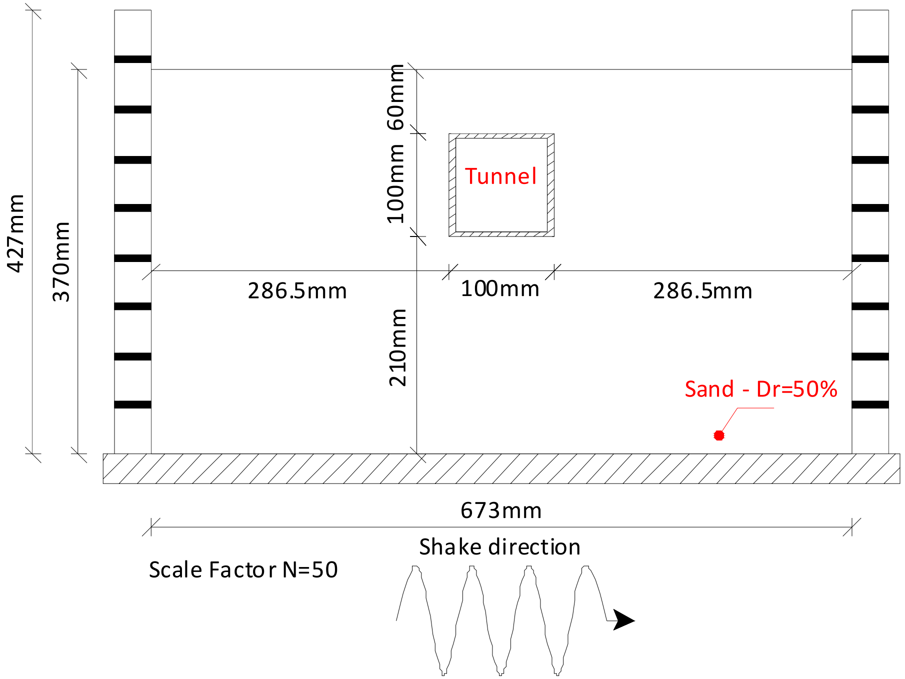
“Investigation of several aspects affecting the seismic behavior of shallow rectangular underground structures in soft soils”

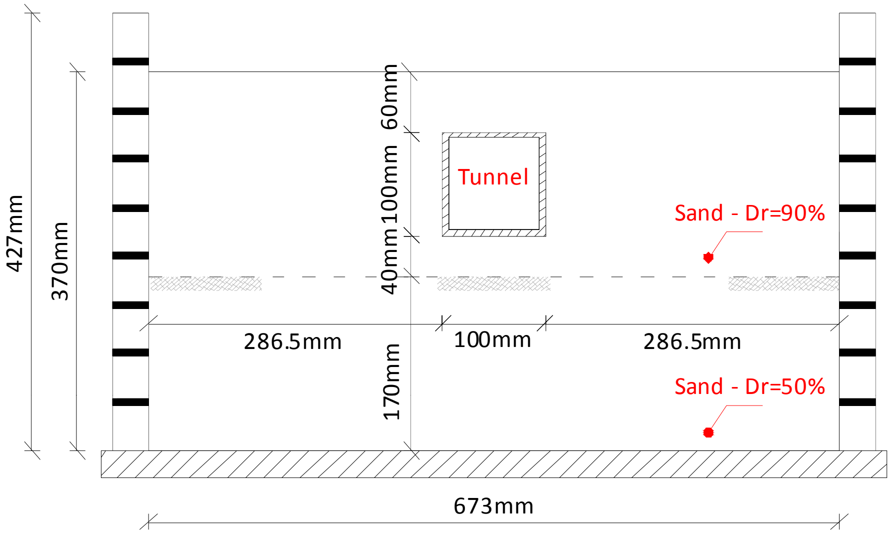
Centrifuge facility of Schofield Center, University of Cambridge, UK

General description

- **Centrifuge tests on square tunnels embedded in dry Hostun S32 sand, under centrifugal acceleration of 50g, performed at the centrifuge facility of the Schofield Center of the University of Cambridge**







- Objectives:
  - Influence of the relative flexibility ratios on the drift displacements
  - Effect of the flexibility ratio on the seismic earth pressures and the seismic shear stresses distribution along the perimeter
  - Effect of the backfill material, on the seismic behavior of an underground structure

- Reduction factor N=50

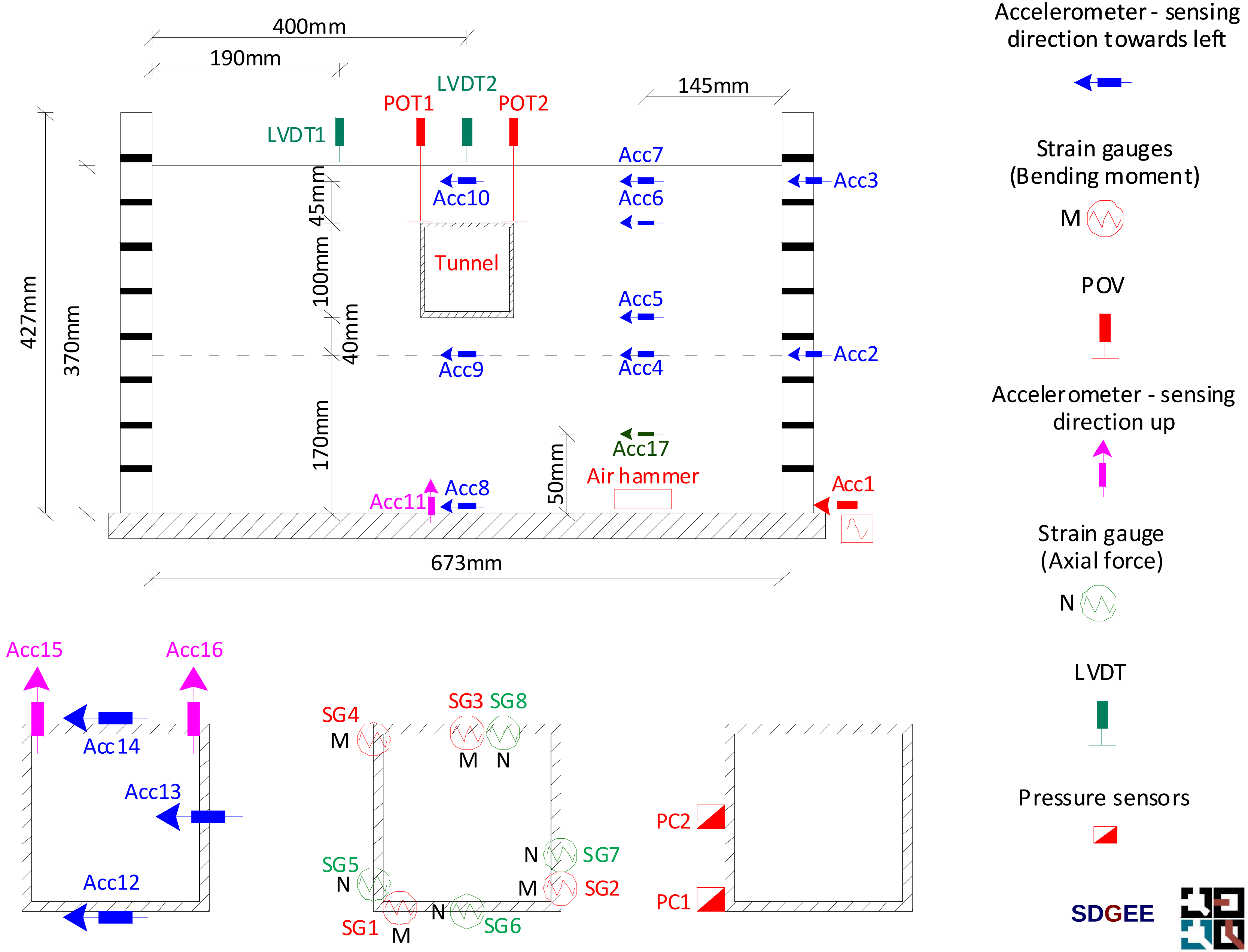
- The tests are performing in the large ESB box (673x427x253 (mm))

