University School for Advanced Studies

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The Different Phenomenology of Dynamic SSI for Buildings, Bridges and Power Plants: Numerical and In-Situ Full-Scale Tests

G. Andreotti and G.M. Calvi

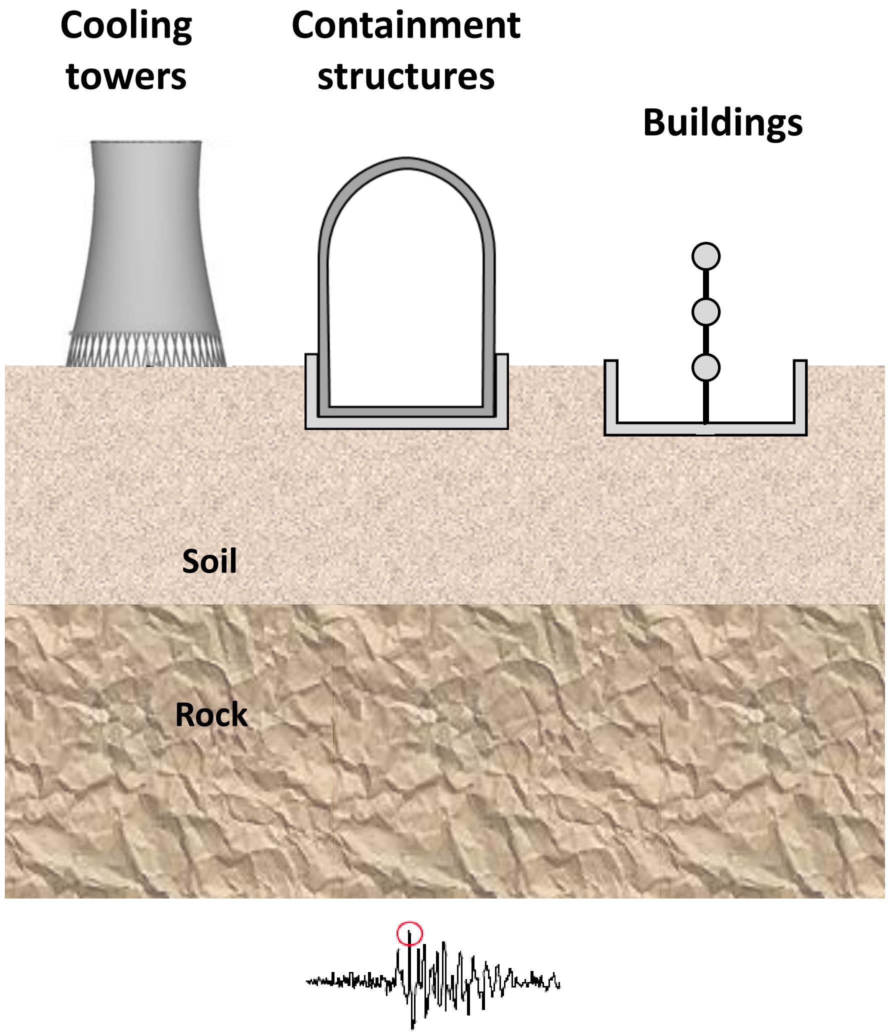
International Workshop on
Large-Scale Shake Table Testing for the Assessment of Soil-Foundation-Structure System Response for Seismic Safety of DOE Nuclear Facilities

University of Nevada, Reno

PEER

May 18, 2021

Above-ground structures of NPPs



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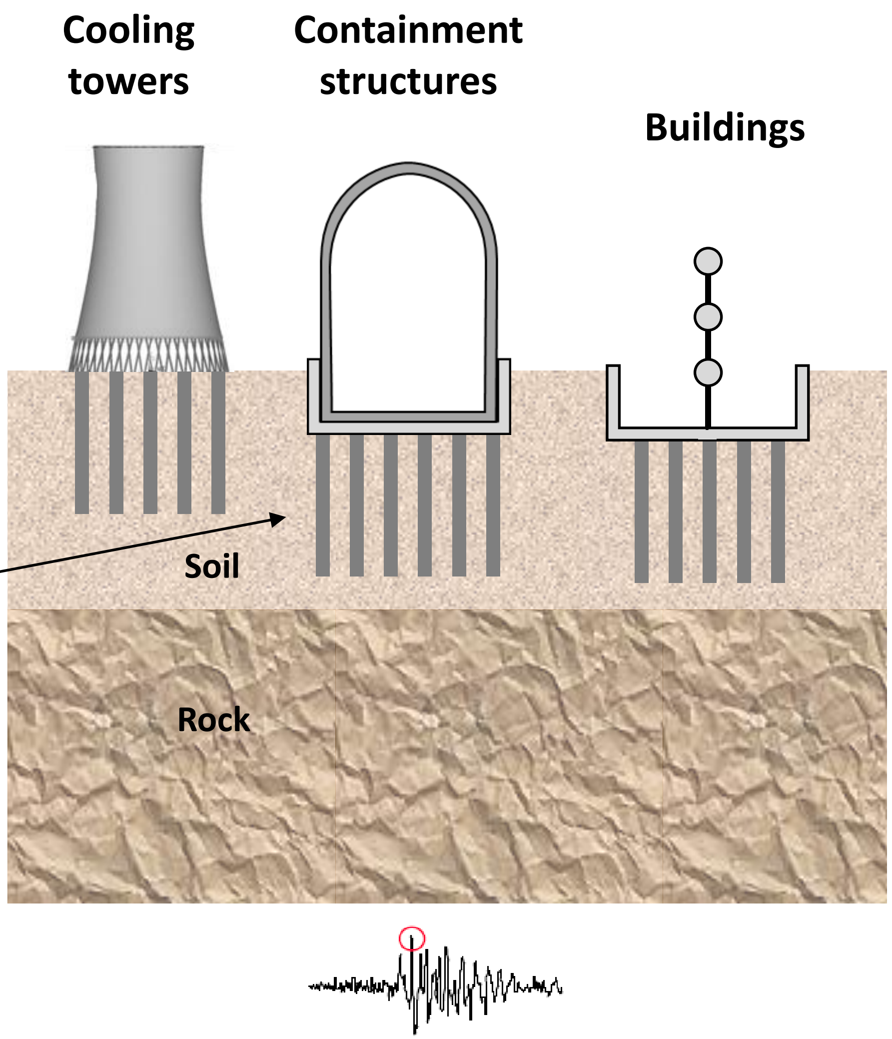


Containment on pile foundations

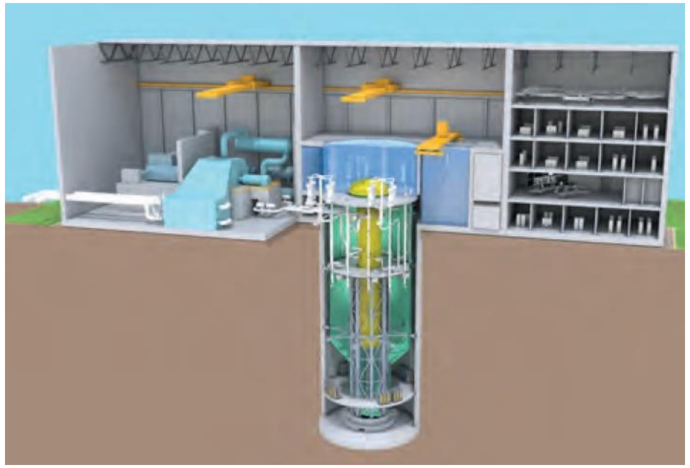
e.g.

- Point-Beach NPP (USA)
- H.B. Robinson NPP (USA)
- Angra NPP (Brazil)
- Gosgen-Daniken NPP (Switzerland)

(Zou et al., 2020)

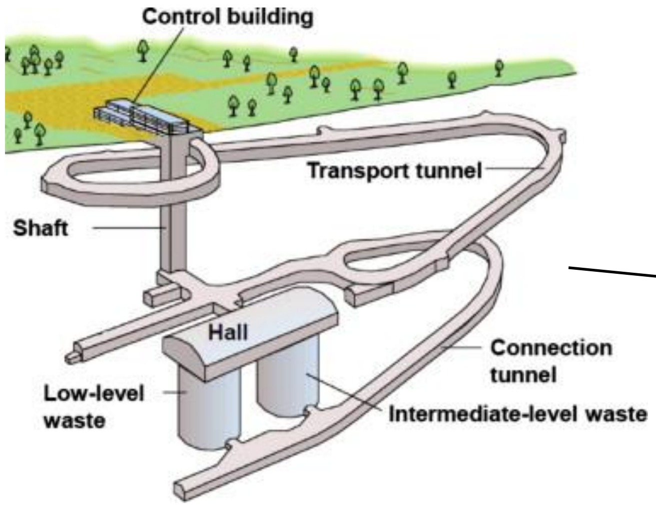
Underground structures of NPPs

Underground reactors

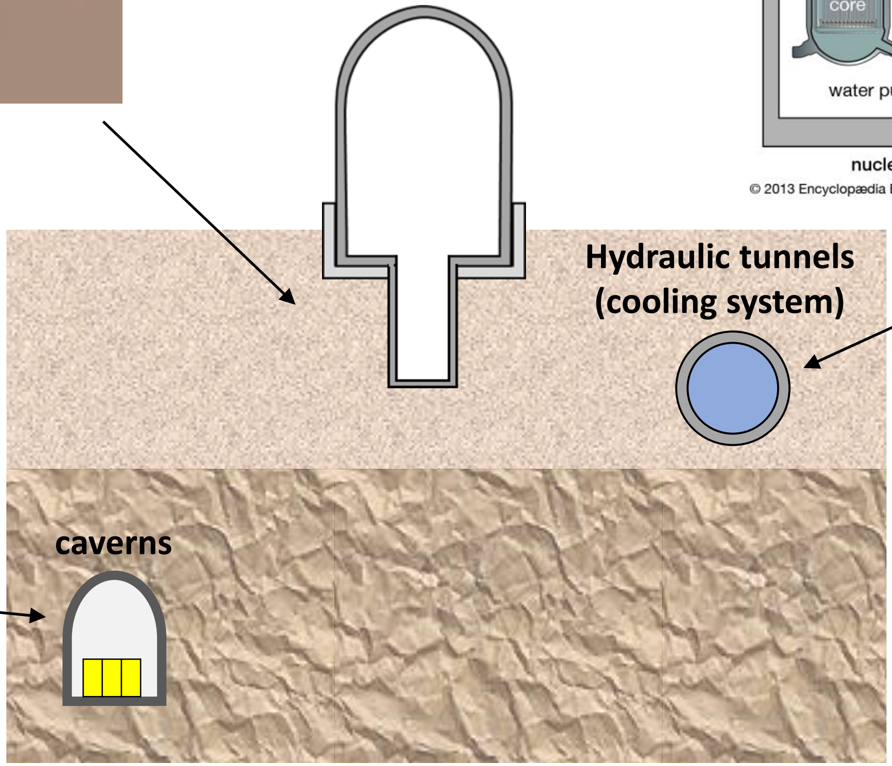


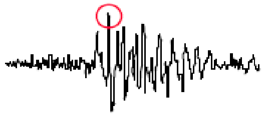
(IAEA, 2020)

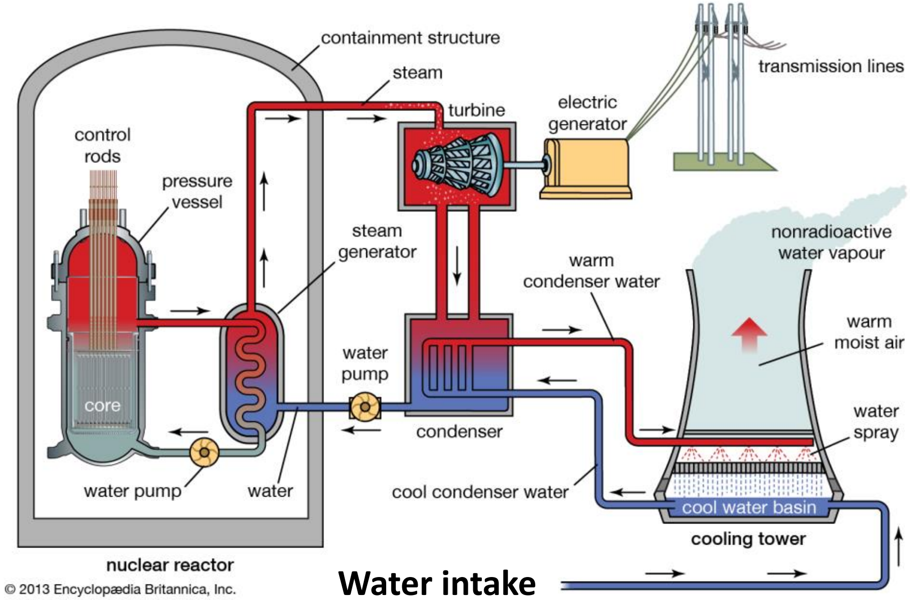
Nuclear waste repositories (e.g. caverns, shafts, tunnels)



(Kari and Puttonen, 2014)

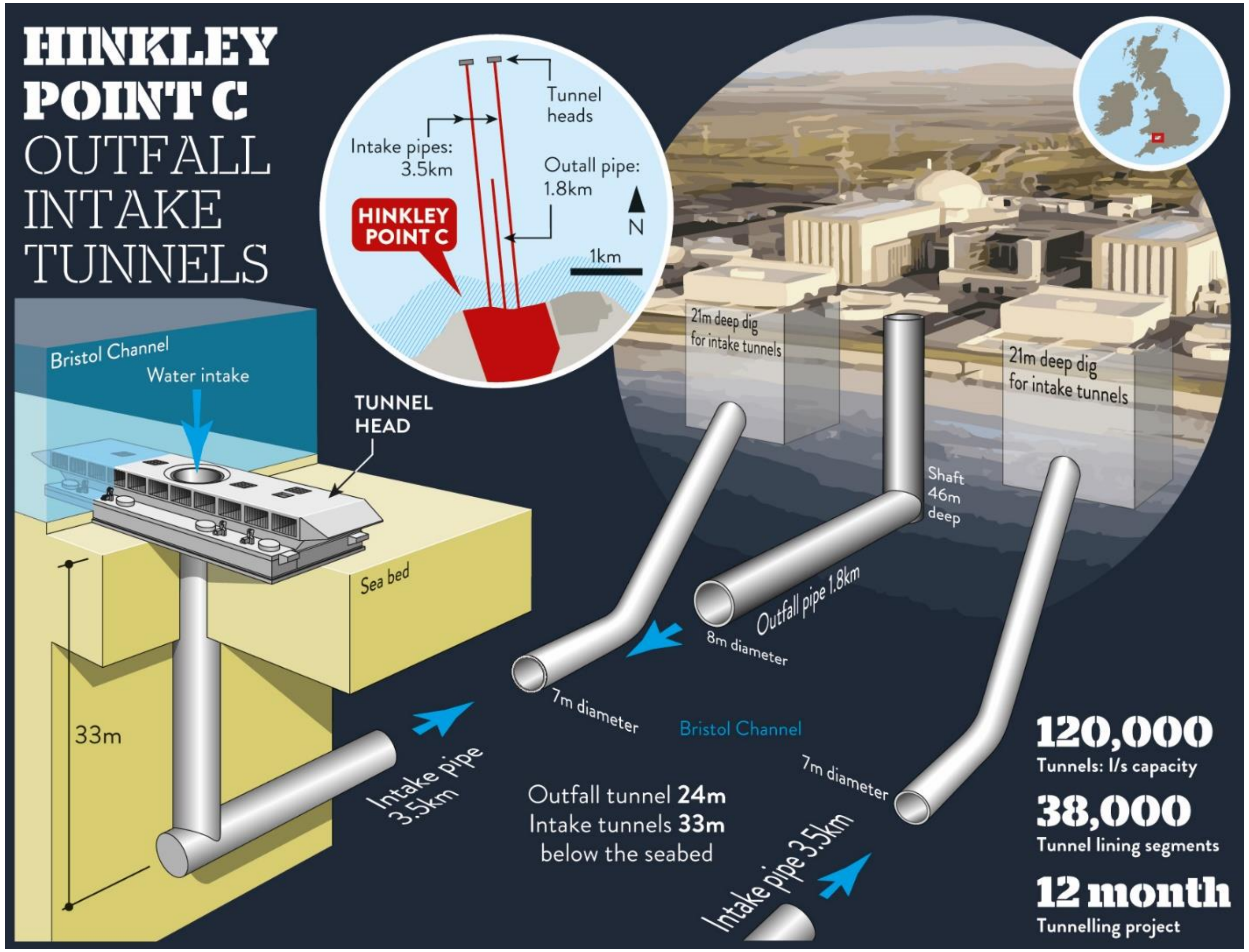






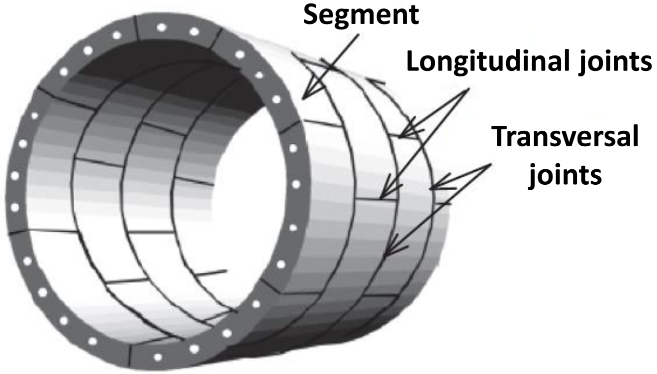
Water intake (lake, sea, river)

Examples of tunnels and shafts of the cooling system in NPPs



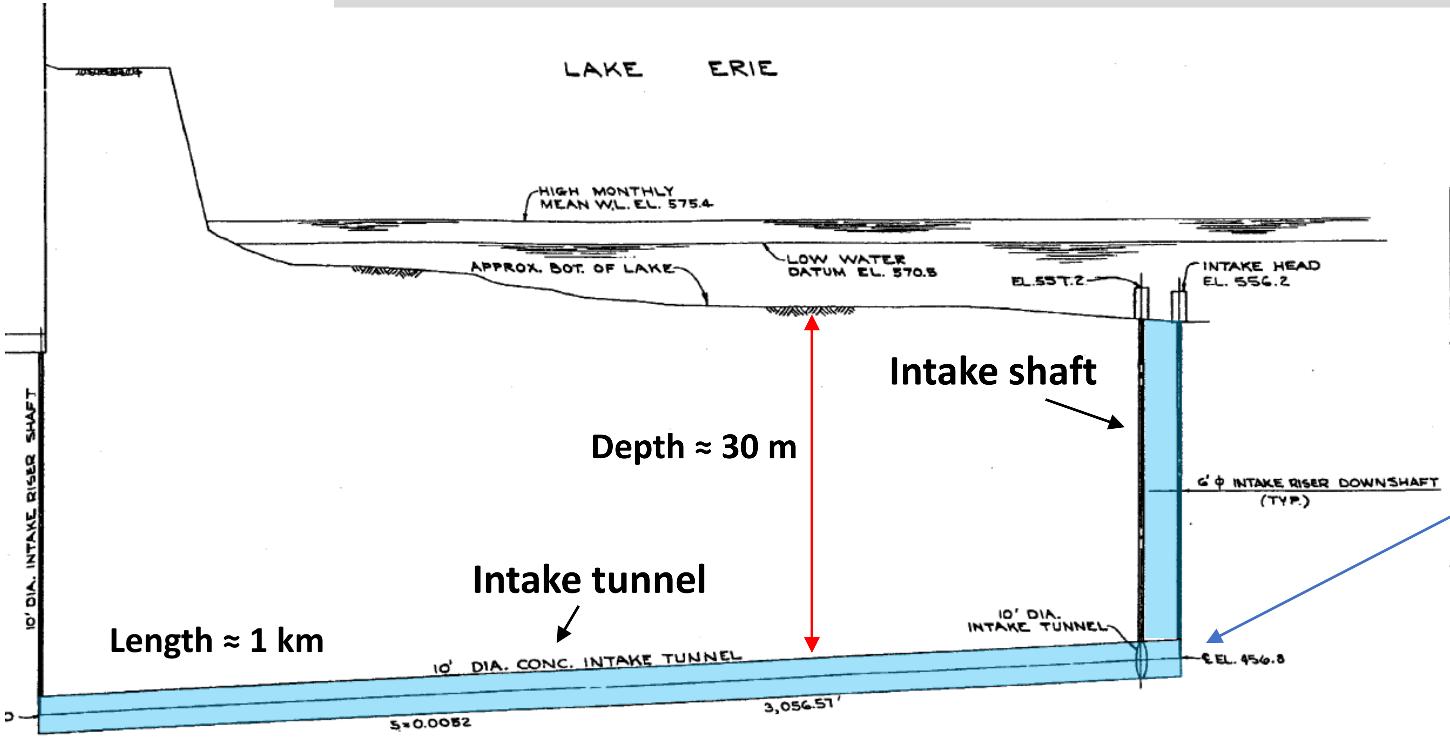
(Kennedy, 2019)

Segmental tunnels (precast segments)

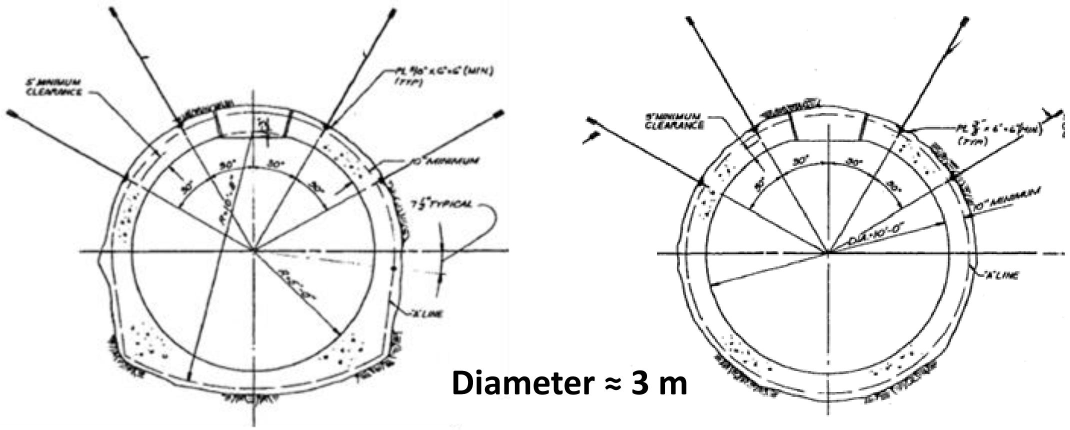


Diameter = 7 m

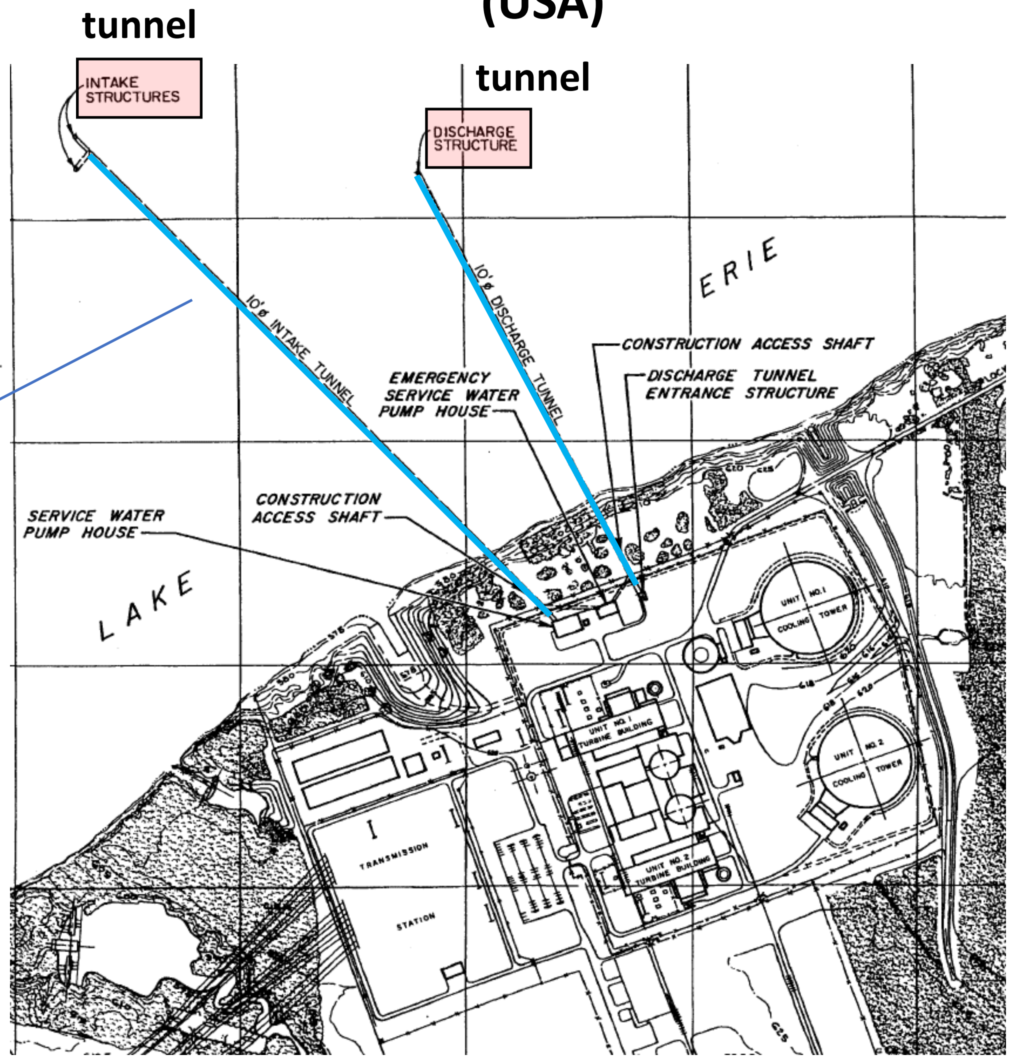
Examples of tunnels and shafts of the cooling system in NPPs



Traditional tunnel



Perry Nuclear Power Plant (USA)



Nonlinear SSI analysis (Structural nonlinearity)

ASCE 4-16: Seismic Analysis of Safety-Related Nuclear Structures

Chapter 5 - SSI

(5.1 GENERAL REQUIREMENTS): (a) **SSI effects shall be considered for all safety-related nuclear structures**.

