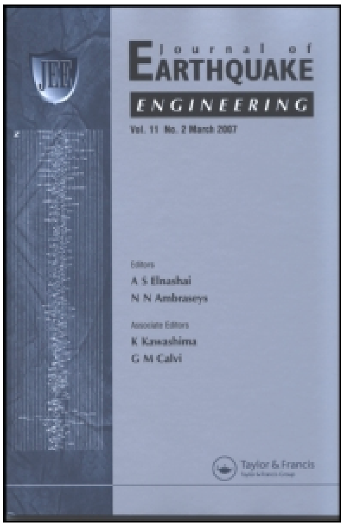

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Database for Earthquake Strong Motion Studies in Italy

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Database for Earthquake Strong Motion Studies in Italy

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We describe an Italian database of strong ground motion recordings and databanks delineating conditions at the instrument sites and characteristics of the seismic sources. The strong motion database consists of 247 corrected recordings from 89 earthquakes and 101 recording stations. Uncorrected recordings were drawn from public web sites and processed on a record-by-record basis using a procedure utilized in the Next-Generation Attenuation (NGA) project to remove instrument resonances, minimize noise effects through low- and high-pass filtering, and baseline correction. The number of available uncorrected recordings was reduced by 52% (mostly because of s-triggers) to arrive at the 247 recordings in the database. The site databank includes for every recording site the surface geology, a measurement or estimate of average shear wave velocity in the upper 30 m (V_{s30})*, and information on instrument housing. Of the 89 sites, 39 have on-site velocity measurements (17 of which were performed as part of this study using SASW techniques). For remaining sites, we estimate* V_{s30} *based on measurements on similar geologic conditions where available. Where no local velocity measurements are available, correlations with surface geology are used. Source parameters are drawn from databanks maintained (and recently updated) by Istituto Nazionale di Geofisica e Vulcanologia and include hypocenter location and magnitude for small events* ($M < \sim 5.5$) *and finite source parameters for larger events.*

Keywords Strong Motion; Database; Ground Motion Prediction Equations; Geophysics; Data Processing

1. Introduction

The characterization of earthquake ground motions for engineering applications generally involves the use of empirical models referred to as ground motion prediction equations (GMPEs) or attenuation relations. GMPEs describe the variation of particular intensity measures (such as peak acceleration, spectral acceleration, or duration) with magnitude, site-source distance, site condition, and other parameters. A review of GMPEs for peak acceleration and spectral acceleration available in the literature prior to 2003 is presented by Douglas [2003a]. The most recent GMPEs for crustal earthquakes in active regions were developed as part of the Next Generation Attenuation (NGA) project [Power *et al.*, 2008].

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Because most GMPEs are empirical, they are dependent on the databases utilized in their development. The development of GMPEs requires a database of strong motion accelerograms and their intensity measures, a databank of site conditions for accelerometers, and a databank of earthquake source parameters. Most of the available GMPEs utilize *inconsistent* databases and databanks, in the sense that the data are derived from different sources of variable quality. One of the major thrusts of the NGA project was to compile consistent strong motion, site, and source databases for the development of GMPEs applicable to shallow crustal earthquakes in tectonically active regions. This consistency took the form, for example, of consistent processing of all recordings, classification of geologic site conditions in uniform formats, and the compilation of source parameters systematically developed in a uniform format by a single agency.

The NGA GMPEs [Abrahamson and Silva, 2008; Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008; Chiou and Youngs, 2008; Idriss, 2008] are intended to be applicable to geographically diverse regions—the only constraint being that the region is tectonically active and the earthquake hypocentral depth is relatively shallow. The database involved is therefore large, consisting of 3,551 recordings from 173 earthquakes [Chiou *et al.*, 2008]. In some regions, there has been a preference towards the use of local GMPEs derived solely from data in that region. This practice has been particularly common in Europe [Bommer, 2006], with Italy and Greece being prominent examples. The current national hazard map for Italy [Working Group, 2004] was developed using slightly modified versions of an Italian GMPE [Sabetta and Pugliese, 1996], a European GMPE [Ambraseys *et al.*, 1996], and GMPEs for particular regions within Italy (e.g., Malagnini and Montaldo, 2004). These relations are based on relatively small databases—for example the Sabetta and Pugliese [1996] GMPE was derived from an Italian database of 95 recordings from 17 earthquakes. Local databases such as this are naturally smaller than world-wide databases, which has obvious implications for the relative robustness of the derived GMPEs.

A second major application of ground motion databases linked to site/source databanks (beyond the development of GMPEs) is for dynamic analyses of structural and geotechnical systems. Major recent research efforts have been directed towards providing guidance on ground motion selection and scaling [Goulet *et al.*, 2008]. The ground motion database utilized in those studies is generally the NGA database described by Chiou *et al.* [2008]. In Italy, dynamic analysis and design using accelerograms has been allowed for civil infrastructure since 2003 [OPCM 3274, 2003], although a recent seismic code [NTC, 2008] specifically requires the use of natural recordings in lieu of synthetic motions for geotechnical applications. There is an urgent need for a database/databank to facilitate such ground motion selection in Italy.

In this article, we critically examine the data resources available for the Italian region with respect to the above three attributes: ground motion, site, and source. We also describe the results of recent work to enhance the breadth, quality, and consistency of the strong motion database and site and source databanks. Our focus in this article is the database itself, not the development or validation of GMPEs for Italy or ground motion selection and scaling procedures.

2. Strong Motion Database

The first large Italian accelerometer network was installed starting from the mid-1970s by ENEL (Ente Nazionale Energia Elettrica). The array, acquired and developed by the Civil Protection Department (DPC: http://www.protezionecivile.it) since 1998, is now defined as RAN (Rete Accelerometrica Nazionale). Of the 298 RAN accelerometers, 130 are analog (e.g., Kinemetrics SMA-1 or RFT250) and the others are relatively modern digital instruments (i.e., Kinemetrics Altus ETNA, Altus Everest). Over time, the RAN analog instruments are being replaced with digital instruments, with the goal being a fully digital network. Other than RAN, additional, relatively small arrays are operated by various agencies including a research institute (Ente Nazionale Energia Ambiente, ENEA) and the University of Trieste.

Despite the increasing prevalence of digital instruments, most of the available strong motion recordings are from older analog instruments. Noise can significantly affect these recordings and limit their usable bandwidth. Moreover, data processing in the presence of this noise can significantly affect ground motion intensity measures evaluated from waveforms. Potential sources of noise and other errors in analog recordings include digitization noise, incorrect baseline, instrument resonance, and unknown initial conditions associated with unrecorded first arrivals of seismic waves (e.g., Boore and Bommer, 2005). Many of these noise sources are significantly reduced for digital instruments, but noise is still present and the useable bandwidth is finite. Hence, it is vital that consistent, rational protocols be employed during digitization, filtering, and baseline correction of recordings so that the processed signal is as reliable as possible, at least within a defined frequency range. Lacking such uniform procedures, the resulting signals have unknown and inconsistent levels of noise affecting the supposedly "corrected" signals.

Italian strong motion recordings can be found from a number of online sources and on compacts disks. Perhaps the most widely recognized source is Volume 1 of the European Strong Motion Database ESD [Ambraseys *et al*., 2004a; http://www.isesd.cv.ic.ac.uk/], which includes over 3,000 recordings including Italian data from ENEA, University of Trieste, and ENEL. Volume 1 ESD records are filtered at common corner frequencies of 0.25 Hz (high-pass) and 25 Hz (low-pass). An additional Volume 2 ESD database consists of 462 European records that were selected because they are of relatively high quality and have associated metadata [Ambraseys *et al*., 2004b]. The Volume 2 ESD records were processed using high-pass corner frequencies that were selected on a record-by-record basis.

Another source of Italian data, which is not publically available, was developed by SSN (Servizio Sismico Nazionale) and ENEA [Paciello *et al*., 1997] and contains ENEA and ENEL recordings that were filtered using high-pass and low-pass corner frequencies selected on a record-by-record basis so as to optimize signal-to-noise ratio [Rinaldis, 2004]. Since the formation of RAN, data from major earthquakes in Italy (namely, 1997–1998 Umbria-Marche and 2002 Molise seismic sequences) are distributed on CDROMs published by SSN [2002] and DPC [2004]. All of the available data (except University of Trieste stations) has recently been assembled by INGV and DPC [Working Group S6, 2007], who also re-processed the data according to a procedure that included baseline correction, instrument correction (for analog signals), and record-by-record filtering (although a consistent low pass filter was applied at 25–30 Hz for all analogue instruments).

For this study, a total of 509 uncorrected (but digitized) 3-component recordings from 100 earthquakes with magnitude >3.7 and 160 different recording stations were downloaded in March 2005. Those data are derived from the Volume 1 ESD database for events from 1972–1998 (479 three-component recordings) and from DPC [2004] for recordings of the 2002 Molise seismic sequence from the RAN array (30 three-component recordings). Our database is comprised solely of data that was available from the aforementioned sources in March 2005. We chose the Volume 1 ESD database so as to be inclusive of the maximum possible number of Italian records.

The downloaded data were then processed in 2005 by the same seismologists responsible for the NGA data processing (Dr. Walter Silva and colleagues). This was done so that the Italian strong motion data set would be compatible with the NGA data in terms of data quality and in the definitions of usable bandwidth on a record-by-record basis. This processing was performed on uncorrected data and included filtering (including instrument corrections), integration of accelerograms to velocity and displacement histories, and baseline correction according to procedures described by Darragh *et al.* [2004]. Pseudo-acceleration response spectral ordinates at 5% damping were also computed.

This processing reduced the size of the usable database to 247 recordings from 89 earthquakes and 101 different recording sites. Figure 1 shows the distribution of the recording sites across Italy. This significant reduction of the number of recordings (by 52%) relative to the uncorrected data results from delayed triggering of analog instruments during shaking associated with shear waves (referred to as S-triggers). Figure 2 shows an example of an S-triggered record from the 1997 Umbria-Marche earthquake. As shown by Douglas [2003b], S-triggered records can have biased response spectral accelerations, and hence it is preferred that such records not be used for strong motion studies.