- 2 tunnel models (BS5251-H24 Aluminum alloy):
  - flexible model: 100 x 100 x 220 (mm), thickness 0.5mm
  - rigid model: 100 x 100 x 220 (mm), thickness: 2mm

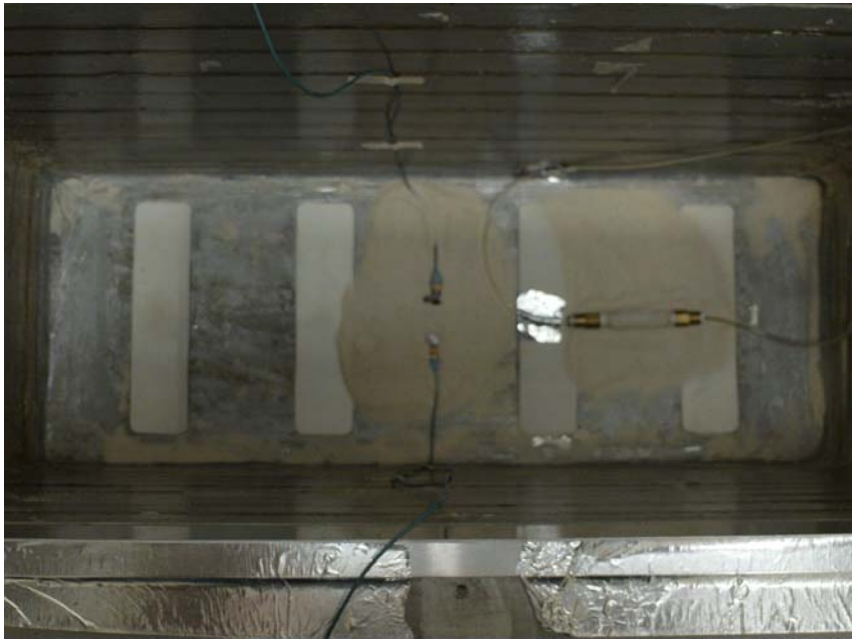
- Teflon plates, 110 x 110 x 10 (mm) in dimensions, bonded with each other with a large screw, were used to avoid the entrance of sand in the tunnel model during the test

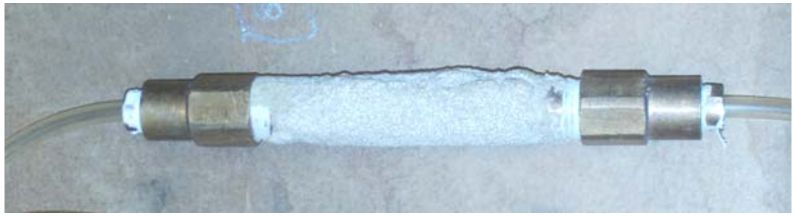
- A two layered soil deposit will be used to study the effect of the commonly used backfill material on the seismic behavior
- Sine wavelets of increasing amplitude
- 3 tests
- Records in terms of:
  - Accelerations in several points in the soil and on the model, using accelerometers
  - Earth pressures at two locations on the one side wall of the structure, using earth pressure cells
  - Settlement of the soil surface at two locations, using LVDTs
  - Movement of the tunnel (i.e. rocking), using potensiometers
  - Strains on the model (axial and bending) using full bridge strain gauges

