MODELLING OF STRONG GROUND MOTION OF THE JULY 2004, M\textsubscript{w} 5.2 EARTHQUAKE IN KRN MOUNTAINS

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ABSTRACT – The effects of the seismic source and of local geology on ground motion are studied in the Upper Soča Valley (western Slovenia), which was struck by two earthquakes, on 12 April 1998 (M\textsubscript{w}=5.6) and on 12 July 2004 (M\textsubscript{w}=5.2). The paper focuses on the latter event, while the former was thoroughly investigated in Gosar et al. (2001). 2D numerical modelling is applied, together with a recently improved technique of ‘sub-structuring’ (source and site effect) of the problem at study (DRM approach). Numerical modelling, used for computing site effects, is thereby coupled with an efficient mathematical method used for source modelling. The combined influence of 1D propagation effects on the dominant frequencies of motion, and of 2D effects on the amplification level and significant frequency band, are highlighted. Ground amplification is high in the frequency range of building vulnerability (1-7 Hz), consistent with Gosar et al. (2001) findings. Comparison with Eurocode 8 spectra shows that the latter may not be conservative for periods up to 0.8 s. The relatively large response at such periods is related to the geological configuration of the valley, which appear to require a reasonably accurate definition of its 2D geometry.

1. Introduction

The Bovec town lies close to the rim of a sedimentary basin in the Upper Soča Valley in the NW of Slovenia, a region undergoing a recent increase in seismic activity. The two earthquakes that struck the Bovec basin, on 12 April 1998, M\textsubscript{w}=5.6 (Zupancic et al., 2001), and on 12 July 2004, M\textsubscript{w}=5.2, caused significant damage to building structures of the area. Maximum intensity was VII-VIII EMS-98. In both events, the distribution of damage could be ascribed only in part to differences in building vulnerability, while local geological conditions seem to have played a significant role (Gosar et al., 2001). This study investigates the distribution of local site effects, that may explain such a variation, by using a model that includes both the valley and the earthquake source. The Bovec basin is filled from bottom to the top with flysch and deep sea clastites, lacustrine (chalk) and glaciofluvial sediments (sand, silt, gravel and till). The modelled cross-section across the basin was constructed from seismic refraction and DC resistivity data as well as sparse drilling information.

Among the different methods available for coupling seismic wave propagation in a halfspace containing the earthquake source to that in a “local” domain containing the near-surface geologic and topographic configurations, the Domain Reduction Method...
(DRM), first proposed by Bielak et al. (2003), and then adapted by Faccioli et al. (2005) to the spectral element method, is applied. The method implies a ‘sub-structuring’ of the problem at study, whereby the analysis of the source and wave propagation in the halfspace (external region) is separated from that of the irregular region, including site effects or structure interaction. Seismic excitation for the local domain is directly introduced in the form of effective localized forces obtained from the free field motion in the external domain and from the mechanical properties of a fictitious interface that separates the external region and the local region. The application of this method is carried out by using an hybrid finite element - spectral element code (AHNSE).

The results of a 2D earthquake response simulation of the valley of Bovec during the 2004 event, based on the coupling between the effective force method and the spectral element model, are presented and compared with the available strong motion accelerogram.

2. Geology and seismicity of Bovec region

Both the 1998 and 2004 Upper Soča valley earthquakes occurred on NW-SE trending near-vertical Ravne fault in Krn mountains at the depth of 7-9 km and caused extensive damage to buildings in the area. The Bovec basin represents a structural barrier for this seismogenic fault. The focal mechanisms (Fig. 1) of both earthquakes show almost pure dextral strike-slip (Kastelic et al., 2006). The epicentral distance to the town of Bovec is 6-7 km. The 12 April 1998 earthquake (MW=5.6) caused maximum intensity VII-VIII EMS-98 (Zupančič et al., 2001) and the 12 July 2004 (MW=5.2) earthquake VI-VII (Živčič et al., 2006). Strong variations in damage to buildings were observed within short distances in the whole Bovec basin. They cannot be explained by the changes of epicentral distance.

