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An application of Stochastic Site Response Analysis

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ABSTRACT
This work deepens the seismic aspects of the geotechnical design of the "Pedemontana Piemontese" highway, sited in Piedmont Region, Northwest of Italy, across the Sesia River, and characterized by 12 viaducts on pile foundations. The down-hole tests carried out have often shown inversions in the diagram of the shear waves velocity with depth; therefore, specific Seismic Local Response (SLR) analyses in order to define the seismic design input, have been performed. The selection of spectrocompatible accelerograms to the rigid seismic substrate has been preliminarily carried out by selecting in the European strong motion database accelerograms characterized by magnitude and epicentral distance that are more likely to determine the same PGA value as that proposed by the Italian Building Code for the named site considering a specific limit state. In the damping soil model adopted (Darendeli 2001), the damping curve depends on five parameters, two of which are significantly influential: overburden pressure and plasticity index. Site conditions are instead expressed through: shear waves velocity; thickness of the seismostrats and depth of the bedrock. Ranges of variability were taken into account in order to study the uncertainty due to the determination of the above quantities. From the combinations caused by the variation of them within the variability ranges, it was possible to obtain a set of statistically plausible results of the seismic input, significantly more precise than the one obtained in the case of deterministic SLR analysis.

1 INTRODUCTION

Seismic amplification of ground motion at the surface is affected by the geotechnical characteristics of the soil formations below the ground surface.

Peculiarly, the definition of a one-dimensional soil profile, requires an identification of layers, to which a single value of a certain number of geotechnical parameters is associated.

Despite of a deterministic analysis of seismic response allows to define the time history of acceleration (or velocity, displacement) at the surface, it cannot undo the uncertainty of design earthquake, due to the changeability of geotechnical parameters. Furthermore the parameters' combinations, may cause a very strong seismic amplification.

In order to take this effect into account, stochastic site response analysis is necessary for evaluating the sensitivity of the surface ground motion to the uncertainty of geotechnical parameters and reference seismic input.

The uncertainty associated to the model can be difficult to estimate, since this is affected by poor informations and aleatory uncertainty. In fact, both physical properties and geotechnical parameters can spatially change increasing the model's uncertainty. Usually, a soil layer is thought as homogeneous from both lithological and geotechnical aspects. On the contrary **Vs** shear wave velocity can change in each direction (vertical or/and horizontal), i.e., it would question the hypothesis of layer's homogeneity. Likewise for the thickness of each layer which can change in the horizontal direction (lateral inhomogeneity).

Furthermore, shallow geophysical investigations (commonly used in design practice in tandem with literature research) cannot estimate with enough degree of precision the outcropping bedrock depth, producing another uncertainty source.

Therefore, the deterministic site response analysis is not effective and a stochastic one is more reasonable, although more elaborate.

A stochastic approach to 1-D amplification analysis was proposed by Faccioli (1976), using a random vibration method for estimating seismic amplification of horizontal soil deposits, featured by an hysteretic soil model. Afterwards, several studies have been focused on site property uncertainty, mostly in 1D conditions, with a statistical analysis of the Monte Carlo type (Andrade and Borja 2006). Despite most of the authors considered the sources of uncertainty in a partial configuration, Rota et al. (2011) proposed a fully probabilistic procedures able to study all the effects on seismic amplification: stratigraphy, Vs distribution, non-linear properties, and input motion. Castellaro and Mulargia (2014) studied the site effect by modelling the subsoil as an oscillator coupled to another oscillator representing the construction, in order to show that the main effect on site response is driven only by: average shear wave velocity of the cover layer; resonance frequency and impedance contrast between the cover and the bedrock. Foti et al. (2019) studied the impact of uncertainties and variabilities on the computed seismic hazard, suggesting a systematic and rigorous analysis of epistemic uncertainties and aleatory variabilities relaying on large databases of experimental data.

In design practice, stochastic site response analysis is compulsory only for nuclear power plant (U.S. Nuclear Regulatory commission 2007; Nori and Di Marcantonio, 2014) even though it has many advantages when it is used for transportation structures as seaport (Rota et al. 2011) or highways (present study). Stochastic site response analysis can be properly useful when structures are founded on piles, due to cyclic skin friction degradation (Mangiola 2005; Mortara et al. 2007).

