Local seismic response prediction and design building code provisions: the case study of Senigallia, Italy

Prévision de la réponse sismique locale et prescriptions des règlements parasismiques: le cas d'étude de Senigallia, Italie

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ABSTRACT

With the aim to contribute to the discussion on the validation of European and Italian design building code spectra, this paper describes and discusses the results obtained by means of equivalent linear analyses performed in a number of well documented test sites located alongside the Adriatic coast, in the town of Senigallia, Central Italy.

Given the medium intensity shaking expected in the area (peak ground acceleration of 0.20g at 'rock-like' formation with a return period of 475 years) and the likely strain levels that can be induced on soils, and also given the geomorphologic characteristics of the site (mainly consisting of a Plio-Pleistocene clayey-marly bedrock underlying Quaternary plain deposits and alluvial terraces where 2-D effects appear to be not influent) a 1-D linear equivalent model was employed for seismic site response evaluation.

The seismic response analyses were performed on eight different soil profiles where dynamic soil properties were accurately measured. In order to reduce the input seismic ground motions uncertainties Both real selected acceleration time histories and simulated accelerograms obtained by a seismic wave propagation model were assumed in the analyses,.

The obtained results are synthesised in this paper and the elastic response spectra obtained at ground surface are compared with those provided by Eurocode 8 for the corresponding ground types. The practical significance, implications and applications of the spectra obtained with respect to the relevant prescriptions of the recently established Italian building codes for seismic areas are also discussed.

RÉSUMÉ

Afin de contribuer à la discussion sur la validation des Eurocodes et des règlements parasismiques italiens pour les bâtiments, cet article se propose de montrer et d'examiner les résultats d'analyses de la réponse sismique locale menées par un modèle 1-D linéaire équivalent dans un certain nombre de 'test sites' bien documentés qui se trouvent le long de la côte adriatique, dans la ville de Senigallia (Italie centrale). En considérant aussi bien l'intensité moyenne-basse du séisme attendu dans la zone étudiée (pic d'accélération 0.20g sur formation rocheuse pour une période de retour de 475 ans) que les caractéristiques géomorphologiques du site, consistant principalement d'une Plio-Pléistocène roche-substratum marno-argileuse située en dessous de dépôts de plaine alluviale et de terrasses étagées où les effets 2-D n'ont pas d'influence, les analyses de la réponse sismique locale ont été menées par un modèle 1-D linéaire équivalent. L'étude a été effectué sur onze verticales où les propriétés dynamiques du terrain ont été soigneusement mesurées. Afin de limiter les incertitudes liées à la donnée sismique, on a employé des enregistrements sismiques réels comme des signaux sismiques simulés. Dans cet article sont présentés les résultats numériques des analyses; les spectres de réponse obtenus sont confrontés aux spectres établis par l'Eurocode 8 et par les récents règlements parasismiques italiens pour les correspondants types de sous-sol.

Keywords: design building code, local seismic response, elastic response spectra, seismic input motion.

1 INTRODUCTION

The influence of local ground conditions on the seismic action is by now generally accounted for in seismic code provisions. European and Italian seismic building codes (EC8-part 1 2003; OPCM 3274 2003; Norme Tecniche per le Costruzioni 2005), in the following respectively mentioned as EC8 and IBC, identify seven ground types (A, B, C, D, E, S1, S2). Whereas special studies are required for the classes S1 and S2, each of the remaining five ground types, A to E, has prescribed: (i) a different soil factor, S, which modifies the reference peak ground acceleration on A-ground type provided from the National Authorities through specific zonation maps defined for fixed return periods; (ii) different horizontal and vertical normalised elastic response spectra. EC8 defines two sets of soil factors S and elastic response spectra, according to the expected surface-wave magnitude, M_S, greater (spectra Type 1) and not greater (spectra Type 2) than 5.5. IBC makes no difference between areas of high and low seismicity, but different spectra are only prescribed for Ultimate Limit State (ULS) and Damage Limitation State (DLS) design. The identification of the ground type is based on the soil stratigraphy and the following geotechnical parameters: (i) the SPT blow count/30cm, N_{SPT},; (ii) the undrained shear strength, c_u; (iii) the equivalent (named *average* in EC8) shear wave velocity, $V_{s,30}$, referred to the top 30 metres of the ground.

Recently, a number of study (Bouckovalas et al. 2007; Cavallaro et al. 2007; Lo Presti et al. 2007; Pitilakis et al. 2007) has been performed in order to discuss EC8 and other National seismic code provisions for seismic site effect evaluation and to ascertain whether: (i) the suggested ground types include every soil conditions generally encountered in practice (and if they should be subdivided into further subclasses); (ii) the parameter $V_{s,30}$ is representative enough for site classification or whether other factors, such as the depth to the bedrock, the impedance ratio between bedrock and soil deposit, the amplification factor between soil surface and outcropping rock, are also needed; (iii) the soil factors and the horizontal normalised elastic response spectra provided by the seismic codes are consistent with the results of numerical response analyses.

