Development and Comparison between Methodologies for the Evaluation of Seismic Hazard in Seismogenic Areas: Application to the Central and Southern Apennines

Coordinator: Dr. Massimo Cocco

Introduction

1 – Project Structure. Several institutional modifications and mobility among researchers working to the project required a further change to the project structure. In particular, two research units (namely, the old UR6 University of Genova and UR4 INGV Milano) have been merged to a single research unit. The updated list of research units is described in the following table:

Table 1: Research Units participating to the project.

Research Units	Scientific Coordinator	Affiliation	External Research Groups (sub-contractors)
UR1	Massimo Cocco	Istituto Nazionale di Geofisica e Vulcanologia **INGV – Roma -**	Istituto Dinamica Processi Ambientali Roberto De Franco CNR Milano
UR2	Enrico Priolo	Istituto Nazionale di Oceanografia e Geofisica Sperimentale (OGS), Trieste - **OGS**	
UR3	Aldo Zollo	Università di Napoli **UniNa**	Università di Bari Agata Siniscalchi
UR4	Paolo Augliera	Istituto Nazionale di Geofisica e Vulcanologia **INGV – Milano -**	Università di Genova Dip. Scienze della Terra Daniele Spallarosso
UR5	Peter Suhadolc	Università di Trieste **UniTri**	
UR7	Alfredo Mazzotti	Università di Milano **UniMi**	

2 – Project Goals.

The project is focused to the study of the Colfiorito area, identified as a training site because of the availability of geophysical data and information on the seismic sources, as well as to the Città di Castello and Val D'Agri zones both recognized as test areas where the methodologies calibrated in the training site will be applied. The activities carried out during the second year respect the working plan expected in the executive program and required the contributions from all the five tasks of the project. In particular, the research activities have been concentrated to the Colfiorito training site and to the Città di Castello test area. The main goals achieved during the second year are presented in the following and they are described for each task.

TASK 1. Geometrical and Mechanical Characterization of Seismic Sources.
(Coordinator P. Montone, INGV – Roma).
Research units involved in this task: UR1, UR3 (Univ. di Bari) e UR7.
Colfiorito Area

- Summary of the results of geophysical investigations.

- Critical review of proposed source models based on the interpretations of profiles of exploration seismology.

<u>Test Areas: Città di Castello and Val D'Agri</u>

- Target Seismic source models for Città di Castello.
- Summary of the knownledge for the Val D'Agri area.

TASK 2. *Characterization of Crus*
tal Structure.
(Coordinator A. Michelini, INOGS – Trieste).
Research units involved in this task: UR1, UR2 e UR4.
<u>Colfiorito Area</u>

- Summary and revision of the proposed velocity models.
- Comparison with the results of exploration seismology.
- 3-D velocity models and evalusation of anelastic attenuation.

<u>Test Areas: Città di Castello and Val D'Agri</u>

- Analysis of seismological data recorded during the field experiment.
- Velocity structure in the Città di Castello area.
- Summary of the knowledge for the Val D'Agri.

TASK 3. Ground motion scaling relationships.
(Coordinator L. Malagnini, INGV – Roma).
Research units involved in this task: UR1.

- Attenuation laws of peak ground motions for Città di Castello.
- Evaluation of PGA, PGV for Colfiorito.
- Seismic Hazard maps for the Umbria region

This last purpose represents a further goal that has been added after the presentation of the proposal, because it was not expected in the approved project. It has been scheduled because it represents a useful and important goal for the project achievable in this task.

TASK 4. Validation of synthetic seismogram computational methods.
(Coordinator A. Zollo, Università di Napoli).
Research units involved in this task: UR1, UR2, UR3, UR4 e UR5.
<u>Colfiorito Area</u>

- Conclusion of methodological Blind Test.
- Ground Shaking Scenarios for Colfiorito.
- Computation of time histories of ground velocity and acceleration.
- Comparison between predicted and observed ground motions.

TASK 5. Site effects characterization.
(Coordinator A. Rovelli, INGV - Roma).
Research units involved in this task: UR1 e UR4.
<u>Colfiorito Area</u>

- Definition of site transfer function for the selected sites.

<u>Test Areas: Città di Castello and Val D'Agri</u>

- Analysis of seismic data recorded during the field experiment.
- Investigations to characterize the site response in Città di Castello.

With few exceptions, all the expected goals have been achieved. The only activities not completed concern the comparison between the velocity models deduced from seismic tomography with the results of the elaboration of profiles from exploration seismology and the determination of the anelastic parameters with tomographic methods. These activities will be completed during the third year and will contribute to the general review of the knowledge on the seismogenic sources in the target areas.

SCIENTIFIC RESULTS

We present here the summary of the scientific results achieved within each task. A detailed description of the investigation will be presented in specific annexes cited in this report.

