RECENT ADVANCES ON EARTHQUAKE ENGINEERING OF GEO-STRUCTURES AND CIVIL INFRASTRUCTURE

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Modernes Erdbebeningenieurwesen-Gegenwart & Zukunft 19.11.20

CONTENT

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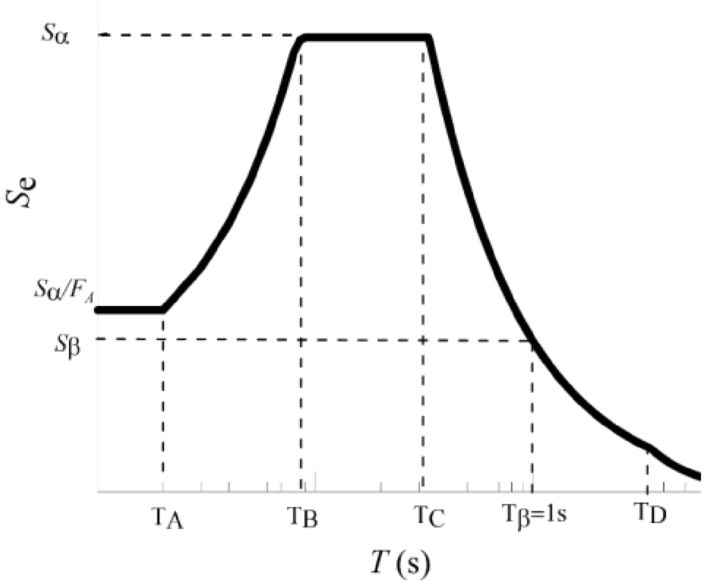
- Definition of design seismic action (soil classification)
- Seismic design concepts for foundations and geo-structures (rocking isolation, structures on faults, tunnels)
- ‘Novelties’ in prEN1998-5 (design of foundations and tunnels)
- Seismic vulnerability assessment of geo-structures (examples: tunnels, pipelines)
- Seismic resilience assessment of Transportation Infrastructure in a multi-hazard environment

SEISMIC ACTION

DESIGN SEISMIC ACTION IN EN 1998-1-1

- Definition of elastic response spectra for different soil classes
- Soil classification? Based on shear wave velocity of the ground, $v_{s,30}$



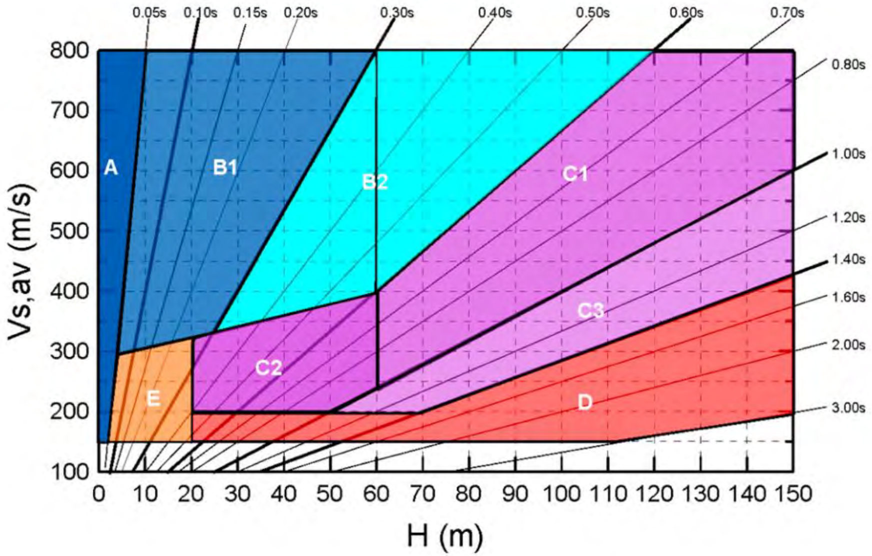
DESIGN SEISMIC ACTION – SOIL CLASSIFICATION?

- Soil classification based on shear wave velocity of the ground, $v_{s,m}$ and depth of the bedrock formation (i.e. V_s > 800 m/s)

	Ground class	stiff	medium	soft
Depth class	$v_{s,H}$ range / H_{800} range	800 m/s > $v_{s,H}$ ≥ 400 m/s	400 m/s > $v_{s,H}$ ≥ 250 m/s	250 m/s > $v_{s,H}$ ≥ 150 m/s
very shallow	H_{800} ≤ 5 m	A	A	E
shallow	5 m < H_{800} ≤ 30 m	B	E	E
intermediate	30 m < H_{800} ≤ 100 m	B	C	D
deep	H_{800} > 100 m	B	F	F

DESIGN SEISMIC ACTION – CLASSIFICATION OF SOIL?

- Soil classification based on shear wave velocity of the ground, $v_{s,m}$ and fundamental period of the soil deposit, $T_0 = 4\ H/V_s$

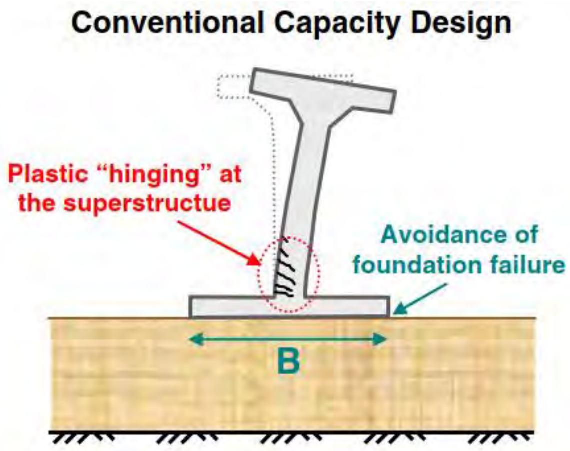


Pitilakis et al. (2018) Towards the revision of EC8: Proposal for an alternative site classification scheme and associated intensity dependent spectral amplification factors. *Soil Dyn. Earthq. Eng.*126, doi: 10.1016/j.soildyn.2018.03.030.

SEISMIC DESIGN CONCEPTS OF FOUNDATIONS AND GEO-STRUCTURES

ROCKING FOUNDATIONS

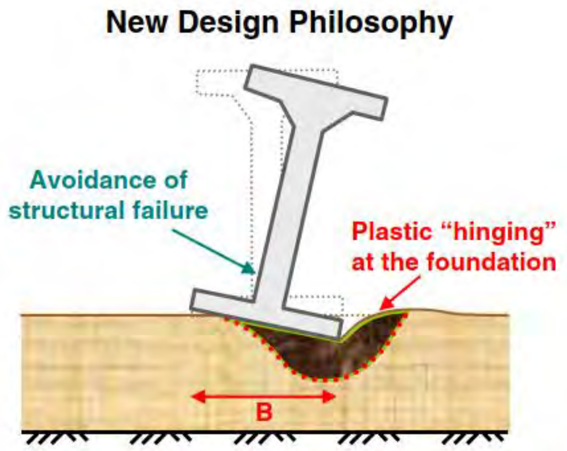
- Conceptual design: failure of the foundation soil should be avoided



Anastasopoulos et al. (2009) Soil failure can be used for seismic protection of structures. *Bull. Earthq. Eng.* doi:10.1007/s10518-009-9145-2.

