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1D non-linear seismic response analysis of soft soil deposits

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ABSTRACT: This paper focuses on the stratigraphic effects and describes the results of 1D non-linear seismic response analyses carried out using the computer code Deepsoil vs. 6.1. A set of ideal profiles of soft soil deposits, belonging to the soil class C according to Eurocode 8 and Italian seismic regulation, were considered varying the bedrock depth H and the average shear wave velocity $V_{S,H}$ and assuming a complaint bedrock. The parameters defining the backbone curve have been calibrated using shear modulus reduction curves available in the literature for soils of low to medium plasticity. A set of horizontal acceleration time histories, recorded on stiff horizontal outcropping bedrock, with peak values in the range 0.044g-0.279g are used as input motions. The analysis results were presented in terms of peak acceleration and acceleration amplification ratio at the ground surface and are compared with a large set of data concerning field and numerical data.

1 INTRODUCTION

The evaluation of local site-effects in terms of amplitude, energy and frequency content of the ground motion at soil surface represent a crucial issue for both geotechnical and structural seismic design procedures. The change in the ground motion characteristics that occur when the seismic waves travel from the bedrock to the ground surface, is generally evaluated, starting from properly selected input ground motions, through seismic response analyses which allow accounting for the only stratigraphic effect of for the coupled stratigraphic and topographic amplification phenomena (Rizzitano *et al.* 2014).

One dimensional (1D) equivalent-linear (EL) or fully non-linear (NL) approaches can be used to assess the influence of the site stratigraphy and of the soil non-linear behavior on site effects. For a given input motion, the results of 1D site response analyses can be used to estimate peak acceleration values, response spectra and the soil factor S_S at the ground surface as well as along the soil profile.

Several studies based on the equivalent-linear approach are available in the literature with reference to soft and very soft soil deposits. Ausilio *et al.* (2007) and Biondi *et al.* (2009) performed 1D seismic response analyses using a set of Italian strong motion records, different bedrock depth and the normalized shear modulus and damping reduction curves proposed by Vucetic & Dobry (1991) for different values of the plasticity index *PI*.

A number of numerical studies involving non-linear seismic site response analyses has been also carried out to suggest modifications of soil classification criteria (e.g. Pitilakis *et al.* 2013, Andreotti G. *et al.* 2013). More recently Tropeano *et al.* (2018) proposed a re-evaluation of stratigraphic amplification factors using experimental records and 1D non-linear seismic response analysis results.

In the framework of the work package "Linea di ricerca MT1 - Site Effect" of the 2014-16 Reluis project the research unit if Messina University examined the seismic response of liquefiable sand deposits and soft cohesive soil deposits. This paper summarizes some of the research activities focusing on the results of 1D seismic response analyses, carried out for soil deposits belongings to the soil class C (180 m/s < $V_{s,30}$ < 360 m/s) according to EC8-1 and to the Italian seismic code (NTC18). The analyses presented herein were carried out through a fully non-linear approach using the computer code Deepsoil vs. 6.1 (Hashash *et al.* 2016): the backbone curve is described by the modified hyperbolic model developed by Matasovic (1993); the *MRDF* model (Phillips & Hashash, 2009) available in Deepsoil was used to introduce a reduction factor into the hyperbolic model which leads to a simultaneous fit of modulus reduction and damping curves. The input motions were selected from the Engineering Strong-Motion database ESM (Luzi *et al.* 2016) and consist of 36 horizontal acceleration time-histories, recorded on rock outcrop (soil class A) in a free field condition. The results of the analyses were described in terms of maximum horizontal accelerations and soil amplification factor at the ground surface and in terms of relationship between acceleration at the ground surface and at rock outcrop. The obtained results were also compared with similar studies available in the literature and with the provisions of EC8-1 and of NTC18, highlighting the influence of the bedrock depth on the characteristics of the expected motion at the ground surface.