TASK 1. Geometrical and Mechanical Characterization of Seismic Sources.
Colfiorito Area. **Processing and Interpretation of profiles from exploration seismology, UR7 A. Mazzotti.** RU 7 has carried out further processing and analysis of the seismic reflection data available to this project. In particular:
1) We have performed the reprocessing of the line MC347, which actually started in the first year, and also of the line MC357. Thus, we have completed the reprocessing of the three seismic profiles adjacent to the Colfiorito area. Although the original data show similar characteristics, essentially a very low signal to noise ratio, it has been necessary to adapt the processing sequences to the specific problems of each line to achieve significant improvements of the final seismic image quality. Also, since it was deemed as necessary to obtain high quality images either at two-way times pertinent to shallow layers and at two-way times pertinent to deep reflectors, our seismic data analysis and processing have followed two different approaches, with different algorithms and choices of parameters, each aimed at optimising the quality in the proper time window. This strategy, besides duplicating our efforts, has led to a significant improvement of the final images that clearly show the structure of the subsurface, in some cases with excellent detail. Examples of the results are shown in the Annex T1.A to this report.
2) Making use of the data of the MC347 profile, we have estimated the P-wave velocity field of the subsurface down to 4 s, corresponding to a depth of about 10 km. This has been made possible by integrating the outcomes from seismic velocity analysis tools, such as stacking velocity analysis, time migration velocity analysis and PSDM focusing analysis, with acoustic well log data and geological knowledge. This result is also shown in the Annex T1.A.
3) On the basis of the P-wave velocity field estimated in 2) we have depth migrated the MC347 stack section by means of a Kirchoff algorithm. Efforts aimed at depth migrating prestack data have been in so far unsuccessful due to the very low S/N. However, the obtained depth section shows interesting correlation with seismological events. As an exercise, we projected onto the section some hypocentral locations, those nearest to the line and with highest magnitude, taken from Amato et alii (1998). Although the hypocenters have been positioned making use of a separate velocity field, derived independently from our seismic reflection data and possibly simpler than the one we estimated, we note a pattern of the hypocenters that lay close to major structures evidenced by the seismic reflection depth section. This result is again shown in the Annex T1.A. We believe this outcome has to be further investigated. In fact, in the third year of the project we plan to extend our velocity

estimation to the other two lines (PG308 and MC357) in order to obtain a quasi-3D velocity field. This could then be used either to obtain depth images of the reflection data and to relocalise the hypocenters and to refine the focal mechanism determinations. It will be interesting to verify whether the matching between hypocenter locations and structural features evidenced by the reflection seismic will increase.

Results from further geophysical investigations. RU 3 A. Siniscalchi.

Data Acquisition: In correspondence of the main discontinuities three geoelectrical tomographies were carried out. The dipole-dipole configuration was used. In particular, in the epicentral area of the 1997 earthquake, which struck the Umbria-Marche region, were carried out: (i) a multiscale geoelectrical tomography oriented perpendicularly to the Annifo-Cesi fault, across the Colfiorito's swamp (we adopted two different electrode spacings, one of 20m, the other of 60m); (ii) two geoelectrical tomographies sub-perpendicular to the M. Pennino-M. Prefoglio fault segment. In particular, one was carried out in correspondence of M. Faeto and the other in correspondence of M. Prefoglio (for both profiles the electrode spacing of 60m was adopted). Numerical inversion of the electrical tomographies provided a 2D high resolution resistivity image of the subsurface until the depth of 200m. The results of these analyses are described in detail in the Annex T1.B.

Critical review of the results, RU1. The re-processing of seismic reflection lines, PG-308, MC-347 and MC-357, is a powerful tool to a better reconstruction of deep fault geometries (Annex T1.C). The final interpretation has been done for the PG-308 line, jointly with the analysis of the seismic sequence occurred in 1998, near to Gualdo Tadino, and it's started the final interpretation of the MC-357: in both cases it's enhanced the Basement involving in the active tectonic with an important correspondence between the step of the Basement and the location of the seismogenic normal fault. During the last year of activity all the available information will be re-elaborated in order to propose a synoptic model of the potential seismic source in the Colfiorito area.

<u>Test Areas: Città di Castello and Val D'Agri</u> **(RU1)**. Two different seismogenic structures have been proposed for the Città di Castello and, then, for Val d'Agri area. The researches (Annex T1.C) allowed us to better constrain the Alto Tiberina Fault (ATF) as a seismogenic regional fault able to produce microseismicity and moderate-magnitude earthquakes (M_d=4.3 of 2001 seismic sequence). The geometric characteristics of the ATF has been showed from analysis of seismic reflection lines acquired from AGIP, in cooperation also with Perugia University. We propose a moderate seismogenic sources, between CROP03 and Sansepolcro 2001 seismic sequence, with a variable direction from NNW-SSE to WNW-ESE, dip around 20° and about 15 km length. In analogy with the southern area (Gubbio, Colfiorito …), it's hypothesised the existence of a west-dipping seismogenic fault maybe cause of historical earthquakes and recent events as the 1997 seismic sequence but, at present, we are not able to produce the relative geometric and cinematic parameters. Now, we can only hypothesised a NW-SE normal fault structure (N130-150) SW dipping (40°-60°). The length is about 10-15 km and located in a more internal position respect to the basin.

Several segments of seismic reflection profiles were analyzed, crossing the central part of the Agri basin (Annex T1.C) with a SSW-NNE direction. In the profiles, the half-graben geometry of the continental basin suggests that the onset and evolution of the Agri basin is related to the activity of a SW-dipping normal fault. The master fault borders the eastern flank of the basin, and can be traced at depth till about 0.6 s TWT, where it tends to become slightly flatter. Some ~NE-dipping antithetic faults have been recognized, but their throw is negligible. In particular, for the 1857 earthquake there is not a general consensus on the fault geometry, although the location is well constrained by intensity data around the high Agri basin. We refer to two alternative hypotheses, with a SW- or NE-dipping normal fault. The interpretation of new seismic profiles and of new data will give us a clearly definition of these seismogenic structures for both areas.

