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A STEP INTO THE DEFINITION OF THE SEISMIC RISK FOR THE CITY OF BENEVENTO (ITALY)

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ABSTRACT

This paper gives a contribution in the definition of the seismic hazard for the city of Benevento in Southern Italy, from a geotechnical engineering viewpoint. To pursue this goal, an extensive geotechnical characterization of the city subsoil was achieved collecting data available at the Department of Geotechnical Engineering, University of Napoli and Benevento municipal technical office. Attention was paid in defining strain dependent shear stiffness and damping ratio for the geomaterials present in the urban area. A new method to correct the Masing criteria was adopted. Numerical analyses were performed considering the subsoil as a continuous one-phase equivalent linear medium. The 1-D analyses were carried out using Shake-like codes. The seismic hazard in the city was evaluated on the basis of two seismic scenarios, respectively characterized by low and high acceleration levels. The final result of the work is a seismic zonation of the city of Benevento. It was found that zonation maps are largely dependent from the chosen seismic scenario.

INTRODUCTION

The "Benevento Seismic Risk Project" (BSRP), financed by the European Union, was developed at the beginning of the '90s by a group of geophysicists, geologists and geotechnical engineers to detect the seismic hazard of the city of Benevento in Southern Italy. In the BSRP a preliminary geological and geotechnical structure of the city was determined and a first seismic zonation map was developed on the basis of an assumed seismic scenario (Marcellini et al., 1995a,b).

In the late '90s, two further projects (Traiano Project and RSV7 Project) were financed by the GNDT (National Group of Defence against Earthquake) and the Italian Ministry of University through the European Union support. Both projects are aimed at defining a damage scenario for the city of Benevento by improving the analyses performed in the past and integrating information from geophysical, geological, geotechnical, urban planning and structural engineering research teams. The operative units cooperate through a Geographic Information System (GIS), which allows the storage of the specific databases and of the synthetic results provided by each task unit. The GIS platform also provides damage scenarios in the urban area, on the basis of suitable relational algorithms linking the different factors contributing to the definition of the seismic risk.

Besides the existence of valuable data gathered from the BSRP, other reasons made the city of Benevento an interesting case study in the field of seismic hazard mitigation. Benevento is a small town of around 60000 inhabitants, located in the Sannio area inside the Southern Apennines, around 200 km SE of Rome. In the last four centuries the Sannio zone was hit by several large earthquakes with maximum intensity I_{max} between VIII and XI MCS. Worth mentioning is the 1688 Sannio earthquake. According to the Italian earthquake parametric catalogue, CPTI (Boschi et al., 1999), this earthquake was located around 35 km N of Benevento, with a maximum intensity I_{max}= XI MCS, corresponding to a macroseismic magnitude Mm=7,1. According to the same catalogue, that includes historical and instrumental Italian earthquakes since 217 BC, this event is the strongest that has ever hit the Sannio area. The earthquakes that struck the city in the Twentieth century had a lower MCS intensity, between VI and VIII. Nowadays, the local seismicity essentially reduces to low energy events, with epicenters located on the boundary of the major Apennine seismogenic faults. Therefore, due to the high past and recent low seismic history, the Sannio area has one of the highest seismogenic potential in Italy. The city of Benevento is characterized by an outstanding monumental heritage (for instance, the Traiano arch of the I century AC and the S.Sofia church of the VIII century AC) and a variety of building typology (reinforced concrete, masonry, mixed). Reinforce concrete buildings were mainly constructed after the WWII between the '50s and '60s. This means that most of them is under-designed with respect to the seismic forces.

This paper accounts for the progress made in evaluating the seismic hazard of the city of Benevento from the geotechnical engineering viewpoint.

The geotechnical characterization of the Benevento subsoil was improved with respect to that produced during the BSRP by adding new data obtained from different public institutions. Several 1-D numerical analyses were carried out considering the Benevento subsoil as a continuous one-phase equivalent linear medium. Two different seismic scenarios were employed. As the soil stress-strain characterization concerns, special attention was paid in defining a more general soil damping ratio variation with the strain level, starting from the decay curve of the shear modulus. The final result of the paper are seismic zonation maps of Benevento city, obtained following different approaches. Seismic zonation maps can be used by structural engineers and urban planners to perform their vulnerability analyses.

SITE DESCRIPTION AND SOIL CHARACTERIZATION

The city of Benevento, whose origins date back to the VIII-VII century BC, rises on a hill dominating the confluence of the Calore (that flows in the E-W direction) and Sabato (that flows in S-N direction) rivers. Several studies performed in the last decades highlighted the complexity of the Benevento subsoil from a geological and tectonic viewpoint (Marcellini et al. 1991). The city subsoil is essentially made of a Pliocenic clay formation covered by coarse alluvial mixed to fluvial clayey deposits (the so-called Ariano unit). The Pliocenic clay formation, whose top ranges from tens of meters (Sabato river valley) to hundreds of meters below the ground level (Calore river valley and the Benevento hill) was often assumed as a bedrock in the site response analyses described in the reminder of the paper. The city historic center lies on a hill made of a Pleistocenic (Rissian) conglomeratic formation, overlying the pliocenic clay. The Rissian conglomerate derives from the deposition and subsequent cementation of the alluvial deposits of the Calore and Sabato rivers. The conglomerate formation is composed by poligenic, heterometric clasts plunged in a sandy matrix, with sandy and silty lenses. Because of weathering effects, the uppermost layers of the rissian conglomerate often result poorly cemented. Towards the S-E side of the hill, fluvio-lacustrine deposits (the so-called Cretarossa unit) overlay the conglomerate formation. The Cretarossa succession consists of silty and clayey layers with polygenic and heterometric clasts in a sandy matrix.

