



Progetto S3 – Scenari di scuotimento in aree di interesse prioritario e/o strategico

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TASK 1 – SCENARI - DELIVERABLES D2 INNOVATIVE APPROACHES TO PREDIC SEISMIC GROUND MOTION

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1. INTRODUCTION

In this report four different approaches to compute seismic shaking scenarios are described.

The first one (Chapter 2) is the hybrid simulation technique, called HIC, obtained combining two main techniques used in the strong ground motion modeling, namely the integral and composite approaches. This technique generate broad band synthetic seismograms, employing the representation theorem to compute the low frequency component and the composite approach, based on the summation of ground motion contributions from the subsources treated as individual point sources, to compute the high frequencies component.

In the frame of the S3 project, the shaking scenarios generated by HIC technique are classified at level 2, in comparison with the shaking scenarios at level 0 and level 1 obtained by simplified approaches (*PS3-Deliverable D1*). It has been adopted in the Task 3 (Molise), Task 5 (Potenza) and Task 6 (Gubbio) to compute the ground motion associated with the occurrence of earthquakes in these areas. Details can be found in the *PS3-Deliverable 7*, *PS3-Deliverable D17* and *PS3-Deliverable D20*, respectively.

The second approach (Chapter 3) is the new integrated probabilistic-deterministic method, proposed by Convertito et al. (2006), with the aim of overcoming some of the limitations of both PSHA and deterministic techniques when applied to a single fault (or fault system) for a scenario-like description of the hazard. In particular, it allows to account for the time variable (in terms, for example, of return period and time of interest) in deterministic scenario studies and for source effects (as, for example, geometry, radiation pattern, and directivity) in the PSHA approach. In the frame of the S3 project, the approach of Convertito et al. (2006) has been used in the Task 6 (Gubbio) to compute the hazard uniform spectra at three sites (GCT, GBB, and GBP) associated with the occurrence of two earthquakes. Details can be found in the *PS3-Deliverable 20*.

In Chapter 3, an original method to compute shaking scenarios in term of intensity (damage), is presented. Two application cases are discussed (Basilica, 1857 and Molise, 2002) and the comparison between the synthetic scenarios and empirical evidences is shown. The results are not conclusive. Infact, the two scenarios of strong earthquakes were satisfactorily validated; instead, in the case of the two moderate shocks of the San Giuliano complex event, the field observations were not sufficient to test the synthetics.

Finally, in Chapter 4, an application of the ground motion synthesis methodology outlined by Hutchings and Wu (1990) and further developed by Hutchings et al. (1991, 1994) based on empirical Green Function is presented. The event chosen for this test is the 31 October 2001, 10:32, Mw=5.7 Molise Earthquake (Italy).

2. HYBRID SIMULATION TECHNIQUE: HIC

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In this section we explain the hybrid simulation technique obtained combining two main techniques used in the strong ground motion modeling, namely the integral and composite approaches.

In the integral approach (Kostrov and Das, 1988; Spudich and Archuleta, 1987; Brokesova, 1993; Bernard *et al.*, 1996), the source process is described by a relatively simple spatial-temporal distribution of slip function over the fault. Strong ground motions generated by such source model are calculated according to the representation theorem by evaluating the well-known surface representation integral along the fault (e.g., Aki and Richards, 2002). Numerically, the fault is discretized and the representation integral is substituted by a sum, so that the finite extent source is represented as a coherent superposition of point sources distributed regularly along the fault with the spacing small enough to avoid numerical problems in the integral evaluation. It is clear that this procedure could require much numerical effort for high frequencies due to the necessity of dense discretization.

The idea of composite models (Hartzell, 1978; Irikura and Kamae, 1994; Zeng *et al.*, 1994; Frankel, 1991, and 1995; Beresnev and Atkinson, 1997; Burjanek, 2002) is based on assumption that the modeled event can be seen as a discrete sequence of individually-rupturing subevents that are treated in point-source approximation (Brune, 1970). The source time function of each subsource is characterized by its spectral shape, corner frequency, seismic moment, and so on. Contributions of subevents are summed in order to get proper seismic moment and spectral shape of the source function corresponding to the whole fault.

2.1 MOTIVATION

Recently, Gallovic and Burjanek (2007) compared two representative members of the integral and composite sources, namely integral k-squared source modeling technique with k-dependent rise time (Gallovic and Brokesova, 2004; Bernard *et al.*, 1996) and composite model with fractal subevent size distribution (FSSD, Burjanek, 2002), with respect to high-frequency directivity inherent to the methods. PGAs were simulated for a set of virtual receivers distributed radially around epicenter of the 1999 Athens earthquake, which was chosen as a representative for unilateral earthquake. The results were compared with Greek empirical PGA empirical model (Skarlatoudis *et al.*, 2003), especially with the observed scatter. While the composite approach provided variations in PGA by a factor of less than 10, the k-squared model by a factor of about 100. The large scatter in k-squared model was attributed to strong high-frequency directivity effect, not present in the FSSD model (see more detailed explanation in Gallovic and Burjanek, 2007). The PGA empirical models are obtained by regression of data under the assumption of their lognormal distribution. Many PGA empirical models provide the data uncertainty (in terms of standard deviation σ) ranging from about one half to double of the mean value (Si and Midorikawa, 1999; Ambraseys *et al.*, 2005; among many others). Then, assuming $\pm 2\sigma$

scatter in the lognormal data distribution, the maximum total variation corresponds to a factor of about 16.

From this point of view, the scatter provided by the k-squared model seems to be larger than what is suggested by the observations. The standard deviation of empirical ground motion models is considered to represent robust information for calibration and possible rejection of strong motion prediction methods. However, the data set has to be sufficiently large including large number of observations close (< 30 km) to the faults, which is not always satisfied. Nevertheless, there are other studies suggesting weak or no high frequency directivity. For example, Somerville *et al.* (1997) showed on empirical data that the amplification due to directivity vanishes for high-frequency ground motions. Boatwright and Boore (1982) analyzed ground accelerations radiated by the 1980 Livermore valley earthquakes and suggest that the total variation of PGA should not exceed a factor of 10. However, the high-frequency directivity is still under debate since these observations are still questionable and very sporadic.

Gallovic and Burjanek (2007) further showed that the integral k-squared method can be supplemented by a formal high-frequency spectral modification (suggested by Bernard and Herrero, 1994) that eliminates the directivity due to the rupture propagation. The formal nature of the modification comes from unclear physical reasons for small high-frequency directivity. A possible explanation is incoherency at the source as discussed further.

The spectral modification itself needs as an input the angle between station azimuth and direction of rupture propagation, which is not always easy to define (e.g., in the case of non-unilateral propagation). This is a drawback of the spectral modification, which limits its applicability.

To conclude, the composite FSSD model provides the PGA scatter in agreement with uncertainty of attenuation relations. Since PGA is mainly affected by high-frequency spectral content, we presume that the composite model represents a suitable description of the rupture process for high frequency radiation. On the other hand, the composite approach is supplemented by a spectral correction at low frequencies in order to fit the seismic moment. From this point of view, the kinematic description is more suitable for low-frequency calculation (see further). This stimulates to introduce a hybrid model that would combine the integral a composite source representations.

2.2 THEORY

In a recent paper, Gallovic and Brokesova (2007) propose a new, hybrid, kinematic finite-extent source model. It is applicable for both large and small scales, combining both integral and composite source descriptions. The faulting process is decomposed into slipping on individual, formal, overlapping subsources of various sizes, distributed randomly along the fault. The properties of the subsources are such that they provide k-squared slip distribution, similarly to the integral model explained above. Although such a decomposition is inherent to the composite approaches, in the proposed hybrid model the same set of subsources is used both in the integral (low-frequency) and composite (high-frequency) calculations. More specifically, at low frequencies one employs the representation theorem assuming the k-squared

slip distribution (obtained by composing subsources slip contributions) and, at high frequencies, the composite approach, based on the summation of ground motion contributions from the subsources treated as individual point sources, is used. In the cross-over frequency range we apply weighted averaging of the real and imaginary parts of the integral and composite parts of the spectrum.

Note that in the paper by Gallovic and Brokesova (2007) the hybrid combination is not treated as a technical problem only but it also includes discussion about faulting mechanism that could underlay such a hybrid model. The source is assumed to behave as follows (see also Figure 2.1 that provides an intuitive idea of the source behavior):

- At large scales, the subsources (of all dimensions) act so that the slipping is equivalent to the integral k-squared model discussed above. Final slip at a point on the fault is given by the sum of slip contributions from individual subsources overlaying the point and the generated wave field is then the same as it would be in the integral k-squared model where the contributions from different source points along the fault sum coherently.
- At small scales, the subsources behavior is assumed to be chaotic, that means that the subsources are assumed to radiate, effectively, isotropic high-frequency wave field. In this way, the subsources act as individual point subevents and they are equivalent to randomly distributed point sources (as in the composite approach). Note that, due to the random subsources positions, their wave field contributions sum incoherently.

Finally, the cross-over filtering can be seen to simulate smooth transition between deterministic and chaotic style of faulting.

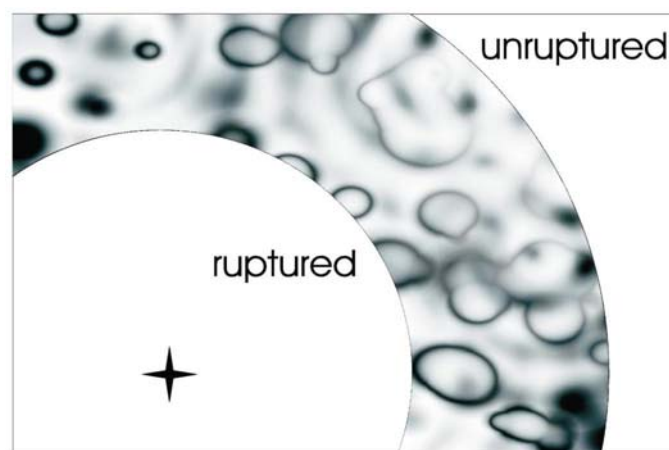


Figure 2.1 – An illustrative picture of the hybrid source model. It corresponds to a snapshot of the slip velocity (the more dark the color, the larger the slip velocity). The star indicates a nucleation point. Note that the small-scale chaotic rupturing takes place within the deterministic large-scale slip pulse. (From Gallovic and Brokesova, 2007).

2.2.1 Source model numerical realization

In the hybrid model presented, the faulting process is decomposed into slipping on individual, formal, overlapping subsources of various sizes, distributed randomly along the fault. Similar decomposition is inherent to the composite approaches (see,

e.g., Hartzell, 1978; Irikura and Kamae, 1994; Zeng *et al.*; 1994, Frankel, 1995, Beresnev and Atkinson, 1997). However, in our hybrid model the same set of subsources is used even in the integral calculations. The specific computational realization of the set of subsources is different in various papers (rectangular, circular, overlapping, non-overlapping, etc.). These features follow also from the scaling law adopted. In our hybrid k-squared source model, the assumption of the k-squared slip distribution on the fault is essential, implying relation between the subsources' mean slips and their number-size distribution. Andrews (1980) has shown that subsources with number-size distribution described by a power law with fractal dimension $D = 2$ and with mean slips proportional to their dimensions (so-called constant stress-drop scaling) compose desired k-squared slip distribution. Note that the same scaling properties of the subsources are assumed by Zeng *et al.* (1994), however, the authors of that paper do not take the advantage of this property. Concerning the numerical implementation, we first build a subsource database, which includes the subsources' positions on the fault, their dimensions, mean slips (and consequently seismic moments) and corner frequencies. Subsource dimensions are taken as integer fractions of the fault's length L and width W , i.e. the subsource length is $l = L/n$ and its width is $w = W/n$. Let us call the integer n the *subsource level*. The number of all the subsources at levels $\leq n$ (i.e. of size $L/n \times W/n$ and larger) is considered to be n^2 . More specifically, the number of subsources $N(n)$ at level n is $N(n) = n^2 - (n-1)^2 = 2n - 1$. At each level the subsources are assumed to be identical in dimensions, mean slip and corner frequency, and their position is random (and, therefore, subjected to variations). The parameters of the subsources in the database are developed in the following way:

- The positions of the subsources are assigned generally randomly (the subsources may overlap) unless constraints, if any, apply. For example, the evidence of clear asperity in the slip inversion result may constrain the positions of the lowest-level subsources to be fixed.
- The mean slip for the subsources at level n is given by $\Delta u_n = c_u/n$ (obtained from the constant stress-drop assumption). In this way, the average slip is proportional to the subsource dimension. The constant of proportionality c_u , assumed to be independent of n , is obtained by matching the seismic moment of the whole earthquake to the sum of the moments of all the subsources at levels from n_{min} to n_{max} .
- The corner frequencies f_n^c of the subsources at level n are considered to be inversely proportional to the subsource dimension (and, consequently, the subsource duration), i.e., $f_n^c = c_f/n$. The reciprocal of c_f , considered independent of n , is comparable to the duration of the whole earthquake. There are several ways of constraining the value of c_f . It can be found, for example, by comparing the synthetic PGAs with the local attenuation relations since f_n^c controls the high-frequency spectral level of the synthetics.
- To simulate that any subsource is again composed of subsources, we prescribe k-squared slip distribution for each individual subsource.

