SPEKTAR ODGOVORA UNIFORMNOG SEIZMIČKOG HAZARDA U SEVEROZAPADNOJ BOSNI I HERCEGOVINI

UNIFORM HAZARD SPECTRA IN NORTWESTERN BOSNIA AND HERZEGOVINA

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Prof. dr Vincent LEE, dipl. matemat.[1)]
Prof. dr Marijan HERAK, dipl. fiz.[2)]
V. prof. dr Davorka HERAK, dipl. fiz.[2)]
Prof. dr Mihailo D. TRIFUNAC, dipl. inž. građ.[1)]

REZIME

Primena metode Andersona i Trifunca za procenu spektra odgovora uniformnog seizmičkog hazarda prikazana je na primerima za severozapadnu Bosnu i Hercegovinu, i opisane su karte seizmičkog zoniranja koje daju elastične spektre odgovora za teritoriju oko Banje Luke. Pokazano je da proračun karata za seizmičko zoniranje ne treba raditi na bazi maksimalnih ubrzanja tla i spektralnih amplituda sa fiksnim oblikom, kao i da je proračun tih karata na bazi metode uniformnog seizmičkog hazarda korisna i racionalna alternativa.

Ključne reči: *spektar odgovora uniformnog seizmičkog hazarda, spektri odgovora za seizmičko projektovanje, Evrokod 8, karte za seizmičko zoniranje.*

ABSTRACT

An application of Anderson-Trifunac method for calculation of uniform hazard spectra is illustrated for seismicity in northwestern Bosnia and Herzagovina, and zoning maps for elastic response spectrum amplitudes are presented for the region surrounding Banja Luka. It is shown that construction of zoning maps for use in seismic design of structures should not be based on hazard analyses of peak ground acceleration and fixed shape design spectra, while the uniform hazard spectra approach provides a useful and rational alternative.

Key words: *uniform hazard spectrum, spectra for earthquake resistant design, Eurocode 8, seismic zoning maps.*

1. UVOD

Prvi postupak u projektovanju seizmički otpornih kontrukcija je izbor elastičnih spektara odgovora koji opisuju amplitude silnih kretanja tla za koje će se vršiti projektovanje. Za potrebe projektovanja koje je zasnovano na propisima, propisuju se spektralni oblici i amplitude iz regionalnih karata, koje odražavaju prostorne odnose regionalne seizmičke aktivnosti i zasnivaju se na parametrima skaliranja, kao što je maksimalno ubrzanje tla, i na utvrđenim spektralnim oblicima. Kod projektovanja koje uzima u obzir probabilističku procenu seizmičkog hazarda, za projektne spektre je karakteristično da se određuju izračunavanjem fiksnih vrednosti maksimalnog ubrzanja tla i te vrednosti se zatim koriste kao faktor skaliranja za neki standardni spektralni oblik. Rezul-

Adrese autora: [1)] Dept. of Civil Engineering, Univ. of Southern California, Los Angeles, CA 90089 USA
E-mail: herak@irb.hr
[2)] Geofizički Odsjek, Univ. u Zagrebu, Horvatovac bb, 10000 Zagreb, Hrvatska
E-mail: vlee@usc.edu; trifunac@usc.edu

1. INTRODUCTION

The first step in the design of earthquake resistant structures involves selection of the elastic response spectra, which describe the amplitude of strong ground motion for which the design will be performed. For design, which follows the code provisions the spectrum shapes and amplitudes are prescribed in terms of regional maps, which reflect the distribution of the regional seismicity, and are based on scaling parameters, like peak ground acceleration, and specified spectral shapes. For designs, which include the probabilistic hazard assessment, the design spectra are typically determined by computing the anchoring value of peak acceleration, which is then used as a scaling factor for some standard spectral shape. This process results in the elastic acceleration spectra, which have fixed shape for large geographic areas.

Modern code regulations which are based on the performance based design principles now require design for more than one levels of strong motion, to satisfy the operational continuity and the safety requirements. To meet these requirements the amplitudes and shapes of tat ovog procesa su elastični spektri ubrzanja tla koji imaju fiksni oblik za velika geografska područja.

Savremeni seizmički propisi, koji se zasnivaju na principima projektovanja očekivanog ponašanja konstrukcije pri različitim nivoima seizmičkog opterećenja, danas zahtevaju projektovanje za više od jednog nivoa silnog kretanja tla u cilju zadovoljenja zahteva za upotrebljivost i za sigurnost konstrukcija. Da bi se ovi zahtevi ispunili, treba omogućiti da amplitude i oblici elastičnog spektra ubrzanja tla variraju u zavisnosti od geografskih koordinata lokacije, da bi se postigla potrebna verovatnoća da će projektne vrednosti biti prevaziđene za sve konstrukcije i sve njihove frekvencije. Pošto amplitude i oblici spektra odgovora istovremeno zavise od svih faktora koji određuju spektralni sadržaj silnog kretanja tla (npr. magnitude zemljotresa ili epicentralni intenzitet, putanje prostiranja seizmičkih talasa, epicentralno rastojanje, lokalni geološki uslovi i uslovi tla, kao i frekvencija kretanja tla), to se elastični spektar ubrzanja tla koji je potreban za projektovanje ne može odrediti pomoću maksimalnog ubrzanja tla i fiksnih spektralnih oblika (Trifunac, 2010). Stoga moraju da se koriste metode skaliranja koje omogućuju doprinos svih faktora skaliranja istovremeno. Jedna od takvih metoda, koja će biti opisana u ovom radu da bi se ilustrovao proces procene spektra odgovora uniformnog seizmičkog hazarda na datoj lokaciji, je metoda procene spektra odgovora uniformnog seizmičkog hazarda Andersona i Trifunca (AT-UHS). Ova metoda razvijena je kasnih 1970-tih godina za projektovanje nuklearnih elektrana (Anderson, 1978; Anderson i Trifunac, 1978a,b; Lee i Trifunac, 1985), a takođe je uspešno korišćena i u mikrorejonizaciji područja metropola (Lee i Trifunac, 1987; Trifunac 1990a).

Metoda procene spektra odgovora uniformnog seizmičkog hazarda Andersona i Trifunaca obuhvata sledeća četiri glavna postupka. (1) Opis dovoljno velikog područja koje okružuje datu lokaciju u pogledu seizmičke aktivnosti, gde će radijus ovog područja zavisiti od stepena seizmičke aktivnosti i može da obuhvata teritoriju i do nekoliko stotina kilometara. (2) Opis uslova date lokacije u smislu lokalnih geoloških uslova i uslova tla – geološki uslovi lokacije mogu se opisati korišćenjem geologoške klasifikacije (Trifunac i Brady, 1975a) ili dubine sedimentnih naslaga od površine do osnovne stene (Trifunac i Lee, 1978, 1979; Trifunac, 1989a, 1991a; Lee, 1991, 1993). Lokalni uslovi tla mogu se opisati preko klasifikacije lokalnog tla (Lee, 1989, 1990, 1991, 1993; Manić, 1996; Trifunac, 1989a,b,c,d, 1991a; Trifunac i Lee, 1992) ili pomoću prosečne brzine smičućih talasa u dubini od 30 do 50 metara ispod površine terena (Lee i Trifunac, 2010). (3) Opis atenuacije amplituda seizmičkog kretanja tla sa rastojanjem. U Kaliforniji, Rihterova funkcija atenuacije prvi put je korišćena 1970-tih godina, a kasnije je zamenjena funkcijom atenuacije koja zavisi od frekvencije (Trifunac i Lee, 1985a,c, 1990; Lee i Trifunac, 1995). Slična funkcija atenuacije silnog kretanja tla koja zavisi od frekvencije, kasnije je razvijena i za područje bivše Jugoslavije (Lee i Trifunac, 1992) i koristiće se u primerima koji su prikazani u ovom radu. (4) Opis jednačine skali-

the elastic acceleration spectra must be allowed to vary with geographic coordinates, to satisfy the required probabilities of exceedance, for all structures and for all of their frequencies. Since the amplitudes and shapes of the response spectra depend simultaneously on all factors, which determine the spectral content of strong ground motion (e.g. earthquake magnitude or epicentral intensity, wave propagation path, epicentral distance, local geologic and soil site conditions, and frequency of motion), required elastic acceleration spectra for design cannot be determined by peak ground acceleration and fixed spectral shapes (Trifunac 2010), and the scaling methods which are capable of considering all scaling factors simultaneously must be used. One such methodology, which will be described in this paper, to illustrate the process for estimating the uniform hazard spectra at a given site, is the Anderson-Trifunac Uniform Hazard Spectrum method (AT-UHS). This method was developed in the late 1970s for use in the design of nuclear power plants (Anderson 1978; Anderson and Trifunac, 1978a,b; Lee and Trifunac, 1985), and has been used successfully also in the microzonation of metropolitan areas (Lee & Trifunac 1987; Trifunac 1990a).

The AT-UHS method involves the following four main steps: (1) Description of a large enough region surrounding the site in terms of the seismic activity. The radius of this region will depend on the levels of seismic activity and may have to include up to several hundred kilometers. (2) Description of the local site conditions in terms of site geology and local soil conditions. The site geology can be described in terms of its site geological classification (Trifunac and Brady, 1975a) or the depth of sedimentary deposits from surface to basement rock (Trifunac and Lee, 1978, 1979a; Trifunac, 1989a, 1991a; Lee, 1991, 1993). The local soil condition can be described in terms of the local soil classification (Lee, 1989, 1990, 1991, 1993, Manić, 1996; Trifunac, 1989a,b,c,d, 1991a; Trifunac and Lee, 1992) or the average shear wave velocity at the top 30 to 50 m below the surface (Lee and Trifunac, 2010). (3) Description of the attenuation of the strong-motion earthquake amplitudes with distance. In California, the Richter attenuation function was first used in the 1970's, and was subsequently replaced with the frequency-dependent attenuation function (Trifunac and Lee, 1985a,c, 1990; Lee and Trifunac, 1995a). Similar frequency-dependent strong-motion attenuation function was later developed for the region of former Yugoslavia (Lee and Trifunac, 1992), and will be used in the examples presented in this paper. (4) Description of the scaling equations for estimating the expected peak amplitudes and Fourier and Response Spectral amplitudes in terms of earthquake magnitude, the frequency-dependent strong-motion attenuation function, local site characteristics and component orientation. The work on such scaling equations for the region of former Yugoslavia started in late 1970s (Trifunac, 1977c; Trifunac and Todorovska, 1989a), and continues to this date (Lee and Manić 2009).

ranja za procenu očekivanih maksimalnih amplituda, Furijeovog spektra i spektralnih amplituda odgovora preko magnitude zemljotresa, funkcije atenuacije silnog kretanja tla koja zavisi od frekvencije, karakteristika date lokacije i orijentacije komponente. Rad na ovakvom skaliranju za područje bivše Jugoslavije započet je kasnih 1970-tih godina (Trifunac, 1977c; Trifunac i Todorovska, 1989) i nastavlja se do danas (Lee i Manić, 2009).

Verovatnoća $p[S(\omega)]$ da će neke spektralne amplitude $S(\omega)$ biti prekoračene barem jednom za Y godina data je jednačinom (Gupta, 2009):

$$p[S(\omega)] = 1 - e^{-N_E[S(\omega)]} \quad (1)$$

gde je $N_E[S(\omega)]$ – očekivan broj puta kada će amplitude $S(\omega)$ biti prekoračene barem jednom za datu lokaciju za Y godina. Povratni period, označen sa $T[S(\omega)]$, date amplitude $S(\omega)$ tada je

$$T\,[S(\omega)] = N_E[S(\omega)]^{-1} \quad (2)$$

za jedinicu vremena od Y godina. U primerima koji su ilustovani u ovom radu, uzeto je da Y iznosi 50 godina, ali za primenu u specifičnom slučaju, korisnik treba sam da izabere jedinicu vremena Y. Očekivani broj pojavljivanja, $N_E[S(\omega)]$, je (uzimajući logaritam jednačine (1))

$$N_E[S(\omega)] = -\ln\,(1 - p[S(\omega)]) \quad (3)$$

U ovom radu ilustruju se rezultati seizmičke rejonizacije severozapadnog dela Bosne i Hercegovine, koji je približno skoncentrisano na područje Banje Luke u Republici Srpskoj. Kompjuterski paket koji je korišćen, EQ-RISK, savremena je verzija programa Andersona i Trifunca i stalno se razvija i generalizuje već tri decenije (Lee i Trifunac, 1985, 1987; Todorovska i Trifunac, 1998; Todorovska i dr., 2007). U primerima prikazanim u ovog radu, sva žarišta u ovom području koja doprinose seizmičkom hazardu biće predstavljena pomoću Poasonovog niza u vremenu. Napominjemo da se u paketu EQRISK mogu uzimati kombinacije zemljotresa, od kojih su neki zasnovani na Poasonovom nizu u vremenu, a za neke se uzima da će se izvesno dogoditi, a može da se uzme u obzir i stepen pojavljivanja zemljotresa zavisan od vremena (na primer, kada seizmička žarišta takođe uključuju identifikovane karakteristične zemljotrese). To znači da, ako se izvrši determinističko predviđanje da će se zemljotres određene magnitude dogoditi u jednom od datih žarišta u ovom području, onda se tom žarištu može pripisati deterministički niz događanja zemljotresa. Ovakvi zemljotresi neće se razmatrati u primerima opisanim u ovog radu, ali treba napomenuti da je ovo moguća alternativa za detaljnije modeliranje i modeliranje specifično za lokaciju. Ovo takođe znači da, ako se zemljotresi predvide, onda može da se koristi i probabilistička procena seizmičkog hazarda i da se izrade karte mikrorejonizacije za procenu uticaja predviđenih zemljotresa, kao i gde i koliko ovakvo predviđanje može da izmeni rezultate koji se zasnivaju samo na Poasonovom procesu. Lee (1992) je prikazao metodu za zamenu Poasonove verovatnoće funkcijama opštije verovatnoće za proračun funkcionala uni-

The probability $p[S(\omega)]$ that some spectral amplitude, $S(\omega)$, will be exceeded at least once in Y years is given by (Gupta 2009)

$$p[S(\omega)] = 1 - e^{-N_E[S(\omega)]} \quad (1)$$

where $N_E[S(\omega)]$ = expected number of times that $S(\omega)$ will be exceeded at the site in Y years. The recurrence time, denoted by $T[S(\omega)]$, of a given amplitude $S(\omega)$ is then

$$T\,[S(\omega)] = N_E[S(\omega)]^{-1} \quad (2)$$

for a time unit of Y years. For the examples illustrated in this work, Y is taken to be 50 years, but in the specific applications it should be selected by the user. The expected number of exceedances, $N_E[S(\omega)]$, is (taking the logarithm of Eq. (1)),

$$N_E[S(\omega)] = -\ln\,(1 - p[S(\omega)]) \quad (3)$$

In this paper we will illustrate the results for seismic zoning of north-western segment of Bosnia and Herzegovina area, roughly centered at Banja Luka in the Republic of Srpska. The computer program we use, EQRISK, is the modern version of the Anderson & Trifunac program, which has been continuously upgraded and generalized during the past three decades (Lee and Trifunac, 1985; 1987; Todorovska and Trifunac 1998; Todorovska et al. 2007). In the examples presented in this paper, all sources in the region contributing to the hazard will be represented by a Poissonian sequence in time. We note that EQRISK can take a combination of events, some of which are Poissonian in time and some that will occur with certainty, and can include the time dependent occurrence rates (when seismic sources include identified characteristic events, for example). This means that if a deterministic prediction is made that an earthquake of a given magnitude will occur at one of the given sources in the region, that source can be assigned a deterministic sequence of earthquake occurrence. In the examples in this paper we will not consider such cases, but note that this is a possible alternative for more advanced site– specific modeling. This also means that if an earthquake prediction is made, one can use the probabilistic hazard calculations and microzonation maps to evaluate the impact of such a prediction, and where and by how much such a prediction may change the results based on the Poissonian process only. Lee (1992) presented a method for replacing the Poissonian probability with more general probability functions for calculating the uniform hazard functionals, like the time-dependent log-normal probability distribution function. Other generalizations of the Poissonian occurrence rates can be found in the work of Todorovska (1994).

