Stochastic analysis of seismic ground response for the verification of standard simplified approaches

Stochastic analysis of seismic ground response for the verification of standard simplified approaches

M. Aimar, A. Ciancimino & S. Foti
Politecnico di Torino, Torino, Italy

ABSTRACT: Site effects represent a fundamental aspect in the definition of the seismic action. For ordinary design applications, several building codes allow the estimate of the seismic ground response through simplified approaches.

The aim of this study is the assessment of the simplified method proposed in the Final Draft of revision of the Eurocode 8. For this purpose, equivalent linear analyses have been performed on a collection of 1-D ground models, generated from a database of real soil profiles through a stochastic procedure.

Firstly, the study evaluated the inter-class dispersion of the new site categorization system, observing a reduction of the variability. Then, it focused on the reliability of the amplification factors. These values provide a good prediction of the seismic action, when referring to a wide range of vibration periods. However, their adoption gives an underestimation at short periods, whereas the estimate is on the safe side at long periods.

1 INTRODUCTION

In recent years, simplified approaches for the estimate of seismic amplification assumed a widespread use in ordinary applications of civil engineering. The principle consists in reducing the complex problem of ground response analysis into a limited number of coefficients that modify the elastic response spectrum of horizontal pseudo-acceleration in shape and amplitude. This approach has been introduced by Borcherdt (1994) and implemented in a large number of building codes (e.g. CEN 2004, FEMA 2015, MIT 2018). Actually, several studies demonstrated the limitations of the proposed approaches, mainly due to the simplified description of the geological layout (e.g. Lee & Trifunac 2010), entailing the loss of reliability of the estimate (e.g. Pitilakis et al. 2013, Ciancimino et al. 2018).

This contribution introduces a tool for the assessment of the reliability of the simplified approaches for the estimate of seismic amplification, based on numerical simulations. In particular, the paper reports the construction of a stochastic database of ground response, generated from the results of numerical analyses with different ground conditions and seismicity levels of engineering interest. The results are compared with the predictions implemented according to the Final Draft of Revision of the EN1998-1 (CEN 2018), henceforth mentioned as “EC8-1 Draft”, aiming at assessing the effectiveness of the simplified approach, focusing on the inter-category dispersion and on the reliability of the amplification coefficients.

2 THE FINAL DRAFT OF REVISION OF THE EUROCODE 8

The EC8-1 Draft introduces specific criteria for the application of the simplified approach for the estimate of site effects.

Firstly, the standard site categorization system is based on the equivalent shear-wave velocity $v_{S,H}$ and the bedrock depth H_{800}. $v_{S,H}$ is equal to the well-known parameter $v_{S,30}$, i.e. the time-averaged shear-wave velocity of the soil column down to 30 m depth, except when bedrock depth is less than 30 m. In this case, its computation is limited down to the bedrock interface. Considering these parameters, the description of the subsoil conditions refers to 6 site categories (A, B, C, D, E and F), covering a wide range of $v_{S,H}$ and H_{800} of engineering interest (Figure 1).

The effect of seismic amplification due to the stratigraphy is an alteration of the 5%-damped elastic response spectrum of horizontal pseudo-acceleration, through two amplification coefficients. On one side, a short period site amplification factor F_α is applied to the maximum spectral acceleration $S_{\alpha,RP}$, where RP is the return period (equal to 475 years for ordinary constructions). On the other side, an intermediate period one F_β is applied to the spectral ordinate $S_{\beta,RP}$ at vibration period equal to 1 s. The EC8-1 Draft prescribes a continuous formulation (CF) for the estimate of each amplification coefficient, as function of $v_{S,H}$, H_{800} and the correspondent spectral ordinate evaluated on outcropping flat rock-like formation. Figure 1 shows an example of application of the proposed formulation. Moreover, in absence of detailed information about seismic and/or geologic conditions, the code prescribes the use of prudential default values (DV), depending only on the site category.