The probabilistic procedure for estimating site amplification of ground motion applied at the site of Pedemontana Piemontese Highway (located in Eastern Piedmont, North-western Italy) is proposed. The chosen methodology takes three main uncertainty sources into account:

1. Depth of outcropping bedrock;
2. Shear wave velocity profile in layer thickness;
3. Constitutive soil model;

2 SELECTION OF SPECTRUM-COMPATIBLE REAL RECORDS

2.1 *Selection's procedure*

An automatically computer aided procedure has been used for the selection of spectrum-compatible records, by using REXEL code (Iervolino et al. 2010). The followed procedure is reported below:

1. definition of the design (reference) horizontal spectra according to National Italian Building Code 2008 (NIBC2008) on the outcropping rock, with the specs reported in Table 1 (a_g = 0.045g for each of them) and the others herein listed:
   - Site Class (EC8): A;
   - Nominal Life: 50 Years;
   - Functional Type: IV;
   - Limit State: Limit state for the safeguard of human life or Ultimate state (USL).

Table 1: Topographic Coordinates identifying each area along the alignment where the procedure has been carried out.

ZONE	Longitude	Latitude
Sesia	8° 23' 38.92" E	45° 35' 36.12" N
Rolino	8° 15' 6.99" E	45° 33' 30.05" N
Marchiazza	8° 19' 39.64" E	45° 35' 54.79" N
Torbola	8° 17' 53.69" E	45° 35' 17.23" N

2. list and plot of the records contained in the European Strong Motion Database (ESD, http:// www.isesd.cv.ic.ac.uk/ Ambraseys et al. 2000, 2004) and embedded in REXEL, comprised into the magnitude and distance ranges specified for the specific site class. NIBC (CS.LL.PP. 2008) links the seismic actions in structural (and geotechnical) design directly to the probabilistic seismic hazard analysis, carried out by the Istituto Nazionale di Geofisica e Vulcanologia (INGV). The probabilistic seismic hazard for each node of a regular grid having 5 km spacing, extended to the whole national territory, has been evaluated. Hazard curves in terms of PGA (Peak Ground Acceleration) and spectral acceleration, for ten different periods from 0.1 to 2 sec, have been computed, and all results can be accessed at http://esse1-gis.mi.ingv.it (see also Montaldo et al. 2007). In the present study, disaggregation of the results of this hazard study for PGA has provided a set of possible events, for the 949 years return period, with the following array: values of magnitude between 4.5 and 6.5; values of epicentral distance between 70 and 120 km, for each area of interest.

3. [0.15-2 sec] is the period range where the average spectrum of the set has to be compatible with the reference spectrum, 10% (lower limit) and 30% (upper limit) have been set as specification of tolerances in compatibility;

4. the search for combinations of seven records, including one component of motion, that, on average, match the design spectrum with parameters specified in step 3.

About the adopted criteria: in the selection, accelerograms recorded on outcropping rock are considered A-category only (EC8), to avoid the influence of possible seismic amplification effects; furthermore, a tolerance on the seismological parameters of magnitude and epicentral distance, which are considered appropriate for the site of interest, has been applied.

From Figure 1 to Figure 4 the records' distribution available in the ESD databases satisfying the constraints of magnitude and epicentral distance chosen, for each area of interest, are shown; from Table 2 to Table 5 the main seismological characteristics of the seven spectrum-compatible real records, for each area, selected for a return period of 949 years, are reported. The correspondence between figures and tables means: earthquake in first line of each table is represented in the diagram at the top of the left column; earthquake in last line of each table is represented in the diagram at the bottom of the right column. With regard to Marchiazza and Torbola area, note that the same earthquakes matched the target spectrum, but with different scale factor.

Figure 5 shows the response spectra and its comparison with the average spectrum, for Sesia area: as shown, different accelerograms provide a contribution in the spectrum at different period ranges.

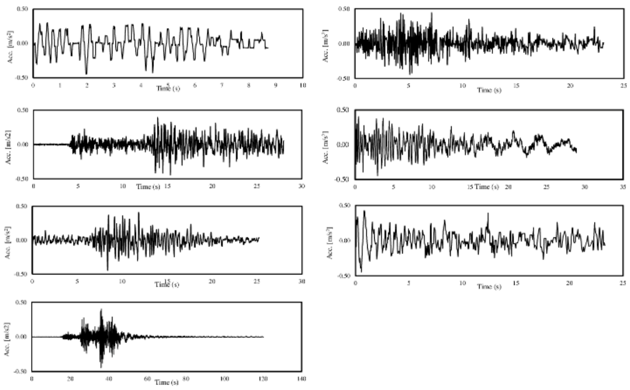

Figure 1: Acceleration time histories of the seven selected real records, compatible with the NIBC2018 code spectrum at the site of Pedemontana Piemontese, Sesia area, for the 949 years return period.

