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Real-Time Generation of ShakeMaps in the Southeastern Alps

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Abstract The aim of this study is the real-time generation of ShakeMaps in the southeastern Alps area. The ShakeMap software has been adapted to the southeastern Alps region and implemented to obtain a stable interface with the Antelope acquisition system in order to extract the ground-motion parameters from the waveforms and to generate ShakeMaps within 5 min of the earthquake occurrence. To evaluate the influence of the station density, synthetic seismograms are computed for the Bovec (northwest Slovenia) 2004 earthquake, and various ShakeMaps are generated by varying the grid size of the simulated recording stations. The results indicate that a dense and uniform spatial distribution of stations in the field is essential to produce accurate ShakeMaps, and the present density of stations in central Friuli is sufficient for a reliable estimate of the extent of the area of strongest shaking. The related maps are generated in real time or quasi-real time using the region-specific ground-motion predictive equations and empirical relations that predict the macroseismic intensity from the recorded ground motion. The model is validated by comparison between observed data and ShakeMap results for both weak motions (Claut 2007 earthquake) and strong motions (Bovec 1998 earthquake).

Introduction

We generate the ShakeMaps in the southeastern Alps, focusing on the Friuli Venezia Giulia area (northeast Italy). This zone is characterized by the junction between the east–west trending Alpine system and a northwest–southeast trending Dinaric system (e.g., Slejko *et al.*, 1989). The seismic activity of relatively medium intensity is due to the collision of the Adria microplate and the Eurasian plate. The return period of strong earthquakes, with magnitude greater than 6, is about 40 yr, and the return period of earthquakes with magnitude greater than 5 is about 7 yr (e.g., Slejko *et al.*, 1989; Costa *et al.*, 1998). In the last decades, the most important seismic event in the area was the destructive 1976 Friuli earthquake (M_w 6.5; e.g., Aoudia *et al.*, 2000). The other relevant earthquakes are the two Bovec (northwest Slovenia) events of 1998 (M_w 5.6) and 2004 (M_w 5.4).

Recently, following the implementation of fast networks and communication systems, a software has been produced that generates shaking maps within 5 min of the earthquake occurrence by integrating the information of the real-time data, the ground-motion predictive equations (GMPEs), and the knowledge of the local soil geology (Wald *et al.*, 1999b). The earthquake parameters that are most rapidly retrieved are the magnitude and the epicenter location. Once these are known, the ShakeMap software combines the real-time recorded signals and the empirical GMPEs to give reliable ShakeMaps in terms of peak ground acceleration (PGA), peak ground velocity (PGV), spectral acceleration (SA), and instrumental intensity, within 5 min of the earthquake occurrence. The generation of ShakeMaps in a selected geographical area requires a regional calibration that is accomplished by using regional GMPEs and identifying the geological site conditions in the studied area. At the present time, shaking maps are produced in the United States, Japan, and Taiwan, while new projects have started to also cover Canada, Italy, Turkey, and New Zealand. In particular, in Italy, Michelini *et al.* (2008) have implemented the ShakeMap software on a national scale in the context of a Department of Civil Protection (DPC) project using the Istituto Nazionale di Geofisica e Vulcanologia (INGV) network. Inside the same DPC research project and in collaboration with INGV, we have generated ShakeMaps in the wider Friuli Venezia Giulia region (northeast Italy), concentrating the software calibration to this smaller area and developing the interaction with the Antelope software (Boulder Real Time Technologies [BRTT]). In our case, the real-time signals are both recorded by the regional accelerometric network (RAF) and retrieved through the data exchange with Centro Ricerche Sismologiche–Istituto Nazionale di Oceanografia e Geofisica Sperimentale (CRS-OGS), and other Austrian and Slovenian networks (G. Costa, L. Moratto, and P. Suhadolc, unpublished manuscript, 2009).

The principal goal of the rapid generation of ShakeMaps is to support the civil defense in coordinating rescue and relief operations. The maps are shown to the public through television and other media networks and can be downloaded from the Internet. A rapid distribution of the automatically generated maps could be, however, quite critical, and should be carefully considered due to the possibility of spreading incorrect information to the public. Operator-revised maps should, therefore, replace the automatic ones as soon as possible.

The ShakeMaps

The U.S. Geological Survey ShakeMap software (Wald *et al.*, 1999b; Wald *et al.*, 2006) is a collection of modules written in Practical Extraction and Report Language (PERL) code; the maps are made using the Generic Mapping Tool (GMT) by Wessel and Smith (1991), and the postscript output from GMT is converted to JPEG format using Imagemagick. The ShakeMap software is based on an algorithm structured in several steps developed by Wald *et al.* (1999b). The ShakeMaps are obtained for PGA, PGV and SA (by default computed at 0.3, 1.0, and 3.0 sec with 5% of critical damping), and they are a combination of both recorded data and data estimated from geological/seismological knowledge in order to produce them as fast and as reliably as possible. The software must be calibrated for each studied area, and different inputs are used for different geographical areas. A specific geological map and reliable GMPEs must be inserted into the software. A good spatial configuration of the recording instruments helps very much to obtain reliable results. Usually, the instruments are concentrated in urban regions with high seismic risk with a smaller number of stations installed elsewhere. In this way, the results should be more accurate in the zones with higher seismic risk, while elsewhere, the use of GMPEs is fundamental to supply the lack of observations.

The software also produces instrumental intensity maps. The instrumental intensity is not a direct physical parameter, but its estimation gives us a useful quantification of earthquake-related effects on buildings and population. The ShakeMap software uses an instrumental intensity derived from the related ground-motion parameters (PGA and PGV) through empirical relationships (e.g., Trifunac and Brady, 1975; Wald *et al.*, 1999a). Generally, PGA is well related to low macroseismic intensities determined by felt accounts (most sensitive to the signal high-frequency content), whereas PGV is more related to the high intensities (I > VII) and is correlated with structural damage (Wald *et al.*, 1999a). Deriving modified Mercalli intensity (MMI) from PGV for high intensities ensures that spurious high-frequency spikes present in acceleration records are not considered, avoiding abnormally high intensity estimations. The results obtained for instrumentally derived MMI can differ from the maps of the observed macroseismic intensity, especially in scarcely populated areas where the ShakeMap estimates the MMI even if no real intensity is reported (thereby accounting for the lack of observations). It is well known that surficial low-velocity layers can strongly affect the site response (e.g., Borcherdt, 1970; Aki, 1993). The software applies the site geology amplification only to the peak value and does not consider resonance (basin) effects or shaking duration (e.g., Olsen, 2000; Choi *et al.*, 2005). However, these effects can be estimated with the mean upper 30 m shear-wave velocity (V_{S30}) measurements, with the site response then converted to the proper National Earthquake Hazards Reduction Program (NEHRP) site class instead of relying only on information about the surface geology. Furthermore, the shaking duration only matters when one is concerned with risk or loss estimates of the built environment, and this is not the goal of the ShakeMap. The model is, therefore, very rough, but it provides a very fast estimation of the ground motion taking into account possible site effects at the receivers. Despite all these limitations, we note that the principal purpose of the generation of real-time ShakeMaps is to quantify the motion in the near-source field for strong earthquakes; however, the generation of ShakeMaps for low-magnitude seismic events is very useful for processing, calibrating, and validating the software.

Regional Calibration

The generation of the ShakeMaps in the southern Alps area requires a regional calibration of the software, knowledge about the specific geological conditions of the area, and the use of appropriate GMPEs (along with the relationship between ground-motion parameters and macroseismic intensity). On the other side, the ShakeMap software requires observed data to be acquired, transmitted to a computer, and analyzed to determine the ground-motion parameters, which are the input data for the program, in real-time.