![Figure 1. Shaded relief map of the Upper Soča valley with epicentres and fault plane solutions (Zupančič et al., 2001; Kastelic et al., 2006) of two recent strong earthquakes in Krn mountains and locations of accelerographs used in this study. Thick line shows trace of modelled cross-section.](image-url)
or by changes of the radiation of seismic energy from the source, although the latter can have some influence. Therefore local geological conditions (site effects) appear to have played the most important role.

NW Slovenia marks a kinematic transition between E-W striking thrust faults of the Alpine system and NW-SE striking faults of the Dinaride system. Before 1998 a relatively weak rate of seismicity had been characteristic for NW Slovenia. Nevertheless, in the seismic hazard map for return period of 475 years the Bovec basin is located in one of three regions of Slovenia with increased seismic hazard having 0.225-0.250 g design ground acceleration. This is due to the vicinity to the active Friuli area (25-30 km to the W) with strongest \( M_w=6.4 \) Friuli event in 1976. The strongest earthquake ever recorded in the Alps-Dinaride junction was the 1511 western Slovenia earthquake (\( M=6.8 \)) whose exact location and mechanism are still debated.

A seismic microzonation study based solely on surface geological data and data from shallow geotechnical boreholes has shown that by using such data set it is not possible to explain most of observed variation in distribution of damage. More promising results were obtained by a combined study using microtremors and 1D modelling of ground motion based on results of shallow geophysical investigations (Gosar et al., 2001). An important influence of the shape of the basin can be expected which justifies a two-dimensional approach to model the observed ground motion.

The Bovec basin (6 km long and 2 km wide) was developed in the otherwise very narrow alpine valley of Soča river. The basement consists of the Mesozoic platform carbonates of Upper Triassic and Jurassic age. They are overlain by a succession of deep water clastites (flysch) or by marly limestone (type scaglia) and interchanging calcarenites, shales, marls and conglomerates of Cretaceous age. Quaternary sediments are represented from bottom to top by partly lithified glaciofluvial sediments (only in the central part of the basin), overlain by the sequence of lacustrine chalk. In Holocene the chalk was eroded and covered by glaciofluvial sand and gravel which are in some part weakly cemented in conglomerate and by unconsolidated moraine (till).

A 2D geological cross-section (Fig. 1) was prepared based on general geological knowledge of the area and sparse geophysical data, because no deep boreholes are available in the vicinity of the modelled profile. Resistivity sounding was used to determine the thickness of glaciofluvial sediments and lacustrine chalk, while the boundary between flysch and carbonates was detectable only in shallower border parts of the basin. The seismic velocities of the different units (Table I) were derived from shallow seismic refraction measurements using P and S-waves and from down-hole seismic velocity measurements in geotechnical boreholes. Both were performed only in the border part of the basin where the main settlements are located, as part of geotechnical investigations for retrofitting of damaged houses. Despite the fact that the overall depth and shape of the basin down to Mesozoic carbonates is only poorly known, we think that this has minor influence on the reliability of ground motion modelling, because the S-velocity in flysch and deep sea clastites present in the lower part of the cross-section is already 1000-1600 m/s.

<table>
<thead>
<tr>
<th>Lithological unit</th>
<th>( V_P [\text{m/s}] )</th>
<th>( V_S [\text{m/s}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glacier and river deposits (sand, silt, gravel, conglomerate)</td>
<td>600-1200</td>
<td>250-550</td>
</tr>
<tr>
<td>Till - unconsolidated moraine (clay, debris)</td>
<td>600-1300</td>
<td>300-600</td>
</tr>
<tr>
<td>Lacustrine chalk</td>
<td>1000-1500</td>
<td>600-800</td>
</tr>
<tr>
<td>Flysch and deep sea clastites (sandstone, marl, calcareous breccia)</td>
<td>2700-3700</td>
<td>1000-1600</td>
</tr>
</tbody>
</table>
3. Simulation of ground motion

