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Seismic microzoning of Belgrade

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ABSTRACT

Seismic microzonation maps for Belgrade (Serbia) and its surroundings are presented based on the uniform-hazard-spectrum (UHS) methodology. Such mapping must satisfy the guidelines for performance-based design (PBD), which at present requires the specification of two sets of spectral amplitudes, one in which the structure would remain essentially linear, and one in which it would undergo nonlinear response. These requirements cannot be achieved by specifying the design spectra using only one (same) fixed spectral shape, and such spectra cannot be scaled by the peak ground acceleration alone. Another source of difficulties in the selection of the design amplitudes for PBD occurs when the standard spectrum shape is not capable of describing excitation by large, distant earthquakes. Furthermore, scaling the site dependent design ground motion only via soil site classification ignores the effects of site geology and thus leads to biased results. The maps we present in this paper avoid these shortcomings and include the effects of near and distant large earthquakes, spatial distribution of seismic activity, site geology, and site soil properties in a balanced way.

1. Introduction

At the beginning of the twentieth century, engineers began to include the effects of earthquake shaking in the design of structures. At first, this was done in terms of the equivalent static horizontal force, and later by analyzis of the dynamic response via the response-spectrum method [104,115,24]. Investigations of earthquake damage, and in particular of its irregular distribution in space, showed that for comparable epicentral distances, these variations were related to the geologic and soil site conditions. To account for these variations, it was proposed that city planners and earthquake engineers should be provided with microzoning maps with coefficients that characterize expected spatial variations in the amplitudes of shaking [37,61,77]. The equivalent horizontal earthquake force, and later, the response-spectrum amplitudes, were then increased or decreased according to the values of the amplification coefficients defined in the microzoning maps.

Preparation of seismic microzonation maps involves many intermediate steps including description of seismic activity surrounding the site, attenuation (from source to the site) of the quantity (peak acceleration or velocity, site intensity, spectral amplitudes, duration of strong shaking, power of strong shaking, energy required to initiate liquefaction, peak strains for design of underground structures and pipes, simultaneous action of surface faulting with strong shaking, and many others that will be subsequently shown in maps), and ultimately their probabilistic combination to determine the balanced outcome(s).

The first systematic attempts to develop seismic microzoning maps go back to the former Soviet Union [2] and Japan [37] in the 1930s. Before the age of strong motion accelerographs, amplitudes of ground motion could be scaled only in terms of site intensity, which was then used to evaluate the design peak ground acceleration. On the basis of many observational studies following earthquakes, guidelines were developed for the prediction of relative increase or decrease of site intensities (and then of the associated peaks of strong motion amplitudes) based on the nature of the site geology and surface soil [23,61]. Many published seismic microzonation maps from that time resembled the spatial distribution of geological and soil deposits in the area [38,59,61,77]. The local spatial variations were first based primarily on site geology [61,77] and then later expanded to include the effects of shallow sediments and local soils. Theoretical and observational studies in Japan eventually evolved into methods that aimed to include properties of the local site characteristics, determined through the measurement of microtremors [79–81].

Many engineering estimates of the expected site-specific strong ground motion have been based on Kanai's [35,36] interpretation, which uses one-dimensional wave-propagation models with vertically

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arriving seismic waves, which upon reflection from free surfaces leads to interference patterns, often referred to as site resonances. Multiple recordings of weak and strong motion do confirm that such resonances exist [20], but observations show that they do not occur with every earthquake and appear only rarely—typically less than about 20% [114]. During large amplitudes of strong shaking, nonlinear soil responses first shift these resonances toward longer periods, and for very large and destructive amplitudes of ground motion, the peaks associated with the resonances usually disappear [103,110–113].

Before the 1960s, peak accelerations were read directly from analog instrument records without the possibility of instrument or baseline corrections [91,92], and frequency-dependent spectral characterization of strong motion amplitudes was not available. After the earthquake magnitude scale was introduced in the 1930s, descriptions of shaking levels gradually shifted to magnitude scale [26,27,75,76]. This resulted in the popular view that, because magnitude is an instrumental measure, it should be used to describe the size of an earthquake. Numerous empirical scaling equations, which determine the peaks and spectral amplitudes of strong motion, also started to favor the magnitude scale. The difficulty caused by this transition was that seismic macrozonation and microzonation both require reliable descriptions of earthquake occurrence rates, which, if available, were given in terms of intensity scales, while the coverage in terms of magnitudes was just starting. This problem was usually "fixed" by "converting" the data on intensities to data on magnitudes, but the price paid involved added uncertainties and multitudes of inconsistent interpretations. We note that it was shown that, in terms of site intensity scaling, seismic microzonation could be carried out with good accuracy and without any use of magnitude scales [46,47,96]. Yet, most contemporary investigators continue to opt for scaling based on magnitudes.

Since the mid-1970s, after the first direct empirical scaling equations of spectral amplitudes started to appear, it become possible to formulate seismic zoning and microzoning in terms of more comprehensive approaches. Such approaches could include the probabilities of earthquake occurrence, the spatial distributions of earthquake sources, the frequency-dependent attenuation of strong-motion amplitudes, and the site geologic and soil conditions [101,53,54,83–89,98]. The advantage of this new approach was that it considered simultaneously, and in a balanced way, all factors that contributed to the end result. Comparisons with earthquake occurrence in southern California have confirmed the merits of this approach. For example, the seismic microzonation maps based on the uniform hazard method (UHM) [6,7] calculated and published in 1987 [47] for the Los Angeles metropolitan area have not been contradicted by any of the earthquakes that have occurred in the area since 1985 [106,99].