An example of distribution of the subsources is shown in the Figure 2.2 (top part).

As regards the subsource radiation, we assume that the subsources contribute differently to the wave field in different spatial wavelengths (or, alternatively, at

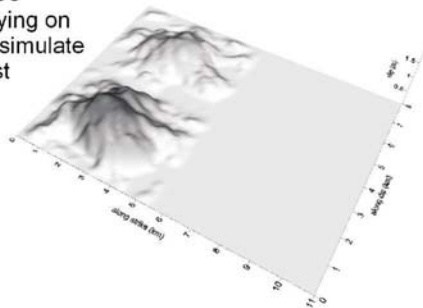
different frequency bands). Let us assume two bounding frequencies f_1, f_2 , with $f_1 < f_2$. For frequencies up to f_2 we use the integral approach and for frequencies larger than f_1 the composite approach.

At large scales (frequencies up to f_2), the subsources (of all dimensions) act so that the fault motion is equivalent to the integral k-squared model discussed above. Final slip at a point on the fault is given by the sum of slip contributions from individual subsources overlaying the point.

Level 2, $l = L / 2$

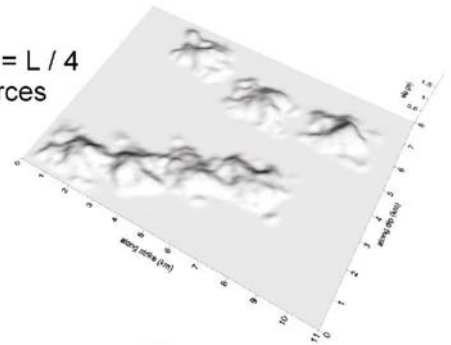
3 subsources

(two of them lying on each other to simulate a high-contrast asperity)



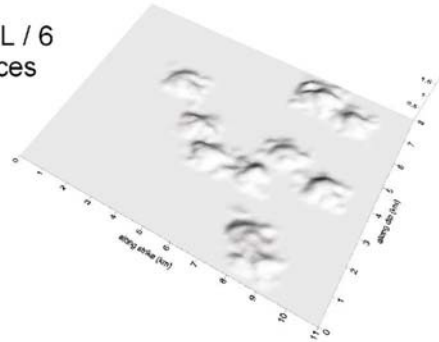
Level 4, $l = L / 4$

7 subsources



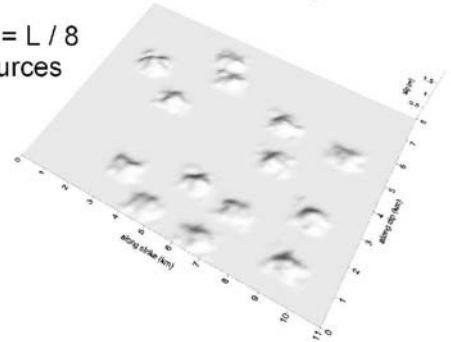
Level 6, $l = L / 6$

11 subsources



Level 8, $l = L / 8$

15 subsources



Total slip
63 subsources
(levels 2 - 8)

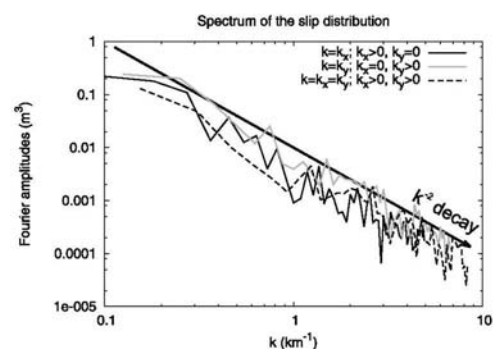
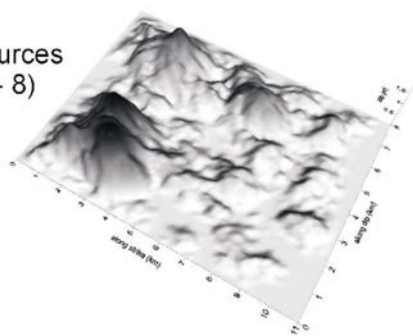


Figure 2.2 – An illustration of the subsurface database. Top panels show examples of four selected levels. The subsources create a slip distribution (sum of all seven levels 2–8), which is shown at the bottom left. Three cross-sections of its spatial amplitude Fourier spectrum are shown at the bottom right. The bold solid line indicates the k -squared decay. Note that level $n = 1$ is neglected. It would correspond to a slip patch over the whole fault, which is, however, not observed in slip inversions of medium-to-large sized earthquakes. (From Gallovic and Brokesova, 2007).

The subsources compose rupture propagating at constant velocity over the whole fault and the slip increases with a given (k -dependent) rise time, so that the rupture process is concentrated in the slip pulse of constant width propagating at constant rupture velocity v_r along the fault. The generated wave field is then the same as it would be in the integral k -squared model where the contributions from different source points along the fault sum coherently. In this way, the representation theorem (Aki and Richards, 2002) is used to compute at position $\mathbf{r}$ the i^{th} component of ground displacement u_i ,

$$u_i = \iint_{\Sigma} G_{ip,q}(\mathbf{r}, t, \xi) * m_{pq}(t, \xi) d\Sigma(\xi)$$

with

$$m_{pq}(t, \xi) = \mu(v_p \Delta u_q(t, \xi) + v_q \Delta u_p(t, \xi))$$

Here the rupture is described by pure shear dislocation $\Delta \mathbf{u}(t, \xi)$ along fault Σ with normal $\mathbf{v}$ (t and ξ being the time and the position along the fault, respectively). Quantities $\mathbf{G}$ and $\mathbf{m}$ are the Green's tensor and the moment tensor density, respectively. The comma in the suffix indicates the spatial partial derivative with respect to ξ (i.e., $G_{ip,q} = \partial G_{ip}/\partial \xi_q$) and symbol $*$ denotes time convolution. Numerically, we discretize the fault densely enough to evaluate the integral correctly up to frequency f_2 . The slip at a point is given by the sum of the slips of all the subsources from the database that contain the point (assuming a k -squared slip distribution at each individual subsurface). An example of the slip distribution constructed in this way is shown in the Figure 2.2 (bottom part). The rupture time is given by the distance of the point from the nucleation point assuming a constant rupture velocity v_r . The slip velocity function is assumed to be Brune's pulse with a constant rise time. At small scales (frequencies above f_1), the approach is different because the behavior of subsources is assumed to be chaotic. The rupture process is likely too complicated to be describable by a relatively simple spatial-temporal distribution of slip function Δu (e.g., by the use of a single distinguished rupture front). An intuitive notion of such a source behavior at small scales can be gained from the snapshot illustrating the slip velocity field in the Figure 2.1. Instead of attempting to simulate the particular subsurface behavior, which may be rather complex, we assume that the radiated high-frequency wave field $u_s^{HF}(\mathbf{r}, t)$ of a given subsurface s can be effectively approximated by

$$u_s^{HF}(\mathbf{r}, t) = C(\mathbf{r}, t, \xi_s) \Omega_s(t)$$

with

$$\Omega_s(t) = \int_{\Sigma_s} \Delta u_s(t, \xi) d\xi$$

Here C comprises the propagation effects and radiation pattern, ξ_s denotes a given point in the subsurface (usually its center) and Σ_s is the subsurface's surface. We call $\Omega_s(t)$ the source time function. Slip rate function Δu_s describes the partial evolution of the rupture on the given subsurface. Being presumably complex and disorganized, evolving chaotically in all directions, we can assume that, effectively, the radiation of the high-frequency wave field is isotropic and that its origin is point ξ_s on the subsurface. Thus, the resulting source time function of the individual subsurface is independent of the receiver position and, consequently, the directivity effect vanishes. In this way, the subsources act as individual point subevents and they are equivalent to randomly distributed point sources (as in the composite approach).

Note that due to the random subsource position, the subsources' wave field contributions sum incoherently. In the composite part of the hybrid model we prescribe directly $\Omega_n(t)$, characterized by seismic moment m_n and corner frequency f_n^c of a given subsource's level n (both of them being taken from the database). More specifically, we assume Brune's source time function, which in the spectral domain reads

$$\Omega_n(f) = m_n (1 + i f / f_n^c)^{-2}$$

where the symbol i represents the imaginary unit. The rupture time is given by the time the rupture needs to reach the subsource's center (assuming the same constant velocity v_r as for the integral approach). Due to the random subsource positions, the wavefield contributions sum incoherently.

In order to simulate smooth transition between the deterministic and chaotic style of faulting, we combine the computed synthetics in the Fourier domain in the crossover frequency range between frequencies f_1 and f_2 , as illustrated in Fig. 2.3. For both the real and imaginary parts of the spectrum, we apply weighted averaging by using the $\sin^2(x)$ and $\cos^2(x)$ weighting functions, where $x = (\pi/2)((f - f_1)/(f_2 - f_1))$ (see also Mai and Beroza, 2003). Frequencies f_1 and f_2 are in fact free parameters. Typically, these bounding frequencies are chosen $f_1 = 0.5\text{Hz}$ and $f_2 = 2.0\text{Hz}$. This frequency interval covers the limiting frequency often used in present slip inversions from local data (about 1 Hz), where the integral approach is employed.

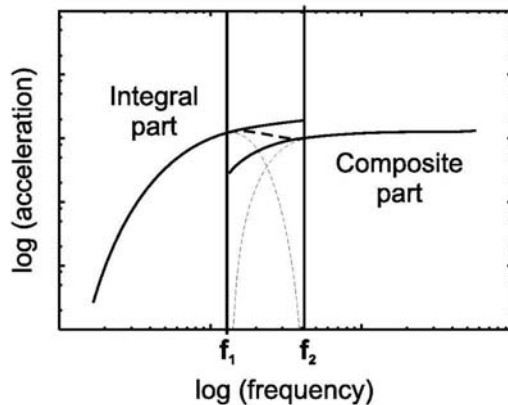


Figure 2.3 – A schematic picture of the hybrid combination of the integral and composite synthetics in the frequency domain. Weighted summation of the synthetics is applied in the cross-over frequency zone (between bounding frequencies f_1 and f_2) to simulate smooth transition between the deterministic and chaotic style of faulting. The weighting functions are $\sin^2$ and $\cos^2$. (From Gallovic and Brokesova, 2007).

2.2.2 Green's functions

The introduced source model can be combined with any method providing Green's function. We use usually either the ray theory (more precisely direct S-waves only) or the discrete wave-numbers method (Bouchon, 1981).