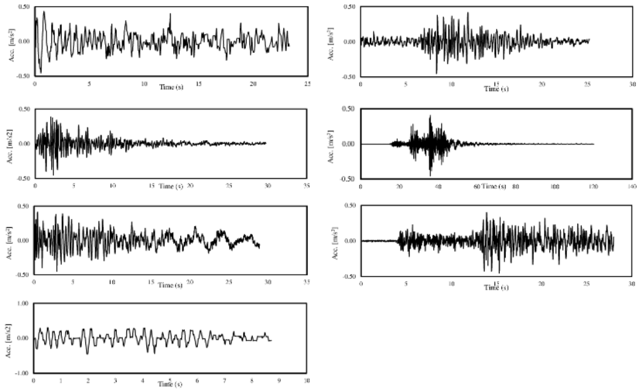

Figure 2: Acceleration time histories of the seven selected real records, compatible with the NIBC2018 code spectrum at the site of Pedemontana Piemontese, Rolino Area, for the 949 years return period.

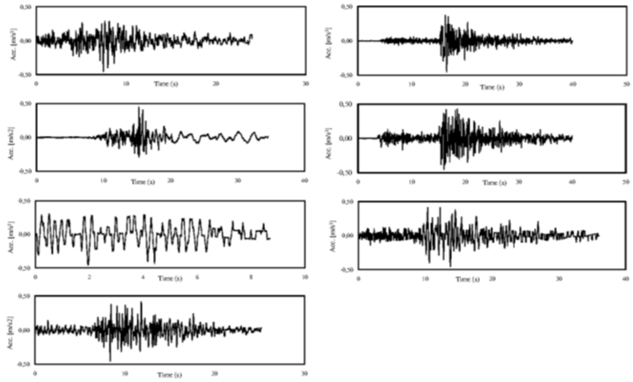

Figure 3: Acceleration time histories of the seven selected real records, compatible with the NIBC2018 code spectrum at the site of Pedemontana Piemontese, Marchiazza Area, for the 949 years return period.

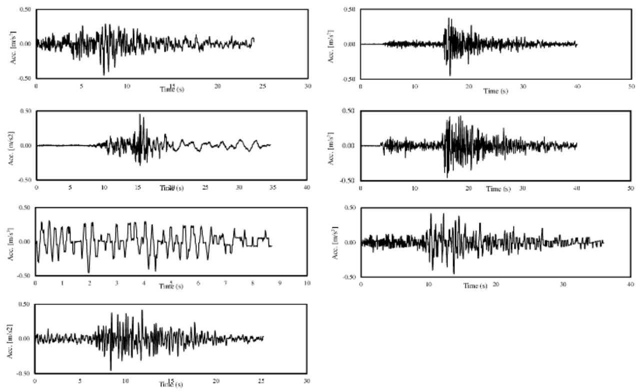

Figure 4: Acceleration time histories of the seven selected real records, compatible with the NIBC2018 code spectrum at the site of Pedemontana Piemontese, Torbola Area, for the 949 years return period.

Table 2: Seismological characteristics of the records selected for this Sesia area, for the 949 years return period.

#	Record set	Date	Mw	Epicentral Distance [km]
1	Griva	21.12.1990	6.1	88
2	Izmit (after shock)	31.08.1999	5.1	73
3	Aigion	15.06.1995	6.5	71
4	South Iceland	17.06.2000	6.5	78
5	Friuli	06.05.1976	6.5	108
6	Umbria Marche	26.09.1997	6.0	100

#	Record set	Date	Mw	Epicentral Distance [km]
7	Friuli	06.05.1976	6.5	91

Table 3: Seismological characteristics of the records selected for Rolino area, for the 949 years return period.

#	Record set	Date	Mw	Epicentral Distance [km]
1	Izmit (aftershock)	31/08/1999	5.10	73
2	Griva	21/12/1990	6.10	88
3	Aigion	15/06/1995	6.50	71
4	South Iceland	17/06/2000	6.50	78
5	Umbria Marche	26/09/1997	6.00	100
6	Umbria Marche	26/09/1997	6.00	79
7	Friuli	06/05/1976	6.50	91

Table 4: Seismological characteristics of the records selected for Marchiazza area, for the 949 years return period.

#	Record set	Date	Mw	Epicentral Distance [km]
1	Kalamata	13/10/1997	6.4	61
2	South Iceland	17/06/2000	6.5	65
3	Griva	21/12/1990	6.1	88
4	Aigion	15/06/1995	6.5	71
5	Izmit (aftershock)	13/09/1999	5.8	97
6	Izmit (aftershock)	13/09/1999	5.8	97
7	Kozani	13/05/1995	6.5	60

Table 5: Seismological characteristics of the records selected for Torbola area, for the 949 years return period.

