Numerical Green's function method: Application to quantifying ground motion variations of $M7$ earthquakes*

Haijiang Wang^{1,3,*} Heiner Igel² and Frantisek Gallovič²

¹ School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China

² Department of Earth and Environmental Studies, Section Geophysics, Ludwig-Maximilians-University, München 80333, Germany

³ Mengcheng National Geophysical Observatory, School of Earth and Space Sciences, University of Science and Technology of China, Mengcheng 233527, China

Abstract The concept of “numerical Green's functions” (NGF or Green's function database) is developed. The basic idea is: a large seismic fault is divided into subfaults of appropriate size, for which synthetic Green's functions at the surface (NGF) are calculated and stored. Consequently, ground motions from arbitrary kinematic sources can be simulated, rapidly, for the whole fault or parts of it by superposition. The target fault is a simplified, vertical model of the Newport-Inglewood fault in the Los Angeles basin. This approach and its functionality are illustrated by investigating the variations of ground motions (e.g. peak ground velocity and synthetic seismograms) due to the source complexity. The source complexities are considered with two respects: hypocenter location and slip history. The results show a complex behavior, with dependence of absolute peak ground velocity and their variation on source process directionality, hypocenter location, local structure, and static slip asperity location. We concluded that combining effect due to 3-D structure and finite-source is necessary to quantify ground motion characteristics and their variations. Our results will facilitate the earthquake hazard assessment projects.

Key words: numerical Green's function; ground motion variation; hypocenter location; static displacement distribution

CLC number: P315.01

Document code: A

1 Introduction

Earthquakes destroy buildings by acting a “load” through ground motions, which are excited by seismic waves propagating away from the earthquake source. At present, the numerical technique has been developed to be capable of accurately calculating the complete wavefield resulted from large potential earthquakes in a given seismically active region of known structure. It is believed to be practical and will play a central role in reliably estimating shaking hazard (e.g., Olsen and Archuleta, 1996; Olsen, 2000; Ewald et al, 2006). Such calculations will complement hazard estimation, includ-

ing probabilistic estimates of seismicity (e.g., Gerstenberger et al, 2005) and/or stochastic means to calculate ground motion scenarios, which usually adopt highly simplified physical models (e.g., Beresnev et al, 1998; Boore, 2003).

Earthquake-induced ground motions strongly depend on: ① velocity structure, ② finite-fault slip histories, ③ source-receiver geometry (also known as directivity effect), ④ local site condition and ⑤ topography. The local and regional velocity model can be estimated and continuously improved using tomographic tools and/or direct measurements (e.g., borehole information). However, the uncertainty coherent with the rupture processes (stress drop, source mechanisms, rupture velocity, slip velocity, etc) remains. Considering source-receiver geometry effects, the uncertainty becomes more complex for the future earthquakes whose initial region is not sure yet. Consequently, to estimate

* Received 20 February 2010; accepted in revised form 11 May 2010; published 10 June 2010.

* Corresponding author. e-mail: hjwang7@ustc.edu.cn

© The Seismological Society of China and Springer-Verlag Berlin Heidelberg 2010

ground motion excited by one or more “scenario earthquakes” of a specific seismically active region could be a formidable problem. One would have to calculate many different slip scenarios for one presumed earthquake in order to account for rupture-related variations. However, in complex 3-D media, the numerical calculation of complete 3-D wavefield can be expensive, hence restricts seismologists to calculate single source scenario (e.g., Graves, 1996; Olsen and Archuleta, 1996; Olsen, 2000; Ewald et al, 2006). Others consider a huge number of source scenarios and assess the corresponding variability with restrictions to simple structures (e.g., Gallovic and Brokešová, 2004, 2007a, b).

Right now, these two branches of researches are not sufficient to systematically quantify the variations due to complex 3-D media plus complex source process. To fulfil this task without running 3-D numerical calculation for each kinematic source scenario, we propose to generate Green’s function database for a discrete model of a fault or fault system embedded in a seismic active areas with well-investigated 3-D structure of media and fault system. The surface ground motions, namely Green’s functions, for each subfault are calculated within a certain frequency range, and stored. The resulted database allows arbitrary finite source scenarios to be synthesized at very little computational costs compared with a normal 3-D wavefield calculation.

