ShakeMap implementation in Italy

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Abstract

Since 2005, the Italian Civil Protection (Dipartimento della Protezione Cilvile, DPC) has funded several projects driven toward fast assessment of ground motion shaking in Italy - the final goal being that of organizing the emergency and direct the search and rescue (SAR) teams. To this end, the Istituto Nazionale di Geofisica e Vulcanologia (INGV) has started to determine shakemaps using the USGS-ShakeMap package within 30 minutes from event occurrence and adopting a manually revised location. In this paper we present the INGV implementation of USGS-ShakeMap for earthquakes occurring in Italy and immediately neighboring areas. Emphasis is put on data acquisition, the adopted ground motion predictive relations and the site corrections for the local amplifications of the ground motion.

Finally, two examples of shakemaps are shown - the first determined for a recent medium size earthquake, the other for the large Irpinia, 1980, M6.9 event. For both events, the maps are compared to the available macroseismic data.

1. Introduction

Italy is a seismically active country, which has been the site of several large and extremely damaging earthquakes since historical times. Tragic examples of these

earthquakes in the past century include among others, the M6.8 1905 Calabria, the M7.0 1908 Messina-Reggio Calabria, the M7.0 1915 Marsica, the M6.7 1930 Irpinia, the M6.5 1968 Belice, the M6.5 1976 Friuli and the M6.9 1980 Irpinia (CFTI, 2000). All these earthquakes caused extended damage and from hundreds to tens of thousands of casualties.

In recent years, the "Dipartimento per la Protezione Civile" (DPC; Italian Civil Protection – an office dependent directly on the prime minister) has supported several projects in the field of seismology, all aimed toward a better understanding of the occurrence of earthquakes, and of the associated shaking on the Italian territory. In this context, the project "DPC-S4 2005-2007" was driven specifically to the fast assessment of ground motion shaking in Italy (see http://www.ingv.it/progettiSV/Progetti/Sismologici/sismologici_con_frame.htm, in Italian). DPC in Italy and Civil Defense agencies in general are indeed in great need of rapid and accurate information on where the earthquake damage is located to direct properly the rescue teams and organize the emergency. For these reasons, the Istituto Nazionale di Geofisica e Vulcanologia (INGV) has implemented the software package ShakeMap® developed by the U. S. Geological Survey Earthquake Hazards Program (Wald et al., 2006) designed specifically to obtain maps of the peak ground motion parameters (PGM), and of the instrumentally-derived intensities.

The package itself generates maps of ground shaking in terms of various peak ground motion parameters (PGA, PGV, PSA at 0.3, 1.0 and 3.0 sec and instrumentally-derived intensities). At its core, ShakeMap is a seismologically-based interpolation algorithm that exploits the available data of the observed ground motions, and the available seismological knowledge, to determine maps of ground motion at local and regional scales. Thus, in addition to the data that are essential to derive realistic and

accurate results, fundamental ingredients towards obtaining accurate maps are *i.)* ground motion predictive relationship as function of distance at different periods and for different magnitudes and *ii.)* realistic descriptions of the amplifications that the local site geology - the site effects – induce on the incoming seismic wavefield. In the current version of the package the generation of the peak ground motion maps relies on regional attenuation laws and on local site amplifications based on the S-wave velocities in the uppermost 30 m (V_{S30}). Thus, fidelity to the "true" ground motion depends heavily on the data available and on the attenuation and site corrections imposed.

It is also worthwhile to stress that the scale-length the ShakeMap procedure implemented is of the order of tens to hundreds of kilometers and the overall aim is to provide only a fast, first-order assessment of the ground shaking. Clearly, this length scale prevents from resolving local site amplifications accurately unless observed data are available. Thus shakemaps are a useful tool in the first minutes to hours after the earthquake has occurred and its relevance progressively decreases as information about the real damage becomes available.

2. Implementation

At INGV, we have installed version 3.1 of the USGS-ShakeMap package.

For the purpose of near real-time generation of maps (few minutes from earthquake occurrence), data are currently provided mainly by the broadband (BB) network, and by the strong motion recorders that are co-located with some of the BB stations. Currently, about 60 INGV broadband stations are paired with strong motion sensors (see Figure 1). Strong motion data exchange with other Italian institutions such as the former "Servizio Sismico Nazionale" (now "Ufficio Valutazione del Rischio

Sismico") that runs the "Rete Accelerometrica Nazionale" (RAN; i.e., national strong motion network) is to be implemented in the near future.

With regard to the "seismological information" required for the "proper interpolation" of the data where no observations are available, the procedure adopted by INGV follows that standard of ShakeMap and it relies on previously determined predictive relationships for the ground motion and on estimates of the amplifications based on the average S-wave velocity in the uppermost 30 m (V_{S30}).

2.1. Regionalized Predictive Relationships for the ground motion

Critical toward faithful prediction of PGM when generating shakemaps is the use of well-calibrated magnitude versus distance ground motion predictive equations (GMPEs). In Italy, attenuation has been found to vary between different regions and the studies of Malagnini and co-workers (Malagnini, et al., 2000; Malagnini, et al., 2002; Morasca, et al., 2006) together with those by the National Seismic Hazard Working Group (Gruppo di Lavoro, 2004) for the generation of the national map of seismic hazard support a preliminary regionalization of Italy into six regions using three separate sets of equations (Figure 2a). These regional GMPEs have been determined using the largest number of available data. Because of the lack of strong-motion records in the Italian region for the larger magnitudes (M>5.5), the National Seismic Hazard Working Group, with the approval of an international review committee, reached a consensus on the strong-motion GMPEs of Ambraseys et al. (1996) and Bommer et al. (2000) determined using a large strong motion data set of European earthquakes, and applied to the entire area, regardless of the regional differences (Gruppo di Lavoro, 2004). Figure 2b and Figure 2c show PGA and PGV versus distance for different magnitudes for the GMPEs referred above.

More technically, in order to account for the different attenuations of PGM with distance in the various parts of our target region, we have exploited some beta-procedures (courtesy of Bruce Worden and David Wald), now included in the standard ShakeMap distribution, that allow for the adoption of the proper attenuation model depending on the earthquake location.

