Site effects : Impact, advances and challenges

Pierre-Yves BARD
Introduction

Interface topic

different disciplinary fields & communities :
- seismology, geophysics, soil and structural
- academic / engineering / regulatory)

(short) overview of the today status of both knowledge and practice,
with a special focus on
the recent advances
the major remaining issues
- in view of a more satisfactory accounting for an improved risk reduction.

Source Path = crustal propagation

Site effects
Crustal propagation
Seismology
Soil dynamics
Structural dynamics
Soil-structure interaction
Building response
Outline

Introduction

Basic Physics

Main tools

Practice : Engineering issues

Conclusions / Comments
Basic Physics

Two kinds of site effects

"Direct" (="ground shaking") site effects : Wave propagation effects
  • resulting in localized amplifications, (or deamplifications), highly variable with frequency, possibly reaching very high levels (> 10)
    - Surface topography
    - "Soft" surface deposits

Induced site effects
  • Soil damage resulting in localized soil failures
    - Liquefaction of water saturated sandy deposits, settlements
    - Slope instabilities (slides, falls, debris flows, ...)

ESC 2010
Effects of surface topography

Various evidence

- "Classical"
  - instrumental recordings
  - observed (heavy) damage
- Remote sensing
- Spatial variability
- Insurance claims

(Nechstchein et al., 1995)
Example cliff damage: the Adames area (Athens, 1999)

(Gazetas et al., 2002; Assimaki et al., 2005)
Evidence from insurance claims
San Simeon 2003 (see McCrink et al. 2010)

Yellow : insurance claim
Black dot : insured house

(McCrink et al., 2010; Courtesy C. Real)
Resonance effects in sediments

- Wave field in surface deposits
  - Refraction, diffraction, focusing
  - Wave Trapping
    - vertical reverberations
    - lateral reverberations

- Consequences
  - constructive interferences: amplification
  - trapping: prolongation
  - resonance at specific frequencies

! + soil non-linearities !
SCT Site

0.75g

T ~ N/10

MEXICO 1985

(Sa (g)

T (s)

(Mouroux, 1999)
Impact of site conditions on hazard curves

Conclusions

Up to a 2 to 3 factor for a given annual probability $p_a$

A factor $u$ to 10 on $p_a$ for a given spectral level
Site effects should not be invoked to explain all damage anomalies

Hellel et al. 2010

Figure 5. Map showing the location of the heaviest damages in the “Cité des 1200 logements” and the “Cité du 11 décembre” urbanizations (hatched areas), with the H/V peak distribution, over a May 2003 Quickbird satellite photography of Boumerdes city. Green areas are zones where a clear H/V peak is identified, red areas are zones where such a peak cannot be identified, and the blue area is zone 3B where a bump rather than a peak is shown of H/V curves. In the gray zone, H/V curves are flat. Note that the most damaged zones correspond to areas without a clear H/V peak, while, for example, only slight damages are observed in the “Cité des 800 logements,” located in a zone where a clear H/V peak is identified.
Physical understanding : main challenges

? Separation source / path / site effects : is it relevant
  ➢ ? sensitivity of site effects to incident wave-field characteristics
  ➢ near-field issues

Surface topography effects
  ➢ ? links to weathering and local heterogeneities
  ➢ can we rely on a modelling approach ?

Sediments
  ➢ effects and amount of non-linearity
    - especially at large depth
    - larger number of soil/rock pairs and/or vertical arrays,
  ➢ 2D / 3D effects : "overamplification" and duration

Wave-field composition
  ➢ complexity and origin (regional, local ? natural / anthropic ?)
  ➢ effects of soil short wavelength heterogeneities - natural or anthropic - on the spatial variability of ground motion
Ideally, a site response study should include:

- rupture mechanism (source)
- wave propagation in the crust to bedrock top (path)
- how surface motion is influenced by soil layers located above the bedrock top
- possible coupling
  (wavefield, azimuth/incidence, shock waves, ...)

In practice:

- ? Experimental evidence for such sensitivity?
- ? Feasibility for routine analysis
Expected sensitivity to incident wavefield

Scattering effects induced by topography (LA area)

Effects of incidence angle on valley response (linear case)

(Ma et al., 2007) (Gélis et al., 2008)
? Observed dependence on azimuth and distance?