Practical applications of earthquake modelling often require an integral approach which extends - with appropriate frequency and space constraints - from the seismic source to the response of a given structure. This is not allowed by the current approaches for seismic wave propagation and soil-structure interaction analyses, that are usually based on a sub-structuring philosophy. The problem is generally decoupled in simpler sub-problems, such as seismic source, site effects, SSI analysis, each one treated with a specific analytical and/or numerical approach. The combination of different methods represents an effective tool for reducing the computational effort otherwise required by large-scale 3D numerical wave propagation from the source to the region of interest. The main challenge is the coupling of the solutions obtained by the different methods in the different domains.

3.1. Method

One substructuring method, termed Domain Reduction Method (DRM), has been proposed by Bielak et al. (2003) and Yoshimura et al. (2003), who rigorously formulated an approach first traced by Herrera and Bielak (1977), and then developed and applied in 2D configurations e.g. Loukakis (1988). Faccioli et al. (2005) subsequently extended the method in a hybrid finite element-spectral element (FE-SE) environment, implementing the whole procedure in the code called AHNSE (Faccioli et al. 1997, Casadei et al. 2002). Referring to Bielak et al. (2003) for the formulation of the method, we just briefly recall here the essence of the approach.

As in Fig. 2, a fictitious interface $\Gamma$ subdivides the total domain into two separate subdomains: $\Omega$, containing the localized geological features, and $\Omega^+$; containing the seismic source; $\Gamma^+$ is the boundary that restricts the whole computational domain to a finite region. $P_b$ are the nodal forces exchanged by the two subdomains (effective forces generating free field displacements in the undisturbed halfspace). Processing of these forces shows that they only depend on the stiffness matrix of the interface elements and on the displacement free field of the so called auxiliary problem (the whole domain where $\Omega$, without geological heterogeneities, contains the same material as $\Omega^+$). Once the latter field has been determined (step I), the effective forces can be calculated and wave propagation solved (step II) for a reduced model tailored around the localized region of interest. The analysis is thus simplified because wave propagation in the external domain can be calculated with numerical or analytical methods suitable for simplified

![Figure 2. Sub-structuring of the computational domain (from Bielak et al., 2003). (a) Outer boundary $\Gamma^+$ restricts computation to a finite domain; fictitious interface $\Gamma$ divides region into two subdomains: $\Omega^+$, which includes the seismic source, and $\Omega$, which contains the localized geological features. (b) $P_b$ are nodal forces transmitted from the two substructures, $\Omega^+$ onto $\Omega$; $P_b$ are corresponding reactions; nodal displacements $u_b$ are required to be continuous across $\Gamma$.](image-url)
configurations, e.g. a layered half-space, while the internal domain can be dealt with more general approaches such as finite element (FE) or spectral element (SE) methods.

For the solution of the wave propagation problem in the internal domain, use has been made of the code AHNSE, based on pseudo-spectral approximations of the wave field combined with domain decomposition techniques, allowing to couple spectral elements with finite elements. (Casadei et al., 2002). The main features of AHNSE include: an explicit time-advancing scheme with a 2\textsuperscript{nd} order finite difference approximation, spectral elements with high-order Lagrange polynomial shape functions, and Legendre-Gauss-Lobatto quadrature formula, a wide library of solid and structural finite elements, and linear viscoelastic material with a linear dependence of the quality factor Q on frequency.

The main advantage of SE vs. FE is that, for the same number of nodes used in approximating smooth solutions, the former yields a more accurate result, because of the higher order approximations employed. Alternatively, SE provide solutions within the same error tolerance of FE using a significantly reduced number of grid points, saving much computational effort and memory storage.

