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# Influence of the variability of the geotechnical properties of soils on computed response spectra for 1D stratigraphies

## Influence des propriétés géotechniques des sols sur les spectres de réponse calculés pour des stratigraphies 1D

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**ABSTRACT:** Predicting the response spectra for different sites is a critical aspect of the seismic design process. Two design acceleration response spectra are defined in the Eurocode 8 (EC8) depending on the earthquake magnitude, but in both of which the site effect is taken into account only by the average shear velocity in the upper 30 m, $V_{s,30}$. Type 1 spectra are enriched in long period and are suggested for high seismicity regions. However, Type 2 spectra are proposed for low to moderate seismicity areas (like France), and exhibit a larger amplification at short period, and a much smaller long period contents, with respect to Type 1 spectra.

In this study, the efficiency of considering only the $V_{s,30}$ parameter to characterize the site effects is investigated analysing the differences between the EC8 response spectrum and the spectra obtained by finite element simulation of seismic waves propagation in 1D columns, under the assumption of linear soil behavior. This study considers 30 m deep columns constituted by 4 different soil layers that can have different soil type, thickness and shear velocities but respecting a given value of the average shear velocity $V_{s,30}$. A set of geotechnical parameters (i.e. plasticity index, shear modulus reduction curves, friction angle) is assumed associated to each soil type. The influence of the uncertainty related to the mechanical parameters as well as the stratigraphic parameters (i.e. layer position and thickness) of the considered soils is generated through a Monte Carlo simulation. Differences between the obtained numerical response spectra and the reference EC8 response spectrum associated to a given value of $V_{s,30}$ are analysed in order to highlight the influence of other relevant parameters such as the fundamental frequency $f_0$ and the vertical velocity gradient $B_{30}$.

**RÉSUMÉ:** Prédire les spectres de réponse pour des sites différents est un aspect critique de la conception sismique. Deux spectres de réponse pour la conception sont définis dans l'Eurocode 8 (EC8) selon la magnitude

du séisme, mais dans lesquels l'effet de site est pris en compte seulement via la vitesse moyenne dans les 30 premiers mètres de profondeur, $V_{s,30}$.
Dans cette étude, la pertinence du seul paramètre $V_{s,30}$ pour caractériser les effets de site est examinée, en analysant les différences entre le spectre de réponse de l'EC8 et les spectres obtenus par des simulations numériques de la propagation des ondes sismique dans des colonnes 1D. Des colonnes de 30 m de profondeur constituées par 4 couches de sol avec différentes valeurs d'épaisseurs et vitesses des ondes et respectant une valeur donnée de $V_{s,30}$ sont considérées.
L'influence de l'incertitude liée aux paramètres mécaniques aussi bien que les paramètres stratigraphiques (i.e. position et épaisseur de la couche) des sols considérés est prise en compte par une simulation de type Monte Carlo. Les différences entre les spectres de réponse numériques obtenus et le spectre de référence proposé par l'EC8 associé à une valeur donnée de $V_{s,30}$ sont analysées pour mettre en évidence l'influence d'autres paramètres pertinents comme la fréquence fondamentale $f_0$ et le gradient vertical de vitesse $B_{30}$.

**Keywords:** Soil variability; average velocity; fundamental frequency; impedance contrast; Eurocode 8

# 1 INTRODUCTION

Predicting the response spectra for different sites is a critical aspect of the seismic design process.

It is widely known that the response of a soil profile due to a strong ground motion is mainly affected by the stratigraphy, surface topography, and the non-linear and dynamic geotechnical characteristics of the soil deposits. Thus, the amplification or de-amplification phenomena should be related both to the fundamental frequency $f_0$ of the site and to the impedance contrast between the shallow soil and the underlying bedrock (Semblat et al., 2005).
In the last decades, $V_{s,30}$ (the average shear velocity in the upper 30 m) is the main parameter proposed to classify soils in regulation codes, such as Eurocode 8 (EC8, 2004) and the National Earthquake Hazard Reduction Programme (NEHRP, Boore, 2004). This parameter was introduced for the first time by Borcherdt (1994).