2. SEISMIC ZONATION OF THE WESTERN PART OF THE REPUBLIC OF SRPSKA

As in the case of the microzonation of the Los Angeles metropolitan area (Trifunac and Lee, 1987), the formnog seizmičkog hazarda kao što je log-normalna funkcija distribucije verovatnoće zavisne od vremena. Ostala uopštavanja Poasonovih modela pojavljivanja zemljotresa mogu se naći u radu Todorovske (1994).

2. SEIZMIČKA REJONIZACIJA ZAPADNOG DELA REPUBLIKE SRPSKE

Isto kao u slučaju mikrorejonizacije područja metropole Los Angelesa (Lee i Trifunac, 1987), i gore navedena metoda biće primenjena u primeru proračuna za karte seizmičke rejonizacije seizmičkog hazarda zapadnog dela Republike Srpske, koji je približno koncentrisan oko Banje Luke, u pravouganom području od 44°N do 45.5°N i od 16.6°E do 18°E. Na slici 1, prikazana je seizmička aktivnost oko ovog područja.

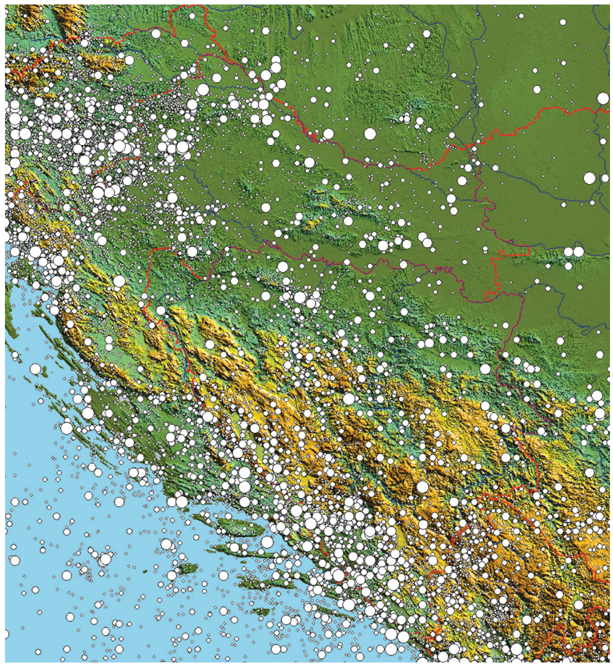
Seizmička aktivnost ovog područja opisana je pomoću stepena događanja zemljotresa (na 10.000 km² po godini) korišćenjem lokalnih magnituda, M:

$$N(M) = \begin{cases} 10^{a-bM} & M_{\min} \le M \le M_{\max} \\ 0 & \text{za sve druge vrednosti} \end{cases} \quad (4)$$

gde je $N(M)$ broj zemljotresa sa magnitudama većim od ili jednakim M, a $M_{\min} \le M \le M_{\max}$ je procenjeni dozvoljeni opseg vrednosti magnituda za to područje.

U ovom radu odlučeno je da se za model seizmičke aktivnosti ovog područja koristi varijanta pristupa koji koristi zaglađenu kontinualnu seizmičku aktivnost [npr. Frankel (1995) i Frankel i dr. (2000); videti i Lapajne i dr. (2003) za primenu na model seizmičke aktivnosti Slovenije]. Ovakvo modeliranje često se koristi kada lokacija, aktivnost, potencijal, karakter i/ili dimenzije seizmički aktivnih raseda nisu dovoljno pouzdani i tačno poznati ili nisu uopšte poznati. Proračun u ovom slučaju uglavnom se oslanja na zapise seizmičke aktivnosti iz prošlosti, koji su navedeni u regionalnim katalozima zemljotresa, a ovde se koriste podaci iz kataloga glavnih udara koga su opisali u svom radu Herak i Herak (2009) i u kome je takođe data i njihova analiza, posebno u pogledu određivanja kompletnosti granica magnituda u prostoru i vremenu. Detaljni podaci o korišćenim metodama mogu se naći u radu Herak i dr. (2009).

Za potrebe izračunavnja, područje je podeljeno u pravilni mozaik kvadratnih ćelija. Za svaku ćeliju, parameteri a, b, i M_{max}, zajedno sa njihovim neizvesnostima, izračunati su uzimajući u obzir kompletnost granica magnituda. Parameter b određen je pomoću Weichert-ovog (1980) algoritma za proračun maksimalne verovatnoće, uzimajući u obzir samo zemljotrese koji su iznad njihovih odnosnih granica kompletnosti, unutar najmanjeg kruga sa njegovim centrom u svakoj ćeliji koja obuhvata najmanje 60 takvih zemljotresa. Procena parametra a vrši se pomoću brojanja broja zemljotresa unutar kruga, $N_1 = N(M \ge 3.0)$, $N_2 = N(M \ge 3.5)$, $N_3 = N(M \ge 4.0)$, koji se događa posle odgovarajućeg početka kompletnog izveštavanja. Za svaki N_i, $N_{0i}(b) = 10^a$ se određuje jednačinim (4) i uprosečavanjem,



Slika 1. Seizmička aktivnost Bosne i Hercegovine i susednih područja (samo glavni udari). Kartiranje pomoću krugova sa magnitudom, gde su najveći krugovi zemljotresi sa $M_L \ge 6{,}5$.

Figure 1 – Seismicity of Bosnia and Herzegovina and the neighbouring regions (main shocks only). Circles scale with magnitude, the largest ones marking events with $M_L \ge 6.5$.

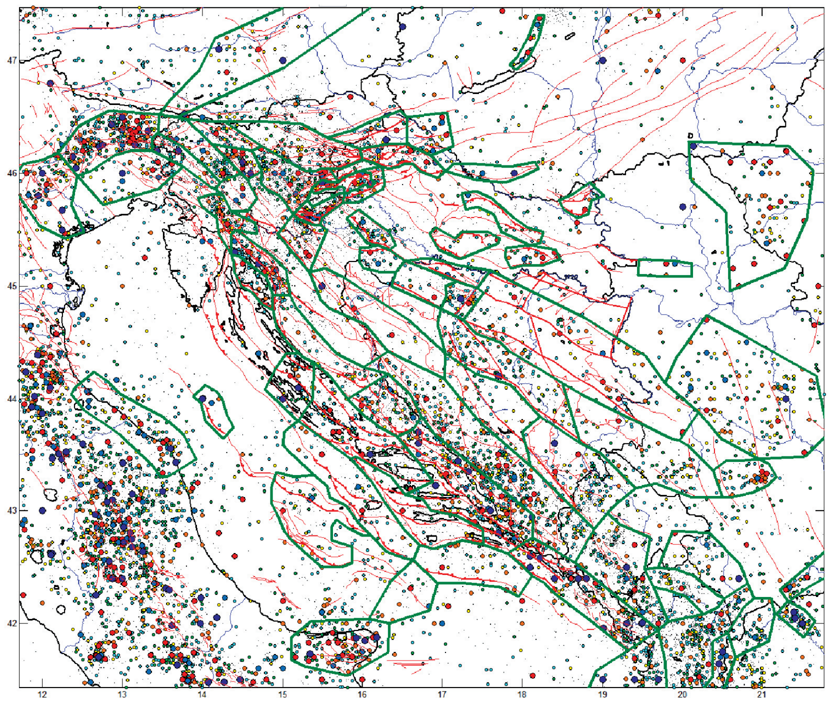
above methodology will be applied next to illustrate computations for the earthquake hazard zoning maps of the western part of the Republic of Srpska, centered roughly around the city of Banja Luka, in the rectangular area from 44°N to 45.5°N, and from 16.6°E to 18°E. Fig. 1 shows the seismic activity in the region surrounding this area.

We describe the seismicity of the region by the occurrence rate of earthquakes (per 10,000 km², per year) in terms of local magnitude, M:

$$N(M) = \begin{cases} 10^{a-bM} & M_{\min} \le M \le M_{m} \\ 0 & \text{za sve druge vredn} \end{cases} \quad (4)$$

where $N(M)$ is the number of events with magnitudes greater than or equal to M, and $M_{\min} \le M \le M_{\max}$ is the allowable range of magnitudes specified for the region.

We decided to model seismicity of the region using a variant of the distributed smoothed seismicity approach [*e.g.* Frankel (1995) and Frankel *et al.* (2000); see also Lapajne et al. (2003) for application to model seismicity of Slovenia]. Such modeling is often used when location, activity, potential, character and/or geometry of seismically active faults are known with insufficient confidence and accuracy, or are not known at all. The computation in this case mostly relies on records of the past seismicity as listed in the regional earthquake catalogs, and here we use the mainshock catalog described by Herak and Herak (2009). The same reference also presents its analyses, in particular regarding determination of the magnitude com-



Slika 2. Zone raseda (zelene linije) koje su korišćene u analizi za definisanje M_{max}, za koju je uzeto da je uniformna unutar svake zone. Aktivni rasedi su prikazani crvenim linijama (prema Hrvatoviću (2006), Ivančiću i dr. (2006), Piccardi-ju i dr. (2007), Poljaku i dr. (2000) i podacima uzetim iz arhiva Geofizičkog instituta iz Zagreba).

Figure 2. Fault zones (green) which were used in the analysis to define M_{max}, assumed to be uniform within each zone. Active faults are shown in red [after Hrvatović (2006), Ivančić et al. (2006), Piccardi et al. (2007), Poljak et al. (2000), and the data from the archive of the Geophysical Institute, Zagreb].

a reprezentativni parametar *a* se dobija preko logaritma proseka. Za procenu M_{max}, prvo se izrađuje karta površinskih glavnih raseda u području (slika 2). Poređenjem geografske rasprostranjenosti prethodne seizmičke aktivnosti sa poznatim sistemom raseda, dobijaju se zone raseda koje obuhvataju pojedinačne aktivne rasede, njihove segmente ili veće zone raseda. Ovo je očigledno subjektivni proces, koji povećava epistemičku neizvesnost konačne procene seizmičkog hazada. Obično se za ovakvu neizvesnost koristi pristup putem metode logičnih-grana, u kojoj su alternativni modeli žarišta uključeni kao grane. Na primer, može se uzeti različite gustine ćelija i stepena konačnog zaglađivanja, različite parametre koji se koriste za procenu granica kompletnosti kataloga ili grupe prostornih, 3-D površinskih i linearnih zona seizmičkih žarišta.

Tumačenje zona raseda koje su dali autori ovog rada dato je na slici 2. Detaljnijim uvidom u ovu sliku vidi se da je poznavanje aktivnih raseda u ovom području veoma neujednačeno. U nekim delovima područja, kartirani su samo najizraženiji rasedi, dok je za druge delove data gusta mreža raseda, obično bez ikakve klasifikacije prema njihovoj aktivnosti ili značaju. Nažalost, parametri, kao što je segmentacija raseda ili procenjena kvartarna aktivnost ili brzina prirasta seizmičkog momenta, uglavnom nisu dostupni. U takvim okolnostima, maksimalna magnituda $M_{\max}$ unutar svake zone određena je tako da bude jednaka magnitudi najvećeg uočenog zemljotresa koji je naveden u katalogu i koja je uvećana za neku prethodno definisanu vrednost. U retkim slučajevima, gde su utvrđeni aktivni segmenti raseda, korišćena je njihova dužina da bi se dodatno ograničila maksimalna magnituda $M_{\max}$ pomoću empirijskih relacija Wells-a i Coppersmith-a (1994). Za područja dalje od zona raseda (seizmičnost pozadine), uzeta je maksimalna magnituda $M_{\max} = 5{,}0$.

pleteness thresholds in space and time. Details of the procedure used may also be found in Herak et al. (2009).

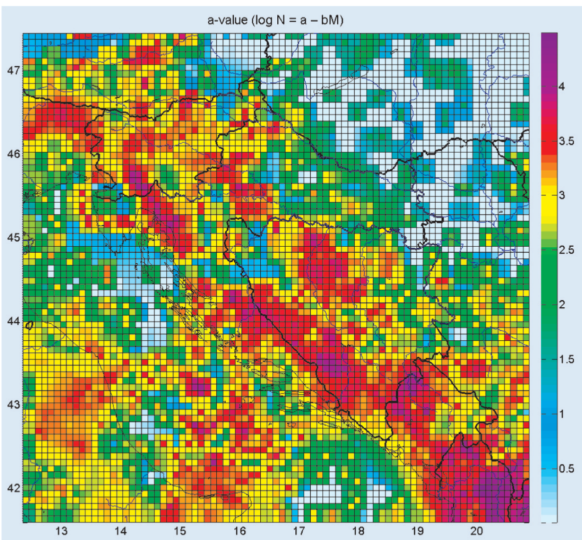
For computations, the region is divided into a regular mosaic of square cells. For each cell, parameters *a*, *b*, and M_{max}, along with their uncertainties, are calculated taking the magnitude completeness thresholds into account. Parameter *b* is estimated using the maximum-likelihood algorithm of Weichert (1980), considering only earthquakes above their respective completeness thresholds, within the smallest circle with its center in each of the cells that holds at least 60 such events. *a* is assessed by counting the number of events $N_1 = N(M \geq 3.0)$, $N_2 = N(M \geq 3.5)$, $N_3 = N(M \geq 4.0)$ within the circle, that occurred after the corresponding onset of complete reporting. For each N_i, $N_{0i}(b) = 10^a$ is estimated using eq. (4), and averaged, and representative *a* is obtained by taking the logarithm of the average. To estimate M_{max} we first map surface traces of major faults in the region (Fig. 2). Comparing the geographical distribution of historical seismicity to the known fault systems, we delineate fault zones, which cover individual active faults, their segments, or larger fault zones. This is clearly a subjective process, which increases epistemic uncertainty of the final hazard estimate. Usually such uncertainty is dealt with by a logic tree approach, where alternative source models are included as its branches. For instance, one may consider changing the density of cells and the degree of final smoothing, different parameters that are used to assess the catalog completeness thresholds, or sets of areal, 3-D planar, and linear sources.

Our interpretation of fault zones is presented in Fig. 2. A closer look reveals that the level of knowledge on active faults in the region varies significantly. In some areas only the most prominent ones are mapped, whereas

U ovom radu, seizmička aktivnost se diskretizuje kroz mozaik kvadratnih ćelija 8,3 x 8,3 km^2. Nakon što se parametri *a*, *b*, i M_{max} pripišu svakoj od ćelija kao što je gore opisano, dobijena prostorna rasprostranjenost zagladi se pomoću bivarijantnog, normalnog, elipsastog kernela sa dve promenljive (videti, na primer, Lapajne i dr., 2003), sa glavnom osom usmerenom duž predominantnog pravca pružanja raseda unutar odgovarajuće zone žarišta. Njihova se širina (sa standardnim odstupanjem) duž glavnih i manjih osa skalira na maksimalnu očekivanu dužinu raseda, odnosno na širinu projekcije površine rasedne ravni, koje su određene za odgovarajuću M_{max} unutar ćelije pomoću relacije Wells-a i Coppersmith-a (1994). Ukoliko je potrebno, da bi se izjednačile nerealno brze lokalne promene parametara (posebno *b*-vrednosti), dobijena polja parametara konačno se uglade sa cirkularnim 2-D filterom.