2.3 APPLICATION CASE

The paper by Gallovic and Brokesova (2007) includes also two applications on numerical examples. In the first one, the hybrid model is applied to the 1999 Athens earthquake and it is shown that it predicts directivity in correspondence with

observation (ground motion empirical models) in terms of PGA scatter (on the contrary to the pure integral k-squared source model). The asperities in the slip distribution (location of the largest subsources) are constrained by the result of slip inversion by Roumelioti *et al.* (2003). The inverted slip model is characterized by two asperities (stronger and weaker). Both of them are located to the east from the hypocenter, the stronger one being situated down-dip from the hypocenter while the weaker one up-dip. In this way, the directivity effect shifts highest PGA values to the east of the epicenter. This holds for both the purely integral k-squared and the hybrid techniques because the composite (high-frequency) part of the hybrid simulation modifies mainly the synthetics in the direction opposite to the rupture propagation.

As a second example, the hybrid model is applied to the 1997 Kagoshima earthquake. Basic properties of the adopted source and structural models are set according to Horikawa (2001). Simulated peak values (PGA and PGV) are compared to the observed ones. The agreement is satisfactory at most of the considered stations. The discrepancies could be addressed to significant site-effects not included in the modeling. At stations, which are not affected by strong site effects, the model relatively well reproduces the complexity of measured waveforms in terms of envelope, duration, polarity, spectral amplitudes, their decay, etc.

To summarize, the hybrid combination of the integral and composite approaches is numerically efficient, keeping advantages of both the approaches while minimizing their problems. Contrary to the integral k-squared approach, the chaotic small-scale behavior is involved in the hybrid model (resulting in more realistic directivity effect). In contrast to the composite approach, the hybrid model is better constrained for low-frequency calculation, e.g., for slip inversions, because, for example, no artificial low-frequency filtering is necessary.

In the frame of the S3 project, the HIC technique has been used in the Task 3 (Molise), Task 5 (Potenza) and Task 6 (Gubbio) to compute the ground motion associated with the occurrence of earthquakes in these areas. Details can be found in the Deliverable 7, Deliverable D17 and Deliverable D20, respectively.

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3. PROBABILISTIC-DETERMINISTIC APPROACH TO THE SEISMIC HAZARD ASSESSMENT

UR10 - A.Emolo, A.Zollo, and V.Convertito

The probabilistic seismic hazard analysis (PSHA), introduced by Cornell (1968), is one of the most used technique for evaluating the threat of seismic events in earthquake-prone areas. It finds large application in regions where information about seismogenic structures are poor or not available and then deterministic approaches cannot be used. The results of PSHA are usually provided as hazard curves for a given site. These curves represent the values of a selected ground motion parameter having a fixed probability of exceedance in a specific period (e.g., PGA having 10% probability of exceedance in 475 years). Each value accounts the integrated effect of all the earthquakes of different size that occur in different seismic zones with a different probability of occurrence. In the PSHA the effect of an earthquake occurring at a given distance from the site of interest is represented by the amplitude reached by the selected ground motion parameter. In general this is done by using ground motion empirical models (GMEM). When a single causative fault (and an associated maximum credible earthquake) is considered as the threat for the site of interest, the application of PSHA is not obvious. In particular, problems could arise from the formulation of a recurrence relationship and the computation of the activity rate, especially for large-magnitude earthquakes, for which the catalogs are in general not complete. Moreover, because their empirical nature, GMEMs provide ground motion parameters estimates and related uncertainties that account only partially for the characteristics of earthquake source processes and seismic waves propagation. This is of main concern for those sites located in the near fault distances range where the effect of source heterogeneity could be responsible of the complexity of high frequency ground motion records.

On the other hand, the use of a purely deterministic technique for simulating the effect of a seismic event occurring on a given causative fault does not account for earthquake recurrence, thus providing a sort of “static” scenario that is a little use for probabilistic hazard evaluation.

In a recent work, Convertito et al. (2006) have proposed a new integrated probabilistic-deterministic method aimed at overcoming some of the limitations of both PSHA and deterministic techniques when applied to a single fault (or fault system) for a scenario-like description of the hazard. In particular, it allows to account for the time variable (in terms, for example, of return period and time of interest) in deterministic scenario studies and for source effects (as, for example, geometry, radiation pattern, and directivity) in the PSHA approach.

3.1 THEORY

The computation of a hazard curve requires the evaluation of the hazard integral (Cornell, 1968):

$$E_i(A \geq A_0) = \alpha_i \int_R \int_M f_R(r) f_M(m) p_a[A(m,r) \geq A_0 | m, r] dm dr \quad (1)$$

The quantity $E_i(A \geq A_0)$ represents the frequency of exceedance of a given threshold

value A_0 of the ground motion parameter A . Once the geometry of source and a range of magnitude of interest have been fixed, the probability density functions (PDFs) in equation (1) can be defined. In particular, $f_R(r)dr$ represents the probability of occurrence of a given earthquake at a distance from the site of interest in the interval $(r, r+dr)$. In general, the PDF f_R has no analytical formulation except for some simple geometries as a point or a line. The PDF f_M describes the probability of occurrence of each earthquake having a magnitude in the range of interest. When the Gutenberg-Richter recurrence relationship is used to characterize the occurrence of earthquakes, the f_M PDF is a truncated exponential (Figure 3.1). The probability p_a in the equation (1) represents the probability of exceedance of a given threshold value A_0 for the ground motion parameter A , for a given magnitude m and a given distance r . The probability p_a is computed from the GMEMs, assuming a log-normal distribution for the parameter A . Finally, the coefficient α_i represents the average rate of occurrence of the earthquake for the i -th and it is usually estimated from seismic catalogues.

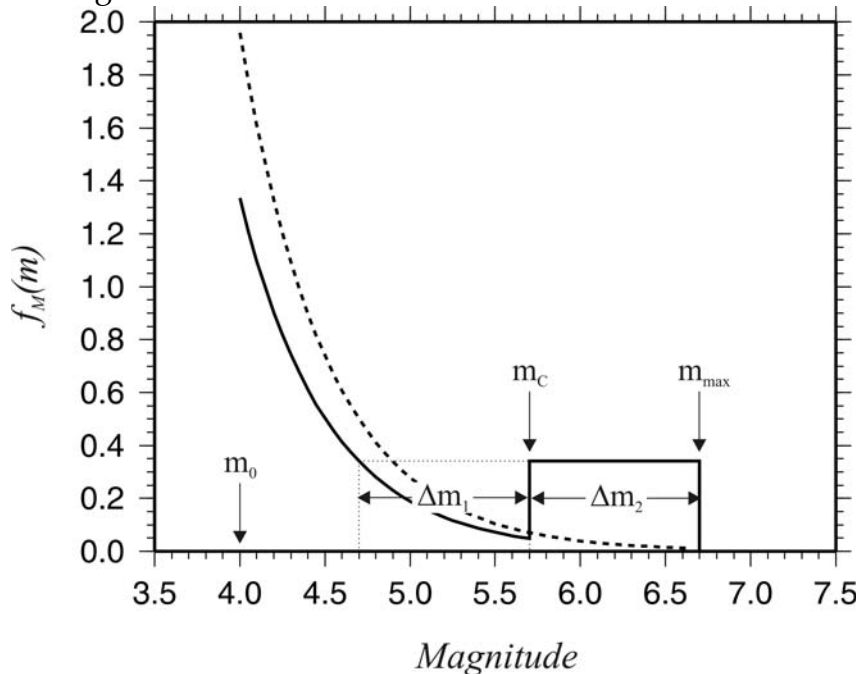


Figure 3.1 – Magnitude PDF for the truncated exponential (dashed line) and for the characteristic earthquake (solid line) earthquake recurrence models. Parameters are described in the text.

Once the frequency of exceedance E has been computed solving the hazard integral in (1), assuming a Poissonian distribution and selecting a time of interest t , the probability of exceedance can be computed by

$$P(A \geq A_0; t) = 1 - e^{-E_i(A \geq A_0)t} \quad (2)$$

When a single causative fault and the occurrence of a given magnitude earthquake are considered for a scenario-like analysis, the equation (1) needs some modifications. In fact, it is not obvious what is the best formulation for the PDFs $f_R(r)$ and $f_M(m)$ and how to compute the parameter α_i . For the definition of distance, the best choice in the case of a single fault, is the minimum horizontal distance to the surface projection of the fault plane (Joyner and Boore, 1981), considering known the fault geometry and assuming that the rupture process involves the whole fault. If this distance definition is chosen, the site-to-source distance becomes fixed and the

integral on R disappears from equation (1). Concerning the $f_M(m)$ PDF, it can be computed if the characteristic earthquake model is assumed. This choice is reasonable for moderate-to-large magnitude seismic events (Schwartz and Coppersmith, 1984). This model is based on the hypothesis that individual faults tend to generate similar size, or “characteristic”, earthquakes. In any case, the characteristic earthquakes occur on a given fault not at the exclusion of all other magnitude events, but with a frequency distribution different with respect to the exponential one. If the characteristic earthquake model is assumed, the corresponding PDF $f_M(m)$ and the activity rate can be computed following the approach of Youngs and Coppersmith (1985). They demonstrated that the PDF $f_M(m)$ is given by (Figure 3.1):

$$f_M(m) = \begin{cases} 0 & \text{for } m < m_0 \\ \frac{\beta e^{-\beta(m-m_0)}}{1 - e^{-\beta(m_{\max}-m_0-\Delta m_2)}} \frac{1}{1+C} & \text{for } m_0 \leq m \leq m_c = m_{\max} - \Delta m_2 \\ \frac{\beta e^{-\beta(m_{\max}-m_0-\Delta m_1-\Delta m_2)}}{1 - e^{-\beta(m_{\max}-m_0-\Delta m_2)}} \frac{1}{1+C} & \text{for } m_c = m_{\max} - \Delta m_2 \leq m \leq m_{\max} \\ 0 & \text{for } m > m_{\max} \end{cases} \quad (3)$$

where the constant C is given by

$$C = \frac{\beta e^{-\beta(m_{\max}-m_0-\Delta m_1-\Delta m_2)}}{1 - e^{-\beta(m_{\max}-m_0-\Delta m_2)}} \Delta m_2 \quad (4)$$

with $\beta = b \ln 10$ (being b the b -value of the Gutenberg-Richter law), and $m_{\max}$ and m_0 , the maximum and minimum magnitude of interest, respectively. The parameters Δm_1 and Δm_2 represent two interval, respectively, below and above the magnitude m_c which is considered as the characteristic earthquake magnitude. The values suggested by Youngs and Coppersmith (1985) for them are $\Delta m_1 = 1.0$ and $\Delta m_2 = 0.5$. It has to be noted that the characteristic behaviour of $f_M(m)$ refers to earthquakes having magnitude in the range $[m_c, m_{\max}]$. Equation (3) for $m < m_c$ accounts for the non-characteristic part of the PDF $f_M(m)$. Starting from equation (3). Youngs and Coppersmith showed that the seismic activity rate α_C for the characteristic part of $f_M(m)$ is given by

$$\alpha_C = \alpha_{NC} \frac{\beta \Delta m_2 e^{-\beta(m_{\max}-m_0-\Delta m_1-\Delta m_2)}}{1 - e^{-\beta(m_{\max}-m_0-\Delta m_2)}} \quad (5)$$

where

$$\alpha_{NC} = \frac{\mu A_f S' [1 - e^{-\beta(m_{\max}-m_0-\Delta m_2)}]}{K M_0^{\max} e^{-\beta(m_{\max}-m_0-\Delta m_2)}} \quad (6)$$

is the seismic activity rate for the non-characteristic part of the PDF $f_M(m)$. In the (6), μ is the shear modulus, A_f is the total fault area, S' is the average slip-rate along the fault, and $M_0^{\max}$ is the seismic moment evaluated for the maximum magnitude $m^{\max}$ by a relationship like $\log M_0 = cm + d$ relating the magnitude to the seismic moment (e.g., Hanks and Kanamori, 1979, law). The constant K in equation (6) is given by

$$K = \frac{b 10^{-c \Delta m_2}}{c - b} \frac{b e^{\beta \Delta m_1} (1 - 10^{-c \Delta m_2})}{c} \quad (7)$$

On the basis of the previous considerations, the classical hazard integral reported in the equation (1) can be finally written, for the characteristic earthquake model, as

$$E(A \geq A_0) = \alpha_C \int_{m_c}^{m_c + \Delta m_2} f_M(m) p_a[A(m, r^*) \geq A_0 | m, r^*] dm \quad (8)$$

where r^* , for each site of interest, represents the minimum distance from the surface projection of the fault, and α_C is given by equation (5). It is then possible to compute the hazard curves for a given causative fault once the magnitude m_c for the characteristic earthquake has been selected.