ROCKING FOUNDATIONS

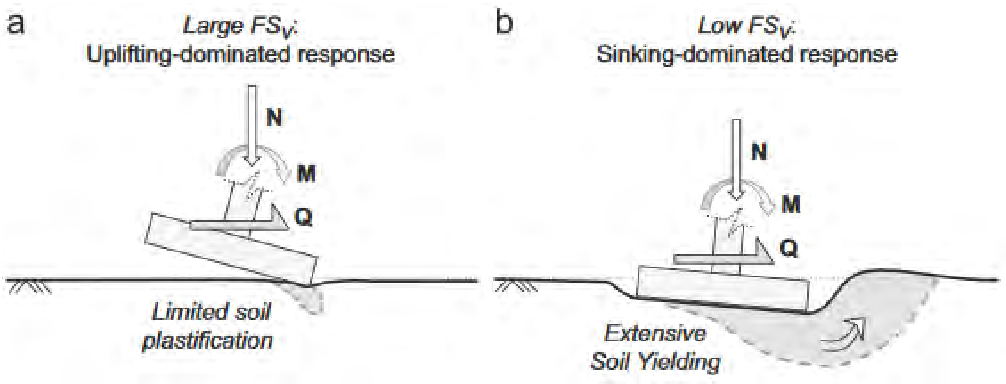
- A rocking response of a structure on the soil can act a 'fuse' leading to reduction of the seismic load acting on a structure
- New design concept: under-design foundations to allow for energy dissipation due to nonlinear phenomena at the soil-foundation interface or via soil plastification…



Anastasopoulos et al. (2009) Soil failure can be used for seismic protection of structures. *Bull. Earthq. Eng.* doi:10.1007/s10518-009-9145-2..

ROCKING FOUNDATIONS

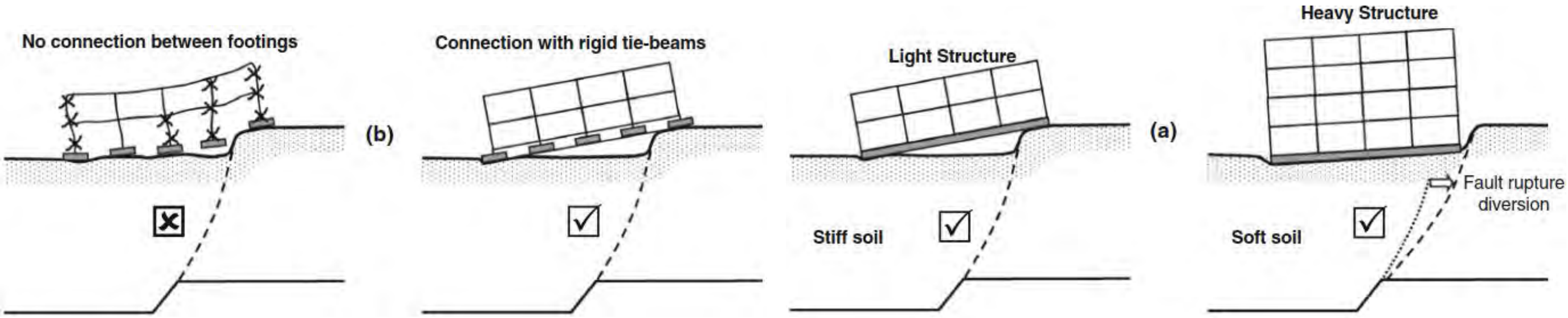
- Induced residual rotation and settlement caused by foundation rocking response should be compatible with the performance criteria of the superstructure at the relevant limit states



Anastasopoulos et al. (2012) Rocking response of SDOF systems on shallow improved sand: An experimental study. *Soil Dyn. Earthq. Eng.*, 40:15-33.

STRUCTURES LOCATED NEAR OR ON SEISMIC FAULTS

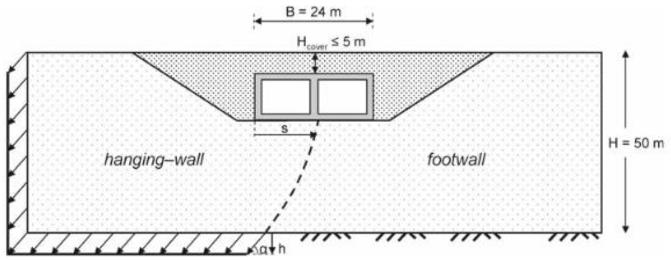
- Structures on potentially active seismic faults
- 'Rigid' foundations designed to accommodate potential fault displacements

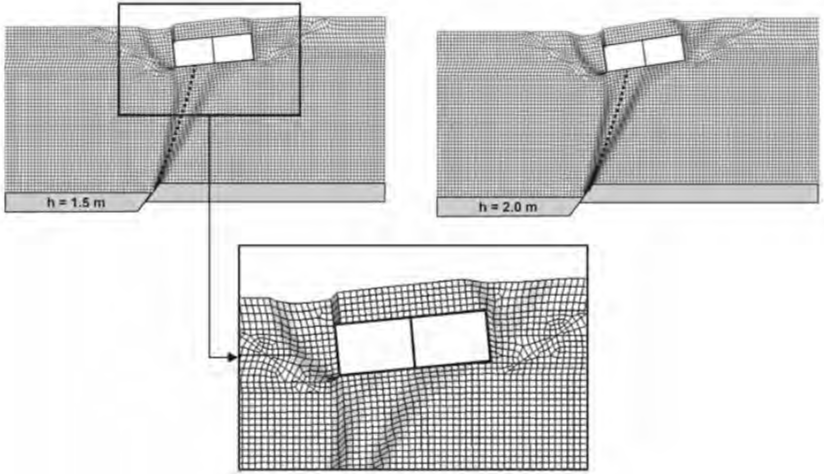


Gazetas et al. (2008) Preliminary design recommendations for dip-slip fault–foundation interaction. *Bull. Earthq. Eng.*, 6:677–687.

STRUCTURES LOCATED NEAR OR ON SEISMIC FAULTS

- Permanent ground deformations on tunnels and underground structures
- Numerical 2D or 3D approaches





Anastasopoulos & Gazetas (2010) Analysis of cut-and-cover tunnels against large tectonic deformation. *Bull. Earthq. Eng.*, 8:283–307.