Prostorne promene parametara *a*, *b*, i M_{max} prikazane su na slikama 3, 4 i 5. Da bi se uzele u obzir posledice neizvesnosti prilikom procene seizmičke aktivnosti, u odnosu na parametre *a*, *b*, i M_{max}, uzima se distribucija verovatnoće za logaritam broja zemljotresa, $\log_{10}(N(M))$, u jednačini (4):

$$\log_{10}(N(M)) = a - bM \quad \text{za} \quad M_{min} \leq M \leq M_{max} \quad (5)$$



Slika 3.Regionalne varijacije parametra seizmičke aktivnosti a.

Figure 3. Regional variations of seismicity parameter a.

U primerima u ovom radu, uzima se da $\log_{10}(N(M))$ sledi trougaonu distribuciju (videti primer b, Deo 4.3 u radu Lee-a i Trifunca, 1985). Ova distribucija se može objasniti pomoću dodatnih parametara δa i δb (koji su određeni na standardni način, npr. Weichert, 1980) i pomoću δM_{max}, za koju se uzima da je svugde 0,5. Zatim se konačni model diskretizovane seizmičke aktivnosti unosi u softver za probabilističku procenu seizmičkog hazarda (PSHA) sa sledećim vrednostima za svaku ćeliju:

Geografska širina Geografska dužina b δb a δa H(km) δH (km) M_{max}

in the others a dense network is given, often without any classification by activity or importance. Unfortunately, parameters as the fault segmentation, or estimated Quaternary activity and the moment release rates are generally not available. In such circumstances, M_{max} within each zone was determined to be equal to the magnitude of the largest observed earthquake listed in the catalog increased by some predefined increment. In rare instances where active fault segments have been identified, their lengths were used to put additional constraints to M_{max} by way of empirical relations proposed by Wells and Coppersmith (1994). For the regions outside of the fault-zones (background seismicity), a constant $M_{max} = 5.0$ was assumed.

Here we discretize seismicity into a grid of square cells 8.3 x 8.3 km^2. After *a*, *b*, and M_{max} had been assigned to each of the cells as described above, the resulting spatial distribution is smoothed using a bivariate normal elliptical smoothing kernel (for an example see *e.g.* Lapajne et al., 2003), with the major axis directed along the predominant strike of faults within the corresponding source zone. Their widths (standard deviations) along the major and minor axes are scaled to the expected maximum fault length, and to the width of the surface projection of the fault plane, respectively, estimated for the corresponding M_{max} in the cell by relations of Wells and Coppersmith (1994). If necessary, in order to even-out unrealistically rapid local changes of parameters (especially the *b*-value), the resultant parameter fields are finally smoothed with a circular 2D filter.

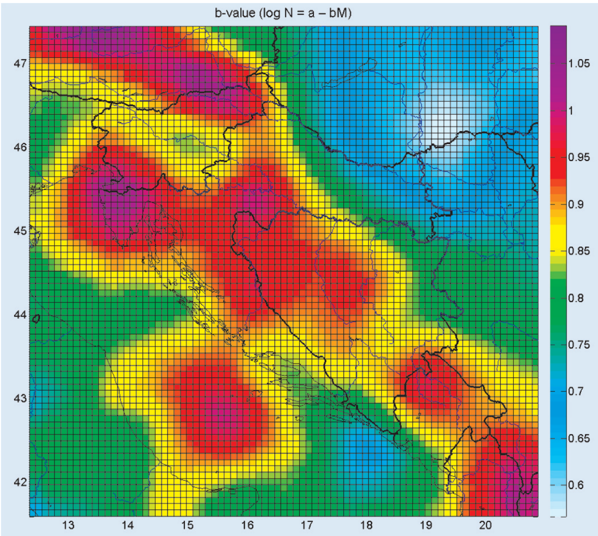
The spatial distributions of a, b, and M_{max} are shown if Figs. 3, 4, and 5. To include the consequences of the uncertainties in estimation of the seismicity, relative to the parameters a, b and M_{max}, a probability distribution is assumed for the logarithm of the number of the events, $\log_{10}(N(M))$, in Eqn. (4):

$$\log_{10}(N(M)) = a - bM \text{ for } M_{min} \leq M \leq M_{max} \quad (5)$$

In the present examples, $\log_{10}(N(M))$ is assumed to follow a triangular distribution (see Example b, Section 4.3 of Lee and Trifunac, 1985). This distribution can be described by additional parameters δa and δb (which were estimated in a standard way, *e.g.* Weichert, 1980) and δM_{max} taken to be equal to 0.5 everywhere. The final discretized seismicity model is then input into the PSHA software as a table, with following entries for each cell:

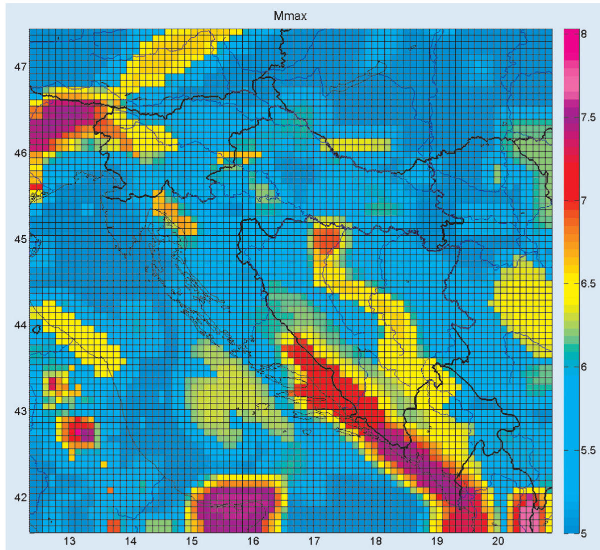
Latitude Longitude b δb a δa H(km) δH (km) M_{max}

The first two columns give the latitude and longitude at the center of each cell. This is followed by the parameters of Eqn. (4) and their corresponding uncertainties: *b, δb, a, δa* in the 3rd to 6th columns. The 7th and 8th columns give the average focal depth, *H,* and its uncertainty, *δH*, both in km. The last (9th) column gives M_{max}, the largest magnitude. The focal depth, *H,* and its uncertainty, *δH*, in each cell, were interpreted in our calculations to define a sub-volume with the given surface area and the depth range from $H - \delta H$ to $H + \delta H$ km.



Slika 4. Regionalne varijacije parametra b.

Figure 4. Regional variations of parameter b.



Slika 5. Regionalne varijacije M_{max}.

Figure 5. Regional variations of M_{max}.

U prve dve kolone date su geografska širina i dužina u centru svake ćelije. Zatim su dati parametri jednačine (4) i njihove odgovarajuće standardne devijacije: *b, δb, a, δa* od 3. do 6. kolone. U 7. i 8. koloni data je prosečna dubina hipocentra, *H,* i njegova standardna devijacija, *δH*, obe u km. U poslednjoj (9.) koloni data je M_{max}, najveća magnituda. Dubina hipocentra, *H,* i njena standardna devijacija, *δH*, u svakoj ćeliji interpretirane su u proračunima tako da definišu zapreminu sa datom površinom svake ćelije 8,3 x 8,3 km^2 i opsegom dubine od *H – δH* do *H + δH* km.

3. JEDNAČINE SKALIRANJA

U daljem tekstu dat je kratak pregled jednačina skaliranja koje je Lee (1995) razvio za teritoriju bivše Jugoslavije. Prikaz metoda može se takođe videti i u radovima Lee-a i Manića (2009) i Lee-a (2002, 2007). Radi kompletnosti ovog rada, u daljem tekstu sažeto su prikazani delovi iz rada Lee-a i Manića (2009).

3.1. Jugoslovenska baza podataka o silnom kretanju tla

Baza podataka o silnom kretanju tla za teritoriju bivše Jugoslavije formirana je iz mreže akcelerografa koji su zapisali silna kretanja tla. Ova mreža bila je instalisana ranih 1970-tih godina (Jordanovski i dr., 1987). Zapisani podaci su digitalizovani i obrađeni koristeći metode Lee-a i Trifunca (1979). Tabela 1 (preuzeta iz rada Lee i dr.,

3. THE SCALING EQUATIONS

The following is a brief summary of the scaling equations, which were developed for the territories of former Yugoslavia by Lee (1995). A review of the procedure can also be found in Lee and Manić (2009), but for the completeness of this presentation the following sections present excerpts from Lee and Manić (2009) paper.

3.1. The Yugoslav Strong Motion Database

The strong motion database for the territory of former Yugoslavia was collected by the strong-motion accelerograph network, which was installed in the early 1970s (Jordanovski et al., 1987). Table 1 (from Lee et al, 1990) illustrates the data available and shows the distribution of records from earthquakes between 1975 and 1983, with magnitudes in the range from 2.5 to 7.25. The earthquakes were mostly of shallow depths (< 25 km),

Tabela 1. Broj zapisa u odnosu na magnitude, M, i rastojanje $D = (R^2 + H^2)^{1/2}$

Table 1. Number of Records versus Magnitude, M, and Distance $D = (R^2 + H^2)^{1/2}$

	$\log_{10} D$ (km)								
M_p	0,7*	0,9	1,1	1,3	1,5	1,7	1,9	2,1	2,3
6,76-7,25			2	2	1	2	1	9	6
6,26-6,75									
5,76-6,25				3	11	5	3	1	
5,26-5,75		1	3		3	2	3	5	1
4,76-5,25		1	3	9	11	5		1	2
4,26-4,75	4	4	13	28	19	4			
3,76-4,25	1	3	15	25	12	6	1		
3,26-3,75	1	1	34	34	10	4	3		
2,76-3,25	2	3	21	21	6	6	2		

* Intervali su na 0,2, koncentrisani na 0,7, 0,9, 1,1 ….

* Intervals 0.2 units wide, centered at 0.7, 0.9, 1.1 ….

1990) opisuje te podatke i pokazuje rasprostranjenost zapisa zemljotresa koji su se dogodili u periodu od 1975. do 1983. godine, sa magnitudama u dijapazonu od 2,5 do 7,25. Zemljotresi su uglavnom bili malih dubina (< 25 km), a zapisi su uglavnom za mala epicentralna rastojanja od < 50 km.

3.2. Klasifikacija lokacije

Geološku klasifikaciju lokacije za studije silnog kretanja uveli su Trifunac i Brady (1975b) da bi opisali širu okolinu stanica za zapisivanja silnog pomerenja, a ona je zasnovana je na geološkim kartama. Te geološke klasifikacije date su za dimenzije izmerene u kilometrima, nasuprot geotehničkim karakteristikama tla na lokaciji za koje se u obzir uzima dubina od samo nekoliko desetina metara ispod površine terena (Trifunac, 1990b). Geološka klasifikacija lokacija je prikazana na tabeli 2.

Prema ovom pristupu, geološka lokacija treba da se klasifikuje kao lokacija koja leži na sedimentima (s = 0) ili na osnovnoj steni (s = 2). Međutim, lokacije koje imaju složenu okolinu ili su na granici između s = 0 i s = 2, klasifikuju se kao "srednje " (s = 1). Kasnije su Trifunac i Lee (1979) uveli detaljniju geološku klasifikaciju koristeći dubinu sedimenata ispod stanice na kojoj se vrši registrovanje zemljotresa, *h*, u km.

Tabela 2.
Table 2.

Geološka klasifikacija lokacije *Geological Site Classification*	Opis *Description*
0	aluvijalne i sedimentne naslage *alluvial and sedimentary deposits*
1	srednje i komplikovane lokacije *intermediate sites*
2	osnovna stena *basement rock*

Radi detaljnijeg opisa lokacija, pored geoloških uslova lokacije, *s*, i dubine sedimenata, *h,* uvedeni su i dodatni parametri 1980-tih godina. Prvo je uveden tip lokalnog tla, s_L, koji opisuje tlo u dubini do 100 ~ 200 m ispod površine (Trifunac, 1990b), tabela 3.

Tabela 4 ilustruje distribuciju parametara tla i geoloških uslova lokacije u bazi podataka o silnom kretanju na teritoriji bivše Jugoslavije.

3.3. Definicija rastojanja za određivanje atenuacije

Tokom 1970-tih godina, funkcionalni oblik atenuacije sa epicentralnim rastojanjem *R* sledio je definiciju lokalne magnitude (Trifunac, 1976), po kojoj je logaritam maksimalne amplitude zapisa na standardnom instrumentu jednak magnitudi zemljotresa (Richter, 1958; Trifunac, 1991b). Korišćen je oblik atenuacije

$$\log A_0 (R) + \ldots - g (T) R \quad (6)$$

and the records are for small epicentral distances, typically < 50 km.

3.2. Site Classification

The geological site classification for strong-motion studies was introduced by Trifunac and Brady (1975b) to describe the broad environment of the recording station and is based on geologic maps. The recording sites are to be viewed on a scale measured in terms of kilometers, in contrast to the geotechnical site characterization, which is viewed in terms of the top several tens of meters only (Trifunac, 1990b). This geological site classification is illustrated in Table 2.

Tabela 3.
Table 3.

Tip tla, s_L *Soil Type, s_L*	Opis Description
0	"stenovito" tlo *"rock" soil site*
1	kruto tlo *stiff soil site*
2	duboko tlo *deep soil site*

According to this approach, a site should be classified either as being on sediments (s = 0) or on the basement rock (s = 2). However, for some sites having a complex environment, an "intermediate" classification (s = 1) was assigned. Trifunac and Lee (1979) later introduced a refined geological site classification and used the depth of sediments beneath the recording site, *h*, in km.

In the 1980s, additional parameters were introduced to refine the characterization of the local site beyond the geological site condition, *s*, and the depth of sediments, *h*. The first introduced was the local soil type, s_L, representative of the top 100 ~ 200 m of soil (Trifunac, 1990b) (Table 3).

Table 4 illustrates the distribution of the soil and geological site conditions in the strong motion database of former Yugoslavia.

3.3 Definition of Distance for Attenuation Relation

During 1970s, the functional form of the attenuation with epicentral distance *R* followed the definition of local magnitude scale (Trifunac, 1976), which states that the logarithm of the corrected peak amplitude on a standard instrument is equal to the earthquake magnitude (Richter, 1958; Trifunac, 1991b). Hence, the functional form of attenuation,

$$\log A_0 (R) + \ldots - g (T) R \quad (6)$$

was used, where $\log A_0 (R)$ is the Richter's empirical attenuation function based on his observations in southern California. The linear term $g (T) R$ was intended to account for the average correction for anelastic attenuation.

Tabela 4. Broj zapisa za različite dijapazone magnituda, geološke klasifikacije (s = 0 i 2) i uslova tla (s_L = 0,1 i 2) za lokacije gde su zapisana silna kretanja na teritoriji bivše Jugoslavije (tabela preuzeta iz rada Lee-a i Trifunca, 1993).

Table 4. (from Lee and Trifunac, 1993). Distribution of records in different magnitude ranges, for different geological site classifications (s = 0 and 2) and for different soil-site classifications (s_L = 0,1 and 2) for the strong-motion records in former Yugoslavia

	s = 2 Osnovna stena *Basement Rock*			s = 1 Srednje tvrdo tlo *Intermediate*			s = 0 Lokacije na sedimentima *Sediment Sites*			Ukupno *Total*
(a)	s_L			s_L			s_L			
	0	1	2	0	1	2	0	1	2	
Sve magnitude: *All magnitudes:*	11	45	0	54	52	0	35	110	6	313
M ≥ 4.25:	11	4	0	40	31	0	8	57	5	156
(b)	$s_L = 0$			$s_L = 1$			$s_L = 2$			
Sve magnitude: *All magnitudes:*	100			207			6			313
M ≥ 4.25:	59			92			5			156

gde je log A_0 (R) Rihterova empirijska funkcija atenuacije zasnovana na njegovim osmatranjima u južnoj Kaliforniji. Linearni član g (T) R uveden je da bi se opisala prosečna korekcija za neelastičnu atenuaciju. Detaljni opis ove funkcije atenuacije može se naći u radu Trifunca (1976).