2 SOIL PROFILES

Three different depths of the compliant bedrock, z_b=30, 60 and 90m, were assumed in the analyses. For each value of z_b, four different ideal shear wave velocity (V_s) profiles were derived using the following procedure. A set of empirical relationships available in the literature and derived using both in situ and laboratory test results, was selected to generate ideal profiles of the small strain shear modulus G_0 (Di Filippo, 2009). These profiles were then fitted using the analytical model proposed by Gazetas (1982) to describe the variation with depth of the small strain shear modulus in heterogeneous soil deposits:

$$G_0(z) = G_{0(z=0)} \cdot \left(1 + \alpha \cdot \frac{z}{z_b}\right)^{2 \cdot m} \quad (1)$$

In eq. (1) z is the depth from the ground surface, $G_{0(z=0)}$ is the values of G_0 at the ground surface, and α and m are numerical parameters describing the heterogeneity of the considered soil deposit. From eq. (1) the V_S profiles were then obtained through the relationship:

$$V_s(z) = \sqrt{\frac{g}{\gamma} \cdot G_0(z)} = V_{s(z=0)} \cdot \left(1 + \alpha \cdot \frac{z}{z_b}\right)^{m} \quad (2)$$

where $V_{s\ (z=0)}$ is the values of V_s at the ground surface, γ is the soil unit weight and g is the gravity acceleration. The parameters α and m were detected, numerically, according to two main criteria: (i) the V_s (eq. 2) and G_0 (eq. 1) profiles should be consistent with the numerical set of data obtained through the selected empirical relationships; (ii) despite different values of z_b, the V_s profiles should be characterized by the same average shear wave velocity $V_{s,30}$ in the top-most 30 m from the ground surface. Values of $V_{s,30}$ were selected according to EC8-1 and NTC18 provisions for soil deposits belonging to class *C*. Specifically, assuming six different values of $V_{s,30}$ in the range 200÷300 m/s and setting proper value of $V_{s\ (z=0)} = V_{s,0}$ and $V_{s\ (z=zb)} = V_{s,b}$ the parameters α and m were detected iteratively (Di Filippo, 2009).

Combining the computed shear wave velocity profiles with the three bedrock depths, 18 ideal soil profiles were obtained. As an example, Figure 1 show the six profiles derived for z_b = 30 m together with the range of variation (grey shaded area) defined by the laboratory- or field-based empirical relationships selected by Di Filippo (2009); the ideal profiles have the same values of V_s at the ground surface ($V_{s,0}$ = 70 m/s) and at the soil-bedrock interface ($V_{s,H}$ = 360 m/s) and different grade of heterogeneity (i.e. different values of the parameters α and m) which leads to different $V_{s,30}$.

Table 1 list the obtained results for the six combinations of soil profiles and bedrock depths considered in this paper: z_b = 30, 60, 90 m, $V_{s,30}$ = 220 and 280 m/s. In all the cases a soil unit weight γ = 20 kN/m^3 was considered for the soil deposit; the values V_b=800 m/s and γ = 22 kN/m^3 were assigned to the compliant bedrock.

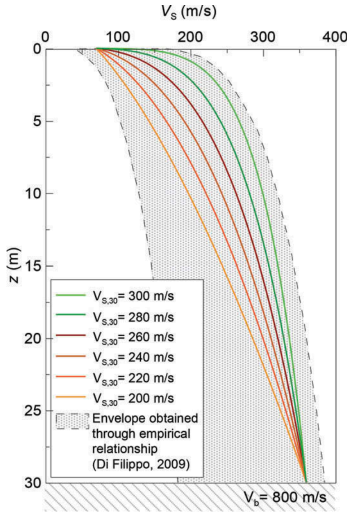

Figure 1. Shear wave velocity profiles derived for z_b = 30 m and $V_{S\ (z=0)}$ =70 m/s.

Table 1. Parameters of the ideal shear wave velocity profiles used in the analysis $V_{S\ (z=0)}$ =70 m/s.

ID	α/*H*	*m*	$V_{S,30}$ (m/s)	$V_{S,b}$ (m/s)	$V_{S,b}/V_{S,30}$
z_b=30 m					
1	1,072	0,468	220	220	1,00
2	48,98	0,225	280	280	1,00
z_b =60 m					
ID	α/*H*	*m*	$V_{S,30}$ (m/s)	$V_{S,b}$ (m/s)	$V_{S,b}/V_{S,30}$
1	2,276	0,364	220	277	1,26
2	50,13	0,224	280	327	1,17
z_b =90 m					
ID	α/*H*	*m*	$V_{S,30}$ (m/s)	$V_{S,b}$ (m/s)	$V_{S,b}/V_{S,30}$
1	3,129	0,332	220	310	1,41
2	57,02	0,219	280	356	1,27

3 SELECTED INPUT MOTIONS

The input motions considered in the analyses were selected from a database of corrected strong motions accelerogram (Luzi *et al.* 2016). The motions consist of 36 horizontal acceleration time-histories, recorded during 18 seismic events, occurred from 1976 to 2019 with magnitude in the range M_W = 5.4 ÷ 6.5, on stiff horizontal rock outcropping sites (soil class A) located at epicentral distances R_{ep}= 3.4 ÷ 60.2 km.