2.2 Site corrections

To address the site corrections in Italy, we have used initially a coarse geological classification based on three litho-types (rock, stiff and soft) to determine V_{S30}. The velocities assigned to the three litho-types were 1000, 700 and 350 m/s for rock, stiff and soft lithologies, respectively. More recently we have implemented a classification based on the 1:100,000 geology map of Italy compiled and published by the "Servizio Geologico Nazionale" (see http://www.apat.gov.it/Media/carta_geologica_italia/default.htm). In this case, the geologic units have been gathered into five different classes A, B, C, D, and E according to the EuroCode8 provisions, EC8, after Draft 6 of January 2003 on the base of the ground acceleration response (e.g., http://www.eurocodes.co.uk/EurocodeDetail.aspx?Eurocode=8) . For the classification we have followed lithological and age criteria (see Table 1) and the following velocities have been assigned: A=1000, B=600, C=300, D=150, and E=250 m/s. Stepping from the 3-class to the 5-class Geological Map has been performed to adhere to the EC8 guidelines for soil identification. Figure 3a maps the resulting Geological-Class Map (GCM). The adopted map has been sampled at a space interval of one minute for the ShakeMap program.

In general, the procedure that accounts for the site corrections within ShakeMap consists of reducing the observed ground motions to a common reference "bedrock" and then apply the site corrections (Wald et al., 1999). In practice, the recorded peak ground motion amplitudes are first converted into rock-site conditions, and ground motion predictions are calculated to the phantom points to obtain a rock-site grid. Secondly, the amplitude-dependent (and frequency- for PSA) amplification factors are applied to the rock-site estimates using the V_{S30} map of Figure 3a. The amplification factors adopt the Borcherdt relation (Borcherdt, 1999), Table 2. It is important to remark that this site correction procedure is designed to return the original, observed data at each station. Note that the most important ingredient of the site correction procedure in ShakeMap are the near surface velocities, V_{S30}, which, however, suffer of low accuracies (Field et al. 2000; Wald and Mori, 2000; Mucciarelli and Gallipoli, 2006).

For comparison, we show in Figure 3b also the classification resulting from just exploiting the topographic relief as proposed by Wald and Allen (2007). When using this approach, V_{S30} is determined using the gradient of topography as a proxy. Steep topographies (i.e., large gradient values) are assimilated to hard rock sites whereas plain areas (i.e., zero or very low gradients) are thought to represent areas that feature thick alluvial low velocity deposits. These maps follow a very simplified approach to site condition mapping, although they have been found to correlate well to those obtained using more thorough geology-based classification criteria. In Italy, we note a remarkable correspondence between the surface velocities obtained using the two approaches (Figure 3a and 3b). The only differences arise in areas where flat calcareous rocks occur (e.g., Karst areas). An example is in the Salento peninsula (the "heel" of Italy) where the topographic gradient approach of the Wald and Allen

procedure produces very low velocities whereas our classification based on geology results in fast near surface velocities consistent with the Karst limestone rock type. We note that our choice can be equally unfit since Karst calacareous rocks are most likely weathered and therefore little representative of the true V_{S30} values. Nonetheless, in absence of "in situ" data, we have preferred to preserve consistency with the geology based criteria adopted and no corrections have been introduced for these areas.

2.3 Technical aspects

The generation of shakemaps at INGV relies currently on two independent data flux streams. The first, which has been adopted since the very beginning of the project, avails of the Earthworm (e.g., http://www.iris.iris.edu/newsletter/FallNewsletter/earthworm.html) processing package and of the modules *gmew* and *localmag* – the latter opportunely modified. The second data stream gets the data directly from the SAC format waveforms assembled for each event.

Currently, for each earthquake the shakemaps are determined automatically immediately using the (automatic) earthworm location (max 4-5 minutes from event occurrence), and the manual location using the SAC data and using an "ad hoc" procedure independent from the earthworm automatic processing. This redundancy in determining shakemaps assures cross-checking between the different results and it increases the robustness of the system. In addition, we also installed the module *plotregr* of ShakeMap (contributed to the ShakeMap community by Pete Lombard) that plots the actual data versus the adopted regression curves. This latter module is particularly important in that it allows for prompt checking of the PGM data scatter

and it helps to identify at a glance possible instrumental malfunctioning. To keep track of the various maps generated, a unique event identification coding has been envisaged and implemented so that it is always possible to maintain a processing history for each map. Maps are all published on an INGV internal server and the official ones are "pushed" to the publicly accessible server using an "ad hoc" procedure developed during the project (see http://earthquake.rm.ingv.it/shakemap/shake/index.html for standard shakemap layout and http://earthquake.rm.ingv.it/earthquakes.php for the event layout access).

3. Examples

In the following we present two examples. The first consists of the shakemaps generated automatically for the August 1st, 2007, M4.1 (M_W=4.2) earthquake in the Crotone area in Calabria, southern Italy. The second is taken from the shakemaps determined for all the M>5.5 earthquakes that have occurred in Italy since the 1976 - the Friuli, 1976 main shock (M6.5), the Irpinia 1980 event (M6.9), and the Colfiorito September 26 (M5.7 and M5.9) events. For conciseness, however, we have chosen to show here only the shakemaps for the 23 November 1980, M6.9 Irpinia (Southern Italy) earthquake.

The instrumental intensity maps presented below are derived from instrumentally recorded ground-motions. In our implementation, we have chosen to use the regressions of the Modified Mercalli Intensities (MMI) of Wald et al. (1999b) although in future work we plan to calibrate the instrumental intensity used in Shakemap against the MCS (Mercalli Cancani Sieberg) intensity scale that is widely adopted in Italy. In this work, however, we compare the maps of instrumental intensity generated with ShakeMap with the MCS intensities obtained through the

macroseismic Internet questionnaire available on the INGV web site. In general, we have found a consistent match between instrumentally and Internet questionnaire derived maps although the MMI and the MCS scales differ between each other to some extent. This suggests that the differences are likely to lie within the inherent calibration uncertainties of the scales and therefore that the MMI adopted instrumental intensities can be of use for quick assessments of the strong ground motion in Italy.

3.1 Crotone, Calabria, August 1st, 2007, M4.1

The results obtained for the recent Crotone earthquake are shown in Figure 4 where we present the maps of PGA, PGV, and instrumental intensity.

We note that since M equals 4.1, the predictive relations come from zone 4 of the regional GMPEs of Malagnini and co-workers. No strong motion data were available in near-real time. To generate the shakemaps, we have used the broadband recordings of the Italian National Seismic Network (international code IV) and MedNet networks (MN). The instrumental intensity map shows that the area where the earthquake has been felt matches closely with reports through the on-line Internet questionnaire. In particular, a maximum intensity of MCS V had been reported for Crotone and Isola di Capo Rizzuto, both around 10 km from the epicenter. This value is consistent with the instrumental intensity IV-V predicted by shakemap using the PGM data. The attenuation of ground motion with distance is also consistent with the intensity reported through the online questionnaire. The only differences appear to arise for some felt reports at the fringes of the predicted felt area. In particular, the MCS IV for the Catanzaro area indicates that the predicted instrumental intenisty underestimates the actual level of ground shaking.

