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ANALYSIS OF EARTHQUAKE SITE RESPONSE AND SITE CLASSIFICATION FOR SEISMIC DESIGN PRACTICES

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ABSTRACT

In general, seismic provisions worldwide present different criteria for site classification, based on specific soil and rock properties, in order to determine representative design spectra for seismic design. On the other hand, results of site–specific analysis and seismic microzonation studies have shown not only the main properties of soil-rock profile that have marked influence on site response, but also site characteristics where it is necessary to carry out detailed and particular studies of earthquake ground response.

This paper analyzes and compares site classification for seismic design of some seismic codes worldwide, with results of site-specific analysis and seismic microzonation studies. These comparative analyses were carried out for different kind of soil profiles such as fine-grained alluvial deposits, hard and coarse alluvial deposits, lake deposits, colluvial deposits, deposits of volcanic ashes, residual soils of igneous, metamorphic and sedimentary rocks, among others. Results of these analyses show that site classifications of seismic provisions are not always representative of earthquake site response. Results and conclusions of this paper emphasize the importance of site-specific analysis for some soil-rock conditions, as well as illustrate the influence of some variables such as thickness of the soil profile until reaching bedrock, relationships of shear modulus reduction with cyclic shear strain, and bedrock stiffness on earthquake site response. Based on these results, this paper propose a methodology for site-specific analysis and seismic microzonation studies.

INTRODUCTION

Seismic codes worldwide have defined design spectra taking into account some site variables. However, those spectral shapes are not always representative of site response. This condition implies risks of underestimating or overestimating the earthquake site response, which has disadvantages since economical and seismic protection points of view.

Authors worldwide such as Dobry, R. (1991), Cruz, E.F. et al (2000), Estrada, G.M. (2001a), Lang, D. H. and Schwarz, J. (2006), Musaid A. (2006), Lang and Schwarz (2006), Rodríguez-Marek, A. et al (1999), Rodríguez-Marek, A. et al (2000), and Nikolaou, S. (2008) have analyzed cases and variables with influence on earthquake site response. The main conclusions of the works of these authors point out some characteristics and clue site variables that control the earthquake site behavior, as follow:

- Total thickness of the soil profile until reaching bedrock.
- Dynamic stiffness of the soil profile.
- Damping of the soil profile.
- Impedance ratio between the soil profile and the underlying rock.
- Geological origin of strata that compose the soil profile.
- Variation of seismic site response characteristics as a function of the ground motion intensity.

In addition, a correct quantification of site effects is necessary for a complete assessment of seismic hazard. In fact, the quantification of site effects must include a measure of uncertainty for its incorporation into a probabilistic seismic hazard assessment analysis.

Since it is not economically feasible to carry out detailed exploration and evaluation of site response for all building projects, seismic microzonation studies constitute a representative way to characterize earthquake site response of a region.

That is why it would be absolutely useful that seismic codes adopt seismic microzonation studies as a provision for cities with medium and high population.

SEISMIC CATEGORIES OF SOIL PROFILES ACCORDING TO SOME SEISMIC CODES

In general, site classification approaches established by international seismic codes can be divided into three different types:

- Site classification approaches based on soil stiffness variables: These approaches take into account shear wave velocity of the soil profile only until a certain depth to classify the site.

- Site classification approaches based on soil stiffness and depth variables: These approaches consider variation of the soil profile stiffness until the bedrock.

- Hybrid classification approaches: This kind of classification schemes analyzes stiffness of soil profile until a specific depth, as well as the total depth of the soil profile until the bedrock.

This paper analyzes site classification criteria of the 2006 International Building Code (IBC), the 2003 EuroCode 8, the German earthquake code DIN 4149:2005, and the 2000 Building Japanese Code. The site classification approach of the 2006 IBC and the Eurocode 8 disregards soil profile depth and uses only average shear wave velocity until 30m. The German earthquake code DIN 4149:2005 uses an hybrid approach for site classification, which takes into account average shear wave velocity of the uppermost 25 m and total thickness of soil profile above bedrock. The site classification of the 2000 Building Japanese Code require site-specific analysis to characterize earthquake ground response. Tables 1 to 3 summarize site classification criteria of these seismic codes.

The 2006 IBC and Eurocode 8 ignore soil profile depth until the bedrock, and use mean shear wave velocity over the upper 30 m as the primary parameter for site classification. Earlier versions of the United States Uniform Building Code before the 1997 UBC (e.g., 1976 UBC) evaluated site effects through a classification scheme based on natural site period, including both stiffness and soil profile depth parameters. The current approach of the 2006 IBC and Eurocode 8 has many practical advantages, but in some cases may lead to significant shortcomings in site response prediction (Rodríguez-Marek, A., et al, 2000).

In order to analyze criteria of these seismic codes to estimate earthquake site response, a group of nine soil profiles was chosen. These soil profiles involve alluvial deposits, colluvial deposits, deposits of volcanic ashes, and residual soils. Figures 1 to 9 illustrate geometrical characteristics and shear wave velocity variations of these soil profiles. These soil profiles have been studied in detail, and their transfer functions have been estimated using data of stiffness variation and total depth (until reaching the bedrock), as well as actual accelerograph records. Figures 10 to 18 show comparisons of these transfer functions with those resulting from applying criteria and provisions of the mentioned seismic codes.

Table 1. Reference variables for soil classification of the 2006 IBC, EuroCode 8, and DIN 4149: 2005.

Seismic Code	Reference variables for soil classification
2006 IBC EuroCode 8	Average shear wave velocity of the top 30 m of the soil profile (V_{S-30}), applying Equation (1): $V_{S-30} = \frac{30}{\sum_{i=1}^{L} \frac{h_i}{V_i}}$ (1) Where: *L*: Number of soil layers between the soil surface and the bedrock. *hi*: Thickness of the *i*-th soil layer. V_i: Shear wave propagation velocity of the *i*-th soil layer.
DIN 4149:2005	Average shear wave velocity of the top 25 m of the soil profile (V_{S-25}). Total height of soil profile until reaching bedrock.
2000 Building Japanese Code	The soil layers until the bedrock are reduced to an equivalent single soil layer, in terms of equivalent shear wave velocity of soil layers (V_{se}), equivalent mass density of soil layers (ρ_e) and equivalent damping ratio of soil layers (h_{se}), according to Equations (2) to (4). $V_{se} = \frac{\sum V_{si}.di}{H}$ (2) $\rho_e = \frac{\sum \rho_i.di}{H}$ (3) $h_{se} = \frac{\sum H_i.W_{si}}{W_{si}}$ (4) Where, V_{si}: Shear wave velocity of the soil layer *i* (m/s). d_i: Thickness of the soil layer *i* (m) . ρ_i: Mass density of the soil layer *i* (t/m^3). d_i: Thickness of the soil layer *i* (m). h_i :Viscous damping ratio of the soil layer *i*. W_{si} : Potential energy of soil layer *i*.

Table 3. Site classifications of the 2006 IBC, EuroCode 8, and DIN 4149: 2005.