TST site, Volvi

Data still too few to ground unambiguous experimental evidence

(Riepl, 1997)
Recent results on surface topography effects

Additional consistent evidence of amplification
- convex parts: hill-tops and cliffs
- mixed with geological / lithological effects
  - especially at high frequencies

+ Diffraction / scattering effects
- increased variability
  - ? Larger \( \sigma \) for GMPE in mountainous areas?
- significant strains
  - (upper bounds from displacements and Rayleigh velocity)

Still (most) missing and welcome
- Dense array recordings coupled with detailed geophysical surveys
- HF issue: short wavelength characterization at shallow depth
- convincing statistics for building codes
- ? effects of strains on landslide triggering
Non-linear behavior

Origin: Soil degradation under large deformation

- decrease of shear modulus
- Increase of damping

Consequences

Fundamental frequency $f_0$

$$f_0 = \beta_1/4h, \ \beta_1 = (G_1/\rho_1)^{0.5}$$

$\Rightarrow$ Decrease of $f_0$

Amplification $A_0$

$$A_0 = C / (1 + 0.5 \pi \xi_1 \ C)$$

$C = \rho_2 \beta_2/\rho_1 \beta_1 \ \Rightarrow, \ \xi_1 \ \Rightarrow$

$\Rightarrow$ Decrease of $A_0$
Non-linear behavior, Kariwa-Kashiwazaki NPP

Obvious from vertical array recordings (main shock / aftershock)

BUT

Highly variable within the NPP site

From Sekiuchi et al., 2008; Mogi et al., 2010
Recorded Maximum Acceleration in EW direction (in gal)

<table>
<thead>
<tr>
<th>NS</th>
<th>EW</th>
<th>UD</th>
</tr>
</thead>
<tbody>
<tr>
<td>347</td>
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<td>179</td>
</tr>
<tr>
<td>403</td>
<td>647</td>
<td>174</td>
</tr>
</tbody>
</table>

Maximum acceleration at Service Hall downhole array (in gal)
Reversible velocity changes, consistent with lab measurements

From Mogi et al., 2010
NL behavior in L'Aquila?

Indirect evidence from HV ratios

(No vertical array)

From Amori et al., 2010
Short wavelength spatial variability

(cf. H. Igel presentation)

Multiple origins

- oblique incidence
- complex wavefield
  - near source
  - near site
  - scattering
Old example: Landers aftershocks (Steidl, 1993)
Example: Rio Dell Bridge, N. California
Dense cities on soft sites

The seismologist viewpoint

? May (massive, stiff) buildings modify the ground motion?

The engineer viewpoint

Site city interaction
SSSI: Experimental evidence from centrifuge testing

Reference:
Building 1 alone

Maison 1 Seule Enterrée - Capteur 1-1

Maison 1 Enterrée - (Maison 2 posée en 2) Capteur 1-1

Maison 1 Enterrée - (Maison 2 en position 4)

Maison 1 Enterrée - (Maison 2 en position 2,50m)

Building 1 with Building 2 at 22,5 m
Building 1 with Building 2 at 7,5 m
Building 1 with Building 2 at 2,5 m
Ground motion: BEM results for Mexico City
(after Clouteau / Ishizawa, 2003)

City effect

With buildings vs without buildings

Modification of average response

Scatter on ground response
Main tools

Observations

Numerical simulation

(Shallow geophysics and geotechnics)
Main tools / Observations

Direct estimation of site amplification

- Single station estimates : H/V
- Site / reference spectral ratio ➔ "small" inter-station distance
- Generalized inversion techniques ➔ "average" reference
  - require sensitive instruments

- 2D arrays : very few, not so dense
- Vertical arrays

- Amplitude / phase
Generalized inversion

Main interest: does not require a specific nearby reference site

Basic equation:

\[ O_{ij}(f) = E_{ij}(f) \cdot P_{ij}(f) \cdot S_{ij}(f) \]

Propagation term:

\[ P_{ij}(f) = \frac{1}{r_{ij}} \]

\[ = \left( \frac{1}{r_{ij}} \right)^\gamma \cdot e^{-\pi f t_{ij}} / Q(f) \]

(---no account for focal mechanism, or directivity effects...)

