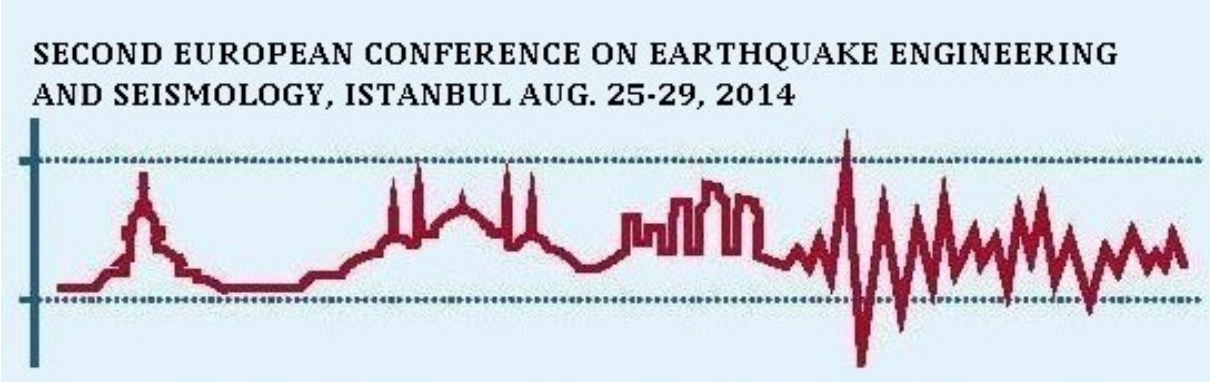

WAVEFORM MODELING AND SITE COEFFICIENTS FOR BASIN RESPONSE AND TOPOGRAPHY : MAIN RESULTS FROM THE NERA WP11

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The effects of *surface* (topography) and *subsurface* (valley, basin, lateral discontinuity) geometry on seismic ground motion have been recognized for a long time, and have been the topic of many instrumental and numerical investigations over the last decades. Yet, their complexity, combined with the imitations of geophysical investigation techniques and numerical simulation as well, made it impossible till now to include such effects in earthquake mitigation and risk reduction policies: the vast majority of building codes do not include any provision for basin and surface topography effects.
WP11 objectives were to build on recent advances and results from instrumental seismology, geophysical exploration and numerical simulation to propose physically sound, economically acceptable and simple enough models for including proper account to the effects of surface and subsurface geometry in building codes, microzonation studies or improved GMPEs.

Tha achieved work can be grouped in three main items, as decribed below:

1. Surface topography effects, directionality and fracturation

A careful survey of the recent literature indicated a high variability in the amount and characteristics of reported amplification associated to surface topography features, ranging from moderate to very large effects in an unpredictable manner. However, the analysis of the available Italian, Swiss, Greek and Japanese data suggests that unexpectedly high, directional amplifications observed on ridges could be associated to rock fracturation. The analysis of existing data sets and associated studies has outlined the frequent coincidence of significant directional effects and larger than expected amplification on top of reliefs. These results are consistent with large directional effects found on unstable slopes in Swiss Alps, where large amplifications on unstable rock blocks at azimuths perpendicular to the open cracks whereas stable portions of the mountain do not show neither amplification nor polarization.

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They are also consistent with the significant polarization found in fault zones in Italy in probable relation with fracturation anisotropy. The homogeneous reprocessing work undertaken (ETHZ, INGV, ISTerre) for about 40 Italian and Swiss rock sites, together with Japanese KiK-net sites, and a few RAP sites, together with the geophysical experiments performed at the two Italian sites, led us to the following conclusion to be proposed to the engineering community:

- whenever significant, topographical effects exhibit a pronounced frequency and directional dependence, which is presently NOT taken into account in EC8 recommendations
- the "topographical coefficient" τ is therefore only partially linked with the geometry of the topography, and (i) the present EC8 dependence on slope / height does not seem to be very relevant and (ii) it does not seem useful to assign a high priority to a set of comprehensive computations to relate the topographic amplification to the sole surface geometry
- Our proposal for accounting for surface topography effects in seismic design is thus a "recipe" for in-situ studies (based on geology, noise measurements, geophysics) in order to decide, on a case-by-case basis, whether topographic amplification should be considered for a given site