With the aim to contribute to such discussion, the present paper describes and discusses the results of an extended investigation on seismic site responses performed at Senigallia, a representative town of the Adriatic coast in Central Italy, repeatedly struck by destructive earthquakes and where, recently, a multidisciplinary seismic microzonation study was performed (Mucciarelli and Tiberi 2007).

A specific wide geotechnical survey was planned and carried out on the whole studied area for soil characterization and geotechnical parameter estimation; it includes 12 boreholes, 10 CPT tests, 8 DH tests, 1 CH test and microtremor measures.

Laboratory tests were performed on 38 undisturbed samples taken from the boreholes to determine physical and mechanical properties both in static and dynamic loading conditions (measures of index properties, oedometric tests and resonant column tests).

The dynamic properties of the encountered soils were carefully analysed in the strain ranges of interest for the amplification effect analyses and are accurately described and discussed in the companion paper of Crespellani and Simoni (2007).

In the following, the geological, morphological and seismological features of the examined area are briefly described. Furthermore the soil stratigraphy and geotechnical properties of eight selected sites are summarised together with the time histories of acceleration adopted to perform the seismic response analyses.

2 GEOMORPHOLOGICAL AND SEISMOLOGICAL SETTINGS

At a large scale, the geological pattern of the subsoil of the region within the investigated area falls, can be represented by two main formations: (i) a Plio-Pleistocene marine deposit prevalently composed of marly clay with a thickness of hundreds of meters underlying a Quaternary (Holocene-Pleistocene) continental covering soil of variable thickness (generally not greater than 40 m) which mainly consists of alluvial, eluvial-colluvium and coastal deposits.

As shown in Figure 1, the area under study completely lies on the prevalently flat Quaternary deposits whereas the underlying marine Plio-Pleistocene marly clay crops out further from the investigated area in the surrounding hills (not coloured area of Figure 1) and partially in the southern part.

Senigallia falls within a medium seismicity region characterised by frequent events of medium local macroseismic intensity (6.5 – 7.5 MCS) due to a significant seismic activity originating from the central part of the Appennino mountains in the north of the Marche region where several seismogenetical sources are present especially close to the Adriatic coast (Valensise and Pantosti 2001).
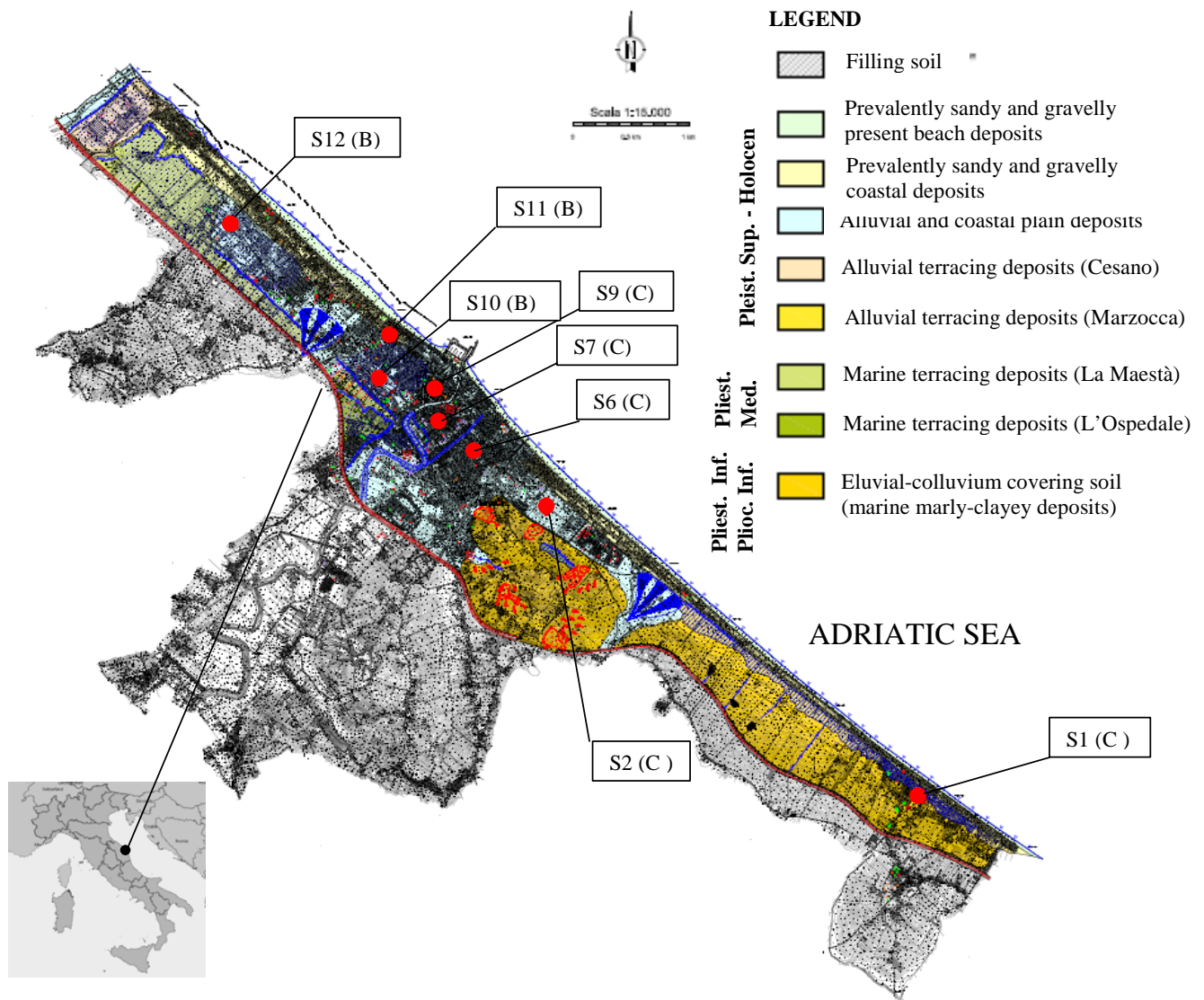
LEGEND

