EFFECT OF SHEAR WAVE VELOCITY INVERSION ON 1D SEISMIC SITE RESPONSE

S. Fabozzi[1], G. Falcone[1], M. Moscatelli[1], A. Pagliaroli[2], E. Peronace[1], A. Porchia[1], G. Romagnoli[1]

[1] Institute of Environmental Geology and Geoengineering IGAG - National Research Council of Italy CNR, Italy

[2] Department of Engineering and Geology – University of Chieti Pescara G. D'Annunzio, Italy

Introduction. The shear wave velocity, Vs, profile of the subsoil is one of the most important controlling parameters of the seismic site response (Rathje *et al.*, 2010), i.e. the motion modification during the wave propagation through the stratigraphic series, from the bedrock upward to the ground surface. Despite the high heterogeneities and complexities of the geological conditions, generally the shear wave velocity increases with depth due to the effects of geologic age, cementation and overburden stress. This is the condition indicated by the Italian Building Code (ItBC2018) for the application of the simplified approach, based on subsoil categories, to definte the seismic action at the ground surface. They exist, however, particular geological settings for which this condition does not occur and specific seismic site response analyses are reqired by the ItBC2018. This is the case, for instance, of the shear wave velocity inversion, when the top layer is stiffer (i.e. exhibiting higher Vs) than the one below (i.e. exhibiting lower Vs) overlaying the bedrock. The present work identifys the most common Italian geological settings where Vs profile inversions are possible, associating typical mechanical and geotechnical properties to each layer. Based on this preliminary subsoil models, 1D site response analyses have been then performed to evaluate the influence of the stiffness inversion on ground shaking in terms of shear strain profiles and acceleration response spectra at the ground surface. In particular, stochastic 1D analyses were carried out via Monte Carlo method assuming assigned statistical distribution for Vs profiles and nonlinear G/G_0-g and D-g curves.

Geological settings with Vs profile inversion. Three main geological-depositional settings in Italian territory, generally exhibiting Vs inversion profiles, have been identified in this work as it follows:

1) FLUVIAL AND MARINE TERRACES

It is the case, for example, of Floridia village area (Panzera *et al.*, 2019).

- STIFF LAYER → FLUVIAL TERRACES: terraced alluvial deposits mainly consisting of sandy-silty gravels, a mixture of gravels, sands and silts. MARINE TERRACES: terraced marine deposits consisting of breccias, conglomerates and slightly cemented calcarenites. The finer fluvial and marine terraced deposits (sands and silts) are excluded since they are characterized by lower Vs and can hardly give rise to phenomena of Vs reversal profile.
- SOFT LAYER → Plio-Pleistocene marly-clays and clays deposits, covered by fluvial and marine terraced deposits, generally distributed near the coast lines.

2) *CLIFFS AND LAVA ROCK LAYER*

It is the case, for example, of Orvieto, Gerace and Bisaccia cliffs (Lanzo *et al.*, 2004) and Catania (Catalano *et al.*, 2017).

- STIFF LAYER: tuffs and lava rocks;
- SOFT LAYER: Plio-Pleistocene marly-clays and clays deposits.

3) *TRAVERTINE PLATEAU ON ALLUVIAL PLAINS*

It is the case, for example, of Rieti hill where, in the east side of the intermontane plain, a large plateau of travertine, is located above a silty-sandy alluvial and lacustrine deposits.

- STIFF LAYER: travertine or similar lithic layer;
- SOFT LAYER: sand and silt with clayey intercalations and peaty levels.

As it can be deduced from the above description, the identified geological domains could exhibit different geometrical and geotechnical properties. A detailed analysis of numerous data in such domains, extrapolated from the *data-base* of the seimic *microzonation studies* (*DB-MS*) available for consultation on www.webms.it and created by CNR IGAG for the Italian National Civil Protection Department (DPC 2018), has been conducted in order to identify, for both stiff and soft layer: 1) the variation, in terms of minimum and maximum values, of the shear wave velocity, Vs, and layer thickness, H_{stiff} and H_{soft}; 2) the soil unit weight (g_{soil}). In particular, SMs of the municipalities of the centre of Italy, SMs of Sicilia and Calabria regions were used for the case of fluvial and marine terraces; Orvieto and Catania cliffs were considered for the case of cliffs and lava rock layer; finally, the case of Rieti plain was considered studying the case of travertine plateau in alluvional plains. Tab. 1 synthesizes the identified ranges of values for the geometrical and geotechnical properties.

Table 1 - Geometrical and mechanical characterization of the stiff and soft layers, in the case of Vs inversion, for 1) fluvial and marine terraces, 2) cliffs and lava rocks, 3) travertine plateau on alluvional plains in Italian territory.