It should be mentioned that in a region where plenty of seismic records are available, Green’s functions can be acquired from real recordings. This method is called empirical Green’s function (EGF) method, which has been developed and widely used since 1970s. Roughly, EGF approaches can be distinguished into two main classes: the composite and the rupture parameter approaches. The composite method (e.g., Hartzell, 1978; Irikura, 1983) is not based on the representation theorem (Aki and Richards, 2002). It assumes that the large event is composed of small to moderate-sized events ($M_0 \geq 2.3 \times 10^{15}$ N·m). One bigger fault plane could be described by a simple geometrical summation of its different pieces. The summation of the small events (EGFs) is thus based on linear scaling relations between small and large events, while the stress drop is assumed to be constant throughout the fault plane. The discretization of rupture process is usually quite coarse, which produces spatial and temporal high-frequency aliasing effects (Bour and Cara, 1997). This method has the advantage of simplicity, but its potential is limited by the fact that suitable empirical records are not always available.

The rupture parameter method (Hutchings and Wu, 1990; Hutchings, 1991) uses very small events ($M_0 < 1.5 \times 10^{14}$ N·m) to derive Green’s functions. Each small earthquake is considered to be excited by effective step-impulsive source time function. After de-convolved by the specifically assumed source time function and normalized with its moment, recordings of a small event can be used directly as (empirical) Green’s functions in the representation relation (Aki and Richards, 2002). The actual seismograms from a hypothetical rupture process are calculated by superposing EGFs, and using an appropriate kinematic rupture model. Thus one can easily simulate the rupture process by varying the hypocenter location, rupture velocity, fault plane geometry, slip distribution, and rise time. But for a sub-fault without recording, its EGFs are acquired by interpolating the EGFs excited by its adjacent elements with necessary corrections with respect to radiation pattern, attenuation, and P and S travel times. At the same time, a relatively simple spectral division is adopted to obtain the source pulses from real recordings and thus errors will be introduced in the frequency range, where the amplitude is small, inevitably.

Similarly, Graves and Wald (2001) also calculated a database of Green’s functions. They put the source (double couple point source) at a station and recorded the response at all the 3-D grids. Those responses can, reciprocally, be used as Green’s functions. Their work focuses on a few stations on the surface where ground motions are available. The fault discretization can reach the same scale of the grid-length adopted by the numerical method. We are interested in providing the spatial map of the ground motion variation. In this paper we will put the source on the fault plane (with an appropriate discretization) and obtain the Green’s functions at each point of the study area.

2 Numerical Green’s function method

As shown in Figure 1, the numerical Green’s function (NGF) method is summarized with graphical description. Ground motion is recorded at one station (triangle in Figure 1) on the surface during an earthquake. When an earthquake occurs, each part of the fault plane, roughly described with a rectangular (Figure 1, bottom right), is excited one by one, cracks with specific pattern, and radiates energy propagating through the media to the station on the surface (Figure 1, top right). The above-mentioned ground motion is actually the summa-

tion of all the individual ones. The individual ones are referred as the NGFs, which include the effect of source and propagation path. So the general idea behind the NGF method is to provide all these individual energies and present an appropriate way to synthesize them for source scenario simulations.

Figure 1 Schematic illustration of the numerical Green's function method. The fault plane (solid rectangle in the bottom left corner) for a large earthquake is buried underground and zoomed into a larger one (bottom right). This fault plane is discretized into subfaults (equilateral rectangles in the bottom right corner), and their corresponding Green's functions at a specific station (solid triangle) are calculated (top right). The seismic motion of the large earthquake (top left) at the station (solid triangle) can be synthesized with those individual Green's functions.

2.1 Theory

Aki and Richards (2002) used the Green's function, $G_{ip}(\mathbf{x}, t, \boldsymbol{\xi})$, to define the i -th component of the ground displacement response at position $\mathbf{x}$ and time t due to a unit impulse force in p -direction exerted at time $t=0$ and location $\boldsymbol{\xi}$. For a pure shear fault, Σ , embedded in an isotropic medium, by taking a time derivative on both sides of equation (3.19) (Aki and Richards, 2002), the representation theorem describing the velocity wavefield introduced by a pure shear fault is

$$v_i(\mathbf{x}, t) = \iint_{\Sigma} s(\boldsymbol{\xi}, t) \mu(\boldsymbol{\xi}) \tilde{M}_{pq}(\boldsymbol{\xi}) * \frac{\partial G_{ip}(\mathbf{x}, t, \boldsymbol{\xi})}{\partial \xi_q} d\Sigma, \quad (1)$$

where $v_i(\mathbf{x}, t)$ is the i th component of ground velocity at position $\mathbf{x}$ and time t . Scalar function $s(\boldsymbol{\xi}, t)$ is the slip rate function located at $\boldsymbol{\xi}$ on the fault plane. Parameter $\mu(\boldsymbol{\xi})$ is the shear modulus of the medium. Moment density tensor is represented with $\tilde{M}_{pq}(\boldsymbol{\xi}) = u_p(\boldsymbol{\xi})n_q(\boldsymbol{\xi}) + u_q(\boldsymbol{\xi})n_p(\boldsymbol{\xi})$ for describing the source mechanism, where