Debris and colluvial deposits deriving from the disintegration of the rissian conglomerates and/or remoulding of Phlegrean and Vesuvian pyroclastic materials, are finally present along the hill slopes of the city.

In the Sabato and Calore river valleys terraced alluvia are present. The alluvial materials of the Sabato river are found along the western marginal areas of the hill, where they overlay the Rissian conglomerates.

Throughout the whole urban territory, man-made grounds, including large masonry blocks and archaeological ruins, are present. As it will be underlined later, these materials might strongly influence the seismic response of the studied area.

Figure 1 shows a sketch of the geological map of the city of Benevento.

The geotechnical characterization of the soils in the urban area was achieved integrating data published in the BSRP (Marcellini et al., 1995) with new information provided by local administrations.

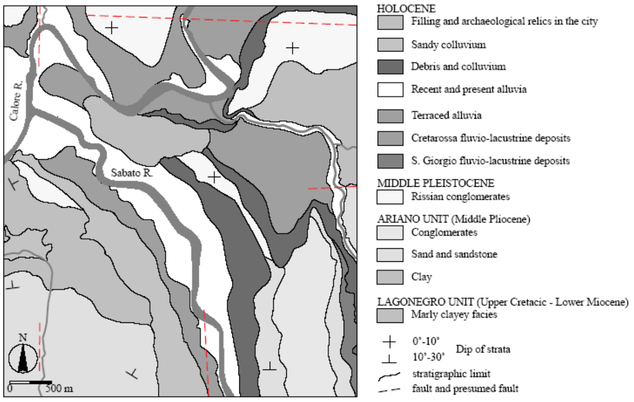

Fig. 1. Geological map of Benevento (after Marrara & Suhadolc, 1998)

Even if 236 boreholes were carefully analyzed and relevant geotechnical data properly stored in the GIS, a quantitative definition of all soil parameters needed for seismic response analyses has been achieved in only 19 verticals, placed within the urban territory. These verticals were selected because seismic shear wave velocities were available, or by in-situ measurements or by reasonably well-established correlations with other geotechnical properties. In situ measurements were obtained by Down-Hole tests, apart from one case (at ENEL site) where a Cross-Hole was performed.

Any soil layer was characterized by its total unit weight, shear stiffness and damping ratio including their initial value (G_0 and D_0) and their variation with the shear strain level ($G(\gamma)$ and $D(\gamma)$). The decay of the stiffness with shear level was summarised through the well-known Ramberg-Osgood (R-O) model. It is worth remembering that:

1. the stress-strain behaviour in this model is represented by:

$$\gamma(\tau)=\frac{\tau}{G_0}\left[1+\mathrm{H}(\tau)\right] \tag{1}$$

where H(t) represents the shift from the strain that material exhibits in linear elasticity;

2. Eq. (1) can be formulated through:

$$\gamma=\frac{\tau}{G_0}+C\left(\frac{\tau}{G_0}\right)^R \tag{2}$$

where the parameters C and R do not have a physical meaning;

3. If we assume a linear threshold γ_l as the strain level corresponding to $G/G_0=0.95$ and a reference threshold γ_r corresponding to G/G0=0.50 then we have:

$$\gamma_l=\left(\frac{0.05}{C\cdot 0.95^R}\right)^{\frac{1}{R-1}} \tag{3}$$

$$R=\frac{1+\log\dfrac{\gamma_r}{\gamma_l}}{\log\dfrac{\gamma_r}{\gamma_l}-\log\dfrac{0.95}{0.5}} \tag{4}$$

4. R-O model does not define a constitutive relationship for soils but just a convenient tool to represent experimental results analytically.

Regarding the variation of the damping ratio with the strain level, when experimental data are not available, the conventional geotechnical engineering method correlates such curves to the G(γ) values. A well-known analytical relationship of this type is provided by the Masing criteria, that can be conveniently employed when a non linear model (for example, the R-O model) is adopted to describe the backbone curve (see for instance Ishihara, 1996). The relationship is represented by:

$$D(\gamma) = \frac{2}{\pi}\frac{(R-1)}{(R+1)}\left(1 - \frac{G(\gamma)}{G_0}\right) \qquad (5)$$

Apart from the lack of physical correlation between the shear modulus and the damping ratio, the main shortcomings of the Masing criteria are: 1) the underestimation of the damping ratio in the pseudo-linear range; and, 2) the overestimation of the same parameter in the medium-high strain levels. To overcome the first problem, an initial damping factor D_0 was added to the damping-shear strain curve (Ni, 1987). Thus, the analytical relationship becomes:

$$D(\gamma) = D_0 + \frac{2}{\pi}\frac{(R-1)}{(R+1)}\left(1 - \frac{G(\gamma)}{G_0}\right) \qquad (6)$$

With respect to point 2), since it is not correct to use an amplification factor *n* different from 2 to enlarge the loop of the τ-γ curve, it was decided to multiply the loop area by a corrective empirical factor α. Then eq. (7) is obtained:

$$D(\gamma) = D_0 + \alpha\frac{2}{\pi}\frac{(R-1)}{(R+1)}\left(1 - \frac{G(\gamma)}{G_0}\right) \qquad (7)$$

It is worth underlying that using an *n* value greater than 2 unloading-reloading curves do not peak on the backbone curve. If *n* is lower than 2, starting for instance from (x_0,y_0), the unloading branch intersects the backbone curve in a point different from (-x_0,-y_0) and then moves without intercepting the backbone curve. If *n* is equal to 1, the unloading curve intercepts the backbone curve at the axis origins.