However, several researchers (Cadet et al., 2008-2012; Castellaro et al., 2008; Gallipoli and Mucciorelli, 2009; Luzi et al., 2011) have shown that the use of this single parameter is not able to capture the physics of 1D site amplification, confirming $V_{s,30}$ to be a proxy of limited applicability in capturing linear site-response. There have been several propositions of alternative or complementary proxies to $V_{s,30}$ to suggest new characterization of soils and for site-effect assessment. Most of these works reported that the most relevant pair of proxies seems to be $V_{s,30}$ and the $f_0$ (Cadet et al., 2012).

In this regard, the present work aims at investigating the influence of simple site parameters on the prediction of the site response phenomena without excessive cost. For the purpose of this study, a preliminar approach is proposed in order to assess the role of velocity profile, the fundamental frequency and the impendance contrast on site classification and site amplification functions.

Following the recent works of Castellaro and Mulargia (2013) and Regnier et al. (2014) that suggested the relevant influence of $V_S$ profile, fundamental frequency $f_0$, and the impedance contrast between sediments and bedrock, their influence on a wide variety of sites associated to a given $V_{s,30}$ is investigated. In particular, the influence of the fundamental period $f_0$ obtained from numerical simulations and the vertical velocity gradient $B_{30}$ is investigated as complementary proxies to $V_{s,30}$.

The gradient $B_{30}$ is defined as the slope of the linear regression between the logarithm in base 10 of shear-wave propagation velocity and the logarithm to base 10 of the depth $z$ (Equation 1) (Regnier et al. 2014).

$$log_{10}V_s(z) = B_{30}log_{10}(z) + A_{30} \pm \sigma_{30} \quad (1)$$

where:
$B_{30}$ is the gradient of the $V_s$ profile calculated from the regression between $V_s$ and $z$, down to 30m, $A_{30}$ is the origin ordinate of the regression, $\sigma_{30}$ is the standard deviation associated to the linear regression.

In the second section, the wide set of numerical sites is presented. Thereafter, the dynamic analysis and the effect of the parameters $V_{s,30}$, $f_0$ and $B_{30}$ on the response spectra are investigated.

## 2 SOIL PARAMETERS VARIABILITY

In this work, the influence of proxy parameters such as the shear-wave velocity profile, the fundamental frequency and the velocity gradient is studied through computations of seismic wave propagation in 1D columns (considering horizontally layer soil), in a finite element scheme, under the assumption of linear soil behaviour. A database including 200 soil profiles of different impedance contrast and layers thicknesses was developed. It considers 30 m deep columns, which respect a given value of $V_{s,30}$, constituted by 4 different soil layers with plastic indexes between 0-20%. The soil profiles are randomized by a Monte Carlo simulation sampling of the soil type, thickness and shear velocities ([100 – 800 m/s]) values using a uniform distribution. Each soil layer has a different set of geotechnical and geometrical parameters in order to evaluate the uncertainty of stratigraphic and mechanical parameters on the site amplification.

In particular, all the 30 m deep columns have the same value of $V_{s,30}$ = 270 m/s that result of soil of class C according to EC8 and the shear wave velocity increasing with the depth (Fig. 1). Fig. 1 shows that the variability of the site $V_s$ profiles, for all the considered 1D columns, is large for the given $V_{s,30}$ value.

The soil profile is discretized, using a finite element scheme, using quadratic line elements having three translational degrees of freedom per node. An elastic half-space bedrock underlies the entire soil profiles. The physical properties assumed for the bedrock are the density $\rho_b$ = 2100 kg/m$^3$ and the shear velocity in the bedrock $V_{sb}$ = 1000 m/s. The finite element model applied is completely described in Santisi d'Avila et al. (2012, 2013, and 2018).

