RELIABILITY ANALYSIS OF REINFORCED CONCRETE STRUCTURES: ACCOMPLISHMENTS AND ASPIRATIONS

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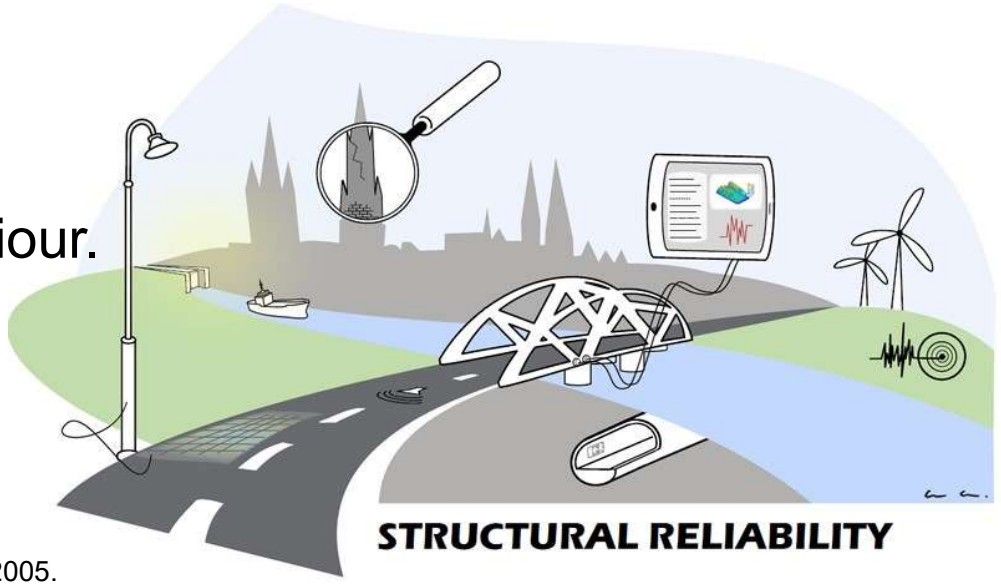
TNO workshop: Computational Challenges in the Reliability Assessment of Engineering Structures
2018, Delft

MOTIVATION

- Built infrastructure: >50% of national wealth[1].
- Ageing infrastructure[2].
- Uncertainty of parameters, models[2].

- Aim:
  - Better understanding of structural behaviour.
  - Uncertainty reduction.
  - More economical asset management.

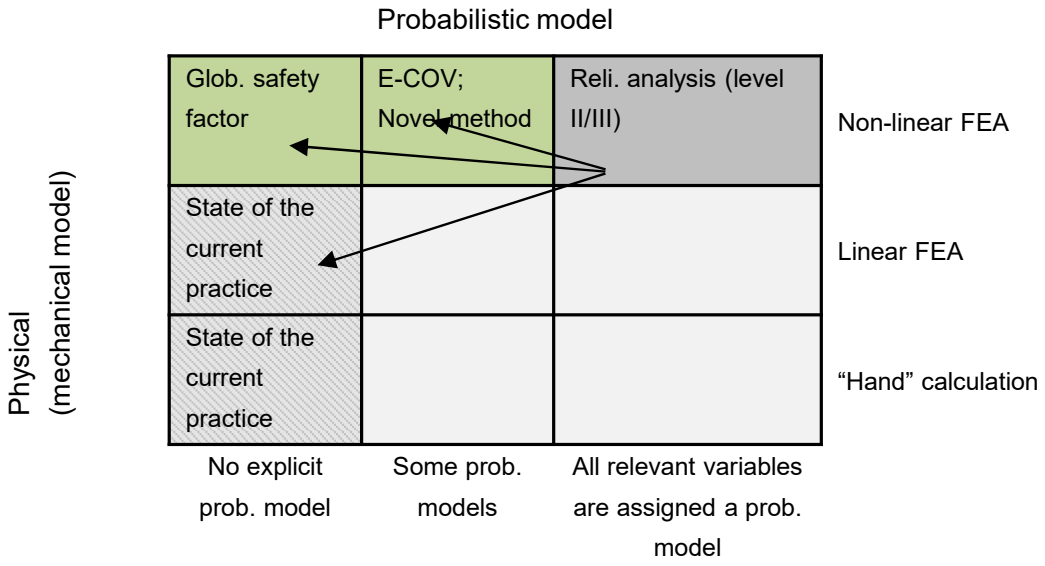


[1] Sarja A. (2005). *Integrated Life Cycle Design of Structures*. e-Library: Taylor & Francis, 2005.