Seismic Code	Site Classifications
EuroCode 8	A: $V_{S-30}>800$ m/s B: $360<V_{S-30}\leq 800$ m/s C: $180<V_{S-30}\leq 360$ m/s D: $V_{S-30}<180$ m/s E: A particular kind of soil stratigraphy in which a soft surface layer (type C or D) is placed over a hard soil (type A).
2006 IBC	A: $V_{S-30}>1500$ m/s B: $800<V_{S-30}\leq 1500$ m/s C: $360<V_{S-30}\leq 800$ m/s D: $180<V_{S-30}\leq 360$ m/s E: $V_{S-30}<180$ m/s E: Any profile with more than 10 feet of soil having the following characteristics: - Plasticity index PI>20 - Moisture content W≥40% - Undrained shear strength Su<500 psf. F: Any profile containing soils having one or more of the following characteristics: - Soils vulnerable to potential failure or collapse under seismic loading such as liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils. - Peats and/or highly organic clays (*H* > 10 ft of peat and/or highly organic clay where *H* = thickness of soil). - Very high plasticity clays (*H* > 25 feet with plasticity index *PI* > 75) - Very thick soft/medium stiff clays (*H* > 120 feet). Profiles containing distinctly different soil and/or rock layers shall be subdivided into those layers in the upper 30,48 m.
DIN 4149:2005	A-R: $V_{S-25}>800$ m/s | $h_{total}<25$ m B-R: $350<V_{S-25}<800$ m/s | $h_{total}<25$ m C-R: $150<V_{S-25}<350$ m/s | $h_{total}<25$ m B-T: $350<V_{S-25}<800$ m/s | $h_{total}<100$ m C-T: $150<V_{S-25}<350$ m/s | $h_{total}<100$ m C-S: $150<V_{S-25}<350$ m/s | $h_{total}>100$ m
2000 Building Japanese Code	Soil profiles are characterized by the soil amplification factor $G_s(T)$, which is estimated through the ratio of response spectra. This analysis is based on evaluation on earthquake ground motion by an equivalent soil layer above the engineering bedrock applying the one-dimensional wave propagation theory.

Figures 10 to 18 show that estimation of earthquake ground response through site classifications of seismic provisions is not always representative.

In general, the analysis of transfer functions of Figures 10 to 18 indicates that total soil profile depth above the bedrock has a marked influence on seismic site response. Results of these comparative analysis show differences not only on ratio of response spectra, but also on region of periods with maximum ratio of response spectra. These differences are more marked in soft soils than in stiff soils. However, only transfer functions associated with soil profiles from ECC and SPE sites adjust to tendencies of the amplification functions of the studied seismic codes.

It is important to highlight that ECC and SPE sites correspond to the stiffest soil profiles from those analyzed in this paper. Figure 15, which represents the earthquake site response of SPE site, shows differences on amplification values of site-specific analysis and the selected building codes ranging from 10% up to 300%. The same evaluation at ECC site points out differences of about 140% to 220% in amplification levels obtained through site-specific analysis and the selected building codes. These differences may lead to underestimate or overestimate spectral accelerations for the specific seismic design of a building.

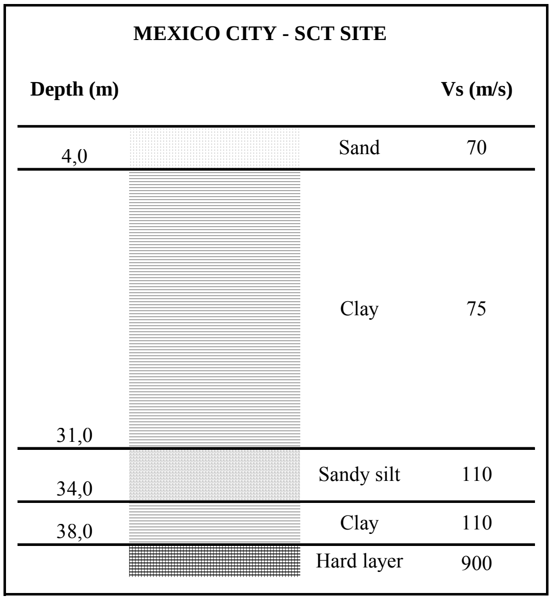

Figure 1.Soil profile at SCT site in Mexico City (Dobry, R., 1991).

Representative quantification of site effects is required to reach optimal cost of design, construction and maintenance of buildings during their useful life, which means to obtain an equilibrium point between initial investment on design and construction of the building and its expected performance under earthquake. The higher costs of site-specific analysis can lead to more representative earthquake design for the specified limit states of each seismic code, which can imply better structural performance, and therefore, lesser costs of reparation or reconstruction of the building during its useful life. In this way, the quantification of site effects must be incorporated into probabilistic seismic hazard assessment, so that, uncertainties on soil properties must be included. This consideration emphasizes the need of adopting requirements of site-specific analysis or seismic microzonation studies in design provisions.

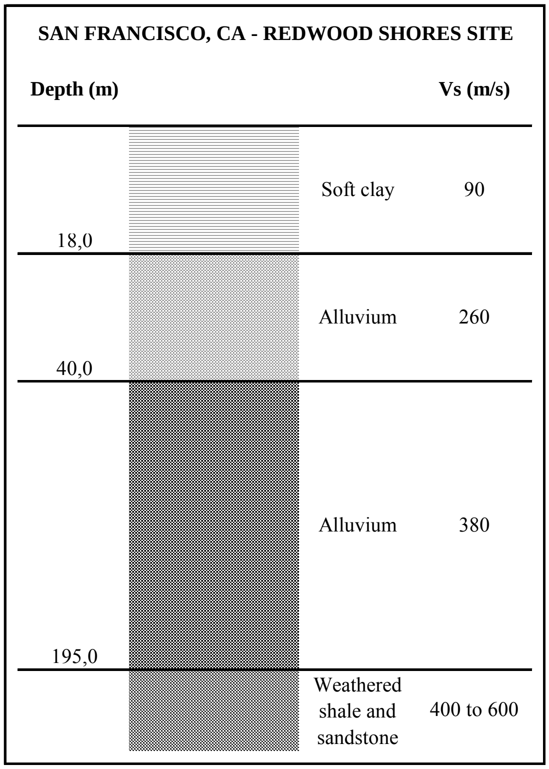

Figure 2.Soil profile at Redwood Shores site in San Francisco (Dobry, 1991).

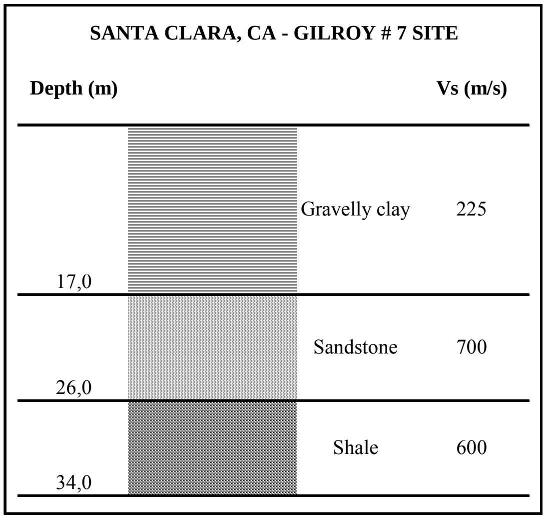

Figure 3.Soil profile at Gilroy # 7 – Mantelli Ranch site in Santa Clara, California (Gibbs, J.F et al, 1993).