Task 2. Characteristics features of the Crustal structure.

Velocity Models. UR2 (Alberto Michelini) e UR1 (Claudio Chiarabba)

1. Gualdo Tadino, Colfiorito and Norcia training sites:

1.1 Colfiorito 1-D Crustal model. The global search approach described above has been applied to the data set oif Colfiorito. Goal of this study were i.) to determine a 1-D model to be used as initial model for 3-D tomographic reconstructions and ii.) to provide a 1-D model which can be adopted for the generation of Green's functions (see task 4). We have used a total of 522 earthquakes for about 12700 P- and 12200 S-onset phases from the merged INGV and GNDT data sets of the 1997 Colfiorito eaerthquake sequence. The main result of this study is that in an area featuring relevant lateral velocity heterogeneities like that of Colfiorito, very diverse 1-D velocity can match the data equivalently. This has important consequences when one of the main goals of the inversion is to resolve 1-D models that can be used in the calculation of waveform synthetics for earthquake scenario purposes (task 4). Clearly, this intrinsic indeterminacy in the velocity models will map into the waveform field and the shake maps *(see Annex T2.A)*. This requires and motivates the join use of seismological data and information from seismic exploration data (see Task 1).

1.2 Waveform data analysis of the P- and S-waves, earthquake location and 3-D structure. We have computed a 3D Vp and Vp/Vs model for the upper crust of the Colfiorito region. The resolution of the model is 2 km in x and y and 1 km in z. The distribution of Vp and Vp/Vs anomalies shows a large heterogeneity and the main tectonics settings of the sub-surface. The crustal structure consists of different east-verging thrusts and folds. The normal faults develop in the back limb of the thrust units. We have computed cross-correlation of waveforms and relative locations for the Colfiorito aftershocks to gain high resolution images of the fault system. The aftershocks distribution, with hypocentral errors less than 50 m, yields the very fine geometry of faults at depth. This detailed investigation confirms the proposed source model and used in Task 4 for the simulations.

1.3 Inversione 3-D di Qp e Qs per l'area "training" di Colfiorito. This activity has not been pursued during the second year of the project.

2. Città di Castello experiment.

2.1 Complete data processing and preliminary analysis. We have identified a total of 2472 earthquakes for about 26500 and 24000, P- and S-wave onset phases, respectively. In contrast to our expectations the total number of earthquakes recorded by the mobile has been at least four times larger than what predicted. We have tested the quality of the data set by applying a simple procedure relying solely on the arrival time difference between correspondent P- and S-wave onset phases (a variant of the Wadati analysis, see *Annex T2.B*).

2.2 P*reliminary results of the earthquake locations and crustal structure in1-D and 3-D*: ***1-D Structure**:* It has been performed a global search for the best fitting 1-D velocity model using the Genetic Algorithm as search driver and the standard hypocentral location program HYPOELLIPSE for the forward modeling. The data set that has been used consisted of 166 events with an average of about 17.2 and 16.7 P- and S-onset phases, respectively. Our best fitting models result in data misfits (mean of the individual location root mean square) of about 0.13 s. This value is low when the extension of the area, the fact the a 1-D model is adopted, and a relatively large number of phases are all considered. Our results show that the set of best matching models feature a shallow jump in seismic velocities which we have found impossible to replicate having an arbitrary number of layers *(Annex T2.B)*. *Event relocation using the double-difference technique:* The earthquakes recorded during the experiment have been also read using a cross-correlation technique and relocated using the double-difference method. Application of the technique has shown that the earthquakes tend to align along in a manner otherwise impossible to find using standard phase picks and location programs (see Figure 1).

3-D Structure: For the 3-D model, in one case we have performed the inversion using the same set of earthquakes adopted for the 1-D model. The technique used follows from Thurber (1983) for the cubic B-spline velocity model (Michelini and McEvilly, 1991) and it adopts the LSQR sparse matrix solver. Also, a similar inversion has been carried out independently using the standard technique with linear interpolation of Thurber (1983). The preliminary results indicate a fair correspondence between the geologic structures mapped at the surface and the resolved model at depth *(Annex T2.B)*.

2.3 Anelastic Attenuation Qp, Qs. We have computer t* values from local earthquakes spectra. Tomographic results will be completed and presented during the third year.

TASK 3. Ground motion scaling relationships.

UR1 Luca Malagnini

Goals of this Task for the second year of the project were the determination of the ground motion scaling relationships for the region around Citta' di Castello, where a large data set of recordings from the background seismicity exists, and the computation of peak values for the region around Colfiorito, done by using the results published by Malagnini and Herrmann (2000). In a later stage of the present project we decided to present also an important application of the results by Malagnini and Herrmann (2000), that is a hazard map of the region surrounding the area struck by the earthquakes of the Umbria-Marche sequence of 1997-98. The ground motion scaling at regional distance is quantified by regressing very large data sets of ground motion waveforms, generally the peak values of narrowband-filtered versions of the time histories, but also the Fourier amplitudes (see Malagnini et al, 2000, 2002 for detais). Logarithms of observed filtered peaks are written as:

PEAK(r,f)=EXC(f)+D(r,f)+SITE(f), where PEAK(r,f)=Log(peak(r,f)), EXC(f) is an excitation (source) term, SITE(f) represents the site behavior, and D(r,f) is a quantity

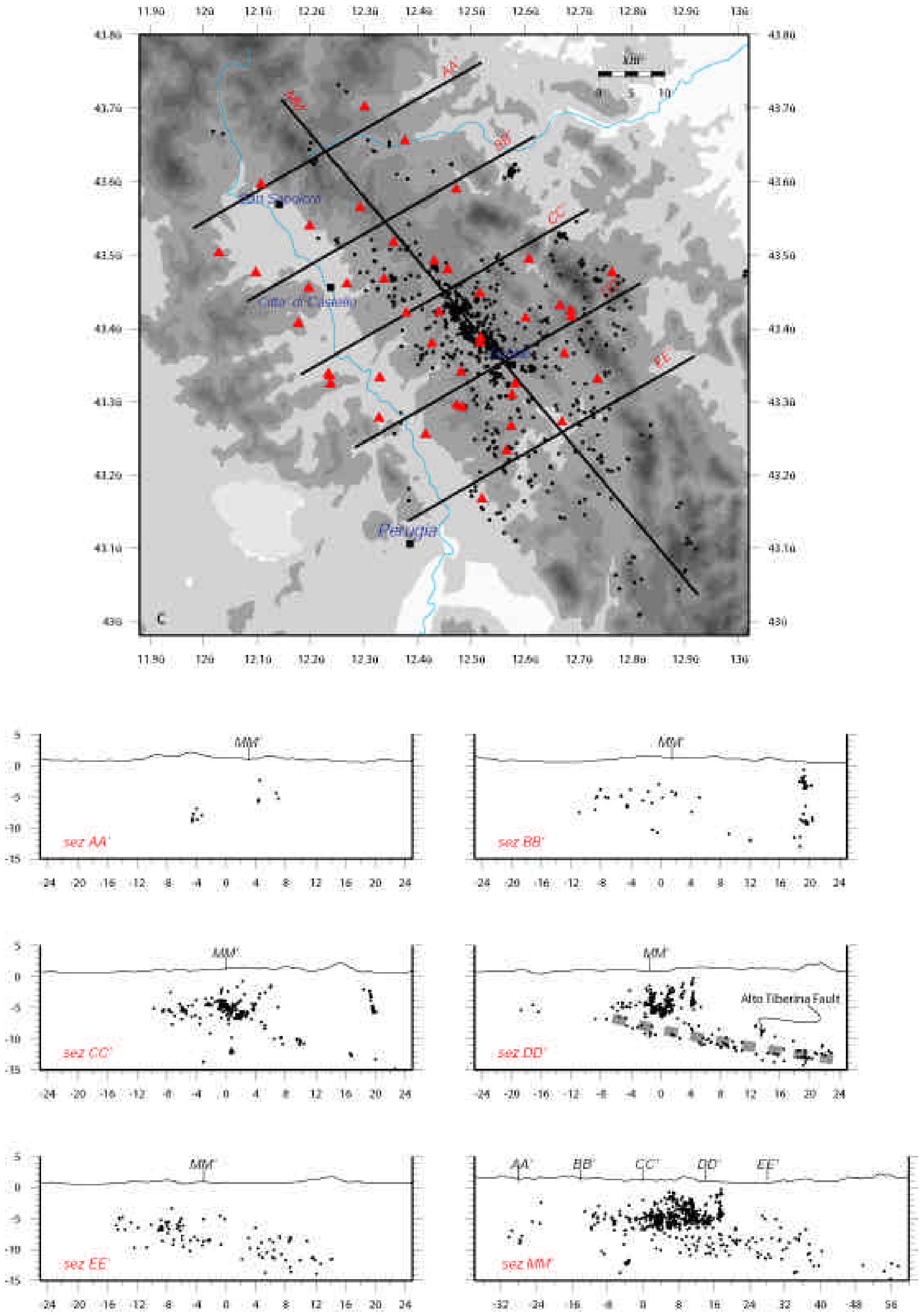

Figure 1. Map of seismicity recorded durino the field acquisition experiment in the Città di Castello area. These new original data allowed the identification of the geometry of the Alto Tiberina Fault (ATF). The recorded data have been used in this project to perform accurate earthquake locations with a double difference technique (Tasks 1 & 2), to image the crustal structure in this area (Task 2), to constrain the attenuation laws of peak ground motions (Task 3) and to characterize the local site response (Task 5).

