Elastic Demand Spectra
World Data Base and Effects of Soil improvement
Non-Linear Soil Response
and SSI

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Soil Reinforcement, SSI and Performance Based Design

How reliable are the EC8 Elastic Demand Spectra compared to a set of well constrained worldwide records?

How much are affected the design EDS of a coupled soil-structure system, considering both non-linear soil behaviour and SSI

“Any modification of the foundation soil properties may affect the structural response through soil-structure interaction mechanisms”

“The influence of SSI on effective damping, ductility demand and capacity must be considered” (Priestley et al. 2007)
Summary

The aim of the paper is to discuss a few issues regarding the use of elastic demand spectra in engineering practice.

- Compilation of almost 1000 world wide records from USA, Japan and Europe. Well defined soil conditions, in terms of depth of bedrock, Vs profile and dynamic soil properties. Classification according to EC8 and AUTH proposal. Comparison with design EDS proposed in EC8 and AUTH
- Effects of compliant foundation and SSI with non-linear soil behavior, on the elastic demand spectra for few selected soil conditions and structural configurations.
- Effects of improved or/and modified soil conditions (soil densification, stone columns, soil mixture with light granular or synthetic materials) and SSI on the elastic demand spectra of specific SDOF structures.
Worldwide Database of Strong Motion Records

M - PGA (gal)

- USA (n=634)
- JAPAN (n=164)
- ITALY (n=248)
- GREECE (n=58)
Worldwide Database of Earthquake Records

Number of available records for two levels of seismic excitation (M<5.5, M>5.5)

<table>
<thead>
<tr>
<th>Countries</th>
<th>M&gt;5.5</th>
<th>M&lt;5.5</th>
<th>SUM</th>
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<tbody>
<tr>
<td>JAPAN</td>
<td>116</td>
<td>48</td>
<td>164</td>
</tr>
<tr>
<td>GREECE</td>
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<td>U.S.A.</td>
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<td>142</td>
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<tr>
<td>ALL</td>
<td>742</td>
<td>362</td>
<td>1104</td>
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</tbody>
</table>
Processed of Strong Ground Motion Records

Number of records used for this study for two levels of seismic excitation (M<5.5, M>5.5) for each country

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<td>ALL</td>
<td>194</td>
<td>114</td>
<td>308</td>
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Absolute Response Spectra vs EC8

Soil B (ξ=5%)  
n=92 records
Normalized Response Spectra

Soil B \( (\xi=5\%) \)

n=92 records
Definition of soil/site categories according to
(a) EC-8, (b) Pitilakis et al. (2006)

(a) EC-8

(b) Pitilakis et al.
Processed of Strong Ground Motion Records

Number of records – stations used for each soil class, for two levels of seismic excitation (M<5.5, M>5.5)

- B, C, E according to EC8
- B1, B2, C1, C2, C3, E according to Pitilakis et al., 2004
Normalized demand spectra ($M>5.5$: 92 records) and ($M<5.5$: 46 records)

\[ D_{\text{max}} = 0.025 \ [a_g \ S] \ T_C \ T_D \]  

EC8
Normalized Demand Spectra - Soil Class B

M<5.5: 46 records

Soil Class B, Type 2 (M<5.5)

- Mean Values (Records)
- Mean Values + 1σ (Records)
- Design
- EC8 B, Type 2
- B1, Type 2
- B2, Type 2
- T(s) - EC8 Spectrum shapes

Normalized Displacement Spectral Values $S_d$
Normalized Acceleration Spectral Values $S_e$

Normalized Displacement Spectral Values $S_d$
Normalized Acceleration Spectral Values $S_e$
Normalized Demand Spectra - Soil Class B

M>5.5: 92 records

Soil Class B, Type 1 (M>5.5)

- Mean Values (Records)
- Mean Values + 1σ (Records)
- Design
- EC8 B, Type 1
- B1, Type 1
- B2, Type 1

Normalized Displacement Spectral Values Sd

Normalized Acceleration Spectral Values Se

T(s) - EC8 Spectrum shapes

\( \tau = 0.15 \)
\( \tau = 0.5 \)
\( \tau = 0.7 \)
\( \tau = 1.0 \)
\( \tau = 1.2 \)
\( \tau = 1.5 \)
\( \tau = 2.0 \)
Normalized demand spectra \((M>5.5: 70\) records) and \((M<5.5: 52\) records)
Normalized Demand Spectra - Soil Class C