In Figure 5, we show the regressions of PGA and PGV obtained for this event using the software *plotregr*. The plots show overall agreement between the data and the adopted regressions with larger data scatterings for distant stations. In addition, the plot shows the effect of the "bias correction" (see Wald et al., 2006 for details) that ShakeMap applies in order to match the observed data and predicted ground motions. This correction has been introduced to account for various factors such as errors in magnitude, inter-event variability (e.g., Boore et al., 1997) and it is a very important correction in that it levels out observed and predicted ground motions. For the Crotone earthquake, the bias is of -0.3 for PGA and -0.15 for PGV. These values indicate that either the earthquake magnitude or the attenuation relations (or both) adopted tend to overestimate the actual recorded motion, although the observed systematic bias would suggest magnitude overestimation. Thus the bias correction attempts to account for this and makes a correction – in this case by slightly reducing the predicted motion with distance – to all the phantom points used to generate the shakemap.

3.2 Large earthquakes: Irpinia (Southern Italy), 23 November, 1980, M6.9

In order to verify the performance of the ShakeMap package and of our implementation at INGV for large earthquakes, we have used the strong motion data available at the Internet-Site for European Strong-Motion Data (ISESD, Ambraseys et al., 2004). The shakemaps for the Irpinia earthquake are shown in Figure 6 in terms of PGA, PGV, SA at 0.3 and 1.0 s and in Figure 7 as instrumentally-derived intensity and reported macroseismic field. The ground motion parameters are derived from GMPEs of Ambraseys et al. (1996) and Bommer et al. (2000) (see section 2 Implementation). Before describing the results, it is important to note that the event

featured multiple ruptures along different parts of the fault (i.e., roughly at 0, 20 and 40 s from origin time) and individually they were never larger of an equivalent M6.6 earthquake (e.g., Bernard and Zollo, 1989). This contributes to make the largest accelerations never larger than those expected for each single event (i.e., the largest acceleration of 0.32 g was recorded at Sturno, STR, in the northern part of the strong motion area) resulting in instrumental intensities that are somewhat lower than those expected for a M6.9 rupturing at once. This considered, we note that the finiteness of the fault is represented adequately mainly because of the favorable source receiver geometry which we found captured already the NW-SE fault trend (e.g., see the contour lines of PGA and PGV in Figure 6). (This was also confirmed independently by the adoption of point source GMPEs for the same data set where it was found that the PGM recorded at the available stations allowed for a realistic reconstruction of the observed ground motions - the data themselves reproduced the finiteness of the fault.) In any event, the comparison between instrumental intensity and MCS maps (from the Database of Macroseismic Information, http://emidius.mi.ingv.it/DBMI04/) of Figure 7 shows that instrumental intensity displays VII to VIII maximum intensities whereas the reported MCS features maximum values as high as X near the fault. This all indicates that the predicted instrumental intensities are somewhat lower than those observed. However and as stated above, this discrepancy can be reconciled if we consider that i.) the maps are represented using different intensity scales and ii.) the source featured multiple distinct (in time and space) ruptures.

Focusing on the MCS VII area (yellow solid circles; i.e., considerable damage in poorly built or badly designed structures), we note that its perimeter is reasonably similar to the VI level of the instrumental intensity map (i.e., strong shaking). Similar considerations can be made for the MCS IX area (red solid circles; i.e., damage great

in substantial buildings, with partial collapse) and the instrumental intensity VIII area that extends mainly close and including the causative fault.

To substantiate the results presented in terms of peak ground motion, the regressions obtained using the *plotregr* routine are shown in Figure 8. For both PGA and PGV the bias regression nearly overlaps to that obtained when no bias correction is introduced. There is however some consistent scatter of the PGA for the nearby stations BSC and STR that account most likely for unaccounted site effects or, more likely, for details of the source finiteness unaccounted by the simplified ShakeMap procedure. The scatter is to some extent smaller for PGV perhaps indicating that local variations in acceleration are filtered out when integrating to velocity. In any event, this observation supports that in the case of the Irpinia earthquake the adopted regressions together with the observation available can provide realistic first-cut shakemaps.

4. Conclusions

In this note, we have shown the implementation of the ShakeMap using the data acquired by INGV. In its current implementation the maps of peak ground shakings are determined relying on broadband and some strong motion data acquired by the Italian digital broadband network and MedNet. We recognize that this is certainly unsatisfactory in the case of a large earthquake that will most likely saturate the nearby stations but efforts are made to include all the strong motion data available in Italy in quasi real-time. These include both those acquired by INGV itself and by other networks such as the national accelerometric network (RAN).

In its current implementation we have used the attenuation relations previously proposed for Italy and, to the end of predicting as accurately as possible the PGM, we have subdivided the Italian territory into six main regions. For larger events (i.e.,

M>5.5), however, the relations of Ambraseys et al. (1996) and Bommer et al. (2000) are used for PGA and PGV, respectively. For the site effect corrections, we have adopted a V_{S30} classification based on the 1:100,000 geological map of Italy opportunely calibrated against the observed in-situ velocities. Our V_{S30} classification relies on five main categories with velocities spanning from nearly 1000 m/s for hard rocks to as low as 180 m/s for very soft sediments.

Application of the procedure to a M4.1 earthquake near Crotone (Calabria) and the comparison of the instrumental intensity map to the on-line internet macroseismic map show good correspondence between the predicted and reported intensities. The same conclusion is reached when comparing the shakemaps of the M6.91980 Irpinia earthquake determined with the available strong motion data and the reported macroseismic intensities.

In future developments, it is thought that the adoption of other intensities scales that take into account also the source duration (e.g., the Arias intensity, which captures the potential destructiveness of an earthquake as the integral of the square of the acceleration-time history) can generate more engineering-oriented maps of ground motions.

With regard to the instrumental intensity scale adopted, comparison of the calculated instrumental intensity maps to the reported macroseismic intensities showed that, for our analyzed earthquakes, instrumental and MCS intensities do not seem to differ substantially. This indicates an overall agreement between observed intensities and those predicted by ShakeMap but the latter are potentially available within few minutes from earthquake occurrence. The important issue here is to provide rapid "ballpark" estimates of the true level of ground shakings. It is important to remark that in the future it will be important to address the calibration of the instrumental

intensity scale against the MCS scale and to verify what are the effective differences between the two.

For the purpose of rapid quantitative assessment of the area where the strong motions have occurred, within the limitations inherent to the ShakeMap procedure, we think that the results obtained can be of much value to the purpose of civil protection fast response. This is eventually the final goal of the ShakeMap approach toward fast earthquake shaking assessment.

