Uncertainties in civil engineering: a FE-model based process for research and application

Authors: **Vladimir Cerisano Kovačević**, Michele Betti, Gianni Bartoli, Lorenzo Papini
Kobe Innovation Engineering and University of Florence

Summary

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01
introduction

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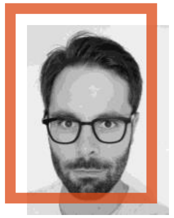
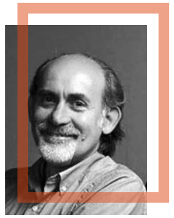
kobe

Vladimir Cerisano Kovačević
CEO
Structural Engineer and Researcher

Michele Betti
Scientific Coordination
DICEA-UNIFI Researcher

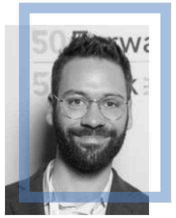


Riccardo Corazzi
CEO
Civil and Site Engineer



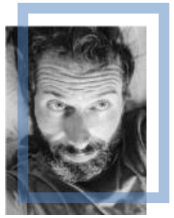
Gianni Bartoli
Scientific Mentorship
DICEA-UNIFI Associate Professor
CRIACIV chairman

Giacomo Zini
Collaborator
Signal Analysis and Processing



Andrea Giachetti
Collaborator
Wind Engineering

Luigi Paone
Collaborator
Software Development



Alessandro Valli
Collaborator
Computer Vision

About us

Kobe Innovation Engineering is an approved spin-off within the Department of Civil and Environmental Engineering at the University of Florence. Research transferred to application.

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engineering

structural, seismic, wind engineering and simulation

data analysis

data collection and elaboration

structural health monitoring

sensor layout design, data interpretation

code development

scientific algorithms, web based visualization

Expertise

Based in the civil engineering field, expanded towards a multidisciplinary approach.

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02

shm - the model calibration problem

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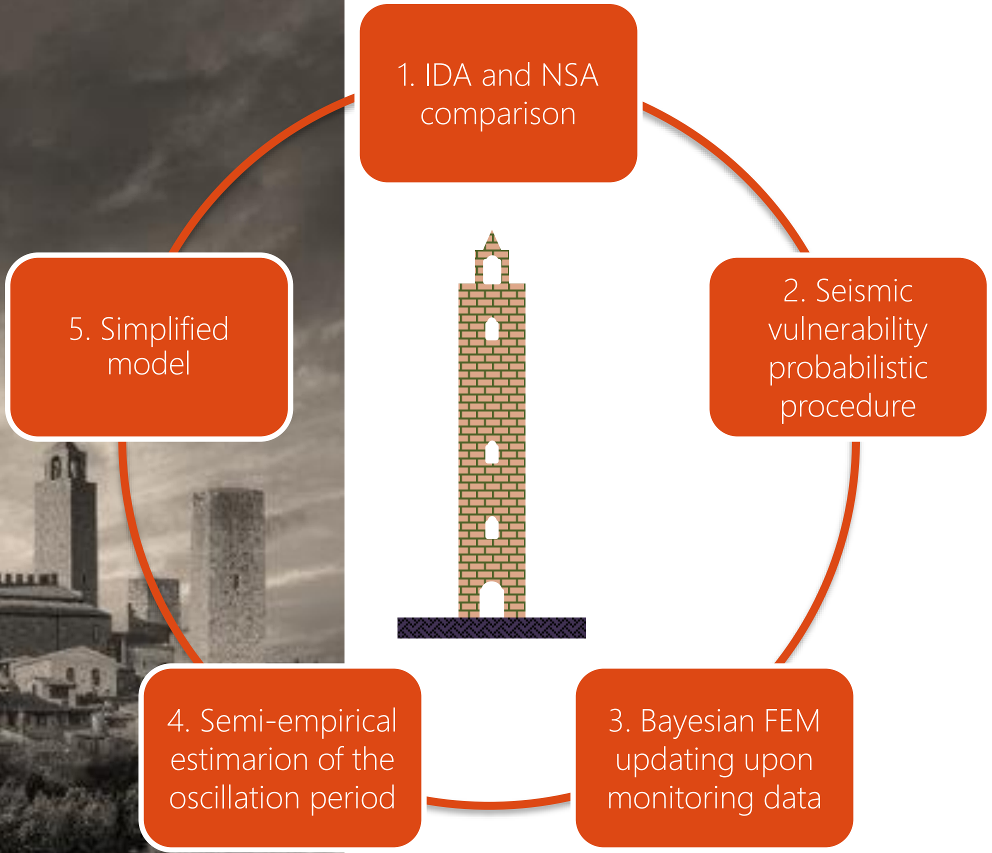
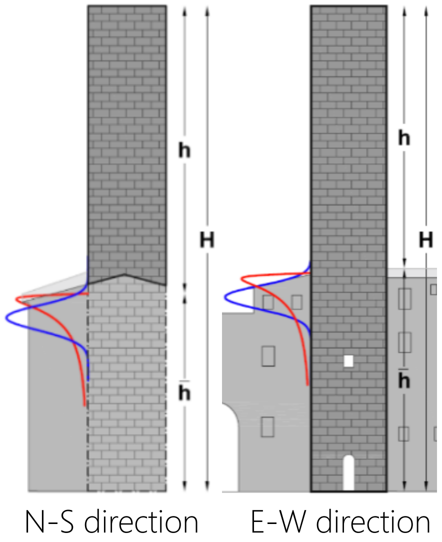
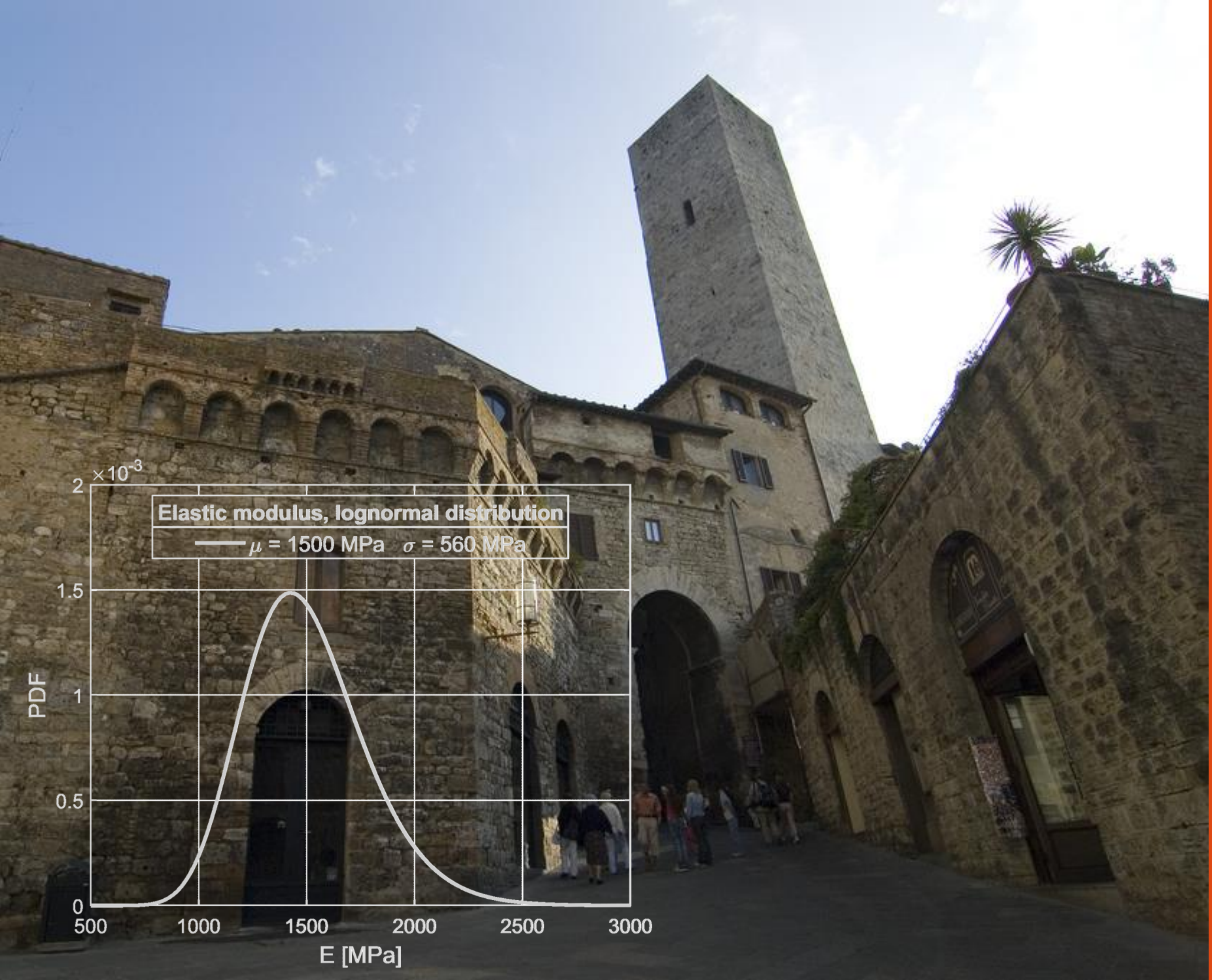




SHM

Past and actual experiences: San Gimignano towers modeling and monitoring workflow (RiSEM project).



Masonry

A non-homogeneous anisotropic material with uncertain properties.

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Complexity: a challenge

Historic building aggregates are functionally and structurally complex.

A deterministic procedure for the vulnerability assessment could be misleading.

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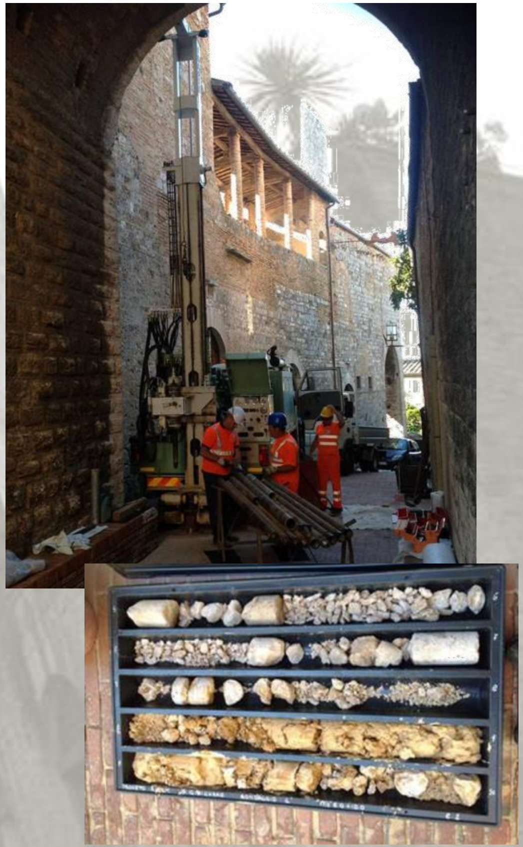
Useful data

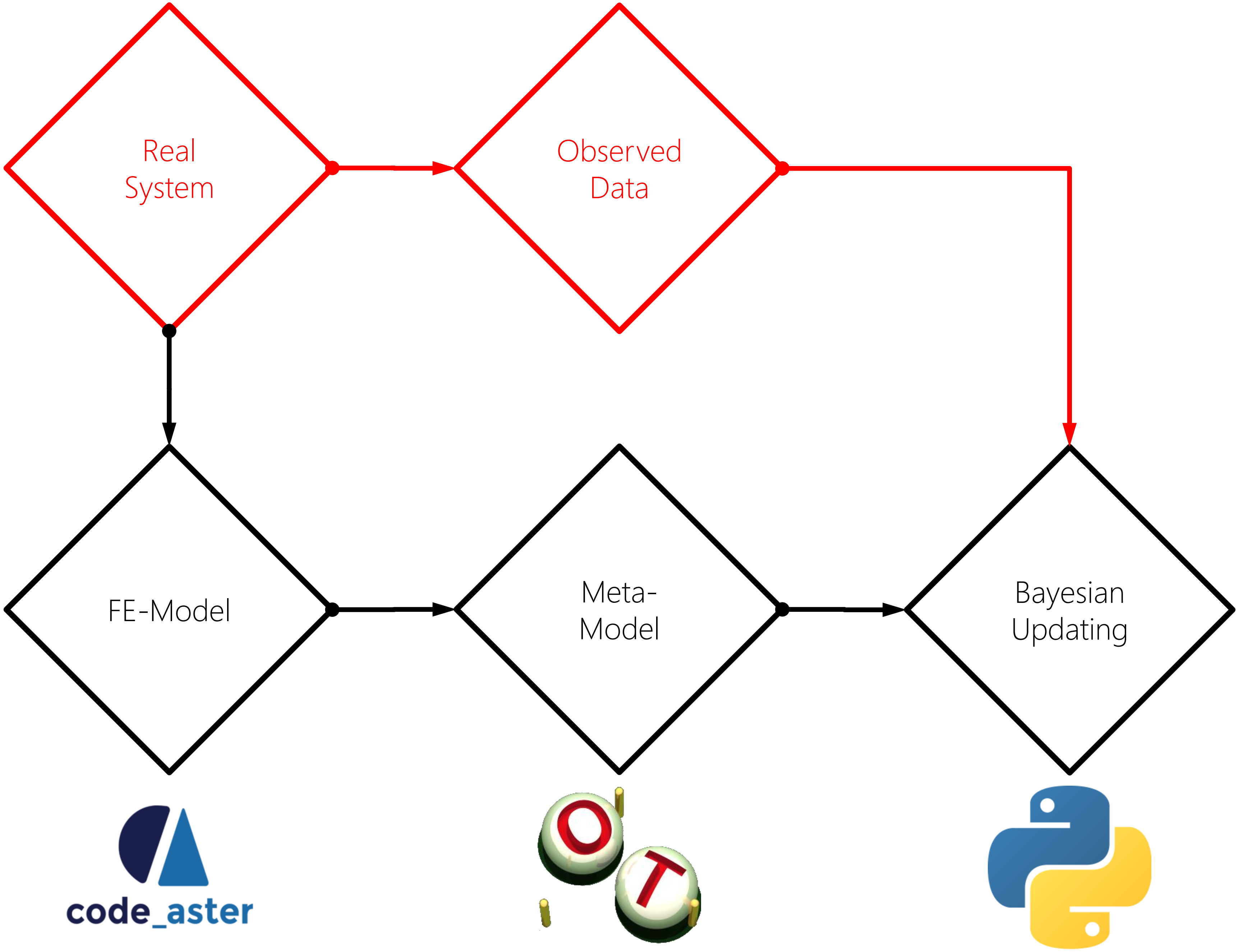
The useful ingredients that are able to help in reducing the uncertainties over the model parameters.

Geometrical survey

Natural frequencies measurement



Soil characterization



The workflow

From the observed system to the FE-model updating.

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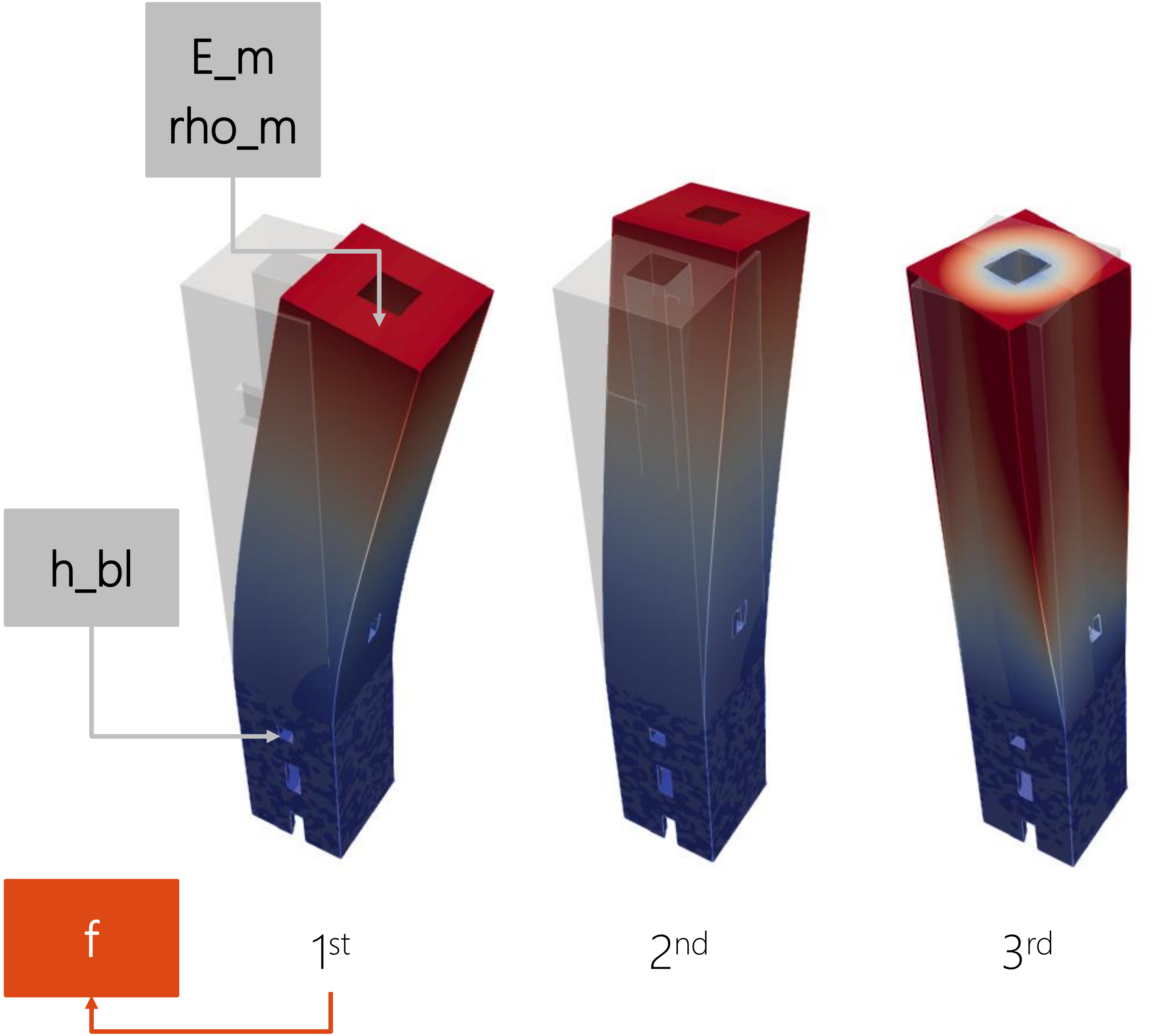
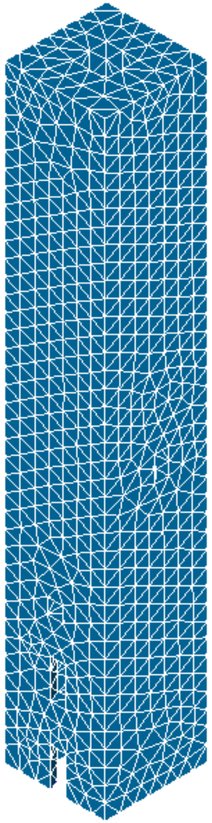
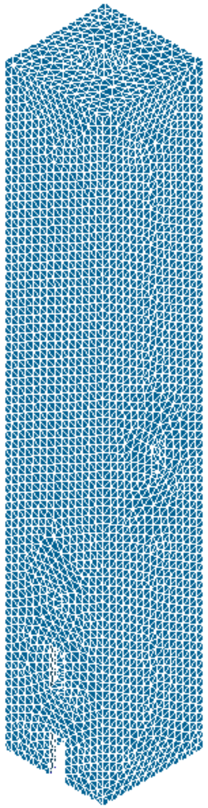
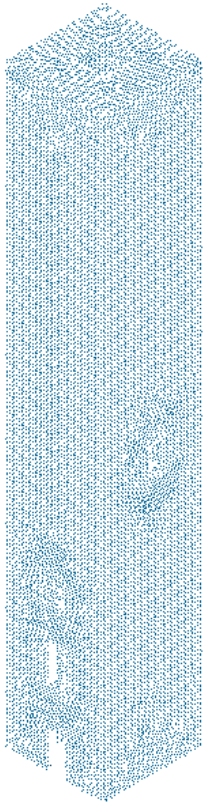
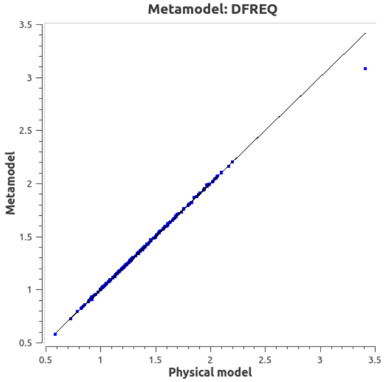


The FE-Model

Different variable input parameters (elastic modulus, blocked height, density) in order to obtain the output frequencies and modal shapes.

Metamodel efficiency

Comparison of the computational time. The metamodel has been created with the Kriging approximation.