For what concerns the solution of the wave field in the outer region, use has been made of the efficient analytical method of Hisada (2003), for the computing of displacements and stress of static and dynamic Green’s functions for viscoelastic horizontally layered halfspaces. This method uses an analytic form for the asymptotic solutions of the integrands of Green’s functions, stemming from the generalized R/T (reflection and transmission) coefficient method and the stress discontinuity representations for boundary and source conditions respectively.

3.2. Source modelling

The 12 July 2004, M\textsubscript{w} 5.2, earthquake has been recorded by three stations located at short distance from the epicentre: Kobarid, Dreznica and Bovec (Fig. 1). For modelling of the source, the method of Hisada has been used. This requires some knowledge of main parameters, such as: fault area, focal mechanism, rise time and halfspace geophysical parameters. Information on source parameters comes from ETH (Swiss Federal Institute of Technology), INGV (Istituto Nazionale di Geofisica e Vulcanologia) and OGS (Istituto Nazionale di Oceanografia e Geofisica Sperimentale), which gave a static seismic moment M\textsubscript{0} between $6.24 \times 10^{16}$ N\textcdot m and $8.7 \times 10^{16}$ N\textcdot m. All focal mechanisms indicate a dextral NW–SE strike slip. For fault geometry we used the solution proposed by OGS: depth of hypocenter at 7.9 km, strike, rake and dip of 135°, 173° and 83° respectively.

To check the reliability of the other fault parameters we tested all source solutions and compared results. In particular, following Brune (1970), the seismic moment M\textsubscript{0} was estimated from the area of the displacement pulse using the classical procedure. The estimation of the corner frequency has been carried out using (from Andrews, 1986):

$$f_c = \frac{1}{2\pi} \frac{\int_0^\infty V^2(f) df}{\int_0^\infty D^2(f) df}$$

where $V(f)$ and $D(f)$ are respectively velocity and displacement source spectra computed from recorded acceleration spectra corrected for attenuation factors (Rovelli et al., 1991). The computation has been carried out with both horizontal components of Kobarid (Kbd) and Dreznica (Drz) records (Fig. 1). The Bovec record was not used, since that is the target of our simulations. Results are shown in Table II: the average values have been used in Hisada’s method. From these parameters rise time has also been calculated (0.3 s).
The velocity structure used in the simulations is shown in Table III, which includes bedrock and basin parameters. For what concerns bedrock properties, because of the lack of data, the model of Cotton et al. (2006) has been taken into account (using an hypothetic S-wave velocity of 1500 m/s for the first 30 m).

In order to test the reliability of estimated source and basin parameters, the 12 July 2004 event, at Bovec site, was first simulated solely with Hisada method. Fig. 3 shows the

Table II. Tested source parameters calculated with Brune’s method.

<table>
<thead>
<tr>
<th></th>
<th>DREZNICA</th>
<th>KOBARID</th>
<th>Average values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corner frequency [Hz]</td>
<td>1.14</td>
<td>1.04</td>
<td>1.09</td>
</tr>
<tr>
<td>Seismic moment [dyne-cm]</td>
<td>6.13E+23</td>
<td>9.32E+23</td>
<td>7.73E+23</td>
</tr>
<tr>
<td>Stress drop [bar]</td>
<td>173.62</td>
<td>209.70</td>
<td>191.66</td>
</tr>
</tbody>
</table>

Table III. Velocity model used for analysis. \(V_s\) is the S-wave velocity, \(\rho\) the density, \(\nu\) the Poisson ratio, \(Q\) the quality factor and \(H\) the thickness (for layers inside the basin we refer to the centre position).