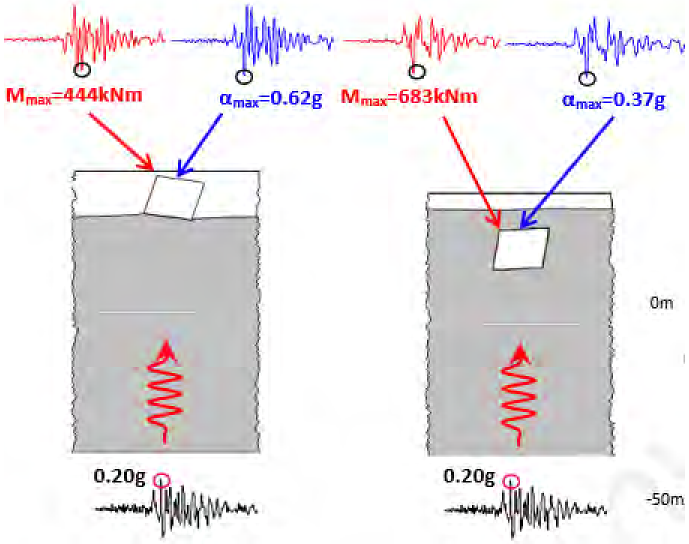
SEISMIC ANALYSIS OF TUNNELS AND UNDERGROUND STRUCTURES

- How important is to design underground structures against seismic hazard?
- Collapse of the Daikai subway station in Kobe during the major 1995 Hyogoken-Nambu earthquake
- Designed in 1962 with poor seismic design considerations

The Daikai subway station collapse. *Special Issue of Soil and Foundations*, 1996.

SEISMIC ANALYSIS OF TUNNELS AND UNDERGROUND STRUCTURES

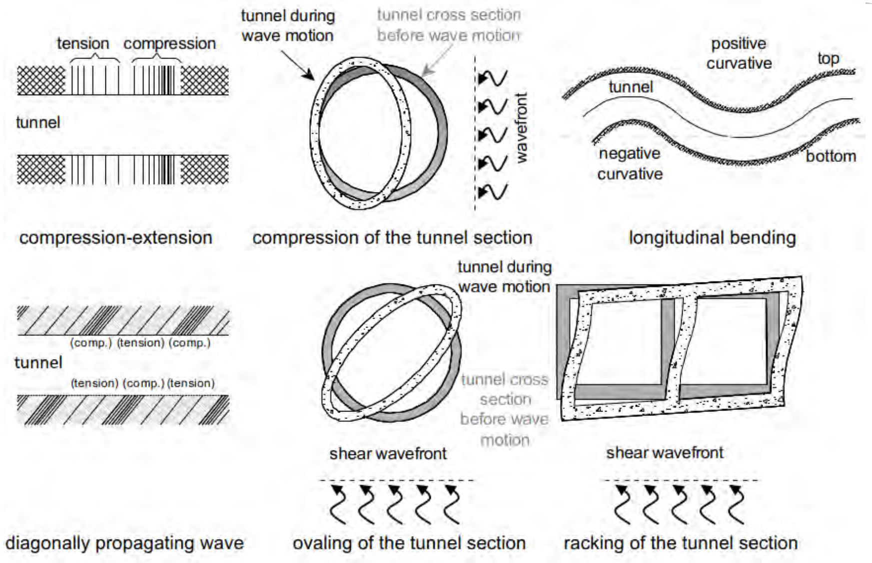
- Kinematic loading on embedded structures caused by seismic ground movement prevails over the inertial response of the structure itself



Pitilakis & Tsinidis (2014) Performance and seismic design of underground structures. In: Maugeri M, Soccodato C (Eds), Earthquake Geotechnical Engineering Design. *Geotech. Geological Earthq. Eng.*, 28, Springer, Switzerland, pp: 279-340.

SEISMIC ANALYSIS OF TUNNELS AND UNDERGROUND STRUCTURES

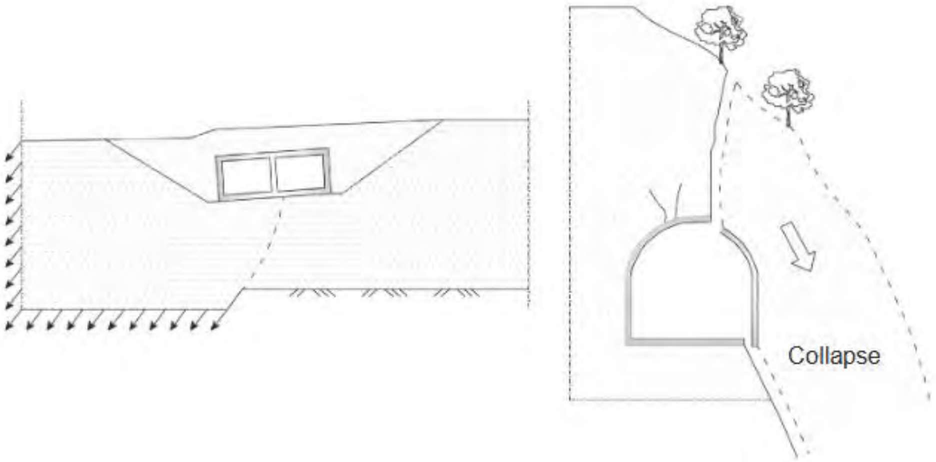
- Deformation patterns of underground structures due to ground shaking



Tsinidis et al. (2020) Seismic behaviour of tunnels: From experiments to analysis. *Tunn. Underg. Space Tech.*, 99:103334.

SEISMIC ANALYSIS OF TUNNELS AND UNDERGROUND STRUCTURES

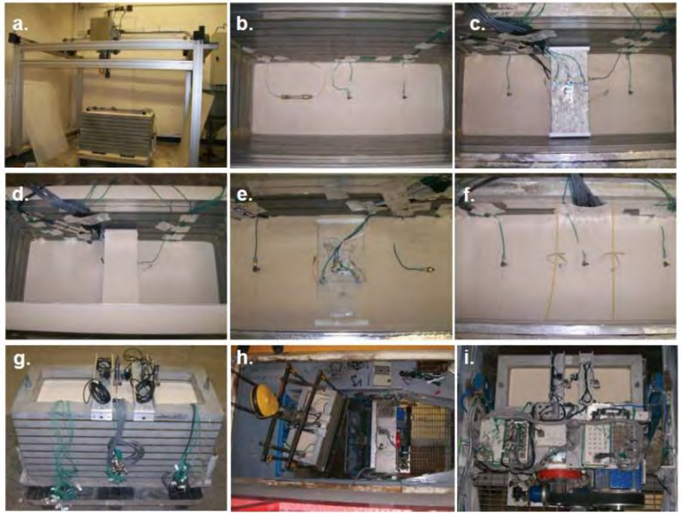
- Deformation patterns of underground structures due to permanent ground deformations

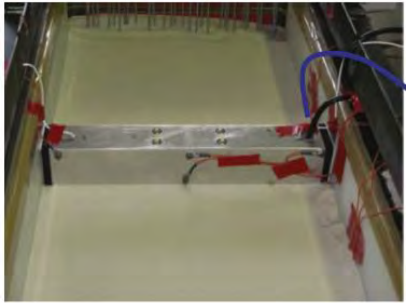


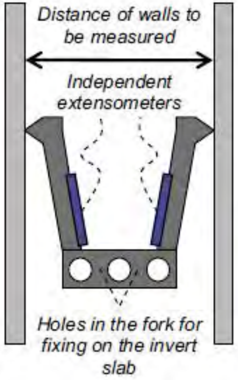
Tsinidis et al. (2020) Seismic behaviour of tunnels: From experiments to analysis. *Tunn. Underg. Space Tech.*, 99:103334.