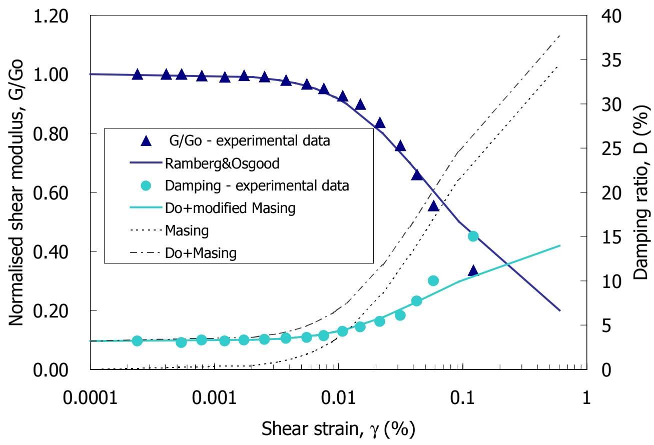

Fig. 2. Interpretation of the decay of shear modulus and increment of damping ratio with shear strain in RC tests on Bologna clay

The corrective value α was deduced by interpreting the relationship existing between several G(γ) and D(γ) curves obtained from RCTS tests performed at the Department of Geotechnical Engineering, University of Naples, on both natural and artificial soils. Figure 2 shows a typical dataset, which refers to a Resonant Column test on a intact specimen of Bologna clay. In this figure, the experimental G/G_0 and D values, plotted versus the shear strain, are indicated with solid points. In the same figure, the normalized stiffness data are interpolated by the R-O equation to get appropriate C and R values. Then, the damping dependency from shear strain was predicted using the Masing criteria: a) without considering the initial value D_0 (eq. 5); b) considering the initial value D_0 (eq. 6); and c) considering D_0 and the empirical correction parameter α (eq. 7) . From Figure 2 it is thus evident that a best prediction may be achieved by adopting the case c) approach. From all the available data it was deduced that a value of α equal to 0.8 was suitable to match the experimental damping-shear strain curves.

The G(γ) curves of the medium-fine grained soils were obtained here by the Resonant Column tests performed by the Italian Electric Power Company, at the ENEL site. For the Rissian conglomerate, non-linear curves were deduced from experimental data obtained on dense gravels at the University of Tokyo. Such data were obtained using local strain measurements and are therefore free from bedding errors.

Quite surprising to the Authors, this new available data are well in accordance with the previous geotechnical characterization employed by the BSRP. A summary of geotechnical soil properties for the lithological units found in the city of Benevento is given in table I, which combines new data with those assumed in the BSRP.

INPUT MOTION

To study the seismic vulnerability of the city of Benevento, the seismological team is detecting the main seismogenic faults on the basis of geological and seismotectonic features, damage distribution data together with instrumental recordings of the recent low-intensity earthquakes. The radiation pattern for the 1688 Sannio earthquake will be simulated using a hybrid statistical-deterministic approach. This approach simulates the main features of the fault rupture process by using a variable set of cinematic and dynamic parameters. Seismic radiation pattern is then obtained by an *ad-hoc* regional velocity model. The whole methodology provides as final result a large set of synthetic seismograms, which are assumed to be representative of the input motion that was generated by the strong 1688 Sannio earthquake at the bedrock level.

Table I. Geotechnical characterization of materials constituting the Benevento subsoil

Soil type		**D_o (%)**	**γ_l (%)**	**γ_v (%)**	**Non-linear parameters**	
					C	**R**
Man-made ground	Shallow MG-s	5	0.001	0.01	436407	2.38
	Deep MD-d	4				
	Masonry MG-am	0.5	0.01	0.1	18294	2.38
Debris colluvium	Fine D/C-f	3	0.0029	0.0371	552591	2.54
	Coarse D/C-c	2.5	0.0076	0.0617	12990307	3.03
Pyroclastites Pi		1	0.004	0.04	64640	2.38
Recent alluvium RA		2	0.001	0.01	436407	2.38
Terraced alluvium	Dense TA-d	1	0.002	0.02	167956	2.38
	Cemented TA-c	0.5	0.01	0.1	18294	2.38
Fine fluvio lacustrine	Shallow FL-f	5	0.005	0.05	47533	2.38
	Intermediate FL-f	4	0.005	0.05	47533	2.38
	Deep FL-f	3	0.005	0.05	47533	2.38
Coarse fluvio lacustrine	Shallow FL-c	1	0.002	0.02	167956	2.38
	Intermediate FL-c	1	0.002	0.02	167956	2.38
	Deep FL-c	1	0.002	0.02	167956	2.38
Rissian conglomerate	Weathered RC-w	1	0.0015	0.042	10308	2.09
	Cemented RC-c	0.5	0.02	0.2	7041	2.38
Pliocenic clay	Shallow AP-s	3	0.01	0.1	18291	2.38
	Deep AP-d	2	0.01	0.1	18291	2.38