The selected accelerograms were characterized by peak horizontal acceleration a_g in the range 0.044g ÷ 0.279g and Arias Intensity I_a varying from 1.8 cm/s to 80.3 cm/s; the mean period T_m (Rathje et al., 1998) and the strong-motion duration $D_{5\text{-}95}$ (Trifunac & Brady, 1975) vary in the intervals 1.4 ÷ 2.5 s and 3.6 ÷ 15.6 s, respectively; finally, the number of equivalent load cycles, evaluated according to Di Filippo et al. (2012), is in the range 3.3 ÷ 38.4.

Figure 2 shows the normalized response spectra S_a/a_g computed (for a structural damping ratio ξ = 5%) for each of the selected accelerograms together with the shape of the elastic

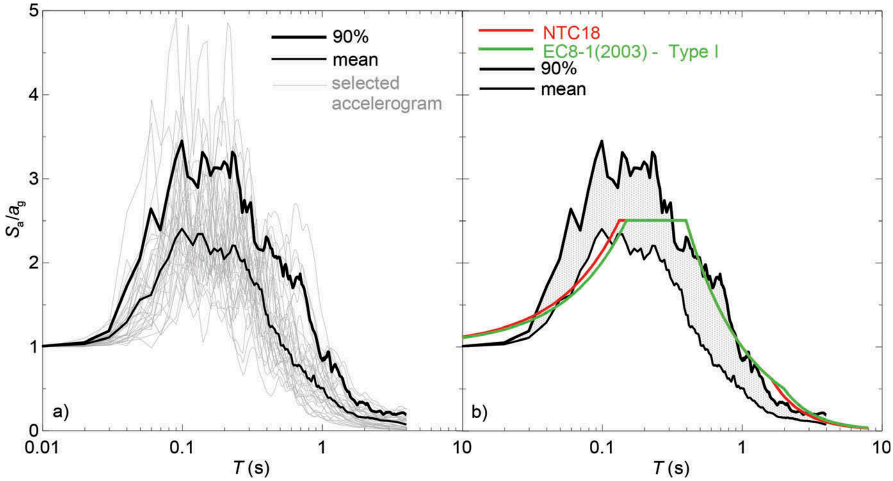

Figure 2. Normalized response spectra of the selected input motions and shapes of the elastic response spectra proposed by EC8–1 (type I) and NTC18 (T_c^*=0.4, F_o=2.5).

response spectrum proposed by EC8-1 and NTC18 for soil class A and ξ = 5%. Specifically, all the normalized response spectra are plotted in Figure 2a together with the curves representing the mean and the 90 % percentile of the data; in Figure 2b the mean and the 90% curves are compared with the shape of the Type 1 (M > 5.5) elastic response spectrum proposed by EC8-1 and with the shape of the elastic response spectrum computed according to NTC18 assuming in the latter case a value of the upper limit of the period of the constant spectral acceleration branch $T_c = C_c \cdot T_c^*$ equal to 0.4 s (C_c = 1, T_c^* = 0.4 s) and a values of the maximum spectral amplification factor F_0 equal to 2.5.

4 ANALYSIS RESULTS

The results of all the seismic response analyses carried out for the soil profiles listed in Table 1 are presented in terms of relationship between the peak acceleration at the ground surface $a_{max,s}$ and the peak acceleration at rock outcropping a_g (Figure 3) and in terms of soil amplification factor S_s (Figure 4). The data are presented separately for z_b = 30 m (Figures 3a and 4a), 60 m (Figures 3b and 4b) and 90 m (Figures 3c and 4c).

In the same figures the values of $a_{max,s}$ and S_s suggested by EC8-1 and NTC18 for soil class C (180m/s < $V_{s,30}$ < 360m/s) are also plotted. The results clearly show that the computed values of S_s are generally higher than those suggested by EC8-1, regardless the bedrock depth z_b, and frequently are also higher than those prescribed by NTC18, especially for the case z_b = 30 m. These differences may be ascribed to two different reasons:

- the values of S_s specified in EC8-1 for soil deposits belonging to class C were derived as ratios of modified Housner Spectrum Intensities calculated on average response spectra of a set of European accelerograms (Rey et al., 2002); conversely, the values of S_s derived herein represent the ratio between peak acceleration values at the ground surface;
- due to low peak values of some of the selected input motions, low shear strain levels are attained in the soil deposit and, for some of the analyses, the effect of soil non-linearity does not significantly influence the seismic response of the overall soil deposit.