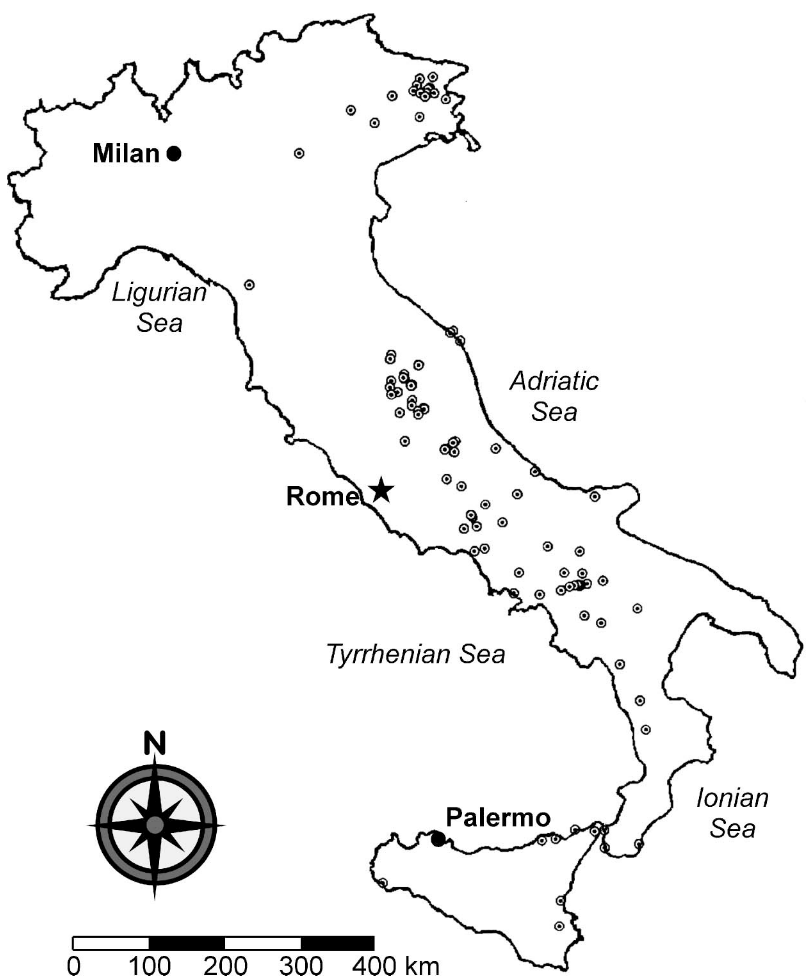

FIGURE 1 Spatial distribution of recording stations included in the database.

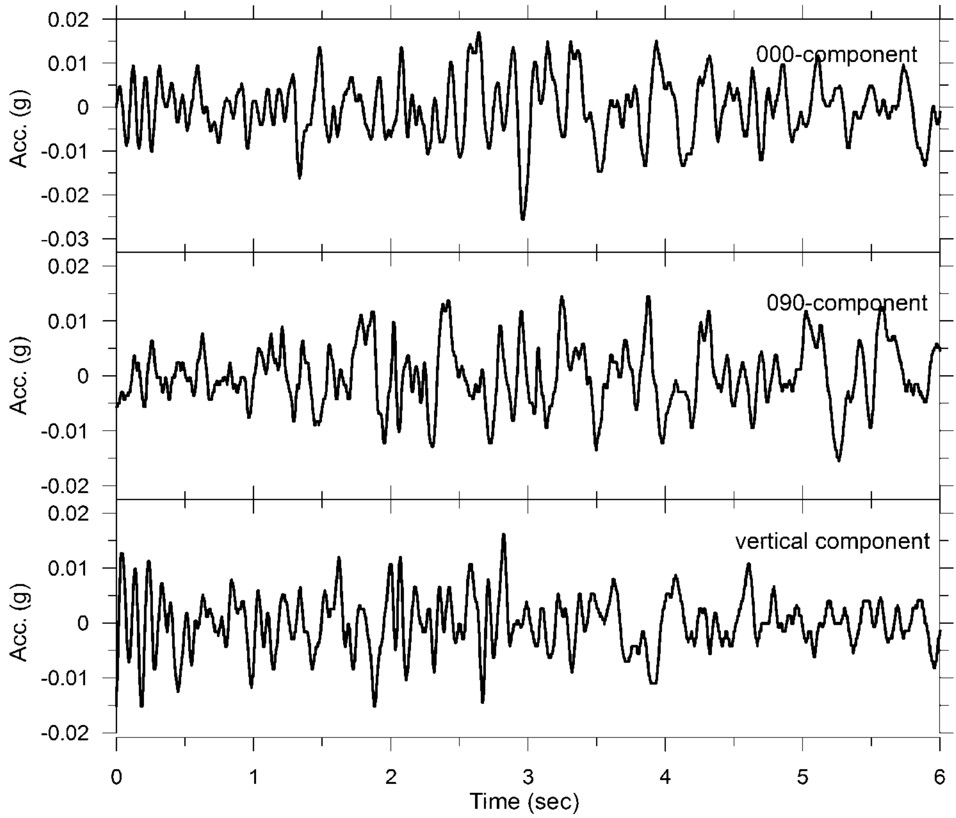

FIGURE 2 Example of S-triggered strong motion recording, Cascia station from 1997 Umbria-Marche earthquake.

In Figs. 3–6, we compare several recordings processed as part of this study (labeled as "PEER," which is short for "Pacific Earthquake Engineering Research Center") to the processed records from the Volume 1 ESD database. Figure 3 shows an example of "wobble" of a displacement history double-integrated from a processed Volume 1 ESD accelerogram. The differences in filter characteristics do not significantly affect peak acceleration, but produce noticeable differences in peak velocity and displacement, which represent intensity measures sensitive to longer-period components of the waveform. Figure 4 shows Fourier amplitude spectra and 5%-damped pseudo acceleration response spectra for this same recording. The Fourier spectra show similar amplitudes across the frequency range of 1–15 Hz. At higher frequencies, the PEER amplitudes generally exceed those from Volume 1 ESD due to a higher Nyquist frequency (100 Hz for PEER versus 25 Hz for ESD). However, these differences occur at relatively low values of Fourier amplitude ($< 10^{-4}$ g $\times$ sec), and do not significantly affect intensity measures of typical engineering interest such as peak quantities (acceleration, velocity, displacement) or spectral accelerations. On the other hand, at lower frequencies, the PEER amplitudes are significantly smaller than ESD due to differences in high-pass filtering and baseline correction, and the effected Fourier amplitudes are relatively large (approximately 10^{-3} g $\times$ sec). Those differences in the low frequency components of the waveform result in different values of peak velocity and displacement (Fig. 3) and spectral acceleration for periods

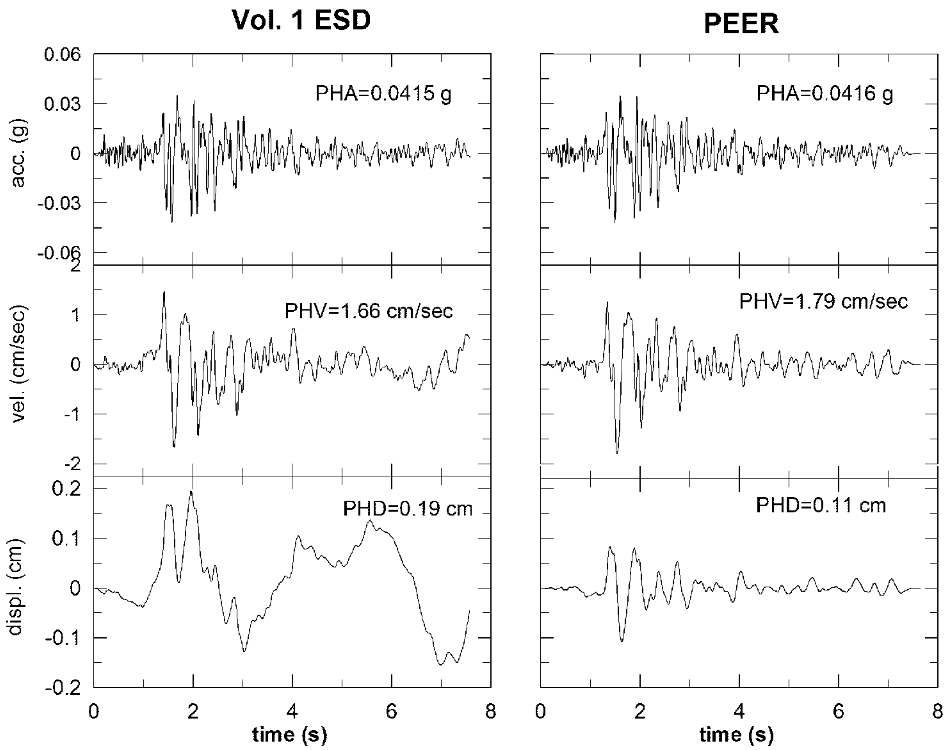

FIGURE 3 Comparison between Vol. 1 ESD- and PEER-corrected waveforms using accelerometer recording at the Genio Civile station during the 1972 M_L = 4.7 Ancona earthquake.

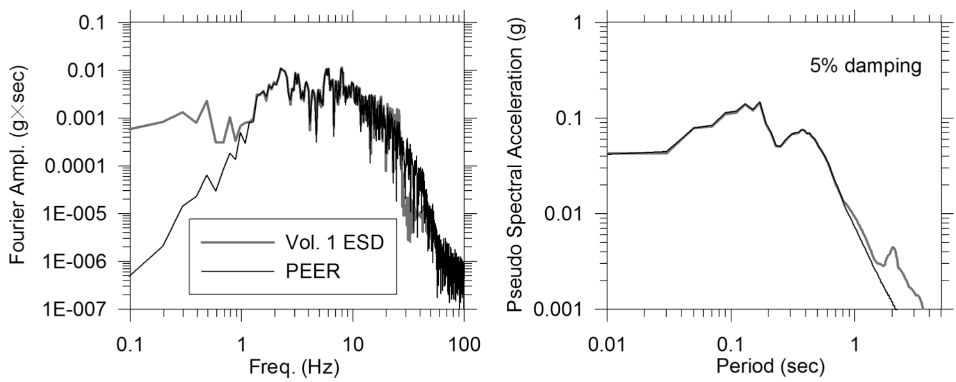

FIGURE 4 Comparison between Fourier and pseudo acceleration response spectra calculated from Vol. 1 ESD- and PEER-corrected accelerograms using data from the Genio Civile station during the 1972 M_L = 4.7 Ancona earthquake.

$T > 0.8$ sec. Because the Volume 1 ESD waveform is richer in low-frequency energy, the long-period spectral accelerations are higher for Volume 1 ESD than for PEER processing. Akkar and Bommer [2007] had similar observations regarding ESD data processing to those noted above.