At the moment of writing this paper, the whole set of synthetic accelerograms was not yet available. Only the horizontal peak ground acceleration at the bedrock for the city of Benevento was known, being equal to 0.38g (Iannaccone et al., 2003). Then, in the attempt to perform a preliminary evaluation of the effects of the 1688 Sannio earthquake in the city of Benevento, the acceleration time history recorded during the 11/23/1980 Irpinia earthquake at the station of Sturno (Av), which is located on a rock outcrop, was used as bedrock input motion. This accelerogram, with an original peak ground acceleration, (PGA) of 0.31g, was amplified in the ordinate to match the maximum acceleration of the 1688 event. The distance from Sturno to the Irpinia 1980 epicenter is approximately of the same order of the distance spanning from the city of Benevento and the epicenter of the 1688 Sannio earthquake. Then, apart from the peculiar focal mechanism characteristics, the recorded signal in Sturno during the 1980 Irpinia earthquake might probably have a comparable frequency content as that of the 1688 Sannio event, if recorded in Benevento.

A second seismic scenario aimed at simulating the effect of the 11/23/1980 Irpinia earthquake in the city of Benevento was also adopted in numerical analyses. A record of this event just inside the urban area (at the ENEL site) was available and then employed in the subsequent analyses.

It must be remembered that the 11/23/1980 Irpinia earthquake (Ms=6.9) had a quite long acceleration history, being characterized by three distinct sub-events occurring along different faults. Due to a larger distance between the epicenter of the1980 Irpinia earthquake and the city of Benevento, the record at the ENEL site has low acceleration amplitude (PGA= 0.059 g) and predominant frequencies lower than those pertaining to the Sturno recording.

To account for the effects of local soil conditions on the recorded signal, a deconvolution analysis was performed to properly define the bedrock input motion. Figure 3 shows the shear wave velocity profile together with the main lithological units (see Table I). In the same figure, the recorded and the numerical deconvoluted signal are also indicated. The analysis was performed using the EERA code. This code operates in the frequency domain and assumes that soil behaves as a continuous 1-phase equivalent linear material. This code uses the same

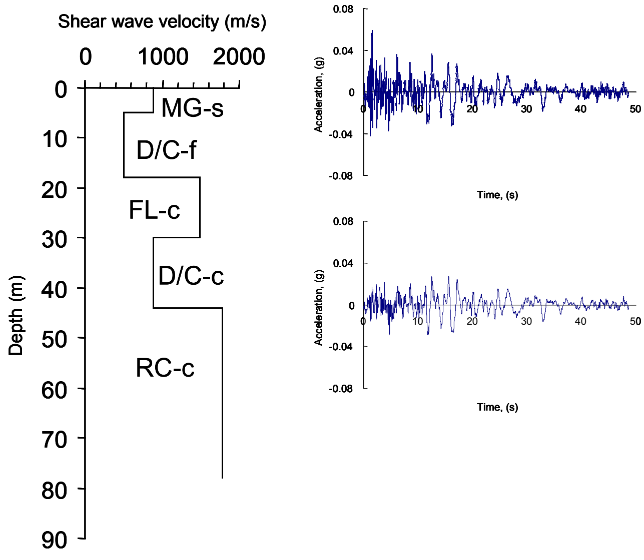

Fig. 3. Deconvolution analysis at ENEL site in Benevento for the 11/23/1980 Irpinia earthquake.

algorithm employed in the well-known Shake program, with its advantages and limits, but it has a more convenient user-interface.

Mechanical properties other than the shear wave velocity are those indicated in table I for the lithological units present in this location. Due to the local geotechnical conditions, the recorded signal at ground level is amplified with respect to the motion at the bedrock level. As a matter of fact, the PGA of the deconvoluted signal reduces to 0.029 g.

NUMERICAL ANALYSES AND RESULTS

Simplified analyses

Once the geotechnical characterization of the Benevento subsoil was established and the reference input motions defined, let's us discuss the seismic hazard of the city under the hypothesis of 1-D layered subsoil. Initially we will show some simplified methodologies and then we will include soil non linear behaviour in the numerical analyses.

The first simplified approach adopted here is based on correlations between shear wave velocity profiles and response spectra at the ground level under free-field condition. This approach is included in several national building codes, including the recent Italian building code (DM 20.03.2003) and the Eurocode 8 that is now in preparation (CEN, 2003). Referring to the latter (please, notice that the Italian code is very close to the proposed EC8) shear wave velocity profiles can be summarized by the $v_{s,30}$ value that is defined as:

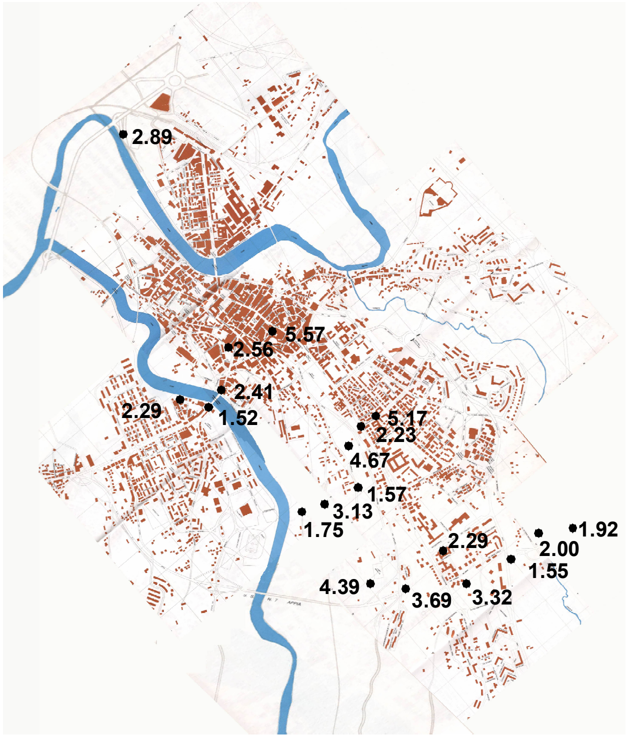

Fig. 5. Map of amplification factors assuming linear behaviour of soil layers

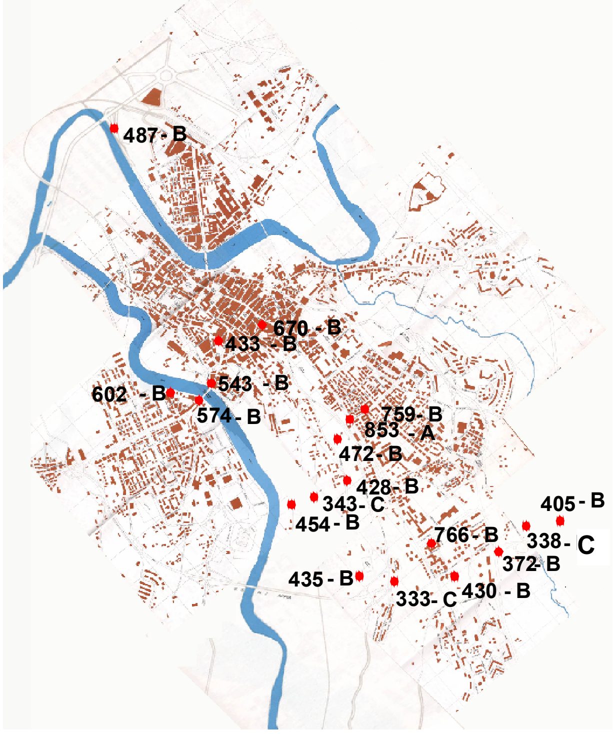

Fig. 4. Distribution of $v_{s,30}$ (in m/s) and site classification according to EC8 for the city of Benevento

$$v_{s,30} = \frac{30}{\sum_{i=1}^{N} \frac{h_i}{v_i}} \qquad (8)$$

where h_i and v_i denote respectively the thickness and the shear wave velocity of the i-th formation or layer existing in the top 30 meters.

A single vertical can be classified into one of the five EC8 categories according to the $v_{s,30}$ value; a normalized response spectrum is associated to each category. The horizontal elastic spectrum can be finally obtained once the design acceleration on a stiff ground is established. Such acceleration will be fixed by National Macroseismic zonation maps. It must be empathized that, unfortunately, EC8 and the derived Italian code allow site classification to be performed not only on the basis of shear wave profiles but also on N_{SPT} values.

Figure 4 shows a map of the city of Benevento. In this map each dot corresponds to the location of the before mentioned 19 verticals; numbers represent the $v_{s,30}$ values and labels indicate site category according to the EC8. It can be observed that $v_{s,30}$ spans from 333 m/s to 853 m/s but it is mostly concentrated around 500 m/s. The majority of the sites belongs to the class B, only one to class A and three to C category. We can conclude that according to the EC8 guidelines in the whole urban area of Benevento site effects are not relevant, since an almost homogeneous distribution of acceleration response spectra was obtained.

To validate the results previously shown, in Figure 5 the amplification factors computed for each vertical in the hypothesis that soil layers have a linear elastic behaviour are mapped. Computations were made with the EERA code whose solution algorithm, when only one iteration is performed, reduces into the well-known scheme of wave propagation in a layered elastic body (see, for instance, Rosset, 1970). As well known, under such hypotheses, the site amplification function is totally independent from the input motion.

From Figure 5 it appears that at least three different zones can be found in the city: an area approximately along the Sabato river with amplification factors between 1.5 and 2.5; an area in the Southern part of the city with amplification factors between 3.3 and 4.3; and an area in the central part of the city with amplification factors spanning from 4.5 to 5.5. Therefore, in terms of site response effects, conclusions from Figure 5 are different from those previously deduced from Figure 4.

1-D analyses considering soil non-linearity

More detailed and reliable analyses could be performed considering soil nonlinearity. Numerical results presented here were again obtained using the EERA code.