[2] Frangopol, D. M. (2011). Life-cycle performance, management, and optimisation of structural systems under uncertainty: accomplishments and challenges. *Structure and Infrastructure Engineering*, 7(6), 389-413.

PROBLEM STATEMENT

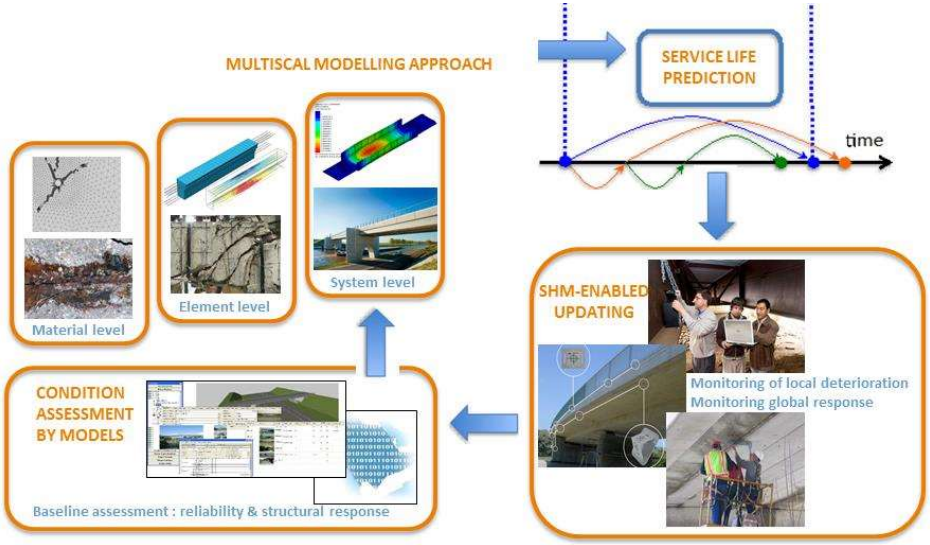
- Current practice and methods:
  - Almost exclusively for new structures.
  - How to deal with deterioration?
  - What to do with non-complying structures? (reserves?)
  - How to use NLFEA for verification?



- Reliability assessment can help, but:
  - NLFEA based limit state functions are **computationally expensive**.
  - Model uncertainty?
  - Random fields?
  - How to translate to methods usable in practice?