- **Instrumentation scheme**

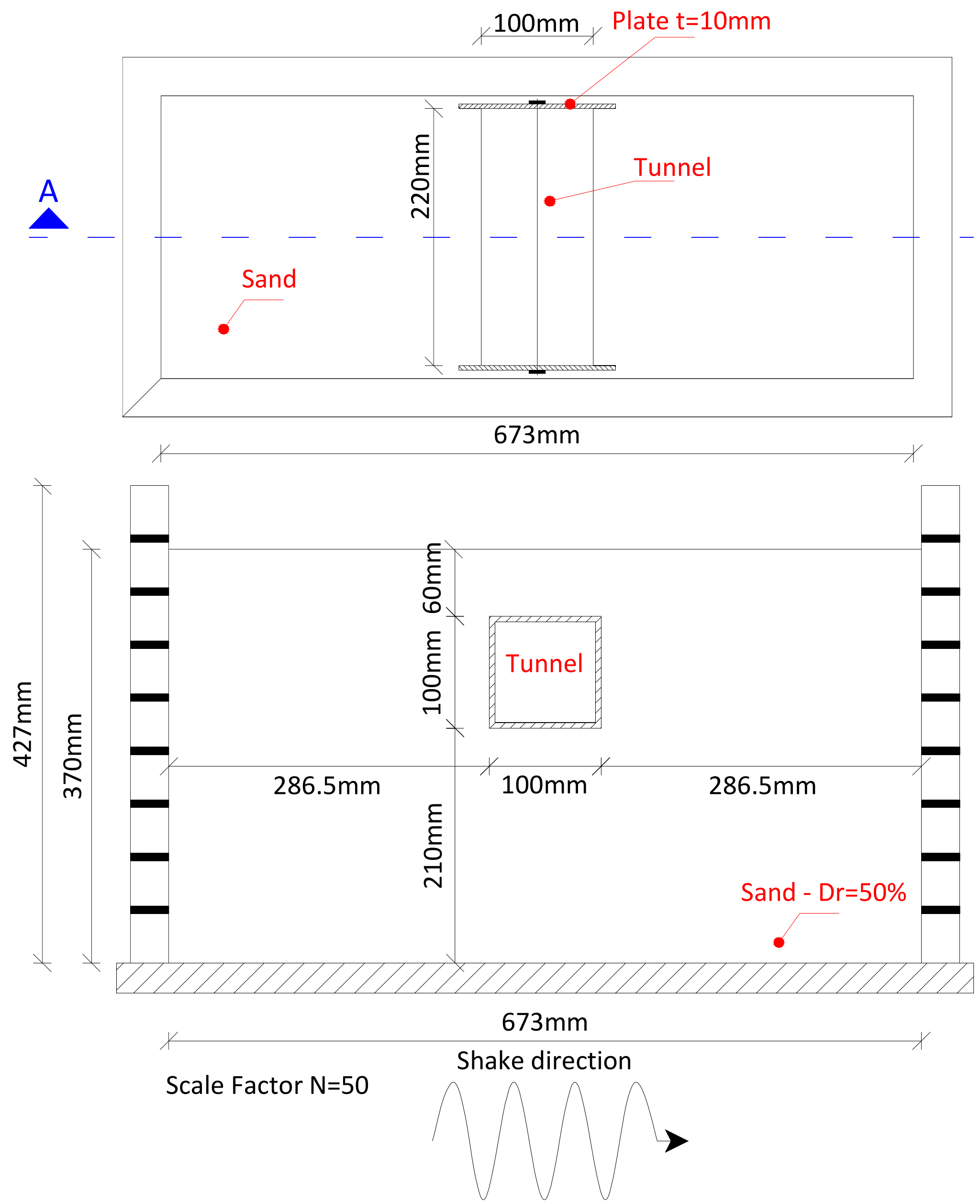


- 2 flights per test
  - 1 flight: main test using CDAQS (sampling rate: 4kHz)
  - 2 flight: Air hammer testing using Dasylab (sampling rate: 50kHz) to estimate the Vs profile



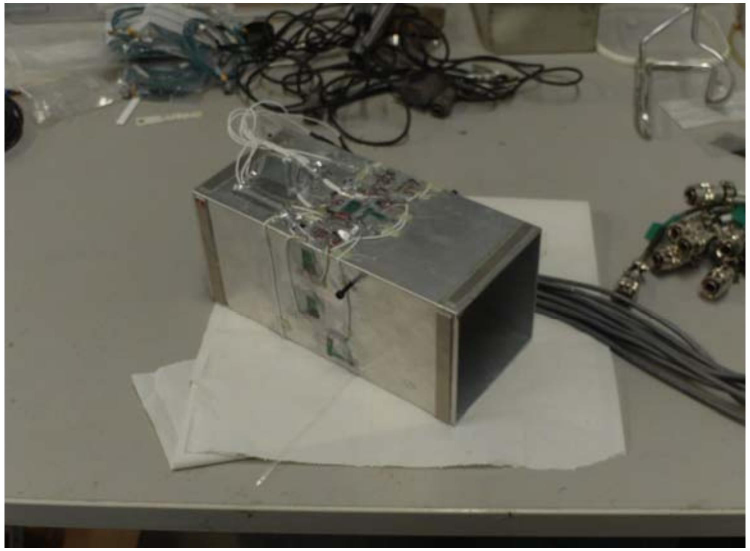


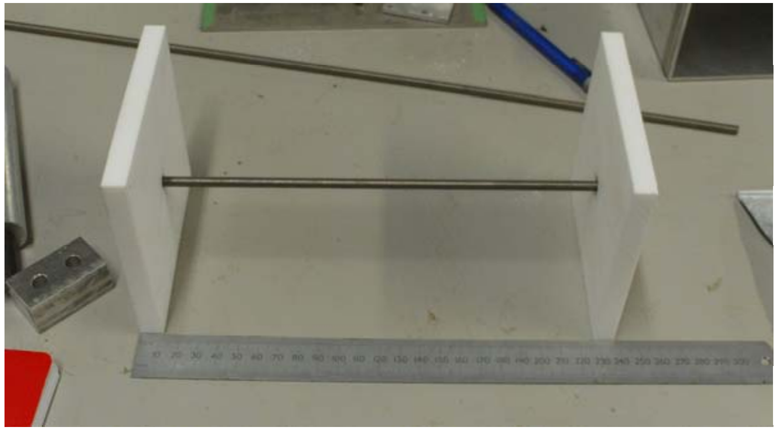
- **Model configuration for the first test (performed on 26-27/1/2012)**