2. Experiments on basin effects and spatial variability of ground motion

An analysis of the existing and available data has been performed in view of (i) investigating the link between ground motion spatial variability, strains, seismic wavefield and subsurface properties, and (ii) comparing numerical estimates of ground strain with actual measurements. It turned out that dense array data were still missing and it was decided to use the mobile instrumentation available within the partnership to install temporary, very dense arrays in two carefully selected sites. 64 instruments from four institutions (CNRS/ISTerre, INGV, ITSAK and GFZ) have been deployed from September 2011 to April 2012 in a small alluvial valley (***1 km wide, 60 m thick, 2 Hz fundamental frequency***) located south of Argostoli in Kefalonia island (Greece). This is one of the most active seismic areas in Europe, and hundreds of local and regional events have been recorded along ***two EW and NS lines across the valley*** and ***two very dense arrays*** in the central part of the valley (21 BB sensors over a 2 ha area) and the valley edge (10 short period sensors). A similar array of larger size (≈1 km aperture) has been deployed from April to September 2012 in the Fucino basin east of Roma, a much thicker basin (0.3 Hz fundamental frequency, 15 km wide, 1km thick). It did record the Emilia-Romagna sequence of May – June 2012.

The underground structure of both sites has been investigated with specific geophysical surveys involving active and passive non-invasive techniques (MASW and microtremor array), with a special emphasis on the Argostoli site.

About 700 events (mostly local and regional) have been recorded by the Argostoli array with a good signal-to-noise ratio. Local events were relocalized by ITSAK-EPPO using a few stations specially installed on Kefalonia and neighboring islands during the temporary experiment. The systematic analysis of a large subset of events with "classical" spectral ratio techniques (site-to-reference, H/V) exhibits significant 2D or 3D effects as presented in Cultrera et al. (2014). The dense array recordings have been analyzed with a 3Component, array processing technique (MUSIQUE) combining the MUSIC approach with quaternion techniques as presented in Hobiger et al. (2012) for wavefield identification, and also with engineering oriented tools for investigating the short distance spatial variability and coherence. As detailed in Imtiaz et al. (2014), the systematic analysis for the same subset of events indicate strong local, stable scattering of surface waves (Rayleigh and Love) beyond the local fundamental frequency, which opens a new way for interpreting and extrapolating coherency analysis.

3. Numerical simulation of basin effects and derivation of aggravation factors

The objective was primarily to use numerical simulation tools to derive "aggravation factors" quantifying the difference between 2D or 3D response and the 1D response, the latter being supposed to be the "standard" accounted for in building codes or first level site-specific studies.

This has been achieved through the design of a comprehensive parametric study of the linear response of more than 1000 2D valleys (162 trapezoidal or triangular geometries combined with six velocity profiles involving realistic velocity gradients for both sediments and rock, plus 32 similar geometries combined with 3 different homogeneous velocity profiles). The valley width range from 500 m to 20 km, the sediment thickness from 30 m to 1 km, V_{S30} values from 125 m/s to 500 m/s, and velocity

contrast at depth from 1.5 to 8. The 2D response has been computed for at least 100 surface receivers under vertical incidence of pulse-like SH and SV waves, and later convolved with 10 real input accelerograms. These computations were performed with the various modeling techniques and codes available with the consortium : Finite Difference, Finite Element, and Spectral Element, in the linear case and for some cases taking into account the soil non-linearities.
The results are described first in terms of average "amplification factors AF" (average ratio of output response spectrum to input response spectrum for various realistic input signals), and ultimately in terms of 2D/1D "aggravation factors AGF" quantifying the additional effect of the 2D geometry by comparing the 2F AF to the 1D AF (taking into account only the local vertical soil column). A preliminary analysis indicates that these AGF are found in the range 1.3 – 2 in most cases, with a maximum near the valley edges and sometimes in the center of embanked valleys, while they almost systematically exhibit some deamplification (AGF values smaller than 1) on the very edges of valleys (over dipping sediment-basement interface). These aggravation factors decrease with increasing input ground motion because of non-linearity, while they may increase in case of pronounced 3D geometries. The final objective is to propose simple formulae relating these AGF to the geometrical and mechanical characteristics of the valley and the receiver position.

The presentation will briefly outline the work accomplished over the 4 year project for the three main addressed items, the main findings and the propositions for updating building codes and microzonation studies.

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