Final equations:

\[ \ln \left( E_{ij}(f_k) \right) + \ln \left( S_{ij}(f_k) \right) = \ln \left( O_{ij}(f_k) \right) - \ln \left( P_{ij}(f_k) \right) \]

K(J + I) unknowns

Maximum KIJ equations

-----> weight \( o_{ijk} \) depending on signal to noise ratio

(From Hartzell, 1992)
Generalized inversion of S-wave displacement spectra

Assumptions:

- Far-field approximation (Dist>$15 \text{ km}$)
- Brune’s type source (1970)
- Average radiation pattern
- $v_S$ constant along the path
- Geometrical decay constant between 15 and 200 km
- $Q(f)=Q_0f^\alpha$

\[ A_{ij}(r_{ij},f_k) = \frac{2R_{\theta q}M_{0i}}{4\pi \rho v_s^3} \times \frac{1}{1+\left(\frac{f_k}{f_{ci}}\right)^2} \times \exp\left(-\frac{\pi r_{ij} f_k}{Q(f_k)v_s}\right) \times \frac{1}{r_j^\gamma} \times S_j(f_k) \]

Source \quad Propagation \quad Site

Drouet, Chevrot, Cotton, Souriau, 2008, BSSA, in press
Generalized inversion for estimating site amplification factors for French accelerometric sites

Alps:

Pyrenees:

Rhine Graben:

Drouet et al., 2008
Vertical arrays

Deconvolution

- S-wave velocity profile
- Damping
- NL characteristics

Still too few in the EuroMed area

(Parolai, 2010)
Amplification vs Duration / Phase

- Low frequency, short input signal
- Broader band, longer input signal
- High frequency, short input signal
Amplification vs Duration / Phase

Known techniques

- group delay (Sawada et al., Beauval et al.)
- sonogram (Parolai et al.)
- time-frequency analysis

Still missing

- systematic investigations in parallel in amplification studies
Main tools / Observations

Direct estimation of site amplification : reference / non-reference
- Site / reference spectral ratio ➔ "small" inter-station distance
- Generalized inversion techniques ➔ "average" reference
- single station estimates : H/V
- Vertical arrays (? depth)
- Amplitude / phase

Seismological observations as an exploration tool for subsurface structure ?
- Small-scale tomography / inversion : ex Tokyo

Interpretations and statistical studies : link with site conditions at considered observation sites : need for metadata !
- permanent stations (SM, BB)
- temporary stations
Example: Ongoing studies in Tokyo (dedicated semi-permanent array)
Main tools / Observations

Direct estimation of site amplification: reference / non-reference
- Site / reference spectral ratio ➔ "small" inter-station distance
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THE example to follow: Japan

- EuroMed instrumentation: a step behind
- Too few test sites

Usefulness of a dedicated large pool (several hundreds) of compatible mobile stations at the European level (for temporary, very dense studies on small, typically ct-scale areas)
Main tools / Numerical simulation

Invaluable tool in understanding the physics of site effects
- Various excellent teams and techniques in Europe
- BEM, FDM, FEM, SEM, DGM, DEM

Verification / validation issues
- still faces big challenges for actually predicting them for complex 3D structures. Numerous sophisticated codes do exist, but their use without due caution can be harmful
- Verification = evaluate the accuracy of current numerical methods when applied to realistic 3D applications
  ➔ cross-checking that different codes provide similar results on same cases
- Validation = (successful) comparison with instrumental observations
  ➔ quantify the agreement between recorded and numerically simulated earthquake ground motion
  - (source + path + site)

- Recent initiatives / projects in Europe
  - SPICE, QUEST, NERA
  - ESG2006, Cashima

Present capabilities : at reach up to frequencies around 4-5 Hz ?
Example: the ESF2006 3D benchmark (Grenoble)

- 2 real weak events
  - W1, W2

- 2 hypothetical strong events
  - S1, S2 (M=6)
  - Extrapolation from W1, W2
  - Source: imposed geometry and kinematics
Iteration process: 3 teams (/6)

September 1, 2006

ID15: bug in basin model definition
ID17: bug in extended source definition
ID08: bug in extended source definition

