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M4.1 ShakeMap
State of the art and bibliographic synthesis

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3. UPC, Universitat Politècnica de Catalunya
4. IGN, Instituto Geografico Nacional
5. BRGM

Synopsis

In order to develop a proper shake map for the Pyrenees a state of the art and bibliographic syntheses is done. The existing ground motion maps and the current implementations of USGS ShakeMap are studied and reported, in order to learn from the other implementations.

After this the ShakeMap methodology is studied, with special interest on the main issues of the development: Ground Motion Prediction Equations (GMPE) and Intensity Prediction Equations (IPE) and the way of selecting them, Instrumental intensity relations and site effects corrections.

Finally the technical requirements and the details of the regionalization process are summarized. This chapter summarize what we have to do in order to adapt the USGS ShakeMap software to our region.

Contents

List of illustrations

1. Post seismic ground motion maps

1.1. *Definitions*

Shake maps depict the level and distribution of seismic ground shaking caused by a real or scenario earthquake. For Wald et al (2005), this information is essential for the:

(1) emergency response and loss estimation in the aftermath of strong earthquakes (if provided in near real-time),
(2) public information and education,
(3) earthquake engineering and seismological research,
(4) planning and training of task forces and stakeholders

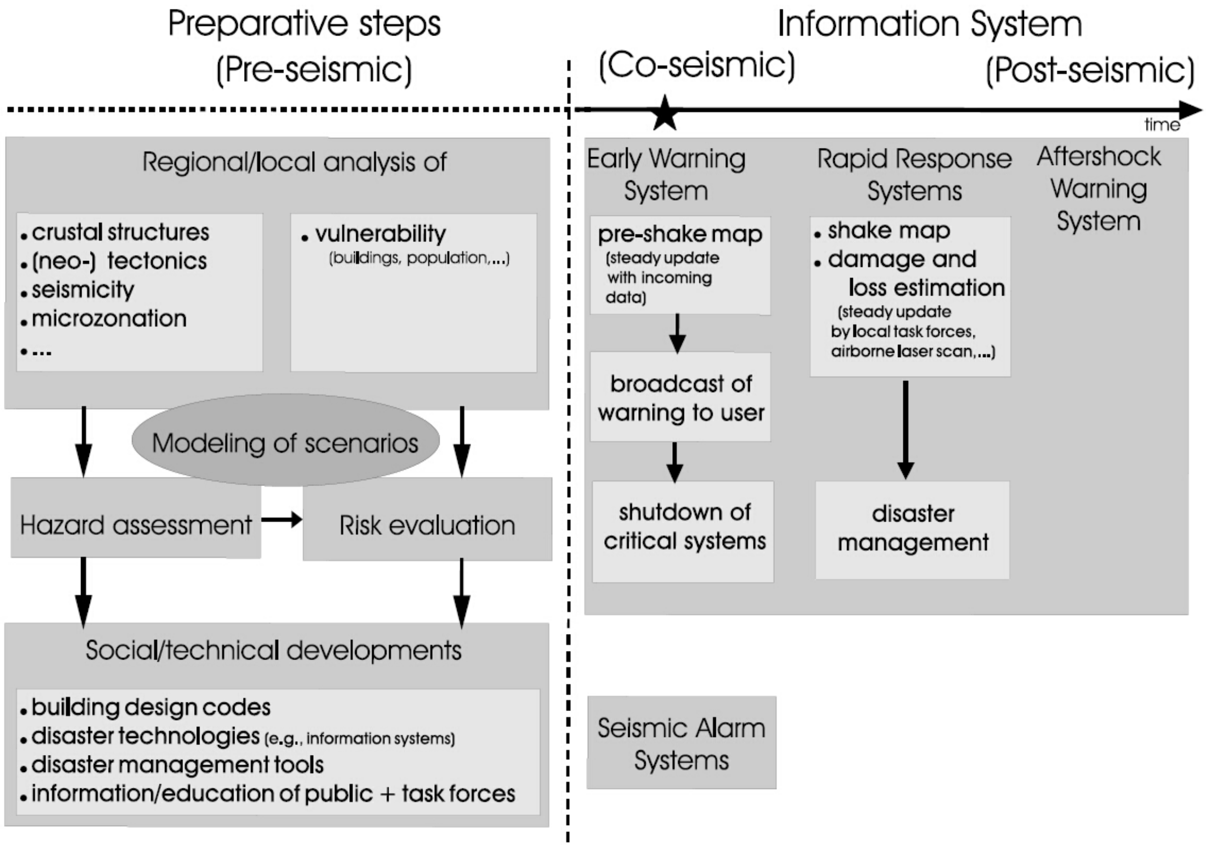

Figure 1 - Preparative steps as well as co- and post-seismic components of a Real-Time Earthquake Information System for seismic risk reduction. The later include early warning, alert, rapid response and aftershock warning systems. (M. Böse, 2006).

Shake maps are part of Rapid Response Systems which give the first post-seismic information in the minutes just after the earthquake and give basic data to rapid damage and loss estimation systems (cf. Figure 1).

Shake maps can be produced by different ways:

- from seismic source parameters calculation (epicentre, depth, magnitude, and eventually fault geometry and dimension) and site condition maps. Ground motions at rock sites are calculated with Ground Motion Predictive Equations (GMPE) and amplification factors are applied depending on site condition maps;
- from seismic stations networks: real time measured ground motion are directly used to produced shakemaps.
- from internet questionnaires and automatic intensity assignation.
- from mixed approach using real ground motion data and shaking distribution interpolated using sources parameters, empirical ground motion attenuation relationships and amplification factors (p.e. ShakeMap v.< v3.5).
- from mixed approach using real ground motion data, real intensity data and shaking distribution interpolated using sources parameters, empirical ground motion attenuation relationships, empirical intensity attenuation relationship and amplification factors (p.e. ShakeMap v3.5)

1.2. *Ground motion and intensity maps from seismic sources parameters*

We present here what have been done with the Interreg ISARD project and the software Armagedom developed in BRGM. These two examples are damage estimation tools, no real-time ShakeMaps. But in a preliminary step of the process, Intensity or PGA maps are produced.

1.2.1. ISARD

ISARD is a damage and loss estimation rapid response tool, operating in Catalonia since 2005.

The seismic network includes 15 stations (12 in Catalonia, 3 in France) with real-time transmission to an automatic detection system (DAS) created from modules of the automatic software Earthworm (USGS, 2005) adapted to the network (Romeu et al. 2006). An automatic earthquake location is used to build maps of damage scenario with methodologies from Susagna et al. (2006) and Roca et al. (2006).

Ground motions maps indicate only PGA and PGV observed on the seismic stations without any spatial interpolation (Figure 2). A specific regional relationship is used to produce intensity map. The goal is to provide a preliminary estimate of potential damage, not a precise map of ground motion. The isoseismal are circular and amplifications site are not taken into account (Figure 3.

1.2.2. Armagedom©

Armagedom© is a BRGM software designed to simulate damage scenarios. On a first step, Armagedom© produces PGA and intensity maps (Figure 4 and Figure 5), taking into account soil conditions and geometry and size of the fault. This intensity map is used on a second step to estimate damages. But Armagedom© is not designed for use in real time.