M<5.5: 52 records

Soil Class C, Type 2 (M<5.5)

- Mean Values (Records)
- Mean Values + 1σ (Records)
- Design
- EC8 C, Type 2
- C1, Type 2
- C2, Type 2
- C3, Type 2

Normalized Acceleration Spectral Values Se

Normalized Displacement Spectral Values Sd

T(s) - EC8 Spectrum shapes
Normalized Demand Spectra - Soil Class C

M>5.5: 70 records

Soil Class C, Type 1 (M>5.5)

Normalized Acceleration Spectral Values $S_a$

Normalized Displacement Spectral Values $S_d$

Mean Values (Records)
Mean Values + 1σ (Records)
EC8 C, Type 1
C1, Type 1
C2, Type 1
C3, Type 1

T(s) - EC8 Spectrum shapes

T=0.2
T=0.4
T=0.6
T=1.0
T=1.5
T=2.0
Normalized demand spectra \((M>5.5: 32 \text{ records})\) and \((M<5.5: 14 \text{ records})\)

Soil Class E, Type 1 (M>5.5)

Soil Class E, Type 2 (M<5.5)
Normalized Demand Spectra - Soil Class E

M>5.5: 32 records

Soil Class E, Type 1 (M>5.5)

Normalized Displacement Spectral Values $S_d$

Normalized Acceleration Spectral Values $S_e$

Mean Values (Records)
Mean Values + 1σ (Records)
EC8 E, Type 1
E, Type 1
$T(t)$ - EC8 Spectrum shapes

$T=0.15$
$T=0.5$
$T=0.65$
$T=0.8$
$T=1.1$
$T=1.5$
$T=2.0$
Effect of Soil Non-Linearity and SSI

Ricker (PGA=0.1g)

Water tower

\[ m = 100t \]
\[ f_0 = 3.19\text{Hz} \]
\[ \zeta = 5\% \]
found. 4m x 4m

Layer No.1
\[ h = 6\text{m} , V_s = 133\text{m/s} , \rho = 2012\text{g/m}^3 \]

Layer No.2
\[ h = 6\text{m} , V_s = 206\text{m/s} , \rho = 2069\text{kg/m}^3 \]

Layer No.3
\[ h = 8\text{m} , V_s = 237\text{m/s} , \rho = 2072\text{kg/m}^3 \]

Layer No.4
\[ h = 10\text{m} , V_s = 284\text{m/s} , \rho = 2097\text{kg/m}^3 \]

Deformable Bedrock
\[ V_s = 1010\text{m/s} , \rho = 2200\text{kg/m}^3 \]
Effect of Soil Non-Linearity and SSI

San Rocco (PGA=0.23g)

Water tower

Layer No.1
h = 6m, Vs = 133 m/s, ρ = 2012 kg/m³

Layer No.2
h = 6m, Vs = 206 m/s, ρ = 2069 kg/m³

Layer No.3
h = 8m, Vs = 237 m/s, ρ = 2072 kg/m³

Layer No.4
h = 10m, Vs = 284 m/s, ρ = 2097 kg/m³

Defeformable Bedrock
Vs = 1010 m/s, ρ = 2200 kg/m³

Demand PSA/Sd spectrum at the base of the foundation

- Linear soil
- Linear SSI
- EqL soil
- EqL SSI
Effect of Soil Non-Linearity and SSI

Aegion FP (PGA=0.49g)

Water tower

Layer No.1  
\[ h = 6\text{m}, \, V_s = 133\text{m/s}, \, \rho = 2012\text{g/m}^3 \]

Layer No.2  
\[ h = 6\text{m}, \, V_s = 206\text{m/s}, \, \rho = 2069\text{kg/m}^3 \]

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Deformable Bedrock  
\[ V_s = 1010\text{m/s}, \, \rho = 2200\text{kg/m}^3 \]
Effect of Soil Non-Linearity and SSI

San Rocco (PGA=0.23g)

12-storey building

- **Layer No. 1**
  - $h = 28.5\text{m}$, $V_s = 270\text{m/s}$, $\rho = 2000\text{kg/m}^3$

- **Layer No. 2**
  - $h = 45.5\text{m}$, $V_s = 380\text{m/s}$, $\rho = 2000\text{kg/m}^3$