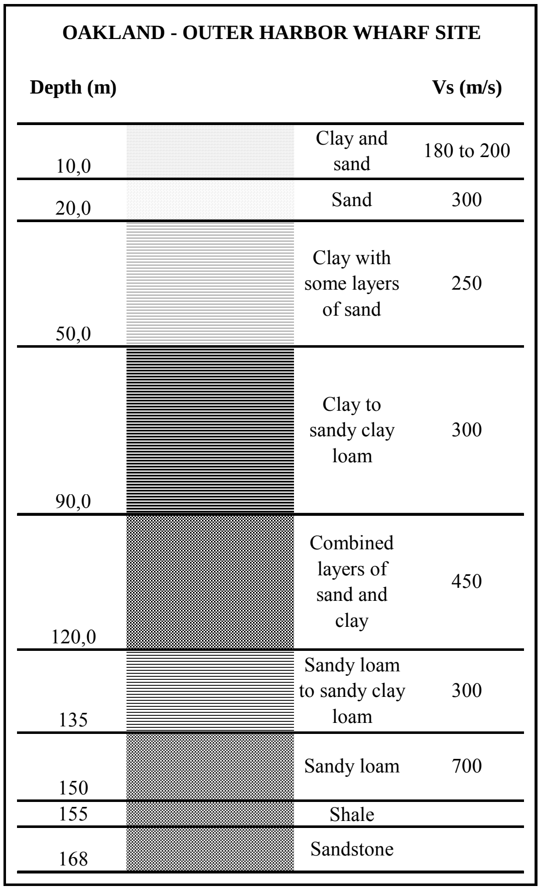

Figure 4.Soil profile at Outer Harbor Wharf site in Oakland, California (Gibbs, J.F et al, 1992).

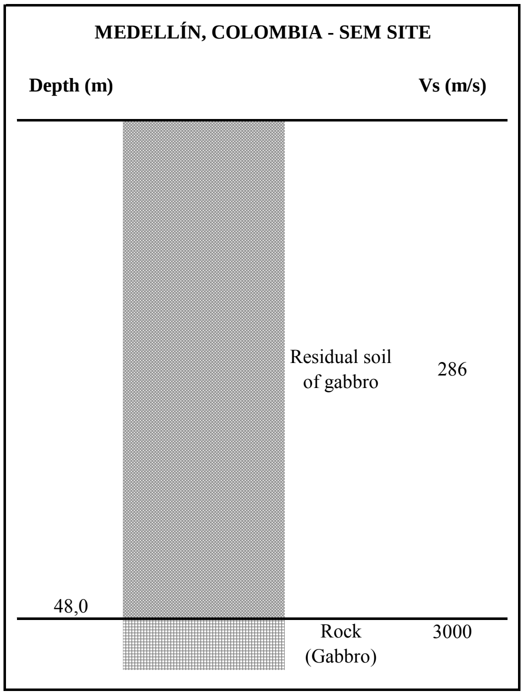

Figure 5.Soil profile at SEM site in Medellín, Colombia (Integral S.A. et al, 1999).

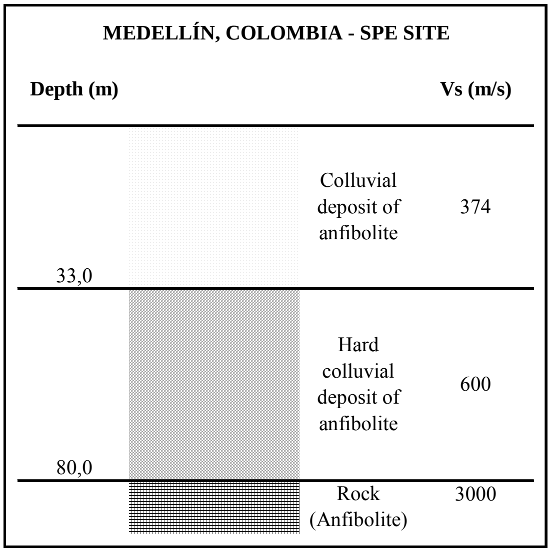

Figure 6.Soil profile at SPE site in Medellín, Colombia (Integral S.A. et al, 1999).

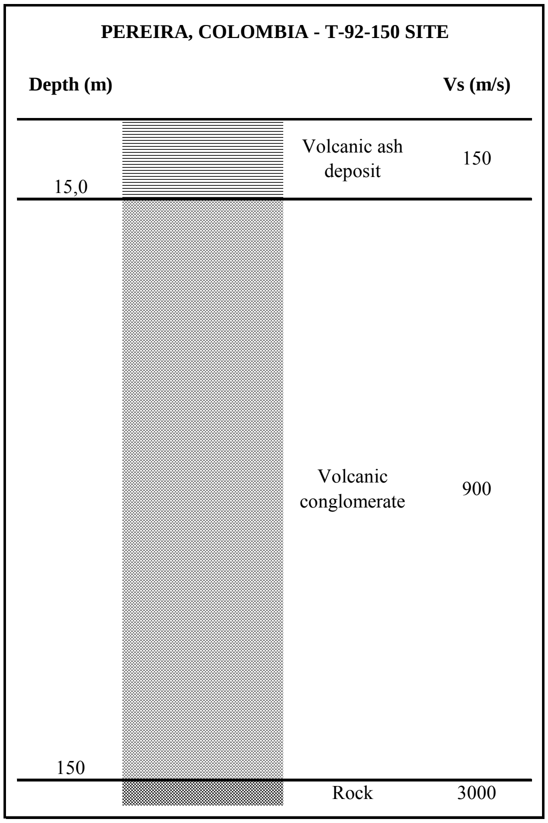

Figure 7. Soil profile at t92-150 site in Pereira, Colombia (Estrada, G.M and Jaramillo, J.D., 2001).

The 2000 Building Japanese Code constitutes a good example of this approach, because it rules site-specific analysis to evaluate earthquake ground response. This code require estimation of ratio of response spectra for the soil profile under study, based on definition of an equivalent soil layer that represents the soil profile properties above the bedrock. This requirement involves earthquake site response analysis using the one-dimensional wave propagation theory.