<table>
<thead>
<tr>
<th>Lithological unit</th>
<th>(V_s) [m/s]</th>
<th>(\rho) [kg/m(^3)]</th>
<th>(\nu)</th>
<th>(Q)</th>
<th>(H) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glacier and river deposits</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sublayer a</td>
<td>240</td>
<td>2080</td>
<td>0.40</td>
<td>20</td>
<td>16</td>
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<tr>
<td>sublayer b</td>
<td>480</td>
<td>2100</td>
<td>0.39</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Lacustrine chalk</td>
<td>650</td>
<td>2270</td>
<td>0.33</td>
<td>80</td>
<td>50</td>
</tr>
<tr>
<td>&quot;Wild&quot; flysch</td>
<td>1200</td>
<td>2400</td>
<td>0.39</td>
<td>150</td>
<td>220</td>
</tr>
<tr>
<td>Flysch and deep sea clastites</td>
<td>1500</td>
<td>2500</td>
<td>0.36</td>
<td>200</td>
<td>240</td>
</tr>
<tr>
<td>Dolomite and limestones (bedrock)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sublayer a</td>
<td>1824</td>
<td>2700</td>
<td>0.33</td>
<td>250</td>
<td>100</td>
</tr>
<tr>
<td>sublayer b</td>
<td>2267</td>
<td>2750</td>
<td>0.30</td>
<td>260</td>
<td>90</td>
</tr>
<tr>
<td>sublayer c</td>
<td>2687</td>
<td>2800</td>
<td>0.30</td>
<td>270</td>
<td>1100</td>
</tr>
<tr>
<td>sublayer d</td>
<td>3072</td>
<td>2850</td>
<td>0.29</td>
<td>280</td>
<td>1000</td>
</tr>
<tr>
<td>sublayer e</td>
<td>3337</td>
<td>2900</td>
<td>0.27</td>
<td>290</td>
<td>2000</td>
</tr>
<tr>
<td>sublayer f</td>
<td>3513</td>
<td>2950</td>
<td>0.25</td>
<td>300</td>
<td>4000</td>
</tr>
</tbody>
</table>

The velocity structure used in the simulations is shown in Table III, which includes bedrock and basin parameters. For what concerns bedrock properties, because of the lack of data, the model of Cotton et al. (2006) has been taken into account (using an hypothetic S-wave velocity of 1500 m/s for the first 30 m).

In order to test the reliability of estimated source and basin parameters, the 12 July 2004 event, at Bovec site, was first simulated solely with Hisada method. Fig. 3 shows the

Figure 3. Comparison between observed data and Hisada simulations in terms of velocity time histories and acceleration response spectra for Bovec site. Band pass filter was applied (0.5-5Hz).
comparison between simulated and recorded velocity time histories. As seen, while there is good agreement in the frequency content up to the high frequency cutoff of the source, amplitudes of recorded traces are quite higher than simulated ones. This fact may be explained considering that with Hisada we efficiently simulate source effects; local site effects, such as 2D configurations, are not specifically taken into account as the method works with horizontally stratified halfspaces (for this test we used the velocity structure beneath Bovec site).

Using Hisada code and the bedrock structure, we simulated source effects in terms of displacement time histories (step I of DRM computation); these signals, properly manipulated, have then been used to calculate the effective forces for the internal computational domain (step II). At that stage we expect site effects to amplify considerably ground motion.

3.3. 2D numerical modelling of the basin

This section illustrates the general characteristics of the 2D model used for the numerical analyses and the main assumptions for its formulation.

Fig. 4 shows the geometry of the basin (a) and the numerical mesh (b). The numerical domain has been modelled using an hybrid mesh with spectral elements (with 5 x 5 integration points per element) for the bedrock and triangular finite elements for the valley. In red the boundary for the DRM internal domain is shown. The spatial resolution of the model is such that frequencies up to about 5 Hz can be propagated, with a sampling rate of 2.5 points per wavelength. The computational mesh contains 428 spectral elements, 5302 finite elements and a total of 9899 grid points. Absorbing boundaries have been introduced on all the vertical sides of the model and on its bottom face.

Numerical simulations were performed with AHNSE code for a total duration of 30 s, with a time step of ~0.0103 s, on a Microsoft Windows XP system with 512 Mb of Ram (total time steps: 55300, total CPU time: 1.34 hours).

