The 42nd Risk, Hazard & Uncertainty Workshop

Hydra Island, June 22-25, 2016

Design of structures for tolerable seismic risk using non-linear methods of analysis

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Introduction and motivation

- Current building codes do not support design for a target seismic risk
- Basic research project: development of the methodology and tools for the design of structures for tolerable seismic risk using non-linear methods of analysis

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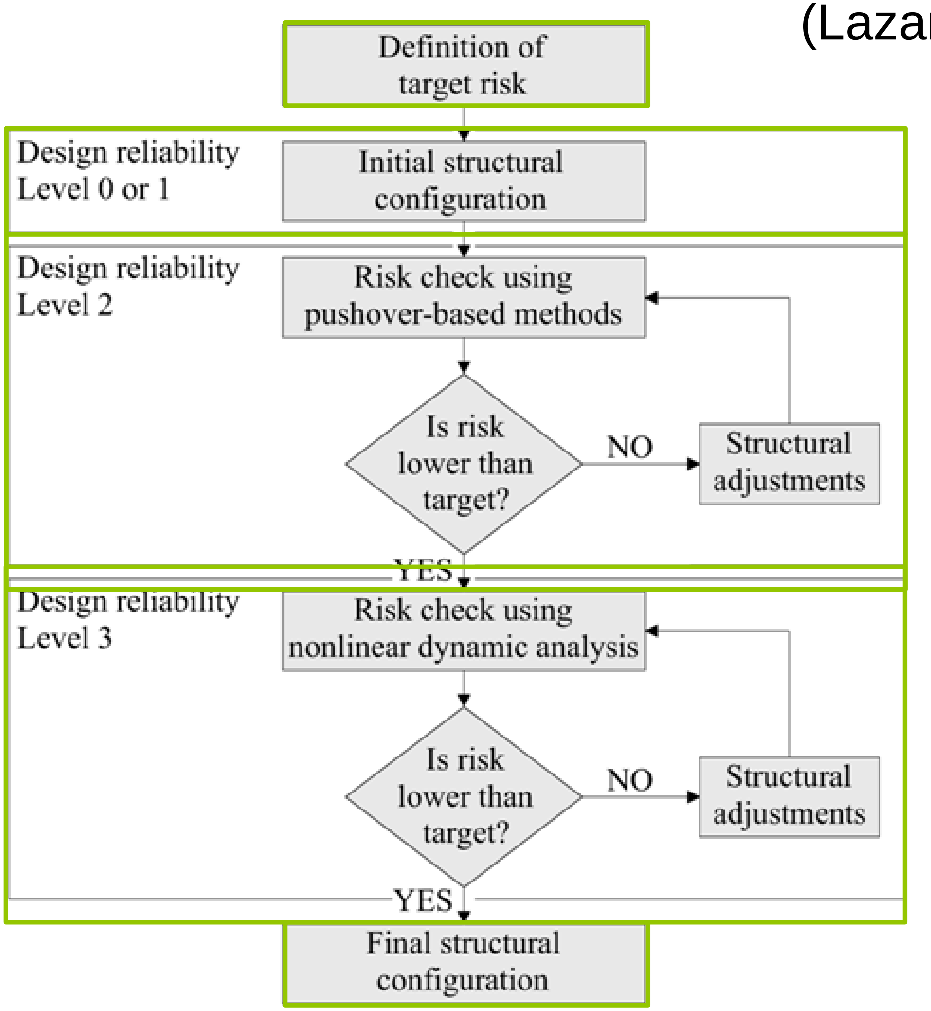
Risk-based seismic design

One possible realization of risk-based seismic design

(Lazar Sinković, Brozovič & Dolšek 2016)



- Risk-targeted force-based design (Žižmond & Dolšek, 2015)
- **SMART Web Application for the selection of risk-targeted q-factors**
- Guidelines for the structural adjustment of RC frames using pushover analysis
- 3R Method (Dolšek & Brozovič, 2016)
- Risk-based decision making: NRHA for 7 GMs at a single intensity
- **SMART CGM Web Application**

Risk-based seismic design

Adjustment of the structure using PA:

- Adjustment guidelines (Lazar Sinković, Brozovič & Dolšek, 2016):

0) Basic guideline: Apply the SCWB principle

1) Improve deformation capacity of the system by increasing the longitudinal reinforcement in the columns (50% of maximum drift) and check if longitudinal reinforcement ratio do not exceed max value.