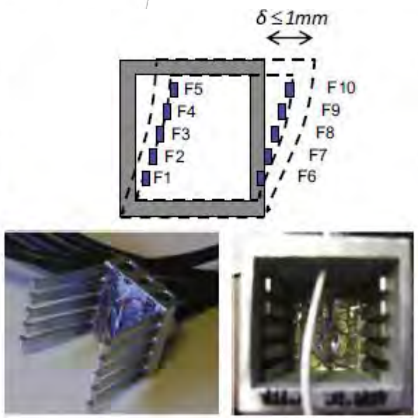
SEISMIC ANALYSIS OF TUNNELS AND UNDERGROUND STRUCTURES

- Experimental/numerical studies to examine the deformation patterns of tunnels and culverts









Tsinidis et al. (2016) Seismic response of box-type tunnels in soft soil: Experimental and numerical investigation. *Tunnel. Undergr. Space Tech.*, 59:199-214.
Tsinidis et al. (2015) Dynamic response of flexible square tunnels: Centrifuge testing and validation of existing design methodologies. *Géotechnique*, 65(5):401-417.

pr EN 1998-5:2019.2

EN1998-5: GEOTECHNICAL ASPECTS, FOUNDATIONS, RETAINING AND UNDERGROUND STRUCTURES

- **EN 1998-5: 2004**

1. General
2. Seismic action
3. Ground properties
4. Requirements for siting and for foundation soils
5. Foundation systems
6. Soil-structure interaction
7. Earth retaining structures

- **pr EN 1998-5: 2019.2**

1. Scope, references, terms & definitions
2. Basis of design
3. Seismic action
4. Ground properties
5. Requirements for siting and for foundation soils
6. Soil-structure interaction (extended chapter)
7. Foundation system
8. Earth retaining structures
9. Underground structures (new chapter)

prEN1998-5: FOUNDATIONS

- Surface and shallow embedded foundations
  - Verifications
    - Sliding
    - Bearing capacity
    - Rotational failure
    - Settlements

prEN1998-5: UNDERGROUND STRUCTURES

- Transient effects – transverse direction
- Closed form analytical solutions, considering or ignoring SSI effects, to compute seismic deformations and seismic internal forces of circular tunnels
- Simplified analyses methods considering or ignoring SSI effects to estimate seismic deformations and seismic internal forces of box-shaped structures
- Dynamic time-history analyses

prEN1998-5: UNDERGROUND STRUCTURES

- Transient effects – longitudinal direction
- Closed form analytical solutions and simplified analysis methods, considering or ignoring SSI effects
- Beam-on-Dynamic-Winkler foundation approach
- Dynamic time history analysis

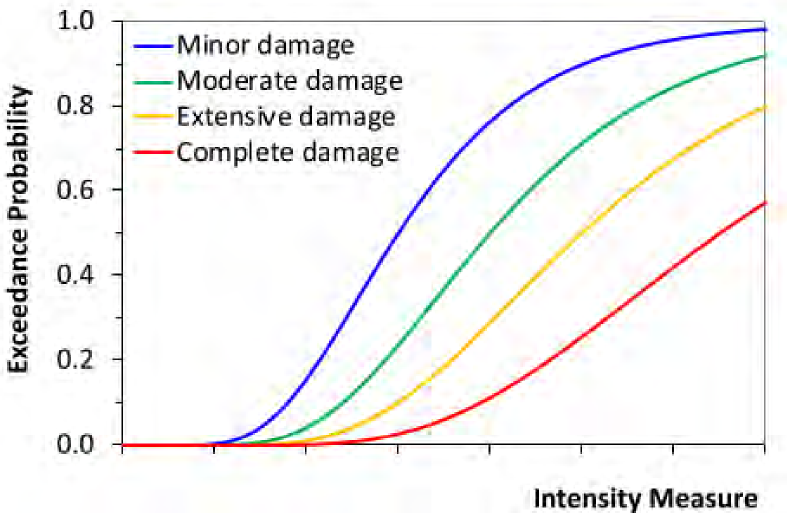
prEN1998-5: UNDERGROUND STRUCTURES

- Permanent ground deformations
- Evaluation of relevant hazards (e.g. seismically induced faulting, liquefaction, landslides) as per provisions of pr EN1998-5
- For high seismic action classes, numerical 2D or 3D approaches should be used

SEISMIC VULNERABILITY ASSESSMENT OF GEO-STRUCTURES

FRAGILITY FUNCTIONS

- Fragility functions give the probability that the asset exceeds some undesirable limit state, e.g. serviceability, for a given level of environmental excitation

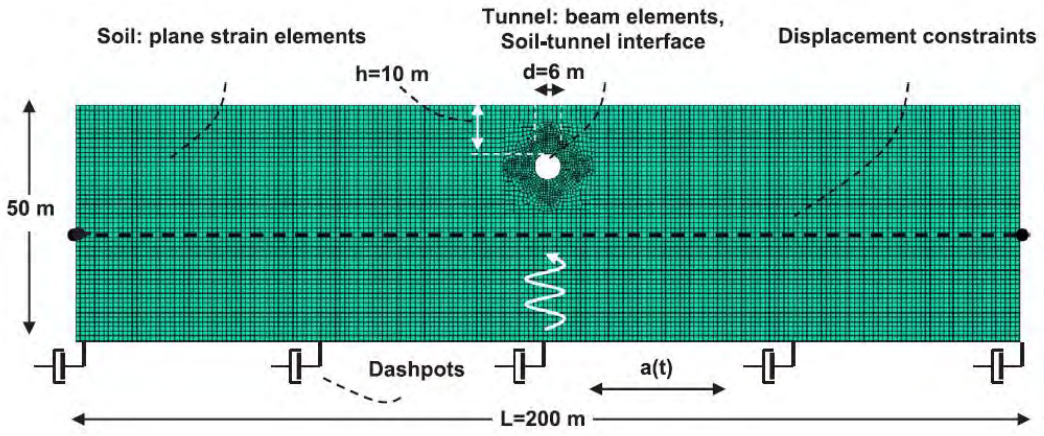


$$P[DS_d|IM] = \Phi\left[\frac{\ln(IM) - \ln(m_d)}{\zeta_d}\right]$$

Argyroudis et al. (2019) Fragility of transport assets exposed to multiple hazards: State-of-the-art review toward infrastructural resilience. *Reliability Eng.System Safety*, 191:106567.