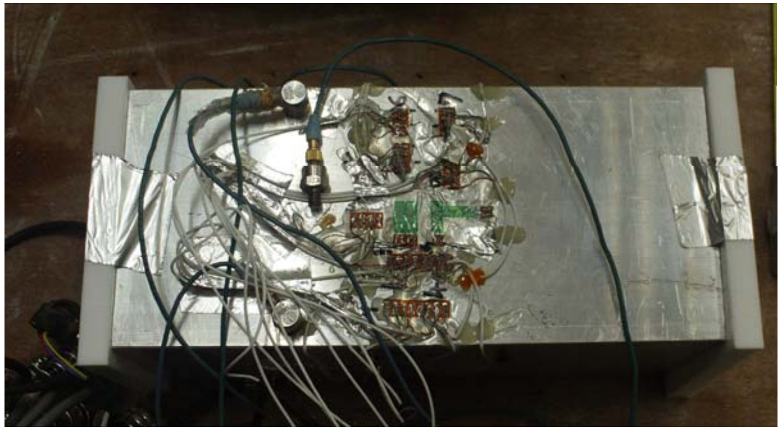


1st test

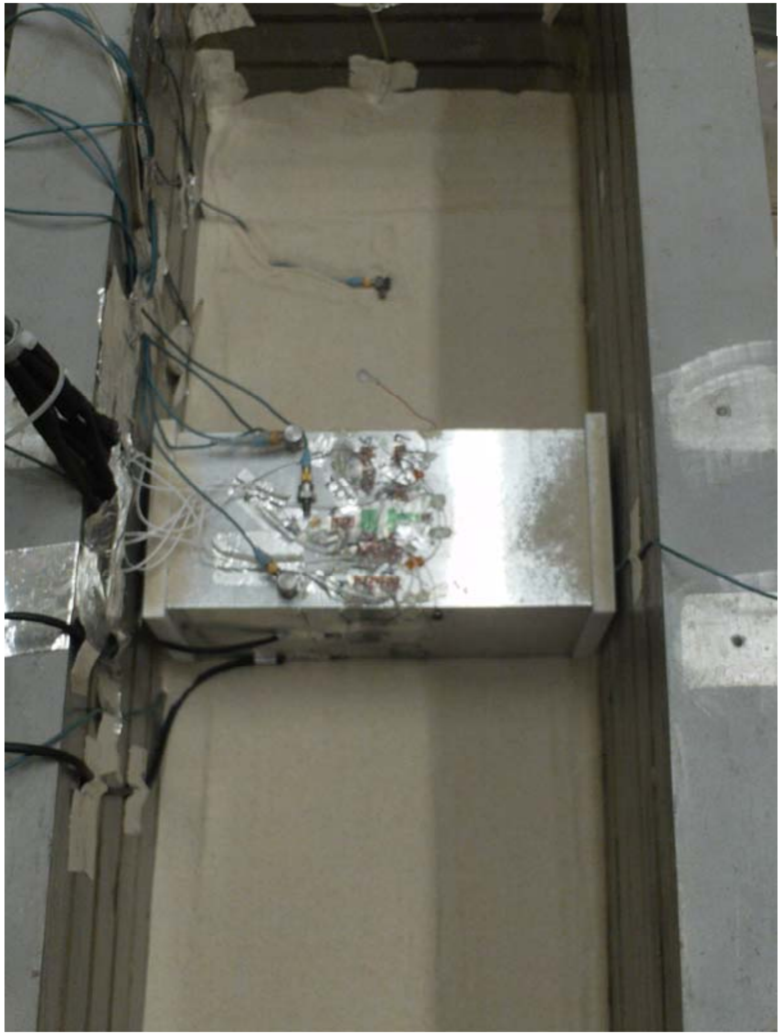
- **Relatively rigid model (t=2mm)**

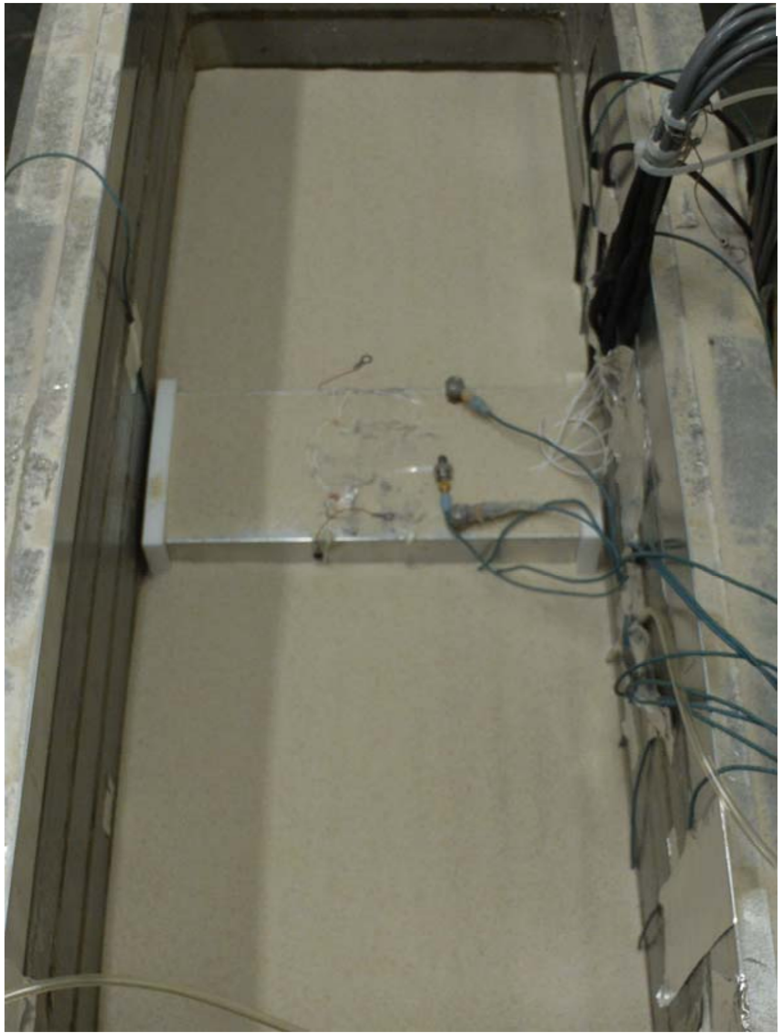




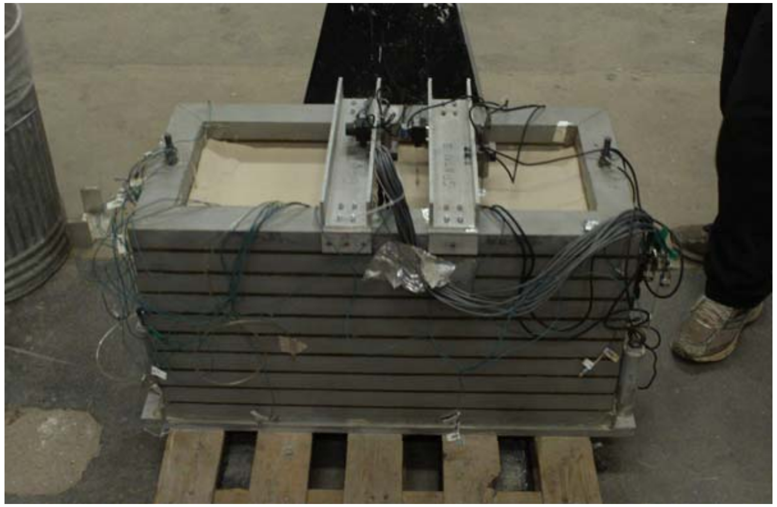


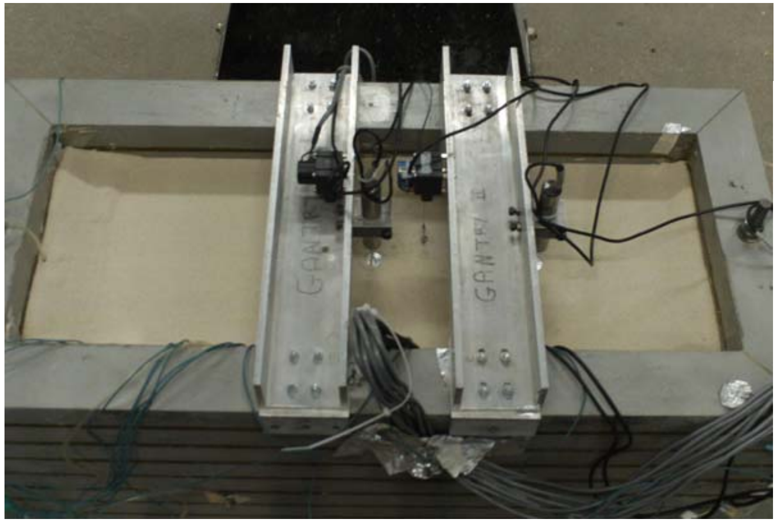
- **Tunnel model embedded in soil**



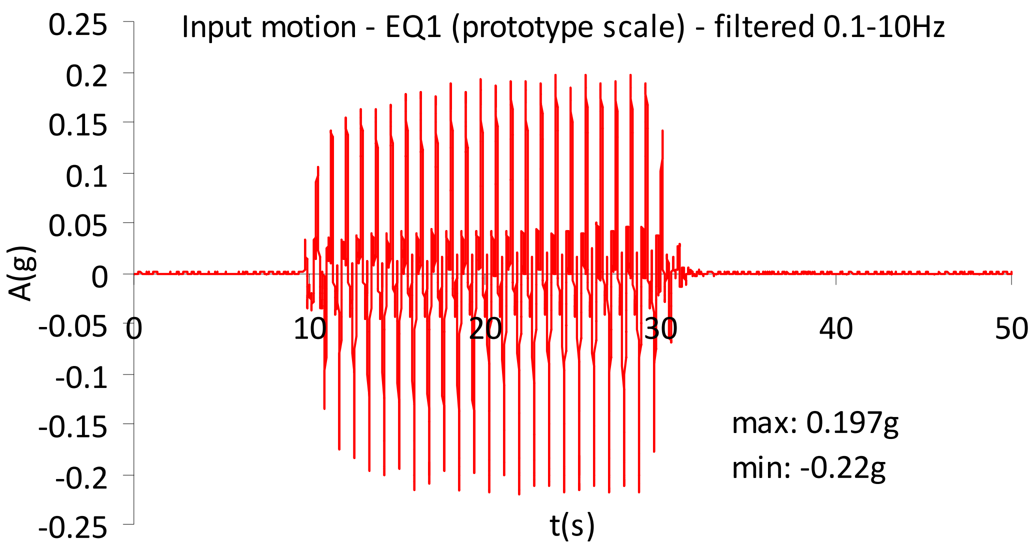


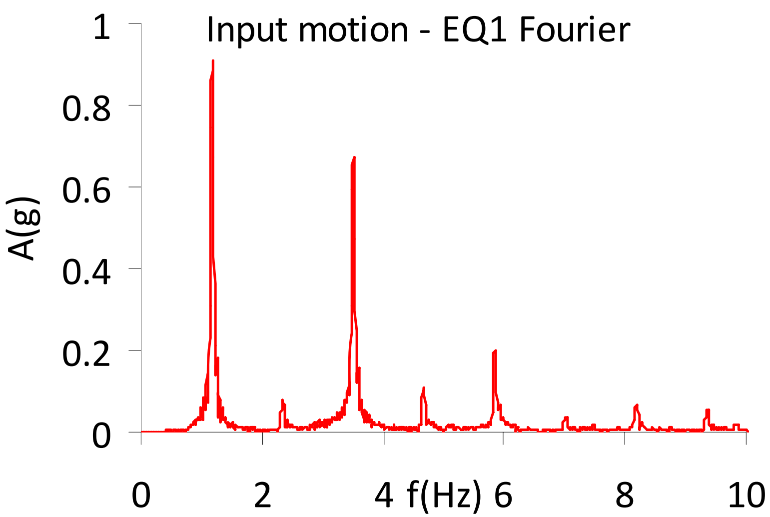
- **Final model**



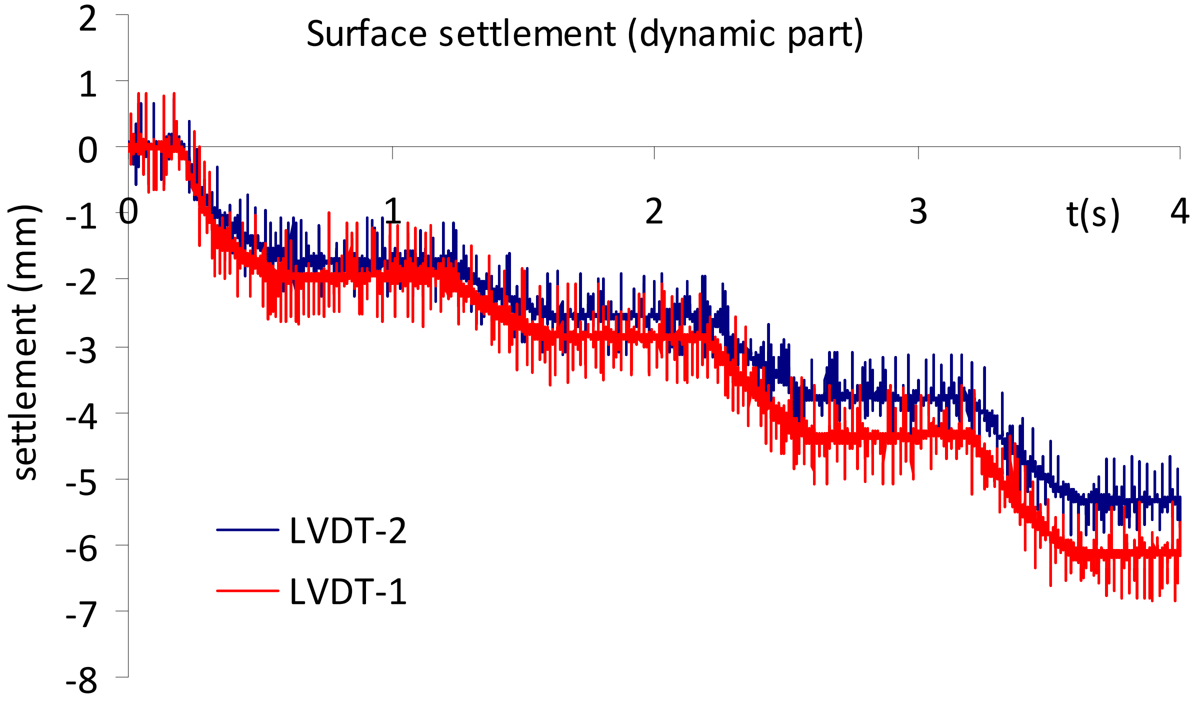


