Session 1: Qualification of probabilistic seismic hazard assessment

AMPLIFICATION AND AGGRAVATION FACTORS FOR SITE AND BASIN EFFECTS
SUMMARY

1. FRAMEWORK

2. INTRODUCTION

3. PART I: PSHA AT EUROPEAN SCALE: THE SHARE EUROPEAN PROJECT

4. PART II: PROPOSALS FOR IMPROVEMENT OF EC8 DESIGN SPECTRA

   ✔ DATA SELECTION
   ✔ VALIDATION OF EC8 NORMALIZED RESPONSE SPECTRA
   ✔ IMPROVED S FACTORS FOR THE EC8 CLASSIFICATION SCHEME
   ✔ IS VS,30 APPROPRIATE FOR SITE – SOIL CLASSIFICATION?
   ✔ NEW SITE – SOIL CLASSIFICATION SCHEME
   ✔ SOIL AMPLIFICATION FACTORS AND NORMALIZED RESPONSE SPECTRA FOR THE NEW CLASSIFICATION SCHEME PROPOSED BY PITILAKIS ET AL. 2013

5. PART III: AGGRAVATION FACTORS FOR COMPLEX SUBSURFACE GEOMETRY (VALLEYS)

   ✔ DEFINITION AND EVALUATION OF THE AGGRAVATION FACTORS
   ✔ PROPOSALS FOR EC8

6. EXAMPLE
Definition of seismic action at the base of the earth dam *(CIGB/ICOLD 2016)*

1. PSHA, Deterministic-Scenario based
2. OBE, SEE (MDE)
3. Local soil and site effect
Definition of seismic action at the base of the earth dam *(CIGB/ICOLD 2016)*

- Path effects
- Interaction dam-foundation-reservoir
- Spatial variability of ground motion along the base of the dam
- N-L soil and rock behavior
- Treatment of uncertainties (50%-84% percentiles)
Definition of seismic action at the base of the earth dam (CIGB/ICOLD 2016)

- Appurtenant structures:
  - OBE (10/50): Pen stocks, powerhouse, intake structures, cavers
  - SEE: Critical Structures: Bottom outlet, spillway gates, control units and power supply
Definition of seismic action at the base of the earth dam (CIGB/ICOLD 2016)

1. PGA and Response Spectra (with appropriate damping) at bedrock from probabilistic or deterministic seismic hazard assessment

2. Proper evaluation of period dependent soil amplification of the ground motion at the foundation level according to the foundation and embankment soil type
Definition of seismic action at the base of the dam

1. PGA and Response Spectra at bedrock
2. Probabilistic Seismic Hazard Assessment (SHARE project)
3. Period dependent soil amplification factors of the ground motion at the foundation level
4. Complex basin effects
Introduction

Seismic ground motion = Source * Path * Site effects

Site effects: geology, stratigraphy, surface and subsurface topography, lateral discontinuities and heterogeneities...

Modern seismic codes account for 1D effects but ignore complex 2D effects.

Influence of site effects in seismic codes is described through site-dependent elastic response spectra based on different soil categories. These spectra may deviate sometimes seriously from recorded data (Stewart et al., 2001; Choi & Stewart, 2005; Pousse et al., 2005).

Site classification is mainly based on $V_{s,30}$ which has been questioned by several recent works (Wald & Mori, 2000; Stewart et al., 2003; Park & Hashash, 2005; Castellaro et al., 2008; Kokusho & Sato, 2008; Lee & Trifunac, 2010).
Part I:

PSHA at European scale:
the SHARE European Project
Part I: SHARE European Project

- Harmonization of methodologies used for seismic hazard assessment in Europe

- Probabilistic seismic hazard assessment for rock-site conditions, for different return periods (72 – 5000 years) and for a grid of 10km size (120,000 points).

- Intensity measures: PGA, spectral acceleration SA (0.1-10sec)

- Uncertainties are accounted for through a “logic tree” approach.

- The ultimate goal is to contribute to an update of EC8.

Project information: www.share-eu.org
Data access: www.efehr.org
SHARE Partners

- 18 universities and research centers from 12 European countries
Seismicity in Europe
Seismic zones in Europe
Ground Motion Prediction Equations

Active Shallow Crustal Regions

<table>
<thead>
<tr>
<th>GMPE</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Akkar &amp; Bommer (2010)</td>
<td>0.35</td>
</tr>
<tr>
<td>Cauzzi &amp; Faccioli (2008)</td>
<td>0.35</td>
</tr>
<tr>
<td>Zhao et al. (2006)</td>
<td>0.10</td>
</tr>
<tr>
<td>Chiou &amp; Youngs (2008)</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Uncertainties - Logic tree

Types of seismic sources

- Zone based
- Zoneless

Logic tree structure for each seismic source zone

- $M_{\text{max}}$
- 25 $\gamma_0-\beta$ pairs
- GMPE

Fault SZ and areal background SZ

Areal SZ

Weights as examples only
Uncertainties - Logic tree

- Traditional Area Source Model (AS)
  Activity Rates based on observed seismicity