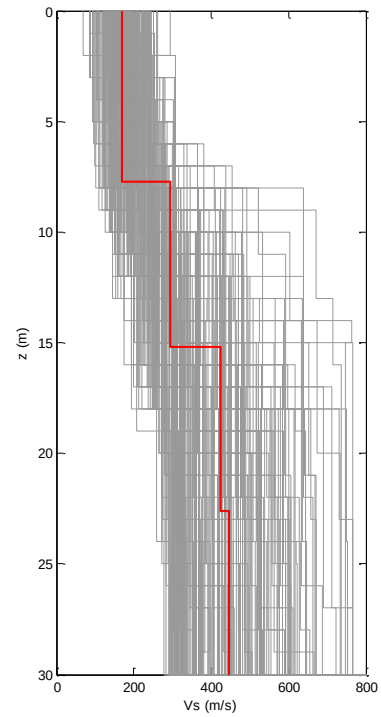


*Figure 1. Variation of Vs with depth for the 30 m deep soil profiles.*

All the soil columns were subjected to the same input motion to assess the site classification and soil amplification proposed by EC8 for site classes C. A recorded signal of the 6 May 1976 Mw 6.5 Friuli earthquake is used as rock outcropping motion. The signal is recorded at the Tolmezzo station of the Italian strong motion network, localized in Friuli-Venezia Giulia region (Italy), at an epicentral distance of 14.97

km and the PGA is 0.24 g, $V_{s,30}$ at the Tolmezzo station site is 505 m/s. The characteristics of the ground motion are presented in Table 1.

*Table 1. Properties of Friuli earthquake.*

| Event | Year | Station | $M_w$ | R (Km) | $V_{s,30}$ (m/s) |
|---|---|---|---|---|---|
| Friuli | 1976 | Tolmezzo | 6.5 | 14.97 | 505 |

## 3 LINEAR SITE-RESPONSE COMPUTATIONS

One-directional (1D) linear wave propagation employing the previously mentioned input motion were conducted for a specific $V_{s,30}$ value (270 m/s) to assess the role of the variability of the shear-wave velocity profiles and different values of $B_{30}$ and $f_0$.

The influence of these proxy parameters was studied for each soil profile in order to evaluate the importance of complementary information in terms of $f_0$ and potentially available complete $V_s$ profiles by in-situ investigations.

In the following paragraphs the influence of the site proxy parameters $f_0$ and $B_{30}$ on the site response spectra is investigated.

### *3.1 Influence of fundamental frequency $f_0$*

For the purpose of this study, the $f_0$ value is chosen as proxy parameter because of its availability by relatively low-cost surface investigations, such as HVSR from ambient vibrations or earthquakes measurements. The use of the HVSR method has been tested in geotechnical engineering for foundation worksites controlled by classical soil investigations (Brûlé et al., 2014).

First of all, the fundamental frequency for each multi-layered soil profile is evaluated and compared to the fundamental frequency of a homogeneous 30 m soil profile with the same $V_{s,30}$.

The calculated $f_0$ for the homogeneous case results to be 2.25 Hz. Fig.2 illustrates the range of the $f_0$ obtained for each soil profile compared to the homogeneous case (green). It shows that they vary from 1.75 Hz to 3.5 Hz.

In order to investigate the influence of the proxy $f_0$ on the soil site response, the results of analyses sorted by ranges of $f_0$ values. In particular, they are divided into 3 groups: the first group considers values of $f_0$ from 1.75 to 2.5 Hz, the second from 2.5 to 3.0 Hz and the third from 3.0 to 3.5 Hz (the first group is larger than the others because there were only few cases with $f_0$ < 2.0Hz) (Fig.2).

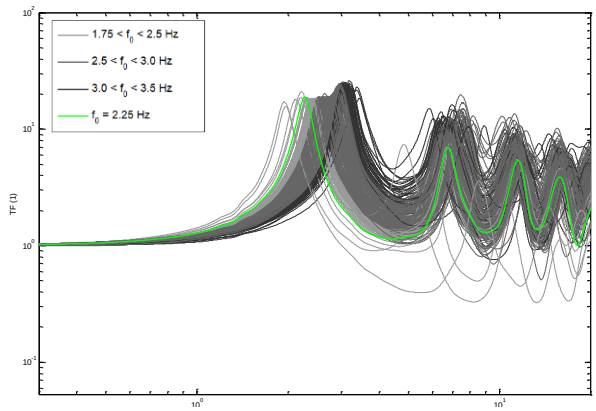


*Figure 2. Transfer function of the 30 m deep soil profiles, theoretical transfer function (green).*