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Tables

Ground type	Description of stratigraphic profile	*Vs30 (m/s)*
A	*Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface*	**> 800**
B	*Deposits of very dense sand, gravel, or very stiff clay, at least several tens of m in thickness, characterised by a gradual increase of mechanical properties with depth*	**360 – 800**
C	*Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of m*	**180 – 360**
D	*Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil*	**<180**
E	*A soil profile consisting of a surface alluvium layer with Vs values of type C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with Vs > 800 m/s*	250

Table 1. Site classification and corresponding V_{S30} values

Vel (m/s)		Short Period (PGA)					Mid-Period (PGV)			
			150	250	350			150	250	350
686		1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00
724		0.98	0.99	0.99	1.00		0.97	0.97	0.97	0.98
464		1.15	1.10	1.04	0.98		1.29	1.26	1.23	1.19
372		1.24	1.17	1.06	0.97		1.49	1.44	1.38	1.32
301		1.33	1.23	1.09	0.96		1.71	1.64	1.55	1.45
298		1.34	1.23	1.09	0.96		1.72	1.65	1.56	1.46
163		1.65	1.43	1.15	0.93		2.55	2.37	2.14	1.91

Table 2. Site correction amplification factors. Short-Period (0.1 to 0.5 s) factors come from equation 7a, Mid-Period (04 to 2.0 s) from equation 7b of Borcherdt (1994). Vel is velocity in m/s; PGA is cutoff PGA in gals. Vel is the upper bound of the velocity range.

Figures

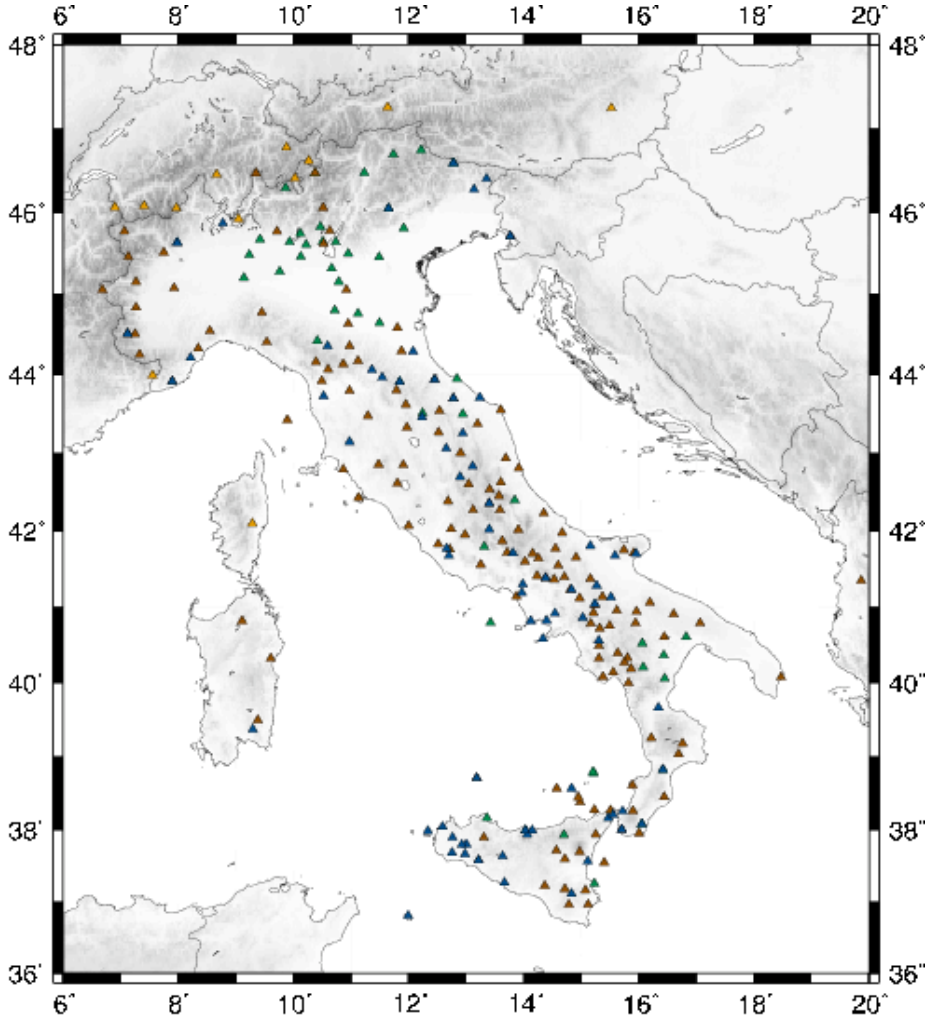


Figure1. The stations of the Italian National Seismic Network of INGV (international code IV). The network (February 2008) consists of 217 stations (124 stations have broadband sensors with natural period, T0, larger or equal to 40 s (red in picture); the remaining are either short period or extended short period and are not used as shakemap input data (blue in picture)). 45 stations of the broadband network are paired with strong motion sensors (green in picture). The MedNet stations within the Italian national borders (8) feature both broadband and strong motion sensors. The INGV Milano-Pavia section in northern Italy has 20 strong motion stations which also provide data to shakemap. The yellow triangles represent stations which waveform data are available in real-time at the INGV seismic center in Rome.