Computational effort for each calculation step

M1	**M2**	**M3**	**Metamodel**
t [s]	*t [s]*	*t [s]*	*t [s]*
~8	~18	~41	0.00062

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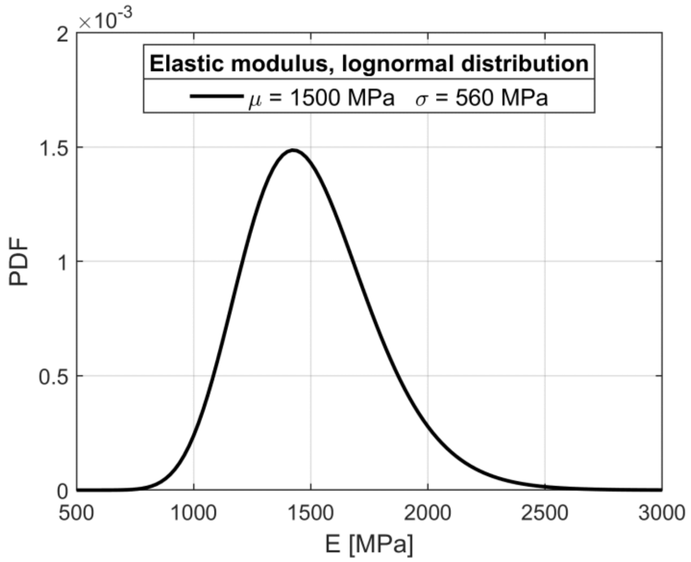

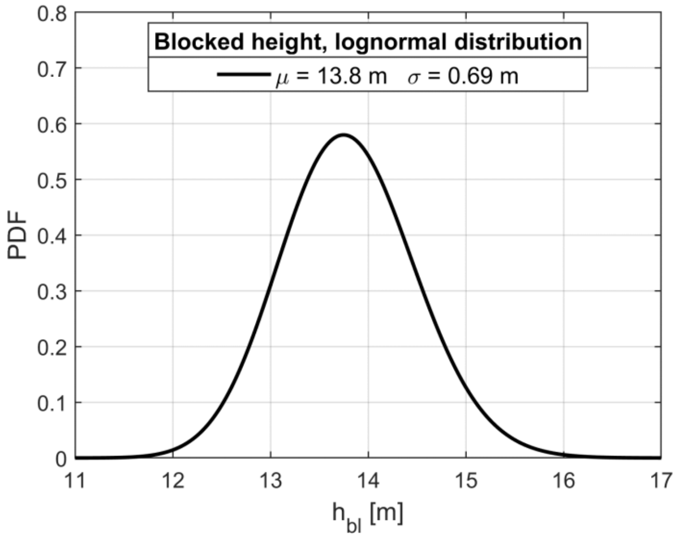

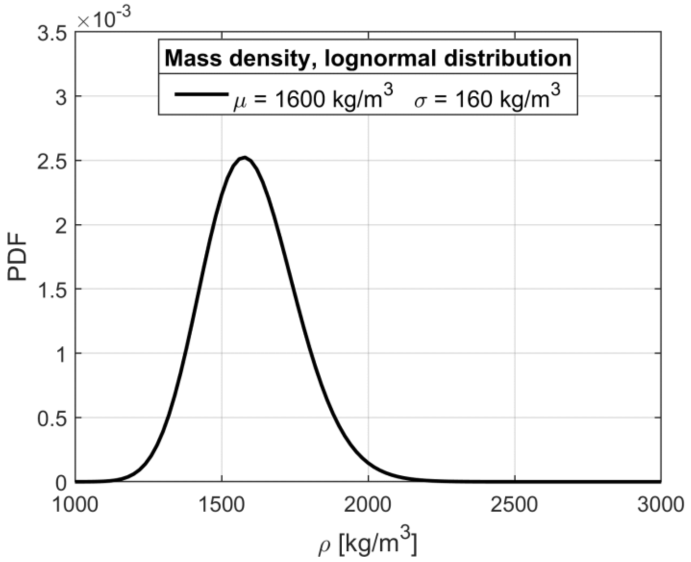

Bayesian updating

First step: definition of the prior distributions for each input parameter. The parameters are considered to be initially independent.

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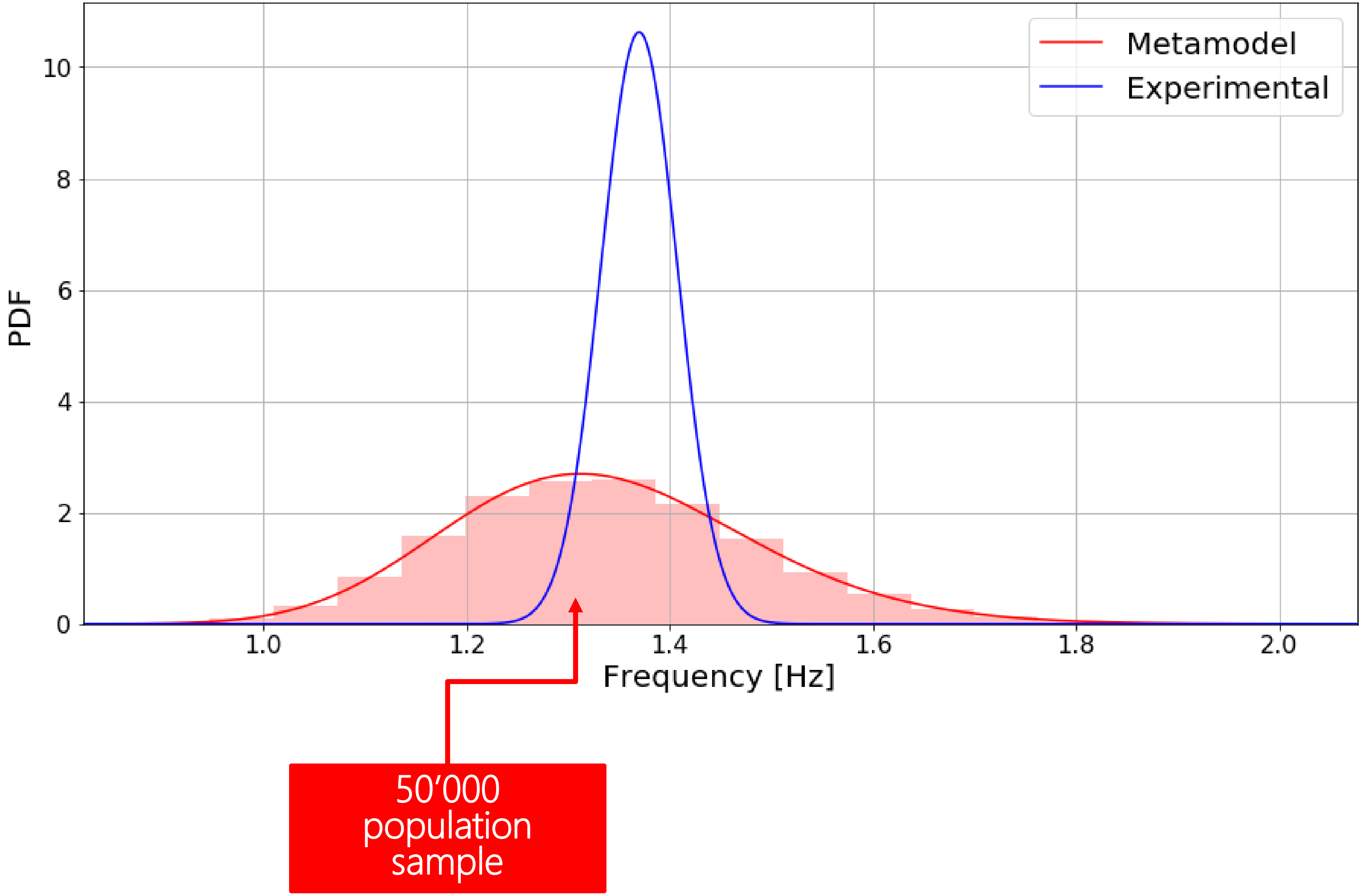

Bayesian updating

Second step: calculation of the output distribution and comparison with the experimental one.

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Bayes theorem

$$p_T(\boldsymbol{\theta}) = p(\boldsymbol{\theta} \mid \bar{T}) = \frac{p(\bar{T} \mid \boldsymbol{\theta})\, p_0(\boldsymbol{\theta})}{\int p(\bar{T} \mid \boldsymbol{\theta})\, p_0(\boldsymbol{\theta})\, d\boldsymbol{\theta}}$$

$$p(\bar{T} \mid \boldsymbol{\theta}) = \int p(\bar{T} \mid T, \boldsymbol{\theta})\, p(T \mid \boldsymbol{\theta})\, dT$$

$$p_0(\boldsymbol{\theta}) = p_0(E, h) = p_0(E)\, p_0(h)$$

Bayes theorem applied with two variables (E, h), one observed (T) output, with:

a) updating
b) likelihood funct.
c) prior distrib.

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Bayesian updating

Third step: the implemented code for the updating procedure.

$$p\left(\mathbf{E}\middle|\bar{f}_1\right) = \frac{p\left(\bar{f}_1\middle|\mathbf{E}\right)p_0(\mathbf{E})}{\int p\left(\bar{f}_1\middle|\mathbf{E}\right)p_0(\mathbf{E})d\mathbf{E}}$$

```python
### SCRIPT FOR BAYESIAN UPDATING SCHEME OF AN EXISTING DISTRIBUTION ###
### by Vladimir Cerisano Kovacevic (Kobe Innovation Engineering) ###

from __future__ import print_function
import pandas as pd
import scipy as sp
import numpy as np
import math as m
import matplotlib.pyplot as plt
import openturns as ot
from openturns import *
from openturns.viewer import View as otview
import xml.etree.ElementTree as ET

## 0. INPUT DATA FROM EXTERNAL SOURCES

## Set the source of the sample
datasource = '/home/vkova/Documenti/Analisi/1903_torre/02_updating/ev_meta_4.csv'
gridsource = '/home/vkova/Documenti/Analisi/1903_torre/02_updating/ev_grid_meta_1.csv'

## Read the data
data = pd.read_csv(datasource)
# Preview the first 5 lines of the loaded data
data.head()

## Create the sample for the distribution estimation
sample = ot.Sample.ImportFromCSVFile(datasource, ',')
sample = ot.Sample(np.array(sample)*np.array([1, 1, 10**12, 1]))

## Set the colum number to be assumed in the calculation (the last column is the output)
n_c = sample.getDimension()-1

## 1. FITTING OF THE DISTRIBUTION TO THE EXTERNAL DATA

## Create the search interval of (mu, sigma, gamma): the constraint is gamma = 0
lowerBound = [-1.0, -1.0, 0]
upperBound = [1.0, 1.0, 0]
finiteLowerBound = [False, False, True]
finiteUpperBound = [False, False, True]
bounds = ot.Interval(lowerBound, upperBound, finiteLowerBound, finiteUpperBound)

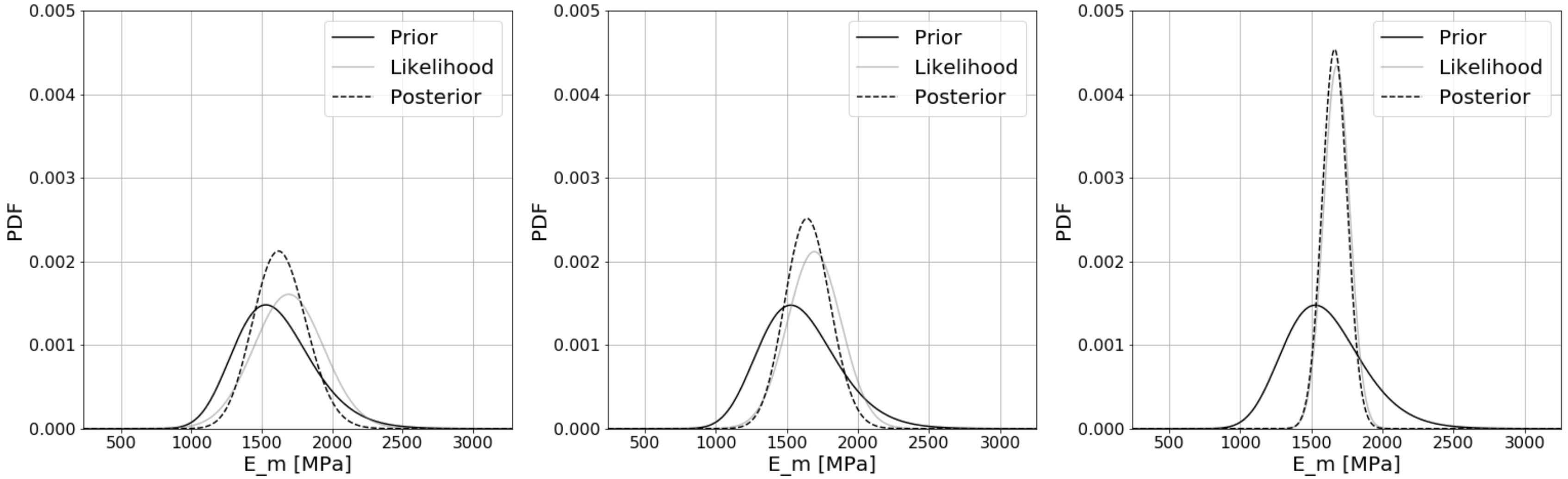
## Create the starting point of the research
## For mu : the first point
## For sigma : a value evaluated from the two first points
## For gamma : it will be fixed to 0

distColl=[]

pointColl=[]

i = 0
for i in range(n_c+1):
    mu0 = m.log(sample[0][i])
    sigma0 = m.sqrt((m.log(sample[1][i]) - m.log(sample[0][i])) * (m.log(sample[1][i]) - m.log(sample[0][i])))
```

$$p(\boldsymbol{E}|\overline{f_1}) = \frac{p(\overline{f_1}|\mathbf{E})p_0(\mathbf{E})}{\int p(\overline{f_1}|\mathbf{E})p_0(\mathbf{E})d\mathbf{E}}$$



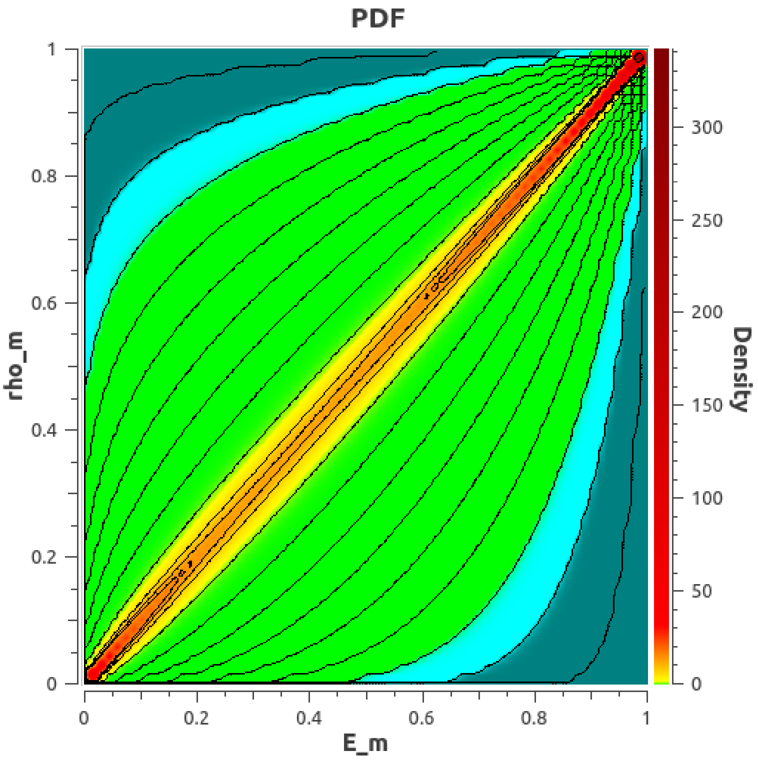
rho_m = 1600 kg/m^3

rho_m = 1600 kg/m^3
h_bl= 13.8 m

Bayesian updating

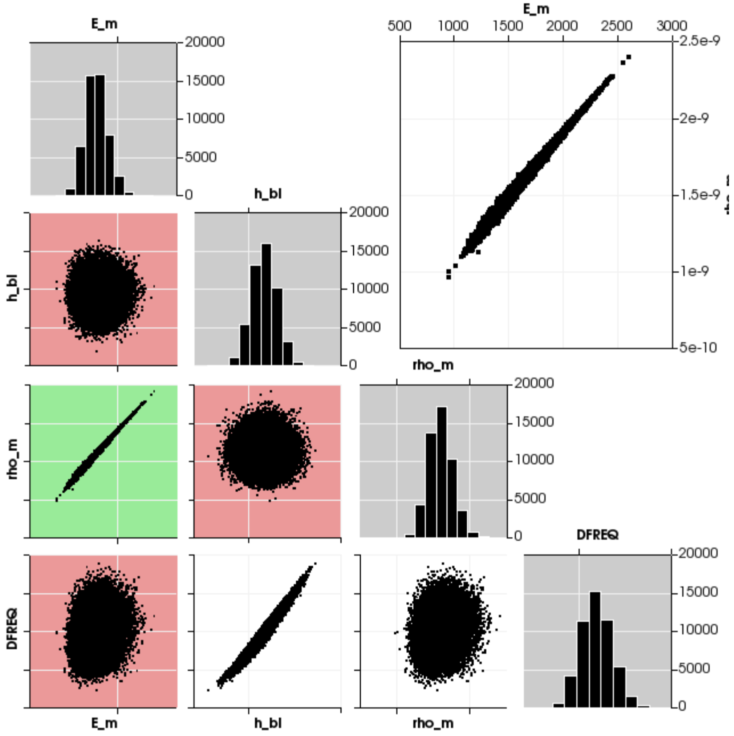
Updating the aleatory variable (elastic modulus), within a 3 parameters, 2 parameters and 1 parameter variability data set.

$$p(\boldsymbol{E}|\bar{f}_1) = \frac{p(\bar{f}_1|\mathbf{E})p_0(\mathbf{E})}{\int p(\bar{f}_1|\mathbf{E})p_0(\mathbf{E})d\mathbf{E}}$$



Gumbel copula

$$\exp\left[-\left((-\log(u))^{\theta} + (-\log(v))^{\theta}\right)^{1/\theta}\right]$$



Bayesian updating

Using correlation to decrease uncertainty on engineering parameters (elastic modulus and density of the structural masonry).

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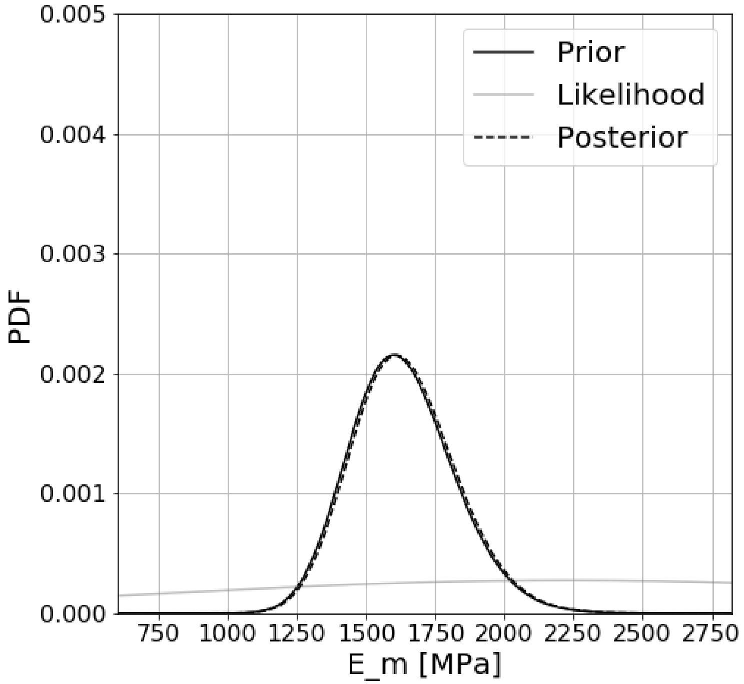
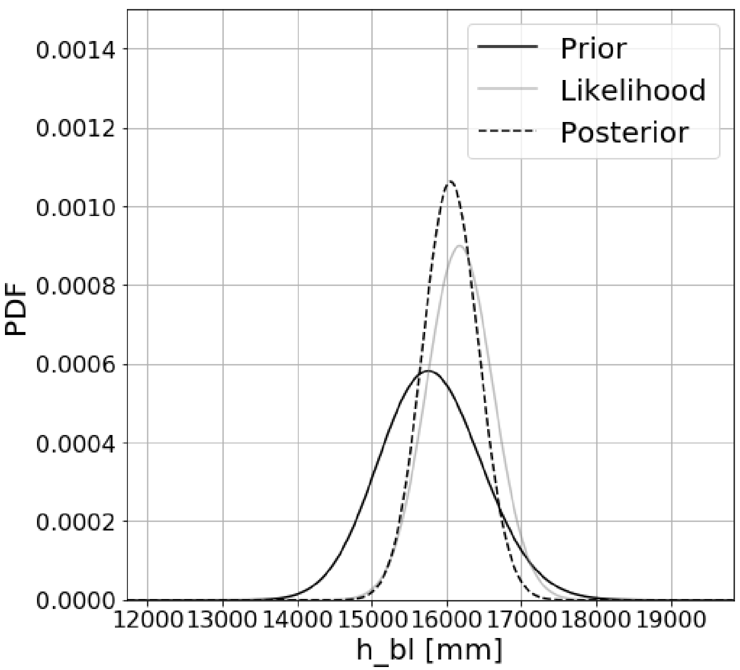
$$p(\boldsymbol{E}|\bar{f}_1) = \frac{p(\bar{f}_1|\mathbf{E})p_0(\mathbf{E})}{\int p(\bar{f}_1|\mathbf{E})p_0(\mathbf{E})d\mathbf{E}}$$



Elastic Modulus



Blocked Height

Bayesian updating

The gain on the elastic modulus is null!

On the contrary, the blocked height is evidently updated.