that describes the regional attenuation of the specific frequency component of the Fourier amplitude spectra, as a function of hypocentral distance, r. Along with source, attenuation, and site terms, the regressions are done also on a functional form that quantifies the duration of the signal as a function of frequency and hypocentral distance. The mathematical tool of Random Vibration Theory is extensively used to model/predict peak values as a function of distance and frequency, or even as absolute values (e.g. PGA, PGV). Modelling efforts carried out to fit the regional attenuation and the excitation terms will yield a regional, crustal attenuation model as well as estimates of the shallow attenuation term κ. All the mentioned information may be used for predicting the ground motion in the region, and in order to produce modern hazard maps. For the moment we selected about 521 events, for a total of 8079 waveforms, recorded in the region surrounding the town of Citta' di Castello. The entire data set available is made of about 2000 earthquakes (~60,000 waveforms), and will be exploited more extensively for future applications. Figure 2-a shows the regional attenuation for Città di Castello, with the parameters used to fit the empirical attenuation curves. Horizontal lines in Figure 1 decay as 1/r. A stable estimate of the shallow parameter κ is yet to be quantified for the region. The region in the immediate vicinity of the Umbria-Marche sequence of 1997-98 is characterized by a different attenuation function, with a stronger frequency dependence of the crustal attenuation parameter ($Q(f)=130\ f^{0.1}$ for the rest of the Apennines Colfiorito region, $Q(f)=65f^{0.63}$ for Città di Castello). Nevetheless, when the surface parameter κ will be available also for Città di Castello, we expect the two attenuation models to be practically equivalent in terms of total attenuation. The different distance ranges spanned by the two data sets resulted in slightly different tradeoffs between Q_0 and g(r), and thus in slightly different apparent attenuation models. About the higher frequency dependence parameter η, that reflects a "true" difference between this specific region and the entire Apennines. Figure 2-b displays peak values of ground acceleration (left) and ground velocity (right), as observed at accelerometric sites during the mainshock of 6/5/1997 (Mw=5.9), superimposed to estimates obtained using the attenuation information taken from Malagnini and Herrmann (2002). Figure2-c, finally, show probabilistic estimates of hazard for the Umbria region, in terms of peak ground acceleration (PGA), obtained using ground motion scaling information by Malagnini and Herrmann (2002), the CPTI catalogs (1999), the database of potential for earthquakes larger than M5.5 in Italy (Valensise and Pantosti, 2001), a BC-kind of stiff site, for which 50% of the probability is assigned to characteristic behavior, and 50% to a Gutenberg-Richter model.

TASK4. Validation of methodologies for synthetic seismogram computation.
UR1, UR2, UR3, UR4, UR5.
The task includes all methodological and applicative studies aimed at the strong motion prediction using realistic models of both seismic fracture and wave propagation. The seismic source is described and simulated through numerical techniques which take into account heterogeneous fractures.