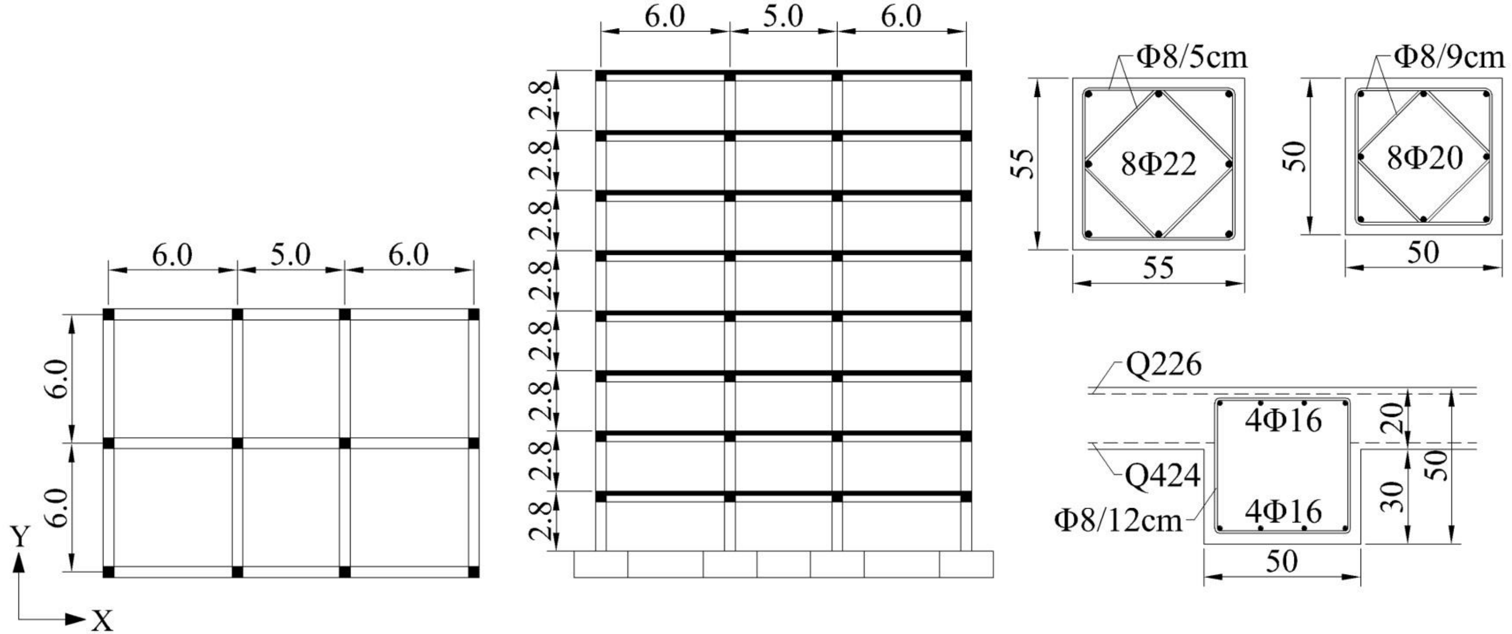
2) Increase strength of the structure by increasing cross-section area of beams in all stories when it is required to increase the strength significantly. Check SCWB.

3) Increase strength of the structure by increasing cross-section area of columns if the maximum utilization ratio is large.

Risk-based seismic design

Example application: 8-storey RC frame

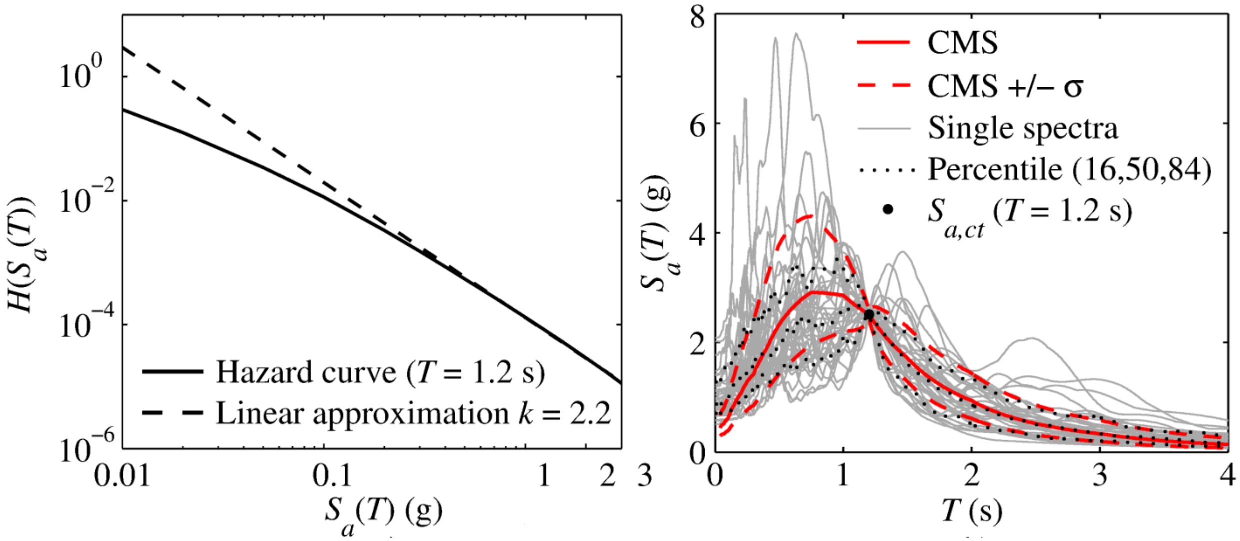
- Target collapse risk: P_t=10^{-5}
- Initial structure configuration: minimum requirements according to EC2 and EC8
- Material: Concrete class C30/37 and reinforcing steel S500



Risk-based seismic design

Seismic hazard and ground motion selection

- Hazard: Sa(T=1.2 s) for Ljubljana (Slovenia), soil type C
- Ground motion selection (according 3R method):
- 40 GMs selected according to conditional spectrum
  for the characteristic (16 th percentile) value of the target fragility curve: Sa,ct=2.5 *g*
- Target scenario: ε=2.0, M=7.3, R=19.2 km



