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PRELIMINARY ASSESSMENT OF SITE STRATIGRAPHIC AMPLIFICATION FOR SHAKEMAP PROCESSING

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ABSTRACT

ShakeMap® is the most widespread software generating maps showing spatial distributions of several ground motion parameters. Non-linear relationships describing the amplification induced by site effects are fundamental ingredients to obtain reliable maps for emergency issues**.** In this study, site effects were evaluated through the stratigraphic amplification factor, S_S, which can directly multiply the reference peak ground acceleration to obtain the peak acceleration at surface.
Significant accelerometric records were selected from the Italian network, and the subsoil profiles of several stations were classified according to the criteria specified by the National Technical Code (NTC, 2008). A first set of experimental amplification factors was computed, selecting those stations on deformable soil for which a record of the same event exists also at a nearby station located on outcropping rock. A second set of semi-empirical data was obtained by analyzing the accelerograms at sites where the subsoil was adequately characterized: the recorded ground motions were de-convoluted to the bedrock, allowing to back-figure the reference motion. A third set of barely analytical data came from 1D site response analyses performed on 'virtual' stratigraphic profiles, consistent with the ground classification of the NTC (2008), subjected to the acceleration time histories recorded at those Italian stations classified as rock sites.
For each class of subsoil, the three datasets were merged and interpreted to obtain straightforward relationships between the stratigraphic amplification factor, S_S, and the ground motion amplitude at bedrock. The empirical relationships were finally assessed by simulating the ground motion distribution associated to the 23.XI.1980 Irpinia earthquake (M_W = 6.9).

Keywords: shakemap, site amplification, ground motion, Irpinia earthquake.

INTRODUCTION

A *shakemap* is a map of the peak ground motion parameters (GMP) generated by the open code package *ShakeMap*® developed by the U.S.G.S. (Wald et al, 1999). The software is currently implemented in four seismic monitoring centers in Italy, which have been jointly participating in the INGV-S3 project ('Fast evaluation of parameters and effects of strong earthquakes in Italy and in the Mediterranean', http://s3.rm.ingv.it/) for the last two years.
The fundamental ingredients towards obtaining reliable maps are the following:

- a distribution of the seismic stations, providing the dataset of the recorded GMP during a seismic event, which is subsequently integrated by a dense grid of 'phantom stations', in which the ground motion is analytically estimated;
- a ground motion predictive relationship as a function of magnitude, distance and period;

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- a realistic site classification of the whole territory affected by the recorded earthquake;
- reliable relationships describing the non-linear and site-dependent amplification.

Broadly speaking, site effects are implemented in the *Shakemap®* code as an amplification factor, which can directly multiply the reference peak ground motion parameter, GMP_r to obtain the peak value at surface, GMP_s. The code version currently implemented in Italy accounts for site effects by assigning a correction factor dependent on the reference peak ground acceleration, PGA_r, and on the equivalent shear wave velocity, V_{S30}, used as a proxy of site conditions (Michelini et al, 2008). The amplification factors are computed using the relationships developed in USA by Borcherdt (1994) for the peak ground acceleration, velocity, and peak spectral acceleration at 0.3s, 1.0s and 3.0s. The procedure considers only stratigraphic amplification, using a simplified V_{S30} map of the Italian territory derived from the national geology map 1:100.000 (http://www.apat.gov.it/Media/carta_geologica_italia/default.htm) and sampled at a space interval of one minute (≈ 2 km). This so-called 'QTM map' assigns a fixed single value of V_{S30} to each gridpoint according to the presence of Quaternary, Tertiary or Mesozoic deposits.
In the framework of the INGV-S3 Project, the research activity carried out by University of Naples Federico II was aimed to update the procedure to include non-linear site effects in *Shakemap®*, on the basis of national data records. The main results of the research activity are summarized in the following.

SITE STRATIGRAPHIC AMPLIFICATION FACTORS FOR SHAKEMAP PROCESSING

In this work, the site stratigraphic amplification on peak ground acceleration (PGA) was represented by the factor $S_S = PGA_s/PGA_r$, where PGA_r is the reference ground motion amplitude predicted on a stiff and flat rock outcrop, and PGA_s is the peak amplitude of the surface motion. It has been widely recognized in literature (e.g. Idriss, 1990) that the relationship between S_S and PGA_r is non-linear and decreasing with PGA_r, due to the inelastic and dissipative soil behavior. As a consequence, non-linear amplification factors have been introduced into seismic design codes (e.g. NEHRP Provisions; NTC, 2008) with different expressions according to the site classification, which is usually referred to the equivalent shear wave velocity along the shallowest 30 m of subsoil, V_{S30} (Dobry et al., 2000).
Three different approaches have been followed in this study, collecting and merging empirical, semi-empirical and analytical datasets to compute non-linear relationships referring to different classes of subsoil profiles. Accelerometric records of the Italian network were selected from ITACA (http://itaca.mi.ingv.it/ItacaNet/) and SISMA (http://sisma.dsg.uniroma1.it/) on-line databases. The recording stations were individually assigned to the site classes A, B, C, D, according to the V_{S30} – based criteria specified by the National Technical Code (NTC, 2008). In the following, procedures and examples relevant to each one of the approaches followed will be described in detail.

Empirical amplification factors

A first set of barely empirical amplification factors has been identified, selecting those stations on deformable soil, for which a record of the same event exists also at a nearby station located on rock outcrop. Three sites have been selected, representative of as many NTC (2008) classes:
- class B ($360<V_{S30}<800$ m/s): Forgaria Cornino (deformable) / San Rocco (bedrock);
- class C ($180<V_{S30}<360$ m/s): San Giuliano di Puglia School (deformable) / Church (bedrock);
- class D ($V_{S30}<180$ m/s): Cesi Valle (deformable) / Monte (bedrock).

