SELECTION OF THE APPROPRIATE METHODOLOGY FOR THE DETERMINISTIC SEISMIC HAZARD ASSESSMENT ON THE TERRITORY OF THE REPUBLIC OF SERBIA

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Abstract. *This paper presents a discussion regarding the most common approaches to the deterministic seismic hazard analysis, as well as their relation with the probabilistic hazard analysis. Different methodologies for estimation of the strong earthquake ground motion at a site of interest on the territory of the Republic of Serbia are also discussed. When generation of the synthetic ground motion time histories on the territory of the Republic of Serbia is concerned, a method developed by Trifunac and his associates is suggested, having in mind that this approach uses only those input parameters that can be easily and accurately defined while at the same time being able to model all properties of strong earthquake ground motion that are presently known, as well as to consider the probabilistic nature of earthquake occurrence.*

Key words: *Deterministic hazard analysis, estimation of the strong earthquake ground motion at a site of interest, Republic of Serbia*

1. INTRODUCTION

There are two basic philosophies for the seismic hazard analysis, the so-called deterministic seismic hazard analysis (DSHA) and the probabilistic seismic hazard analysis (PSHA). Although there is no generally accepted deterministic approach for all parts of the world and all application areas, in its most commonly used forms, the DSHA approach proposes design either for the so-called "scenario" earthquakes [1,2,3], i.e., for the earthquakes that are estimated to produce most severe ground motion at a site, or for the strong earthquake ground motion that is compatible with the results of the probabilistic seismic hazard analysis [4,5]. The PSHA approach, on the other hand, estimates the *probability* that a particular level of the strong earthquake ground motion will be experi-

enced or exceeded during the life period of a structure. In the following sections, we will briefly discuss the important issues regarding the DSHA approach, including the issues regarding selection of the appropriate methodology of deterministic seismic hazard analysis for the territory of the Republic of Serbia.

2. PROBABILISTIC VS. DETERMINISTIC SEISMIC HAZARD ANALYSIS

As already mentioned, there are two basic philosophies for the seismic hazard analysis, the deterministic (DSHA) and the probabilistic (PSHA) one. While the PSHA approach estimates the *probability* that a particular level A of strong earthquake ground motion amplitude *Agmp*, calculated for the whole ensemble I, of different earthquakes (i) that are expected to occur in the selected region, will be exceeded during the life period t of a structure [6]:

$$P_t(A) = 1 - \left\{ \exp[-\sum_{i \in I} v_i \int_{M_0}^{M_{max}} \int_{R_{min}}^{R_{max}} G(Agmp > A|M,R) f_{m_i}(M) f_{r_i|m_i}(R|M) dMdR] \right\}^t , \qquad (1)$$

where v indicates the annual rate of earthquakes exceeding the lower bound magnitude M_0, M_{max} is the upper bound magnitude value, R_{min} and R_{max} define the bound values for the distance for each source zone, $G(Agmp>A|M,R)$ denotes the conditional cumulative distribution function defining the probability that the expectation A of the ground motion amplitude *Agmp* is exceeded under the condition that an event of magnitude M occurred at distance R, f_m denotes the probability density function on magnitude, and $f_{r|m}$ is the probability density function on distance (which depends on the spatial relationship between the source and the site), the DSHA approach on the other hand proposes design for only several (or only one) earthquakes that are estimated to produce the most severe ground motion at a site. However, there is no generally accepted deterministic seismic hazard analysis approach for all parts of the world and all application areas, and in this section we are going briefly to describe the most common deterministic methods, as well as their relation with the probabilistic methodology.

First of all, it is important to say that no matter whether the PSHA or the DSHA approach is going to be used for a seismic hazard analysis, the basic input data that must be collected are practically the same (the data on all past earthquakes within an area of a several hundred km radius around the site of a structure of interest, the seismotectonic and geological features of the region, the local soil conditions for different sites, and the ground motion attenuation characteristics), and before any further step in the analysis, the seismic source zones and their properties must be defined on the base of the available data. Then, the DSHA approach can be aimed either at finding the maximum possible strong earthquake ground motion at a site of interest [1,2,3], or at finding the values of the selected ground motion parameter that are compatible with the results of the corresponding probabilistic seismic hazard analysis [4,5].