April 8, 2007
The Cashima / Euroseistest site
Cashima / Euroseistest components

Initial checks
- Site selection → Volvi / Euroseistest
- Contacting several teams (about 10)
- Careful scheduling with 3 phases for iteration; 1 kick-off meeting + 4 workshops (May 2008, Fall 2008, Spring 2009, Fall 2009, Spring 2010 = Final)

Verification: cross-comparison of different simulation techniques
- 3D: Up to 4 Hz
  - Plane wave / point source
  - With and without damping
  - Discrete layering / smooth gradient
- 2D: Target = 8-10 Hz
  - Linear / Non-Linear

Validation: comparison with actual recordings (3D only)
- Local, moderate magnitude events
Conclusions 1 - Verification

3D

- numerical simulation of ground motion is not yet a "press-button" procedure,
- Good match up to 4 Hz obtained between various simulation techniques indicates a very encouraging level of maturity.
  - teams and codes who already compared their results are more likely to provide satisfactory results at the first iteration
- Emphasis on the importance of
  - the actual implementation of damping
  - the details of the discretization process for interfaces with large impedance contrast

• 2D NL: not yet mature, ongoing
  - Usefulness of preliminary checks on 2D L
  - Key importance of damping in NL models
    - classical "Seed like" curves yield strong NL effects at least in deep deposits
    - ? Large effects at high frequencies because of damping?
Verification 2: layered model, NO damping

Rather satisfactory PGV maps
NL verification: Model to model comparison of response spectra

Significant variability in NL modelling results
Conclusions 2 - Validation

Limited to local, weak to moderate magnitude events with significant high frequency contents

- Satisfactory match of "overall" characteristics (amplitude, envelope, duration)
  - to be balanced by
- Large differences in the details of waveforms

Limitations to increase in maximum frequency are mainly related to

- uncertainties in source parameters
- capabilities of geophysical surveys
  - underground structure at short wavelength
  - still a few very badly known parameters (e.g., material damping)

next challenge?
Engineering interface

"Routine" : building codes (Non-site specific assessment)

- Site classification : which parameter ?
  - VS30
  - ? Alternative

- Associated amplification factors / spectra

Large scale hazard/risk maps, Shake maps

- ? which simple proxy to site effect (from remote sensing)
  - slope
  - others ?

Microzonation: area specific

- Cost constraints

Site specific assessments (critical facilities)

- Open !
- Europe : instrumental approach drastically neglected
  - single station sigma, major impact on the reduction of uncertainties, and therefore hazard levels at large return periods.
Needs

Reliable, affordable site survey techniques for
- subsurface conditions at SM and seismological stations
- microzonation studies at the city scale (a few to hundreds of km²)
- identification of site class for building codes ($V_{s30}$, $f_0$, ???)

Target
- Large depth (low frequency)
- Shallow depth over short wavelengths

Required
- wide areas or numerous sites: cost efficiency
- reliable, quantitative estimates of relevant parameters

Move to non-invasive techniques
Techniques used to extract subsurface properties from ambient vibration recordings

Endrun et al., 2009
Systematic comparison with borehole data

Selection of 20 representative sites

- variable and representative subsurface geology and topography.
- Stiffness + Thickness, + 1D/2D/3D, + reliability of the existing information + EC8 classes

9 in Italy, 7 in Greece, 3 in Turkey, 1 in France

(see Renalier et al., SSA2009)
Good agreement for "normal to soft" sites (EC8 classes C, D, E)

Noticeable and systematic differences for stiffer sites (EC8 classes A, B):
- $V_{s30}$ (non-invasive) < $V_{s30}$ (invasive)
  (Similar trend reported in Moss, BSSA 2008)
Several possible explanations
  - Frequency range
  - Averaging effect
  - Anisotropy
Is it a concern?
Complementary measurements

New cross-holes close to "old" ones

Selected sites
- Forli (EC8 B)
- Bagnoli Irpino (EC8 A)
- Sturno (EC8 A)

Similar results for all 3: decrease of velocity
- Forli: B → C
- Bagnoli: A → B
- Sturno: A → B

Does raise questions about the reliability of (old) borehole data

Hailemikael et al., 2008
Sturno (distance 1991-2007: 45 m)

Prof. E. Cardarelli University of Rome “La Sapienza”
2007; EC8=B

ISMES 1991; EC8=A

Hailemikael et al., 2008
Most relevant parameter for site conditions?
How to best explain the variance of site amplification factors?