The Forgaria Cornino station is located on a heterogeneous deposit of gravels, sands and silts about 45 m thick, lying on a stiffer marl and clay layer of unknown depth. The V_S profile from a CH test, reported by ITACA, results into a $V_{S30} = 454$ m/s, corresponding to a class B subsoil according to NTC (2008) criteria; the ITACA database does not report any data either on physical and mechanical properties of the soils, or on the experimental frequency of the deposit.
The mobile station at San Giuliano di Puglia School was located on a deposit as thick as 250 m of weathered and intact marly clays, overlying a stiffer flysch formation. From an accurate geotechnical characterization of the site (d'Onofrio et al., 2009), the equivalent shear wave velocity V_{S30} results

290m/s, i.e. class C according to NTC (2008). At the station location, linear 2D seismic response analyses by Puglia et al. (2009) predicted a surface amplification consistent with that of weak motion records.
The Cesi Valle station lies on a lacustrine clayey deposit of about 35 m, overlying the marl-limestone bedrock (Fig. 1). No data are available from the ITACA database about the physical and mechanical properties of the soils, including V_S; nevertheless, the subsoil is classified as C. ITACA however indicates a dominant frequency of the deposit, determined by the H/V spectral ratio of microtremors, of 1 Hz, corresponding to an average shear wave velocity as low as 135 m/s. Also, Decanini et al. (2000) assumed V_S = 80-100 m/s at depths between 0 and 10 m, and V_S = 200-400 m/s between 10 and 35 m, which implies V_{S30} = 120-185 m/s. For the above reasons, a class D was assigned to the station in this study.
In the three cases considered, the distance between the two stations is less than 1 km, so it has been assumed that the attenuation due to the travel path effect is negligible and that the difference between the two recorded accelerograms is produced only by the stratigraphic amplification. Moreover, topographic amplification has been considered not significant, because of the low slope (less then 15°). For each site, all the events recorded at the same time by the two stations have been considered, obtaining 80 (PGA_r, S_S) data points: 16 for class B, 24 for class C, 40 for class D (Silvestri et al., 2010).

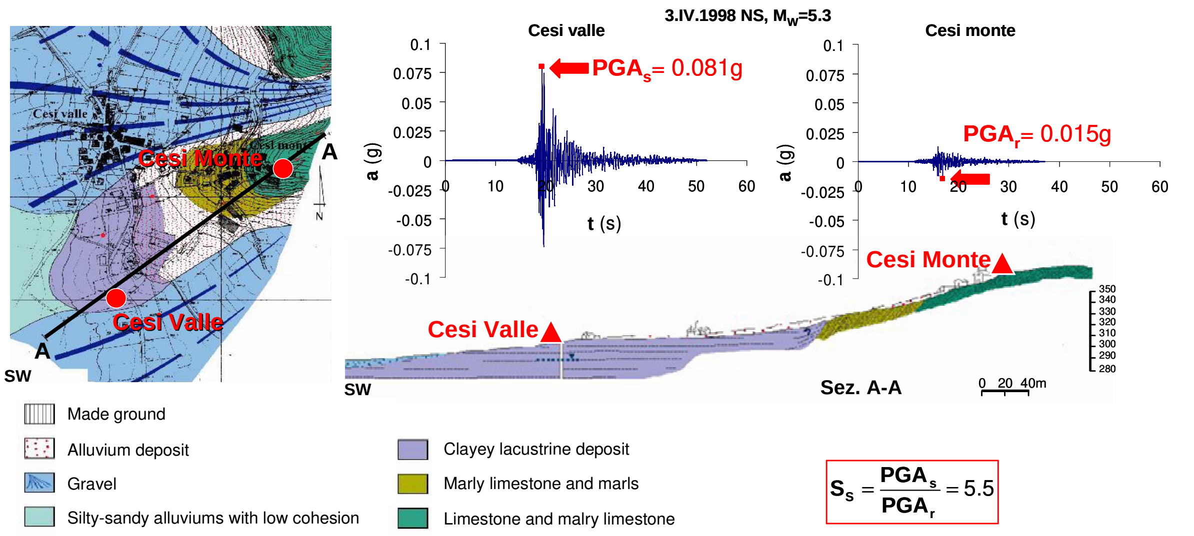


Figure 1. Cesi site: geological map and section and comparison between the accelerograms recorded at Cesi valle and at Cesi monte stations during 3.IV.1998, M_W = 5.3 event (data from ITACA).

Semi-empirical amplification factors

A second set of semi-empirical amplification factors was obtained by back-analyzing the accelerograms at those stations where the deformable subsoil was adequately characterized, in terms of both layering and mechanical properties most significantly affecting the non-linear site response. In such stations, the recorded data could be de-convoluted to the bedrock, allowing to back-figure the reference motion.
One-dimensional de-convolution analyses have been carried out by the software EERA (Bardet et al. 2000) which adopts the equivalent-linear approach to approximate the non-linear, inelastic behaviour of the materials. For such purpose, it is required to characterize each layer by field measurements of the shear wave velocity profile down to the bedrock, as well as by laboratory determinations of the soil unit weight and of the curves showing the variation of shear modulus, G, and damping ratio, D, with the shear strain, γ. In the ITACA database, only 7 stations (typed in boldface in Table 1) have been found to have a site characterization satisfying the above requirements and where the bedrock depth was clearly individuated. For such sites, significant experimental data from geotechnical investigations were collected from the report by Palazzo (1993) and interpreted for this study.

Table 1. Station classification and dataset for the validation tests (bold text indicates the values used as input in the validation tests).