3 METHODOLOGY

The stochastic database of ground response analyses is a collection of the results of 3,202,500 numerical simulations performed over a set of 91,500 1-D ground models, representative of different stratigraphic conditions. The analyses refer to the Equivalent-Linear (EQL) approach (Idriss et al. 1968), whose choice derives from its numerical stability and low computational cost. Computations have been performed with the SHAKE91 code (Sun et al. 1992). The seismic action consists of a suite of accelerograms covering a wide range of seismicity in the Italian territory.

A description of the generation of the ground models, the selection of the seismic inputs and the procedure of interpretation of the results is presented in the following sections. Further details are available in Aimar et al. (2019).

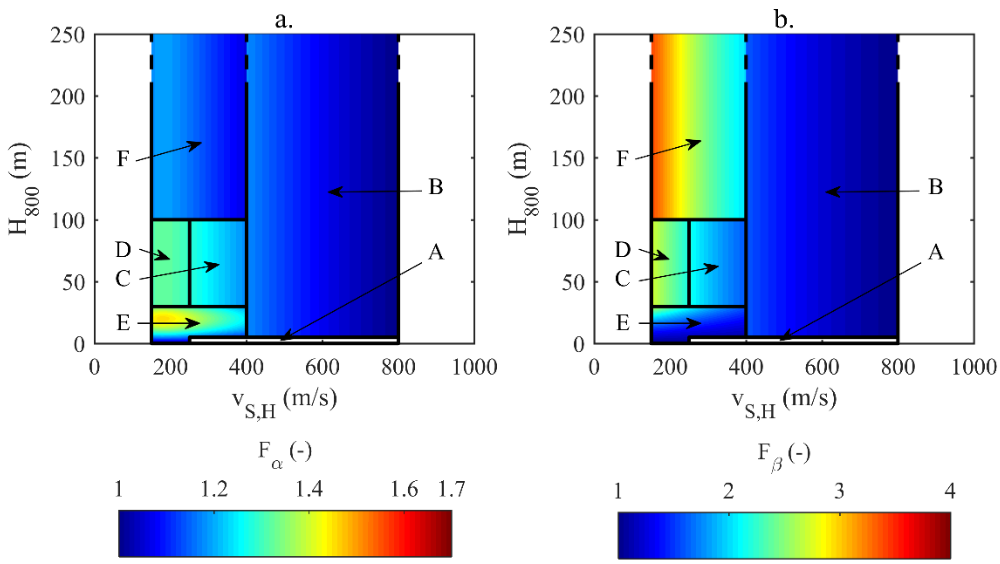

Figure 1. Standard site categorization with distribution of short period amplification factor (a) and intermediate period amplification factor (b) as function of $v_{S,H}$ and H_{800}, for $S_{\alpha,RP}$ = 4 m/s^2 and $S_{\beta,RP}$ = 0.16 m/s^2.

3.1 *Generation of the ground models*

The ground models have been generated from a collection of 252 real soil deposit models (Figure 2a), extracted from accredited databases and integrated with geological and shear-wave velocity (v_S) information. A Monte Carlo procedure has been used for the generation of the v_S profiles. The adopted procedure firstly randomizes the layering, assuming the Poisson distribution and deriving the statistical parameters from the real deposits (Teague et al. 2016). As for v_S values, the approach does not directly randomize velocities but it generates a distribution of travel times and then it derives velocities (Passeri et al. 2018, Passeri 2019), referring to the Toro model (Toro 1995) for the statistical properties. This solution allows the definition of a more realistic and physical model.

In order to guarantee a homogeneous distribution of the models with respect to the site categories, a check of the characteristics of the distribution is performed. The check verifies that each site category includes the same number of generated v_S profiles and whether they are regularly distributed inside the domain. Each site category is divided into 100 blocks and 200 models per block are included for site categories C, D, E and F. In site category B, 200 models are selected when $v_{S,H}$ and H_{800} are small and to 20 when they are both large. The last condition, indeed, collects models representative of deep soil models with stiff surficial layers, whose rarity induces to assign them less weight in the models' population. Figure 2b summarizes the introduced restraints, showing that the reference domain is limited to the $v_{S,H}$ range from 150 m/s to 800 m/s and the H_{800} range up to 200 m, i.e. the typical ranges of practical interest.