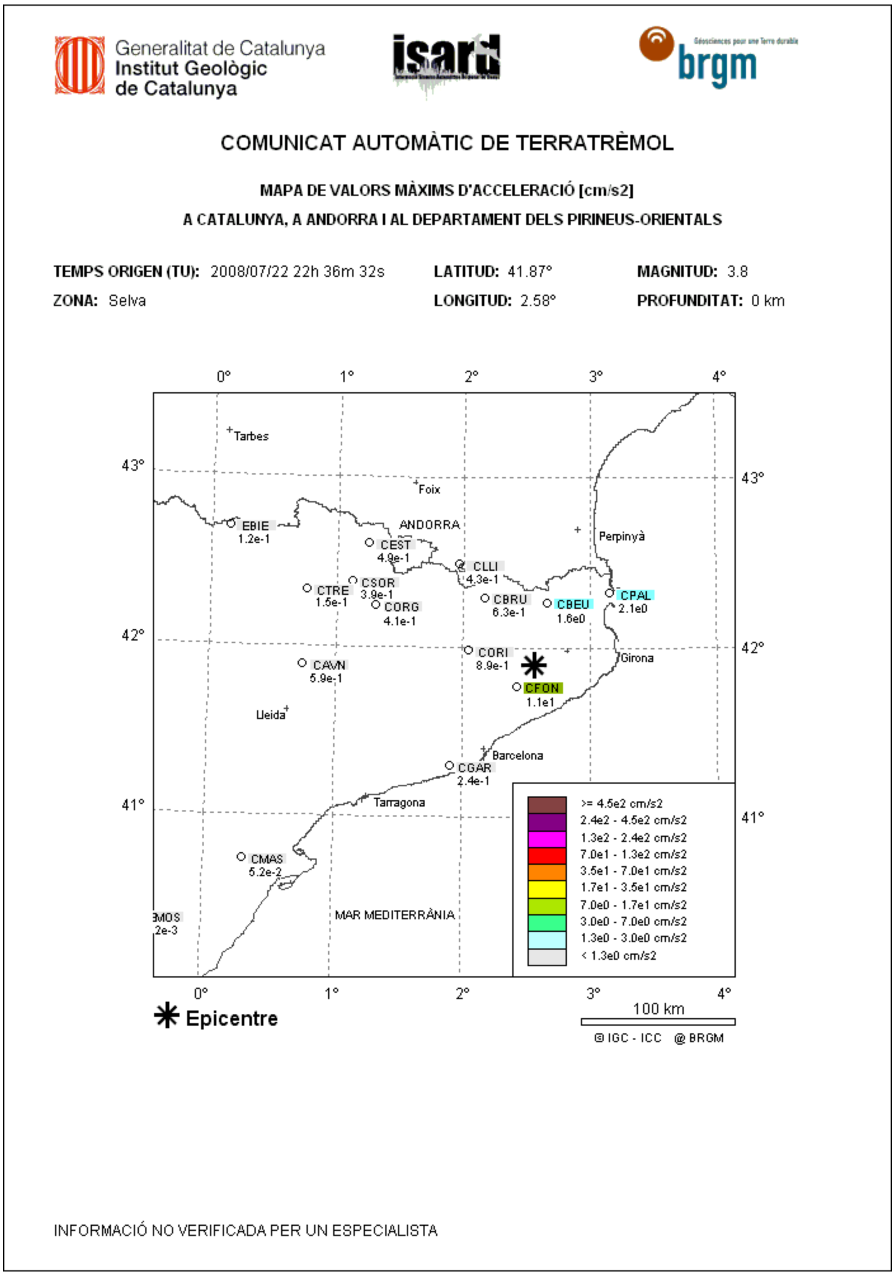

Figure 2 - Example of near-real time pga map produced by ISARD

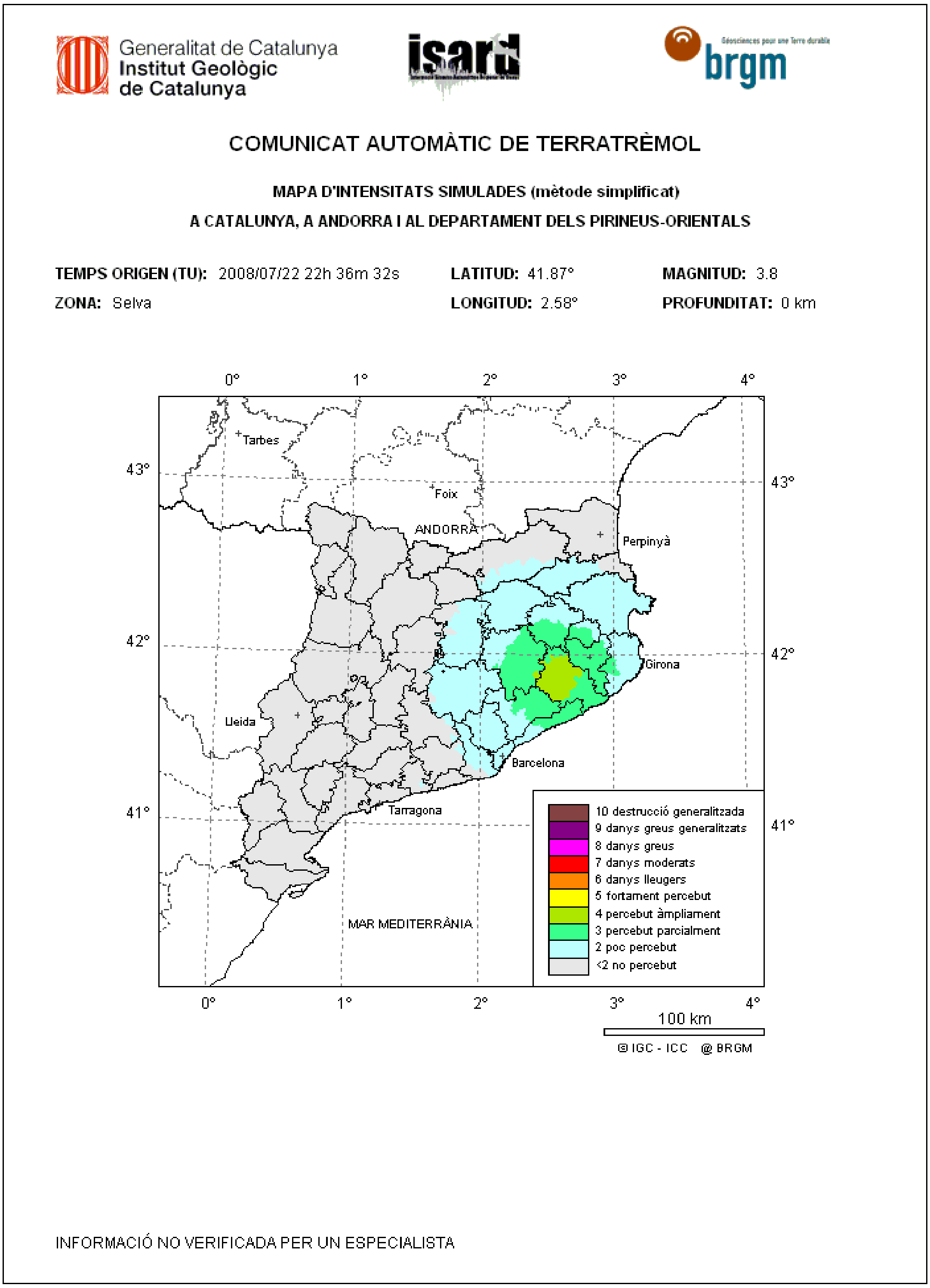

Figure 3 - Example of near-real time pga map produced by ISARD

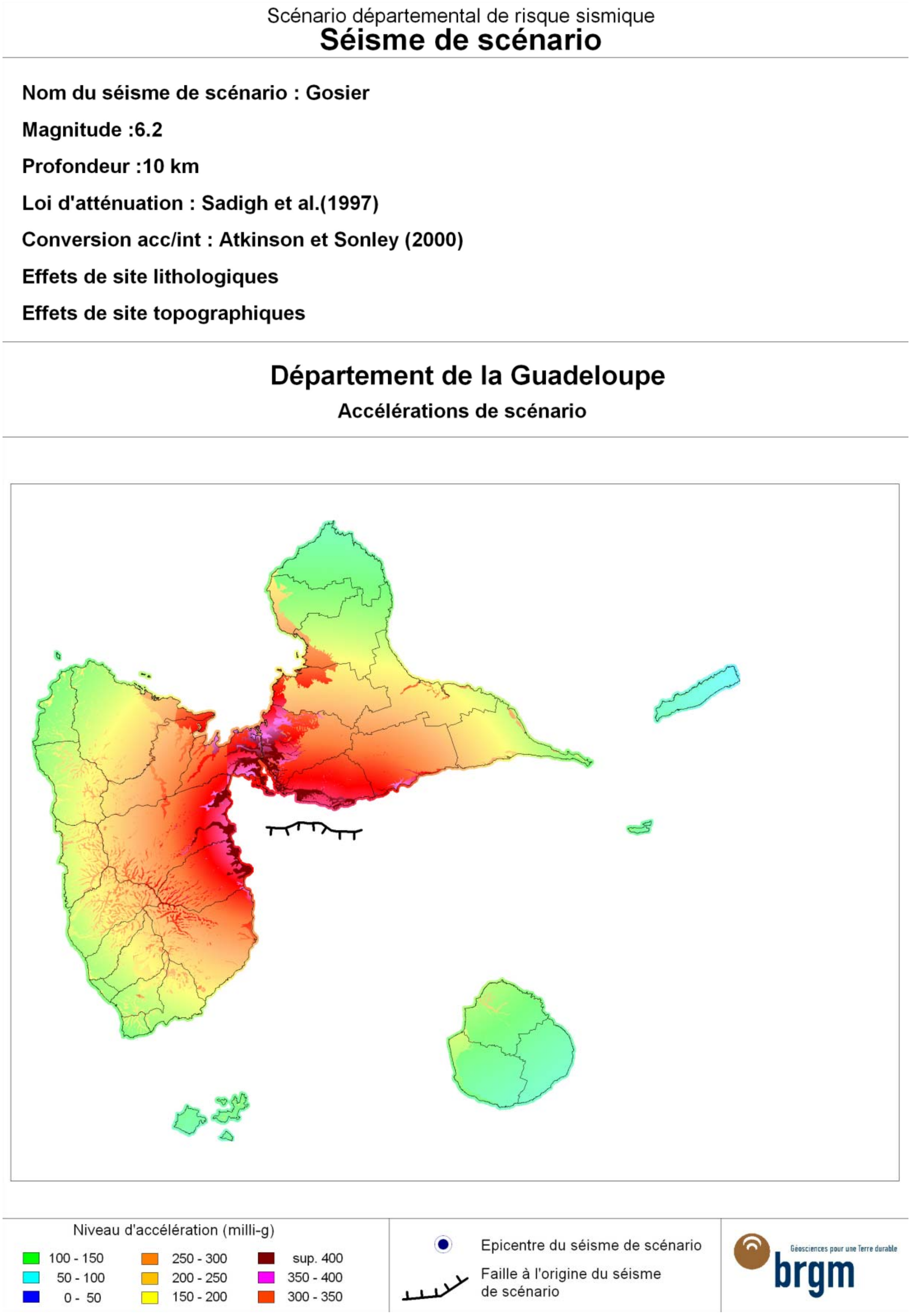

Figure 4 - PGA map for an earthquake on Gosier fault M=6.2, depth =10 km

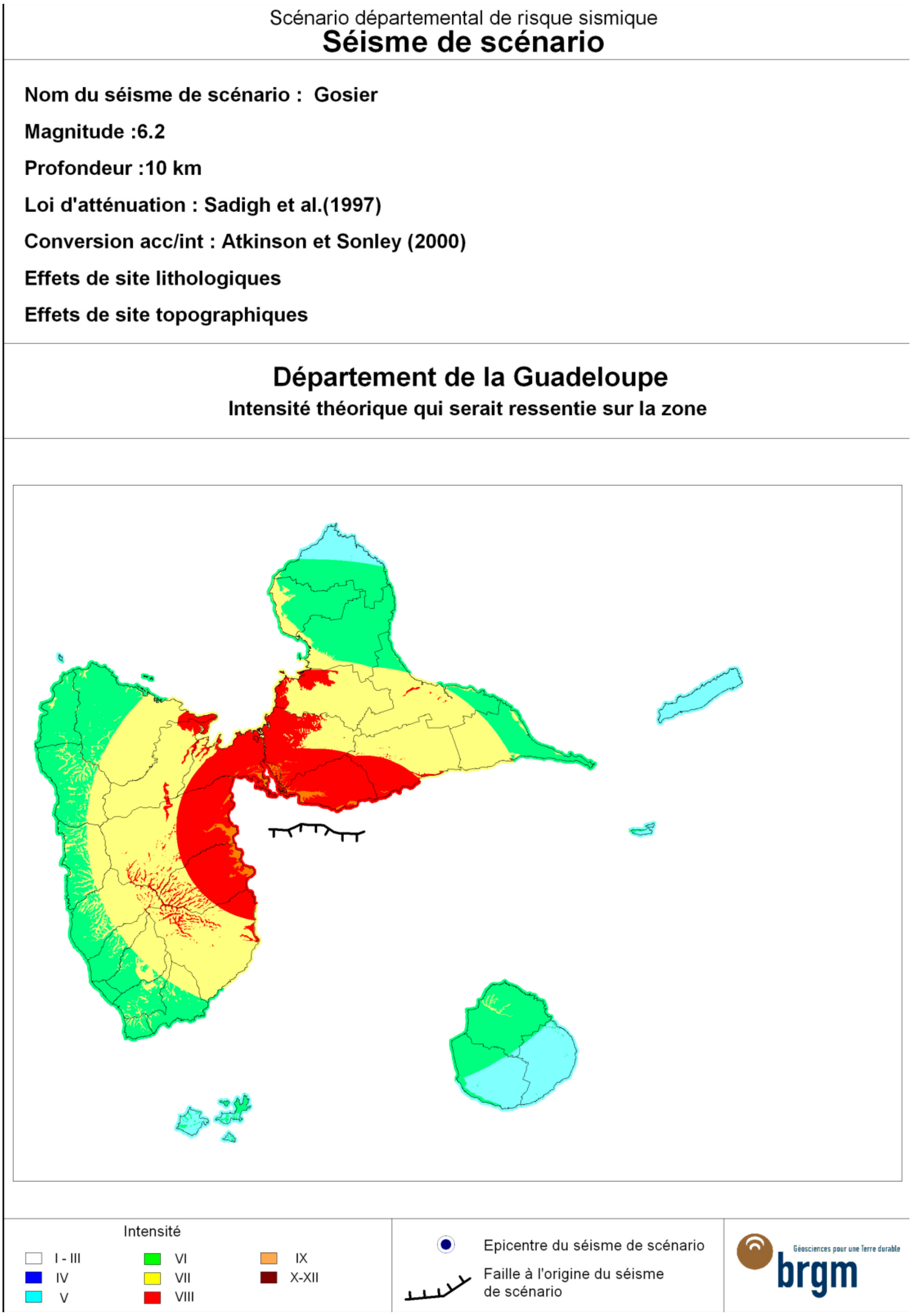

Figure 5 - Intensity map for an earthquake on Gosier fault M=6.2, depth =10 km

1.3. *Shakemaps from real-time information provided by seismic networks*

1.3.1. JMA – Japan

For the monitoring of earthquakes, JMA operates an earthquake observation network comprised of 180 seismographs and 600 seismic intensity meters. In addition to observational data from the network, JMA collects data from about 2,800 seismic intensity meters run by local governments.

Upon the occurrence of an earthquake, JMA immediately issues information on the epicenter and magnitude of the earthquake as well as spatial distribution of observed seismic intensity (Figure 6). The information is provided to the disaster prevention authorities through dedicated lines and to the public through mass media.

(http://www.jma.go.jp/jma/en/Activities/Earthquakes/act_Earthquakes.html); Yamazaki (2001)

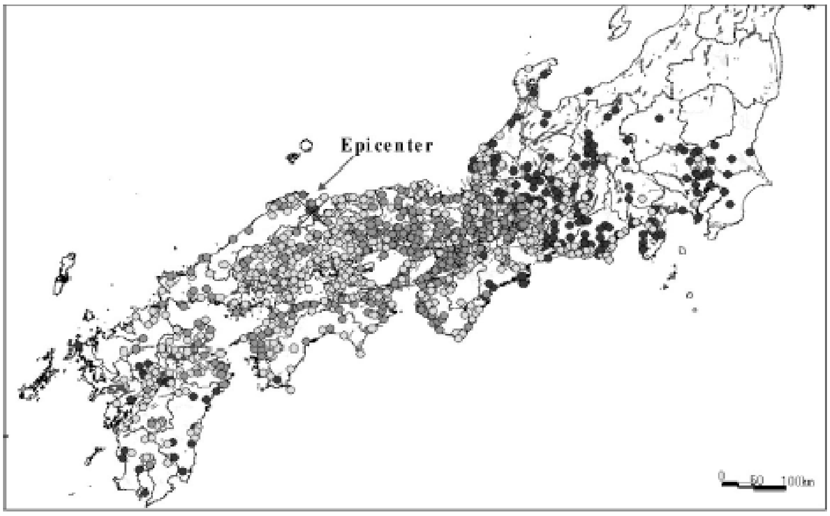

Fig. 1 JMA instrumental seismic intensity recorded by national seismic networks in the Tottori-ken Seibu earthquake, 6 October 2000

Figure 6 - JMA instrumental intensity map – example from Yamakazi (2001)

1.3.2. Rapid Response and Disaster Management System in Yokohama, Japan

Within Yokohama city 150 accelerographs are installed in free-field stations for ground shaking monitoring. Spacing between stations is about 2 km. A high precision digital accelerograph is used to record weak to very strong ground motion. In addition to the accelerographs at ground surface, borehole accelerometers are installed at 9 stations for liquefaction hazard assessment. All of these stations are connected to three observation centers, the disaster preparedness office of the city hall, the fire department office of the city and Yokohama City university, by the high-speed telephone lines. At 18 stations, the backup communication system by satellite is available. The full operation of the monitoring system started on May, 1997 (Midorikawa, 2005). When an accelerograph is triggered by an earthquake, the station computes ground-motion parameters such as the instrumental seismic intensity, peak amplitudes, predominant frequency, total power, duration and response spectral amplitudes. These parameters are automatically reported to the centers. On receiving more than 10 reports in a prescribed time interval, the centers activate alert systems. The seismic intensity data is conveyed to the city officials by the pager, and the intensity map of the city is drawn within a few minutes after the earthquake. The map is immediately open to the public through the Internet (www.city.yokohama.jp/me/bousai/eq/index.html) and local cable TV. The map is utilized as the earliest information for disaster management. The ground motion data from the stations are used for the real-time seismic hazard and risk assessment. The assessed items are ground motion, liquefaction and building damage. Operation of the assessment system started on June, 1998. In the mapping of ground motion hazard, the city is divided into cells of 50 x 50 m size. The hazard and risk maps are created within twenty minutes after the earthquake, almost in real-time, so that the maps can be used for selecting strategy of emergency response activities (Midorikawa, 2005). (Figure 7 and Figure 8)