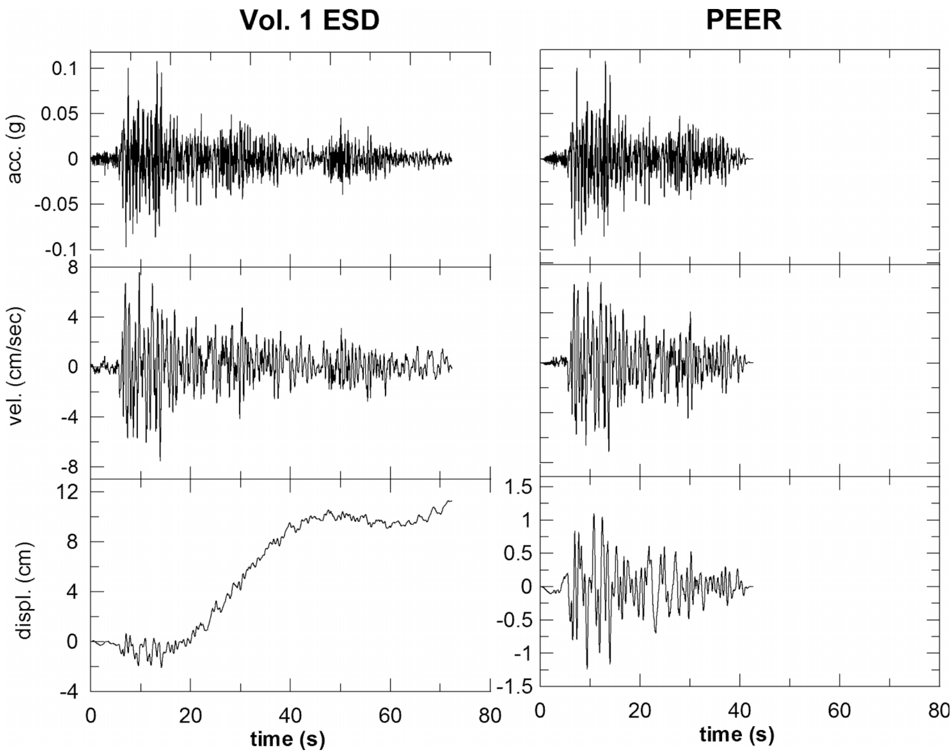

FIGURE 5 Comparison between Vol. 1 ESD- and PEER-corrected waveforms using accelerometer recording at the Mercato Sanseverino station during the 1980 M_w = 6.9 Irpinia earthquake. The uncorrected data and ESD processed data are interpreted to contain multiple triggering events.

Some of the uncorrected data contain multiple events within the acceleration histories. Waveforms from secondary events were generally removed in the PEER processing but were retained in Volume 1 ESD processing. This situation is evident in recordings of the M_w = 6.9 1980 Irpinia Mainshock, as shown in Fig. 5. It is not clear that the second event in the ESD data affected amplitude-related parameters (PHV, PHD, spectral acceleration) beyond the previously noted effects related to low-frequency energy content. However, the duration is clearly affected.

To evaluate potential for bias between the two datasets, we compare intensity measures calculated using the ESD and PEER databases in Fig. 6. Parts a-b utilize the Volume 1 ESD data whereas Parts c-d utilize the Volume 2 ESD data. Note that there are a number of records for which the Volume 1 ESD data have higher ordinates that PEER, whereas the Volume 2 data are more comparable to PEER. This is expected, because both the Volume 2 ESD and PEER records were filtered on a record-specific basis. Our opinion is that both databases can be used with confidence, although the PEER database contains a larger number of Italian records (247 records from 89 earthquakes versus 174 records from 37 earthquakes in Volume 2 ESD). On the other hand, the processed data from Volume 1 ESD should be used with caution because of the potential for errors of the type described above.

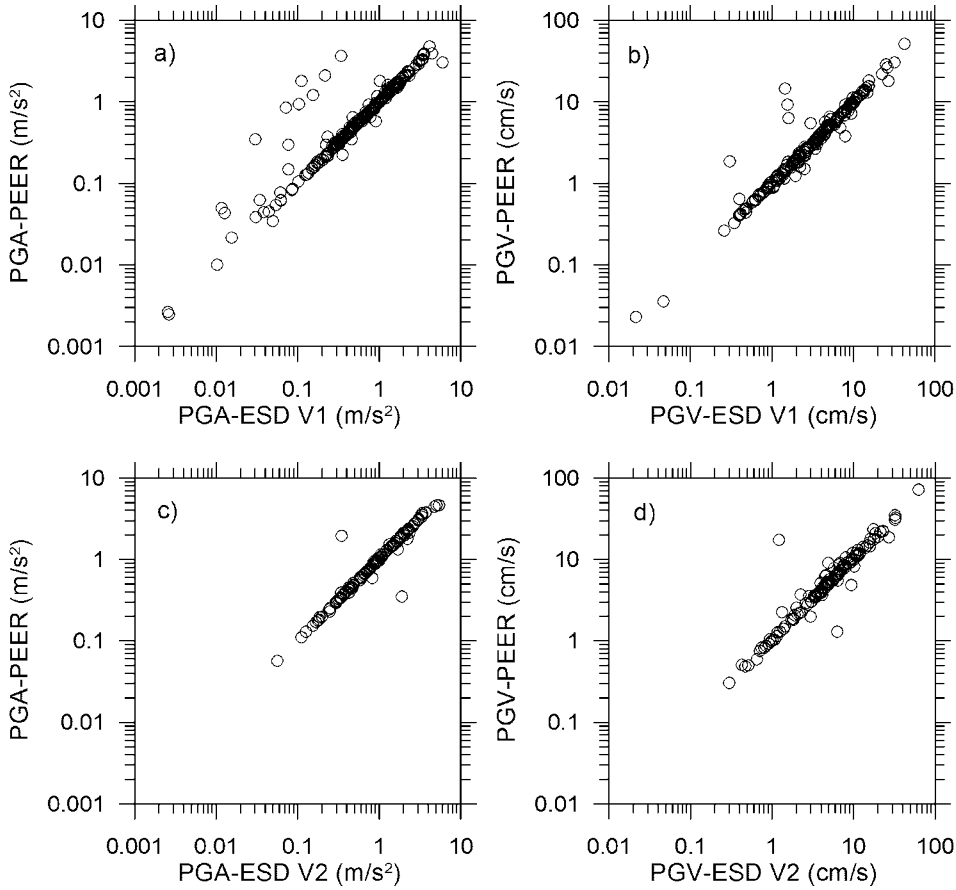

FIGURE 6 Comparison of peak accelerations and velocities for corrected records in the ESD and PEER databases. Parts a-b apply for the Vol. 1 ESD database and Parts c-d apply for ESD Vol. 2.

3. Site Databank

Attributes of the recording sites that are important for the development of GMPEs and ground motion selection include the geotechnical site conditions and the instrument housing. These attributes are discussed in the following sub-sections. The site databank compiled for this study is for Italian strong motion stations that have produced the 247 recordings referenced in the previous section (101 sites).

3.1. Geotechnical Site Characterization for GMPEs: General Considerations

Wave propagation theory suggests that ground motion amplitude should depend on the density and shear wave velocity of near-surface media (e.g., Bullen, 1965; Aki and Richards, 1980). Density has relatively little variation with depth, and so shear wave velocity is the logical choice for representing site conditions. Two methods have been proposed for representing depth-dependent velocity profiles with a single representative value. The first takes the velocity over the depth range corresponding to one-quarter wavelength of the period of interest [Joyner *et al.*, 1981], which produces frequency-dependent values. A practical problem with the quarter wavelength V_s parameter is that the associated depths are often deeper than can economically be reached with boreholes. A practical alternative is the average shear wave velocity in the upper 30 m of the site (V_{s30}), which has found widespread application.

Based on empirical studies by Borcherdt and Glassmoyer [1994], Borcherdt [1994] recommended V_{s30} as a means of classifying sites for building codes, and similar site categories were selected for the NEHRP seismic design provisions for new buildings [Dobry *et al.*, 2000]. GMPEs have since been developed that incorporate V_{s30} as the site parameter, including each of the NGA GMPEs except Idriss [2008]. To develop those GMPEs, each site in the NGA database was assigned a V_{s30} value, with approximately 1/3 coming from on-site measurements and 2/3 coming from correlations with other, more readily available site information.

In the development of the NGA database, protocols were followed for estimating V_{s30} when on-site measurements (extending to a depth of at least 20 m) are not available. Those protocols are as follows [Borcherdt, 2002]:

1. Velocity estimated based on nearby measurements on same geologic formation (site conditions verified based on site visit by geologist).
2. Velocity estimated based on measurements on same geologic unit at site judged to have similar characteristics based on site visit by geologist.
3. Velocity estimated based on average shear wave velocity for the local geologic unit; presence of the unit verified based on site visit by geologist.
4. Velocity estimated based on average shear wave velocity for the geologic unit as evaluated from local geologic map (1:24,000–1:100,000).
5. Velocity estimated based on average shear wave velocity for the geologic unit as evaluated from regional geologic map (1:250,000–1:750,000).

We adopt similar procedures for estimation of V_{s30} at Italian strong motion stations with the results given in Table 1. Each site has been assigned a V_{s30} value in the table along with an index pertaining to how the value was derived. Those indices are defined as:

- Category A: Velocity measured on-site using cross-hole, down-hole, or spectral analysis of surface wave methods;
- Category B: Velocity estimated based on nearby measurements on same geologic formation (site conditions verified based on site visit by geologist). This is similar to Categories (1)–(2) by Borcherdt [2002].
- Category C: Velocity estimated based on measurements from the same geologic unit as that present at the site (based on local geologic map). This is similar to Categories (2)–(3) by Borcherdt [2002].
- Category D: Velocity estimated based on general (non local) correlation relationships between mean shear wave velocity and surface geology.

The following three sections describe how velocities were assigned to strong motion sites. As described in the next section, for 36 sites, velocity profiles from the literature and the files of practicing engineers, geologists, and public agencies are used to assign V_{s30} values compatible with Categories A, B, or C. We then describe velocity profiling performed for 17 additional sites as part of this study (Category A). Next, we describe how V_{s30} values are assigned on the basis of surface geology for the remaining 48 sites.

3.2. Site Conditions for Italian Strong Motion Stations – Data from Others

Previous site characterization for Italian strong motion stations can be grouped into the following major categories: (1) investigations at selected instrument sites that recorded the 1976 Friuli earthquake [Fontanive *et al.*, 1985] and 1980 Irpinia earthquake [Palazzo, 1991a, b; Faccioli, 1992]; (2) microzonation and other studies for local municipalities such as Ancona [Working Group, 1981], Tarcento [Brambati *et al.*, 1979], and San Agapito [Isernia Administration, 1998]; and (3) individual site studies documented in the literature (e.g., Catania-Piana site, Frenna and Maugeri, 1993) and from the files of consulting engineers and geologists with local experience (e.g., Naso station; personal communication, G. Copat, 2007).

The Friuli and Irpinia site investigations were generally performed at the recording sites and are listed in Table 1 as Category A. The work in the Friuli region examined seven accelerograph sites. For each site, two boreholes were drilled to 60 m depth and cross-hole measurements were made to evaluate shear wave velocity profiles. Additional on-site tests included seismic refraction measurements to estimate the p-wave profile. The Irpinia investigation examined 16 strong motion stations. Two boreholes were drilled to 100 m depth at each site and cross-hole measurements were made to profile shear wave velocity. Additional in situ and geotechnical laboratory testing was also performed.

The microzonation and individual site studies were used to assign velocities to strong motion stations that are listed as Categories A-C depending on the proximity of the measurement to the strong motion station and the verification, from a site visit by a geologist, of similar geologic conditions (or lack thereof) at the two locations. Most of these velocity profiles are from cross-hole or down-hole measurements.

