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On the modeling of strong motion parameters and correlation with historical macroseismic data: an application to the 1915 Avezzano earthquake

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Abstract

This article describes the results of a ground motion modeling study of the 1915 Avezzano earthquake. The goal was to test assumptions regarding the rupture process of this earthquake by attempting to model the damage to historical monuments and populated habitats during the earthquake. The methodology used combines stochastic and deterministic modeling techniques to synthesize strong ground motion, starting from a simple characterization of the earthquake source on an extended fault plane. The stochastic component of the methodology is used to simulate high-frequency ground motion oscillations. The envelopes of these synthetic waveforms, however, are simulated in a deterministic way based on the isochron formulation for the calculation of radiated seismic energy. Synthetic acceleration time histories representative of ground motion experienced at the towns of Avezzano, Celano, Ortucchio, and Sora are then analyzed in terms of the damage to historical buildings at these sites. The article also discusses how the same methodology can be adapted to efficiently evaluate various strong motion parameters such as duration and amplitude of ground shaking, at several hundreds of surface sites and as a function of rupture process. The usefulness of such a technique is illustrated through the modeling of intensity data from the Avezzano earthquake. One of the most interesting results is that it is possible to distinguish between different rupture scenarios for the 1915 earthquake based on the goodness of fit of theoretical intensities to observed values.

Key words *Fucino area (Central Italy) – isochron – envelope – extended fault – macroseismic intensity – strong ground motion*

1. Introduction

The synthesis of earthquake ground motion and related seismic input parameters is a research area of particular relevance for engineering studies dealing with the characterization of potential earthquake ground motion. While the emphasis of studies of this nature is on their predictive capability, in principle they could be used as an aid in the study of historical seismicity. From another perspective, information regarding earthquake damage to historical monuments and populated habitats certainly serves as a data set which can be used to validate or reject the premises of a ground motion modeling study. It is from this latter perspective that we present the results of a ground motion modeling study in the area of Avezzano, Italy.

This study was motivated, in part, due to the uncertainties regarding the actual fault which ruptured during the 1915 Avezzano, earthquake. This event, with a MCS intensity of XI, is qualified as one of the largest Italian earthquakes of this century (Basili and Valensise, 1991). The earthquake caused the collapse of a large portion of civil and military structures in the towns of the Fucino plain. At least 30000 people were killed, of which, 10000 only in the town of Avezzano (Galadini and Galli, 1994). It is clear then that the problem of quantitatively evaluating the impact of the re-occurrence of a similar event is of great interest, compounded by the fact that the Fucino plain is located only 80 km to the northeast of the highly populated metropolitan area of Rome.

The methodology used here to evaluate the potential damage of an earthquake, with characteristics similar to those of the 1915 earthquake, is based on the generation of synthetic strong motion time histories. From these, it is possible to abstract seismic input parameters such as peak ground acceleration, strong ground motion duration, predominant period of ground shaking, etc., which can then be used to assess the probable damage to a given structure. A necessary first step in this type of analysis is the specification of the fault on which the earthquake is presumed to have occurred. Following Ward and Valensise (1989), this study starts from the premise that the Serrone fault (fig. 1) was ruptured during the 1915 event. The validity of this assumption is explored by correlating the historical information regarding damage to specific buildings in the towns of Avezzano, Celano, Ortucchio, and Sora with the seismic input parameters derived from synthetic strong motion time histories calculated at these sites.

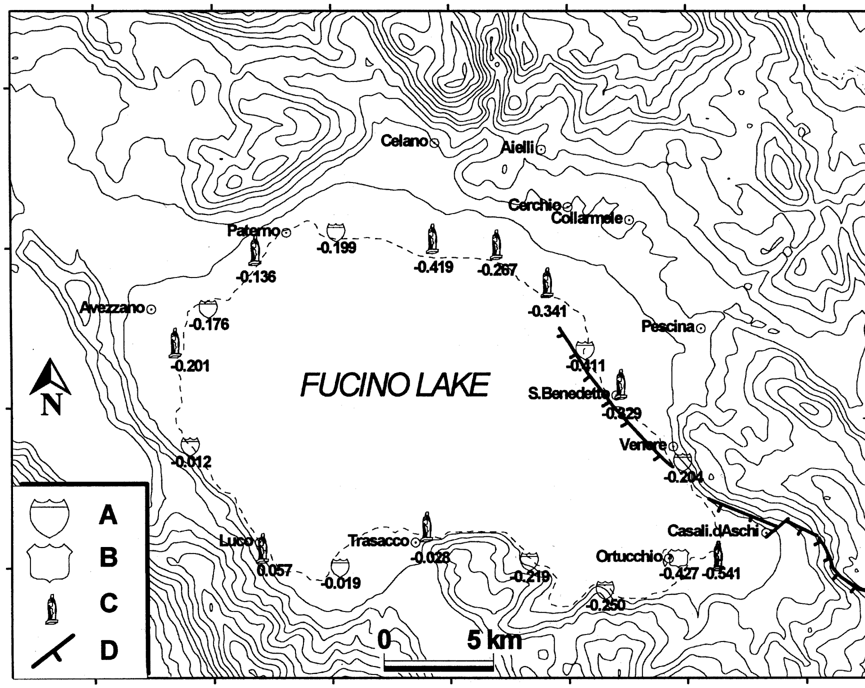

Fig. 1. Epicentral region of the 1915 Avezzano earthquake (modified from Galadini *et al.*, 1995). The fault scarp of the 1915 earthquake is represented with the symbol labelled D. The different types of benchmarks surrounding the Fucino lake basin and used in two levelling campaigns performed in a time interval spanning the occurrence of the earthquake, are shown with symbols labelled A, B and C.

The degree to which high-frequency synthetic ground accelerations can be taken as representative of those that actually took place depends on a variety of factors. Even if the precise geometry of the fault ruptured during the 1915 earthquake and the medium of propagation between fault and site were well known, a remaining question is how to assess the importance of those factors affecting seismic wave generation and propagation which, because of their complexity, are not readily included in deterministic calculations. More specifically, it is known that ground motions are characterized by a certain degree of incoherence due, in part, to the presence of scatterers in the Earth's crust. This incoherence has been documented over a wide frequency range which includes that of engineering interest (for example, Reinke and Stump, 1988; and Menke *et al.*, 1990). The practical consequence of the incoherence due to scattering is that strong motion time histories, recorded at relatively close sites, can present large variations in waveform characteristics. This fact raises doubts about the validity of any methodology that is used to make inferences about ground motion parameters at a site through the generation of only one synthetic seismogram for the site. While scattering can be thought of as a phenomenon responsible for spatial incoherence in earthquake ground motion, the complexity of the rupture process itself is a phenomenon responsible for the temporal incoherence. By temporal incoherence we mean the phenomenon whereby the radiated seismic energy does not interfere constructively nor destructively (Cocco and Boatwright, 1993). The cause of this incoherency, as succinctly stated by Lomnitz-Adler and Lund (1992), is that «fracture is essentially a non-linear process whereby seismic radiation is generated in frequencies of the order of the time scale of changes in the source region». Again, the practical consequence of this «source induced» incoherence is that it raises doubts about the validity of any methodology that is used to make inferences about ground motion parameters at a site through the generation of synthetic seismograms based on only one possible realization of the rupture process.