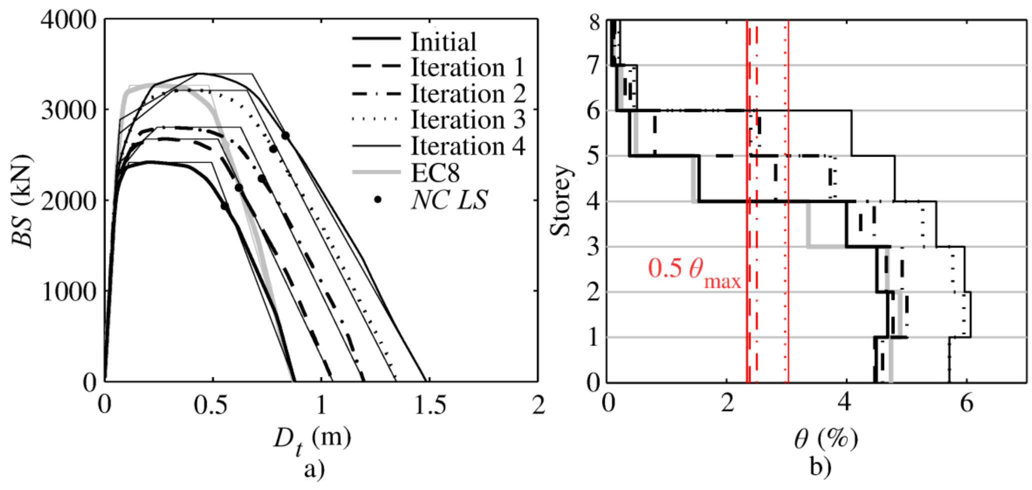
- $P_t=10^{-5}$
- frag. *LN*
- β=0.4

Risk-based seismic design

Adjustment of the structure and risk check using PA:

Iteration	Adjustment by guidelines a) AsC	b) AcB	c) AcC	BS (kN)	ΔBS (%)	$D_{t,NC}$ (m)	$\Delta D_{t,NC}$ (%)	$S_{a,C,16}$ (g)	P_C $(\cdot 10^{-5})$	ΔP_C (%)
Initial	/	/	/	2417	/	0.56	/	1.56	3.06	/
1	1–8 0.002	/	10%	2674	11	0.62	11	1.87	2.02	−34
2	1–5 0.004	/	/	2801	5	0.73	18	2.22	1.36	−33
3	1–8 0.004	5%	10%	3210	15	0.78	7	2.38	1.14	−16
4	1–6 0.004	/	/	3392	6	0.84	8	2.60	0.93	−18

AsC 1-x $\Delta\rho$: Increment of the longitudinal reinforcement ratio $\Delta\rho$ of the columns in the storeys from 1 to x
AcC ΔA_c: Increment of the cross-sectional size ΔA_c of the columns in all the storeys
AcB ΔA_c: Increment of the cross-sectional size ΔA_c of the beams in all the storeys



Risk-based seismic design

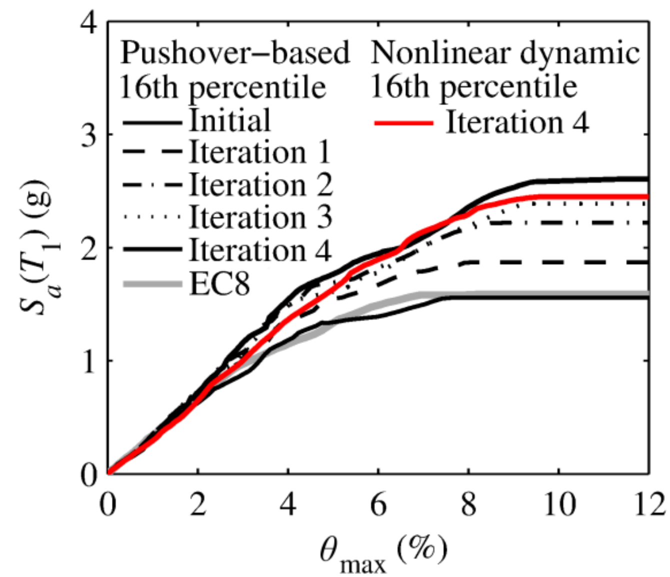
Design check – 3R method (Dolšek & Brozovič, 2016)

- Procedure:
  - 7 GMs are selected – median is close to the 16th percentile of the proxy for the collapse fragility curve (SDOF approximation)
  - Dynamic analysis for 7 GMs, scaled to Sa,ct (target value)
  - 3 GMs out of 7 caused collapse: *r*=3/7<0.5

The seismic risk < $P_t=10^{-5}$

(actual risk based on IDA is $P_c=0.98 \cdot 10^{-5}$)

- Key assumptions:
  - β is assumed (e.g. Kosič, Dolšek & Fajfar, 2016)
  - The pushover analysis provides a good approximation of the 16th percentile collapse fragility curve



Risk-based seismic design

Remarks and Conclusions:

- Advantages:
  - Includes an explicit check of risk-based performance objectives in the design (increased reliability of design solutions)
  - Engineer controls adjustment of structure (better insight into the behavior of the structure during earthquakes)

- Efficiency of the design:
  - Depends on guidelines for the adjustment of structure
  - Depends on engineer's knowledge and experience