If we firstly consider as bedrock input motion the scaled accelerogram recorded in Sturno, an acceleration response spectrum (with 5% of structural damping) at the ground level was obtained for each studied verticals. Then a zonation map of the city of Benevento was sketched (see Figure 6) grouping together the response spectra having similar features. The spectra have been classified in four classes and compared with the spectrum of the bedrock input motion. The first group (indicated as zone (a) in Figure 6) is characterized by large spectral accelerations at high frequencies essentially due to the presence of small layers of man-made soils above the stiffer formations of conglomerate or pliocenic clay. The second group (indicated with (b) in Figure 6) is characterized by small amplification on the whole range of significant frequencies from an engineering point of view. Such results can be explained considering the low impedance ratio between the soil layers constituting these verticals. In the third group (zone c) large amplification are present in the period interval 0.15÷0.3 s, i.e. in the dominant period range of the input motion. The fourth group in Figure 6 (zone d) shows higher amplification between 0.3 and 0.4 s: the corresponding verticals are, in fact, characterized in the upper parts by man-made landfill strata, whose thickness is higher than that of verticals of group (b).

From the results of the numerical analysis it appears that the maximum spectral accelerations are very high, reaching even the value of 4.5g. In particular, ordinary buildings, with natural periods of 0.15 e 0.3 s (typically, reinforced concrete buildings with 1-3 stores) are very sensitive to a seismic event with the same features of that used in this set of analyses. While spectra ordinate are very large, the maximum amplification factors is always lesser than three.

A second set of analyses was performed with the goal of simulating the effect of the 11/23/1980 Irpinia earthquake in the city of Benevento. As before the numerical results are plotted in terms of acceleration response spectra with a structural damping of 5%, grouping similar spectra, as can be seen in Figure 7. In the same figure, a zonation map for the city of Benevento, corresponding to this new seismic scenario, is also proposed.

The first zone in Figure 7, labeled with (a), is characterized by a reduced amplification of the seismic motion in the whole frequency range, so that response spectra lay close to the spectrum of the reference input motion. In zone (b) of Figure 7, noticeable seismic amplification effects are present in the period range 0.2-0.5 s. Finally, in the zone (c), response spectra peak in the range periods of 0.2-0.4 s with large amplification factors.

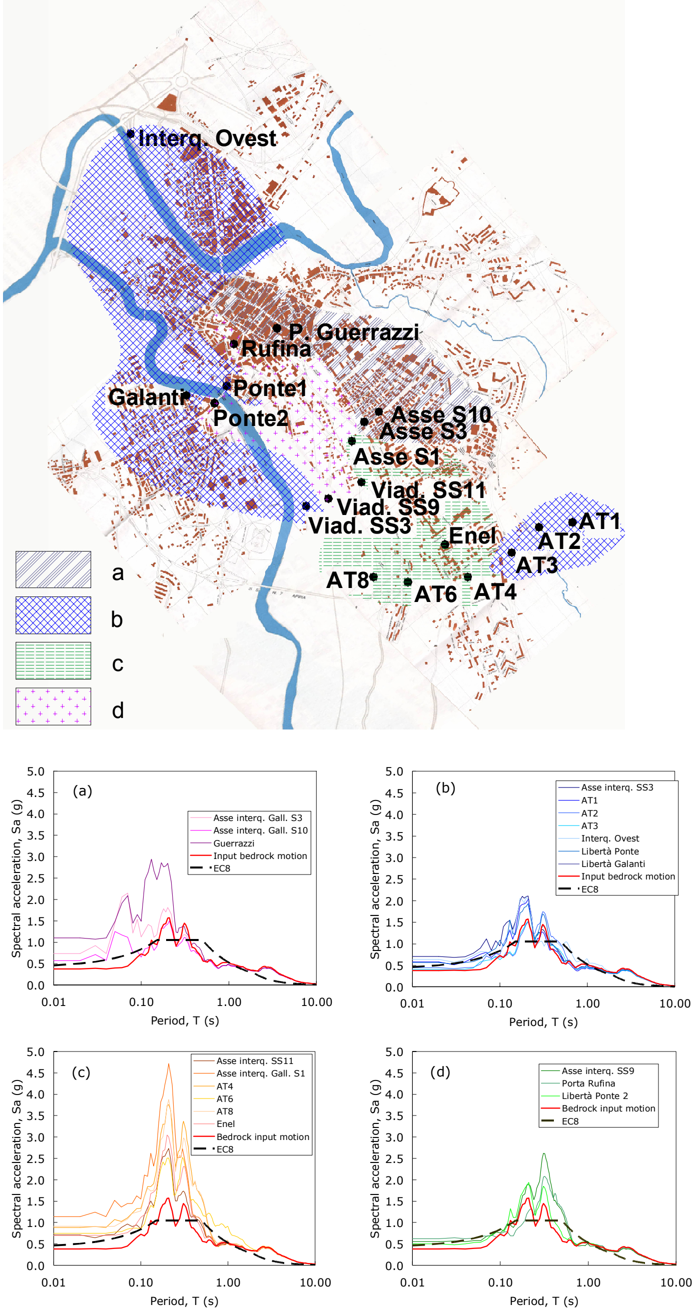

Fig. 6. Zonation map of the city considering soil non-linearity and Sturno scaled accelerogram as input motion

From the two sets of results presented above, it clearly emerges the influence of the input motion variability on the results of a seismic zonation analysis. The extent of each zone and the associated response spectra are substantially dependent on both frequency content and amplitude of the input motion. Particularly, the degree of nonlinearity that is mobilized during the shaking is directly linked to the amplitude of input signal. This point is highlighted comparing the two previous results. In