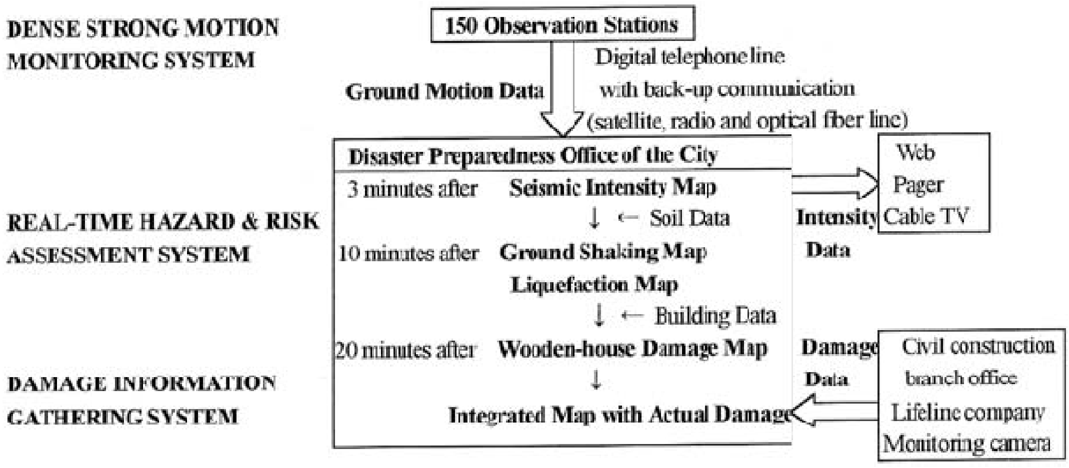

Figure 7 - Structure of system for Real-time assessment of earthquake disaster in Yokohama (Midorikawa, 2005)

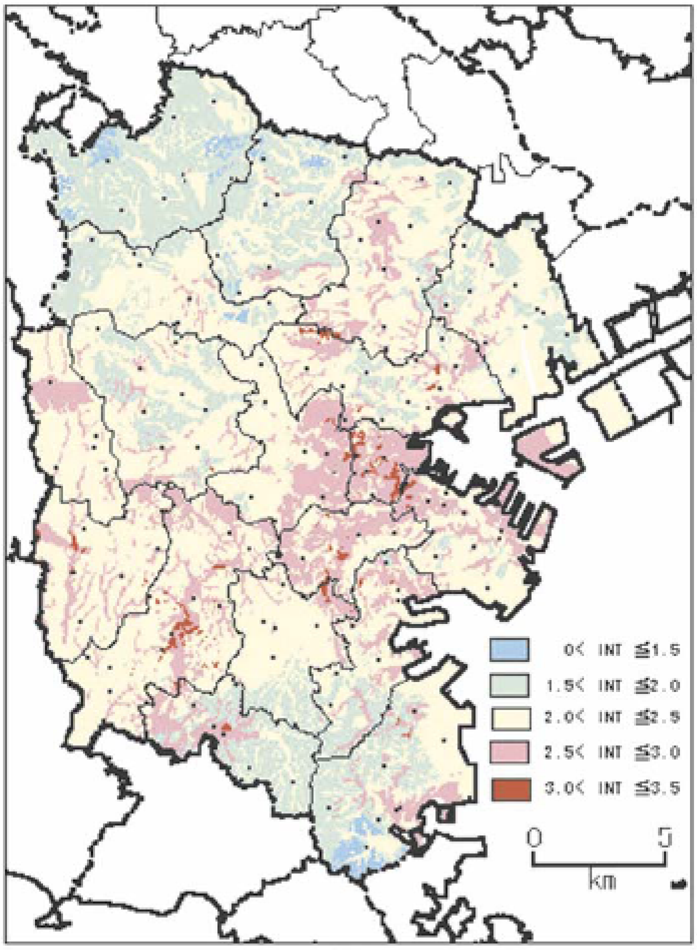

Figure 8 - 50m-mesh ground shaking map constructed from observed ground motion data and soil amplification factors (Midorikawa, 2005)

1.3.3. Earthquake Rapid Reporting and Early Warning Systems in Taiwan

Earthquake Rapid Reporting and Early Warning Systems in Taiwan use a real-time strong-motion accelerograph network that currently consists of 82 telemetered strong-motion stations distributed across Taiwan, an area of 100 km x 300 km and monitored by Taiwan Central Weather Bureau (CWB) (Figure 9). Each station has 3-component force-balanced accelerometers. The rapid reporting system can offer information about one minute after an earthquake occurrence. Information includes earthquake location, its magnitude and shaking maps of Taiwan area.

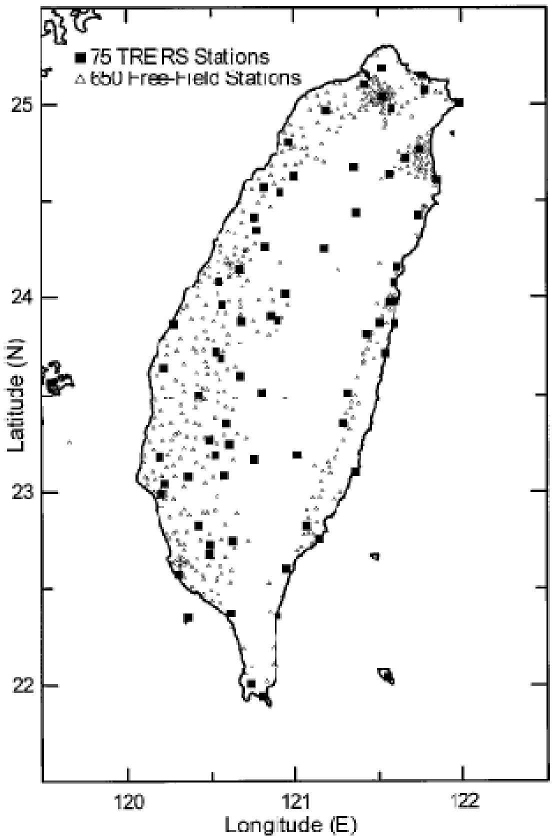

Figure 9 - Strong motion network in Taiwan from Wu et al. (2001)

The PGA and PGV attenuation relationships are deduced with data from the Taiwan Strong Motion Instrumentation Program (TSMIP) and the Taiwan Rapid Earthquake Information Release System (TREIRS). Site corrections of the attenuation relationships for shallow and large earthquakes in Taiwan region are obtained from earthquake already recorded on TSMIP stations. TSMIP site correction S can be determined empirically by averaging the residuals between the observed and predicted values

Peak values of earthquake strong ground motion can be well determined in Taiwan as soon as the earthquake location is determined and magnitudes are calculated by the TREIRS. This peak ground motion value information can be immediately turned into the calculated PGA and PGV maps that can be issued within two minutes of the earthquake origin time. (Figure 10).

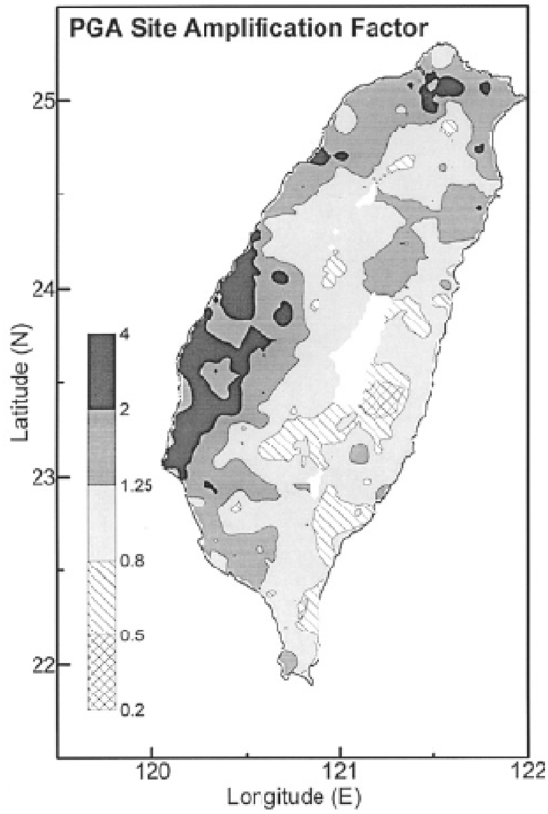

Figure 10 - Pga site amplification factor from Taiwan strong motion stations (Wu et al., 2001).

1.4. *Shakemaps from felt effects*

This way of produce shakemaps consist in assign an automatic intensity to each municipality according to the internet answered polls (automatic interpreted questionnaires).

These maps are produced by:

· USGS: http://earthquake.usgs.gov/earthquakes/dyfi/

· IGN: http://www.ign.es/ign/es/IGN/Sismologia30Espana.jsp

· CSEM: http://www.emsc-csem.org

1.5. *Shakemaps from mixed approach*

The rapid post-earthquake maps of ground shaking seen below with examples from Japan and Taiwan give detailed picture of the shaking distribution. Interpolations are not necessary because of the high density of the observations.

When the station distribution is very sparse as it is the case in many countries, the contribution of information from these stations need to be combined with geological information, geotechnical to produce ground shaking shake maps over large geographic areas.

This mixed approach has been developed by USGS with the ShakeMap system (Figure 11). To increase the density of required nodes for interpolation, ShakeMap, initially developed for earthquakes in California (Wald et al. 1999a), integrates estimated seismic ground shaking at a grid of phantom stations in sparsely covered areas. Ground motions at these sites are estimated from empirical attenuation relations and geology-dependent amplification factors for different soil types (Wald et al. 1999b).

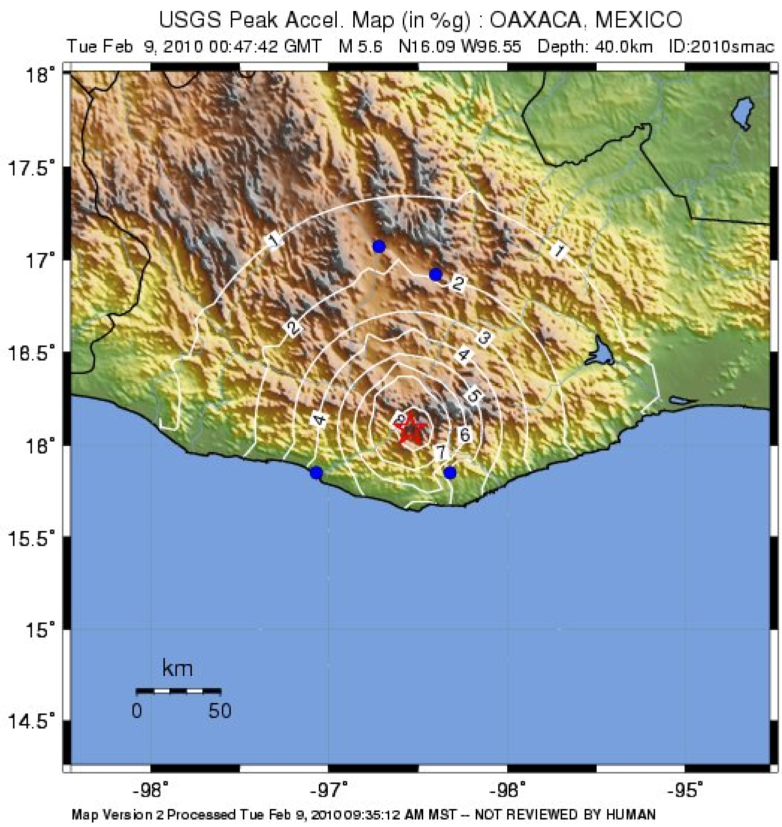

Figure 11 - PGA ShakeMap example (http://earthquake.usgs.gov/eqcenter/shakemap /)

2. ShakeMap current implementations

This section summarizes the current ShakeMap implementations in order to evaluate the different methodologies and customizations realized.

2.1. *US ShakeMap implementations*

The US Geological Survey (USGS) is the institution that developed the ShakeMap methodology. It has different implementations depending on the region, and nowadays they elaborate ShakeMaps worldwide.

Apart from the direct implementation by USGS other agencies in the United States implement de ShakeMap methodology at their states or regions.

Table 1 summarizes the US implementation and references associated:

Region	Year	Agency	Reference/Comments
Global	2007?	USGS	·http://earthquake.usgs.gov/eqcenter/shakemap/
South California,	2006	USGS	Wald et al. (1999a, 2005)
North California,	2006	USGS	Wald et al. (2005)
Cascadia region	2006	USGS	Wald et al. (2005)
Alaska	2006	AEIC	Martirosyan et al. (2006);· Wald et al. (2005) http://www.aeic.alaska.edu/~shake/shake/archive/
California	2006	CISN	http://www.cisn.org/shakemap.html
Pacific NW	2006	PNSN	Hartog et al. (2007); Wald et al. (2005) http://www.geophys.washington.edu/shake/archive/
New Madrid	2006		Brackman (2006)
Ontario	2006	POLARIS/ Carleton University	Kaka et Atkinson (2006) http://www.shakemap.carleton.ca/.
Utah	2006	UUSS	http://www.seis.utah.edu/shake/archive/
Nevada	>2006	NSL	http://www.seismo.unr.edu/shakemap/shake/archive/

Table 1 - US ShakeMap implementations (based on technical reports and published works).