- Kernel Smoothed Seismicity and Fault Model (SEIFA)
  Activity Rates based on observed seismicity
  Spatial distribution reflecting fault moment release

- Fault Source + Background Model (FSBG)
  Activity rates based on fault slip rates
New Seismic Hazard Map (PGA) : Bedrock Vs>800m/s

Return Period = 475 years
Part II:
Proposals for improvement of EC8 elastic response spectra


Soil classification and elastic response spectra in EC8

- Local site effects are taken into account through appropriate elastic design spectra based on different soil categories and levels of shaking intensity:
  - "Soil factor" $S$
  - Normalized response spectra (parameters $T_B$, $T_C$, $T_D$)

Soil Class-dependent

<table>
<thead>
<tr>
<th>Ground Type</th>
<th>$S$</th>
<th>$T_B$ (s)</th>
<th>$T_C$ (s)</th>
<th>$T_D$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.00</td>
<td>0.15</td>
<td>0.40</td>
<td>2.00</td>
</tr>
<tr>
<td>B</td>
<td>1.20</td>
<td>0.15</td>
<td>0.50</td>
<td>2.00</td>
</tr>
<tr>
<td>C</td>
<td>1.15</td>
<td>0.20</td>
<td>0.60</td>
<td>2.00</td>
</tr>
<tr>
<td>D</td>
<td>1.35</td>
<td>0.20</td>
<td>0.80</td>
<td>2.00</td>
</tr>
<tr>
<td>E</td>
<td>1.40</td>
<td>0.15</td>
<td>0.50</td>
<td>2.00</td>
</tr>
</tbody>
</table>

Type 2 Spectrum - $M_s \leq 5.5$

<table>
<thead>
<tr>
<th>Ground Type</th>
<th>$S$</th>
<th>$T_B$ (s)</th>
<th>$T_C$ (s)</th>
<th>$T_D$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.00</td>
<td>0.05</td>
<td>0.25</td>
<td>1.20</td>
</tr>
<tr>
<td>B</td>
<td>1.35</td>
<td>0.05</td>
<td>0.25</td>
<td>1.20</td>
</tr>
<tr>
<td>C</td>
<td>1.50</td>
<td>0.10</td>
<td>0.25</td>
<td>1.20</td>
</tr>
<tr>
<td>D</td>
<td>1.80</td>
<td>0.10</td>
<td>0.30</td>
<td>1.20</td>
</tr>
<tr>
<td>E</td>
<td>1.60</td>
<td>0.05</td>
<td>0.25</td>
<td>1.20</td>
</tr>
</tbody>
</table>

$\alpha_g$: design ground acceleration for rock-site conditions
Data selection

- Validation of the present EC8 elastic response spectra:
  - SHARE database (www.share-eu.org)
  - soil/site documentation: $V_{s,30}$ and EC8 soil class
  - only records with $M_s \geq 4$ and $T_{usable} \geq 2.5$ sec were used
  - compilation of three subsets with different PGA levels
    - DS1: all PGA values
    - DS2: PGA $\geq 20$ cm/s$^2$
    - DS3: PGA $\geq 150$ cm/s$^2$
Data selection

- Proposal of the new soil classification scheme and design spectra:
  - SHARE-AUTH database (Pitilakis et al., 2013)
  - 3,666 records from 536 stations from Greece, Italy, Turkey, Japan and USA with a well-documented soil profile up to the ‘seismic’ bedrock ($V_s>800\text{m/s}$)
  - For all sites: $H_{\text{bedrock}}$, $V_{s,\text{average}}$, $V_{s,30}$, $T_0$, the geotechnical profile
  - Dataset DS4: $M_s \geq 4$, $T_{\text{usable}} \geq 2.5$ sec and PGA $\geq 20$ cm/s$^2$
**Data selection**

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Database of origin</th>
<th>Number of records</th>
<th>$M_s$ range</th>
<th>PGA range (cm/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS1</td>
<td>SHARE</td>
<td>7,161</td>
<td>4–7.9</td>
<td>≤1,400</td>
</tr>
<tr>
<td>DS2</td>
<td>SHARE</td>
<td>3,500</td>
<td>4–7.9</td>
<td>20&lt;PGA≤1,400</td>
</tr>
<tr>
<td>DS3</td>
<td>SHARE</td>
<td>559</td>
<td>4–7.9</td>
<td>150&lt;PGA≤1,400</td>
</tr>
<tr>
<td>DS4</td>
<td>SHARE-AUTH</td>
<td>715</td>
<td>4–7.5</td>
<td>20&lt;PGA≤1,302</td>
</tr>
</tbody>
</table>

**DS1 dataset**

(a) ![Graph](image1.png)