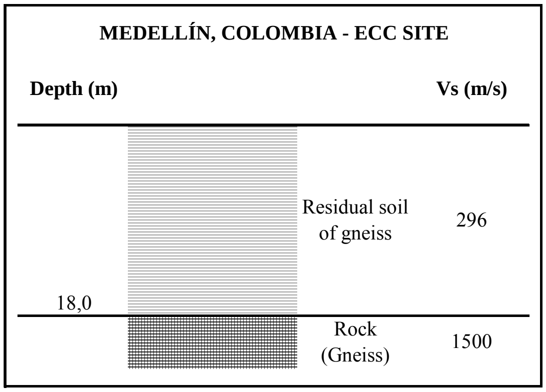

Figure 8. Soil profile at ECC site in Medellín, Colombia (Integral S.A. et al, 1999).

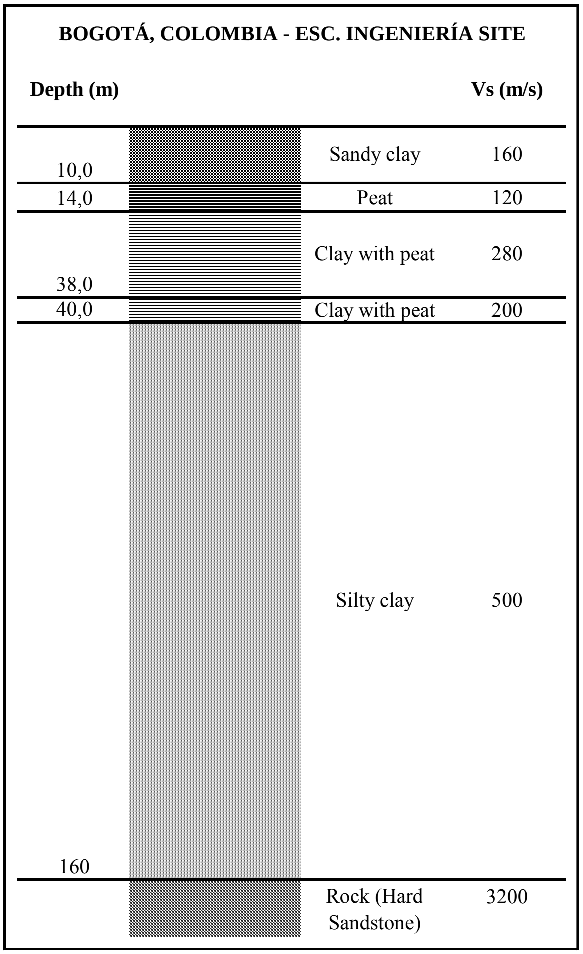

Figure 9.Soil profile at ESC. INGENIERIA site in Bogotá, Colombia (U. de Los Andes et al, 2000).

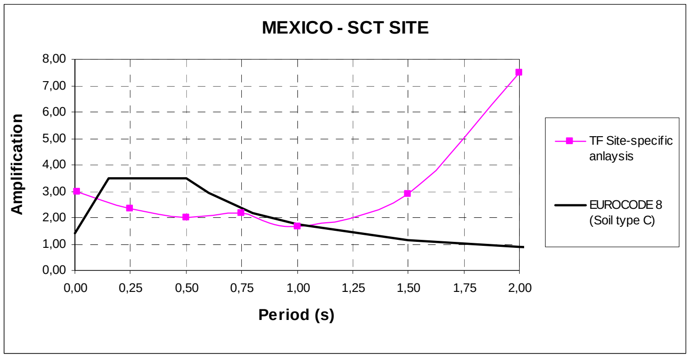

Figure 10. Transfer function of site-specific analysis with amplification functions of some seismic codes – Mexico (SCT site).

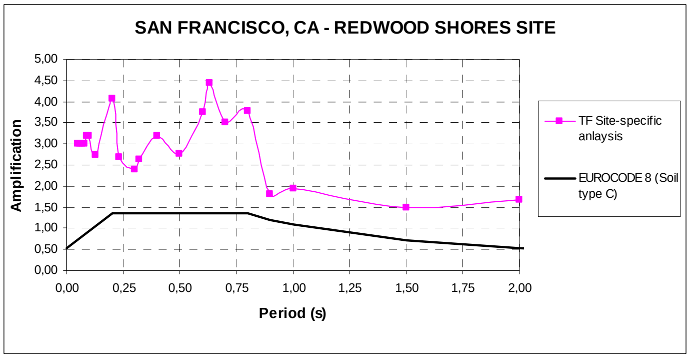

Figure 11. Transfer function of site-specific analysis with amplification functions of some seismic codes – San Francisco (Redwood shores site).

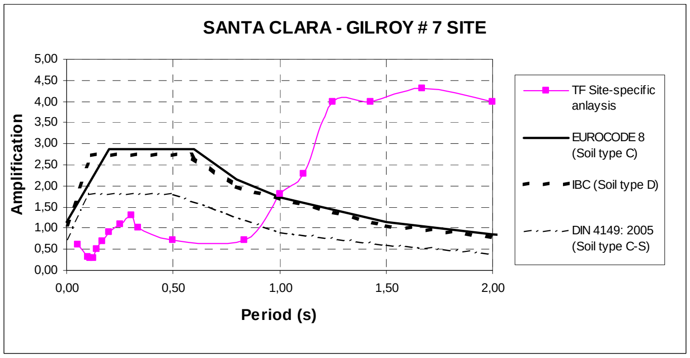

Figure 12. Transfer function of site-specific analysis with amplification functions of some seismic codes – Santa Clara (Gilroy # 7 site).

On the other hand, the 1998 Building Colombian Code incorporates seismic microzonation studies (for cities with more than 100.000 inhabitants) as a methodology to estimate earthquake site response.

Microzonation studies have been adopted widely in Colombia, including the installation of accelerograph networks as their first stage. The results of these studies have been very useful on characterization of earthquake ground response. In fact, soil profiles shown in Figures 5 to 9, correspond to studied soil profiles as part of seismic microzonation studies of the cities of Medellín, Bogotá and Pereira (Colombia).

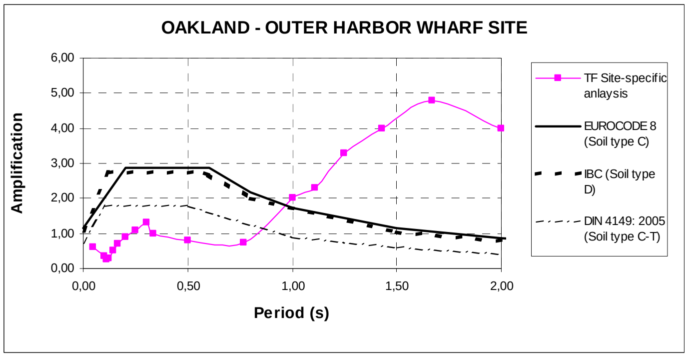

Figure 13. Transfer function of site-specific analysis with amplification functions of some seismic codes – Oakland (Outer Harbor Wharf site).