$u(\boldsymbol{\xi})$ is the unit vector normal to the fault and unit vector $n(\boldsymbol{\xi})$ indicates the slip direction. After subdividing the fault plane, Σ , into elements, σ_n ($n=1, 2, \dots, N$), equation (1) is then reformulated as

$$v_i(\mathbf{x}, t) = \sum_{n=1}^N \iint_{\sigma_n} s(\boldsymbol{\xi}, t) \cdot \mu(\boldsymbol{\xi}) \cdot \tilde{M}_{pq}(\boldsymbol{\xi}) * \frac{\partial G_{ip}(\mathbf{x}, t - \tau(\boldsymbol{\xi}), \boldsymbol{\xi})}{\partial \xi_q} d\sigma, \quad (2)$$

where the time term $\tau(\boldsymbol{\xi})$ is introduced to describe the time delay due to the rupture front propagation from the hypocenter to point $\boldsymbol{\xi}$ on the fault. We assume that the subfault σ_n can be approximated as a point source located at its center and the differences between the individual $s(\boldsymbol{\xi}, t)$, $\mu(\boldsymbol{\xi})$, $\tilde{M}_{pq}(\boldsymbol{\xi})$ and $\tau(\boldsymbol{\xi})$ within σ_n can be neglected. Here we refer the approximate variables as $s^n(t)$, μ^n , $\tilde{M}_{pq}^n$ and τ^n . After moving them outside the integration, equation (2) is approximated as

$$v_i(\mathbf{x}, t) \approx \sum_{n=1}^N \left(\tilde{M}_{pq}^n \iint_{\sigma_n} \frac{\partial G_{ip}(\mathbf{x}, t - \tau^n, \boldsymbol{\xi})}{\partial \xi_q} d\sigma \right) * s^n(t) \mu^n. \quad (3)$$

We further neglect the difference between the individual Green's function derivative, $G_{ip,q}$ (comma stands for the space derivative) inside each subfault σ_n , and refer the representative approximation as $G_{ip,q}^n(\mathbf{x}, t - \tau^n)$, finally we get

$$v_i(\mathbf{x}, t) \approx \sum_{n=1}^N \left(\tilde{M}_{pq}^n G_{ip,q}^n(\mathbf{x}, t - \tau^n) \right) * s^n(t) \mu^n A^n, \quad (4)$$

where A^n is the area of the n th small source σ_n . We take the part enclosed in the square brackets as numerical Green's function, $g_i^n(\mathbf{x}, t - \tau^n)$, which can be calculated using an impulse slip rate with pre-determined direction and fault geometric parameters. We finally obtain the basic equation for synthesis of ground motions as following:

$$v_i(\mathbf{x}, t) \approx \sum_{n=1}^N g_i^n(\mathbf{x}, t - \tau^n) * s^n(t) \mu^n A^n. \quad (5)$$

Therefore, with these known numerical Green's functions saved, we can simulate arbitrary finite fault source scenarios very fast and economically by simple and fast time convolving with the corresponding source rupture. For example, to calculate the ground motion at one station, the memory occupation is 250 Mb and the

CPU time is in the magnitude of seconds. This work can be fulfilled with a single PC.

The NGF calculations can be carried out with a numerical solution to the 3-D wave propagation problem. Here we employ a fourth-order staggered-grid finite-difference approach (e.g., Igel et al, 1995; Graves, 1996) with efficient absorbing boundaries based on the concept of perfectly matched layers (e.g., Collino and Tsogka, 2001; Marcinkovich and Olsen, 2003).

The target fault is uniformly divided into rectangular subfaults, for which the Green's functions are calculated separately with double-couple point sources and then stored afterwards. The source mechanism of each point source is determined by the target fault source mechanism, or exactly speaking, by the slip direction according to the described moment tensor density $\tilde{M}_{pq}(\xi) = u_p(\xi)n_q(\xi) + u_q(\xi)n_p(\xi)$. Thus if we calculate NGF for two point sources with slip direction parallel to the strike and the dip direction, respectively, we can obtain the NGF excited by a subfault with arbitrary slip direction, by appropriate summation of the two separate NGFs. For each subfault of a pure strike-slip fault, only one point source is necessary. This pure strike-slip fault will save the total amount of work by a half time. The slip rate time function takes the form of a delta function, which can be easily convolved with any kind of slip rate function of an arbitrary earthquake rupture process description.