Software development

- enhance iterative risk-based design
- desktop and web applications

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- web -> accessible, user friendly, manageable

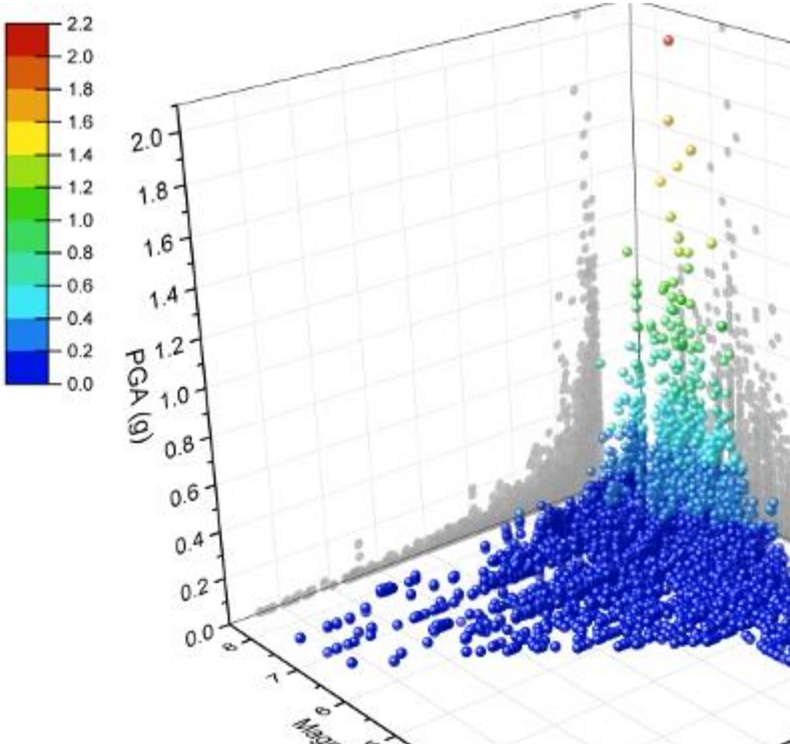
Software development

Strong ground motion database

- PEER
- RESORCE

PEER Ground Motion Database
Pacific Earthquake Engineering Research Center

Resorce
REFERENCE DATABASE
FOR SEISMIC GROUND-MOTION
IN EUROPE



Total records: 9188
Unique records: 9030

More than 18000 horizontal ground motion components

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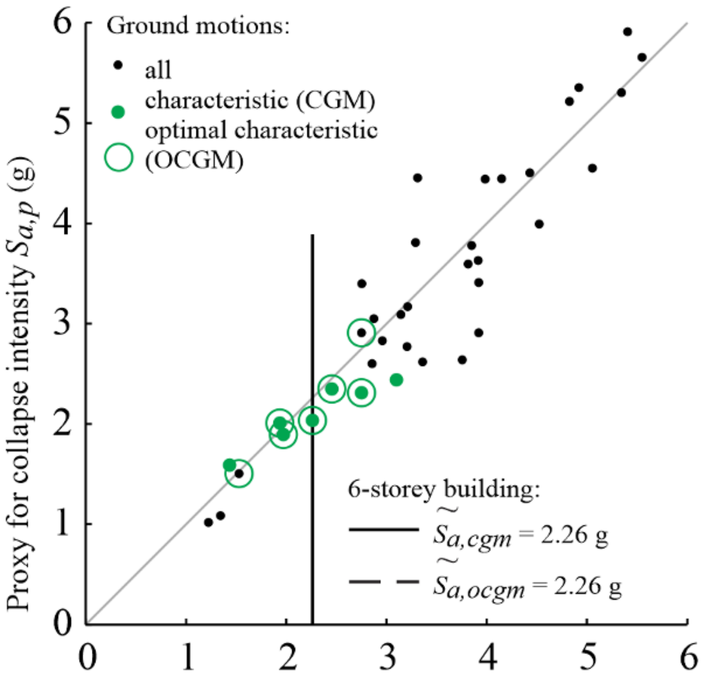
- CGM application
  - selection of so called Characteristic Ground Motions (3R method – Dolšek, Brozovič)
- Qfactor application
  - assessment of risk targeted design seismic intensity & behavior factor q
- Strong ground motion database application
  - interface (access, search, download)