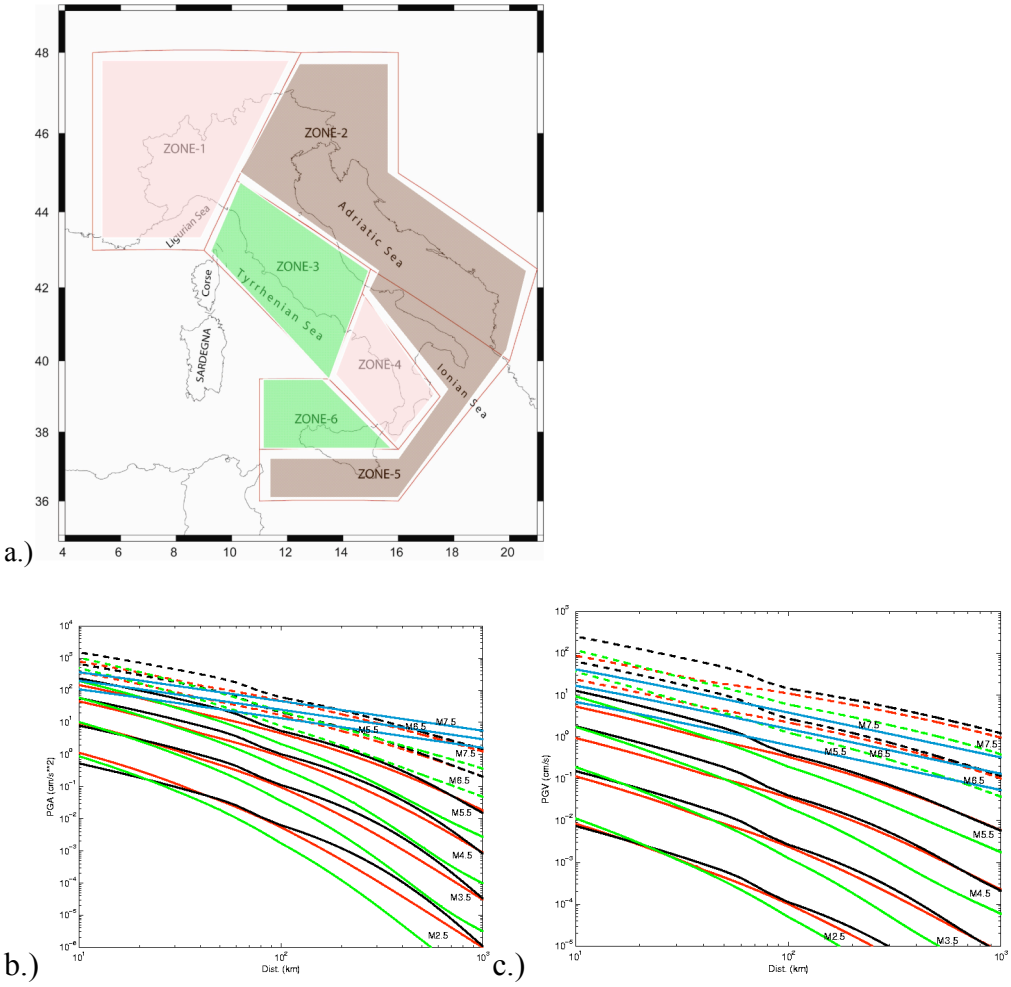
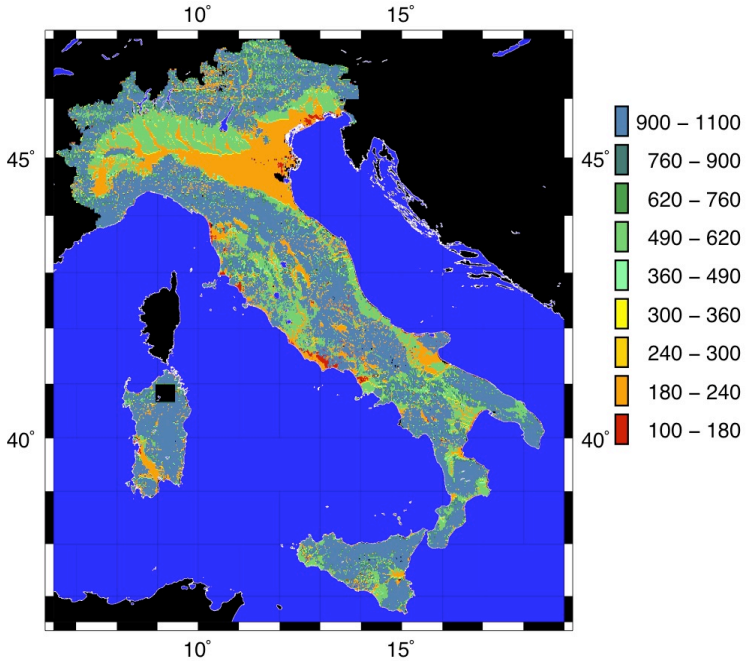
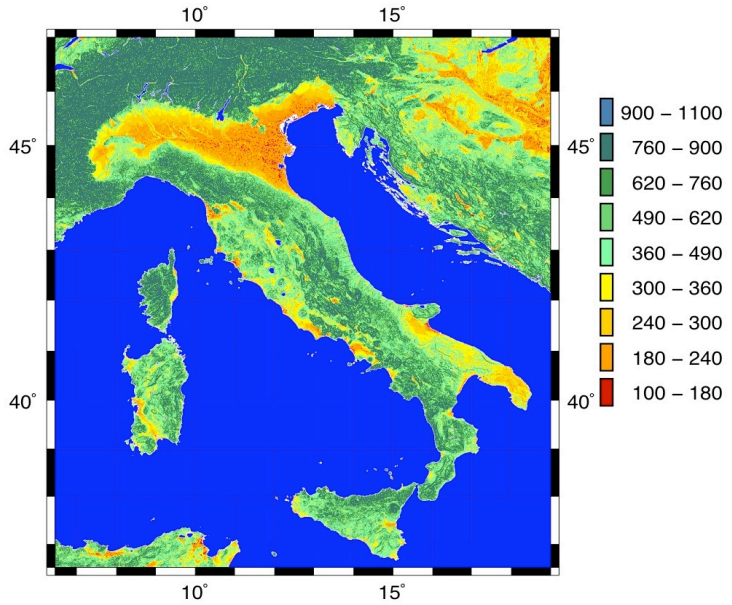


Figure 2. Attenuation relations used in the implementation of ShakeMap at INGV. a.) Regionalization of the attenuation relations. b.) attenuation relations expressed as PGA. For magnitude larger than 5.5, the relation of Ambraseys et al. (1996) is used (light blue solid lines). c.) attenuation relations expressed as PGV (Bommer et al. (2000) is used for M>5.5 - light blue solid lines - is used. Colors of the attenuation curves in b.) and c.) match the zones of a.).



a.)



b.)

Figure 3. a.) V_{S30} site classification based on geology and with mean velocities compliant with the EuroCode8 (A=1000, B=600, C=300, D=150 and E=250 m/s). b) V_{S30} site classification on the basis of the topography (Wald and Allen, 2007; see http://earthquake.usgs.gov/research/hazmaps/interactive/vs30/).