3.3. Velocity Measurements from this Study at Italian Strong Motion Stations

The 1997–1998 Umbria-Marche earthquake sequence produced a significant number of recordings, but prior to this study velocity profiles had been evaluated and disseminated for relatively few of the recording sites in that region. Accordingly, on-site measurements were performed at numerous sites using a controlled sine wave source and the spectral analysis of surface waves (SASW) method [Heisey *et al.*, 1982; Nazarian and Stokoe, 1983]. The SASW method of testing is a portable, inexpensive, and efficient means of non invasively estimating the stiffness properties of the ground. The equipment utilized in the present work can typically be used to profile velocities to depths of approximately 40 m. Although the SASW technique is widely known, we describe in some detail here the specific procedures used for this study, since it has not been published previously outside of the grey literature. Additional details on this work, including full results for each investigated site, are presented in Kayen *et al.* [2008].

The testing program investigated 17 sites in Umbria and Marche. Typically, the strong motion recording (SMR) stations are located in residential or light industrial sites outside the town center, in parks, or on private farm land. We located next to the SMR stations, or the GPS location of the site if we could not observe the SMR.

We performed profiling using a surface wave testing system to collect dispersion data. The equipment consists of 1-Hz seismometers, a low-frequency spectrum analyzer, two computer controlled electro-mechanical harmonic-wave sources (shakers) and their amplifiers, cables, and approximately 4.0 kW of total electrical output from generators made available in each test region. The 1-Hz Kinemetrics receivers we used are designed for capturing vertical motions and cover the frequency range of interest in the active-source surface-wave test (1–100 Hz). The source consists of two APS Dynamics Model 400 electro-mechanical shakers that produce in-phase continuous harmonic vertical excitation of the ground. The shakers are controlled by the spectrum analyzer, which produces a sine wave signal that is split into a parallel circuit through two separate power amplifiers that interface with the shakers. Two receivers record the waves and in near-real

TABLE 1 Data on geologic condition, seismic velocity, and instrument housing at selected Italian strong motion recording sites

	Station				Geology					V_{s30} (m/sec)						
#	Name	Agency	Latitude	Longitude	Age	Description	Scale (plan/section)	Wills-Clahan class.	Our class.	Source (1)	Type	Measured	Estimated	Preferred	Reference	Housing (2)
1	Ancona-Palombina	ENEA	43.602	13.474	Pleistocene	clay with silt and sand	1:50000 / 1:2000	QT		A	CH	256	455	256	Working group (1981)	SB
2	Ancona-Rocca	ENEA	43.621	13.513	Miocene	marls	1:50000 / 1:2000		Tm	A	CH	549	680	549	Working group (1981)	SB
3	Aquilpark-Citta	DPC	42.346	13.401	Pleistocene	coarse alluvium	local	QT		C			455	455		FF
4	Aquilpark-Galleria	DPC	42.346	13.401	Pleistocene	coarse alluvium	local	QT		C			455	455		T
5	Aquilpark-Parcheggio	DPC	42.346	13.401	Pleistocene	coarse alluvium	local	QT		C			455	455		SB
6	Arienzo	DPC	41.027	14.469	Pleistocene	cinerities, pyroclastic and conoid material (5m), campanian ignimbrite, overlying limestones of campano-lucana platform	1:50000 / 1:2000		Mv	A	CH	905	1000	905	Palazzo (1991)	CA
7	Assergi	DPC	42.42	13.52	Tertiary	sandy clay and marls	1:50000 / 1:2000		Tm	C			680	680		CA
8	Assisi-Stallone	DPC	43.075	12.607	Cretaceous	limestone and marls	1:50000 / 1:2000		Ml	C			1000	1000		SB
9	Atina	ENEA	41.620	13.801	Jurassic	dolomitic limestone	1:50000 / 1:2000		Ml	C			1000	1000		CA
10	Atina-Pretura Piano Terra	ENEA	41.645	13.783	Miocene	clay and clay with marls with layers of gray and yellow sandstone	1:50000 / 1:2000		Tm	C			680	680		SB
11	Atina-Pretura Terrazza	ENEA	41.645	13.783	Miocene	clay and clay with marls with layers of gray and yellow sandstone	1:50000 / 1:2000		Tm	C			680	680		SB
12	Auletta	DPC	40.556	15.395	Pliocene	lacustrine and deltaic polygenic conglomerate with sandy-clay cement	1:50000 / 1:2000		Pc	A	CH	1156	1000	1156	Palazzo (1991)	CA
13	Avezzano	DPC	42.03	13.43	Quaternary	lacustrine	1:100000	Qi		B	CH	120	160	120	A.G.I. (1991)	CA
14	Bagnoli-Irpino	DPC	40.831	15.068	Cretaceous	limestone	1:50000 / 1:2000		Ml	A	CH	1163	1000	1163	Palazzo (1991)	CA
15	Barcis	DPC	46.187	12.554	Holocene	debris on marls	1:50000 / 1:2000	Qal,coarse		D			354	354		CA
16	Barga	DPC	44.068	10.461	Pleistocene	coarse non cemented alluvium deposit on gravel and conglomerate	1:50000 / 1:2000	Qoa		D			387	387		CA

17	Bevagna	DPC	42.932	12.611	Holocene	Alluvium and palustrine clay and clay/sand deposits	1:50000 / 1:2000	Qi		A	SASW	182	160	182	This study	CA
18	Bisaccia	DPC	41.010	15.376	Pliocene	cemented conglomerate with sandy thin layers	1:50000 / 1:2000		Pc	A	CH	972	1000	972	Palazzo (1991)	CA
19	Borgo-Cerreto Torre	ENEA	42.814	12.915	Tertiary	limestone	1:50000 / 1:2000		Ml	C			1000	1000		SB
20	Bovino	DPC	41.249	15.342	Pliocene	sand and sandstone with conglomerate and sandy clay	1:50000 / 1:2000	QT		A	CH	356	455	356	Palazzo (1991)	CA
21	Brienza	DPC	40.472	15.634	Holocene	recent alluvium on red flysch	1:50000 / 1:2000	Qal,coarse		A	CH	516	354	516	Palazzo (1991)	CA
22	Buia	ENEA	46.222	13.090	Holocene	alternance of gravels and pebbles, mix of gravelly sand and silty sand	1:50000 / 1:2000	Qal,coarse		A	CH	254	354	254	Fontanive et al. (1985)	CA
23	Cairano 1	DPC	40.890	15.296	Pliocene	marls	1:50000 / 1:2000		Tm	C		625	680	625	Faccioli (1992)	CA
24	Cairano 2	DPC	40.887	15.312	Pliocene	marls	1:50000 / 1:2000		Tm	C		625	680	625	Faccioli (1992)	CA
25	Cairano 3	DPC	40.887	15.334	Pliocene	marls	1:50000 / 1:2000		Tm	C		625	680	625	Faccioli (1992)	CA
26	Cairano 4	DPC	40.886	15.348	Pliocene	marls	1:50000 / 1:2000		Tm	C		625	680	625	Faccioli (1992)	CA
27	Calitri	DPC	40.898	15.439	Pliocene	sandstone, sand with levels of marls	1:50000 / 1:2000	Tss		A	CH	518	515	518	Palazzo (1991)	CA
28	Cascia	DPC	42.719	13.013	Oligocene	marls	1:50000 / 1:2000		Tm	A	SASW	760	680	760	This study	SB
29	Cascia-Cabina Petrucci	DPC	42.755	13.004	Pleistocene	sandy and gravelly deposit	1:100000	Qoa		A	SASW	430	387	430	This study	SB
30	Cassino-Sant' Elia	ENEA	41.523	13.864	Miocene	clay and clay with marls with layers of gray and yellow sandstone	1:50000 / 1:2000		Tm	C			680	680		CA
31	Castelnuovo-Assisi	DPC	43.007	12.591	Holocene	recent alluvium of clay layers on sands and silt	1:50000 / 1:2000	Qal,deep		A	SASW	288	280	288	This study	CA
32	Castiglione Messer Marino	DPC	41.868	14.449	Miocene	marls	1:100000		Tm	C			680	680		CA
33	Catania-Piana	DPC	37.447	15.047	Holocene	alluvium clayey and sandy deposit on Pleistocene clay	1:50000 / 1:2000	Qal,deep		A	CH	261	280	261	Frenna & Maugeri (1993)	CA
34	Chieti	DPC	42.36	14.14	Quaternary	gray clay and marls	1:100000	Qoa		D			387	387		CA
35	Codroipo	DPC	45.959	12.984	Quaternary	coarse gravelly alluvium	1:50000 / 1:2000	Qoa		D			387	387		CA
36	Colfiorito	DPC	43.037	12.921	Pleistocene	lacustrine	1:50000 / 1:2000	Qi		A	SASW	168	160	168	This study	CA

(*Continued*)

TABLE 1 (*Continued*)

	Station				Geology					V_{s30} (m/sec)						
#	Name	Agency	Latitude	Longitude	Age	Description	Scale (plan/section)	Wills-Clahan class.	Our class.	Source (1)	Type	Measured	Estimated	Preferred	Reference	Housing (2)
37	Colfiorito-Casermette	DPC	43.028	12.900	Holocene	lacustrine and fluvial-lacustrine sandy-clayey sediments	1:100000	Qi		A	SASW	296	160	296	This study	SB
38	Conegliano Veneto	DPC	45.883	12.288	Quaternary	gravely alluvium	1:50000 / 1:2000	Qoa		D			387	387		CA
39	Contrada Fiumicella-Teora	ENEA	40.881	15.255	Pleistocene	alluvium	1:100000	Qoa		D			387	387		FF
40	Conza-Base	DPC	40.875	15.327	Pliocene	marls and clay	1:50000 / 1:2000		Tm	C		625	680	625	Faccioli (1992)	CA
41	Conza-Vetta	DPC	40.872	15.329	Pliocene	gravely and sandy conglomerate on Pliocene clay	1:50000 / 1:2000	QT		D		406	455	406	Faccioli (1992)	CA
42	Cosenza	DPC	39.304	16.247	Pleistocene	gray clays	1:50000 / 1:2000	QT		D			455	455		CA
43	Feltre	DPC	46.019	11.912	Holocene	recent sandy-silty alluvium on Quaternary deposit	1:50000 / 1:2000	Qal,coarse		D			354	354		CA
44	Ferruzzano	DPC	38.051	16.132	Miocene	varicoloured clay	1:100000		Tm	C			680	680		CA
45	Foligno Santa Maria Infraportas-Base	ENEA	42.955	12.704	Holocene	recent alluvium	1:50000 / 1:2000	Qal,deep		A	SASW	380	280	380	This study	SB
46	Forgaria-Cornino	ENEA	46.221	12.997	Pleistocene	Pleistocene alluvium deposit (50 m) on Miocene marls and sandstone	1:50000 / 1:2000	Qoa		A	CH	454	387	454	Fontanive et al. (1985)	CA
47	Garigliano-Centrale Nuc. 1	DPC	41.258	13.833	Holocene	alluvium deposit	1:50000 / 1:2000	Qal,deep		A	CH	187	280	187	Palazzo (1991)	CA
48	Garigliano-Centrale Nuc. 2	DPC	41.258	13.833	Holocene	alluvium deposit	1:50000 / 1:2000	Qal,deep		A	CH	187	280	187	Palazzo (1991)	CA
49	Gemona-Li Furmie	trieste univ	46.267	13.115	Oligocene	gravel, sand and silt	1:50000 / 1:2000	Qal,coarse		D			354	354		n.r.
50	Gemona-Scugelars	trieste univ	46.283	13.142	Oligocene	gravel, sand and silt	1:100000	Qal,coarse		D			354	354		n.r.
51	Genio-Civile	DPC	43.623	13.516	Miocene	marls	local		Tm	B	CH	549	680	549	Working group (1981)	SB
52	Gubbio	DPC	43.357	12.602	Miocene	marls with levels of sandstone	1:50000 / 1:2000		Tm	A	SASW	922	680	922	This study	CA
53	Gubbio-Piana	DPC	43.313	12.589	Pleistocene	alluvium	1:50000 / 1:2000	Qoa		A	SASW	281	387	281	This study	CA
54	Lab.Gran Sasso	DPC	42.436	13.554	Eocene	limestone	1:100000		Ml	C			1000	1000		SB
55	Lauria-Galdo	DPC	40.021	15.89	Jurassic	limestone	1:50000 / 1:2000		Ml	C			1000	1000		CA
56	Maiano-Piano Terra	DPC	46.187	13.069	Holocene	gravely alluvium with sand and silt	1:50000 / 1:2000	Qal,coarse		A	CH	344	354	344	Palazzo (1991)	SB