The methodology applied here for the synthesis of acceleration time histories is developed in Mendez and Pacor (1994) and represents an approach to address the issues raised in the previous paragraph. It combines the stochastic modeling approach of Boore (1983) with elements of the isochron formulation of Bernard and Madariaga (1984) and Spudich and Frazer (1984). In this hybrid approach, the high-frequency oscillations characteristic of actual earthquake ground motion records are generated stochastically, while the envelope of these oscillations is calculated in a deterministic way starting from a simple kinematic description of a plausible rupture scenario. For any given site, the stochastic component of the methodology is used to generate several ground motion time histories, thus attempting to address the issue of spatial incoherence. The envelopes of these oscillations are calculated based on several plausible rupture scenarios, thus attempting to address the issue of source induced incoherence. The theoretical basis for the deterministic calculation of envelopes is the so called isochron formulation for the calculation of radiated seismic energy. The ground motion envelopes calculated in this way have durations and amplitudes which physically take into account how the energy released by the propagation of a rupture throughout an extended fault is ultimately received at any given site. It should be noted that the problem of generating synthetic ground motions which realistically reflect source complexity, is an active field of research. The methodology used in this study is one among several. For example, Lomnitz-Adler and Lund (1992) propose a semi-phenomenological model for rupture on extended fault planes (Lomnitz-Adler and Lemus-Díaz, 1989) coupled with the formulation of Lund (1986) for the calculation of near-source synthetics. Cocco and Boatwright (1993) present another approach in which an analytical model is derived for the envelope of acceleration time histories radiated by a dynamic rupture process and based on the same isochron formulation used here.

In addition to historical information regarding damage to specific buildings, another important data set regarding the 1915 Avezzano earthquake consists in the intensity map derived from historical accounts of the damage inflicted throughout populated habitats. The second part of this paper deals with an attenuation model for these intensity data. The model includes a simple characterization of site effects and also takes into account source effects on strong ground motion. By using a variant of the same methodology employed in the deterministic calculation of waveform envelopes, a relation between the rupture on an extended fault plane and strong motion parameters such as duration and amplitude of ground shaking can be established. More specifically, the isochron formulation is used to identify zones on an extended fault where the release of seismic energy is particularly strong as viewed by an observer at any given site. These zones of strong energy release generally vary from site to site. This suggests the possibility of characterizing, for each site, an otherwise complex rupture process on an extended fault plane by a few essential parameters describing the rupture in these zones. The idea is to combine these parameters so as to obtain a number characteristic of the strength of ground motion, in the same way as macroseismic data are combined to obtain an intensity value of ground motion. We illustrate how an attenuation model for intensity data, which includes such a term to account for source effects, can be used to distinguish between plausible rupture scenarios on an extended fault plane.

2. Definition of rupture scenarios

The starting point for the synthesis of ground motion time histories, or of strong motion parameters such as duration and amplitude of ground shaking, is the selection of physical parameters to characterize a possible rupture on an extended fault plane. For our purposes, a rupture scenario description consists in specifying a hypocenter, from which a rupture propagates in a radial way with a velocity equal to some percentage of the mean shear wave velocity of the medium. The circular rupture front, which propagates throughout the given fault plane, is perturbed in shape by the addition of a small stochastic component to rupture times. For the case of the Avezzano earthquake, Mendez *et al.* (1994) carried out a study to define plausible ranges of these parameters and others such as spatial slip distribution and seismic moment, which would serve as the basis for defining a rupture on the Serrone fault. Their study proposes six plausible rupture scenarios from which a representative family of broadband synthetic acceleration time histories were generated at a site in close proximity to the town of Avezzano. In the present study, we follow a similar methodology, but the focus is on the generation of high-frequency synthetics. In the following we briefly review those points of the methodology pertinent to the present study.

The definition of plausible rupture scenarios was conducted through a parametric study where in a first step we repeated the inversion of geodetic data used by Ward and Valensise (1989) in their study of the 1915 earthquake. The goal was not so much a study of the exact source characteristics of the 1915 earthquake, but a study to obtain plausible slip distributions which could be used to provide information on plausible hypocenters for a future rupture of the Serrone fault. Using a method described in Mendez and Pacor (1994), the inversion was performed to obtain not one, but a family of slip distributions. These slip distributions are all compatible with the geodetic measurements and have moments ranging within $\pm 10\%$ of the seismic moment of the slip distribution producing the best fit to the geodetic data. This latter is shown in fig. 2, and is characterized by a seismic moment of $9.7\ 10^{25}$ dyne · cm and 84 cm of average dip-slip motion.

The general features of the inferred slip distribution shown in fig. 2 are very similar to those previously inferred by Ward and Valensise (1989). There are two areas presenting large slip amplitudes separated by at least 15 km. One disturbing feature of the slip distribution is that slip amplitudes tend to increase near the edges of the Serrone fault, suggesting that the actual length of faulting was greater than that used here. In fact, Ward and Valensise (1989) used a fault 36 km in length in their inversion for a variable slip model while the length used in this study is 24 km. Although

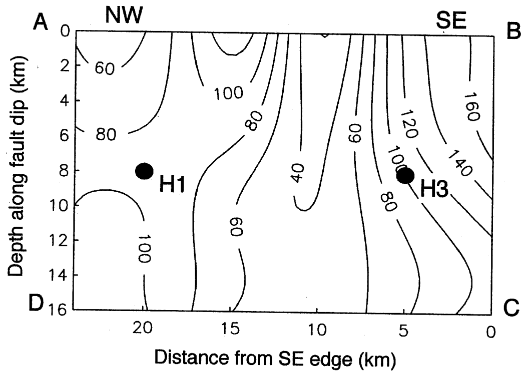

Fig. 2. Spatial slip distribution on the Serrone fault inferred from the inversion. Contour values are in cm. The two areas of high slip values were selected as areas of nucleation of possible ruptures. The precise nucleation points are labelled H1 and H3. This selection is intended to be representative of ruptures initiating at opposite ends of the fault, and therefore representative of the different directivity effects that could have been produced during the 1915 earthquake.

the results are not reported here, we repeated the geodetic inversion using a longer fault and found that the resulting slip distribution is similar to the one shown in fig. 2 with the exception that the areas of large slip amplitudes were now almost completely enclosed by the enlarged fault. The reason for not using the enlarged fault as representative of the faulting area on the Serrone fault is mainly practical. From the computational point of view, it was easier to calculate synthetics based on the rupture of a rectangular fault and assuming a constant slip distribution equal to the average value inferred from the geodetic inversion, than based on the rupture of an irregularly shaped area enclosing a spatially variable slip distribution similar to the two-lobed distribution inferred from the inversion.