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03
incipient damage detection

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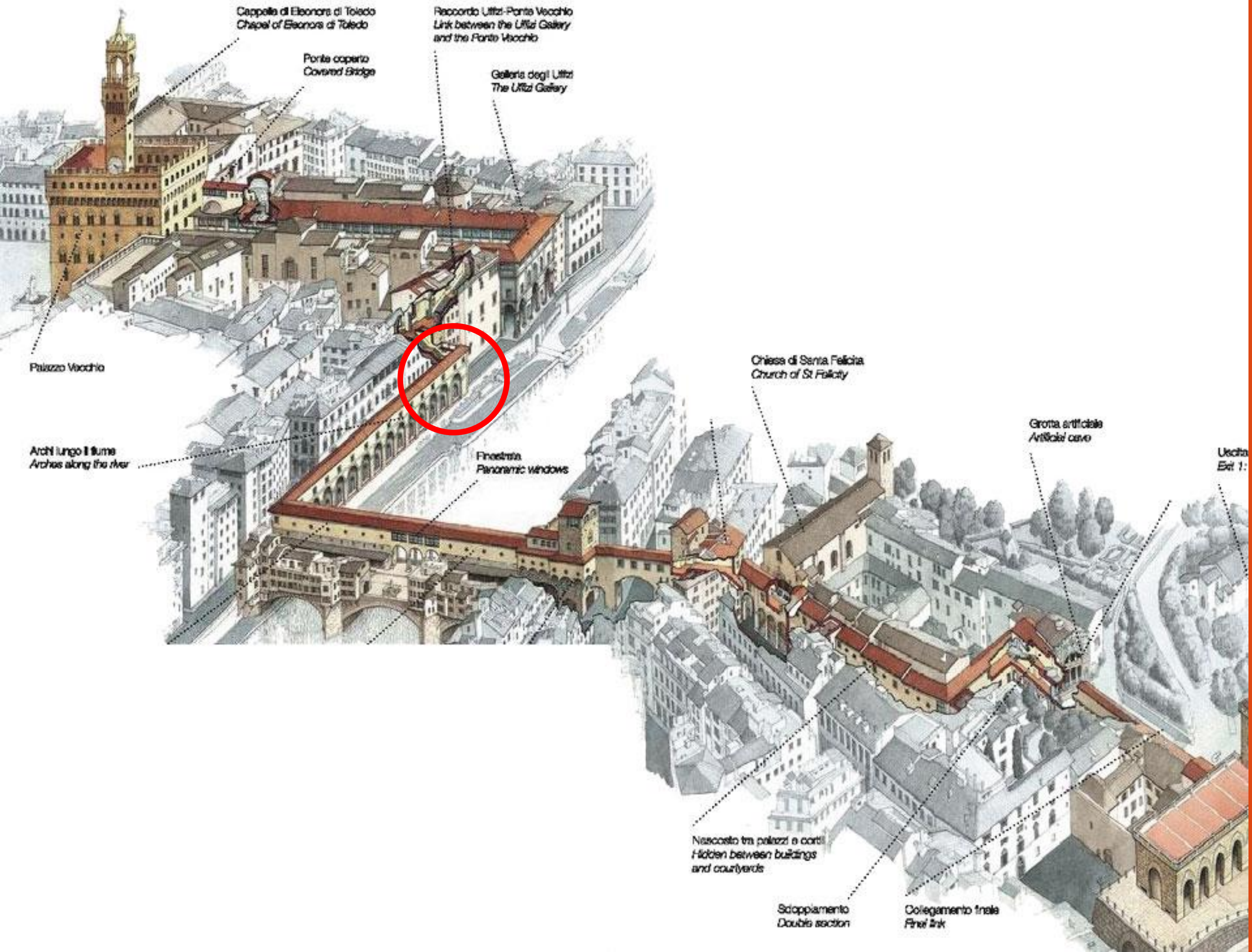

General overview

Corridoio Vasariano, a gallery that extends from the Uffizi to Palazzo Pitti.

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Cracking pattern

Thin cracks appearing at the connection with the Uffizi.

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Cracking pattern

Thin cracks appearing at the connection with the Uffizi.

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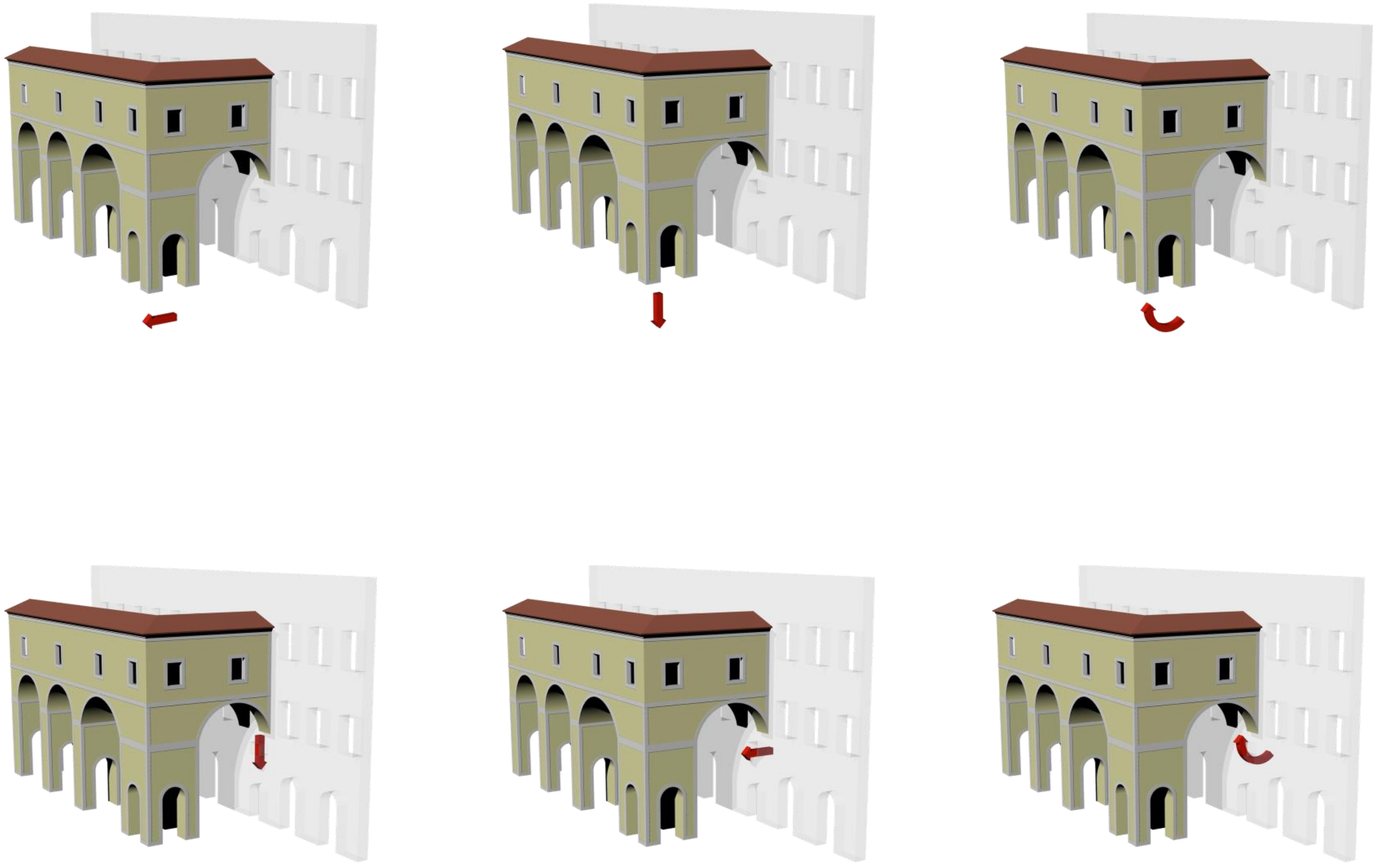

Kinematics

The most probable causes are of cracking appearance in masonry structures are differential kinematic conditions. But what is the entity to initialize the damage?

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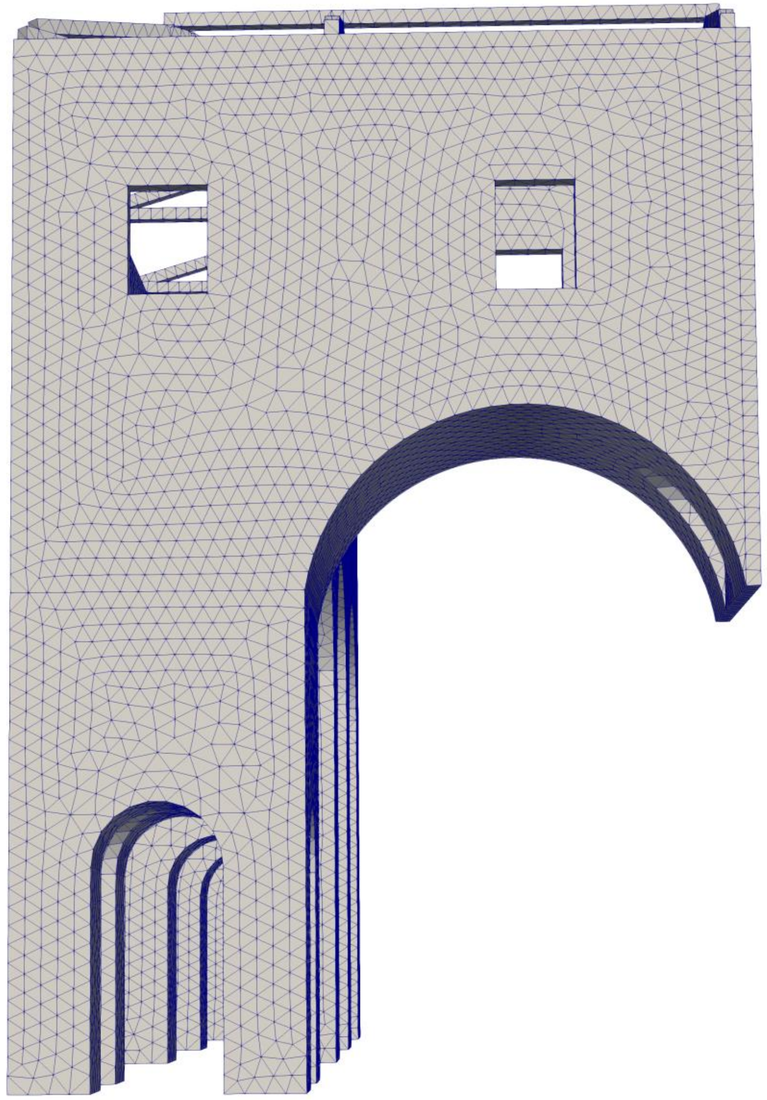
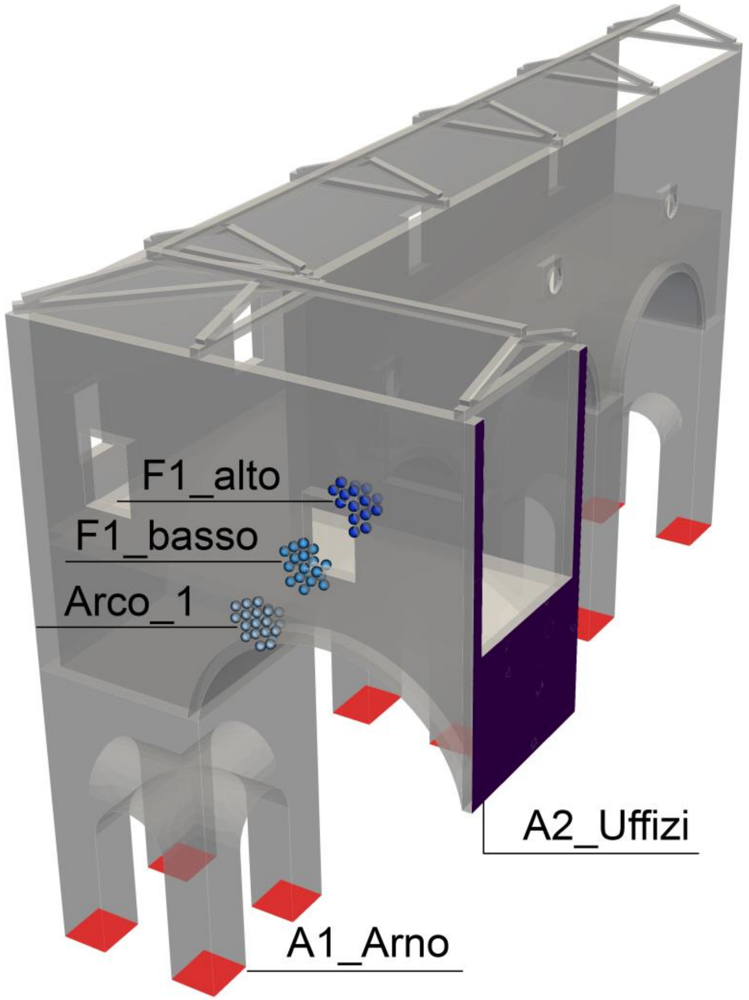
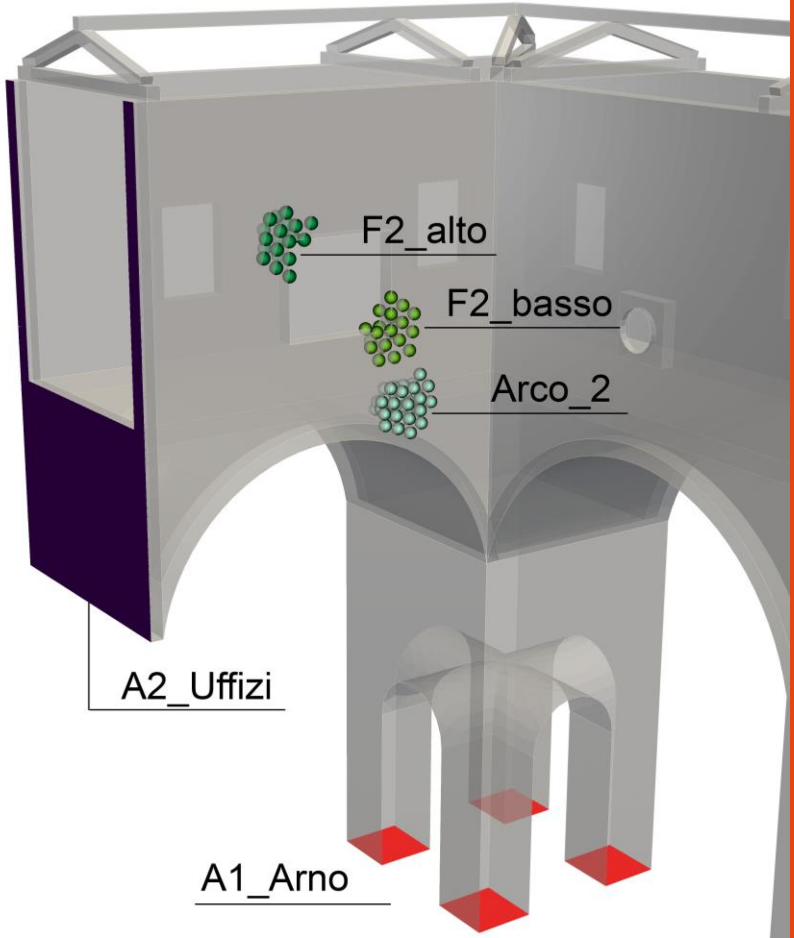


FE-Model

Geometry and discretization.





FE-Model

Kinematic conditions and control nodes.

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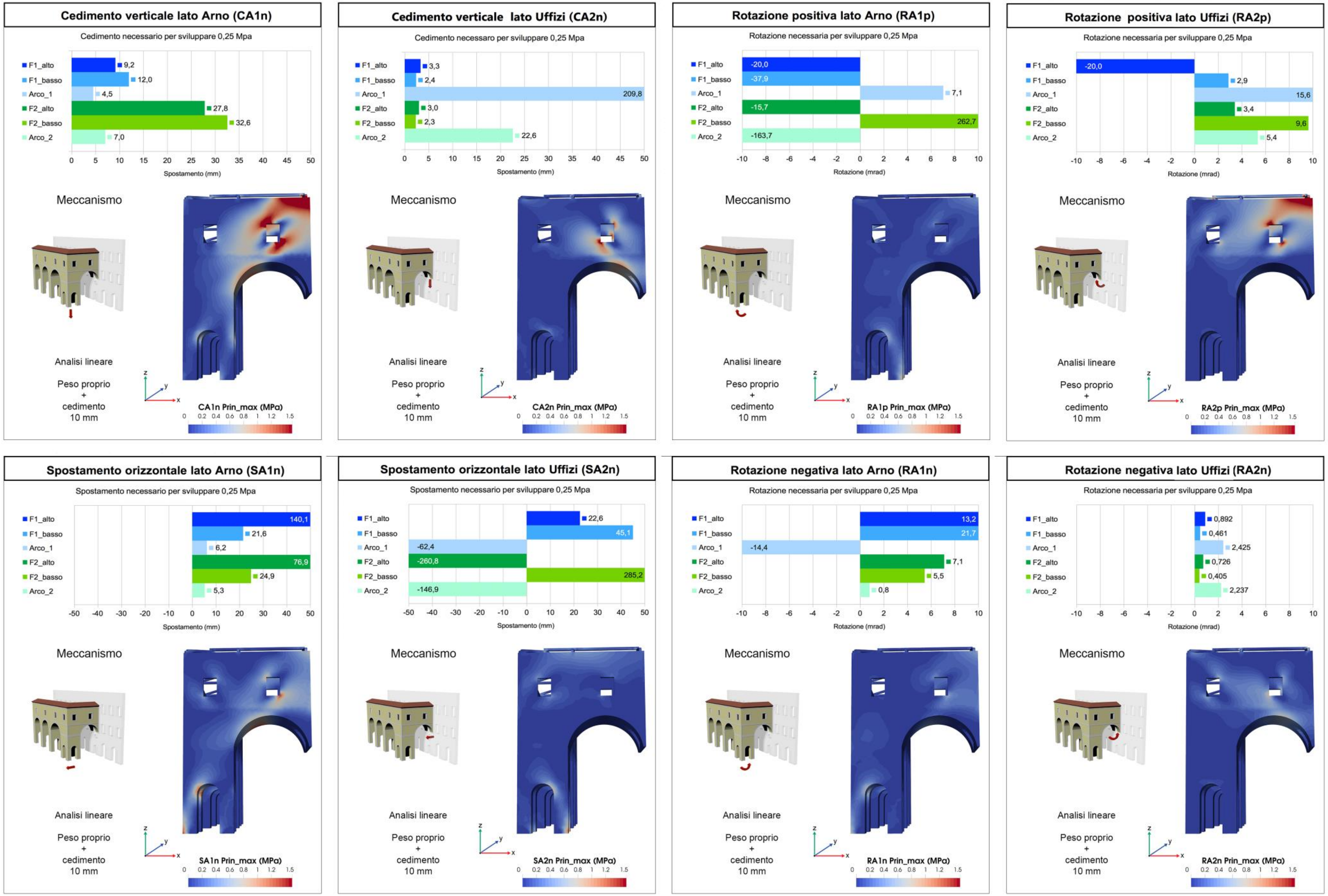
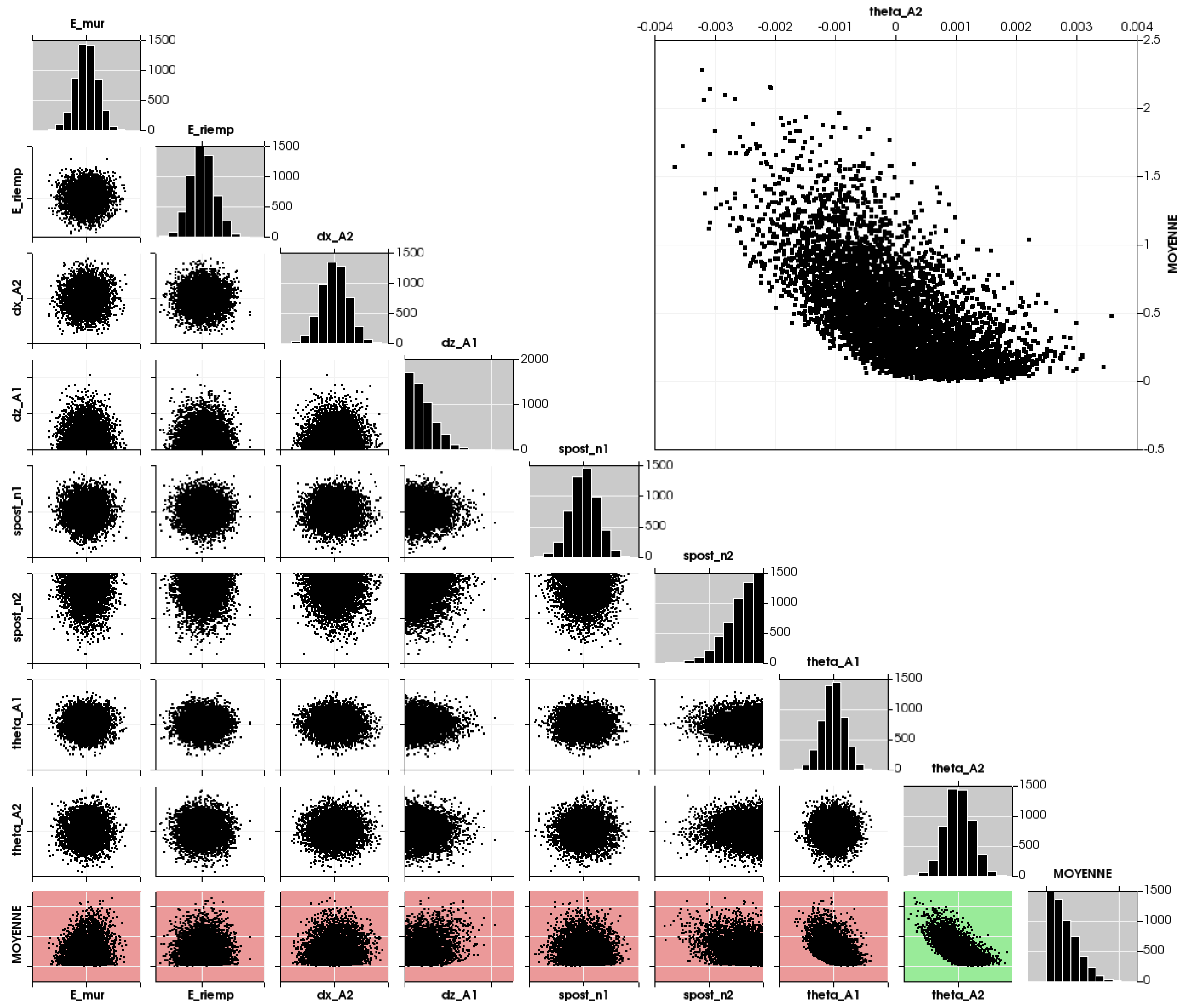