2.2. *European ShakeMap implementations*

One of the Joint Research Activities (JRA) of the NERIES project (http://www.neries-eu.org), JRA3, was focused on shake and loss map. In the context of this joint research activity and the SAFER project (http://www.saferproject.net), different European agencies implement de USGS software in order to perform shake maps.

The Deliverable document 2 (D2) of the JRA3 (Oye V. & H. Bungum, December 2008), assured that INGV, ETHZ, KOERI and NORSAR had installed a regionally adapted USGS software (ShakeMap). They made national implementation, instead of European implementation, for the different reasons, mainly for the availability of real-time accelerometric data and the fact that is preferred for this kind of sensitive predictions to be published by or through national agencies.

Apart from the JRA3 deliverables there are some papers relating the European ShakeMaps implementations

In order to summarize the different European implementations the basic information of them is presented on Table 2.

Region	Year	Agency	Reference & Comments
Italy	2008	INGV	Michelini (2008) ·http://earthquake.rm.ingv.it/shakemap/shake/archive/
South-eastern Alps	2009		Moratto et al. (2009)
Iceland		IMO	·http://hraun.vedur.is/ja/safer/shake/index.html
Turkey		KOERI	Oye V. & H. Bungum (2008)
Norway		NORSAR	Oye V. & H. Bungum (2008)
Switzerland	2007	ETHZ	Wiemmer et al. (2007)
Spain	2009?	IGN	Implementation for Granada·(SISPYR communication)
Romania	2007	RO-NDC	Ionescu et al. (2007)
Romania (Vrancea)	2009	--	Bose et al. (2009); They propose an alternative method for determining amplification factors. This method doesn't require Vs30 maps· Only for Vrancea earthquakes

Table 2 - European ShakeMap implementations (based on technical reports and published works, see bibliography).

Finally within the Neries project they don't adapt the USGS software, they program their own ShakeMap integrated with the loss software in the ELER, Matlab programmed, software.

3. ShakeMap methodology

3.1. *Global methodology*

Methodology is resumed on Figure 12. The main steps are following:

- Acquisition of real strong motion data and homogenize seismic parameters (PGA, PGV, Spectral Acceleration …..) at bedrock condition (steps A , B on figure)
- Acquisition of interpreted macroseismic data (if it is available).
- Modelling strong motion parameters on the target area with a grid of regularly spaced “phantom” stations (step C)
- Ensuring consistency between measured and simulated data, bias correction (step D and E)
- Taking account soil amplification (step F)
- Producing maps (step G and H)

Two different types of data are necessary:

<u>Event data</u>

- Earthquake location and magnitude
- Strong motion parameters
- Fault finiteness information
- Felt intensity data (if it’s available)

<u>Permanent data</u>

- Mapping data (MNT, cities, roads, etc …)
- Soil information (from geological, geotechnical or topographic slope data)
- Soil amplification factors
- Seismic stations characteristics and grid of phantom stations
- Specific Peak Ground Motion versus Intensity (PGMvsI) relationship
- Specific Ground Motion Predictive Equations (GMPEs)
- Specific Intensity Predictive Equations (IPEs)

This permanent data is to calculate:

- soil amplification from soil information
- ground motion parameters (PGA, PGV, SA…) from macroseismic intensity
- macroseismic intensity from ground motion parameters
- ground motion parameters (PGA, PGV, SA…) from earthquake location and magnitude
- macroseismic intensity from earthquake location and magnitude

Permanent data are parameters previously defined, tested and then introduced into the software. Event data is the input data of the process. The near real time process of Shake Map depends on the process for acquisition and transmission of event data.

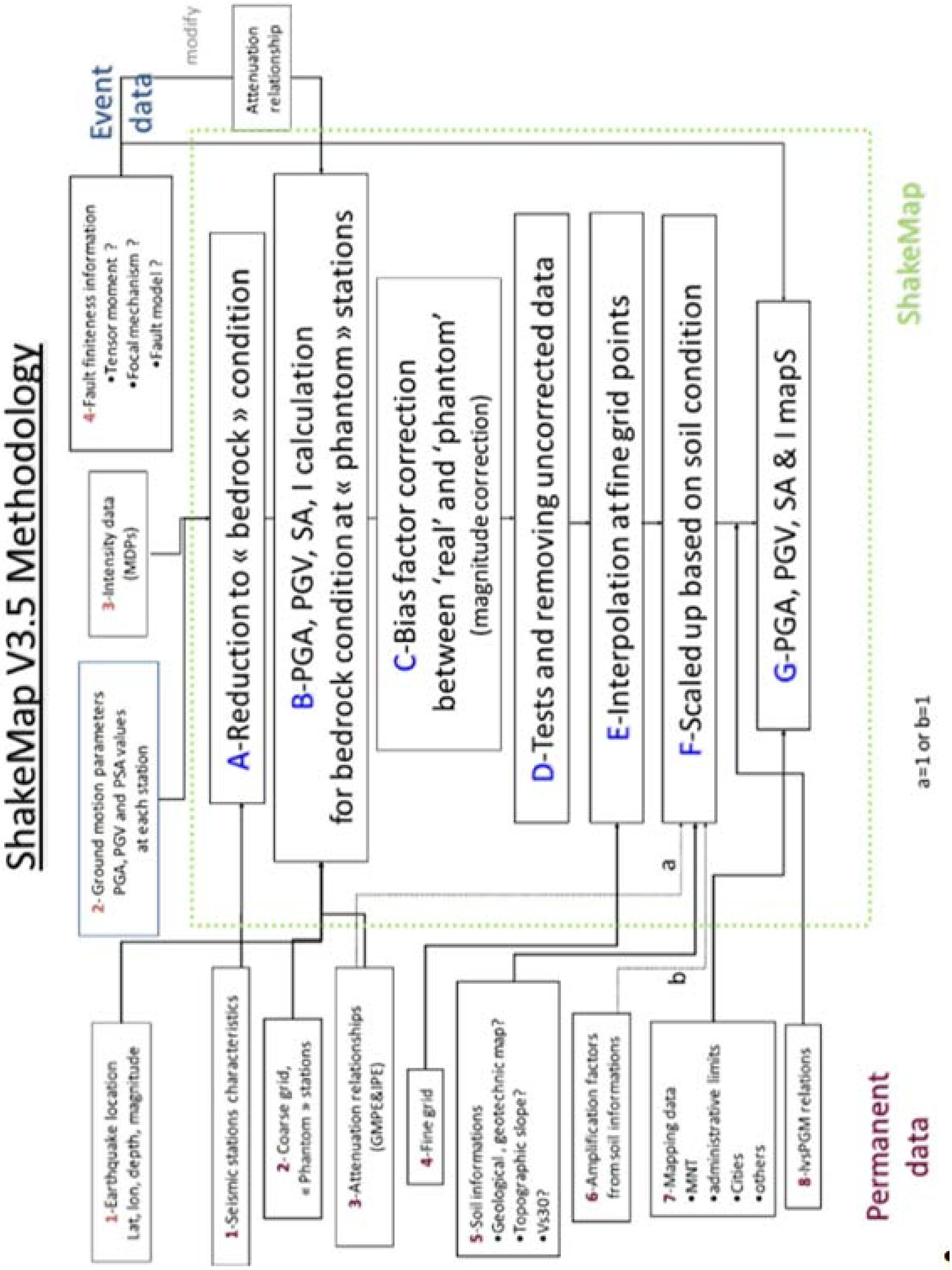

Figure 12 - ShakeMap v3.5 global methodology

3.2. *Regionalized predictive relationships for ground motion*

Synthesis from US and other countries implementations

Region	***GM attenuation***
South California, default regression	*Boore et al. (1997),* *PGV modified by Newmark & Hall (1982)*
North California, default regression	*Boatwright et al., (2003)*
Cascadia region (SO)	*Atkinson & Boore, (2003)*
Alaska	*Shallow: Boore et al. (1997)* *Deep (>41Km): Youngs et al (1997)*
California	*M>5.5 Boore et al. (1997)* *M≤ 5.5 regional relationship*
Pacific NW	*Shallow: Boore et al. (1997) Deep: Youngs et al. (1997)*
New Madrid	*M≤6 Kaka and Atkinson (2005)* *M>6 Toro et al. (1997)*
Ontario	*Kaka and Atkinson (2005)*
Nevada	*Large: Pankow and Pechman (2004) M<5.3: generic regression*
Region	**GM attenuation**
Italy	M>5.5 PGA Ambraseys et.al. (1996) M>5.5 PGV Bommer et al (2000). M< 5.5 specific regional GM attenuation
South-eastern Alps	3.5< M <5.5 Massa et al (2008)M>5.5. Sabetta and Pugliese (1996)
Swiss	Region-specific using Cua and Heaton (2007) approach
Iceland	Boore et al. (1997), and Joyner and Boore (1988)
Romania (Vrancea)	Region-specific (azimuth-dependent) attenuation relations.

Table 3 - GMPEs used for ShakeMap implementation in US and Europe.

In most cases, regional specific GMPE are used for M< Mo with Mo between 5 to 6 and general GMPE for large magnitudes.

In Italy, Ambraseys et al. (1996) for PGA and Bommer et al. (2000) for PGV are selected.

From Oye & Bungum (2008) for NERIES JRA-3, Akkar & Bommer (2007) seems to be a good solution for large magnitudes in Europe.

Pyrenees context and specificity

Existence of a regional GMPE :

- Tapia et al. (2007). Model is obtained from 30 earthquakes and 9 of them from Pyrenees. Validity domain: Ml 3.8 to 5.2
- Drouet et al. (2007) test 8 GMPE with French Pyrenees ground motion records. Lussou et al (2001), Berge-Thierry et al. (2003), Bay et al. (2003) must be examined.
- Souriau (2006) presented a regional GMPE with French data (including Pyrenees) and for magnitudes 3.0-5.4.
- Marin, et al (2004) presented a regional GMPE with French data (including Pyrenees) and for magnitudes 3.0-5.4.

3.3. *Intensity-Ground motion parameters relation (Instrumental intensity)*

3.3.1. Main relationships bibliography

Auclair and Rey (2009) have made a synthesis of the main relationships existing between Intensity and PGA, PGV, PGD, PSA, PSV, CAV, Arias Intensity. References are reported on tables below.

Author	Region	Type I	I validity
Tselentis et Danciu (2008)	Greece	MM	IV à VIII
Atkinson et Kaka (2007)	Central U.S (CUS) + Californie	MM	II à IX
Atkinson et Kaka (2007)	North America	MM	II à IX
Atkinson et Kaka (2006)	New-Madrid (Missouri - USA) + California	MM	II à IX
Souriau (2006)	France	EMS98	II à VI
Faccioli et Cauzzi (2006)	Italia	MCS	IV-V à IX
Marin *et al.* (2004)	France	MSK	-
Davenport (2003)	New-Zealand	MM	IV à VIII-IX
Boatwright *et al.* (2001)	California	I_{tag}[1]	V à IX
Atkinson et Sonley (2000)	California	MM	III à IX
Wald *et al.* (1999b)	California	MM	V à IX
Koliopoulos *et al.* (1998)	Greece	MM	III à VIII-IX
Theodulidis et Papazachos (1992)	Greece	MM	IV à VIII
Margottini *et al.* (1992)	Italia	MSK	IV à VIII-IX
Murphy et O'Brien (1977)	West USA + Japon + South Europe	MM	I à X
Trifunac et Brady (1975)	West USA	MM	IV à X
Ambraseys (1974)	Europe	MM	IV à VII
Gutenberg et Richter (1956)	West USA	MM	III à VIII
Hershberger (1956)	West USA	MM	III à VIII

Table 4 - I/PGA relationships main references from Auclair & Rey (2009).

[1] Thywissen and Boatwright, 1998

Author	Region	Type I	I validity
Tselentis et Danciu (2008)	Greece	MM	IV à VIII
Atkinson et Kaka (2007)	North America	MM	II à IX
Atkinson et Kaka (2007)	Central US (CUS) + California	MM	II à IX
Atkinson et Kaka (2006)	New-Madrid (Missouri - USA) + California	MM	II à IX
Kaka et Atkinson (2004)	SE-Canada + NE USA : East of North America (ENA)	MM	II à VIII
Kaka et Atkinson (2004)	SE-Canada + NE USA : ENA	MM	II à VIII
Wu *et al.* (2003)	Taïwan	It	I à VII
Boatwright *et al.* (2001)	California	I_{tag}^{2}	V à IX
Atkinson et Sonley (2000)	California	MM	III à IX
Wald *et al.* (1999b)	California	MM	V à IX
Koliopoulos *et al.* (1998)	Greece	MM	III à VIII-IX
Theodulidis et Papazachos (1992)	Greece	MM	IV à VIII
Trifunac et Brady (1975)	West USA	MM	III à X

Table 5 - I/PGV relationships main references from Auclair & Rey (2009)

Author	Region	Type I	I validity
Atkinson et Sonley (2000)	California	MM	III à IX
Trifunac et Brady (1975)	West USA	MM	III à X
Tselentis et Danciu (2008)	Greece	MM	IV à VIII

Table 6 - I/PGD relationships main references from Auclair & Rey (2009).