#	Record set	Date	Mw	Epicentral Distance [km]
1	Kalamata	13/10/1997	6.4	61
2	South Iceland	17/06/2000	6.5	65
3	Griva	21/12/1990	6.1	88
4	Aigion	15/06/1995	6.5	71
5	Izmit (aftershock)	13/09/1999	5.8	97
6	Izmit (aftershock)	13/09/1999	5.8	97
7	Kozani	13/05/1995	6.5	60

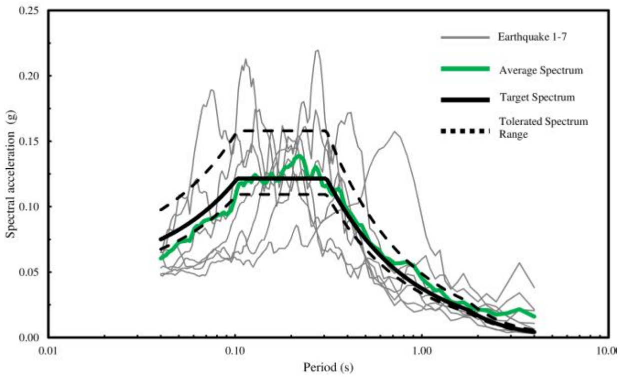

Figure 5: Acceleration response spectra of the seven selected real accelerograms for Sesia Area, scaled to a PGA 0.045g (949 years return period) and comparison with their mean response spectrum, structural damping 5%.

2.2 *Site description and geotechnical characterisation*

The region crossed by the alignment includes, starting from E towards W, the municipalities of Romagnano Sesia (VC), Ghemme (NO), Gattinara (VC), Lozzolo (VC), Roasio (BI), Brusnengo (BI), and Masserano (BI), passing through Vercelli, Novara, and Biella districts. The entire alignment, 15 km long, is showed in Figure 6.

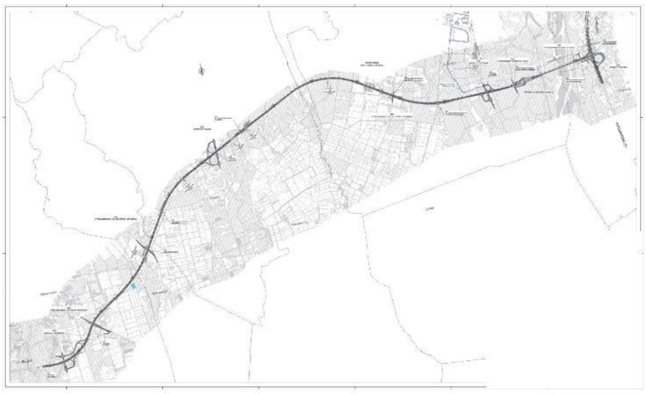

Figure 6: full alignment of Pedemontana Piemontese – 15 km – from Masserano (Biella) to Ghemme (Novara).

The alignment area is complex from a seismic hazard point of view, due to the significant depositional nature of the area close to the Alps. Site investigations allow to recognize the following formations:

Upper level: consisting of the terraced surfaces inside the deposits of fluvioglacial origin of the "Fluvioglaciale Riss" (Middle Pleistocene) covered by an essentially clayey paleosol. Along the alignment, the rissiano terrace upon the current valley bottom of the Sesia river of about 25 m insists on almost all the alignment (75%);

Intermediate level: consisting of the terraced surfaces modelled inside the deposits of fluvioglacial origin of the "Fluvioglacial Wurm-Riss" (Upper Pleistocene - Middle Pleistocene) belonging to the fundamental level of the plain, located both on the left and on the right orographic side of the river Sesia, in the most eastern sector of the alignment (Ghemme interchange included);

Lower level: formed by the plain of the river Sesia, close to the riverbed, more extensive in the orographic right. This level is characteristic of the easternmost sector of the alignment (Ghemme interchange included).

Except for the mountain sector, the general situation relating to the surface distribution of stratigraphic complexes and structural units can be summarily described, from N to S, as written below:

a hilly area where the outcropping units are:

- mostly "Pliocene deposits" (Pliocene cover), Marine and transitional sediments in the continental environment in Astiana facies (sands), Piacenziana (sandy silts) and Fossaniana (gravelly sands);
- "Quaternary deposits" (quaternary cover). Sandy gravels, gravelly sands, sandy silts whose origin is linked to the phases of flooding by the current hydrographic network (holocene deposits) and past (Pleistocene deposits).