Chapter 4 - Analysis of structures

(4.1 GENERAL REQUIREMENTS): (a) The seismic analysis of safety-related structures is **typically** performed by analysis of **linearly elastic** mathematical **models**. **Nonlinear analysis <u>may be</u> performed in some cases**, especially for **beyond design basis calculations** or **evaluation of existing facilities**.

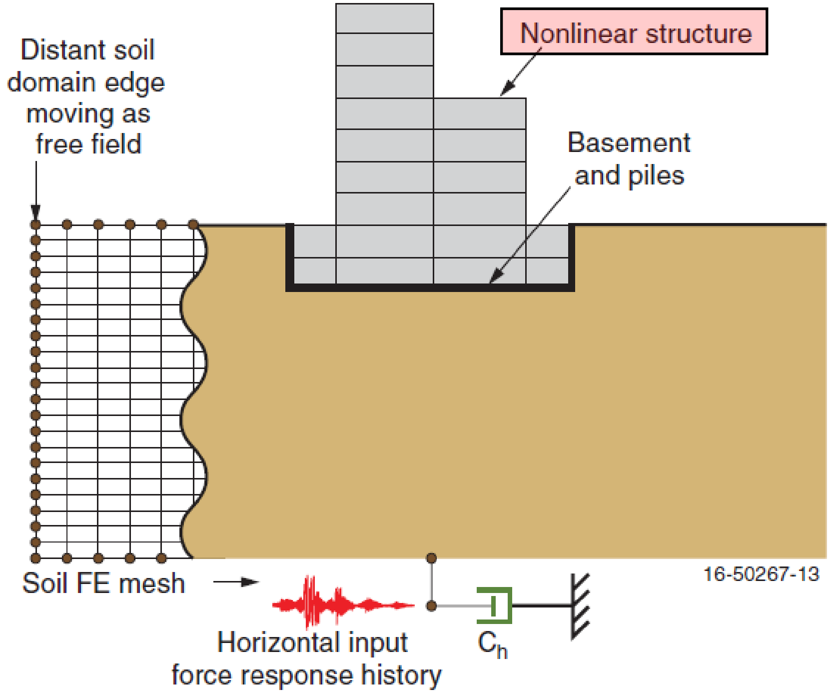
Design peak ground acceleration and recorded peak ground acceleration at NPPs.

	Kashiwazaki-Kariwa, Japan	Fukushima Daiichi, Japan	North Anna, USA
Design value	0.20 g	0.26 g[a]	0.18 g
Recorded value (year)	0.32 g (2007)	0.56 g (2011)	0.26 g (2011)

[a] Design basis updated in 2009 to 0.45 g (The National Diet of Japan, 2012).

(Coleman et al., 2016)

Recorded seismic demand exceeded design value



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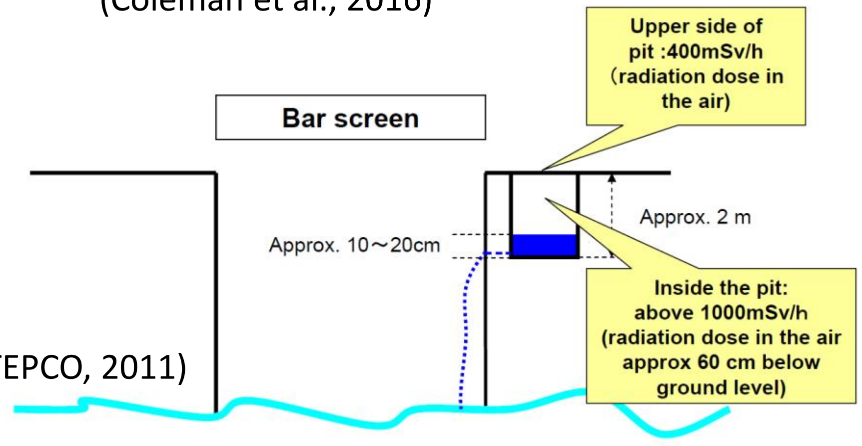


(TEPCO, 2011)

Press Releases (TEPCO, 2011)

Press Release (Apr 02,2011)

Out flow of fluid containing radioactive materials to the ocean from areas near intake channel of Fukushima Daiichi Nuclear Power Station Unit 2

Today at around 9:30 am, we detected water containing radiation dose over 1,000 mSv/h in the pit* where supply cables are stored near the intake channel of Unit 2. Furthermore, there was a crack about 20 cm on the concrete lateral of the pit, from where the water in the pit was out flowing. At around 12:20 pm, we reaffirmed the event at the scene.

We have implemented sampling of the water in the pit, together with the seawater in front of the bar screen near the pit. These samples were sent to Fukushima Daini Nuclear Power Station for analysis.

In addition to seawater sampling conducted in the coastal areas of Fukushima Daiichi/Daini Nuclear Power Station (sampling conducted at 4 points), we have initiated additional seawater sampling at 3 points in the areas 15 km offshore from the relevant power stations. Taking into account the result of these monitoring, we are intending to conduct a comprehensive assessment.

Currently, we are preparing to block up the leakage by injecting concrete to the crack. Moreover, we will investigate the influx route of contaminated water in the pit and implement necessary measures to prevent such influx.

*pit: a shaft made of concrete

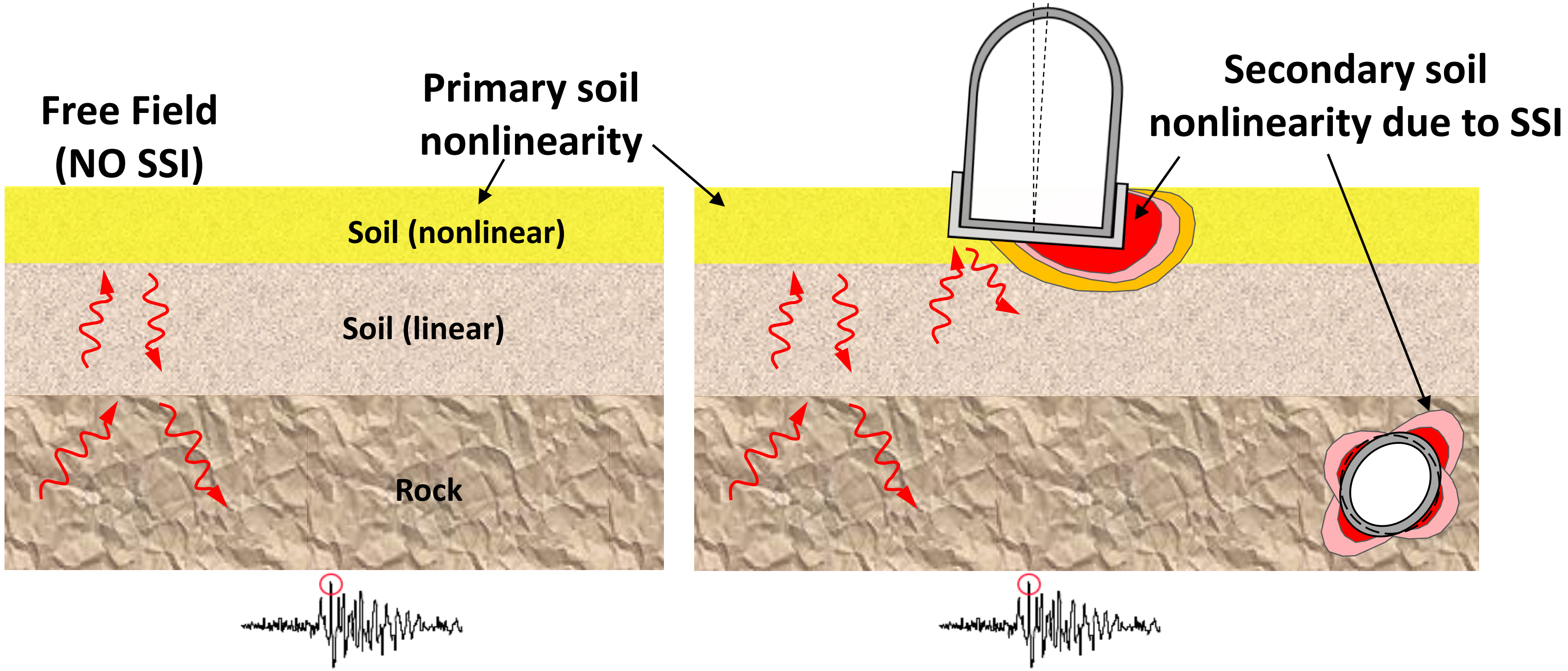
Underground structures were damaged

Often designed to remain elastic

Nonlinear SSI analysis
(Soil nonlinearity)

ASCE 4-16: Seismic Analysis of Safety-Related Nuclear Structures

Chapter 5 – SSI: Nonlinear Behavior of Soil: **Primary and secondary soil nonlinearity**



5.1.4 (d) **Primary nonlinearities shall be considered** in the SSI analysis. **Secondary nonlinearities**, including local soil nonlinear behavior in the vicinity of the soil-structure interface, **need not be considered**, except for the calculation of seismic soil pressure.

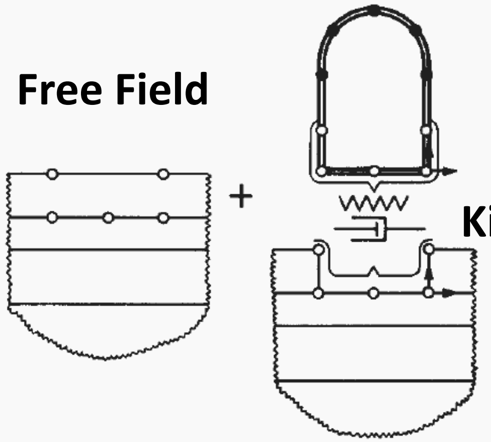
COMMENTARY: C5.1.4 Nonlinear Behavior of Soil

(…) **rigorous nonlinear analysis** of a typical nuclear structure requires a fully three-dimensional model and an appropriate set of constitutive equations for soil. These requirements **are currently beyond the state of the art for design**.

Solution of dynamic SSI: linear vs nonlinear

SUBSTRUCTURE METHOD

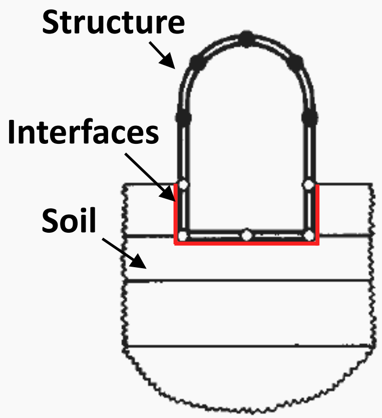
Free Field



Inertial SSI + Kinematic SSI

- Superposition of effects
- Frequency domain

DIRECT METHOD



Complete model

⬇

No superposition of effects

Frequency domain

Time domain

Linear analysis (equivalent-linear)

⬇

Problems to capture moderate-to-high nonlinearities

Fully nonlinear dynamic analysis

⬇

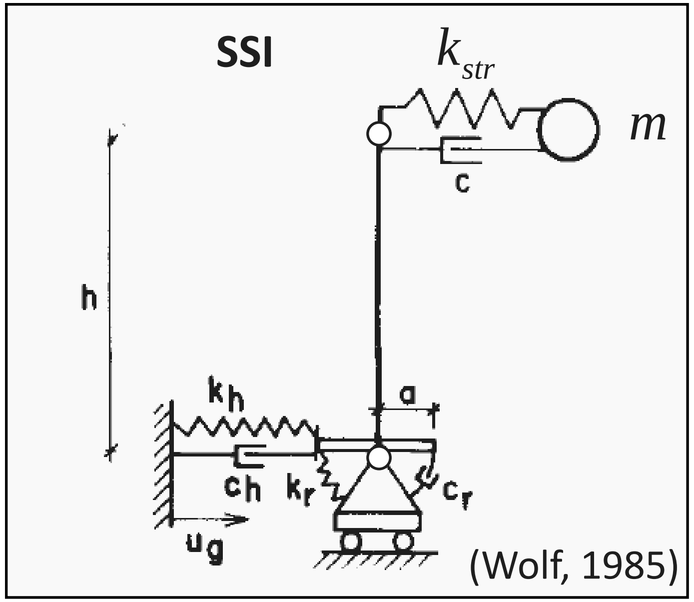
NLSSI

- NL structure
- NL soil
- NL interfaces

Some questions

Soil-structure stiffness ratio $\dfrac{K_{struct}}{K_{soil}}$ ➡ One of the main variables of SSI

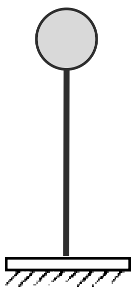
Simple models for above-ground structures



Fixed base

$$\omega_{FixB} = \sqrt{\frac{k_{str}}{m}}$$

$$\xi_{str}$$



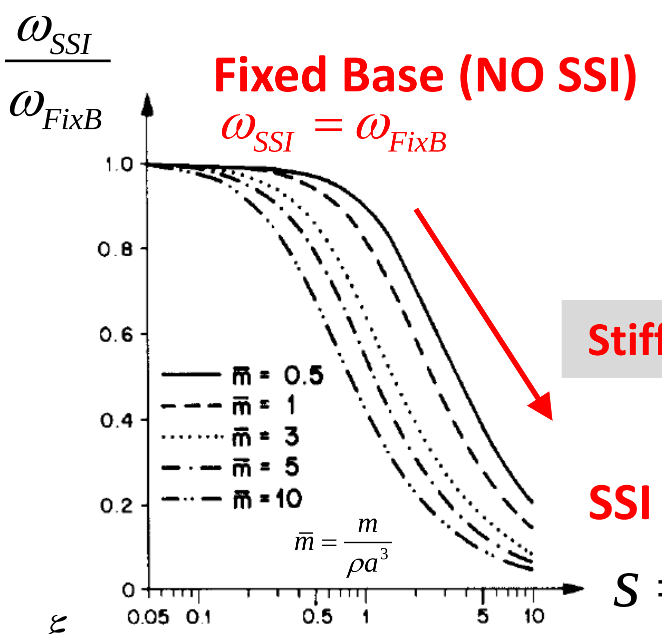
Equivalent SSI

$$\omega_{SSI} = \sqrt{\frac{k_{eq}}{m}}$$

$$\xi_{SSI} = \xi_{str} + \xi_{soil} + \xi_{rad}$$

$$\frac{1}{k_{eq}} = \frac{1}{k_{str}} + \frac{1}{k_h} + \frac{h^2}{k_r}$$

Reference model ➡ Fixed base

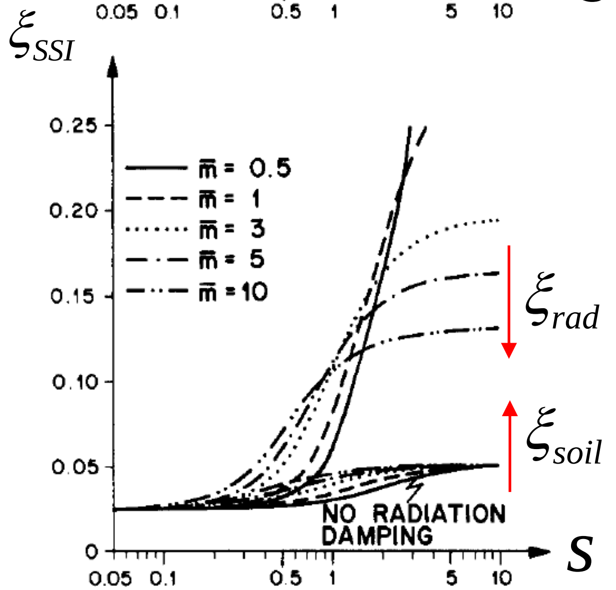


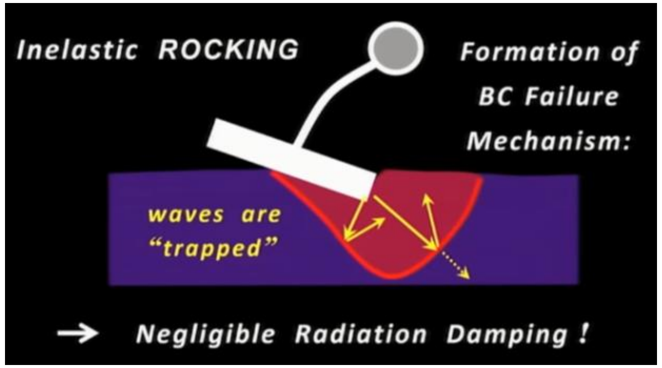
SSI

$$s = \frac{\omega_{FixB} h}{V_S}$$

Structural stiffness

Soil stiffness (shear wave vel)

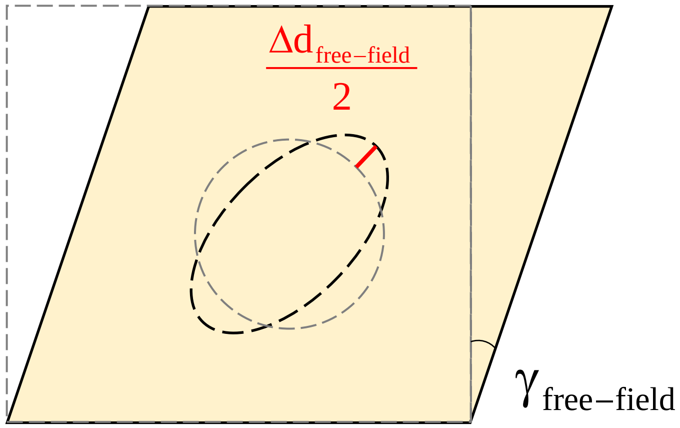


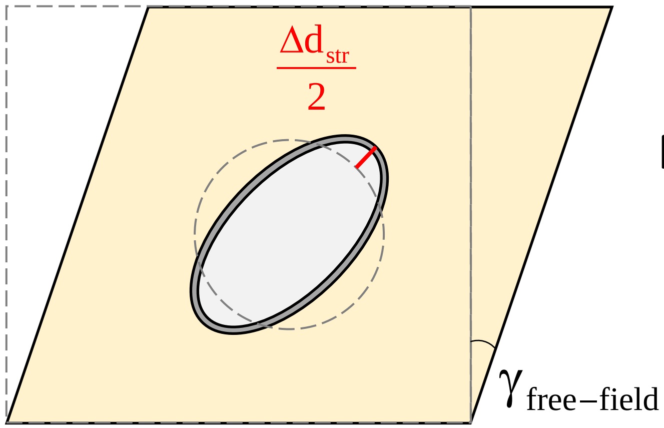


(Prof. Gazetas, Rankine lecture 2019)

Simple models for underground structures

Free-field | **Presence of the structure**

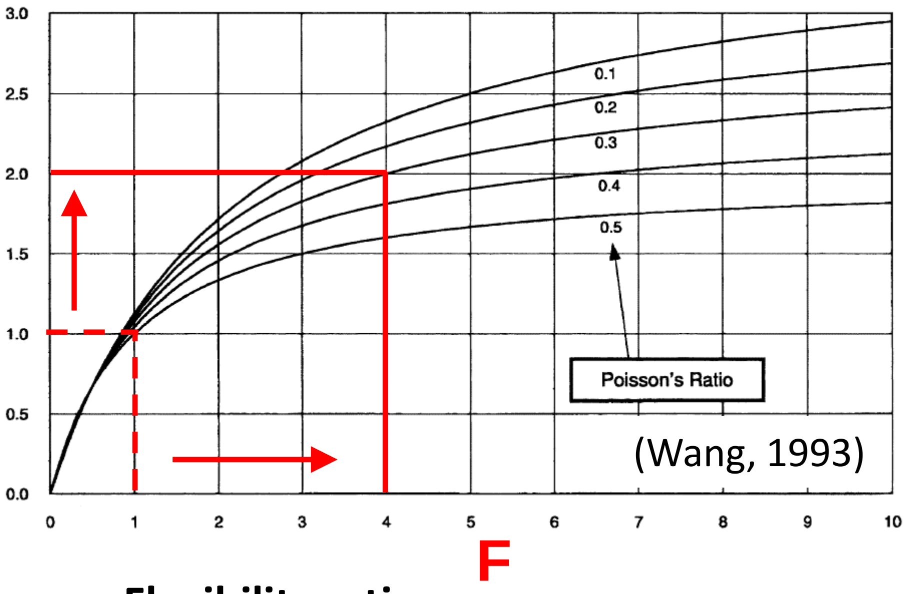




Reference model ➡ **Free-field (no structure)**

Displacement structural demand

$$\frac{\Delta d_{str}}{\Delta d_{free-field}}$$



Flexibility ratio

$$\uparrow F = \frac{E_{soil} \cdot (1-\nu_{str}^2) r^3}{(1+\nu_{soil}) \cdot 6E_{str}I_{str}} = \frac{K_{soil}}{K_{str}} \downarrow$$

Stiffness contrast

Could not be constant during earthquakes

⬇

Evolution of soil and structural nonlinearity

Some questions

Soil-structure stiffness ratio $\frac{K_{struct}}{K_{soil}}$ ➡ One of the main variables of SSI

NLSSI implies nonlinearity of the whole system (structure + soil) ➡ Stiffness ratio is not constant

- **What happens to the whole system with the evolution of structural damage and soil nonlinearity?**

- **Does structural nonlinearities affect soil nonlinearity?**
- **Does soil properties affect structural capacity?**

} **YES numerical evidence**

Two case studies:

1) Tunnels ➡ 2D fully nonlinear time history analysis

2) CIDH bridge columns ➡ 3D detailed modelling with experimental benchmark

- **Is the gap between geotechnical and structural engineers detrimental to solve NLSSI problems?**

1) Fragility analysis of underground tunnels: fully nonlinear SSI

M_w=7.9
Epicentral distance ≈ 14.2 Km

2008 Wenchuan earthquake (China)

(Li, 2012)

M_w=6.9
Epicentral distance < 15 Km

1980 Irpinia earthquake (Italy)

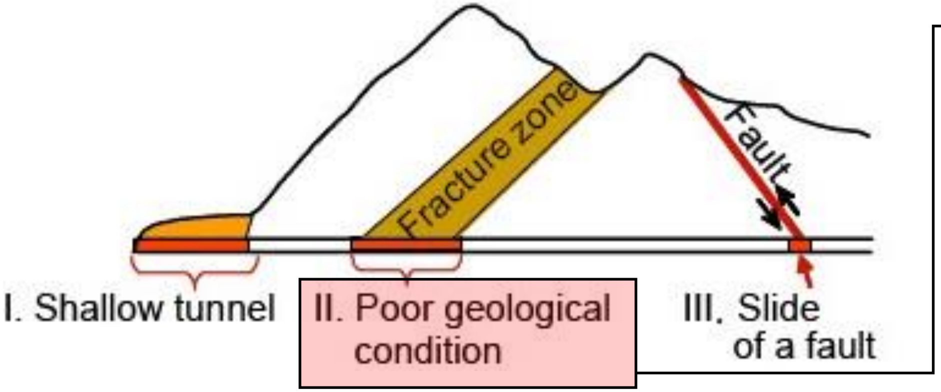
(Cotecchia, 1986)

M_w=7.4
Epicentral distance < 32 Km

1990 Manjil earthquake (Iran)

(Wieland, 2011)

Critical scenarios for tunnels



Early objective

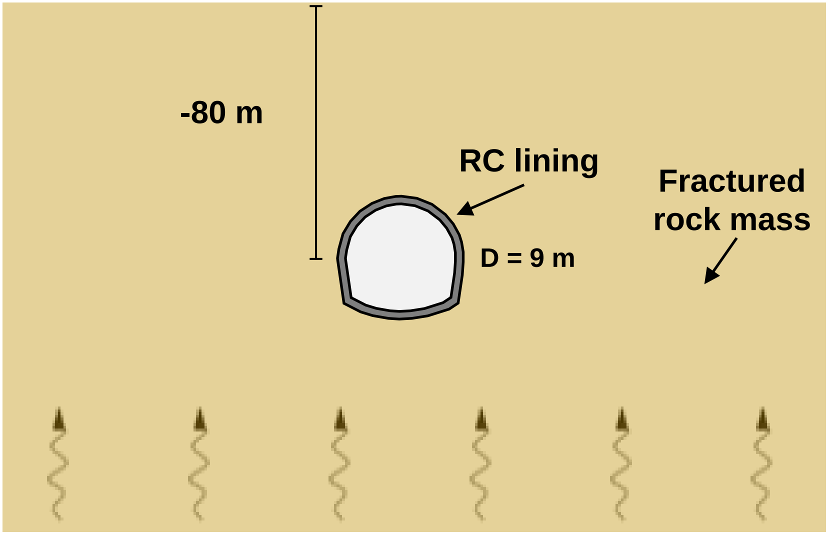
Definition of numerical fragility curves considering variability of seismic input, structural and geotechnical nonlinearities, depth of tunnel.