At this point, we also need a tool for evaluating the level reached by the strong motion parameter A (e.g., the earthquake effect) and the associated exceedance probability p_a . In their original work, Convertito et al. (2006) estimated the earthquake effects adopting the simulation technique proposed by Zollo et al. (1997) that computes the ground motion associated with the rupture of a given fault solving the representation integral. By this modelling technique, a family of synthetic accelerograms was obtained simulating a large number of rupture scenarios for a given fault plane. Each rupture scenario can be obtained combining different final slip distributions on the fault plane, different positions of the rupture nucleation point and different value for the rupture propagation velocity. Then the ground motion parameters of interest (e.g., PGA) can be retrieved for the synthetics. The large number of simulated seismograms allows histograms to be built for each receiver, representing the frequency distribution of the ground motion parameters values. The families of parameters can then be characterized by a mean value and a standard deviation. Thus, for each site, the probability of exceedance p_a in equation (8) can be finally computed by using the statistical properties of the ground motion parameters.

3.2 APPLICATION CASE

The integrated deterministic-probabilistic technique for seismic hazard assessment was initially applied by Convertito et al. (2006) to the hazard evaluation in the Umbria region assuming as threat a fault having the same geometry and mechanism as the September 26, 1997, Colfiorito earthquake (M_w 6). As example, in Figure 3.2 are reported the hazard maps for PGA in the case of 50,000 years return period. For comparison, the results obtained using two GMEMs (i.e., Sabetta and Pugliese, 1987; Abrahamson and Silva, 1997) for evaluating the PGAs, and two earthquake recurrence models (i.e., exponential and characteristic models) are shown.

In the frame of the S3 project, the approach of Convertito et al. (2006) has been used in the Task 6 (Gubbio) to compute the hazard uniform spectra at three sites (GCT, GBB, and GBP) associated with the occurrence of two earthquakes. Details can be found in the Deliverable 20.

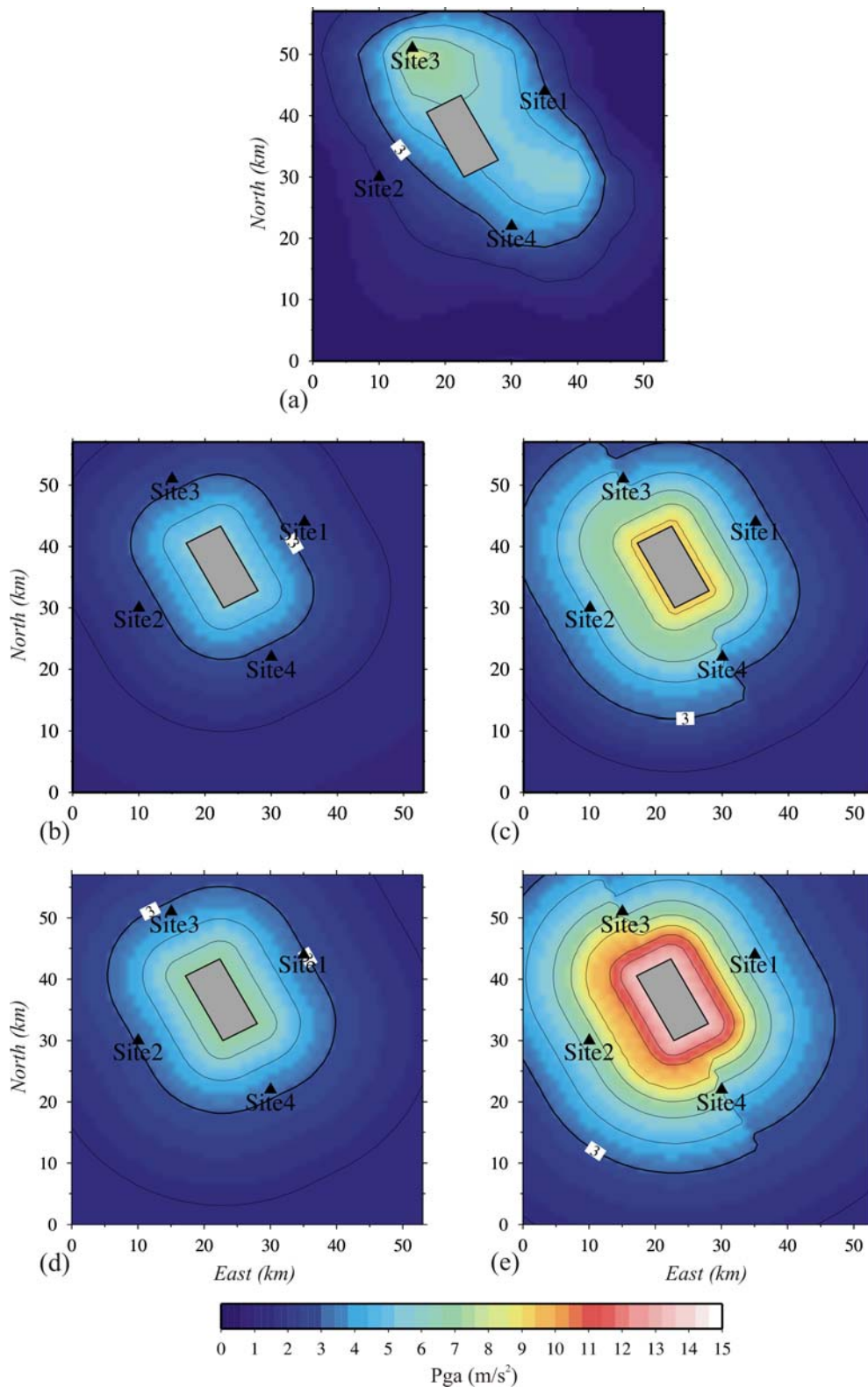


Figure 3.2 – Hazard maps for PGA in the case of 50,000 years return period. The grey box represents the surface fault projection. (a) Results for the characteristic earthquake models and simulated PGA values. (b) Hazard map for the characteristic earthquake model when the Sabella and Pugliese (1987) GMEM is used for estimating PGAs. (c) Hazard map for the characteristic earthquake model when the Abrahamson and Silva (1997) GMEM is used for estimating PGAs. (d) Hazard map for the exponential earthquake model when the Sabella and Pugliese (1987) GMEM is used for estimating PGAs. (e) Hazard map for the exponential earthquake model when the Abrahamson and Silva (1997) GMEM is used for estimating PGAs.

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4. INTENSITY SCENARIOS

UR3 – L. Sirovich –F. Pettenati

The term “scenario” is widely used, and perhaps even abused; in the sense that the users often forget to make strict reference to empirical evidence for validating the results of their modelling attempts. In other words, in our opinion, one should validate his technique – whenever this is possible – by reproducing the regional effects of well known earthquakes of the past.

Then, it is often proposed to use predictive scenarios in real time, or semi-real time, after destructive earthquakes, for civil protection purposes. In this specific case, the scenario producers should pay attention not to ill-pose the matter, that is to say not to generate the expectation that the Civil protection could directly use a theoretical scenario to send urgent aids after a catastrophe. In our opinion, this holds even if the scenario in question is continuously updated by instrumental rapid response arrays; because it will never become so realistic as to overgo direct alarm calls, for example in case of collapse of structures where urgent rescue is needed. We think that planning (and training of personnel) is the principal field of application of scenarios.

Coming to the results presented here in, our research unit used an original technique to calculate parametric scenarios of damage (intensity). In the S3 project, we produced three synthetic scenarios; here, we show two of them and compare them with the empirical evidence which is available for three earthquakes (the San Giuliano, 2002 event included). It is worth noting that the two scenarios of strong earthquakes were satisfactorily validated; instead, in the case of the two shocks of medium size of the San Giuliano complex event, the field observations were not sufficient to test our synthetics conclusively.

4.1 THEORY

The premise of our work on intensity scenarios is the validation of the intensity-based source inversions of five earthquakes with our new “KF” technique: the M_L 5.9 Whittier Narrows, 1987 earthquake in the Greater Los Angeles Region (*B.S.S.A.*, 93, pp. 47-60; *B.S.S.A.*, 94, pp. 1737-1747), the M 5.8-6.2 Cansiglio, 1936 earthquake in NE Italy (*J.G.R.*, 109, 2003JB002919, 2004), and three more destructive events in California (*Pettenati and Sirovich*, 2007, *B.S.S.A. Volume 97-5*, in press). Recently, we used our kinematic “KF” approach in the direct mode to produce two seismic hazard scenarios in California (for the Northridge, 1994, and the Loma Prieta, 1989, earthquakes). The “KF” was used in a parametric, deterministic-Montecarlo, way. The Montecarlo technique was applied to eleven source parameters of the “KF” formula. In so doing, we obtained several tenths of thousands of sources to calculate each scenario, allowing us to take into account the variabilities of the sources within the considered seismotectonic settings. In particular, our scenario sources included all sources that were found from instrumental measurements, independently from our work. The validation of our scenarios was performed by quantitatively comparing our intensity scenarios with the site intensities observed by the U. S. Geological Survey in the field. Then, we also produced the traditional scenarios obtained by the widely used attenuation of intensity with distance, and made a quantitative comparison with our

KF scenarios; this was done by computing the intensity residuals at the surveyed sites. Our scenario was slightly better than the traditional one for the Northridge earthquake; on the other hand, there is a significant improvement for the Loma Prieta, 1989 event. This is due to the compact shape and the up-dip directivity of the former source, as well as to the extended shape and horizontal directivity of the latter one. Regarding this, we recall that our simplified model is able to simulate only the horizontal directivity (to avoid overparametrization when treating the pre-instrumental earthquakes). In particular, to obtain the pre-1989 scenario for Loma Prieta, we considered only the sources that were hypothesized before 1988 by various authors. Given the geologic and seismotectonic knowledge of the time, if our technique had been available, the 1989 pattern of damage south of San Francisco would have been cautiously foreseen even from 1983. The proof of this is in the comparison contained in Fig. 4.1; here, on the left, you see the intensities observed in the field by the US Geological Survey after the 1989 Loma Prieta earthquake. The white star and the white rectangle are the epicentre and the projection of the fault source by Wald et al. (1991). The upper beach ball shows the fault-plane solution of the initial rupture and is by both Oppenheimer (1990) and Choy et al (1990); the lower one shows an example of the almost pure strike-slip mechanism proposed by various authors for the southern part of the fault (the one shown rounds the rake by Beroza, 1991, and Steidl et al., 1991, to 160° - 170° ; also see Wald et al., 1991). On the right of Fig. 4.1, you see our KF intensity parametric scenario (mean intensities, in arabic numbers) obtained by using a family of rupture planes as they could be guessed before 1989. Fig. 4.2 shows the standard deviations (intensity, in real numbers) of the parametric scenario.