If the DSHA approach is aimed at finding the maximum possible ground motion at a site of interest, then the size of the largest possible earthquake is estimated for each of the previously defined seismic source zones, assuming it will occur at the closest distance from the site, and the magnitude and distance combination that produces the largest value

of the strong ground motion parameter (to be used for quantifying the seismic hazard) is used for further hazard analyses. The underlying philosophy behind such approach, also termed as the "scenario" ground motions procedure [2], is that "scenario" earthquake is both scientifically reasonable and estimated to produce most severe strong ground motion at the site, so that the public can be educated about the earthquake hazards and a wide audience can be fully assured to the safety of important structures and critical facilities even for the largest possible seismic events. The most important issue of such approach is obviously the reliable estimation of the so-called "maximum credible" earthquake, for each of the identified seismic source zones, on the base of the available data on past earthquakes and the seismotectonic and geological features of a source zone. However, the definition of the source characteristics, the estimation of the maximum credible earthquake magnitudes, as well as the estimation of the corresponding ground motion at a certain distance from the earthquake source, are all issues that are commonly associated with large uncertainties. Furthermore, the scenario earthquakes often have a very low probability of occurrence which is sometimes not of comparable level as the probability of other hazards that threaten the engineering structures. Thus, for hazards-intercomparable seismic safety assessments and for more objective and cost-effective seismic resistant design of important engineering structures, the *probability* of earthquake occurrence (during a specified time interval) should be also estimated, and the uncertainties related to the definition of the various inputs in the hazard analysis should be also taken into account and comprised in the presentation of the deterministic seismic hazard estimates. It should be also mentioned that if for some of the seismic sources there is enough data to define a spatial and temporal earthquake occurrence distribution of the largest events (different from the general earthquake occurrence distribution that is used in a probabilistic seismic hazard analysis), i.e., enough data to make independent estimates for the probability of exceedance, $P(A)$ or $P_t(A)$, it is possible to incorporate the corresponding (deterministic) seismic hazard estimates into the PSHA procedure, either by the direct extension of the probabilistic procedure [7,8,9,10,11], or by choosing, e.g., the highest hazard value (for each considered site) from the two procedures [12], or perhaps by making an appropriate weighted sum of the results.

The DSHA approach can be also aimed at finding those earthquakes that will not necessarily produce the largest possible ground motion at a site in a region, but which will *contribute most* to the seismic hazard that has been estimated (for the considered site) by the PSHA approach. For the past few decades, it has become clear that the return period, T_r, defined as the reciprocal value of the annual probability of exceedance, $P(A)$, of a chosen ground motion level A, cannot be directly converted into the definition of a single event that will contribute most to the seismic hazard at a site, because the outputs values of the PSHA are composed of the respective contribution from each of the considered seismic source zones. The inverse process of decomposition of PSHA estimates into the respective contributions of different seismic events is called the "de-aggregation" (of the seismic hazard) [5], and its purpose is to identify the "hazard-consistent" [13] earthquakes. These earthquakes can be identified in terms of ranges of magnitudes and distances [5,14,15,16,17] for which the relative contribution to the corresponding hazard estimate, $P(A)$ or $P_t(A)$, is the largest, or in terms of the latitudes and longitudes, that define the locations of the earthquake sources, instead of the distances [18,19] so that the predominant earthquakes can be directly identified in specific source zones or on specific active faults.

Beside the size and the location of the hazard-consistent earthquakes, by the de-aggregation procedure it is usually defined also some measure of the uncertainty, like, e.g., the number of standard deviations from the median ground motion as predicted by a strong ground motion attenuation relation [5,18], and the finding of the most appropriate de-aggregation procedure that includes the treatment of the uncertainties is still a subject of the extensive research ([20], [21], etc.). Furthermore, it should be noted that the PSHA estimates of the strong ground motion for the same site and the same probability level but for the different frequency ranges, are sometimes governed by earthquakes with significantly different size and distance [4], and in general it is not possible to define only one (or few) predominant earthquake for all ordinates of the so-called uniform hazard spectra (see Section 3).