- Filling soil
- Prevalently sandy and gravelly present beach deposits
- Prevalently sandy and gravelly coastal deposits
- Alluvial and coastal plain deposits
- Alluvial terracing deposits (Cesano)
- Alluvial terracing deposits (Marzocca)
- Marine terracing deposits (La Maestà)
- Marine terracing deposits (L'Ospedale)
- Eluvial-colluvium covering soil (marine marly-clayey deposits)

Pleist. Sup. - Holocen

Pliest. Med.

Pliest. Inf. Plioc. Inf.

Scala 1:15.000

ADRIATIC SEA

S12 (B)
S11 (B)
S10 (B)
S9 (C)
S7 (C)
S6 (C)
S2 (C)
S1 (C)

Figure 1 – Geological map of the investigated area and tested site location (ground type identified according to EC8 and Italian seismic building codes is bracketed)

The reference earthquake on outcropping rock, with a return period of 475 year, has been estimated with a peak gound acceleration, PGA_{rock}, of 0.20g (INGV 2004) and a local magnitude, M_L, of 6.5.

Given the medium intensity shaking expected in the examined area and the likely low-to-medium strain levels that can be induced on soils, and also given the geomorphological characteristics of the site, prevalently flat, a 1-D linear equivalent method seemed to be sufficiently adequate for seismic site response analyses.

3   LOCAL SEISMIC RESPONSE ANALYSES

Eight among the more accurately characterised sites were selected in a way to cover the whole studied area and to be representative of the main possible situations. They correspond to the boreholes hereinafter named as S1, S2, S6, S7, S9, S10, S11, S12, and are evidenced on the geological map drawn in Figure 1.

The 1-D equivalent linear soil response analysis was performed on each selected site by using

PROSHAKE computer program (the Windows version of SHAKE, Schnabel et al. 1972).

Soil profiles and geotechnical properties assumed in the numerical analyses are briefly described in the following chapters together with the seismic inputs applied.

3.1   *Soil profiles and geotechnical properties*

Soil profiles deduced from the borehole investigations are shown in Figure 2, where the more superficial Quaternary deposits (alluvial, coastal and eluvial-colluvium soils) and the marine marly-clayey substratum are evidenced with the respective V_s profiles measured in down-hole tests and the corresponding values adopted in the numerical model. Ground type was identified for each tested site from the $V_{s,30}$ value, according to the EC8 and IBC classification (in Figures 1 and 2 note that only B and C soil classes are present).