Trifunac i Lee (1985a,b) su 1980-tih godina razvili funkciju atenuacije zavisnu od magnitude i frekvencije, $\mathcal{A}tt$ (Δ, *M, T*), a kasnije su je Lee i Trifunac (1992) usvojili za proučavanje empirijskih podatka o silnom kretanju na teritoriji bivše Jugoslavije. $\mathcal{A}tt$ (Δ, *M, T*) je funkcija "reprezentativnog" rastojanja Δ od žarišta do lokacije, za magnitudu M i za periodu T silnog kretanja tla. Detaljan opis ove funkcije čitalac će naći u gore navedenim radovima. Ukratko,

$$\mathcal{A}tt\,(\Delta, M, T) = \mathcal{A}_0\,(T)\,\log_{10}\Delta,$$

gde je

$$\mathcal{A}_0(T) = \begin{cases} a + b\log_{10}T + c\left(\log_{10}T\right)^2 & T < 1.8\,\mathrm{sec} \\ -0.761 & T \geq 1.8\,\mathrm{sec} \end{cases} \qquad (7)$$

a $\mathcal{A}_0$ (T) je funkcija periode T, aproksimirana parabolom za T < 1.8 sec i konstantom za periode duže od 1.8 sec, gde je a = –0.831, b = 0.313, i c = –0.161. Rastojanje između žarišta i stanice sa instrumentom, Δ, definisano je kao u radu Gusev-a (1983):

$$\Delta = S\left(\ln\frac{R^2+H^2+S^2}{R^2+H^2+S_0^2}\right)^{-1/2}, \qquad (8)$$

gde je R površinsko rastojanje od epicentra do lokacije, H je dubina hipocentra, $S = 0.2 + 8.51\,(M - 3)$ je veličina žarišta zemljotresa sa magnitudom M, a S_0 je radijus korelacije za funkciju žarišta. Aproksimiran je pomoću

A detailed description of this attenuation function can be found in Trifunac (1976).

In 1980s, Trifunac and Lee (1985a,b) developed the first magnitude-frequency-dependent attenuation function, $\mathcal{A}tt$ (Δ, *M, T*), and later, Lee and Trifunac (1992) adopted the same procedure for empirical studies of strong-motion data in former Yugoslavia. $\mathcal{A}tt$ (Δ, *M, T*), is a function of the "representative" distance Δ from the source to the site, for magnitude M and for period T of strong motion. For a complete, detailed physical description of such a function, the reader is referred to the above references. Briefly,

$$\mathcal{A}tt\,(\Delta, M, T) = \mathcal{A}_0\,(T)\,\log_{10}\Delta,$$

where

$$\mathcal{A}_0(T) = \begin{cases} a + b\log_{10}T + c\left(\log_{10}T\right)^2 & T < 1.8\,\mathrm{sec} \\ -0.761 & T \geq 1.8\,\mathrm{sec} \end{cases} \qquad (7)$$

with $\mathcal{A}_0$ (T), a function in T, approximated by a parabola for T < 1.8sec and a constant beyond that, where a = –0.831, b = 0.313, and c = –0.161. The source-to-station distance, Δ, was defined as in Gusev (1983):

$$\Delta = S\left(\ln\frac{R^2+H^2+S^2}{R^2+H^2+S_0^2}\right)^{-1/2}, \qquad (8)$$

where R is the surface distance from the epicenter to the site, H is the focal depth, $S = 0.2 + 8.51\,(M - 3)$ is the size of the earthquake source at magnitude M, and S_0 is the correlation radius of the source function. It was approximated by $S_0 = c_S\,T/2$, where c_S is the shear-wave velocity in the rocks surrounding the fault.

Trifunac & Lee (1990) modified this attenuation function to the following form:

$S_0 = c_S\ T/2$, gde je c_S brzina smičućih talasa u stenama koje okružuju rased.

Trifunac i Lee (1990) modifikovali su ovu funkciju atenuacije u sledeći oblik:

$$\mathcal{A}tt(\Delta, M, T) = \begin{cases} \mathcal{A}_0(T)\log_{10}\left(\dfrac{\Delta}{L}\right) & R \leq R_{max} \\ \mathcal{A}_0(T)\log_{10}\left(\dfrac{\Delta_{max}}{L}\right) - \dfrac{(R - R_{max})}{200} & R > R_{max} \end{cases} \quad (9)$$

gde su Δ and R definisani kao što je gore opisano. Δ_{max} and R_{max} predstavljaju rastojanje van koga $\mathcal{A}tt$ (Δ, M, T) ima nagib koji je definisan preko Richterove lokalne magnitude M_L. Novi parametar, $L = L(M)$, uveden je da predstavlja aktiviranu dužinu raseda. Aproksimiran je sa $L = .01 \times 10^{0.5M}$ km (Trifunac, 1993a,b). Δ/L je bezdimenzionalno reprezentativno rastojanje između žarišta i merne stanice.

Treba napomenuti da, iako je metoda za razvijanje funkcije atenuacije koja je zavisna od frekvencije, koju su koristili Lee i Trifunac za teritoriju bivše Jugoslavije, identična onoj koju su koristili i za Kaliforniju, funkcija atenuacije dobijena za Jugoslaviju različita je od odgovarajuće funkcije za Kaliforniju i može se primeniti samo za regione bivše Jugoslavije.

3.4. Jednačine skaliranja

Na osnovu atenuacije jakih seizmičkih kretanja koja zavisi od frekvencije za teritoriju bivše Jugoslavije (Lee i Trifunac, 1992) izvedeno je empirijsko skaliranje Furijeovih spektara amplituda (Lee i Trifunac, 1993), a zatim i skaliranje pseudo-relativnih brzina (Lee i Manić, 1994; Lee, 1995). Jednačina skaliranja za Furijeove spektre ima oblik:

$$\begin{aligned} \log_{10} FS(T) = M + \mathcal{A}tt(\Delta, M, T) + \\ b_1(T)M + b_2^{(1)}(T)S^{(1)} + \\ + b_2^{(2)}(T)S^{(2)} + b_3(T)v + \\ + b_4(T) + b_5^{(1)}(T)S_L^{(1)} + \\ + b_5^{(2)}(T)S_L^{(2)} + b_6(T)M^2 \end{aligned} \quad (10)$$

gde je $\mathcal{A}tt$ (Δ, M, T) definisana u prethodnom tekstu, v je orijentacija komponente, $v = 0$ za horizontalne i $v = 1$ za vertikalne komponente; $S^{(1)}$, $S^{(2)}$ su pokazne promenljive za geološke uslove lokacije s, definisane kao

$$S^{(1)} = \begin{cases} 1 & \text{ako je } s = 1 \text{ (srednje lokacije)} \\ 0 & \text{ako je } s \neq 1 \end{cases}$$

$$S^{(2)} = \begin{cases} 1 & \text{ako je } s = 2 \text{ (osnovne stene)} \\ 0 & \text{ako je } s \neq 2 \end{cases} \quad (11)$$

i $S_L^{(1)}$, $S_L^{(2)}$ su pokazne promenljive za tip tla, s_L, na lokaciji, definisane kao

$$\mathcal{A}tt(\Delta, M, T) = \begin{cases} \mathcal{A}_0(T)\log_{10}\left(\dfrac{\Delta}{L}\right) & R \leq R_{max} \\ \mathcal{A}_0(T)\log_{10}\left(\dfrac{\Delta_{max}}{L}\right) - \dfrac{(R - R_{max})}{200} & R > R_{max} \end{cases} \quad (9)$$

with Δ and R defined as above. Δ_{max} and R_{max} represent the distances beyond which $\mathcal{A}tt$ (Δ, M, T) has a slope defined by the Richter local magnitude scale M_L. The new parameter, $L = L(M)$, was introduced to model the length of the earthquake fault. It was approximated by $L = .01 \times 10^{0.5M}$ km (Trifunac, 1993a,b). Δ/L is the dimensionless representative source-to-station distance.

Note that even though the procedure used by Lee and Trifunac for developing the frequency-dependent attenuation function in former Yugoslavia is identical to what they used for California, the resulting attenuation function in Yugoslavia is different from that in California and can apply only to the regions of former Yugoslavia.

3.4. The Scaling Equations

Following the development of the frequency-dependent attenuation of strong earthquake ground motions for the former Yugoslavia (Lee and Trifunac, 1992), the empirical scaling of the Fourier amplitude spectra was derived (Lee and Trifunac, 1993), and then the scaling of pseudo relative velocity (Lee and Manić, 1994; Lee, 1995). The scaling equations for Fourier spectra take the form:

$$\begin{aligned} \log_{10} FS(T) = M + \mathcal{A}tt(\Delta, M, T) + \\ b_1(T)M + b_2^{(1)}(T)S^{(1)} + \\ + b_2^{(2)}(T)S^{(2)} + b_3(T)v + \\ + b_4(T) + b_5^{(1)}(T)S_L^{(1)} + \\ + b_5^{(2)}(T)S_L^{(2)} + b_6(T)M^2 \end{aligned} \quad (10)$$

where $\mathcal{A}tt$ (Δ, M, T) was defined in the previous section, v is the component orientation, $v = 0$ for horizontal and $v = 1$ for vertical components; $S^{(1)}$, $S^{(2)}$ are indicator variables for the site condition s, defined as

$$S^{(1)} = \begin{cases} 1 & \text{if } s = 1 \text{ (intermediate sites)} \\ 0 & \text{otherwise} \end{cases}$$

$$S^{(2)} = \begin{cases} 1 & \text{if } s = 2 \text{ (basement rock sites)} \\ 0 & \text{otherwise} \end{cases} \quad (11)$$

and $S_L^{(1)}$, $S_L^{(2)}$ are indicator variables for the soil type, s_L, at the site, defined as

$$S_L^{(1)} = \begin{cases} 1 & \text{if } s_L = 1 \text{ (stiff soil sites)} \\ 0 & \text{otherwise} \end{cases}$$

$$S_L^{(2)} = \begin{cases} 1 & \text{if } s_L = 2 \text{ (deep soil sites)} \\ 0 & \text{otherwise} \end{cases} \quad (12)$$

$$S_L^{(1)} = \begin{cases} 1 & ako\ je\ \ s_L = 1\,(kruto\ tlo) \\ 0 & ako\ je\ \ s_L \neq 1 \end{cases}$$

$$S_L^{(2)} = \begin{cases} 1 & ako\ je\ \ s_L = 2\,(duboko\ tlo) \\ 0 & ako\ je\ \ s_L \neq 2 \end{cases} \qquad (12)$$

Ovaj model, koji je korišćen za empirijsko skaliranje podataka o silnom kretanju tla u Jugoslaviji, sličan je modelu *Mag-lokacija+tlo* (eng. *Mag-site+soil*), koji su, za zapadni deo SAD-a, razvili Trifunac i Lee (1989). Opis postupaka potrebnih za razvijanje ovih jednačina regresije, ilustracije rezultata i poređenja sa stvarnim podacima mogu se naći u radu Lee-a i Trifunca (1993).

Zatim su Lee i Manić (1994) i Lee (1995) koristili iste postupke i metode za regresiju spektra pseudo-relativnih brzina (PSV):

$$\begin{aligned} \log_{10} PSV(T) = M + \mathrm{Att}(\Delta, M, T) + \\ +b_1(T)M + b_2^{(1)}(T)S^{(1)} + \\ +b_2^{(2)}(T)S^{(2)} + b_3(T)v + \\ +b_4(T) + b_5^{(1)}(T)S_L^{(1)} + \\ +b_5^{(2)}(T)S_L^{(2)} + b_6(T)M^2 \end{aligned} \qquad (13)$$

Jednačina (13) je identična jednačini (10) u kojoj je $\log_{10}$ *FS* (*T*) zamenjen sa $\log_{10}$ *PSV* (*T*). Opis detaljnih postupaka neophodnih za razvijanje ovih jednačina regresije, ilustracije rezultata i poređenja sa stvarnim podacima, mogu se naći u radu Lee-a (1995).

Lee (1995) je pokazao kako se koeficijenti jednačine skaliranja (13) mogu odrediti pomoću analize rasipanja oko regresionih jednačina, i to obuhvata dva postupka. Prvi postupak u analizi regresije je određivanje zavisnosti spektralnih amplituda od magnituda, reprezentativnog rastojanja između žarišta i lokacije, geoloških uslova lokacije i orijentacije komponenti, ali ne uzimajući u obzir lokalne uslove tla. Drugim rečima, članovi $b_5^{(1)}(T)\,S_L^{(1)} + b_5^{(2)}(T)\,S_L^{(2)}$ su izostavljeni u prvom delu analize:

$$\begin{aligned} \log_{10} PSV(T) = M + \mathrm{Att}(\Delta, M, T) + c_1(T)M + \\ +c_2^{(1)}(T)S^{(1)} + c_2^{(2)}(T)S^{(2)} + \\ +c_3(T)v + c_4(T) + c_5(T)M^2 \end{aligned} \qquad (14)$$

Dalje, parabolična zavisnost spektralnih amplituda od magnitude u gornjoj jednačini modifikovana je na sledeći način da bi se izračunale spektralne amplitude, $\log_{10} P\hat{S}V(T)$:

$$\begin{aligned} \log_{10} P\hat{S}V(T) = M_{<} + \mathrm{Att}(\Delta, M, T) + c_1(T)M_{<>} + \\ +c_2^{(1)}(T)S^{(1)} + c_2^{(2)}(T)S^{(2)} + c_3(T)v + \\ +c_4(T) + c_5(T)M_{<>}^2 \end{aligned} \qquad (15)$$

gde sa:

This model, used for empirical scaling of Yugoslav strong motion data is similar to the *Mag-site + soil* model, which was developed for the western U.S. by Trifunac & Lee (1989). Descriptions of the steps required for the development of these regression equations, illustrations of the results, and comparison with the actual data can be found in Lee and Trifunac (1993).

Lee and Manić (1994) and Lee (1995) then used the same steps and procedures to perform regressions on pseudo relative velocity (PSV), spectra:

$$\begin{aligned} \log_{10} PSV(T) = M + \mathrm{Att}(\Delta, M, T) + \\ +b_1(T)M + b_2^{(1)}(T)S^{(1)} + \\ +b_2^{(2)}(T)S^{(2)} + b_3(T)v + \\ +b_4(T) + b_5^{(1)}(T)S_L^{(1)} + \\ +b_5^{(2)}(T)S_L^{(2)} + b_6(T)M^2 \end{aligned} \qquad (13)$$

Eqn. (13) is identical to Eqn. (10) with $\log_{10}$ *FS* (*T*) replaced by $\log_{10}$ *PSV* (*T*). Descriptions of the detailed steps required for the development of these regression equations, illustrations of the results, and comparison with the actual data can be found in Lee (1995).