As previously stated, the result of the geodetic inversion can be used as a guide in the selection of possible hypocenters from which to nucleate the rupture of the Serrone fault. Specifically, Mendez *et al.* (1994) assumed three plausible hypocenters. Two would be centered in the two areas of maximum slip derived from the geodetic inversion. Another hypocenter would be placed in the central area of the Serrone fault; the idea being that this area could represent a candidate for a future rupture since, as inferred from the inversion, it experienced little slip during the 1915 event. In this study, however, high-frequency synthetics were generated for ruptures nucleating at only two of the proposed hypocenters (denoted by H1 and H3 in fig. 2). This selection was intended to be representative of ruptures initiating at opposite ends of the fault, and therefore representative of the different directivity effects that could have been produced during the 1915 event.

The other main parameter needed to complete the definition of a rupture scenario is the rupture propagation velocity. Mendez *et al.* (1994) selected two values for this parameter. A «slow» event was characterized by an average rupture propagation velocity equal to 70% of the mean shear wave velocity of the medium: 3.07 km/s. A «fast» event had a mean rupture propagation velocity equal to 85% of the mean shear wave velocity. This classification into slow and fast is not meant to imply any underlying physical difference between these two types of rupture. The classification is purely kinematic and arose simply because, in the aforementioned study, it was observed that low-frequency synthetics presented significant variations in amplitude, duration, and frequency content for ruptures with velocities of propagation confined between these two limits. In the present study, we limit our attention to «fast» events since, in general, the corresponding synthetic time histories tended to exhibit the largest amplitudes.

In summary, two plausible rupture scenarios were selected for the generation of synthetic ground motion and strong motion parameters. The two scenarios are identified by their hypocenter, H1 or H3 (fig. 2), from which the rupture propagates in a radial way with a mean velocity equal to 85% of the mean shear wave velocity. The circular rupture front is perturbed in shape by the addition of a small stochastic component to the actual time of rupture of each point on the fault, as determined by the mean rupture propagation velocity value. In the following, these two models are referred to as H1V2 and H3V2.

3. High-frequency synthetics

High-frequency synthetics were generated using the method developed in Mendez and Pacor (1994). This method is a hybrid technique based on the stochastic simulation method of Boore (1983) and the isochron formulation of Bernard and Madariaga (1984) and Spudich and Frazer (1984). In a typical application of stochastic modeling, a large number of synthetic time histories are generated so that, on the average, the properties of the time histories mimic those of earthquake ground motion. In Boore's (1983) method, this is accomplished by windowing white Gaussian noise with an envelope function which generally has some simple mathematical representation. In order to replicate the spectral characteristics of earthquake ground motion, these time limited noise waveforms are filtered with a reference spectra such as an omega square model with anelastic attenuation.

This technique is capable of efficiently generating realistic earthquake ground motion time histories and requires the specification of only a limited number of parameters to characterize the source, propagation medium and site. One major limitation is that this method is based on a point source description of an earthquake. For the case of near-source modeling, it would be desirable to take into account the finite dimensions of the fault so as to incorporate effects such as source directivity. We approached this problem by using the isochron formulation for the calculation of radiated seismic energy from an extended fault. In our application, this formulation is used to generate ground motion envelopes based on the simple kinematic description of a rupture as defined in section 2. For a given rupture scenario, the isochron formulation is used to identify the locus of points on the fault that emit seismic radiation characterized by the same travel time to a given observer. These loci are called isochrons. As the rupture propagates throughout a fault, each observer will perceive the rupture as an isochron which changes shape as it sweeps through the fault. At this point, it is important to emphasize that two observers situated at different positions respect to the fault, will receive the radiated source energy in a different way. For example, the recorded amplitude and duration at two sites, will vary depending on whether the rupture propagates towards or away from each site. Each instant of time of the envelope for a given site is constructed by summing the contributions to ground motion from the corresponding isochron. In this way it is possible to introduce the information concerning the emission of energy by a finite fault and the way in which this energy ultimately arrives at a given site through time.

4. Synthesis of strong ground motion at four sites

The stochastic modeling technique using envelopes generated in a deterministic way, based on the isochron formulation, was employed to simulate high-frequency ground acceleration at 4 sites shown in fig. 3a: Avezzano, Celano, Ortucchio, and Sora. This figure shows the relative location of these sites with respect to the Serrone fault, and also the isochron generated envelope for each site. These envelopes were generated for the case of rupture scenario H3V2. Representative acceleration time histories are shown in fig. 3b. The mean peak acceleration value is indicated below each envelope in fig. 3a and was obtained by averaging the results of 20 realizations of stochastic modeling for each site.

Table I lists other parameters of interest and the reported intensity (MCS) at the four sites. In this table, the column labelled R refers to the hypocentral distance used in the stochastic modeling code to calculate geometrical attenuation. In the near-source region of an extended fault, it is not immediately clear how to specify this distance, especially when fault dimensions are of the same order as the site distance. The procedure used in Table I is to define R as the average value of the distance between the site and each point along the isochron which is re-

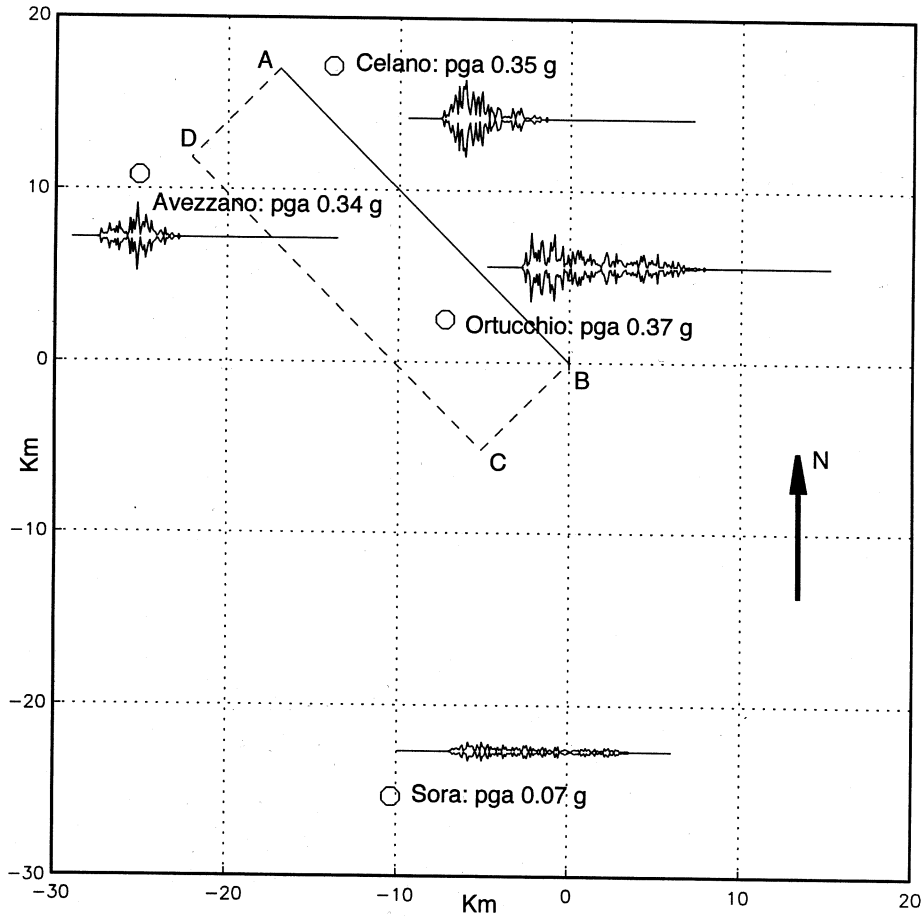

Fig. 3a. Schematic view of the Serrone fault and location of the sites: Avezzano, Celano, Ortucchio, and Sora, where the horizontal ground acceleration was synthesized. Envelopes generated using the isochron formulation are shown for each site along with the average peak acceleration obtained from 20 realizations of stochastic modeling.

sponsible for the greatest amplitude in the synthetic envelope. This definition is not unique. In the following section, where a theoretical expression for the source contribution to macroseismic intensity is developed, another possible definition is postulated. At this moment, we have no reasons for preferring either.