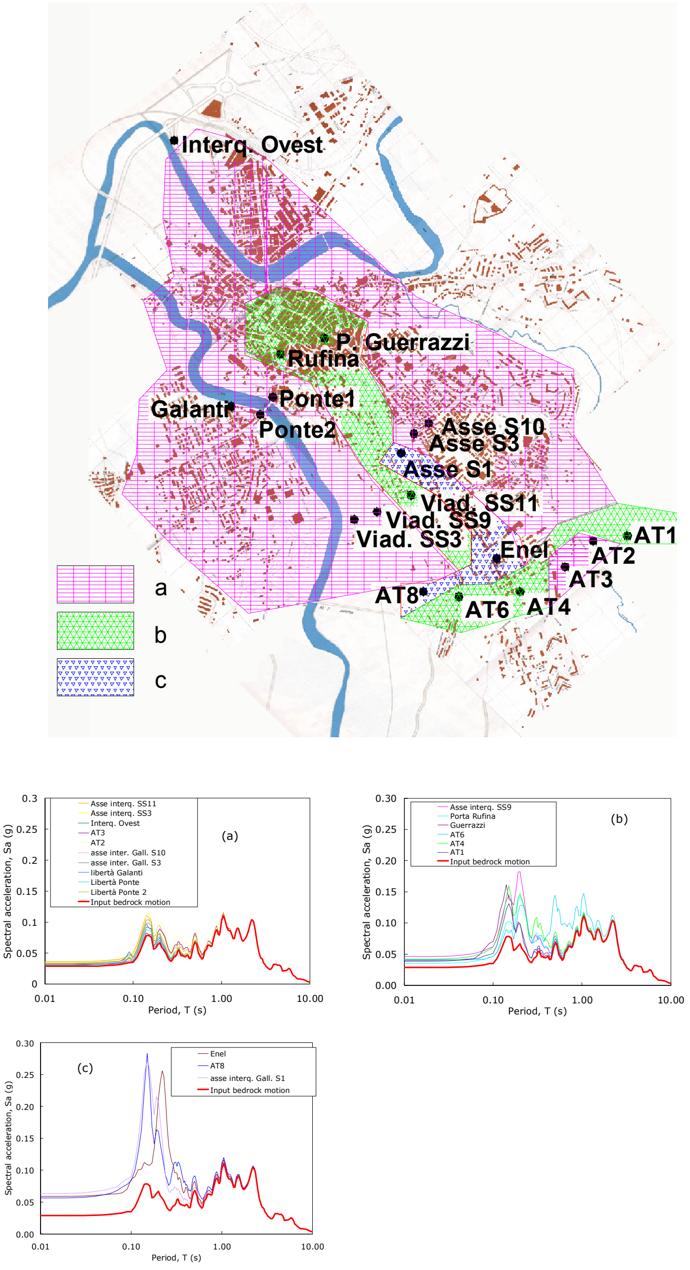

Fig. 7. Zonation map of the city when the 1980 Irpinia earthquake recorded in Benevento is simulated

the first seismic scenario, due to the large PGA value, soil nonlinearity is very important, because the mobilized strain levels are well beyond the linear threshold γ_l. On the other hand, for the second seismic scenario the PGA of the input motion is relatively low, and therefore all geomaterials are substantially loaded within their linear threshold during shaking. In this case, it follows that the suggested seismic zonation is very close to that obtained trough the amplification factor previously evaluated by simplified linear analyses as shown in figure 5.

DISCUSSION AND OPEN QUESTIONS

This paper presents a detailed geotechnical characterization and seismic zonation for the city of Benevento. This research represents a first step in defining the seismic risk of the area. This will be accomplished combining and integrating analyses provided by seismologists, geotechnical and structural engineers together with urban planners. Here, only a preliminary contribution of the geotechnical engineers is presented.

All the analyses presented were performed under the hypothesis of 1-D wave propagation from bedrock to ground level. A 2-D f.e.m. analysis was executed along a cross-section perpendicular to the Sabato river. In this case, the influence of geometrical factors on the seismic response appears negligible. On the other hand, experimental and numerical analyses performed using a geophysical approaches on another section crossing the Benevento hill show that 2-D effects are of some relevance (Marrara & Suhadolc, 1998). In the Authors' opinion, however, detailed 2-D dynamic analyses are worth performing only when reliable cross sections can be drawn, both from the geometrical viewpoint and in the definition of material properties. At the moment the available data set does not accomplish for the two conditions mentioned above. Further studies are required on this topic.

The zonation maps reported in Figure 6 and 7 were drawn by grouping together surface response spectra with similar features, even if the adopted criteria to put together the curves can be questionable. In an attempt to overcome such uncertainty, it may be useful to adopt other parameters to synthesize the results of the numerical analyses. "Integral parameters" such as the Arias intensity or the rms acceleration, which can be directly obtained from the computed acceleration time histories, can be effective, since they represent a global measurement of the energy content of the seismic signal. In order to use such parameters for seismic response analyses, it might be convenient to normalize them with respect to the value pertaining to the input motion. Figure 8, for instance, shows the distribution on Benevento city of the normalized Arias intensity as obtained from the first seismic scenario, which is represented by the scaled Sturno accelerogram. The normalized Arias intensity ranges from 1.05 to 5.86 with an average value of around 2.5. It can be observed that the areal distribution of these parameters approximately matches that depicted in Figure 6, which is based on response spectra. The large value of Arias intensity for the vertical "Asse S1" is due to the high value of the amplification function in correspondence to the dominant frequencies of the input signal, while the lowest value at "Asse interq. SS3" is due to the previous mentioned low impedance ratio between soil layers.