The basic idea of the numerical Green's function method comes from the numerical solution of the representation theorem (e.g., Aki and Richard, 2002), which also forms the mathematical foundation of another broadly used ground motion synthesis method, i.e., empirical Green's functions (e.g., Hutchings and Wu, 1990; Bour and Cara, 1997). Even it is not correct in a strict mathematical sense, we use the term Green's function here on contrast to the so-called 'empirical Green's functions' in the other papers in which real recordings are used as Green's functions.

From equation (2) to equation (3), we approximate a subfault by a point source and neglect the source parameter differences between individual points. The resulting discontinuous behaviour, compared to the continuous solution, will introduce errors into the final synthesized ground motions. The larger the subfault is, the more misfits will be introduced. Considering the structure effect on wave propagation and the complex ruptured process, this misfit will become more unpredict-

able. One should try to find a minimum number of subfaults to ensure the ground motion to be accurate enough for a given earthquake, since generation of a NGF database is computationally time-consuming. For a homogeneous structure, the optimal (largest) size of such subfaults is expected to depend on: ① the properties of the ruptures themselves including rupture speed, slip velocity, rise time, etc, ② the azimuth of the receiver (directivity) and location (distance) relative to the rupture propagation, and ③ the desired frequency band for the synthesized ground motions. These dependencies are thoroughly investigated with a hypothetical homogeneous medium present. The optimal subfault size will generally increase with the increase of the hypocentral depth and rupture velocity. For the case of cut-off frequency, it behaves inversely. More detailed descriptions are referred to Wang et al (2008).

In summary, the basic idea and step-by-step process of NGF method is as follows.

1) Find an appropriate way to discretize the target fault (or the minimum number of subfaults), with which the discretization of the fault will not introduce too much misfit to the synthesized ground motions.

2) Calculate the ground motions over the study area with point sources substituting subfaults. For a pure strike-slip fault system, only one point source with slip in strike direction is necessary. For other fault system, the point sources with slip in both strike direction and dip direction are needed.

3) Collect geometrical information and build up fault model for a future certain earthquake. Prepare a few of kinematic source processes based on the well-built database to check and select the optimal subfault size.

4) Discretize the fault according to the optimal subfault size and calculate NGFs.

5) Design rupture processes for arbitrary earthquakes, and then conduct time convolution according to equation (5) to yield ground motions in the study area.

2.2 Example: Los Angeles basin

The Newport Inglewood fault system (NI), shown in Figure 2, is chosen as target fault to apply the NGF method because: ① it hosted the *M*6.4 Long Beach earthquake in 1933 (Hauksson and Gross, 1991), causing serious damages; ② it is still considered to be the most potential damaging source to Log Angeles area in the future; ③ the near-vertical plane can be approximated to the first order accuracy by a vertical plane in

Figure 2 Los Angeles area with modelled region (dashed rectangle) and the idealized Newport-Inglewood fault. Inset is the final slip distribution of a $M7$ earthquake on the vertical Newport Inglewood fault plane and hypothetical hypocenter grid (black asterisks, for investigation of hypocentral effect on ground motion). H_1 and H_2 show the two example hypocenter locations for more detailed exhibition of hypocentral effect on ground motion.

numerical calculations, and the predominant right-lateral slip can be approximated with a pure strike-slip mechanism (Grant and Shearer, 2004). The fault has a length around 79 km. Thus an area of $96 \times 87 \text{ km}^2$ horizontally, with a depth of 30 km, is selected as the study area, and rotated to have the longer side parallel to the fault (Figure 2). The velocity model is derived as the elastic part of the SCEC 3-D velocity model for the Los Angeles basin (Version 3, Kohler et al, 2003). To reduce the computational effort and the size of the finally created database we limit the seismic velocities to the values above 1.4 km/s. The contour map of the sedimentary basin (cut off with iso-surface of shear velocity) is shown in Figure 3. With a grid-length of 300 m implemented within the 3-D staggered finite-difference method, ground motion with frequency less than 0.5 Hz

is usable, which means the artificial numerical dispersion could be neglected. This will of course limit the applicability of this method. At first, no topographic effect is considered although it has been shown to be important both for translations (Zhang and Chen, 2008) and rotations (Godinho et al, 2009).