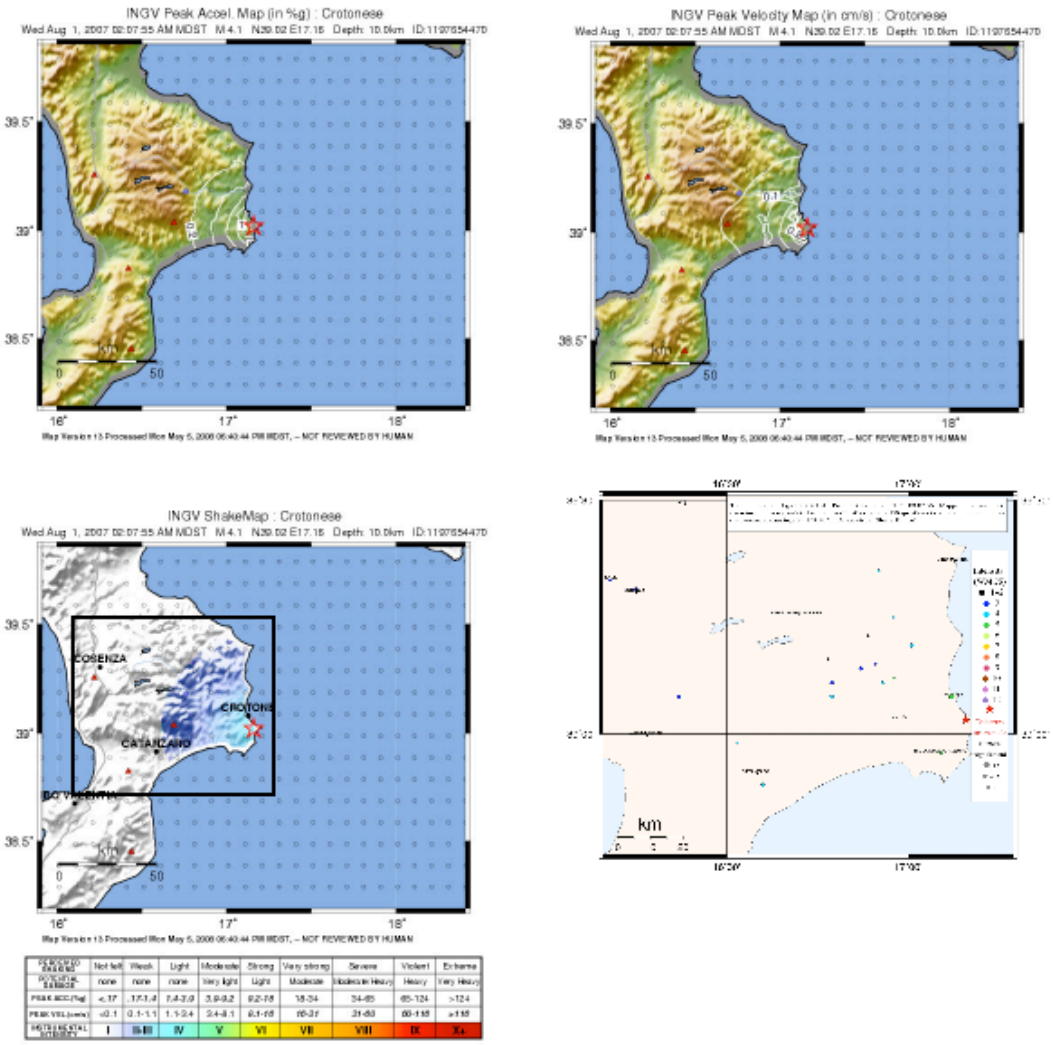
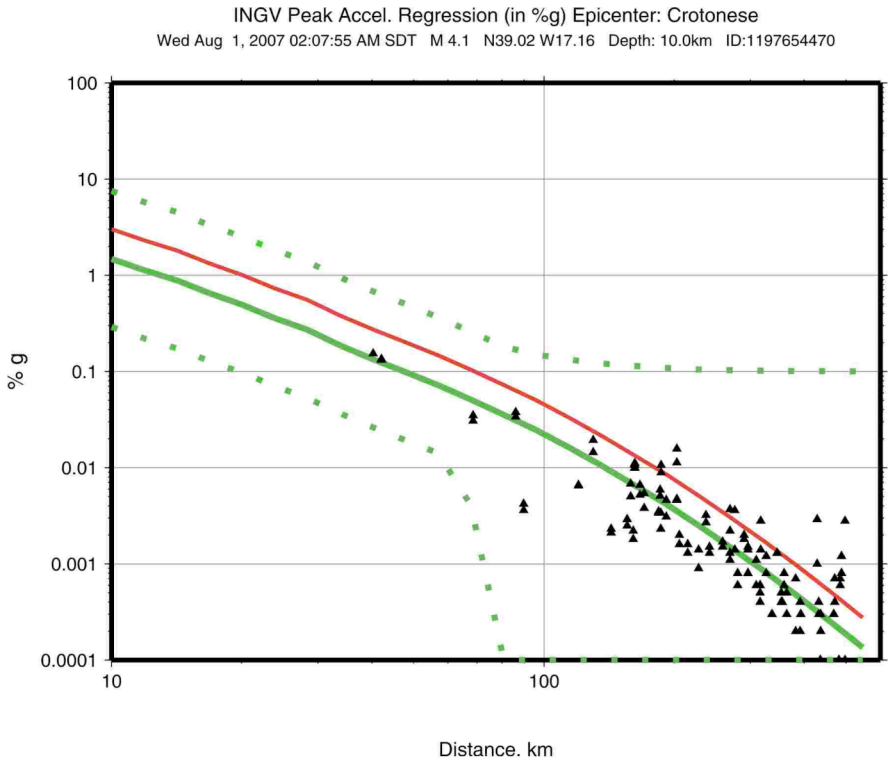


Figure 4. Shakemaps of the 2 August, 2007, M4.1 Crotone earthquake. PGA (top left); PGV (top right); Instrumental intensity (bottom left) and Internet questionnaire macroseismic intensity (bottom right). The Shakemap instrumental intensities rely on the Wald et al. (1999b) relationship for earthquakes in California.