Station classification					Earthquake 23.XI.1980, M_W = 6.9					
Site	V_{S30} QTM	V_{S30} ITACA	Site Class	Topogr. factor	R_{epic}	R_{jb}	PGA NS surface (*amplified* PGA_{rec})	PGA WE surface (*amplified* PGA_{rec})	PGA NS bedrock (*reference* PGA_{rec})	PGA WE bedrock (*reference* PGA_{rec})
	m/s	m/s			km	km	g	g	g	g
Tricarico	600	446	B	1	73.00	52.62	**0.046**	0.035	0.017	**0.026**
Vieste	603	447	B	1	143.40	135.28	**0.034**	0.030	**0.016**	0.013
S. Severo	600	386	B	1	102.40	87.53	**0.022**	0.022	**0.013**	0.013
Brienza	600	522	B	1.2	42.21	22.17	**0.181**	0.148	**0.118**	0.104
M.S.Severino	230	452	B	1	46.23	32.17	0.107	**0.141**	0.057	**0.079**
Calitri	600	548	B	1.2	18.90	12.78	0.132	**0.146**	0.102	**0.125**
Sturno	600	384	B	1	33.26	14.39	0.225	**0.316**	0.163	**0.233**
Garigliano	230	192	C	1	135.96	118.35	**0.039**	0.034	**0.021**	0.019
Bisaccia	1000	937	A	1	28.30	18.88	0.096	0.083	**0.150**	0.150
Bagnoli Irpino	1000	1153	A	1.2	21.80	6.14	0.108	**0.156**	0.108	**0.156**
S. Giorgio LM	1000	1100	A	1	65.30	46.43	0.017	**0.017**	0.017	**0.017**
T. del Greco	1000	1050	A	1	78.273	63.71	**0.080**	0.065	**0.080**	0.065

Six of the selected stations, characterised by V_{S30} = 386-548 m/s can be classified as class B sites, according to NTC (2008); the Garigliano station (V_{S30} = 192 m/s) is clearly a class C site (see Table 1). The thickness of the soil deposits range from 32 to 100 (bedrock depth) and the fundamental frequency from 1.0 to 4.5 Hz. All the accelerograms recorded by the above stations were de-convoluted; for three stations, located on gentle slopes, the signals were first scaled by a topographic coefficient equal to 1.2. The final dataset consists of 54 (PGA_r, S_S) points: 48 for class B and 6 for class C (Silvestri et al., 2010). Fig. 2 shows the example of the Mercato San Severino site, with the subsoil layering, the shear wave velocity measured in a cross-hole test down to 100 m (grey line), the V_S profile used in the 1D analyses (black line) and the depths of SPT and of the samples on which different laboratory tests were executed.

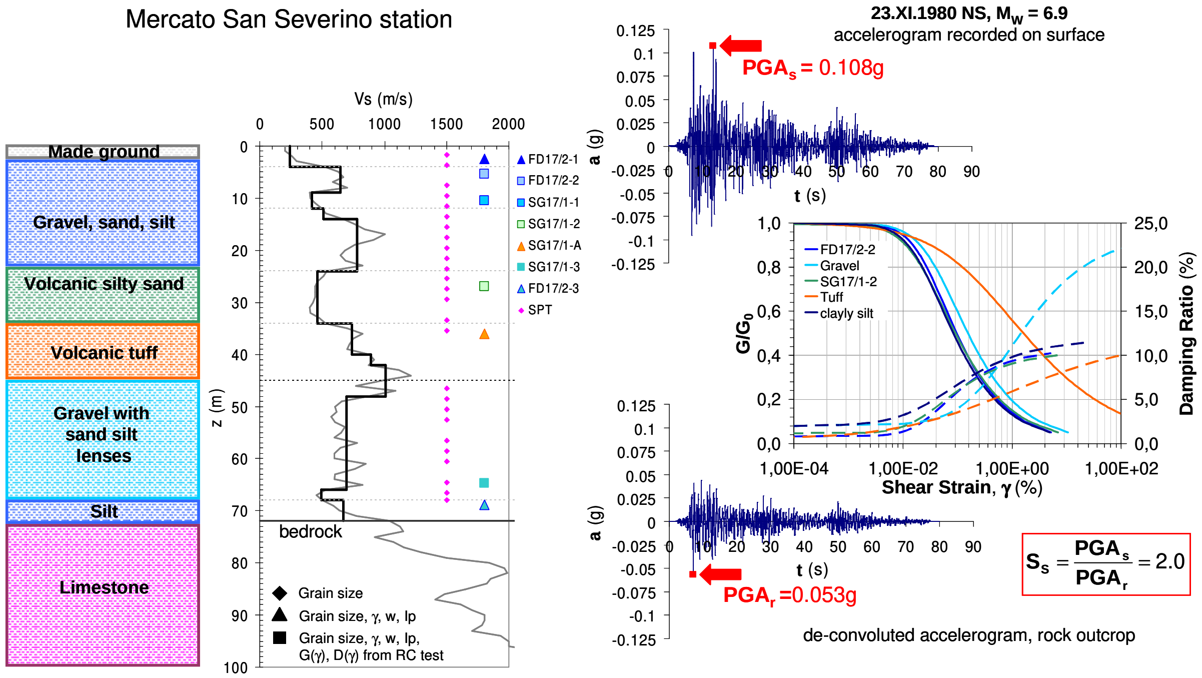


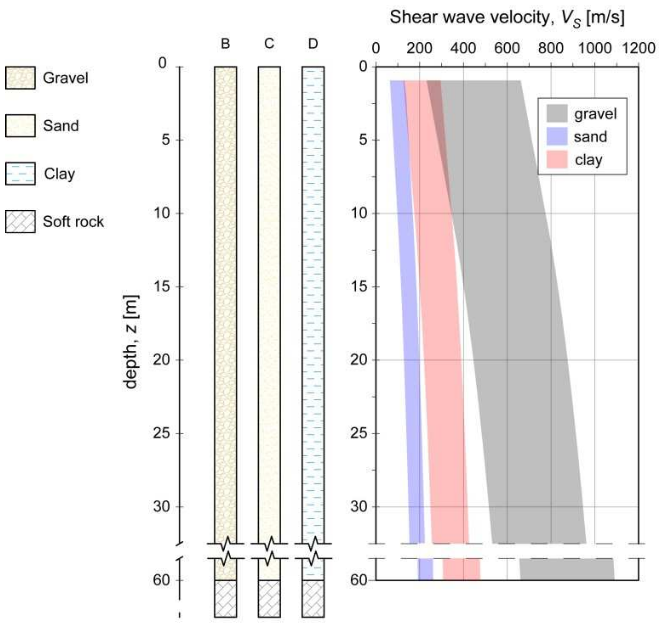
Figure 2. Mercato San Severino site: layering, V_S profile with depths of SPT and samples, RC test results and literature curves for the different soils, recorded and de-convoluted accelerograms.