GEOLOGICAL SETTINGS	LAYER PROPERTIES	STIFF LAYER	SOFT LAYER
FLUVIAL AND MARINE TERRACES	H_{min}-H_{max} (m) $V_{s,min}$-$V_{s,max}$ (m/s) γ_{soil} (kN/m^3) G/$G_{0-\gamma}$ and $D_{-\gamma}$ curves	5-20 320-530 21 Rollins *et al.*, 1998 upper-medium-lower bound	10-30 200-460 19 Vucetic and Dobry, 1991 PI 0-15-30
CLIFFS AND LAVA ROCKS	H_{min}-H_{max} (m) $V_{s,min}$-$V_{s,max}$ (m/s) γ_{soil} (kN/m^3) G/$G_{0-\gamma}$ and $D_{-\gamma}$ curves	15-50 600-1000 15 Pagliaroli *et al.*, 2014 tuff curves	10-30 200-460 19 Vucetic and Dobry, 1991 PI 0-15-30
TRAVERTINE PLATEAU ON ALLUVIAL PLAINS	H_{min}-H_{max} (m) $V_{s,min}$-$V_{s,max}$ (m/s) γ_{soil} (kN/m^3) G/$G_{0-\gamma}$ and $D_{-\gamma}$ curves	20-50 550-1000 20 Curves from Rieti SM study	50-400 200-350 18 Vucetic and Dobry, 1991 PI 50-100-200

One dimensional site response analysis: Monte Carlo simulations. The characterization proposed in Tab. 1 has been adopted to carry out a set of stochastic equivalent-linear site response analyses, performed with STRATA code (Kottke *et al.*, 2013), for one-dimensional columns set up by combining the minimum and the maximum value of H_{stiff} and H_{soft} for a total of four different geometrical configurations. To take into account the natural variability of Vs profile in the range identified in Tab. 1 and the uncertainties related to the nonlinearity of the stiff and soft soil layers, Monte Carlo simulations were performed. V_S profiles were generated using Toro (1995) random field model described by a log-normal distribution, while the nonlinarity uncertainties were considered adopting Darendeli (2001) model, where the variability around the mean value is assumed to be normally distributed through the mean (m) and standard deviation (σ) values. For the scope, literature G/G_0-g and D-g curves, listed in Tab. 1, have been selected. For the soft layer in particular, Vucetic and Dobry (1991) curves were used for a variation of the plasticity index, PI, ranging between 0 and 30 (PI=15 represent the target curve) in the case of fluvial and marine terraces and the cliffs and lava rocks domains, while the curves for PI ranging between 50 and 200 (PI=100 represent the target curve) were used in the case of travertine plateau on alluvional plains. In this case, the use of very high PI values allows to reproduce a pronounced linear and low dissipative behaviuour that is typical of very deep deposits and organic clays frequently encountered in alluvial plains (Pagliaroli *et al.*, 2014). For the stiff layer, Rollins *et al.* (1998) upper-medium-lower curves were adopted for fluvial and marine terraces (the medium curve is the target curve); Pagliaroli *et al.* (2014)

tuff curves have identified the variation zone of G/G_0-γ and D- γ for cliffs and lava rocks; finally, for travertine plateau on alluvional plains, the decay curves from Rieti SM study have been adopted. As example, Fig. 1 shows one hundred randomized Vs inversion profile for each geometric configuration and the corresponding m and $m \pm \sigma$ nonlinear soil properties predicted for the fluvial and marine terraces. Once defined the set of 1D columns for each geological domain, three groups of 20 non-scaled real accelerograms, recorded at outcropping stiff soil were selected for three different PGA levels: Class 1 ($PGA<0.1g$), Class 2 ($0.1g \leq PGA < 0.2g$), Class 3 ($0.2g \leq PGA < 0.4g$), respectively. In this way, for each geological setting, 100 Vs profiles have been generated for 4 different geometrical configurations, for a total of 400 1D profiles → 400profiles x 60signals = 24000 analyses for each geological setting for a total of 72000 performed analyses. The results have been processed in terms of shear deformation profile, γ_{max}-z, and respose spectra, T-Sa. Fig. 2 for instance shows, as example, g_{max}-z profiles and T-Sa relation for Class 3 of PGA, associated to the fluvial and marine terraces, as the envelope of the minimum and the maximum reached value. It can be appreciated an attenuation effect of the seismic motion (Fig. 2b) at low periods and an amplification mode at higher periods, that tends to be more emphasized when $H_{soft}>H_{stiff}$ and with the increasing of H_{soft}.