Author	Region	Type I	I validity
Atkinson et Kaka (2007)	North America	MM	II à IX
Atkinson et Kaka (2007)	Central US (CUS) + California	MM	II à IX
Atkinson et Kaka (2006)	New-Madrid (Missouri - USA) + California	MM	II à IX
Kaka et Atkinson (2004)	Est of North America (ENA)	MM	II à VIII
Atkinson et Sonley (2000)	California	MM	III à IX

Table 7 - I/PSA relationships main references from Auclair & Rey (2009).

Author	Region	Type I	I validity
Boatwright *et al.* (2001)	California	I_{tag}^2	V à IX
Levret et Mohammadioun (1984)	France	MSK	V à IX

Table 8 - I/PSV relationships main references from Auclair & Rey (2009).

Author	Region	Type I	I validity
Tselentis et Danciu (2008)	Greece	MM	IV à VIII
Koliopoulos *et al.* (1998)	Greece	MM	III à VIII-IX
Cabañas *et al.* (1997)	Italia	MSK	V à VII-VIII

Table 9 - I/CAV relationships main references from Auclair & Rey (2009).

Author	Region	Type I	I validity
Cabañas *et al.* (1997)	Italia	MSK	V à VII-VIII
Schmidt (2008)	Costa Rica	MM	II-VII
Tselentis et Danciu (2008)	Greece	MM	IV à VIII
Koliopoulos *et al.* (1998)	Greece	MM	III à VIII-IX
Cabañas *et al.* (1997)	Italia	MSK	V à VII-VIII
Margottini *et al.* (1992)	Italia	MSK	IV à VIII-IX

Table 10 - I/Arias Intensity relationships main references from Auclair & Rey (2009).

In the same report, Auclair and Rey (2009) test the different relationships between Intensity and seismic parameters calculated from 55 strong motion records of the Italian network during Aquila 2009 earthquake. Tselentis & Danciu (2008) and Atkinson & Kaka (2007) give the best correlation for I/PGV, Souriau (2006) is good for I/PGA. This report will be public in a few months.

For ShakeMap implementations, Intensities are calculated from PGA or PGV (Table 11 - Intensity/PGA/PGV relationships used for ShakeMap in US and Europe.

). For USA two relationships are used: Wald et al. (1999b) which is the default relation for Global ShakeMap , Kaka and Atkinson (2004, 2005) from North East America and Southeast Canada.

In Europe, the default Wald et al (1999b) is used. For South eastern Alp, Morato et al. (2009) used Facciolli and Cauzzi (2006).

In Romania, for Shakemaps associated with Vrancea earthquakes, Böse et al. (2009) used specific regional relationship (Sokolov, 2008).

Region	Instrumental I
Global	Wald et al. (1999b)
South California, default regression	Wald et al. (1999b)
North California, default regression	Wald et al. (1999b)
Cascadia region (SO)	Wald et al. (1999b)
Alaska	Wald et al. (1999b)
New Madrid	Kaka and Atkinson (2004, 2005)
Ontario	Kaka and Atkinson (2004, 2005)
Region	**Instrumental I**
Italy	Wald et al. (1999b)
South-eastern Alps	Faccioli and Cauzzi (2006)
Iceland	Wald et al. (1999b)
Romania (Vrancea)	Sokolov et. al. (2008)

Table 11 - Intensity/PGA/PGV relationships used for ShakeMap in US and Europe.

Figure 13 and Figure 14 show some comparisons of Intensity relationships. Variability is much greater for intensities less than VI than for I >= V. Some relations are linear. Other use two different relations for I≤V and for I>V.

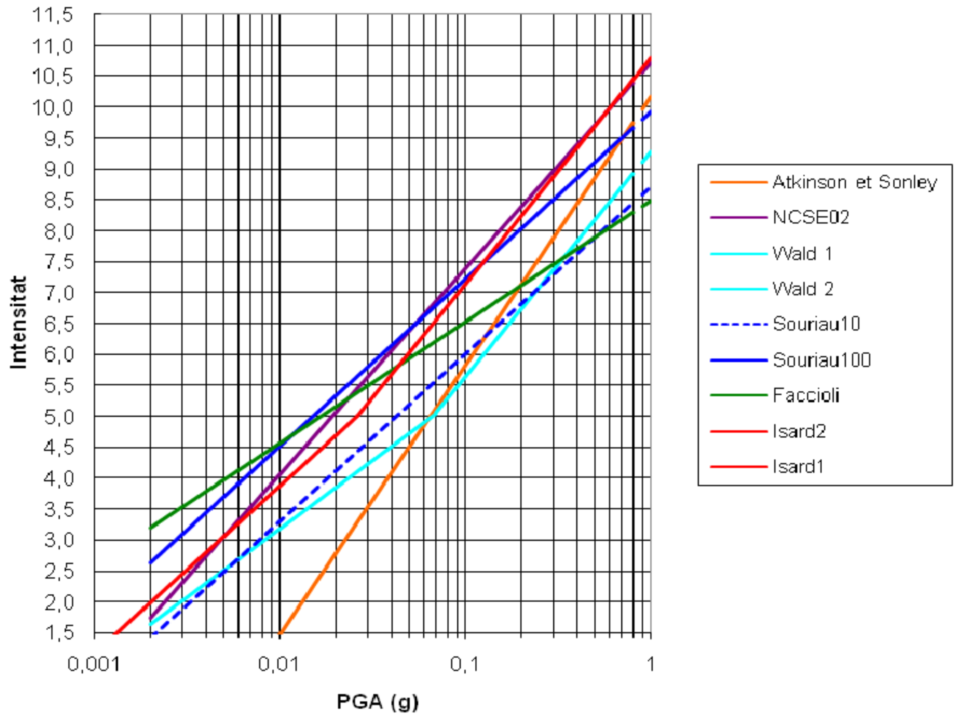

Figure 13 - Comparison of intensity relationships as function of PGA

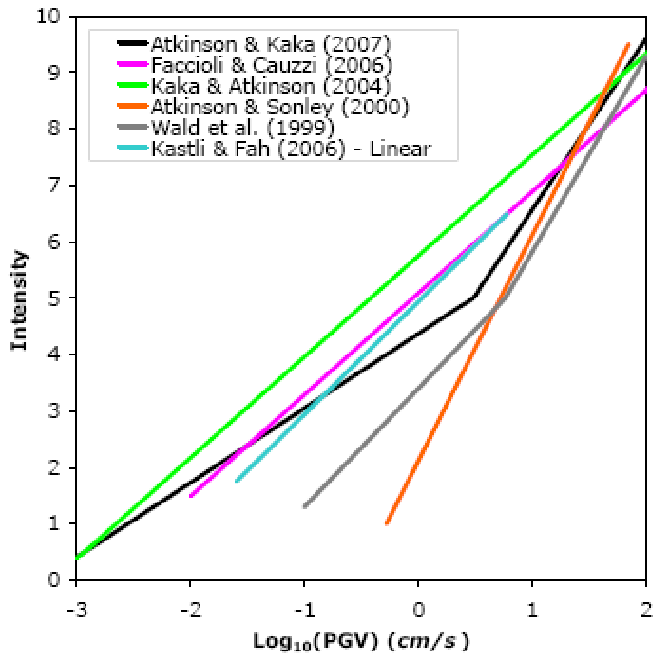

Figure 14 - Comparison of intensity relationships as function of PGV from Oye & Bungum(2008)

3.3.2. Correspondence between Intensity scale and others seismic parameters scales in ShakeMaps

In function of relationships used for our ShakeMap, correspondence between perceived shaking, PGA, PGV and intensity must be adapted (Figure 15).

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+

Global ShakeMap Wald (1999)

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)	NA	NA	NA	NA	NA	NA	NA	NA	NA
PEAK VEL.(cm/s)	<.004	.004-.06	.06-.2	0.2-0.7	0.7-2.6	2.6-9.5	9.5-34	34-124	>124
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Brackman (2006) – New Madrid

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)	<.03	.03-.29	.29-.93	.93-3.0	3.0-9.7	9.7-31	31-102	101-330	>330
PEAK VEL.(cm/s)	<.01	.01-.13	.13-.47	.47-1.7	1.7-6.1	6.1-22	22-78	78-262	>262
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Moratto et al. (2009) - South-eastern Alp

Perception Humaine	non ressenti	très faible	faible	légère	modérée	forte	très forte	sévère	violente	extrême
Dégâts Potentiels	aucun	aucun	aucun	aucun	très légers	légers	modérés	importants	destructions	généralisés
Accélérations (mg)	< 1.5	1.5 - 3.2	3.2 - 6.8	6.8 - 15	15 - 32	32 - 68	68 - 150	150 - 320	320 - 680	> 680
Intensités EMS98	I	II	III	IV	V	VI	VII	VIII	IX	X+

Communiqués IPGP – Observatoire de Guadeloupe

Figure 15 – ShakeMap Instrumental Intensity Scale Legend: different ranges of peak motions for Instrumental Intensities

3.3.3. Pyrenees context and specificity

In the ISARD project, specific relationships have been defined (Table 12)

In France:

Marin et al (2004) propose a relationship between local magnitude (LDG) and epicentral intensity (MSK) established for France from the common events of the

SIRENE and LDG databases. This can be combined with another empirical relation between PGA, MI and focal distance.

Souriau (2006) gives relationship between Intensity and PGA, distance and frequency. This relation is derived from French earthquakes and strong motion records.

I	PGA(cm/s^2)	PGV(cm/s)
<2	<1.3	<0.01
2	1.3-3	0.01-0.04
3	3.0-7	0.04-0.13
4	7.0-17	0.13-0.5
5	17-35	0.5-1.7
6	35-70	1.7-6.0
7	70-130	6.0-22
8	130-240	22-80
9	240-450	80-300
10	>=450.	>300

Table 12 - Isard Intensity vs PGM relations (derived from the scale of the figures 2)

3.4. *Intensity Prediction equation (IPE)*

In Iberian peninsula some IPE have been developed. The main studies are summed up at Table 13.

In France the most important studies are Levret (1996) and Marin et al. (2004).

rea	No eq.	Earthq. used	Time Interv.	M Interv.	M scale	I Interv.	No MDP used	I scale	Type data	Source Macroseismic Data	Type distance	Relationship
ain												I=Io + 12.55 - 3.53ln
tugal												I=6.8 + 1.13M - 1.68 l
rian nsula	254	-	1428-1994	2.0-6.9	mb	I-8		MSK	Isoseismal	Mezcua (1982); Mezcua and Martínez (1983) updated (1997)	**Radii of the circle of equal area of mapped isoseismal lines	I=3.506 + 0.171 I₀ − 0.078 I₀²-0 I=6.016 + 0.093 I₀ − 0.069 I₀²-1 I=4.927 + 0.571 I₀ − 0.057 I₀²-1 I=5.557 + 0.902 I₀ − 0.014 I₀²-1 I=7.900 + 0.902 I₀ − 0.014 I₀²-2
donia	>100		XX century+4 middle age events?						Isoseismal + MDP?		"Hypocentral"	I=-3log (x²+h²)^1/2 +1.99M
rian nsula	5	1969.02.28 1993.12.23 1994.01.04 1997.05.21 1999.02.02	1969-1999	5.0-6.0	Mw	Unknown 3-7 Unknown 3-7 Unknown	115 52 45 132 31 (total= 375)	MSK	MDP	Mezcua (1982) Martínez Solares and Pascual (1996) Rueda y Mezcua (2001) IGN data file?	Median Epicentral	I = 1.96+1.41Mw-2
nees nce	8	1923.11.19 1950.01.31 1967.08.13 1980.02.29 1981.09.28 1982.01.06 1989.01.06 1996.02.18	1923-1996	Mw for 1980 None for the others	Mw	4-6 4-5 3-7 3-7 3-5 3-6 3-5 3-6	362 154 628 909 454 322 401 757 (total= 4060)	MSK	MDP	SisFrance (2008) database	* Median Hypocentral	I = 4.81+1.27 Mw-(3.87

Table 13 - Intensity attenuation relations. Extracted from NA4 state of the art for Iberian Península (2008).

3.5. *Methodologies to define or select GMPE and IPE*

In order to have the best GMPE or IPE for the study zones this relations could be defined as new relations, or could be selected from the broad set of existing relations.

Over the past decades different procedures to define new GMPE have been developed. Each method has its advantages and its limitations. Douglas (2008) presents a detailed study evaluating the advantages and limitations of the different methods to define new relations.

About the selection of the best relation recent studies have sought to evaluate the applicability of existing GMPE developed for a host region to other regions. These studies are also important for weighting multiple Ground Motion Prediction Equations (GMPEs) in probabilistic seismic hazard analyses in order to capture the epistemic uncertainty.

- ***Campbell, 2003-Hybrid empirical method***- uses the ratio of theoretical ground motion estimates to adjust empirical ground motion relations calculated to host region to study regions with sparse data. The application accounts for differences in stress drop, source properties, crustal attenuation, regional crustal structure, and generic-rock site profiles between the two regions.