57	Maiano-Prato	DPC	46.187	13.069	Holocene	gravely alluvium with sand and silt	1:100000	Qal,coarse		A	CH	344	354	344	Palazzo (1991)	FF
58	Matelica	DPC	43.249	13.007	Pleistocene	gravely and sandy alluvium	1:50000 / 1:2000	Qoa		A	SASW	491	387	491	This study	CA
59	Mazara del Vallo	DPC	37.653	12.611	Pleistocene	cemented deposit	1:100000		Pc	C			1000	1000		CA
60	Mercato San Severino	DPC	40.789	14.763	Holocene	recent alluvium (20m) on volcanic rock(20m) on recent alluvium (20m) on limestone	1:50000 / 1:2000	Qal,thin		A	CH	451	349	451	Palazzo (1991)	CA
61	Messina 1	DPC	38.207	15.516	Pre-triassic	volcanic and metamorphic rock	1:100000		Mg	B	CH	1800	1000	1000	Baldovini et al. (1993)	CA
62	Milazzo	DPC	38.232	15.244	Pre-triassic	metamorphic rock	1:50000 / 1:2000		Mg	B	CH	1800	1000	1000	Baldovini et al. (1993)	CA
63	Moggio	trieste univ	46.406	13.189	Triassic	limestone	1:100000		Ml	C			1000	1000		CA
64	Naso	DPC	38.119	14.786	Pliocene	clayey sand and conglomerate	1:100000	QT		B	DH	223	455	223	Dott. Copat. Personal com.	CA
65	Nocera Umbra	DPC	43.113	12.785	Miocene	sandstone on marls	1:100000	Tss		A	SASW	477	515	477	This study	CA
66	Nocera Umbra 2	DPC	43.113	12.785	Miocene	sandstone on marls	1:100000	Tss		A	SASW	477	515	477	This study	CA
67	Nocera Umbra-Biscontini	DPC	43.103	12.805	Miocene	sandstone on marls	local	Tss		A	SASW	393	515	393	This study	n.r.
68	Nocera Umbra-Salmata	DPC	43.149	12.797	Holocene	detritus	1:50000 / 1:2000	Qal,coarse		A	SASW	585	354	585	This study	CA
69	Norcia	DPC	42.791	13.096	Pleistocene	sandy and gravely alluvium and detritus	1:50000 / 1:2000	Qoa		A	SASW	568	387	568	This study	CA
70	Norcia-Altavilla	ENEA	42.796	13.089	Quaternary	recent alluvium, palustrine and lacustrine deposit	1:50000 / 1:2000	Qi		A	SASW	218	160	218	This study	SB
71	Norcia-Zona Industriale	ENEA	42.775	13.097	Quaternary	lacustrine with fluvial gravels possibly overlying marl	1:50000 / 1:2000	Qal,thin		A	SASW	508	349	508	This study	CA
72	Ortucchio	DPC	41.953	13.642	Holocene	sandy-clayey recent alluvium, locally gravely	1:50000 / 1:2000	Qal,coarse		D			354	354		CA
73	Patti-Cabina Prima	DPC	38.134	14.976	Miocene	sandy limestone	1:50000 / 1:2000		Tm	C			680	680		CA
74	Pellaro	DPC	38.024	15.654	Holocene	weak alluvium fixed by vegetation on marls	1:100000	Qal,thin		D			349	349		CA
75	Poggio-Picenze	DPC	42.322	13.540	Pleistocene	alteration of silt and breccias	1:50000 / 1:2000	QT		D			455	455		CA

(Continued)

TABLE 1 (*Continued*)

#	Station: Name	Agency	Latitude	Longitude	Geology: Age	Description	Scale (plan/section)	Wills-Clahan class.	Our class.	V_{s30} (m/sec): Source (1)	Type	Measured	Estimated	Preferred	Reference	Housing (2)
76	Ponte Corvo	DPC	41.499	13.683	Pleistocene	limestone and sandstone	1:50000 / 1:2000		Ml	C			1000	1000		CA
77	Pradis	trieste univ	46.248	12.888	Cretaceous	limestone	1:50000 / 1:2000		Ml	C			1000	1000		CA
78	Procisa Nuova	ENEA	40.87	15.190	Pleistocene	recent alluvium	1:100000	Qoa		D			387	387		CA
79	Rieti	DPC	42.430	12.821	Holocene	alluvium deposit	1:100000	Qal,deep		D			280	280		CA
80	Rionero in Vulture	DPC	40.927	15.669	Pleistocene	volcanic silt and gravel	1:50000 / 1:2000	Qoa		A	CH	539	387	539	Palazzo (1991)	CA
81	Roccamonfina	DPC	41.287	13.980	Holocene	weakly cemented detritus (10m) on volcanic rock	1:100000	Qal, coarse		D			354	354		CA
82	Roggiano-Gravina	DPC	39.619	16.171	Pliocene	sand and conglomerate weakly cemented	1:100000	QT		D			455	455		CA
83	San Agapito	DPC	41.567	14.233	Pleistocene	alluvium deposit	local	QT		B	DH	553	455	553	Isernia Adm: Microzo-nation	CA
84	San Francesco	trieste univ	46.309	12.935	Triassic	limestone	1:100000		Ml	C			1000	1000		CA
85	San Marco dei Cavoti	DPC	41.306	14.880	Miocene	yellow sand and sandstone	1:100000	Tss		D			515	515		CA
86	San Rocco	ENEA	46.221	12.997	Cretaceous	limestone	1:50000 / 1:2000		Ml	C		600	1000	600	Fontanive et al. (1985)	FF
87	Sannicandro	DPC	41.833	15.572	Pleistocene	silty clay	local		Tm	A	CH	865	680	865	Palazzo (1991)	CA
88	Sellano Ovest	DPC	42.87	12.92	Miocene	marls	local		Tm	A	SASW	503	680	503	This study	CA
89	Sirolo	DPC	43.517	13.619	Miocene	marls with weak level on top	1:50000 / 1:2000		Tm	C			680	680		CA
90	Sortino	DPC	37.163	15.030	Miocene	volcanic rock (15m) on limestone	1:50000 / 1:2000		Mv	C			1000	1000		CA
91	Spoleto	DPC	42.736	12.737	Pleistocene	cemented conglomerate	borehole		Pc	C			1000	1000		CA
92	Sturno	DPC	41.021	15.115	Oliogocene	clay and marls	1:50000 / 1:2000		Tm	A	CH	1134	680	1134	Palazzo (1991)	CA
93	Tarcento	DPC	46.226	13.210	Holocene	sandy deposit (10m) on marls and sandstone	1:50000 / 1:2000	Qal,coarse		A	CH	540	354	540	Brambati et al (1979)	CA
94	Tolmezzo-Diga Ambiesta	DPC	46.382	12.982	Cretaceous	limestone	1:50000 / 1:2000		Ml	A	CH	1092	1000	1092	Fontanive et al. (1985)	D

95	Torre del Greco	DPC	40.797	14.383	Holocene	weak volcanic rock (high voids)	1:50000 / 1:2000		Mv	C			1000	1000		CA
96	Tregnago	DPC	45.525	11.134	Cretaceous	limestone	1:50000 / 1:2000		Ml	C			1000	1000		CA
97	Tricarico	DPC	40.619	16.156	Miocene	fractured limestone and marls	1:50000 / 1:2000		Tm	A	CH	446	680	446	Palazzo (1991)	CA
98	Valle	trieste univ	46.158	13.393	Eocene	marls and sandstone in alteration with limestone breccias	1:100000		Tm	C			680	680		CA
99	Vasto	DPC	42.111	14.710	Pleistocene	yellow sand in alteration with sandy clay	1:100000	Qoa		D			387	387		CA
100	Villa San Giovanni	DPC	38.216	15.647	Pleistocene	conglomerate	1:50000 / 1:2000		Pc	C			1000	1000		CA
101	Villetta Barrea	DPC	41.759	13.989	Cretaceous	limestone	1:50000 / 1:2000		Ml	C			1000	1000		D

(1) A = direct investigation (Cross-Hole, Down-Hole, SASW).

B = info from investigations on same area and same material.

C = info from investigfations on same formation.

D = info from literature.

(2) FF = Free Field.

CA = ENEL/ENEA Cabin ($3 < H < 5$ m; $1.5 \times 1.5 < A < 3 \times 3$ m^2).

SB = Structure Basement.

D = Dam.

T = Tunnel.

time, the Fourier spectra, cross power spectra, and coherence are computed. The ability to perform near real-time frequency domain calculations and monitor the progress and quality of the test allows us to adjust various aspects of the test to optimize the capture of phase data. These aspects include the source-wave generation, frequency step-size between each sine-wave burst, number of cycles-per-frequency, total frequency range of all the steps, and receiver spacing.

The dual shaker-sources are arrayed orthogonally to the SASW seismometer line. The test steps through a suite of frequencies, and for each frequency phase computations are made. This method of swept-sine surface wave testing sweeps through a broad range of low frequencies in order to capture the surface wave-dispersion characteristics of the ground. This approach is a modification of the Continuous Sine Wave Source Spectral Analysis of Surface Waves (CSS-SASW) test procedure presented by Kayen *et al.* [2004, 2005].