In table I it is seen that the total duration of the time histories at Sora and Ortucchio is approximately twice the duration at Avezzano and Celano. This is due to the fact that, for scenario H3V2, the rupture nucleates at a point below Ortucchio and propagates predominantly to the NW towards Avezzano and Celano. The synthetic acceleration time histories in fig. 3b also display characteristics which reflect the mode of rupture propagation. The synthetic record at Ortucchio exhibits a strong motion portion comparable to that at Avezzano and Celano, but the large amplitudes are due to the fact that the rupture nucleates almost directly

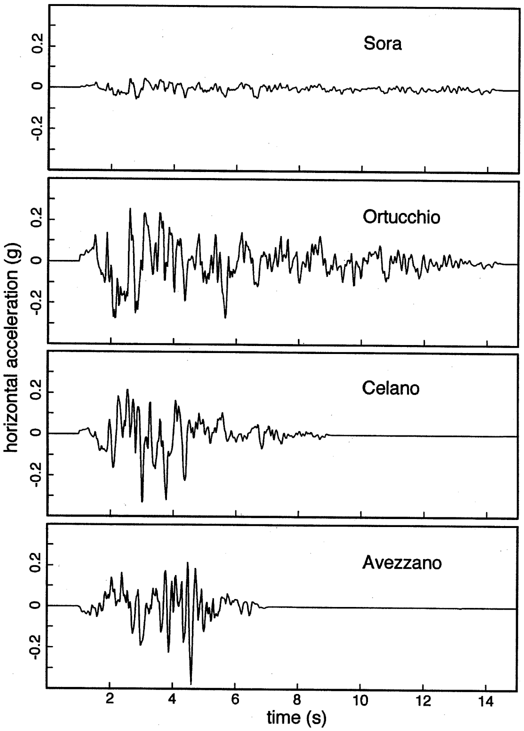

Fig. 3b. Representative horizontal acceleration time histories based on rupture scenario H3V2 for the sites: Avezzano, Celano, Ortucchio, and Sora.

Table I. Summary of 20 realizations of stochastic modeling.

Site	*R* (km)	*I* (MCS)	A_{max} (g)	Duration (s)
Avezzano	17.0	XI	0.34	5.9
Celano	13.7	IX	0.35	7.9
Ortucchio	6.4	XI	0.37	13.4
Sora	27.8	IX	0.07	13.3

underneath this site. In contrast, the large amplitudes at Avezzano and Celano are due to directivity effects.

Upon comparing the strong motion parameters of table I with the reported intensities, it appears that a straightforward correlation is not possible. For example, it is difficult to explain the difference in reported intensities at Ortucchio and Celano (XI vs. IX) when the calculated ground accelerations exhibit similar peak values. One factor that could help to explain this discrepancy is that the duration of ground shaking at Ortucchio is 1.7 times greater than that at Celano. The duration factor can also help to explain why the intensity at Sora is equal to that of Celano, even though peak acceleration is much lower. But it still remains difficult to explain the difference in reported intensities at Avezzano and Celano (XI vs. IX) when the calculated ground motions are similar both in duration and peak acceleration.

A possible explanation lies in the fact that local site conditions have not been taken into account. We are currently in the process of incorporating site effects in the methodology used to synthesize ground motion. The technique consists in using the synthetic acceleration time histories to excite the base of a laterally inhomogeneous medium characteristic of each of the 4 sites considered. The response at the surface is calculated using a finite element code. The effect of local site conditions can then be analysed by taking spectral ratios between surface and base acceleration. The preliminary results of this study indicate that surface amplification is greatest at Avezzano, next Sora, followed by Celano and finally Ortucchio. These preliminary results suggest qualitatively how ground motion at Avezzano and Sora could have been amplified to produce intensities of XI and IX, respectively.

In addition to comparing the synthetic strong motion parameters with measures of global damage, given by the intensity, we have also carried out a comparison with damage to historical monuments. In this analysis, the principal structural elements of churches at the four sites were studied using a finite element code to estimate the peak ground acceleration values for the onset of damage and for structural collapse. The churches for which damage is well documented are listed in table II, and are all characterized by similar structural elements. The structural layout of these churches is such that, in the central nave zone, the resistance to seismic forces is provided by a transverse septum. This septum is formed princi-

Table II. List of selected churches.

Locality	Church	Characteristics	Damage	A_d (g)	A_c (g)	A_{max} (g)
Avezzano	S. Bartolomeo	Rebuilt in the baroque period, on the site of an ancient IX church. Three interior naves with a central nave twice the height of the lateral ones. Damaged during earthquakes occurring in 1700-1800.	Completely destroyed except for the inferior portion of the facade rebuilt in the XVIII century.	0.12	0.27	0.34
	S. Francesco	Built in 1300, with subsequent baroque additions. One interior nave with 2 square halls covered by ogival vaults, and separated by an acute arch supported by pillars.	Strongly damaged, total collapse of several lateral walls and part of the XVIII century facade.	0.1	0.24	0.34
Celano	S.S. Giovanni Battista ed Evangelista	Built in the XIII century on slightly sloping terrain. Three interior naves supported by large octagonal pillars. Damaged during the earthquake of 1703.	Collapse of campanile. Serious damage to the apse, collapse of the central nave roof and XVIII century vault.	0.12	0.27	0.35
	S. Francesco	Built in 1345. One interior nave with lateral parastras that support flat arches.	Serious damage, especially to left walls. Collapse of central dome and vault.	0.1	0.24	0.35
Ortucchio	S. Orante	Built on a prehistoric foundation. Rock site. Exact date of construction unknown although cited in documents from the XII century. Three interior naves supported by columns and masonry walls.	Almost completely destroyed, except for presbytery walls and the lateral chapel of S. Giovanni.	0.12	0.27	0.37
Sora	SS. Maria e Pietro (Cathedral)	Built in the IX century on the foundation of a Roman temple. Rock site. Three interior naves supported by columns having a square base.	No damage.	0.12	0.27	0.07
	Santa Restituita	Alluvial site in proximity to the Liri River. Dates from the XI century and was reconstructed after the earthquake of 1654. Three interior naves.	Completely destroyed except for a portion of the facade and perimetrical walls.	0.12	0.27	0.07
	Santa Chiara and San Pietro Celestino	Alluvial sites in proximity to the Liri River. Dating from the XIV and XIII centuries, respectively. One interior nave.	Both completely destroyed.	0.1	0.24	0.07
	S. Bartolomeo	Alluvial site. Dates from the XIV century. Three interior naves divided by pillars. The presbytery is covered by a dome.	Damage to campanile and facade.	0.12	0.27	0.07