At the end of this section we should further add that although it may be difficult to establish a seismic hazard analysis approach that will be appropriate for all regions and all application areas [22], it is obvious that the probabilistic and the deterministic seismic hazard analysis do not exclude each other. In fact, these two approaches have shown to be inherently complementary [2,3,23], if the probabilistic analysis is allowed to guide the choice of the maximum credible and/or the hazard-consistent seismic events, and if the DSHA estimates are used to refine the probabilistic ones, or to asses the economic losses during the "worst-scenario" earthquakes, or, e.g., to educate the public about the earthquake hazards in the considered region.

3. ESTIMATION OF THE STRONG EARTHQUAKE GROUND MOTION AT A SITE OF INTEREST

For the seismic safety assessment and seismic-resistant design of engineering structures it is important to have a very reliable estimate of the site specific design motions. The current Serbian seismic hazard maps use a macroseismic intensity scale to describe the severity of ground shaking at a site. Having in mind the shortcomings of such approach for Serbia (see [24]) and the fact that the new hazard maps should be in compliance with the Eurocode 8 [25] regulations, we suggest that the new maps should be expressed through the values of the peak strong ground motion acceleration (abbreviated further by PGA). However, right after deriving such maps (or in a parallel analyses), the seismic hazard for the Republic of Serbia should be also characterized in terms of some other ground motion parameters that could be of more interest for the earthquake-resistant design and seismic safety assessment purposes in Serbia (e.g., response and Fourier spectra, duration of strong ground shaking, artificial time histories, etc.), having in mind that the design spectra that have a normalized standard shape are not able to take into account that attenuation of the strong earthquake ground motion with distance depends on the frequency of the seismic waves and that the earthquakes of different size generate waves with different predominant frequency content [26].

If the new seismic hazard maps for the territory of the Republic of Serbia are to be expressed through the values of the PGA, the strong earthquake ground motion should be estimated at a site of interest by using an appropriate attenuation relations (e.g., [27], [28]). The estimated values of the PGA would be then used for scaling of the Eurocode 8 [25] design spectra of standard shape. However, if instead of the attenuation relations for the PGA, we use the frequency-dependent scaling equations for different spectral ampli-

tudes that have been developed for the territory of former Yugoslavia [29,30,31], then by applying completely the same PSHA procedure as for the PGA values, we can derive the so-called "uniform probability" (also termed as "uniform hazard") spectra [7,8], with expectations of all spectral amplitudes having the same probability of exceedance, $P(A)$ or $P_t(A)$. It is however important to mention that in the PSHA every probability of exceedance value is obtained by considering all earthquakes in the region that contribute to the seismic hazard at a site, and thereby a uniform hazard spectrum does not correspond to only one of those earthquakes (see, e.g., the discussion regarding the physical meaning of the return period in Section 2). Therefore, strictly speaking, it is incorrect to apply the modal response spectrum analysis by combining the modal responses using a uniform hazard spectrum, and such spectra can be used only if the dynamic response of a structure can be modeled by an equivalent single-degree-of-freedom oscillator. Gupta [32] and Todorovska [33] have recently presented the method of how to carry out a probabilistic seismic hazard analysis for the multi-degree-of-freedom systems, at least for the buildings with small modal damping and with natural frequencies that are not too close, but such issues will remain out of the scope of the present discussion. For the analysis of the simple (and elastic) multi-degree-of-freedom systems, one could still apply the common multi-modal analysis but only if using the specific response spectra, defined, by the same frequency-dependent scaling equations, for the particular sets of the hazard-consistent earthquake parameters (obtained by the DSHA de-aggregation procedure). We should only further mention that several recent seismic hazard analyses in the United States [34] and Canada [12,35], have shown that only a few spectral acceleration values are sufficient to construct spectra (to be used in design and seismic safety assessment) that will closely match the shape of the uniform hazard spectra, namely, 0.1, 0.3, 0.5, 1.0 and 2.0 sec for the U.S., and 0.2, 0.5, 1.0, and 2.0 sec for Canada. To determine how many and which one of the spectral acceleration values will be sufficient for derivation of the uniform hazard spectra for the territory of the Republic of Serbia, a thorough analysis of such spectra should be done beforehand, including the comparison of these spectra (along with the specific spectra defined for the hazard-consistent events) with the design spectra that are given by the Eurocode 8 [25] regulations.