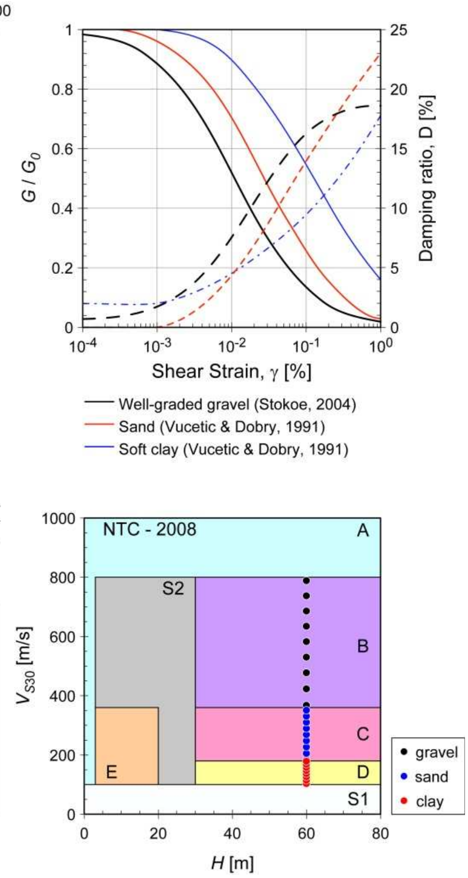
The results of the resonant column (RC) tests have been interpreted in terms of Ramberg-Osgood curves (Ramberg & Osgood, 1943), representing the shear strain dependency of normalized shear modulus, G/G_0, and damping ratio, D. All these elements allowed to build-up the geotechnical model for de-convolution analyses, carried out to back-figure the accelerograms at the rock outcrop, using the recorded accelerograms as input. The figure also reports the acceleration recorded at surface during the most significant event (23.XI.1980, $M_W = 6.9$) and the reference input motion back-figured by de-convolution to the bedrock. The amplification factor in this case resulted 2.0.

Analytical amplification factors

A third set of purely analytical data was gathered from 1D numerical site response analyses performed on 'virtual' stratigraphic profiles, corresponding to different subsoil classes specified by NTC, and subjected to acceleration records representative of Italian seismicity.

Virtual subsoil profiles of medium dense gravel, medium dense sand and soft clay, with a shear wave velocity increasing with depth, were created to represent the different soil classes B, C and D of the NTC (2008), respectively (Tropeano, 2009). Fig. 3 shows with different colours the ranges of the V_S profiles relevant to the three lithologies. In all the profiles, the bedrock depth, H, was assumed at 60 m; the dots in the V_{S30}-H plot demonstrate that these profiles span over a wide range of fundamental periods across the three classes.





soil	IP [%]	γ [kN/m³]	$V_{S,30}$ [m/s]	Soil class NTC
gravel	0	21	361 - 797	B
sand	0	20	181 - 353	C
clay	30	18	101 - 174	D
soft rock	-	22	800	-

Figure 3. Analytical amplification factors: virtual subsoil models and related V_S profiles, shear modulus and damping curves used in the 1D analyses. The chart on the right low side shows the 30 subsoil columns properties plotted against NTC 2008 classification.

Literature curves were used to describe the shear strain dependency of the shear modulus and damping ratio (Stokoe, 2004, for gravel; Vucetic & Dobry, 1991, with I_P=0 for sand; Vucetic & Dobry, 1991, I_P=30 for clay). The profiles were subjected to 40 accelerometric input signals (M_L = 4.3 – 6.6, PGA = 0.03 – 0.38g) recorded at those Italian stations classified as rock sites, extracted from the SISMA Italian accelerometric database (Tropeano, 2010). In such way 40 (S_S, PGA_r) data points for each soil class were obtained.

Non-linear amplification relationships

The whole data points obtained for each soil class from the three different approaches were expressed in terms of S_S values pertaining to homologous horizontal components (EW and NS), and were plotted against the reference PGA_r at bedrock (Fig. 4). The datasets were interpreted by the power function:

$$S_S = a \cdot PGA_r^{\ b} \tag{1}$$

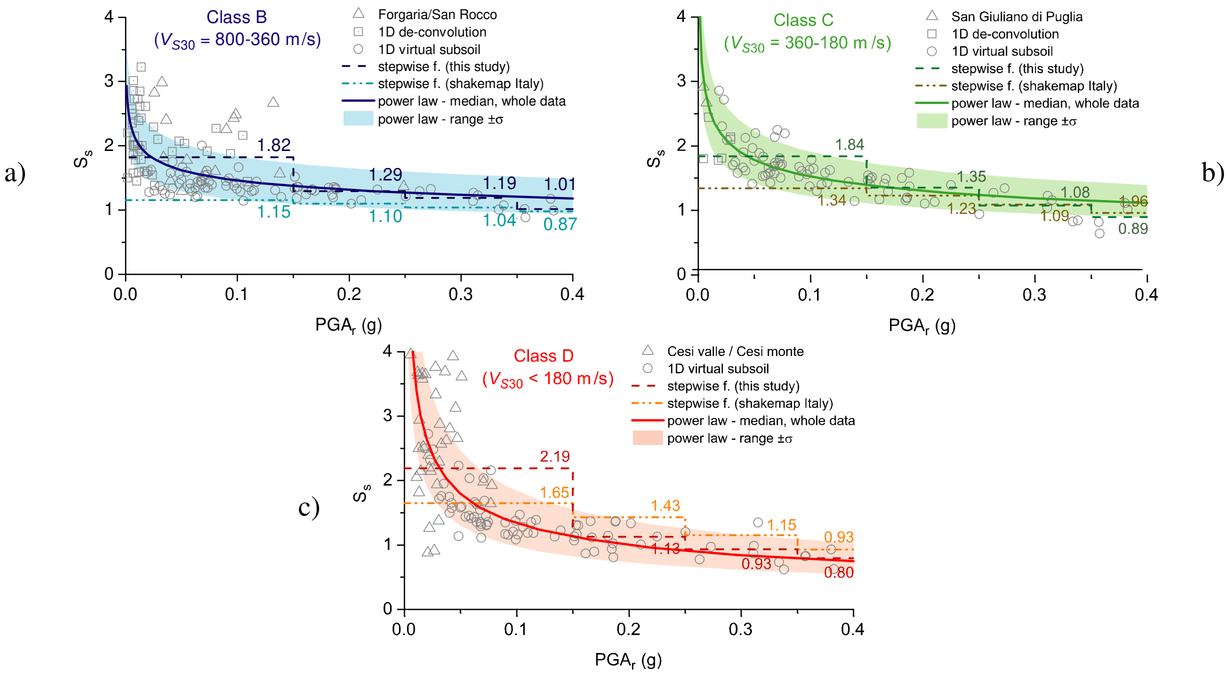


Figure 4. Non-linear amplification factors for subsoil classes B (a), C (b), D (c).