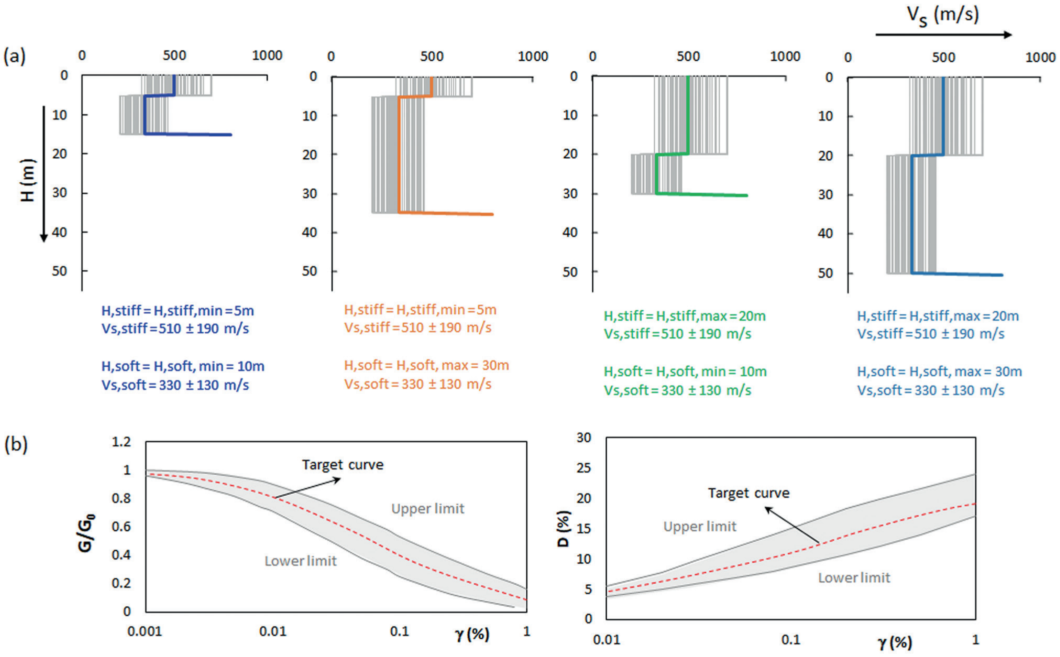

Fig. 1 - (a) Randomized Vs profiles and (b) variability of G/G_0-γ and D-γ curves for fluvial and marine terraced deposits.

This trend highlights the influence of the stiffness contrast due to Vs profile inversion on the 1D seismic behavior of the column. Note that the stiff layer exerts a confining action on the soft layer that exhibits higher level of deformation (see Fig. 2a) with respect to the case of increasing value of V_S with depth; the soft layer thus represents the controlling element of the 1D column in these complex geological conditions through the variation of $V_{s,soft}$ and $H_{soft.}$ Finally, a comparison between the above defined geological settings and the three different PGA classes is proposed in Fig. 3 in terms of spectral acceleration and spectral ratio (i.e. $Sa_{surface}/Sa_{input}$). As expected, in the case of travertine plateau in alluvional plains