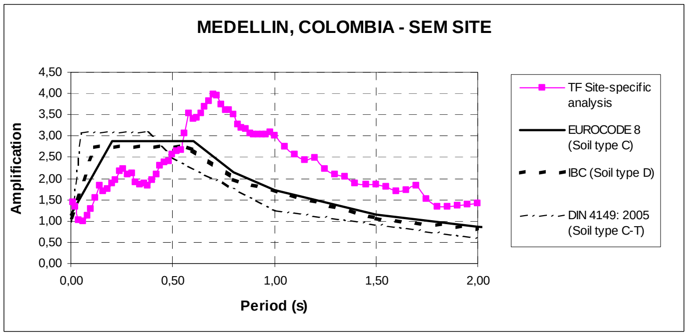

Figure 14. Transfer function of site-specific analysis with amplification functions of some seismic codes – Medellín, Colombia (SEM site).

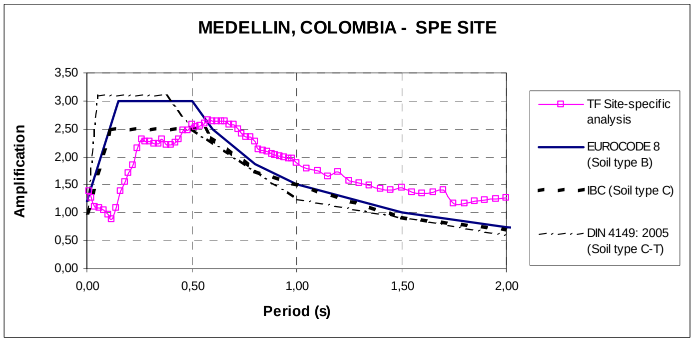

Figure 15. Transfer function of site-specific analysis with amplification functions of some seismic codes – Medellín, Colombia (SPE site).

ANALYSIS OF EARTHQUAKE SITE RESPONSE

The characteristic transfer functions of the nine soil profiles presented in this paper, confirm the strong influence of local site conditions on the characteristics of ground surface motions, and therefore on the results of the seismic hazard assessment. These analysis have also pointed out that the amplification phenomena are not only associated to soft soils, but also to stiff soils. Moreover, the accelerograph networks in regions, where detailed seismic microzonation studies are carried out, have confirmed these issues (Integral S.A. et al, 1999; Integral S.A. et al, 2002).

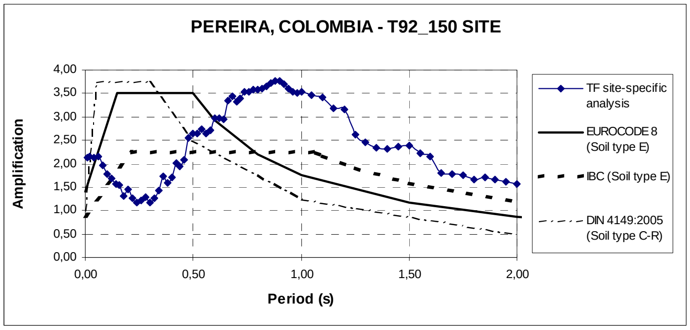

Figure 16. Transfer function of site-specific analysis with amplification functions of some seismic codes – Pereira, Colombia (T92-150 site).

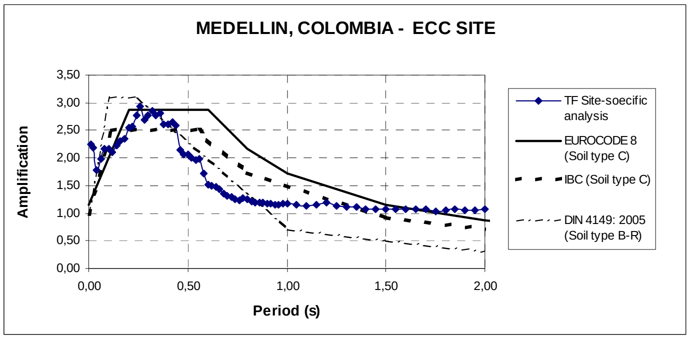

Figure 17. Transfer function of site-specific analysis with amplification functions of some seismic codes – Medellín, Colombia (ECC site).

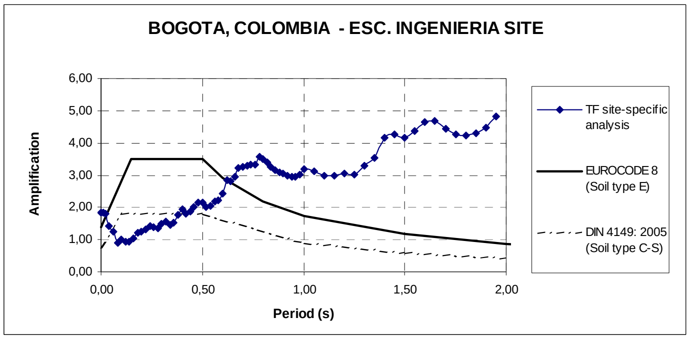

Figure 18. Transfer function of site-specific analysis with amplification functions of some seismic codes – Medellín, Colombia (ESC. INGENIERIA site).

In general, results of the analysis presented in this paper emphasize the importance of site-specific analysis for some soil-rock conditions, as well as illustrate the influence of some variables such as thickness of the soil profile until reaching bedrock, relationships of shear modulus reduction with cyclic shear strain, and bedrock stiffness on earthquake site response.

The differences on seismic response of different sites are related to topographical and geotechnical diversity. In general, the earthquake ground response of a soil profile is a function of parameters such as the following:

- Impedance ratio rock-soil, which is a function of the total unit weight of rock and soil, and the shear wave velocities of rock and soil (Dobry, 1992).

- Total thickness of the soil profile: In general, it is necessary to know in a detailed way the complete soil profile above the bedrock to understand and estimate its seismic response.

- Dynamic properties of the soil profile: The measurement of dynamic soil properties may be carried out by field and laboratory tests, such as seismic down-hole and cross-hole tests, piezoelectric bender element tests, cyclic triaxial shear tests, among others. The results of this kind of tests supply information to determine the pattern of variation of the shear wave velocity with depth, and compute relationships of modulus reduction and damping ratio of soils with cyclic shear strain. The empirical data of the dynamic properties resulting from the mentioned field and laboratory tests, reflect the epistemic uncertainty associated to the measurement of these parameters. In general, variation of dynamic properties with depth depends on soil origin, weathering levels, and moisture conditions.

  Uncertainty associated to the measurement of soil dynamic properties is considered through the random generation of dynamic properties of each stratum of the representative soil profiles at the site, based on the variation ranges obtained from the statistical analysis of empirical data. The random generation of the cases of variation of dynamic properties of each soil profile should be carried out using the probability density function that best adjusts to empirical data. The beta probability density function may be an useful function, because it is so flexible and usually shows a good choice to describe empirical data (Integral S.A. et al, 2002). For each soil profile is recommendable to define at least 30 cases of random generation of soil dynamic properties, in order to obtain a representative sample (Integral S.A. et al, 2002) for executing the theoretical analysis of earthquake ground response.