Now, in the case when the performance-based engineering requires that structures be modeled as complex, non-linear multi-degree-of-freedom systems, the entire time series of the strong earthquake ground motion are needed as a seismological input. However, the real records of strong ground motion are commonly not available for all the required earthquake parameters, geological conditions, and source-to-site path characteristics and thus the synthetic records are usually generated instead of the real ones. Even if some real records were available, a future strong earthquake ground motion should be characterized in terms of an ensemble of different records, having in mind the variability in the characteristics of the earthquake ground motions that are recorded even under similar conditions. The synthetic ground motion time histories should be able to realistically and accurately describe the amplitudes, frequency content, and duration of the expected motions and there are numerous approaches for their generation. However, due to the possibility of the very large parametric uncertainties when using very sophisticated strong earthquake ground motion models, what is desired in a method for generation of synthetic ground motion time histories is (just like for the PSHA) the combination of only those input parameters that can be easily and accurately defined and sufficient sophistication that cap-

tures the dominant and stable features of source, distance, and site dependencies observed in recorded strong ground motions. In other words, a method for synthesizing ground motion time histories (to be used for the seismic-resistant design and seismic safety assessment purposes) should be based only on those ground motion properties that are determined (for a region of interest) from the actually recorded seismograph records and on those seismotectonic and geological features of the region that can be specified with reasonable accuracy and reliability, while at the same time being able to model all properties of strong earthquake ground motion that are presently known as well as to consider also the probabilistic nature of earthquake occurrence [36,37]. One such approach, which can be applied for the territory of the Republic of Serbia, is the method developed by Trifunac and his associates [38; 39; 40]. This method assumes that the realistic ground motion records can be generated by using a semi-empirical model of the source radiation and wave propagation (in the form of an empirically obtained Fourier amplitude spectra and random phases uniformly distributed between $-\pi$ and π, and a frequency-dependent (also defined empirically) ground motion duration), when this model is combined with further modeling of the wave propagation, i.e., by adding the phases associated with source-to-site propagation effects. The corresponding equation for the synthetic accelerogram $a_{cc}(t)$ is [38,39,40]:

$$a_{cc}(t) = \sum_{n=1}^{N}\left(\sum_{m=1}^{M} A_{nm} \frac{\sin[\Delta\omega_n(t - t_{nm}^*)]}{t - t_{nm}^*}\right)\alpha_n \cos(\omega_n t + \phi_n) ,$$ (2)

where t designates the time, N is the total number of frequency bands $\omega_n \pm \Delta\omega_n$, M is the total number of wave modes m, A_{nm} is the relative amplitude of the m-th mode (it is estimated empirically on the basis of previous acceleration recordings), t_{nm}^* is the arrival time of the m-th mode (defined from the calculated dispersion curves at the site), ϕ_n is the phase of the wave at the given frequency band (it is introduced to include the effect of the source dislocation and other miscellaneous effects along the path, and is assumed to be a random number between $-\pi$ and π), while α_n:

$$\alpha_n = \frac{2\Delta\omega_n FS(\omega_n)}{(\pi/2)\int_{\omega_n - \Delta\omega_n}^{\omega_n + \Delta\omega_n}\left|\sum_{m=1}^{M} A_{nm} \exp\{-i[(\omega - \omega_n)t_{nm}^* - \phi_n]\}\right|d\omega} ,$$ (3)

is the scaling factor used to determine the final Fourier amplitude $FS(\omega_n)$ expected at the site. The Fourier amplitude $FS(\omega_n)$ for each frequency ω_n is estimated from a statistical empirical analysis on the basis of the available acceleration records in the considered region, and is scaled using the earthquake parameters specified at the site.

The Trifunac's method is especially convenient when the territory of the Republic of Serbia is concerned, since the empirical scaling equations for both the Fourier amplitude spectra and the frequency-dependent duration have been already derived for the region of former Yugoslavia [41,42,43,44,45,46,47] by using the available real seismograph records. The additional phases, (i.e., beside the random ones, ϕ_n) are added into the procedure by deriving the times of arrival of the main bursts of seismic energy, t_{nm}^*, from the known dispersive properties of the earthquake waves guided through shallow low velocity layers of the earth's crust. These dispersive properties of the surface waves can be estimated theoretically, assuming that the inhomogeneous medium below the site may be