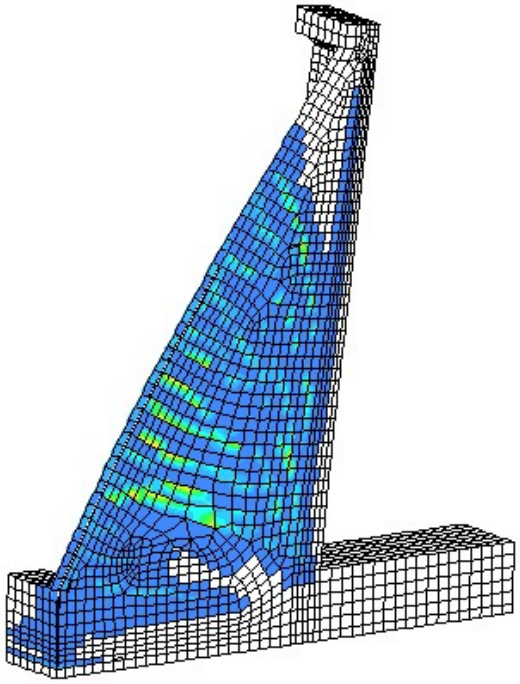
RELATED TNO PROJECTS

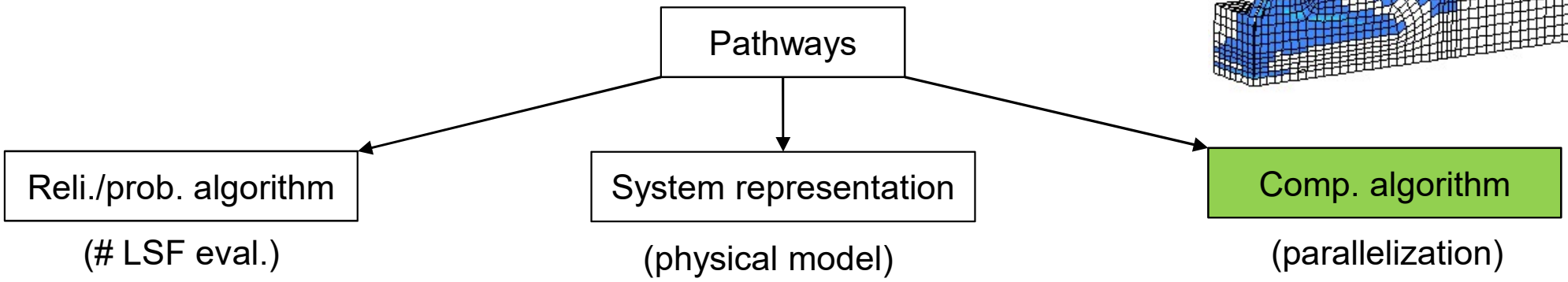
- Reinforced concrete bridges (deterioration).
- Hydraulic structures (soil-structure interaction + deterioration).
  - Advanced NLFEA
  - Probabilistic assessment:
    - Reliability assessment.
    - Structural health monitoring.
    - Probabilistic damage identification.
  - Probabilistic modelling of corrosion.



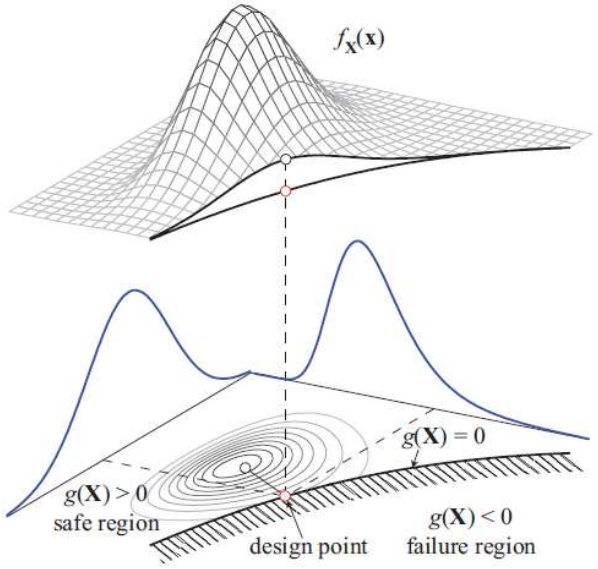
COMMON UNDERLYING CHALLENGES

- Computational challenge: attain reasonable running times.
  - Multiple failure modes
  - Random fields
  - Probabilistic updating for existing structures.
  - Code calibration (optimization).





TOOLS – RELIABILITY ANALYSIS



- In-house:
  - Prob2B (+ Python + Openturns)
  - FERUM (Matlab) – extended:
    - Adaptive direction sampling[1]:
      - multiple of response surface types (polynomial, kriging, goodness-of-fit)
  - Coupling with FEM, e.g. Diana, OpenSees.

[1] Grooteman, F. (2011). An adaptive directional importance sampling method for structural reliability. *Probabilistic Engineering Mechanics*, 26(2), 134-141.