The resulting distribution is a population of 91,500 v_S profiles, which are realistically representative of different soil conditions and different site categories in the same measure.

The generation of the ground models requires the introduction of other geotechnical properties that, together with v_S, affect the dynamic soil behavior: the modulus reduction and damping curves, the plasticity index, the over-consolidation ratio, the at-rest lateral pressure coefficient, the groundwater depth and the unit weight. The computation of some parameters requires the preliminary definition of the material type, starting from the stratigraphic information of the real profiles (when available) or from the soil index derived from the generated v_S profile (Ohta et al. 1978).

The estimate of the modulus reduction and damping curves refers to literature formulations: Darendeli model (Darendeli 2001) for clays and sands; Rollins model (Rollins et al. 1998) for gravels; Idriss model (Sun & Idriss 1992) for weathered rocks. As far as the remaining parameters are concerned, their evaluation follows the procedure adopted in Ciancimino et al. (2018) and Pettiti et al. (2013).

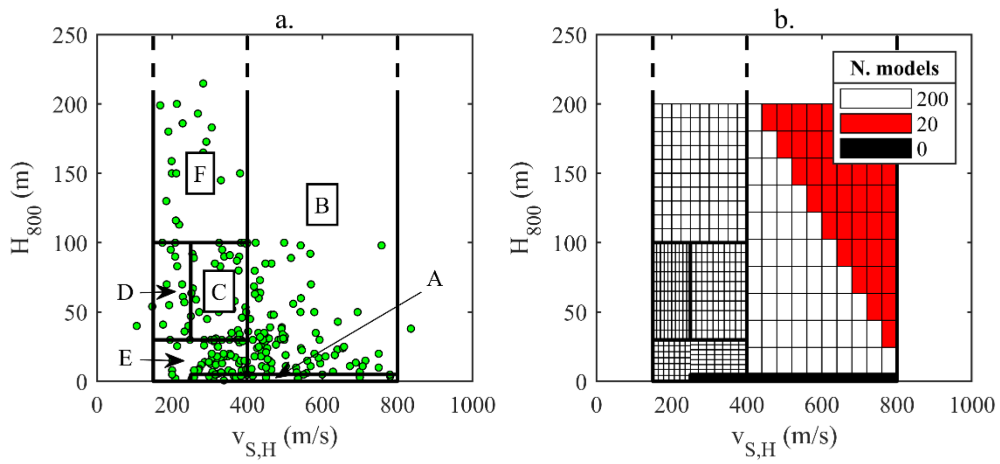

Figure 2. Distribution of the real soil deposits (a) and scheme of resampling (b) in the $v_{S,H}$-H_{800} domain.

3.2 *Selection of the seismic inputs*

The seismic action is composed by a collection of acceleration time histories, which cover a broad range of seismological features in the Italian territory. The selected time histories derive from accredited accelerometric databases.

Due to the site-specific formulation of the amplification coefficients, the selection took place with reference to 5 locations characterized by different levels of seismic intensity, expressed by a_g (i.e. expected peak ground acceleration), $S_{\alpha,475}$ and $S_{\beta,475}$ (Table 1, Figure 3). This solution ensures the representativeness of typical features of the seismicity in Italy (Andreotti et al. 2013). For each reference site, seven acceleration time histories have been selected in compliance with the seismological compatibility criterion, i.e. the magnitude, the epicentral distance and the source mechanism should be consistent with the site-specific ones (Stewart et al. 2014). Information about seismological parameters for each location derives from the results of a specific probabilistic seismic hazard analysis conducted in Italy (Spallarossa et al. 2007).

Table 1. Geographical position and seismic hazard parameters of the reference sites.