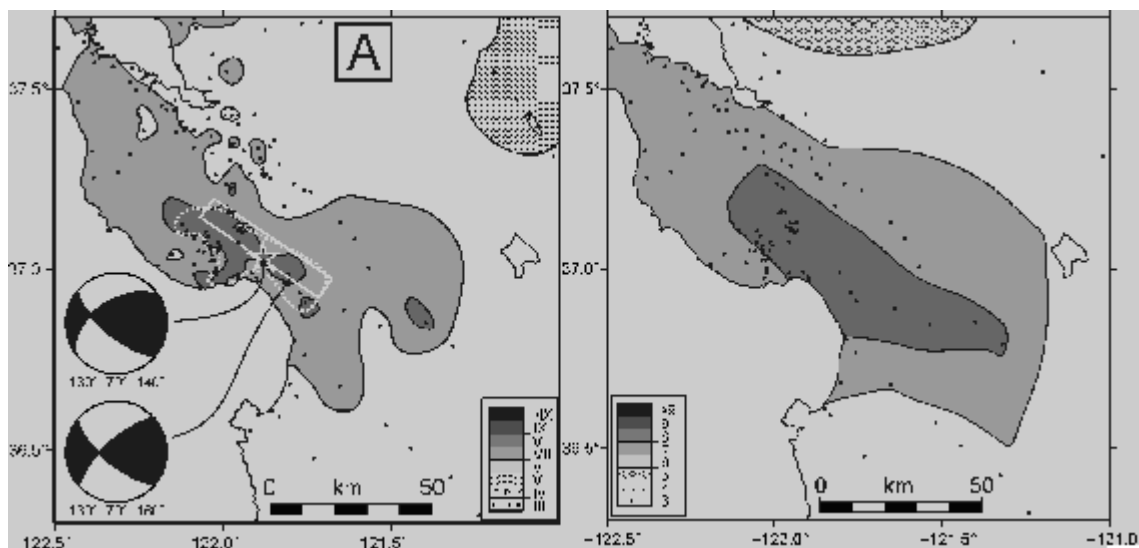


Figure 4.1

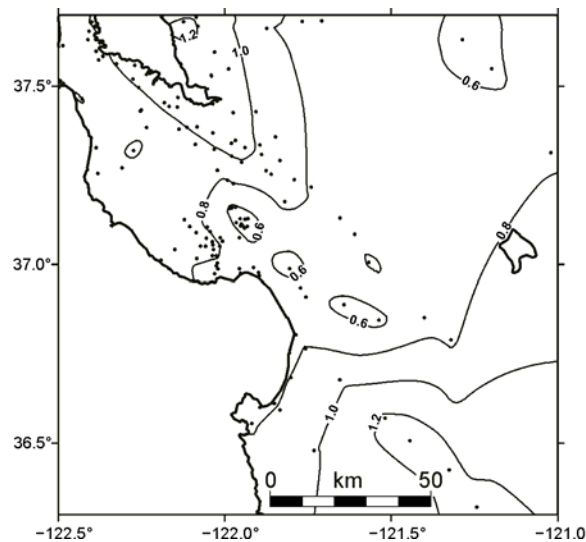


Figure 4.2

4.2 APPLICATION CASE

4.2.1 Reference earthquake: Basilicata 1857 $M=7$

In the first year of activity, we calculated a parametric scenario for the great Basilicata, 1857 earthquake (we assumed for it a central value of $M=7$). Regarding the other central parameters, defining the family of fault sources taken into account, we based on the DISS3 data base (<http://www.ingv.it/DISS>) and on the CPTI04 catalogue (<http://emidius.mi.ingv.it/CPTI/home.html>). The family of fault sources is defined by the central values and incremental variations reflecting the degree of uncertainty of each parameter. In this case, the source family belongs to the so-called Apenninic sources (with normal mechanisms, striking NW-SE and NE dipping, similarly to that of the Irpinia, 1980 event. Table 4.1 summarizes the used parameters obtained from DISS3 and CPTI04. Note that, in DISS3, GG marks parameters obtained from geologic and geophysical information; MP and MW indicate those from quantitative treatment of non-instrumental seismological data (intensity) in case of so-called historical earthquakes.

Ref./Param.	DISS3(GG)	DISS3(MP)	DISS3(MW)	CPTI04
Latitude N [°]	40.39	40.35		40.35
Longitude E [°]	15.65	15.85		15.833
Focal mechanism	Strike=316°, Dip=60°, Rake=270°		Strike=306°	
Depth [km]	12.7			
Length. [km]	23		49	
Magnitude	6.5	7.0	7.0	7.0

Table 4.1: summary of the parameters available.

Regarding the aforementioned incremental variations, which reflect the degree of uncertainty of each source parameter, we used the ranges and the increments (sampling step) of Table 4.2.

Notwithstanding the apparent simplicity of this parameter structure, its combination gave 50.400 scenario sources, which are however necessary to comprehend, in particular, the large excursion of the suggested magnitudes and longitudes. It is worth mentioning that, for comparison purposes, we calculated the scenario intensities in the 238 sites of the DBMI04 catalogue (they are the sites within a 200x200 km window around the baricentre of the epicentral coordinates (15.85°E, 40.37°N).

The baricentre of the suggested hypocentral depths was 12.7 km, but in this case – provisionally- we adopted an asymmetric range because both the inversion of the intensities of the earthquake of 1857 and the Irpinia scenario discouraged from adopting deep values. Similarly, being no indications on V_s and Mach values available, we assumed the values obtained from the source inversion of the Irpinia 1980 event, that we performed before. Finally, for simplicity and not to increase the sources' number, we did not change the source lengths.

Parametre	Minimum value	Maximum value	increment
Latitude [°] N	40.27	40.47	0.04
Longitude [°] E	15.75	15.95	0.05
Strike [°]	296	321	5
Rake [°]	256	284	7
Dip [°]	44	76	8
Depth [km]	3	12	3
Mach +	0.55 (fixed)	/	/
Mach -	0.50 (fixed)	/	/
V_s [km · s ⁻¹]	3.62 (fixed)	/	/
Length +	24 (fixed)	/	/
Length -	24 (fixed)	/	/
Mo [dine · cm] · 10 ²⁶	1.12	7.12	3

Table 4.2: uncertainties of the source parameters and calculation steps used for the production of a scenario similar to that of the Basilicata, 1857 earthquake.

Figure 4.3 shows the reference isoseismals for the 1857 earthquake, interpolated by means of the N-N algorithm (Sirovich et al., 2002) based on the natural neighbours

principle. We call the reader's attention on the fact that the mentioned figure can be used to validate our scenario because N-N strictly honours the experimental data (our choice was to refer the doubtful degrees – such as V-VI – to the upper value; VI in this case). Fig. 4.4 presents the parametric scenario obtained by using the values of Tabs. 4.1 and 4.2; in the figure we show the mean values of intensity (from 50.400 sources). Fig. 4.5 shows the standard deviations of Fig. 4.4; note that they reach two degrees, mainly toward NW. The mean values of Fig. 4.4 are able to match acceptably the intensities observed in the field, but are not cautious in the epicentral area (where in 1857, in two sites, the XI degree is reported [perhaps exaggerated?]) and toward ENE. In this direction, the experimental isoseismals show a promontory of degree VIII with two sites of IX. Referring to this, let us mention that during an S3 workshop our colleague Riccardo Caputo called our attention on the geological hypothesis of a possible secondary fault source in that area (the Caputo source is not yet included in the family of the parametric sources of Tabs. 4.1-4.2). Finally on this point, if you use the standard deviations of Fig. 4.5, the scenario of Fig. 4.4 become cautious everywhere.

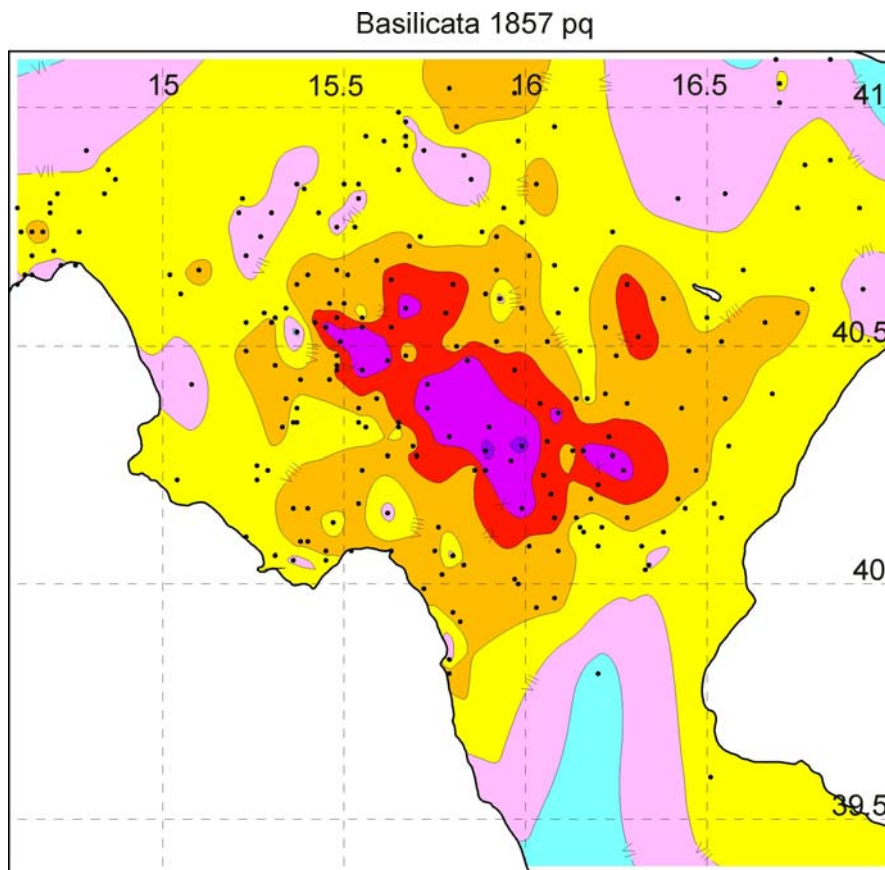
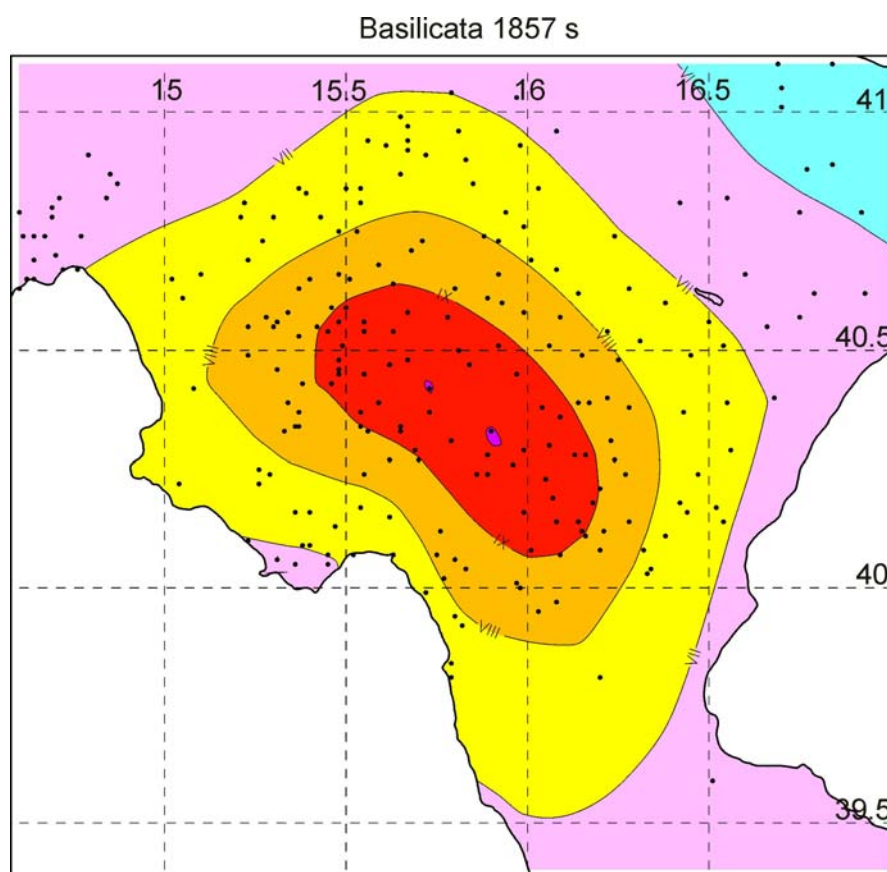
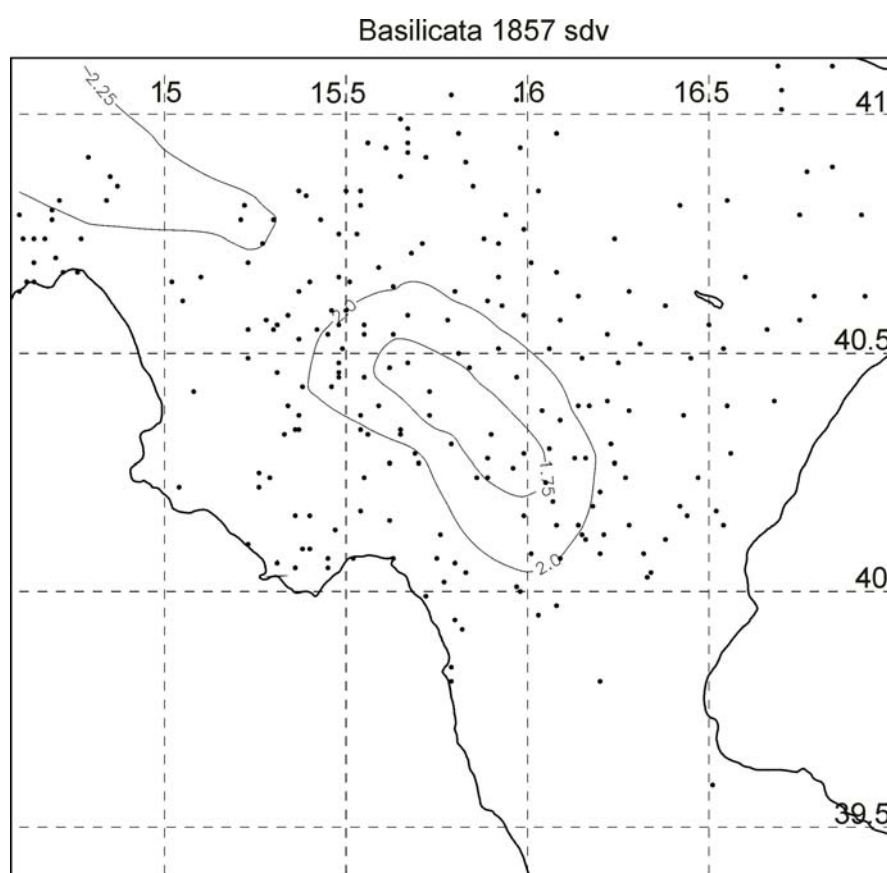


