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Practical seismic microzonation in complex geological environments

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ABSTRACT

The seismic design of buildings and infrastructure components requires the estimation of the hazard considering the dynamic response of the soil deposits, which substantially modifies the characteristics of the input motion at the rock basement. Seismic microzonation studies attempt to identify geologic zones of an area of interest with similar seismic hazard at a local scale. This paper presents a methodology to obtain seismic spectral amplification factors within each soil zone characterization considering the main sources of uncertainty. Results are presented in terms of spectral amplification factors for various seismic intensities and soil profile vibration periods. Design soil amplification factors can then be mapped using the measured vibration period of the soil profile at each location and the seismic intensity at bedrock for a given design return period. Response and design spectra may then be estimated at surface level for every location. Results can be easily integrated into probabilistic risk assessment platforms such as CAPRA (www.ecapra.org) for hazard and risk evaluations.

1. Introduction

The seismic design of buildings and infrastructure components requires the selection of a set of seismic records or a design spectra that adequately represent the seismic hazard at a certain location. The design spectrum represents the maximum seismic intensities for design in terms of ground acceleration, velocity or displacement. Seismic design parameters near the surface shall consider the hazard assessment at the bedrock level and the effects generated by the dynamic response of the soil deposits. Since the 1950s, increased research interest in seismic microzonation studies has been observed. After the occurrence of earthquakes such as those in San Francisco (1906), Mexico City (1985) and Kobe (1995), it was clear the need for more detailed assessment of the response of soft sedimentary deposits subjected to earthquakes. In the United States, Gutenberg [1,2] analyzed the differences between ground motions due to variations in geological conditions in Southern California. Richter [3] determined probabilistic seismic intensity variations due to geologic conditions for Los Angeles basin. Borcherdt [4] correlated seismograms measured on surface with the ones obtained at a nearby reference stations located on competent bedrock; this methodology assumed that the difference in the response was due to the local geological or topographical characteristics of the site and that epicentral distance and source radiation were similar for near sites. Aki [5] observed a dependency between the site amplification factor on the response spectra and the frequency of the ground motion. According to the author, soil sites showed higher amplifications than rock sites for periods longer than 0.2 s; this trend was opposed for periods lesser than 0.2 s. Between 1976 and 1994, U.S. seismic building codes used site categories and coefficients S_1 to S_3 that were defined based on statistical studies [6,7]. A fourth category and factor, S_4, was later added after the observations made during the 1985 Mexico City earthquake [8]. In this approach, each site category was associated to a spectral shape and the S factor only scaled the long period part of the spectrum. Idriss [9,10] showed that peak ground accelerations and spectral level at short periods can be significantly amplified at soft sites. These observations were later used to define two important aspects that were incorporated into the NERPH [11] and the Uniform Building Code UBC [12]: (1) higher values of soil site coefficients for areas of lower shaking and (2) the addition of a hard rock category to better reflect geologic conditions in eastern United States. In addition, further studies indicated the importance of the shear wave velocity variation in the upper 30 m column of soil [13,14]. These findings were considered in the 1994 and 1997 NEHRP [15,16] provisions and 1997 UBC [12], which included five new site classes (A to E) in terms of the average shear wave velocity to a depth of 30 m (V_{s30}). In addition, the old site coefficient S (NEHRP versions prior 1994) were replaced by the site amplification factor F_v at long periods and a new coefficient F_a was introduced for short periods [17]. More recently, Schneider et al., [18] used data from cone

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penetration tests (CPTs) to assist the mapping of the seismic hazard in the Memphis and Shelby County area. Similarly, Liao et al., [19] studied the geotechnical site characterization of the New Madrid seismic zone in central USA. Nichols et al. [20] presents the recommendations of the seismic hazard mapping act advisory committee for the development of appropriate maps of expected ground shaking hazard. The authors provide recommendations regarding general considerations for mapping expected ground shaking hazard (such as scale), seismic source modeling, earthquake frequency ranges, maximum and minimum magnitude, and seismic wave attenuation models.

In Japan, many efforts have been made to define seismic zones. Imamura [21] developed a microzonation study of Tokyo city based on the distribution of damages after the 1854 Tokyo earthquake. An alternative approach was developed by Ohta [22,23] to assess sites where there is scarcity of information from damaging earthquakes. Kanai and Tanaka [24] proposed the use of the relationship between the largest period and mean period, the largest amplitude, and the predominant period of microtremor measurements to generate soil type classifications. This methodology was used by Kanai et al., [25] to construct a soil classification map of the northern Nagano area. Shima [26] proposed a relative amplification factor for various types of soil (e.g. Clay, sand, loam) based on analytical response of soil models. The amplification factors were determined from the ratio between the maximum values of the ground response in the frequency range of 0.1–10 Hz. Following a similar approach, Midorikawa [27] proposed amplification factors for geological units and constructed a distribution of peak ground acceleration in the Kanto plain by combining the amplification factors with empirical attenuation relation for PGV. Wesnousky et al., [28] integrated geological and seismological data to deterministic probabilistic seismic zoning in Japan. Nakamura [29] showed that the H/V ratio is highly related to the ground properties. The author demonstrated that the horizontal motion is larger than vertical motion on soft soil while on rock, both horizontal and vertical motions, are similar on its maximum value and waveform. In addition, several studies have shown the importance of assessing source and site factors (e.g. near field effects, directivity, duration, topographical and basin effects, and soil nonlinearity) to understand the ground motion characteristics.

In South America, Cardona and Yamin [30] conducted unidimensional and bi-dimensional seismic response analyses for the city of Bogotá, using computer programs SHAKE 91 [31], ANSYS [32] and QUAD4M [33]. The authors calibrated the model with signals recorded on rock and soil sites in the city and used one hundred and seventeen microtremor measurements to identify the zones of the city with similar dynamic behavior [34]. In addition, the soil types of the city were characterized through dynamic laboratory studies using samples obtained from 38 deep boreholes between 20 and 200 m. A microzonation was proposed for the city of Bogotá and adopted for the design of buildings by a municipal decree. Vasquez and Alva [35] used microtremor measurements to characterize the soils of the city of Nazca in Peru. The dynamic characteristics of the soils were determined based on microtremor measurements carried out in the study area. The results of the measurements allowed finding the ranges of predominant periods of the soil that agree with the soil conditions and observed seismic damage observed after the 1996 Nazca earthquake. Yamin et al., [36] proposed a design spectra for the 3 principal cities of the Colombian Coffee Growing area (Pereira, Manizales and Armenia). These results were used to evaluate the expected dynamic response of representative soil deposits, which were compared with available acceleration records for the 1999 Armenia earthquake. CISMID [37] developed an initial microzonation map of Lima, Peru, based on geotechnical studies to obtain the deep soil profiles of representative sites in the city. The information gathered was complemented and an updated with geotechnical studies and microtremor measurements developed in the framework of the SATREPS project [38,39]. Several studies have been conducted to develop the microzonation of Quito, Ecuador. EPN [40] developed a complete soil classification in the city proposing nineteen seismic zones that were used to characterize the shear modulus and damping values. In addition, ERN [41] developed a comprehensive microzonation study based on all previous available information.

Most of the above-mentioned efforts aimed at establishing design spectral parameters for buildings considering the expected dynamic soil response at specific locations. Given the relative scarcity of acceleration measurements to propose a microzonation based in actual measured amplification factors, analytical and computational methods are usually the unique available option. To obtain consistent and rigorous results, those methods shall integrate the following: (1) a probabilistic hazard assessment model to obtain uniform hazard spectra at bed rock, (2) detailed information on the geologic and geotechnical profiles to estimate soil response with analytical methods, (3) field measurements to assess the geographical variations of soil response, and (4) some actual seismic records at particular representative locations that allow a validation of the analytical results. In general, soil deposits present a high degree of variations both geographically and in terms of the soil profile itself. Considering the limitation in budget for the design phase of most relatively small building infrastructure projects, the definition of the soil profile for seismic classification turns out to be extremely expensive and highly unreliable. To conform a reliable soil model including possible variations in soil depth, profile characteristics and soil static and dynamic properties is a difficult and expensive endeavor for most urban projects. Therefore, seismic microzonation studies point at establishing the expected soil effects in a particular urban zone in order to propose seismic design parameters which account for the local conditions of the soils deposits. These studies are especially useful in conventional construction projects where a complete geotechnical characterization study is not justified. The results from the seismic microzonation evaluation include the soil amplification effects at every location of the study zone. These results are expressed as soil amplification factors which are usually integrated into standard probabilistic hazard assessment models or into pre-defined building design methodologies (see for example, ASCE 41–17 [42] or NSR-10 [43]). Despite of the multiple options and information usually available, a rational and practical method is required to standardize and spatially integrate all the available information in terms of the geological, geotechnical and static and dynamic soil properties, thus maintaining the rationality of the analytical methods available.

This paper presents a methodology to assess the seismic soil effects in a particular area of interest in the framework of seismic microzonation studies in complex geological environments. The methodology integrates all pieces of information commonly available in the process and includes the consideration of all common sources of uncertainty. The results are presented as set of spectral amplification factors for various seismic intensities and ranges of the soil vibration period within each geological zone. Maps of soil amplification parameters are generated for design applications. The final seismic design recommendations in terms of spectral values at the surface of the deposits are integrated in a web based application that allows potential users to consult all related seismic information in the area of interest, in particular the final design spectra at bedrock or at the soil surface. These results can be easily integrated into common probabilistic risk assessment platforms such as CAPRA (www.ecapra.org) in order to consider soil amplification effects into seismic hazard and risk evaluations.