The curve describing the values of S_s suggested by Tropeano et al. 2018 appear a reasonable fit of the average trend of the stratigraphic amplification factor computed herein; Andreotti et al. (2013) evaluates amplification factors slightly higher than NTC 18 and according to our numerical analyzes only for z_b = 30m and a_g > 0.10g.

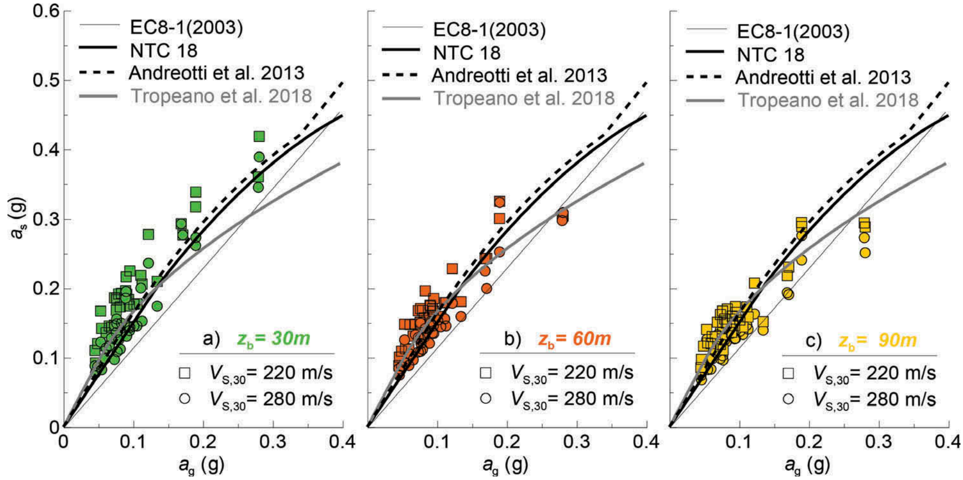

Figure 3. Relationship between computed peak horizontal acceleration at the ground surface ($a_{max,s}$) and at rock outcropping (a_g).

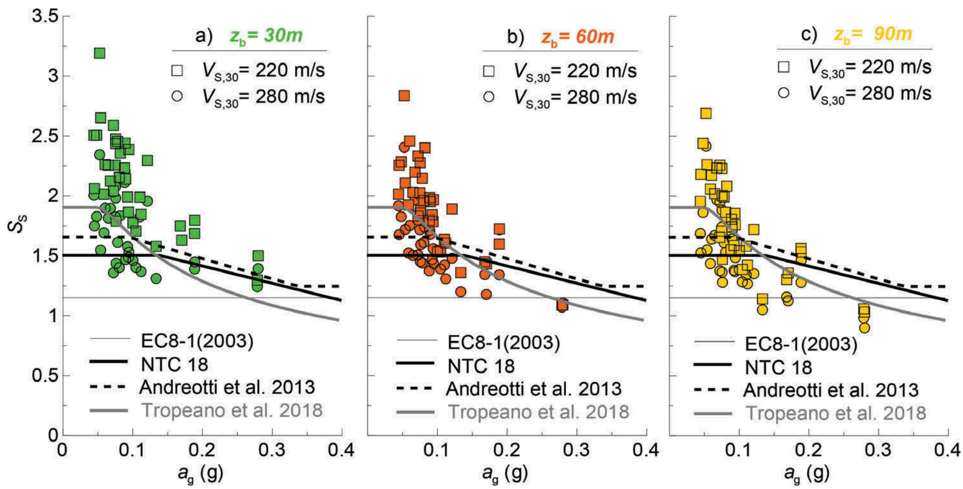

Figure 4. Soil amplification factor (S_s) versus peak acceleration at rock outcropping (a_g).

Finally, in Figure 5, the results of all the analyses are compared with several set of data available in the literature in terms of relationship between $a_{max,s}$ versus a_g.

Specifically, in Figure 5a, the obtained results are compared with the results of the equivalent-linear seismic response analyses (EL–SRA) carried out by Idriss (1979) for soft soil sites and with the data collected by Idriss (1990) concerning some records of the 1985 Mexico City and 1989 Loma Prieta earthquakes.