represented by the horizontal parallel layers. The advantages of using the Trifunac's method (for synthesizing ground motion time histories) for the seismic hazard analyses in the Republic of Serbia are numerous. First of all, the empirical scaling relations are based on the strong ground motion properties determined from the actually recorded seismograph records, and when new records in the region become available, these relations can be easily updated and refined and thereby also the corresponding seismic hazard estimates. Second, through the dispersive properties of the surface waves, the geologic environment of each specific site is introduced into the synthetic seismograms. Third, the resulting strong earthquake ground motion time histories will have non-stationary characteristics in time because the times of arrival of different seismic waves are incorporated into the synthesis of ground motion. Furthermore, Todorovska *et al.* [40] and Lee [48] have shown that this method can be used to generate rocking and torsional ground motions, surface strains and ground curvatures (associated with passage of seismic waves), having in mind that these ground motion components can be all related to the translational components of body, Rayleigh, and Love waves in the half space, and evaluated exactly in three-dimensions by using the linear theory of wave propagation. Thus, all relevant components of strong motion can be synthesized in a similar manner to that used in synthesis of translational components of ground motion. At the end of this discussion, we should also mention that in the case when the seismic hazard that is compatible with the PSHA results is to be estimated, the Fourier spectra and frequency-dependent durations can be simply scaled (just like the specific empirical response spectra to be used for the multi-modal spectral analyses) for the particular sets of the hazard-consistent earthquake parameters obtained by the de-aggregation procedure, and used for generation of the synthetic ground motion time histories. Alternatively, the parameters defining the characteristics of the most menacing earthquake(s) can be used for scaling the empirical Fourier spectra and duration, and thereby the scenario hazard estimates also obtained.

4. CONCLUSION

This paper has presented a discussion regarding the most common approaches to the deterministic seismic hazard analysis, as well as their relation with the corresponding probabilistic methodology. In its most commonly used forms, the DSHA approach proposes design either for the so-called "scenario" earthquake, i.e., for the earthquake that is both scientifically reasonable and estimated to produce most severe ground motion at a site, or for the strong earthquake ground motion that is compatible with the results of the probabilistic seismic hazard analysis. Although it may be difficult to establish a seismic hazard analysis approach that will be appropriate for all regions and all application areas, it is obvious that the probabilistic and the deterministic seismic hazard analysis do not exclude each other. In fact, these two approaches have shown to be inherently complementary if the probabilistic analysis is allowed to guide the choice of the maximum credible and/or the hazard-consistent seismic events, and if the DSHA estimates are used to refine the probabilistic ones or to asses the economic losses during the "worst-scenario" earthquakes, or, e.g., to educate the public about the earthquake hazards in the considered region.

Different methodologies for estimation of the strong earthquake ground motion at a site of interest on the territory of the Republic of Serbia are also discussed, having in mind that, for the seismic safety assessment and seismic-resistant design of engineering structures, it is important to have a very reliable estimate of the site specific design motions. When generation of the synthetic ground motion time histories on the territory of the Republic of Serbia is concerned, a method developed by Trifunac and his associates is suggested, having in mind that this approach uses only those input parameters that can be easily and accurately defined while at the same time being able to model all properties of strong earthquake ground motion that are presently known as well as to consider also the probabilistic nature of earthquake occurrence.

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ODABIR ODGOVARAJUĆE METODOLOGIJE ZA DETERMINISTIČKO OCENJIVANJE SEIZMIČKOG HAZARDA NA TERITORIJI REPUBLIKE SRBIJE

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U ovom radu diskutovani su najčešći pristupi determinističkoj analizi seizmičkog hazarda, kao i njihov odnos sa probabilističkom analizom hazarda. Diskutovane su takođe i različite metodologije za ocenjivanje jakog kretanja tla usled zemljotresa za lokaciju od interesa na teritoriji Republike Srbije. Kada je u pitanju generisanje sintetičkih vremenskih istorija kretanja tla na teritoriji Republike Srbije, predloženo je korišćenje metode koju je razvio Trifunac sa svojim saradnicima, imajući u vidu da ovaj pristup koristi samo one ulazne parametre koje je moguće jednostavno a tačno definisati, dok istovremeno omogućava modelovanje svih trenutno poznatih osobina jakog kretanja tla usled zemljotresa, kao i uzimanje u obzir probabilističke prirode pojave zemljotresa.