As evidenced in Figure 2, the marly-clayey substratum reveals a weathered layer in its upper part.
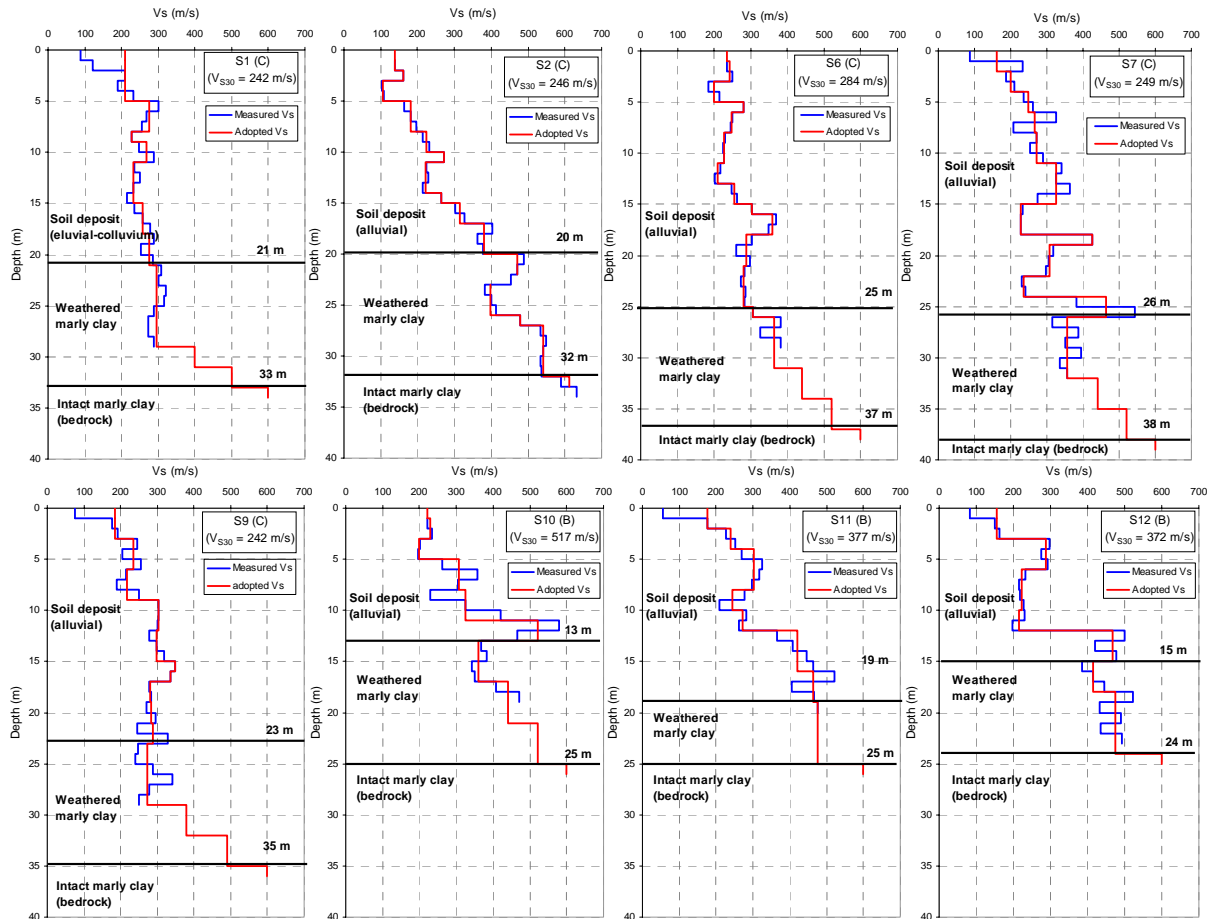
Figure 2 – Soil profiles and V_s values measured at the tested sites grouped by soil type according to EC8 and IBC criteria

In the borehole S2 (the only sounding in which the intact part of the marly-clayey formation was reached) the weathered layer has a thickness of approximately 12m and the V_s values increasing with the depth from about 400 m/s at the bottom of the upper layer to 600 m/s in the lower intact base rock.

As the other soundings were not unfortunately driven into the intact substratum, the thickness and Vs pattern for the weathered layer in each soil profile were assumed on the ground of Vs values measured to the investigated depth and of geological information. The adopted Vs profiles are shown in Figure 2.

The maximum shear wave velocity measured in the intact marly-clayey formation is 630 m/s; such value is kept even at greater depth (more than 60 m from the ground level) as detected in a further sounding performed close to S2 borehole. For the foregoing reason and according to the evident change of mechanical properties and shear wave velocity values (and so high impedance ratios) between the covering soils and the intact substratum, the marly-clayey formation was assumed as a bedrock in the seismic response analyses, although it could not be properly considered as a "seismic bedrock" (Vs > 800m/s).

In Table 1, the assumed depth to bedrock, H, the impedance ratios $\mu = V_{S(rock)}/V_{S(soil)}$, calculated with reference to the bottom of the covering soil deposits and the top of the intact substratum, and the corresponding ground type of each selected site are summarised. In this case the soil classification performed following the code seismic provided criteria leads to compose two different groups of sites that can be considered rather homogeneus. Soil profiles of ground type B are characterised by a depth of the bedrock of about 25 m and lower impedance ratios, otherwise soil profiles of class C generally shows higher values of impedance ratios and greater depth of the bedrock. The equivalent shear wave velocity $V_{s,30}$ can be considered comparable for all the sites falling within class C (240 – 280 m/s), but reveals more widespread values for soil of class B (see borehole S10). Such site was deeply investigated in the following analyses to verify if the ground seismic response could be different from the other sites belonging to same class. The calculated surface response spectra revealed a good agreement with the corresponding ones of the same soil class.

For the fine grained soils and for the marly substratum, shear modulus reduction curves G/Go and damping ratio D versus shear strain, γ, were assumed

according to the resonant column test results (Crespellani and Simoni 2007) to perform the numerical analyses using PROSHAKE computer program; the curves proposed by Vucetic e Dobry (1991) for material with plasticity index equal to zero were attributed to sands. For gravelly layers the equations of Rollins (1998) were assumed.