2. Proposed methodological approach

In this study, we propose a methodology to obtain soil spectral amplification factors that represent the dynamic response of any given zone in which it is expected a similar seismic response. These spectral amplification factors are applied to uniform hazard spectra at bedrock to obtain amplified spectra at ground level. The novel contribution of the proposed approach is the possibility to integrate in a consistent and practical way all the typical pieces of available information for microzonation studies considering all sources of uncertainties: the probabilistic hazard assessment at bedrock, the soil amplification factors obtained from non-linear dynamic soil response and all information available from field measurements and seismic records. The soil fundamental period map, obtained mainly from in situ vibration measurements, serves as the linking parameter between the measured soil dynamic response and the corresponding analytical models, thus allowing the development of a consistent approach to integrate and interpolate the spectral parameters at surface level. In addition, the integration of the resulting seismic spectral amplification factors for a representative range of structural vibration periods leads to the construction of amplification spectra surfaces at different ground accelerations levels, allowing a comprehensive characterization of each soil geological zone.

In order to consider the main sources of uncertainty, statistical variations of the parameters that characterize the soil profile are evaluated using the available representative geotechnical information within each zone. Monte Carlo simulation techniques are used to generate a set of representative one-dimensional simulation models considering all possible variations in the soil profile and assigned parameters. Each representative model is used to obtain the corresponding spectral amplification factors for the set of seismic records selected for the dynamic analysis. In general, the dynamic response will present significant variations in each zone of uniform response. Spectral amplification factors are calculated for the range of expected soil vibration periods that are measured inside each zone. Simultaneously, a soil vibration period map is generated using all possible sources of information, mainly field measurements. The soil vibration period map is used to geographically assign the corresponding spectral amplification factor. The resulting amplification factors obtained from a purely analytical approach are combined with the measured local soil vibration period to generate the final spectrum recommendation at each location. The proposed hazard assessment methodology for microzonation purposes includes the following main activities, which will be explained in detail later:

a) Perform a probabilistic hazard assessment at bedrock level of the area of interest using standard available models (e.g. Crisis [44–46]. The model will generate a continuous geographical variation of uniform response spectra at bed rock and will identify relative participation of main fault systems in the response at various return periods.
b) Select groups of seismic records representing the activity at bedrock level of the main seismic sources for several seismic intensity levels, each associated with a particular return period. The set of records selected shall be representative of the seismic hazard.
c) Define a geologic and geotechnical zonation and characterization, dividing the complete area of interest into zones with uniform expected seismic response. Characterize static and dynamic parameters within each zone considering a representative soil layer stratification.
d) Perform a soil dynamic response assessment and propose a set of spectral acceleration amplification factors for the expected range of soil vibration periods in each particular uniform zone and for different seismic intensity levels associated to several return periods. In this step, Monte Carlo simulations are required to conduct the analysis for a sufficient number of stochastic one-dimensional soil models considering as random variables the depth to bedrock, the shear wave velocity of the rock basement, thicknesses of the soil layers, geotechnical parameters and dynamic nonlinear properties (shear stiffness and damping) of each soil layer.
e) Assign the spectral amplification factor at each geographical location, as a function of the specific soil profile vibration period and the return period of analysis. Those amplification factors will be compatible with the corresponding uniform hazard spectra at bedrock at that same location.
f) For design purposes, obtain the acceleration response spectra at surface level by multiplying each ordinate of the uniform hazard spectrum at bedrock by the corresponding soil amplification factors. Then, obtain the soil amplification factors for the short and long period ranges which shall multiply the design spectra at bedrock. In this step, a Latin hypercube sampling (LHS) technique [47–49] is implemented to generate random response spectra at surface level considering the main sources of uncertainty. A sufficient number of iterations must be performed to guarantee the stabilization of the results.
g) For hazard and risk assessment purposes, use the corresponding spectral amplification factors to obtain the spectra at the surface level for each seismic scenario.

In this article, a simplified approach is proposed to consider both the aleatory and epistemic uncertainties. The epistemic uncertainty is introduced in the form of an estimated dispersion in the bedrock uniform hazard spectrum; the aleatory uncertainty is obtained by combining the uncertainties of the input datasets that will generate the final uncertainty in the response spectrum at each location. The uncertainties corresponding to the input datasets are: (1) the seismic hazard uncertainty associated to the selection of a set of seismic records with different intensities, frequency contents and durations; and (2) the uncertainties associated with the soil profile itself, such as the soil layers depths, the bedrock level, the shear wave velocity profile and the static and dynamic geotechnical properties of soil layers. The uncertainties associated to all these parameters are included by assigning probabilistic distribution functions obtained from a statistical analysis of the geotechnical properties available. The combination of all these uncertainties will generate the final uncertainty in the response spectrum at each location. In order to validate these considerations, the resulting response spectra are compared with those obtained from all seismic records available at certain locations. The results of this comparison are presented in Section 4.

2.1. Probabilistic hazard assessment at bedrock level

The proposed methodology is mainly based in a geographical distribution of the uniform hazard spectra (UHS) at bedrock level, which is obtained by means of a probabilistic seismic hazard analysis (PSHA). PSHA entails the definition of a set of active seismic sources in the area of interest. The seismicity is characterized by estimating the magnitude recurrence curves for each of the seismic sources and the selection of adequate ground motion prediction equations (GMPE), which represent the energy attenuation condition for a particular seismic source. In this study, GMPE are specified for the same basement rock type as the one defined in the analytical 1D soil profiles to maintain compatibility (e.g. A, B or C according to NEHRP classification). The probabilistic integration of the seismic hazard from all potential seismic sources in the area generates hazard curves at each location, which represent the variation of any seismic intensity parameter as a function of the annual exceedance rate or its inverse, the return period in years [50]. The most common seismic intensities used in hazard assessment and seismic risk studies are the peak ground acceleration (PGA), the spectral accelerations $S_a(T)$ for a collection of structural periods T and a given damping factor; and the peak ground velocity and displacement (PGV and PGD, respectively). In addition, UHS can be constructed from the collection of seismic hazard curves associated to PGA and $S_a(T)$ for a specific return period at any particular location within the study area. Finally, probabilistic hazard maps can be generated through the selection of any seismic intensity parameter for a given return period at several locations.

Fig. 1 summarizes the information required and the results obtained from a PSHA. Additional results obtained from PSHA correspond to the seismic hazard de-aggregation which allows identifying the combination of magnitude and distance that presents the greatest contribution to the site seismic hazard. Subsequently, these results are used for the

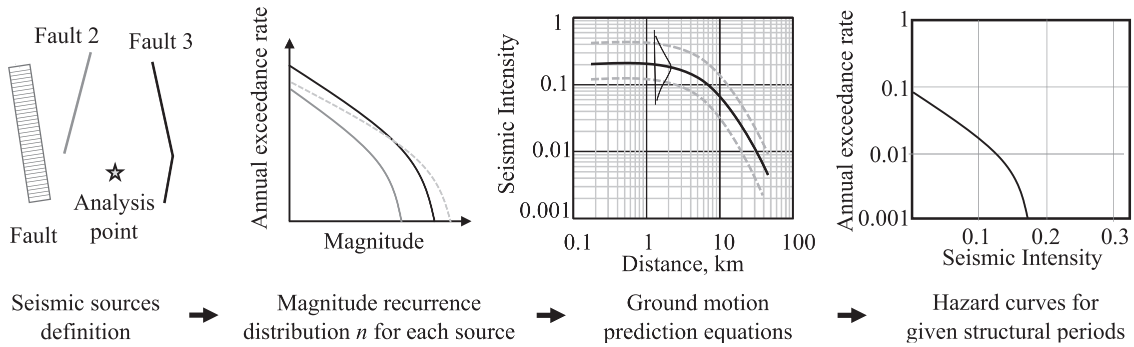

Fig. 1. Methodological approach for probabilistic hazard assessment.

selection of a set of seismic records to conduct detailed soil dynamic analyses for several seismic intensity levels, corresponding to various return periods. For risk assessment purposes, the results of the seismic hazard is usually expressed in terms of a set of stochastic events, each one with a particular geographical distribution of the selected intensity parameter in agreement with the PSHA parameters and a corresponding annual rate of occurrence [51]. For design purposes, several return periods are selected according to the general design criteria (e.g. 475 years for capacity design of buildings, 1000 years for capacity design of bridges, 1500 years for financial protection of insurance companies, or any other). In this article, results are shown only in terms of acceleration response spectra at surface level. However, the same methodology can be implemented to obtain seismic intensities in terms of velocity or displacement. In order to account for the epistemic uncertainty, which is associated with the uncertainty in the modeling techniques adopted, an empirical dispersion is introduced in the estimated UHS at rock level. For that purpose, a lognormal distribution is assigned to each intensity measurement with the mean corresponding to the resulting value of the UHS from the PHSA and a variance factor. This variance is later calibrated to obtain a total uncertainty similar to the one calculated from the available accelerographic records at the seismic stations located within the area of study.

2.2. Seismic record selection

Several sets of seismic records that adequately represent the seismic hazard at bedrock level must be selected for each seismic intensity level of analysis. The selected seismic records have to represent the seismotectonic environment including the rupture mechanism, the magnitude-distance relations that control the PGA, the frequency content, the intensity levels and the duration of the expected seismic records in the area of study. Several methodologies for seismic records selection have been included in building code standards, such as the ASCE 7–10 [52], FEMA P695 [53], and NSR-10 [43]. Usually, a collection of seismic records from different active fault systems is conducted to maintain its relative contribution as indicated by the probabilistic hazard model at each intensity level. The records as a group must be representative of the seismic hazard uncertainty in the region.