Lee (1995) has shown how the coefficients of the scaling equation Eqn. (13) can be estimated in terms of a 2-step residue model. The first step of regression is to estimate the dependence of the spectral amplitudes on magnitude, representative source-to-station distance, geological site conditions and component direction, but without consideration of the local soil condition. In other words, the term $b_5^{(1)}(T)\,S_L^{(1)} + b_5^{(2)}(T)\,S_L^{(2)}$ is absent in this first step of regression:

$$\begin{aligned} \log_{10} PSV(T) = M + \mathrm{Att}(\Delta, M, T) + c_1(T)M + \\ +c_2^{(1)}(T)S^{(1)} + c_2^{(2)}(T)S^{(2)} + \\ +c_3(T)v + c_4(T) + c_5(T)M^2 \end{aligned} \qquad (14)$$

Further, the parabolic dependence of the spectral amplitudes on magnitude in the above regression equation is modified to the following to calculate the estimated spectral amplitudes, $\log_{10} P\hat{S}V(T)$:

$$\begin{aligned} \log_{10} P\hat{S}V(T) = M_{<} + \mathrm{Att}(\Delta, M, T) + c_1(T)M_{<>} + \\ +c_2^{(1)}(T)S^{(1)} + c_2^{(2)}(T)S^{(2)} + c_3(T)v + \\ +c_4(T) + c_5(T)M_{<>}^2 \end{aligned} \qquad (15)$$

where, with

$$\begin{aligned} M_{\min}(T) = \frac{-c_1(T)}{2c_5(T)},\ \text{i}\ \ M_{\max}(T) = \frac{-\left(1 + c_1(T)\right)}{2c_5(T)}, \\ M_{<} = M_{<}(T) = \min\left(M, M_{\max}(T)\right) \\ M_{<>} = M_{<>}(T) = \max\left(M_{\min}(T), M_{<}(T)\right) \end{aligned} \qquad (16)$$

With $\log_{10} PSV(T)$ and $\log_{10} P\hat{S}V(T)$ the logarithms of respectively the actual and estimated response spectral amplitudes at period T, the residues, $\varepsilon\,(T)$, are defined as

$$M_{\min}(T) = \frac{-c_1(T)}{2c_5(T)}, \quad \text{i} \quad M_{\max}(T) = \frac{-(1+c_1(T))}{2c_5(T)},$$

$$M_< = M_<(T) = \min(M, M_{\max}(T))$$

$$M_{<>} = M_{<>}(T) = \max(M_{\min}(T), M_<(T)) \tag{16}$$

Sa $\log_{10} PSV(T)$ i $\log_{10} P\hat{S}V(T)$, logaritmima stvarnih, odnosno procenjenih spektralnih amplituda odgovora u periodi T, rasipanja oko regresionih jednačina $\varepsilon(T)$ definisana su kao

$$\varepsilon(T) = \log_{10} PSV(T) - \log_{10} P\hat{S}V(T) \tag{17}$$

Ova rasipanja, na svakoj lokaciji za koju postoji klasifikacija tla, zatim su analizirana regresijom u odnosu na promenljive $S_L^{(1)}$ i $S_L^{(2)}$. Međutim, ranije data tabela 4 pokazuje da je, od ukupno 313 zapisa sa poznatom klasifikacijom tla, samo 6 bilo za duboko tlo ($s_L = 2$). Stoga, za lokacije koje leže na dubokom tlu, nema dovoljno podataka. Iz ovog razloga, samo su zapisi sa klasifikacijom tla $s_L = 0$ ("stenovito" tlo) i $s_L = 1$ (tvrdo tlo) bili uključeni u drugi postupak regresije, sa

$$\varepsilon(T) = c_6^{(1)}(T) S_L^{(1)} + c_7(T) \tag{18}$$

Kombinovanjem jednačina (16) i (18) iz dva postupka (koraka) za regresiju, dobija se:

$$\begin{aligned}\log_{10} P\hat{S}V(T) = {} & M_< + \mathrm{Att}(\Delta, M, T) + \\ & b_1(T) M_{<>} + b_2^{(1)}(T) S^{(1)} + \\ & + b_2^{(2)}(T) S^{(2)} + b_3(T) v + \\ & + b_4(T) + b_5(T) M_{<>}^2 + \\ & + b_6^{(1)}(T) S_L^{(1)}\end{aligned} \tag{19}$$

gde $b_i(T) = c_i(T)$, osim za $b_4(T) = c_4(T) + c_7(T)$.

Koeficijenti skaliranja u jednačini (19) ukratko su prikazani u tabeli 5, za 12 perioda, u dijapazonu od 0.04 do 2.00 s.

$$\varepsilon(T) = \log_{10} PSV(T) - \log_{10} P\hat{S}V(T) \tag{17}$$

The residues at each site where the soil classification is available were next regressed relative to the soil classification indicator variables $S_L^{(1)}$ and $S_L^{(2)}$. However, Table 4 above shows that of the total 313 records, with known soil site classification, only 6 of those records are on deep soil ($s_L = 2$). There is thus inadequate data for deep soil sites. It is for this reason that only records with soil classification $s_L = 0$ ("rock" soil) and $s_L = 1$ (stiff soil) were included in the second step of regression, with

$$\varepsilon(T) = c_6^{(1)}(T) S_L^{(1)} + c_7(T) \tag{18}$$

Combining Eqns. (16) and (18) from the two steps of regression gives:

$$\begin{aligned}\log_{10} P\hat{S}V(T) = {} & M_< + \mathrm{Att}(\Delta, M, T) + \\ & b_1(T) M_{<>} + b_2^{(1)}(T) S^{(1)} + \\ & + b_2^{(2)}(T) S^{(2)} + b_3(T) v + \\ & + b_4(T) + b_5(T) M_{<>}^2 + \\ & + b_6^{(1)}(T) S_L^{(1)}\end{aligned} \tag{19}$$

where $b_i(T) = c_i(T)$, except that $b_4(T) = c_4(T) + c_7(T)$.

The scaling coefficients in Eqn. (19) are summarized in table 5, at 12 periods, in the range from 0.04 to 2.00 s.

3.5. Vertical PSV Spectral Amplitudes and Geological and Soil Site Conditions

The plots in this work that present the uniform hazard spectral amplitudes for PSV spectra using Eqn. (19) are for geological sites $s = 0$ (alluvium), soil sites $s_L = 1$ (stiff soil) an for $v = 0$ (horizontal ground motion), because those site conditions are among the most common. For other site conditions, it is necessary to estimate the PSV spectral amplitudes at basement rock ($s = 2$) or in-

Tabela 5. Koeficijenti za proračun amplituda pseudo-relativnih brzina (u jednačini (19)), uključujući korekcije za geološke uslove lokacije ($b_2^{(1)}$, $b_2^{(2)}$), orijentaciju komponente (b_3) i klasifikaciju tla ($b_6^{(1)}$)

Table 5. Coefficients for Computing PSV Amplitudes (in Eqn (19)), including Corrections for: site Geology ($b_2^{(1)}$, $b_2^{(2)}$), Component Orientation (b_3) & Soil Classification ($b_6^{(1)}$)

Perioda (Period) – T, s

T =	0,040	0,060	0,080	0,100	0,150	0,200	0,400	0,600	0,800	1,000	1,500	2,000
$b_1(T)$	0,331	0,339	0,374	0,401	0,417	0,377	0,138	0,002	-0,047	-0,048	0,024	0,111
$b_2^{(1)}(T)$	-0,130	-0,121	-0,099	-0,075	-0,024	0,007	0,016	-0,022	-0,058	-0,086	-0,131	-0,157
$b_2^{(2)}(T)$	-0,011	-0,051	-0,092	-0,127	-0,188	-0,220	-0,230	-0,207	-0,202	-0,212	-0,267	-0,326
$b_3(T)$	-0,141	-0,145	-0,156	-0,169	-0,200	-0,223	-0,267	-0,266	-0,250	-0,231	-0,183	-0,144
$b_4(T)$	-3,565	-3,354	-3,560	-3,582	-3,566	-3,462	-2,935	-2,639	-2,536	-2,540	-2,723	-2,940
$b_5(T)$	-0,070	-0,072	-0,077	-0,079	-0,082	-0,078	-0,056	-0,043	-0,039	-0,039	-0,047	-0,055
$b_6^{(1)}(T)$	0,230	0,218	0,221	0,228	0,241	0,242	0,194	0,141	0,101	0,072	0,027	0,000

3.5. Spektralne amplitude vertikalnih pseudo-relativnih brzina i geološki uslovi i uslovi tla lokacije

Slike u ovom radu koje predstavljaju spektralne amplitude uniformnog hazarda za pseudo-relativne brzine dobijene putem jednačine (19), i date su za lokacije geološkog tipa $s = 0$ (aluvijum), lokacije na tlu tipa $s_L = 1$ (kruto tlo) i za $\nu = 0$ (horizontalno kretanje tla), jer su ovi uslovi lokacije među najčešćim. Za druge lokalne uslove, potrebno je odrediti spektralne amplitude pseudo-relativnih brzina na osnovnoj steni ($s = 2$) ili za srednje geološke uslove ($s = 1$) ili za lokacije na "stenovitom" tlu ($s_L = 0$) i za vertikalna kretanja tla ($\nu = 1$). Da bi se omogućila procena ovih razlika, u tabeli 5 uključeni su svi koeficijenti koji su neophodni za modifikaciju proračunatih amplituda spektra odgovora uniformnog seizmičkog hazarda. U daljem tekstu, opisano je kako treba dodati članove koji daju $\log_{10} P\hat{S}V(T)$ za datu geološku lokaciju s, tip lokacije na tlu s_L i orijentaciju komponenete v, koje su različite od $s = 0$, $s_L = 1$ i $\nu = 0$.

$$\log_{10} P\hat{S}V(T) = \log_{10} P\hat{S}V(T)^* + b_2^{(1)}(T)S^{(1)} + b_2^{(2)}(T)S^{(2)} + b_3(T)\nu - b_6^{(1)}(T)S_L^{(0)}$$

gde je

$\log_{10} P\hat{S}V(T)^*$ = PSV izračunato za $s = 0$, $S_L = 1$ i $\nu = 0$,

$$S^{(1)} = \begin{cases} 1 & \text{ako je } s = 1 \text{ (srednje lokacije)} \\ 0 & \text{ako je } s \neq 1 \end{cases}$$

$$S^{(2)} = \begin{cases} 1 & \text{ako je } s = 2 \text{ (osnovna stena)} \\ 0 & \text{ako je } s \neq 2 \end{cases} \quad \text{(11) gore}$$

i iz jednačine (12):

$$S_L^{(0)} = 1 - S_L^{(1)} = \begin{cases} 0 & \text{ako je } s_L = 1 \text{ (kruto tlo)} \\ 1 & \text{ako je } s_L \neq 1 \end{cases} \quad (20)$$

Treba napomenuti da $S_L^{(2)}$ (za lokacije na dubokom tlu $s_L = 2$) ovde nije uzeto u obzir jer nije korišćeno u gore navedenom drugom koraku regresije.

3.6. Efekat dužine raseda i konačnih dimenzija žarišta u odnosu na žarišta u tački

Za epicentralno rastojanje $R >> L$, gde je L dužina raseda i za slučajeve gde je slaba seizmička aktivnost u okolini lokacije može se uzeti da žarišta zemljotresa nemaju dimenzije. Međutim, kada je R jednako L i kraće od L i kada se veliki zemljotres može dogoditi u blizini lokacije, efekat dimenzija žarišta mora da se uključi u proračun amlituda spektra odgovora uniformog hazarda. U primerima koji su opisani u ovom radu, uzima se da je seizmička aktivnost lokacije mala i da se dimenzije žarišta mogu zanemariti. Da bismo ilustrovali koliko spektralne amplitude mogu da se povećaju zbog konačnih dimenzija žarišta, podsetimo se jednog primera iz rada Westermo i dr. (1980), u kome je uzeto da se dužina raseda može aproksimirati pomoću $\log L = 2M/3 - 3.08$, gde je L dato u kilometrima. Ovo odgovara jedna-

termediate ($s = 1$) geological sites, or for "rock" soil sites ($s_L = 0$), and for vertical motions ($\nu = 1$). Table 5 includes all coefficients, which are required to modify the computed uniform hazard spectral amplitudes to account for these differences. In the following we describe the additional terms to be added to $\log_{10} P\hat{S}V(T)$ for given geological site, s, soil site s_L, and component orientation v, other than $s = 0$, $s_L = 1$ i $\nu = 0$.

$$\log_{10} P\hat{S}V(T) = \log_{10} P\hat{S}V(T)^* + b_2^{(1)}(T)S^{(1)} + b_2^{(2)}(T)S^{(2)} + b_3(T)\nu - b_6^{(1)}(T)S_L^{(0)}$$

where

$\log_{10} P\hat{S}V(T)^*$ = PSV computed for $s = 0$, $S_L = 1$ and $\nu = 0$,

$$S^{(1)} = \begin{cases} 1 & \text{if } s = 1 \text{ (intermediate sites)} \\ 0 & \text{otherwise} \end{cases}$$

$$S^{(2)} = \begin{cases} 1 & \text{if } s = 2 \text{ (basement rock sites)} \\ 0 & \text{otherwise} \end{cases} \quad \text{(11) above,}$$

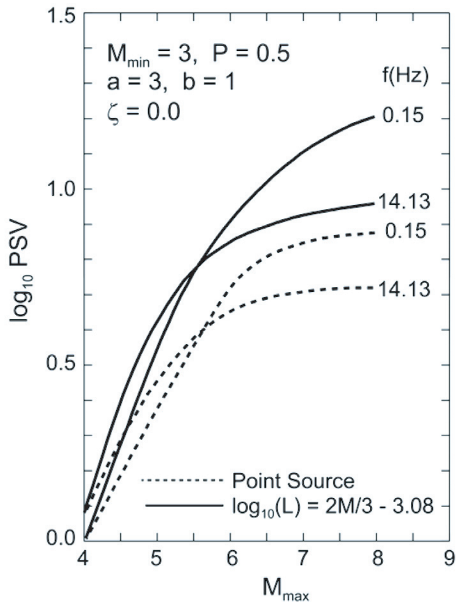
and from Eq. (12):

$$S_L^{(0)} = 1 - S_L^{(1)} = \begin{cases} 0 & \text{if } s_L = 1 \text{ (stiff soil sites)} \\ 1 & \text{otherwise (the case } s_L = 0) \end{cases} \quad (20)$$

Note that $S_L^{(2)}$ (for deep soil site, $s_L = 2$) is not included, here since it is not used in the 2^{nd} step of regression above.

3.6. Effect of Rupture length and Finite Source dimensions versus Point Sources

For epicentral distances $R >> L$, where L is the fault length, and when the seismicity surrounding the site is low, it may be assumed that the earthquake sources have no dimensions. However, when R becomes comparable to and smaller than L, and when large earthquake can occur near the site, the effect of extended source must be included in the calculation of uniform hazard spectral amplitudes. In the examples presented in this paper it is assumed that the seismicity surrounding the site is low and that the source dimension can be neglected in the AT-UHS calculations. To illustrate how the spectral amplitudes can increase due to the finite source dimensions, we recall an example from Westermo et al. (1980), in which it was assumed that the fault length can be approximated by $\log L = 2M/3 - 3.08$, where L is in kilometers. This corresponds to the equation proposed by Thatcher and Hanks (1973) for the stress drop of 30 bars. To compute the probabilistic spectral amplitudes from an earthquake source with epicenter at a point in the diffused source region it is assumed that the orientation of a straight fault is equally likely along all azimuths (Anderson & Trifunac 1978a). Figure 6 illustrates the differences of UHS amplitudes between the point and finite source dimensions versus M_{max}, both on the surface of the half space. With increasing source depth these differences de-



Slika 6. Zavisnost amplituda pseudo-relativnih brzina spektra odgovora uniformnog seizmičkog hazarda (cm/s), sa frekvencijama od 0,15 Hz i 14,3 Hz, od pretpostavke da je žarište u tački i linijskih žarišta, za P = 0,5, tokom seizmičkog dejstva od 50 godina, i u zavisnosti od M_{max}. a = 3, b = 1, i M_{min}= 3,0 se ne menjaju u ovom primeru (iz Westermo i dr., 1980).

Figure 6. Dependence of the UHS PSV amplitudes (cm/s) of the oscillators, with natural frequencies of 0.15 Hz and 14.3 Hz, on the point source and line source assumptions, for P=0.5, during 50 years of exposure, versus M_{max}. a = 3, b = 1 and M_{min} = 3.0 are held constant (from Westermo et al. 1980).

čini koju su predložili Thatcher i Hanks (1973), za pad napona na rasedu od 30 bara. Da bi se izračunale probabilističke spektralne amplitude iz žarišta zemljotresa sa epicentrom u tački u područjima gde se može pretpostaviti da je $L \neq 0$ pretpostavljeno je da je orijentacija raseda jednako verovatna za sve azimute (Anderson i Trifunac, 1978a). Slika 6 ilustruje razlike u amplitudama spektara odgovora uniformnog seizmičkog hazarda između žarišta u tački i žarišta sa konačnim dimenzijama, u zavisnosti od M_{max}, na površini poluprostora. Sa povećanjem dubine žarišta, ove razlike se smanjuju, a kod horizontalnih linijskih žarišta na dubuni $H > L$, ove razlike se gube.