The area covered by the alignment insists on the fluvial, fluvioglacial and glacial deposits of the Quaternary, both Pleistocene and Holocene (ancient, recent and current floods of the main watercourses).

In order to characterize the site, some geotechnical and geophysical testing campaigns were carried out in 2009, 2010 and 2016. These soil investigation campaign consisted of:

- 60 continuous core boreholes;
- 31 piezometers (Casagrande and open tube);
- 17 Down-hole tests;
- 7 Seismic Tomographs MASW type (Multichannel Analysis of Surface Waves);
- many geotechnical laboratory tests on undisturbed soil specimens.

The carried out surveys reveal the presence of loose materials caused by the geological evolution of the area under the designed alignment. Considering all the surveys, the following model can be considered:

- a superficial layer of sandy and clayey silt, from 4 to 6 m thickness; the layer is exhausted nearby to the Sesia river;

- a layer of gravel with pebbles in abundant sandy / sandy-silt matrix placed in direct contact with the silts, from 10 to 20 m thickness;

- a layer of medium-fine to fine sand, from silt to weakly silt, with clasts, which extends throughout the entire alignment, and characterizes the bottom layer of each borehole. In the western area of the alignment, it emerges at a depth of 20 m; then it emerges at a depth of 30 m.

The three geotechnical units mentioned above, always present along the alignment with variable thicknesses, are interspersed with some other geotechnical units, present only in well-delimited sections:

- a layer of brownish silt sandy levels and sandy gravel levels highly altered; this layer is present in the western part of the layout;

- a layer consisting of the alternation of silt sandy levels and sandy gravel levels with darkly altered material, from 8 to 18 m thickness;

- a layer of gravel with pebbles in poor sandy matrix starting from ch 38 + 500 (survey S15 / 2009) in the extreme eastern area of alignment, from 4 to 12 m thickness.

Direct measurements of water table position lead to assume that the water table coincides with the ground surface.

The results of laboratory tests, together with the shear wave velocity profiles obtained by down-hole testing, were the most useful for the construction of the subsoil model. Some significant results of down-hole tests performed at the site are reported in Figure 7 where shear wave velocity is not always increasing with depth, meaning a discontinue growing of mechanical characteristics with depth, a further reason to carry out a specific site response analysis in design stage; moreover this is prescribed by NIBC 2008 § 3.2.2.

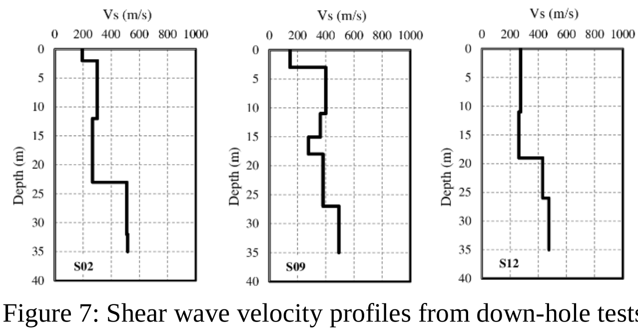

Figure 7: Shear wave velocity profiles from down-hole tests carried out along Pedemontana Piemontese alignment, according the following distribution: S02 – Rolino Area; S09 – Marchiazza Area; S12 – Torbola Area.

The distribution along the path of the down-hole tests, where the shear wave velocity inversion has been found, lead to recognize the four areas mentioned above (see Table 1) classifiable as S2. Each of them is identified by the topographic coordinates of the most relevant work of art located inside.

3 STOCHASTIC 1D GROUND RESPONSE ANALYSIS (GRA)

3.1 Soil model adopted

Based on the results of geological considerations, and supported by geotechnical and geophysical investigations results, the soil deposit can be assumed to be constituted of plane parallel layers. The site is flat and topographic amplification effects are not reasonably expected. In order to estimate ground response, the above allows to adopt a one-dimensional (1D) stratigraphic model, with material properties varying only along the vertical direction.

For initializing a stratigraphic 1D model, the definition of soil layers, with the corresponding depths and thicknesses, by using the information of borehole logs, combined with the geological data available, has been carried out. In Table 6, with reference to Sesia Zone, soil type, soil layers, mean shear wave velocity from Down Hole tests, are reported.

Layer thickness variation has been assumed according to Toro (1995) model, where the layering thickness is modelled as a non-homogeneous Poisson process.