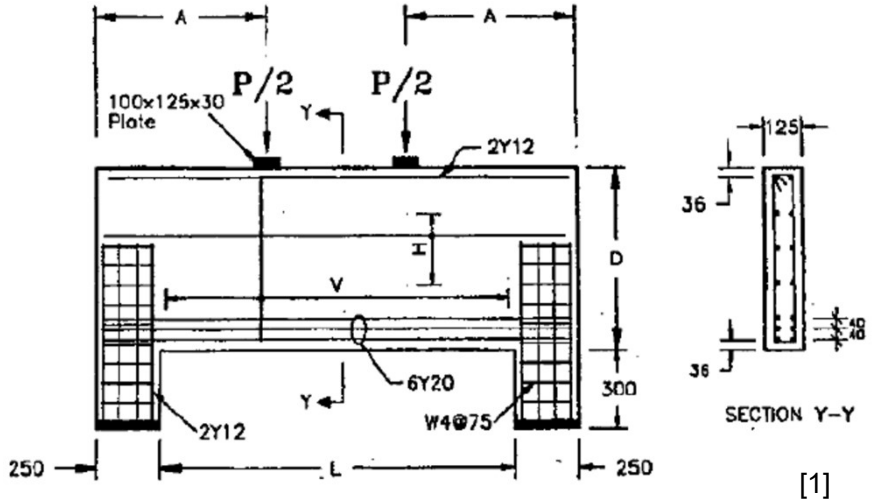
RC STRUCTURES

DEEP BEAM

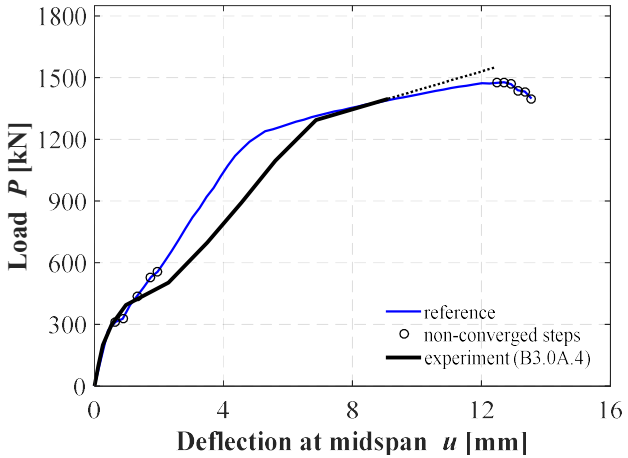
- High-strength RC deep beam.
- Bending failure & diagonal crack at support
- NLFEA in Diana
  - Plane stress elements.
  - Concrete: cracking, crushing.
  - Rebar: hardening and rupture (perfect bond).

- Limit state function (three random variables):

$$g = R(f_{cc}, f_{sy}) - S$$



[1]

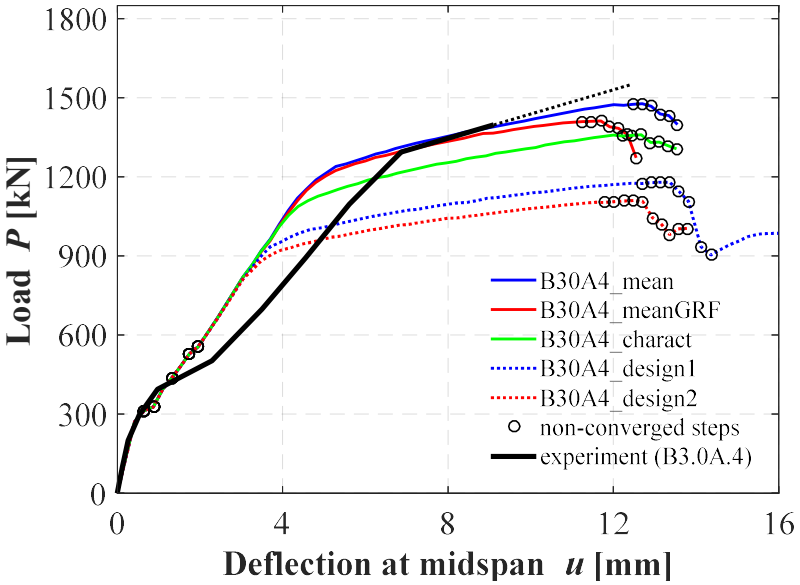


[1] Foster, S.J., Gilbert, R.I. (1998) Experimental Studies on High-Strength Concrete Deep Beams. ACI Structural Journal. 95(4). 382-390.

RC STRUCTURES

DEEP BEAM

Variable	*Distribution*	*Mean*	*Coefficient of variation*
Concrete compressive strength (f_{cc})	Lognormal	88 MPa	0.06
Rebar yield strength (f_{sy})	Lognormal	440 MPa	0.045
External load (S)	Gumbel	600 KN	0.20



Method	*# LSF evaluations*	*Running time*	*β*	*α_i*	*R* [kN]*
DARS[1]	66	2.5 hours*	3.87	{0.05, 0.15, -0.99}	1446

*Diana 10.1 and a Kepler computer was used for the analysis: 16GB Intel(R) Xeon(R) CPU E5-2620 v3 @2.40GHz; 2.40GHz; Windows 10 Enterprise 64-bit SP1.