By expressing PGA_r in g, the following relationships (solid lines in Fig. 4) were obtained:

- class B soil: $S_S = 1.028 \cdot PGA_r^{-0.15}$, $\sigma_{Log(Ss)} = 0.099$ (2)
- class C soil: $S_S = 0.904 \cdot PGA_r^{-0.23}$, $\sigma_{Log(Ss)} = 0.098$ (3)
- class D soil: $S_S = 0.508 \cdot PGA_r^{-0.42}$, $\sigma_{Log(Ss)} = 0.136$ (4)

The standard deviation $\sigma_{Log(Ss)}$ refers to the interpolation function in log scale:

$$log(S_S) = log(a) + b \cdot log(PGA) \pm \sigma \tag{5}$$

and corresponds to the confidence bands shaded in Fig. 4a,b,c for each soil class.

The effects of non-linearity are evident for each dataset analyzed; also, for B and C soil classes, the amplification coefficients obtained are systematically higher than those currently implemented in *Shakemap*® (dashed-dotted lines in Fig. 4). By averaging the values of S_S in the same acceleration ranges suggested by Borcherdt (1994), stepwise functions were also obtained for each soil class (dashed lines in Fig. 4); such coefficients were subsequently introduced in *ShakeMap*®.
For class B subsoils, the factors currently used by *ShakeMap*® appear to underestimate the amplification in the whole range of reference acceleration PGA_r. For class C, both the stepwise and power functions essentially agree with the factors implemented in the code for high values of PGA_r, while they give definitely higher values in the field of low PGA_r. For class D, the factors used by *Shakemap*® appear to underestimate the amplification for the lower values of PGA_r, while they overestimate it in the remaining range of PGA_r.

VALIDATION TESTS

Selected event and dataset

A series of validation tests was carried out, using *ShakeMap*® to generate the peak ground acceleration distribution associated to the 23.XI.1980 Irpinia earthquake (M_W = 6.9) and comparing the simulated values (PGA_{gen}) against the records (PGA_{rec}).
The 23.XI.1980 event was chosen for two main reasons: the expected significant influence of soil non-linearity on site response, and the detailed geotechnical characterization available for 12 stations sites, located within a distance of 200 km from the epicentre (Palazzo, 1993); this latter chance allowed to compare the subsoil classification on the basis of the measured V_{S30} to that provided by the national QTM map (Fig. 5 and Table 1).
A finite fault geometry has been used to generate the peak acceleration maps. The surface projection (Fig. 6) of the finite fault is equivalent to the sum of the two fault segments associated to the sub-events at 0 s and 20 s related to the selected earthquake (Database of Individual Seismogenic Sources, D.I.S.S.: http://diss.rm.ingv.it/diss/).

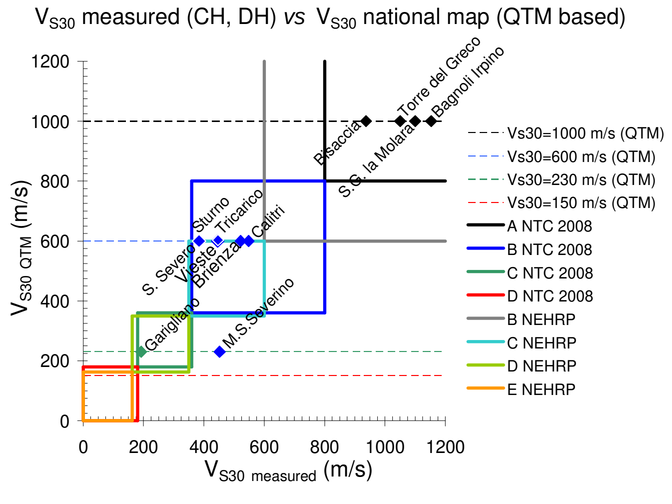


Figure 5. Measured V_{S30} compared to V_{S30} provided by the QTM map and the ranges of values specified by NTC 2008 and NEHRP provisions.

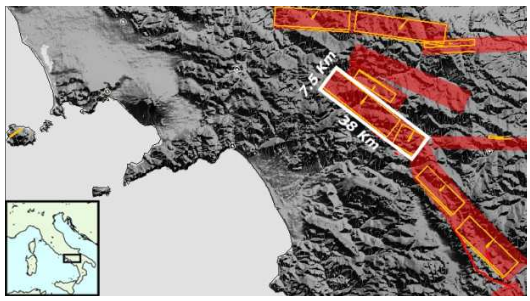


Figure 6. Finite fault location and size used in the tests.

The reference PGA at rock outcrop was back-figured by performing the numerical de-convolution of the records. In this way, two PGA_{rec} datasets resulted available:

- a first set includes the *amplified* PGA_{rec} (Table 1) observed on stiff (Fig. 7a) and soft soils (Fig. 7b); they result quite consistent to those predicted by the attenuation law used by the code (Akkar & Bommer, 2007), once corrected for site effects as suggested by the authors; in Fig. 7 a,b, this latter is also drawn after corrected according to both site corrections proposed in this study (UniNa) and those currently used by the Italian *ShakeMap®* implementation (*ShakeMap®* Italy).
- another set groups the *reference* PGA_{rec} (Table 1), either directly recorded on outcropping rock or analytically de-convoluted to the bedrock; the recorded data seem to be increasingly overestimated by the attenuation law at high distances (Fig. 7c). Only the maximum of the two PGA_{rec} components, NS and WE, has been considered as input data (boldface numbers in Table 1).