The site correction plays an important role in the generation of the shaking maps, even if the bias correction and grid size tend to be the dominant effects in ShakeMap results. In California, Wald *et al.* (1999b, 2006) use the site condition map based on geology and V_{S30} data. In particular, Park and Ellrick (1998) classify the soils into three different categories (Quaternary, Tertiary, and Mesozoic [QTM]) and create a QTM map; the V_{S30} velocity is assigned to each classification (Wills *et al.*, 2000; Holzer *et al.*, 2005), and the amplification factors are computed applying the Borcherdt (1994) model.

The geology of the Friuli area is characterized by sedimentary rocks ranging from Palaeozoic to Quaternary age (e.g., Slejko *et al.*, 1989; Faccenda *et al.*, 2007). The Palaeozoic rocks (volcanic deposits and partly limestones) are located in the north, whereas the geology of the central area is composed of carbonatic rocks (Triassic and Cretaceous age). The Quaternary rocks (composed of flysch and molasse) undergo strong erosion of the outcropping reliefs and fill nearby valleys; conglomerates of moraine, alluvial fan, and lacustrian deposits are present in the central area. In particular, the various geological elements in the area (Carulli, 2006) are

- The basement to the south of the Periadriatic lineament and to the north of the Austro-Alpine lineament.

- The Palaeozoic present in the Paleocarnic chain with different levels of metamorphism.
- The Mesozoic with massive Triassic and Cretaceous carbonate platform units.
- The Tertiary flysch and molasse from the thrust system and the deposits of the Styrian and Pannonian basins.
- The Tertiary Periadriatic intrusive masses and the Tertiary lava effusions.
- The Quaternary deposits.

The Quaternary sediments are made of deposits derived from glacial, lacustrian, and fluvial processes and form the alluvium fans of the regional rivers (Cellina, Meduna, Tagliamento, Torre, Natisone, and Isonzo) that created the Friuli plain. The alluvium and glacial sediments are the most extended bodies in the plain, and they are generated by deposits and sands carried by the regional rivers that flow from the mountains and are deposited following granulometric selection (Carulli, 2006). A detailed geological map has been recently proposed by the Geology Department of the University of Trieste that divides the region into three soil classes (Disgam, 2005). The average V_{S30} values are estimated at 700, 500, and 300 m/sec, respectively, for bedrock, stiff soil, and soft soil. The amplification factors are estimated from the Borcherdt (1994) model. PGA data and SA values computed at 0.3 sec are multiplied by the short-period terms, whereas PGV data and SA values computed at 1.0 and 2.0 sec are multiplied by the long-period terms. We decided to generate ShakeMaps for SA computed at 2.0 sec instead of 3.0 sec because the signals can be too poor for weak motion, and GMPEs are not available for $M < 5.0$; however, 2.0 sec should be a sufficient period for engineering purposes in the studied area.

Other tests are done with the EuroCode 8 classification (EN 1998 EuroCode 8, 2003) and the estimation of the V_{S30} values from the topography, but the maps generated from these various geological classifications are not significantly different.

Various GMPEs are inserted in the ShakeMap software according to the different magnitude ranges. The relationships are used to estimate the ground-motion parameters on a regular spacing grid in case no seismic signal is available in the neighborhood. The final calibration of the software is done using the GMPEs proposed by Massa *et al.* (2008) in the magnitude range 3.5–5.5. Massa *et al.* (2008) merged all the accelerometric data recorded in northern Italy, and they computed the GMPEs for the amplitude and duration parameters and the frequency content. For larger seismic events, the Sabetta and Pugliese (1996) relationships are used to compute PGA and PGV and the Akkar and Bommer (2007) relationships to compute spectral acceleration. We inserted in the software also the relationships of Bragato and Slejko (2005) obtained for all interested ground-motion parameters (only PGA and PGV) in the magnitude range 2.5–3.5. For $M < 2.5$, no ShakeMap is generated by the software. The ShakeMaps are generated when the epicenter is located inside the geographical boundaries fixed at 45° N–48° N and 12° E–15° E.

In the ShakeMap software, the intensity is derived from the ground-motion parameters (PGA and PGV) even if this procedure is not recommended (the intensity is a description of seismic effects, and its estimation through PGA and PGV can lead to unreliable relations and large scattering (Musson and Cecić, 2003). In California, Wald *et al.* (1999a) propose relationships among PGA, PGV, and MMI; the comparison between the observations and the maps of instrumental intensity shows that the relationships derived from PGA for MMI ≤ VII and PGV for MMI ≥ VII, give the best fit with the observed data. Faccioli and Cauzzi (2006) propose new relationships between macroseismic intensity (the MCS scale proposed by Mercalli, Cancani, and Sieberg; the MSK scale proposed by Medvedev, Sponheuer, and Karnik; and the European macroseismic scale [EMS]) and ground-motion parameters for Italy. They also assume $I_{MCS} = I_{MSK}$ (Margottini *et al.*, 1992) for nonItalian earthquakes, and a few intensity values in the EMS scale have been assumed as equivalent to MSK scale values. Such data were observed in Italy from 1976 to 2005 and we also merged their database with macroseismic intensities from nearby geographic areas (e.g., France, Turkey). The final dataset spans a wide intensity range (IV–IX). Regression is done for PGA and PGV data (defined as the largest horizontal component), and the goodness of the regression is estimated computing R^2 value (very low when acceleration is considered, $R^2 = 0.38$). Clearly, the results are strongly related to the input data quality (discrete and few, especially for damaging earthquakes). The results show a low attenuation as a function of the epicentral distance, and the intensity seems not to decrease significantly for distances larger than 50 km.

In Figure 1, different relationships are compared for PGA values; Trifunac and Brady (1975), Murphy and O'Brien (1977), and Wald *et al.* (1999a) use the MMI scale and propose relationships with similar slopes. Faccioli and Cauzzi (2006) use the EMS scale and obtain a less steep slope when estimating high intensities (I > VI) and low intensities (I < VI) compared with other studies (Trifunac and Brady, 1975; Murphy and O'Brien, 1977; Wald *et al.* 1999a). Such comparisons between continuous relationships give only indicative information because the intensity is defined as a discrete parameter that has only integer values. It is also important to notice that different scales are considered in these studies (MMI and EMS), with no possibility to estimate the influence this has on the final results.

We produce the ShakeMaps using the Faccioli and Cauzzi (2006) relationships calibrated on Italian data and use this relationship as the default one in the ShakeMaps' calibration. Some problems remain open about the quality of the regression models between the ground-motion parameters and the instrumental intensity; of course, it is not clear if a linear trend is the best possible model to correlate the ground-motion parameters with the macroseismic intensity. Furthermore, the macroseismic data are discrete, and very