FRAGILITY FUNCTIONS FOR TUNNELS

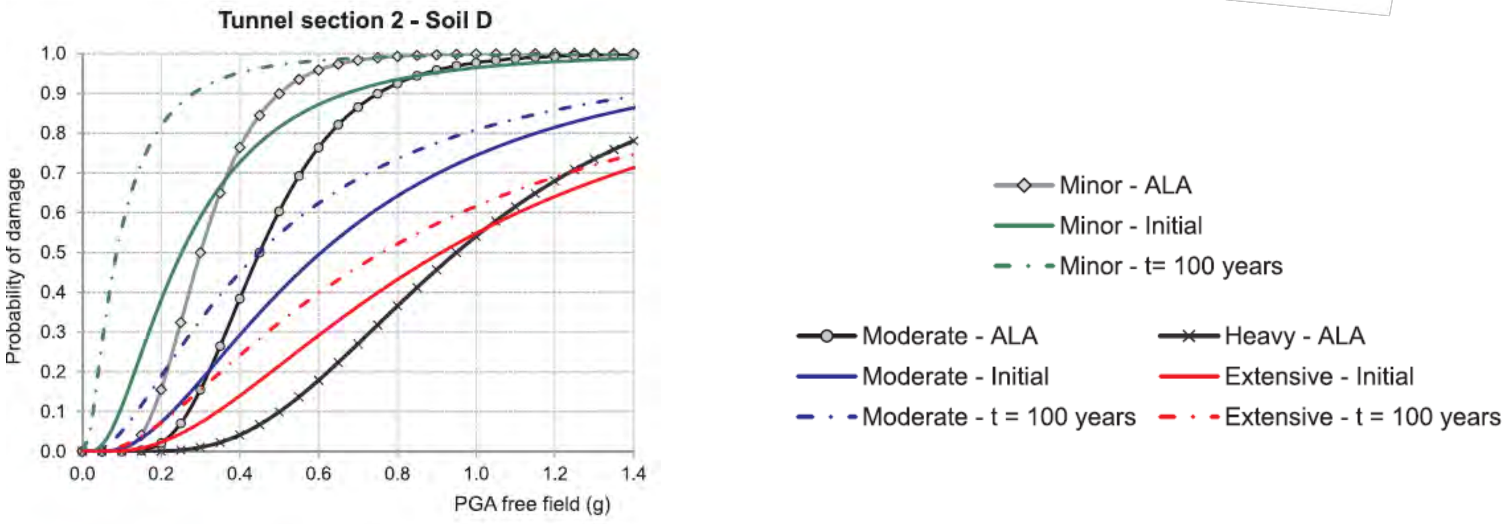
- Development of time-dependent seismic fragility functions for circular tunnels, accounting for the SSI and the ageing effects of the lining



Argyroudis et al. (2017) Effects of SSI and lining corrosion on the seismic vulnerability of shallow circular tunnels. *Soil Dyn. Earthq. Eng.*, 98: 244–256.

FRAGILITY FUNCTIONS FOR TUNNELS

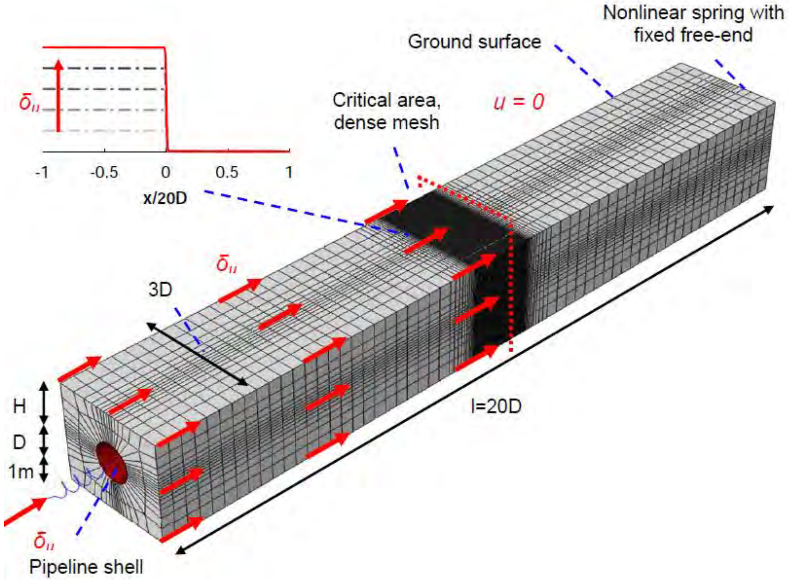
- Numerical vs. empirical fragility curves

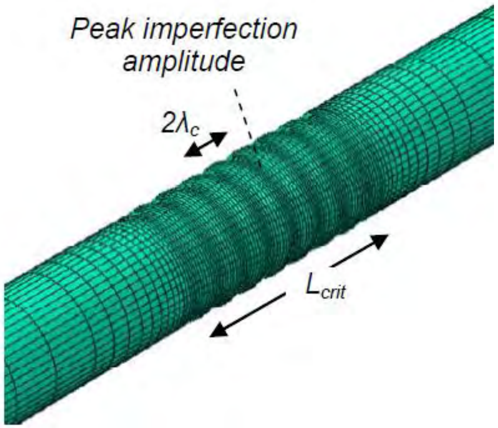


Argyroudis et al. (2017) Effects of SSI and lining corrosion on the seismic vulnerability of shallow circular tunnels. *Soil Dyn. Earthq. Eng.*, 98: 244–256.

FRAGILITY FUNCTIONS FOR PIPELINES

- Soil-pipe interaction analyses – pseudo-static simulation of seismic effects

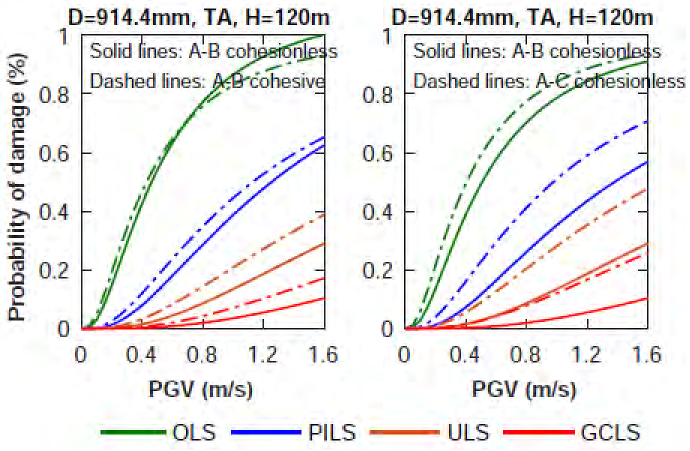




Tsinidis et al. (2020) Seismic fragility of buried steel natural gas pipelines due to axial compression at geotechnical discontinuities. *Bull. Earthq. Eng.*,18:837-906.