Table 1 – Classification of covering soils at the selected sites

Site	H (m)	μ (-)	V_{s30} (m/s)	Type
S1	33	2.0	242	C
S2	32	1.6	246	C
S6	37	2.2	284	C
S7	38	1.3	249	C
S9	35	2.1	242	C
S10	25	1.1	517	B
S11	25	1.3	377	B
S12	24	1.3	372	B

3.2 Input motions

In order to reduce input seismic ground motion uncertainties, eight accelerograms of different kinds were used. Five of them resulted from a 3D seismic wave propagation simulation (Mucciarelli and Tiberi 2007) with reference to the earthquake occurred at Senigallia in 1930 (epicentral intensity I_{max}= 8.5 MCS; estimated magnitude M = 5.9) and assumed as a destructive scenario event. The remaining three accelerograms were selected among the ones recorded during the main shock of 14/06/2007 of the Ancona earthquake (epicentral intensity I_{max} = 8 MCS; estimated magnitude M = 4.9) at the recording station of Ancona-Rocca, at a distance from the tested sites of about 30km. Both events can be considered sufficiently representative of the local seismicity at Senigallia.

The main seismic parameter values of the eight selected accelerograms are summarised in Table 2. Note that they are comparable (especially in terms of PGA and duration), although they were obtained by means of different procedures with reference to different events. Moreover it can be observed that the durations are all quite shorts, about $10 \div 12$ seconds ($1.5 \div 4$ sec for Trifunac durations), according to the seismicity characteristics of the studied area; Arias intensity values are generally rather low and ranges between 4 and 17 cm/sec (larger for recorded accelerograms); whereas the predominant period ranges between 0.1 and 0.5 sec.

Recordings and simulated accelerograms were selected in a way to apply a scaling factor not greater than 2 (it actually ranges between 0.9 and 2) to obtain a PGA of 0.2g, which represents the value expected at Senigallia on outcropping rock with a return period of 475 years.

Table 2 – Main seismic parameter values of the selected accelerograms (PGA = peak ground acceleration, Ia = Arias intensity, Td = predominant period, D = duration, D_T = Trifunac duration)

	PGA [g]	Ia [cm/sec]	Td [sec]	D [sec]	D_T [sec]
IG1EW	0.11	5.92	0.38	12.78	3.60
IG2EW	0.10	4.83	0.46	12.78	4.28
IG2NS	0.10	4.83	0.36	12.78	2.38
IG5EW	0.14	6.58	0.32	12.78	3.25
IG5NS	0.17	17.20	0.20	12.78	1.75
M5009EW	0.23	12.46	0.14	9.53	1.84
M50013EW	0.11	2.39	0.13	11.81	3.10
M50013NS	0.22	11.16	0.07	11.81	1.49

The normalised elastic acceleration response spectra (5% of critical damping ratio) for the adopted input motions are represented in Figure 3 (together with the mean added to the corresponding standard deviation), compared to the normalised elastic acceleration response spectra provided by EC8 and IBC on ground type A. It is quite evident that: (i) recorded spectral accelerations are significantly lower than simulated ones over a large range of periods; (ii) there is a good fitting in terms both of shape and maximum spectral acceleration between the ground type A elastic response spectrum prescribed by EC8 for Type-2 seismic areas (Ms < 5.5) and the elastic response spectra of the selected input motions on outcropping rock; (iii) the elastic response spectra prescribed by EC8 and IBC for the tested sites (Type 1) are definitively too conservative over a large range of periods (from about 0.2 sec).
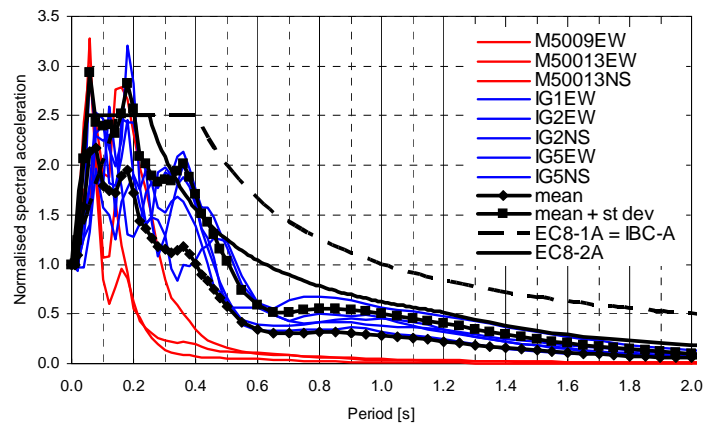

Figure 3 – Normalised elastic response spectra of the selected inputs compared to the ones provided by EC8 and IBC for "rock-like" formation (5% of critical damping ratio)

4 NUMERICAL ANALYSES RESULTS AND SEISMIC CODES PROVISIONS

4.1 Site response spectra

Surface elastic response spectra (5% of critical damping ratio) were numerically obtained by using

PROSHAKE program for each of the eight tested sites in correspondence of the eight selected seismic inputs.