Site	Latitude	Longitude	a_g (m/s^2)	$S_{\alpha,475}$ (m/s^2)	$S_{\beta,475}$ (m/s^2)
Termeno sulla Strada del Vino	46°.36 N	11°.24 E	0.540	1.35	0.47
Godrano	37°.83 N	13°.42 E	1.159	2.79	0.91
Urbino	43°.68 N	12°.59 E	1.739	4.11	1.36
San Severo	41°.72 N	15°.43 E	2.073	4.91	1.6
Atina	41°.63 N	13°.75 E	2.545	5.74	1.99

The selected input motions have also checked for spectral compatibility, verifying the coherence of the average spectrum with the site-specific hazard, by using the software Inspector (Acunzo et al. 2014). The criteria are the ones introduced in the EC8-1 Draft, with restraints either on the average spectrum – it should fall within a range around the target spectrum – or on the single input spectra – they should not be too weak with respect to the target spectrum. The fulfilment of these criteria required the linear scaling of the time histories, according to a factor ranging from 0.5 to 2.

The numerical analyses have been performed for each input motion and then averaged, obtaining a distribution of ground motion amplification for each reference site.

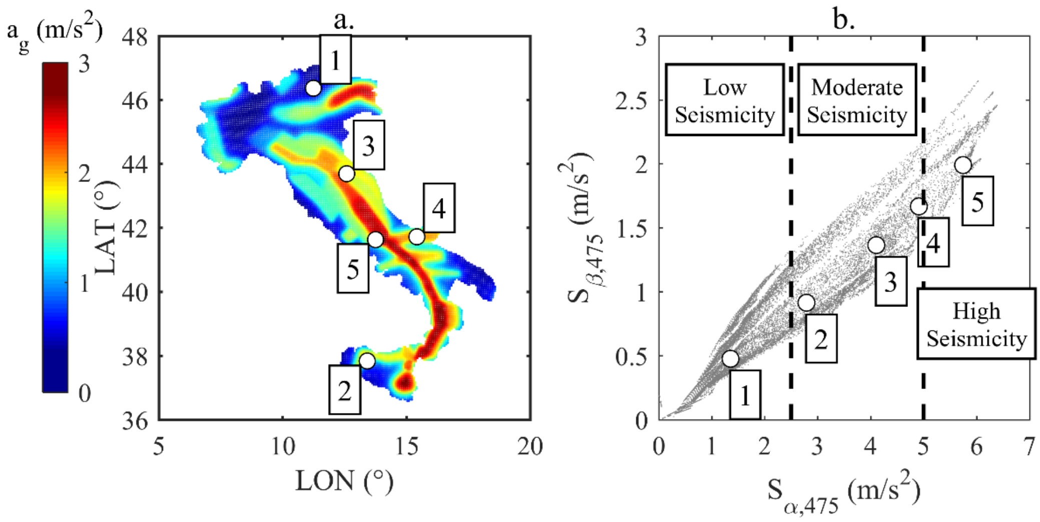

Figure 3. Position of the reference sites in the Italian territory, colored according to different a_g levels (a), and in the distribution of the hazard parameters (b).

4 DEFINITION OF THE AMPLIFICATION PARAMETERS

The interpretation of the results required the definition of a synthetic parameter able to describe the amplification of the seismic action. Since the code describes the seismic action through an elastic response spectrum, the representation of the seismic amplification should refer to a spectral quantity, i.e. spectral amplification factors *SA*, defined as ratio between the spectral intensity I_s measured on the surface and the input one I_i:

$$SA = \frac{I_S}{I_i} \tag{1}$$

Spectral intensities I_s, I_i are integral quantities of the elastic response spectrum *PSA*, evaluated as follows within a given band of vibration periods ranging from T_1 to T_2:

$$I_j = \int_{T_1}^{T_2} PSA(T)\, dT \qquad\qquad j = s,i \tag{2}$$

The bands, ranging from 0.1 s to 0.5 s and from 0.7 s to 1.1 s, define respectively a short period spectral amplification factor *SSA* and a long period spectral amplification factor *LSA* (Centro per la Microzonazione Sismica e le sue applicazioni 2017). The range from 0.05 s to 2.5 s provides the global spectral amplification factor *GSA*. This parameter has been introduced by Rey et al. (2002), as proxy for the averaged variations of the response spectrum at different vibration periods of engineering interest.