Cedimento verticale lato Arno (CA1n)
Cedimento necessario per sviluppare 0,25 Mpa
F1_alto 9,2
F1_basso 12,0
Arco_1 4,5
F2_alto 27,8
F2_basso 32,6
Arco_2 7,0
Spostamento (mm)
Meccanismo
Analisi lineare
Peso proprio
+
cedimento
10 mm
CA1n Prin_max (MPa)
Cedimento verticale lato Uffizi (CA2n)
Cedimento necessaro per sviluppare 0,25 Mpa
F1_alto 3,3
F1_basso 2,4
Arco_1 209,8
F2_alto 3,0
F2_basso 2,3
Arco_2 22,6
Spostamento (mm)
Meccanismo
Analisi lineare
Peso proprio
+
cedimento
10 mm
CA2n Prin_max (MPa)
Rotazione positiva lato Arno (RA1p)
Rotazione necessaria per sviluppare 0,25 Mpa
F1_alto -20,0
F1_basso -37,9
Arco_1 7,1
F2_alto -15,7
F2_basso 262,7
Arco_2 -163,7
Rotazione (mrad)
Meccanismo
Analisi lineare
Peso proprio
+
cedimento
10 mm
RA1p Prin_max (MPa)
Rotazione positiva lato Uffizi (RA2p)
Rotazione necessaria per sviluppare 0,25 Mpa
F1_alto -20,0
F1_basso 2,9
Arco_1 15,6
F2_alto 3,4
F2_basso 9,6
Arco_2 5,4
Rotazione (mrad)
Meccanismo
Analisi lineare
Peso proprio
+
cedimento
10 mm
RA2p Prin_max (MPa)
Spostamento orizzontale lato Arno (SA1n)
Spostamento necessario per sviluppare 0,25 Mpa
F1_alto 140,1
F1_basso 21,6
Arco_1 6,2
F2_alto 76,9
F2_basso 24,9
Arco_2 5,3
Spostamento (mm)
Meccanismo
Analisi lineare
Peso proprio
+
cedimento
10 mm
SA1n Prin_max (MPa)
Spostamento orizzontale lato Uffizi (SA2n)
Spostamento necessario per sviluppare 0,25 Mpa
F1_alto 22,6
F1_basso 45,1
Arco_1 -62,4
F2_alto -260,8
F2_basso 285,2
Arco_2 -146,9
Spostamento (mm)
Meccanismo
Analisi lineare
Peso proprio
+
cedimento
10 mm
SA2n Prin_max (MPa)
Rotazione negativa lato Arno (RA1n)
Rotazione necessaria per sviluppare 0,25 Mpa
F1_alto 13,2
F1_basso 21,7
Arco_1 -14,4
F2_alto 7,1
F2_basso 5,5
Arco_2 0,8
Rotazione (mrad)
Meccanismo
Analisi lineare
Peso proprio
+
cedimento
10 mm
RA1n Prin_max (MPa)
Rotazione negativa lato Uffizi (RA2n)
Rotazione necessaria per sviluppare 0,25 Mpa
F1_alto 0,892
F1_basso 0,461
Arco_1 2,425
F2_alto 0,726
F2_basso 0,405
Arco_2 2,237
Rotazione (mrad)
Meccanismo
Analisi lineare
Peso proprio
+
cedimento
10 mm
RA2n Prin_max (MPa)



Parametric analysis

Distribution of the output (the mean value of the maximum principal stress at the control points), based on the variability of the input kinematic conditions (displacement entity).

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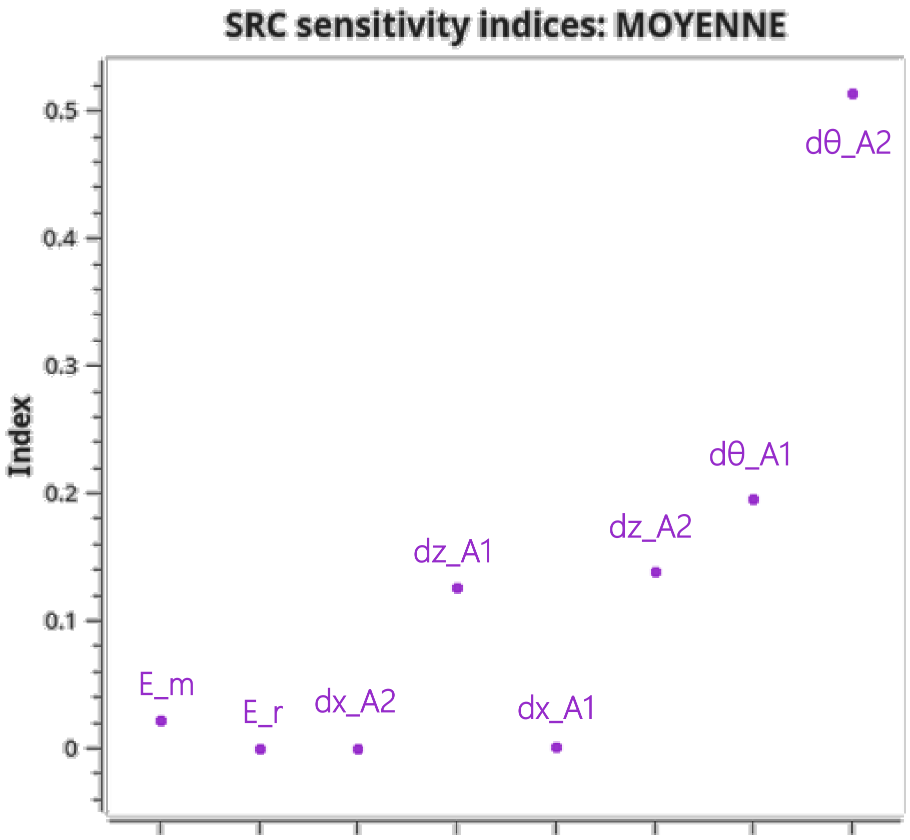

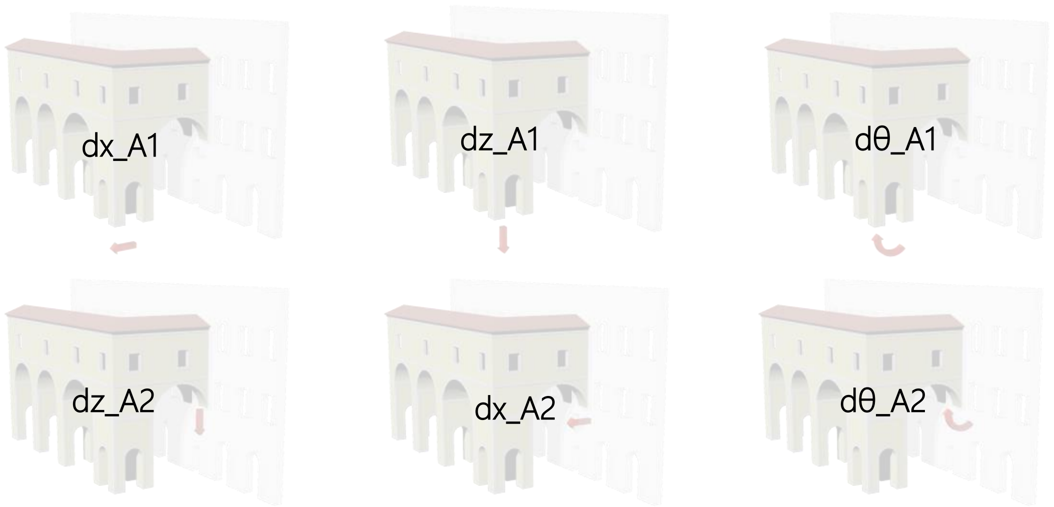

Sensitivity

Sensitivity analysis (with the linear regression SRC method).

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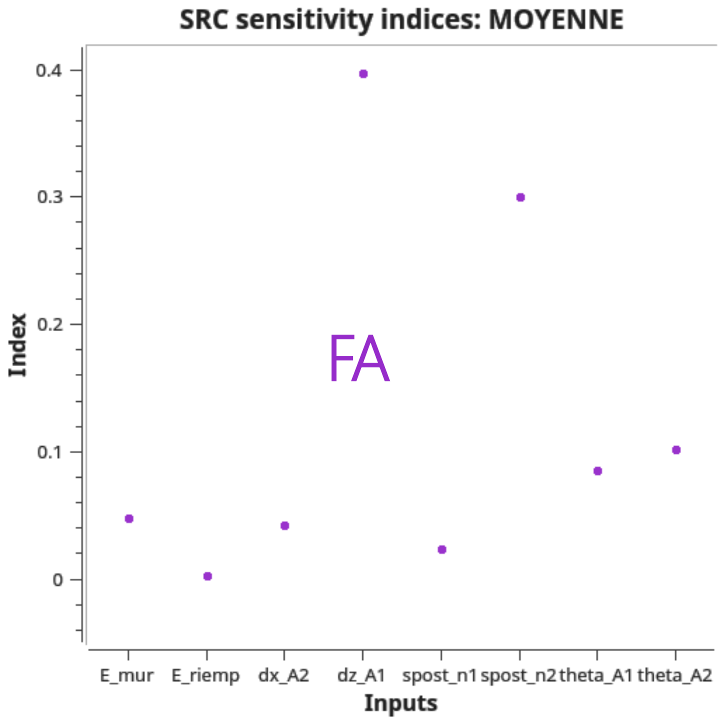
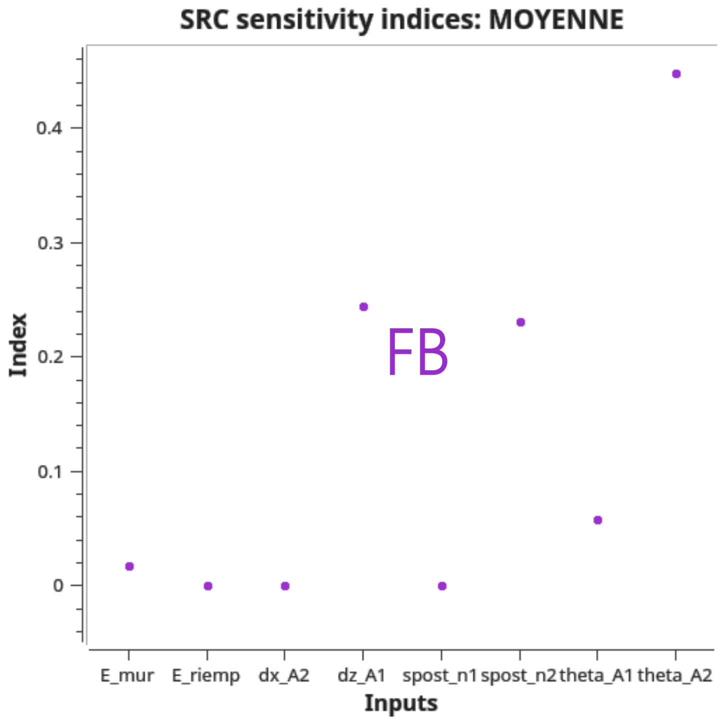
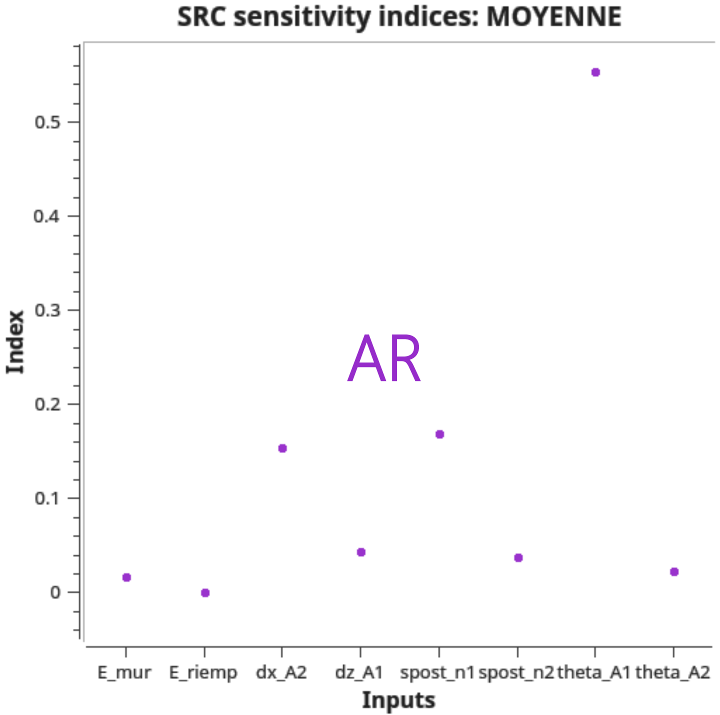
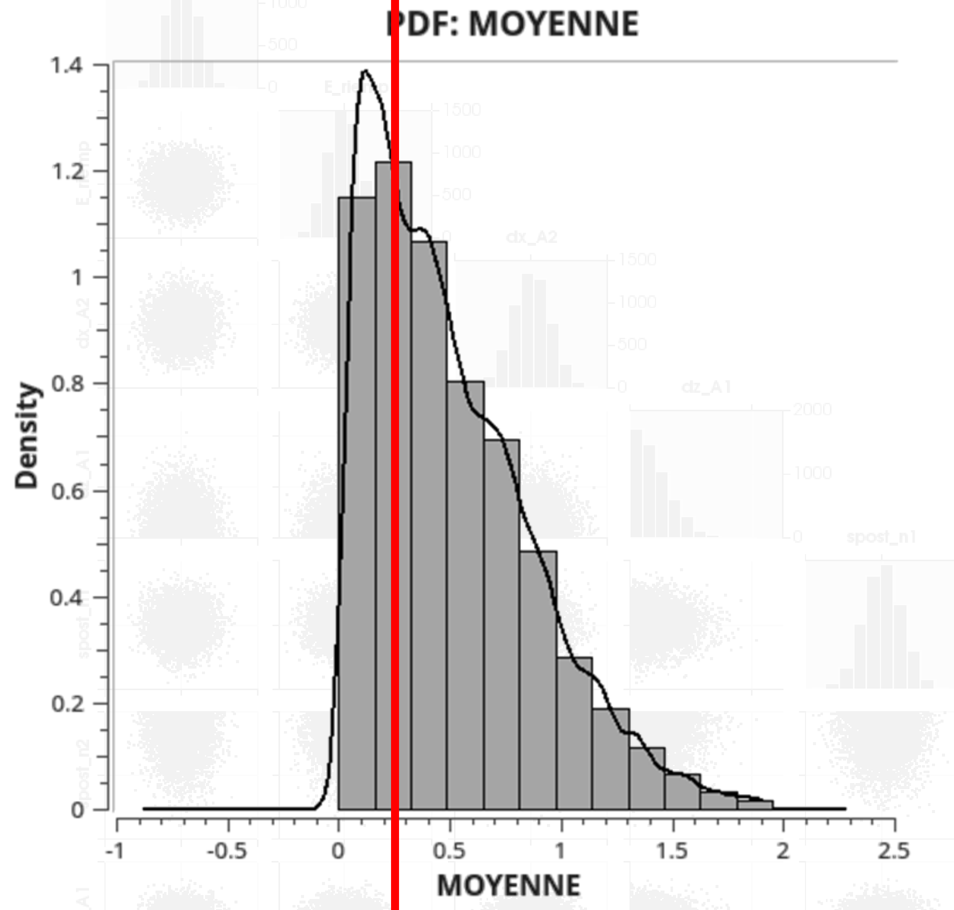


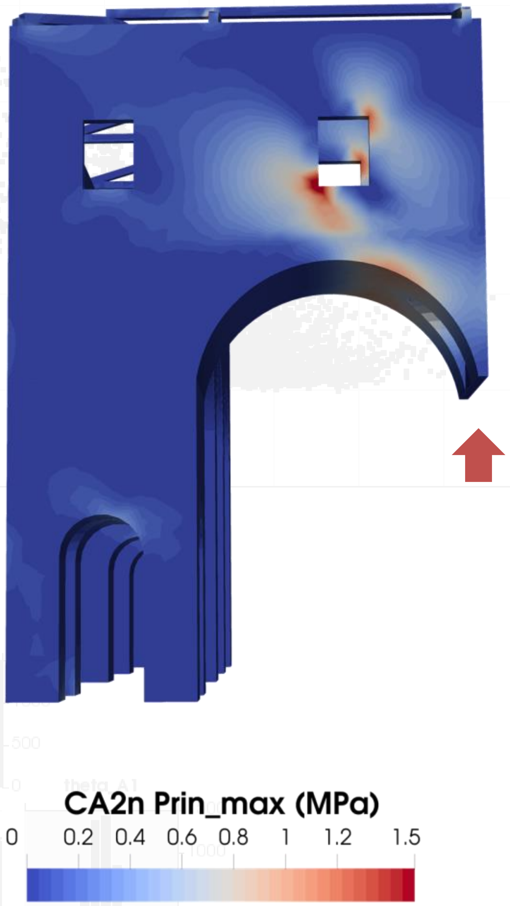




Sensitivity

The facades are sensible to vertical displacements and, in minor quantity, to rotations.





Critical limit exceeding 0.25 MPa

Small displacements (<<5mm) are enough

Critical limit

The exceedance of a supposed critical limit is reached with equivalent displacements with a zero mean value and a standard deviation << 5 mm (extremely small displacements).