CGMapp introduction

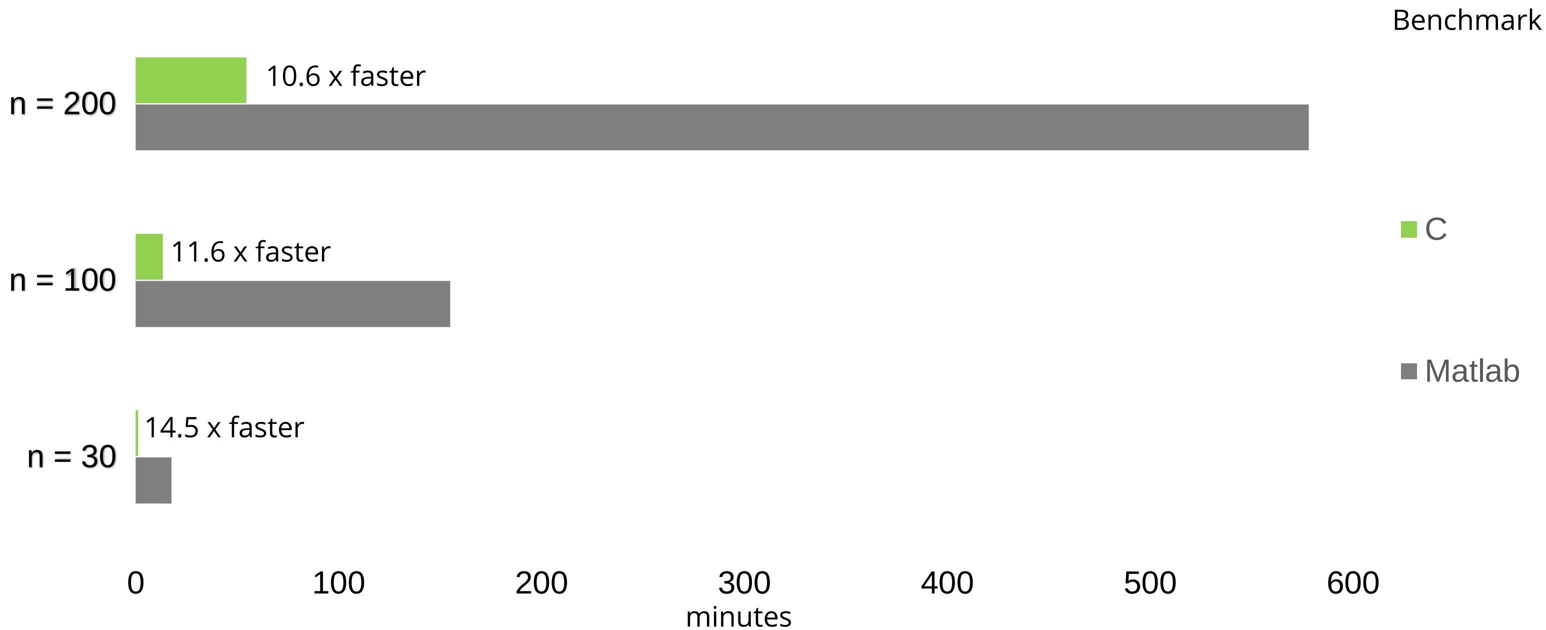
- 3R method (Dolšek & Brozovič, 2016)
  - is collapse risk sufficient?
  - trivial decision model
  - characteristic ground motions
- Application
  - automate selection of CGMs



CGMapp

1.step: selection of hazard-consistent GMs

- Conditional spectrum approach
  Original algorithm (Jayaram et al. – MATLAB)
- Translated into C programming language



9030 records (~18000 spectra)

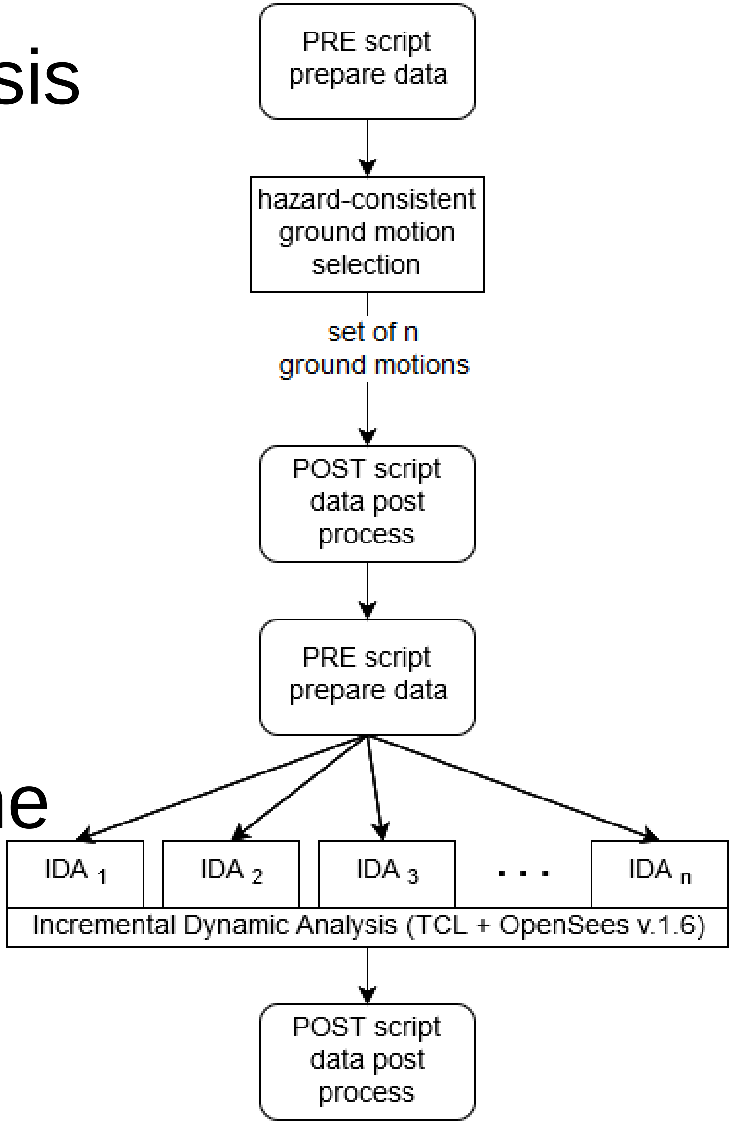
Ubuntu 12.04 64-bit (VM)
Matlab R2013a
Processor: Intel Core i7-3630QM CPU 2.400Hz x 4
Memory: 2.9GiB