pally by perimetrical stone masonry walls exhibiting T shaped sections. For churches of one nave, onset of damage initiates at 0.1 g (labelled A_d in table II) and total collapse occurs at 0.24 g (labelled A_c in table II). For churches of three naves, A_d is equal to 0.12 g while A_c is equal to 0.27 g. Table II also lists the synthetic peak ground acceleration values, which can be considered as bedrock accelerations since local site effects were not taken into account. For the cases of Avezzano, Celano and Ortucchio, the estimated bedrock accelerations are greater than the calculated accelerations necessary to produce the collapse of the examined churches. This fact, together with the actual damage sustained by these churches, is indicative that the synthetic peak acceleration values are reasonably representative of the real motion produced during the Avezzano earthquake. At Sora the synthetic peak ground acceleration (0.07 g) is less than the calculated value for the onset of damage (0.1 g). This would explain the almost total absence of damage to the Cathedral of SS. Maria e Pietro. This church is located on a rock site in the foot hills near Sora. In contrast, the notable damage to the churches on alluvial sites in proximity of the Liri River cannot be explained by the synthetic peak ground acceleration value. One possible explanation would be to invoke strong local amplification due to the sedimentary nature of this terrain (Esu and D'Elia, 1967).

5. Simulation of macroseismic fields

In this section we discuss the problem of relating macroseismic data with ground motion estimates derived from a physical description of the earthquake rupture process. The problem is twofold: that of determining which parameters to abstract from the isochron method used to generate waveform envelopes, and that of determining the way in which to combine these parameters to arrive at a value which can be used as a theoretical measure of the source contribution to macroseismic intensity at given sites. In the following, we refer to the source contribution to macroseismic intensity at a given site as simply source intensity.

Regarding the first problem, there are numerous parameters which suggest themselves as having a fundamental influence on ground acceleration. As discussed in section 3, the rupture process on an extended fault is perceived at a given site as an isochron travelling on the fault with a variable velocity. Even for the case of a simple circular rupture front nucleating from a point, the isochron velocity, as a function of position on the fault plane, can be fairly complex. As a first approximation then, it would seem reasonable to select parameters from the zone where the isochron velocity is maximum in order to characterize strong ground motion at a given site. For example, a characteristic distance to be used in the determination of geometrical spreading could be obtained as the average value, R, from the area on the fault plane where isochron velocities are greatest. In the isochron formalism, ground acceleration amplitudes depend both on isochron velocity and isochron acceleration. Therefore, $C_{\max}$, defined as the maximum isochron velocity over the fault plane, could be postulated as one of the terms to be used as a measure of maximum ground acceleration. Another characteristic of strong ground motion is its duration. In the isochron formulation, duration depends in part on the medium of propagation, which governs travel times, and in part on the time evolution of the rupture. The duration ΔT, is a parameter easily calculated in the isochron formulation as the difference between maximum and minimum isochron values for a given site.

Regarding the second problem, our approach has been to use the simplest possible combination of the parameters discussed in the previous paragraph to arrive at a quantity indicative of source intensity at a given site. It is not our intention to propose that the following characterization of source intensity be the final word on this topic. Rather, as we show in section 6, our purpose is to illustrate that it is indeed possible to abstract, from the methodology used to generate strong motion envelopes, a simple characterization of source intensity to be used in attenuation models of macroseismic intensity data. With this caveat in mind, we postulate a theoretical source intensity, I_{krn}, given by:

$$I_{\mathrm{krn}} = C_{\max} / (R\,\Delta T) \qquad (5.1)$$

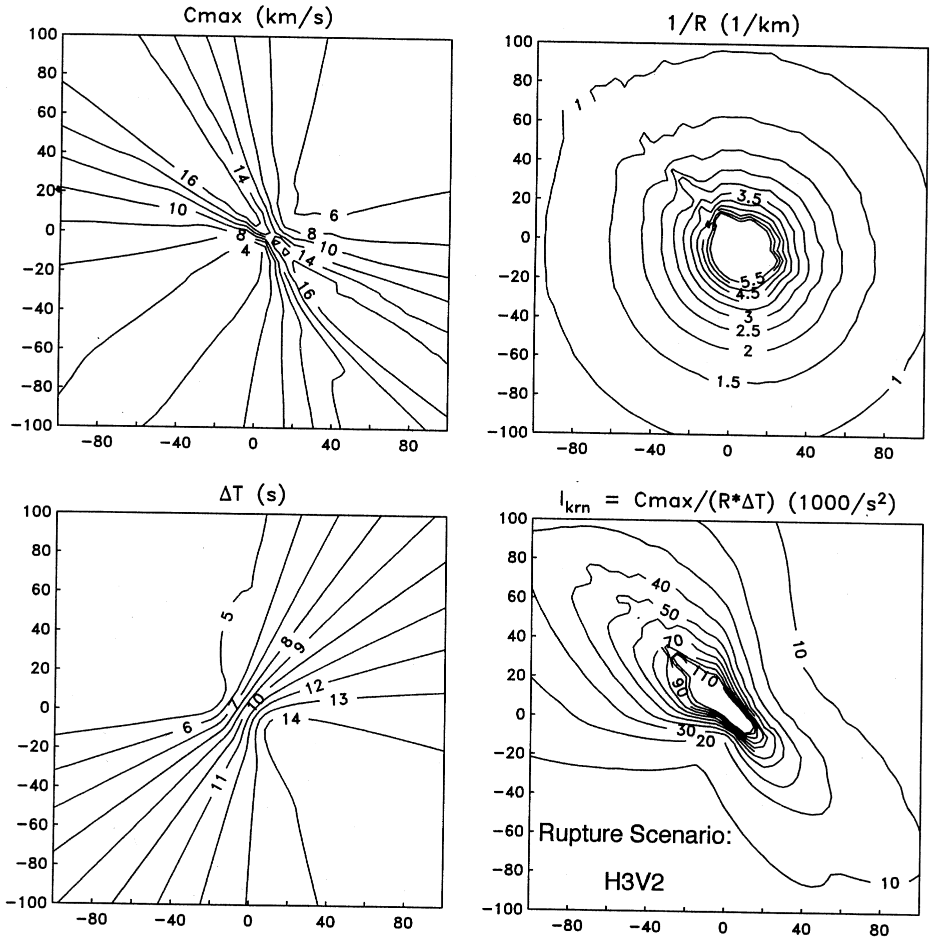

Fig. 4a. Theoretical source isoseismals I_{krn} and fields of constituent parameters calculated on a 200×200 km^2 surface grid for the case of rupture scenario H3V2.