After the layering of the profile has been established, the shear-wave velocity profile has been generated by assigning velocities to each layer, following the framework of Toro (1995) model where the shear-wave velocity at mid-depth of the layer is described by a log-normal distribution. The 1D mean profile and the range of variation of Vs for the various layers are shown in Table 6 and Figure 8 for Sesia area. Shear wave velocity data for depth greater than 40 m have been assumed and not experimetally measured, therefore any standard deviation value is reported in the relative rows of Table 6 .

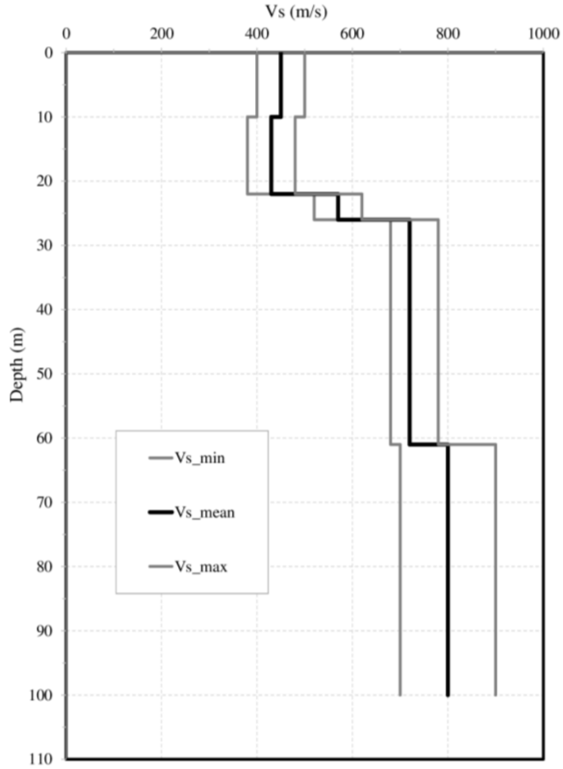

Figure 8: 1D profile of the mean shear wave velocity V_S from Down-Hole Test in Sesia river (black thick line) and ranges of variation assumed (grey thin lines).

Table 6: Synthetic characterization for the stratigraphic reference profile in Sesia area.

Layer (-)	Soil type (-)	Depth (m)	Thickness (m)	Vs mean (m/s)	St. Dev. (-)
1	Gravel	0	10	450	148.95
2	Silt-sandy Gravel	10	12	430	40.95
3	Sand and Gravel in silt matrix	22	4	570	47.11
4	Sand and Gravel in silt matrix	26	15	720	55.71
5	Sand and Gravel in silt matrix	41	20	720	-
6	Bedrock	61	Half-Space	800	-

3.2 Depth of Seismic Bedrock

According to the evidence of geophysical surface investigations, reported in Figure 9 the depth of seismic bedrock has been set at 60 m under the ground surface, and it has been assumed varying in the following range [50 m; 100 m] (respect to the ground surface).

3.3 Material degradation curves

The mass density and the layer height, the shear modulus (G), and finally the viscous damping ratio (D), under seismic shear loading, cause the non-linear soil behaviour, both at low and at moderate deformation levels too (Crespellani e Faciorusso, 2010). Characterization of the stiffness and damping properties, according to the most rigorous approach, would require both field and laboratory testing. Since no dynamic laboratory test results were available, the Darendeli (2001) model has been adopted. Starting from the hyperbolic model (Hardin and Drnevich, 1972) dealing with reduction and damping curves, it takes into account the effects of: confining pressure; plasticity index (PI); over-consolidation ratio (OCR); frequency (f); number of cycles of loading (N). The first two of them play a significant role in affecting the curves, while the others are less relevant. Taking the IP effect on the degradation curves into account makes Darendeli (2001) model suitable for the site of interest, were some layers are constituted of cohesionless soil sand in matrix of fine material. The range of variation of the plasticity index has been defined from standard laboratory test results and it is shown in Figure 10 together with the variation of confining pressure.

3.4 Modus Operandi

Once the one-dimensional stratigraphic model has been completely defined (see Table 6, for Sesia area), local site response analyses have been carried out considering the randomization of the above mentioned parameters. A reasonable estimate of the expected surface response and its standard deviation due to variations in the soil properties can be computed through Monte Carlo simulations.

Monte Carlo simulations estimate the response of the system by a sampling technique, in which input parameters are randomly generated according to previously defined probability distributions, hence simulating the sampling process of a real population. This method, widely adopted in GRA, can be applied by using software STRATA (Rathje and Kottke, 2013).