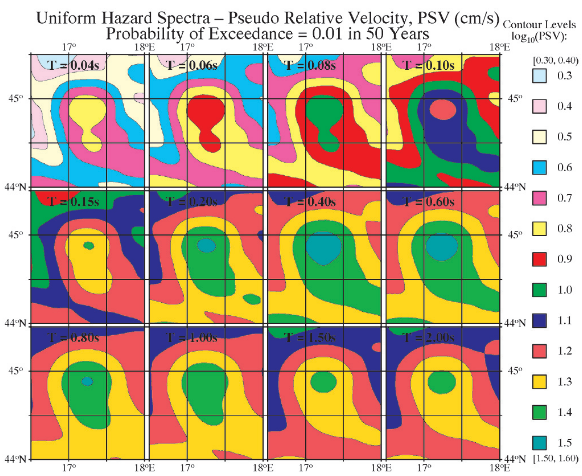
4. SPEKTAR ODGOVORA UNIFORMNOG SEIZMIČKOG HAZARDA U ZAPADNOM DELU REPUBLIKE SRPSKE

Spektri odgovora uniformnog seizmičkog hazarda (UHS) za pravougaono područje sa geografskim koordinatama od 44°N do 45.5°N i od 16.6°E do 18°E, u zapadnom delu Republike Srpske, ilustrovani su na slikama od 7a do 7e. Ovi spektri izračunati su iz niza zemljotresa za žarišta (6720) koja su gore opisana, koja su unutar radijusa od 150 km mereno od tačke gde je seizmički hazard računat. Proučavali smo potrebno rastojanje za integraljenje amplituda spektra odgovora uniformnog se-

crease, and for a horizontal line source at depth $H > L$ the differences disappear.

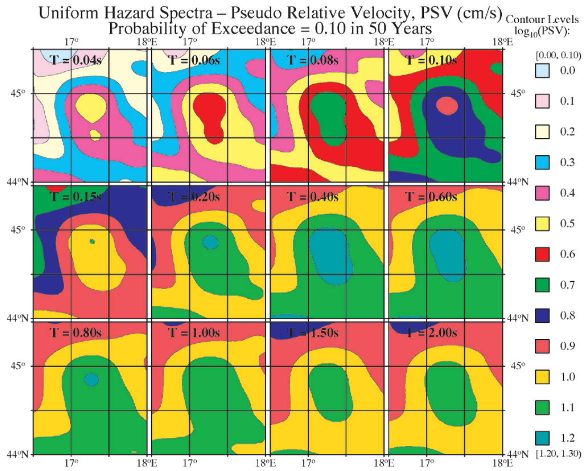
4. UNIFORM HAZARD SPECTRA IN THE WESTERN REPUBLIC OF SRPSKA

The Uniform Hazard Spectra (UHS) for the rectangular area from 44°N to 45.5°N, and from 16.6°E to 18°E, in the western part of the Republic of Srpska are illustrated in Figs. 7a through e. Those were calculated from a sequence of events at those (6720) volume sources described above, which are within 150 km radius of the point where hazard is evaluated. We studied the required distance range for integration of UHS amplitudes and found that for the relatively low seismicity of this region 150 km radius leads to adequate approximation of the total hazard. In seismically more active regions, and in the regions where attenuation of wave amplitudes is slower this radius must be extended to several hundred kilometers (Anderson and Trifunac 1978; Lee & Trifunac 1987). The empirical scaling equations were used at each of the 12 selected oscillator periods independently, to compute the spectral amplitudes. The spectral amplitudes, in the form of $\log_{10}(PSV(T))$, in cm/sec, were then computed for T = 0.04, 0.06, 0.08, 0.10, 0.15, 0.20, 0.40, 0.60, 0.80, 1.00, 1.50, 2.00 seconds. Those are illustrated here for damping of $\varsigma = 0.05$, in terms of the Yugoslav magnitude scaling model (Lee and Manić, 1994; Lee, 1995), for geological site condition of $s = 0$ (alluvium), local soil classification $s_L = 1$ (stiff soil) and $\nu = 0$ (horizontal component of motion). The examples illustrated in the figures have been calculated for a given probability P and for the exposure time of Y = 50 years. As already



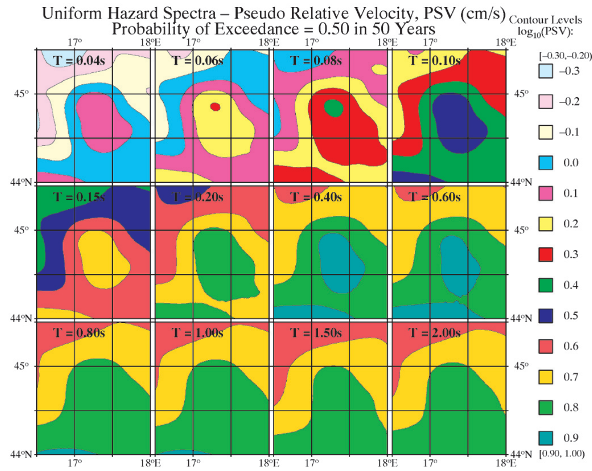
Slika 7a. Geografske varijacije (između 16,5ºE i 18,0ºE i 44,00ºN i 45,50ºN) spektra odgovora uniformnog seizmičkog hazarda pseudo-relativnih brzina (cm/s), za 12 perioda T = 0,4 s do 2,0 s, za P = 0,01 u vremenu izloženosti seizmičkom dejstvu od Y = 50 godina.

Figure 7a. Geographical variations (within 16.5ºE to 18.0ºE and 44.00ºN and 45.50ºN) of UHS of PSV (cm/s), at 12 periods T=0.4s to 2.0s, for P=0.01 in Y=50 years exposure.



Slika 7b. Geografske varijacije (između 16,5°E i 18.0°E i 44.00°N i 45,50°N) spektra odgovora uniformnog seizmičkog hazarda pseudo-relativnih brzina (cm/s), za 12 perioda T = 0,4 s do 2.0 s, za P = 0,10 u vremenu izloženosti seizmičkom dejstvu od Y = 50 godina.

Figure 7b. Geographical variations (within 16.5°E to 18.0°E and 44.00°N and 45.50°N) of UHS of PSV (cm/s), at 12 periods T=0.4s to 2.0s, for P=0.10 in Y=50 years exposure.



Slika 7c. Geografske varijacije (između 16,5°E i 18,0°E i 44,00°N i 45,50°N) spektra odgovora uniformnog seizmičkog hazarda pseudo-relativnih brzina (cm/s), za 12 perioda T = 0,4 s do 2,0 s, za P = 0,50 u vremenu izloženosti seizmičkom dejstvu od Y = 50 godina.

Figure 7c. Geographical variations (within 16.5°E to 18.0°E and 44.00°N and 45.50°N) of UHS of PSV (cm/s), at 12 periods T=0.4s to 2.0s, for P=0.50 in Y=50 years exposure.

izmičkog hazarda i ustanovili da, za relativno slabu seizmičku aktivnost ovog područja, radijus od 150 km daje adekvatnu aproksimaciju ukupnog seizmičkog hazarda. U područjima veće seizmičke aktivnosti i područjima gde je atenuacija amplituda talasa sporija, ovaj radijus mora da se poveća na nekoliko stotina kilometara (Anderson i Trifunac, 1978; Lee i Trifunac, 1987). Jednačine empirijskog skaliranja korišćene su posebno za svaku od 12 izabranih perioda oscilacija da bi se proračunale spektralne amplitude. Zatim su spektralne amplitude, u obliku $\log_{10}(PSV(T))$, u cm/s, proračunate za T = 0,04, 0,06, 0,08, 0,10, 0,15, 0,20, 0,40, 0,60, 0,80, 1,00, 1,50 i 2,00 s. One su ovde ilustovane za prigušenje od ς = 0.05, korišćenjem jugoslovenskog modela skaliranja sa magnitudama (Lee i Manić, 1994; Lee, 1995), za geološke uslove lokacije $s = 0$ (na aluvijumu), lokalno tlo tipa $s_L = 1$ (kruto tlo) i $v = 0$ (horizontalna komponenta kretanja tla). Primeri ilustrovani na slikama izračunati su za datu verovatnoću P i za vreme izloženosti seizmičkom dejstvu od Y = 50 godina. Kao što je već napomenuto, P predstavlja verovatnoću da će izračunate spektralne amplitude biti prevaziđene barem jedanput za vreme od Y = 50 godina.

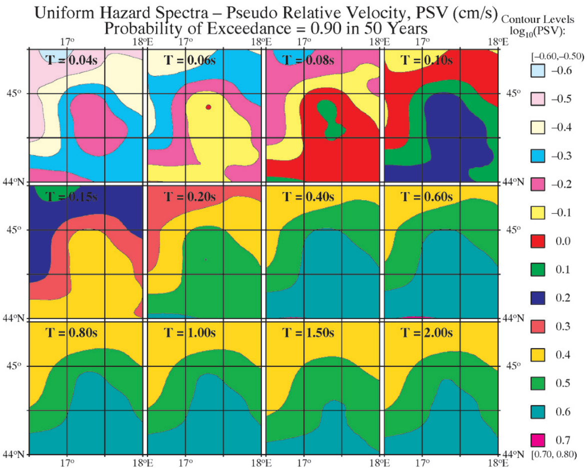
Izračunavanjem amplituda spektra uniformnog seizmičkog hazarda na gustoj mreži tačaka (kao što je prikazano na slikama od 7a do 7e), i za više verovatnoća da će amplitude biti prevaziđene, moguće je izraditi spektre odgovora uniformnog seizmičkog hazarda amplituda elastičnih pseudo-relativnih brzina za svaku lokaciju unutar ovog područja, za svaku verovatnoću da će amplitude biti prevaziđene i svaki period izloženosti seizmičkom dejstvu i to prostim očitavanjem amplituda spektra odgovora uniformnog seizmičkog hazarda sa ovih dijagrama i pomoću interpolacije. Na slici 8 prikazani su primeri noted P represents the probability of at least one exceedance in Y = 50 years.

By calculating UHS amplitudes at a dense grid of points (as shown in Figs. 7a through e), for a set of probabilities of exeedance, and for different exposure periods, it becomes possible to construct the UHS of elastic PSV amplitudes for any site within the area, for any probability of exceedance and for any period of exposure, by manually reading the amplitudes of the UHS amplitudes from these plots and by interpolation. Examples of thus computed spectra at 44.78N, 17.21E for elastic response spectral amplitudes of PSV(T) at 5% damping, for exposure time of Y = 50 years at 1, 10, 50, 90 and 99% probabilities of exceedance P are shown in Fig. 8.

Fig. 8 illustrates such UHS for elastic response spectral amplitudes of PSV(T). From the Response Spectral Velocity, *PSV(T),* one can calculate the corresponding Spectral Acceleration, *PSA(T),* as $PSA(T) = (2\pi/T)\,PSV(T)$ (cm/s²). Fig. 9 shows a plot of such a PSA (in units of g = 9.81 m/s²). It shows the UHS for 5% damping, exposure time of Y = 50 years, and for 1, 10, 50, 90 and 99% probabilities of at least one exceedance.

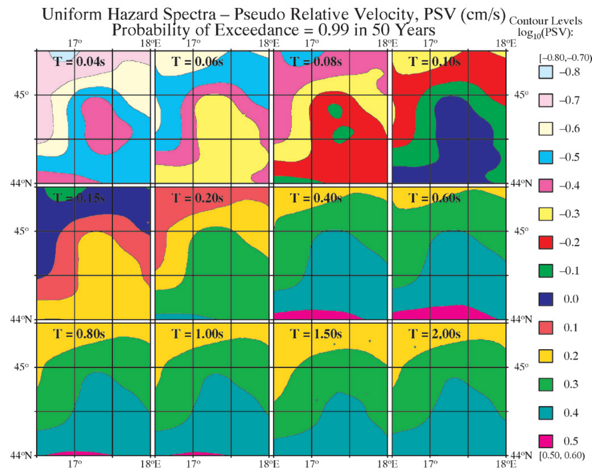
The choice of the exposure time of Y = 50 years is common, but depends on application and must be selected in accordance with the specified design guidelines. Figure 10 illustrates the dependence of UHS for the response spectral amplitudes of PSV(T) at 5% damping for exposure times of Y = 5, 10, 20,50 and 100 years and for 50% probability of exceedance. The spectral amplitudes increase for all periods with increased exposure time.

Perusal of Figs. 7a through e will show that the UHS of PSV amplitude change smoothly and slowly with distance. This is because all spectral amplitudes in these fig-



Slika 7d. Geografske varijacije (između 16,5ºE i 18,0ºE i 44,00ºN i 45,50ºN) spektra odgovora uniformnog seizmičkog hazarda pseudo-relativnih brzina (cm/s), za 12 perioda T = 0,4 s do 2.0 s, za P = 0.90 u vremenu izloženosti seizmičkom dejstvu od Y = 50 godina.

Figure 7d. Geographical variations (within 16.5ºE to 18.0ºE and 44.00ºN and 45.50ºN) of UHS of PSV (cm/s), at 12 periods T=0.4s to 2.0s, for P=0.90 in Y=50 years exposure.



Slika 7e. Geografske varijacije (između 16,5ºE i 18,0ºE i 44,00ºN i 45,50ºN) spektra odgovora uniformnog seizmičkog hazarda pseudo-relativnih brzina (cm/s), za 12 perioda T = 0,4 s do 2,0 s, za P = 0,99 u vremenu izloženosti seizmičkom dejstvu od 50 godina.

Figure 7e. Geographical variations (within 16.5ºE to 18.0ºE and 44.00ºN and 45.50ºN) of UHS of PSV (cm/s), at 12 periods T=0.4s to 2.0s, for P=0.99 in Y=50 years exposure.

ovako izračunatih spektara na geografskim koordinatama 44,78N, 17,21E za spektralne amplitude pseudo-relativnih brzina elastičnog odgovora (T) za prigušnje od 5%, za vreme izloženosti seizmičkom dejstvu od Y = 50 godina i za verovatnoću da će spektralne amplitude biti prevaziđene, P od 1, 10, 50, 90 i 99%.

Slika 8 ilustruje ovakav spektar odgovora uniformnog seizmičkog hazarda za spektralne amplitude pseudo-relativnih brzina elastičnog odgovora *PSV(T)*. Iz spektralne brzine odgovora, pseudo-relativne brzine *PSV(T)* može se izačunati odgovarajuće spektralno ubrzanje *PSA(T)*, kao $PSA(T) = (2\pi/T)\ PSV(T)$ (cm/s²). Na slici 9 prikazan je dijagram ovakvih pseudo-relativnih ubrzanja (u jedinicama g = 9,81 m/s²). On pokazuje spektar odgovora uniformnog seizmičkog hazarda za 5% prigušenja, vreme izloženosti seizmičkom dejstvu od Y = 50 godina i za 1, 10, 50, 90 i 99% verovatnoće da će izračunate amplitude biti prevaziđene barem jedanput.

Izbor vremena izloženosti seizmičkom dejstvu od Y = 50 godine uobičajen je, ali zavisi od toga za šta se primenjuje i mora se izabrati u skladu sa utvrđenim projektnim smernicama. Slika 10 ilustruje zavisnost spektra odgovora uniformnog seizmičkog hazarda za spektralne amplitude pseudo-relativnih brzina odgovora *PSV(T)* za prigušenje od 5% za vremena izloženosti seizmičkom dejstvu od Y = 5, 10, 20, 50 i 100 godina i verovatnoću da će amplitude biti prevaziđene barem jedanput od 50%. Spektralne amplitude se povećavaju za sve periode sa produženjem vremena izloženosti seizmičkom dejstvu.