If the same plot is made with reference to the 1980 Irpinia earthquake recorded in Benevento, the Arias intensity ratios are very low not exceeding the value of 2 (see Figure 9). Such low values are essentially due to the almost coincidence of the input and output motions in the low frequency range. Also in this case, the seismic zones sketched in Figure 7 reproduce the areal distribution of Arias intensity of Figure 9.

Two more open questions still remain, when seismic zonation analyses like those presented here are performed.

The first point is related to the definition of an objective criterion to extend the information obtained in a single vertical (represented by just a point on a plane map) or even along a 2-D geotechnical section (a line on a map) to a given two-dimensional area. While we should admit that at this

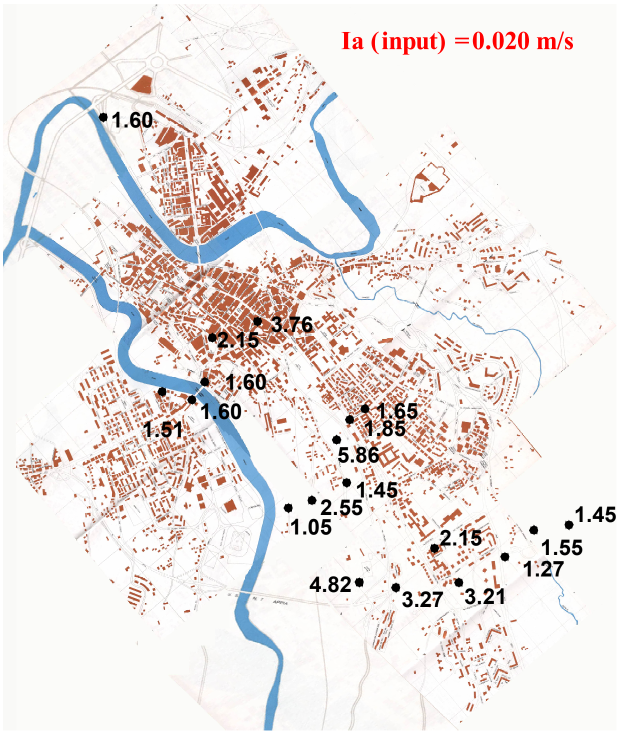

Fig. 8. Normalized Arias intensity when the Sturno scaled accelerogram is adopted as input motion

stage of the research the border of areas of Figures 6 and 7 were drawn in a qualitative way only, a research program is currently in progress at the University of Naples to overtook this limit, based on geostatistical approaches.

The second point is related to the fact that zonation maps are conventionally referred to the current ground level, as it was done in this paper. It means that surface soils, that usually have poor geotechnical properties, strongly influence the zonation maps. Even if we adopt the conventional simplification of free-filed conditions, thus neglecting the soil-structure interaction, we wonder whether zonation maps drawn at the building foundation level have higher engineering significance. Further studies are required on this topic too. Related to the above, if man-made landfills or surface soils are supposed to be important in seismic response analyses, their mechanical characterization under cyclic or dynamic loads is now still a challenging task. Such soils are usually very heterogeneous, could have a wide grain size distribution and, when sampling is possible, specimens should be tested under low confining pressure. In the Authors' opinion no dynamic analyses can be reliably performed without a proper mechanical characterization of the soils in hands.

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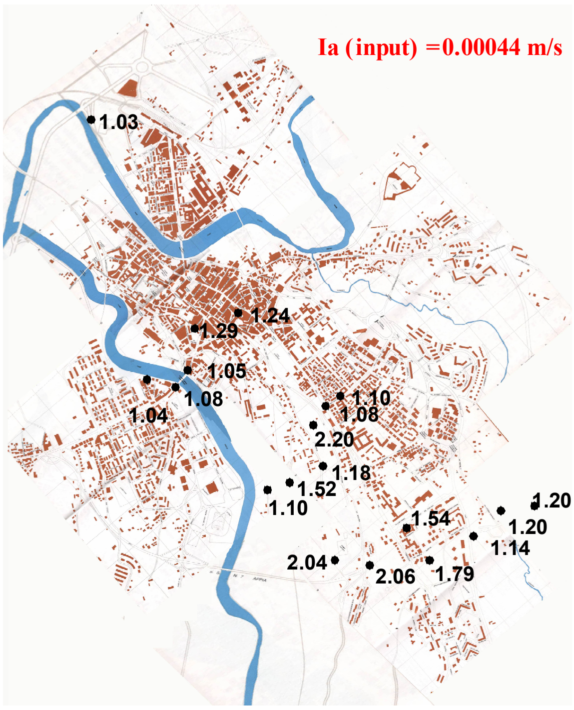

Fig. 9. Normalized Arias intensity when the 1980 Irpinia earthquake recorded in Benevento is adopted as input.

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