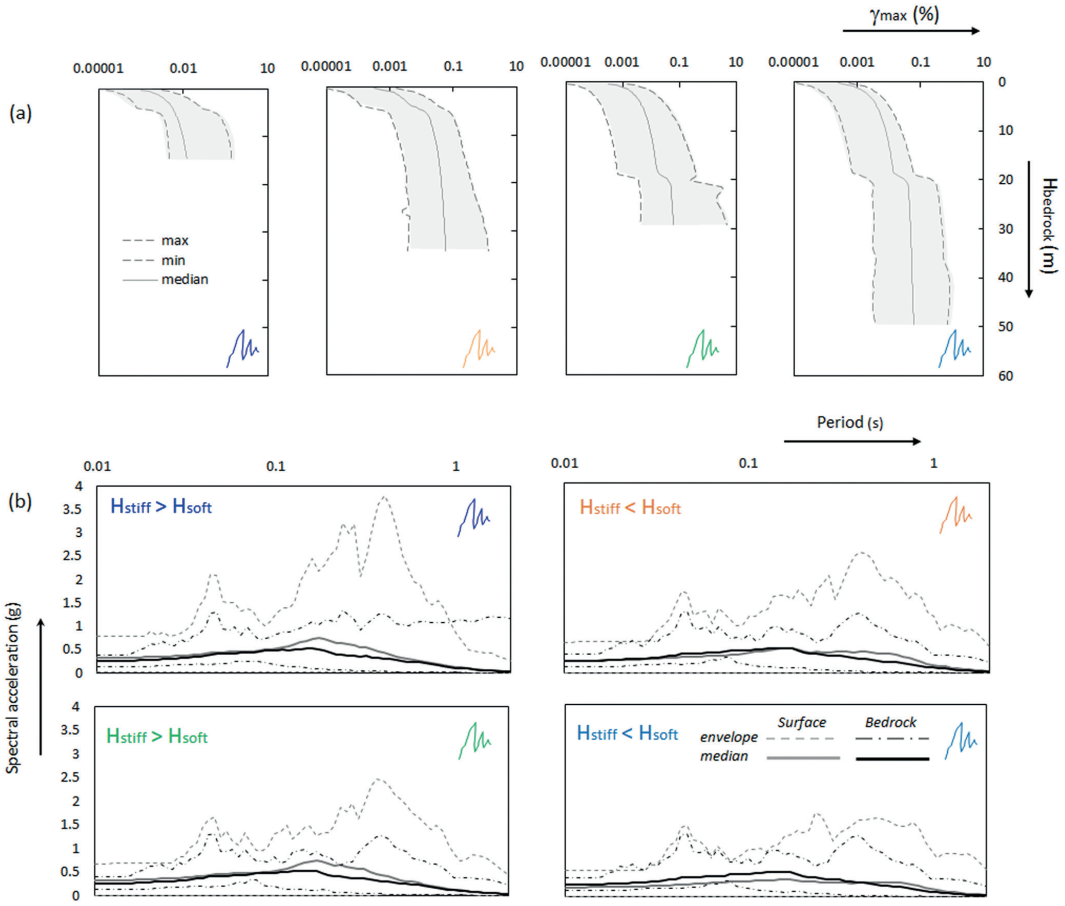

Fig. 2 - Results of Monte Carlo simulations for fluvial and marine terraced deposits in terms of (a) maximum shear strains and (b) acceleration response spectra.

the effect of the Vs profile inversion is more evident respect the case of cliffs and lava rocks and the case of fluvial and marine terraces, respectively, due to the fact that higher values of the contrast of impedence and of H_{soft} are expected in the last case with respect to the first two. Of course, there is also an effect due to the intensity of the input motion that controls the deformation level reached in the soft soil layer. The obtained results can be considered representative of one-dimensional conditions, so any morphological effect can modify the expected behavior.

Conclusions. The most common Italian geological domains exhibiting Vs profile inversions have been identified and studied in terms of geometrical and geotechnical properties. The results of this preliminary study are the input data to carry out a parametric study of 1D site response analyses to investigare the effect of Vs inversions in such conditions. In general, the surface motion response is attenuated with respect to the outcrop. This effect is emphasized with V_s and H of the soft layer increasing, that is the real controlling layer. The increasing of the input motion too increases this effect because of soil nonlinearity. Vs profile inversions are particular and complex geological conditions for which numerical site response analyses are required to better predict the seismic behavior of the colums for design considerations. These conclusions are valid in 1D conditions; in more complex morphological conditions, that can lead also to 2D conditions, the effect of Vs profile inversions can be surpassed by the morphological effects.

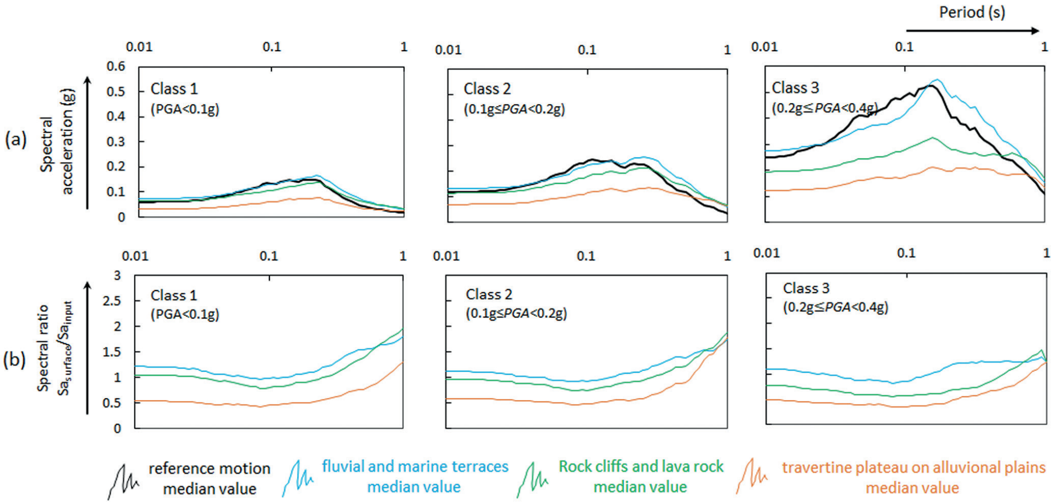

Fig. 3 - Results of Monte Carlo simulations: comparison between fluvial and marine terraces, rock cliffs and lava rock, travertine plateau on alluvional plains for Class 1, Class 2 and Class 3 of PGA in terms of (a) acceleration response spectra and (b) spectral ratio.

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