5 RESULTS

5.1 *Variability of the results*

A first assessment of the effectiveness of the proposed site categorization system is obtained with the evaluation of the dispersion degree of amplification within each class. The assessment of the variability has been evaluated on *GSA*, by computing the correspondent coefficient of variation *CV*, i.e. the ratio between the standard deviation and the mean of the data. The computation assumes lognormal distribution of the numerical results.

The variability is compared with the one obtained according to the categorization system defined in the current version of the EC8-1, for two reference sites, representative of a small and high level of seismicity (Figure 4). In particular, the computation of the *CV* for the EC8-1 Draft accounts for the dependence of the amplification coefficients from $v_{S,H}$ and H_{800}. Regardless the entity of the seismic action, the new approach allows a significant reduction of variability either in deformable soil models – thanks to the introduction of the new site category F – or in less deformable ones – thanks to the continuous formulation with respect to $v_{S,H}$ synthesizing the effect of impedance ratio.

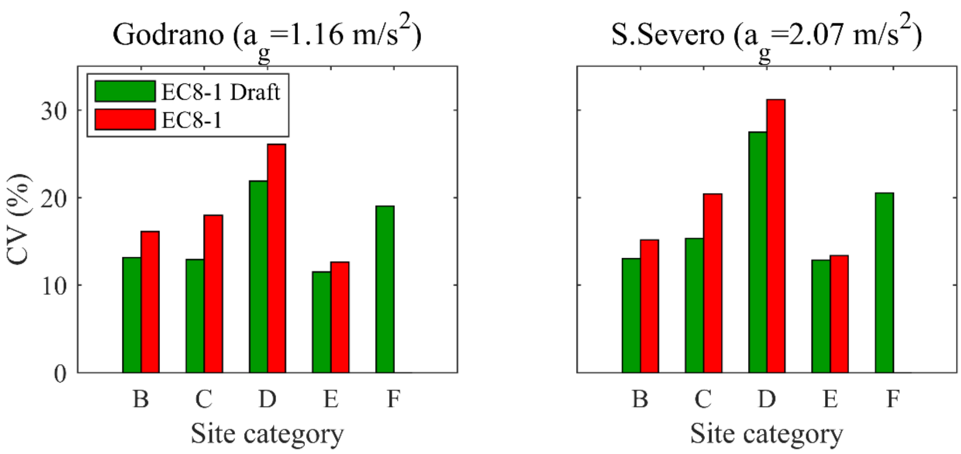

Figure 4. Comparison of the variability between EC8-1 and EC8-1 Draft with reference to two sites.

5.2 *Reliability of the proposed amplification coefficients*

The reliability of the proposed amplification coefficients is evaluated comparing the amplification from the ground response database and the predicted value according to the code prescriptions. A synthetic way to perform this operation is the comparison of the distribution of the stochastic database within each site category – represented by the interval defined by one standard deviation – and the correspondent prescribed value. This solution is of immediate application for the assessment of the DV of the amplification coefficients. As regards the CF, the predicted value corresponds to the average one within each site category. This approach provides an overlook about the global result in each site category in an immediate way, even if a more detailed analysis should refer to the residuals, i.e. the difference between the logarithm of the numerical and the predicted value.

As shown in Figure 5a, d, the CF provides an estimate of the stratigraphic amplification at short vibration periods lying in the lower portion of the distribution of numerical results, especially in rigid soil deposits under small seismic action. Actually, the estimate is safer in deformable soil models subjected to high seismic action, especially when referring to the DV. Conversely, the estimate of *LSA* (Figure 5b, e) is close to the mean value in site categories B and C, whereas the prediction is on the safe side in the more deformable ones. In particular, the estimate according to the DV is larger than the results of the numerical simulations.

As regards *GSA* (Figure 5c, f), the estimate according to the CF is quite on the safe side in deformable site categories, whereas the prediction lies within the mean and the lower bound of the distribution in rigid soil deposits. For increasing seismicity, the degree of safety of the estimate increases. On the other side, the DV provides an estimate close to the mean value of the distribution of results in rigid soil models, whereas it is on the safe side in deformable site categories.