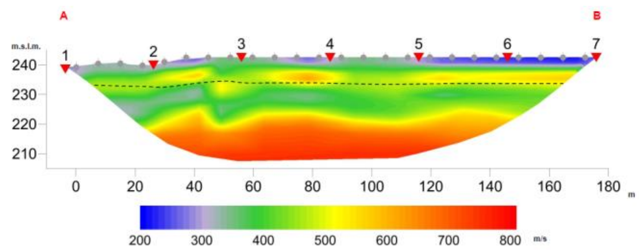

Figure 9: Seismic tomography performed in Sesia area, reporting the estimated depth of seismic bedrock. Note the dashed line representing the inversion in shear-wave velocity about at 10 m depth.

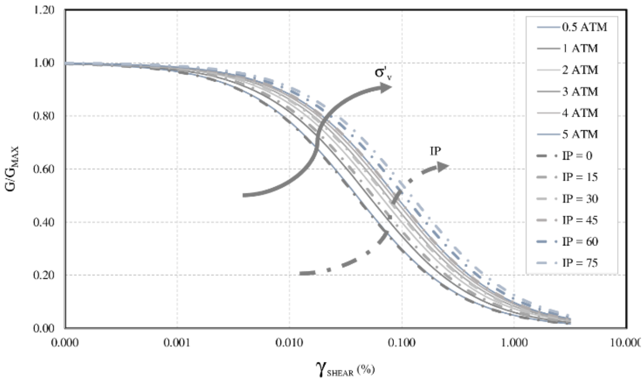

Figure 10: factors affecting degradation curves in Darendeli (2001) model, according to the value of Plasticity Index and Confining Pressure adopted in the present work.

3.5 Results

The variability of the stratigraphic profile used in stochastic analyses is shown in Figure 11, that illustrates more than 350 shear wave velocity profiles, corresponding to random values of Vs extracted from the statistical distributions of Vs and thicknesses of the different layers. It can be noticed that at around 10 m depth there is an inversion of shear wave velocity, and below a depth of 40 m there is the seismic bedrock. Figure 12 shows the acceleration transfer function ratio between the surface one and the bedrock one. It can be observed that the maximum amplification 1,8 is approximately at 3 Hz. Figure 13 reports the PGA profile with depth resulting from stochastic GRA. The increment of PGA can be observed going up from the bedrock to ground surface till 0.063g (median value). Figure 14 illustrates the response spectrum obtained from the average of the spectra of the seven accelerograms, with the response spectra of EC8 for ground types A and D.

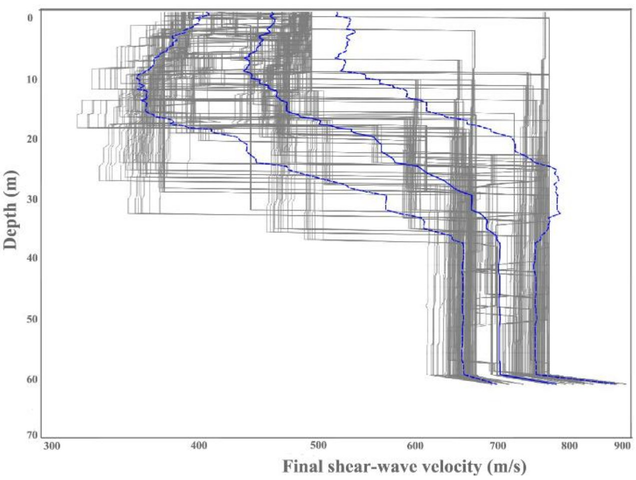

Figure 11: Variability of final shear wave velocity and layer thickness in the simulation carried out by STRATA. Median value (continue blue line); Median +/- Log Standard deviation (dashed blue lines); 1-350 realizzations (grey lines).

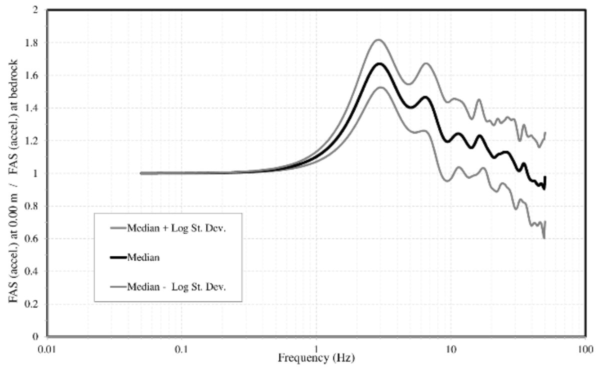

Figure 12: acceleration transfer function ratio: top to bedrock. Median value (black thick line); Median +/- Log Standard deviation (grey thin lines).