The amplification functions change as a function of the fundamental frequency and this is reflected on the site response spectra. In this regard, Fig.3 shows the median elastic acceleration response spectra (the damping ratio is equal to 5%) of all the 200 random soil profiles (red) compared the three groups of $f_0$ and to the one proposed by EC8 for Type 1 (black) for Class Soil C, normalized to the maximal acceleration of the input motion.

Fig.3 also illustrates how different the site response of soil profiles of the same Class for EC8 can be. In particular, it is noticed that for intermediate to large periods, the obtained response spectra are in accordance with EC8 spectrum, while for low period, the amplification of the median spectra results highest.

In this regard, comparisons between different areas under the spectrum are made with respect to the one proposed by EC8 suitable for Class Soil C and Type 1 spectra that are enriched in long period and are suggested for high seismicity regions. In particular, six ranges of period band are considered (as shown in Fig.3 and Table 2) and the relative area variation between the spectra is calculated in the following way:

$$v = \frac{A_r - A_i}{A_r} \quad (2)$$

where:
$A_i$ is the area of the range *i* of frequency $f_0$;
$A_r$ is the area of the given spectrum EC8.

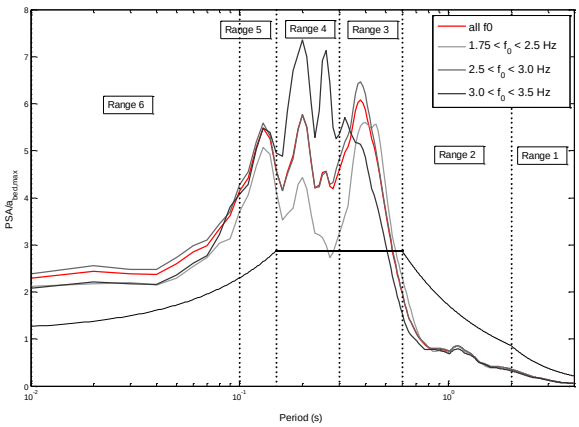


*Figure 3. Median normalised elastic acceleration response spectra (the damping ratio is equal to 5%). for the 30 m deep soil profiles (red), for different values of $f_0$ (grey) compared to EC8 (black).*

The values of the relative area variation *v* are presented in Table 2. First, they are calculated as the difference between the median of all 200 columns compared to the spectrum proposed by EC8 for Type 1, considering all the obtained values of $f_0$ (red in Fig.3 and column 'all $f_0$' in Tab.2). Second, the values of the relative area variation are calculated for each obtained median, relative to the three $f_0$ ranges, compared to the EC8 spectrum (Tab.2). If the value of *v* is positive, it means that the spectrum proposed by EC8 is conservative (the damping ratio is equal to 5%), while if it is negative, the EC8 spectrum results underestimate the obtained response spectrum. As shown in the Tab.2, for intermediate to large periods (i.e. 1°-2° range), the values of *v* are similar for all the obtained spectra. While in the plateau (i.e. 3°-4° range) and low periods (i.e. 5°-6° range), the values are different depending on the $f_0$ values.
This work considers linear simulations, it is possible that non-linear effects may reduce this discrepancy.

Results show that the amplification increases with the increasing of the fundamental frequency $f_0$. This means that response spectra vary depending on the frequency content and a single estimated spectrum may underestimate or overestimate the soil response variability.

This result confirms that $f_0$ can be used as complementary information to $V_{s,30}$ (Luzi et al., 2011; Cadet, Bard, et al., 2012).