(b) ![Graph](image2.png)
Data selection

DS1 dataset
Validation of EC8 normalized spectra

- DS1 and DS2 for Type 2 ($M_s \leq 5.5$) and Type 1 ($M_s > 5.5$) spectra
- DS3 only for Type 1 spectra
- Calculation of geometric mean (GM) of the response spectra for the two orthogonal horizontal components of each record
- Normalization to GM PGA
- Grouping of records based on soil class and spectrum type (1 or 2)
- Calculation of median, 16th and 84th percentiles (average $\pm$ 1 standard deviation) and comparison with EC8
Validation of EC8 normalized spectra

Soil Class A

- EC8 spectra match the empirical data to a satisfactory extent (between median and 84th pctl)

- EC8 spectra become more conservative for datasets with higher mean PGA values

Pitilakis et al. (2012)
Validation of EC8 normalized spectra

Soil Classes B-C

- Good agreement between EC8 and empirical data
- Wide range of normalized values, which becomes more constrained for datasets with higher mean PGA values

Pitilakis et al. (2012)
Validation of EC8 normalized spectra

Soil Classes D-E

- Soil class D: the ordinates of EC8 spectra do not provide a satisfactory fit to the median empirical spectra.

- Soil class E: EC8 spectra are conservative for periods greater than 0.3s. Potential need to increase the plateau.

Pitilakis et al. (2012)
Validation of EC8 normalized spectra

- EC8 normalized response spectra do not seem to have been derived based on a common rationale for all soil classes!
- Good agreement between EC8 and empirical normalized spectra for soil classes A, B and C.
- Discrepancies between the empirical and EC8 spectra for soil classes D and E do not justify the proposal of modifications for the moment.
- It is suggested that Eurocode 8 should prompt for site-specific ground response analyses for the definition of seismic action in class D and E sites, especially for important structures.
Improved Soil Factors for EC8 soil classification

Logic tree approach

Pitilakis et al. (2012)
GMPE selection and weights from Delavaud et al. (2012)
Improved Soil Factors for EC8 soil classification

Approach 1 (Choi & Stewart, 2005)

Main problem: Results depend on the reliability of the GMPEs prediction for rock

\[
S_{ij}(T) = \frac{GM_{r_{ij}}}{(GM_{r_{ij}})} \\
(GM_{r_{ij}})(T) = 0.35 \cdot (GM_{r_{ij,AB}}) + 0.35 \cdot (GM_{r_{ij,CF}}) + 0.10 \cdot (GM_{r_{ij,Zh}}) + 0.20 \cdot (GM_{r_{ij,CY}})
\]

Pitilakis et al. (2012)
Approach 2 (Rey et al., 2002)

Main problem: Lack of reliable and numerous records for rock sites

\[ S = \left( \frac{I_{soil}}{I_{rock}} \right) \cdot \left( \frac{1}{{SR}} \right) \]

\[ I = \int_{0.05}^{2.5} R \cdot S_a(T) \, dt \]

Pitilakis et al. (2012)
## Improved Soil Factors for EC8 soil classification

### Type 2 (Ms ≤ 5.5)

<table>
<thead>
<tr>
<th>Soil Class</th>
<th>SHARE-DS1</th>
<th>SHARE-DS2</th>
<th>SHARE-DS3</th>
<th>EC8</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>0.90</td>
<td>1.55</td>
<td>1.23</td>
<td>1.51</td>
<td>1.37</td>
</tr>
<tr>
<td>C</td>
<td>1.93</td>
<td>2.54</td>
<td>2.23</td>
<td>2.19</td>
<td>2.12</td>
</tr>
<tr>
<td>D</td>
<td>3.36</td>
<td>3.07</td>
<td>3.22</td>
<td>2.92</td>
<td>2.00</td>
</tr>
<tr>
<td>E</td>
<td>0.98</td>
<td>1.79</td>
<td>1.39</td>
<td>1.30</td>
<td>1.96</td>
</tr>
</tbody>
</table>

### Type 1 (Ms > 5.5)

<table>
<thead>
<tr>
<th>Soil Class</th>
<th>SHARE-DS1</th>
<th>SHARE-DS2</th>
<th>SHARE-DS3</th>
<th>EC8</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>1.47</td>
<td>1.34</td>
<td>1.41</td>
<td>1.53</td>
<td>1.08</td>
</tr>
<tr>
<td>C</td>
<td>2.09</td>
<td>2.24</td>
<td>2.16</td>
<td>2.06</td>
<td>1.46</td>
</tr>
<tr>
<td>D</td>
<td>1.74</td>
<td>1.42</td>
<td>1.58</td>
<td>1.56</td>
<td>0.92</td>
</tr>
<tr>
<td>E</td>
<td>0.91</td>
<td>1.07</td>
<td>0.99</td>
<td>0.97</td>
<td>0.83</td>
</tr>
</tbody>
</table>

<sup>a</sup> site specific ground response analysis required

Pitilakis et al. (2012)
Is $V_{s,30}$ appropriate for site – soil classification?

- **Advantages of $V_{s,30}$:**
  - Simple and effective in practice
  - Requires little data: a simple N-SPT of 30m long or less is enough!