By the mid-1980s, a coherent picture started to emerge, in which observational analyses of site intensities and observed damage with site geologic and soil properties [37,61], regression analyses of peaks of recorded motions and their responses, and Fourier spectra could be combined into one, mutually consistent, whole [108,25,28,50,94].

We note that, in terms of the geological site parameters and the soil site parameters, both the derived scaling functions for site amplification, as well as the corresponding parameters in the site database, are correlated. This is to be expected because of the nature of the creation, transport, and deposition of soil materials. In the data set used by Trifunac [97], for example, although there were many (33%) deep-soil sites ($S_L=2$) over sediments ($s=0$) and 10% "rock"-soil sites ($S_L=0$) over basement rock ($s=2$), there were also many (27%) stiff-soil sites ($S_L=1$) over sediments ($s=0$) and 8% "rock"-soil sites ($S_L=0$) over intermediate geologic sites ($s=1$) [101]. Consequently, the use of regression models, which describe the site conditions in terms of only soil or only geological site parameters, averages out the dependence upon the site parameter, which is not used in the analysis. This leads to an erroneous prediction of amplification by the local site conditions and, using the distribution of the site conditions in the study by Trifunac [97] as an illustration, these erroneous predictions occur about 40% of the time. In spite of this evidence, many studies have continued to develop scaling equations using only the soil-site classification variables (e.g., [1,3–5,13,17,16]) as if all strong-motion data has been recorded under identical geologic site conditions.

The modern studies of site effects began in the late 1800s with the field observations of Mallet and Milne in Japan, who provided an insightful analysis of recorded motions [117]. These studies continued with the work of Kanai and his co-workers, and then expanded into the second half of the twentieth century thanks to the rapid increase in the number of high-quality, recorded strong-motion accelerograms [78].

The purpose of this paper is to show how a model of seismic activity in the region can be used to formulate microzoning maps of Belgrade, Serbia. The methodology, scaling equations, and descriptions of seismicity used in this paper are the same as those described by Lee [42,43] and [53,54,56,57] and need not be repeated here. The new features in this work are (1) that the detailed spatial variations of the geologic site conditions are included directly in the calculation of spectral amplitudes, and (2) the consequences of contributions from large distant earthquakes (from Vrancea in Romania) have been included and quantified. The ways in which our results differ from the old approach (based on probabilistic mapping of only peak ground acceleration) will become apparent from what follows.

A recent recommendation for peak ground accelerations to be used in the design of earthquake-resistant structures in Serbia (http://www.seismo.gov.rs/) places Belgrade in the range from 0.02 to 0.08g (0.02–0.03g for the probability of being exceeded p=0.1 during an exposure period of Y =10 years; 0.05g for the probability of being exceeded p=0.1 during an exposure period of Y =50 years; and 0.08g for the probability of being exceeded p=0.05 during an exposure period of Y =50 years.). Fig. 1 shows a preliminary seismic hazard map of peak accelerations for the probability of being exceeded p=0.1 during an exposure period of Y =50 years.

Since 1970s, various projects have been organized with the aim of reducing regional differences in the formulation of earthquake-resistant designs in the Western Balkan Countries (Albania, Bosnia and Herzegovina, Croatia, Macedonia, Montenegro, and Serbia). These projects have focused on a compilation of earthquake catalog data, seismic source modeling, determination of ground motion prediction models, seismic hazard assessment, and development of seismic hazard maps. More recently, these projects have been intended to guide regional committees in their formulation of hazard maps for use with Eurocode 8 [19] (EC8) Type 1 and Type 2 spectra in earthquake-resistant design. An example of such a map is shown in Fig. 1.

Lee and Trifunac [52] have described problems in the procedures used in the development of hazard maps such as the one illustrated in Fig. 1. They noted that the values of design acceleration spectra (PSA) scaled by accelerations in these maps underestimate intermediate and long period PSA amplitudes.

Lee and Trifunac [52] map approximating peak accelerations for Serbia, analogous to the map in Fig. 1, is shown in Fig. 2. It shows the amplitudes of $PSA(T) = 2\pi PSV(T)/T$ where $PSA(T)$ is the Pseudo Absolute Acceleration spectrum, $PSV(T)$ is the Pseudo Relative Velocity Spectrum, and T is the oscillator period. For T=0.04 s, this gives an excellent upper bound for peak ground acceleration, since in the limit as T tends to zero, $PSA(T)$ tends to peak ground acceleration. Although this is similar to what is shown in Fig. 1, working with upper bounds allows only an approximate comparison with Fig. 1. Furthermore, the amplitudes in Fig. 1 are based on scaling for soil site condition A only, while the amplitudes in Fig. 2 are for sites on geological basement rock ($s=2$), and on "rock" soil sites ($S_L=0$), and use attenuation equations determined from strong motion recordings in the former Yugoslavia [48,49].

The approach implied in using the peak accelerations in Fig. 1 is that the acceleration at "rock" sites (represented in Fig. 1 by site class A) can be modified to other soil site classes by an approximate one-