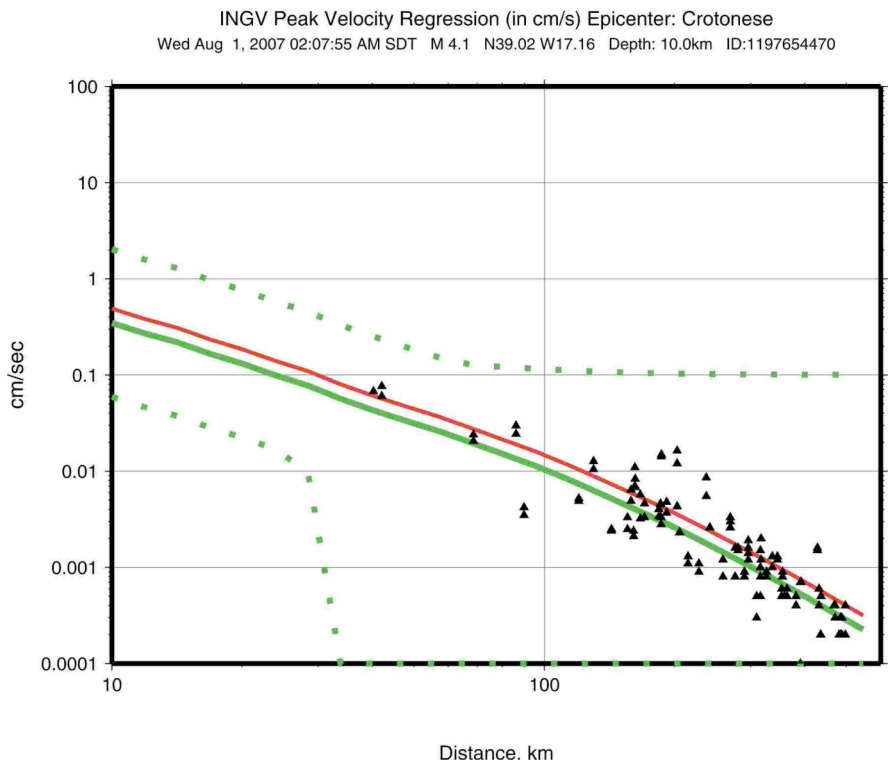


Figure 5. Regressions of the PGA and PGV against the adopted regressions for the M4.1 Crotone, August 1st earthquake. Solid red line: raw regression; Solid green line: biased regression; Dotted green lines: outlier flagging limits, linked to the bias corrections. Station data plotted are corrected to rock.

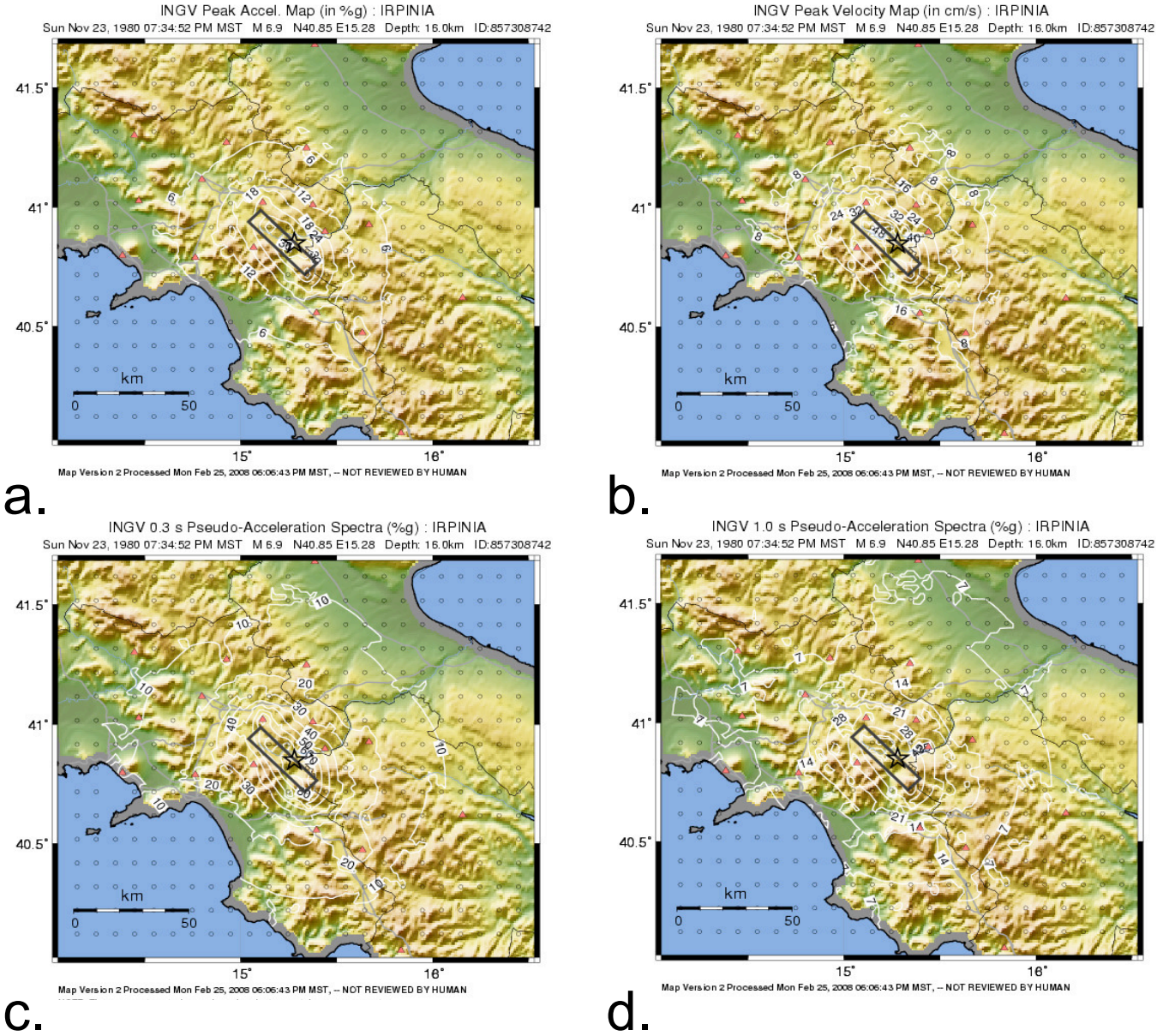
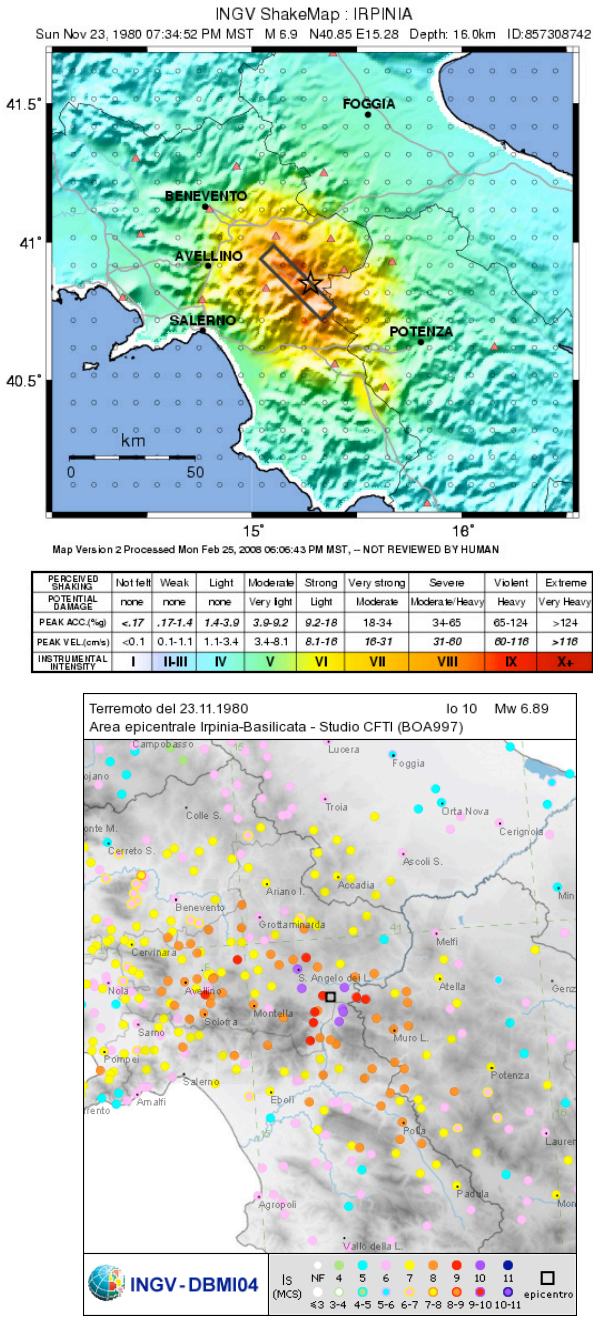
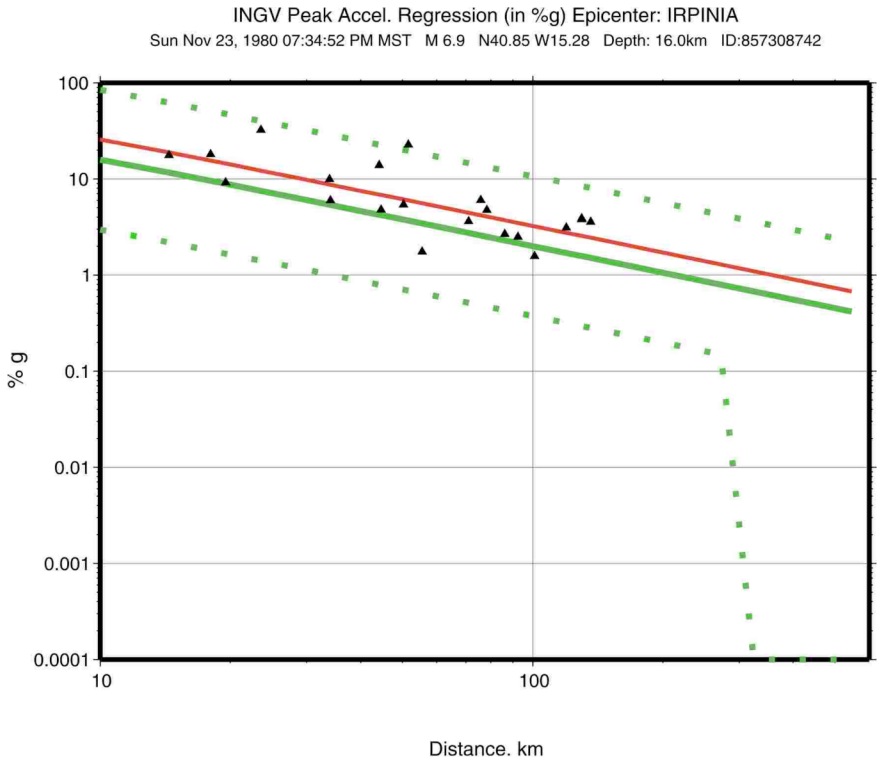