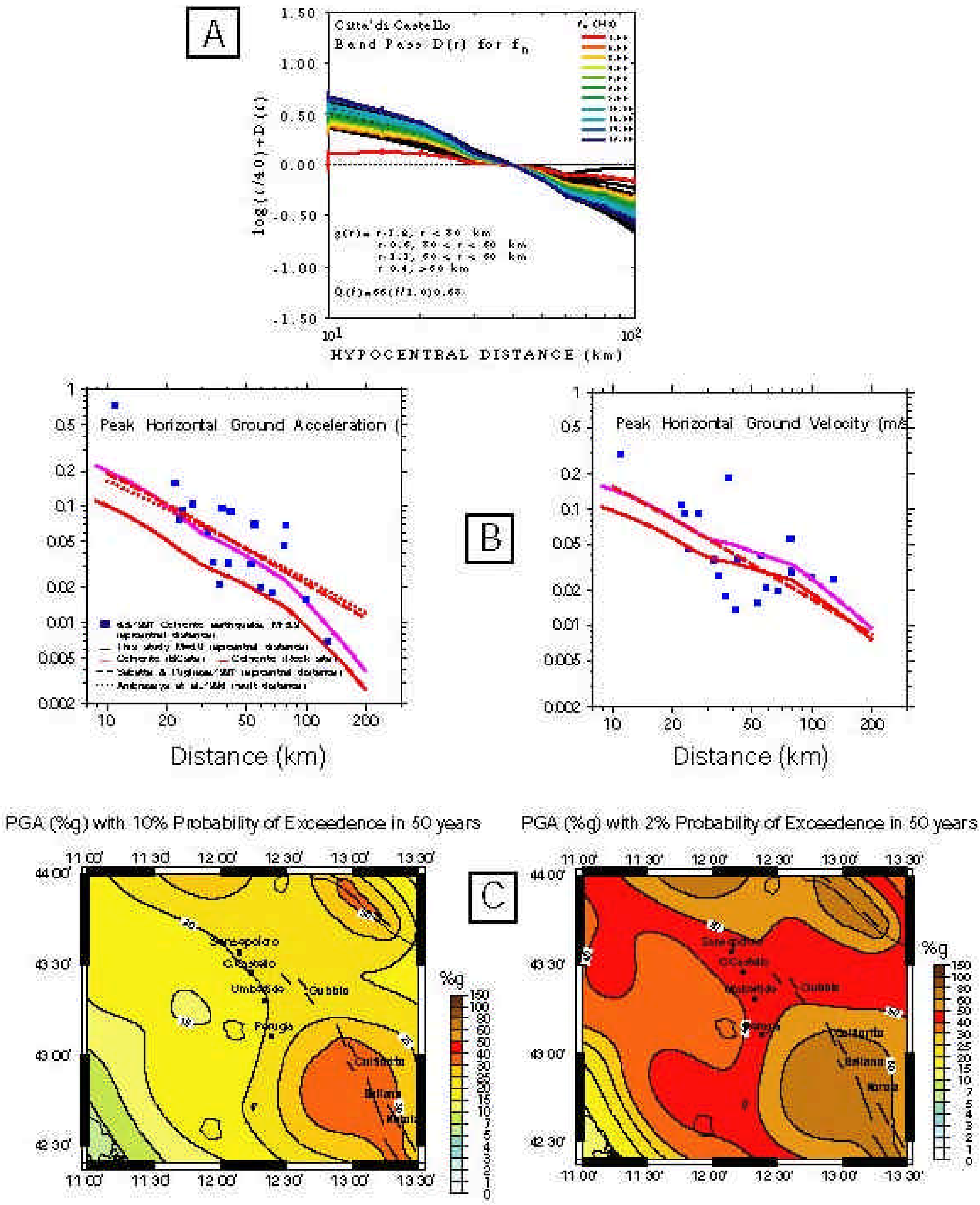

Figura 2. a): empirical crustal attenuation function for the region around the town of Città di Castello (Central Apennines). Indicated in the picture are the parameters used for fitting the empirical functions of frequency and hypocentral distance. b): peak horizontal ground motion (acceleration, left, and velocity, right) observed during the 6/5/1997 (M_W~5.9) Colfiorito earthquake, compared with: i) theoretical estimates based on the attenuation model indicated by Malagnini and Herrmann (2000) (rock sites and BC sites are indicated in different colors), ii) empirical curves by Sabetta and Pugliese (1996), and Ambraseys et al. (1996). c) hazard maps for Umbria (left: PGA, 10% exceedance in 50 years, right: PGA, 2% exceedance in 50 years) based on the predictive relationships for the Apennines by Malagnini et al. (2000), the CPTI catalog of earthquakes (1999), the database of potential earthquakes by Valensise and Pantosti (2001), BC-like sites, logic tree: 50% probability for characteristic earthquake model, 50% probability for the Gutenberg-Richter model.

Wave propagation is computed by using 1D/3D asymptotic and full-wave methods. Second year signs off the strong motion simulations for the Colfiorito training area. The activity has been focused on two main goals: 1) the computation of the strong ground motion generated by and extended fault (see Annex T4.A) and, 2) the construction of earthquake scenarios for the training area (see Annex T4.B). The comparison with observed strong motion parameters and the statistical analysis of the earthquake scenario is still going on. At the same time, the methodological development has gone on, focusing on the sperimentation and validation of the different techniques, i.e. full-wave, asymptotic, and empirical Green's functions (EGF).

RESULTS. During the first year, the RU activity focused on the methodological development and application to the training area of Colfiorito, which has been struck by the seismic sequence of 1997. Synthetic seismograms computed using different numerical methods were compared each other quantitatively by analyzing waveforms and spectra. The reference earthquake simulated the Colfiorito main shock, and it was defined by assigning size, geometry, and mechanism. The following methods were compared: stochastic-deterministic (DSM, asymptotic), asymptotic (ASM), wavenumber integration (WIM, full-wave), and modal summation (MSM, full-wave). A detailed presentation of the results is described in Annex T4.A. During the second year, the methodological tests for the training area have been focused on:

1) The computation of synthetic seismograms and comparison with recorded accelerograms. This test aimed at verifying the capability of each simulation method to reproduce the 1997 September 26, 09:40 GMT, Colfiorito earthquake (M_w=6). Two source models were used: the former was obtained by strong motion data inversion (*Zollo et al., 1999*), the latter by geodetic data inversion (*Salvi et al., 2000*). The URs involved in Task 4 were required to compute the time series for ground acceleration, velocity and displacements for both source models at a regular grid of 64 receivers, and additional 8 sparse stations, on an area of almost 60x60 km^2 surrounding the Colfiorito fault. The maximum frequency was 5 Hz (see Annex T4.A). The results were compared by using peak values and some integral parameters (e.g., Arias and Housner intensities, duration, …). Concerning the asymptotic approach, the two methods used (ASM and DSM) provide similar spatial distributions of peak ground motion parameters (PGA, PGV and PGD) and predict the occurrence of strong directivity effects. Waveform durations are also comparable, even though the stochastic method DSM predicts more complex signals due to the addition of a random component to the phase spectrum. In general, seismograms computed by asymptotic methods feature shorter durations than those computed by full wave methods. This is explained by the fact that the latter account for compressional waves, secondary arrivals, high frequency surface waves and reverberation effects. As a further consequence, full waveforms depend on the assumed velocity structure much more heavily than those computed by asymptotic approaches. This explains the rather different spatial distribution of the peak ground motion parameters, even for the same source model. The comparison with recorded waveforms during the M=6 Colfiorito main shock shows: (i) consistent spectral shapes at low frequencies (f < 3 Hz); (ii) prominent site amplifications on real data, which are not predicted by synthetics; (iii) rather consistent prediction of the peak ground motion values (i.e.,

within a factor 3). Finally, the synthetics computed for the geodetic and accelerometric source models feature significant differences (larger than 30%). This suggests that the source model can influence significantly the ground motion prediction. More details about this activity can be found in the annexes T4.C, T4.D, T4.E and T4.F.