Sa slika 7a do 7e uočava se da se spektar uniformnog seizmičkog hazarda amplituda pseudo-relativnih brzina sporo menja sa rastojanjem. To je zbog toga što ures have been calculated for the same $s = 0$ and $S_L = 1$ everywhere. Had we included the actual site conditions, these plots would have displayed considerably more variations. For an illustration of how the site conditions contribute to these variations over short distances the readers can examine figures 15 and 16 in Trifunac (2010). However, the site conditions will dominate in the variations of the UHS with geographic coordinates only when other factors are relatively constant or change slowly.

As the oscillator period tends to zero, its stiffness increases, and its relative deflections tend to zero. In the limit the PSA amplitudes then tend to the peak ground acceleration. This limit is almost approached for T = 0.04 s, and therefore the maps in Figs. 7a through e for T = 0.04 s also describe the spatial distribution of peak ground accelerations. By multiplying the amplitudes shown in these figures by $\omega_{25Hz} = 6.28/0.04$ one obtains the peak ground acceleration in cm/s², for exposure of 50 years, and for probabilities of exceedance equal to 0.01, 0.10, 0.50, 0.90 and 0.99. Distribution of so computed peak accelerations, or from the PSA amplitudes in Fig. 9, at T=0.04 s, at 44.78ºN and 17.21ºE, for example, is illustrated in Fig. 11. There is obtained 0.07g, 0.11g, 0.23g, 0.55g, and 1.20g for P = 0.99, 0.90, 0.50, 0.10, and 0.01 respectively, for exposure time of 50 years.

In many microzonation studies the seismic hazard analysis is presented only in terms of peak ground acceleration, and hence for such studies the Figs. 7a through e in this paper would be reduced only to one frame per figure, corresponding to T = 0.04 s, in the top left corners. As already noted, when multiplied by $\omega_{25Hz} = 6.28/0.04$ these figures describe spatial variations of peak ground acceleration in cm/s², for exposure of 50 years, and for su sve spektralne amplitude na ovim slikama izračunate svuda za isto $s = 0$ i $S_L = 1$. Da su uzeti u obzir stvarni geološki uslovi i uslovi tla lokacije, ovi dijagrami bi pokazali znatno veće varijacije. Primere o tome kako geološki uslovi lokacije doprinose ovim varijacijama na kratkim rastojanjima čitalac može pogledati na slikama 15 i 16 u radu Trifunca (2010). Međutim, uslovi lokacije će dominantno uticati na varijacije spektra uniformnog seizmičkog hazarda u zavisnosti od geografskih koordinata samo kada su drugi faktori relativno konstantni ili se sporo menjaju.

Kada period oscilacija teži nuli, krutost se povećava i relativna pomeranja oscilatora teže nuli. Na granici, maksimalne spektralne amplitude teže ka maksimalnom ubrzanju tla i gotovo se približavaju toj granici za T = 0,04 s, te karte na slikama od 7a do 7e za T = 0,04 s takođe opisuju prostornu rasprostranjenost maksimalnog ubrzanja tla. Množenjem amplituda prikazanih na ovim slikama sa $\omega_{25Hz} = 6{,}28/0{,}04$, dobija se maksimalno ubrzanje tla u cm/s², za vremene izloženosti seizmičkom dejstvu od 50 godina i za verovatnoću da će amplitude biti prevaziđene barem jednput od 0,01, 0,10, 0,50, 0,90 i 0,99. Na slici 11 prikazana su ovako izračunata maksimalna ubrzanja tla ili izračunata iz, na primer, maksimalnih spektralnih amplituda na slici 9, za T = 0,04 s, na geografskim koordinatama 44,78ºN i 17,21ºE. Dobija se 0,07g, 0,11g, 0,23g, 0,55g i 1,20g za P = 0,99, 0,90, 0,50, 0,10 i 0,01 za vremene izloženosti seizmičkom dejstvu od 50 godina.

U mnogim studijama mikrorejonizacije, analiza seizmičkog hazarda predstavljena je samo korišćenjem maksimalnog ubrzanja tla, pa za takve studije, slike 7a do 7e u ovom radu bile bi svedene samo na jedan okvir po slici, koji odgovara T = 0,04 s, u gornjim levim uglovima slika. Kao što je već napomenuto, kada se pomnože sa $\omega_{25Hz} = 6{,}28/0{,}04$, ove slike opisuju prostorne varijacije maksimalnog ubrzanja tla u cm/s², za vreme izloženosti seizmičkom dejstvu od 50 godina i za verovatnoću od 0,01, 0,10, 0,50, 0,90 i 0,99 da će ampliude biti prevaziđene barem jedanput.

Efekti različitih geoloških uslova lokacije

U ovom radu, ilustrovane su prostorne varijacije spektra odgovora seizmičkog hazarda pseudo-relativnih brzina samo za $s = 0$ i $S_L = 1$. Za modifikaciju izračunatih rezultata za druge lokalne geološke uslove i uslove tla, mogu da se koriste jednačina (20) i tabela 5 da bi se promenile izračunate spektralne amplitude spektra odgovora uniformnog seizmičkog hazarda. Slika 12 ilustruje razlike u spektima odgovora uniformnog seizmičkog hazarda pseudo-apsolutnih ubrzanja za lokaciju koja se nalazi na geografskim koordinatama 44,78ºN i 17,21ºE i za sve kombinacije s i S_L koje mogu da se koriste u jednačini Lee-a (1995). Može se videti da različiti uslovi lokacije mogu dovesti do značajnih promena u spektralnim amplitudama. Takođe se može videti da su te varijacije najizraženije za kratke periode, nasuprot onome što smo

probabilities of exceedance equal to 0.01, 0.10, 0.50, 0.90 and 0.99 respectively.

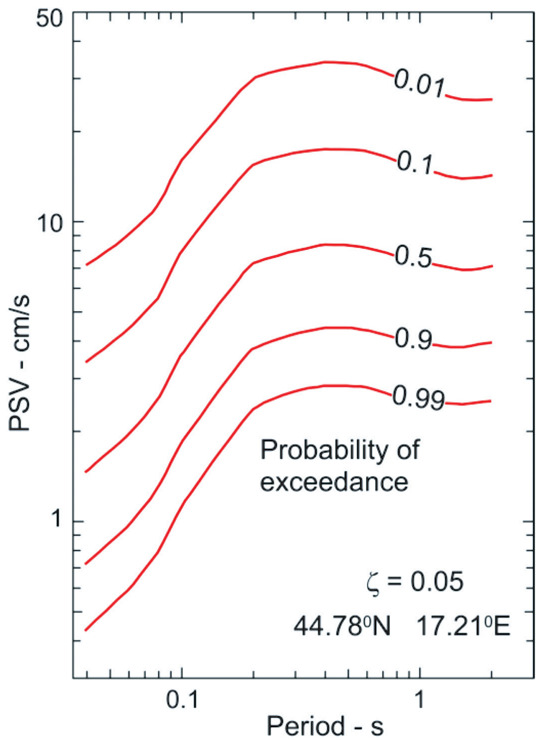
Effects of different site conditions

In this paper we illustrate the spatial variations of UHS of PSV only for $s = 0$ and $S_L = 1$. To modify the computed results to any local site conditions Eqns. (20) and Table 5 can be used to change the computed UHS spectral amplitudes. Fig. 12 illustrates the differences in UHS of PSA for a site at 44.78ºN and 17.21ºE and for all combinations of s and S_L which can be used with equations of Lee (1995). It can be seen that different site conditions can lead to significant variations of spectral amplitudes. It can also be seen that these variations are most pronounced in the short period range, in contrast to what we have found for the strong motion data recorded in California (Trifunac 1990b).

We have emphasized that the strong motion data recoded in different tectonic regions should not be mixed in the development of the empirical scaling equations (Lee 1997), and that the only way to minimize the uncertainties in the empirical scaling of strong motion amplitudes is to work with strong motion database recorded in well defined, well understood, and corresponding tectonic regions. The data recorded in different seismic regions does not differ only because of the differences in regional procedures for determining the earthquake magnitude and intensity levels, but also because of the differences in the physical nature of amplitude attenuation with distance, and as mentioned here (relative to the site effects in California) in terms of the differences the local site conditions bring into the recorded amplitudes.

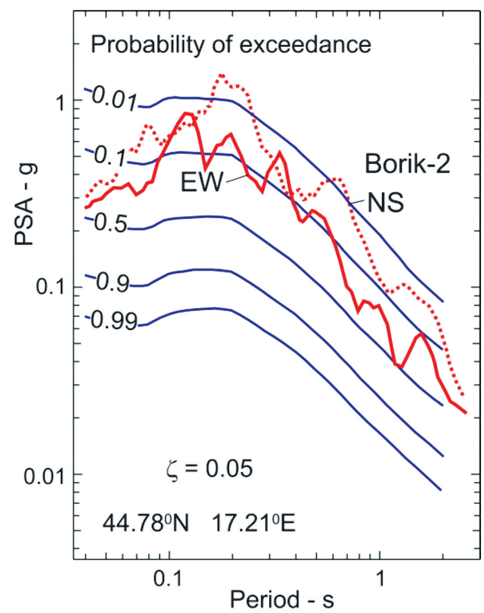
Differences in Spectral Shapes

It has been shown by Trifunac (2010) that the UHS can have very different shapes at sites with relatively small separation distances. These differences can result from different competing factors, and come mainly from the differences in the distances to the most active earthquake sources, frequency of earthquake activity at these sources, and from the local soil and geological site conditions. When seismic hazard is calculated in terms of only one scaling parameter, like peak ground acceleration, and when the spectral amplitudes are determined by a standard spectral shape, as is often done in applications with earthquake design codes, all the above mentioned factors, which contribute to the variation of the spectral amplitudes, are eliminated and the resulting spectra do not represent the UHS. In such cases, the actual UHS may be approximated only in the high frequency range, for frequencies, which are closely related to the peak ground acceleration. Consequently neither the UHS, nor the spectral shapes defined by the earthquake resistant design codes can or should be expected to agree with the spectral shapes of any spectra of the recorded earthquakes. In general, it can be ex-



Slika 8. Spektar odgovora uniformnog seizmičkog hazarda amplituda pseudo-relativnih brzina, u cm/s, na 44,78ºN i 17,21ºE, za 5% prigušenja, vreme izloženosti seizmičkom dejstvu od 50 godina (Y = 50) i za P = 0.99, 0.90, 0,50, 0,10 i 0,01.

Figure 8. UHS of PSV amplitudes, in cm/s, at 44.78ºN and 17.21ºE, 5 percent damping, 50 years of exposure (Y=50), and for P = 0.99, 0.90, 0.50, 0.10, and 0.01.



Slika 9. Poređenje spektra odgovora uniformnog seizmičkog hazarda pseudo-relativnih ubrzanja, u g, na 44,78ºN i 17,21ºE, za 5% prigušenja, vreme izloženosti seizmičkom dejstvu od 50 godina i verovatnoću da će amplitude biti prevaziđene barem jedanput P = 0 ,99, 0,90, 0,50, 0,10 i 0,01, sa spektralnim amplitudama koje su izračunate iz zapisanih silnih kretanja tla na lokaciji zgrade Borik-2 u Banja Luci za vreme zemljotresa sa magnitudom od M = 5,4 koji se dogodio 13.08.1981.g. (Trifunac i dr. 2007; 2010).

Figure 9. Comparison of UHS of PSA, in g's, at 44.78ºN and 17.21ºE, 5 percent damping, 50 years of exposure, and probabilities of exceedance P =0 .99. 0.90, 0.50, 0.10, and 0.01, with PSA computed from the recorded strong ground motion at Borik-2 site in Banja Luka during the M=5.4 earthquake of 13 August 1981(Trifunac et al 2007).

ustanovili za podatke silnog kretanja tla zapisane u Kaliforniji (Trifunac, 1990b).

Naglašeno je da podatke o zapisima silnog kretanju tla koji su zapisani u različitim tektonskim regionima ne treba mešati pri izvođenju jednačina empirijskog skaliranja (Lee, 1997) i da se neizvesnosti u empirijskom skaliranju amplituda silnog kretanja tla mogu smanjiti jedino kada se radi sa bazom podataka o silnim kretanjima tla za tektonske regione koji su dobro definisani, dobro istraženi i za koje su ti podaci odgovarajući. Podaci zapisani u različitim seizmičkim regionima ne razlikuju se samo zbog razlika u korišćenju regionalnih metoda za određivanje nivoa magnituda i intenziteta zemljotresa, već i zbog razlika u fizičkoj prirodi atenuacije amplituda sa rastojanjem i zbog, kao što je ovde pomenuto (u odnosu na efekte lokacija u Kaliforniji), razlika u lokalnim geološkim uslovima i uslovima tla.

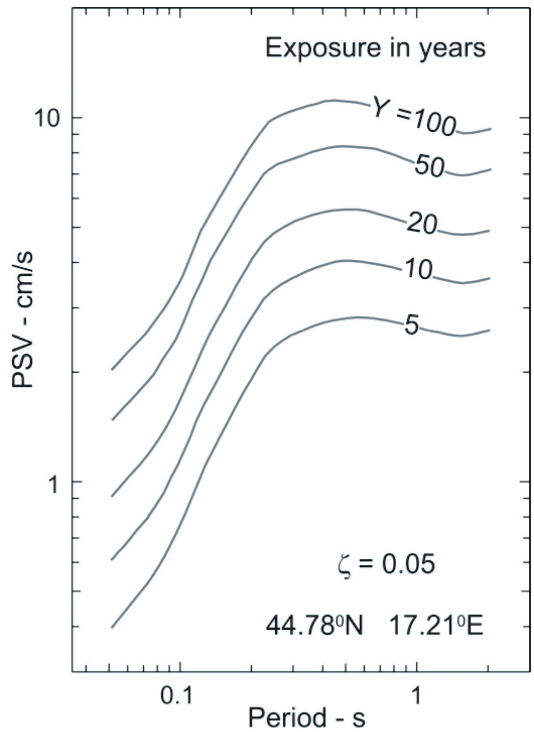
Razlike u spektralnim oblicima

Trifunac (2010) je pokazao da spektar odgovora uniformnog seizmičkog hazarda može da ima veoma različite oblike na lokacijama sa relativno malim međusobnim rastojanjem. Ove razlike mogu biti rezultat različitih faktora i dolaze uglavnom od razlika u rastojanjima od najaktivnijih žarišta zemljotresa, od različitih frekvencija

pected that the spectra defined by the design codes will be closer to the shapes of the spectra of selected recorded motions, because it is by some type of averaging of the spectra of several recorded motions that the majority of the design spectra have been determined. In contrast the UHS can have very different spectral shapes because those are based on the distribution of the amplitudes of very large number of contributing earthquake motions.

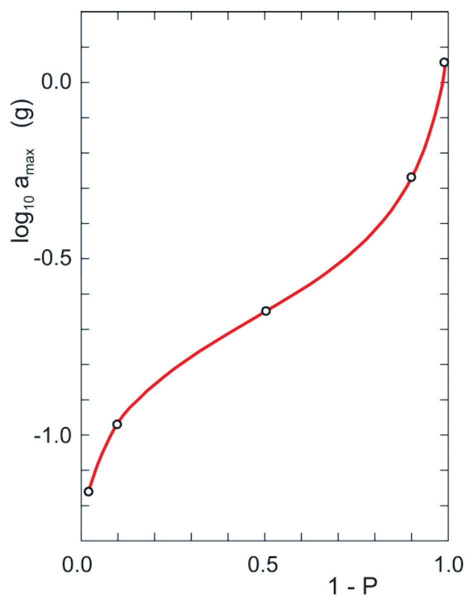
The principles governing the performance based design, and the guidelines for implementing those require precise and well-defined spectral shapes. Linear and nonlinear responses of the same structure are associated with different equivalent periods of response and for balanced design it is then necessary to have the correctly defined probabilities of exceeding the corresponding spectral amplitudes. Since this can be accomplished only with accurately specified distribution functions of response amplitudes, the UHS will provide the needed tool for accomplishing those objectives.