Figure 4. (a) Geometric model with a detail of valley geological layers. (b) Numerical model: spectral and finite elements are shown as well as the boundary of the internal domain used for DRM analysis.
3.4. Results

In Fig. 5 we first compare the 1D analytical transfer functions with the 2D numerical ones, calculated as a spectral ratio between simulated ground motion at the top of sediments and at the exposed bedrock. Two different positions in the valley are taken into account (centre and Bovec site). As expected, 1D transfer functions show the increase of the fundamental frequency of resonance with the decrease of sediments depth, from the centre toward valley edge. At the edges, geometric heterogeneities cause focusing of seismic rays and generation of surface waves: the 2D transfer functions show in fact the same peaks as the 1D functions (though more amplified) at the centre of the valley, while differ as receiver reaches valley edge. Observed H/V ratio exhibits similar characteristics as 2D numerical one: amplification of motion occurs approximately at same frequencies, with peaks slightly shifted towards lower values.

In Fig. 6 the horizontal and vertical velocity time traces, recorded and simulated, are shown for the site of Bovec. The synthetics tend to acceptably reproduce the observations.
both in amplitude and in shape, in particular for what concerns the pulses associated with direct S wave arrivals. As expected, resonance due to site effects amplify motion with respect to Hisada simulations (see Fig. 3). Larger amplitudes are calculated in the last part of the signal, and are related to a resonance frequency of about 1.5 Hz, clearly shown by response spectra. This frequency is directly related to the simulation of the source made with Hisada: displacement traces exhibit the same feature (not shown). A better definition of source parameters, through more refined studies, may improve results. In spite of this, numerical spectral accelerations show a very good agreement with observed ones for the main peak.

A comparison among the observed acceleration response spectrum, the simulated one and the applicable EC8 elastic response spectrum for the site of Bovec is finally shown. The EC8 spectrum has been calculated as type 1, because of the possible occurrence of events with $M_S > 5.5$ (such as the 12 April 1998 earthquake). Furthermore, an acceleration of 0.25 g has been considered. In fact, even though Bovec is classified in the official hazard map of Slovenia with an $a_g = 0.225$ g, it is very near (~ 5 km) the area with $a_g = 0.25$ g (Western Slovenia at border of Italy). Fig. 7 clearly shows that the EC8 response spectrum is far from being conservative up to periods of about 0.8 s. The high peak exhibited by observed and simulated spectra at 0.25 s (4 Hz), is clearly related to 1D site effects, as shown by the 1D analytical transfer function computed for Bovec site in Fig. 4. On the other hand, the overall spectral amplification observed and simulated till 0.8 s (1.25 Hz) is related to 2D site effects as well; in same Fig. 4, numerical and observed spectral ratios show significant peaks at 1.8 and 2 Hz. Lower peaks (at 0.6 Hz) are taken into account by EC8 spectrum.

4. Conclusions

The effects of the earthquake source and of local geology on ground motion have been studied in the Upper Soča Valley by means of a 2D analysis of the July 2004 earthquake. A new substructuring technique has been used, called Domain Reduction Method (DRM). For source modelling the efficient analytical method of Hisada has been applied. The Bovec basin has been modelled with an hybrid FE-SE grid, and wave propagation has been computed with the AHNSE code. Results show a good fit with recorded waveforms; in particular for what concerns response spectral accelerations. Comparison with EC8 acceleration response spectra show that the latter may not be conservative for periods up to 0.8 s. In this frequency range, not only 1D site effects but also 2D ones must carefully be evaluated when predicting seismic response at Bovec site.
5. Acknowledgements

We are grateful to Professor Y. Hisada for providing the latest numerical codes for the use of the Green’s function approach. The study of the Bovec basin was realised with the support of Interreg IIIB Alpine Space project: Seismic hazard and Alpine valley response analysis (SISMOVALP).

6. References