Figure 6. Shakemaps for the November 23, 1980, M6.9 Irpinia earthquake. a.) PGA; b) PGV; c.) Spectral acceleration with 5% damping at 0.3 s period; d.) Spectral acceleration with 5% damping at 1.0 s period. The fault plane is shown as a closed rectangle.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 7. Comparison between the instrumental intensity map predicted by the shakemap package as implemented at INGV and the macroseismic map (MCS) available at http://emidius.mi.ingv.it/DBMI04/.



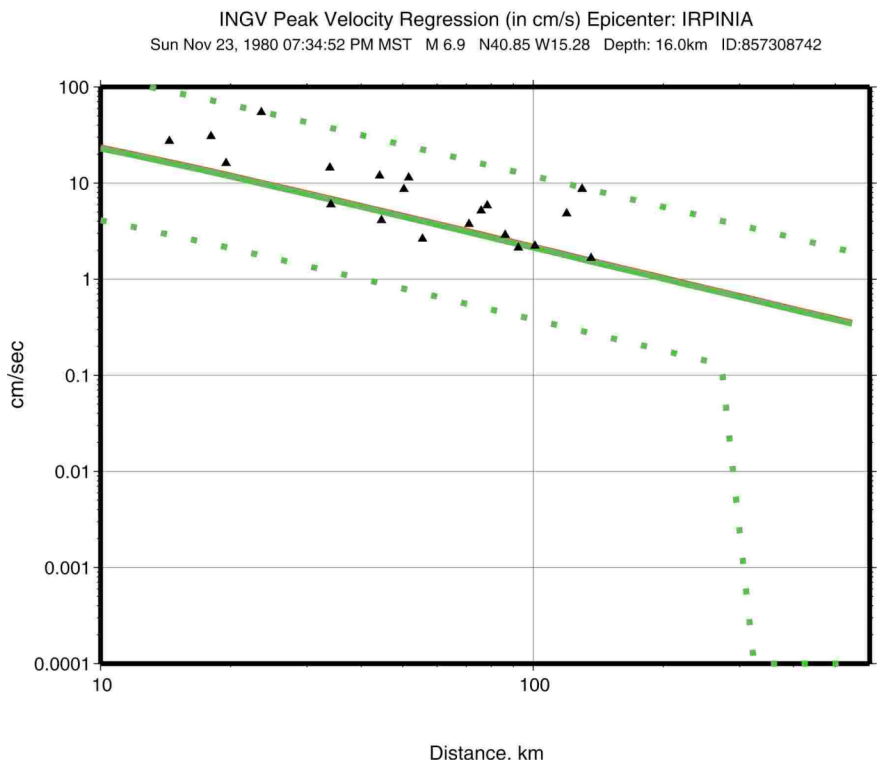


Figure 8. Regressions of the PGM data (PGA and PGV) against the adopted regressions for the Irpinia, M6.9 November, 23 1980, earthquake. Solid red line: raw regression; Solid green line: biased regression; Dotted green lines: outlier flagging limits, linked to the bias corrections. Station data plotted are corrected to rock.