- **Disadvantages of $V_{s,30}$:**
  - It is not a fundamental (neither a geotechnical) parameter
  - Could mislead grossly in different cases like: deep low stiffness deposits lying on much harder rock; sites with a shallow velocity inversion; sites with velocity profiles which are not monotonically increasing with depth or do not exhibit a strong impedance contrast in the first dozen meters or in basin type structures.

- Can the single knowledge of $V_{s,30}$ quantify properly amplification, which is mainly due (and not only) to the effects of impedance contrast?

- Proposal of different alternative parameters ($T_0$, $H$, $V_{s,av}$, $V_{s,10}$, $V_{s,25}$)
Is $V_{s,30}$ appropriate for site – soil classification?

Idriss (2011)

Sites with identical $V_{s,30}$, but differing layering, can have significantly different response!!
New site – soil classification scheme

- Soil classes initially proposed based on theoretical 1D numerical analyses of representative models of realistic soil conditions (Pitilakis et al., 2004, 2006)

- Further developed based exclusively on experimental data from the SHARE – AUTH database (Pitilakis et al., 2013)

- Main parameters:
  - Fundamental period of soil deposit $T_0$
  - Average shear wave velocity of the entire soil deposit $V_{s,av}$
  - Thickness of soil deposit $H$ to the “seismic” bedrock
  - N-SPT, PI, $S_u$
  - More detailed geotechnical soil description and categorization
### New site – soil classification scheme

<table>
<thead>
<tr>
<th>Soil Class</th>
<th>Description</th>
<th>$T_a(s)$</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Rock formations</td>
<td>$V_s &lt; 1500$ m/s</td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>Slightly weathered / segmented rock formations (thickness of weathered layer ~5.0m)</td>
<td>$V_s &lt; 200$ m/s</td>
<td>Rock Formations: $V_s &lt; 800$ m/s</td>
</tr>
<tr>
<td></td>
<td>Geologic formations resembling rock formations in their mechanical properties and their composition (e.g. conglomerates)</td>
<td>$V_s &lt; 800$ m/s</td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>Highly weathered rock formations whose weathered layer has a considerable thickness (5.0m - 30.0m)</td>
<td>$V_s &lt; 0.5$ m/s</td>
<td>Weathered layer: $V_s &lt; 300$ m/s, N-SPT &gt; 50, $S_u &gt; 200$ kPa</td>
</tr>
<tr>
<td></td>
<td>Soft rock formations: great thickness or formations which resemble these in their mechanical properties (e.g. stiff marls)</td>
<td>$V_s &lt; 0.5$ m/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Soil formations of very dense sand – sand gravel and/or very stiff to hard clay, of homogenous nature and small thickness (up to 30.0m)</td>
<td>$V_s &lt; 0.5$ m/s</td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>Soil formations of very dense sand – sand gravel and/or very stiff to hard clay, of homogenous nature and medium thickness (30.0m - 60.0m), whose mechanical properties increase with depth</td>
<td>$V_s &lt; 0.8$ m/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Soil formations of dense to very dense sand – sand gravel and/or very stiff to very stiff clay, of great thickness (&gt; 60.0m), whose mechanical properties and strength are constant and/or increase with depth</td>
<td>$V_s &lt; 1.5$ m/s</td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>Soil formations of medium dense sand – sand gravel and/or medium stiffness clay (PI &gt; 15, fines percentage &gt; 50%) of medium thickness (20.0 ~ 60.0m)</td>
<td>$V_s &lt; 1.5$ m/s</td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>Category C2 soil formations of great thickness (&lt; 60.0m), homogenous or stratified that are not interrupted by any other soil formation with a thickness of more than 5.0m and of lower strength and $V_s$ velocity</td>
<td>$V_s &lt; 1.8$ m/s</td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>Recent soil deposits of substantial thickness (up to 60.0m), with the prevailing formations being soft clays of high plasticity index (PI &gt; 40), high water content and low values of strength parameters</td>
<td>$V_s &lt; 2.0$ m/s</td>
<td>N-SPT &lt; 25, $S_u &lt; 70$ kPa</td>
</tr>
<tr>
<td>D1</td>
<td>Recent soil deposits of substantial thickness (up to 60.0m), with prevailing fairly loose sandy to sandy-silty formations with a substantial fines percentage (not to be considered susceptible to liquefaction)</td>
<td>$V_s &lt; 2.0$ m/s</td>
<td>N-SPT &lt; 25</td>
</tr>
<tr>
<td>D2</td>
<td>Soil formations: of great overall thickness (&gt; 60.0m), interrupted by layers of category D1 or D2 soils of a small thickness (5.0 ~ 15.0m), up to the depth of ~40m, within soils (sandy and/or clayey, category C) of evidently greater strength, with $V_s &lt; 300$ m/sec</td>
<td>$V_s &lt; 3.0$ m/s</td>
<td></td>
</tr>
<tr>
<td>D3</td>
<td>Surface soil formations of small thickness (5.0 ~ 20.0m), small strength and stiffness, likely to be classified as category C and D according to its geotechnical properties, which overlie category A formations ($V_s &lt; 800$ m/sec)</td>
<td>$V_s &lt; 0.7$ m/s</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Surface soil layers: $V_s &lt; 400$ m/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>Loose fine sandy-silty soils beneath the water table, susceptible to liquefaction (unless a special study proves no such danger, or if the soil’s mechanical properties are improved), Soils near obvious tectonic faults, Steep slopes covered with loose lateral deposits, Loose granular or soft silty-clayey soils, provided they have been proven to be hazardous in terms of dynamic compaction or loss of strength. Recent loose landslides. Soils with a very high percentage in organic material. Soils requiring site-specific evaluations.</td>
<td>$V_s &lt; 400$ m/s</td>
<td></td>
</tr>
</tbody>
</table>
# New site – soil classification scheme