2.3. Geologic and geotechnical zonation and characterization

The basic information required to conduct geological and geotechnical zonation and characterization is the following:

a) Geologic and geomorphologic maps and cross sections: this information is required to generate an initial zonation criteria for the area of study. Geologic maps allow establishing the relevant geological units, origin, geological period and a general description of the materials mechanical properties. Geomorphologic maps generally include information regarding landscape units or superficial shapes such as unstable areas, low zones, river flow areas, surface plains, alluvial valleys, hills, among others [54]. These maps are usually presented in scales 1:100.000, 1:50.000, 1:10.000 or higher resolution. Usually, the minimum acceptable scale for city microzonation studies is around 1:10.000.
b) Geotechnical information: borehole information is usually available from private geotechnical logs (e.g. from geotechnical studies for foundations design), public infrastructure development projects and/or hazard or risk studies in the area of interest. Accessible data for microzonation studies must include borehole surveys that meet the following minimum requirements: (*i*) minimum depth of 30 m or down to the bedrock, (*ii*) continuous soil description and soil layer identification, (*iii*) static geotechnical characterization of the main soil deposits including density, classification indices and parameters, and any measure of shear strength and compressibility (SPT, CPT, vane, unconfined compression, triaxial shear, consolidation, among others), (*iv*) dynamic geotechnical characterization of the soil deposits including dynamic triaxial tests, resonant column test,

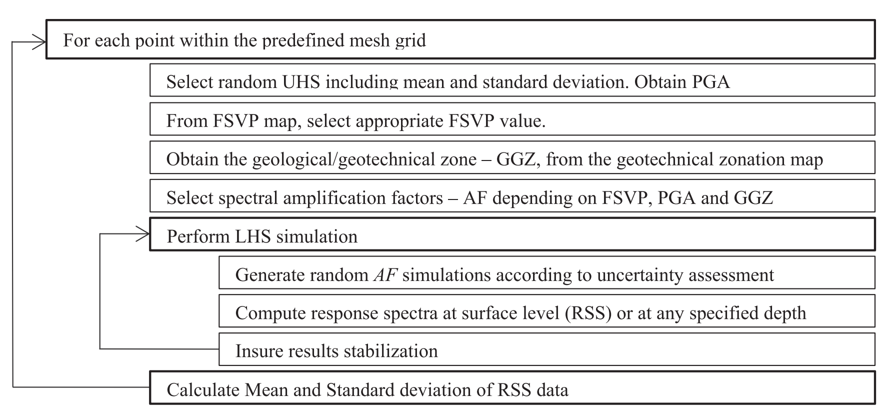

Fig. 2. Procedure to obtain the surface response spectra.

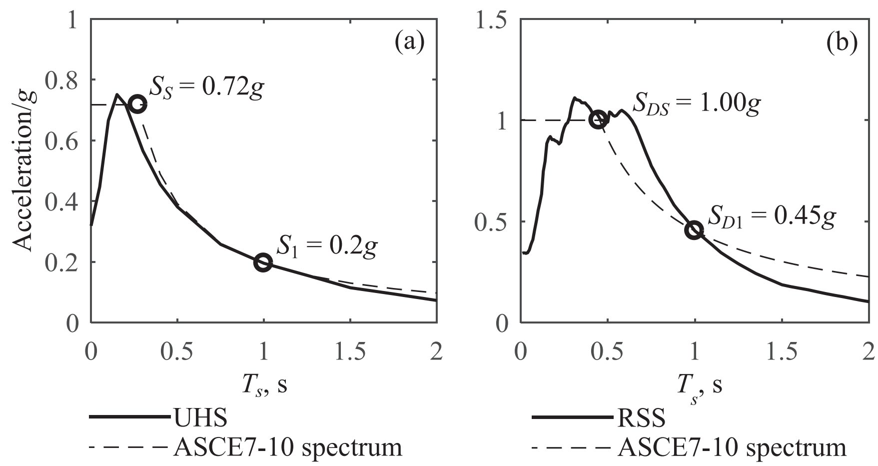

Fig. 3. Schematic methodology to obtain seismic design parameters of ASCE 7–10.

direct shear test, bender element and any other method that allows estimating the shear stiffness and damping for a wide range of shear strain deformations, and (*v*) soil profile characterization using in-situ testing techniques, such as down-hole, up-hole, cross-hole, refraction surveys, reflection surveys, SASW, MASW, microtremor arrays, suspension logging or any other geophysical method.

c) Geotechnical microzonation map: this map is generated based on the digital elevation model and the geological, geomorphological and geotechnical information available. In this map, each geotechnical zone is assumed to represent a relatively homogeneous zone in terms of the depth to competent rock, soil stratigraphy, and mechanical and geotechnical properties. Each zone represents a relatively uniform expected seismic response. The final reliability of the results depends on the scale and data resolution used to construct the zonation map, which can be increased with extensive boreholes surveys. A comprehensive statistical evaluation is required in each geotechnical zone to correctly estimate the variation with depth of the parameter´s mean and standard deviation. In most cases, normal or log-normal distributions are assigned to the random variables (e.g. depth to bedrock, number of sublayers, density, and shear wave velocity profile and soil classification). The definition of the size and resolution of each zones should be based on engineering criteria.

2.4. Soil dynamic response assessment

The spectral amplification factors are obtained analytically for each geotechnical zone using all acceptable geotechnical information available. These factors are estimated for increasing values of the seismic intensity parameter considering all possible sources of uncertainty [55]. The procedure followed for obtaining the soil amplification factors is summarized below.

a) Select a particular geotechnical zone as defined in Section 2.3.
b) Characterize all geotechnical parameters required for the dynamic soil response assessment. Eqs. (1) and (2) are applied to the set of m soil profiles obtained from the log information. This characterization is developed at any z depth within the soil profile for the following parameters: bedrock depth (H), the soil layer thickness (t_i), shear wave velocity profile (V_s), unit weight profile (γ) and the dynamic properties (shear stiffness and damping models). A log-normal and normal distribution functions are commonly used. For simplicity, independence is assumed between random variables.

$$\mu_{parameter}(z) = \sum_{i=1}^{m} Parameter_i(z)/m \tag{1}$$

$$\sigma_{parameter}(z) = \sum_{i=1}^{m} [Parameter_i(z) - \mu_{parameter}(z)]^2/m \tag{2}$$

c) Using a Monte Carlo simulation technique, generate a sufficient number of stochastic one-dimensional soil models. Considering the depth to bedrock, shear wave velocity of the rock basement, thicknesses, geotechnical parameters and dynamic nonlinear properties (shear stiffness and damping) of each soil layer as random variables.
d) Using the set of representative seismic records, perform a series of one-dimensional soil response analyses to obtain the dynamic

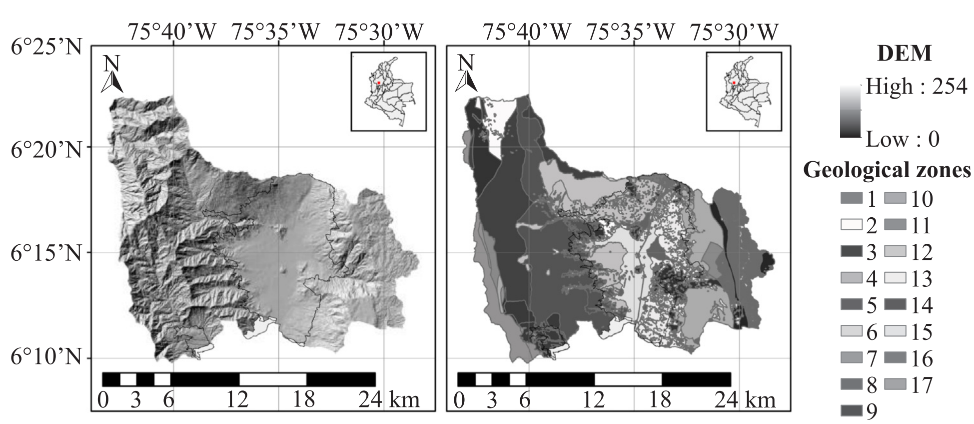

Fig. 4. Location of the area of study. (a) Digital elevation model and (b) Geological zones classification.

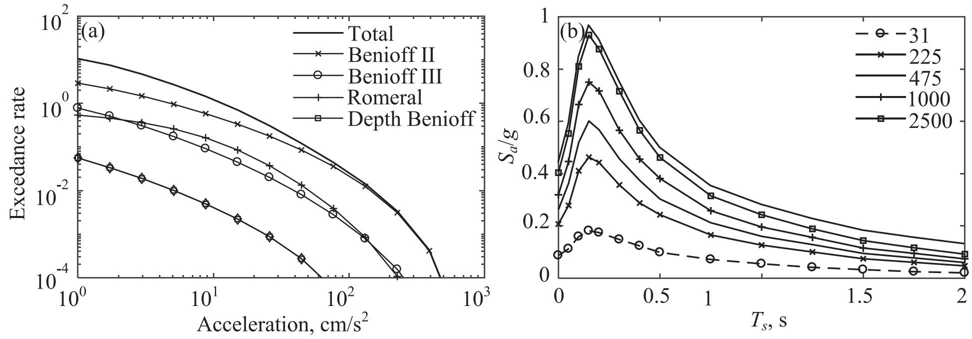

Fig. 5. (a) Seismic hazard curves and (b) UHS for several returns periods for the city of Medellín.

response (acceleration spectrum) at the soil surface or at any other specified depth within the profile.

e) Calculation of the soil amplification factors $AF(T)$ for the range of structural periods T_s using Eq. (3) [56,57] for each one of the n stochastic soil profiles. The nonlinear soil behavior can be modeled using approaches such as equivalent linear simulations of one-dimensional (1D) soil models (e.g. Shake91 [31]).

$$AF(T) = S_A^S(T)/S_A^R(T) \tag{3}$$

where $S_A^S(T)$ denotes the spectral acceleration at the surface calculated through 1D analysis and $S_A^R(T)$ is the acceleration at the base-rock level (ground input motion); the grouping of the results of $AF(T)$ is performed by defining ranges of the fundamental soil vibration periods FSVP at several PGA intervals. A lognormal probability distribution function with the corresponding mean and variance parameters is assigned for each final amplification factor function.

f) Generate a database with all results according to the geotechnical zones in the area of analysis (GGZ), seismic intensity levels (PGA), and expected ranges of elastic fundamental vibration period of the soil profile (FSVP).