It can be observed that the obtained results are in good agreements with other plotted data and the mean curve suggested by Idriss (1979) for soft soil deposits can be considered as a reliable upper bound of the data for $a_g \leq 0.20$g.

In Figure 5b the obtained results are superimposed to the relationship derived by Ausilio et al. (2007), for soil class *C* and bedrock depth z_b ranging from 30 to 60 m, and to the data presented by Chang et al. (1997) including both actual records (Loma Prieta and Northrige earthquakes) and results of equivalent-linear (EL) and fully non-linear (NL) seismic response analyses (SRA).

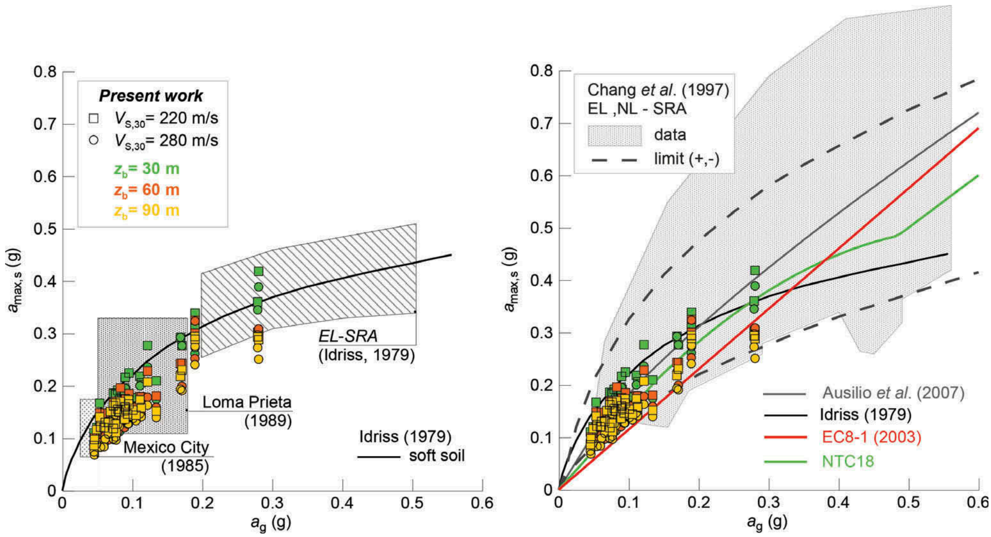

Figure 5. Comparison of the obtained numerical results with literature

The data by Chang et al. (1997), represented by the shaded area in Figure 5b, refers to deep stiff cohesive and/or mix of cohesive with still cohesive soil deposits having $z_b \geq 60$m and $V_s >$ 180 m/s; the two gray lines plotted in Figure 5b represent the upper (+) and lower (-) reasonable limits suggested by the same authors.

From the figure it is evident that for a_g lower than about 0,25g, the results of the seismic response analyses presented herein are well fitted by the relationship derived by Ausilio et al. (2007); regardless a_g all the results match well with both the data (shadow area) and the two limits (+,-) proposed by Chang et al. (1997).

5 CONCLUDING REMARKS

This paper describes the results of 1D non-linear seismic response analyses carried out using a set of ideal soil deposits belonging to class C (180<$V_{s,30}$<360 m/s) according to Eurocode8-1 (2003) and to the Italian seismic regulation (NTC-18). The profiles of the shear wave velocity V_s were defined using empirical relationships available in the literature and the depth of the compliant bedrock vas varied from 30 to 90 m. A set of 36 horizontal acceleration time histories recorded on rock outcropping in a free field conditions, during seismic events which occurred with magnitude M_w=5.4 ÷ 6.5, were used as input motions.

The results of the analyses were presented and discussed in terms of relationship between peak acceleration at the ground surface ($a_{max,s}$) and at rock outcrop (a_g) and, finally, in terms of soil amplification factor S_s defined as the ratio between $a_{max,s}$ and a_g.

The results show a significant influence of the bedrock depth on the computed ground motion amplification; the obtained results were also compared with data available in the literature concerning site response analyses carried out, for similar soil deposits and/or similar set of input ground motions, using both linear-equivalent and fully non-linear approaches. The comparison has shown a general good agreement. Conversely, significant differences were observed with the provisions of the Eurocode8-1 (2003) and of the Italian seismic regulation (NTC-18).

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