Data for conditional spectrum-based ground motion selection
General:
Select ground motions based on:
A: Single arbitrary horizontal ground motion compon...
Number of GM
30
Cond. period T* (s)
1
Ground motion prediction model:
Select ground motion prediction model
Campbell & Bozorgnia 2008
$V_{S,30}$ (m/s)
400
Z_{TOR} (km)
0
δ (º)
90
λ (º)
180
Z_{VS} (km)
2
Mean earthquake scenario:
Earthquake scenario defined by
M, R, Sa,ct
Characteristic value of target collapse intensity $S_{a,ct}$ is automatically calculated when all required fields are set: nGM, Hazard & Fragility function parameters
Define hazard function as:
User-defined
Hazard function:
Target collapse risk
0.00001
β_t
0.4
Acceleration (g) | MAF
1 | 0.0001 | 1.11
2 | 0.001 | 0.982
3 | 0.01 | 0.215
4 | 0.02 | 0.0833
5 | 0.05 | 0.0162
6 | 0.07 | 0.00787
7 | 0.1 | 0.00341
8 | 0.2 | 0.00054
Clear hazard function table
Hazard Function
User-defined
Extrapolation
Return period of Sa,ct = 60276
MAF
Return period (years)
Sa(T*) (g)
Target collapse fragility function
P = 0.15
Sact = 0.571
P(C|Sa(T*))
Sa(T*) (g)
Deaggregation
Magnitude M
7.01
Distance R (km)
25.3
$S_{a,ct}$ (g):
0.571
Parameter ε
2.128
Ground motion restrictions
Magnitude
Min
Max
Closest source-to-site distance
Min (km)
Max (km)
Shear wave velocity Vs30
Min (m/s)
Max (m/s)
Select earthquake origin
All selected
Select database source
PEER
Number of potencial records for selection
3551 records
39 %
Advanced options
Scaling
4
useVar
compute
nPerTgt
20
nLoop
2
penalty
0
Seed
1
weight mean
1
weight sd
2

CGMapp

2. step: Incremental Dynamic Analysis

- Nonlinear dynamic analysis of SDOF model
- Requirement:
  SDOF on the basis of pushover analysis
- OpenSees -> IDA
- Distibuted workload on the computer cluster



CGMapp

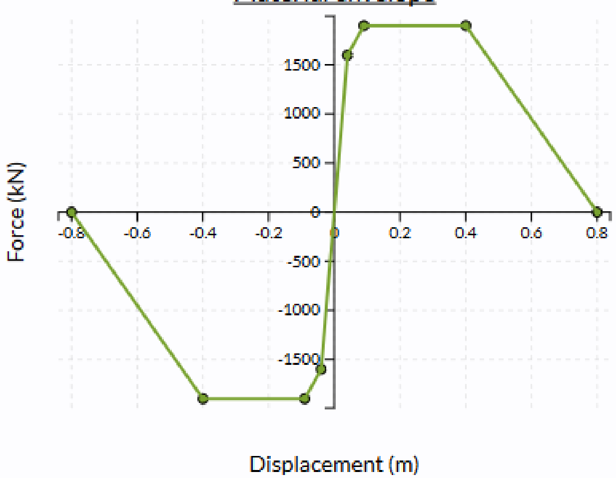
2. step: Incremental Dynamic Analysis

Data for SDOF model

Mass & Damping

Mass (t)	α_M	β_K	β_{Kinit}	β_{Kcomm}
1000	0.63	0	0	0

Material envelope



Material

TakedaDAsym

Envelope type

◉ Symmetrical ○ Non-symmetrical

Positive envelope points:

F1p (kN)	F2p (kN)	F3p (kN)	F4p (kN)
1600	1900	1900	0.1

D1p (m)	D2p (m)	D3p (m)	D4p (m)
0.04	0.09	0.4	0.8

Period of SDOF model in positive direction (s) 0.993

Other envelope data:

Beta

0.8

IDA options

nPoints	tInteg (s)
30	0.005

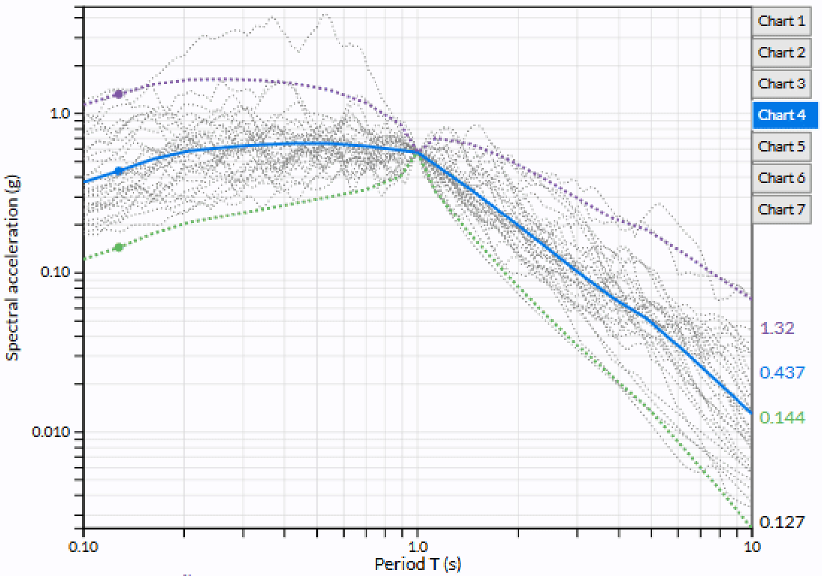
dPGAg (g)	dPGAc (g)
0.05	0.01

Trim ground motions

☐ SaTol Sa toleranc PGATol PGA tolera

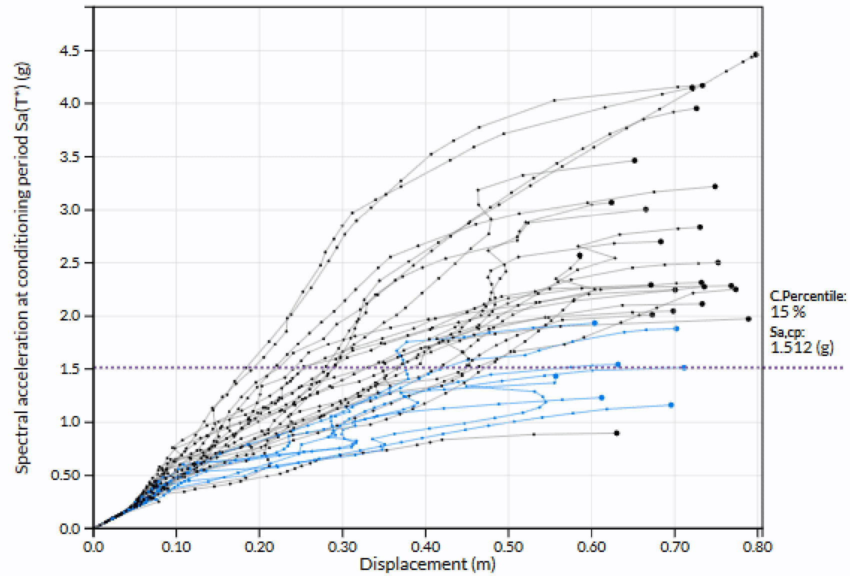
Results

Response spectra of selected ground motions



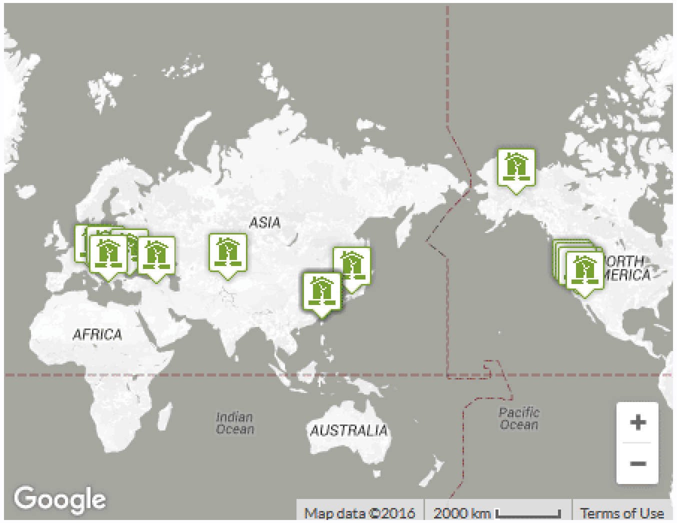
97.5 percentile target response spectrum
Median target response spectrum
2.5 percentile target response spectrum

IDA curves for SDOF model



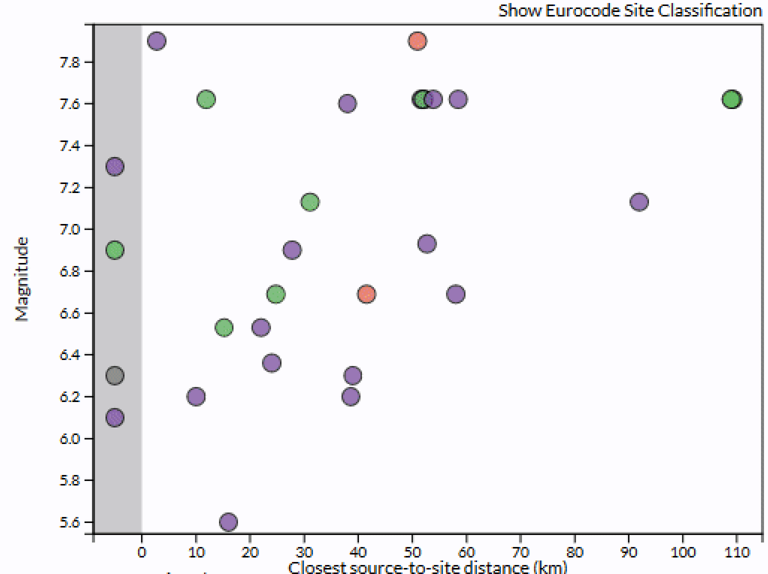
IDA curves of characteristic ground motions
IDA curves of other hazard-consistent ground motions