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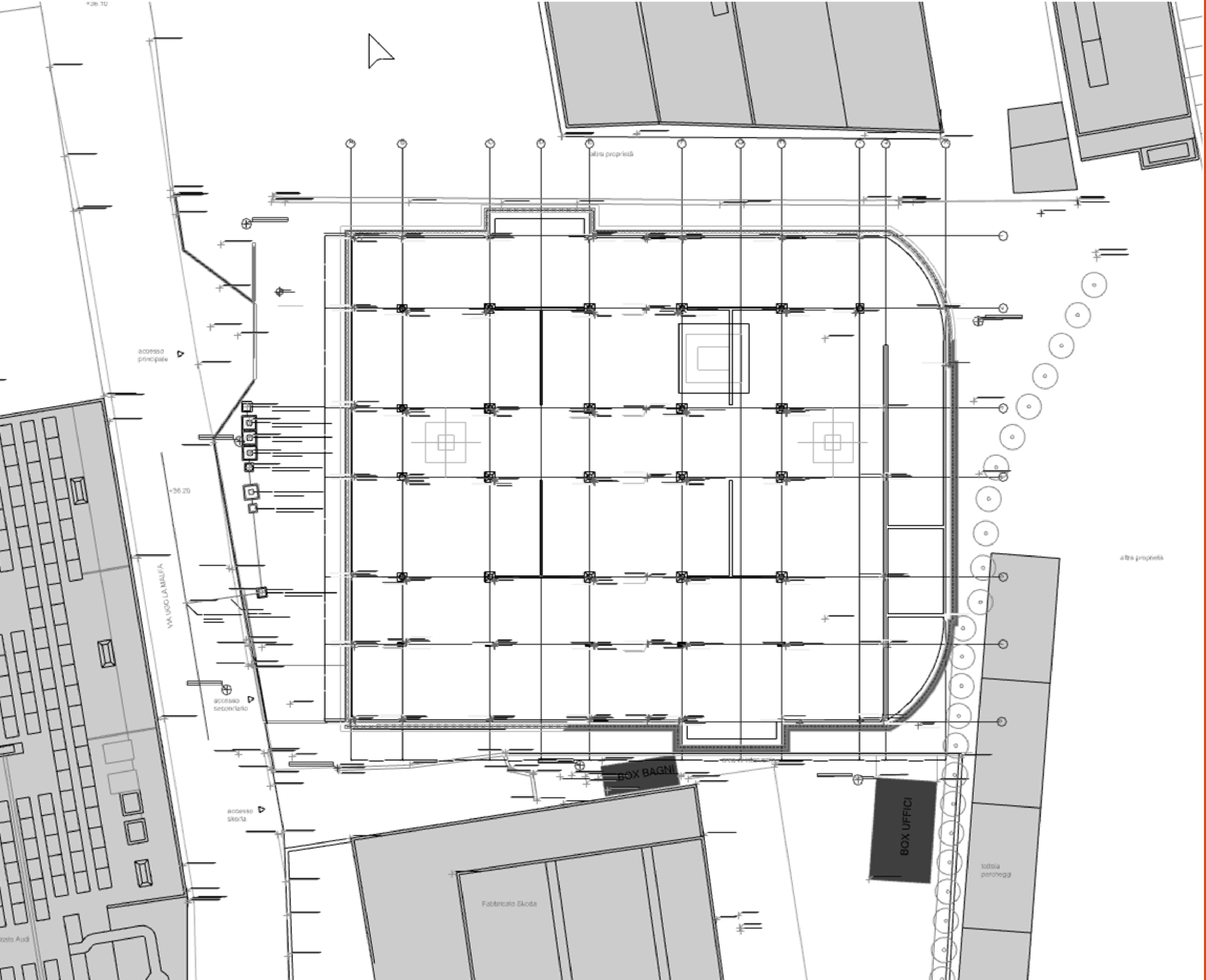
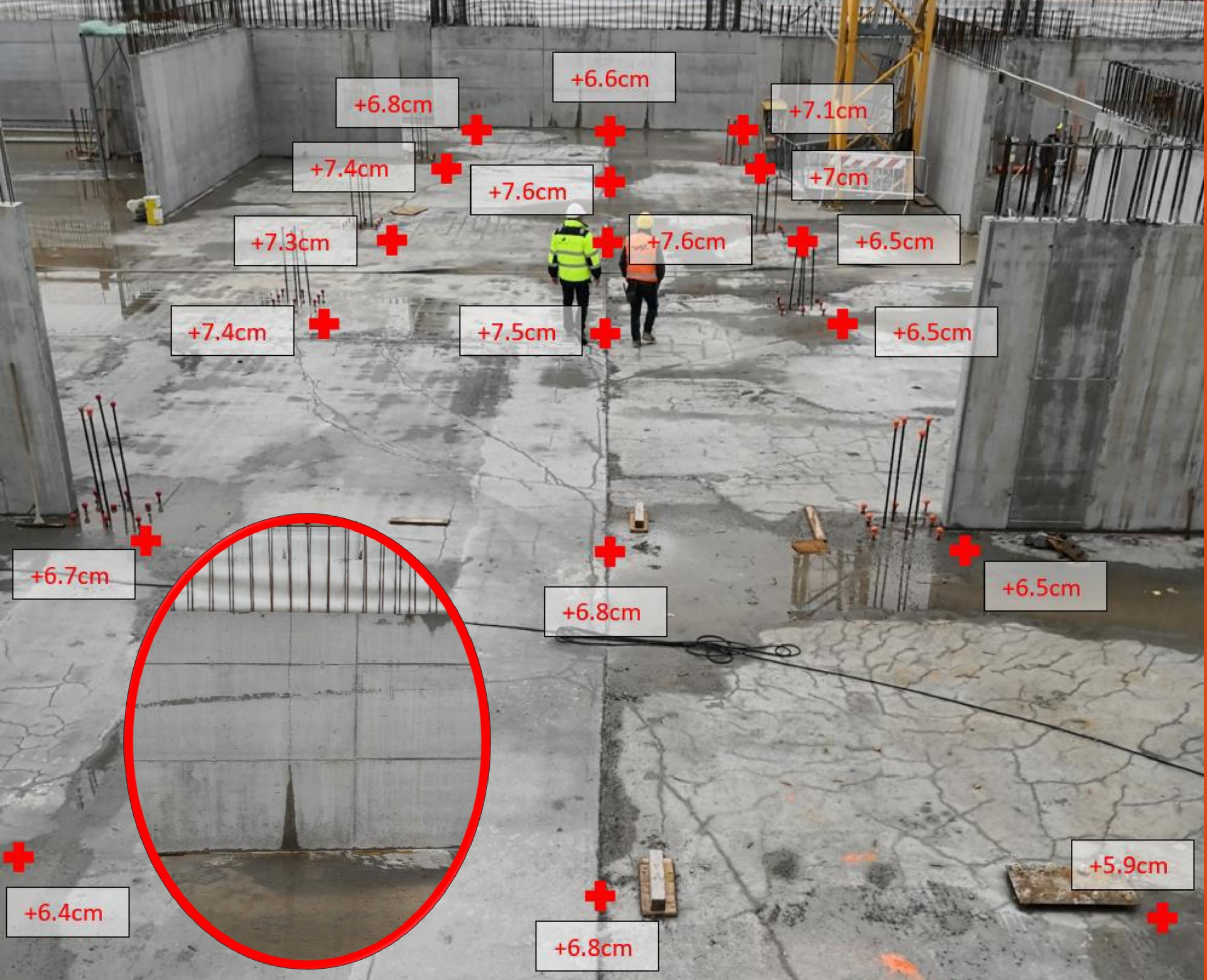
04

surveyed damage evaluation



Overview

Building during the construction phase.



Overview

Raft uplift occured on 12.11.2019, with major damage localized on the perimeter walls.

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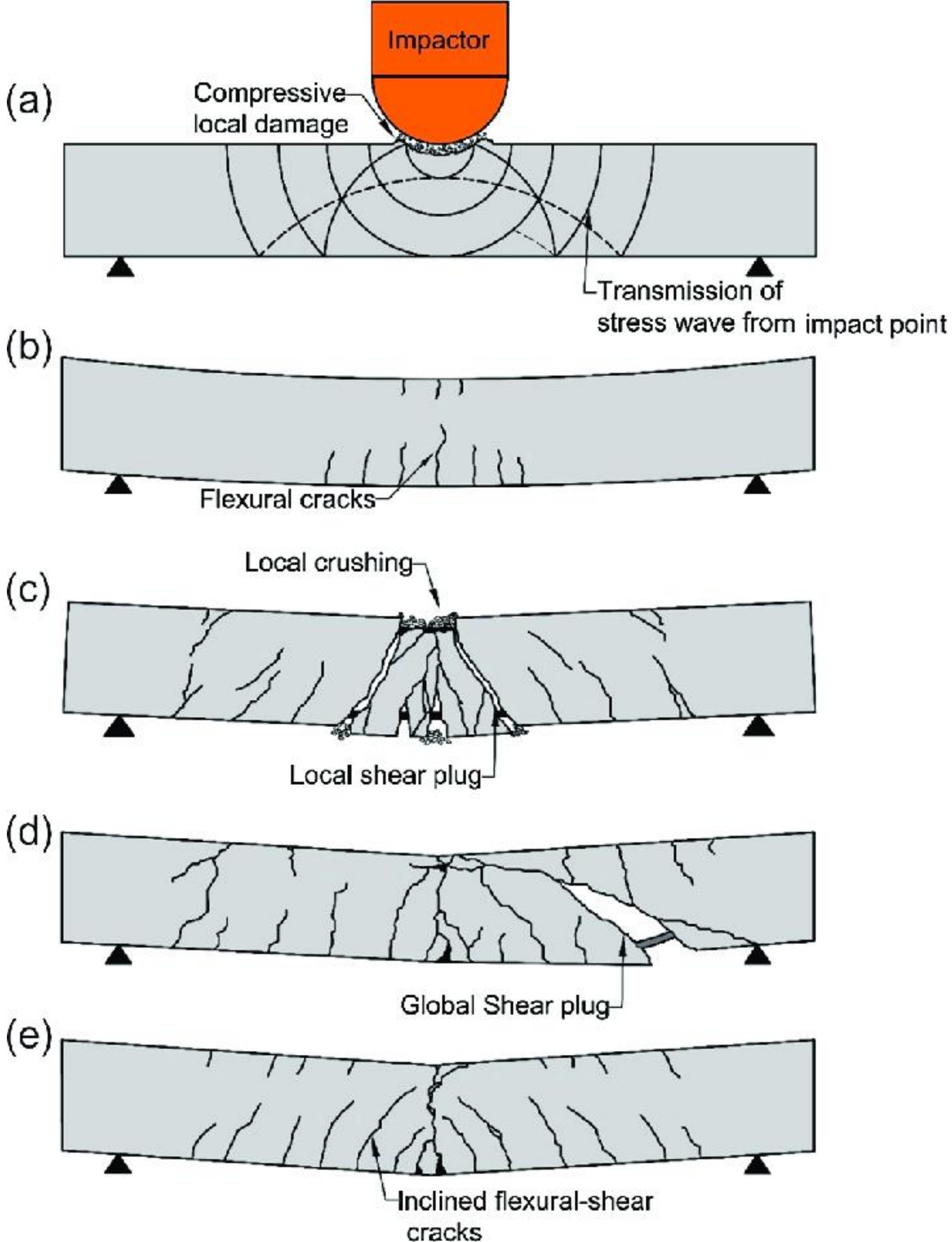
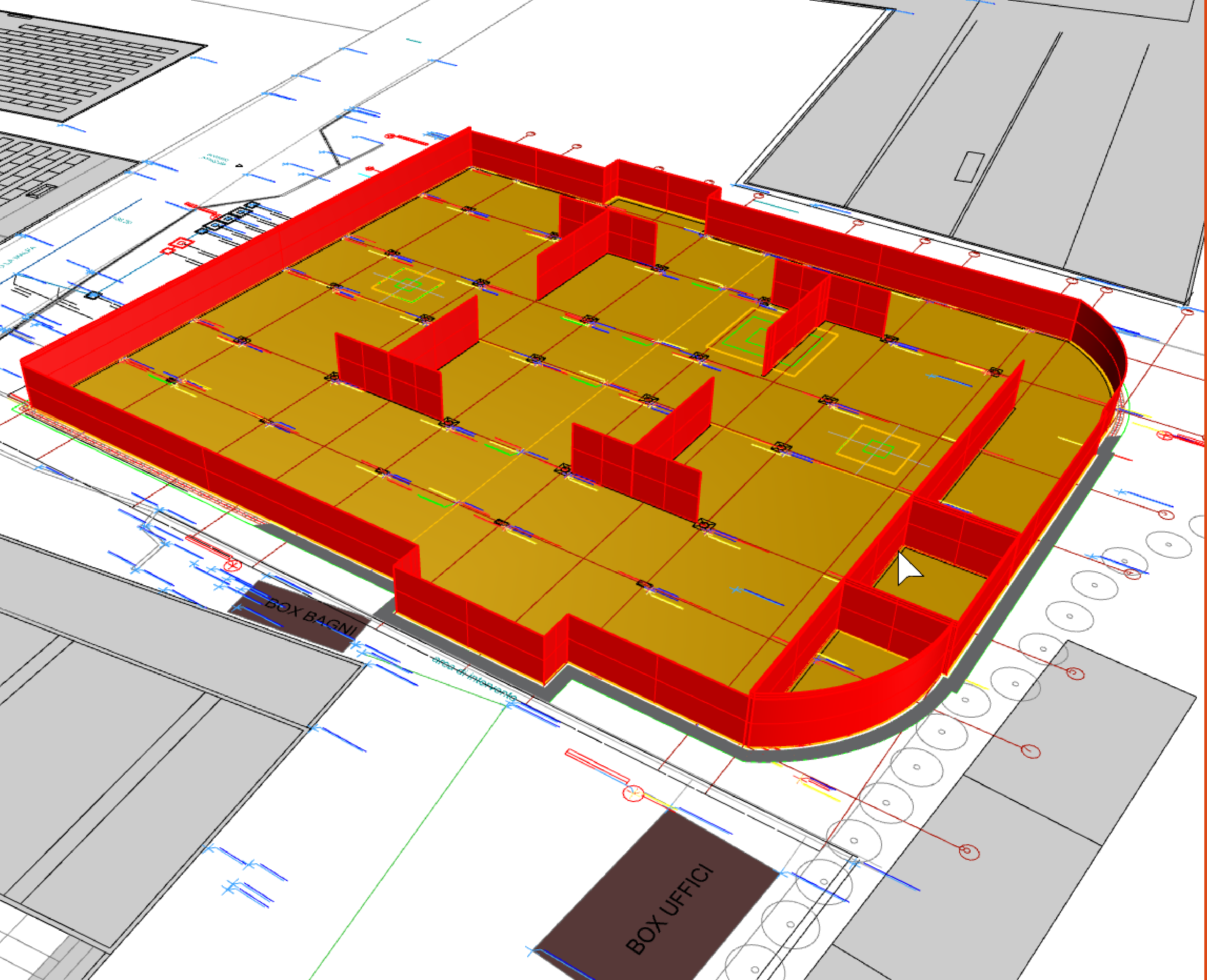


Cracking

Cracking occurs with several mechanisms and severity levels. So what was the cracking sevarity in raft?



Geometry

Geometry of the completed part of the building during the uplift event.

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DZ [mm]

12.11.2019

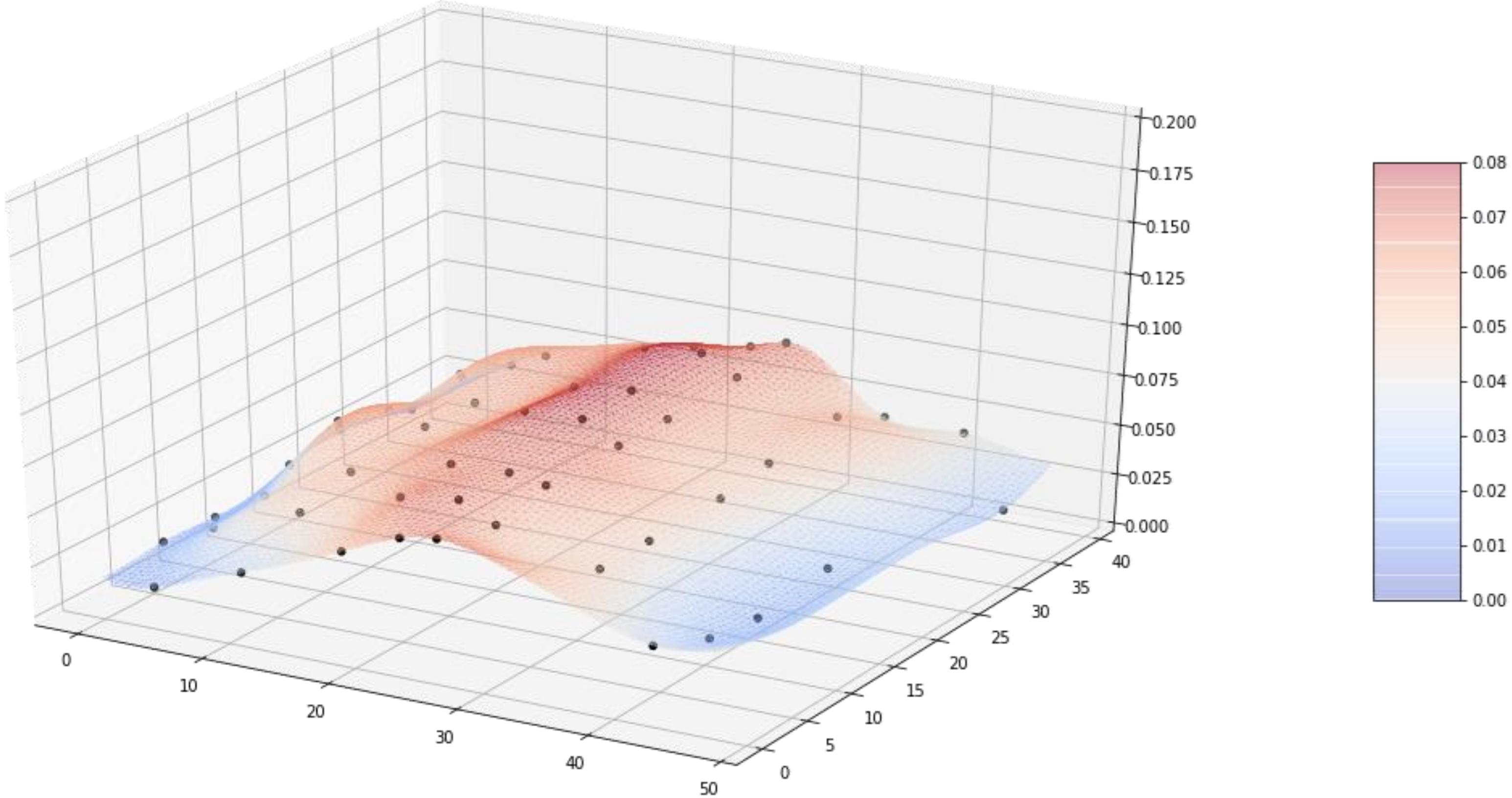
14.11.2019

18.11.2019

12.11.20	A	B	C	E	EF	F	H	I	J	K
1	36.178	35.878		35.91	33.377	33.381	35.89	35.882		
2	36.18	33.339	33.362	33.376	33.368	33.368	33.352			35.878
3	36.19	33.371	33.36	33.376	33.375	33.371	33.356			
4	36.187	33.361	33.358	33.375	33.371	33.359	33.349		36.162	
5	36.192	33.324	33.352	33.364	33.366	33.364	33.352		36.162	
7	36.182	33.331	33.343	33.358	33.375	33.357	33.341		36.166	
8		35.864	35.879	33.372	33.349	33.352			35.852	

14.11.20	A	B	C	E	EF	F	H	I	J	K
1	36.141	35.834	33.301	35.868	33.316	33.317	35.851	35.843		
2	36.155	33.288	33.322	33.329	33.32	33.331	33.31	33.31		35.85
3	36.161	33.322	33.325	33.337	33.32	33.331	33.321		33.287	
4	36.161	33.309	33.328	33.34	33.324	33.328	33.317		36.144	
5	36.175	33.298	33.325	33.337	33.327	33.333	33.328		36.15	
7	36.168	33.311	33.319	33.333	33.338	33.332	33.316		36.154	
8	36.165	35.851	35.866	33.346	33.311	33.312	33.32		35.828	

18.11.20	A	B	C	E	EF	F	H	I	J	K
1	36.154	35.843	33.304	35.849	33.311	33.31	35.848	35.841		
2	36.159	33.295	33.301	33.302	33.292	33.301	33.296	33.303		35.854
3	36.16	33.327	33.304	33.303	33.299	33.306	33.304		33.288	
4	36.162	33.309	33.301	33.301	33.296	33.294	33.301		36.139	
5	36.174	33.29	33.298	33.297	33.298	33.299	33.305		36.143	
7	36.163	33.3	33.296	33.294	33.307	33.298	33.294		36.143	
8	36.168	35.847	35.846	33.319	33.284	33.284	33.301		35.816	



Deformed shape

Displacement implementation with a fitted surface (Kriging Metamodel).

Looking for the effects of the deformation and not for the causes.