Such results, normalised to the expected PGA on outcropping rock, PGA_{rock}, are grouped in Figure 4 for each ground type, according to the site classification previously discussed. The average normalised spectral accelerations and the relative standard deviations were also calculated; the corresponding curves obtained from the average values (hereinafter called as "mean" curves) and by adding the standard deviations to the mean values (herein after called as "mean plus standard deviation" curves) are compared to the normalised elastic response spectra suggested by the EC8 and IBC for the corresponding soil classes (B and C) and both type of seismic areas, Type 1 and 2 (named EC8-1B, EC8-2B, EC8-1C, EC8-2C and IBC-BCE in Figure 4).

As far as concerns the selected sites falling within the B class of soil (Figure 4a), the surface calculated spectra show a good agreement with the 2-Type EC8 spectrum (EC8-2B), with the exception of M50013NS seismic input which determines a very high but localised amplification (normalised spectral acceleration values of about 8-9 at sites S11 and S12 and 6 at site S10) at a period of 0.06 s. Such agreement is even more clear with reference to the "mean" curve of the normalised spectral accelerations which fits very well the EC8-2B spectrum both in terms of shape and values, with the larger values of normalised spectral accelerations (between 1 and 3) at periods lower than 0.5 s and a maximum of 3.8 (slightly over the EC8-2B spectrum) at 0.08 s. If we consider, more conservatively, the "mean plus standard deviation" curve, we definitively obtain a worse agreement. Whereas in any case, 1-Type EC8 and IBC response spectra suggested for the site for ground type B (respectively black dashed line, EC8-

1B, and red line, IBC-BCE) result inadequate and too conservative at periods larger than 0.2 s.

The calculated normalised spectral accelerations for soils of class C (Figure 4b) shows very high amplitudes (from 4 to 9) extended over a wide range of periods (to 0.7 s); also in this case the "mean" curve reveals a good fitting to the 2-Type EC8 normalised spectrum proposed for soils of class C (EC8-2C) even if with a worse agreement respect to the case of class B (the mean values slightly but systematically exceed the EC8-2C spectrum to a period of 0.2 s, with a peak value of 4.5 at 0.16 s). If we make reference to the "mean plus standard deviation" curve, we can observe how it largely exceeds the EC8-2C spectrum values over a wide range of periods (to 0.5 s). Moreover it is clear from Figure 4b as none of the spectra suggested by seismic code provisions for soils of class C (EC8-1C) and IBC-BCE, seems to fit well the calculated spectra, whereas the calculated response spectra show a better agreement in shape with the EC8-2C spectrum but with higher values of the spectral accelerations.

Soil factor S was calculated for each of the eight soil profiles and the eight input motions. The results are synthesised in Figure 5 where the S values obtained from the analyses are compared with the soil factors provided by European and Italian seismic building codes for B and C ground type. Observe that soil factor reach higher and more widespread values for soils of type C (where they range between 1 and 2.6 with a mean of 1.8) than for soils of type B (where they range from 1 to 2 with a mean of 1.6). Moreover the average values, calculated over the whole set of seismic inputs at each site (blue bars) are all comparable for ground type B, whereas they are quite different for soil type C, especially for site S6 and S7 (where lowest values are reached).
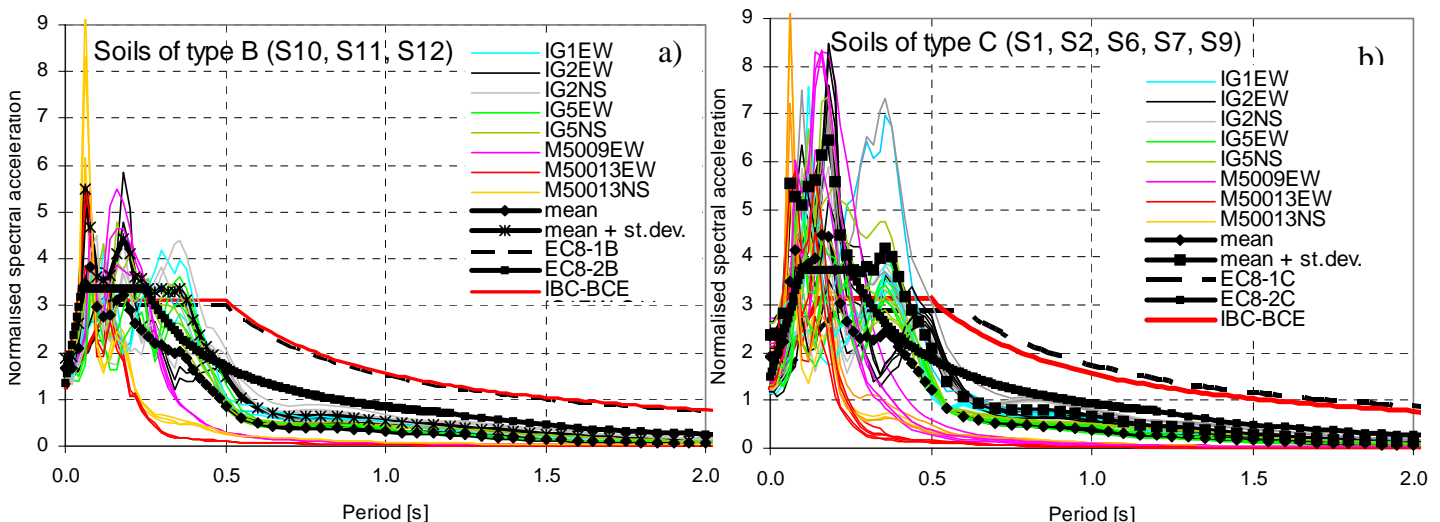