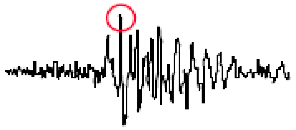
(see Andreotti and Lai, 2017a, 2017b, 2019)

From the suite of analysis: investigation on NLSSI effects

Fragility analysis of underground tunnels: fully nonlinear SSI

Selected scenario to evaluate NLSSI

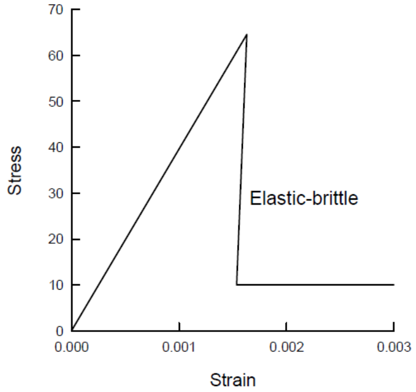




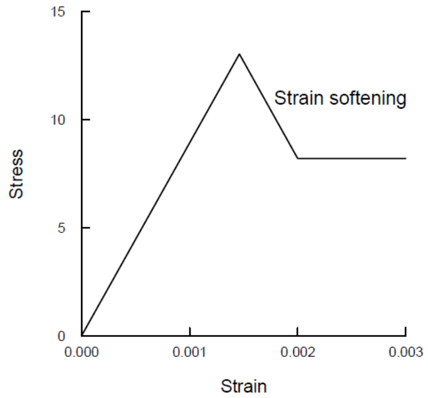
Rock mass parameters

GSI	E [MPa]	ν	ϕ [°]	dilatancy [°]	c [MPa]	γ [kN/m^3]	K_o
25	1100	0.3	22	0	0.5	24	0.6

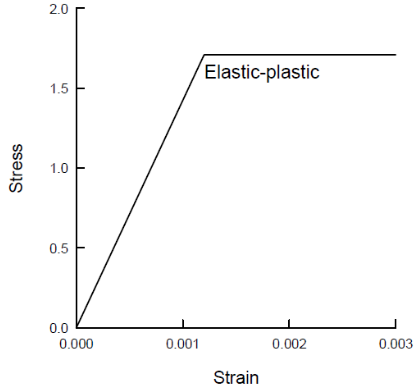
Very good quality (GSI=75)



Average quality (GSI=50)



Very poor (GSI=30)



Hoek and Brown (1997)

Mohr-Coulomb model

RC Tunnel lining

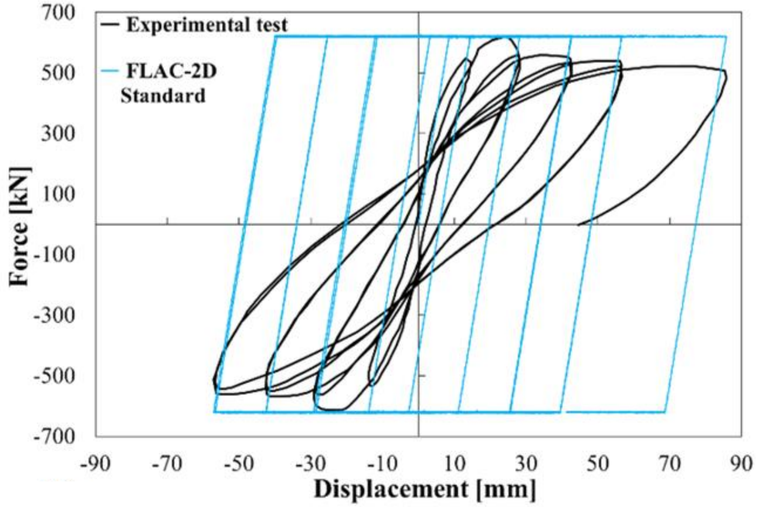
Type		Reinforcement		Concrete			Steel	
Section	Thickness [m]	Steel rebars [kg/m^3]	Stirrups [cm^2]	E_c [MPa]	f_c [MPa]	f_t [MPa]	E_s [MPa]	f_s [MPa]
S1	0.7	50	14.13	33000	25.5	2.55	210000	450
S2	1	80	14.13					

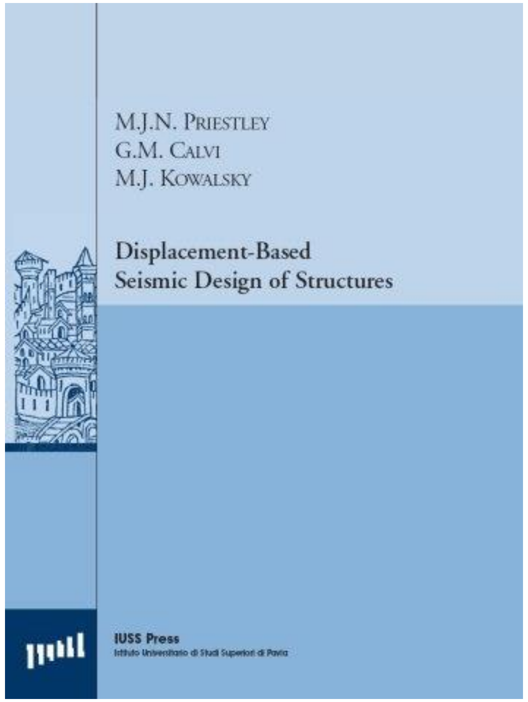
FLAC 2D

Problems to model cyclic nonlinear behaviour of RC structures

Modelling nonlinear cyclic behaviour of structural elements and damage assessment

FLAC 2D Standard Model

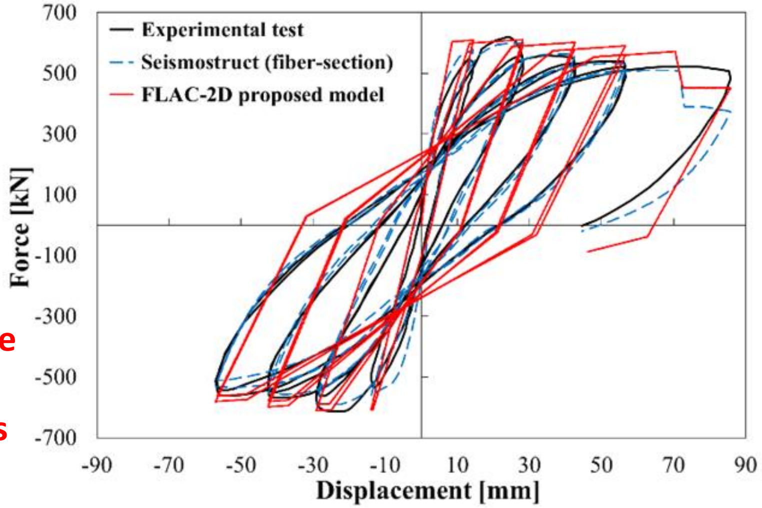




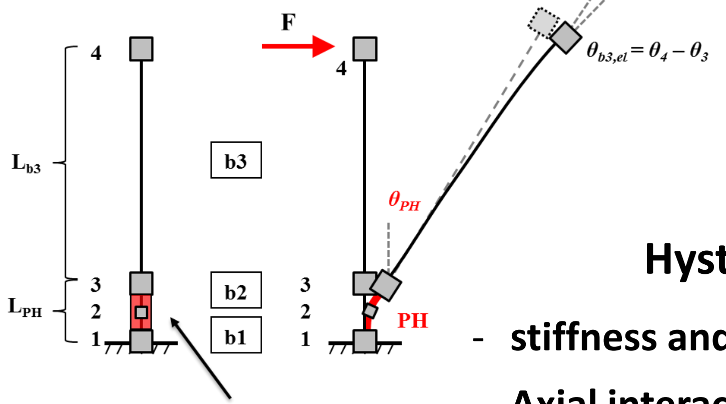
Application of concepts

Transfer of knowledge from structural to geotechnical systems

Implemented Model



Elementary part

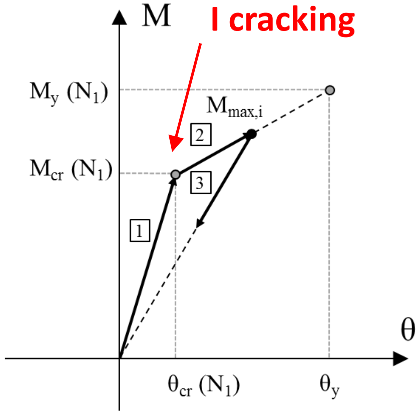


Finite length inelastic zone (plastic hinge region)

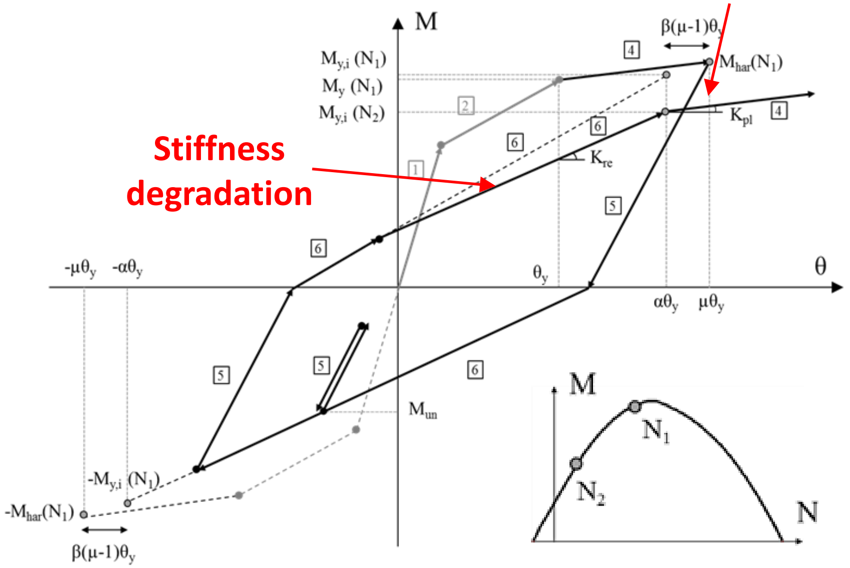
Hysteretic law

- stiffness and strength degradation
- Axial interaction (M-N)