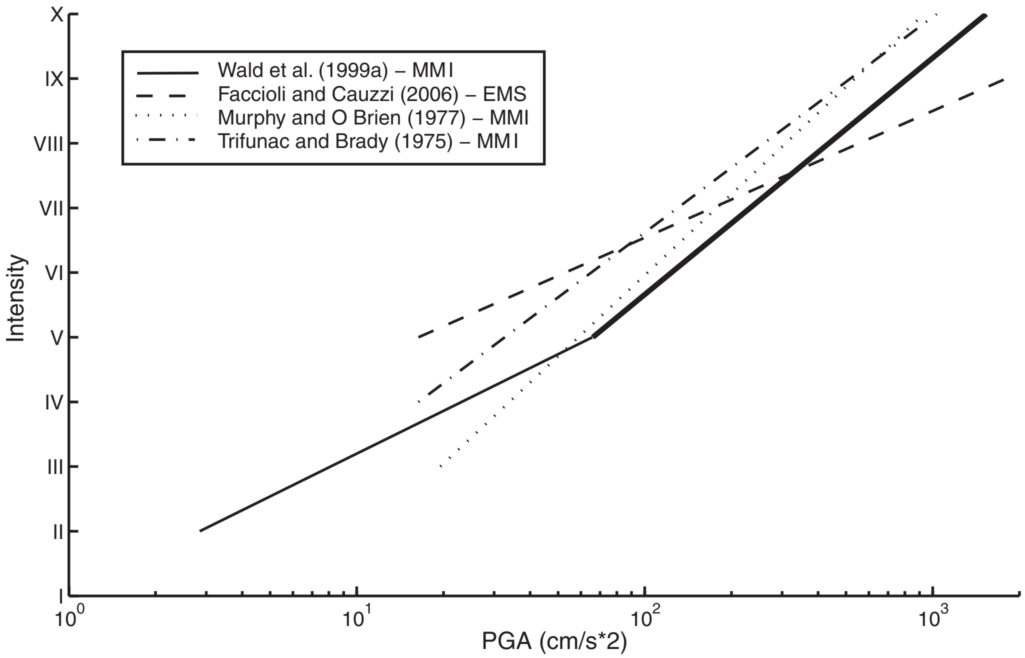


Figure 1. The comparison between different empirical relationships for the macroseismic intensity (with different scales) as a function of the PGA.

few damaging and destructive seismic events concentrated in a limited geographic area are present in the database. Because this affects undoubtedly the statistics, it can be possible to improve such studies by adding data observed in other geographic areas, but this choice could be questionable. In recent years, various studies have been published with interesting suggestions as regards these problems: Kaka and Atkinson (2004) predicted larger instrumental intensities in comparison with results proposed for California (Wald *et al.*, 1999a; Atkinson and Sonley, 2000) for MMI < VII and the same PGV value; they suggest that the frequency content of the signals and the models can change when different geographical areas are considered. While PGV correlates fairly well with high intensities (MMI ≥ VI), it was reported by Atkinson and Kaka (2007) for their relations between felt intensity and instrumental ground motion in the central U.S. and California, that weak magnitude and distance-dependent trends may lead to regional dependencies. At the same time, Atkinson and Kaka (2007) assumed that if such dependencies are adequately modeled, it is possible to adopt a single dataset of MMI and ground-motion parameters for all regions. Furthermore, we do not know what happens outside the studied macroseismic range and what are the real limitations intrinsic to these relationships; further tests are in progress in our department to validate this model.

The Weight of Station Density on ShakeMaps

The number of recording stations, their distribution, and the network geometry are very important to obtain reliable ShakeMaps. We demonstrate this by computing synthetic seismograms for the 12 July 2004 Bovec earthquake; in the simulation these synthetic signals are supposed to be the seismograms really recorded by the instruments so we can change the density and the configuration of the simulated recording stations to understand their influence on the final ShakeMap results and to select the best settings for the Friuli Venezia Giulia region.

The source parameters of the earthquake are estimated by the application of a trial-and-error forward modelling that minimizes the misfit between the observed and the synthetic PGA (largest horizontal component) computed at the stations that recorded the event in the southern Alps area; major details about this method are discussed by Suhadolc *et al.* (2007). The fault geometry is estimated from the relationships proposed by Wells and Coppersmith (1994), with the length fixed at 5 km and the width at 4 km. The propagation of the rupture is bilateral and the seismic moment distribution is uniform. The starting source model is taken from the Eidgenössische Technische Hochschule (ETH) internet site (see Data and Resources section): a strike-slip focal mechanism (strike = 127°, dip = 87°, rake = 175°) and the depth of the hypocenter at 5.6 km with the seismic moment estimated by Suhadolc *et al.* (2006) with M_w 5.1. The finite-fault model with the aforementioned source parameters and an average 1D structural model (Mao and Suhadolc, 1992; Fäh *et al.*, 1993) were selected to compute the synthetic seismograms applying the modal summation technique (Panza, 1985; Panza and Suhadolc, 1987; Florsh *et al.*, 1991). The magnitude ranges between 5.0 and 5.2, considering the uncertainties associated with M_w estimation, and it is fixed at 5.0 to better fit the observed data. The orientation of the fault can strongly affect the radiation pattern and small variations of the strike estimation can change the maxima and minima zones of peak ground acceleration. Two different values for strike estimation (117° and 137°) tested led to insignificant variations in the final results. Because it is more difficult to estimate the hypocentral depth, different values were tested with this parameter ranging from 5 to 9 km; the best fit was found for the depth of 7 km.

The purpose of the test is to study the influence of the network configuration on the final results so the synthetic seismograms substitute the recorded data in the ShakeMap model; it is very important that the simulation is as similar as possible to the real-time ShakeMap configuration. When the synthetic station is missing, the ShakeMap software estimates the ground-motion parameters using consistent GMPEs, so the ground-motion prediction equations are recomputed from the synthetic seismograms data at an upper frequency cutoff of 1 Hz. The regression model is very simple because the magnitude is constant and the ground-motion parameters are assumed to be first-order linear functions of the logarithm of the epicentral distance. No effects due to directivity, fault dimensions, hanging wall, or focal mechanism are considered because a point-source model is used both in the GMPE computation and in the ShakeMap configuration. This can seem too simplified but we need to simulate the real-time situation and, at this time, our system can estimate only the epicenter location and the magnitude value within a few seconds of the earthquake occurrence. In the ShakeMaps' computation, we set the length of the phantom stations grid to 5′ and the interpolation grid size to 0.5′ in agreement with our synthetic data distribution. The synthetic seismograms are computed with the finite-source model previously described at 625 receivers placed on a regular grid of 5′ for an upper frequency cutoff of 1 Hz. The results of PGA values obtained from the synthetic seismograms are inserted into the ShakeMap software as simulated real-time data, and the related shaking maps are generated. In Figure 2, we show the ShakeMaps generated for various distributions of the simulated recording stations. In particular, the first picture shows the map obtained using the 20 stations that actually recorded the seismic event (Fig. 2a), while in the other figures the synthetic seismograms that simulate the recording stations are used as input with a spacing grid of 5′, 20′, and 10′ (Fig. 2b,c,d). Because the grid of phantom stations in the ShakeMap software is set to 5′, the missing data are substituted with the empirical relationship results in the 20′ and 10′ spacing grid cases. No site correction has been applied. The shape of the acceleration contours changes noticeably with the grid size. The isoacceleration contours change is prominent, especially at larger distances. In the near-source zone, the PGA values change, and the maximum peak ground acceleration varies from 0.2%g (grid size of 10′) to 0.3%g (grid size of 20′). The true ground shaking is only known where the recording stations are placed, whereas at other sites the interpolation procedure estimates the motion. It is important to observe that the number and the distribution of receivers strongly influence the final results because the bias is not fixed, and it changes according to the data we insert as input into the ShakeMap software. The choice of a nonfixed bias is selected in order to reproduce the real-time situation, where the bias factor changes in relation to the input data. This test demonstrates the limitations of the empirical ground-motion relationships that cannot reproduce the finite-fault characteristics, which leads to an important lack of information in the near field, especially when the point-source model and the epicentral distances are adopted. The relative differences among the grid spacing of 20′, 10′, and 5′ are shown, respectively, in Figure 2e,f. For the 20′ spacing grid case, there are large relative differences in the near field in the north–south and west–east directions because the GMPEs are not able to model the radiation profile and the fault geometry is not considered. On the other side, the 10′ spacing grid case shows good agreement with the 5′ grid results (the latter considered as the real case). In conclusion, even if the best solution is a network with recording stations spaced 10 km from each other, satisfactory shaking maps can also be obtained with stations 20 km apart from each other. Douglas (2007), in agreement with our results, suggests that shaking within 10 km of a recording stations can be defined with reasonable accuracy, whereas at larger distances the motions cannot be well constrained. The best solution to avoid this problem would be to install a dense seismometric network in the field with an appropriate geometry. However, the ShakeMap uncertainties are dominated not only by the density of stations but also by the aleatory uncertainties associated with GMPEs (Wald *et al.*, 2008); in the model proposed by Lin *et al.* (2005) the uncertainty is decreasing to zero for interstation spacing less than 10 km, and it is constant in other cases. For larger earthquakes ($M > 5.5$) the Joyner–Boore distance must be used to improve the accuracy; in our case the geometry and dimensions of the fault rupture cannot be estimated in real-time, so a point-source model is adopted. However, the uncertainty related to the point-source model does not influence the estimated accuracy of ground motions if a dense distribution of strong-motion stations is operating (Douglas, 2007).