<table>
<thead>
<tr>
<th>Soil Class</th>
<th>Description</th>
<th>Remarks</th>
</tr>
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<tbody>
<tr>
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<td>Rock formations</td>
<td>$V_s &gt; 1500 \text{ m/s}$</td>
</tr>
<tr>
<td>A2</td>
<td>Slightly weathered / segmented rock formations</td>
<td>Surface weathered from $V_s = 200 \text{ m/s}$</td>
</tr>
<tr>
<td>B1</td>
<td>Highly weathered rock formations</td>
<td>Geologic formations with mechanical properties corresponding to sand and/or gravel; not affected by water</td>
</tr>
<tr>
<td>B2</td>
<td>Soft rock formations</td>
<td>Geologic formations with mechanical properties corresponding to sand and/or gravel; affected by water</td>
</tr>
<tr>
<td>C1</td>
<td>Soil formations of dense to very dense sand – sand gravel and/or stiff to very stiff clay, of great thickness (&gt; 60.0m), whose mechanical properties and strength are constant and/or increase with depth</td>
<td>$T_0 \leq 1.5s$ $V_{s,av} : 400-800 \text{ m/s}$ $N_{SPT} &gt; 50$ $S_u &gt; 200 \text{ KPa}$</td>
</tr>
<tr>
<td>C2</td>
<td>Soil formations of medium dense sand – sand gravel and/or medium stiffness clay (PI &gt; 15, fines percentage &gt; 30%) of medium thickness (20.0 – 60.0m)</td>
<td>$T_0 \leq 1.5s$ $V_{s,av} : 200-450 \text{ m/s}$ $N_{SPT} &gt; 20$ $S_u &gt; 70 \text{ KPa}$</td>
</tr>
<tr>
<td>C3</td>
<td>Category C2 soil formations of great thickness (&gt;60.0 m), homogenous or stratified that are not interrupted by any other soil formation with a thickness of more than 5.0m and of lower strength and Vs velocity</td>
<td>$T_0 \leq 1.8s$ $V_{s,av} : 200-450 \text{ m/s}$ $N_{SPT} &gt; 20$ $S_u &gt; 70 \text{ KPa}$</td>
</tr>
</tbody>
</table>
New site – soil classification scheme

EC8

New CS

H (m)

Vs,30 (m/s)

0 10 20 30 40 50 60 70 80

0 10 20 30 40 50 60 70 80

H (m)

Vs,av (m/s)

A
B
C
D
E

A2
B1
B2
C1
C2
C3
D1, D2
D3

Pitilakis et al. 2011
New site – soil classification scheme

Normalized spectra

- SHARE-AUTH database
- 2 spectrum Types (same as EC8)
  - Type 1: Ms > 5.5
  - Type 2: Ms ≤ 5.5
- Same equation forms as in EC8 but with varying spectral amplification parameter $\beta$.
- For each soil class and spectrum type: median, $16^{th}$ and $84^{th}$ pctls
- Parameters $T_B$, $T_C$, $T_D$ and $\beta \rightarrow$ fit to $84^{th}$ ptcl
New site – soil classification scheme

Soil class B1

Soil class C1

Pitilakis et al. (2013)
### New site – soil classification scheme

**Amplification factors S**

- Same logic tree approach as for EC8
- Dataset DS4 from SHARE-AUTH database: $M_s \geq 4$, $T_{usable} \geq 2.5$ sec and $PGA \geq 20$ cm/s²

<table>
<thead>
<tr>
<th>Soil Class</th>
<th>Type 2 ($M_s \leq 5.5$)</th>
<th>Type 1 ($M_s &gt; 5.5$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>1.28</td>
<td>0.99</td>
</tr>
<tr>
<td>B2</td>
<td>1.89</td>
<td>1.17</td>
</tr>
<tr>
<td>C1</td>
<td>2.02</td>
<td>1.46</td>
</tr>
<tr>
<td>C2</td>
<td>2.08</td>
<td>1.39</td>
</tr>
<tr>
<td>C3</td>
<td>2.59</td>
<td>1.61</td>
</tr>
<tr>
<td>D</td>
<td>2.19</td>
<td>2.26</td>
</tr>
<tr>
<td>E</td>
<td>1.54</td>
<td>1.30</td>
</tr>
</tbody>
</table>