- Resulting input accelerograms at the rock level from the earthquake hazard analysis with a particular probability of exceedance: It depends on the assumptions and criteria applied for the definition and characterization of seismogenic zones with influence on the site. In general, these analyses are carried out for different levels of acceleration at rock level, according to the results of the seismic hazard assessment, taking into account several performance levels or limit states such as serviceability, damage control and survival limit states.

- Nonlinear effects for low rock accelerations: In general, soft clays manifest low influence of nonlinearity for low rock accelerations. Based on this condition, some building codes have assumed that values of peak acceleration at rock level lesser than 0,05g do not cause amplification phenomena. However, this behavior can not be generalized for all types of soil profiles, because it depends on the nonlinear effects, reflected through the particular variations of G/G_{max} and damping ratio with cyclic strain. For this reason, the nonlinear effects should be studied for each specific case. Some studies of local site effects in the city of Medellín, Colombia, based on instrumental records, have shown reduction in amplification levels as the rock acceleration increases, for very low rock accelerations levels, lesser than 0,05 g (Estrada, G.M., 2001a).

For optimum results in the estimation of earthquake ground response it is recommendable to count not only on theoretical analysis based on data of soil profile and rock that underlies it, but also on accelerographic records at the site, resulting from the operation of an accelerograph network in the region.

The theoretical analysis of earthquake ground response can be carried out using one-dimensional, two-dimensional or three-dimensional models of wave propagation, according to available data of the site under analysis. If there is not sufficient information to apply two-dimensional or three-dimensional models, the analysis should be effectuated using a one-dimensional model. The selection of an inappropriate model implies additional and unnecessary uncertainty on calculations.

The results of the theoretical analysis and the real records of earthquake ground response at the site can be evaluated using the ratio of response spectra (RRS), dividing the response spectra on soil by the corresponding on rock (Dobry, 1998). The results of the RRS should be separated into ranges of rock acceleration, in order to carry out comparisons of soil nonlinear effects. In this way, it is possible to evaluate all of the recorded earthquakes by an accelerograph network, and estimate the own seismic response of every accelerograph station. So that, the results of theoretical models of earthquake ground response estimation can be validated, in order to achieve an acceptable adjustment between records and numerical analysis.

The theoretical RRS functions are estimated for each case of variation of dynamic properties (random generation) of each representative soil profile. The statistical analysis of the resulting RRS functions calculated for each soil profile involves the following steps:

- Computation of the mean value of RRS for each structural period.

- Estimation of the relation (l) between each case of RRS and the mean value of RRS for each structural period, according to Equation (5).

$$l = \frac{RRS(T)}{\overline{RRS}(T)} \quad (5)$$

- Evaluation of the standard deviation (σ_l) of the values of l obtained for each soil profile, and estimation of $RRS_{characteristic}$, using the Equation (6).

$$RRS_{characteristic} = \overline{RRS}\left(1 + \frac{\sigma_l}{2}\right) \quad (6)$$

- Calculation of the response spectrum of pseudo-acceleration of each soil profile as the $RRS_{characteristic}$ times the spectrum of uniform total hazard at rock level.

The analysis of the ratio of response spectra RRS of real records from accelerograph networks (Integral S.A. et al, 1999; Integral S.A. et al, 2002) shows that modifications suffered by the ground shaking when it passes through the soil profile depend in marked way on site characteristics. This means that the shape of those RRS functions are very stable for every site, independently of seismic source. This condition makes the RRS a very powerful parameter to characterize the earthquake ground response of the site. However, it is important to take into account that the value of amplification always depends strongly on rock acceleration level and on internal damping ratio of the soil, which reflects its specific nonlinear behavior.

Criteria and procedures described above can be applied either to site-specific analysis or seismic microzonation studies.

Site-Specific Analysis

Methods to characterize the earthquake response of the site depend strongly on available information about composition of the soil profile and the corresponding dynamic properties. Figure 19 illustrates the proposed methodology for evaluating the earthquake response at a particular site. This kind of analysis are focused to obtain representative data of earthquake ground response of a particular site. This approach for estimation of earthquake site response for seismic design of buildings was putted into effect by the 2000 Building Japanese Code (Midorikawa et al, 2000a).

Seismic microzonation studies

The possibility to carry out analysis of earthquake ground response considering the properties of the soil profile have led to divide cities into homogeneous zones with similar seismic response and their own design parameters, to be included in seismic building codes as seismic microzonation studies. Therefore, the results of seismic microzonation studies should replace topics about design spectra in the building codes. Figure 20 shows the proposed methodology to carry out seismic microzonation studies.