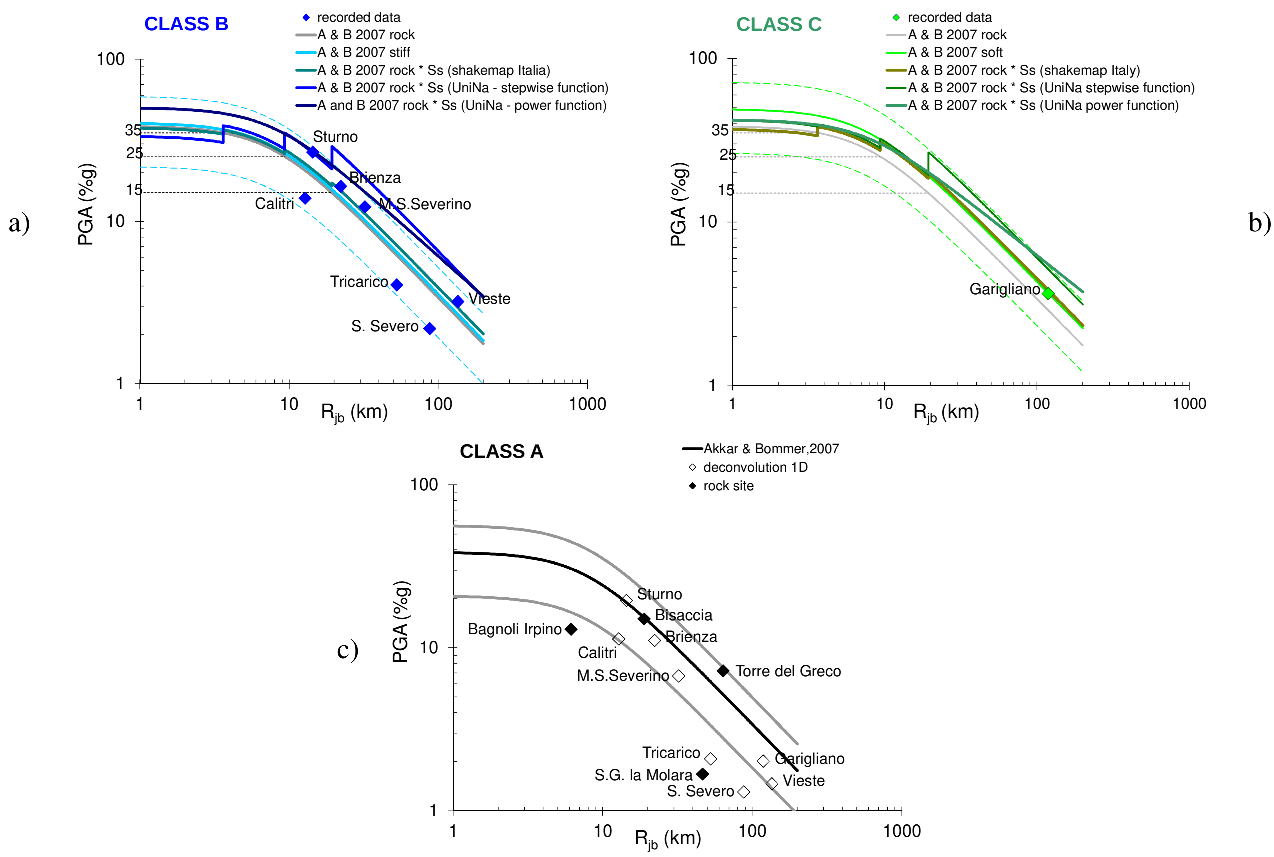


Figure 7. PGA used in the tests plotted against the Joyner & Boore (1981) distance, R_{jb}, and compared with the values predicted by Akkar & Bommer (2007) attenuation law with different site corrections for class B (a), C (b) and A (c).

Organization of the tests and results

The tests consisted of comparing in terms of residuals $\Delta PGA = |PGA_{rec} - PGA_{gen}| / PGA_{rec}$ the values of PGA_{rec} with those of PGA_{gen} simulated by *Shakemap®* at the final grid point closest to each station (i.e. no more than ≈1 km).

Preliminary sensitivity analyses were carried out to find the optimum value of the maximum distance from a station site within which the phantom stations can be neglected (*pthresh* variable). It was found that, in this case, a value *pthresh* = 20 km minimizes the average residual between recorded and generated PGA (Silvestri et al., 2010).

Four tests were planned: 1a, 1b, 2a, 2b. In tests 1a and 1b, the reference PGA_{rec} were introduced as input data and no site corrections were considered to generate the maps; the distributions of PGA_{gen} have been produced as resulting from input data including all stations (test 1a, Figs. 8a,b) or, alternatively, removing ('flagging') one station at each *ShakeMap*® run (test 1b, Fig. 8c). By comparing the residuals (Fig. 8d), it was possible to quantify the influence of the attenuation law, which is non-uniformly reduced by the bias factor used by *ShakeMap*® to minimize the difference between the values recorded at the seismic stations and those estimated by the ground motion predictive equation (Akkar & Bommer, 2007). The strong sensitivity to the completeness and the density of the seismic stations network is testified by an order-of-magnitude increase of residuals when a station is 'flagged'.

a) b) c) d)