- **Scherbaum, 2004-** Study different statistical tests that better could rank the probability that the studied model could be generated by the set of the data of the study region. The method proposed ranks the models according to defined thresholds for the median, std, mean and new defined LH statistic of the normalized residuals. Other studies use this methodology (Drouet, 2007; Stafford et al., 2008; Hintersberger et al., 2007; ...)
- **Cotton, 2006-** Starting from a comprehensive list of available equations and then applying criteria for rejecting those considered inappropriate in terms of quality, derivation or applicability. Once the final list of candidate models is established, adjustments must be applied to achieve parameter compatibility. Additional adjustments can also be applied to remove the effect of systematic differences between host and target regions. These procedures are applied to select and adjust ground-motion models for the analysis of seismic hazard at rock sites in West Central Europe.

- **Allen and Wald 2009b - Evaluation of GMPE for use in Global ShakeMap-** The residuals from a set of models and data for all the world are studied in order to select the better relationship for each tectonic setting (active crust, subduction zone and stable continent) to apply to the Global ShakeMap.

- **Scherbaum et al., 2009 -** The selection of models to predict the ground motion at the sites of interest remains a major challenge. Information theory provides a powerful theoretical framework that can guide this selection process in a consistent way. From an information-theoretic perspective, the appropriateness of models can be expressed in terms of their relative information loss (Kullback–Leibler distance) and hence in physically meaningful units (bits). In contrast to hypothesis testing, information theoretic model selection does not require ad hoc decisions regarding significance levels nor does it require the models to be mutually exclusive and collectively exhaustive. The key ingredient, the Kullback–Leibler distance, can be estimated from the statistical expectation of log-likelihoods of observations for the models under consideration. In the present study, data-driven ground-motion model selection based on Kullback–Leibler-distance differences is illustrated for a set of simulated observations of response spectra and macroseismic intensities. Information theory allows for a unified treatment of both quantities. The application of Kullback–Leiblerdistance based model selection to real data using the model generating data set for the Abrahamson and Silva (1997) ground-motion model demonstrates the superior performance of the information-theoretic perspective in comparison to earlier attempts at data-driven model selection (e.g., Scherbaum et al., 2004).

3.6. *Site corrections*

Except for the very specific methodology developed in Romania by Böse et al (2009), ShakeMaps implementations around the world are illustrated in Figure 16:

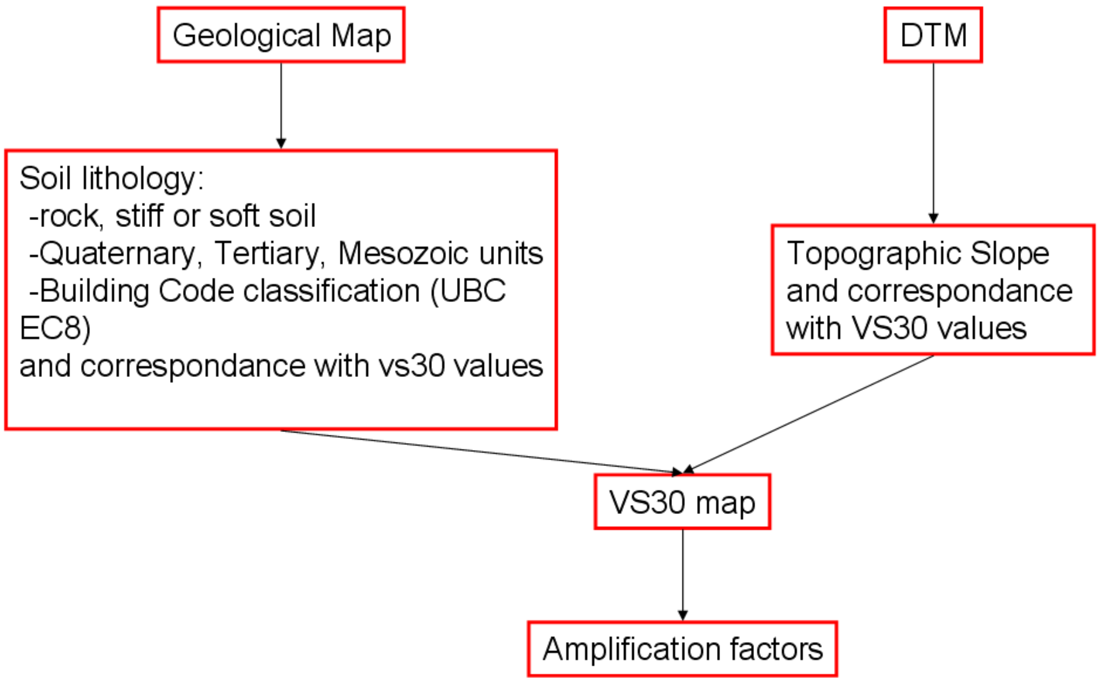

Figure 16 - Two main methodologies to calculate Vs30-amplification factors at a site

On a first step, site condition maps are built. One simple method of accounting for site conditions, considering impedance alone, is to use the shear-wave velocity (Vs) in the shallow subsurface to develop a site conditions factor. Shearwave velocity averaged over the upper 30 m (Vs 30) is the basic parameter.

Amplification factors are usually derived in ShakeMap implementations from Vs30 values using Borcherdt (1994) method.

The default input parameters for ShakeMap site corrections are Vs30 map and amplification factors. The new ShakeMap version 3.5, allows you to compute site corrections direct with the GMPE site corrections term, then the amplification factors are no required.

In order to define the site corrections we have to answer the questions:

1. What parameters do we use to determine the amplification factors?
2. How we obtain these parameters for our area of study?

3. How we compute the amplification factors from this parameters?

The following subsections are a review of some of the studies relating the methods to determine parameters (mainly Vs30) from which could be derived the amplification factors and some methods for determining the amplification.

3.6.1. Vs30 maps from geological and geotechnical data.

In south California, Park and Elrick (1998) used age units shown on geologic maps, which roughly correlate with the common site-conditions terms. Generally, Quaternary units are alluvium, Tertiary are soft rocks, and Mesozoic are hard rocks. Although there are numerous exceptions to this general rule, use of QTM categories should correlate with site categories. Park and Elrick (1998) assembled a database of Vs profiles and used measured Vs30 to characterize QTM units in southern California. They found that Vs30 varied by age and grain size of the units, and that the units could be grouped into eight units with similar Vs 30 values.

Wills et al. (2000) have prepared a site-category map of California by first classifying the geologic units shown on 1:250,000 scale geologic maps. Their classification of geologic units is based on Vs30 measured in 556 profiles and geological similarities between units for which they have Vs data and the vast majority of units for which they have no data. They then digitized the geologic boundaries from those maps that separated units with different site classifications.

This procedure requires both expensive geological and geotechnical data, as well as large numbers of ground motion records in regions, in which ShakeMap shall be established.

Figure 17 shows correspondence between EC8 and UBC subsoil classification and Vs30 values.

Some similar studies have been made in other countries as in Dinar region in SW Turkey by Kanli et al. (2006). Convertito et al. (2009) apply the QTM methodology of Park and Elrick (1998) in Campania region- Italy (see Figure 18). Wills & Gutierrez (2008) search to improve site-condition mapping with some geographic rules using distance to rock or topographic slope to better defined Vs30 in young alluvions.

Table 2. Ground profile (soil) types or classification of subsoil classes according to UBC (Uniform Building Code) and EC8 (Eurocode 8) standards based on the V_s^{30} values (modified from Sêco e Pinto 2002; Dobry *et al.* 2000; Sabetta & Bommer 2002).

Ground profile (Soil) type (UBC) or Subsoil Class (EC8)	Ground description (UBC)	Description of stratigraphic profile (EC8)	Shear wave velocity V_s^{30} (m s^{-1})
S_A(UBC)	Hard rock	—	>1500 (UBC)
S_B(UBC) or A (EC8)	Rock	Rock or other rock-like geological formation, including at most 5m of weaker material at the surface	760–1500 (UBC) or >800 (EC8)
S_C(UBC) or B (EC8)	Very dense soil and soft rock	Deposits of very dense sand, gravel or very stiff clay, at least several tens of m in thickness, characterized by a gradual increase of mechanical properties with depth	360–760 (UBC) or 360–800 (EC8)
S_D(UBC) or C (EC8)	Stiff soil	Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of m.	180–360 (UBC and EC8)
S_E(UBC) or D (EC8)	Soft soil	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil	<180 (UBC and EC8)
S_F(UBC) or E (EC8)	Special soils	A soil profile consisting of a surface alluvium layer with V_s^{30} values of class C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with V_s^{30} > 800 m s^{-1}	—
S_1 (EC8)	—	Deposits consisting—or containing a layer at least 10 m thick—of soft clays/silts with high plasticity index (PI > 40) and high water content	<100 (EC8)
S_2 (EC8)	—	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in classes A–E or S_1	— (EC8)

Figure 17 - EC8 and UBC subsoil classification and Vs30 values (From Kanli et al., 2006)

Table 2 Site class definitions for the Campania-Lucania region and the corresponding EC8 site classes (2003)

Ground type	Age	Vs30 (m/s)	EC8 class
Carbonate platform successions	Mesozoic	>800	A
Sediments, soft rocks and Flysh deposit	Tertiary	360–800	B
Volcanic rocks	Tertiary–Quaternary	360–1000	B
Alluvium and gravel deposits	Quaternary	180–360	C
Very soft soils	Quaternary	<180	D

Figure 18 - Soil lithology and correspondance with Vs30 ranges from Convertito et al. (2009)

An other methodology is proposed in the JRA3 by Oye & Bungum (2008): Digital soil mapping using multiple terrain parameters. This approach is shortly described in Appendix 1.

3.6.2. Vs30 maps from topographic slopes

Wald and Allen (2007) methodology

Recently, Wald and Allen (2007) proposed to derive first-order Vs30 (shear-wave velocity data averaged down to 30 m) maps from topographic data. The authors correlated VS30 from the United States, Taiwan, Italy, and Australia with the topographic slope in active tectonic regions and stable shields, using global 30 arc sec topographic data. They found that the use of topographic slopes and their empirically assigned VS30 values provide a simple approach to a uniform site-condition mapping which might be usable for shake map generation (Wald et al., 2005).Figure 19)

Table 1. Slope ranges for NEHRP V_{S30} categories (WA07).

Class	V_S30 Range (m/sec)	Slope Range (m/m) Active Tectonic	Slope Range (m/m) Stable Continent
E	< 180	< 3.2E-5	< 1.0E-6
D	180 - 240	3.2E-5 -	1.0E-6 -
	240 - 300	2.2E-3 -	2.0E-3 -
	300 - 360	6.3E-3 –	4.0E-3 –
C	360 - 490	0.018 – 0.050	7.2E-3 –
	490 - 620	0.050 – 0.10	0.013 – 0.018
	620 - 760	0.10 – 0.138	0.018 – 0.025
B	> 760	> 0.138	> 0.025

Figure 19 - NEHRP site classes, Vs30 ranges and corresponding topographic slopes from Wald & Allen (2007)

Vs30 (m/s) data is correlated with topographic slope (m/m) at each Vs30 measurement point, at two different regions (active tectonic and stable continental). The overall trend shows increasing Vs30 with increasing slope. There is significant scatter, especially with the data in rock sites (there are less Vs30 data). Overall the trend is sufficient.

Multiple linear regression is also performed on both elevation and slope, correlating jointly with Vs30. Slopes and elevation correlate well, bit elevation alone is, in general, a poorer predictor of Vs30 than slope. Joint analysis is weaker than using slope alone.

Allen and Wald (2009a) modified the correspondences between Vs30 and slopes at 30''; and study the correspondence if higher-resolution (3 and 9 arcsec) digital elevation models (DEMs) are used (Figure 20).

The 3'' STRM slopes data didn't improve the Vs30 prediction. It is too sensitive. The 9'' STRM slopes data improve the detail definition and better estimates the Vs30 where significant contrast in topography gradient exist (basin-hills border zones). However it didn't improve the residuals.

Table 1

Correlations between Topographic Gradient and V_{S30} Using the NED 9c Digital Elevation Models for the National Earthquake Hazard Reduction Program (NEHRP) Site Classes

NEHRP Site Class	V_{S30} Range (m/sec)	9 arcsec Gradient Range (m/m) (Active Tectonic)	9 arcsec Gradient Range (m/m) (Stable Continent)	Modified 30 arsec Gradient Range (m/m) (Active Tectonic)
E	< 180	$<3 \times 10^{-4}$	$< 1 \times 10^{-4}$	$<3 \times 10^{-4}$
	180–240	3×10^{-4}–3.5×10^{-3}	1×10^{-4}–8.5×10^{-3}	3×10^{-4}–3.5×10^{-3}
D	240–300	3.5×10^{-3}–0.010	4.5×10^{-3}–8.5×10^{-3}	3.5×10^{-3}–0.010
	300–360	0.010–0.024	8.5×10^{-3}–0.013	0.010–0.018
	360–490	0.024–0.08	0.013–0.022	0.018–0.05
C	490–620	0.08–0.14	0.022–0.03	0.05–0.10
	620–760	0.14–0.20	0.03–0.04	0.10–0.14
B	> 760	>0.20	>0.04	>0.14

New correlations are developed for active tectonic and stable continental regions. Also indicated are the modified correlations to Wald and Allen's (2007) original slope-V_{S30} correlations for the 30c SRTM data.