Spacing of the receivers stepped geometrically from 1–160 m. The two seismometers are separated by a given distance, d, and the source is usually placed at a distance of d from the inner seismometer. Rayleigh wavelengths (λ) are computed by relating the seismometer spacing (d) and the phase angle (θ), in radians determined from peak of the cross-power spectrum) between the seismometer signals:

$$\lambda = 2\pi d/\theta. \tag{1}$$

The Rayleigh wave surface wave velocity, V_r, is computed as the product of the frequency and its associated wavelength:

$$V_r = f\lambda. \tag{2}$$

Computing the average dispersion curve for a site requires a suite of individual data sets relating Rayleigh wave phase velocities to their corresponding frequencies and wavelengths. Regardless of the array dimensions, we routinely compute phase velocities for phase angles between 120° and 1,080°, corresponding to wavelengths of $3d$ and $d/3$, respectively. If the data are noisy, the range is narrowed to 180° and 720°, or $2d$ and $d/2$. For example, if the array separation was 3 m, velocities are inverted for Rayleigh wavelengths of 1–9 m. Low frequencies produce long wavelengths that sound more deeply into the ground, and hence are used to characterize deeper layers. Figure 7 presents a plot of a group of eight individual dispersion curves that together cover a range of wavelengths from 0.6–400 m for the Cascia site in Umbria. The averaged dispersion curve from these eight profiles is used to invert the velocity structure.

The inversion process is used to estimate a soil velocity model having a *theoretical* dispersion curve that fits the data. The "best-fit" velocity profile minimizes the sum of the squares of residuals between the theoretical and experimental dispersion curves. The inversion algorithm, WaveEq of OYO Corp. [Hayashi and Kayen, 2003] uses an automated-numerical approach that employs a constrained least-squares fit of the theoretical and experimental dispersion curves. Typically, a 10–15 layer model was used for the inversion, with layer thicknesses geometrically expanding with depth. The increasing layer thicknesses correspond with decreasing dispersion information in the longer wavelength (deeper) portion of the dispersion curve. The profiles generally increase in stiffness with depth, though low velocity layers are present at depth in several profiles. Figure 8 shows the inverted shear wave velocity profile for the Cascia, Umbria site, in which velocity rapidly climbs from less than

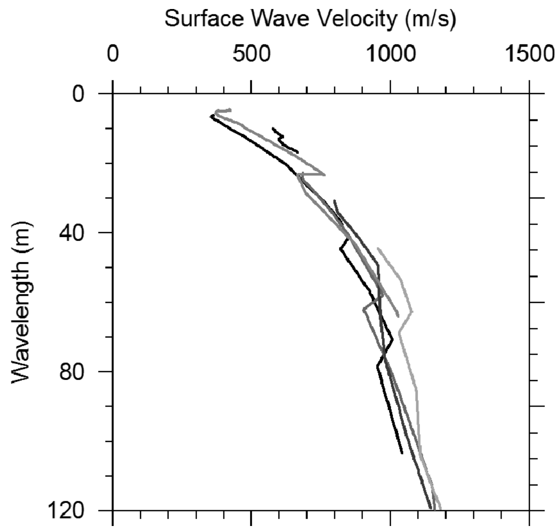

FIGURE 7 A group of eight dispersion curves covering a wavelength range of 1–120 m (Site 267CSC, Cascia, Umbria).

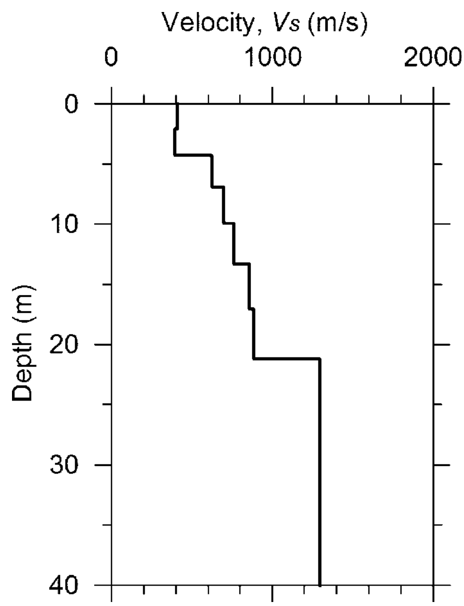

FIGURE 8 Shear wave velocity profile for Cascia, Umbria site 267CSC (V_{s30} = 540 m/s, Site Class C).

300 m/s at the surface to >1300 m/s at 21 m. Values of V_{s30}, calculated as 30 m divided by shear wave travel time through the upper 30 m, are given in Table 1 and range from 182–922 m/s (NEHRP categories B–D).

3.4. Estimating Velocities for Sites Without Measurements

At sites for which no local measurements of seismic velocities are available, we estimate V_{s30} based on correlations with surface geology. Correlations to estimate V_{s30} from surface geology are not available in the literature for geologic units in Italy. Accordingly, we evaluate the effectiveness in Italy of correlations developed for California and develop preliminary additional correlations for geologic units not represented in the California models.

The geologic maps available for Italy include large-scale maps (1:100,000) by Servizio Geologico d'Italia [Working Group, 2004] that provide coverage of the entire country (and hence all recording stations) and local geologic maps/sections (typical scale 1:2,000) by ENEL. The local maps/sections are derived from a site visit by an ENEL geologist and are available for 77 of 104 strong motion sites. Additional geologic information is available for a few sites from local microzonation reports or geologic reports for individual sites (references given in Table 1). The geologic classifications included in Table 1 are based on the smallest map scale that is available for the site. The map scale from which the classification was taken is indicated in the table, with "local" referring to the aforementioned microzonation studies or geologic reports.

We judge the best available correlations for California to be those of Wills and Clahan [2006]. A number of the Wills-Clahan geologic categories are descriptive of conditions encountered at Italian sites. Among these are intertidal Quaternary muds (Qi), Quaternary alluvium categories segregated by sediment depth and material texture (Qal,thin; Qal,deep; Qal,coarse), older Quaternary alluvium (Qoa), Quaternary to Tertiary alluvial deposits (QT), and Tertiary sandstone formations (Tss). The relatively firm rock categories used by Wills-Clahan are generally not descriptive of Italian firm rock sites, which are often comprised of limestone, marls, and volcanic rocks.

Wills and Clahan [2006] provide means and standard deviations of V_{s30} for each geologic category based on California data. We evaluate the applicability of those estimates to Italian sites by calculating V_{s30} residuals as:

$$R_i = (V_{s30})_{m,i} - (V_{s30})_{WC}, \tag{3}$$

where R_i = V_{s30} residual for site i, $(V_{s30})_{m,i}$ = value of V_{s30} from measurement at Italian site i, and $(V_{s30})_{WC}$ = mean value of V_{s30} from Table 1 of Wills and Clahan [2006]. Due to the small number of sites falling in individual categories, we group sites into two general categories for analysis of residuals—Quaternary muds and alluvium (combination of the thin, deep, and coarse sub-categories) and late Quaternary and Tertiary sediments (combination of Qoa, QT, and Tss). Figure 9 shows histograms of residuals grouped in this manner. Also shown in Fig. 9 is the range of velocities within ± two standard deviations of zero using average values of standard deviation from Table 1 of Wills and Clahan [2006] for the grouped categories (taken as σ_{WC} = 85 m/s for the Qi/Qal categories and σ_{WC} = 170 m/s for the Qoa/QT/Tss categories).

The histogram for Qi/Qal categories (Fig. 9a) shows that the mean of residuals is small and about 90% of the data fall within the ± $2\sigma_{WC}$ bands (approximately 95% should fall within this range if the Italian data shared the standard deviation of the California data). The histogram for the Qoa/QT/Tss categories (Fig. 9b) similarly shows a nearly zero mean, and 100% of the data fall within the ± $2\sigma_{WC}$ bands. Similar results are obtained if the grouped categories are broken down to smaller sub-categories (e.g., Qal,deep from Qi/Qal). Hence, our preliminary conclusion is that the Wills-Clahan recommendations provide an unbiased estimate of V_{s30} for Italian alluvium sites of Quaternary to Tertiary age. The standard deviations of the Italian data also appear to be generally similar to those of Wills-Clahan.

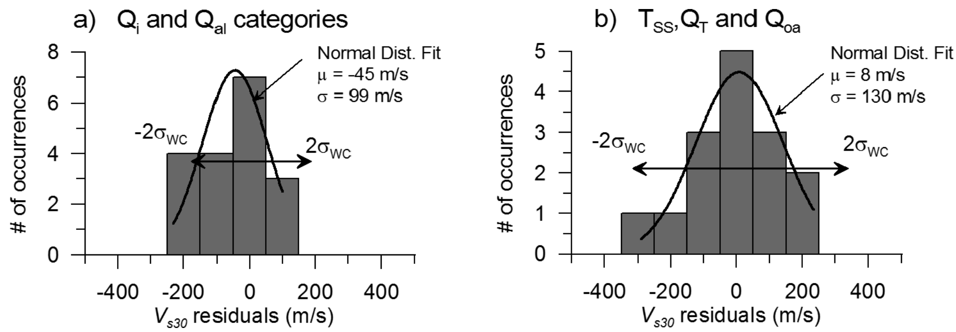

FIGURE 9 Histograms of V_{s30} residuals and normal distribution fits for (a) Lacustrine and Quaternary alluvium categories and (b) older Quaternary, Quaternary-Tertiary, and Tertiary sandstone categories. The $\pm 2\sigma_{WC}$ limits indicate two standard deviations above and below zero from the Wills and Clahan (2006) correlation.

As mentioned above, many of the rock sites listed in Table 1 have conditions geologically dissimilar to California such as limestone, marls, and volcanic rocks. Since we are unaware of existing correlations to V_{s30} for these types of materials, we assembled rock categories descriptive of Italian conditions that generally have similar seismic velocities. These categories are listed in Table 1 and are summarized as follows:

- Tm: This category consists of Tertiary Marl, often with surficial overconsolidated clays. It is common along the central-southern Apennines, and 13 sites in our database have this classification. A histogram of the Tm velocities is given in Fig. 10a, showing a mean V_{s30} = 680 m/s and standard deviation = 180 m/s. We use 680 m/s as our estimate for Tm sites without measurements.
- Pc: This category consists of Pleistocene to Pliocene cemented conglomerate. Its occurrence is widespread in Sicily and the Apennines. Five sites in our database have this classification, two of which have velocity measurements with V_{s30} = 972 and 1156 m/s. We use V_{s30} =1000 m/s for sites without measurements.
- Ml, Mv, and Mg: This category comprises Mesozoic limestone (Ml), volcanic rocks (Mv), and gneiss (Mg). As shown in Fig. 10b, we group these three together for velocity characterization, because the available data is inadequate to justify further discretization. The Ml category includes 14 sites located in the Alps and Apennines. The Mv category applies to three sites located near the active volcanoes of Mt. Etna (Sicily) or Mt. Vesuvius (near Naples). The Mg category is encountered only at the Messina and Milazzo

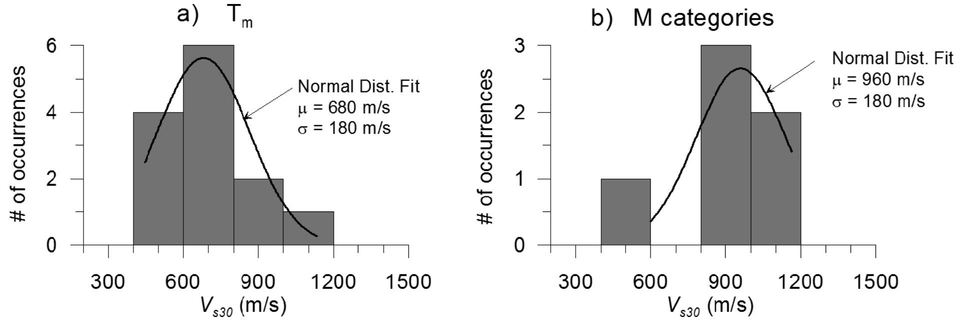

Figure 10 Histograms of V_{s30} values and normal distribution fit for (a) Tm category and (b) M categories.