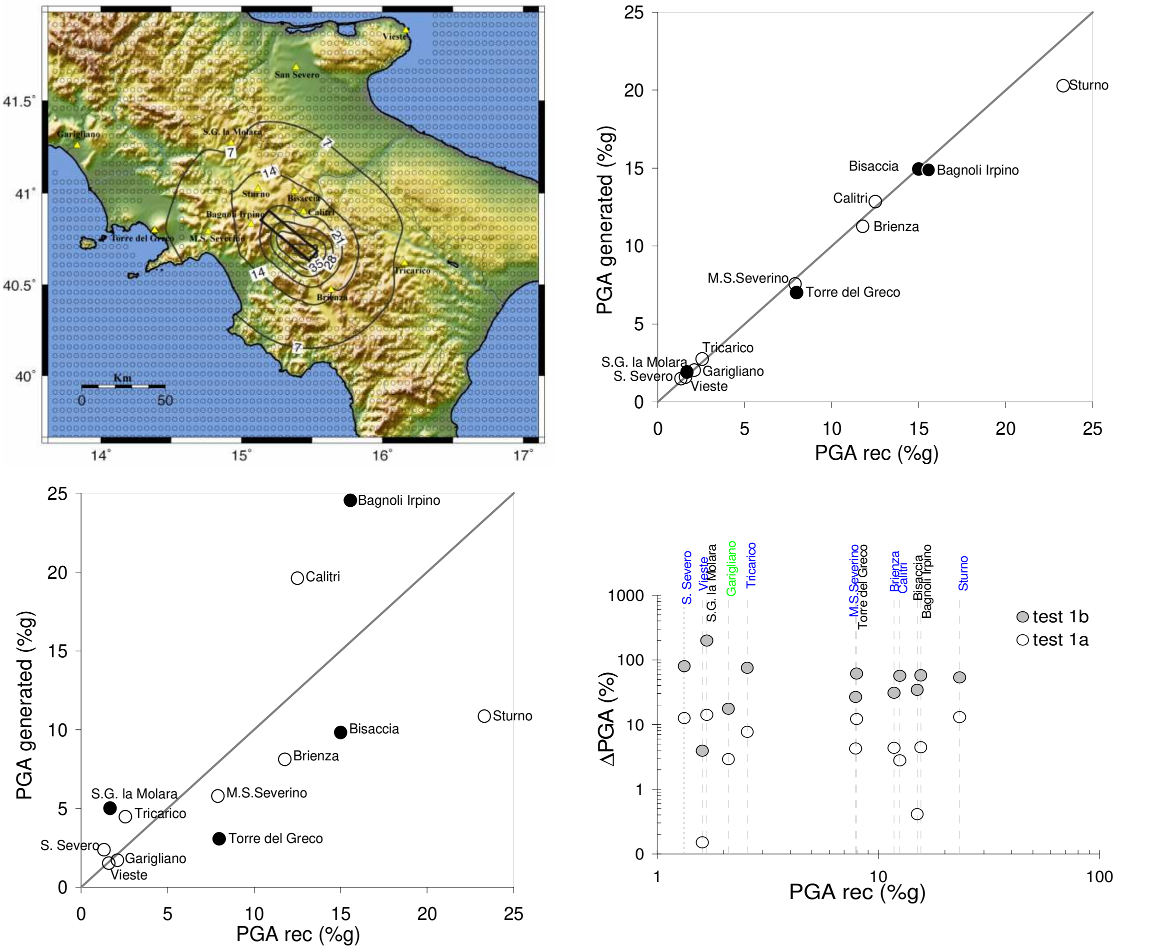


Figure 8. Shakemap of the test 1a (a); comparisons between generated and recorded data for test 1a (b) and 1b (c); comparison of the residuals obtained without site corrections (d).

In the tests 2a and 2b, the previous approach was replicated (test 2a including all stations, Figs. 9a,b; test 2b removing one station at each *Shakemap*® run, Fig. 9c). This time amplified PGA_{rec} were used as input data, and the amplification factors determined in this study were introduced in the generated maps. By comparing the results of the tests 1a *vs* 2a and 1b *vs* 2b (Fig. 9d *vs* Fig. 8d) the sensitivity to the network robustness does not seem to be reduced by site amplification. The influence of the site corrections could be inferred as less significant than that of the geographical distribution of stations network.
A further comparative study was produced repeating the tests 2a and 2b, but using different sets of amplification factors (Table 2): the set currently implemented in *Shakemap*® (shakemap Italy in Table 2),

that proposed in this study (UniNa in Table 2) and that suggested by Barani et al. (2008) (UniGe in Table 2). The residuals (Fig. 10 a,b) do not seem significantly affected from the set of amplification factors adopted, because of the bias correction above mentioned.

a) b) c) d)