*Site specific ground response analysis required

Pitilakis et al. (2013)
New site – soil classification scheme

Elastic acceleration response spectra (5%)

Type 2

Type 1

Pitilakis et al. (2013)
Period – dependent amplification factors

EC8

Improved EC8

New CS

Pitilakis et al. (2012, 2013)
Part III:
Aggravation factors
for complex subsurface geometry

To be published in Soil Dynamics and Earthquake Engineering (SOILDYN)
Parametric analyses

- Numerical parametric analyses of the 2D seismic response of sediment-filled basins for vertically incident plane waves with SV polarization.

- Numerical codes:
  - 2DFD_DVS finite difference code (Moczo et al., 2007; Moczo et al., 2004; Kristek and Moczo, 2003; Kristek et al., 2002) for viscoelastic analyses of homogeneous basins (96 models x 9 input motions)
  - ABAQUS finite element code (ABAQUS, 2010) for nonlinear analyses of inhomogeneous basins (6 models x 6 input motions x 3 levels of shaking)

- Verification of the efficiency of the two codes in reproducing complex 2D as well as 1D site response before proceeding with the analyses.
Parametric analyses

- 96 trapezoidal basin models:
  - 32 geometrical configurations, described by their width, w, depth, h and sloping edge angles, a1-a2

![Trapezoidal Basin Model Diagram]

- Elastic bedrock
- 3 materials for sediments:

<table>
<thead>
<tr>
<th>Sediments</th>
<th>Material property</th>
<th>Material 1</th>
<th>Material 2</th>
<th>Material 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S-wave velocity (V_s in m/s)</td>
<td>250</td>
<td>350</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>Quality factor of S-waves (Q_s)</td>
<td>25</td>
<td>35</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>P-wave velocity (V_p in m/s)</td>
<td>1600</td>
<td>1750</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>Quality factor of P-waves (Q_p)</td>
<td>50</td>
<td>70</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Density (ρ in kg/m^3)</td>
<td></td>
<td></td>
<td>2000</td>
</tr>
</tbody>
</table>
Parametric analyses

Dominant feature of the seismic response of the studied models based on the criterion of Bard and Bouchon (1985):

1D resonance and lateral propagation of surface waves
Nine strong-motion accelerograms (in2-in10) recorded on rock sites were used as input motions.

Loma Prieta, USA, Mw=6.93
L’ Aquila, Mw=5.3
Ano Liosia, Greece, Mw=6.04
Izmit, Turkey, M=6.3
Izmit, Turkey, M=6.3
Northridge, USA, Mw=6.69
Tabas, Iran, Mw=7.35
N. Miyagi Pref., Japan, Mw=6.1
Friuli, Italy, Mw=6.4

Parametric analyses
Parametric analyses

2D analysis

1D analysis

AMPLIFICATION AND AGGRAVATION FACTORS FOR SITE AND BASIN EFFECTS | 2016
Aggravation factors

- The additional effect of the 2D response at different locations at the surface of the basin with respect to the corresponding 1D response of the isolated soil columns in each location is quantified through a period-dependent seismic aggravation factors (AGF):

$$AGF(T) = \frac{\text{Spectral acceleration from 2D analysis}}{\text{Spectral acceleration from 1D analysis}}$$

Chávez-García and Faccioli (2004)

- A period-dependent aggravation factor is computed at each receiver for each model and each input.

- For each model, the average period-dependent aggravation factor is calculated from the 9 accelerograms at each receiver.

- The maximum value of the average period-dependent aggravation factor at each receiver is identified.
Maximum aggravation factors

max AGF

w=2500m, h=120m, Vs=350m/s, a1=a2=45°
center of basin (x/w=0.5)

AMPLIFICATION AND AGGRAVATION FACTORS FOR SITE AND BASIN EFFECTS | 2016
Maximum aggravation factors

Influence of basin thickness (h)

- Increase of thickness $\rightarrow$ higher AGF, especially for sediments with low Vs
Maximum aggravation factors

Influence of basin width (w)

- Increase of width $\rightarrow$ smaller AGF at the center of the basin

$h=120 \text{m}, \alpha_1=\alpha_2=45^\circ, V_s=250 \text{m/s}$
Maximum aggravation factors

Influence of basin width (w)

- Narrow width basins → significant aggravation almost along the entire width of the basin
Maximum aggravation factors

Influence of inclination angles (a1-a2)

Variation in inclination angle affects only the region above the basin edge, where maximum AGF less than one appear for steep angles.
Maximum aggravation factors
Effect of shear wave velocity gradient

- Detrimental (increase of AGF) effect of shear wave velocity gradient at the vicinity of the lateral discontinuity in particular for low Vs values
- Minor effect at the constant-depth part of the basin