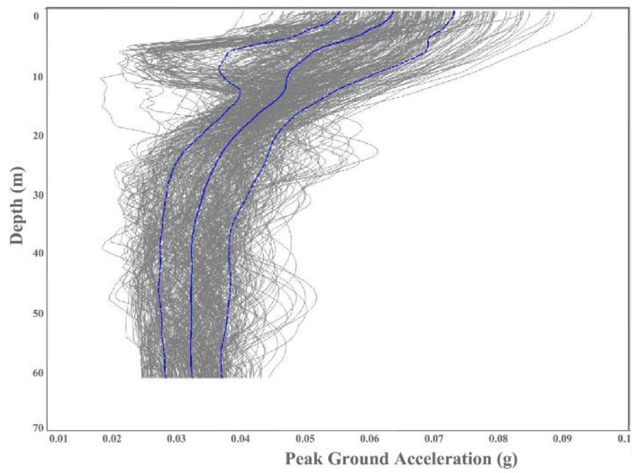

Figure 13: Peak Ground Acceleration profile, resulted by Stochastic GRA. Median value (continue blue line); Median +/- Log Standard deviation (dashed blue lines); 1-350 realizations (grey lines).

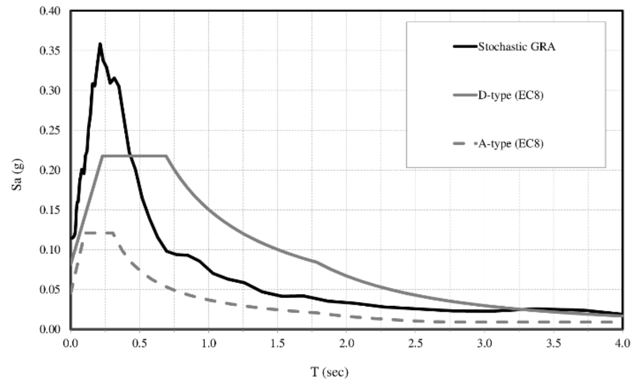

Figure 14: Response spectrum obtained from Stochastic GRA, in Sesia Area. Mean spectrum (black thick line) compared with the response spectra of EC8 for soil type: A and D, (dashed and continue grey line respectively).

4 CONCLUSIONS

Focus of this work is the seismic input for structural and geotechnical dynamic analyses, in order to properly design the works of art located along Pedemontana Piemontese alignment, (Eastern Piedmont, Northern Italy), also because the evidence of some down-hole tests result showing shear wave velocity discontinusly growing with depth.

Recorded accelerograms instead of artificial records have been preferred according to both current literature and EC8 recommendations. Seven real accelerograms have been selected from strong-motion databases such as to satisfy, on average, the spectrum-compatibility criterion, as prescribed by EC8; then they have been scaled to PGA reference site value. The adopted reference spectrum is the elastic spectrum of NIBC 2008, anchored to the local value of PGA that, along alignment, is equal to 0.045g for a return period of 949 years (USL).

Then seismic site response has been carried out by means of one-dimensional analyses using an equivalent linear approach implemented by the computer software STRATA. Once a site-dependent, strati-graphic profile, has been firstly defined, stochastic analyses have been carried out using Monte Carlo simulations, casually varying the definition of the stratigraphic profile and the geotechnical parameters of the soil model and therefore calculating the response on a sample of about 350 realisations.

A comparison of the response spectra of an EC8 for soil type A and D, with the response spectrum obtained from the average of the spectra of the seven accelerograms (reported in Figure 14) shows that the peak amplification takes place for structures with own frequency period of vibration of about 0.2 sec.

Even if the bedrock accelerations are relatively small, future investigations will focus on the comparison of signal amplification between the different stratigraphies along the alignment.

In structural design of the Pedemontana Piemontese Highway, the spectrum obtained by Stochastic GRA (Figure 14), was normalized on the basis of the elastic spectrum calculated for a subsoil of category "D", following the equations of NIBC 2008. Then both a non-linear dynamic analysis and a modal analysis have been carried out using artificial spectrum-compatible accelerograms.

Three groups of spectrum-compatible accelerograms, according paragraphs 3.2.3.6, 7.3.4.2 and 7.3.5 of the NIBC 2008, have been selected, according to the criteria provided by the paragraph 3.2.3.6. The three accelerograms of each group have been applied simultaneously (one in the X direction, one in Y and one in Z), as prescribed by the mentioned above standard.

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