With a 3-D heterogeneous structure, the conclusion about the trend of the fault discretization accuracy as a function of cut-off frequency (as shown for the homogeneous case) still holds. With a tolerable misfit energy introduced by the discretization, the optimal subfault size is chosen as $1.5 \text{ km} \times 1.5 \text{ km}$ (more detailed descriptions refer to Wang et al, 2008). The other parameter setups, including the numerical technique, the study area, and the working fault system, are shown in Table 1. The seismograms for the 145×165 equally spaced surface grids at 600 m distance are stored to save the final database volume, which reaches up to 187.5 Gb.

Figure 3 Depth of shear wave velocity isosurface at 2.0 km/s (grey scale). The thick white line represents the fault trace of the $M7$ earthquake. Profile PQ (black dashed line) is used for detail discussion in later section.

Table 1 Simulation setup for Newport Inglewood fault in Los Angeles basin

Fault dimensions		Length of subfault /km	Temporal discretization /s	Lowest v_s /(m·s ⁻¹)	Simulation time /s	Frequency range/Hz	Dimensions of working area			Grid length /m
Length/km	Width/km						x/km	y/km	Depth/km	
60	19	1.5	0.018	1 400.0	65	<0.5	96	105	30	300
Number of cells	Absorbing boundary nodes (Perfectly matched layer)		Fault top depth /km	Ground motion components		Memory occupation for one NGF calculation/Gb		CPU time for one NGF calculation/h		Total database size/Gb
320×350×100		15	1.5	3 velocities plus 3 rotation rates		6.8		28		187.5

3 Application: Quantifying ground velocity variations

Huge variation of strong ground motion observed in the near-source can be described and explained with several phenomena, such as directivity, near-source impulse, and static offsets, which are strongly affected by the geometrical and dynamic characteristics of the faulting. The NGF database calculated allows us, within the limits of the method (e.g., reliable frequency range), to synthesize ground motions from arbitrary strike-slip histories on the Newport Inglewood (NI) fault for the complete study area, and thus enables us to investigate how the ground motion varies with the source and the basin structure. Benefiting from the method for calculating quasi-dynamic rupture process (Guatteri et al, 2004), we can fix the final slip distribution, vary the hypocenter location, calculate the corresponding ground motions and investigate the complex variation of ground motion (translation and rotation). This method allows the slip distribution, the rupture velocity and slip rate to be changed over the fault plane and thus is capable of accounting for the accelerating tendency of the crack front due to dynamic loading and the high stress-drop promotion of fast rupture propagation. At the same time, we can also focus on the source scenarios with fixed hypocenter but varied slip distribution.

At first, the method is verified against other researches. The comparison is carried out between our results and one attenuation relationship of the pseudo response spectral acceleration (PSA) decaying with the fault distance, which was developed and has been widely used for the southern California region (Campbell and Bozorgnia, 2003). The figures are published in Wang et al (2008). We only briefly describe some results in this paper. First, the mean value of our results fits well with that predicted by the attenuation relationship at all distance ranges for the averaged horizontal component and the vertical component. Secondly, the PSAs from our simulations saturate, too, at short distances from the fault plane. Thirdly, for the horizontal component, there are obviously high PSAs in the fault distance range including the small basin where basin amplification is observed. Those predicted by the empirical relation, however, decrease smoothly in this range.

A question of considerable practical relevance to estimate the seismic hazard is how variations of the hypocenter location, for a given final slip distribution,

influence the shaking for a scenario earthquake of a given magnitude. How the ground motion varies with different slip histories but same hypocenter location is essential, too. We assume the existence of a scenario $M7$ earthquake on the NI fault. For this earthquake, we synthesize ground motions by varying hypocenter locations with fixed slip distribution (24 hypocenters in Figure 2, inset). We also investigate the case of fixed hypocenter (black star in Figure 5b) location but with varied slip distributions. The 20 different static displacements are shown in Wang (2007).

The ground velocities simulated with two hypocenters, H_1 and H_2 (Figure 2, inset), are shown, as examples. The input final slip distribution is shown in Figure 2 (inset). H_1 is located at the right edge of the fault plane and thus unilateral rupture propagation is implemented into the source; whereas H_2 is close to the middle of the fault plane and the rupture propagates bilaterally. The velocities on the profile PQ (Figure 3) are shown in Figure 4. The profile is located at $y=28.80$ km, parallel to the fault trace and across the basin. Basin effects, such as amplitude amplification and duration time elongation, are clearly observed in the range of $x \in [15, 30]$ (unit in km) for all the three components. Because of the widely known basin amplification effect, large velocities are observed close to the basin edge as Olsen (2000) noted. The amplification of the medium introduces larger ground motions when compared to those predicted with attenuation relationships (Wang et al, 2007). In the range of $x \in [0, 15]$, which is already outside the basin, for the hypocenter H_1 , the velocity amplitudes of y -component (Figure 4b) are compatible to those inside the basin ($x \in [15, 30]$), but it is not the case for velocities of x - and z -components (Figure 4a and 4c). Thus the directivity effect (restricted to the fault-perpendicular component) is confirmed. Outside the basin, in the range of $x \in [0, 15]$, unilateral rupture process (hypocenter H_1) creates larger velocities of the fault perpendicular component than bilateral rupture process (hypocenter H_2). The explanation lies in the directivity effect.