Figure 4 – Surface elastic response spectra numerically obtained for soils of class B (a) e C (b) compared to the corresponding spectra prescribed by EC8 and IBC (5% of critical damping ratio)
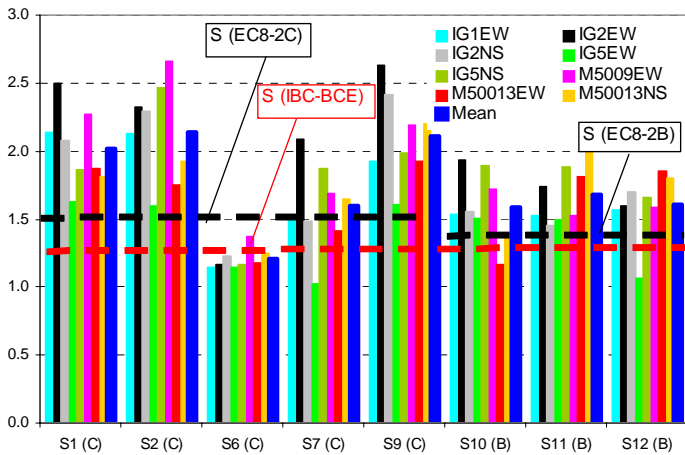
Figure 5 – Calculated and suggested soil factors for each class of soil

Figure 6 – Adopted model for numerical analyses at S6 and S9 soil profiles (kind of soil and thickness, in percent, are indicated for each layer)

A deeper analysis of Figure 5 reveals that:

- as already observed from the surface response spectra, EC8 and IBC are not adequate to protect the site for the expected earthquake. Soil factor values provided by the seismic codes are significantly lower than the calculated values from the numerical model, especially for ground type C;

- in each soil profile the soil factor is greatly related to the input motion, apart from the kind (real or simulated) of the seismic signal. For the examined cases a maximum difference of 105% was observed in S7 soil profile with reference to IG5EW and IG2EW seismic input;

- in several soil profiles belonging to the same ground type very different values of the soil factor were obtained for the same seismic signal (with a maximum difference of 125% for B ground type between S6 and S9 with reference to IG2EW accelerogram and of 59% for C ground type between S10 and S12 with reference to M50013EW accelerogram) and also the average values of soil factor were greatly different (maximum difference of 77% was observed between S2 and S6 soil profiles). This differences can not be ascribed to the parameters considered in Table 1 (which are quite similar in each class of soil), but to others peculiar aspects of the soil profile, such as thickness and location of soil layers with different mechanical properties (shear modulus and damping ratio curves versus shear strain). As an example the S6 and S9 soil profiles which fall both within ground type B and exhibit very similar parameters, (depth to bedrock, impedance ratio, $V_{s,30}$) but very different average values of soil factor, are compared. The detailed model adopted for numerical analyses for the two soil profiles is represented in Figure 6. Normalised shear modulus and damping ratio curves versus shear strain for the covering soil layers encountered in the two soil profiles are shown in Figure 7a and 7b respectively.
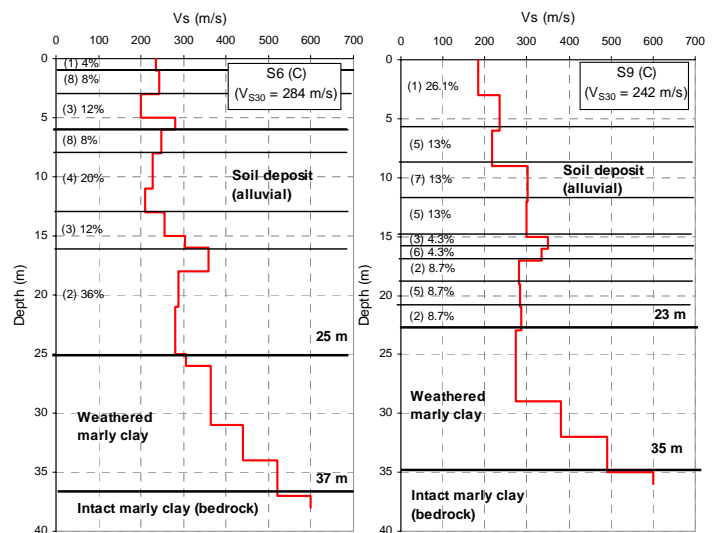
Note that: (i) the two considered soil profiles consist of the same kind of soils (1, 2 and 3 in Figures 6 and 7) for more than 50%, as evidenced in Figure 6; (ii) the remaining kind of soils (with the exception of 8) are characterised by comparable normalised shear modulus and damping ratio curves.