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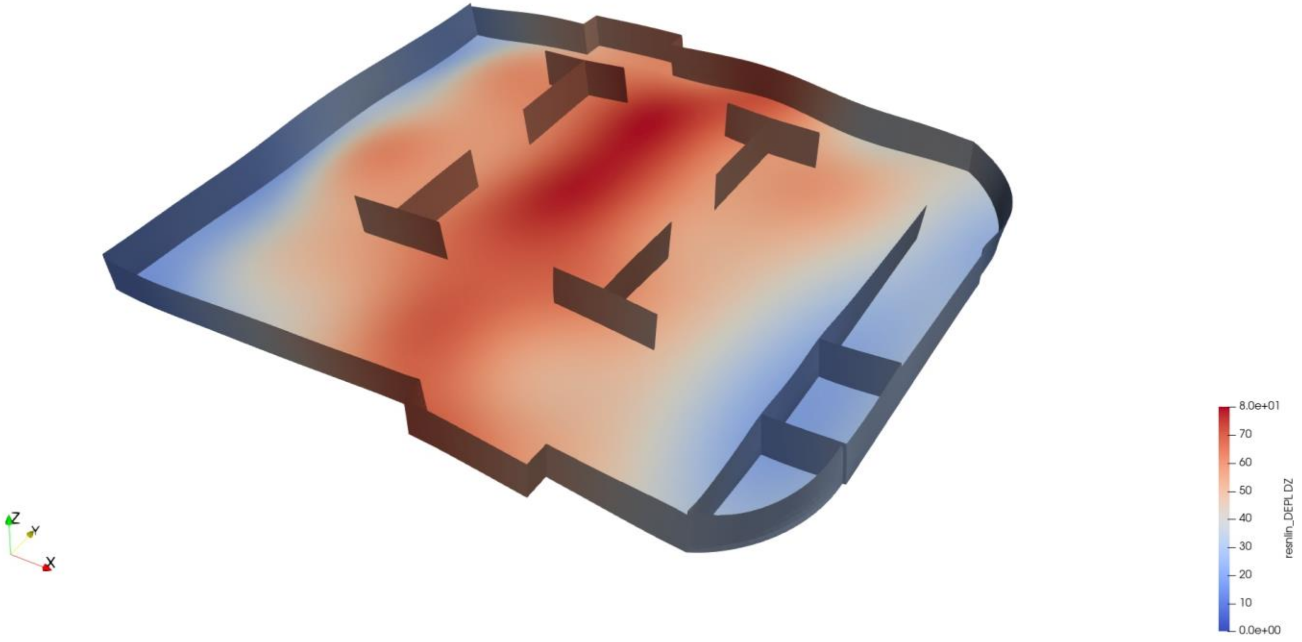
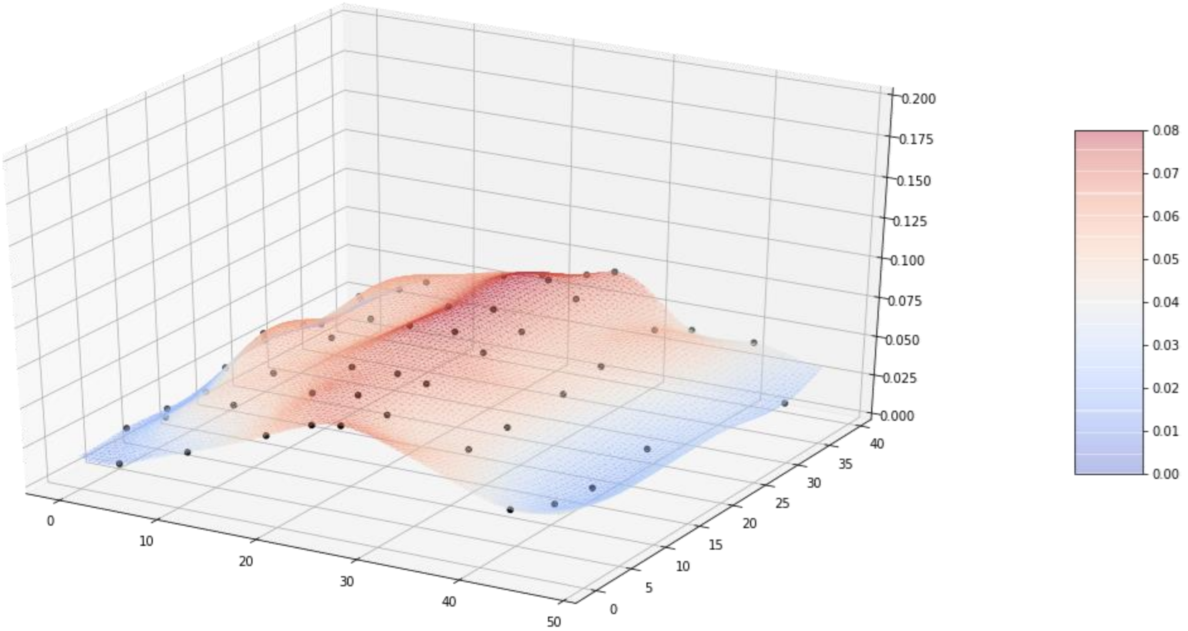
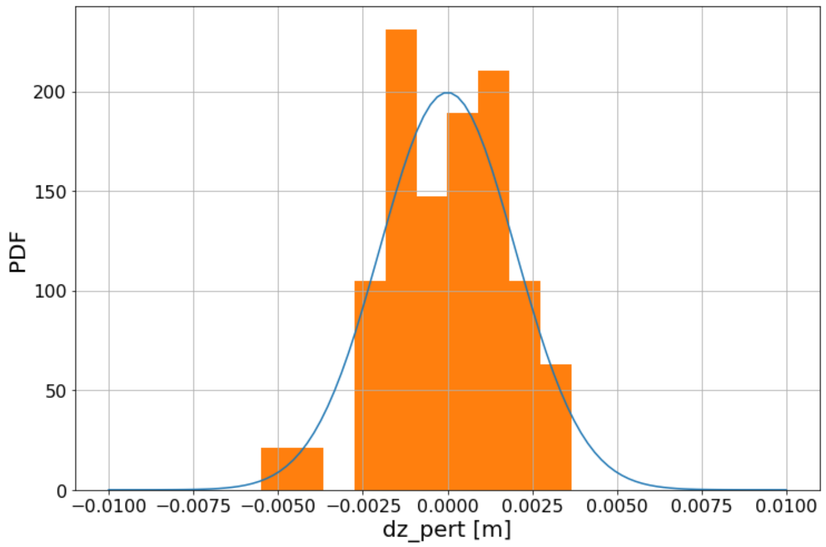
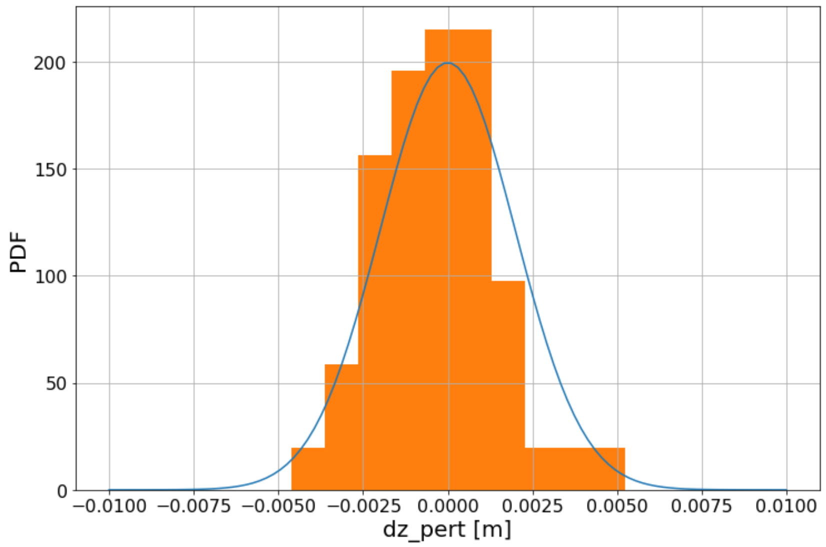


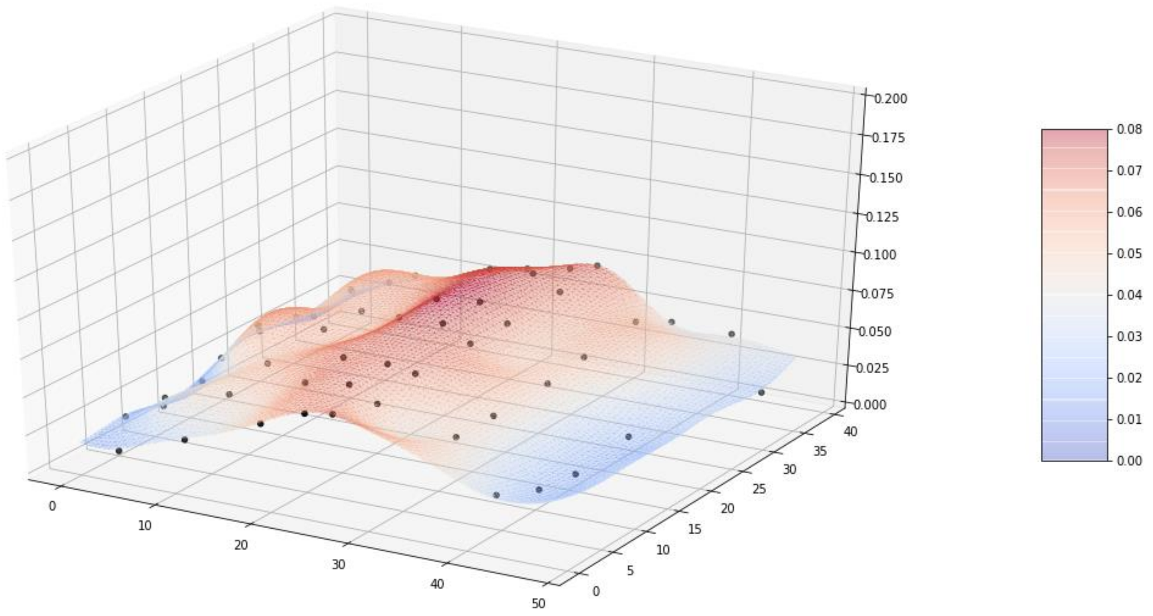


Results

Vertical displacement comparison.

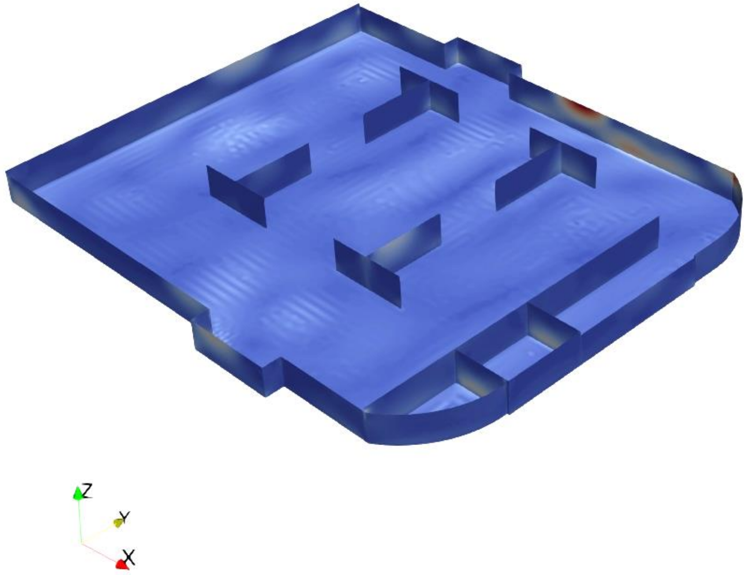


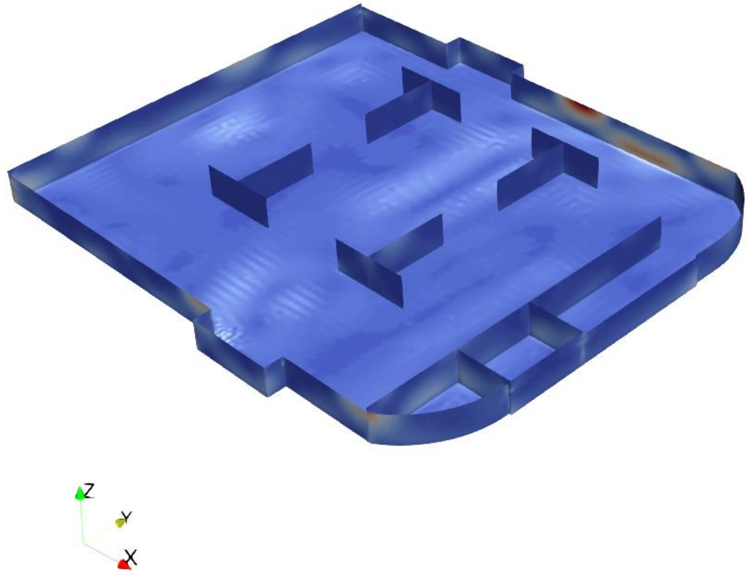


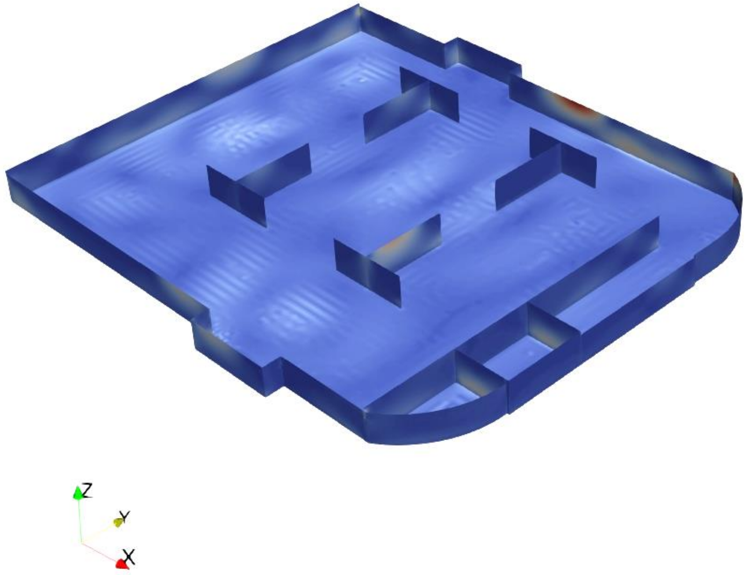


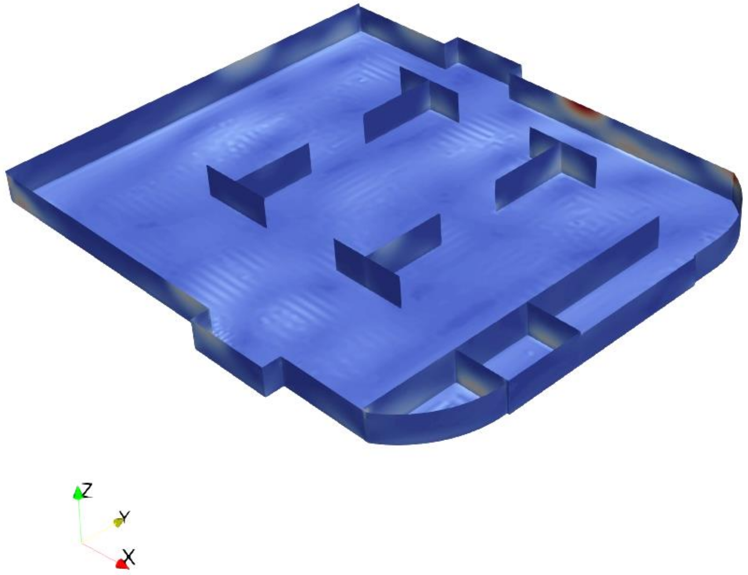
Results

Sensitivity to perturbation (max entity 5.5 mm). Perturbation standard deviation is approximately equal to 30% of the mean vertical distorsion









Results

Damage level comparison.

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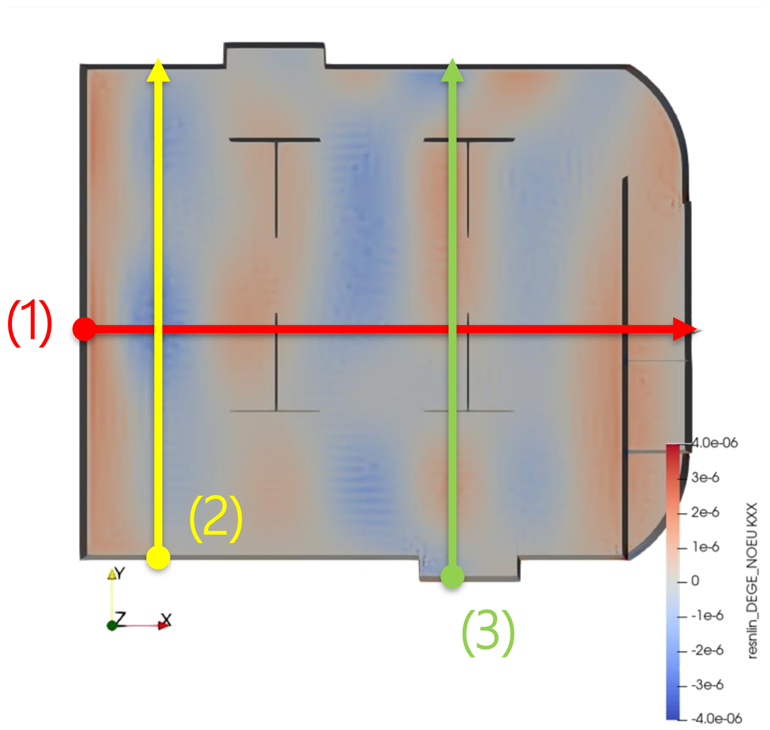
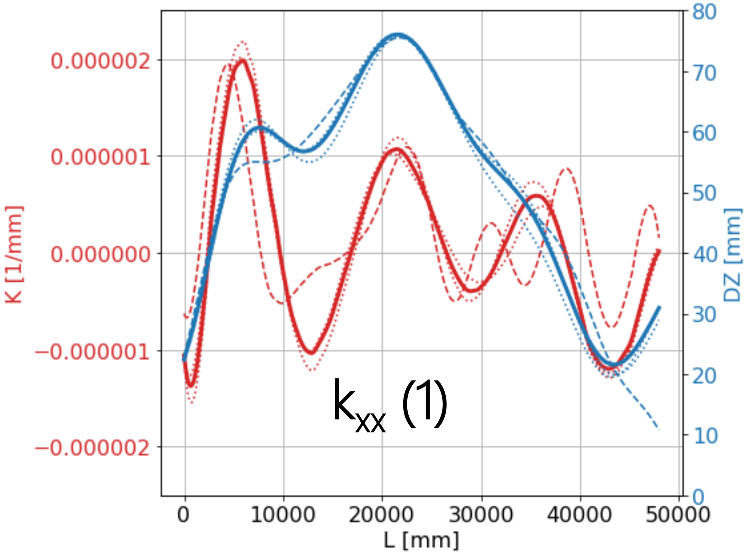
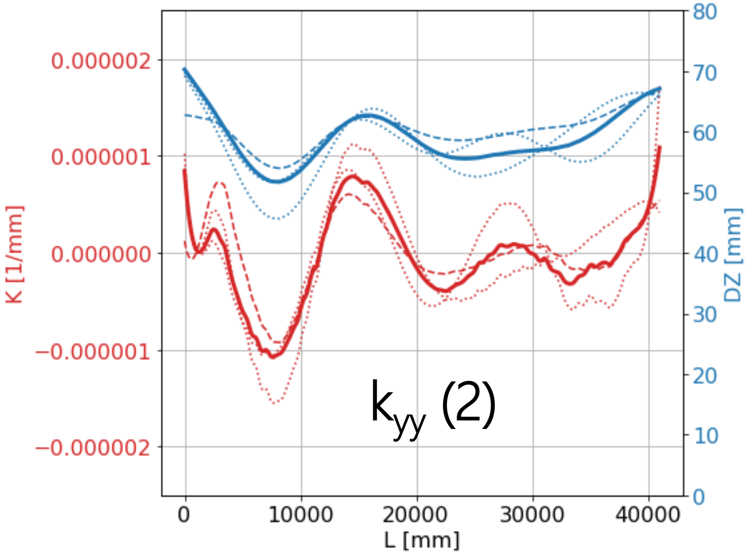
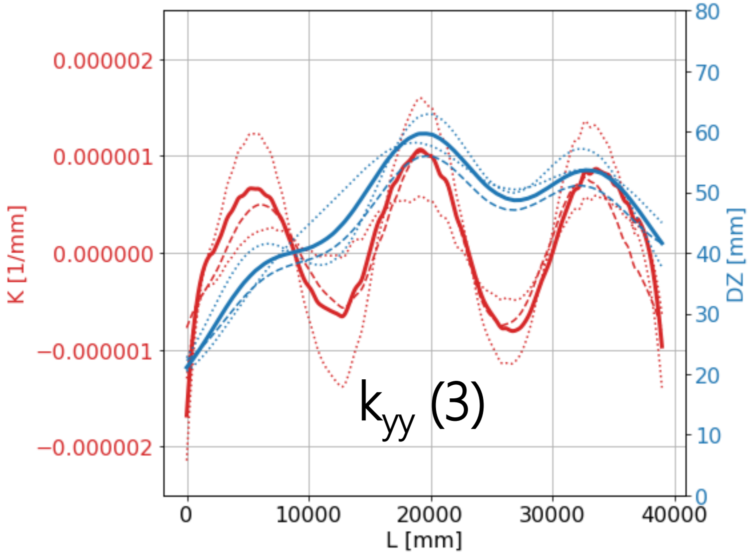


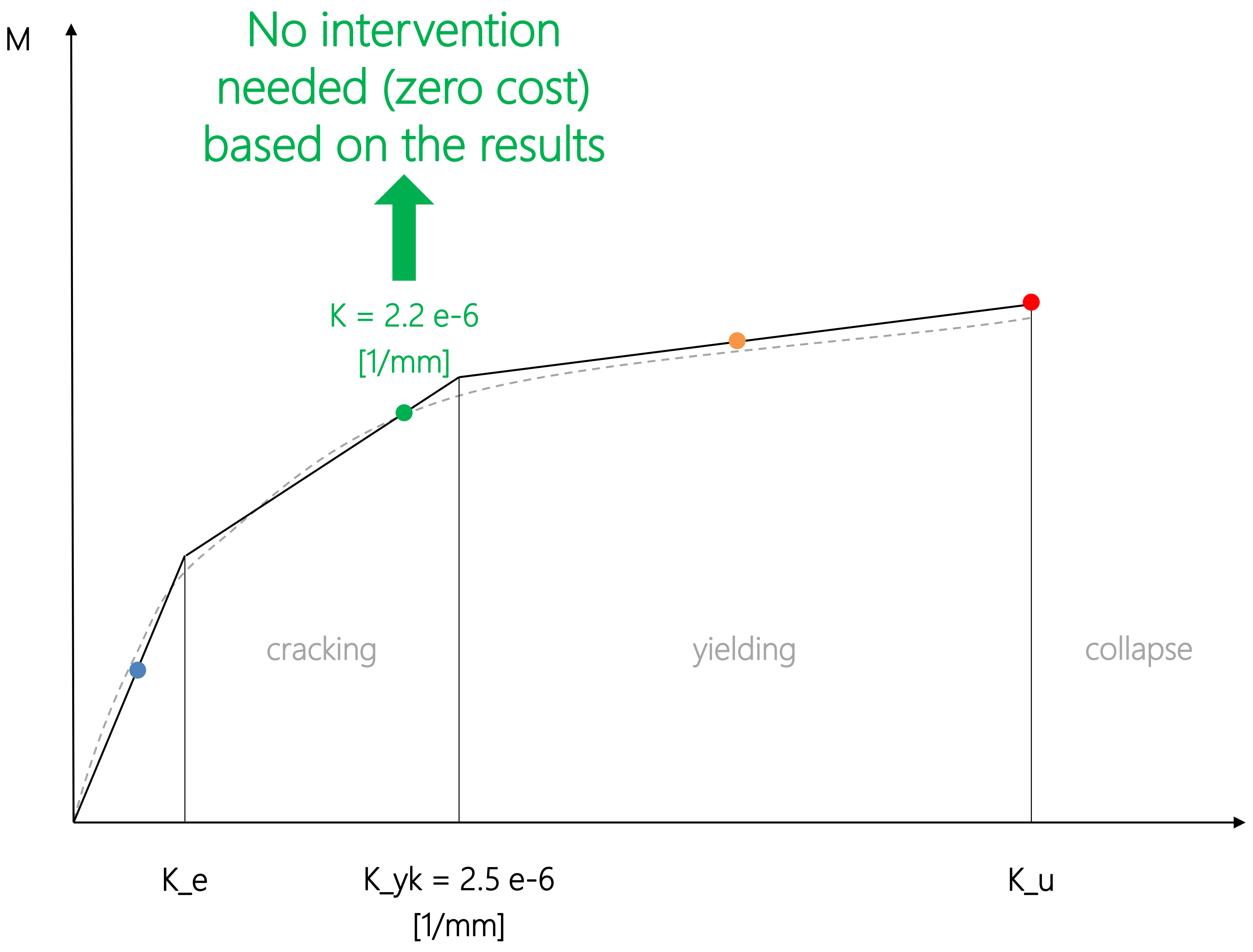


Results

The result is an increase of 10% of the maximum curvature.