The parameter study allows us to extract the PGVs of all 24 simulations, which contain the dominant features of the two previously shown examples (e.g., basin wide shaking, fault-distance dependency, and ground motion elevation by the slip asperity). The variations of the hypocenter-dependent ground motions can be expressed by the variance such as the maximum of the PGV to the mean PGV at each point of the surface grid.

Figure 4 Velocities in profile PQ (located at $y=28.8$ km, Figure 3) of x - (a), y - (b) and z -components (c) simulated with two example hypocenters H_1 and H_2 and the same static displacement (Figure 2, inset). The shear wave velocity isosurface depth (at 2.0 km/s) is depicted at the bottom as the shadowed area. The maximum velocity amplitude $v_{\max}$ across this profile is also shown.

One ratio term is calculated and shown to characterize the variations: $R_{\max}$, the ratio of maximum value to mean value. The results are illustrated for all the three components in Figure 5a. For the case of varied static displacement with fixed hypocenter, there will be 20 PGV distributions according to 20 static displacements. The distributions of ratio, $R_{\max}$, are shown in Figure 5 for three velocity components.

For the case of varied hypocenters, the largest $R_{\max}$ values of x -component (Figure 5a, left) are observed in regions A and B near the basin edges. Large ratios of y -component (Figure 5a, middle) are observed in regions C and D . Regions C and D are aligned with almost equal angle to the fault trace, which is possibly related to the S-wave radiation pattern. In the region D , outside the basin, high ratios are observed. For z -component

(Figure 5a, right) the ratios are more evenly distributed with maximum values inside the basin (region E). The largest deviation from the mean value (factor 3) is thus predicted for x -component of motion close to the edges of the basin.

For the case of varied static displacements (Figure 5b), large values of $R_{\max}$ of both x - and z -components are observed in region F (right in Figure 5b) far from the epicenter and the fault projection, where the corresponding medium parameters change rapidly. These $R_{\max}$ values are comparable to those observed around the fault projection where source scenarios change rapidly. The basin structure obviously introduces large variations to the seismic motion. For the y -component (fault perpendicular), large $R_{\max}$ values are mainly restricted in the region G (middle in Figure 5b) surrounding the epi-

central region where source effect are obvious. It seems that the variations of y -component (fault perpendicular) are controlled by the source, while structure has equivalent effect on the two fault parallel components. The directivity effect is also observed in the realistic measurements and considered to be a crucial aspect in earthquake hazard and risk analysis (Shabestari and Yama-

zaki, 2002). The reason resides in its transverse position when the S-wave radiation pattern from a double couple point source is taken into account. The fault perpendicular component is dominated by the directivity effect even with the presence of the obvious basin amplification effect.

Figure 5 Ratio between the maximum PGV and the mean PGV for the case of varied hypocenter with fixed static displacement (a), and for the case of varied static displacement with fixed hypocenter (b). For figure (a) and (b), left, middle and right are for x -, y -, and z -components. The dashed rectangle indicates the fault trace. Thin lines are contours of the seismic velocity model. Black star marks the epicenter for the case of varied static displacement with fixed hypocenter. Region A, B, C, D, E, F and G are picked up for more detailed discussion. Note the gray scale difference.

The largest $R_{\max}$ values of x -, y - and z -components over the entire study area for the varied hypocenters are roughly 3.2, 2.5 and 2.5, respectively. However, those for the varied static displacements are roughly 2.1, 2.2 and 2.5 for the x -, y - and z -components, respectively. Changing the rupture starting point will introduce more variations on ground motions than changing the final slip distribution of kinematic rupture description.

The results briefly described in this section indicate that to reliably estimate shaking hazard for specific earthquake scenarios, the source dependent effects should be taken into account. This necessitates calculation of many different slip histories to fully account for the associated uncertainties. In the long period range considered in this work, there is a marked difference between the finite-source effects on the various motion

components, mixed with effects of the 3-D structure. More simulations will be necessary in the future to quantitatively estimate the contributions of small scale structures and source effects at higher frequencies.