This approach allows a comprehensive characterization of the spectral amplification factors (mean value) and its variation for each range of FSVP and at each intensity level (PGA) within the same geotechnical zone. A tridimensional surface of spectral amplification factors can be constructed to compare soil effects between zones. Fig. 12, shown later, illustrates a typical surface of spectral amplification factors. A software package called FUNSAMP V1.0 was developed to perform the Monte Carlo simulations. As input, the program requires a geotechnical zonation map (ASCII format), a set of spatially referenced geotechnical borehole data, and a set of seismic records to be used in the one dimensional analysis. Output data includes the soil amplification spectra factors (mean value and corresponding variance) for each defined zone and ranges of FSVP. This application, an illustrative example and the user manual can be found in the CAPRA platform (www.ecapra.org), an initiative that promotes and facilitates the understanding, communication and decisions related to disaster risk management.

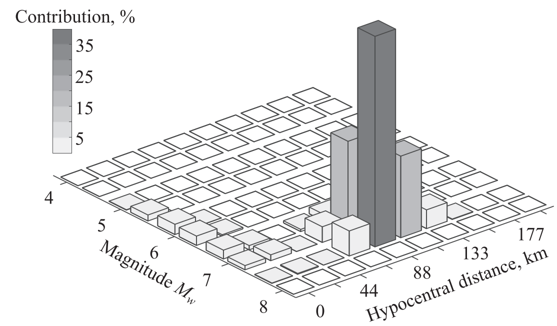

Fig. 7. Seismic de-aggregation for the city of Medellín.

2.5. Spectral amplification factors at each geographical location

The key parameter to assign a given spectral amplification factor at each geographical location is the fundamental soil vibration period (FSVP). The FSVP is the most important dynamic parameter that represent the soil response in the study area. This parameter accounts for the soil stratification at each location, the heterogeneity of the geological units, the static and dynamic properties of the soil layers and the boundary conditions. Therefore, only field measurements that allow a reliable estimation of fundamental soil vibration periods are used to

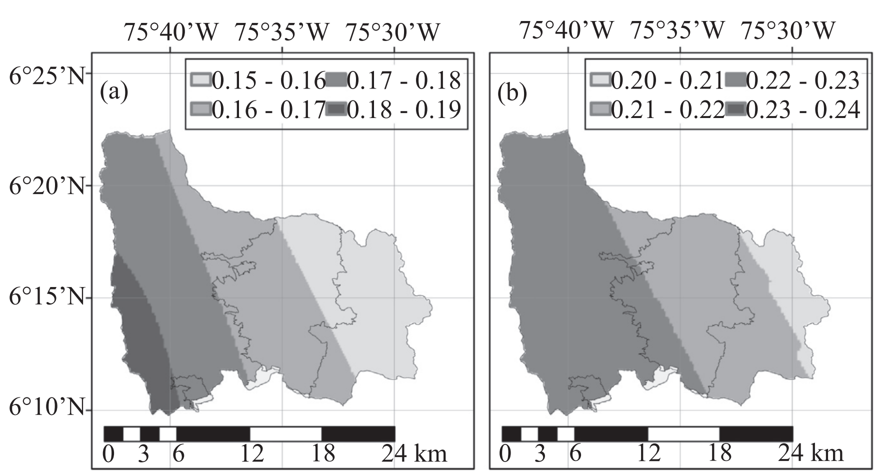

Fig. 6. Spatial distribution for design parameters at bedrock (a) S_s, (b) S_1 for the city of Medellín.

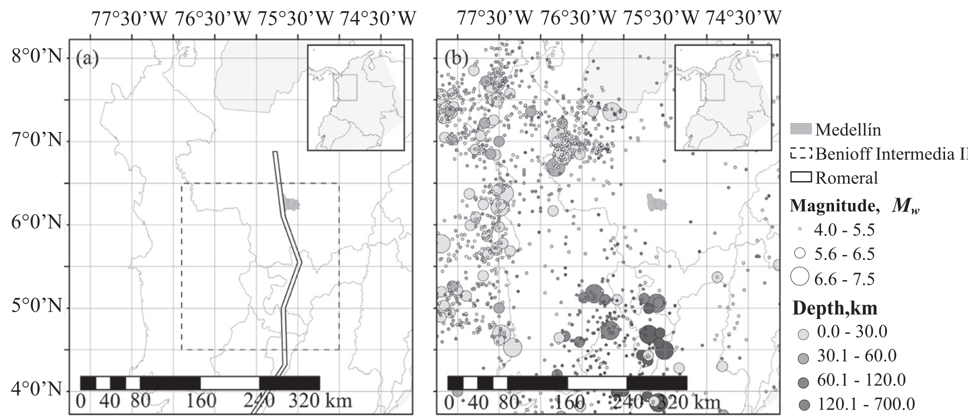

Fig. 8. (a) Location of the Benioff zone and the Romeral fault system and (b) epicenter of the selected GMs to evaluate the dynamic response of the 1D soil models.

generate the FSVP map. The map is then constructed using information from different sources such as: (1) digital elevation models (DEM); (2) slope maps; (3) geological maps; (4) geomorphologic maps; (5) V_{s30} maps (e.g. USGS, [58,59]); (6) microtremor measurements; (7) FSVP estimation from available seismic records; and (8) FSVP estimation from other geophysical measurements. The construction of the map has to fulfill the following conditions: (1) the FSVP values correspond to the elastic fundamental vibration period at low soil deformations, (2) the mapping should include only the fundamental period of the soil and (3) the map requires to be adjusted based on the controlling geological and geotechnical conditions, such as the outcropping rock units, very deep deposits difficult to characterize, and spatial distribution of the representative geologic units, among others. The range of fundamental vibration periods that results from the 1D or 2D analytical models should be in agreement with the resulting FSVP map at that same location. Once a reliable FSVP map is available, a particular surface of spectral amplification factors can be assigned at each location.

2.6. Acceleration response spectra at surface level

To obtain the acceleration response spectra at surface level (RSS), it is necessary to multiply each ordinate of the uniform hazard spectrum at bed rock (UHS) by the corresponding soil amplification factor (AF). A Latin hypercube sampling (LHS) technique [47–49], is implemented to generate random response spectra at surface level considering the main sources of uncertainty. A sufficient number of iterations is performed to guarantee the stabilization of the results. Fig. 2 summarizes the steps required to obtain the acceleration response spectra at surface level and a measure of the uncertainty.

A software package called SIS-LHS V1.0 was developed to allow the integration of the methodology. As input, the software requires georeferenced maps (ASCII format) containing probabilistic seismic hazard, fundamental soil vibration period and geotechnical microzonation. The results from the spectral amplification factors (see Section 2.4) are introduced in a particular database format. Outputs correspond to the acceleration response spectra at surface level RSS including the statistical analysis of mean and standard deviation from LHS simulations. The application, an illustrative example and the user manual can be found in the CAPRA website (www.ecapra.org).

2.7. Soil amplification factors for design

A structural design spectrum is generated by using standardized methodologies. Although several spectral design formulations have been proposed in the literature, we adopted the American standard "Minimum Design Loads for Buildings and Other Structures" ASCE7-10 [52] since it is one of the most recognized worldwide design spectra specifications. The reference rock level can be assumed to be located at the depth corresponding to a value of the shear wave velocity (V_s) equal to 760 m/s. At this level, the seismic hazard corresponds to the UHS which results from the PSHA at the return period of analysis. For structural design purposes (building code regulations), design spectra are usually specified by only two parameters, the spectral acceleration S_S for the short period range (e.g. 0.2 s) and the spectral acceleration S_1 for the long period range (1 s). In this study, these spectral accelerations are obtained from the UHS using Eqs. (4) and (5).

$$S_S = \max[S_a(0.2),\quad 0.9\max(S_a)] \tag{4}$$

$$S_1 = \max[S_a(1.0),\quad 2.0S_a(2.0)] \tag{5}$$

Here S_a is the spectral acceleration from the UHS at the rock level. The values of S_S and S_1 are usually mapped into probabilistic hazard maps for several return periods (e.g. 475 years). In addition to the definition of the seismic hazard at rock level, it is required to specify the soil amplification factors for the short and long period ranges. These amplification factors are used to modify the seismic hazard at the rock level to obtain the design spectra at the surface level. The procedure mentioned in Section 2.6 of this article leads to the definition of the response spectra at the surface level (RSS), based on a probabilistic seismic hazard analysis for the selected return period. This response

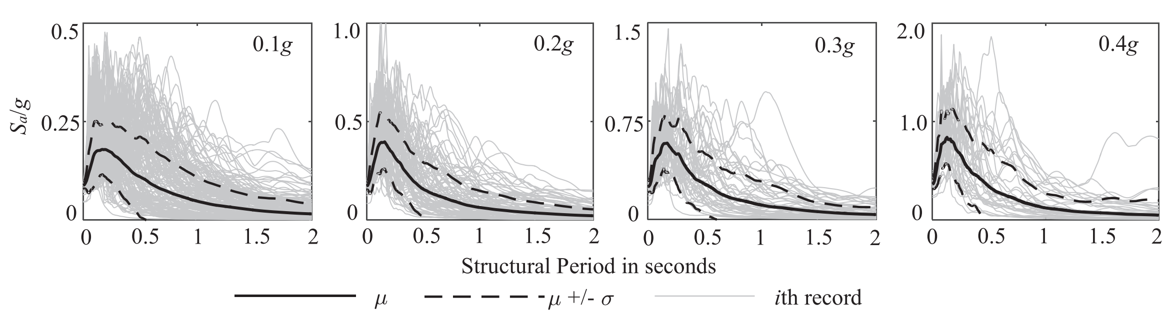

Fig. 9. Elastic response spectra (S_a) for sets of seismic records representing different PGA levels for the Benioff zone.