Actually, this representation of the results does not fully account for the variability in the stochastic database, since it performs a comparison in averaged terms. A direct superposition of the distribution of the numerical results and the predicted value would allow a more refined evaluation of the reliability of the code prescriptions. Focusing on *GSA*, the distribution with respect to the models – represented in Figure 6 in terms of $v_{S,H}$ for the Urbino site – assumes a large degree of variability, since the parameters ranges within a broad interval of values. The scattering derives from the presence of family of soil deposits with different features in each site category, ranging from deep deposits with large impedance contrasts (Figure 6.1) to shallow ones with gradual increase of stiffness with depth (Figure 6.2). Different characteristics entail different behavior in dynamic conditions, resulting in large variability in the overall response. The effect of the high variability is a loss of the reliability of the prescribed amplification coefficients, due to the presence of situations for which the estimate is on the safe side and ones for which the estimate is not prudential.

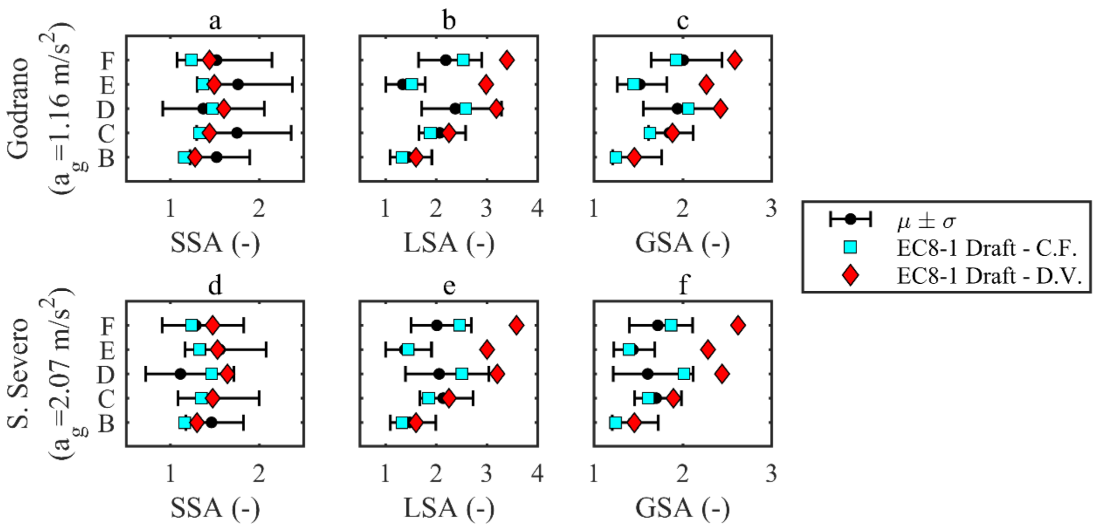

Figure 5. Comparison of the predicted values of SSA (a,d), LSA (b,e) and GSA (c,f) versus the ones from the numerical analyses.