In eq. (5.1), the proportionality of I_{krn} with isochron velocity and inverse proportionality with geometrical spreading is intuitively clear. A heuristic argument, based on dimensional analysis, can be made in order to understand why the remaining term, ΔT, appears in the denominator. Since the term $C_{max} / \Delta T$ has dimensions of acceleration, eq. (5.1) states that the greater the acceleration of the rupture, as perceived at a given site, the greater the theoretical source intensity at that site.

Figures 4a,b are contour plots of the various terms of eq. (5.1) and of I_{krn} for rupture scenarios H3V2 and H1V2, respectively. The surface area over which the calculations are performed is 200×200 km^2. Figures 5a,b are analogous to 4a,b, but now the surface area is only 40×40 km^2. In addition, the surface projection of the Serrone fault plane has been introduced for reference purposes. The only difference in the rupture scenarios is the location of the hypocenter: H1 is located on the NW portion of the fault plane while H3 is located on the SE portion. This difference can be seen in the theoretical source in-

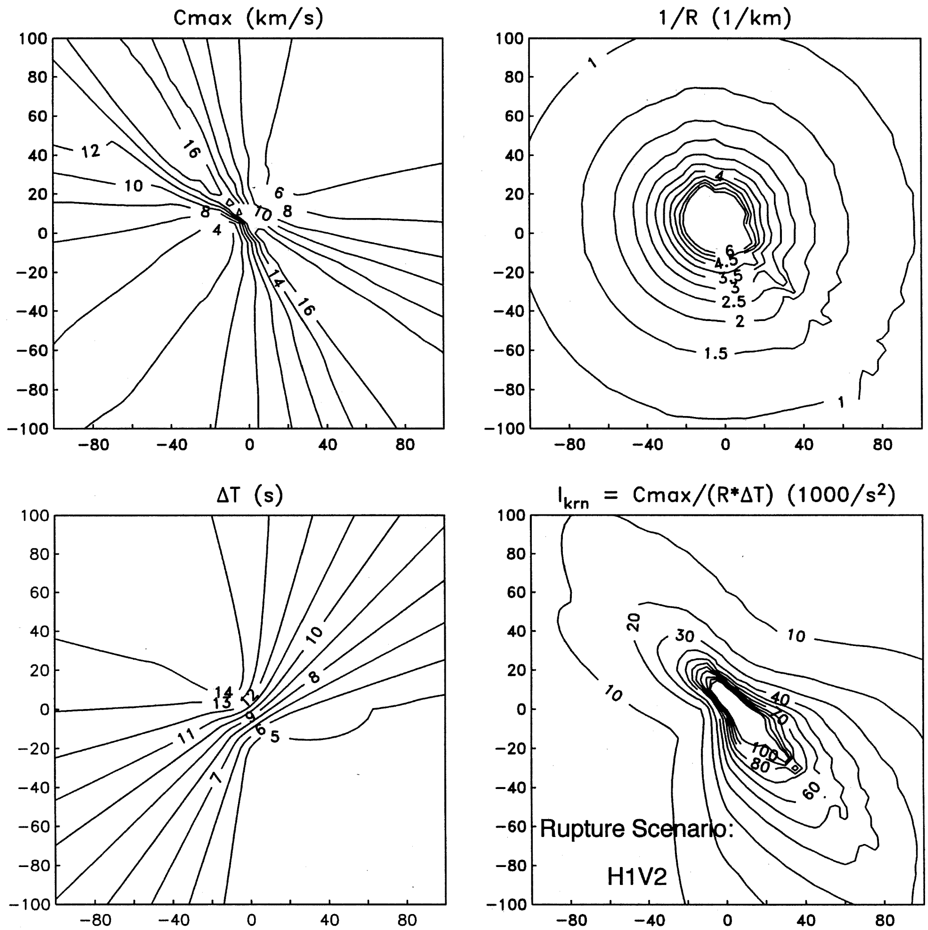

Fig. 4b. Theoretical source isoseismals I_{krn} and fields of constituent parameters calculated on a 200×200 km^2 surface grid for the case of rupture scenario H1V2.

tensity plots: ground motion intensity tends to be larger and decay more slowly with distance from the fault for those superficial sites towards which the rupture front propagates. Another observation that can be made regarding these figures is the following. Whereas the characteristics of the fields C_{max} and ΔT persist out to large distances from the fault plane, the isovalues of the field $1/R$ define curves which become more circular as distance from the fault increases. This implies that at large distances from a fault, the degree to which the theoretical source isoseismals depart from a simple circular shape depends on the exponents of the terms in eq. (5.1). In the example that we have illustrated, all exponents have been set to one.

6. A model for the attenuation of intensities for the Avezzano earthquake

We have calculated an attenuation model for the intensity of the Avezzano earthquake which includes both source and site effects. The analy-

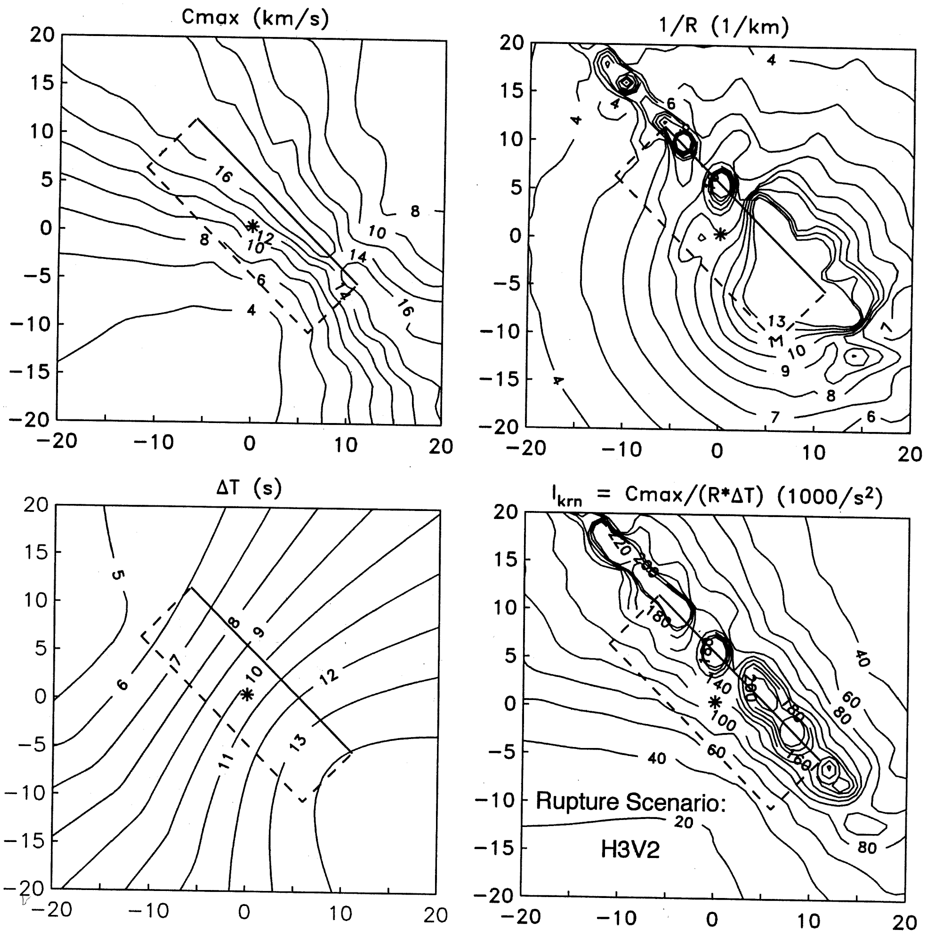

Fig. 5a. Theoretical source isoseismals I_{krn} and fields of constituent parameters calculated on a 40×40 km^2 surface grid for the case of rupture scenario H3V2.