Earthquake epicentre locations



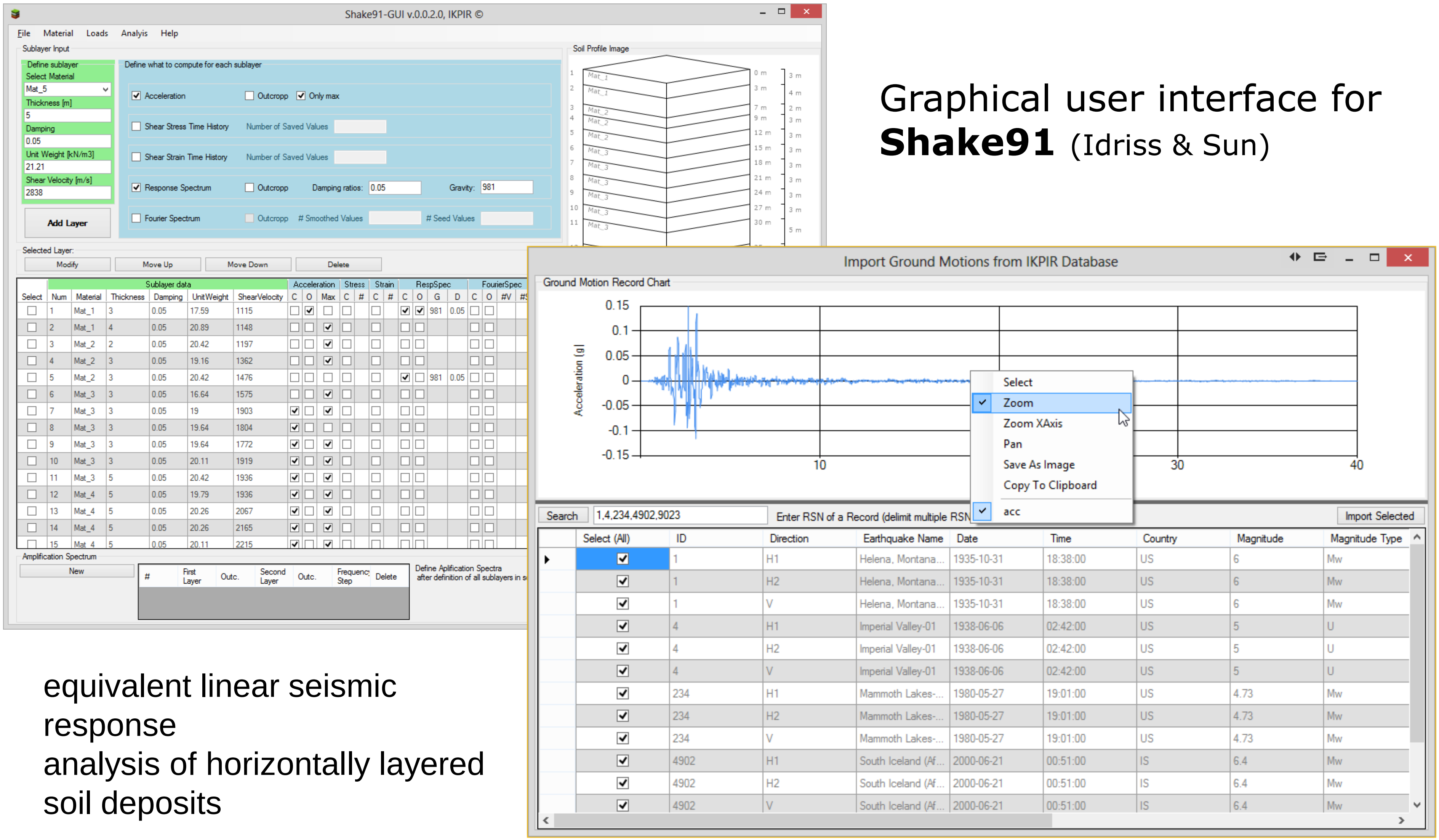
Distribution

Show Eurocode Site Classification



NEHRP Site Classes
A: Vs30 > 1524 m/s
B: 762 m/s < Vs30 < 1524 m/s
C: 366 m/s < Vs30 < 762 m/s
D: 183 m/s < Vs30 < 366 m/s

Strong Ground Motion Database public API (example usage)



Graphical user interface for **Shake91** (Idriss & Sun)

equivalent linear seismic response
analysis of horizontally layered soil deposits

Thank you for your attention

- Publications:

  - Dolšek M, Brozovič M. Seismic response analysis using characteristic ground motion records for risk-based decision making. *Earthquake Engineering and Structural Dynamics* 2016; 45(3):401–420.
  - Lazar Sinković N, Brozovič M, Dolšek M. Risk-based seismic design for collapse safety. *Earthquake Engineering and Structural Dynamics* 2016, 45: 1451–1471.
  - Kosič M, Dolšek M, Fajfar P. Dispersions for the pushover-based risk assessment of reinforced concrete frames and cantilever walls. *Earthquake Engineering and Structural Dynamics* 2016; doi: 10.1002/eqe.2753.
  - Žižmond J, Dolšek M. Risk-targeted force-based design and performance check by means of nonlinear analysis. In: Tenth Pacific Conference on Earthquake Engineering, 6-8 November 2015, Sydney, Australia. Building an Earthquake Resilient Pacific. Sydney: Australian

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SMART APPLICATIONS

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