Real-Time ShakeMaps

In the Friuli Venezia Giulia region, the Department of Earth Sciences of the University of Trieste (DST-UNITS) manages the strong-motion network Rete Accelerometrica del Friuli Venezia Giulia (RAF) and the northeast Italy Broadband Network (NEI) in collaboration with CRS-Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS). In the same region the national strong-motion network Rete Accelerometrica Nazionale (RAN) of the Italian Civil Defense also operates, locally managed by the DST. The first stations of the RAF were installed by the DST during 1993–1995 in the framework of international scientific projects and in cooperation with CNEN-ENEL (Italian electric company); see G. Costa, L. Moratto, and P. Suhadolc (unpublished manuscript, 2009). Since the year 2000, RAF

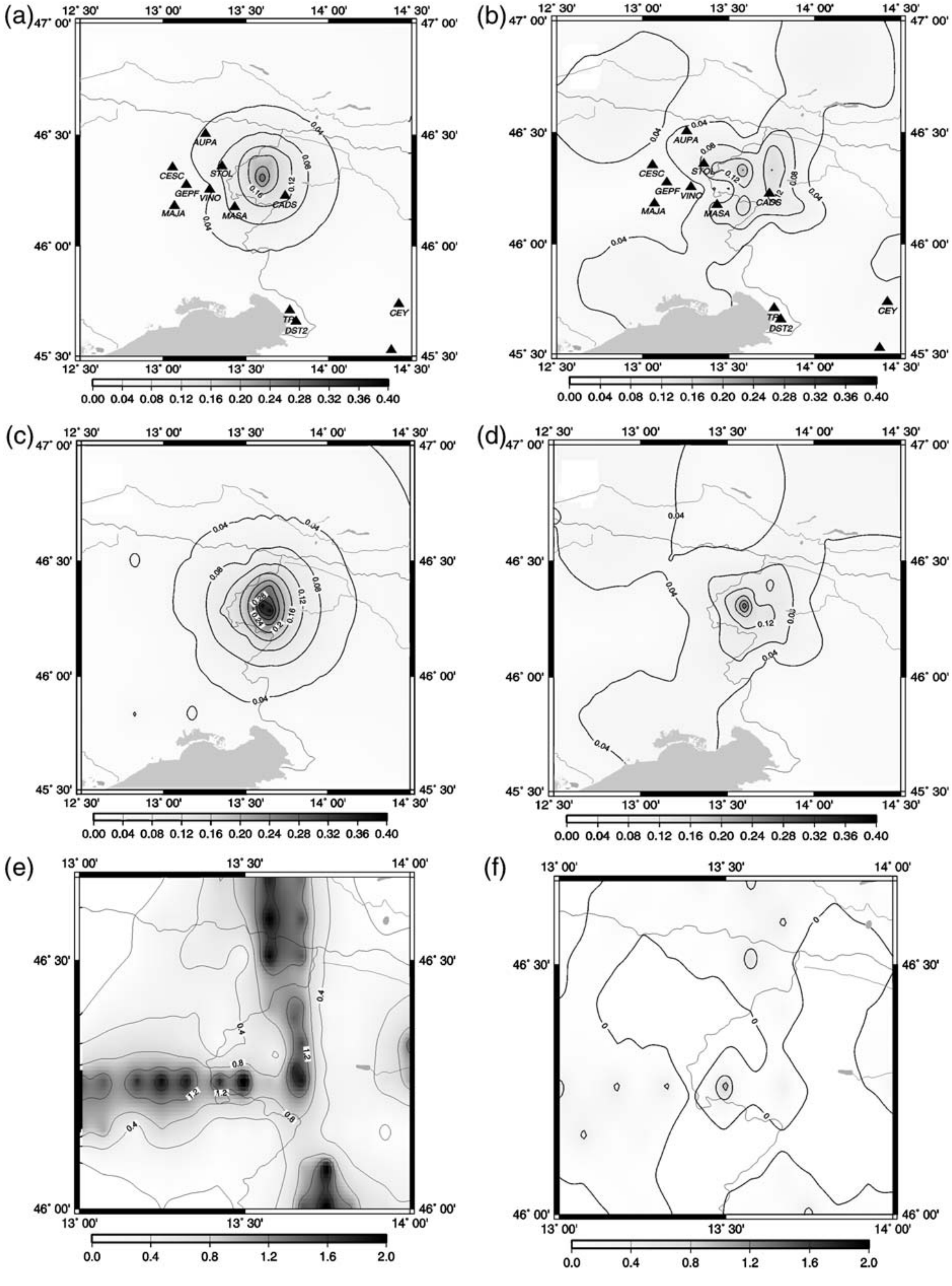


Figure 2. Scenarios generated using (a) 20 recording stations and three different spacing grids of simulated recording stations, (b) 5′, (c) 20′, and (d) 10′. (e) The relative differences between (c) and (b) are shown, whereas (f) shows the relative differences between (d) and (b).