Riga (2015)

AMPLIFICATION AND AGGRAVATION FACTORS FOR SITE AND BASIN EFFECTS | 2016
Effect of soil nonlinearity

Consideration of soil nonlinearity for the sediments material does not affect the estimated aggravation factor significantly (small decrease of AGF far from the basin edge and minor increase close to the basin edge).
Towards practical recommendations: Spatial distribution of AGF

Symmetrical models:

Region d1 of model w1h3a1Vs1
w=2500m
h=250m,
\(a_1=a_2=20^\circ\)
\(V_s=250m/s\)

\(T_{0,c}=4h/V_s\)
(1D fundamental period at the flat part of the basin)
Mean aggravation factors for specific regions

Model \( w1h3a1Vs1 \)
\( (w=2500m, h=250m, a1=a2=20^\circ, Vs=250m/s) \)
Mean aggravation factors for specific regions

Shallow and medium-thickness basins (thickness of 60m - 120m)

Region a1
Region b1
Region c1
Region d1
Region e1

(w=2500m, h=60m, a1=a2=20°, Vs=250m/s)

(w=2500m, h=120m, a1=a2=65°, Vs=250m/s)
Mean aggravation factors for specific regions

Deep basins (thickness of 250m - 500m)

Region a1
Region b1
Region c1
Region d1
Region e1

(w=2500m, h=250m, \(a_1=a_2=20^\circ\), Vs=250m/s)

(w=5000m, h=500m, \(a_1=a_2=65^\circ\), Vs=250m/s)
Mean aggravation factors for specific regions

- Shallow and medium-thickness basins (thickness of 60m or 120m):
  - Symmetrical models: regions \( c1 \) and \( d1 \) are the most affected
  - Non-symmetrical models: region \( c1 \) is the most affected
  - Maximum AGF \( \sim1.1-1.5 \)

- Deep basins (thickness of 250m or 500m):
  - Symmetrical models: regions \( a1 \) and \( e1 \) are the most affected
  - Non-symmetrical models: regions \( e2 \) and \( c2 \) are the most affected
  - Maximum AGF \( \sim1.4-2.4 \)
Towards practical recommendations: Period-dependency of AGF

- So far, maximum aggravation factors have been mainly presented
- However, there is a strong period-dependency of AGF
Towards practical recommendations for EC8

Region d1 of model w1h3a1Vs1
(w=2500m, h=250m, a1=a2=20°, Vs=250m/s)

- Short-period average for periods less than 0.75T_{0,c}:
  \( \text{AGF}_S = 1.2 \)

- Long-period average for periods between 0.75T_{0,c} and 1.50T_{0,c}:
  \( \text{AGF}_L = 1.6 \)
Towards practical recommendations for EC8

Short-period average AGF<sub>S</sub>

Long-period average AGF<sub>L</sub>

Region a1
Towards practical recommendations for EC8

Short-period average AGF$_S$

Long-period average AGF$_L$

Region b1

- Short-period average AGF$_S$
- Long-period average AGF$_L$

$\text{AGF}_S$ vs $T_{ac}$

$\text{AGF}_L$ vs $T_{ac}$

$\text{AGF}_S$ and $\text{AGF}_L$ for different regions and sites.
Towards practical recommendations for EC8

Short-period average AGF_S

Long-period average AGF_L

Region c1

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Towards practical recommendations for EC8

Short-period average AGF$_S$

Long-period average AGF$_L$

Region d1
Towards practical recommendations for EC8

Short-period average AGF$_s$

Long-period average AGF$_L$

Region e1

Graphs showing the distribution of AGF values for short and long periods in region e1.
Towards practical recommendations for EC8

- Above the edges (regions a1 and b1):
  - median AGF_S and AGF_L < 1.0 regardless of T_{0,c}.

- At the flat part of the basin (regions c1, d1, e1):
  - median AGF_S are quite low (around 1.1) regardless of T_{0,c}, with a narrow band between the 16^{th}-84^{th} pctls (84^{th} pctls not greater than 1.2)
  - AGF_L increase moving towards the center of the basin.
  - AGF_L increase for increasing T_{0,c}. High-T_{0,c} basins have higher median AGF_L (up to 1.5 for region e1), as well as much wider band between the 16^{th}-84^{th} pctls (84^{th} ppctls as high as 1.8) compared to low- T_{0,c} basins.
  - The limit value of T_{0,c} for the distinction between low- and high-T_{0,c} basins could be indicatively set equal to 3.0s
Towards practical recommendations for EC8