Bi-linear elastic phase



Plastic phase

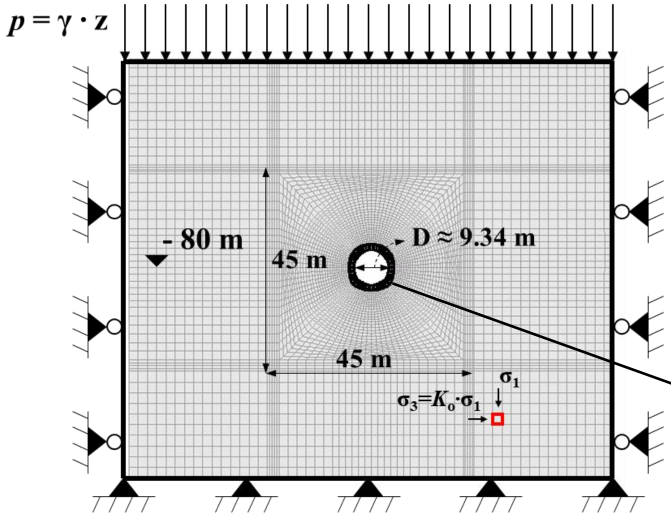


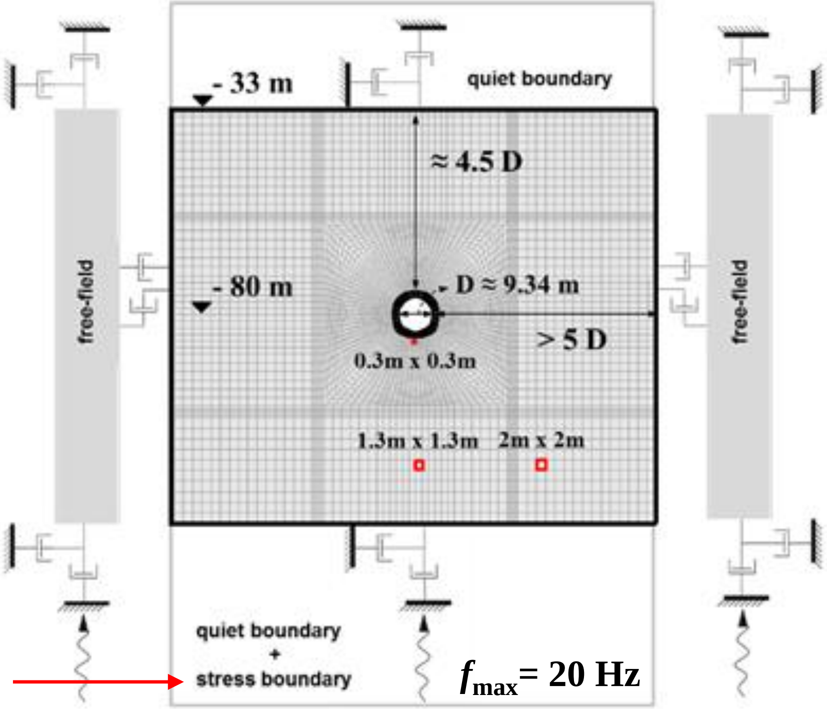
FLAC 2D numerical model

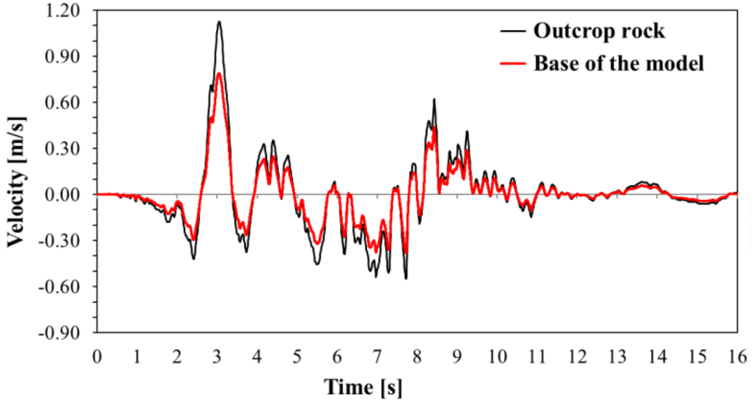
Multi-step static analysis

Initial conditions

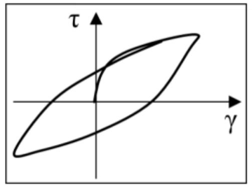
Nonlinear time history analysis

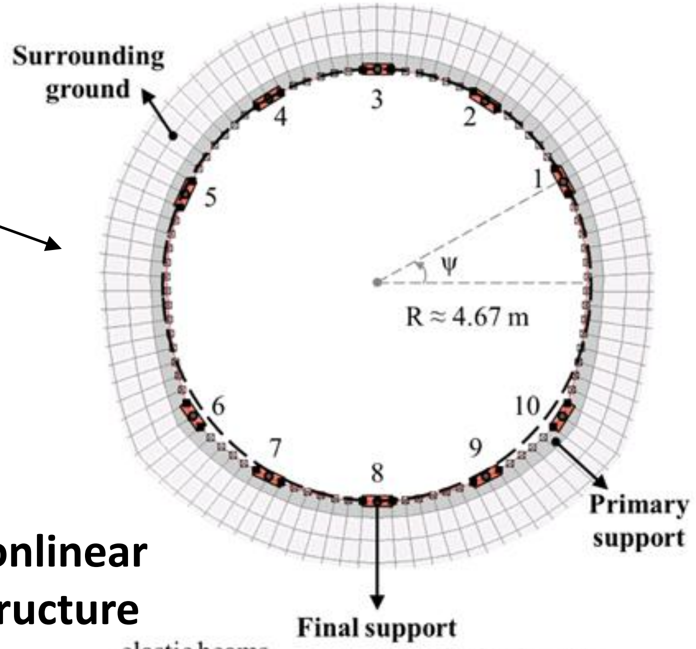




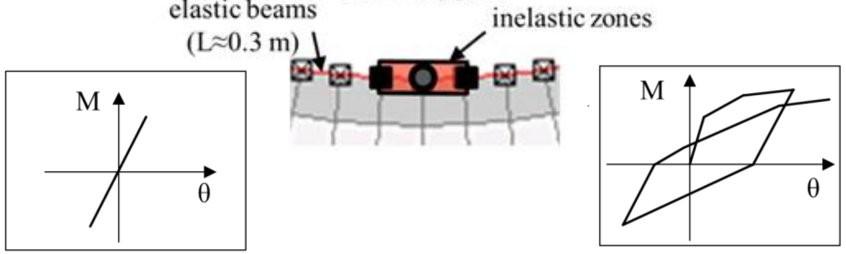


Nonlinear soil



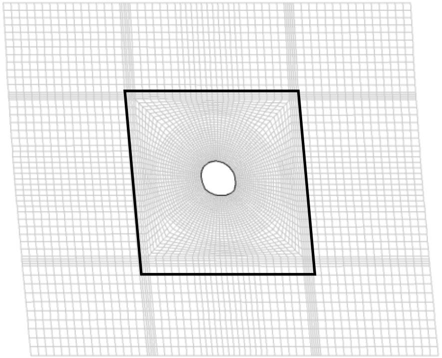


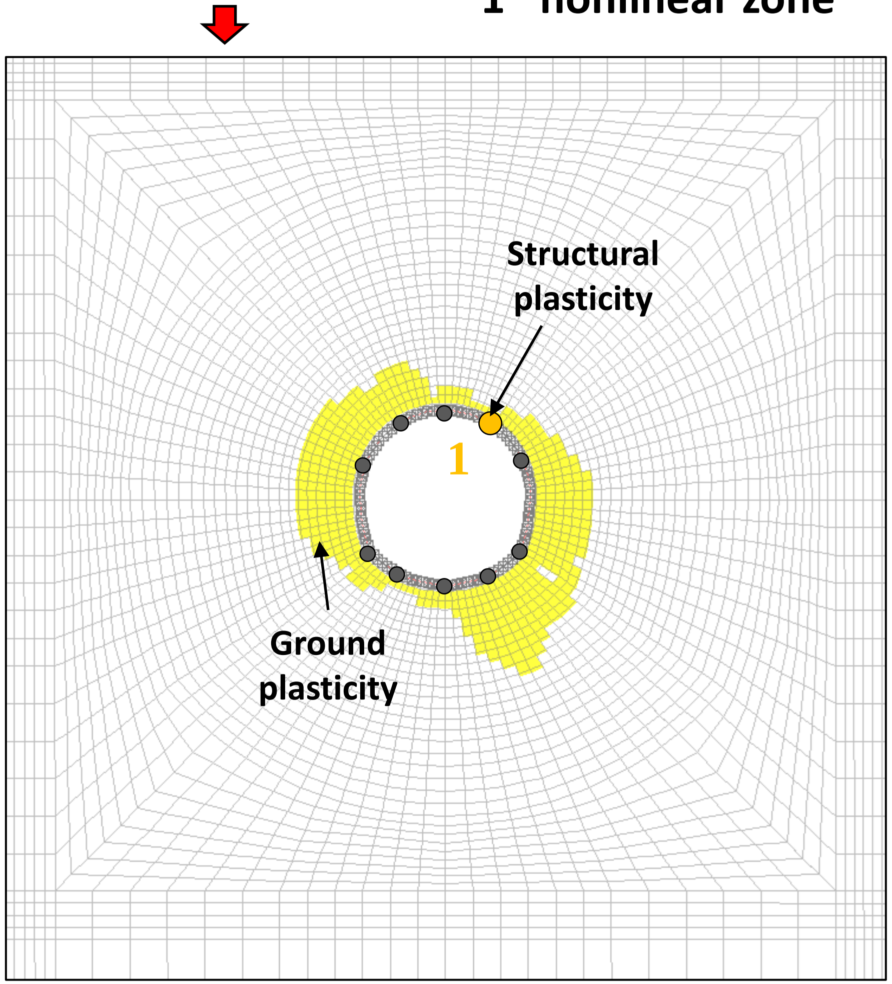
Nonlinear structure



Results: NLSSI tunnel

Evolution of ground and structural nonlinearity





Ground Plasticity Index

$$\mathrm{GPI} = \frac{N^{pl}_{dyn}}{N^{pl}_{static}} - 1$$

nº plastic zones dyn analysis

nº plastic zones static analysis

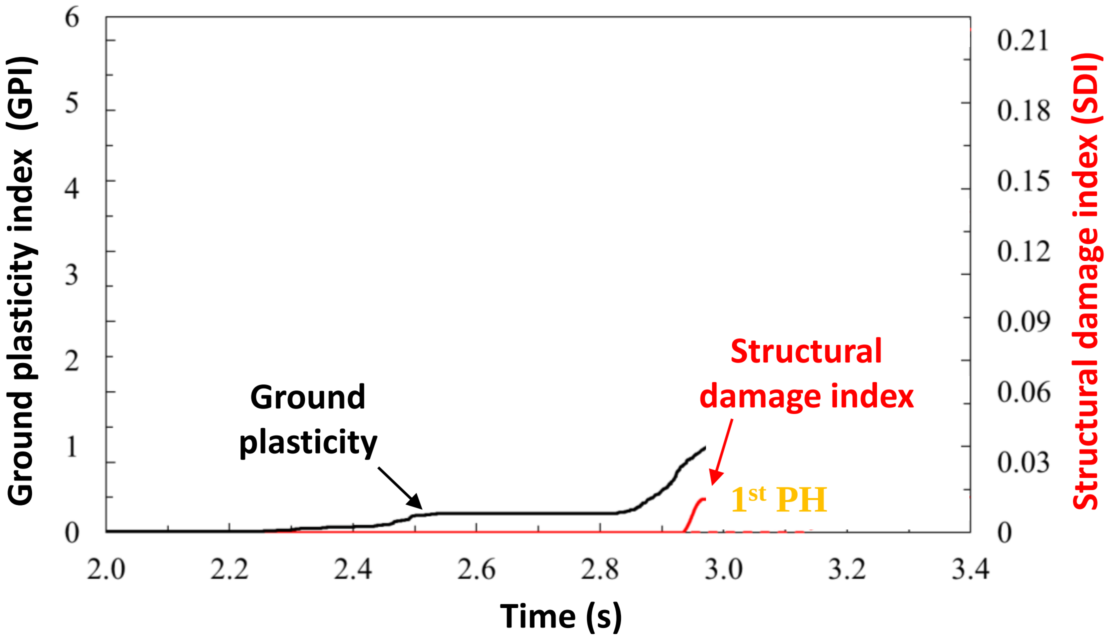
Structural Damage Index

$$\mathrm{SDI} = \sum_{i=1}^{n} \frac{\theta^{i}_{pl}}{\theta^{i}_{pl,u}}$$

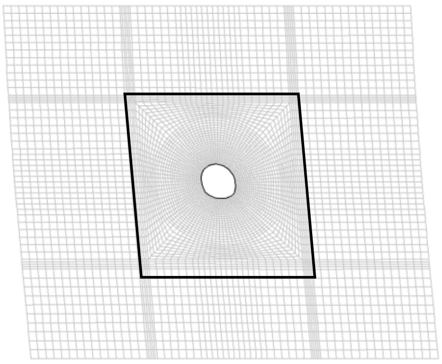
nº of PH

Plastic rotation

Plastic capacity

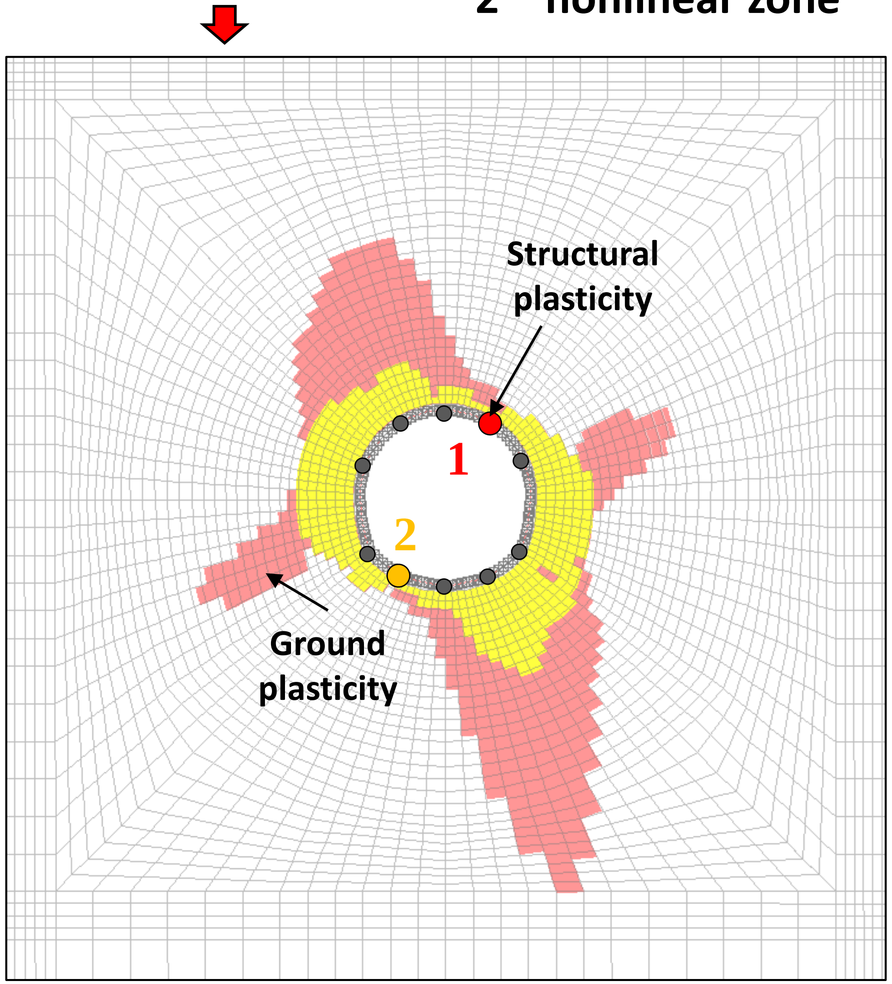


Results: NLSSI tunnel



Evolution of ground and structural nonlinearity

Activation of 2nd nonlinear zone



Ground Plasticity Index

$$GPI = \frac{N^{pl}_{dyn}}{N^{pl}_{static}} - 1$$

N^{pl}_{dyn}: nº plastic zones dyn analysis

N^{pl}_{static}: nº plastic zones static analysis

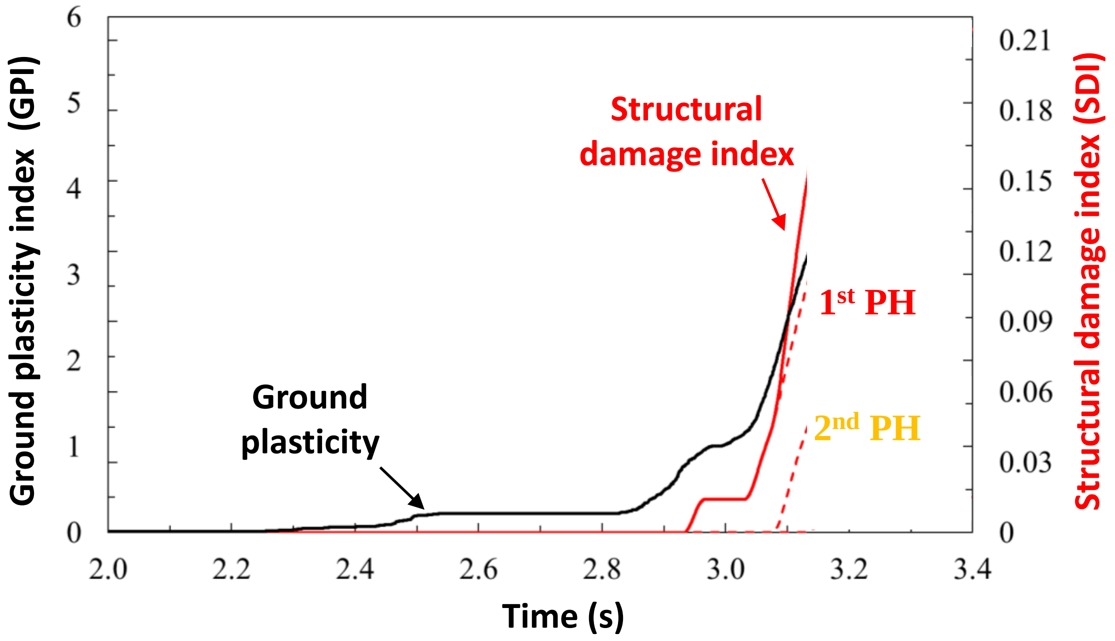
Structural Damage Index

$$SDI = \sum_{i=1}^{n} \frac{\theta^{i}_{pl}}{\theta^{i}_{pl,u}}$$

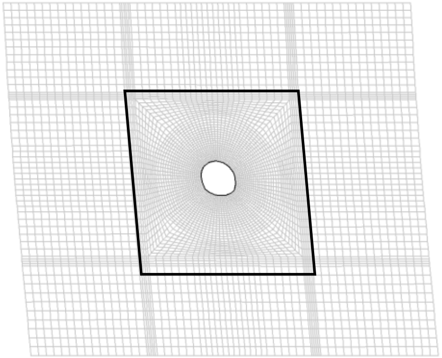
n: nº of PH

θ^{i}_{pl}: Plastic rotation

$\theta^{i}_{pl,u}$: Plastic capacity

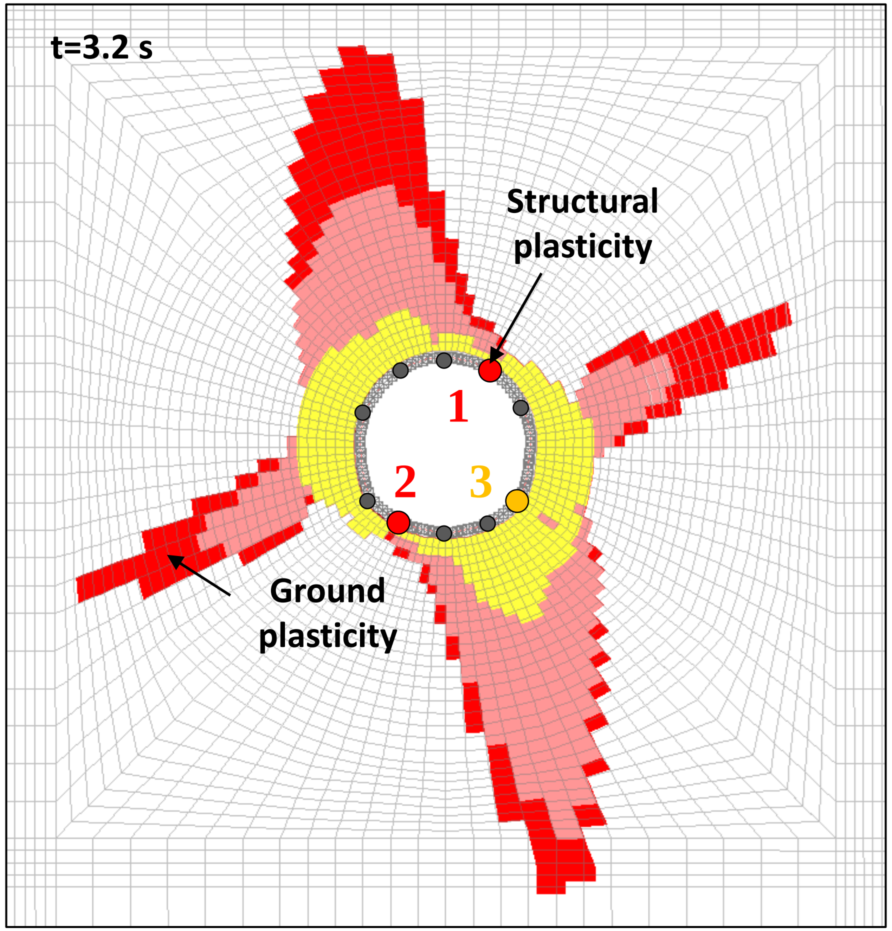


Results: NLSSI tunnel



Evolution of ground and structural nonlinearity

Activation of 3rd nonlinear zone



Ground Plasticity Index

$$GPI = \frac{N^{pl}_{dyn}}{N^{pl}_{static}} - 1$$

N^{pl}_{dyn}: nº plastic zones dyn analysis

N^{pl}_{static}: nº plastic zones static analysis

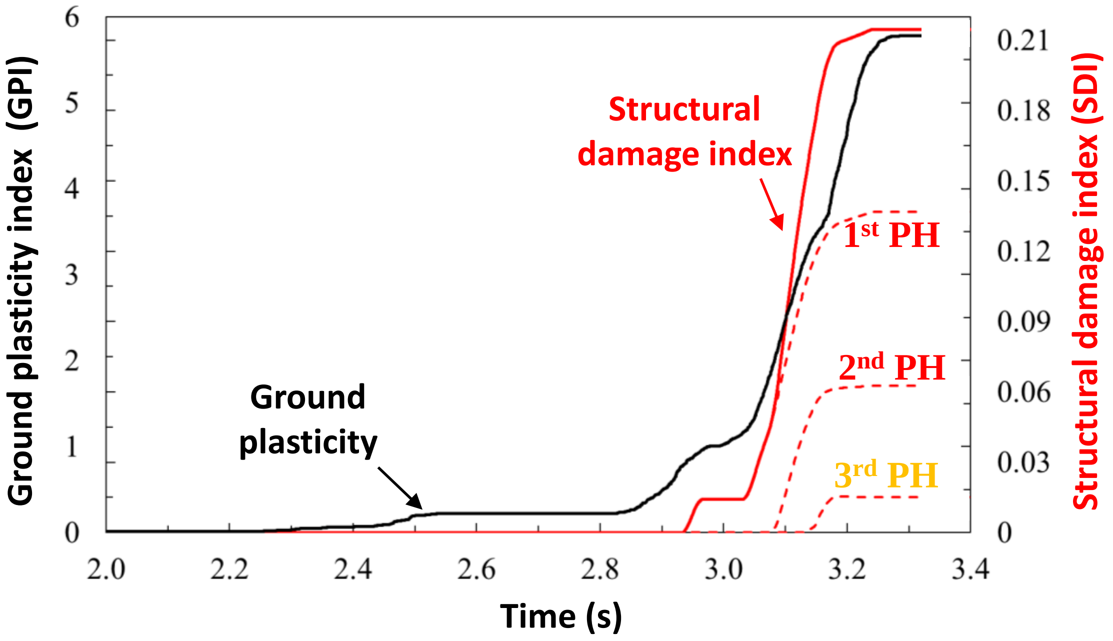
Structural Damage Index

$$SDI = \sum_{i=1}^{n} \frac{\theta^{i}_{pl}}{\theta^{i}_{pl,u}}$$

n: nº of PH

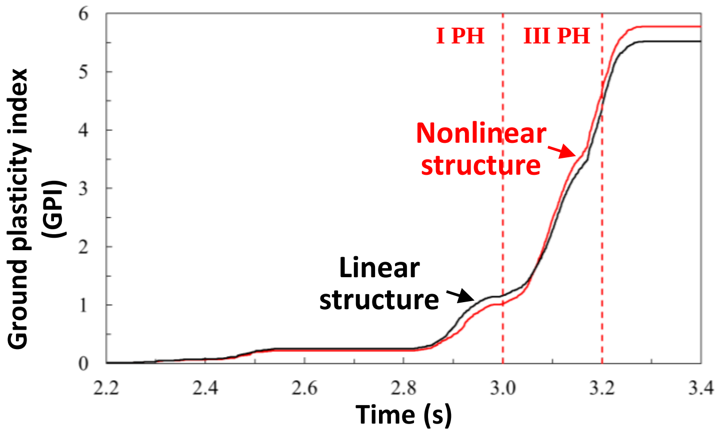
θ^{i}_{pl}: Plastic rotation

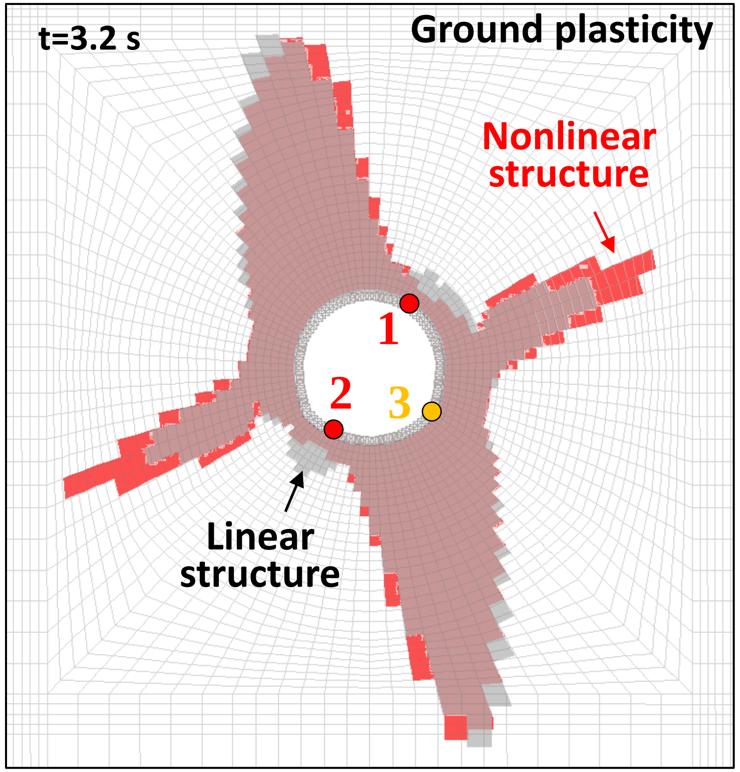
$\theta^{i}_{pl,u}$: Plastic capacity

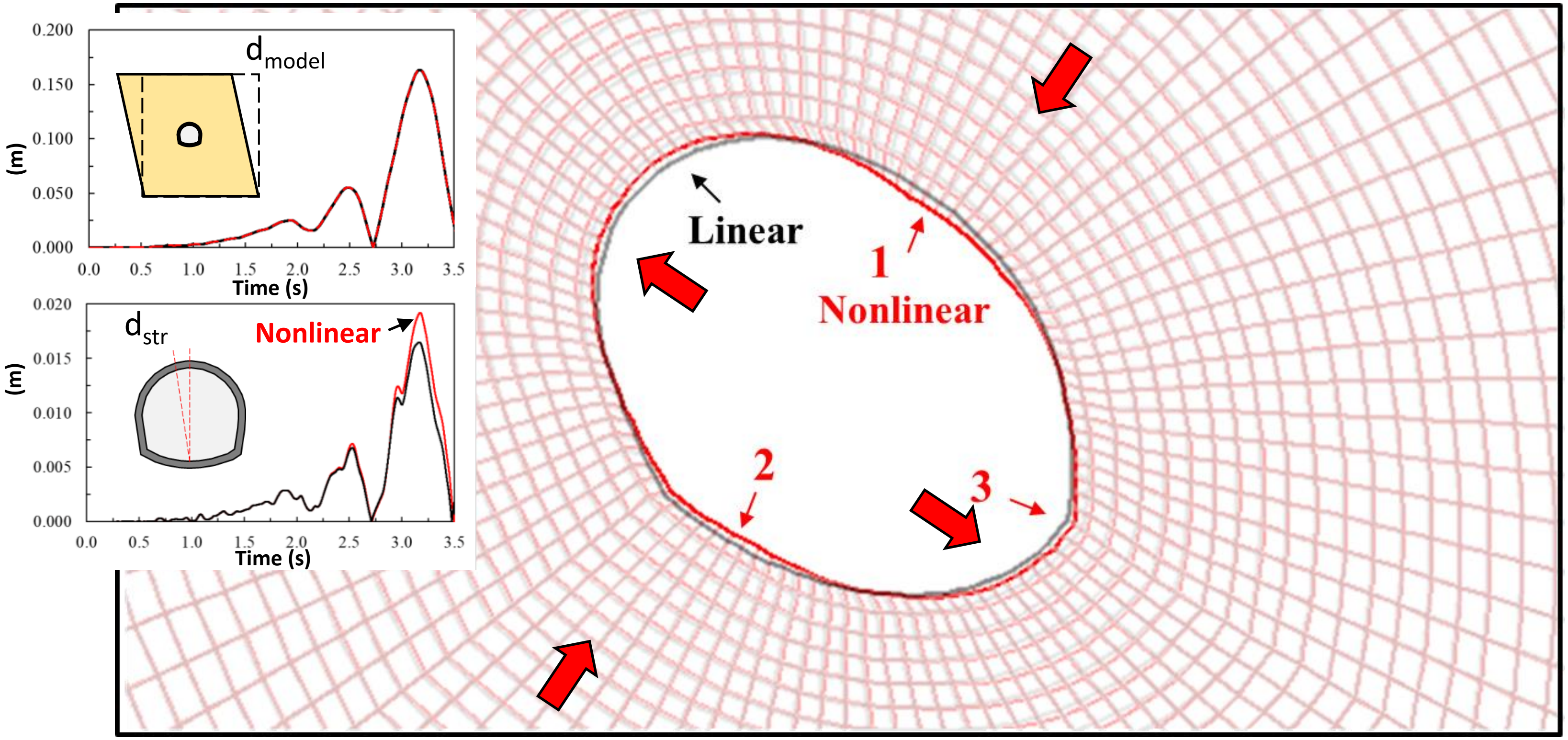


Results: NLSSI tunnel

Linear vs Nonlinear structure

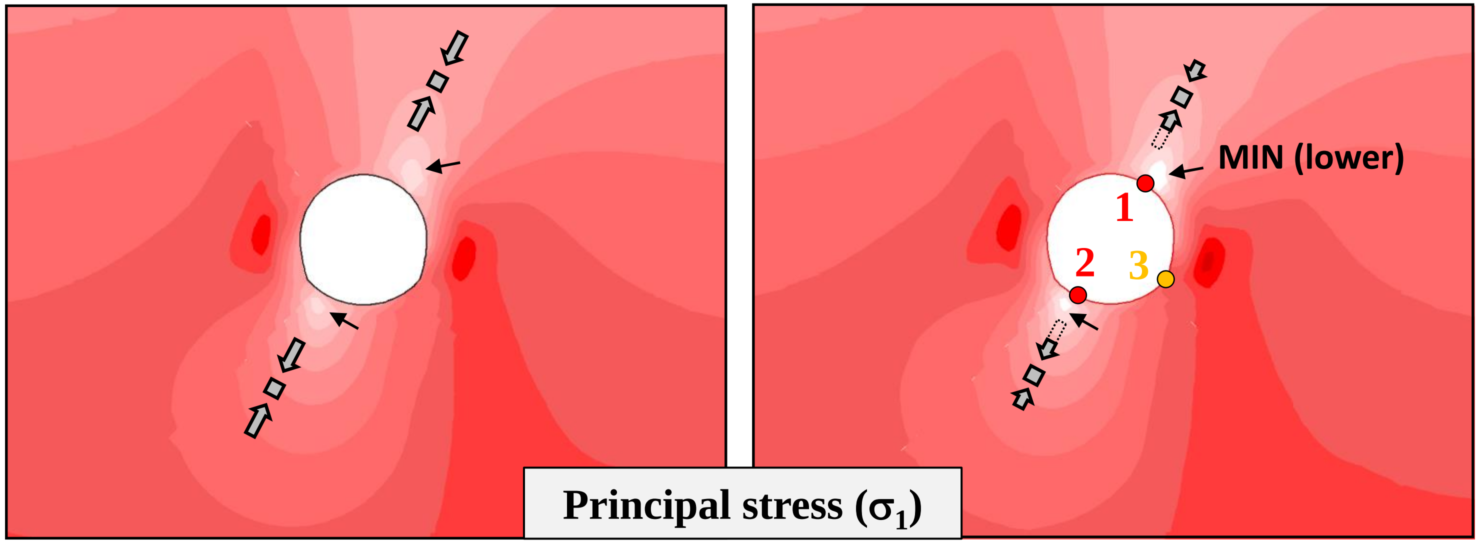




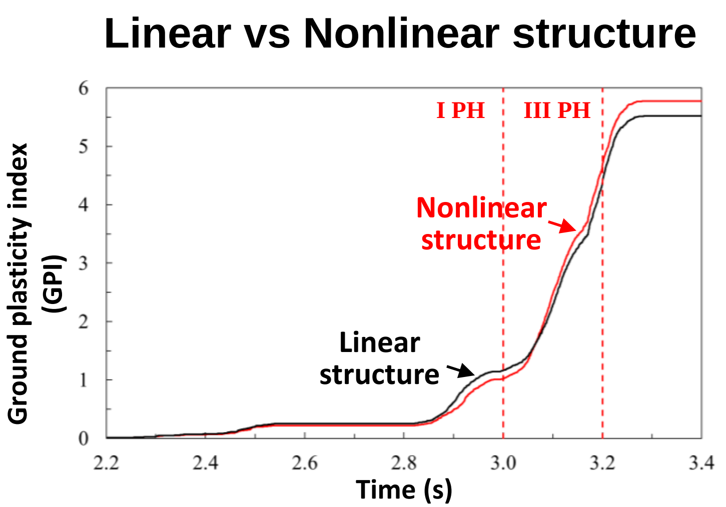


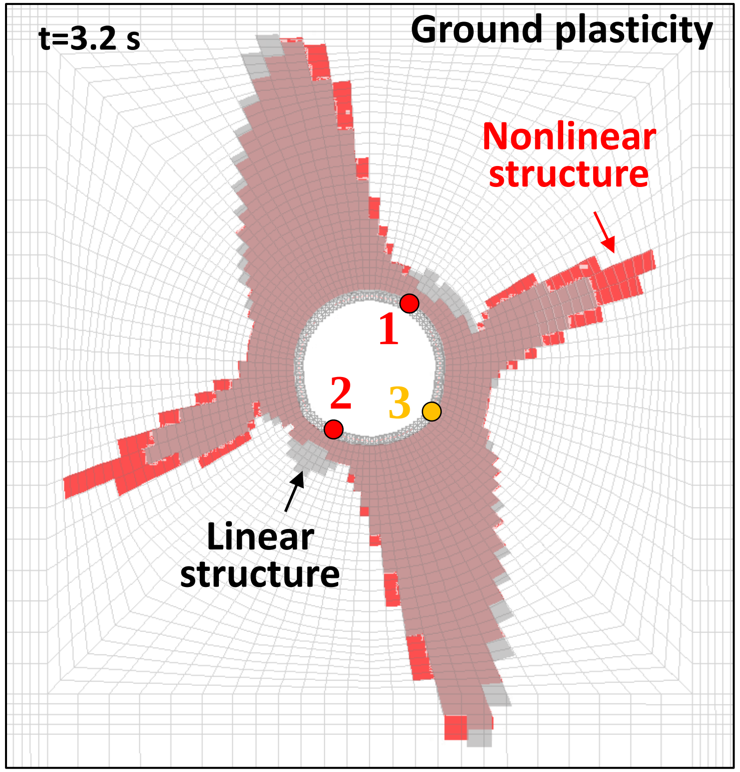
Linear structure (t=3.2 s)