Figure 20 - NEHRP site classes, Vs30 ranges and corresponding topographic slopes from Allen & Wald (2009a)

Why topographic slope works as a proxy for VS30 ? (Fumal and Tinsley, 1985)

Of the physical properties of soils void ratios are one of the most important factors affecting shear modulus. Soil texture and the relative grain-size distribution can be a good measure of the void ratio. In general, shear velocity increases as mean grain size increases and particle size decreases as the available energy in the depositional environment decreases (with lower slopes). This could explain why lower Vs and lower topographic slope correlate so well.

Of the physical properties of rocks, the two dominant properties are hardness and fracture spacing. Rocks with higher Vs hold a steeper slope.

There are also several reasons why topographic slope should be limited in its ability to recover Vs30 by several known geological processes and overall variations in geological materials. The simple assumption done in the study will break down for some obvious topographic and geomorphic combinations.

Topographic slope revisited for Europe (JRA3, 2007)

This method to derive the soil condition maps directly from topographic slope have been applied and tested in Euro-Mediterranean region. The method was applied in Italy, Sweden and Turkey during the NERIES Project.

Conclusions from the study are: [2]:

[2] Extracted from D2 of JRA3

- The method is easily implemented and seems to work well also for Europe. However, more Vs30 measurements are clearly needed to establish better constrained slope-soil class relation.
- The approach is simple and needs limited computer resources. It requires high-resolution topographic data and some information about the geologic and morphological environment.
- Further research is needed to resolve the question of the correct resolution. Depending on the roughness of the area, the scale change the slopes critically.
- There are many pitfalls with the interpretation of slopes and the slope-soil relation varies from region to region and needs regional correlation.

3.6.3. Amplification factors from Vs30

Borcherdt et al. (1991) showed a correlation between amplification of ground motions and shearwave velocity averaged over the upper 30 m (Vs 30). Then, they prepared a map that grouped the geologic units in San Francisco into four shear-wave velocity classes. More recent mapping of site conditions has generally followed this method of grouping geologic units with similar shear-wave velocity characteristics, and describing those characteristics in terms of the Vs30. Vs30 has become a standard element for consideration of site conditions based on further empirical ground-motion studies of Borcherdt (1994), which show a consistent relationship between site response and Vs30.

The amplifications can be calculated for short-period (0.1-0.5 s) and mid-period (0.4-2.0 s) ranges from Borcherdt (1994, equations 7a and 7b, respectively) at four ranges of input acceleration levels (see Borcherdt, 1994, table 2). These amplification factors are given in Figure 21. The amplification for the soil sites decreases with increasing ground-motion levels; the rock units have a less pronounced amplitude dependency.

The proposed relations for determining the amplification factors at low periods (Fa) and mid-periods (Fv) are (Borcherdt, 1994):

$$F_a(v, I) = (v_o / v)^{m_a},$$

$$F_v(v, I) = (v_o / v)^{m_v},$$

$$m_a = Log[F_a(v_{SC-IV}, I)] / Log[v_o / v_{SC-IV}],$$

$$m_v = Log[F_v(v_{SC-IV}, I)] / Log[v_o / v_{SC-IV}],$$

Vsc-iv is the shear velocity for the soil type IV; Vo is the shear velocity of the basement, and I is the input ground motion level.

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

Figure 21 - 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

A detailed study on the dependence of amplification factors on base acceleration for each type of soil was done at Borcherdt, 2002. On it, the group of data is separated in two subgroups (<0.2g and >0.2g). These two subgroups present important differences in the amplification factors at low periods (Fa) and little differences at mid periods (Fs).(see Figure 22, Figure 23). For our region the values of PGA are typically lower than 0.2g.

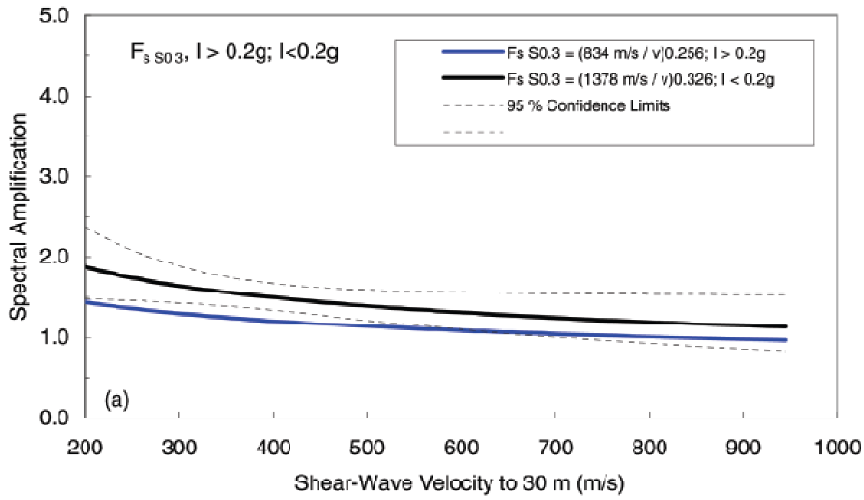

Figure 22 - Amplification factor versus Vs30 at low periods (0.3s) from Borcherdt (2002)

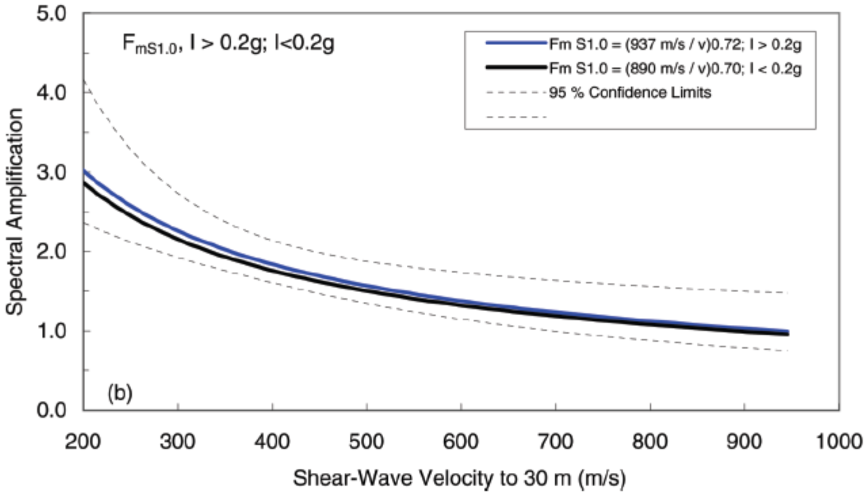

Figure 23 - Amplification factor versus Vs30 at medium periods (1s) from Borcherdt (2002)

There are other papers that study the amplification factors derived from Vs30:

Boore, 2004- Can site effects be predicted? The author concludes that due to the inter-event and intra-event variability, the site effects estimation have a probability nature and this fact has to be added on the site effects estimations.

Choi, 2005 is a more detailed study than Borcherdt, 1994. It determines amplification (F_{ij}) as a function of Vs30, input acceleration, a random effect of the interevent variation and another one of the intra-event variation. The general expression is:

$$\ln(F_{ij}) = c \ln\left(\frac{V_{s\text{-}30_{ij}}}{V_{ref}}\right) + b \ln\left(\frac{PHA_{r_{ij}}}{0.1}\right) + \eta_i + \varepsilon_{ij},$$

The regression parameters are determined for three models (Figure 24):

Atten. Model	Parameter	b_1	b_2	b_v	c	V_{ref} (m/s)	τ	σ	σ_{total}[1]
A1	*F(0.3)*	−0.41	−0.11±0.05	300	−0.46±0.07	532±93	0.35	0.54	0.64
	F(1.0)	−0.39	0.02±0.05	300	−0.69±0.07	519±69	0.41	0.55	0.69
A2	*F(0.3)*	−0.49	−0.21±0.04	300	−0.44±0.07	601±103	0.29	0.55	0.62
	F(1.0)	−0.48	−0.12±0.05	300	−0.66±0.08	646±90	0.35	0.57	0.67
A3	*F(0.3)*	−0.51	−0.05±0.05	300	−0.44±0.07	610±106	0.29	0.53	0.61
	F(1.0)	−0.49	−0.04±0.06	300	−0.67±0.07	709±107	0.39	0.56	0.68

[1] $\sigma^2_{total}=\tau^2+\sigma^2$

Figure 24 - Regression parameters for amplication vs Vs30 with Choi(2005) relation.

Mucciarelli & Gallipoli, 2006- they revise the relation of the Vs30 with other measures of the amplification. The study concludes that the Vs30 is not a good proxy for the amplification. The authors have participated in other articles defending/proving the same idea (Gallipoli & Mucciarelli, 2009; ...)

Cadet, 2007 determines the amplification based on fo and Vs5-Vs30.

Castellaro et al., 2008, did the study of Borcherdt (1994) with the same data, and shows that the correlation derived from the previous study is no significant. He calculates the regression, for the first period class (Figure 25). R^2=0.09 and the other three periods class has little significance R^2=0.3. He critics that the study doesn't show the R^2 regression coefficient, neither any estimator of the "goodness" of the linear relation. The study shows how biased is represented the data (it is shown in Figure 25).

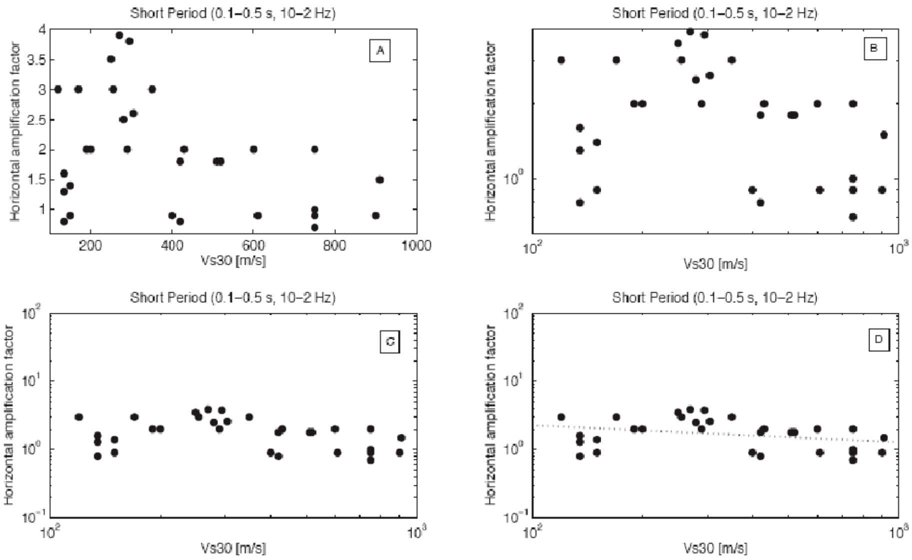

Figure 25 - Amplication factor versus Vs30 from Castellaro et al. (2008)

3.6.4. Amplification factors from other methods

Amplification factor based on seismological information

This newly method was developed on Sokolov (2008) and was proposed in order to develop shakemaps without site effects data by Böse et al. (2009) for Vrancea earthquakes in Romania.

His study (and the method) could be divided in these steps:

1. Divide the study zone in characteristic regions.
2. By averaging Fourier amplification Spectra (FAS) at sites within each of the characteristic regions, Sokolov et al (2008), determine generalized region-specific amplification functions.
3. Average site amplifications functions over different earthquakes and stations. This smoothes the peaks and can hence lead to an underestimation of true ground shaking.
4. They determine amplification factors AMP (IMregion/IMrock) from the ratios of ground motions IM predicted in the eight regions. The amplification factors depend on moment magnitude Mw, epicentral distance R, and source depth H.

Amplification factor based on macroseismic information (Roca, 2005)

This method consists in assigning to each village with enough macroseismic data an amplification factor in terms of intensity. This could be done at high and low frequencies. For the availability, the quality and the typology of the data this method couldn't be applied for our study. However it could be used to validate the obtained results.

3.6.5. Site effects methodology used in ShakeMap implementations

Table 14 resumes methodology used to calculate site effects for ShakeMap in US and Europe.

Region	Site effects
Global	Topographic slope Wald and Allen (2007) Amplification: Borcherdt (1994)
South California, default regression	Vs30: Wills et al.(2000) Amplification: Borcherdt (1994)
North California, default regression	Vs30: Wills et al.(2000) Amplification: Borcherdt (1994)
California	Vs30: Wills et al.(2000); and Wentworth (?)

New Madrid	Vs30: Bauer et al. (2001) Amplification: Borcherdt (1994)
Ontario	Assume vertical component doesn't have amplification. Use H/V relations for each station for obtain the horizontal component. A rock site relation is assumed for no data stations.
Utah	Vs30: Ashland (2001), Ashland and McDonald (2003). Amplification: Borcherdt (1994)
Italy	Geology simplification based on EC8. Amplification: Borcherdt (1994)
Southeastern Alps	Geology simplification. Basic resolution. Amplification: Borcherdt (1994)
Romania	Topographic slope Wald and Allen (2007)
Romania (Vrancea)	New method: determines the amplification functions from seismological information.

Table 14 - Site effects implementation for ShakeMap in US and Europe.