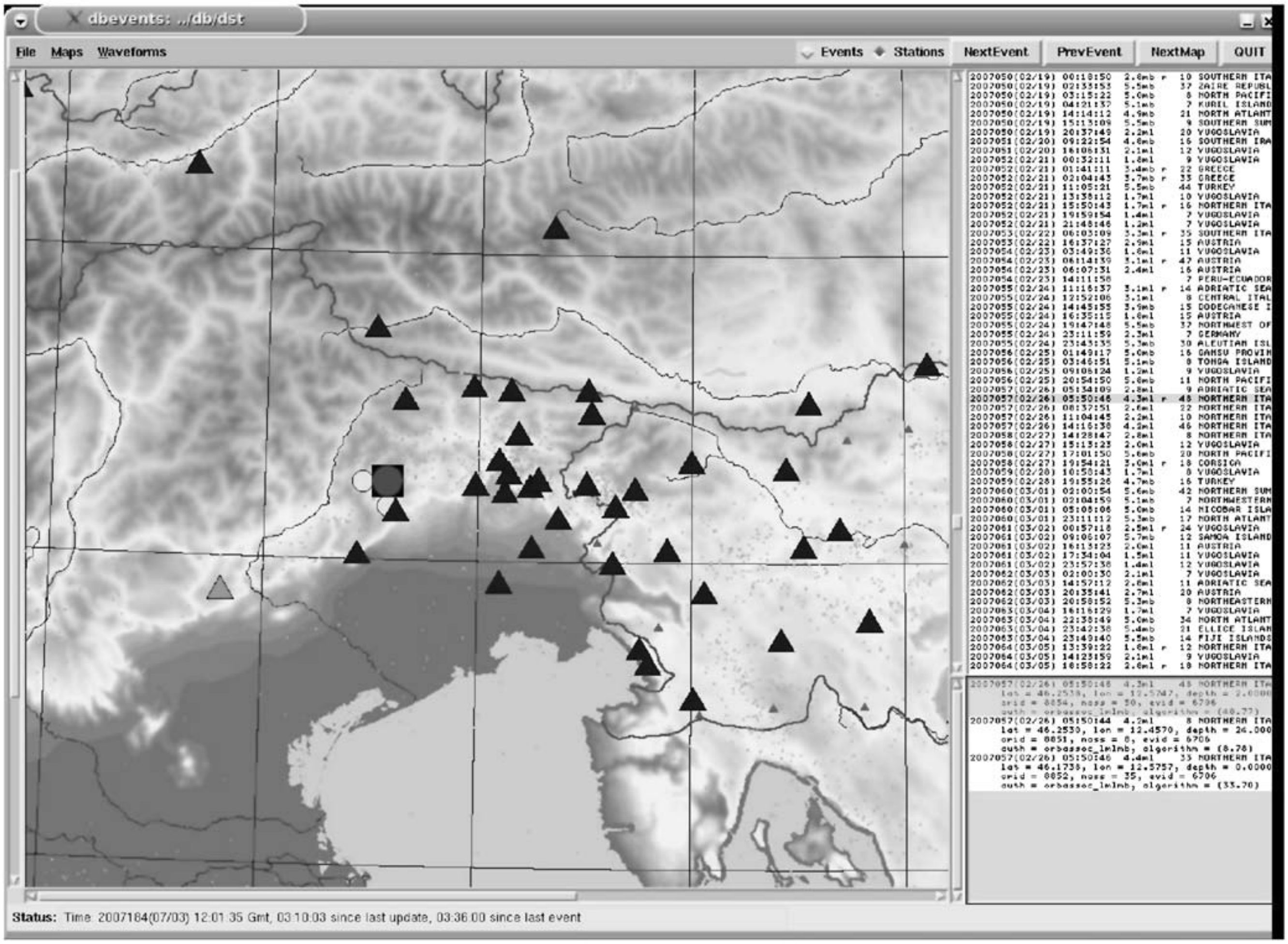
has also been supported for civil defense purposes by the Protezione Civile della Regione Autonoma (FVG).

Three-component digital force-balance accelerometric instruments are used with mostly 18 to 24 bits digitizers. The acquisition units have a large dynamic range (more than 120 dB) and a large frequency range (DC to 200 Hz). The trigger thresholds depend on the station noise; at some stations the short term averaging/long term averaging (STA/LTA) trigger is used to better discriminate seismic events. Both station sites and instrumentation have been changing during the last 10 years. Today, 12 stations are installed on bedrock and four stations are installed on soil for site effects studies.

Real-time data are acquired and stored by the Antelope software operated by the Department of Earth Science of the University of Trieste since 2002. This software exchanges the seismicity data with CRS-OGS in Udine, Zentralanstalt fűr Meteologie und Geodynamik, Hauptabteilung Geophysik (ZAMG) in Vienna, and Agencija Republike Slovenije za Okolje, Urad za seizmologijo in geologijo (ARSO) in Ljubljana. In this way, it is possible to cover the whole southeastern Alps area, more or less uniformly, with the recording instruments. At the same time, the redundancy criteria among the various archiving nodes enhances the system security.

Antelope is a system of software modules that implement the acquisition, transport, buffering, processing, archiving, and distribution of environmental monitoring information. Antelope was constructed with an open-system design criterion so that it could be easily implemented by the users. The Antelope real-time system brings raw data from the remote field sites in real-time to one or more central processing facilities where automated real-time processing of the data is performed.

Antelope was installed on the DST workstations and the parametric files set. The picking procedure (usually with *P* and *S* waves) starts when a threshold between short time average/long time average (STA/LTA) is exceeded, and the location is done on a searching grid for a minimum number of picked phases. The location can be redone manually applying a more accurate inversion procedure. An example of real-time location is shown in Figure 3 and refers to the Claut 2007 earthquake (M_L 4.4) with 58 phases used to locate this seismic event. After the steps of acquisition, picking, and location the waveforms are included in the database



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2007050(02/19) 04:21:37  5.1mb     7 KURIL ISLAND
2007050(02/19) 14:14:12  4.9mb    21 NORTH ATLANT
2007050(02/19) 15:13:09  5.5mb     9 SOUTHERN SUM
2007050(02/19) 20:37:49  2.2ml    20 YUGOSLAVIA
2007051(02/20) 09:22:54  4.8mb    16 SOUTHERN IRA
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2007060(03/01) 05:08:06  5.0mb    14 NICOBAR ISLA
2007060(03/01) 23:11:12  5.3mb    17 NORTH ATLANT
2007061(03/02) 00:57:18  2.5ml r  24 YUGOSLAVIA
2007061(03/02) 09:06:07  5.7mb    12 SAMOA ISLAND
2007061(03/02) 16:13:23  2.0ml    11 AUSTRIA
2007061(03/02) 17:34:04  1.5ml    11 YUGOSLAVIA
2007061(03/02) 23:57:38  1.4ml    12 YUGOSLAVIA
2007062(03/03) 02:00:30  2.1ml     7 YUGOSLAVIA
2007062(03/03) 14:57:12  2.8ml    11 ADRIATIC SEA
2007062(03/03) 20:35:41  2.7ml    20 AUSTRIA
2007062(03/03) 20:58:52  5.3mb     8 NORTHEASTERN
2007063(03/04) 16:16:29  1.7ml     7 YUGOSLAVIA
2007063(03/04) 22:38:49  5.0mb    34 NORTH ATLANT
2007063(03/04) 23:42:38  5.4mb    21 ELLICE ISLAN
2007063(03/04) 23:49:40  5.5mb    14 FIJI ISLANDS
2007064(03/05) 13:39:22  1.8ml r  12 NORTHERN ITA
2007064(03/05) 14:23:59  2.1ml     9 YUGOSLAVIA
2007064(03/05) 18:58:22  2.8ml r  18 NORTHERN ITA
```

```
2007057(02/26) 05:50:48  4.3ml    48 NORTHERN ITA
      lat = 46.2538, lon = 12.5747, depth = 2.0000
      orid = 8854, nass = 50, evid = 6706
      auth = orbassoc_lmlmb, algorithm = (48.77)
2007057(02/26) 05:50:44  4.2ml     8 NORTHERN ITA
      lat = 46.2530, lon = 12.4570, depth = 24.000
      orid = 8851, nass = 8, evid = 6706
      auth = orbassoc_lmlmb, algorithm = (8.78)
2007057(02/26) 05:50:46  4.4ml    33 NORTHERN ITA
      lat = 46.1738, lon = 12.5757, depth = 0.0000
      orid = 8852, nass = 35, evid = 6706
      auth = orbassoc_lmlmb, algorithm = (33.70)
```