### Short-period average AGF$_S$

<table>
<thead>
<tr>
<th>$T_{0,c}$</th>
<th>Region a1</th>
<th>Region b1</th>
<th>Region c1</th>
<th>Region d1</th>
<th>Region e1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{0,c} &lt; 3.0s$</td>
<td>median</td>
<td>0.81</td>
<td>0.62</td>
<td>1.08</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>84th</td>
<td>0.89</td>
<td>0.94</td>
<td>1.13</td>
<td>1.09</td>
</tr>
<tr>
<td>$T_{0,c} \geq 3.0s$</td>
<td>median</td>
<td>0.74</td>
<td>0.65</td>
<td>1.11</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td>84th</td>
<td>0.91</td>
<td>1.02</td>
<td>1.19</td>
<td>1.14</td>
</tr>
</tbody>
</table>

### Long-period average AGF$_L$

<table>
<thead>
<tr>
<th>$T_{0,c}$</th>
<th>Region a1</th>
<th>Region b1</th>
<th>Region c1</th>
<th>Region d1</th>
<th>Region e1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{0,c} &lt; 3.0s$</td>
<td>median</td>
<td>0.94</td>
<td>0.68</td>
<td>1.01</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td>84th</td>
<td>1.02</td>
<td>0.84</td>
<td>1.05</td>
<td>1.12</td>
</tr>
<tr>
<td>$T_{0,c} \geq 3.0s$</td>
<td>median</td>
<td>0.91</td>
<td>0.85</td>
<td>1.08</td>
<td>1.29</td>
</tr>
<tr>
<td></td>
<td>84th</td>
<td>1.58</td>
<td>1.08</td>
<td>1.31</td>
<td>1.54</td>
</tr>
</tbody>
</table>
Preliminary proposals for introduction of basin effects into EC8

- Proposal of a short-period aggravation factor $AGF_S (T \leq 0.75T_{0,c})$ and a long-period aggravation factor $AGF_L (0.75T_{0,c} < T \leq 1.50T_{0,c})$, where $T_{0,c}$ is the 1D fundamental period at the center of the basin.

- The proposed aggravation factors should multiply in the two period ranges the spectral values of the design elastic response spectrum of EC8.

- Above the basin edge: $AGF_S$ and $AGF_L$ are in general below 1.0. It is on the safe side to use the EC8 design response spectrum without any modification.

- Flat part of the basin: the use of 84\textsuperscript{th} pctls of $AGF_S$ and $AGF_L$ is proposed. Different values for $AGF_S$ and $AGF_L$ are proposed for basins with high or low values of fundamental period at the center of the basin.

- The proposed AGF depend on the selected parameters. Higher values for AGF may occur for other types of basins. Detailed site-specific analyses should be performed for important structures.
Example: Definition of input motion across the dam foundation

PSHA (SHARE): PGA and UHS at rock-site conditions for SEE: $a_g = 0.3g$
Example: Definition of input motion across the dam foundation

Bedrock: PGA = 0.30g

PSHA (SHARE): PGA and UHS at rock-site conditions for SEE: $a_g = 0.3g$

Points P1, P2, P3 with EC8 soil factors for soil class B (foundation soil):

PGA = 0.36g
Example: Definition of input motion across the dam foundation

PSHA (SHARE): PGA and UHS at rock-site conditions for SEE: $a_g=0.3g$

Bedrock: PGA=0.36g

Points P1, P2, P3 with EC8 soil factors for soil class B:

PGA=0.36g

Point P1 with aggravation factors:

PGA=0.21g
Example: Definition of input motion across the dam foundation

PSHA (SHARE): PGA and UHS at rock-site conditions for SEE: $a_g=0.3g$

Bedrock: PGA=0.30g

Points P1, P2, P3 with EC8 soil factors for soil class B:
PGA=0.36g

Point P2 with aggravation factors:
PGA=0.45g
Example: Definition of input motion across the dam foundation

PSHA (SHARE): PGA and UHS at rock-site conditions for SEE: $a_g = 0.3g$

Bedrock: PGA=0.30g

Points P1, P2, P3 with EC8 soil factors for soil class B:

PGA=0.36g

Point P3 with aggravation factors:

PGA=0.38g
In summary

- This work contributes to the improvement of the definition of seismic actions at the base of earth dams based on recent progress in the frame of EC8 improvement

- Proposals for improvement of EC8 design spectra:
  - Improved S factors for the current EC8 classification scheme → need for an increase in S factors at least for soil class C
  - New site – soil classification scheme with corresponding period dependent elastic response spectra

- Proposal of extra aggravation factors (AGF) for complex subsurface geometry:
  - AGF are not uniform along the basin
  - AGF depend mainly on the dimensions of the basin (width, depth) and impedance - shear wave velocity of the sediments (uniform and gradient)
  - AGF are strongly site (along the basin) and period-dependent
  - Short-period aggravation and long-period aggravation factors to account for the complex basin effects.
Selected references


4 full days: Prof. N. Ambraseys Distinguished Lecture, more than 20 Keynote & Theme Lectures, more than 1200 Oral & Poster Presentations, Special & Technical Sessions, Technical committee meetings, Exhibition, Pre & Post Conference Tours

Looking forward to welcoming you to Thessaloniki in June 2018
THANK YOU FOR YOUR ATTENTION