3.6.6. Pyrenees context and specificity

Regional geological and geotechnical data

Seismic microzonations have been processed for Lourdes (Bernardie et al., 2006) and for Cerdanya and Andorra in the context of ISARD Project (Colas et al., 2006; Macau et al., 2006a, 2006b)

In SISPyr A4.2, local hazard will be studied in Val d'Aran, Bagnère de Luchon and Girona. Results of this task could be used to refine the site condition map to use in ShakeMap

A new geological map 1/400000 for Pyrenees has been edited in 2009 by BRGM-IGME.

A study about a Vs30 map of France with Wald and Allen (2007) methodology is currently underway for French ministry of Environnement. Final report will be available in the second half of 2010. In this study a compilation of Vs30 measures from public reports is made. For Pyrenees, outside Lourdes microzonation, only some points in Pyrenées Orientales exist.

4. USGS ShakeMap technical description: installation and regionalization requirements

4.1. *Hardware and Software specification*

ShakeMap Version 3.5 was developed and tested on systems running the MacOS X and Linux. Version 3.0 and earlier was developed for the SPARC version of Solaris V2.6, V2.7 and V2.8 (i.e., SunOS 5.6, 5.7, and 5.8). Version 3.0 and higher of ShakeMap will run on FreeBSD, and V3.2 and later support Linux.

Apart of the ShakeMap software other programs are required in order to compile and run ShakeMap.

The list of the required programs and how to install them are described in the ShakeMap manual (Wald, 2005).

Once the regionalization is done in a machine, it will be easy to install different versions of the same regionalization to other machines.

4.2. *Regional specifications*

From "state of the art" described in the uppermost paragraph, we will describe here the regional specifications needed to be studied more precisely for ShakeMap implementation.

Four main issues must be developed

- PGM attenuation relationships
- Intensity attenuation relationships
- Instrumental intensity
- Site condition effects

Apart of this main issues there are other regional requirements relating how to use the regional relationships, what has to be plotted in the maps and how has to be plotted. These requirements are specified at the subsection mapping

4.2.1. PGM attenuation relationship

The GMPE is programmed in an independent Perl module. ShakeMap v3.5 has some programmed relations by default. Table 15 shows the default ones.

To develop a module, the interface must be modelled after the ones found in *<shake_src>/src/lib/GMPE* (e.g., Small.pm). It will probably be easiest to select a module from the table that is closest in behavior to the new GMPE, copy it, and edit it as necessary. Once the module has been written, it will need to be added to the list of modules in the *Makefile*. A ‘use’ line for the module should also be added to the file *<shake_src>/src/lib/GMPE.pm.* Then run ‘make.’ Then *grind.conf* could be configurable to use the new module.

The default programmed functions are stored in the sub-directory: src/lib/GMPE

Module Name	Reference	Mag	Dist (km)	Metric	PGV	PSA	Uncertainty Type	Site Term	Rupture Types[3]	Region
AB06_ENA_BC	Atkinson & Boore (2006)	≥ 4.0	0-1000	R_{Rup}	Yes	Yes[4]	Spatially constant[5]	Yes[6]	N/A	Eastern North America
AkkarBommer07	Akkar & Bommer (2007)	5.0 ≤ M ≤ 7.6	5 – 100	R_{Rup}	Yes	Yes[7]	Spatially constant	Yes[8]	RS, NM, ALL	Europe
BA08	Boore & Atkinson (2008)	5.0 ≤ M ≤ 8.0	0 – 200	R_{JB}	Yes	Yes	Spatially constant[9]	Yes	SS, RS, NM, ALL	NGA Active Tectonic
BJF97	Boore, Joyner, Fumal (1997)	5.0 ≤ *M* ≤ 7.4	0 – 80	R_{JB}	No[10]	Yes	Spatially constant	Yes	SS, RS, ALL	Western North America
Boatwright03	Boatwright, et al. (2003)	3.5 ≤ M ≤ 7.1	0 – 300	R_{Hypo}	Yes	No[11]	Spatially constant	Yes[12]	N/A	Northern California

[3] SS = strike slip; RS = reverse slip; NM = normal; ALL = unspecified.

[4] Module uses 0.315 sec coefficients for 0.3 sec PSA, and 3.13 sec coefficients for 3.0 sec PSA.

[5] No inter-/intra-event differentiation; constant sigma for all frequencies.

[6] Uses site terms from BA08.

[7] Relation produces spectral displacement, module converts to SA.

[8] Relation provides amplification terms for “soft soil,” and “stiff soil,” which are taken to be Vs30 < 360 m/s and 360 ≤ Vs30 < 760, respectively.

[9] Inter-event uncertainty changes with specified/unspecified fault type.

[10] Module uses PGV from Joyner & Boore (1988).

[11] The module calls BJF97 for PSA.

[12] Uses BJF97 site amplification term.

Module Name	Reference	Mag	Dist (km)	Metric	PGV	PSA	Uncertainty Type	Site Term	Rupture Types[3]	Region
CY08 CY08_SMM_CCal CY08_SMM_SCal	Chiou & Youngs (2008), Chiou, et al. (2009)	3.0 < $M \leq$ 7.7	0 – 200	R_{Rup}[13]	Yes	Yes	Spatially variable[14]	Yes	SS, RS, NM	NGA Active Tectonic, CA for SMM
Campbell2003	Campbell (2003; 2004)	≥ 5.0	0 – 1000	R_{Rup}	N&H'82	Yes	Spatially constant[15]	No[16]	N/A	Eastern North America
HazusPGV	Boore, Joyner, Fumal (1997)	5.0 ≤ $M \leq$ 7.4	0 – 80	R_{JB}	N&H'82[17]	Yes	Spatially constant	Yes	SS, RS, ALL	Western North America
Kanno2006	Kanno, et al. (2006)	≥ 5.5	0 – 500	R_{Rup}	Yes	Yes	Spatially constant	Yes	N/A	Subduction, Active Tectonic
MA2005	Motazedian & Atkinson (2005)	3.0 ≤ $M \leq$ 8.0	2 – 500	R_{Rup}	Yes	Yes	Spatially constant	No[18]	N/A	Puerto Rico
PP04	Pankow & Pechmann (2004)	5.0 ≤ $M \leq$ 7.7	0 – 100	R_{JB}	Yes	Yes[19]	Spatially constant	Limited[20]	N/A[21]	Extensional Tectonic
Small	Quitoriano	3.0 ≤ $M \leq$ 5.2	0 – 200	R_{JB}	Yes	Yes	Spatially constant[22]	Yes	N/A	Active Tectonic (CA)

13 Hanging wall term uses R_{JB} and a custom distance measure, R_X.

14 Magnitude, site, and amplitude dependent.

15 No inter-/intra-event differentiation.

16 Module uses site corrections from AB06_ENA_BC.

17 PGV from PSA 1.0 sec, via Newmark & Hall 1982 conversion.

18 Module uses site correction terms from HazusPGV (i.e., BJF97) module.

19 Module uses 2.0 second coefficients for 3.0 second PSA.

20 "Soil" and "rock" corrections.

21 Assumed to be normal faulting.

22 No inter-/intra-event differentiation.

Module Name	Reference	Mag	Dist (km)	Metric	PGV	PSA	Uncertainty Type	Site Term	Rupture Types[3]	Region
Youngs97 Youngs97_interface Youngs97_intraslab	Youngs et al. (1997)	$5.2 \leq M \leq 8.0$	0 – 300	R_{Rup}	N&H'82	Yes	Spatially constant[23]	No[24]	interface, intraslab[25]	Subduction

Table 15 - Default programmed GMPEs inside ShakeMap v3.5

4.2.2. Intensity attenuation relationship

The procedure is the same that the one followed in GMPE. The IPE is programmed in a Perl module. There are two default programmed IPEs, they are detailed on Table 16.

The default programmed functions are stored in the sub-directory: src/lib/IPE

Module Name	Reference	Magnitude Range	Distance Range (km)	Distance Metric	Uncertainty Type	Site Term	Region
AW07_CA AW07_CEUS	Atkinson & Wald (2007)	$2.0 \leq M \leq 7.9$	0 – 500 0 – 1000	R_{JB}	Spatially constant[26]	No	California Central and Eastern U.S.
TA09	Trevor Allen (2009)			R_{Rup}	Distance dependent[27]	No	Active Tectonic

Table 16 - Default programmed IPE inside ShakeMap v3.5

4.2.3. PGMvsI

There is a set of PGM-intensity conversion functions default programmed in the version v3.5. As with IPE or GMPE new conversions could be programmed.

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[23] No inter-/intra-event differentiation. Magnitude dependent.

[24] Module requires operator to configure and use Borcherdt-style site tables.

[25] Rupture type need only be specified for Youngs97, the *_interface and *_intraslab modules have the rupture type hardwired.

[26] No inter-/intra-event differentiation.

[27] No inter-/intra-event differentiation.

These functions convert PGA-PGV to I and viceversa. The default programmed functions are stored in the sub-directory: src/lib/GMICE.

4.2.4. Site effects

For defining the site effects two options are available:

1) Compute it via the GMPE site effects term (then the data is always on the surface and never corrected to the rock base).
2) Correct the data to basement rock and calculate the values at the surface via amplification computing at each place.

Both options require a site condition map. This map has to be entered to ShakeMap as a GMT .grd file of VS30 over the entire region of interest.

For the first option the second requirement is to have the proper GMPE with the site effects term well programmed.

For the second option the second requirement is a file containing site amplification factors as a function of Vs30 and frequency of input ground motion.

4.2.5. Mapping and configuration files

In order to define what modules to use and how to use them the configuration files have to be edited (mainly grind.conf). This files could be edited whit any text editor and the program reads this parameters every time it is run (they don't have to be compiled).

Relating what to be plotted in the maps (roads, faults, ...) GMT xy files have to be prepared for each of this issues.

For the representation details, the configuration files have to be edited (mainly mapping.conf)

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APPENDIX

Digital soil maping using multiple terrain parameters (Oye & Bungum; 2008, JRA3 D2)

This approach is studied at the JRA3 and is based on Debella-Gilo et al, 2007. In this study they develop and test a methodology for predicting the spatial distribution of soil classes using digital terrain analysis combined with multinomial logistic regression. They use 15 terrain attributes derived from a digital elevation model (DEM), combined with 13 different soil types, where logit models are used to predict the probability of existence of each of the soil classes. The results are promising, when compared against empirical soil maps.

The methodology proposed in the JRA3 (Oye & Bungum, 2008):

..Identify an area with varying topography and with size of the order of 50x50 km where exist a good number of boreholes. In addition data from geophysical or geotechnical surveys might be available.

· Around 50 or more data points within the study should preferably be acquired. These points must be spatially scattered to avoid spatial autocorrelation.

· For each data point, acquire the depth to bedrock.

· Estimate all of the above terrain parameters for each pixel within the study area, based on 25x25m Digital Elevation Map (DEM).

· Correlate the measured or estimated sediment thickness with the topography parameters.

· Perform a multiple regression and variance analysis between sedimentary depth and the terrain parameters, based on whatever number of boreholes that we may have access to within the study area.

Some conclusions of the application of this method could be interesting for our study. The next paragraphs of this subsection are some parts of Oye & Bungum *(2008)* copied literally (the text in italics). These summarize the conclusions of the use of this method:

The work by Debella-Gilo et al. (2007) demonstrated how digital terrain analysis can be used for digital soil mapping. What they found was that (1) all soil types are influenced at least by two terrain attributes to a certain extent, and (2) that the most influential terrain attributes as obtained from the logistic regression analysis are elevation, flow length, slope, mean daily duration of radiation, aspect and topographic wetness index. These parameters are believed to govern the distribution of moisture, temperature, radiation and flux of material which in turn dictate pedogenesis within the scale frame of the study.

The interesting question in the present situation is then if there a potential also for using other terrain parameters than slope for predicting the regional distribution of VS30, and thereby also the regional distribution of what seismologists call soil response?

A first approach to the multiple terrain parameters analysis have been done. This analysis was preliminary, however some concluding remarks were assigned:

· Based on the use of slope alone we do get a correlation with depth to bedrock which is significant but at the same time uncertain due to a large scatter in the original data base.

· When using additional terrain parameters (elevation, upslope slope, total curvature, wetness and flowlength), selected due to their presumed relevance, we derive a prediction model which is clearly better than the one based on slope alone, but still with large uncertainties.

In this sense there preliminary conclusions are positive in that they confirm that there is a potential gain in using multiple terrain parameters and not only slope. It is possible that this could also be interesting to test against a VS30 data base such as the one used by Wald and Allen (2007).

This approach is new and as always in such cases there are many unanswered questions, such as:

· The quality of the data base used and the dependence of the particular region where data are taken from. There are significant differences between the two regions tested in this study, also in terms of the derived prediction equations. It is uncertain to which extent the derived relations could be applied elsewhere.

· The selection of terrain parameters used and their relative importance also needs more work. We have for example not tested the effects of adding one parameter at a time.

· The analysis itself also leaves several questions unanswered, including the binning procedure (which also could be done on the depth to basement axis) and the potential use of the scatter (standard deviations) in the regressions. In addition, the data base should ideally have been divided in two, one for deriving the prediction equations andone for testing them.

· Also, the results should have been evaluated numerically in a more precise way,including the calculation of predicted minus observed.

· Finally the question of the relevance of sedimentary depths with respect to ground motion variation is important, where different regions again may behave differently.