sis was performed over a rectangular area of 2° in latitude by 4° in longitude centered on the macroseismic epicenter of the Avezzano earthquake. Regarding source effects, the parameter I_{krn} described in section 5, was calculated for the two rupture scenarios H1V2 and H3V2 at every point for which macroseismic derived intensity values were available (over 400 points). Local site effects were introduced by carrying out a sampling of the local geological conditions as read from the Italian Geological Map (scale 1:100000) by the Italian National Geological Service. Following the site classification proposed by Mucciarelli and Albarello (1994), three different typologies of sites were established: attenuating (parameter $S=-1$), normal ($S=0$) and amplifying ($S=1$). The definition of the above-mentioned typologies is based on lithological and/or morphological characteristics.

The best fit to the intensity data for the Avezzano earthquake was obtained using the following attenuation model:

$$I_s = I_0 - \alpha(R)^{(1/3)} + \beta(C_{\max} / (R\,\Delta T)) + \varepsilon S \quad (6.1)$$

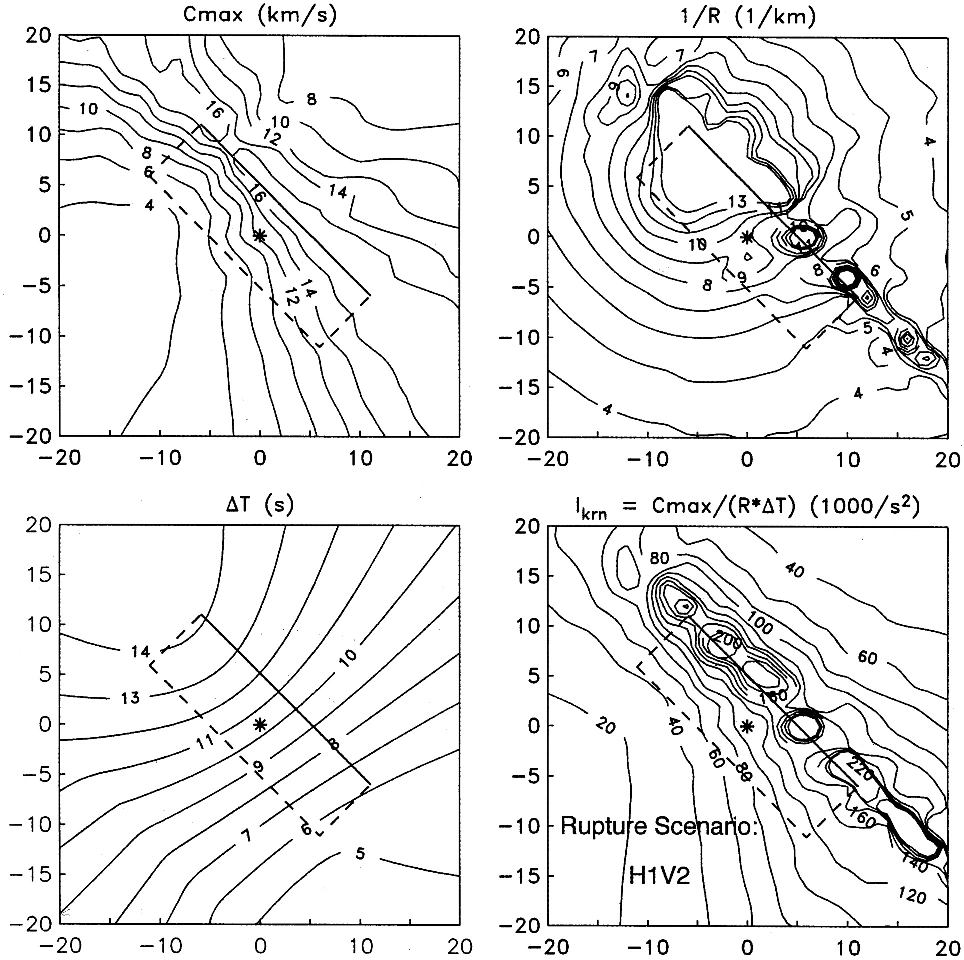

Fig. 5b. Theoretical source isoseismals I_{krn} and fields of constituent parameters calculated on a 40×40 km^2 surface grid for the case of rupture scenario H1V2.

This model for site intensity, I_s is an extension of that proposed in Berardi *et al.* (1990). The latter is an isotropic model consisting of only the first two terms: I_0 being the epicentral intensity with the epicenter determined by the inversion of the macroseismic field; and $R^{(1/3)}$ representing attenuation with distance from the macroseismic epicenter. The extension of this isotropic model as embodied in eq. (6.1) consists in using an attenuation term $R^{(1/3)}$ where R is now the distance from the fault as defined in section 5, and in introducing two new terms: one related to the source intensity (I_{krn}) and the other a site term (S). The distribution of residuals between data and model is shown in fig. 6, for four different cases: 1) I_0 plus the term $R^{(1/3)}$; 2) I_0 plus the term $R^{(1/3)}$ plus the source intensity term I_{krn} calculated for scenario H1V2; 3) I_0 plus the term $R^{(1/3)}$ plus the source intensity term I_{krn} calculated for scenario H3V2; and 4) I_0 plus the term $R^{(1/3)}$ plus the source intensity term I_{krn} calculated for scenario H3V2 plus the local site factor S.

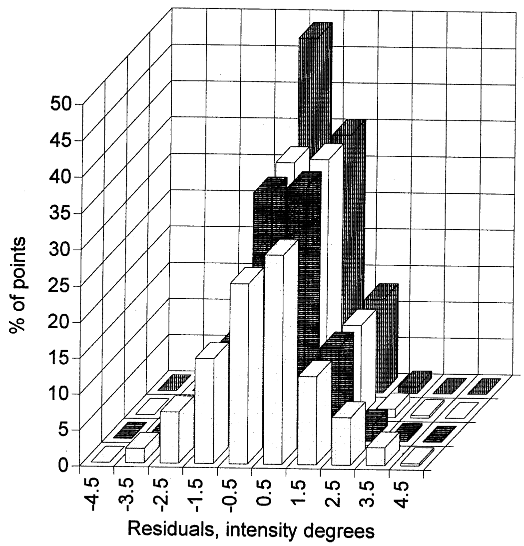

Fig. 6. Bar chart of residual distributions. Four different cases are displayed (from front to back): distance dependent model plus the source term I_{krn} calculated for the H1V2 scenario; distance dependent model only (case 1 in text); distance dependent model plus the source term I_{krn} calculated for the H3V2 scenario; and, distance dependent model plus the source term I_{krn} calculated for the H3V2 scenario plus a local site term S (case 4 in text).