4 Discussion and conclusions

We have developed the concept of numerical Green's function (NGF) that can be applied to discretized faults or fault systems in 3-D media. With the NGF database calculated and stored, earthquake scenario simulations from arbitrary slip histories can be carried out very fast compared to one full-scale simulation. This work can be done on a single PC.

As first application, NGF databases are used to systematically study the source related uncertainties/variations of seismic hazard relevant wave field

properties (peak ground motions, static displacements, shaking duration, etc) with varied slip distributions (e.g. asperity locations), slip and rupture velocities, hypocenter locations, etc. This application takes into account, also, the possibility to apply high-resolution slip histories from dynamic rupture simulations and to investigate their relevance to shaking hazard.

The influence of hypocenter location on the resulting ground motions is quite complex together with dependence of PGV distribution and its variation on local sedimentary structure, directionality and slip asperity location. Seismic shaking variations due to varied static displacements are also investigated. Directivity effect is dominant in controlling the fault perpendicular component of ground motion. The fault parallel components are obviously affected by the structure at the same time. The variations become more complex when the slip asperity elevation effect is taken into account. The comparison between two cases, referred as varied hypocenter and varied static displacement, indicates simply changing the hypocenter location will dramatically affect the ground motion and its variation. It is important to acquire the exact information of stress concentration zone and thus locate the starting point of a future earthquake when the earthquake hazard assessments are carried out.

The NGF method is subject to severe limitations. Amongst others, ① the fault is approximated by a vertical plane and pure strike-slip source mechanism; ② the lowest frequency resolution (less than 0.56 Hz) is too low to be useful for realistic hazard estimates. The highest frequency (0.56 Hz) is only relevant for very tall buildings; ③ our investigations are limited to only $M7$ earthquakes happening on the same fault; ④ the topographic effect is not considered. Yet, for the first step, the main purpose is to illustrate the potential functionalities of an NGF database. Source related uncertainty in 3-D media is an issue that has so far not been addressed properly, partly due to limitations of computational resources. With the NGF method, it is possible to systematically investigate source related uncertainties in 3-D areas with intensive seismic hazard.

It is important to note that such NGF databases only make sense in the area where the crustal structure is well known. The NGF database needs to be recalculated with every model update. Yet, considering the combining complex effect due to source and structure property revealed by this study, we suggest collecting as much information as possible about future earthquake

and its possible damage to buildings inside a seismic active area. So we suggest applying this methodology to one seismic active region of China, for example, the metropolitan circle where a few historical large earthquakes have occurred and is quite industrial and population dense. When an incoming earthquake happens, by taking advantage of the NGF method, ground motion information can be provided timely. Together with background information of local buildings, this instant information can be used to assess the seismic hazard and make up the corresponding rescue plans.

Acknowledgements We acknowledge funding from the International Quality Network: Georisk (German Academic Exchange Service), and the Elite Graduate College THESIS (Bavarian Government). We also acknowledge financial support from the European Human Resources Mobility Program (Research Training Network SPICE). The provision of computational resources by the Leibniz Computing Centre Munich is appreciated.

References

- Aki K and Richards P G (2002). *Quantitative Seismology*. Second ed. University Science Books, Sausalito, California, 27–28.
- Beresnev I A, Atkinson G M, Johnson P A and Field E H (1998). Stochastic finite-fault modelling of ground motions from the 1994 Northridge, California, earthquake. II. Widespread nonlinear response at soil sites. *Bull Seism Soc Amer* **88**: 1 402–1 410.
- Boore D M (2003). Simulation of ground motion using the stochastic method. *Pure Appl Geophys* **160**: 635–676.
- Bour M and Cara M (1997). Test of a simple empirical Green's function method on moderate-sized earthquakes. *Bull Seism Soc Amer* **87**: 668–683.
- Campbell K W and Bozorgnia Y (2003). Updated near-source ground-motion (attenuation) relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra. *Bull Seism Soc Amer* **93**: 314–331.
- Collino F and Tsogka C (2001). Application of the PML absorbing layer model to the linear elastodynamic problem in anisotropic heterogeneous media. *Geophysics* **66**: 294–307.
- Ewald M, Igel H, Hinzen K G and Scherbaum F (2006). Basin-related effects on ground motion for earthquake scenarios in the Lower Rhine Embayment. *Geophys J Int* **166**: 197–212.
- Gallovic F and Brokešová J (2004). The k^{-2} rupture model parametric study: example of the 1999 Athens earthquake. *Studia geoph et geod* **48**: 589–613.
- Gallovic F and Brokešová J (2007a). Hybrid k -squared source model for strong ground motion simulations: Introduction. *Phys Earth Planet Inter* **160**: 34–50.
- Gallovic F and Brokešová J (2007b). Probabilistic aftershock hazard assessment II: Application of strong ground motion modeling. *J Seismology* **12**(1): 65–78.
- Gerstenberger M C, Wiemer S, Jones L M and Reasenberg P A (2005). Real-time forecasts of tomorrow's earthquakes in California. *Nature* **435**: 328–331.
- Godinho L, Mendes P A, Tadeu A, Cadena-Isaza A, Smerzini C, Sanchez-Sesma F J, Madec R and Komatitsch D (2009). Numerical simulation of ground rotations along 2D topographical profiles under the inci-