Fig. 13 compares the Eurocode 8 spectra (Type 1 and 2), at ground types A and C with the motions recorded in the basement of Borik-2 building in Banja



Slika 10. Spektar uniformnog seizmičkog hazarda amplituda pseudo-relativnih brzina, u cm/s, na lokaciji 44.78ºN i 17.21ºE. za 5% prigušenja, vreme izloženosti seizmičkom dejstvu od 5, 10, 20, 50 i 100 godina i P = 0,50.

Figure 10. UHS of PSV amplitudes, in cm/s, at 44.78ºN and 17.21ºE. for 5 percent damping, 5, 10, 20, 50, and 100 years of exposure, and P = 0.50.



Slika 11. Maksimalno ubrzanje tla, a_{max}/g (g = 9.81 m/s), na 44.78ºN i 17.21ºE, za vreme izloženosti seizmičkom dejstvu od 50 godina i verovatnoću da ampltude neće biti prevaziđene, 1 – P = 0,01, 0,10, 0,50, 0,90 i 0,99 (prikazano malim krugovima).

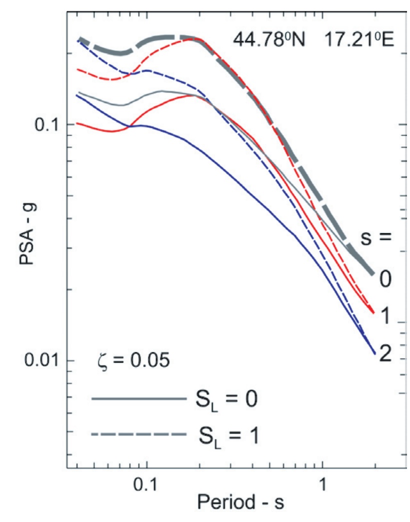
Figure 11. Peak accelerations, a_{max}/g (g = 9.81 m/s), at 44.78ºN and 17.21ºE. for 50 years of exposure, and probability of no exceedance 1 – P = 0.01, 0.10, 0.50, 0.90, and 0.99 (shown by small circles).

Luka, during a M=5.4 earthquake in 1981. By comparing this figure with Fig. 9 it will be seen how different are the spectral shapes of UHS and of the spectral shapes recommended by Eurocode 8. It can also be seen how different are the implied probabilities of exceeding most of the spectral amplitudes. For periods longer than about 0.1 s Fig. 9 suggests that the motions recorded at Borik-2 site have the probability of being exceeded at least once in 50 years of about 0.10. The peak acceleration of the motions at the basement of Borik-2 building was near 0.28 g, which according to Fig. 11 would be associated with probability of at least one exceedance in 50 years near 0.38. Unfortunately we cannot test those inferences by considering the recorded data, because the length of the observation period (less than 15 years, starting in 1972) is too short to provide reliable estimate.

5. CONCLUSIONS

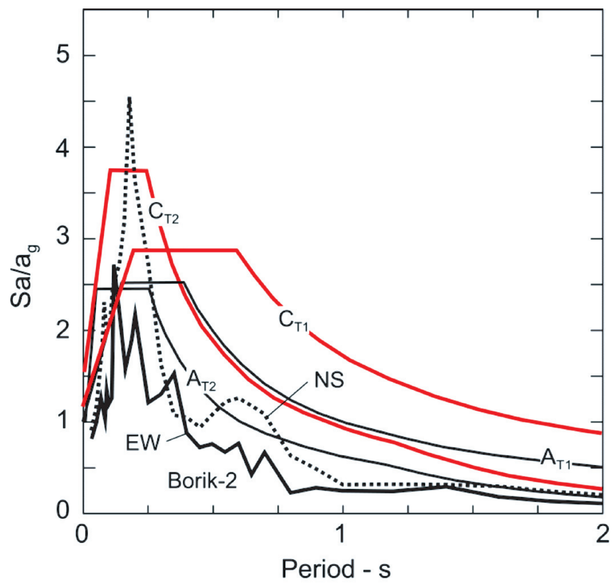
The lessons learned and the general conclusions of this work are similar to those we found for the microzonation of the Los Angeles area in California (Lee and Trifunac, 1987; Trifunac 2010). Those can be summarized as follows:

1. The AT-UHS method can be used to construct maps of Response and of Fourier spectral amplitudes



Slika 12. Varijacije spektra uniformnog seizmičkog hazarda pseudo-apsolutnih ubrzanja u jedinicama g, na 44.78ºN i 17.21ºE, za različite geološke uslove lokacije (s = 0 za segmente, s = 1 za srednje lokacije i s = 2 za lokacije na osnovnoj steni) i uslove tla (S_L = 0 za "stenovite" lokacije i S_L = 1 lokacije na krutom tlu), za 5% prigušenja, vreme izloženosti seizmičkom dejstvu od 50 godine i P = 0,50. Puna linija za s= 0 i S_L = 1 odgovara slučajevima koji su ilustrovani na slikama od 7a do 7e.

Figure 12. Variations of UHS of PSA in g's, at 44.78ºN and 17.21ºE, for different geologic (s = 0 for sediments, s = 1 for intermediate sites, and s = 2 for sites on the basement rocks), and soil (S_L = 0 for "rock" sites, and S_L = 1 for stiff soil sites) site conditions, for 5 percent damping, exposure of 50 years and P = 0.50. The heavy line for s = 0 and S_L = 1 corresponds to the cases illustrated in Figs. 7a through e.



Slika 13. Poređenje oblika spektra Evrokoda 8 (tipovi 1 i 2) na tlu tipova A i C, sa spektrima kretanja tla zapisanih u podrumu zgrade Borik-2 u Banjoj Luci, za vreme zemljotresa magnitude M = 5,4 koji se dogodio 13.08.1981. godine.

Figure 13. Comparison of the shapes of Eurocode 8 spectra (Type 1 and 2) at ground sites A and C, with spectra of the recorded motions in the basement of Borik-2 building in Banjoj Luka, during M = 5.4 earthquake of 13 August 1981.

aktivnosti zemljotresa u tim žarištima i od razlika u uslovima lokalnog tla i geološkim uslovima lokacije. Kada se sizmički hazard izračunava pomoću samo jednog parametra skaliranja, kao što je maksimalno ubrzanje tla i kada se spektralne amplitude određuju pomoću standardnih spektralnih oblika, što se često dešava kada se primenjuju seimički propisi, onda se svi gore pomenuti faktori koji doprinose varijacijama spektralnih amplituda eliminišu i rezultirajući spektri ne predstavljaju spektar odgovora uniformnog seizmičkog hazarda. U takvim slučajevima, stvarni spektar odgovora uniformnog seizmičkog hazarda može da se aproksimira samo u dijapazonu visokih frekvencija, za frekvencije koje su usko povezane sa maksimalnim ubrzanjem tla. Stoga se ni spektri odgovora uniformnog seizmičkog hazarda ni spektralni oblici koji su definisani pomoću propisa za projektovanje seizmički otpornih konstrukcija ne slažu, niti treba očekivati da odgovaraju spektralnim oblicima bilo kog spektra zapisanih zemljotresa. Uglavnom se može očekivati da će spektri koji su definisani seizmičkim propisima biti bliži oblicima spektara izabranih zapisanih kretanja tla, jer je većina projektnih spektara određena pomoću neke vrste uprošćavanja spekatara nekoliko zapisanih kretanja tla. Nasuprot tome, spektar odgovora uniformnog seizmičkog hazarda može imati veoma različite spektralne oblike, jer se zasniva na rasprostranjenosti amplituda velikog broja kretanja tla usled dejstva zemljotresa.

Principi koji regulišu projektovanje, zasnovano na očekivanom ponašanju konstrukcije i smernice za njegovu primenu zahtevaju precizne i dobro definisane spektralne oblike. Linearni i nelinearni odgovori nekih kon-

with given constant probability of being exceeded, at all frequencies of ground motion, and at least once in Y years.

2. The method offers excellent means to account simultaneously for all factors, which contribute to the site-specific spectral amplitudes, and can combine in a balanced way all variations of the regional sources of seismicity. It is efficient and demonstrates well the relative significance of different types and locations of earthquake sources, of their maximum magnitudes, their different epicentral distances, of different levels of seismic source activity, and of the local geologic and soil site conditions.

3. Even though the examples of UHS have been presented only for geological site condition of $s = 0$ (alluvium), local soil classification of $s_L = 1$ (stiff soil) and $\nu = 0$ (horizontal ground motion) everywhere, the computed UHS amplitudes can easily be modified to apply for other site and soil conditions, by using table 5 and Eqns. (20).

4. The results confirm that the spatial variability of the UHS spectral shapes is considerable, so that for correct implementation of the design principles in modern earthquake design codes, and in particular for implementation of the performance based design, the shapes of the site specific elastic design spectra cannot be taken to be the same (e.g. Type 1 and 2 spectral shapes in Eurocode 8) even in the small seismically active areas, and for sites separated by relatively small distance.

5. To implement the No-collapse requirement (e.g. $P < 0.10$ in $Y = 50$ yrs) and Damage-limitation requirement (e.g. $P < 0.10$ in $Y = 10$ yrs) in Eurocode 8, for example, it is necessary to determine spectral amplitudes at two different system periods, for two different probabilities of exceedance and for two different exposure time intervals. Since the shape of UHS changes with P and Y, the required spectral amplitudes cannot be evaluated via two hazard estimates of peak acceleration and a fixed spectrum shape, like Type 1 or Type 2 spectra in Eurocode 8, for example. The AT-UHS method however provides the required spectral amplitudes accurately and consistently.

6. For the development and implementation of the rational and economically sound earthquake design guidelines in urban areas it is necessary to reduce uncertainties in the selection of the elastic spectral amplitudes of strong earthquake ground motion, and to require that the design forces which have been adopted for all buildings and structures have comparable levels of accuracy and probabilities of exceedance. This can be accomplished only by eliminating the uncertainties caused by large fluctuations in the elastic spectral amplitudes, which result from hazard mapping based on peak acceleration, and constant spectral shapes.

strukcija povezani su sa različitim periodama odgovora i stoga je za izbalansirano projektovanje neophodno da postoje tačno definisane verovatnoće prekoračenja odgovarajućih spektralnih amplituda. Pošto se ovo može postići samo pomoću tačno utvrđenih funkcija rasprostranjenosti amplituda odgovora, upravo procena spektra odgovora uniformnog seizmičkog hazarda predstavlja metodu pomoću koje će se to i postići.

Na slici 13, pokazano je poređenje spektara Evrokoda 8 (tipovi 1 i 2) na tlu tipova A i C sa kretanjima tla zapisanim u podrumu zgrade Borik-2 u Banja Luci, za vreme zemljotresa sa magnitudom od M = 5,4 koji se dogodio 1981. godine. Poređenjem ove slike sa slikom 9, može se videti koliko su spektralni oblici spektra odgovora uniformnog seizmičkog hazarda različiti od spektralnih oblika koji se preporučuju u Evrokodu 8. Takođe se može videti koliko su različite verovatnoće da će spektralne amplitude biti prekoračene. Za periode duže od oko 0,1 s, slika 9 nagoveštava da kretanje tla zapisano na lokaciji zgrade Borik-2 ima verovatnoću od oko 0,10 da će biti prekoračeno barem jednom u 50 godina. Maksimalno ubrzanje kretanja tla u podrumu zgrade Borik-2 bilo je 0,28 g, što se, prema slici 11, može povezati sa verovatnoćom od blizu 0,38 da će barem jednom u 50 godina ta vrednost biti prevaziđena. Nažalost, ove rezultate ne možemo proveriti uzimajući u obzir zapisane podatke, jer je period posmatranja (manje od 15 godina, počev od 1972. godine) isuviše kratak da bi se izvršila pouzdana procena.

5. ZAKLJUČCI

Saznanja i opšti zaključci ovog rada slični su onima koje smo upoznali kroz mikrorejonizaciju područja Los Anđelesa u Kaliforniji (Lee i Trifunac, 1987; Trifunac 2010) i mogu se ukratko izraziti kroz sledeće tačke:

1. Metoda procene spektra odgovora uniformnog seizmičkog hazarda Andersona i Trifunaca može da se koristi za izradu karata seizmičkog odgovora i Furijeovih spektralnih amplituda sa zadatom konstantnom verovatnoćom da će svi zemljotresi, pri svim frekvencijama kretanja tla, prevazići spektralne amplitude barem jednom u periodu od Y godina.

2. Ova metoda predstavlja odličan način da se istovremeno uzmu u obzir svi faktori koji doprinose određivanju spektralnih amplituda, specifičnih za datu lokaciju i pomoću nje se mogu uključiti, na izbalansiran način, sve varijacije regionalnih seizmičkih žarišta. Ova metoda je efikasna i dobro pokazuje relativni značaj različitih tipova i lokacija žarišta, njihovih maksimalnih magnituda i njihovih različitih epicentralnih rastojanja, različitih nivoa aktivnosti i lokalnih geoloških uslova i uslova tla.

3. Iako su prikazani samo primeri spektra odgovora uniformnog seizmičkog hazarda za geološke uslove lokacije $s = 0$ (aluvijum), klasifikacije lokalnog tla $s_L = 1$ (kruto tlo) i $v = 0$ (horizontalna kretanja tla), izračunate amplitude spektra mogu lako da se modifikuju za primenu na drugim lokacijama i uslovima tla pomoću tabele 5 i jednačine (20).

4. Rezultati potvrđuju da je prostorna promenljivost spektralnih oblika spektra odgovora uniformnog seizmičkog hazarda znatna, tako da se za tačnu primenu projektnih principa iz savremenih seizmičkih propisa, a naročito za projektovanje zasnovano na očekivanom ponašanju konstrukcije, ne može uzeti da su oblici elastičnog projektnog sprektra svuda isti (npr. tipovi 1 i 2 spektralnih oblika u propisima Evrokoda 8) čak ni u područjima sa slabom seizmičkom aktivnošću i za lokacije koje se nalaze na relativno malim rastojanjima.

5. Za primenu, na primer, zahteva za sprečavanje rušenja (npr. P < 0,10 u Y = 50 g.) i zahteva za ograničavanje štete (npr. P < 0,10 u Y = 10 g.) iz Evrokoda 8, potrebno je odrediti spektralne amplitude za dve različite periode sistema, za dve različite verovatnoće pojavljivanja zemljotresa i za dva različita vremenska intervala izloženosti seizmičkom dejstvu. Pošto se oblik spektra odgovora uniformnog seizmičkog hazarda menja sa P i Y, zahtevane spektralne amplitude ne mogu se proceniti preko dve procene seizmičkog hazarda maksimalnog ubrzanja tla i fiksnog oblika spektra, kao što su, na primer, spektri tipa 1 ili tipa 2 u Evrokodu 8. Međutim, metoda procene spektra odgovora uniformnog seizmičkog hazarda daje potrebne spektralne amplitude tačno i dosledno.

6. Da bi se izradile i primenile smernice za racionalno i ekonomično projektovanje seizmički otpornih konstrukcija u urbanim područjima, potrebno je smanjiti neizvesnost pri izboru elastičnih spektralnih amplituda silnih kretanja tla i zahtevati da projektne sile koje su usvojene za sve zgrade i konstrukcije imaju odgovarajuću tačnost i verovatnoću da će biti prevaziđene. Ovo se može postići samo eliminisanjem neizvesnosti koje su posledica velikih fluktuacija elastičnih spektralnih amplituda, koje rezultiraju iz izrade karata seizmičkog hazarda zasnovanog na maksimalnom ubrzanju tla i konstantnim spektralnim oblicima.

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