*Table 2. Comparison to EC8.*

| **Range of f (Hz)** | **All $f_0$ (Hz)** | **$1.75<f_0$ $f_0<2.5$ (Hz)** | **$2.5<f_0$ $f_0<3.0$ (Hz)** | **$3.0<f_0$ $f_0<3.5$ (Hz)** |
|---|---|---|---|---|
| Range 1 0.25-0.5 | 0.64 | 0.65 | 0.63 | 0.66 |
| Range 20.5-1.6 | 0.55 | 0.54 | 0.54 | 0.58 |
| Range 3 1.66-3.3 | -0.52 | -0.5 | -0.57 | -0.33 |
| Range 4 3.3-6.6 | -0.62 | -0.21 | -0.63 | -1.14 |
| Range 5 3.6-10 | -0.9 | -0.75 | -0.94 | -0.91 |
| Range 6 10-100 | -0.61 | -0.58 | -0.67 | -0.52 |

### *3.2 Influence of vertical gradient $B_{30}$*

For the selected sites, the vertical gradient of velocity was calculated from the surface to the depth until the bedrock situated at 30 m depth as shown in Eq.1. If $B_{30}$ is 0, it means that the velocity is constant with depth and the larger the $B_{30}$ value, the faster the velocity increases with depth (Regnier et al., 2014).

The linear correlation between $f_0$ and $B_{30}$ is calculated for the specific value of $V_{s,30}$. This correlation results to be sufficiently high as shown in Fig.4 ($r$ = 0.68).

The result of the correlation has been used in order to separate the sites into two different groups. In fact, it is used as a line of transition for the values of $B_{30}$ for each $f_0$ range previously defined (Fig.4): for the Group 1 (green), $B_{30}$ is lower than the line of correlation and for the Group 2 (red), $B_{30}$ is upper the line.

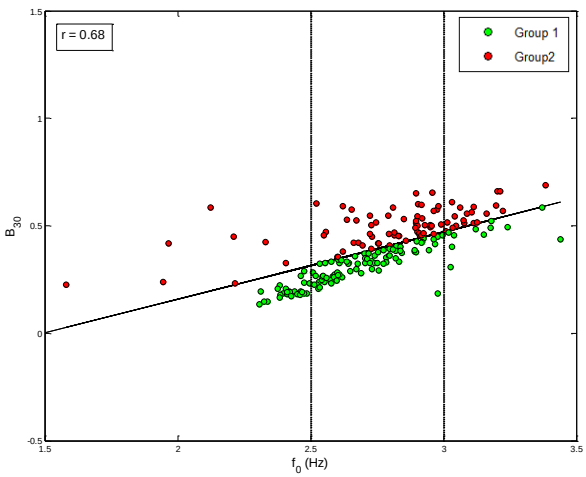


*Figure 4. Linear regression between $f_0$ and $B_{30}$ for the 30 m deep soil profiles (r=0.68). The line represents the linear regression.*

It is chosen in this manner in order to evaluate the influence of the impedance contrast on the response spectra. Thus, Group 1 represents sites with a low gradient value (i.e. small impedance), while Group 2 represents sites with a high gradient value (i.e. large impedance), as illustrated in Fig.5 for the three range of $f_0$.

The obtained median response spectra for the three $f_0$ ranges are presented in Fig. 6 to estimate the effects of $B_{30}$.

It is noticed that Group 1 presents a larger amplification for low values of fundamental frequency $f_0$ (Fig. 6a), whereas Group 2 is characterized by larger amplification at higher frequencies (Fig. 6b and c).

## 4 CONCLUSIONS

The purpose of this work is to determine the influence of the 1D 30 m deep soil profiles on site response in terms of response spectra. In this regard, 200 soil profiles were randomized by a Monte Carlo simulation sampling of the soil type, thickness and shear velocities values using a uniform distribution maintainly the same value of $V_{s,30}$ = 270 m/s.