RC STRUCTURES

DEEP BEAM

- Added value of more advanced modelling:

Probabilistic model

Physical (mechanical model)	Glob. safety factor	E-COV; Novel method	Reli. analysis (level II/III)	
	State of the current practice			Non-linear FEA
	State of the current practice			Linear FEA
	State of the current practice			"Hand" calculation
	No explicit prob. model	Some prob. models	All relevant variables are assigned a prob. model	

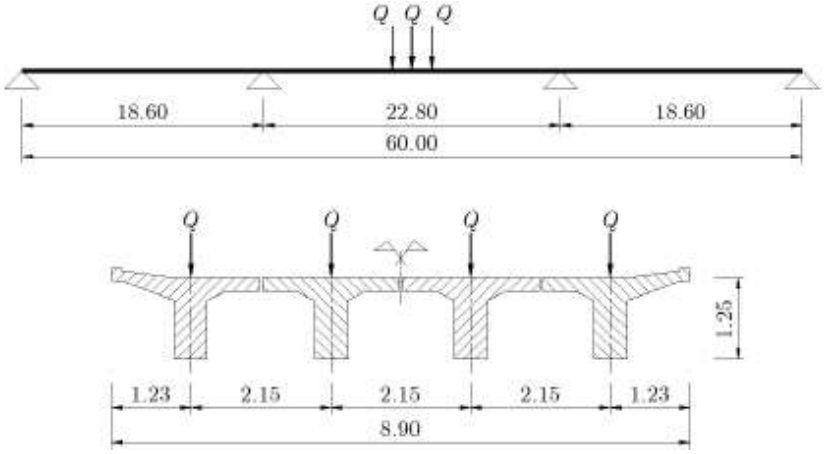
	analytical modelling	*nonlinear finite element modelling*			
		semi-probabilistic methods			*full-probabilistic method*
	EC	*PF*	*GRF*	*E-COV*	*DARS*
R_d [kN]	771	1110	1110	1196	-
S_d [kN]	1367	1367	1367	1367	equivalent prob. model
S_d / R_d [-]	1.77	1.23	1.23	1.14	-
β [-]	-	-	-	-	3.87
β/β_t [-]	-	-	-	-	1.02

RC STRUCTURES
CONTINUOUS BEAM

- Three-span beam.
- Bending failure (mechanism).
- NLFEA in Diana:
  - Beam-column elements.
  - Concrete: cracking, crushing.
  - Rebar: hardening and rupture (perfect bond).

- Limit state function (five random variables):

$$g = R(f_{cc}, f_{sy}, f_{su}, \varepsilon_{su}) - Q$$



[1]

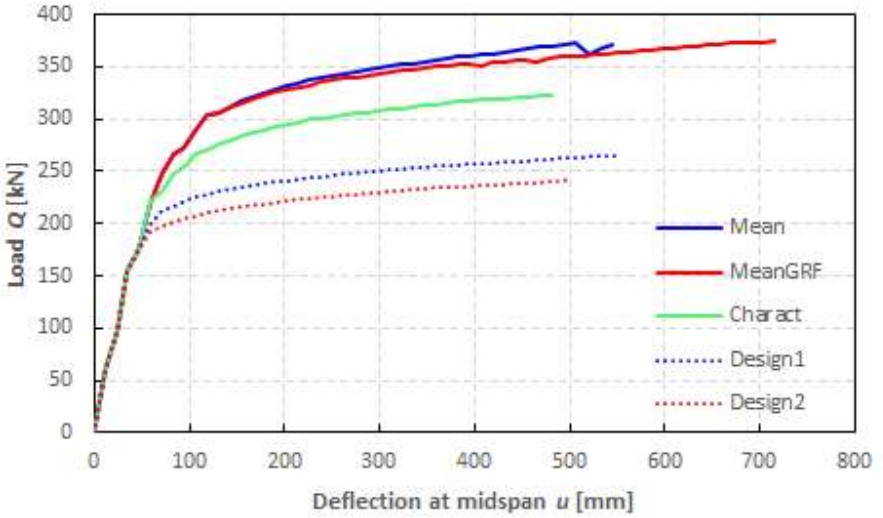
[1] Jacinto, L., Neves, L.A.C., Santos, L. (2015). Bayesian assessment of an existing bridge: a case study. *Structure and Infrastructure Engineering*, 12(1), 1-17.