FRAGILITY FUNCTIONS FOR PIPELINES

- Fragility curves for NG steel pipelines

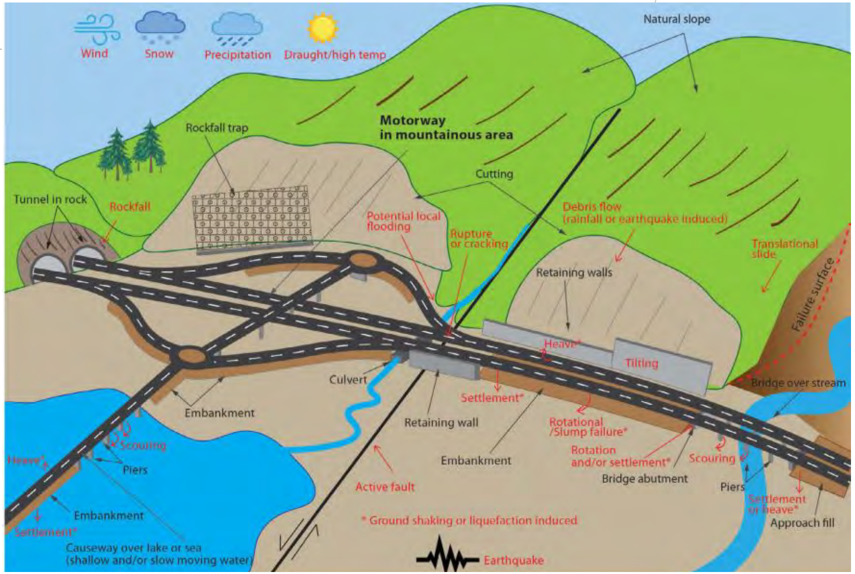


Tsinidis et al. (2020) Seismic fragility of buried steel natural gas pipelines due to axial compression at geotechnical discontinuities. *Bull. Earthq. Eng.*,18:837-906.

RESILIENCE ASSESSMENT OF TRANSPORTATION INFRASTRUCTURE

TRANSPORTATION INFRASTRUCTURE IN A MULTI-HAZARD ENVIRONMENT

- Road infrastructure
- Critical elements: Bridges, tunnels, embankments, retaining structures, culverts
- Hazards: earthquake ground shaking, active faults, rockfalls, soil erosion, extreme climate effects, fluvial/river flood due to extreme precipitation, pluvial/surface flood due to extreme precipitation



Argyroudis et al. (2019) Fragility of transport assets exposed to multiple hazards: SoA review toward infrastructural resilience. *Rel. Eng. System Safety*, 191:10656.

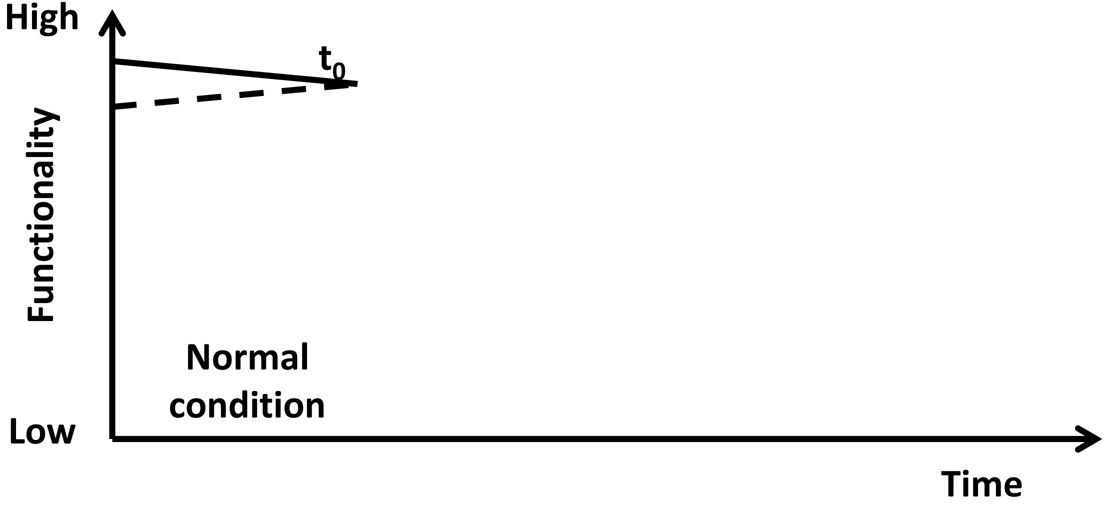
RESILIENCE - DEFINITION

- *Disaster resilience is defined as the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events*
- Enhanced resilience allows better anticipation of disasters and better planning to reduce disaster losses – rather than waiting for an event to occur and paying for it afterward
- To achieve such enhanced resilience, civil infrastructure systems must not only survive natural disasters, but recover to functional levels within acceptable time and cost limits

Cutter & Carolina (1996) Vulnerability to environmental hazards. *Progress in Human Geography*, 20(4), 529–539.

RESILIENCE - QUANTIFICATION

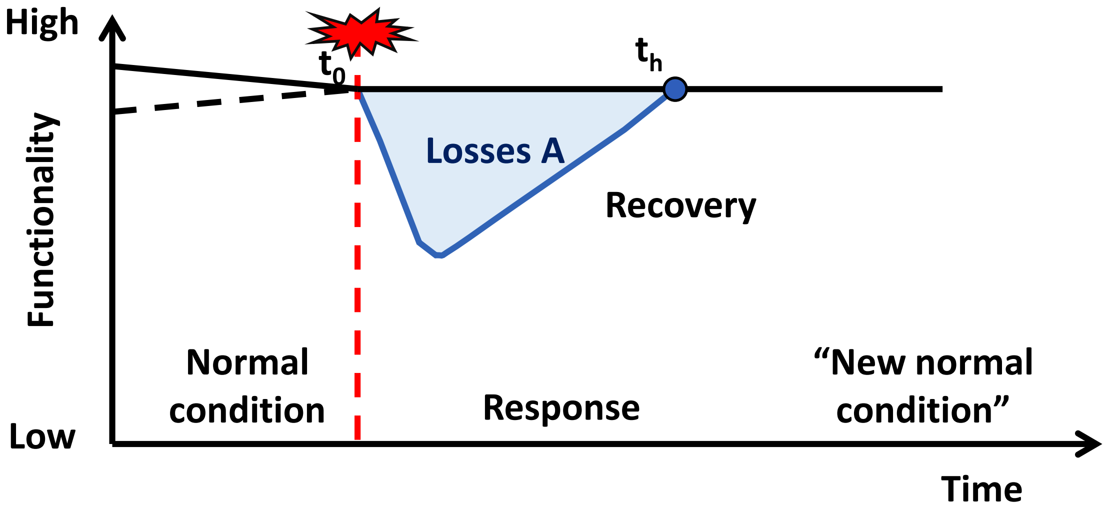
- Resilience may be quantified at element or regional (network) level via Resilience Index



Cimellaro et al. (2010) Framework for analytical quantification of disaster resilience. *Eng. Struct.*, 32:3639–3649.