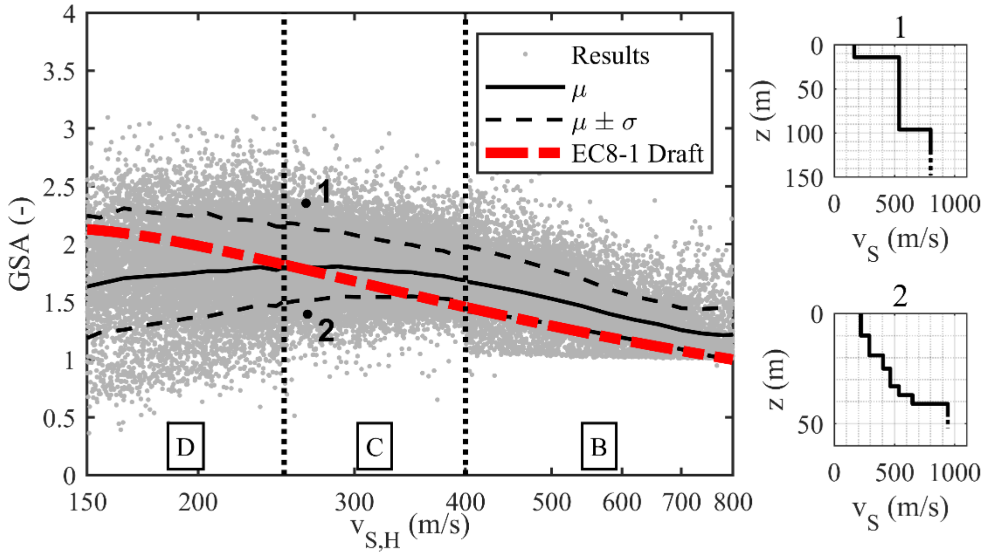

Figure 6. Distribution of GSA results for site categories B, C and D in Urbino site (ag = 1.739 m/s2).

6 CONCLUSIONS

The Final Draft of Revision of the EN1998-1 introduces new prescriptions for the simplified approach for the estimate of the seismic amplification, aiming to overcome the limitations of the methodologies of current practice. In order to assess its reliability, a stochastic ground response database has been constructed, obtaining a distribution of seismic response of soil deposits under different stratigraphic and seismological conditions.

The comparison between the predicted and the numerical ground motion amplification has been performed with reference to integral spectral amplification factors, describing the modifications in shape and amplitude of the elastic response spectrum in different ranges of vibration periods. The new site classification method allows for the reduction of the degree of variability with respect to the current version. This can be attributed to the adoption of the site parameter $v_{S,H}$ and to the introduction of the site category F, which separates the deformable soil models according to the bedrock depth. The proposed continuous formulation results in a moderate underestimation of the numerical results at short vibration periods, whereas the estimate is quite on the safe side for intermediate ones. Focusing on a wide range of vibration periods, there is a slight underestimation of the seismic amplification with respect to the numerical results in less deformable soil models, whereas the predicted value is larger than the results in the remaining cases. The default value, instead, provides an estimate on the safe side, especially in the case of deformable soil models under strong seismic actions. Actually, the large degree of inter-category dispersion highlights one problem of the simplified approaches, i.e. the clustering of large families of soil models representing deposits with different behavior in dynamic conditions, with negative effects on the reliability of the approach. The new approach represents an improvement of the quality of the simplified approach, but further studies are required to overcome these limitations. However, it should be noted that, in general terms, these approaches are not necessarily conservative. Therefore, rigorous ground response analyses should always be preferred for critical structures.

As regards the stochastic database, in the future it will incorporate nonlinear analyses to increase its reliability, especially in deformable soil models under strong seismic actions.

ACKNOWLEDGEMENTS

Special thanks go to Federico Passeri (Politecnico di Torino), for letting us use his procedure of generation of soil profiles. The study has been partially supported by the ReLUIS 3 project, funded by the Italian Civil Protection Agency.

REFERENCES

Acunzo, G., Pagliaroli, A. & Scasserra, G. In-spector: un software di supporto alla selezione di accelerogrammi naturali spettro-compatibili per analisi geotecniche e strutturali. *Proceedings of 33rd conference of GNGTS, 2014 Bologna*. Gruppo Nazionale di Geofisica della Terra Solida. (*in Italian*)

Aimar, M., Ciancimino, A. & Foti, S. 2019. An assessment of the NTC18 simplified procedure for stratigraphic seismic site amplification prediction. *Rivista Italiana di Geotecnica*. (*Submitted*)

Andreotti, G., Lai, C. G., Bozzoni, F. & Scandella, L. New soil factors for the Italian Building Code (NTC08) derived from 1D fully stochastic ground response analyses. *XV Convegno ANIDIS, 2013 Padova*. Associazione Nazionale Italiana di Ingegneria Sismica.

Borcherdt, R. D. 1994. Estimates of Site-Dependent Response Spectra for Design (Methodology and Justification). *Earthquake Spectra*, 10, 4: 617-653.