1D linear wave propagation employing the same input motion was conducted to evaluate the site response variability as a function of two proxy parameters: the fundamental frequency $f_0$

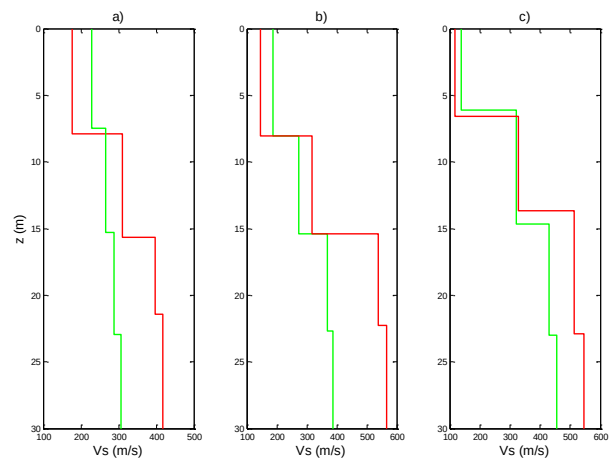


*Figure 5. Variability of the shear-wave velocity profiles for different ranges of $f_0$ (a. 1.75-2.5 Hz; b) 2.5-3.0 Hz; c) 3.0-3.5 Hz), considering the two groups of $B_{30}$.*

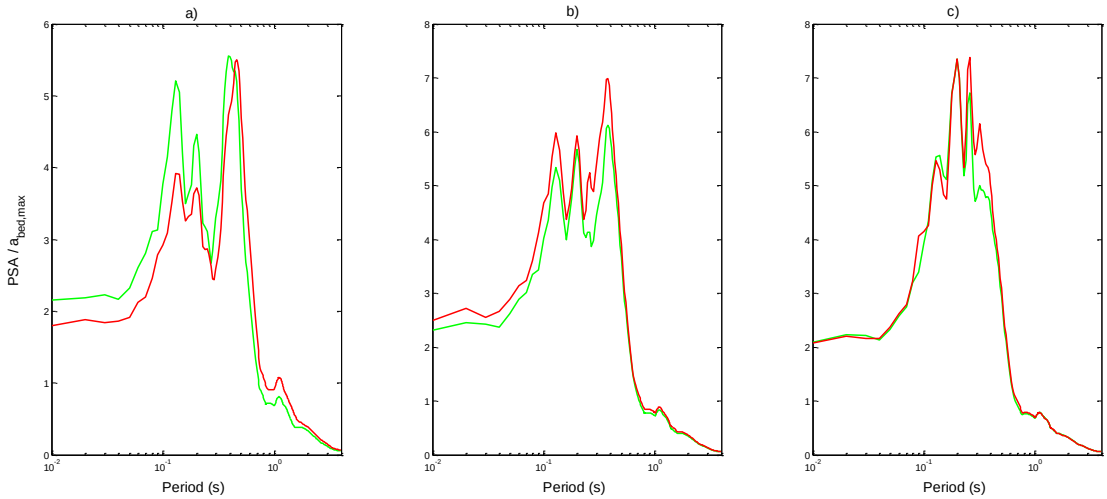


*Figure 4. Median normalised elastic acceleration response spectra for the 30 m deep soil profiles for different ranges of $f_0$ (a. 1.75-2.5 Hz; b) 2.5-3.0 Hz; c) 3.0-3.5 Hz), considering the two groups of $B_{30}$.*

and the vertical velocity gradient $B_{30}$.

This analysis indicates that these two parameters could be an improvement to the classical site classification based on $V_{s,30}$. This means that for different values of $f_0$ and $B_{30}$, considering only one response spectrum, as nowadays EC8 depicts, may be an underestimation or an overestimation of the site response.

In addition, the results of these analyses emphasize the importance of taking into account the complementary information of $f_0$ and $B_{30}$ in addition to the $V_{s,30}$ in terms of frequency content, impedance contrast and type of additional information, confirming their relevance for site-effect assessment.

In particular, it is interesting the fact that $B_{30}$ and $f_0$ can be both easily available with relatively low cost investigation and they can be used in order to improve the evaluation of the site response spectra that vary depending on the site location.

This study can be considered as a first step to develop this approach and many further investigations must be considered: comparing and investigating the changes in the shapes of the amplification curve with soil non-linear behaviour, complementing the analyses with other input motions and other values of $V_{s,30}$.

## 5 ACKNOWLEDGEMENTS

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