RESILIENCE - QUANTIFICATION

- Resilience may be quantified at element or regional (network) level via Resilience Index



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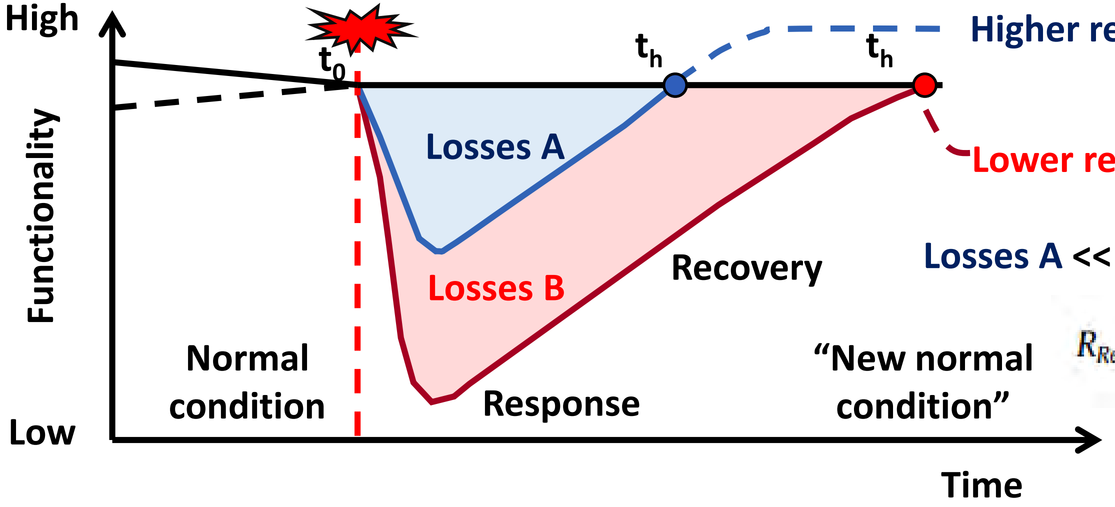
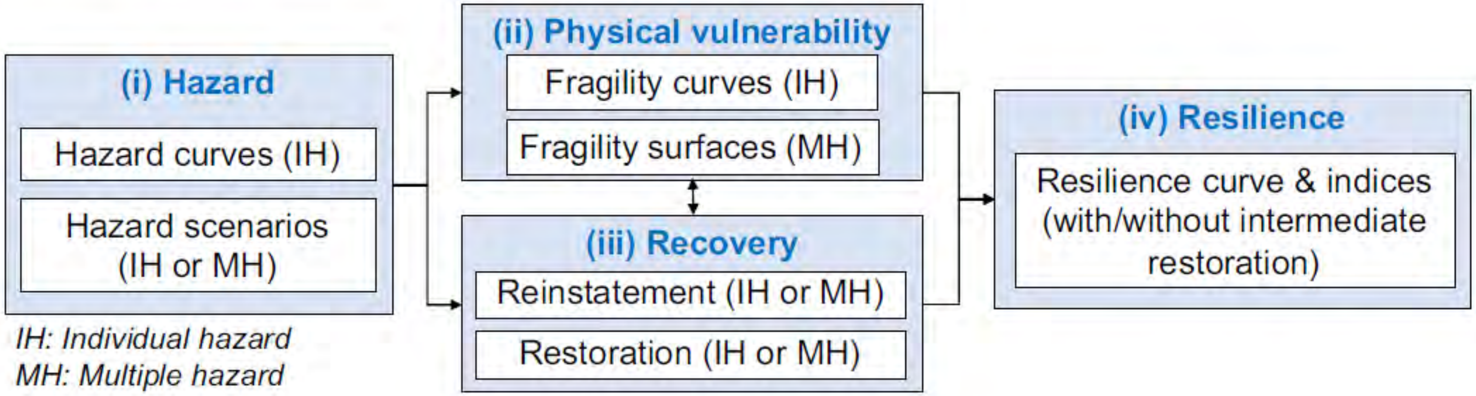


Losses A << Losses B

$$R_{Resi} = \frac{1}{t_h - t_0} \int_{t_0}^{t_h} Q(t)\,dt$$

Cimellaro et al. (2010) Framework for analytical quantification of disaster resilience. *Eng. Struct.*, 32:3639–3649.

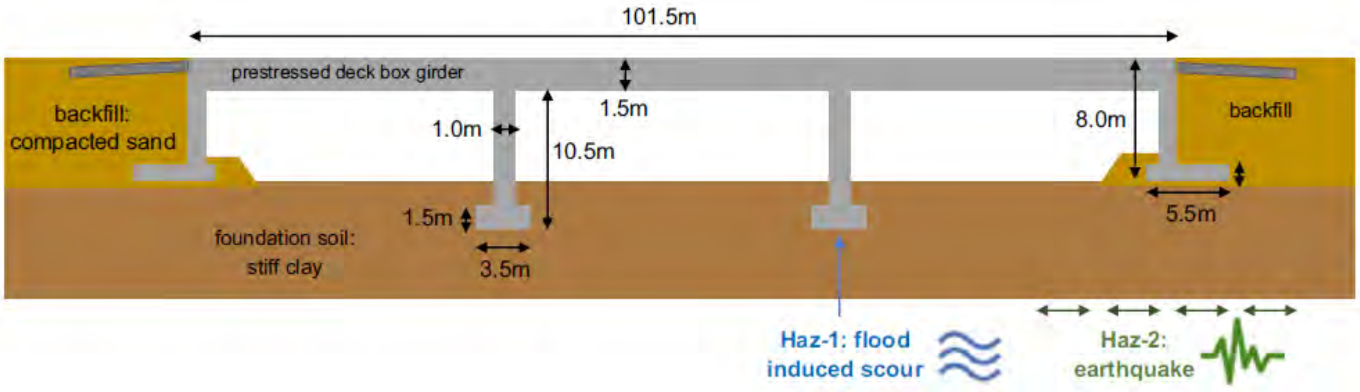
MULTI-HAZARD RESILIENCE ASSESSMENT FRAMEWORK (STEPS)



Argyroudis et al. (2020) Resilience assessment framework for critical infrastructure in a multi-hazard environment: Case study on transport assets. *Sci.Total Env.*, 714:136854