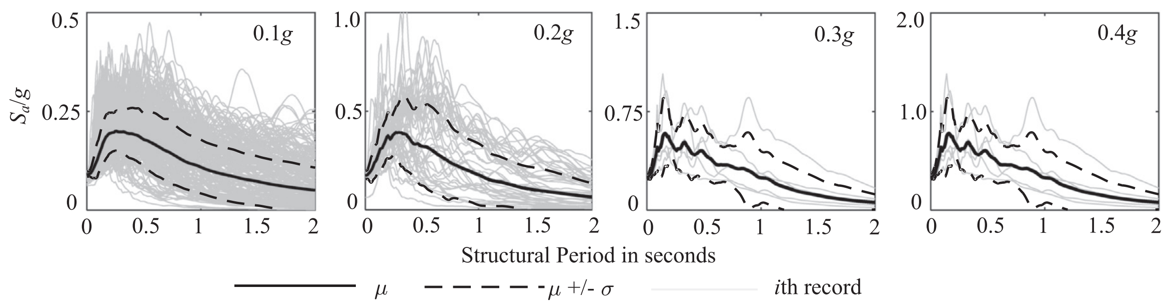

Fig. 10. Elastic response spectra (S_a) for sets of seismic records representing various PGA levels for the Romeral fault system.

spectrum is equivalent to the required site-specific procedure described in Chapter 21.4 of the ASCE7-10 [52]. In this study, we propose the use of Eqs. (6) and (7) to calculate the design spectral response accelerations S_{DS} at short period and S_{D1} at long period, for the amplified response at surface level. In Eqs. (6) and (7), S_a corresponds to the spectral accelerations estimated at surface level (see Section 2.6).

$$S_{DS} = \max[S_a(0.2),\quad 0.9\max(S_a)] \tag{6}$$

$$S_{D1} = \max[S_a(1.0),\quad 2.0S_a(2.0)] \tag{7}$$

In order to account for the amplification effects of soft soil deposits, the ASCE7-10 [52] introduces site coefficients for short-periods, F_a, and long-periods, F_v, which are explained in Chapter 11.4 of the standard. The expressions used to evaluate these parameters are shown in Eqs. (8) and (9).

$$F_a = S_{DS}/S_S \tag{8}$$

$$F_v = S_{D1}/S_1 \tag{9}$$

The computed site coefficients F_a and F_v represent the dynamic behavior of the soil and account for the probabilistic soil amplification factors mentioned in Section 2.4 of this paper. The obtained bedrock acceleration parameters S_S and S_1 provide updated probabilistic seismic hazard for the area of study. S_{DS} and S_{D1} represent the expected design parameters at surface level. Those parameters can also be mapped into the study area to propose a uniform and consistent geographical distribution of the design parameters. The application of the methodology require the following additional considerations: (1) a compatibility has to be maintained between the quality and material properties of the bedrock as specified in the PSHA model and the one adopted for the 1D or 2D soil profile models for assessing dynamic response; (2) the UHS at bedrock is usually defined by national regulations for all territories and therefore consistency with microzonation specification is required; and (3) all spectra are specified for a 5% effective structural damping unless otherwise noted. Fig. 3 summarizes the main parameters adopted for design at both rock level and surface level according to the previous formulation.

3. Study case and application

A study case is presented for the city of Medellín, located in the Andean region of Colombia. The city has an extension of approximately 381 km^2 [60] with a population of about 2,529,403 [61]. This area is prone to a medium to high seismic hazard controlled by one local superficial fault system (Romeral fault system) and by the Benioff zone of the subduction process that characterizes all the Pacific shoreline of Colombia [62]. Although no catastrophic earthquake has been reported in the zone in the recent history, several small events and seismologic studies demonstrate that the Romeral fault and the Benioff zones could generate earthquakes with magnitudes of 7.6 and 8.0, respectively [63]. In addition, the region is characterized by complex geological and geotechnical conditions including rocks from different geological periods, origin and compositions and soils deposits with several meters thick composed by residual soft soils, alluvial deposits, and colluvium deposits generated from hillsides flows, thus producing a highly heterogeneous soil profile in the study area [64]. Fig. 4 presents the digital elevation model and a simplified version of the geological map for the region of study.

3.1. Probabilistic hazard assessment

A standard probabilistic hazard assessment was conducted using the updated information available and by following the same methodological approach followed by the National Seismic Hazard Assessment Study for Colombia [63]. A set of ground motion prediction equations (GMPE) was used to represent the attenuation of the ground motion intensity for the fault systems. The Campbell and Bozorgnia Strike model for shallow crust zones [65], the Campbell and Bozorgnia Reverse model for subduction zones [65], and the Chiou & Youngs model [66] for the Benioff zones. These GMPE were selected based on results published in previous studies [63,64]. The seismic hazard assessment

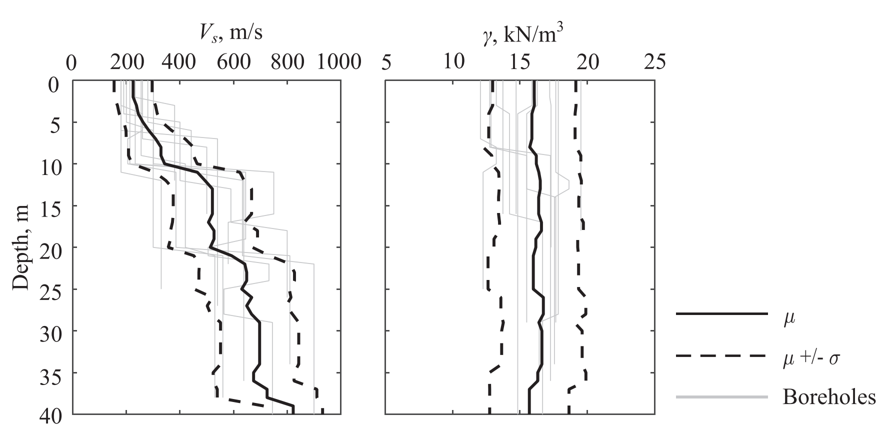

Fig. 11. Statistical characterization of the shear wave velocity and unit weight for the alluvial deposits.

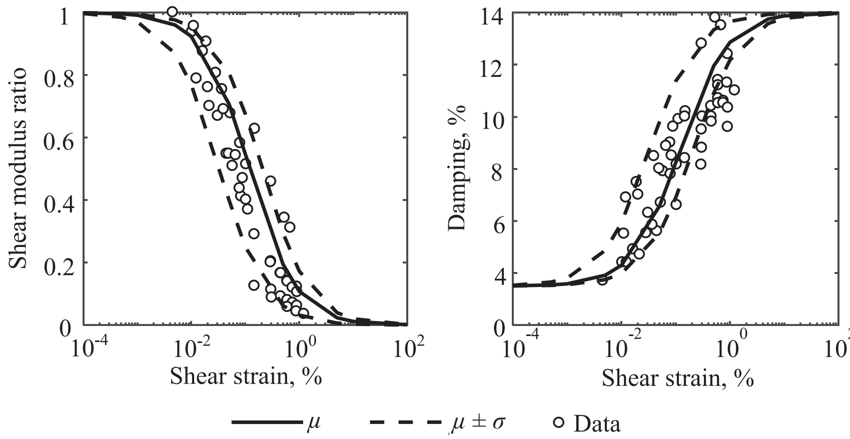

Fig. 12. Dynamic models characterization for the alluvial deposits.

was performed using the software CRISIS 2015 [67]. As result, seismic hazard curves, UHS and maps for different intensity parameters (e.g. PGA or S_a for several structural periods) were obtained at any location within the area of study (see Fig. 5a). Uniform hazard spectra were calculated for the following return periods: 31, 225, 475, 1000 and 2500 years. Fig. 5b illustrates representative results of the probabilistic hazard assessment at bedrock for the area under analysis. In addition, the bedrock ground motion parameters S_S and S_1 were obtained for a 10% probability of exceedance in 50 years. The resolution used to calculate the spatial distribution of these parameters corresponded to a uniform grid spaced every 100 m. Fig. 6 presents representative results of the probabilistic hazard assessment at bedrock for the area of study.

3.2. Seismic record selection

A seismic de-aggregation was conducted to obtain the hazard contribution of the different magnitude-distance combinations for a return period of 475 years and the source participation ratios from the seismic hazard curves shown in Fig. 5a. Fig. 7 shows the de-aggregation for an exceedance rate of 1/475. Several databases were used to select ground motions for the two seismic sources with the largest contributions to the seismic hazard of Medellín (see Fig. 8a), such as: CSN Universidad de Chile [68], Laboratorio de Ingeniería Sísmica Costa Rica UCR [69], Red Sísmica Mexicana UNAM [70], CEMOS Universidad Nacional de Ingeniería, Perú [71] and PEER NGA-West2, USA [72]. Seismic records from the South American databases above-mentioned characterize the seismic sources corresponding to Benioff zones (subduction). In addition, seismic records from the NGA2 West PEER database represent the Romeral fault system (shallow crustal). A total of 832 ground motion acceleration records from all databases were selected to evaluate the dynamic response of the 1D soil models (see Fig. 8b, 436 records for the Benioff zone and 369 for the Romeral fault system). The criteria followed to select the seismic records is listed below.

a) Range of magnitudes: $7 \leq M_w \leq 8$ (Benioff) and $5.5 \leq M_w \leq 6.5$ (Romeral)
b) Range of distances: $80 \leq R_{epicenter} \leq 150$ (Benioff) and $20 \leq R_{epicenter} \leq 40$ (Romeral)
c) Effective peak ground acceleration (PGA) of 0.1, 0.2, 0.3 and 0.4 g corresponding for the city of Medellín to return periods in the order of 50, 200, 500 and 2500 years.
d) Free field records
e) Soil types A or B.