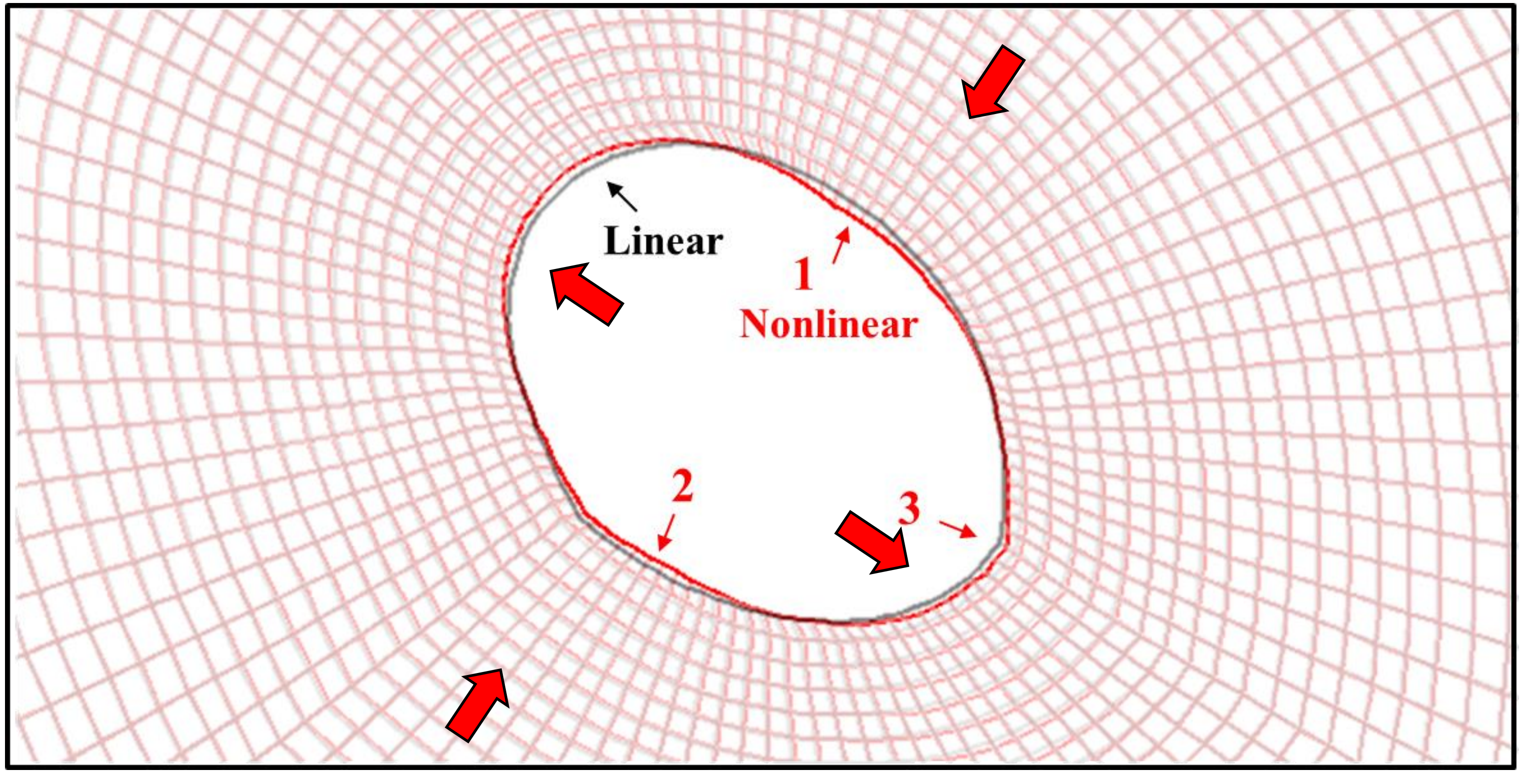
Nonlinear structure (t=3.2 s)

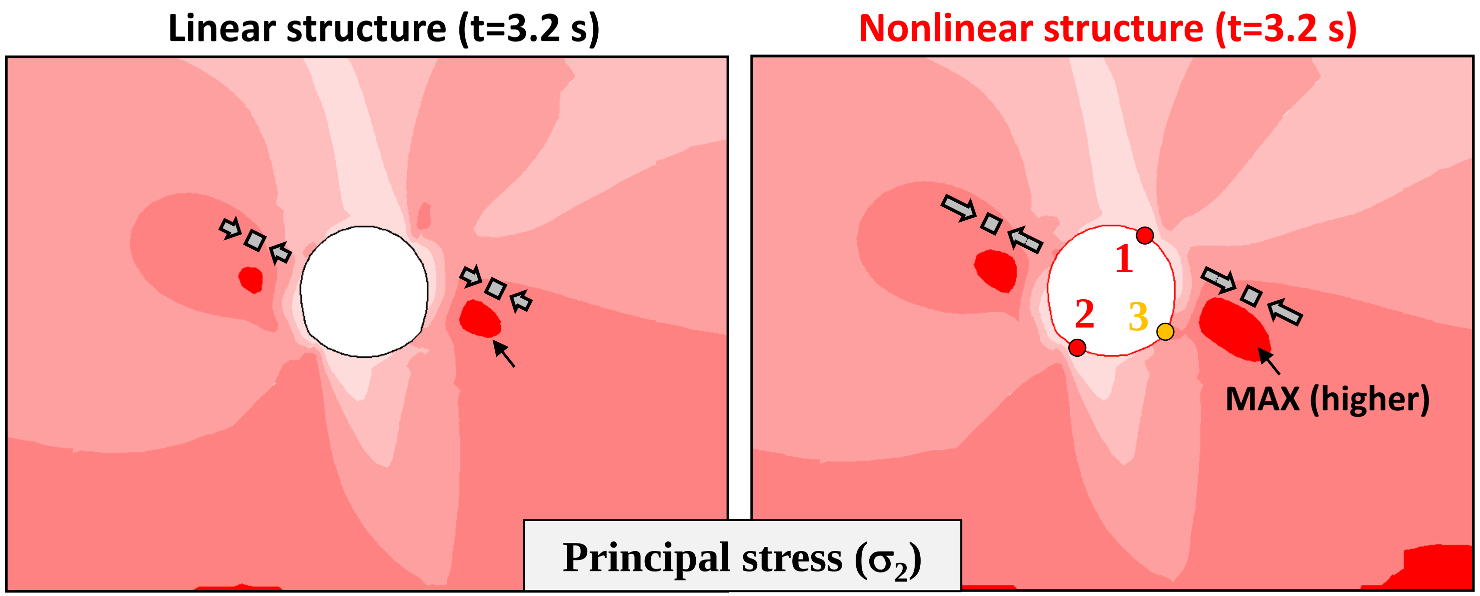


Results: NLSSI tunnel



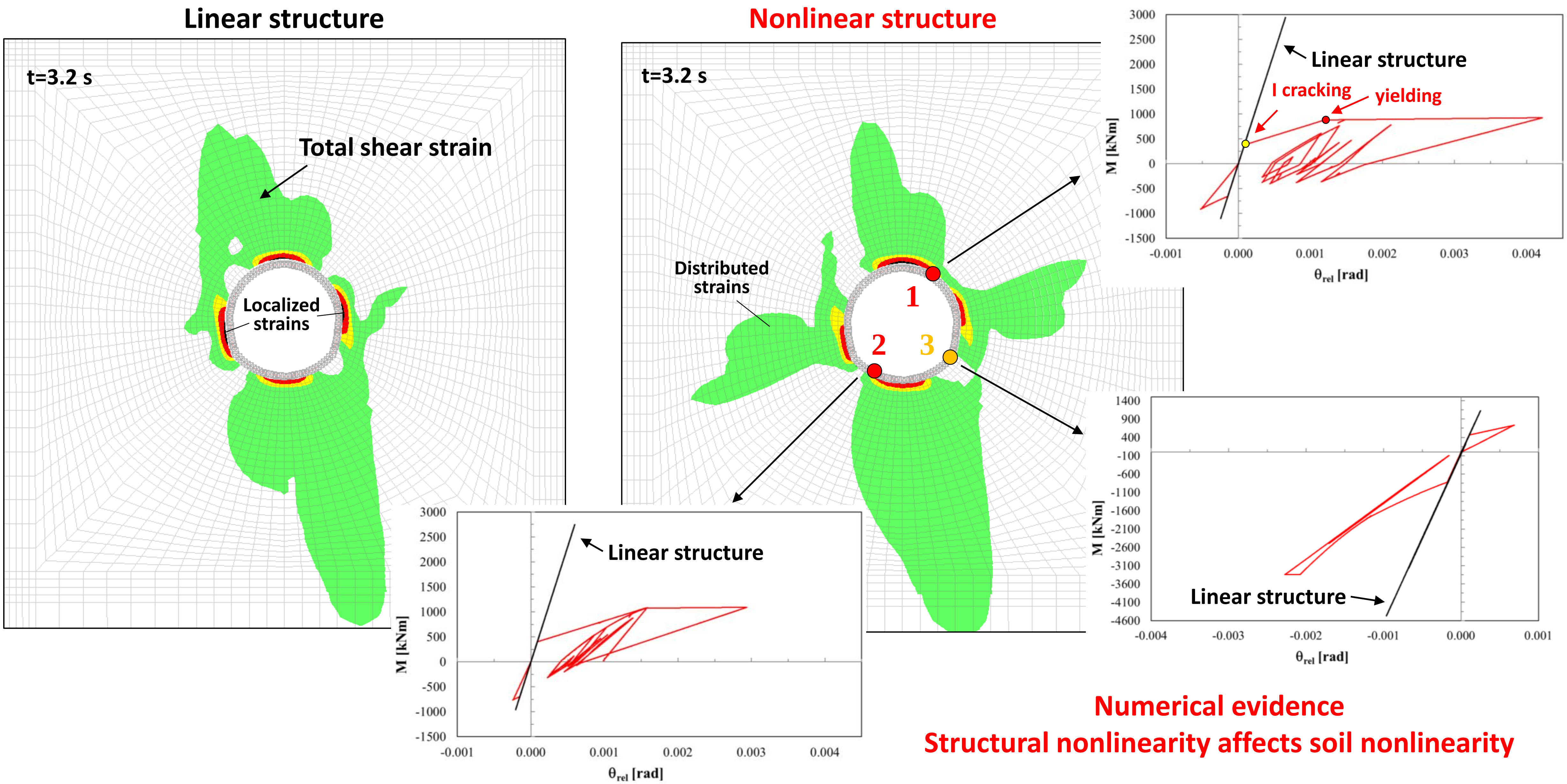






Results: NLSSI tunnel

Linear vs Nonlinear structure: shear strains and structural deformations



Numerical evidence

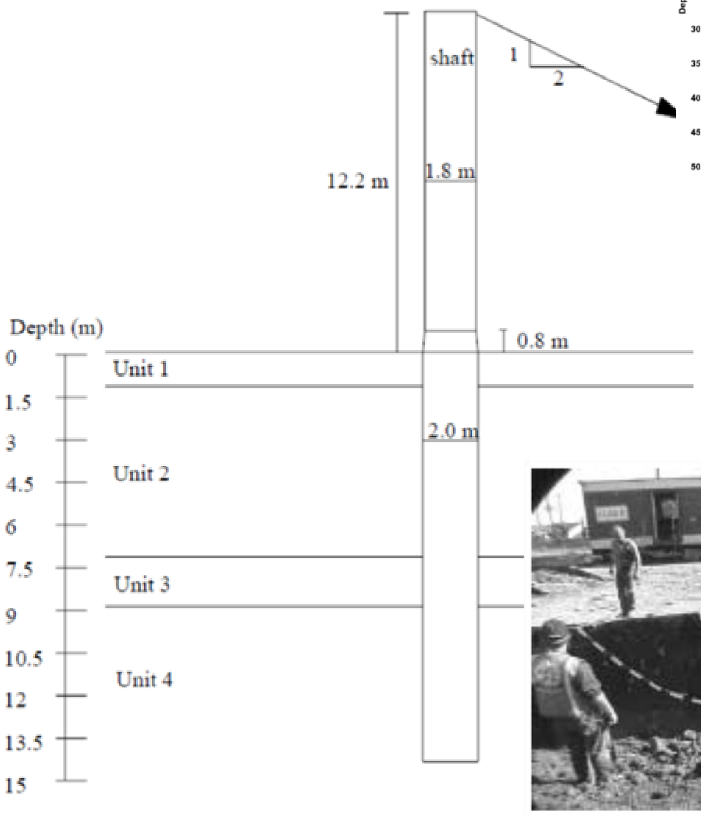
Structural nonlinearity affects soil nonlinearity

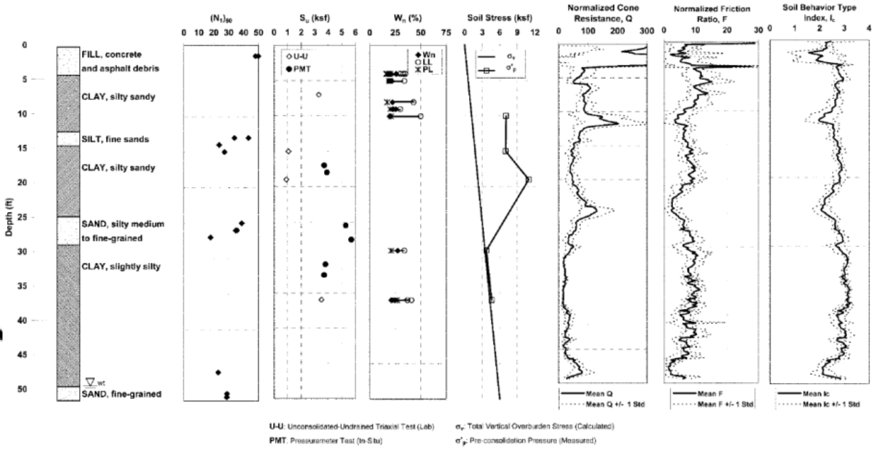
2) Detailed modelling of CIDH bridge column

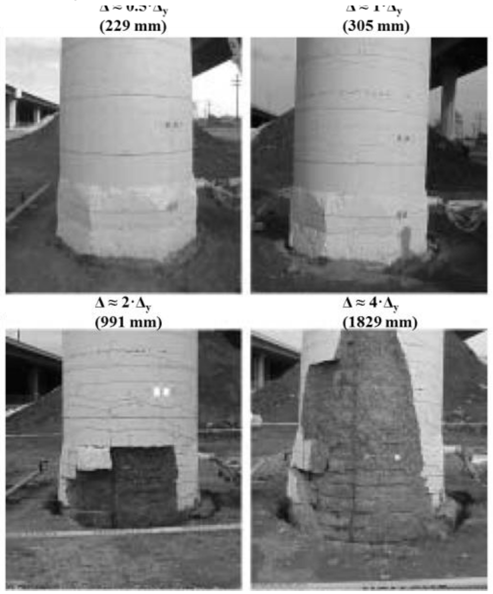
Experimental benchmark: full-scale cyclic test by UCLA (Janoyan, Wallace and Stuart, 2006)

Why this test?

- Severe nonlinearity of both soil and structure
- Full-scale test
- High quality experimental data: soil + structure

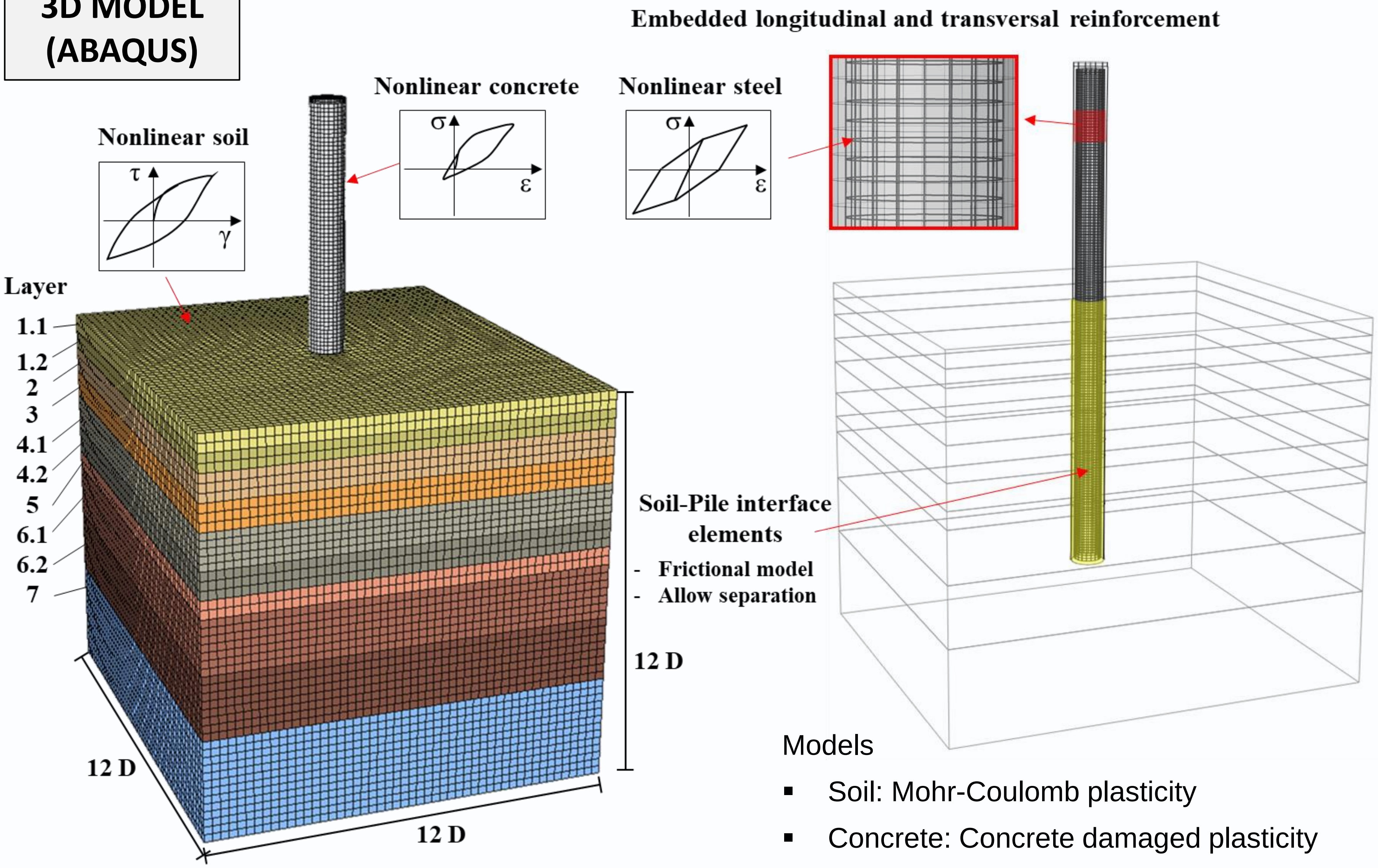






2) Detailed modelling of CIDH bridge column

3D MODEL (ABAQUS)