Figure 4.3

**Figure 4.4****Figure 4.5**

4.2.2 Reference earthquake: Molise 2002 $M=5.7$

In the case of the San Giuliano sequence of Oct. 31 and Nov. 1, 2002 we could use two kinds of intensity values: a) 42 intensity values by the QUEST group, plus 10 data which together made the 52-value file called INGVAM (refer to the data base DBMI04); b) more than 1000 data from the Bollettino Macrosismico INGV (file: ott3102a(Boll).dat), these data were collected from volunteers through Internet.

From the beginning, it was clear the data (a) alone were not sufficient to constrain the inversion of the sources; not to mention the problem of site corrections. Fig. 4.6 shows our frustrating attempt to correlate data (a) and (b) in the same sites, to be able to use them together somehow. Due to this unfavourable situation, there is not enough empirical evidence to validate our parametric scenarios of the two earthquakes (mean intensity from about 32.000 sources); see them in Figs. 4.7 e 4.8 respectively (colour key: orange = VIII; light blue = V; red points = sites surveyed by the QUEST group). To calculate our KF parametric scenarios, we used the source information available from the literature, which is summarized in Tab. 4.3 (as always, see the lower and upper bounds and the incremental steps). In this case, the standard deviations of the two scenarios (not shown) are irregularly distributed in spots and reach one degree. Let us stress that the validation of the results was difficult also due to the low territorial sampling, and to the absence of sampling (sites) outside the epicentral area.

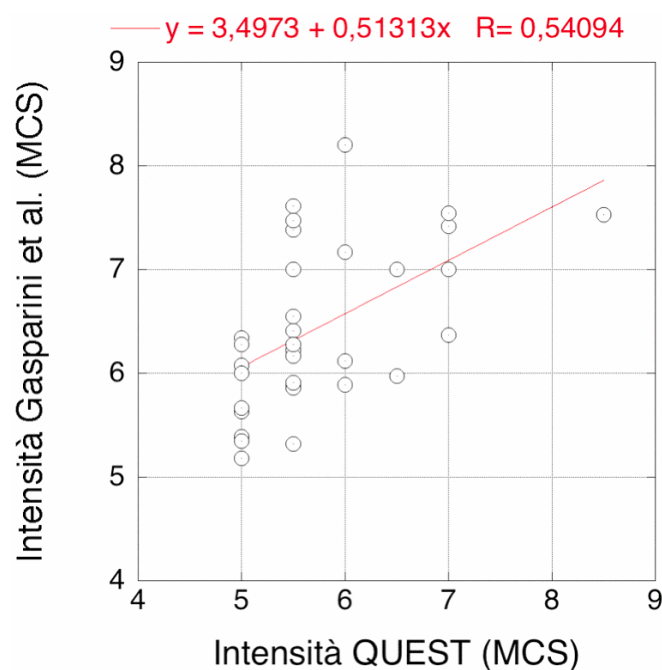


Figure 4.6

Scenario sorgente 31 ottobre 2002			
	Lower bound	Upper bound	step
Longitude [°]	14.89	14.95	0.02
Latitude [°]	41.67	41.71	0.02
Strike [°]	264	279	3
Rake [°]	183	203	5
Dip [°]	82	Fixed	Fixed
Depth [°]	11	19	2
Length + [km]	2	5	3
Length - [km]	2	5	3
Vr [km sec ⁻¹]	2.56	Fixed	Fixed
Vs [km sec ⁻¹]	3.0	3.4	0.2
Mo [dyne cm] · 10 ²⁴	1.42	7.92	2
Scenario sorgente 1 novembre 2002			
	Lower bound	Upper bound	step
Longitude [°]	14.79	14.83	0.02
Latitude [°]	41.68	41.72	0.02
Strike [°]	255	279	6
Rake [°]	182	196	7
Dip [°]	71	86	5
Depth [°]	13	16	1
Length + [km]	2.5	6.5	2
Length - [km]	2.5	6.5	2
Vr [km sec ⁻¹]	2.56	Fixed	Fixed
Vs [km sec ⁻¹]	3.0	3.4	0.2
Mo [dyne cm] · 10 ²⁴	2.42	5.62	1.6

Table 4.3

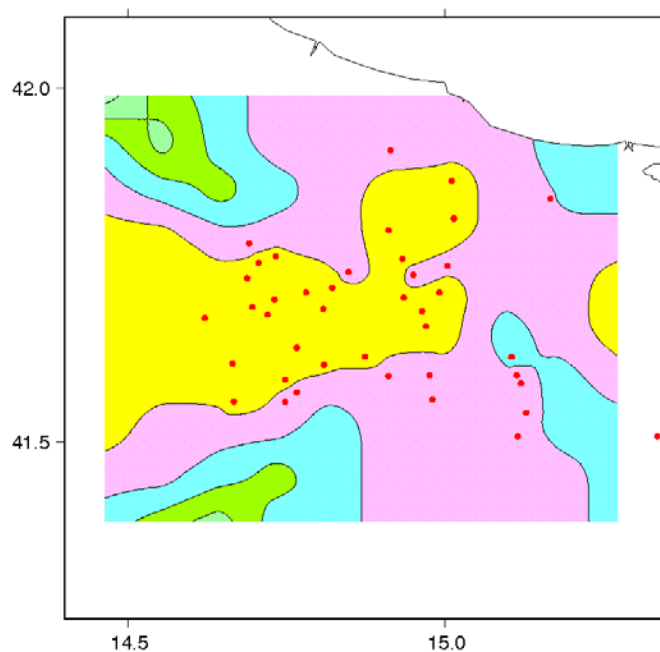


Figure 4.7

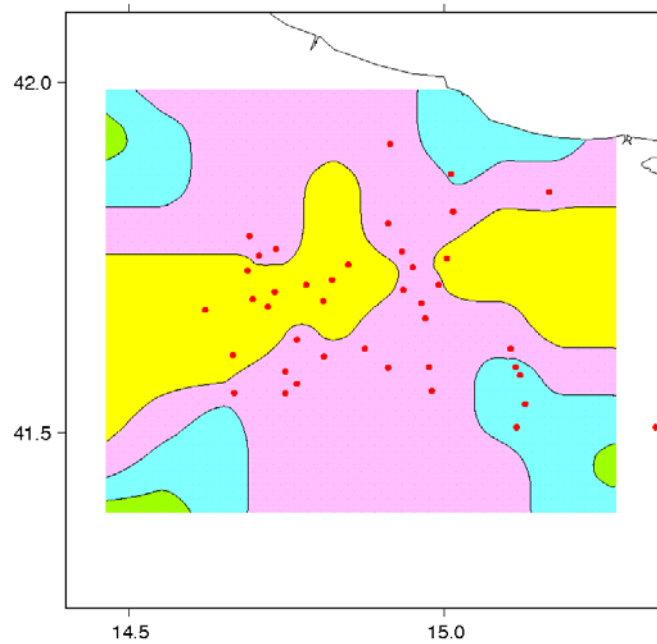


Figure 4.8

4.3 DISCUSSION

UR3 tried to homogenize the 52 macroseismic data by INGVAM, for the two events of Molise in 2002 (see the data base DBMI04), with the data by Bollettino Macrosismico INGV (file: ott3102a(Boll).dat, collected via Internet). This step would have rendered a large data set available for validating our scenarios. Unfortunately, this attempt failed, and the DBMI04 data alone did not allow reliable validations of the events of Oct. 31 and Nov. 1, 2002. Vice versa, the Basilicata 1857 experiment was successful (and also that of Irpinia 1980; let us also refer to the experiments cited in chapter 4.1, Theory). In the light of the present results and of the previous ones, we think that our parametric intensity scenarios, are worth to be tested more for future applications. Our technique could be particularly useful to forecast future scenarios in areas where some hypotheses about the potential fault sources are available.

It is worth mentioning that, in the case of the Loma Prieta, 1989 earthquake, our scenario was much more realistic than a traditional one produced by an isotropic "attenuation" relation of intensity obtained in the same area. Thus, there is hope also for the KF formula substituting in the future the "attenuation" relations in rapid response procedures like ShakeMap, and perhaps also in probabilistic hazard studies.

5. EMPIRICAL GREEN'S FUNCTION SIMULATION METHOD: EMPSYN

UR2 – Laura Scognamiglio

The purpose of this study is to test the ground motion synthesis methodology outlined by Hutchings and Wu (1990) and further developed by Hutchings et al. (1991, 1994), and compare the results obtained with those from other two methodologies tested during this project: HIC and DSM (see Deliverable d7). The event chosen for this test is the 31 October 2001, 10:32, Mw=5.7 Molise Earthquake (Italy). This is the last significant magnitude event to have occurred in Italy.