Station in Sicily. As shown in Fig. 10b, the average V_{s30} = 960 m/s, and we use 1000 m/s as our estimate for Mesozoic sites without measurements. A measured shear velocity of 1800 m/s is reported in Table 1 for Messina, but this measurement was made in a tunnel deep in the ground. Shallow velocities should be slower and hence the preferred V_{s30} value is given as 1000 m/s to be consistent with the other Mesozoic categories.

3.5. Instrument Housing

The characteristics of the structure housing a strong motion accelerometer are an important component of the site databank, because soil-foundation-structure interaction (SFSI) affects the recording. Whether the SFSI effect is significant on ground motion intensity measures of engineering interest (e.g., spectral acceleration) depends principally on the embedment of the foundation, the size (in plan view) of the structure, and the structural mass [Stewart, 2000]. Instrument housings considered "free-field" for the NGA project and previous similar work in California have generally consisted of small (1 m square) instrument huts or small 1–2 story structures without basements.

Housing information for the 101 strong motion stations is given in Table 1. Most of the buildings (75) are in small cabins (CA), which are described further below. Fifteen stations are at the foundation level of small buildings (typically single-story buildings, 3–5 m in height, with footprint areas ranging from 10–30 m^2. Four instruments are on small slabs with no overlying structure, similar to the instrument huts used widely in California; these are denoted as FF in Table 1. Remaining instruments have either unknown housing conditions or are located on dams (D) or in tunnels (T).

The small cabins (CA designation) are typical of ENEL instruments. The cabins are electrical substations of masonry construction approximately 3–9 m square in plan view and 3–5 m tall. A typical example is shown in Fig. 11. The instrument is mounted on a short pillar 20 cm in height above the floor slab and 60 cm in diameter. The pillar extends into the natural ground approximately 0.3–1.0 m and is isolated from the floor slab by a gap [Berardi *et al*., 1991]. Analysis by Berardi *et al*. [1991] indicates that this configuration would not be expected to introduce any significant modification to the recording from SFSI. Based on those analyses and empirical studies (e.g., Stewart, 2000), we believe that recordings from structures of this type can be assumed to provide a reasonable approximation of free-field conditions.

Figure 11 ENEL electrical substation housing a recording instrument in Gubbio-Piana site (Umbria).

4. Source Databank

Attributes of the seismic source that are important for the development of GMPEs and ground motion selection for response history analysis include magnitude, source location and dimensions, and focal mechanism. We compile in Table 2 available source characteristics extracted from publications and internal files of the Istituto Nazionale di Geofisica e Vulcanologia (INGV; F. Mele and B. Castello, personal communication, 2007).

Point source information such as seismic moment and hypocenter location is extracted from a web site [INGV, 2007a] that reports the results of an INGV study termed "Project S6." As described by Pondrelli *et al.* [2006], the Project S6 source parameters are available for most events between 1972 and 2004. Pondrelli *et al.* [2006] take CMT solutions from the Harvard moment tensor catalogue (e.g., Elkström *et al.*, 2005) where available, which is for $M_w > 5.5$. For events since 1977, Pondrelli *et al.* [2002, 2006] extend the Harvard dataset with the European-Mediterranean Regional CMT (RCMT) catalogue for $4.5 < M_w < 5.5$. Both Harvard CMT and RCMT solutions are based on model fits to medium- and long-period seismograms. Moment magnitudes are taken in Project S6 based on CMT and RCMT solutions. As explained by Pondrelli *et al.* [2006], additional magnitudes are obtained as follows: surface wave magnitude (M_s) is taken from the IRIS data management center [IRIS, 2007]; body wave (m_b) and local magnitude are taken from the USGS National Earthquake Information Center (http://wwwneic.cr.usgs.gov/neis/epic/) with some modifications by INGV.

For events not characterized by Project S6, hypocenter locations and magnitudes were taken, in order of preference, from the Parametric Catalogue of Italian Events [Working Group CPTI04, 2004] or from the ESD database [Ambraseys *et al.*, 2004a].

The finite fault parameters shown in Table 2 (strike, dip, rake, along-strike length, down-dip width, depth to top of rupture) have been compiled by INGV into the Database of Individual Seismogenic Sources (DISS; INGV, 2007b; Basili *et al.*, 2008). Those finite source parameters were compiled from the literature, and hence were developed using a variety of techniques (surface faulting, geologic investigations, magnitude-area scaling relationships, etc.).

5. Summary and Conclusions

In this article, we describe the development of a strong motion database as well as site and source databanks for strong motion studies utilizing Italian data. Our intent was to assemble and disseminate Italian data in a format that is similar to that used in the Next Generation Attenuation project, which applies to world-wide active tectonic regions (but which only sparsely sampled Italian data). The principal users of these data resources are expected to be researchers performing empirical ground motion studies and engineers selecting ground motions for dynamic analyses of structural and geotechnical systems in Italy. In addition to this paper, the database and supporting metadata from databanks are available at http://sisma.dsg.uniroma1.it [Scasserra et al., 2008].

The ground motion database developed here includes only about half of the available recordings due to various issues such as s-triggers that can bias ground motion intensity measures evaluated from the data. We describe these biases, which affect principally long-period measures of ground motion as well as duration-related parameters.

A databank of site conditions at Italian ground motion recording stations is compiled that includes geologic characteristics and seismic velocities at 101 sites with strong motion recordings. Geologic characterization is derived principally from local geologic investigations by ENEL that include detailed mapping and cross sections. For sites

TABLE 2 Source parameters for selected Italian earthquakes

	Date	Time	Point source parameters										Finite source parameters									
Earthquake name	dd/mm/yyyy	(UTC)	Mw	Ms	ML	Mb	lat	long	Focal mech.	Epicentral intensity (MCS)	Focal depth (km)	ref.	center lat	center long	strike	dip	L (km)	W (km)	z-top (ikm)	rake	slip	ref.
Ancona	25/01/1972	23:22:17		4.0	4.0	4.8	43.70	13.41	normal		10	ESD										
Ancona	04/02/1972	02:42:18	5.2	4.8	4.6	4.5	43.633	13.550	oblique		8	CPTI04										
Ancona	04/02/1972	09:18:30		4.3	4.4	4.3	43.73	13.38	oblique		8	ESD										
Ancona	04/02/1972	18:17:25		4.0	4.1	4.8	43.70	13.40	normal		10	ESD										
Ancona	05/02/1972	01:26:30		4.2	4.3	4.3	43.72	13.40	oblique		10	ESD										
Ancona	06/02/1972	01:34:19		4.1	4.3	4.6	43.70	13.43	oblique		5	ESD										
Ancona	06/02/1972	21:44:45			3.0		43.70	13.40	normal		2.5	S6_D5										
Ancona	08/02/1972	12:19:10			3.9		43.683	13.400	normal		2.5	S6_D5										
Ancona	14/06/1972	18:55:53	4.8	5.2	4.7	4.9	43.65	13.60	strike slip	8.5	3.0	S6_D5										
Ancona	14/06/1972	21:01:02			4.2		43.667	13.417	normal		21.0	S6_D5										
Ancona	21/06/1972	15:06:53			4.0		43.817	13.600	normal		4.0	S6_D5										
Friuli	06/05/1976	20:00:13	6.4	6.5	6.4	5.9	46.35	13.26	thrust	9.5	12.0	S6_D5	46.2507	13.1447	290	30	16	9	2	105	1.32	DISS-IS
Friuli (aftershock)	07/05/1976	00:23:49	4.9		4.9		46.24	13.27	thrust		26.0	S6_D5										
Friuli (aftershock)	11/05/1976	22:44:01	5.0		5.3	4.9	46.29	12.99	thrust		13.0	S6_D5										
Friuli (aftershock)	18/05/1976	01:30:09	4.1		4.1		46.250	12.867	normal		5.0	S6_D5										
Friuli (aftershock)	09/06/1976	18:48:17	4.3		4.1		46.350	13.067	normal		16.0	S6_D5										
Friuli (aftershock)	11/06/1976	17:16:36	4.5		4.3		46.267	12.967	normal		18.0	S6_D5										
Friuli (aftershock)	17/06/1976	14:28:51	4.7		4.5		46.177	12.798	normal		15.0	S6_D5										
Friuli (aftershock)	07/09/1976	11:08:16	4.2		4.1		46.300	12.983	normal		5.0	S6_D5										
Friuli (aftershock)	11/09/1976	16:31:11	5.3	5.5	5.5	5.0	46.29	13.18	thrust	9	10.0	S6_D5										
Friuli (aftershock)	11/09/1976	16:35:03	5.6	5.4	5.8	5.3	46.300	13.317	thrust	9	9.0	S6_D5	46.2392	13.2634	277	30	6	4.5	2	90	0.45	DISS-IS
Friuli (aftershock)	13/09/1976	18:54:47	4.6		4.3		46.283	13.200	normal		14.0	S6_D5										
Friuli (aftershock)	15/09/1976	03:15:19	5.9	6.0	6.1	5.7	46.30	13.19	thrust		2.0	S6_D5	46.2665	13.2151	274	35	8	5.5	2	90	0.83	DISS-IS
Friuli (aftershock)	15/09/1976	04:38:53	4.9		4.8	4.8	46.267	13.167	normal		21.0	S6_D5										
Friuli (aftershock)	15/09/1976	09:21:18	5.9	5.9	6.0	5.4	46.300	13.183	thrust	8,5	21.0	S6_D5	46.2754	13.2009	276	35	10	6.4	6.5	110	0.75	DISS-IS
Friuli (aftershock)	16/09/1977	23:48:07	5.3	5.1	5.3	5.1	46.28	12.98	thrust	7.5	21.0	S6_D5										
Calabria	11/03/1978	19:20:48	5.2	5.1	5.3		37.979	16.184	normal	8	5.0	S6_D5	38.01	15.98	86	45	6.4	4				DISS-MSw
Basso Tirreno	15/04/1978	23:33:48	6.0	5.8	5.5	5.5	38.268	15.112	strike slip	9	22.0	S6_D5	38.2589	15.0500	147	83	12.1	8.6	1.5	180	0.6	DISS-IS
Marche	21/05/1979	14:34:19			3.6		43.050	12.962	n.r.		33.0	S6_D5										
Colle	17/06/1979	04:49:38			3.8		43.153	12.881	n.r.		1.0	S6_D5										
Valnerina	19/09/1979	21:35:37	5.8	5.9	5.5	5.8	42.80	13.04	normal	8.5	6.0	S6_D5	42.71	13.07	156	45	9.7	5				DISS-MSw
Umbria	21/09/1979	00:52:45			4.2		42.733	13.033	normal		1.0	S6_D5										
Umbria	28/09/1979	04:41:21			3.6		42.733	13.100	normal		6.0	S6_D5										