RESILIENCE ASSESSMENT – EXAMPLE

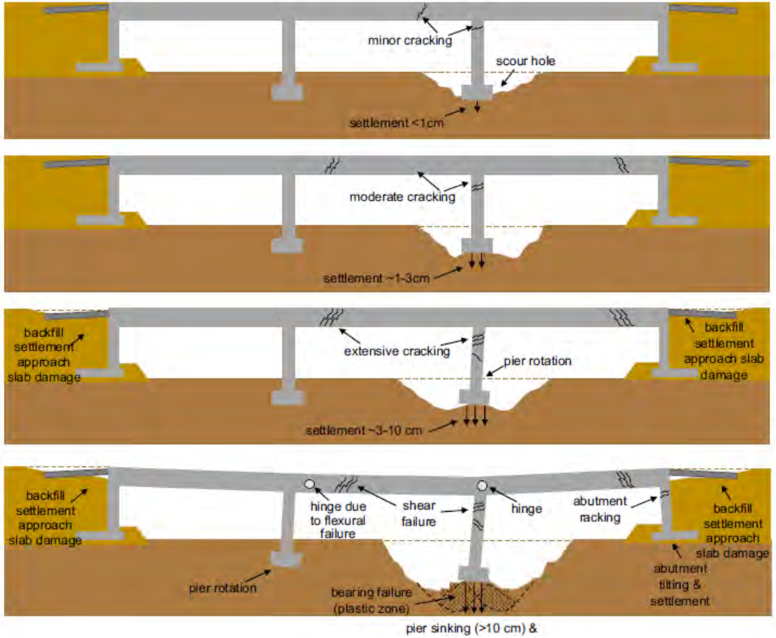
- Integral bridge subjected to a sequence of scouring and earthquake hazards



Argyroudis et al. (2020) Resilience assessment framework for critical infrastructure in a multi-hazard environment: Case study on transport assets. *Sci.Total Env.*, 714:136854

RESILIENCE ASSESSMENT – EXAMPLE

- Damage states and restoration tasks for local scour effects on bridge



Minor damage

Restoration tasks:

STR: repair cracks and spalling with epoxy and/or concrete

GEO: rip-rap and/or gabions for filling of scour hole and scour protection

Moderate damage

Restoration tasks:

STR: repair cracks and spalling with epoxy and/or concrete

GEO: rip-rap and/or gabions for filling of scour hole and scour protection

Extensive damage

Restoration tasks:

STR: repair cracks and spalling with epoxy and/or concrete; realignment of pier; jacketing

GEO: erosion protection measures; rip-rap and/or gabions for filling of scour hole and scour protection; installation of deep foundation system

Complete damage

Restoration tasks:

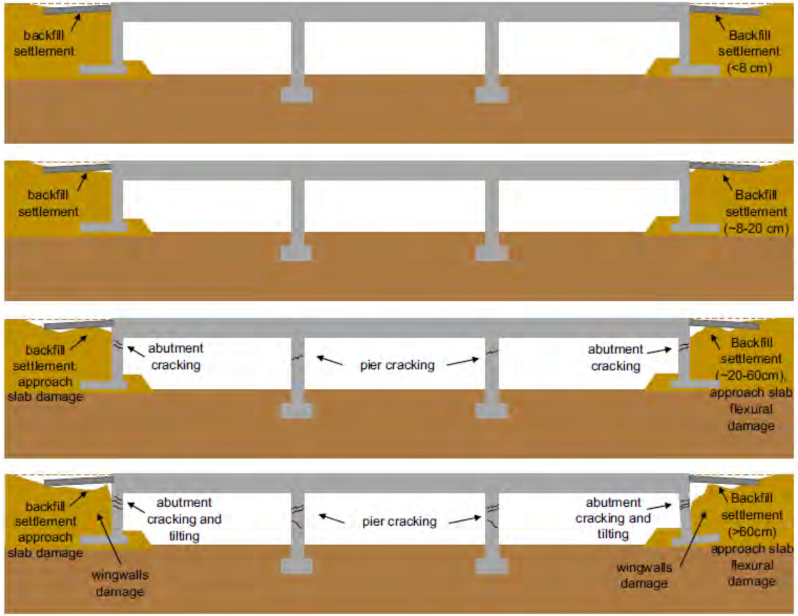
STR: demolition of existing, reconstruction of new bridge,

GEO: scour and erosion protection measures

Argyroudis et al. (2020) Resilience assessment framework for critical infrastructure in a multi-hazard environment: Case study on transport assets. *Sci.Total Env.*, 714:136854

RESILIENCE ASSESSMENT – EXAMPLE

- Damage states and restoration tasks for seismic effects on bridge



Minor damage
Restoration tasks: GEO: filling of the backfill gap; repair of road pavement

Moderate damage
Restoration tasks: GEO: filling of the backfill gap; repair of road pavement and approach slab

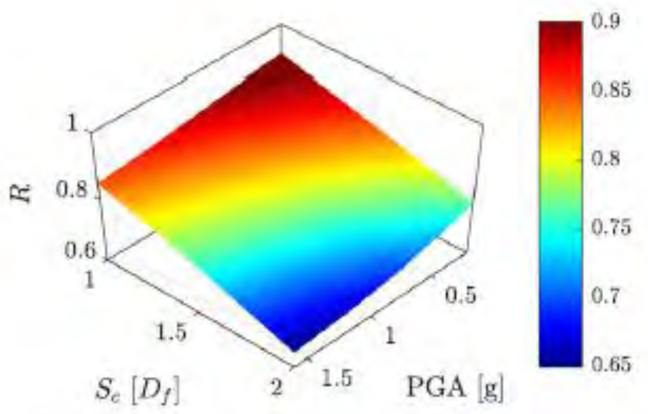
Extensive damage
Restoration tasks: STR: repair of cracks and spalling with epoxy and/or concrete GEO: filling of the backfill gap, repair of road pavement and approach slab

Complete damage
Restoration tasks: STR: repair of cracks and spalling with epoxy and/or concrete, realignment of the abutment GEO: filling of the backfill gap, repair of pavement, approach slab, wingwalls,

Argyroudis et al. (2020) Resilience assessment framework for critical infrastructure in a multi-hazard environment: Case study on transport assets. *Sci.Total Env.*, 714:136854

RESILIENCE ASSESSMENT – EXAMPLE

- Behaviour of the **resilience index** as function of scour depth (Sc) and shaking level (PGA)



Argyroudis et al. (2020) Resilience assessment framework for critical infrastructure in a multi-hazard environment: Case study on transport assets. *Sci.Total Env.*, 714:136854

SUMMARY - CONCLUSIONS

SUMMARY

- Recent advances on the following topics were briefly presented
  - Design seismic action
  - Seismic design concepts for foundations and geo-structures (rocking isolation, structures on faults, tunnels)
  - ‘Novelties’ in prEN1998-5 (design of foundations, tunnels)
  - Vulnerability assessment of geo-structures (tunnels, pipelines)
  - Seismic resilience assessment of Systems of Assets of Transportation Infrastructure in a multi-hazard environment

THANK YOU FOR YOUR ATTENTION!