Results

Comparison with the critical limits: the concrete in the raft has not exceeded the elastic limit in compression and the steel hasn't reached the yielding limit.

05

simulated damage scenarios

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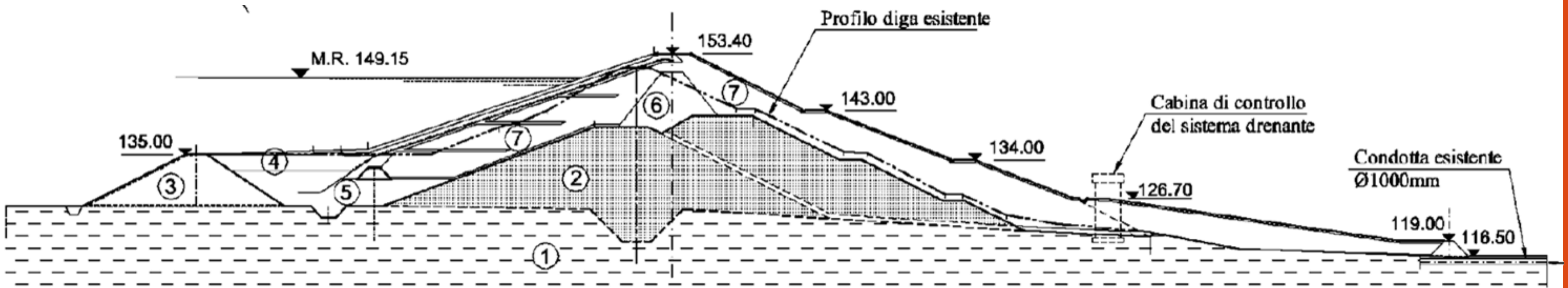

Context

Earth dam.

1975 - costruction

1990 - landslide

1993 – refurbishment for temporary reuse

1995 – Executive design and modifications for a total renovation.

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Aims

1. Stability assessment in seismic conditions;

2. Vertical displacements assessment in seimic conditions (compliance with vertical freeboard);

3. Post-earthquake vulnerability.

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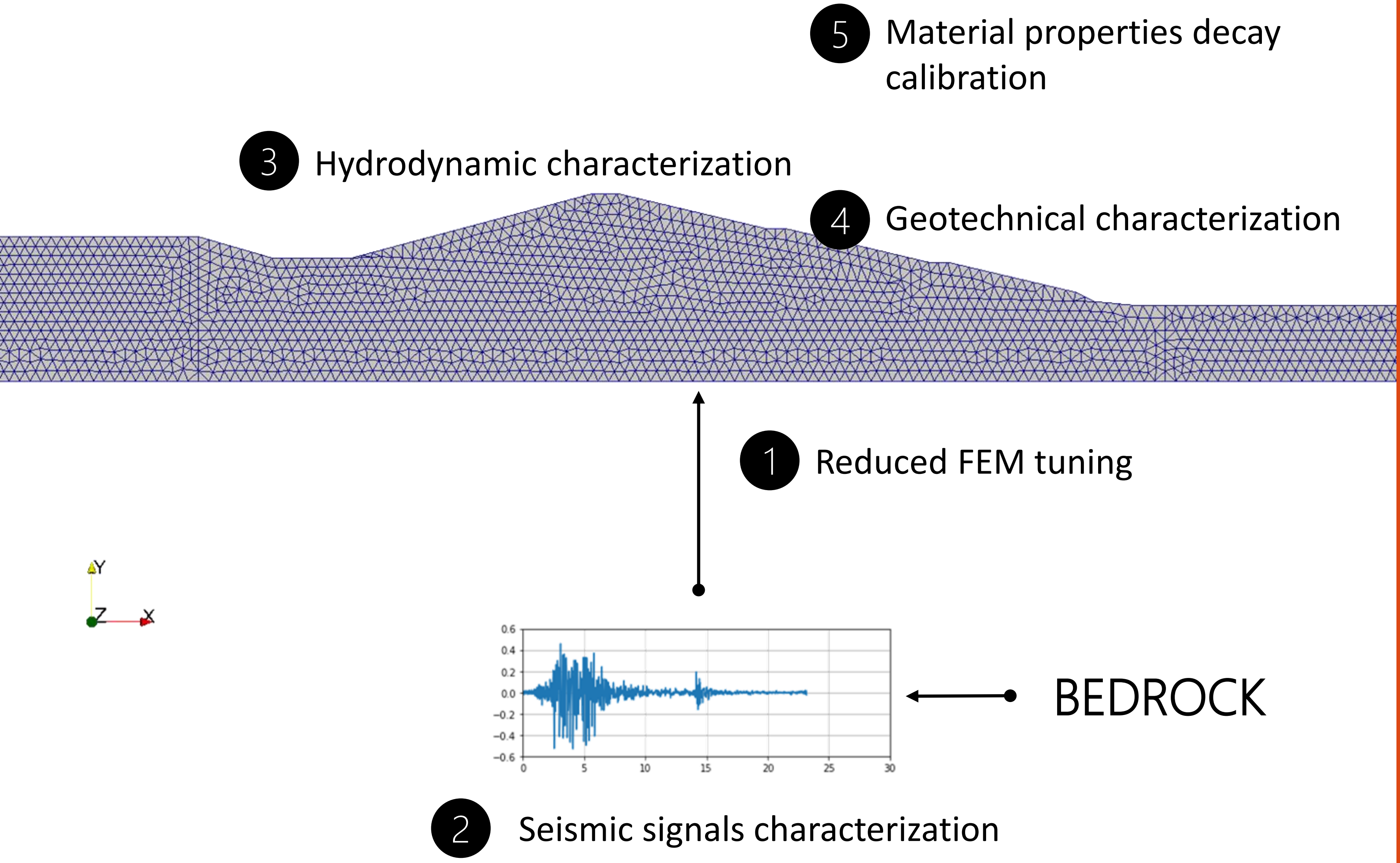

Critical issues

Physical problem (earthquake) transposed into FE analysis through **nonlinear dynamic analysis.**

1) Reduced FEM tuning
2) Seismic signals characterization
3) Hydrodynamic characterization
4) Geotechnical characterization
5) Material properties decay calibration

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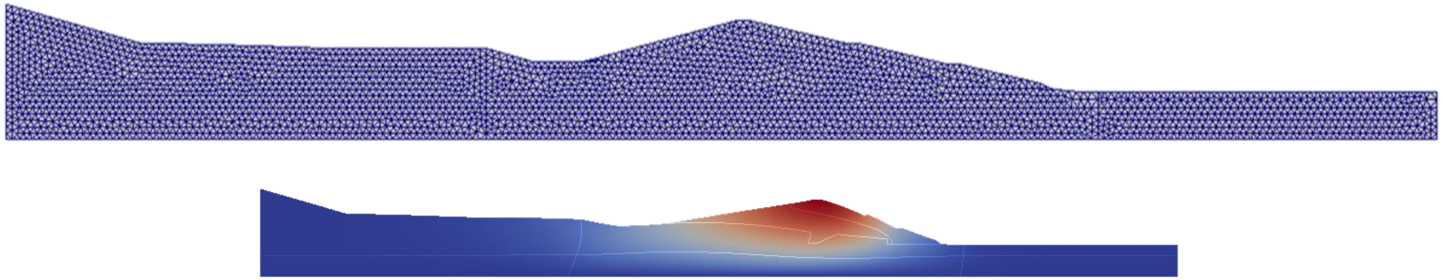
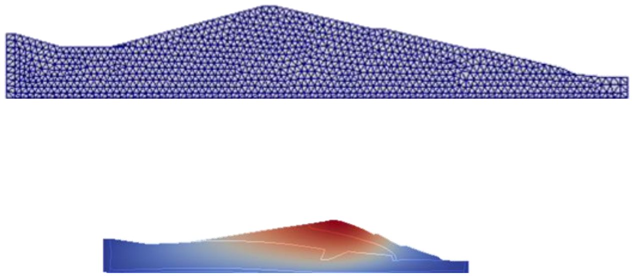
Reduced FEM tuning

Need of limit/reduce the computational burden. A tuning procedure of the **reduced model (b)** in its **extended environment (a)** is implemented through a **parametric modal analysis**.

a Full model



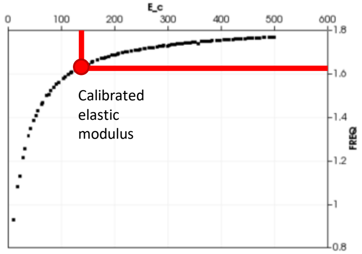
b Reduced model



Extreme borders areas replacement with two thin elastic layers (stiffness is the calibration parameter).

salome_meca
EXPERIENCE OPEN SIMULATION

OpenTURNS



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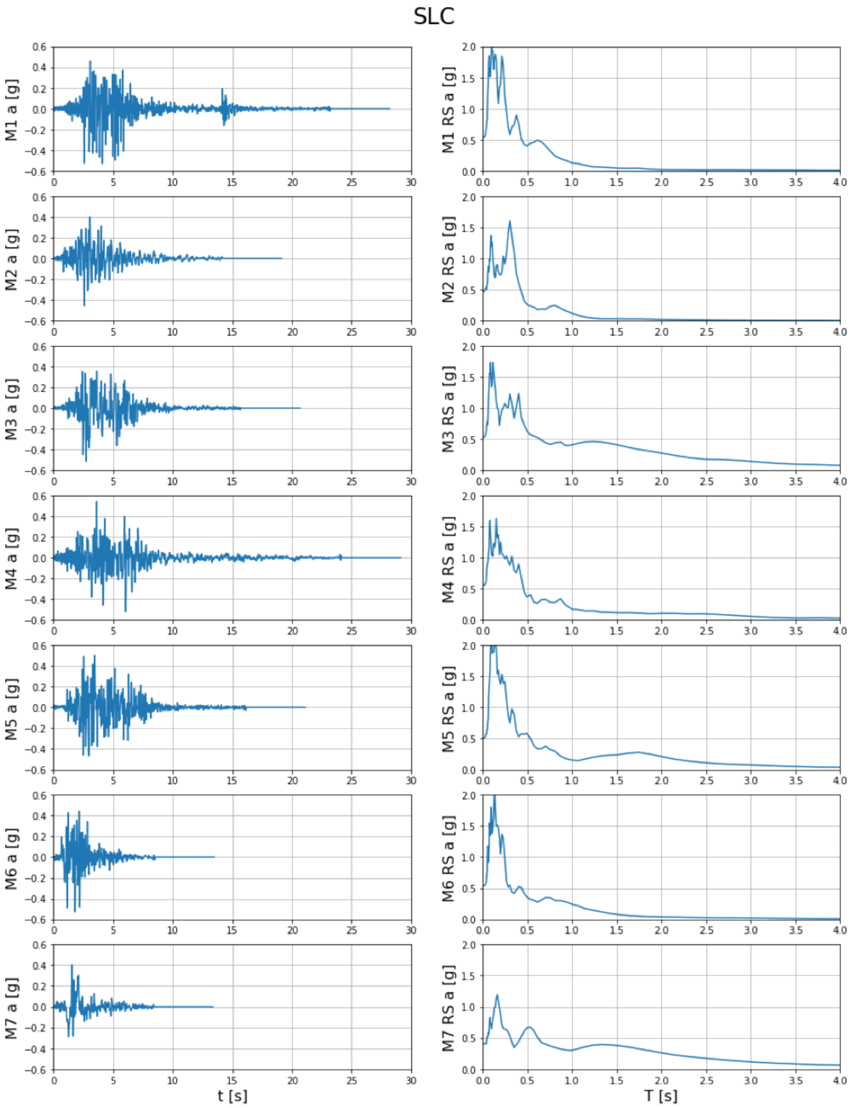
Seismic input characterization



28 SEISMIC SIGNALS

- 7 SLO (Operability Limit State),
- 7 SLD (Damage Limit State);
- 7 SLV (Life's Safeguard Limit State);
- 7 SLC (Collapse Limit State).

A constant zero value tale of 5 seconds is added at the end of each signal to observe the free oscillations state.

Signal are **applied at the dovetail's level** (hp. of close bedrock) and are filtered by the upper layers, generating an amplification compared to the "free field" signal.

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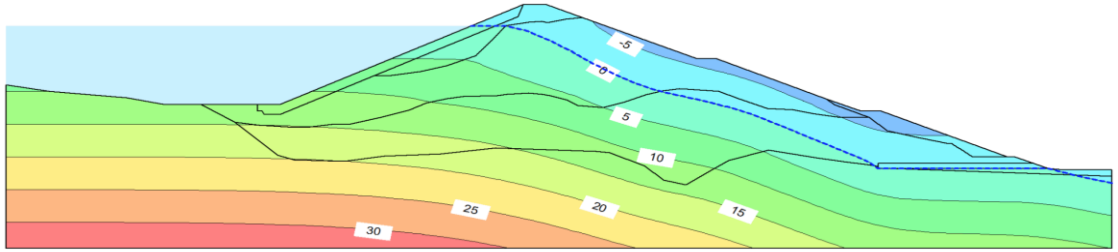
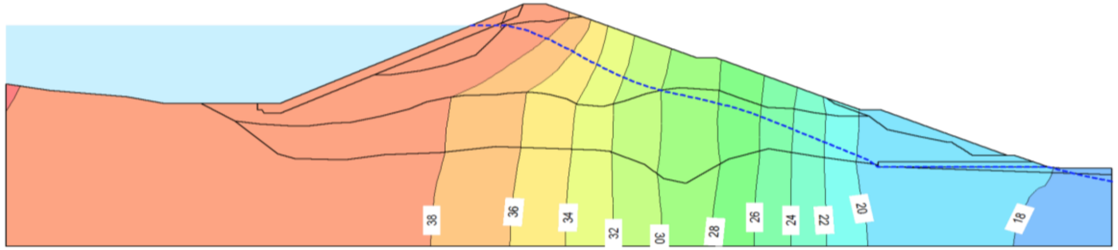
Initial distribution of interstitial pressures





Interstitial pressures effect is more influent in drained conditions, where the resistance is also governed by effective pressure.

Hydrodynamic characterization

The **THM** (Thermo-Hydraulique-Mecanique) modellation allows the definition and the evolution's study of porous materials (saturated and unsaturated). The hydrodynamic load is negligible compared to the seismic one.

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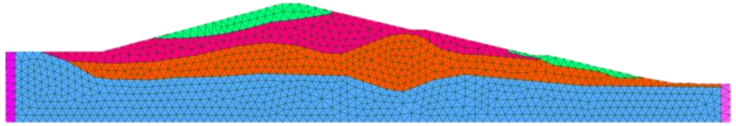

Proprietà	Descrizione	UDM	LA	AL	LA2	SUB
K_0	Compressibility modulus	[MPa]	401,2	759,3	1274	12122
E_0	Elastic modulus	[MPa]	231,5	400,5	735,4	1810,8
G_0	Shear modulus	[MPa]	82,44	141,80	147	599
ν_0	Poisson's coefficient	[MPa]	0,40	0,41	0,44	0,46
ρ	Material density	[kg/m³]	2044,5	1935,5	2109,0	2169,3
φ	Internal friction angle	[°]	21,6	24,2	23,4	23,6
ψ	Dilatancy angle	[°]	21,6	24,2	23,4	23,6
c'	Effective cohesion	[MPa]	0,024	0,023	0,022	0,024
c_u	Undrained cohesion	[MPa]	0,074	0,076	0,073	0,146
e	Porosity	[%]	31,85	34,94	30,4	32,3
p	Permeability	[m/s]	1,00E-07	1,00E-08	1,00E-07	1,00E-08

```
| MOHR_COULOMB = _F (
                ♦ PHI = phi, [R]
                ♦ ANGDIL = angdil , [R]
                ♦ COHESION = cohes, [R]
                )
```

Geotechnical data

The available geotechnical data are insufficient to define Hujeux parameters (and also Cam-Clay one). Mohr-Coulomb's law is adopted as its definition requires only few parameters.

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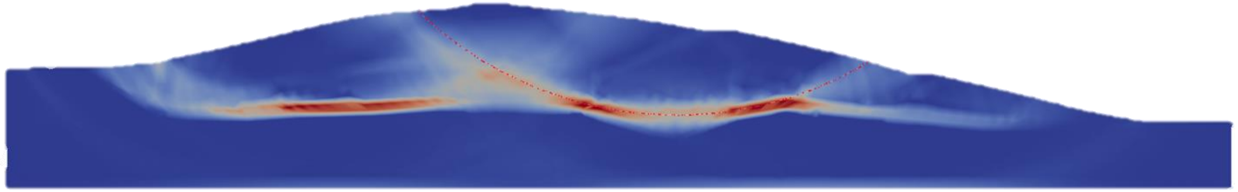
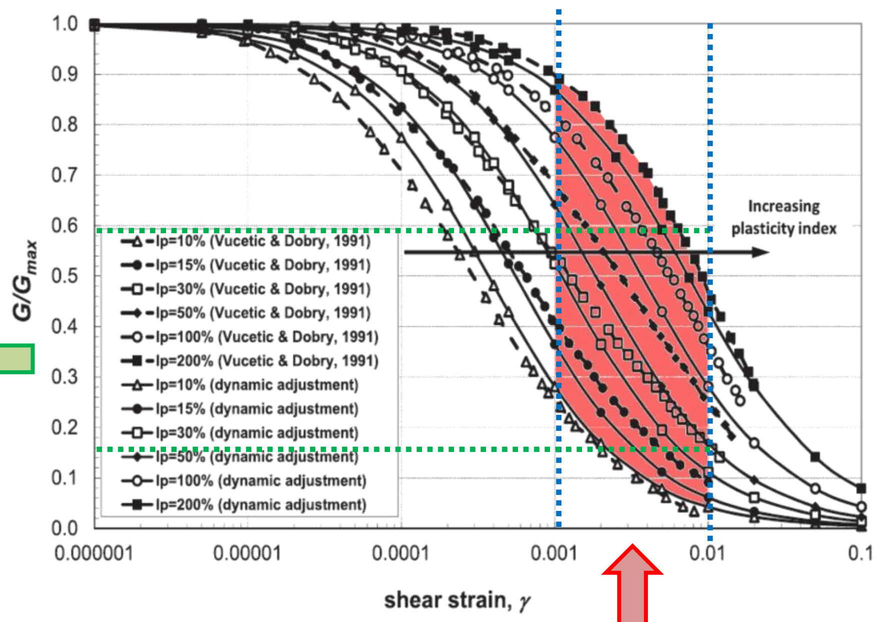
Parameters decay

Assumed according to the cyclical behaviour of the material. A decay factor is hypothesized for the reduction of elastic properties (c_Ered is applied to shear modulus).



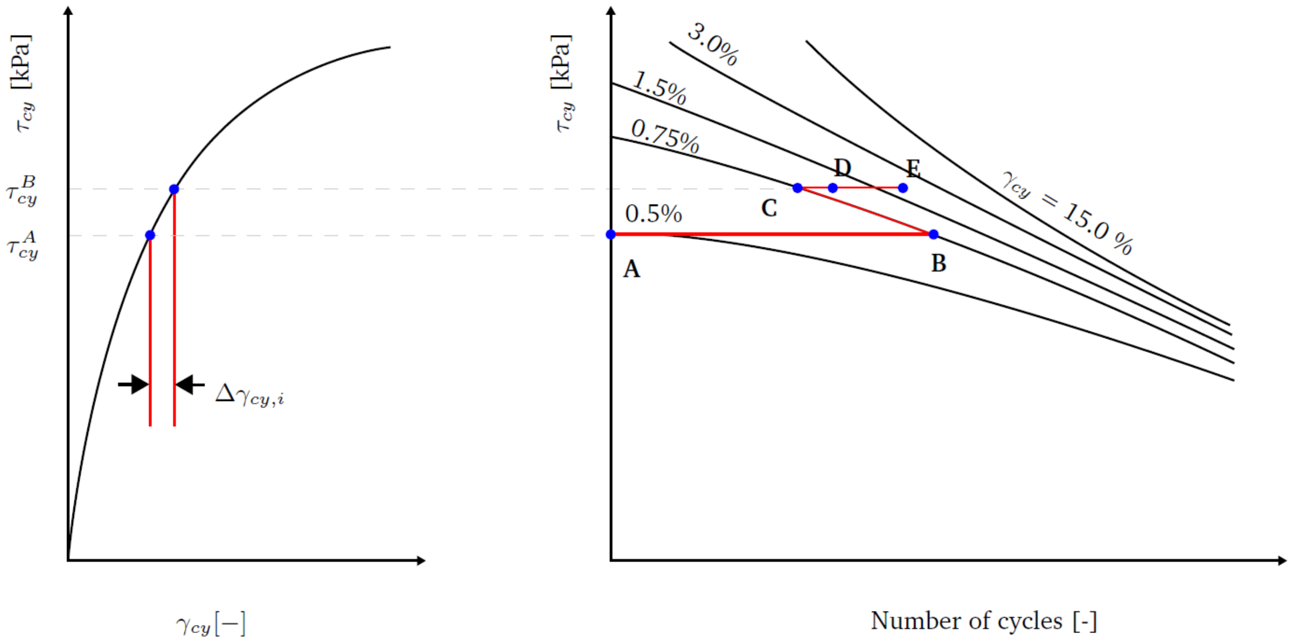
- Sliding surfaces identification (maximum shear strain);
- Assumption of deformation cycles between 0.1 and 1% contained into those surfaces.