```
Status: Time 2007184(07/03) 12:01:35 Gmt, 03:10:03 since last update, 03:36:00 since last event
```

Figure 3. Antelope-generated map with the final epicenter of the Claut (2007) earthquake (circle in the black square); 58 phases (triangles) are used in the location analysis.

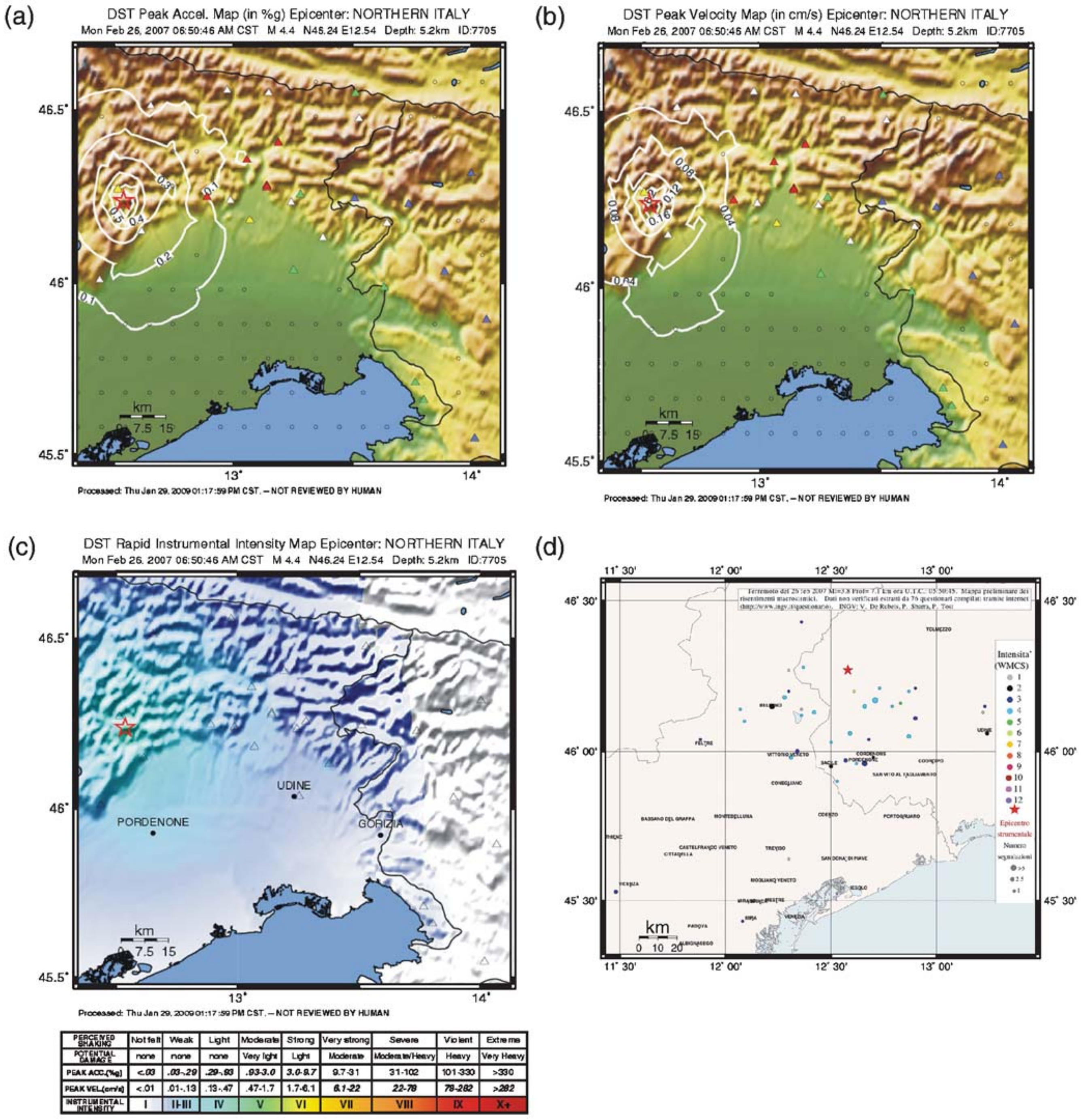
and stored on the disks. The wfmeas module computes the ground-motion parameters related to the seismic signals and adds a new entry to the database. The geographical region is limited in epicenter location and a minimum threshold for magnitude is selected ($M_L \geq 2.5$) in agreement with the available ground-motion relations.

In order to estimate possible effects on the built environment, accelerometric data are also used to generate ShakeMaps. It has been shown in the previous section that a large number of accelerometric stations uniformly distributed throughout the area is crucial to estimate ground motion and to produce realistic ShakeMaps. The ShakeMap software is installed on a Sun workstation with the MySQL server. All the parametric files are set, in particular the file called grind.conf that is critical because it involves the detailed settings of ground shaking computations. Local ground-motion relationships and site conditions previously discussed are also inserted in this file. The grid of phantom stations is reduced from 0.3° to 0.1° (Douglas, 2007) to take into account the network configuration, and as a consequence the interpolation grid size decreases from 1.5′ to 0.5′. This choice is justified by the density of recording stations placed in the southern Alps area and because the spacing size of the phantom stations grid must be comparable to the density of recording stations in the field. The surface tension for the interpolation, a flexible parameter that takes a degree of freedom and relaxes the constraints inside the gridding procedure (Smith and Wessel, 1990), is set to 0.9, whereas the calculation of the bias between the observed and the estimated data adopts the L1 norm, and it is computed for magnitudes lower than 7 and distances (epicenter to station) shorter than 120 km. The minimum number of stations considered in the computation is 6, and the maximum value that the bias is allowed to take is 4. The epicenter-to-station distance within which the computed epicenter will not be used as a data point, is zero and the phantom-station-to-real-station distance within which the phantom station will not be used as a data point, is set to 15 km. Data are considered as outliers if they exceed 3 standard deviations, but if the magnitude is larger than 7, this hypothesis is rejected. The software also generates Web pages of the earthquake-related ShakeMaps in real time.

All procedures of the Antelope system and the ShakeMap software are automated, and the maps are generated within 5 min of the earthquake occurrence; the ShakeMaps are generated in real time, and data are recorded by several networks (RAF, NEI, RAN, Rete Sismometrica del Friuli Venezia Giulia (RSFVG), ARSO, ZAMG) operating in the area are used for this purpose. We recall that INGV has already implemented ShakeMap in Italy (Michelini *et al.*, 2008) and shares the data with DST inside the National Civil Defense project (DPC)-S4 2004–2006 in order to obtain the most reliable ShakeMaps as possible. In particular, DST concentrates the research study on the northeast Italy area by merging its recorded signals with Austrian and Slovenian data and implementing the ShakeMap procedure within the Antelope system.

An example of real-time ShakeMaps (the Claut 2007 earthquake) is shown in Figure 4 using the real-time data, and the location is shown in Figure 3. The circles on the maps denote the sites where there are no observations, and the ground motion is estimated by the empirical relationships. The ShakeMaps are generated within 5 min of the earthquake occurrence using the Antelope system; the real-time data are recorded by several networks such as RAF (red triangles), RAN (yellow triangles), RSFVG (white triangles), NEI (green triangles), and ARSO (blue triangles). The bias factor is 0.12 for PGA (Fig. 4a) and 0.13 for PGV (Fig. 4b) suggesting an underestimation of the magnitude value or a bias in the GMPE relationships; the results are good, and the distribution of the recording stations seems to be appropriate. The instrumental intensity map (Fig. 4c) indicates that a degree V intensity affected the mountain area near Claut and Cellina Valley, whereas the intensity degree became IV at Pordenone and to the west of Tagliamento River. The intensity is reduced to degree II–III to the east of Tagliamento River at Udine and in Fella Valley. Our results are validated by the comparison (Fig. 4d) with the macroseismic intensities derived from INGV felt reports (see Data and Resources section). The comparison is good in the zone of Pordenone and to the west of Tagliamento River (degree III–IV), but there are no observations in the mountain area near the epicentre. Furthermore, a degree II is reported at Udine city in agreement with the intensity map generated by ShakeMap.