2) Construction of ground shaking scenarios: comparison among the different methods and with recorded data. The aim of this test is to compare the ground motion scenarios simulated by the different methods. The reference earthquake is the September 26, 1997 M_W=6 Colfiorito earthquake. Fault geometry, source mechanism and model structure are constrained. The input variability is associated with the rupture parameters, i.e. nucleation position, final slip distribution, and rupture velocity. The rupture velocity is left free to vary in the range from 0.75 V_S to 0.95 V_S. The maximum frequency is 10 Hz. In order to emphasize the directivity effects associated to rupture propagation, the results of the simulations are grouped into three families, depending on the position of the rupture nucleation. For each family of rupture scenarios, a statistical analysis is performed to evaluate the variability of the strong motion parameters. The construction of the ground shaking scenarios and their comparison is currently at its final stage: all seismograms have been computed, while the compilation of the statistics and the analysis of the results will be concluded in a short time. Preliminary results indicate that the ground motion amplitude strongly depends on the value of the rupture velocity. For instance, a variability of the peak values by a factor of about 3 is predicted by asymptotic methods. Simulated and observed ground motion values at stations that recorded the Colfiorito main shock exhibit some discrepancies, which can be attributed to unaccounted site amplification effects. For a detailed description see Annexes T4.B and T4.F.

3) Validation of the full-wave simulation methods. The following methods have been analyzed: a) EXWIM, based on the Wavenumber Integration Method (Hermann, 1996); b) two different modal summation methods, i.e., MSM by Panza et al. (1985) and EXMSM based on the modal method by Herrmann (1996), respectively; c) COMPSYN by Spudich and Xu (2002), based on the Discrete Wavenumber-Finite Element Method by Olson et al. (1984). The tests performed using both point and extended source (see Annex T4.E) show that the three methods provide similar results when forced to discretize the fault plane by the same number of Green's function and at some distance from the source. However some relevant differences exist among the examined methods. The modal summation method computes accurate synthetic seismograms only at distances larger than the source depth. In finite source simulations and earthquake scenario studies critical conditions are easily met. Thus particular care must be taken in order to avoid inaccuracies and asses the quality of computations. The modal summation method is much more efficient than the wavenumber integration method, and it is therefore to be preferred for computations at distance from the source. The methods based on the wavenumber integration, i.e., COMPSYN and EXWIM, use similar descriptions of the extended fault rupture and show similar results. COMPSYN is much more efficient since it exploits the reciprocity theorem; however, it does not take into account medium attenuation, and therefore some approximate corrections must be applied at post-processing stage, especially far from the source. The computational efficiency of EXWIM has been improved, by using an interpolation technique for the finite source.

In addition, synthetic seismogram computation at high-frequencies has been made more realistic and efficient, by introducing a stochastic hybridization. The basic methodological development of the 3-D pseudo-spectral staggered Fourier method has been concluded. Its efficiency for multiple-source-simulations has been improved by using the reciprocity principle. Finally, an approach has been developed using Gocad© software for building up the 3-D model and the creation of a regular mesh.

4) Simulation methods based on the empirical Green's functions (EGF) (Laura Scognamiglio). A methodology has been implemented to predict ground motion hazard for a fixed magnitude earthquake along a specific fault or within a specific source volume. The methodology relies on empirical Green's functions to constrain propagation path effects. In our test, we develop constraints on rupture parameter of the 1997 Colfiorito earthquake based on previous studies. We started by generating a suite of rupture scenarios using a range of source parameters coming from literature about the 26 September 1997, Mw 6.0 Colfiorito earthquake (target event). (see Annex T4.A). Then we synthesized observed strong motion records for each scenario using, as EGF, 33 aftershocks of the Colfiorito sequence .We use the program HAZARD (Hutchings, 2002) to randomly select rupture parameters, and the program EMPSYN (Hutchings, 1991) to synthesize strong ground motion with empirical Green's functions. We have chosen to quantify the agreement between simulated and observed ground motion by examining how well the velocity response spectra (PSV), computed from the 100 synthesized accelerograms, match the Colfiorito earthquake. The best model for reproducing the target event was selected using as criteria the match on the response spectrum. The results are described in detail in Annex T4.G.

GENERAL REMARKS. After the simulations performed on the Colfiorito training area, we can point out a number of aspects and problems that must be considered adequately whenever these methods will be used to solve scenario studies in other test areas:

1) 1-D Velocity models. Even under the simplifying assumption of a 1D crustal structure, both waveforms and strong motion indices feature a clear dependence on both depth and acoustic impedance contrast of the discontinuities. This statement is important especially for full-wave methods. In the particular case of Colfiorito training area, the tomographic re-interpretation of the available data-set performed under Task 2 provides a highly heterogeneous set of 1D equivalent structures, and outlines a general uncertainty in defining a model univocally. For strong motion estimation purposes, the analysis should consider models able to increase the ground motion level. For instance, the presence of strong discontinuities in the vertical upper structure – a highly probable situation in Appenninic areas – can generate strong wavefield reflections and conversions and show up with strong phases in seismograms. It is therefore very important to validate and constrain the discontinuities of the velocity model using different sources of data, i.e. seismic prospecting and/or well data.

2) Source models. The deterministic source parameters (expected size and geometry of the fault segment, fault mechanism, slip, and seismic moment) should be defined accurately. For each of them, the variability range should be assigned and used to build up the scenario simulations. In the (lucky) case of Colfiorito, where two different source models were available, the simulation results show significant differences.

3) Site effects. A scenario study should always take into account the effect of a shallow soil layer, if any, with an average thickness characteristic for the study area (e.g, of about 250 m for the Colfiorito area). This statement comes dearly out from the comparisons between synthetic and observed data as well as from several past studies, which point out the need of simulating the site amplification/attenuation, even approximately. The site response can also be computed at post-processing, by convolving seismograms computed for rock with the pulse response of the soil layer for the different situations representative of the geology of the study area. If possible, the scenario should also consider the site spatial variability.

