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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