The Claut 2007 earthquake is used also to test the influence of the local site amplification on the ShakeMap results. In particular, our aim is to understand if the bias correction can compensate for the lack of information about the geological setting of the recording stations. We generate the PGA ShakeMap with two different assumptions: in the first case we consider all recording stations as placed on bedrock (Fig. 5a), whereas in the second case the same stations are assumed to be all placed on soft soil (Fig. 5b). If there are only bedrock stations, no correction factor is applied to consider the soil amplification, whereas in other cases the recorded PGA values are reduced to bedrock to take into account the soil amplifications. Clearly, the bias factor changes in the two cases because its role is to minimize the difference between PGA values estimated by GMPE and recorded data reduced to bedrock conditions. In Figure 5b the bias is computed using deamplified data, which have thus lower values than the PGA of Figure 5a. When the stations are assumed as bedrock sites the ShakeMap (Fig. 5a) is very similar to the map of Figure 4a generated with real geological conditions below the recording stations. In the near-field, there is no difference, but Figure 5a overestimates the ground motion around the stations placed on the sedimentary basin in the Gemona area. On the other hand, when the stations are assumed to be placed on soft soil, the ShakeMap (Fig. 5b) is identical to the map of Figure 4a generated with real geological conditions below the recording stations; the only



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.03	.03-.29	.29-.93	.93-3.0	3.0-9.7	9.7-31	31-102	101-330	>330
PEAK VEL.(cm/s)	<.01	.01-.13	.13-.47	.47-1.7	1.7-6.1	6.1-22	22-78	78-282	>282
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 4. (a) The PGA ShakeMap for the Claut 2007 earthquake. The networks that recorded the event are RAF (red triangles), RAN (yellow triangles), NEI (green triangles), RSFVG (white triangles), and ARSO (blue triangles). (b) The PGV ShakeMap for the Claut 2007 earthquake. (c) The instrumental intensity map for the Claut 2007 earthquake. The triangles denote the triggered stations. (d) The observed intensity map taken from INGV felt reports (see Data and Resources section).

exception is the station called CESC that is better fitted when the site is considered as soft soil. The unusual behavior of this bedrock station has been already shown (Costa *et al.*, 2006). The bias factor is larger in the case of Figure 5a because the recorded data have not been deamplified, so the difference with the estimated PGA is larger. However, this test indicates that the bias factor could supply the lack of information about the geological knowledge under the recording stations, even if detailed geological studies at the recording stations are needed to improve the adopted ShakeMap model.

Another example validating our ShakeMap computations is related to the M_L 5.7 earthquake that occurred on 12 April 1998 at Bovec (northwest Slovenia) near the borders of Italy, Austria, and Slovenia. Only seven RAF

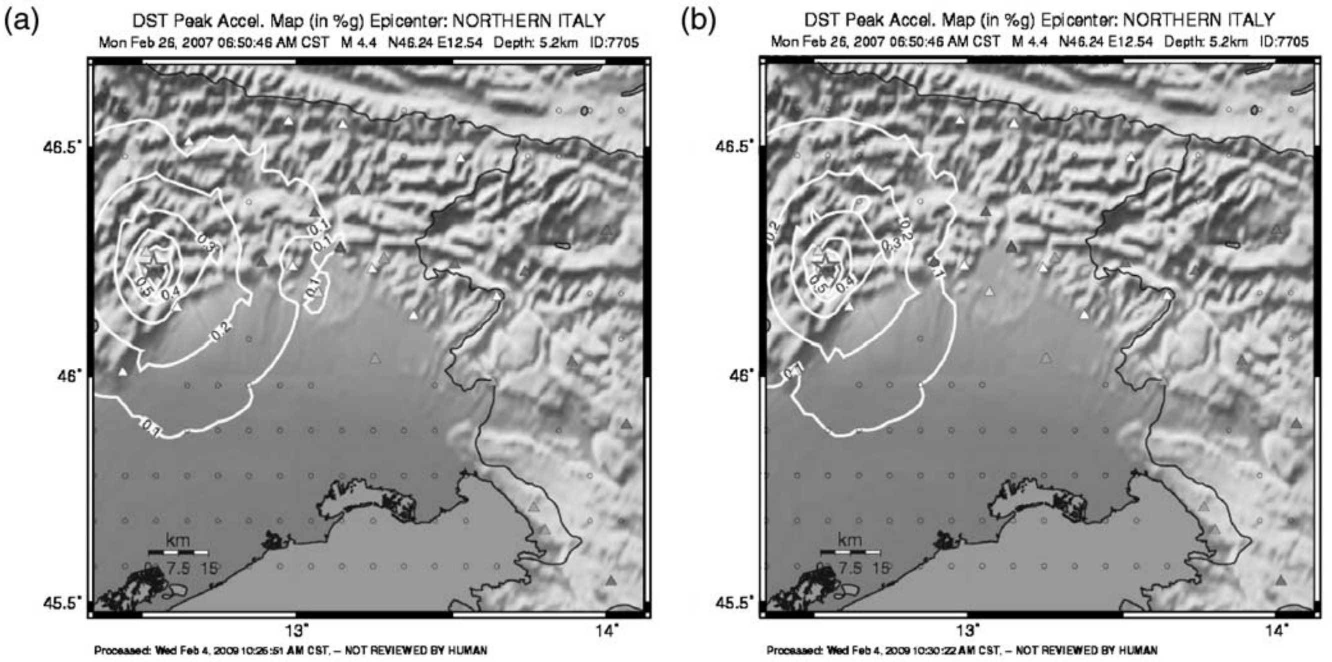


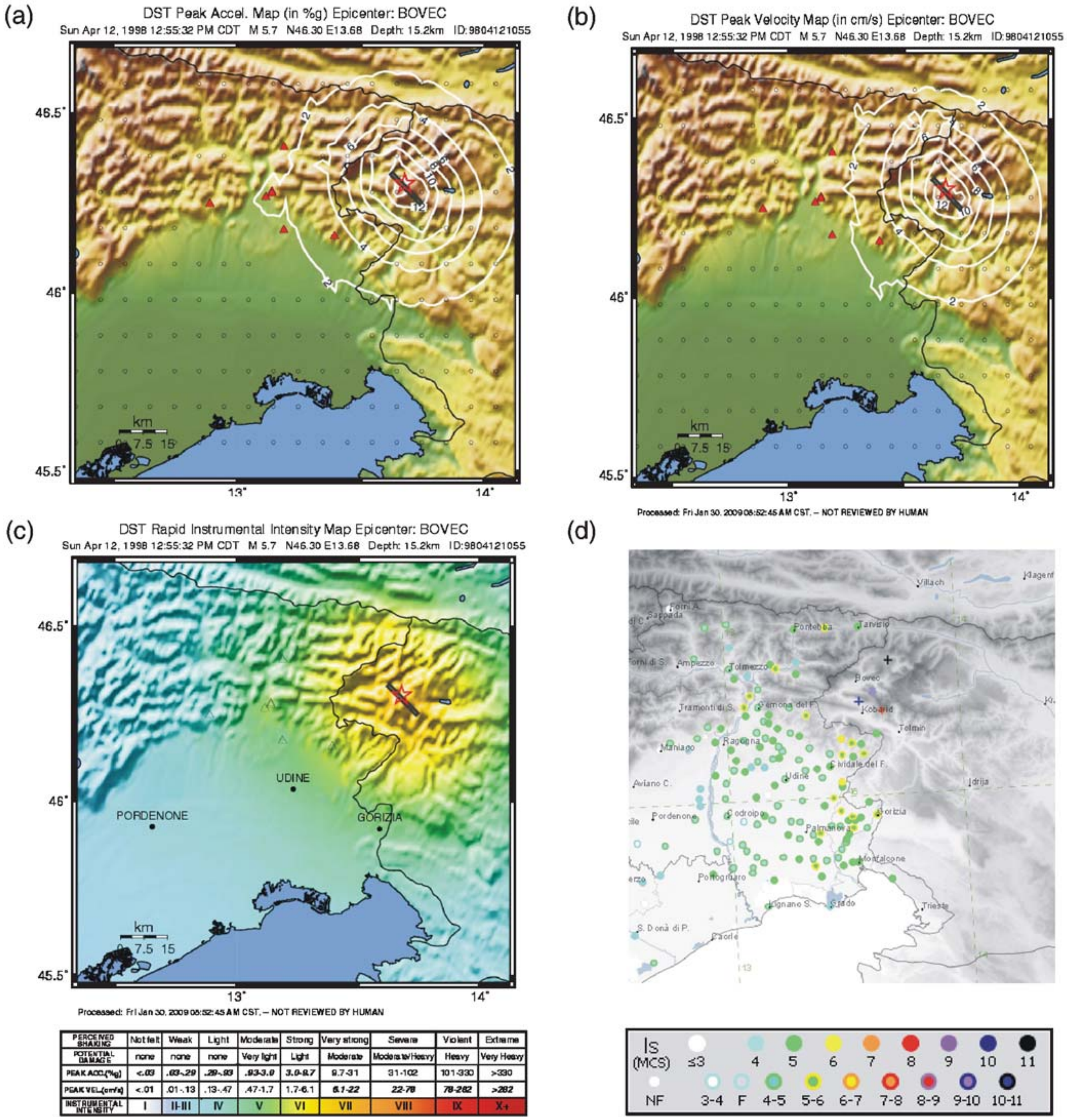
Figure 5. (a) The PGA ShakeMap for the Claut 2007 earthquake where all recording stations are assumed to be on bedrock sites. (b) The PGA ShakeMap for the Claut 2007 earthquake where all recording stations are assumed to be on soft soil.

stations were operating at that time, mostly concentrated in the Gemona area, so the ShakeMaps (Fig. 6) are not as detailed as those related to the Claut 2007 earthquake (Fig. 4). The finite-fault geometry as proposed by Bajc *et al.* (2001) was inserted into the ShakeMap computation to correctly compute the fault-to-station distance. The resulting bias factor is 0.38 for PGA (Fig. 6a) and 0.37 for PGV (Fig. 6b), suggesting also in this case an underestimation of the magnitude value or a bias in the GMPE relationships. Because detailed geological maps for Slovenia and Austria are not available, we consider all these areas as bedrock, even if this condition influences the bias computation. However, since our aim is to validate the ShakeMap only inside the Friuli Venezia Giulia region, this assumption is irrelevant. In the future, we hope to insert in the ShakeMap computation the geological soil maps for all the southeastern Alps regions.