From the complete set of records meeting the indicated criteria, subgroups of record, complying with the participation of the different magnitude-distance pair combination indicated before were selected for the 1D nonlinear analysis of all soil models. Fig. 9 shows the elastic response spectra (S_a) for different sets of seismic records for Benioff, and Fig. 10 presents the elastic response spectra for each set of records selected for Romeral fault system. As noted in the figures, a lower number of records were available for PGA of 0.3 and 0.4 g.

3.3. Geologic and geotechnical zonation and characterization

This study proposes a total of 17 geotechnical zones classification based on a careful revision of the geological, geomorphological, and geotechnical information available. In addition, available data comprises 113 geotechnical well-characterized soil profiles from previous studies developed in the region. The characterization of the soil stratigraphy includes the following criteria: (1) selected borehole logs must reach the bedrock depth (V_S = 760m/s) and (2) only boreholes with reliable information on the shear wave profile are included. Borehole logs are grouped for each geotechnical zone in order to obtain the statistical representation of the main parameters (depth to bedrock, number and type of soil deposits, shear wave velocity profile, unit weight and the dynamic soil properties and their variation with depth). Representative results of the gathered data are shown in Fig. 11, were the statistical characterization for the alluvial geological zone in terms of the shear wave velocity and unit weight are presented. In addition, each zone was characterized in terms of the dynamic behavior using all available results of cyclic triaxial, resonant column and bender element tests [73]. Models for the estimation of the shear modulus and hysteretic damping ratios at different shear strains were defined using the procedure proposed by Caicedo et al., [74] (see Fig. 12).

3.4. Soil dynamic response assessment

As explained previously, the characterization of each geological zone involves a series of Monte Carlo simulations. A total of 200 stochastic soil profiles were generated to assess the variability on the geotechnical and dynamic properties per zone. Lognormal probability distribution functions were assigned to the shear wave velocity profiles (V_s), whereas normal probability distributions were assigned to the unit weight profiles (γ) and to the dynamic properties (shear stiffness and damping). Soil layers thicknesses were modeled with a uniform distribution and depths to bedrock were defined as the depth at which (V_s) reached a value of 760 m/s for each stochastic profile. Subsequently, one-dimensional dynamic analyses were conducted for each stochastic profile using the group of records selected the procedure described in Section 3.2. To account for the nonlinearity effects, equivalent linear analyses were performed using SHAKE-91 [31]. The spectral amplification factors were grouped for different levels of seismic intensity (PGA in the ranges of 0.1 g, 0.2 g, 0.3 g, 0.4 g) as well as for FSVP ranges

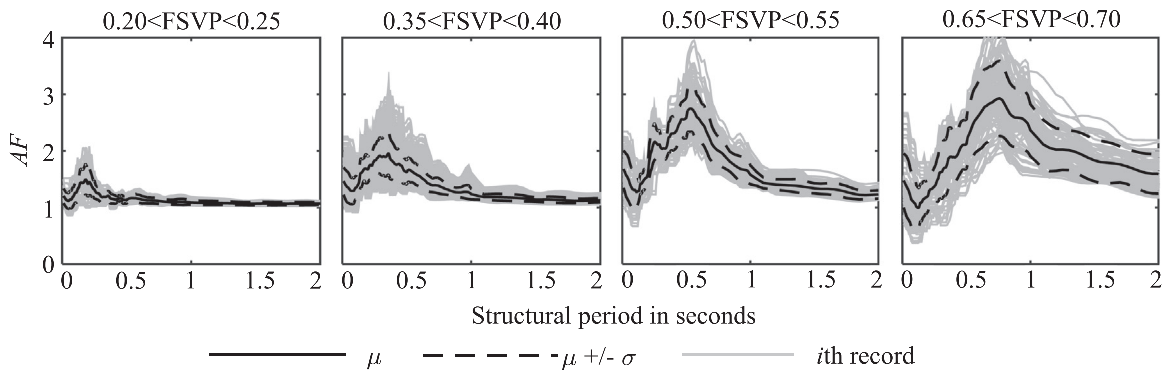

Fig. 13. Soil Amplification factors for different FSPV ranges and a ground motion PGA of 0.2 g for alluvial deposits.

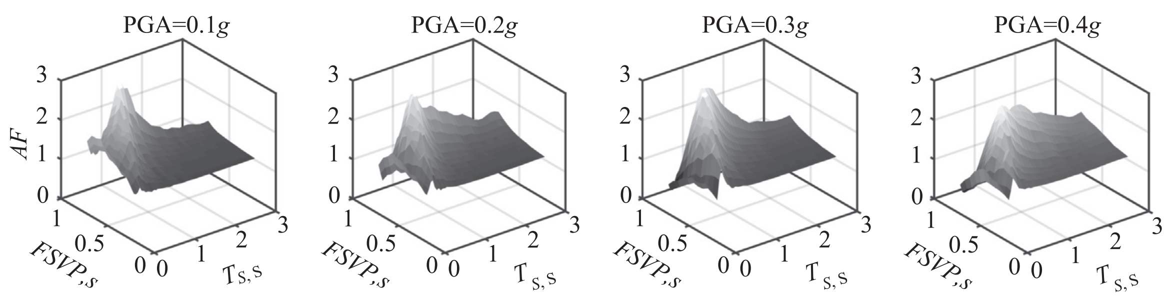

Fig. 14. Surface amplification factor spectra.

spaced every 0.05 s and starting at 0.2 s. Mean and standard deviation of spectral amplification factors were calculated for each combination. Fig. 13 shows the resulting mean and deviation values of the spectral amplification factors for PGA of 0.2 g and several FSVP ranges for the alluvial deposits. Additionally, the procedure explained in Section 2.4 allowed the generation of surfaces of amplification factor spectra (AFS) for the alluvial zone (see Fig. 14). These surfaces integrate all the results of the amplification factors spectra, fundamental soil vibration periods and structural periods of vibration at different intensity levels for a determined geotechnical zone.

3.5. Soil vibration period map

Data collected from a large set of microtremor measurements and borehole surveys allowed the generation of the fundamental soil vibration period map (FSVP map). Geological boundaries were delineated to include the firm rock deposits boundaries where an FSVP of about 0.2 g was assigned. These geological boundaries were defined based on geological and geomorphological maps as well as the information extracted from the digital elevation model. The construction of an FSVP map involves the interpolation of the available data before-mentioned, resulting in a spatial distribution of the fundamental vibration period of the soil deposits. Fig. 15 shows the collection of points where information was available, the geological boundaries and the FSVP map obtained from the interpolation process.

3.6. Illustrative evaluation of response spectra at surface level

The results of the PSHA and spectral amplification factors were integrated following the proposed methodology (see Section 2). The area of study was discretized with a uniform grid where the UHS at rock level and the spectral amplification factors were obtained through the implementation of the LHS technique explained in Section 2.4. Fig. 16 illustrates some of the results that are obtained in the calculation process and Fig. 17 shows the spatial distribution of acceleration values at surface for different structural periods, T_s. The presence of deep deposits of soft soil materials in the valley considerably increases the acceleration at large periods, an observation that is consistent with the FSPV distribution in the area (see Fig. 15c). The maximum PGA at surface is about 0.5 g, 65% larger than the maximum PGA obtained at the bedrock.

3.7. Soil amplification factors for design

The methodology presented in Section 2.7 is used to calculate the soil amplification parameters at the short and long structural period ranges (F_a and F_v). As shown in Fig. 18, the spatial distribution of the soil amplification parameters is highly related to the spatial distribution of FSPV (see Fig. 15c). The largest values of F_a are located in areas where the FSPV ranges between 0.2 and 0.4 s (short period range), a behavior that agrees with the amplification functions showed in Fig. 13. In this figure, the peak response is found to be at a period less than 1.0 s. In addition, the values obtained for F_v increase in areas with FSPV values in the long period range. For every point within the study area, the calculation of the short-period site coefficient (F_a) and long-period site coefficient (F_v) entails the use of Eqs. (4)–(9). Design parameters for this study case can be found in the web-based application www.sis-va.tk, where S_S, S_1, F_a and F_v are displayed in a uniform grid with 100 m spacing.