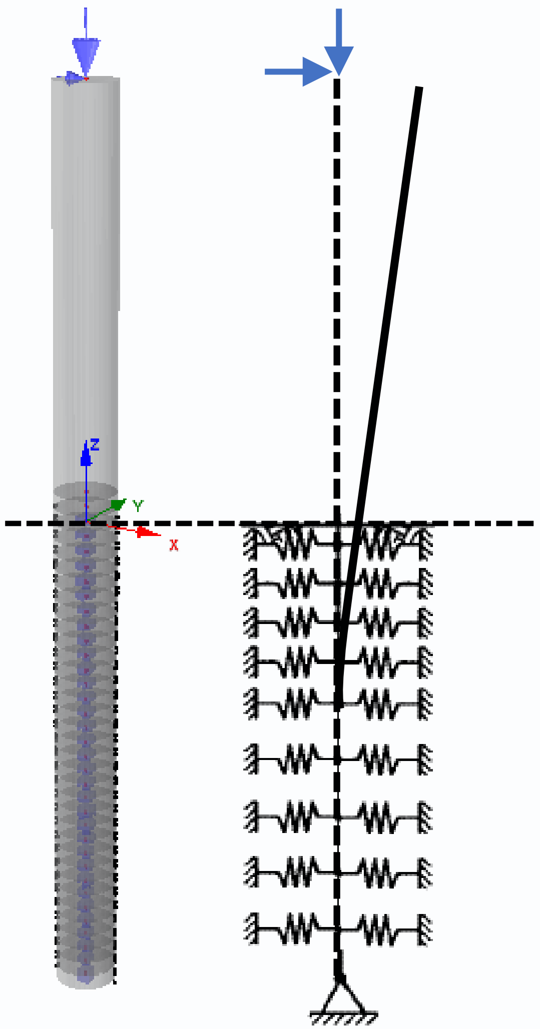


Models

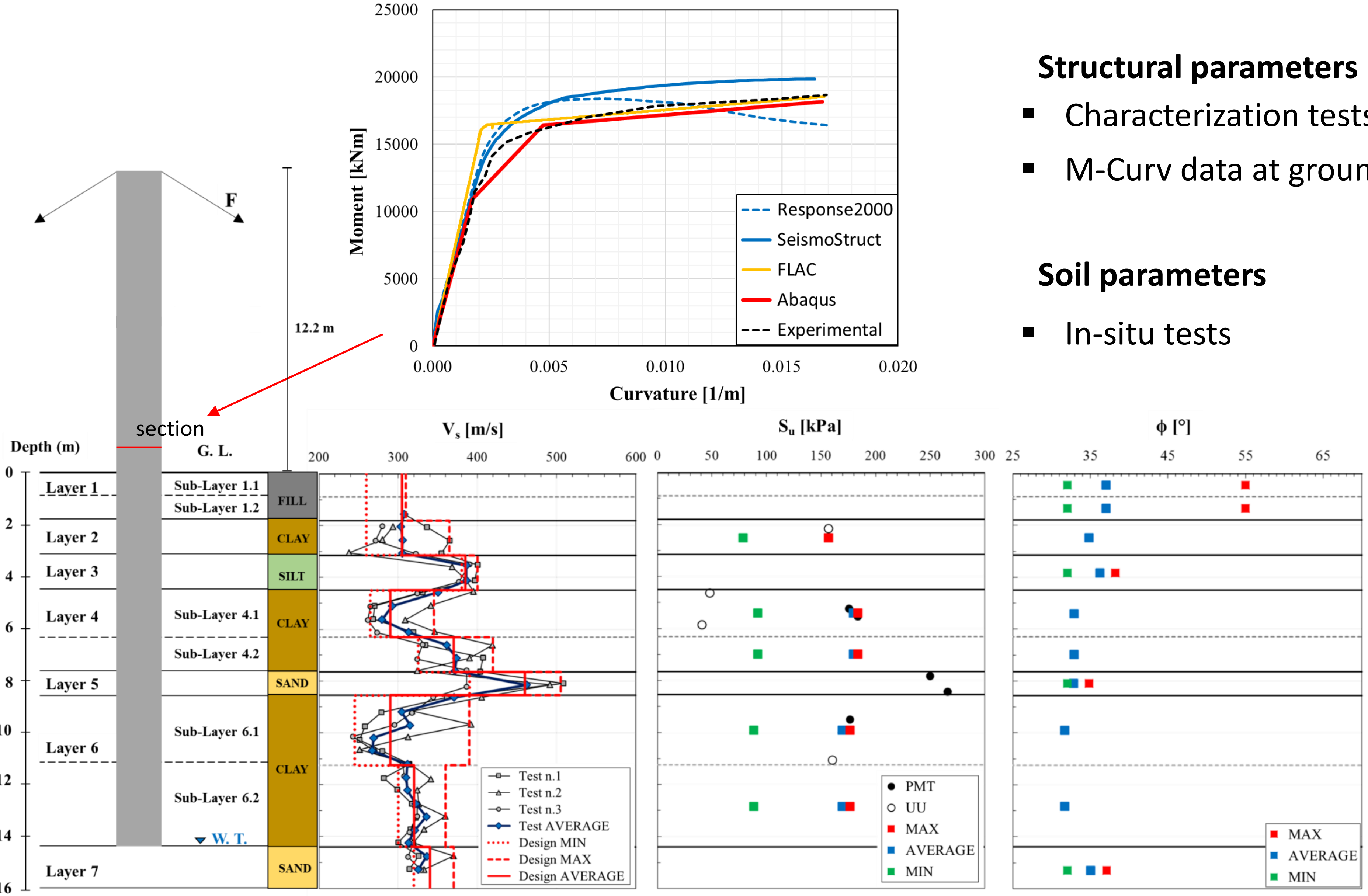
- Soil: Mohr-Coulomb plasticity
- Concrete: Concrete damaged plasticity
- Steel: bi-linear with hardening
- Interface: Frictional model allowing separation

(Andreotti and Calvi, 2021)

Fiber sections and p-y curves (SeismoStruct)



Calibration of model parameters



Structural parameters

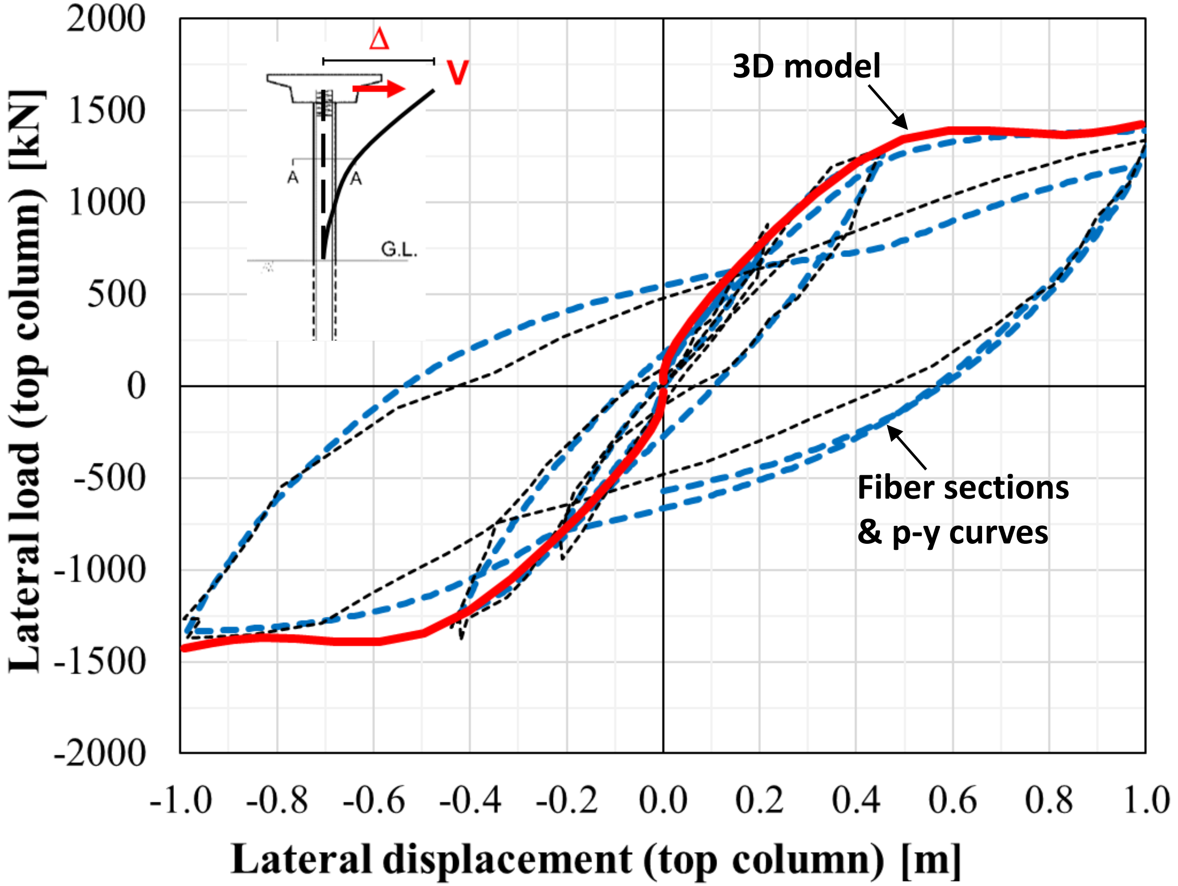
- Characterization tests small specimens
- M-Curv data at ground level

Soil parameters

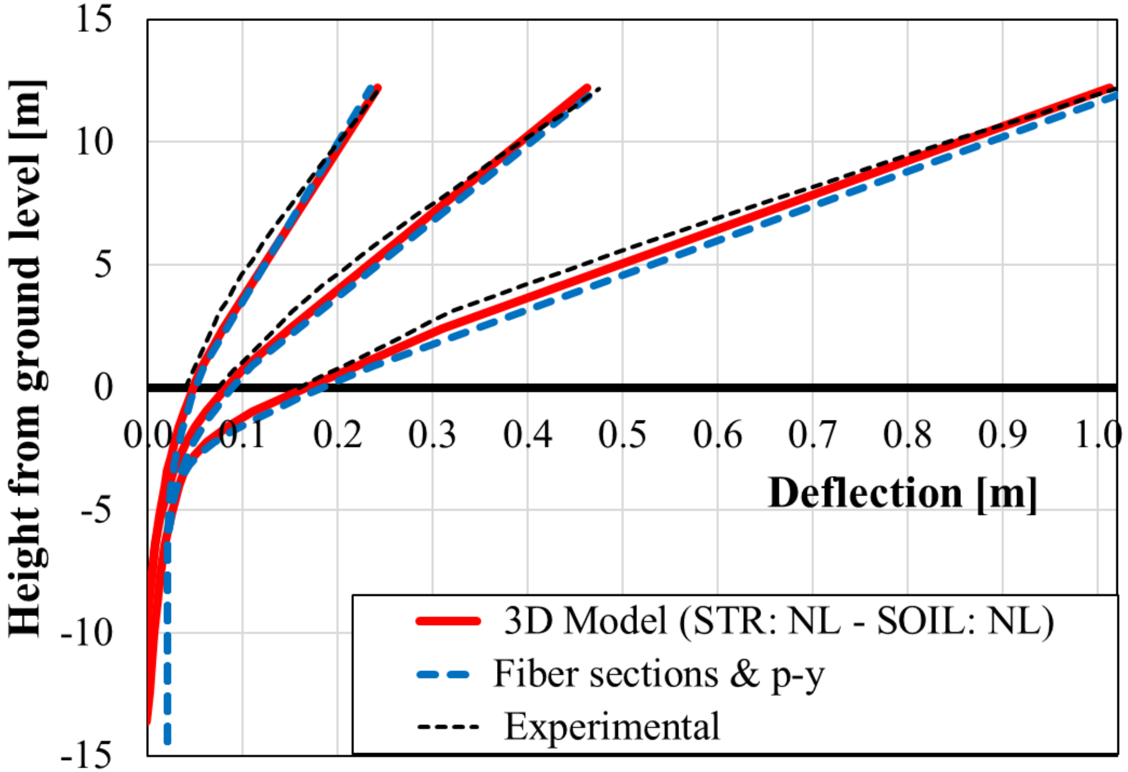
- In-situ tests

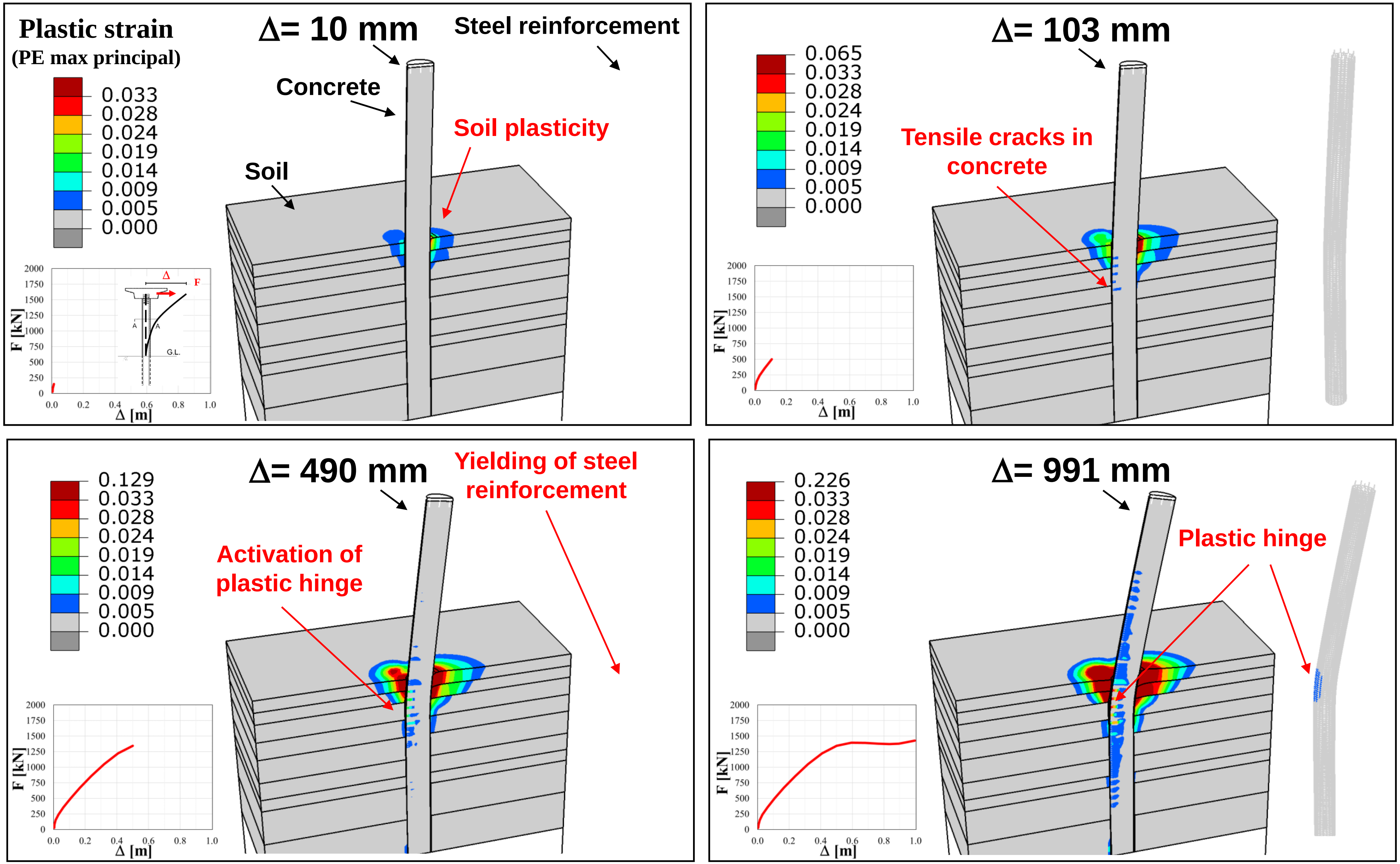
Comparison 3D model and fiber sections/p-y curves

Force-displacement



Displacement profile



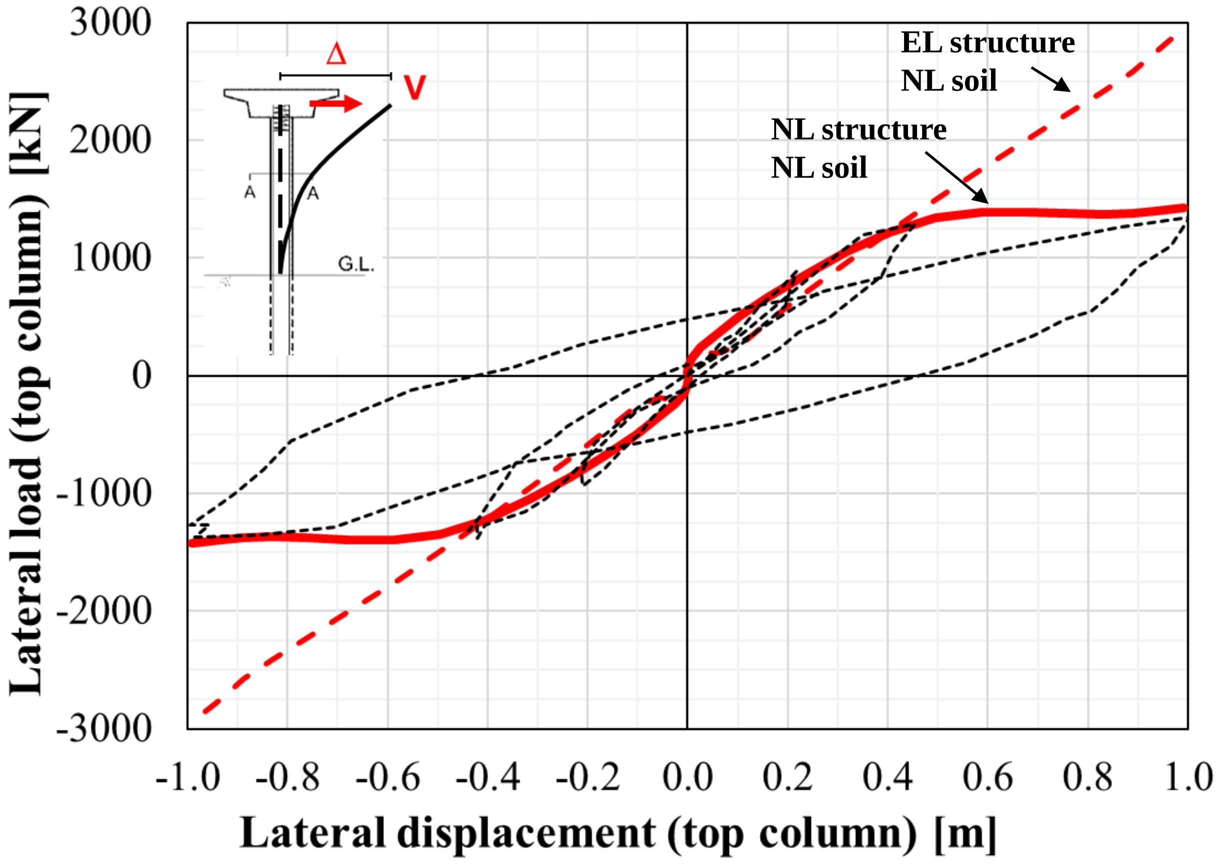


Plastic strain
(PE max principal)
0.033
0.028
0.024
0.019
0.014
0.009
0.005
0.000
Δ= 10 mm
Steel reinforcement
Concrete
Soil plasticity
Soil
F [kN]
Δ [m]
Δ
F
G.L.
Δ= 103 mm
0.065
Tensile cracks in concrete
Δ= 490 mm
0.129
Yielding of steel reinforcement
Activation of plastic hinge
Δ= 991 mm
0.226
Plastic hinge

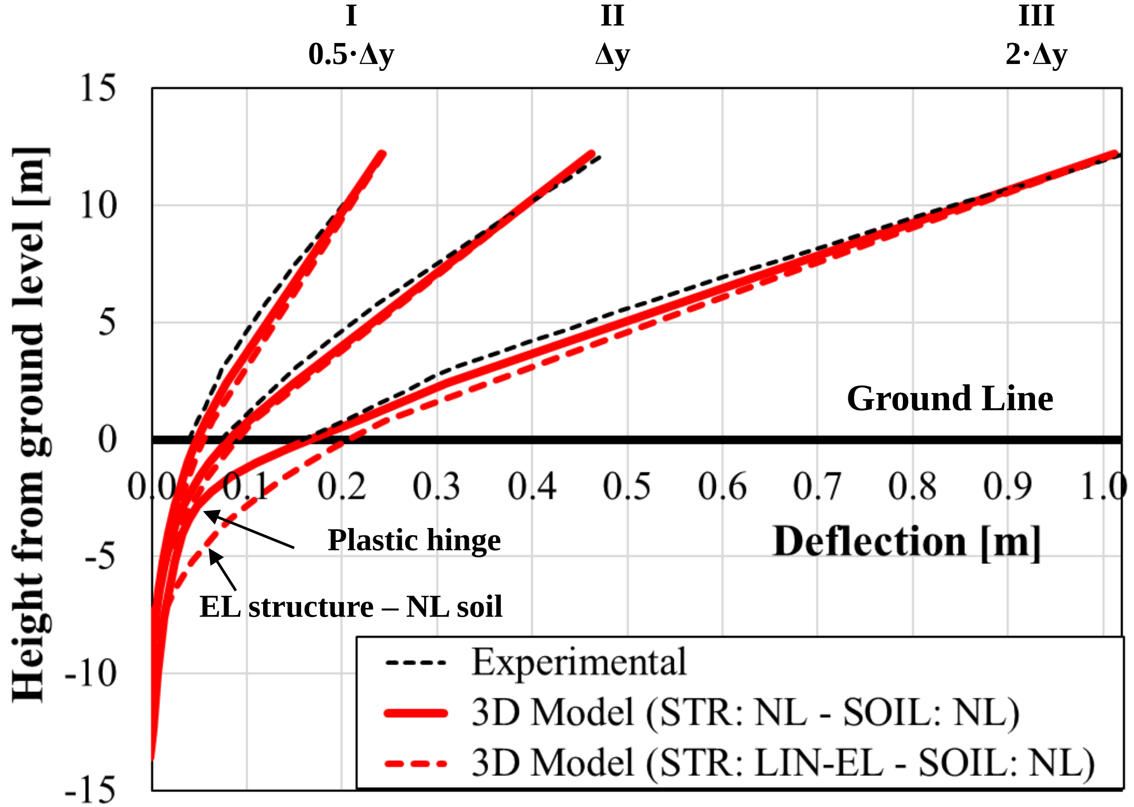
3D model: Elastic vs Nonlinear structure

Results with identical soil and different structural behaviour (LIN vs NL)

Force-displacement

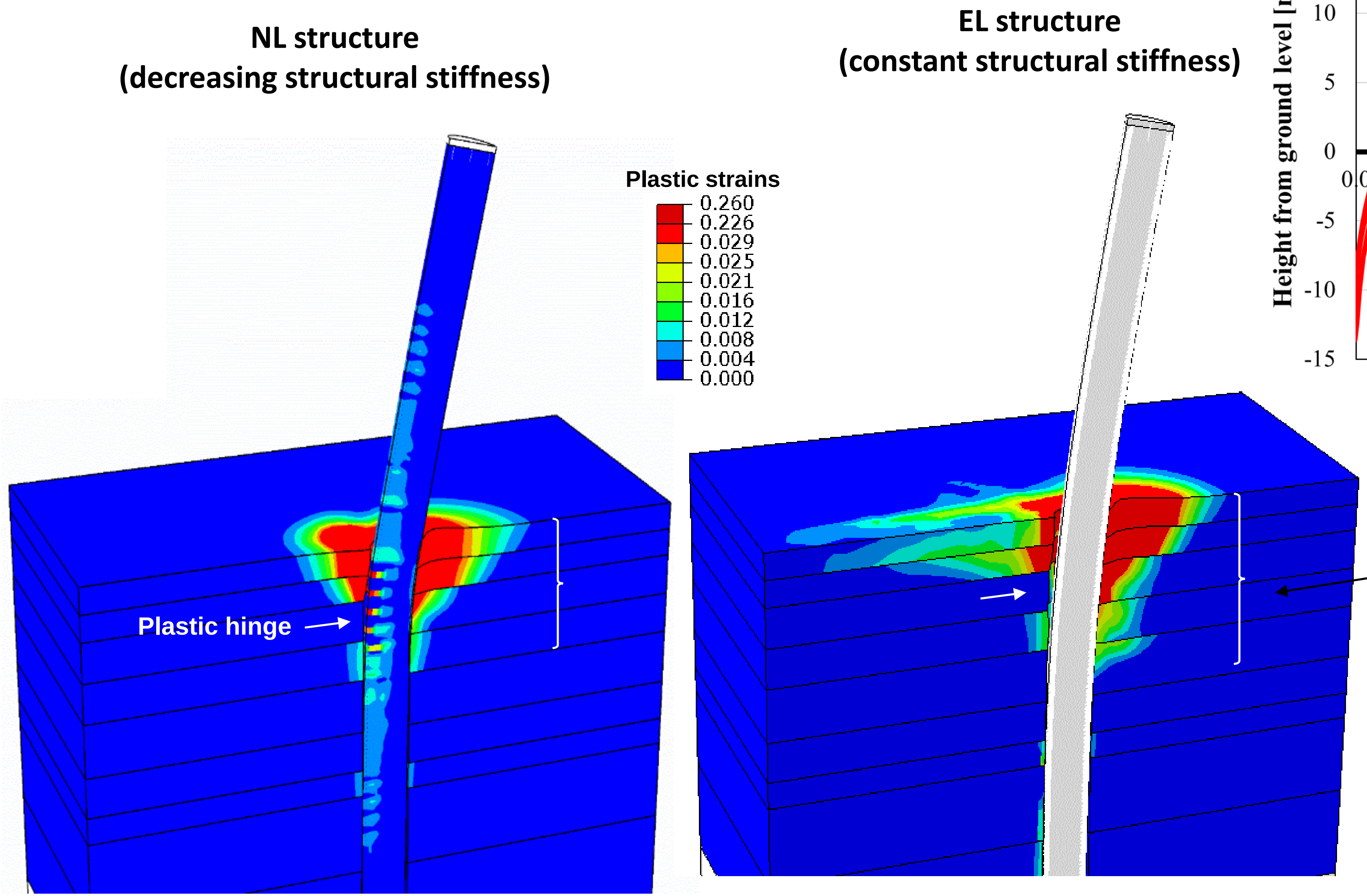


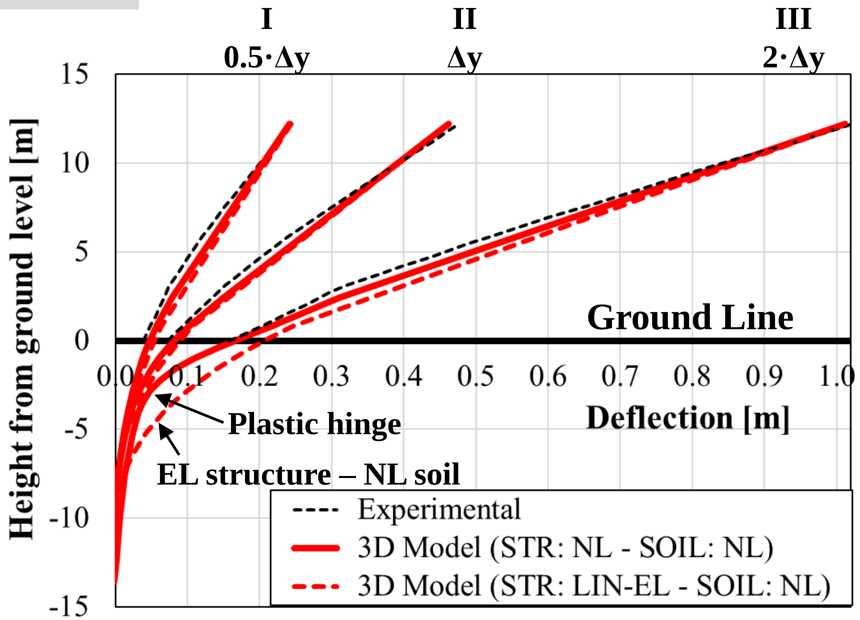
Displacement profile



Structural influence on soil nonlinearity

Results with identical soil and different structural behaviour (LIN vs NL)