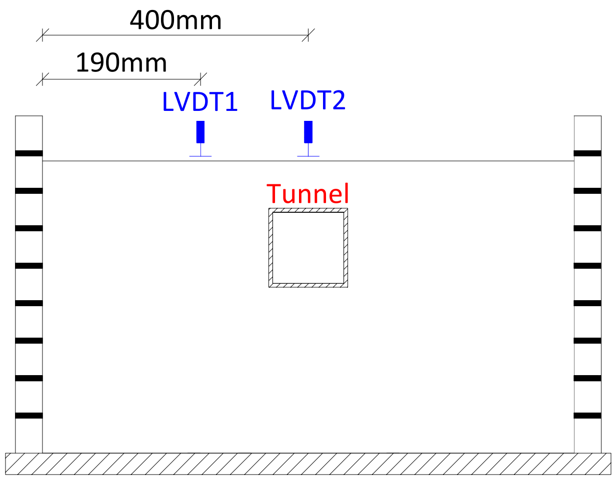
- **Four sine wavelets of increasing amplitude and same frequency were fired in a row, having maximum amplitudes: 0.2g, 0.26g, 0.32g, 0.38g respectively**
- **Unfortunately, the strain gauges did not record something measurable because the model was rather rigid and the strains quite small to be measured**
- **Indicative results**
- **Acceleration at base of the model - EQ1**