Centro per la Microzonazione Sismica e le sue applicazioni 2017. *Protocolli di acquisizione dati ed elaborazione relativi alle attività di Microzonazione di Livello III nei 140 Comuni di cui all'Ordinanza n.24 del 12 maggio 2017 della Presidenza del Consiglio dei Ministri*.

Ciancimino, A., Foti, S. & Lanzo, G. 2018. Stochastic analysis of seismic ground response for site classification methods verification. *Soil Dynamics and Earthquake Engineering*, 111: 169-183.

Comité Européen de Normalisation (CEN) 2004. *Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings*.Brussels.

Comité Européen de Normalisation (CEN) 2018. *Final Document EN1998-1 NEN SC8 PT1*.Brussels.

Darendeli, M. B. 2001. *Development of a new family of normalized modulus reduction and material damping curves.* Doctoral Dissertation, University of Texas at Austin.

FEMA 2015. *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures*.

Idriss, I. M. & Seed, H. B. 1968. Seismic response of horizontal soil layers. *Journal of the Soil Mechanics and Foundations Division*, 94: 1003-1031.

Lee, V. W. & Trifunac, M. D. 2010. Should average shear-wave velocity in the top 30m of soil be used to describe seismic amplification? *Soil Dynamics and Earthquake Engineering*, 30, 11: 1250-1258.

Ministero delle Infrastrutture e dei Trasporti (MIT) 2018. *DM 17/01/2018 - Aggiornamento delle "Norme Tecniche per le Costruzioni"*.

Ohta, Y. & Goto, N. 1978. Empirical shear wave velocity equations in terms of characteristic soil indexes. *Earthquake Engineering & Structural Dynamics*, 6, 2: 167-187.

Passeri, F. 2019. *Development of advanced geostatistical models of shear wave velocity profiles to account for uncertainties and variabilities in Ground Response Analyses.* Doctoral dissertation, Politecnico di Torino.

Passeri, F., Aimar, M. & Foti, S. Modelli geostatistici per la valutazione delle incertezze e delle variabilità nei profili di Vs. *Incontro Annuale dei Ricercatori di Geotecnica, 2018 Genova*. Associazione Geotecnica Italiana. (*in Italian*)

Pettiti, A. & Foti, S. Valutazione stocastica dell'influenza dei parametri del terreno nella risposta sismica locale. *Incontro Annuale dei Ricercatori di Geotecnica, 2013 Perugia*. Associazione Geotecnica Italiana. (*in Italian*)

Pitilakis, K., Riga, E. & Anastasiadis, A. 2013. New code site classification, amplification factors and normalized response spectra based on a worldwide ground-motion database. *Bulletin of Earthquake Engineering*, 11: 925-966.

Rey, J., Faccioli, E. & Bommer, J. J. 2002. Derivation of design soil coefficients (S) and response spectral shapes for Eurocode 8 using the European Strong-Motion Database. *Journal of Seismology*, 6, 4: 547-555.

Rollins, K. M., Evans, M. D., Diehl, N. B. & Daily III, W. D. 1998. Shear modulus and damping relationships for gravels. *Journal of Geotechnical and Geoenvironmental Engineering*, 124, 5: 396-405.

Spallarossa, D. & Barani, S. 2007. *Disaggregazione della pericolosità sismica in termini di M-R-e*. (*in Italian*)

Stewart, J. P., Afshari, K. & Hashash, Y. M. A. 2014. *Guidelines for performing hazard-consistent one-dimensional ground response analysis for ground motion prediction*, Berkeley.

Sun, J. & Idriss, I. M. 1992. *User's manual for SHAKE91: a computer program for conducting equivalent linear seismic response analyses of horizontally layered soil deposits*, Davis, California.

Teague, D. P. & Cox, B. R. 2016. Site response implications associated with using non-unique Vs profiles from surface wave inversion in comparison with other commonly used methods of accounting for Vs uncertainty. *Soil Dynamics and Earthquake Engineering*, 91: 87-103.

Toro, G. R. 1995. *Probabilistic models of site velocity profiles for generic and site-specific ground-motion amplification studies*, Upton, New York.