RC STRUCTURES
CONTINUOUS BEAM

Variable	*Distribution*	*Mean*	*Coefficient of variation*
Concrete compressive strength (f_{cc})	Lognormal	51.2 MPa	0.07
Rebar yield strength (f_{sy})	Lognormal	440 MPa	0.065
Rebar ultimate strength (f_{su})	Lognormal	550 MPa	0.07
Rebar ultimate strain (ε_{su})	Lognormal	0.08	0.09
External load (Q)	Gumbel	$1.5 \cdot 10^2$ kN	0.20

Method	*# of iteration/ simulation steps*	*# of limit state function evaluations*	*Reliability index, β*	*Total comp. time [hr]* †
DARS	-	113	3.80	12

† Diana 10.1 and a Kepler computer was used for the analysis: 16GB Intel(R) Xeon(R) CPU E5-2620 v3 @2.40GHz; 2.40GHz; Windows 10 Enterprise 64-bit SP1.



RC STRUCTURES
CONTINUOUS BEAM

- Added value of more advanced modelling:

	analytical modelling	*nonlinear finite element modelling*			
		semi-probabilistic methods			*full-probabilistic method*
	EC	*PF*	*GRF*	*E-COV*	*DARS*
R_d [kN]	293 (or 211)	242	295	271	-
S_d [kN]	342	342	342	342	equivalent prob. model
S_d / R_d [-]	1.62	1.41	1.16	1.26	-
β [-]	-	-	-	-	3.80
β/β_t [-]	-	-	-	-	1.00

RC STRUCTURES
CONTINUOUS BEAM

- Extension (ongoing):
  - Random field representation of corrosion.
  - Pitting corrosion of rebars.
  - NLFEA also in OpenSees to reduce the calculation time.

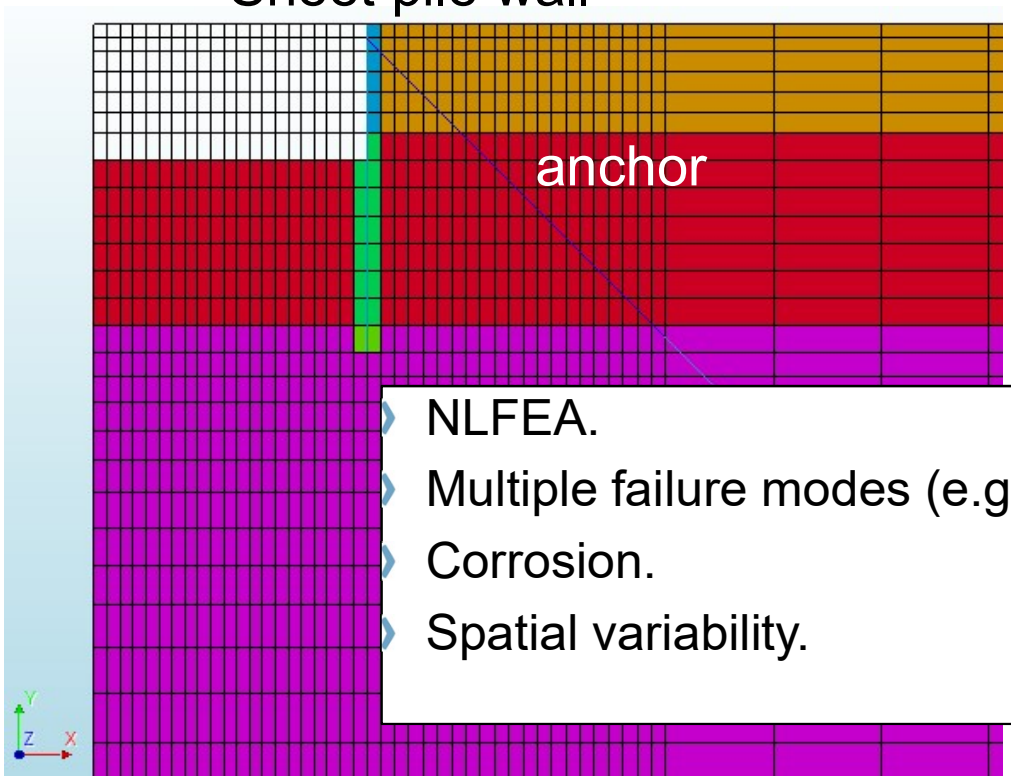
- Promising results/directions from the literature:
  - GPU parallelization: 10x speed-up[1].
  - Cloud computing[2].