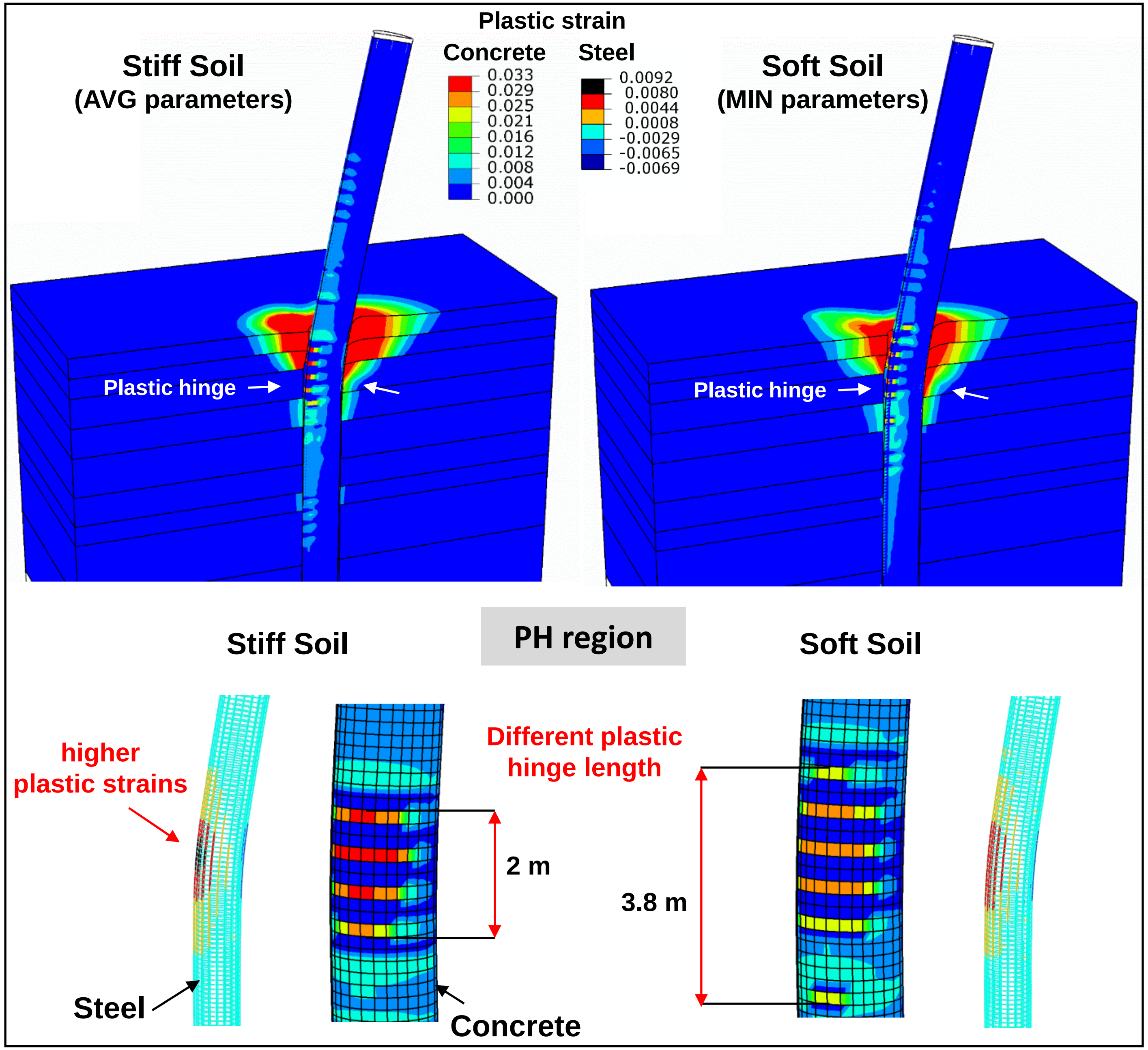


- Greater volume of nonlinear soil
- Soil nonlinearity goes deeper

- **Evaluation of inertial interaction only!**

Identical structure
different soil

Influence of soil stiffness on structural nonlinearity



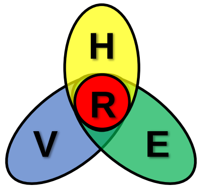
Stiff soils

- Concentration of strains (soil & structure)
- Smaller plastic hinge length
- Higher curvature demand

Soft soils

- Distribution of strains
- Larger plastic hinge length
- Lower curvature demand

Numerical evidence
Soil properties affect structural capacity



Seismic risk

Seismic demand is modified by secondary soil nonlinearity

Hazard
Vulnerability
Exposure

NLSSI

Structural capacity affected by soil properties

How much?

Experimental tests: issues of NLSSI

- Centrifuge tests

Artificial gravity field

Small scale structural models (1/20 – 1/50)

➡ **Correct reproduction of soil properties and confinement**

Problems to reproduce detailing and damage of reinforced concrete elements

- Shake tables with small soil boxes

Larger structural models (scale 1/10 – 1/5)

Small soil vertical stress

➡ **Less problems to reproduce RC elements**

Problems to reproduce soil properties and confinement

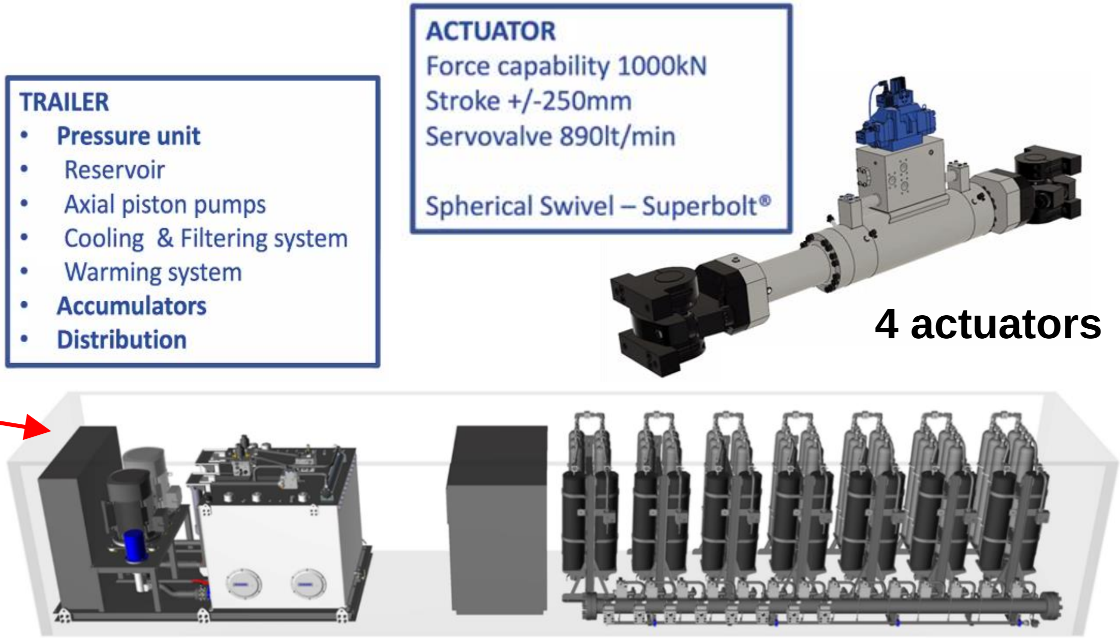
- Mobile laboratory for in-situ dynamic tests

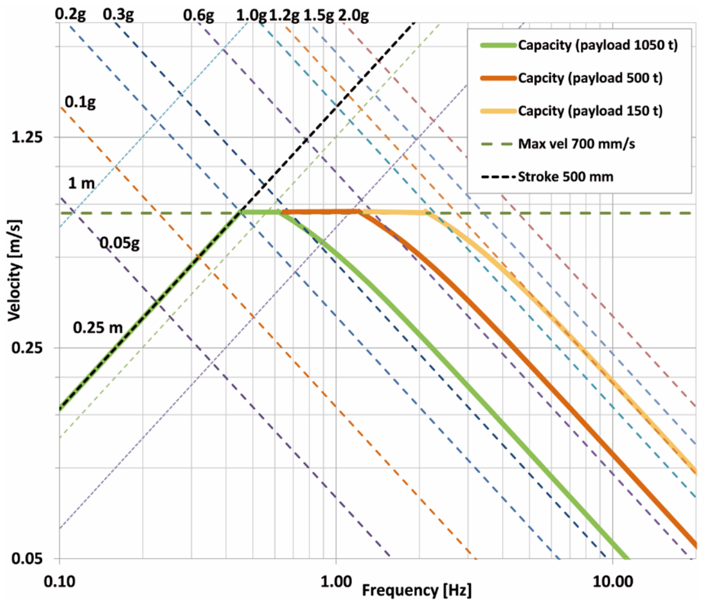
(Calvi et al., 2021)

➡ **Full scale tests in-situ (dynamic inertial SSI interaction)**

Feasibility study to reproduce kinematic SSI interaction

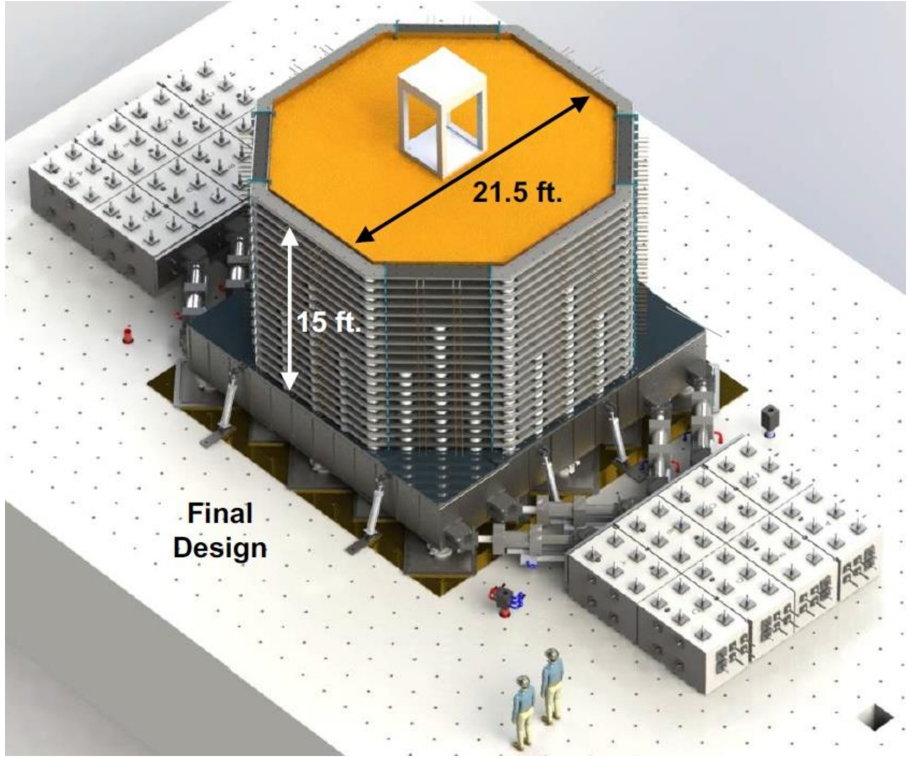
EUCENTRE FOR YOUR SAFETY.





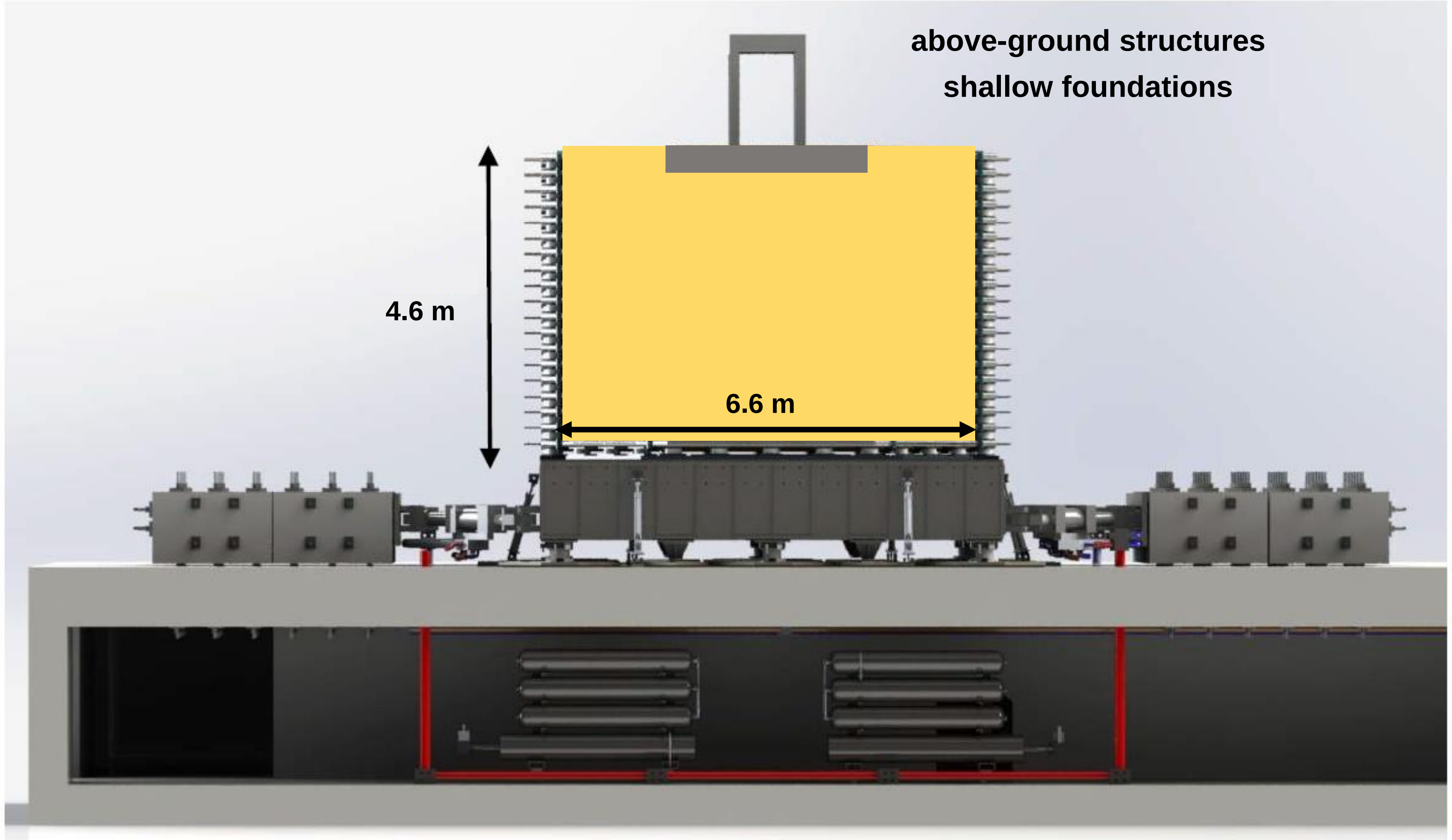
Experimental tests on NLSSI: fill the gap between research and practice

New shake table with big soil box
University of Nevada, Reno



Important contributions to dynamic NLSSI

- Structural damage of RC elements
- Failure mechanisms of the system
- Kinematic and inertial interaction
- Soil properties
- Primary and secondary soil nonlinearity
- Damping (e.g. radiation)



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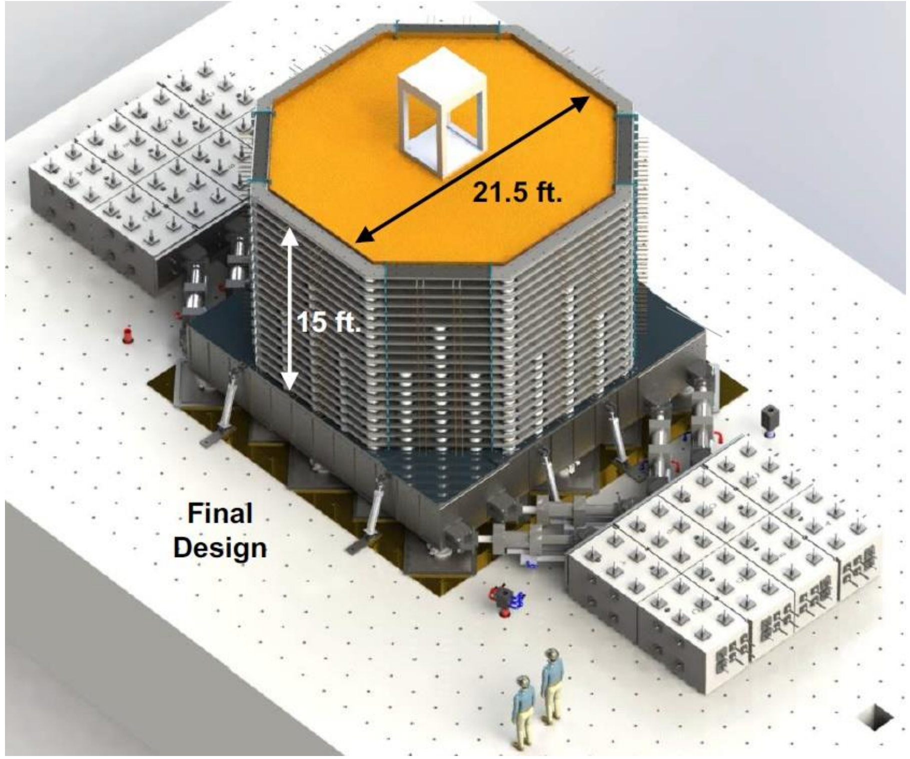

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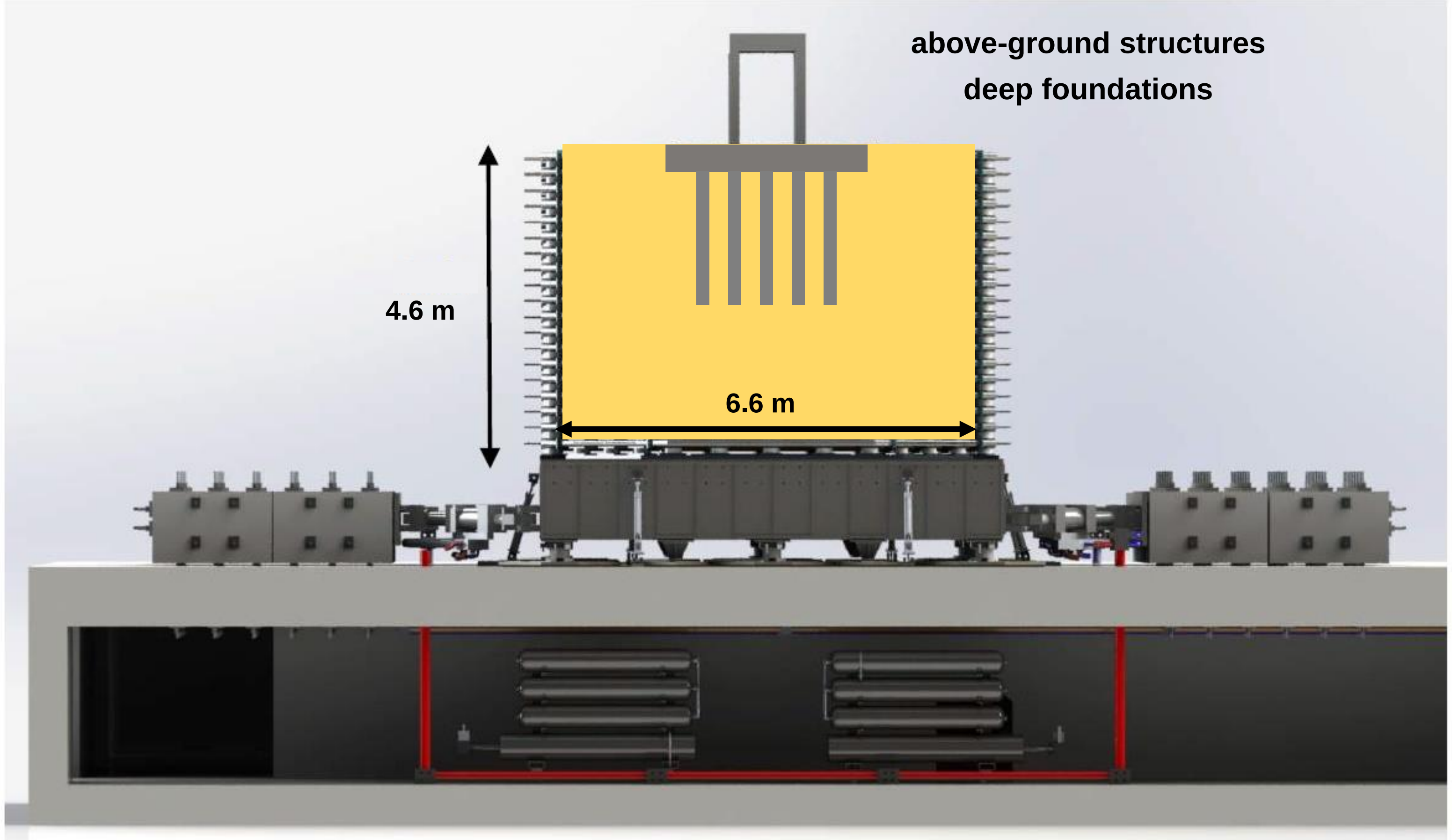