5.1 THEORY

The prediction methodology involves developing a set of rupture scenarios based upon bounds on rupture parameters and then calculating strong-motion synthetics for each rupture scenario. The bounds on rupture parameters are limited to what is known about the earthquake, its tectonic and geologic environment. Rupture parameters include rupture geometry, hypocenter, rupture roughness, rupture velocity, healing velocity, slip distribution, asperity size and location, and slip vector. These are the free parameters. The fixed parameter is the moment of the earthquake and the Kostrov slip model with healing. Stress drop, slip velocity and rise times are dependent variables derived from the Kostrov slip function with healing as described below. Parameters are varied about a central preferred value with a triangular distribution and selected by a Monte Carlo technique. The resulting rupture models could have variable slip amplitudes that can include multiple areas of high slip and variable stress drop.

The ground motion synthesis approach tested here models large earthquakes by solving the representation relation for a finite earthquake rupture, and it requires very small events that may be assumed as having an effective step-impulsive source time functions (Fortran code EMPSYN, Hutchings and Wu, 1990, and Hutchings, 1991).

A threshold moment exists whereby the recorded seismograms behave as step-impulsive, point, shear dislocation sources, and below that threshold the EGF will satisfy the representation relation and they scale linearly with differences in moment. Hutchings and Wu (1990) showed that the threshold is about 1.5×10^{21} dyne-cm for earthquakes recorded in the San Fernando Valley and a similar value for aftershocks recorded from the Loma Prieta earthquake (Hutchings, 1991), and the Northridge earthquake (Hutchings, 1996).

The earthquake is synthesized by discretizing a potential fault rupture surface into elemental areas small enough to model continuous rupture up to highest frequency of interest, then all available recordings of effectively impulsive point source events are used as empirical Green's functions for each elemental area, convolved with a slip function and interpolated to model a continuous rupture (Figure 5.1).

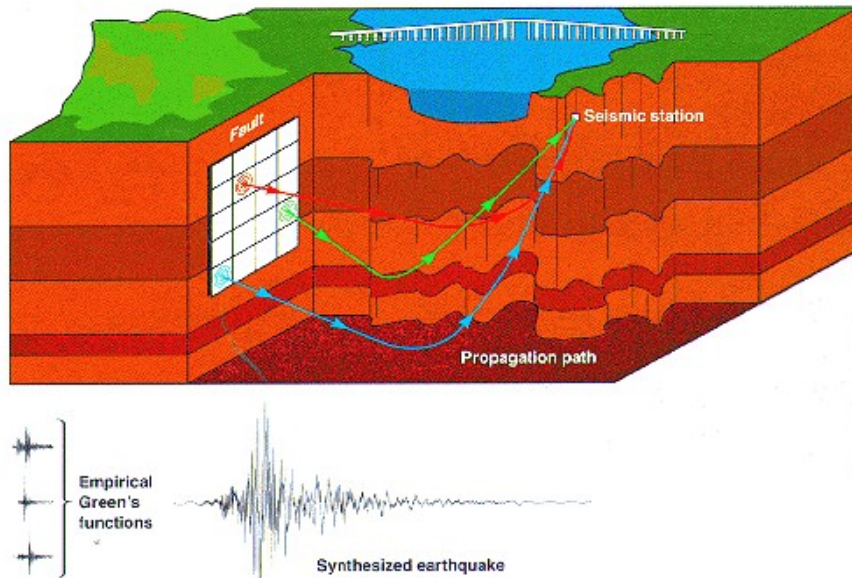


Figure 5.1. Sketch model of empirical Green's functions synthesis approach.

This modeling approach only requires that the number of times small earthquakes are used in the synthesis is such that the sum of their moments add up to the moment of the large earthquake. Therefore, low frequency amplitudes match those of observed seismograms. The high frequency is matched simply by using appropriate rupture parameters (Hutchings, 1994).

If the events used as EGF have moments larger than the threshold identified for a point source earthquake, it is possible to utilize the output of the source parameter study, performed using the Fortran program NetMoment (Hutchings 2002), to deconvolve out the Brune source from the recordings. This extends the methodology originally proposed by Hutchings and Wu to include events larger than those that satisfy the criteria of being effectively impulsive point shear source earthquakes. The deconvolution is with spectra amplitude only so that it is a zero phase shift deconvolution (Hutchings, 2002). It is not possible to record empirical Green's functions from all locations along a fault of interest and with the same focal mechanism solution, so that source locations of empirical Green's functions have also been interpolated to fill in the fault. Interpolation is performed by correcting for attenuation, $1/R$, and P and S-wave arrival times due to differences in source distance

5.2 APPLICATION CASE

The earthquake selected to test the capability of this strong ground motion prediction methodology is the first main-shock of the 2002 Molise seismic sequence. The source parameters of this event are listed in Table 5.1.

Data set selected for this study consists of 25 small events recorded during the Molise seismic sequence by the stations: MNT9, ROT2, CIGN, PEP9. These events have hypocenter reliable to the main event fault and are recorded in the same location where the main shock was (fig. 5.2). The stations were deployed by the INGV "Rete Mobile Group" after the event here analyzed occurred, these means that these stations didn't record the 31/10/2002, 10:40 earthquake.

Fault Parameters	
Time, GMT	021031 10:32
Latitude (degrees)	41.686
Longitude (degrees)	14.907
Depth (km)	19.9
M_0 (N m)	6.048×10^{17}
M_w	5.8
Strike (degrees)	267
Dip (degrees)	82
Rake (degrees)	-157
Length (km)	10.5
Width (km)	8.0
Displacement (m)	0.20
Top of the rupture surface (km)	12.0
Rupture Velocity (km/s)	2.56

Table 5.1. Source parameters of the Molise earthquake, DISS Working Group (2005).

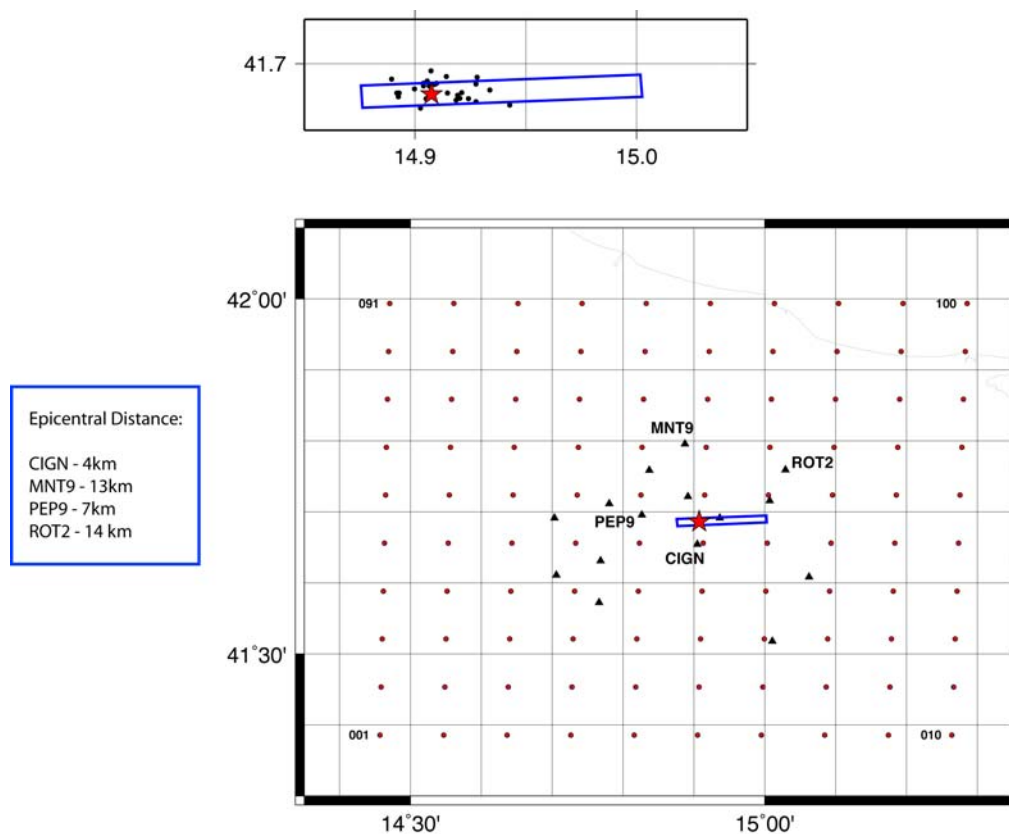


Figure 5.2 Molise Earthquake the fault geometry, stations used, and the EGF epicentral location.

5.2.1 EGF's Seismic Moment, Corner Frequency

Seismic moment, and corner frequency of the events are calculated in a window of 10s following the S-wave arrival time. First, in each 10s window, a signal to noise analysis has been done in order to constrain the frequency range in which to estimate the parameters. For these EGF the range is between 1.0 and 10.0 Hz. Once the frequency range for the analyses was chosen, seismograms were corrected for the instrument response, rotated to radial and transverse components, and vertical and radial were square of sum of squared added to get one S_v spectrum, the S_h spectrum

is from the transverse component. Prior to the inversion, the S_v and S_h components EGF's spectra were corrected for the Fourier amplitude spectra of equation ?? in Aki and Richards (1980), to represent moment at the long period asymptote, and for whole path attenuation. Corrected spectra were fit to the modified Brune (1971) displacement spectral shape in the frequency range showed before. The best fitting combination of free parameters M_0 , and f_c are displayed in Table 5.2. M_w , is obtained using Kanamori equation for moment magnitude (1977).

EGF origin-time	Seismic moment (10^{20} dyne cm)	Corner frequency (Hz)	Mw
021102104809	0.23+/-0.06	4.9+/-2.8	2.2
021102114359	0.15+/-0.08	4.9+/-0.9	2.1
021103014719	0.05+/-0.01	3.1+/-0.4	1.7
021103020419	0.88+/-0.39	3.1+/-0.7	2.6
021103031359	0.87+/-0.55	3.1+/-0.3	2.6
021103035259	0.06+/-0.03	4.0+/-0.3	1.8
021103073019	0.11+/-0.07	5.1+/-0.1	2.0
021103133810	9.55+/-8.42	3.1+/-0.6	3.3
021103154459	0.20+/-0.07	4.0+/-0.4	2.2
021103155049	0.26+/-0.49	3.6+/-4.1	2.2
021103192319	0.87+/-0.93	4.4+/-8.9	2.6
021105141209	0.12+/-0.04	7.0+/-2.0	2.0
021105205229	0.08+/-0.01	5.7+/-1.1	1.9
021106021459	0.55+/-0.65	4.4+/-1.0	2.5
021106032619	0.06+/-0.02	3.0+/-0.1	1.8
021107005839	0.05+/-0.01	3.0+/-0.1	1.8
021107024239	0.03+/-0.00	2.8+/-0.0	1.6
021107024559	0.09+/-0.04	4.9+/-0.2	1.9
021107043129	0.13+/-0.17	3.5+/-0.1	2.0
021108125159	0.27+/-0.24	4.5+/-0.2	2.3
021108203139	0.05+/-0.01	2.4+/-0.0	1.7
021114011549	0.05+/-0.01	5.2+/-0.2	1.8
021114064429	0.09+/-0.06	4.5+/-7.5	1.9
021117162719	0.04+/-0.02	4.4+/-0.2	1.7
021120080839	0.19+/-0.09	4.8+/-0.5	2.2

Table 5.2. Seismic moment, corner frequency, and moment magnitude obtained for the EGF events.

5.5.2 Synthesis of the Molise Earthquake

Rupture Scenarios

The first step of the validation procedure outlined in this study consists in reproducing the Molise earthquake using all the information existing in the literature about the event's source. Starting from the source parameters in Table 5.1, a physically based kinematic source model is utilized by HAZARD program to generate 10 rupture scenarios that span the variability in strong ground motion due to the source uncertainties (Tab 5.3). In this case these uncertainties are not much, and they are mainly linked with the number and the dimension of the asperities on the fault plane, and on the percentage of roughness.