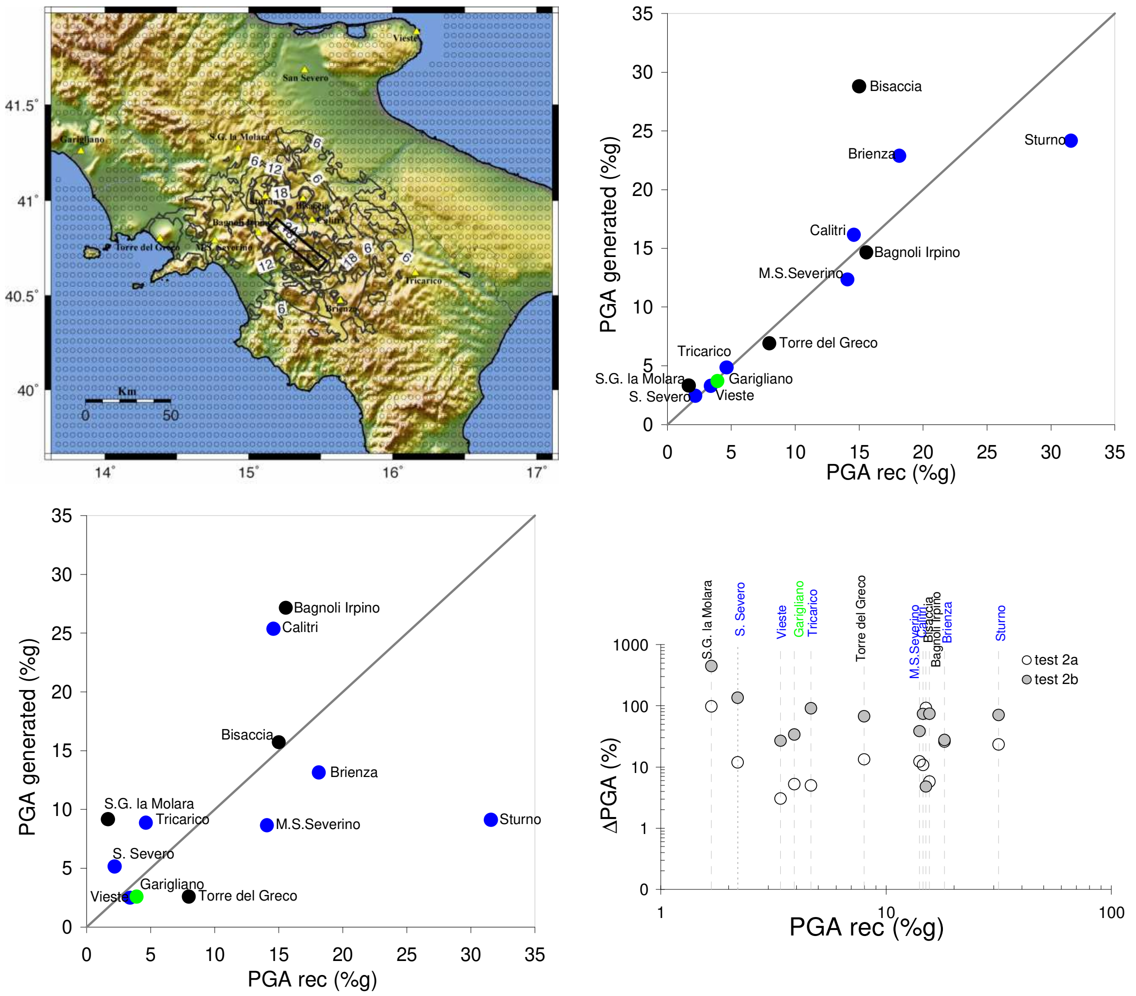


Figure 9. Shakemap of the test 2a (a); comparisons between generated and recorded data for test 2a (b) and 2b (c); comparison of the residuals obtained with site corrections (d).

Table 2. Site stratigraphic amplification factors from different approaches.

UniNa						shakemap Italy					UniGe					
V_{S30} m/s	soil class NTC	a_r (g) 0.00	0.15	0.25	0.35	V_{S30} m/s	a_r (g) 0.00	0.15	0.25	0.35	V_{S30} m/s	a_r (g) 0.00	0.05	0.15	0.25	0.35
>800	A	1.00	1.00	1.00	1.00	1000	1.00	1.00	1.00	1.00	1000	1.00	1.00	1.00	1.00	1.00
800-360	B	1.82	1.29	1.19	1.01	724	0.98	0.99	0.99	1.00	800	1.27	1.25	1.37	1.54	1.34
360-180	C	1.84	1.35	1.08	0.89	600	1.15	1.10	1.04	0.98	700	1.31	1.32	1.42	1.57	1.40
180	D	2.19	1.13	0.82	0.80	372	1.24	1.17	1.06	0.97	600	1.37	1.40	1.49	1.60	1.45
						350	1.33	1.23	1.09	0.96	500	1.43	1.50	1.57	1.65	1.52
						298	1.34	1.23	1.09	0.96	400	1.52	1.63	1.68	1.70	1.60
						163	1.65	1.43	1.15	0.93	300	1.54	1.81	1.82	1.78	1.72

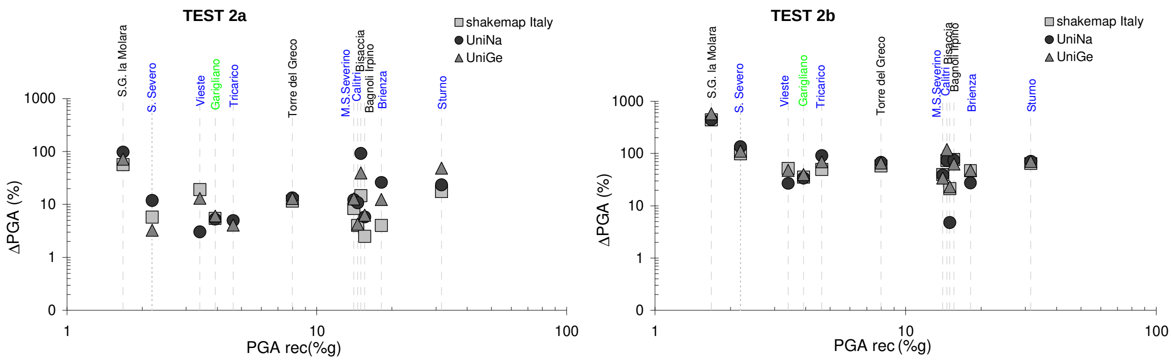


Figure 10. Residuals in test 2a (a) and 2b (b) using different sets of amplification factors.

CONCLUSIONS

The main objective of this study was to produce simplified coefficients for a fast reliable evaluation of site stratigraphic amplification, to be implemented in *ShakeMap*® in Italy. Such coefficients were conceived to account for non-linearity and to be consistent with the approach currently used by the national technical provisions, NTC (2008), about soil classification.

Power functions were obtained interpolating the datasets related to three different NTC (2008) soil classes (B, C, D). Such relationships may easily be implemented in *Shakemap*®, instead of stepwise functions which were obtained by averaging the S_S values in the same range of PGA_r currently adopted by *Shakemap*®. These validation tests, referred to stepwise coefficients, showed that the influence of the site corrections appears less significant than that of the geographical distribution of stations network and that of the attenuation law.

In the future, more tests should be performed, to assess the actual influence of the non-linear site amplification factors proposed. Events with different magnitude and source characteristics should be selected. The reliability of new proposals of amplification factors should be further submitted to sensitivity tests related to the choice of different attenuation relationships, such as those specifically relevant to the Italian seismicity. Finally, the validation showed the need of a more detailed V_{S30} national map (e.g. at 1:25.000 geological scale or higher, to locate the presence of amplifying shallow covers) and a more extended and detailed site characterisation of the strong-motion stations network, as a fundamental basis for the assessment of more reliable site correction procedures.

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