Consequently, the different results obtained by numerical analyses obtained at site S6 and S9 could be ascribed to the presence in S6 of a layer (named as 8 in Figures 6 and 7) of significantly different dynamical properties, as clearly shown in Figure 7 and/or the different thickness and location of soil layers 1 and 2.
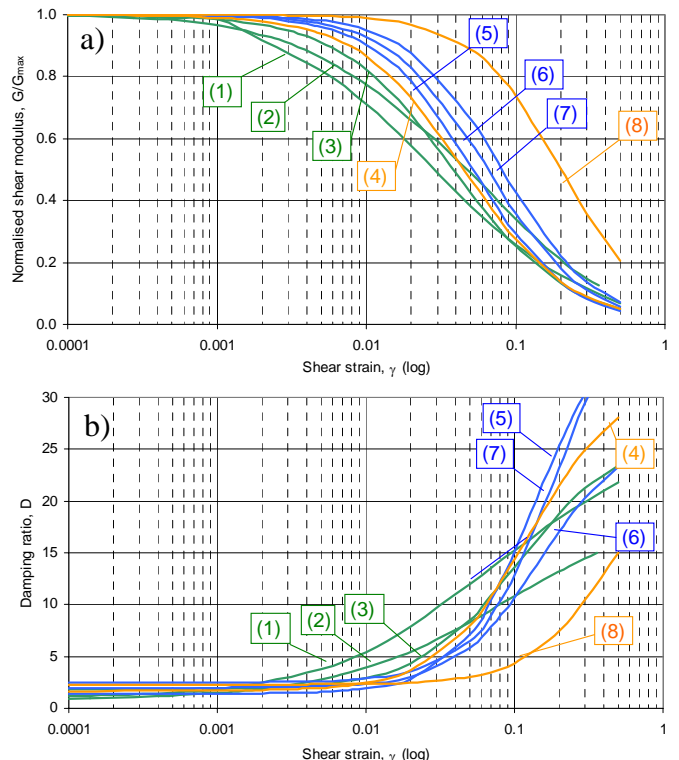

Figure 7 – Normalised shear modulus and damping ratio curves for encountered soil layers in boreholes S6 and S9 (as indicated in Figure 6)

5 CONCLUSIONS

The present paper illustrates results and considerations from 1-D local seismic response analyses performed within the more wide multidisciplinary seismic microzonation study of Senigallia.

Eight sites were selected and grouped in two classes, B and C, from the stratigraphic profiles and the equivalent shear waves velocity, V_{S30}, as prescribed by EC8 and Italian seismic building codes. The soil deposits falling within the same class revealed rather homogeneous also in terms of bedrock depth, impedance ratio, and no further class o subclass was needed to define.

Eight seismic inputs were adopted to represent the expected event on outcropping rock for the investigated area (PGA of 0.2g). They resulted consistent in terms of seismic parameters and seemed to well represent the local seismicity. Although the expected magnitude at the site (M = 6.5) is greater than 5.5, the elastic acceleration response spectrum proposed by EC 8 at 'rock-like' formation for Type 2-seismic areas (expected magnitude not greater than 5.5) revealed a better agreement with the calculated spectra than EC8- Type 1-seismic area (expected magnitude greater than 5.5) and Italian seismic building code spectra.

The surface calculated spectra from the 1-D model show for sites falling within the class of soil B a good agreement with the 2-Type EC8 spectrum, especially if we consider the "mean" curve of the normalised spectral accelerations; a worse agreement is obtained with the "mean plus standard deviation" curve. Whereas the suggested EC8- Type 1 and Italian seismic building codes response spectra result inadequate and too conservative at periods larger than 0.2 s. For soils of class C, calculated spectral "mean" curve reveals an acceptable fitting to the 2-Type EC8 spectrum even if with a worse agreement respect to the case of ground type B. Also in this case neither the Type1 spectrum suggested by EC8 for the examined area nor spectrum provided by Italian seismic building codes seems to fit well the calculated spectra.

A more detailed analysis of numerical results in terms of soil factor revealed that amplification response calculated at sites falling within C ground type are greatly different. Such differences can not only be ascribed to parameters that can be easily determined for soil classification (such equivalent shear wave velocity, depth to bedrock and impedance ratio) and they require a more deepen investigation of stratigraphic and geotechnical conditions (layer thickness and location, normalised shear modulus and damping ratio curves).

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