From fig. 6 it is possible to distinguish between different rupture scenarios for the 1915 earthquake based on the goodness of fit of theoretical intensities to observed values. In fact the fit using the model H1V2 gives a worse result than using only a distance dependent model ($I_0+R^{(1/3)}$), whereas the fit obtained with the model H3V2 is slightly better than this distance dependent reference model. The best fit is obtained when the model given by eq. (6.1) is used. It should be noted that the relative weight of local site effects to source effects depends on the sampling density of the observed intensity values as a function of distance. In effect, since the source term of eq. (6.1) decays as $1/R$, it is evident that if only a few near-source intensity values are available, the optimization algorithm used to determine the coefficients α, β, and ε, will associate a larger weight to the local site effect term.

7. Conclusions

This paper has discussed a methodology to simulate ground acceleration waveforms based on a simple kinematic description of the rupture of an extended fault plane to model the earthquake source. Whereas the high-frequency oscillations characteristic of earthquake ground motion are generated stochastically, the envelope of these oscillations is calculated in a deterministic way from possible rupture scenarios of an extended fault plane.

This methodology was used to synthesize acceleration time histories at the towns of Avezzano, Celano, Ortucchio and Sora. The purpose was to simulate the ground motion actually experienced at these sites during the 1915 Avezzano earthquake.

For this purpose, the Avezzano earthquake was modeled as a rupture propagating towards the NW on the Serrone fault. It is interesting to note that Oddone (1915) mentions eye witness accounts of the 1915 earthquake which suggest a SE to NW rupture for this event, although not necessarily on the Serrone fault. A comparison was made between ground motion synthetics and well documented structural damage to churches in the four towns. Although such damage reasonably substantiates our working hypothesis for the Avezzano earthquake, the results of the comparison point out the need to include local site conditions as an important factor influencing ground motion amplitudes.

Another important data set regarding the 1915 Avezzano earthquake consists of the isoseismals derived from historical accounts of the damage inflicted throughout populated habitats. An attenuation model for these data was proposed which includes a simple characterization of site effects and also takes into account source effects on strong ground motion. We illustrate how an attenuation model, which includes such a term to account for source effects, can be used to distinguish between plausible rupture scenarios on an extended fault plane. As was the case when analyzing damage to specific structures in the Avezzano region, the inclusion of local site conditions in the model provides a better fit to the reported intensity values.

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REFERENCES

BASILI, A. and G. VALENSISE (1991): Contributo alla caratterizzazione della sismicità dell'area marsicano-fucense, in *Atti II Workshop su «Aree Sismogenetiche e Rischio Sismico in Italia»*, Erice 26 August-4 September 1986 (Il Cigno Galileo Galilei, Roma, Italia), 197-214.

BERARDI, R., L. MAGRI and M. MUCCIARELLI (1990): Do different experts and computer programs agree on the interpretation of the same intensity map?, in *Proceedings of the XXII General Assembly European Seismological Commission*, Barcelona, 17-22 September 1990, 371-376.

BERNARD, P. and R. MADARIAGA (1984): A new asymptotic method for the modeling of near-field accelerograms, *Bull. Seismol. Soc. Am.*, **74**, 539-558.

BOORE, D.M. (1983): Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra, *Bull. Seismol. Soc. Am.*, **73**, 1865-1894.

COCCO, M. and J. BOATWRIGHT (1993): The envelope of acceleration time histories, *Bull. Seismol. Soc. Am.*, **83**, 1095-1114.

ESU, F. and D'ELIA B. (1967). L'influenza dei terreni sugli effetti del terremoto del 13 gennaio 1915 nei centri abitati del Lazio meridionale, *Riv. It. Geot.*, 1 (4 bis), 299-311.

GALADINI, F. and P. GALLI (1994): Terremoto della marsica 1915: i primi interventi dello stato e la nascita del concetto di «protezione civile», in *Atti VIII Convegno Nazionale del Consiglio Nazionale di Geologia*, Roma, 21-23 January 1994 (in press).

GALADINI, F., P. GALLI and C. GIRAUDI (1995): Gli effetti geologici del terremoto del 1915, in *Il Terremoto di Avezzano del 13 Gennaio del 1915. Monografia del Servizio Sismico Nazionale*, edited by S. CASTENETTO, F. GALADINI (in press).

LOMNITZ-ADLER, J. and P. LEMUS-DÍAZ (1989): A stochastic model for fracture growth on a heterogeneous seismic fault, *Geophys. J. Int.*, **99**, 183-194.

LOMNITZ-ADLER, J. and F. LUND (1992): The generation of quasi-dynamical accelerograms from large and complex seismic fractures, *Bull. Seismol. Soc. Am.*, **82**, 61-80.

LUND, F. (1986): A note on the synthesis of near-field ground motion, *Bull. Seismol. Soc. Am.*, **76**, 1790-1800.

MENDEZ, A. and F. PACOR (1994): A study of rupture characteristics of the 40 s subevent of the 1980 Irpinia earthquake, *Annali di Geofisica*, **37**, 1601-1620.

MENDEZ, A., F. PACOR, R. BERARDI and C. PETRUNGARO (1994): Strong motion modeling at a near-source site in Avezzano, Italy, in *Proceedings of the Second International Conference on Earthquake Resistant Construction and Design*, Berlin, 15-17 June 1994, edited by S.A. SAVIDIS (Balkema, Rotterdam), vol. 1, 61-68.

MENKE, W., A.L. LERNER-LAM, B. DUBENDORFF and J. PACHECO (1990): Polarization and coherence of 5 to 30 Hz seismic wave fields at a hard-rock site and their relevance to velocity heterogeneities in the crust, *Bull. Seismol. Soc. Am.*, **80**, 430-449.

MUCCIARELLI, M. and D. ALBARELLO (1994): Source effects, propagation and site effects in intensity patterns, in *Proceedings of the Second International Conference on Earthquake Resistant Construction and Design*, Berlin, 15-17 June 1994, edited by S.A. SAVIDIS (Balkema, Rotterdam), vol. 1, 35-43.

ODDONE E. (1915): Gli elementi fisici del grande terremoto marsicano-fucense del 13 gennaio 1915, *Boll. Soc. Sismol. It.*, **19**, 71-215.

REINKE, R.E. and B.W. STUMP (1988): Stochastic geologic effects on near-source ground motions in alluvium, *Bull. Seismol. Soc. Am.*, **78**, 1037-1058.

SPUDICH, P. and L.N. FRAZER (1984): Use of ray theory to calculâte high-frequency radiation from earthquake sources having spatially variable rupture velocity and stress drop, *Bull. Seismol. Soc. Am.*, **74**, 2061-2082.

WARD, S.N. and G.R. VALENSISE (1989): Fault parameters and slip distribution of the 1915 Avezzano, Italy earthquake derived from geodetic observations, *Bull. Seismol. Soc. Am.*, **79**, 690-710.