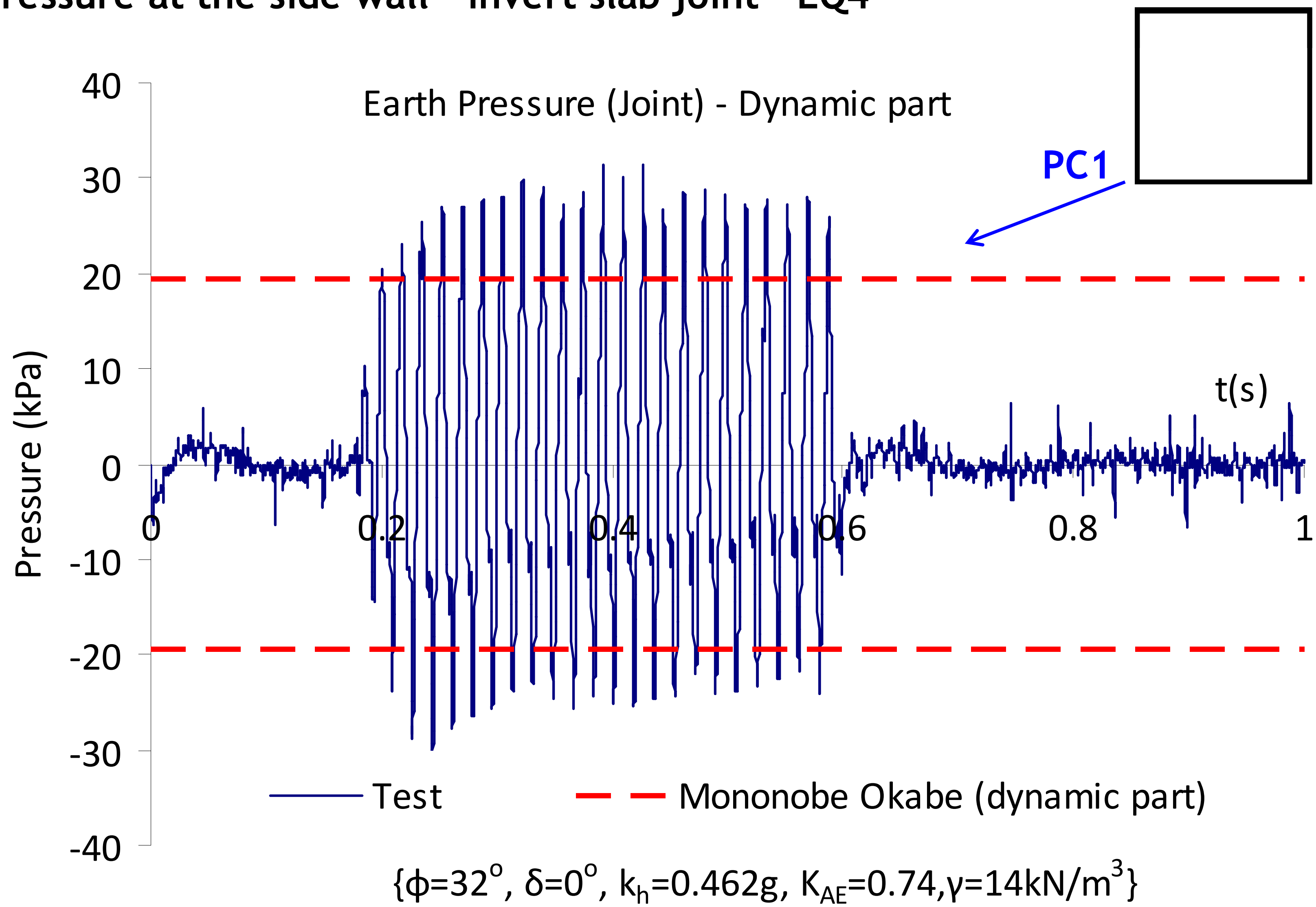


- **Settlement of the soil surface - dynamic part**
- **Smaller settlements above the tunnel - rigid structure**
- **ε = 2% !!**