- dence of elastic plane waves. *Bull Seism Soc Amer* **99**(2B): 1 147–1 161.
- Grant L B and Shearer P M (2004). Activity of the offshore Newport-Inglewood Rose Canyon fault zone, coastal Southern California, from relocated microseismicity. *Bull Seism Soc Amer* **94**: 747–752.
- Graves R W (1996). Simulating seismic wave propagation in 3-D elastic media using staggered-grid finite differences. *Bull Seism Soc Amer* **86**: 1 091–1 106.
- Graves R W and Wald D J (2001). Resolution analysis of finite-fault source inversion using one- and three-dimensional Green's functions 1. Strong motions. *J Geophys Res* **106**: 8 745–8 766
- Guatteri M, Mai P M and Beroza G C (2004). A pseudo-dynamic approximation to dynamic rupture models for strong ground motion prediction. *Bull Seism Soc Amer* **94**: 2 051–2 063.
- Hartzell S H (1978). Earthquake aftershocks as Green's functions. *Geophys Res Lett* **5**: 1–4.
- Hauksson E and Gross S (1991). Source parameters of the 1933 Long Beach earthquake. *Bull Seism Soc Amer* **81**: 81–98.
- Hutchings L and Wu F (1990). Empirical Green's functions from small earthquakes: A waveform study of locally recorded aftershocks of the San Fernando earthquake. *J Geophys Res* **95**: 1 187–1 214.
- Hutchings L (1991). "Prediction" of strong ground motion for the 1989 Loma Prieta earthquake using empirical Green's functions. *Bull Seism Soc Amer* **81**: 88–121.
- Igel H, Mora P and Riollot B (1995). Anisotropic wave propagation through finite-difference grids. *Geophysics* **60**: 1 203–1 216.
- Irikura K (1983). Semi-empirical estimation of strong ground motions during large earthquakes. *Bull Disaster Prevention Res Inst Kyoto Univ* **33**: 63–104.
- Kohler M, Magistrale H and Clayton R (2003). Mantle heterogeneities and the SCEC three-dimensional seismic velocity model version 3. *Bull Seism Soc Amer* **93**: 757–774.
- Marcinkovich C and Olsen K B (2003). On the implementation of perfectly matched layers in a 3-D fourth-order velocity-stress finite-difference scheme. *J Geophys Res* **108**: 2 276–2 293.
- Olsen K B and Archuleta R J (1996). 3-D-simulation of earthquakes in the Los Angeles fault system. *Bull Seism Soc Amer* **86**: 575–596.
- Olsen K B (2000). Site amplification in the Los Angeles basin from 3-D modelling of ground motion. *Bull Seism Soc Amer* **90**: S77–S94.
- Shabestari K T and Yamazaki F (2002). Attenuation relationships of the ground motion parameters considering directivity effects in the 1999 Chi-Chi, Taiwan earthquake. *U.S. National Conference on Earthquake Engineering (7NCEE)* v.2. July 21 to 25, 2002, Boston, MA, US.
- Wang H J (2007). *Source-dependent Variations of M7 Earthquakes in the Los Angeles Basin*. PhD Dissertation. Ludwig-Maximilians-University, Munich, 61.
- Wang H J, Igel H, Gallovič F, Cochard A and Ewald M (2008). Source-related variations of ground motions in 3-D media: Application to the Newport-Inglewood fault, Los Angeles basin. *Geophys J Int* **175**: 202–214, doi:10.1111/j.1365-246X.2008.03878.x.
- Zhang W and Chen X F (2008). Numerical simulation of strong ground motion for the M_s 8.0 Wenchuan earthquake of 12 May 2008. *Science in China (Series D)* **51**(12): 1 673–1 682.