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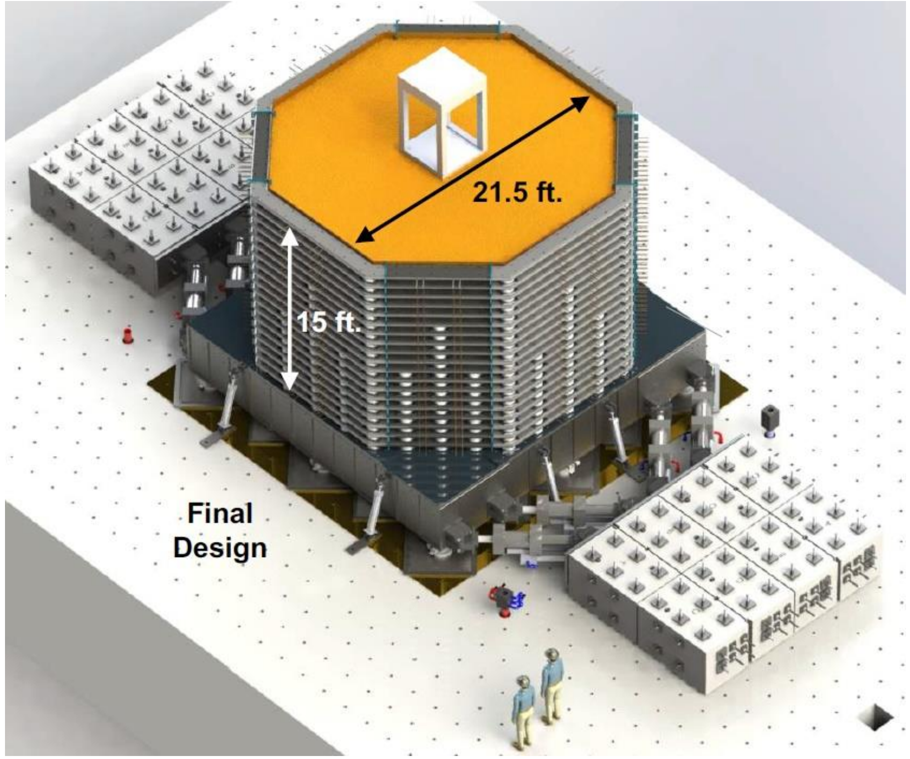

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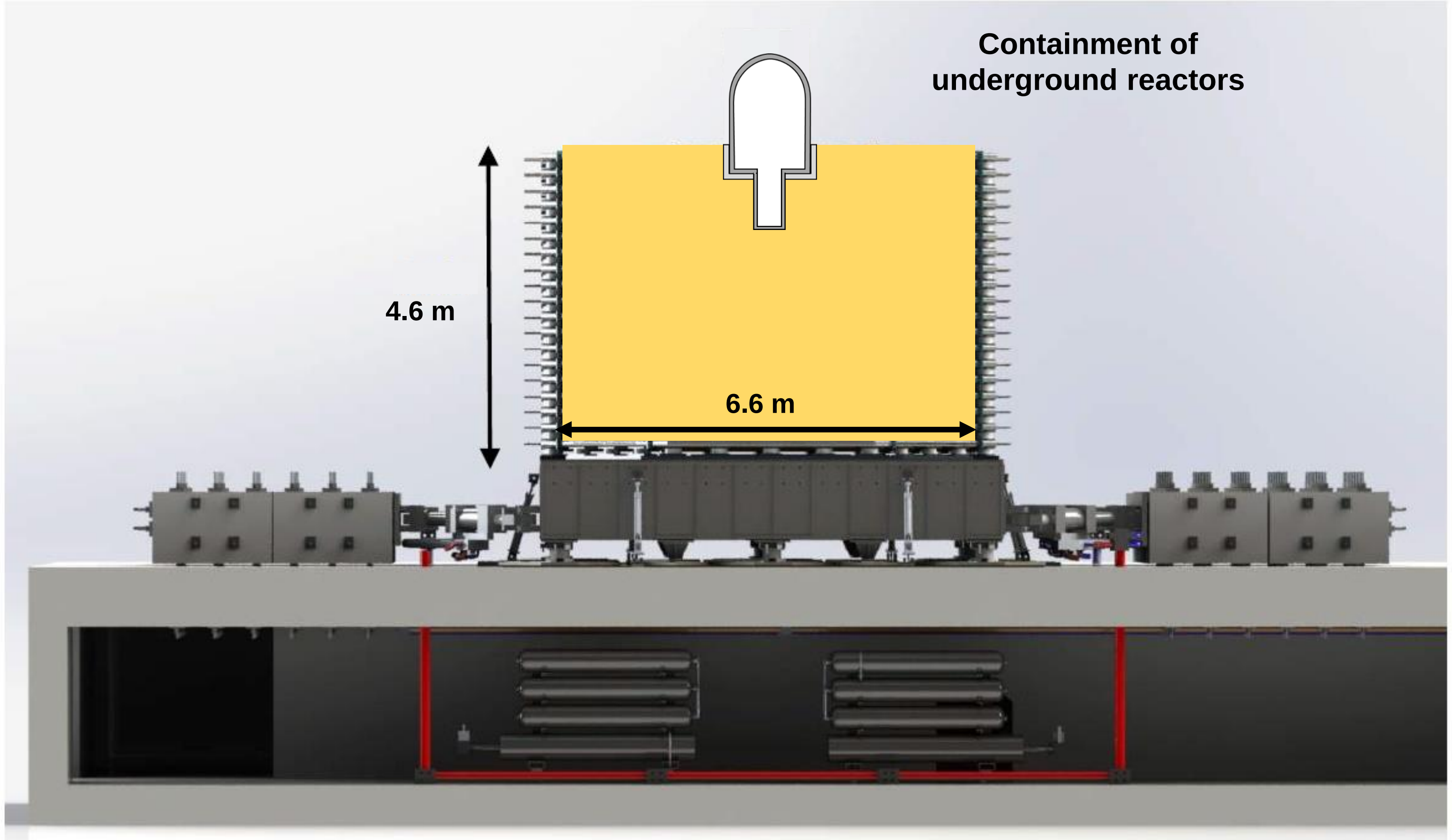

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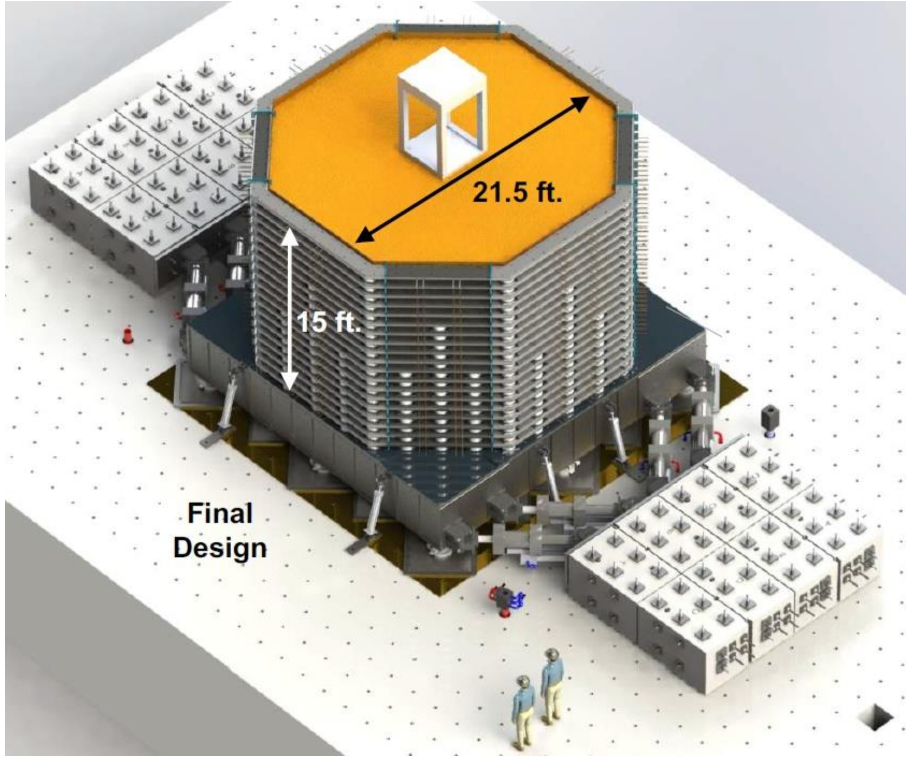

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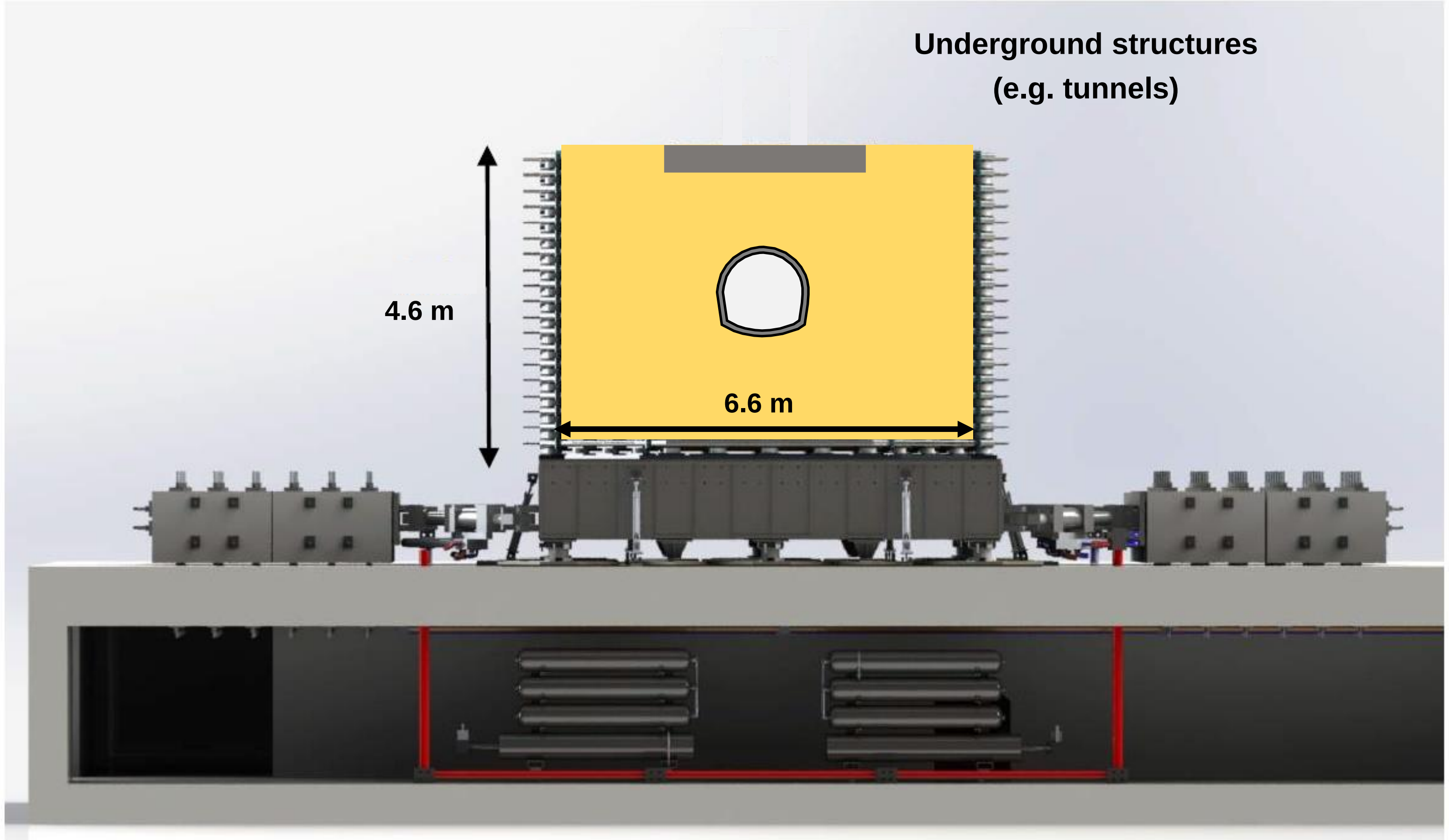

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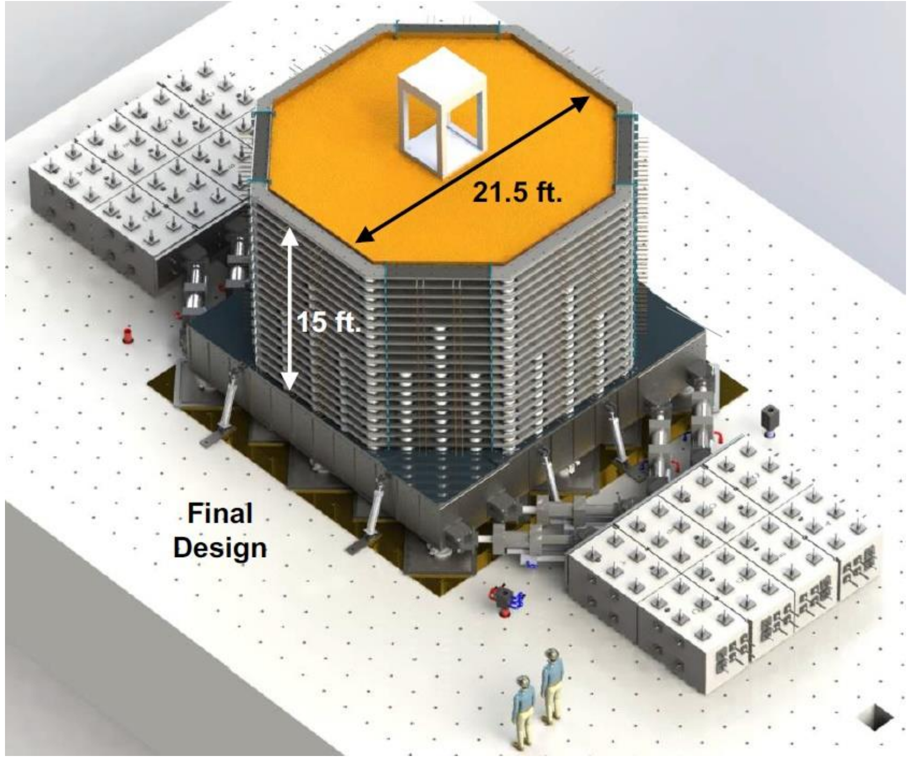

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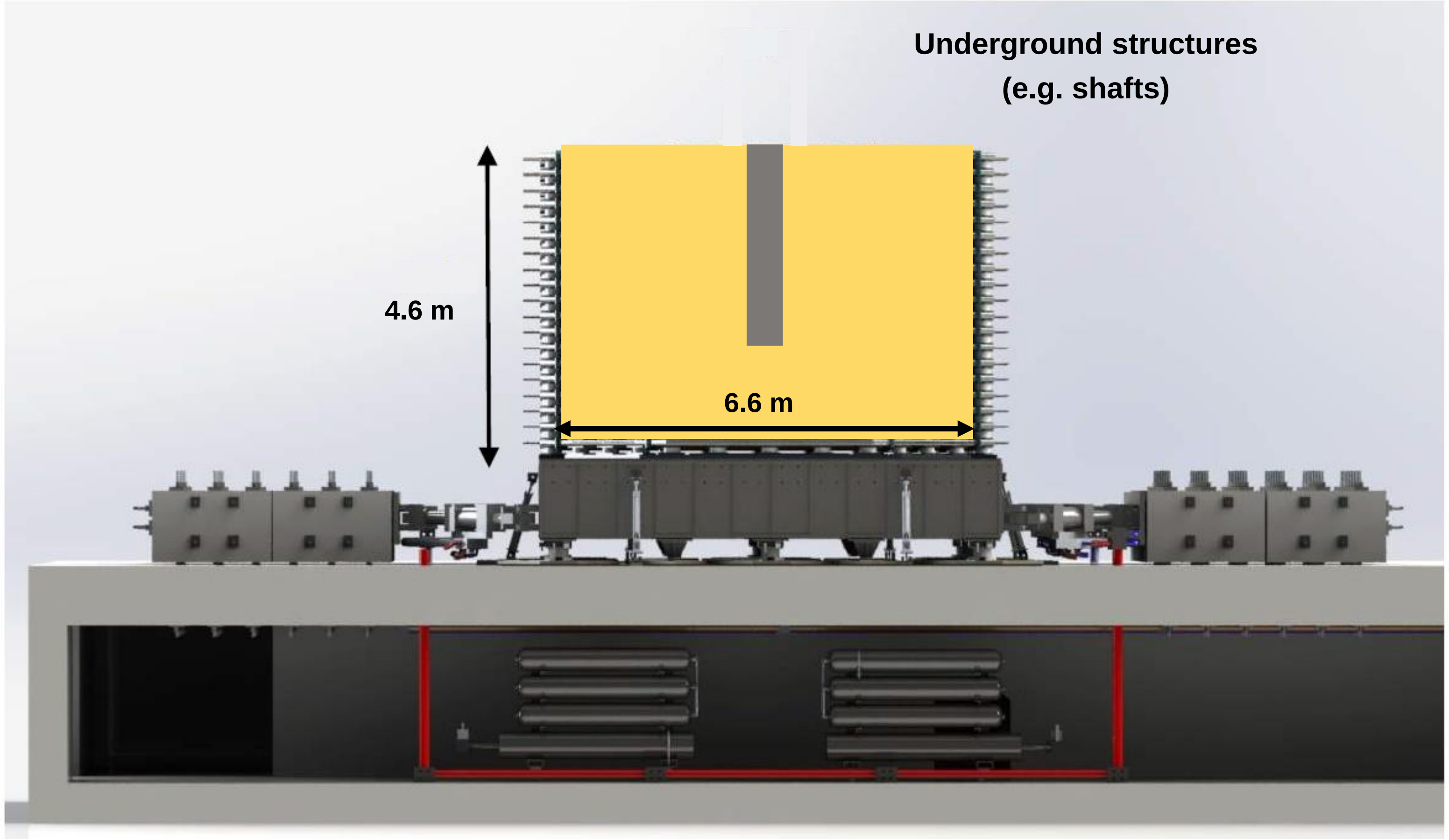

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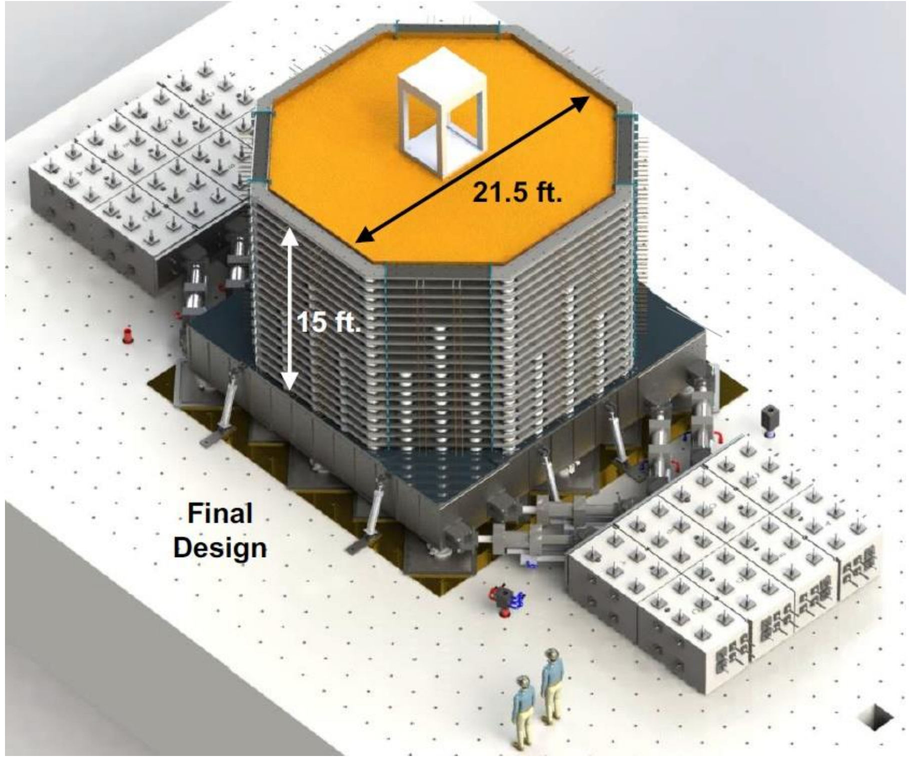

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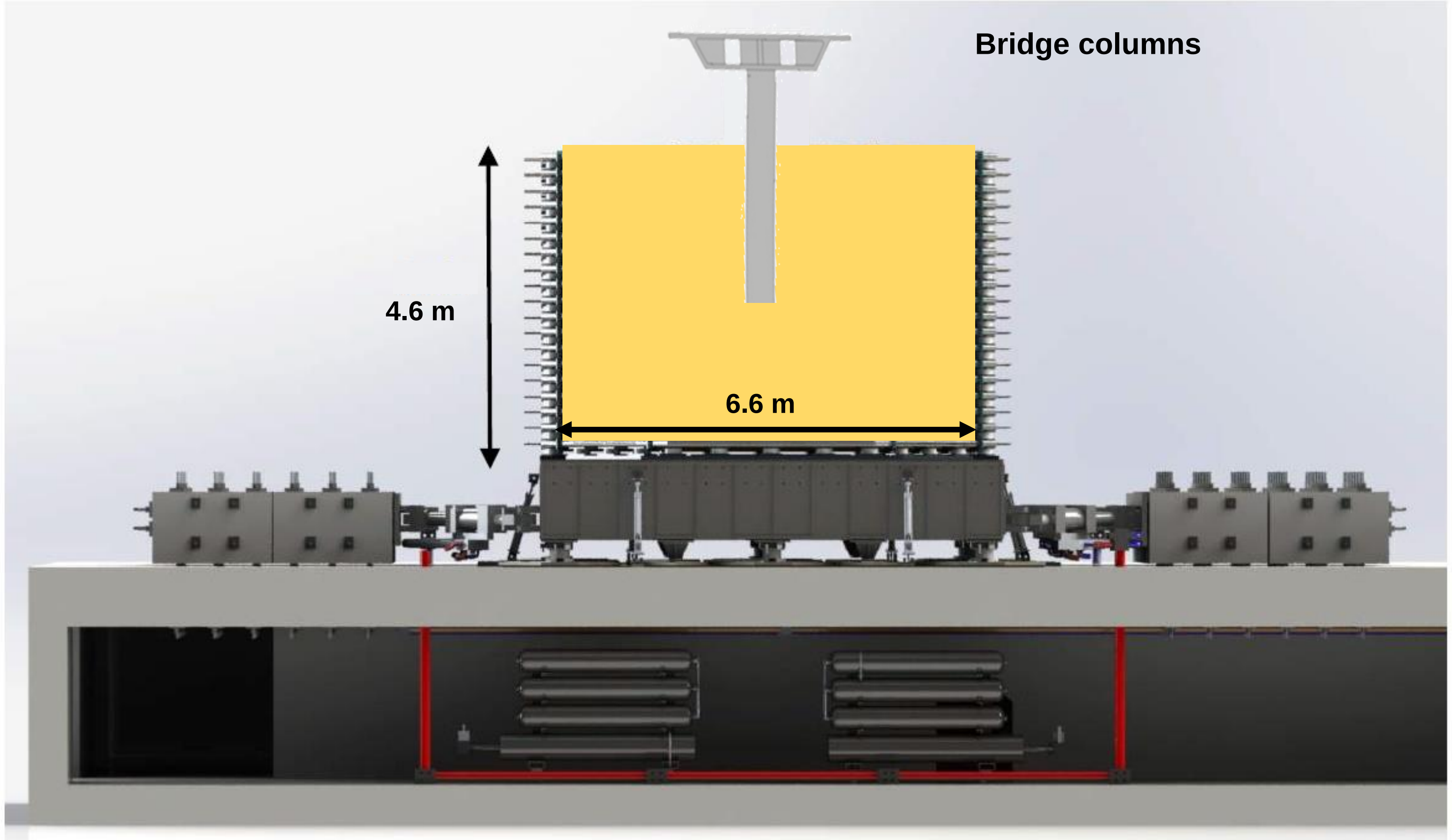

Is the gap between geotechnical and structural engineers detrimental to solve NLSSI problems?

"If our small minds, for some convenience, divide this glass of wine, this universe, into parts -- physics, biology, geology, astronomy, psychology, and so on -- remember that nature does not know it! So let us put it all back together, not forgetting ultimately what it is for. Let it give us one more final pleasure; drink it and forget it all!"

Prof. Richard P. Feynman

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