<table>
<thead>
<tr>
<th>Considered parameters</th>
<th>Misfit (log10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{S5} ) and ( f_0 )</td>
<td>0.168</td>
</tr>
<tr>
<td>( V_{S10} ) and ( f_0 )</td>
<td>0.164</td>
</tr>
<tr>
<td>( V_{S20} ) and ( f_0 )</td>
<td>0.159</td>
</tr>
<tr>
<td>( V_{S30} ) and ( f_0 )</td>
<td>0.158</td>
</tr>
<tr>
<td>( f_0 ) only</td>
<td>0.159</td>
</tr>
<tr>
<td>( V_{S30} ) only</td>
<td>0.174</td>
</tr>
<tr>
<td>Original ( \sigma )</td>
<td>0.202</td>
</tr>
</tbody>
</table>

Best = couple of parameters \( f_0 \) and \( V_{S20} \) or \( V_{S30} \),
\( f_0 \) alone much better than \( V_{S30} \) alone.

Cadet et al., 2010
Accounting for non-linear effects

Building codes?  
? In-situ measurements?

Before 1985

After 1990

0.13 g

0.4 g
Post-1994

Separate amplification factors for short- and long-period spectra

- C = stiff soil/weathered rock
- D = soil
- E = soft soil
Regulatory spectra

"Old" Spectra

EC8 : Hz Spectra

EC8 Type I Spectra

EC8 Type II Spectra
In-situ measurement of NL characteristics

Example device (heavy and expensive...)

- Vertical Shaking
- Ground Force Estimates
- 3C Accelerometers
- $\Delta t = 0.005\text{-sec} \Rightarrow f_{\text{max}} = 100\text{-Hz}$
- Sweep Band: 10-Hz to 50 Hz

- and limited strains...

From Pearce et al., 2006
Proxies to site conditions for wide regional use
(shake maps, hazard curves)

Inventory of possibilities

- Mandatory: available from remote sensing
- slope
- ? Other: $f_0$, ...

Ongoing investigations

- $V_{S30}$ / slope FOR EUROPEAN SITES
  Robustness for different data subsets (California vs Italy or Turkey ???)
  is a weak correlation better than nothing?
- Tests in GMPE
Proxys for shake maps: "local slope"
(proposal by Wald et Allen, 2007, 2009)
French slope vs Vs30 on SRTM30 with active tectonics settings
f0 / subsidence rate: the Grenoble case

Périodes de résonance

Taux de tassement

 Courtesy S. Michel / C. Cornou
Conclusions: Challenges ahead

Improving the quality of instrumental observations in Europe

- Site metadata (permanent SM + BB)
- Denser instrumentation
  - more vertical arrays (NL)
  - more rock / site couples (NL)
  - more short aperture arrays (wavefield analysis)
- Dedicated mobile pool for urban studies (≈ 200 stations)
- Critical facilities: promote the instrumental approach
  - sensitive instrumentation, continuous recording
  - free-field, vertical arrays, + structure (SSI)
Conclusions: Challenges ahead

Imagery of "shallow" subsurface (10 m - 1 km)

- Average velocities $V_{SZ}$
- Velocity structure (1D-2D-3D), including deep bedrock (last contrast)
  - Cross-correlation tomography?
- Highly heterogeneous soils (volcanic areas, slopes / landslides)
- Damping values (possibly frequency dependent)
- NL characteristics

Numerical simulation

- Verification of NL models (1D, 2D)
- More test sites for validation
  - (long term funding)
Conclusions: Challenges ahead

Engineering use

- Promote the routine use of non-invasive techniques in geotechnical engineering
  ( ! Warning: low cost tools - non-invasive techniques - require high expertise and good instruments! )

- Propose relevant proxies for building codes and shake maps
  - Alternative to $V_{530}$ for the next generation of EC8
  - Relevant remote sensing parameters (subsidence, ...)

- Propose physically sound, simple amplification factors for
  - surface topography effects
  - valley effects