4. Validation of results

Precise calibration of soil amplification effects has always been a matter of intensive debate due to the high degree of uncertainties involved, lack of reliable and detailed information from past events and high variability of observed measurements. Aspects such as the seismological characteristics of the event, the geographic location, the local geological and geotechnical conditions may have a major influence in the resulting acceleration spectra. In this study, the information available for validation corresponds to seismic records obtained from the local strong motion network, Red Acelerográfica del Valle de Aburrá (RAVA). We used 973 seismic signals recorded in a total of 32 strong motion stations, from over 255 seismic events. Most stations were located on relatively soft soil profiles, and only three stations were

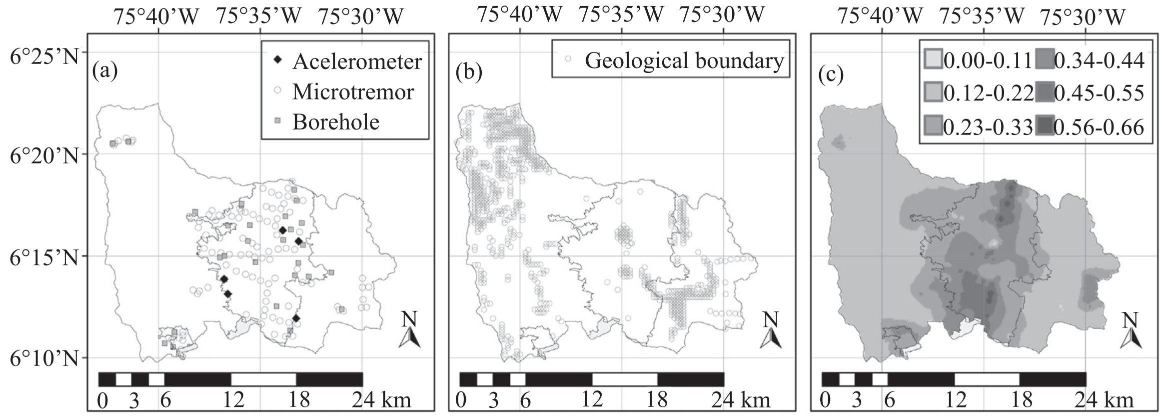

Fig. 15. (a) Location of seismic stations, microtremor measurements, and boreholes, (b) geological boundaries map, and (c) FSVP spatial distribution map.

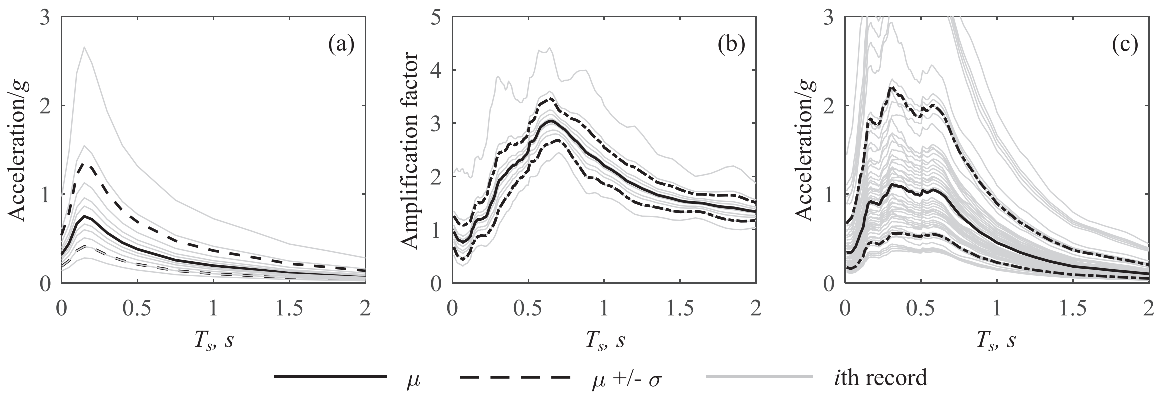

Fig. 16. LHS method used for obtaining UHS at surface: (a) UHS at bedrock, (b) Amplification Factor Spectra, (c) UHS at surface.

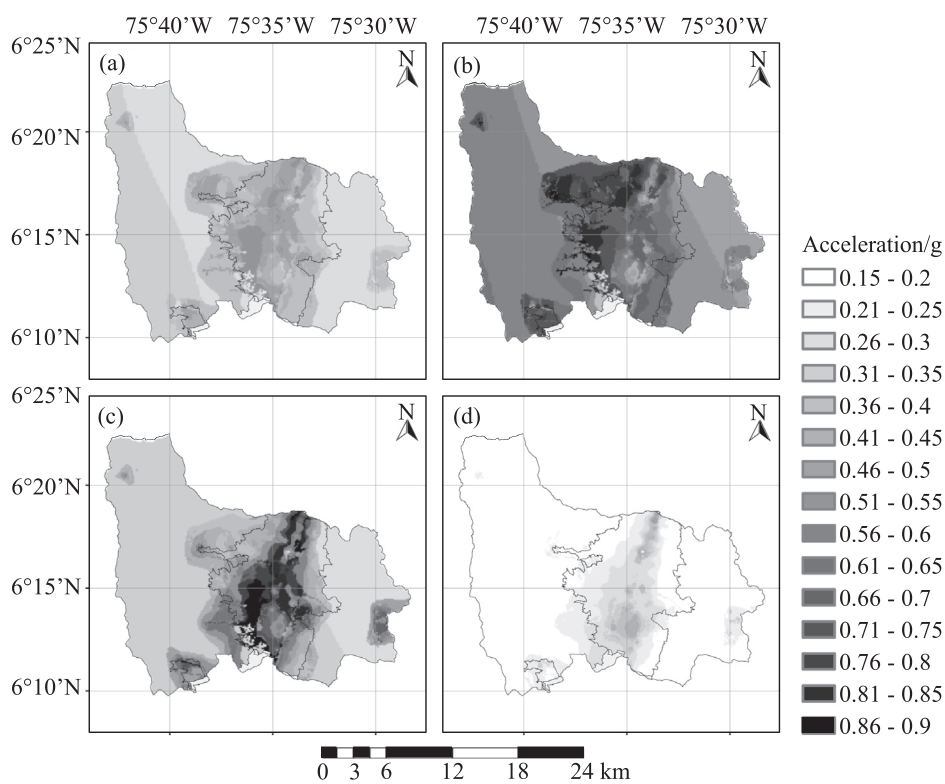

Fig. 17. Spatial distribution of accelerations for a return period of 475 years. (a) T_s = 0s (PGA), (b) T_s = 0.1s, (c) T_s = 0.5s, and (d) T_s = 1s.

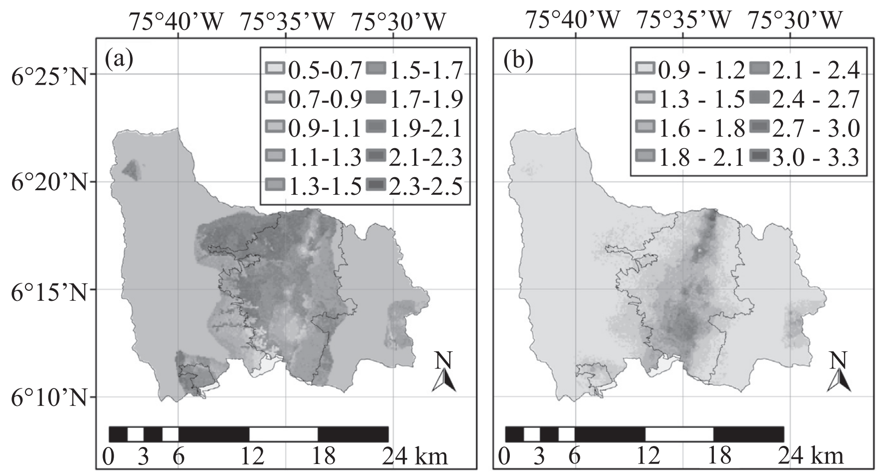

Fig. 18. Spatial distribution of the design parameters (a) F_a and (b) F_v.

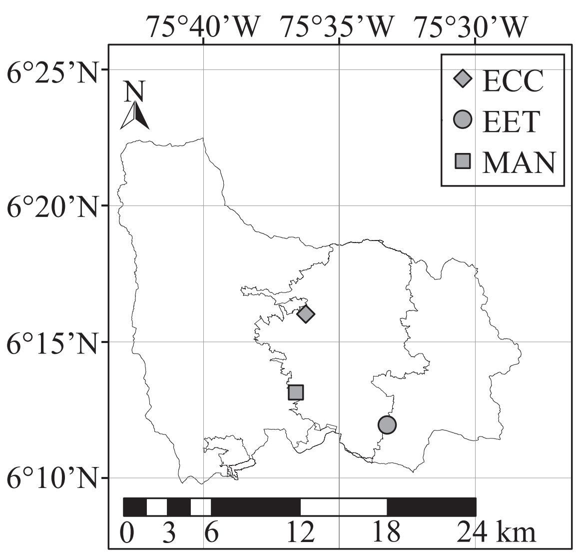

Fig. 19. Location of three reference accelerographic station.

located on verified bedrock outcropping formations. The network has recorded low magnitude earthquakes from multiple seismic sources, all of them with a PGA lower than 0.1 g. No significant nonlinear response is then expected considering the maximum seismic intensities available in the data recorded by the local seismic network. The seismic records were useful to estimate site response parameters for validation and calibration, as they entail key information about the seismicity conditions of the region as well as the dynamic soil response of the soil where each station is located. The information was used to validate amplification factors as well as predominant vibration periods at the precise locations of the accelerographic stations. A raw depuration of the catalog was performed removing incomplete or not seismic associated measurements. Standard baseline correction and noise filtering processes were applied to all seismic records. Results are presented for three representative stations, "Centro Control EPM" – ECC, "Colegio Padre Mayanet"– MAN, and "El Tesoro" – EET, (located as shown in Fig. 19) corresponding to the Alluvial deposits zone, Mud and Debris flow deposits zone, and the "Gabros" residual soil zone, respectively.