Norcia	08/11/1979	18:44:43			4.1		42.81	13.04	n.r.		4	ESD										
W of Cosenza	20/02/1980	02:34:01	4.4		4.2		39.286	16.152	normal		12.0	S6_D5										
Norcia	05/03/1980	06:23:37			3.4		42.785	13.085	n.r.		21.0	S6_D5										
Norcia	11/03/1980	05:20:08			3.4		42.812	13.090	n.r.		13.0	S6_D5										
Norcia	24/05/1980	20:16:05			4.3		42.815	13.126	n.r.		15.0	S6_D5										
Toscana	07/06/1980	18:35:01	4.6	4.1	4.3		44.05	10.60	normal		30.0	S6_D5										
Irpinia	23/11/1980	18:34:52	6.9	6.8	6.5	6.0	40.760	15.309	normal		15.0	S6_D5	40.8021	15.2944	310	60	28	15	1	270	1.65	DISS-IS
Irpinia	23/11/1980	18:35:13	6.2				40.846	15.332	normal		7.0	NGA	40.6842	15.4826	300	60	9	15	1	270	0.7	DISS-IS
Irpinia (aftershock)	24/11/1980	00:24:02	5.0		4.9		40.811	15.268	normal		13.0	S6_D5										
Irpinia (aftershock)	24/11/1980	03:03:56	5.0		4.5		40.861	15.374	normal		9.0	S6_D5										
Irpinia (aftershock)	25/11/1980	21:53:37			3.8		40.986	15.222	n.r.		17.0	S6_D5										
Irpinia (aftershock)	26/11/1980	14:55:43			4.3		40.942	15.268	n.r.		15.0	S6_D5										
Irpinia (aftershock)	26/11/1980	15:56:44					40.857	15.711	normal		n.r.	ESD										
Irpinia (aftershock)	30/11/1980	07:41:59			4.5		40.761	15.316	n.r.		18.0	S6_D5										
Irpinia (aftershock)	01/12/1980	19:04:31			4.6	4.3	40.885	15.308	n.r.		9.0	S6_D5										
Irpinia (aftershock)	16/01/1981	00:37:47	5.2	5.3	4.6	5.0	40.838	15.441	normal		10.5	S6_D5										
Irpinia (aftershock)	16/01/1981	04:36:51			3.9		40.782	15.352	n.r.		16.1	S6_D5										
Irpinia (aftershock)	16/01/1981	06:31:26			3.8		40.835	15.501	n.r.		12.9	S6_D5										
Irpinia (aftershock)	14/02/1981	17:27:46	4.9	4.8	4.7		41.061	14.794	thrust	7	10.1	S6_D5										
SW of Campobello di Mazara	07/06/1981	13:01:00	4.9		4.8		37.631	12.718	thrust		45.0	S6_D5										
Near coast of Scalea	21/03/1982	09:44:02			5.0		39.704	15.639	n.r.		18.9	S6_D5										
Arpiola	22/03/1984	00:16:25			3.5		44.27	9.91	n.r.		22.1	S6_D5										
Umbria	29/04/1984	05:02:59	5.6	5.2	5.2	5.1	43.208	12.568	normal	7	6.0	S6_D5	43.2251	12.5682	140	21	10	7	4	270	0.5	DISS-IS
Lazio Abruzzo	07/05/1984	17:49:42	5.9	5.8	5.9	5.4	41.701	13.863	normal	8	20.5	S6_D5	41.6964	13.9470	152	50	10	7.5	5	264	0.27	DISS-IS
Lazio Abruzzo (aftershock)	11/05/1984	10:41:50	5.5	5.2	5.7	5.2	41.708	13.890	normal		12.1	S6_D5										
Lazio Abruzzo (aftershock)	11/05/1984	13:14:56	4.8		4.6		41.754	13.919	normal		12.2	S6_D5										
Lazio Abruzzo (aftershock)	11/05/1984	16:39:18			4.4		41.685	13.880	n.r.		11.8	S6_D5										
N of Reggio di Calabria	14/05/1985	05:44:36			3.8		38.231	15.668	n.r.		11.8	S6_D5										
Casamaina	20/05/1985	10:00:28			4.2		42.266	13.372	n.r.		11.5	S6_D5										
Off coast of Numana	22/06/1986	14:07:51			3.7		43.569	13.745	n.r.		5.3	S6_D5										

(*Continued*)

TABLE 2 (*Continued*)

	Date	Time	Point source parameters										Finite source parameters									
Earthquake name	dd/mm/yyyy	(UTC)	Mw	Ms	ML	Mb	lat	long	Focal mech.	Epicentral intensity (MCS)	Focal depth (km)	ref.	center lat	center long	strike	dip	L (km)	W (km)	z-top (ikm)	rake	slip	ref.
Potenza	05/05/1990	07:21:17	5.8	5.6	5.2	5.2	40.640	15.860	strike slip	7	22.5	S6_D5	40.6780	15.8520	95	88	7.9	6.2	14.8	175	0.26	DISS-IS
Sicilia-Orientale	13/12/1990	00:24:26	5.6	5.2	5.4	5.3	37.270	15.322	strike slip	7	7.0	S6_D5										
Umbria Marche	26/09/1997	00:33:16	5.7	5.6	5.6	5.5	43.023	12.891	normal		3.5	S6_D5	42.9990	12.9267	148	40	9	6	4	277	0.38	DISS-IS
Umbria Marche	26/09/1997	09:40:30	6.0	6.1	5.8	5.7	43.015	12.854	normal	8.5	9.9	S6_D5	43.0874	12.8358	152	40	12	7.5	4	280	0.37	DISS-IS
Umbria Marche (aftershock)	03/10/1997	08:55:22	5.2		5.0		43.043	12.825	normal		12.1	S6_D5										
Umbria Marche (aftershock)	04/10/1997	16:13:33	4.7		4.5		42.916	12.906	normal		6.2	S6_D5										
Umbria Marche (aftershock)	06/10/1997	23:24:00	5.4		5.4		43.028	12.847	normal		3.9	S6_D5										
Umbria Marche (aftershock)	07/10/1997	01:24:34	4.2		4.1		43.037	12.846	normal		4.9	S6_D5										
Umbria Marche (aftershock)	07/10/1997	05:09:57	4.5		4.3		43.036	12.859	normal		1.7	S6_D5										
Umbria Marche (aftershock)	11/10/1997	03:20:56			3.7		43.105	12.790	n.r.		3.5	S6_D5										
Umbria Marche (aftershock)	12/10/1997	11:08:36	5.2		5.1		42.906	12.920	normal		0.1	S6_D5										
Umbria Marche (aftershock)	12/10/1997	20:15:29			4.0		n.r	n.r.	normal		10	ESD										
Umbria Marche (aftershock)	13/10/1997	13:09:21	4.4		4.1		42.862	12.940	normal		0.7	S6_D5										
Umbria Marche (aftershock)	14/10/1997	15:23:00	5.6	5.6	5.5	5.3	42.898	12.899	normal		7.3	S6_D5	42.9133	12.9342	144	40	6	6	2.5	260	0.28	DISS-IS
Umbria Marche (aftershock)	14/10/1997	23:23:28			4.1		42.956	12.872	n.r.		4.1	S6_D5										
Umbria Marche (aftershock)	16/10/1997	12:00:31	4.3		4.5		43.044	12.884	strike slip		2.4	S6_D5										
Umbria Marche (aftershock)	08/11/1997	15:31:54			4.1		42.863	12.974	n.r.		0.3	S6_D5										
Umbria Marche (aftershock)	09/11/1997	19:07:33	4.9		4.5		42.846	12.988	normal		1.5	S6_D5										
Umbria Marche (aftershock)	01/12/1997	22:37:05			3.5		42.858	12.978	n.r.		1.8	S6_D5										
Umbria Marche (aftershock)	21/03/1998	16:45:10	5.0		4.4		42.949	12.914	normal		1.1	S6_D5										
Umbria Marche (aftershock)	26/03/1998	16:26:18	5.3	4.8			43.146	12.809	n.r.	6	44.8	S6_D5										
	03/04/1998	07:26:00	5.1		5.3		43.185	12.757	normal		1.9	S6_D5										

Umbria Marche (aftershock)																					
Umbria Marche (aftershock)	05/04/1998	15:52:20	4.8		4.5		43.190	12.767	normal		4.4	S6_D5									
Trasaghis-Friuli	28/05/1998	09:39:19			4.1		46.295	13.049	n.r.		11.0	ESD									
Molise	31/10/2002	07:40:48	5.7	5.6	5.4	5.2	41.717	14.893	strike slip	7.5	25.2	S6_D5	41.6876	14.9391	267	82	10.5	8	12	203	DISS-IS
Molise	11/01/2002	01:55:12	5.7	5.6	5.3	5.5	41.742	14.843	strike slip		21.4	S6_D5	41.6959	14.8141	261	86	9.4	8	12	195	DISS-IS

Reference Legend:

ESD = European Strongmotion Database (http://www.isesd.hi.is/ESD_Local/frameset.htm) [Ambraseys *et al.*, 2004a].

CPTI04 = Parametric Catalogue of Italian Earthquakes [Working Group CPTI, 2004].

DISS = Database of Individual Seismogenic Sources (*IS = Individual Seismogenic Sources Method; MSw = Macroseismic Sources-well constrained*) [INGV, 2007b].

S6_D5 = Working Group, 2007. Project 6: Database of Italian accelerometric data related to the 1972–2004 period -Deliverable 6. INGV-Milano, DPC-USSN.

NGA = NGA database [Chiou *et al.*, 2008].

lacking such detailed study, geologic characterization is from 1:100,000 scale maps by Servizio Geologico d'Italia. Seismic velocities are extracted from the literature for 22 sites with on-site measurements and 14 additional sites with local measurements on similar geology. Data sources utilized include post earthquake site investigations (Friuli and Irpinia events), microzonation studies, and miscellaneous investigations performed by researchers or consulting engineers/geologists. Additional seismic velocities are measured using a spectral analysis of surface wave (SASW) technique for 17 sites that recorded the 1997–1998 Umbria-Marche earthquake sequence. The compiled velocity measurements provide data for 53 of the 101 sites. For the remaining sites, we estimate average seismic velocities in the upper 30 m (V_{s30}) using a hybrid approach as follows: (1) for sites on Quaternary mud or alluvium and Quaternary-Tertiary sediments, we assign V_{s30} based on regional correlations for California validated against the available Italian data; and (2) for sites on Tertiary Limestone, conglomerate, and Mesozoic-age rocks, we assign V_{s30} based on average velocities from similar units elsewhere in Italy.

A source databank is compiled from the results of recent projects by INGV. Moment tensor solutions derived from instrumental recordings are available for most events, providing estimates of source location, seismic moment, and moment magnitude. For earthquakes with $M_w > \sim 5.5$, finite source parameters include fault strike, dip, rake, along-strike rupture length, down-dip width, and depth to top of rupture.

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