TASK5. Site Effects Characterization.

UR1- UR4

Data and Method of Analysis:

1) Strong-motion and weak-motion recordings of stations operating during the Umbria-Marche seismic sequence were analyzed (see Annex T5.A and T5.B). The available information concerning the geological, geotechnical and topographical characterization has been collected as well. In an empirical approach, two methods are adopted: the first one is a joint inversion that separates the source from propagation path and site contributions (Andrews, 1986), the second one computes the spectral ratio between horizontal and vertical components (HVSR). These empirical estimates are compared with 1D theoretical transfer functions derived from linear (Haskell-Thomson) and linear-equivalent (Shake91) models. The details of these investigations are shown in the Annex T5.B.
2) After the Città di Castello experiment in 2001, small-magnitude events recorded in the urban area were analyzed to infer the basin geometry as well as P and S velocity of the sedimentary infilling. The soft layer thickness was investigated through microtremor measurements as well (see Annex T5.C).

Results:

1) The comparison between empirical and theoretical estimates indicates that theory often underestimates observations. This reduces the applicability of nonlinear models, which would be optimal to simulate the Mw 6.0 event of 26 September 1997, to a few stations only. In general, HVSR represent a good compromise between the low amplitudes of 1D theoretical transfer functions and the site effect estimate of the Andrews' method inversion that gives moderate to high values (see Annex T5.B). Unfortunately, HVSRs are based on the assumption that the vertical component is representative of the bedrock input and this hypothesis is not valid *a priori*. Therefore, also HVSRs cannot be adopted systematically as the station transfer functions. In conclusion, there is not a unique method proposed as the optimal one. After a comparative discussion for each station, the most suitable operator is chosen on the basis of all the available information.
2) For the urban area of Città di Castello, conventional spectral ratios (CSR) were computed using a reference station on a nearby limestone outcrop (Middle Miocene). The small magnitude (M<2) of the recorded events and the low signal-to-noise ratio in the densely populated area make it impossible using CSR at frequencies $f < 1$ Hz (see annex T5.C). Unfortunately, the application of the Nakamura's technique to microtremors in Città di Castello indicates that the

fundamental frequencies are lower than 1 Hz for a large part of the urban area, consistently with a geological reconstruction based on P and S delays read on seismograms of local earthquakes. Therefore, the role of the silty clayey deposits of Val Tiberina has been investigated for different thickness and strain level using a 1D linear-equivalent approach (Shake91). Earthquakes of different magnitude and epicentral distance have been simulated as bedrock input, and the 1D transfer functions have been computed as a function of the bedrock interface depth (see Annex T5.D). We have found that the amplitude of the transfer function can change significantly in the different situations.

Research Products

The project has stimulated important research activities, which were aimed to the evaluation of ground shaking scenarios and seismic hazard maps in the selected areas. The main products of these activities are:

1. Interpreted seismic profiles (from exploration seismology) re-processed with modern methodologies.
2. A 3-D crustal model for the Colfiorito Area and its reduction to 1-D models useful to model seismic wave propagation and earthquake ruptures.
3. Seismograms and earthquake locations for the Città di Castello area obtained with the field experiment performed within this project.
4. Site transfer functions for Città di Castello.
5. Attenuation laws of peak ground motions calibrated for Città di Castello and Colfiorito and obtained from digital seismograms with an innovative methodology.
6. Indications and results from the methodological comparison among the different numerical procedures used to predict the ground motion time series.
7. Ground shaking scenarios for the Colfiorito area and comparison with existing data.
8. Site transfer function for the recording sites in the Colfiorito area.
9. Seismic hazard maps for the Umbria Region.

Conclusions

During the second year of activity all the expected and principal goals included in the executive plan were achieved. Some of the investigations require to be completed during the last year of activity. Data collection, analysis and interpretation for the Colfiorito area are completed. Ground shaking scenarios and seismic hazard maps were computed, although further investigations will be performed during the third year. It is now necessary to summarize in a synoptic framework the results of all the different activities focused on the Colfiorito training site. Further efforts are required to obtain a synthesis of all these activities. These results will provide useful indications to take the decisions needed to calculate ground shaking scenarios in the test areas. These will be performed during the third year of activity. The achieved knowledge allows an immediate application to the Città di Castello area, while further studies are necessary for the Val D'Agri. The reduced availability of data ad information for this zone demands new investigations to compute ground shaking scenarios and seismic hazard maps.

The state of the knowledge in the Colfiorito training site allows the evaluation of a three-dimensional model for the whole area, which will be used to calculate synthetic seismograms aimed to the proposition of ground shaking scenarios that include a detailed modelling of seismic wave propagation. This goal was not explicitly included in the executive project, but is nowadays achievable.
An important success has been realized with the field experiment and the acquisition campaign performed in Città di Castello during the first year, which has been economically supported by this project for 75% of the total costs. The recorded data allow us to obtain new information either on the geometry of the active fault systems or on the crustal structure and the Città di Castello basin. These data allowed the evaluation of attenuation laws of peak ground motions calibrated for this area, which will promote detailed investigations on the local site response useful to compute reliable ground shaking scenarios.
The results of this project have been achieved with a good interaction among the different research units contributing to the different tasks.