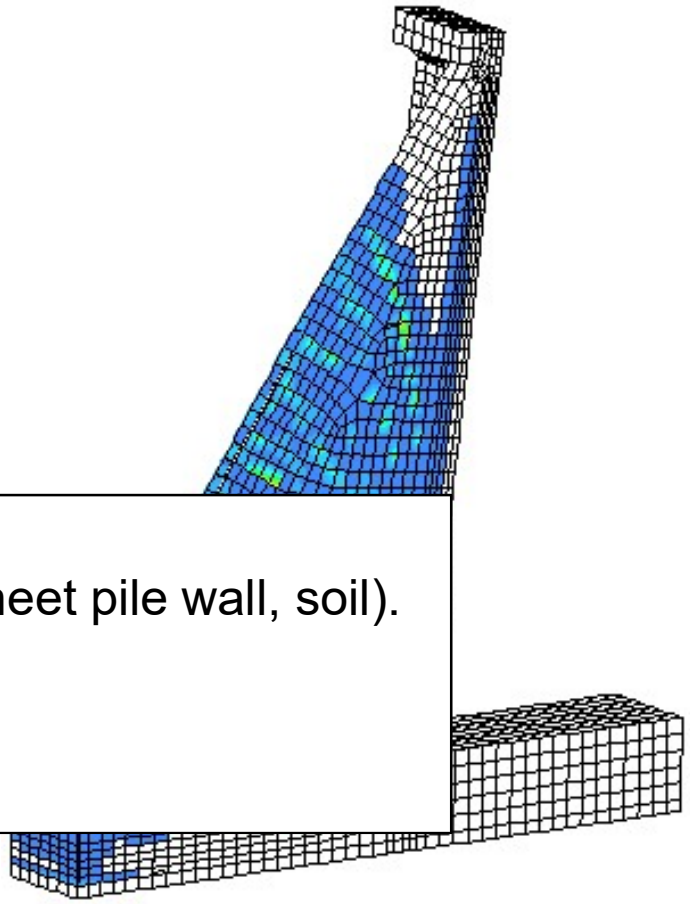
[1] Tian Y., Xie L., Xu Z., and Lu X.. (2015). GPU-Powered High-Performance Computing for the Analysis of Large-Scale Structures Based on OpenSees. 2015 *International Workshop on Computing in Civil Engineering*.

[2] Ventura C.E. and Bebamzadeh A. (2013). Los Angles Tall Buildings Structural Design Council. *Annual meeting*. Presentation slides.