Shear modulus reduction between 20÷50 % of the original one (c_Ered=0.2÷0.5).



$0.1\% < \gamma < 1\%$

From P. J. Vardanega, and M. D. Bolton, *Stiffness of Clays and Silts: Normalizing Shear Modulus and Shear Strain*, JOURNAL OF GEOTECHNICAL AND GEOENVIRONMENTAL ENGINEERING, ASCE / SEPTEMBER 2013



From C. Rasch, *Modelling of cyclic soil degradation, Development of a cyclic accumulation model and the application to a gravity based foundation*, Phd thesis from Delft University of Technology, Faculty of Civil Engineering and Geosciences, 2016

Parameter sdecay

The increment of deformation caused by cyclic behaviour is taken into account also by a reduction factor **c_Cred** applied to resistance properties (cohesion, firiction/dilatance angles).

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```
VALE=(
_F(c_Ered=0.25, c_Cred=0.7),
_F(c_Ered=0.25, c_Cred=0.75),
_F(c_Ered=0.25, c_Cred=0.8),
_F(c_Ered=0.25, c_Cred=0.85),
_F(c_Ered=0.25, c_Cred=0.9),
_F(c_Ered=0.3, c_Cred=0.7),
_F(c_Ered=0.3, c_Cred=0.75),
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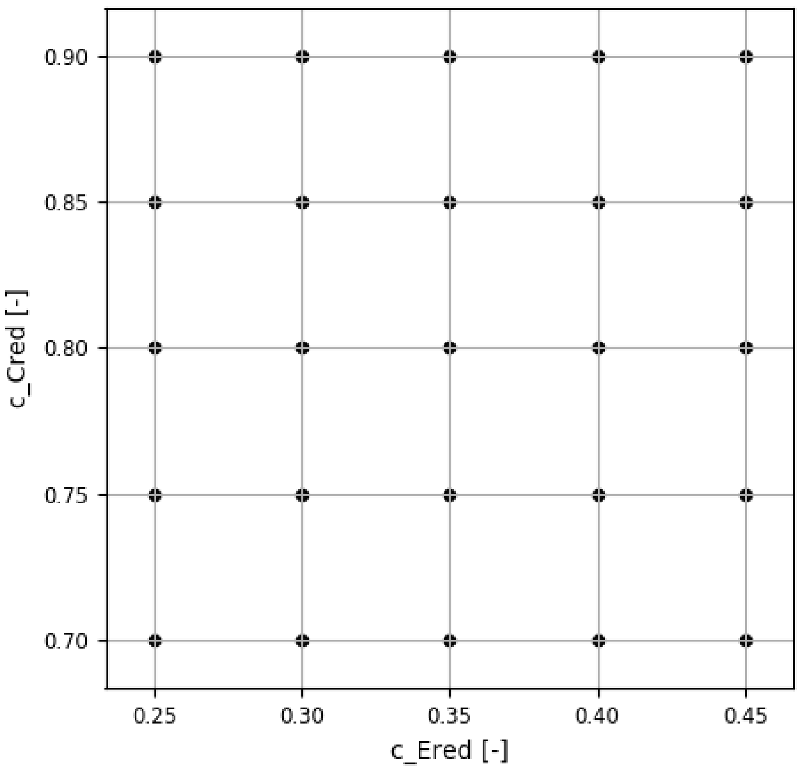

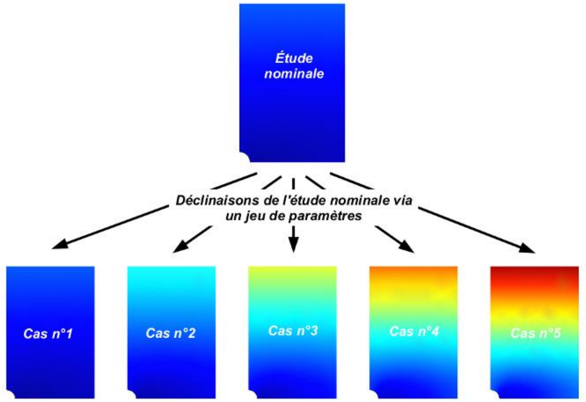

Parametric analysis

Creation of a grid of reduction factors values used as inputs for **25 analysis**. The output is set as the maximum vertical displacement of the freeboard.

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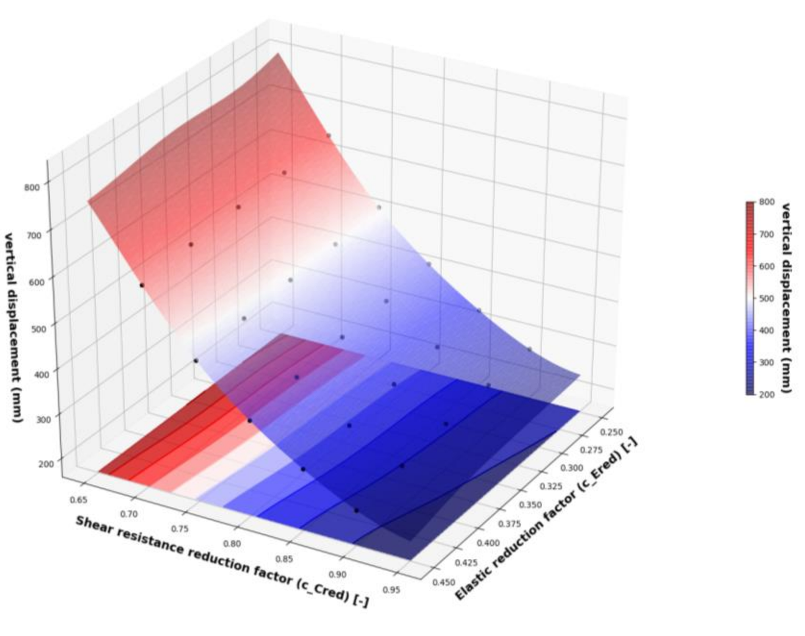
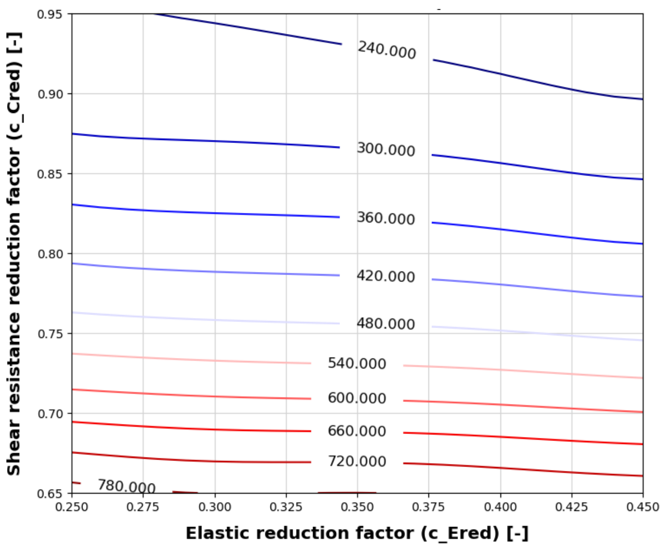
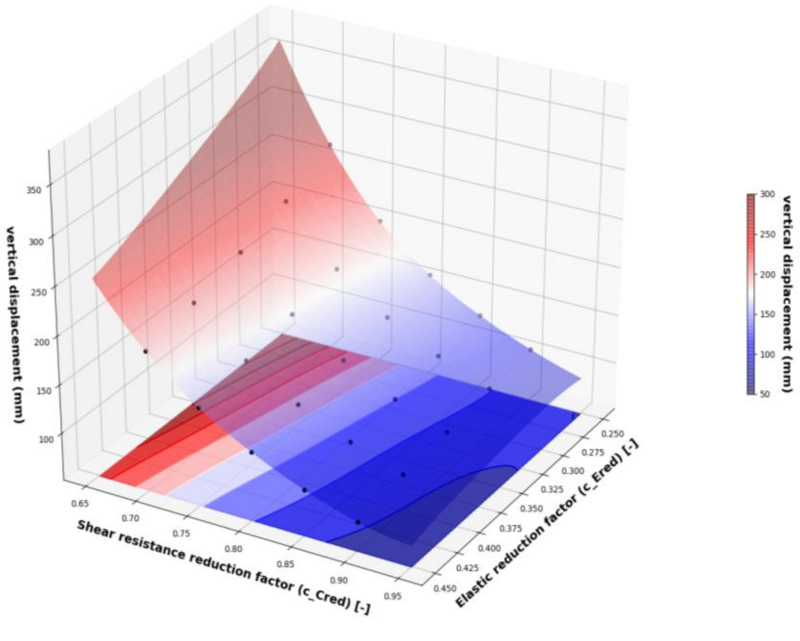
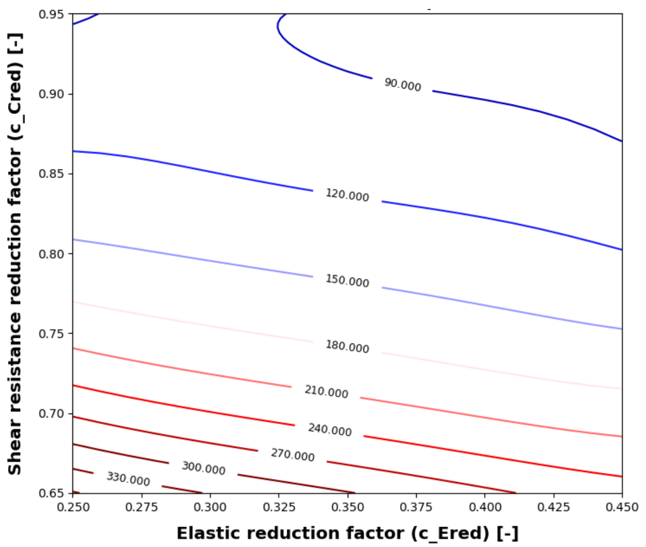
SLC_M3 metamodel





SLC_M7 metamodel





Metamodel

A **metamodel** (Kriging) has been set up based on different time history. The **input-output relation** is described by an interpolating surface. It allows to explore the design space, make predictions on untried values and assess the influence of each parameters on the output.

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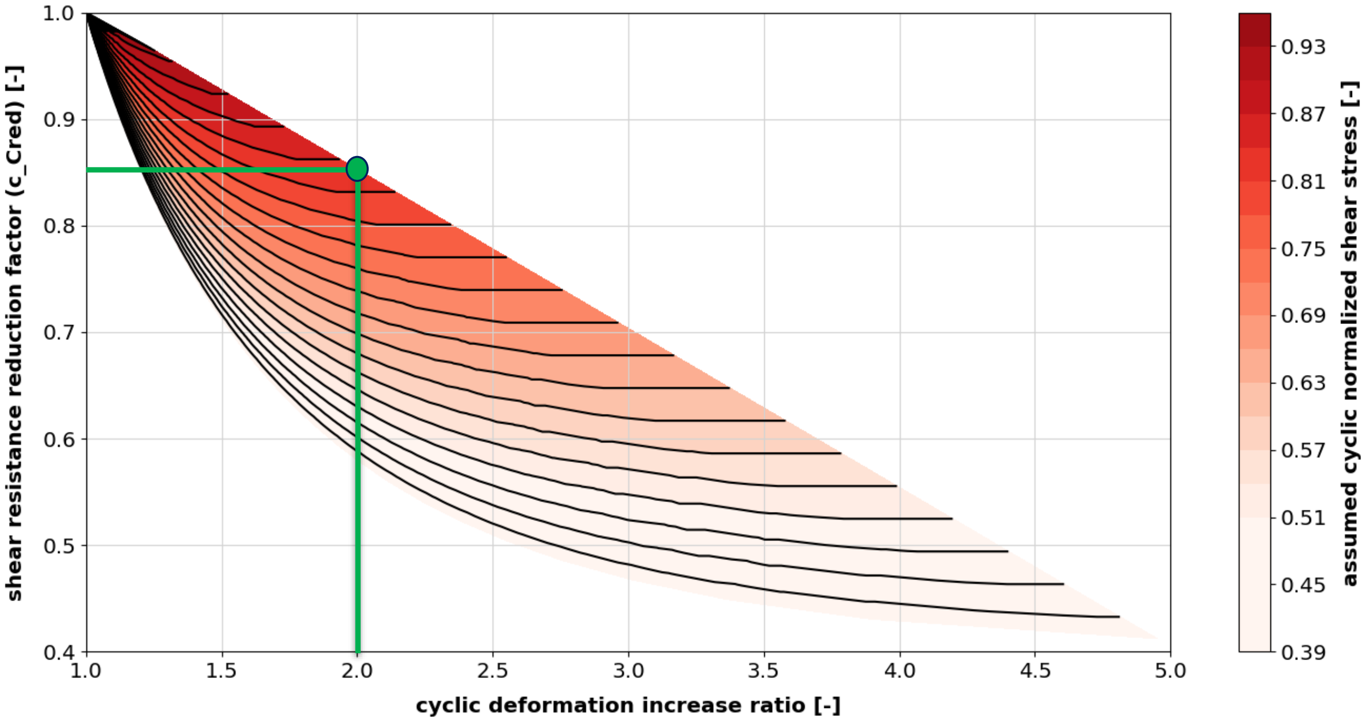

Analytical estimation

A metamodel (Kriging) has been set up based on 25 analysis (SLC_M7) where at each set of input variables (c_Ered, c_Cred) is associated an output (freeboard vertical displacement).

It allows to explore the relationship between inputs and outputs and make predictions on untried values.

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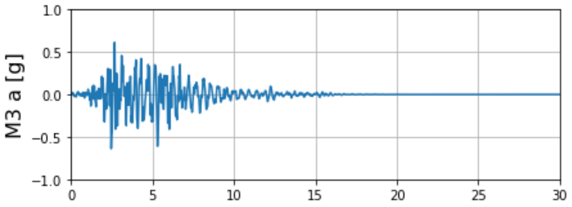
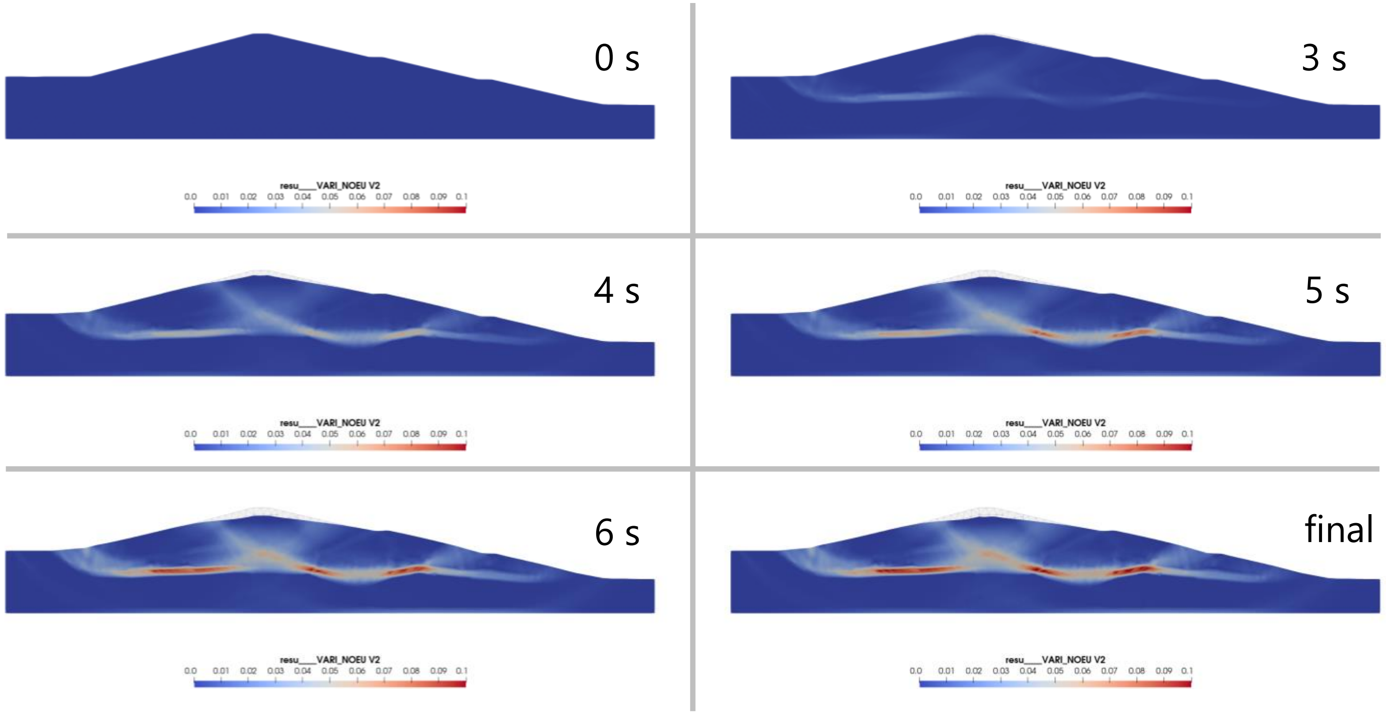
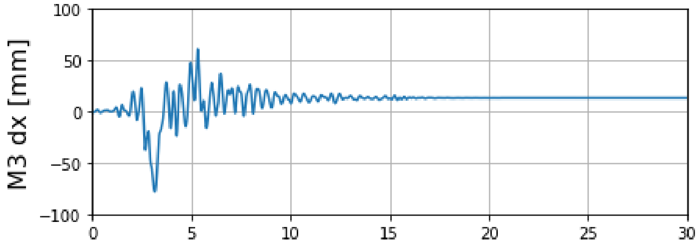
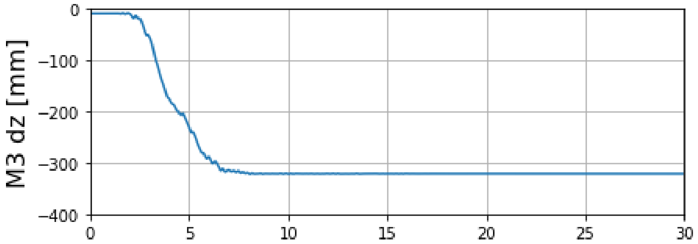
Damage and sliding surfaces evolution during the seismic signal for SLC_M3 time history





Horizontal and vertical displacement (top of dam) for SLC_M3 time history

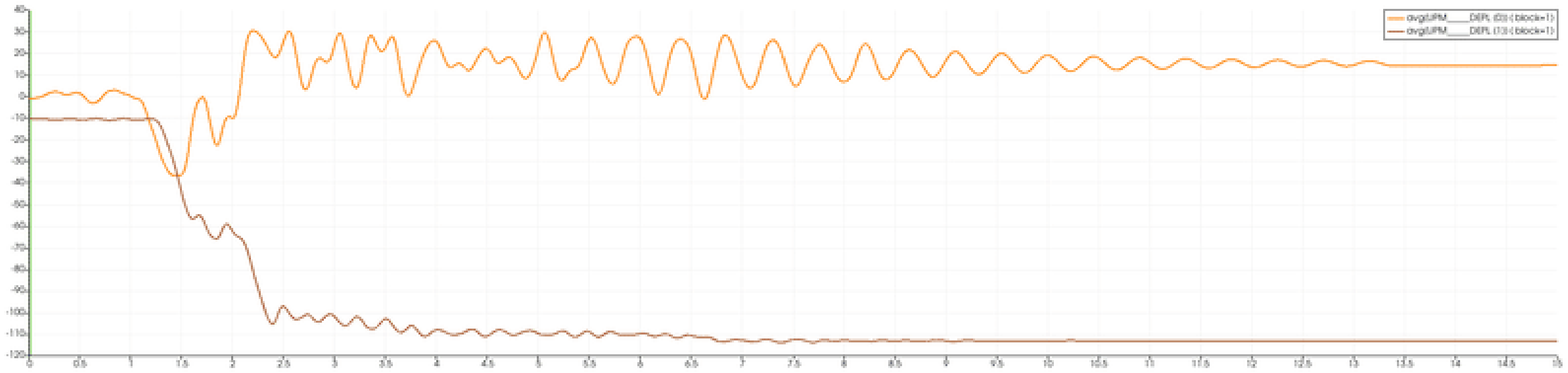




Results

Vertical and horizontal displacements are evaluated for each time history.

Damage evolution



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conclusions and perspectives

Conclusions

OpenTURNS and code_aster, combined or standalone, offer an extremely useful set of tools the following purposes:

- The **model calibration**, an important phase of the structural health monitoring is feasible combining different techniques;
- Validated surrogate or **meta-models** have a great efficiency and can be adopted for different purposes;
- The **damage identification** procedure can be applied both in qualitative and quantitative approaches;
- The **uncertainty quantification** can be approached to better understand the input or output parameters correlation;
  - These techniques become application-prone in the engineering context as **decision tools**.

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