- **Layer No. 3**
  - $h = 66\text{m}$, $V_s = 440\text{m/s}$, $\rho = 2000\text{kg/m}^3$

- Deformable Bedrock
  - $V_s = 2000\text{m/s}$, $\rho = 2200\text{kg/m}^3$

Demand PSA/Sd spectrum at the base of the foundation:

- Linear soil
- Linear SSI
- EqL soil
- EqL SSI
Effect of Soil Non-Linearity and SSI

Aegion FP (PGA=0.49g)

12-storey building

m = 5630t  
f_o = 0.56Hz

rigid massless foundation
30x12m

Layer No. 1
h = 28.5m, Vs = 270m/s, ρ = 2000kg/m³

Layer No. 2
h = 45.5m, Vs = 380m/s, ρ = 2000kg/m³

Layer No. 3
h = 66m, Vs = 440m/s, ρ = 2000kg/m³

Deformable Bedrock
Vs = 2000m/s, ρ = 2200kg/m³

Demand PSA/Sd spectrum at the base of the foundation

- Linear soil
- Linear SSI
- EqL soil
- EqL SSI
Comparison with EC8

Aegion FP (PGA=0.49g)

Water tower

\[ m = 100t \]
\[ f_0 = 3.19\text{Hz} \]
\[ \zeta = 5\% \]

found. 4m x 4m

Layer No.1
\[ h = 6\text{m} \], \[ V_s = 133\text{m/s} \], \[ \rho = 2012\text{g/m}^3 \]

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Layer No.4
\[ h = 10\text{m} \], \[ V_s = 284\text{m/s} \], \[ \rho = 2097\text{kg/m}^3 \]

Deformable Bedrock
\[ V_s = 1010\text{m/s} \], \[ \rho = 2200\text{kg/m}^3 \]
Soil Reinforcement
Stone columns reduces
Foundation Rocking

Soil Reinforcement and SSI effect on Seismic Capacity
Soil Reinforcement and SSI effect on Seismic Demand

Demand Spectrum and Fundamental Period are modified due to Soil Improvement with Stone-columns and SSI

![Graph showing displacement versus acceleration with different periods and soil categories.](image)

- Soil category D, Kozani '95
- Free field
- Stone columns
- SDOF, initial soil
- SDOF, stone columns
Soil Mixture with Rubber (RSM)

Initial soil profiles
Soil profile B (EC-8): $V_{s,30}=400\text{m/s}$
Soil profile C (EC-8): $V_{s,30}=290\text{m/s}$

Mixture of Soil: RSM5 and RSM15 composite materials
Width of RSM: Twice the width of the foundation
Depth of RSM mixture: 10m
Structure’s acceleration and displacement time histories

soil profile B & RSM15

- Acceleration time history
- Displacement time history
- Spectral ratio

Us / Uff
DS for Soil Mixture with Rubber – SSI

Soil Category B

- T=0.2 sec
- T=0.6 sec
- T=1.0 sec

Graph showing acceleration (g) vs. displacement (cm) for different time periods and rubber mixtures:

- free field
- 5% RSM
- 15% RSM
- SDOF initial
- SDOF, 5% RSM
- SDOF, 15% RSM
DS for Soil Mixture with Rubber – SSI

![Graph showing acceleration vs. displacement for different soil categories and rubber mixtures.]

- Soil Category C
- T=0.2sec
- T=0.6sec
- T=1.0sec

Legend:
- Free field
- 5% RSM
- 15% RSM
- SDOF initial
- SDOF, 5% RSM
- SDOF, 15% RSM
### Foundation flexibility effect on Seismic Capacity

Foundation compliance affects Capacity (Priestley et al. 2007)

<table>
<thead>
<tr>
<th>System</th>
<th>$\Delta F/\Delta y$</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>2.0</td>
<td>2.7</td>
</tr>
<tr>
<td>Reinforced</td>
<td>1.0</td>
<td>3.5</td>
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Conclusive Remarks

- Elastic Demand Spectra compiled from a world data base vs EC8
- Demand Spectra in case of Non-Linear Soil behavior
- Demand Spectra in case of NL soil behavior and SSI
- Demand spectra in case of soil improvement with Stone Columns
- Demand Spectra in case of foundation soil replacement with RSM
- Capacity