HYDRAULIC STRUCTURES

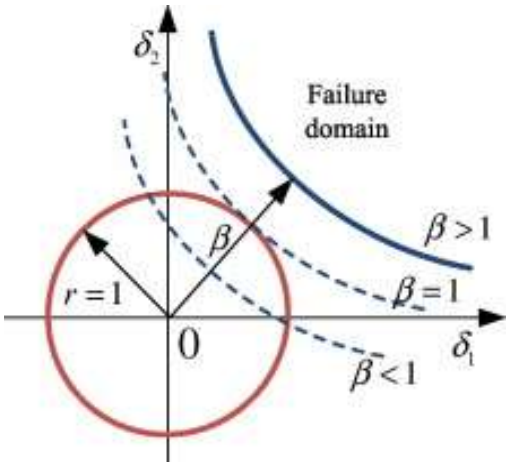
Sheet pile wall





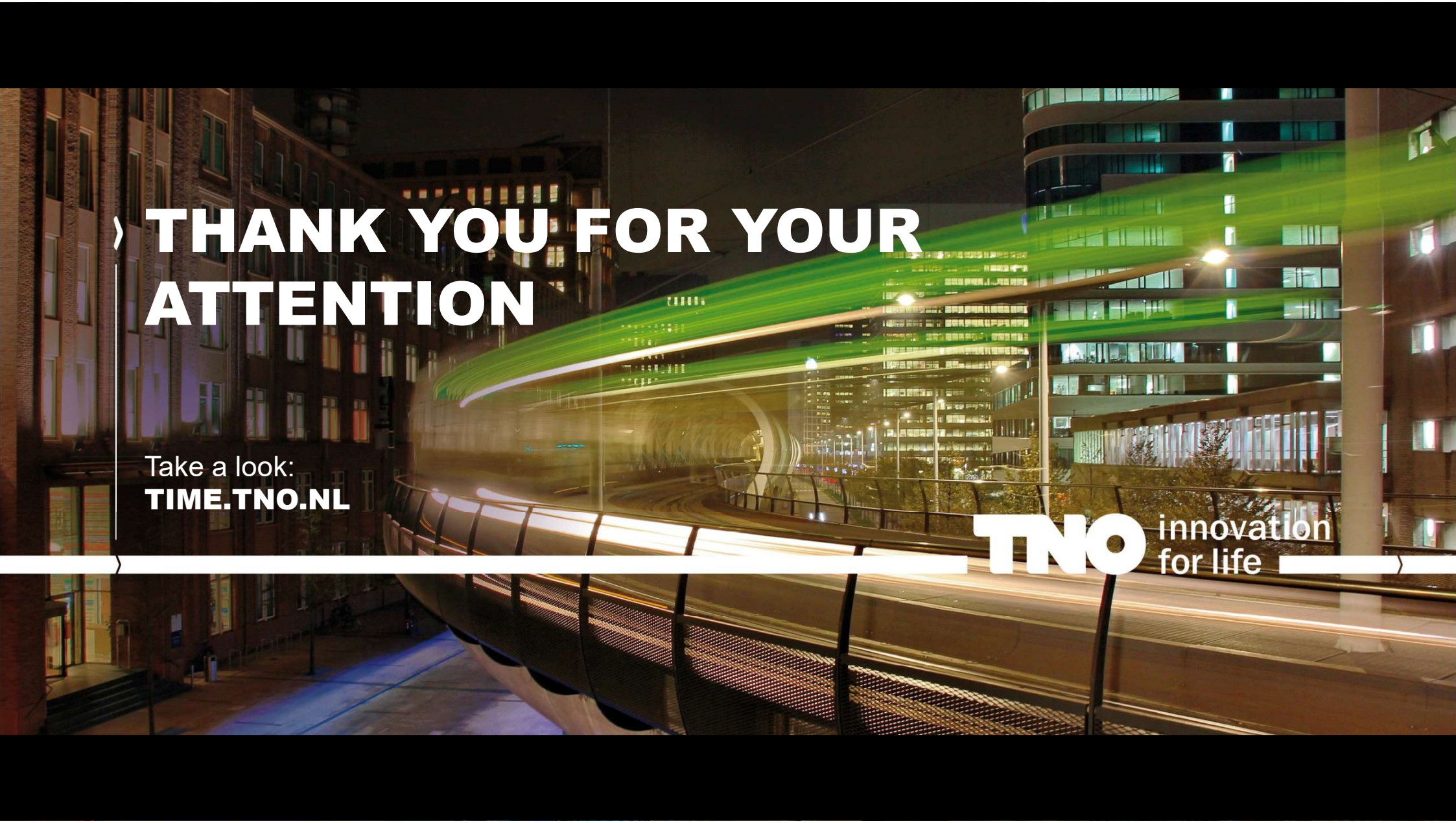
- NLFEA.
- Multiple failure modes (e.g. anchor, sheet pile wall, soil).
- Corrosion.
- Spatial variability.

CHALLENGES – QUESTIONS



- Computationally demanding physical models → reduce the computational time:
  - Parallelization.
  - “Smart” algorithms.
- Solving reliability problems with random fields (1D-2D-(3D)), (large number of correlated variables).
- Multiple failure modes.
- Reliability based calibration of methods for practice, e.g.:
  - NLFEA-based verification and/or design.

- We are looking, open for:
  - Join our efforts on implementing and testing algorithms/methods.
  - Benchmark problems (the showcased examples).
  - Joint effort to compile an open document with reliability methods (pros, cons).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