MODEL	asperities	rg	mo	mo1	mo2	mo3	stk	dp	sv	vr	Vh
VeB001	01	20	0.047	0.014			267.0	82.0	157.0	2.56	0.88
VeB002	01	25	0.012	0.049			267.0	82.0	157.0	2.56	0.87
VeB003	01,02	10	0.016	0.037	0.007		267.0	82.0	157.0	2.56	0.81
VeB004	01	25	0.015	0.045			267.0	82.0	156.9	2.56	0.90
VeB005	01,02,03	33	0.014	0.027	0.007	0.014	267.0	82.0	157.1	2.56	0.86
VeB006	01,02	10	0.044	0.013	0.003		267.0	82.0	156.9	2.56	0.89
VeB007	01	33	0.027	0.033			267.0	82.0	157.0	2.56	0.82
VeB008	01	20	0.011	0.050			267.0	82.0	157.0	2.56	0.87
VeB009	01	25	0.048	0.013			267.0	82.0	157.0	2.56	0.99
VeB010	01,02	20	0.017	0.008	0.036		267.0	82.0	157.0	2.56	0.98

Table 5.3 10 rupture scenarios evaluated. The first column is the identification number of the model; the second one the number of asperities included in the rupture; the third one is the percentage of roughness; the fourth one is the seismic moment of the rupture without asperities while the following three columns are the seismic moment of the asperities. For each model the sum of the seismic moments is equal to the moment of the big earthquake to reproduce. Event latitude, longitude, and depth are fixed as in Table 5.1.

Strong ground motion synthesis

Strong-motion synthetics were generated for each rupture scenario, following the procedure illustrated in paragraph 5.1. It was tested whether one of the 10 models provides the ground motions synthesized, for the same earthquake, and using the same source parameters, by the HIC and/or the DSM methods.

For each station, and rupture model, the comparison has been performed both for velocity spectra, PGA, and PGV values shown in Figure 5.3.

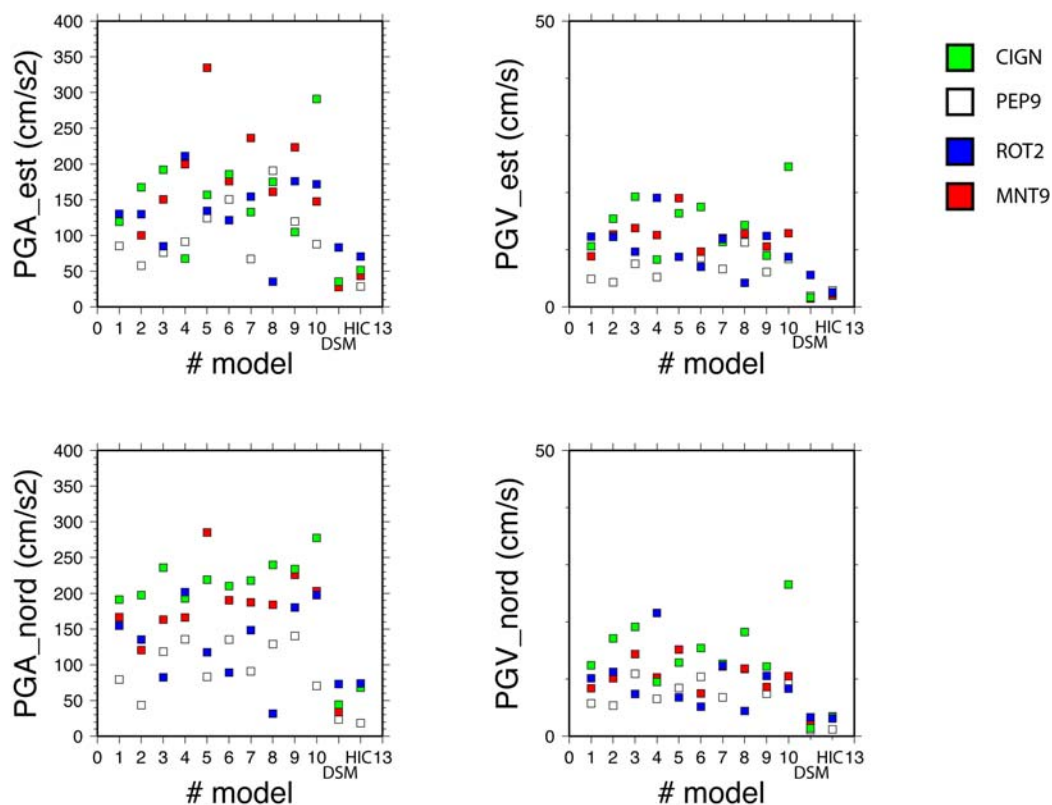


Figure 5.3 Comparison between pga, and pgv computed using the synthetic seismograms obtained with EMP SYN, HIC and DSM.

Almost all the pga, and pgv computed with the methodology outlined in this study are greater than values obtained by using DSM and HIC.

In order to understand if the results were realistic, I have compared the 10 pga values obtained at MNT9 to the attenuation law showed in the Deliverable *d7* (Fig. 5.4). With the exception of model 002, showing the same pga of the average Sabetta and Pugliese attenuation law (red curve in fig. 5.4), all the rupture models obtained with EMPSYN results higher than the predictive relationship proposed by Sabetta and Pugliese (1996) (SP96), Ambraseys (1995) (AMB95), and the one computed in *d7*. The higher value comes from the model 005, the only one with 3 asperities. DSM and HIC pga (white squares in Fig. 5.4) underestimates the expected ground motion at MNT9, for SP96, and AMB95 laws, while fits the d7-attenuation law prediction.

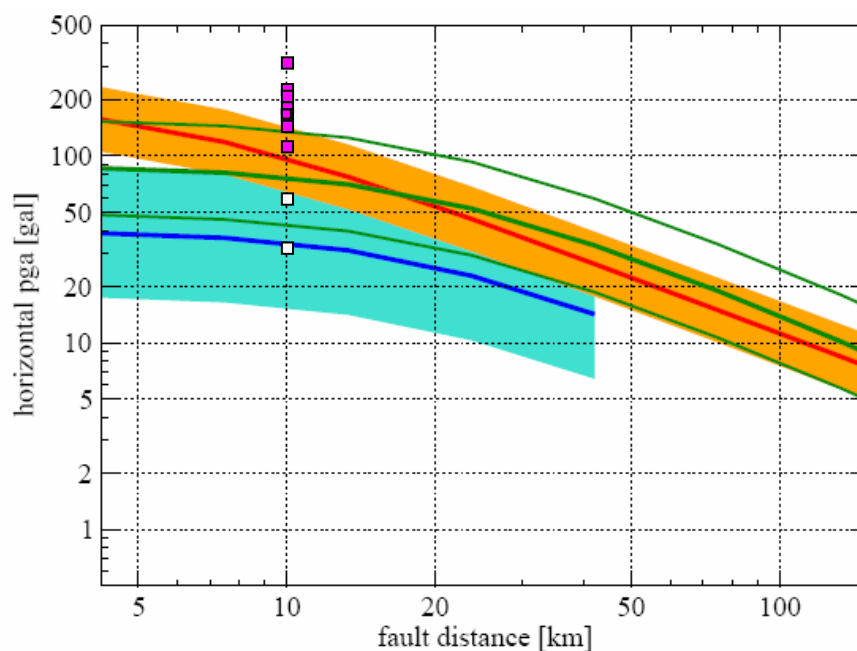


Figure 5.4 (Fig. 12 Deliverable *d7*). Horizontal PGA attenuation curves for rock sites predicted for the October 31, 2002 Molise earthquake by equation (2) in Deliverable *d7* (blue line); Sabetta and Pugliese [1996] (red line) and Ambraseys [1995] (thick green line). Shaded areas and thin green lines correspond to ± 1 std. Pink squares are the pga obtained with the Empsyn simulation technique, while the white squares are obtained using DSM (the lower) and HIC.

Lastly, I verified if the gap between the methods could be reduced by correcting the HIC and DSM synthetics for the site transfer functions, computed at the 4 stations by Pacor et al. (personal communication). The following figure is just an example of the results obtained for the stations PEP9 and MNT9. For the other stations I got similar results.

The site correction seems to be not enough to account for the difference in the spectral amplitude that could probably be related to the whole propagation path, not taken into account by HIC and DSM.

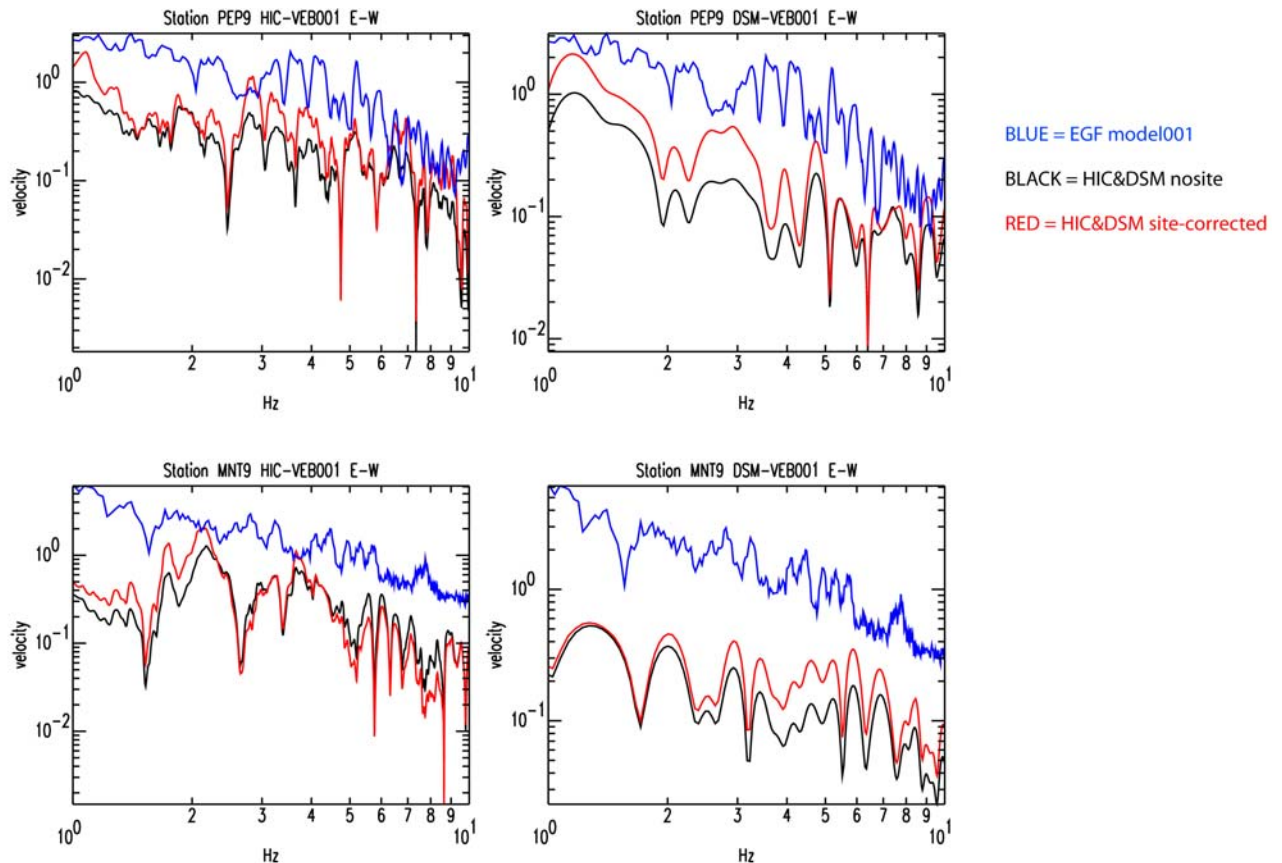


Figure 5.5. Comparison between velocity spectra obtained at PEP9, and MNT9 for the EGF 001 rupture model (blue curve), and the HIC and DSM methods. Black curves show the original HIC and DSM spectra, while red curves are the same spectra corrected with the site transfer function.

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