The computed instrumental intensity map (Fig. 6c) shows a degree VI intensity in the Italian zones near the border with Slovenia (Tarvisio, Resia Valley, Torre Valley, and Cividale). At the same time, the degree V is estimated in eastern Carnia and at the cities of Udine and Gorizia. The intensity decreases to degree IV in other areas of Friuli Venezia Giulia. We validate the ShakeMap results by comparing them with the observed intensity map (Fig. 6d) taken from the DBMI08 database (Rovida *et al.*, 2008, see Data and Resources section). The comparison is good: a VI degree of intensity is observed near Cividale (same value as estimated by our ShakeMap results), while degree V is observed in Eastern Carnia and in the areas of Udine, Gorizia, and Monfalcone, again in excellent agreement with our ShakeMap results. In the epicentral area our ShakeMap results predict an intensity VI–VII; the latter value is in agreement with the one reported by Živčić *et al.* (2000) who observe an intensity (EMS) VII in the epicentral area of Bovec-Tolmin (Slovenia).

Conclusions

In this article, the earthquake-related ground motion is estimated in the southeastern Alps area with the help of the ShakeMap software (Wald *et al.*, 1999b), which integrates the data observed in real time with the estimates derived from our knowledge of the soil geology and ground-motion prediction equations (GMPEs). In particular, the software implemented for the southeastern Alps area generates in real-time (within 5 min) ShakeMaps for PGA, PGV, SA (0.3, 1.0, and 2.0 sec), and instrumental intensity. The necessary waveforms, retrieved from the real-time system Antelope, are integrated with the estimates based on our knowledge of the soil geology and GMPEs specific for the interested region and lead to fast and reliable shake maps. Although various soil classifications are available (EC8, NEHRP, regional map), we use the digital maps for the Friuli Venezia Giulia region that classify soils into three categories: rock, stiff soil, and loose soil. Two different GMPEs are used in different magnitude ranges: the relationships proposed by Massa *et al.* (2008) for weak motion valid in northern Italy and the relationships for strong motion proposed by Sabetta and Pugliese (1996) valid for the whole Italian territory. To compute the instrumental intensity, the relationship proposed by Faccioli and Cauzzi (2006) is used. The number of recording stations is critical as demonstrated by the test done



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.03	.03-.29	.29-.93	.93-3.0	3.0-9.7	9.7-31	31-102	101-330	>330
PEAK VEL.(cm/s)	<.01	.01-.13	.13-.47	.47-1.7	1.7-6.1	6.1-22	22-78	78-282	>282
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 6. (a) The PGA ShakeMap for the Bovec 1998 earthquake. The network that recorded the event is RAF (red triangles). (b) The PGV ShakeMap for the Bovec 1998 earthquake. (c) The instrumental intensity map for the Bovec 1998 earthquake. The triangles denote the triggered stations. (d) The observed intensity map taken from the DBMI08 database.

computing the synthetic seismograms for the Bovec 2004 earthquake and varying the grid size of the simulated recording stations. The setting of the ShakeMap software takes into account the geometry and the characteristics of the integrated network of stations available in the area, with a mean interstation spacing in Friuli Venezia Giulia of about 20 km. The comparison between instrumental and observed intensity maps for weak motion (Claut 2007 earthquake) and strong motion (Bovec 2004 earthquake) validates our results and our software configuration. Furthermore, we demonstrate that the bias factor can supply the lack of geological knowledge about the recording stations, even if detailed geological studies at the recording stations are needed to improve the ShakeMap model.

Future developments include the validation of the model by comparing, for important past seismic events in the studied area, the results obtained using the actually observed data with the ShakeMaps derived from synthetic seismograms only. Further studies should also be done on the empirical relationships between the ground-motion parameters and the instrumental intensity and on the soil classification of the whole southeastern Alps area. Finally, the computation of synthetic seismograms on the grid nodes in quasi-real time could refine the shake maps because in such a case it will be possible to also take finite-fault effects into account.

Data and Resources

The Bovec 2004 source model data can be obtained from the ETH Web site at www.ethz.ch (last accessed June 2006). The DBMI08 and INGV felt reports can be obtained from INGV Web site at www.ingv.it (last accessed March 2009). Other data used in this article came from published sources listed in the references. Some plots were made using the Generic Mapping Tools (Wessel and Smith, 1991).

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