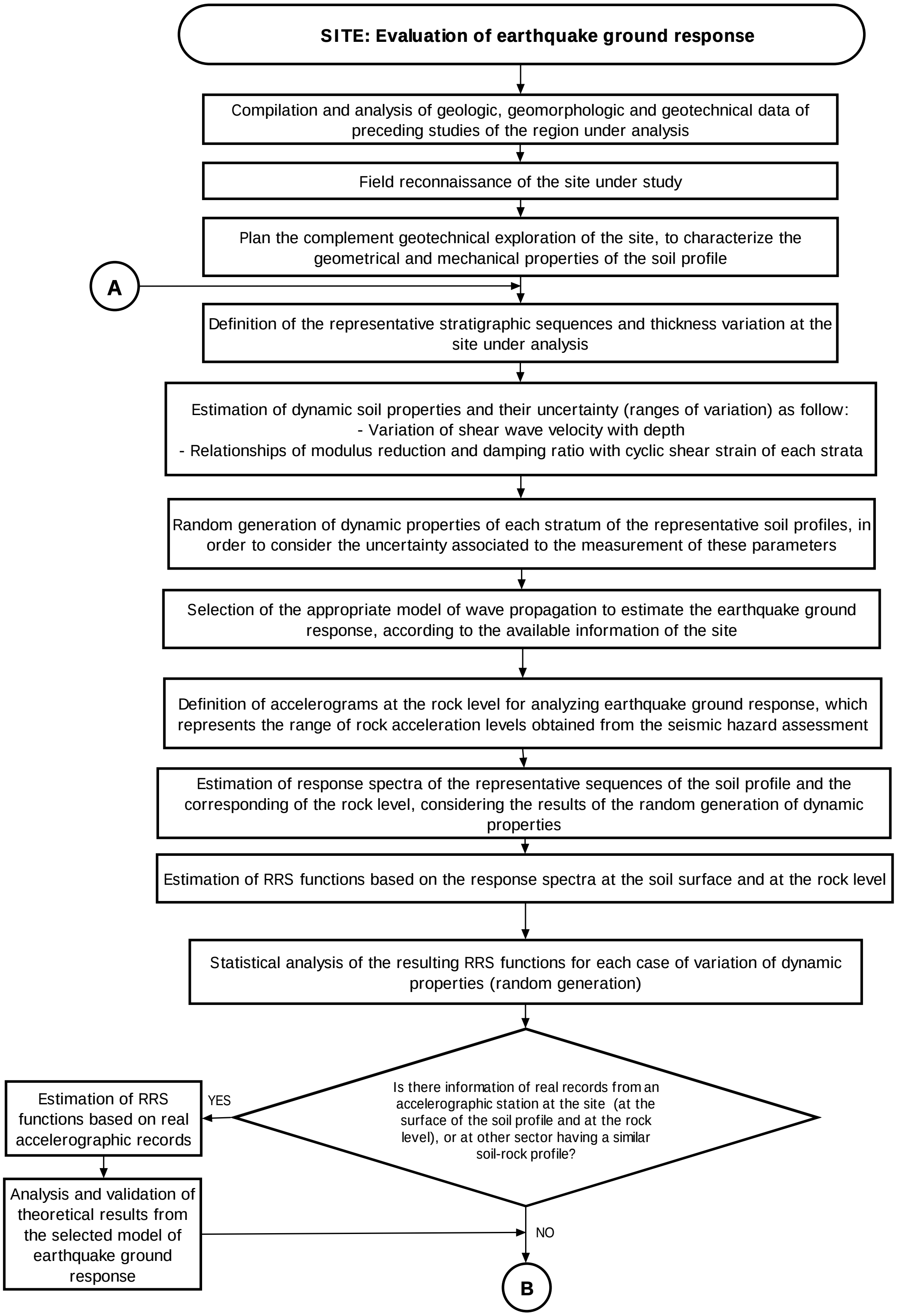

Figure 19. Proposed method to evaluate earthquake ground response based on site-specific analysis.

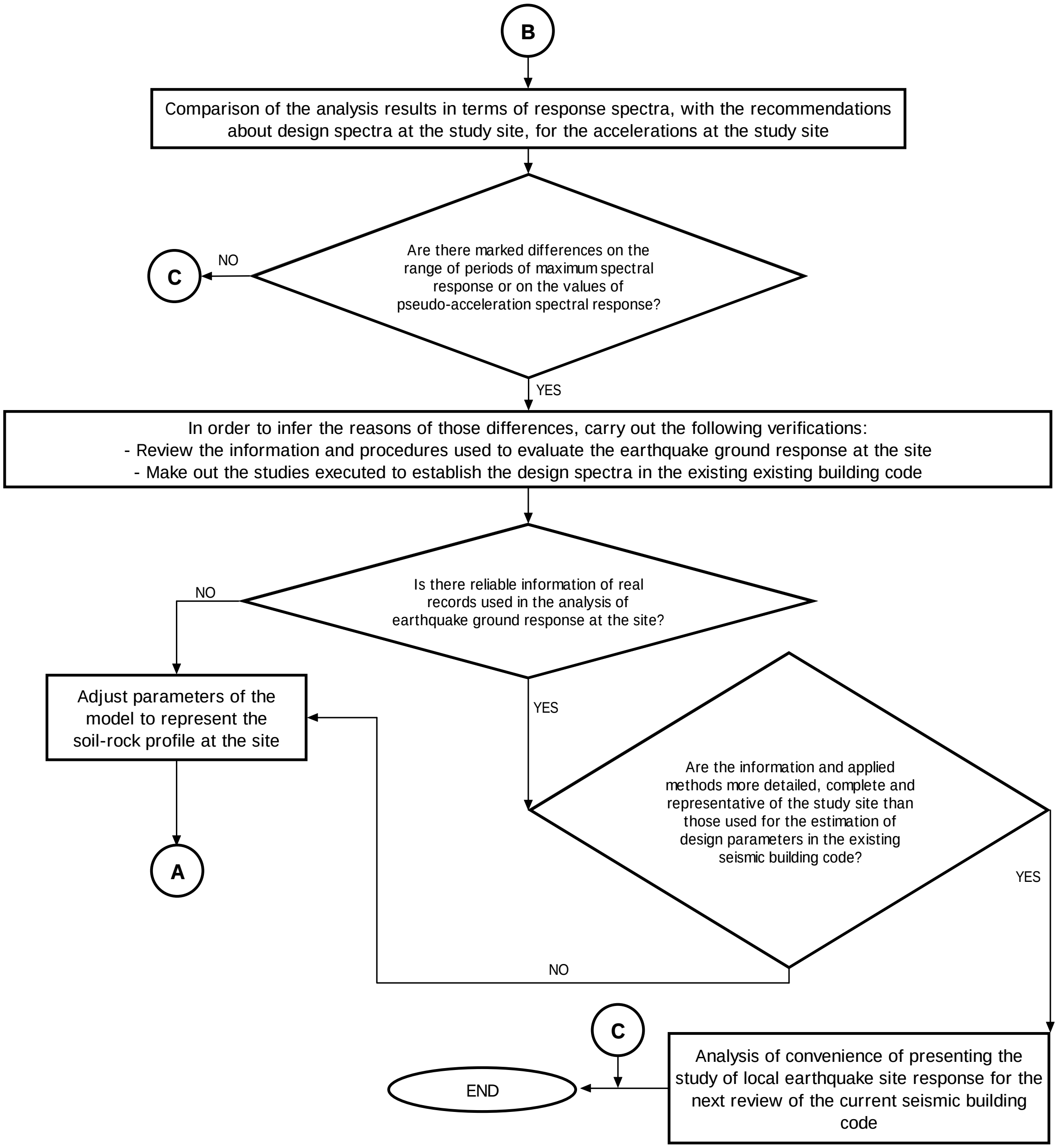

Figure 19. Proposed method to evaluate earthquake ground response based on site-specific analysis (Continued).

Seismic microzonation studies are based on the same data described above for a particular site. Since it is a study for a bigger area, it is required sufficient information composed by previous and complementary geotechnical studies to construct a geotechnical model of the city. This model allows the identification of thickness variation of strata, and of variations on layer sequences of the representative soil profiles.

The instrumentation with an accelerograph network constitutes an interesting complement to carry out studies of seismic microzonation. The location of those instruments should consider topographical and geotechnical characteristics, so that they are well distributed in representative soils of the region. In addition, it is necessary to install at least one instrument on rock, in order to obtain appropriate data of earthquake records to determine the influence of the different kind of soils which lie above the bedrock on the ground response motion.