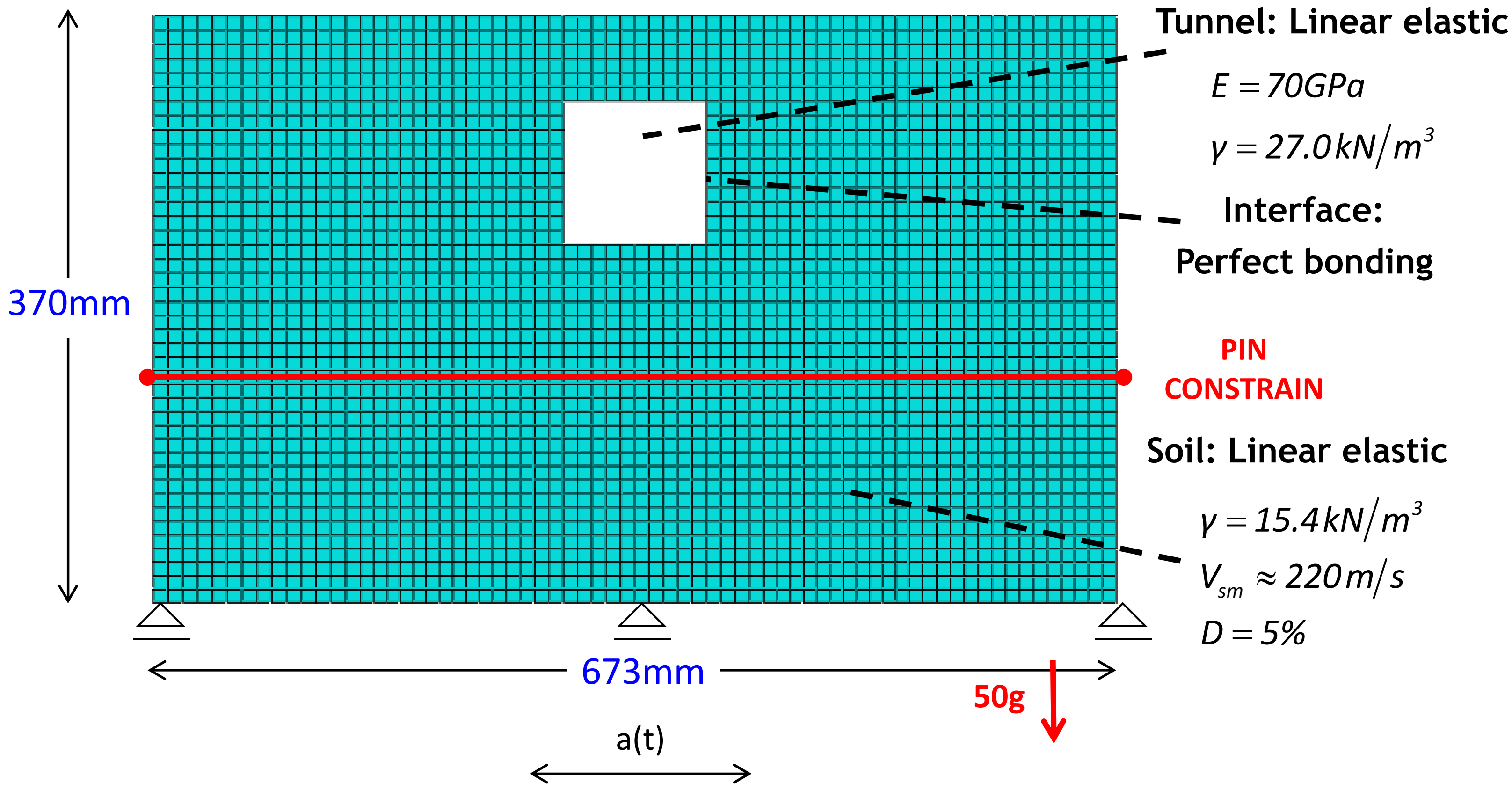


- **Pressure at the side wall - invert slab joint - EQ4**

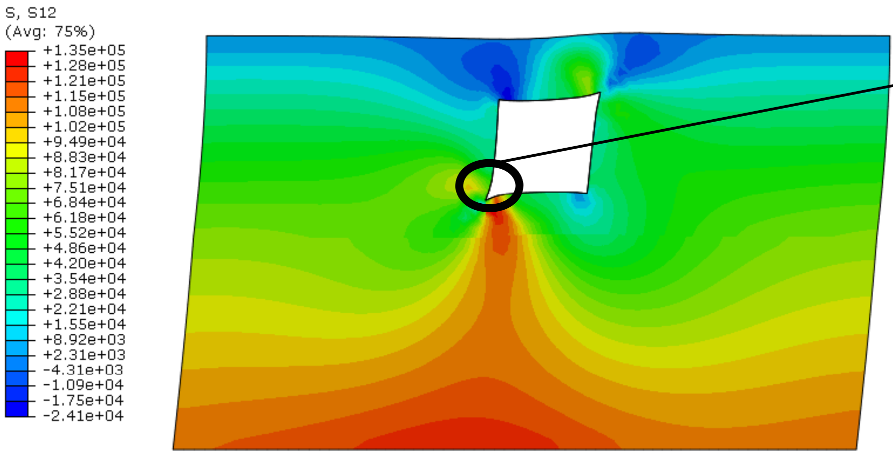


Preliminary numerical analysis

- **Numerical simulation in model scale using the ABAQUS, 2009)**



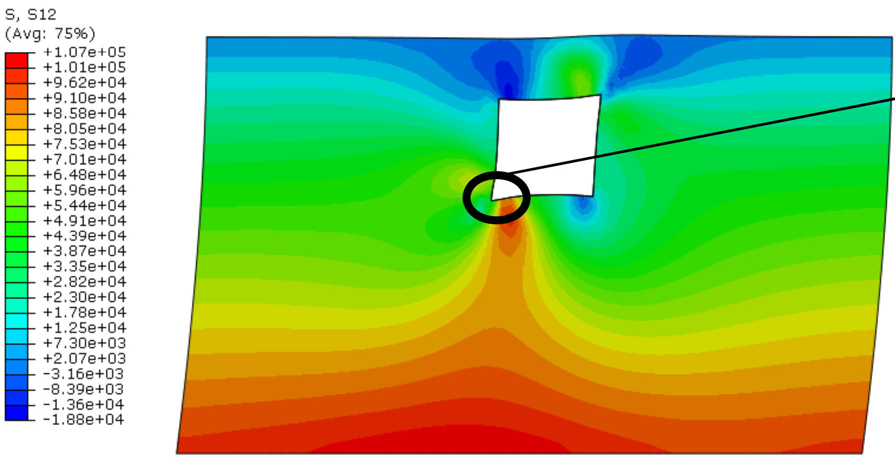
- Dynamic step
- Soil shear stresses around the tunnel for different tunnel section thickness



Maximum value

τ=128 kPa

t=1mm



Maximum value

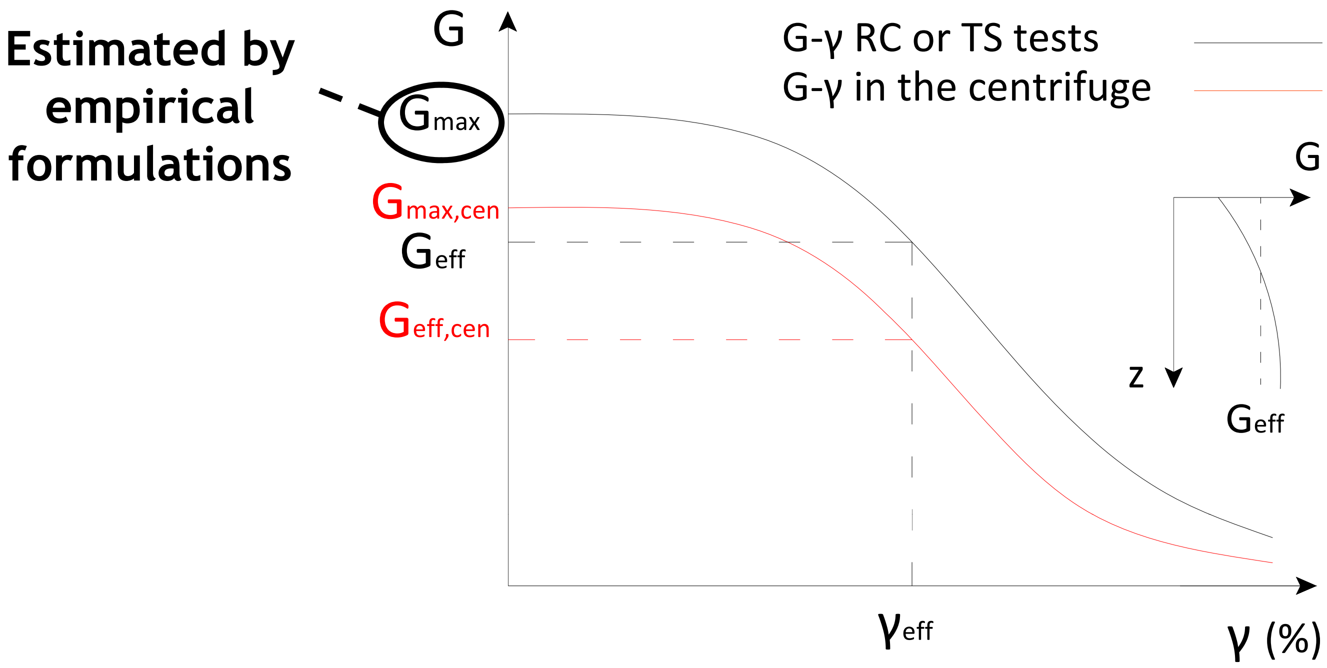
τ=80.5 kPa

t=2mm

Some important issues controlling the tests

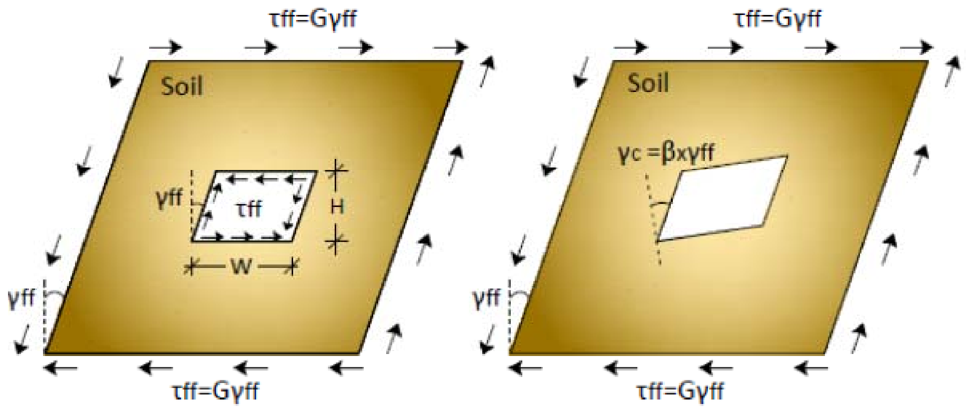
Estimation of soil properties

- Elastic mechanical properties (E,v) - G_{max} profile estimation (G(z))
- G_{max} compatible to the actual test intensities and deformations (i.e. Brennan et al., 2005) - CPT tests before and after each flight or bender elements
- Empirical expressions (i.e. Hardin and Drnevich,1972) may overestimate Gmax (i.e. Brennan et al., 2005)