Spectral amplification factors for the three selected stations are presented in Fig. 20. The top row presents the spectral amplification factors obtained from analytical models considering all sources of uncertainty. The bottom row shows the corresponding spectral amplification factors obtained from the analysis of all available seismic records. Note that alluvium sites (ECC) show lower amplification factors than Gabros sites (ETT). This is due to the high consolidation level of most alluvial deposits, and the considerable degradation of the residual soils (Gabro) due to weathering effects, particular conditions of the area under analysis. As shown in the figure, the mean values of the amplification factors, spectral shape, and structural period of the maximum amplification from the analytical and the measured data present a fairly well correspondence. The resulting variability from the analytical models are in all cases, somewhat higher than the ones from the set of measurements, a fact that is reasonable considering the limited extent of the available records. It is also clear that the uncertainty tend to increase as the fundamental soil vibration period of the deposit increases (softer soil profiles) which again seems reasonable considering the higher variability of profiles and properties of softer soils as compared to stiffer deposits. Finally, it becomes evident that the set of analytical models representing the dynamic response at each location is overestimating the uncertainty, especially for the long period range of the response. It is the opinion of the authors that the proposed method to model the expected soil response is consistent with the available records from several low magnitude events. In addition to the previous analysis, the available information allows a validation of results in terms of the fundamental soil vibration periods, FSVP, the key parameter that allows the integration of all the analytical information and the actual expected dynamic behavior of the soil deposits. Predominant vibration periods were computed using the H/V ratio from micro tremor measurements [29,75] and from all sets of available seismic records. Fig. 21 presents the results for the three selected stations (see Fig. 19). The upper row corresponds to the microtremor measurements and the lower row correspond to the results from seismic records. Results demonstrate a fairly good agreement in the shape of the H/V relation for the frequency range of interest and on the final range of the FSVP values (peak responses).

Seismic records present, as expected, a higher variability of results. The main differences observed may be attributed to: (1) the seismic records comes from different sources and a range of magnitude earthquake; (2) microtremors may be easily affected by local noise such as traffic or any other disturbance; and (3) microtremor measurements are usually more reliable for softer deposits than for rigid ones. All previous results highlight the importance of having an acceptable, representative and reliable set of in-field measurements of the seismic response using different sources such as strong motion accelerographs and/or microtremor measurements. The reduction of uncertainties and the final validation of analytical models depend completely on the availability of high quality information on the actual seismic response of soil deposits.

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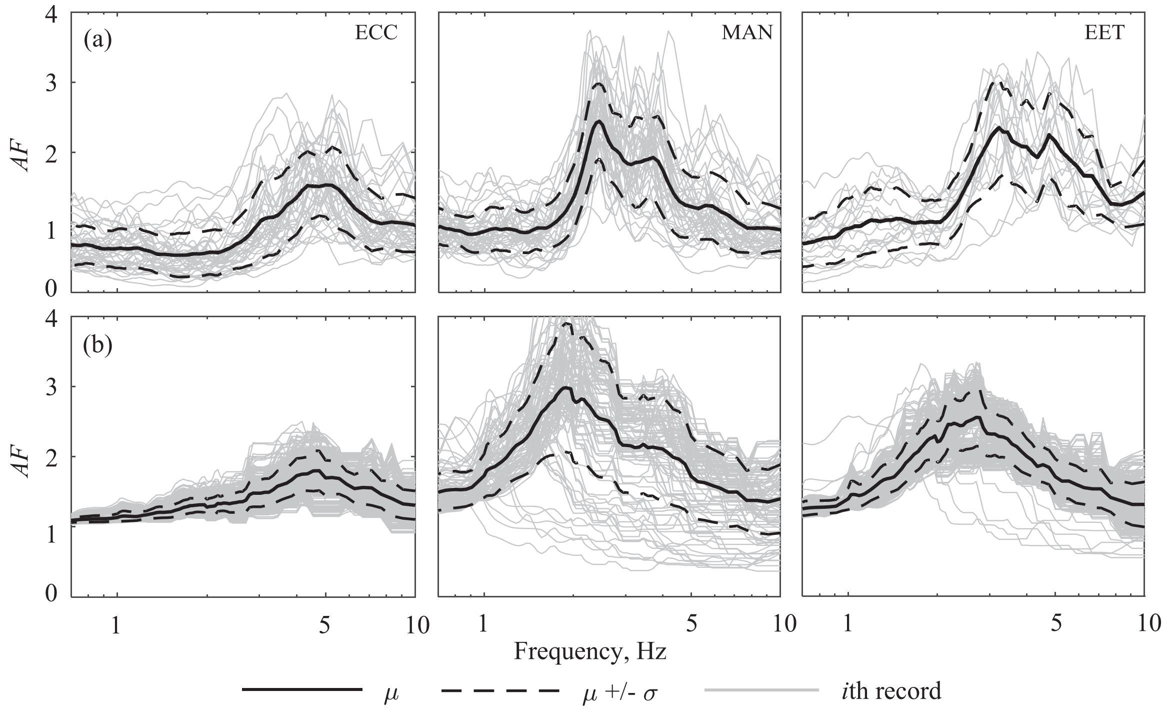

Fig. 20. Spectral amplification factors (a) seismic records and (b) analytical 1D model.

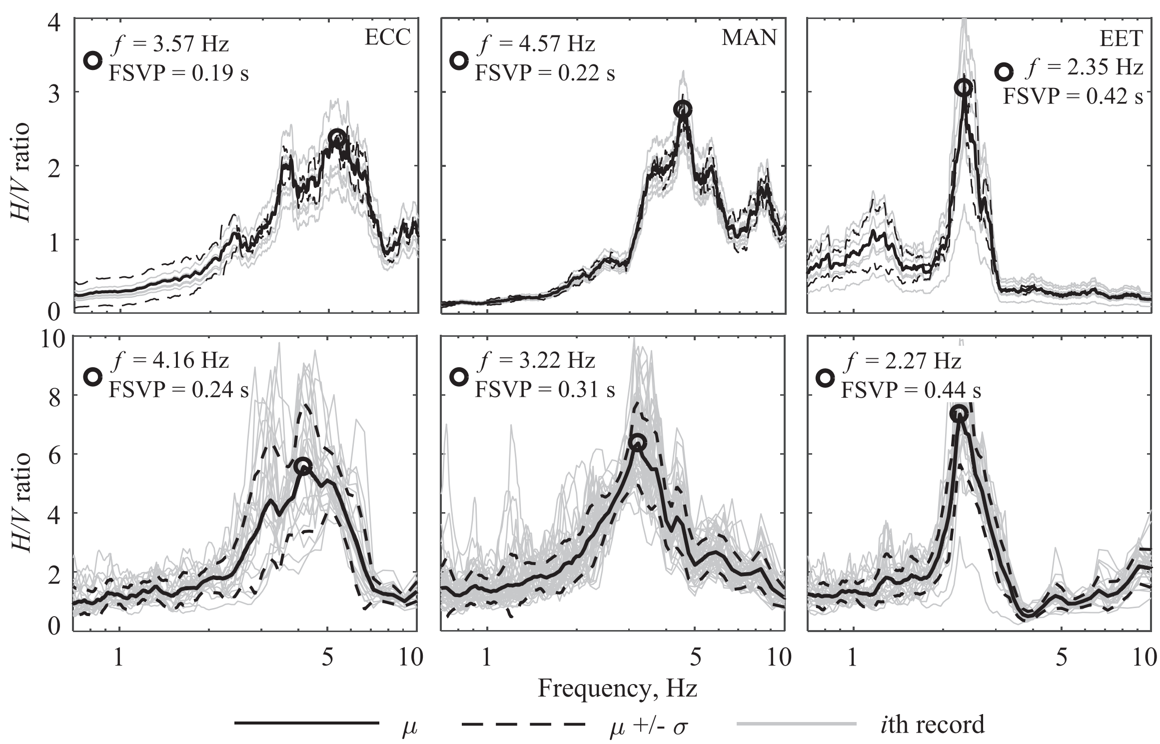

Fig. 21. H/V ratio comparison (a) microtremor measurements and (b) seismic records.

5. Conclusions

We propose a novel approach for assessing the dynamic response of soils deposits in complex geological environments and integrate them for seismic microzonation purposes. The methodology integrates in a practical, consistent and rational way all the available information, both from analytical modeling and from field measurements. First, a standard probabilistic hazard assessment is used as the basic input at the rock basement. An integrated geologic and geotechnical model is used to estimate the geographical variation of the soil profile amplification factors in the area of analysis. A computational algorithm which generates Monte Carlo simulations using the Latin Hypercube sampling method is proposed to assess the uncertainties in the seismic response. Spectral amplification factors are generated at each location for a representative range of fundamental soil vibration periods and ground acceleration levels. In order to integrate the results obtained from the analytical modeling process, a fundamental soil vibration period map is generated using all available field measurements (seismic records, microtremor measurements or any other data that allows a reliable estimation of the soil profile vibration period). Acceleration uniform hazard spectra are generated both at bedrock and the surface of the soft soil deposits. Using these results, soil amplification factors are determined for the short and long period range of the design spectra.

The proposed methodology is applied to a practical case, the seismic microzonation of the city of Medellín, Colombia. The urban area of the city was divided into 17 geotechnical zones. A 100×100 m grid was used to estimate the spectral amplification factors and to generate maps for the main seismic design parameters. A web-based application (www.sis-va.tk) integrates the final seismic design recommendations for the case study, in terms of spectral values at the surface of the deposits that allows potential users to consult all related seismic information in the area of interest, in particular the final design spectra at bedrock or at the soil surface. The results are also presented as a set of spectral amplification factors for different seismic intensities for a given grid distribution in the area of interest. The validation of results was possible using an existing catalog of seismic records. The analysis demonstrates that the set of analytical models proposed to estimate the expected seismic response at any particular site represents fairly well both the amplification effects and the expected variability of results. The model slightly overestimates the uncertainty, especially for the long period range of the response, something that is reasonable considering the limitations of the available information. The application of the proposed methodology for the seismic microzonation of the city of Medellín clearly represent a significant advance in the assessment of the seismic hazard considering the local soil response. The modular step-by-step process allows periodic improvements of each piece of information. The results allow an immediate use in practical applications such as the seismic design of buildings and the seismic risk assessment using platforms such as CAPRA (www.ecapra.org).

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