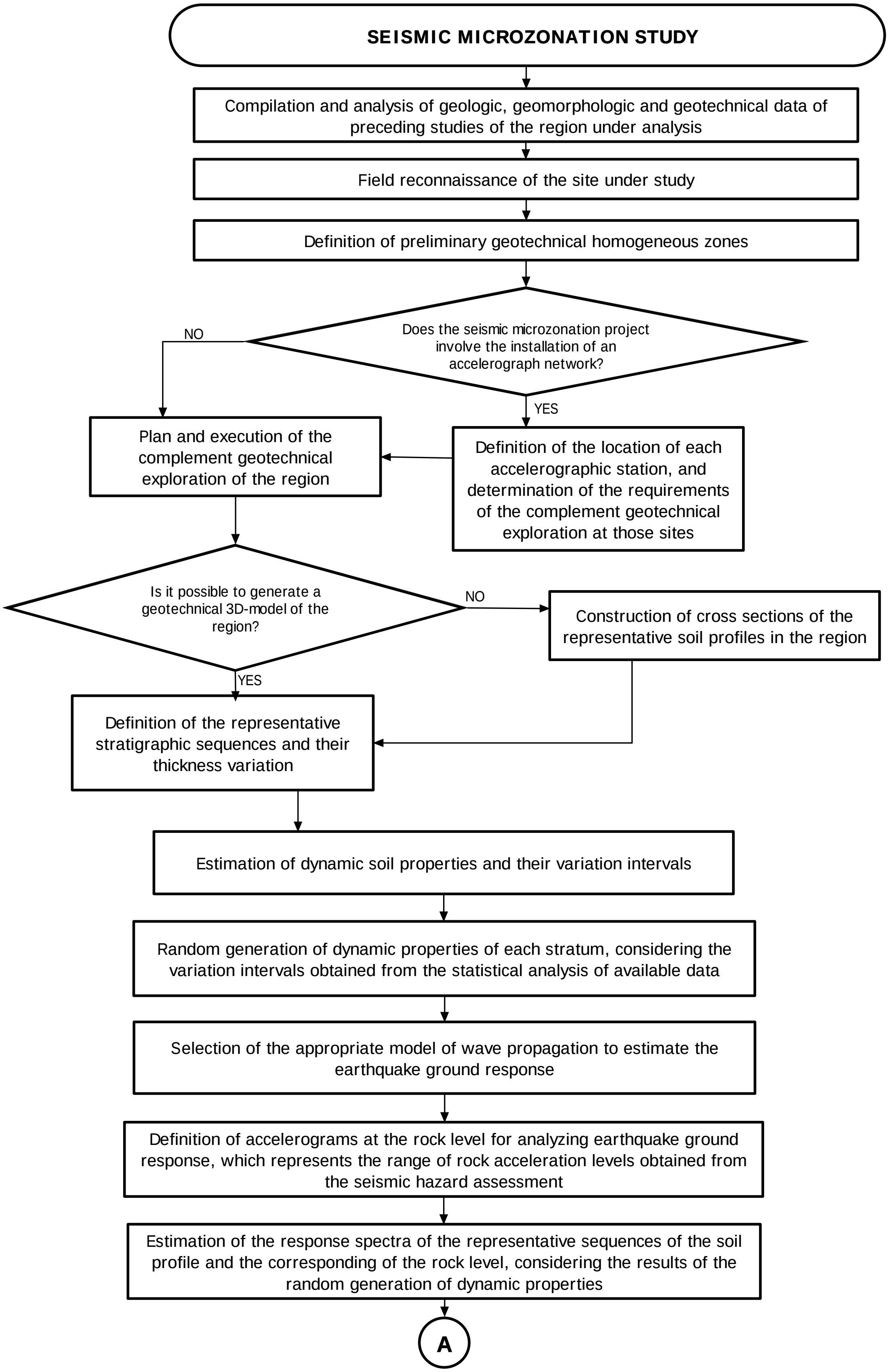

Figure 20. Proposed method for seismic microzonation studies.

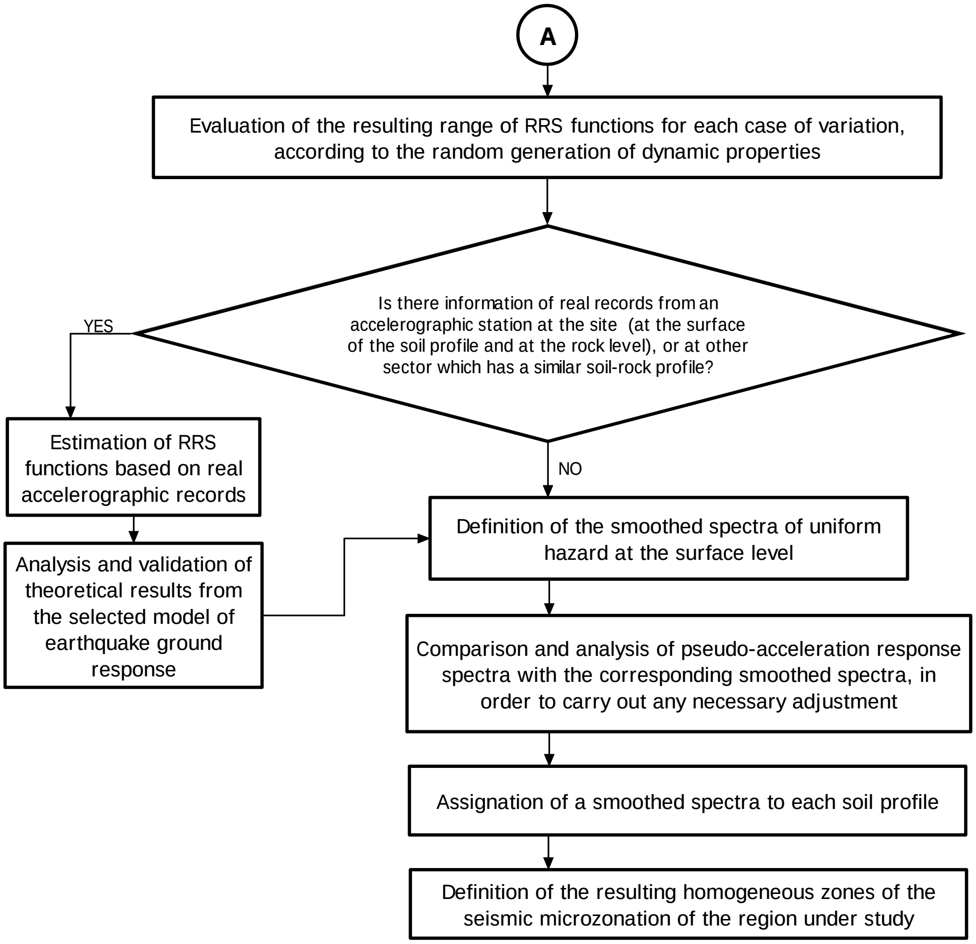

Figure 20. Proposed method for seismic microzonation studies (Continued).

CONCLUSIONS

Comparative analysis of resulting transfer functions of site-specific analysis and amplification functions of some seismic codes worldwide, show that site classifications of seismic provisions are not always representative of earthquake site response. These analyses were carried out for different kind of soil profiles such as alluvial deposits, colluvial deposits, deposits of volcanic ashes, and residual soils.

Results of the studies presented in this paper emphasize the importance of site-specific analysis, and point out the influence of some variables such as thickness of the soil profile (until reaching bedrock) on earthquake site response.

The need of site-specific analysis can be widely justified, taking into account the requirement of a representative quantification of site effects to reach optimal cost of design, construction and maintenance of buildings during their useful life. The higher costs of site-specific analysis can lead to more representative earthquake design for the specified limit states of each seismic code, which can imply better structural performance, and therefore, lesser costs of reparation or reconstruction of buildings during their useful life. This condition shows the advantages of adopting requirements of site-specific analysis or seismic microzonation studies in design provisions.

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