Flexibility ratio

- Penzien, 2000
- Deformations of rectangular cavity

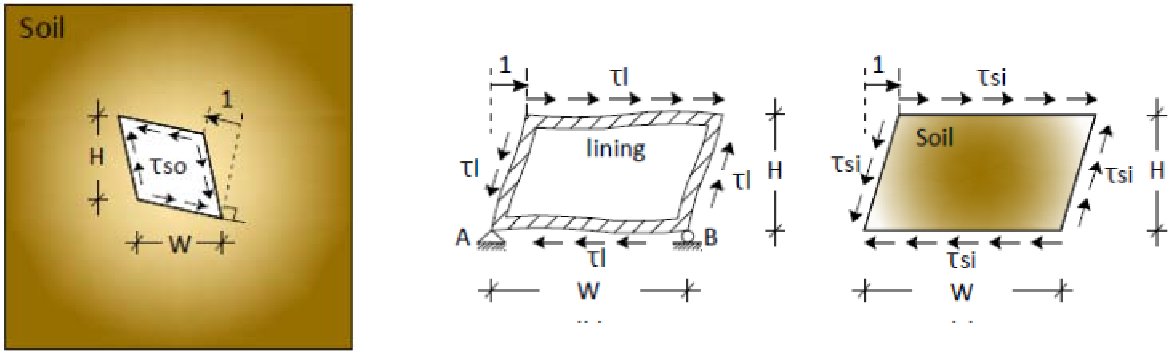


$$\tau_{ff} = G_s \gamma_{ff}$$

$$\gamma_c = \beta \gamma_{ff}$$

$$\beta = \gamma_c / \gamma_{ff} = 4(1 - v_s)$$

- Stiffness of outside soil, inside soil and lining
- Compatibility of deformations

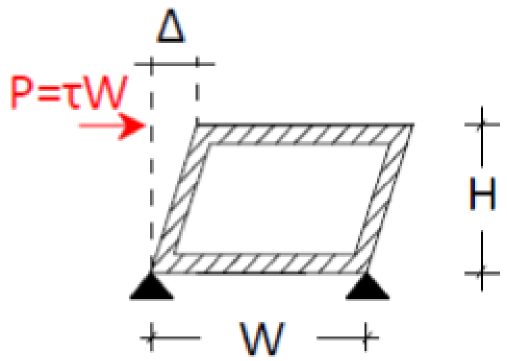


$$k_{soil} = \tau_{si} = G_s / H$$

$$k_{soilo} = k_{soil} / (3 - 4v_s)$$

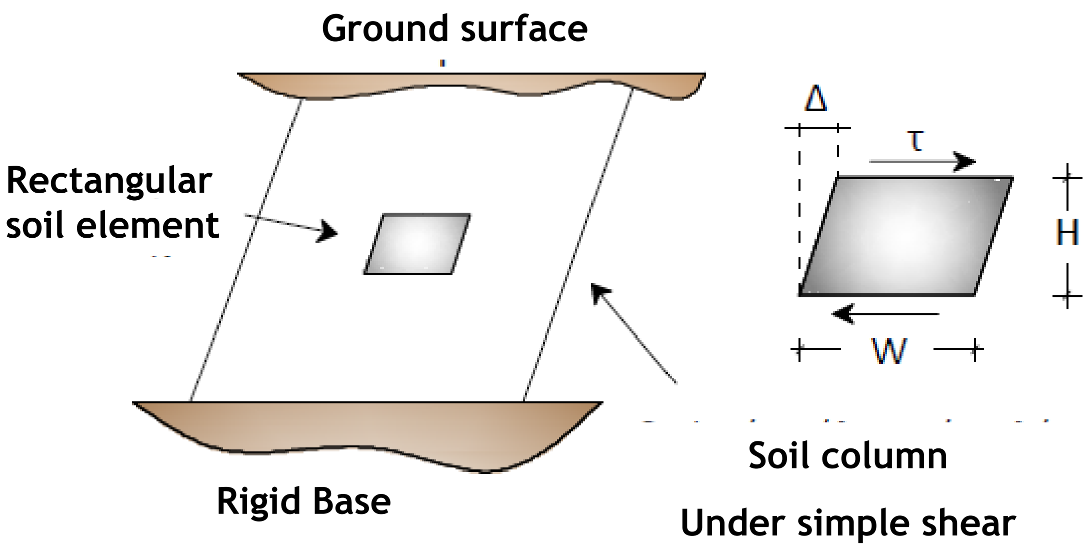
$$\Delta d_{stru} + \Delta d_{is} = 4(1 - v_s)\gamma_{ff} H$$

- **Depended on the actual soil shear modulus (degraded during the shaking)**
- **An overestimation of the shear modulus can lead to an overestimation of the flexibility ratio**
- **Assumptions for the calculation of the flexibility ratio?**
- **Example: Wang, 1993, Hashash et al., 2001 etc.: static analysis for the determination of the flexibility ratio assuming fix invert slab. Is the invert slab fixed during the shaking? Deformation modes? Rocking of the tunnel?**



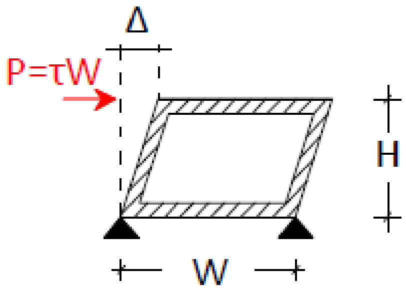
$$F = \frac{G_m W}{S_1 H}$$

- **Estimation according Wang, 1993**
- **Concentrated load P - Fixity of the invert slab**
- **S_1: force required to cause unit racking to structure - estimate from simple static analysis**



$$\gamma_s = \frac{\Delta}{H} = \frac{\tau}{G_m}$$

$$\frac{\tau}{\gamma_s} = \frac{\tau}{\Delta / H} = G_m$$



$$\gamma_s = \frac{\Delta}{H} = \frac{P}{HS_1} = \frac{\tau W}{HS_1} \rightarrow \frac{\tau}{\gamma_s} = \frac{\tau}{\Delta / H} = \frac{HS_1}{W}$$

$$F = \frac{G_m W}{HS_1}$$

Thank you

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