Charles University in Prague
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DOCTORAL THESIS

Kinematic Modeling of Strong Ground Motions

by

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1 Abstract

Strong ground motion modeling is studied with the emphasis on the source effects. The classical integral k-squared model is generalized and applied to the 1999 Athens earthquake. Problems of this model are revealed concerning strong (perhaps overestimated) high-frequency directivity effect in terms of large PGA variations with respect to observation (attenuation relations). This is explained by improper representation of small-scale rupture behavior in the integral k-squared approach. Although the integral k-squared model is acceptable at large scales where the faulting process is assumed to be deterministic (supported, e.g., by low-frequency slip inversions), at small scales the real rupture behaves presumably chaotically, requiring stochastic description. This is involved in a composite approach, in which the source acts as a discrete sequence of individually rupturing subevents. However, this model usually leads to incorrect spectral amplitudes in low-frequency band (when compared to the integral model). Therefore, a hybrid model combining the integral k-squared model at low frequencies and composite model at high frequencies is proposed. Such a model then provides the PGA variations in agreement with attenuation relations. The hybrid model is successfully applied to the 1997 Kagoshima earthquake, showing that, despite the neglected site-effects, the complexity of measured waveforms is relatively well reproduced. The hybrid model is also utilized for the probabilistic prediction of strong ground shaking due to aftershocks after a large earthquake. As an example, it is applied to the A25 aftershock (M5.8) of the 1999 Izmit earthquake.

2   Introduction

Strong ground motion seismology concerns ground shaking due to moderate to large earthquakes at close epicentral distances. The shaking is recorded by short period instruments that are able to register relatively large acceleration peaks ($\sim 2g$) in broad frequency range. The aim of the strong motion seismology is to model such shaking in order to understand better the physics of the seismic source and to be able to predict the ground motion due to future earthquakes that could threat an area of interest. In this respect, the strong ground motion seismology plays a key role in mitigating possible damage caused by earthquakes in active regions.

From very first strong motion recordings it was clear that the records are rich in broad frequency range. They are a complicated mixture of low-frequency ($\lesssim 1$ Hz) part that can be handled in deterministic way, and high-frequency ($\gtrsim 1$ Hz) part, requiring stochastic description. The observed seismograms are formed and influenced by a number of physical phenomena. Besides instrument effects, it is common to distinguish them to those associated with source, path and site effects. The last two are usually jointly called as the propagation effects. Note that neither propagation nor instrument effects are subjects of this thesis.

The main subject of this thesis are the source effects and how they are manifested in synthetic seismograms. The recorded waveforms contain information about heterogeneities of the rupture process, e.g. acceleration and deceleration of slipping. These complexities are linked to the dynamics of the rupture, namely complexities of the dynamic rupture properties studied by the fault mechanics, e.g., static and dynamic frictional coefficients, strength, etc. However, the dynamics of the seismic source is not a subject of this work. It concerns mainly the kinematic description of the faulting process. Note that the suitable description is not being looked for by means of slip inversions for a specific earthquakes. Instead, general source properties retrieved from such slip inversions and/or physical-mathematical considerations are used together with suitable stochastic component to develop a general broad-band earthquake source model.

2.1   Motivation

General motivation for this work is the waveform modeling of past earthquakes to explain the spatial distribution of strong ground shaking that occurred during an earthquake under study. One of the existing approaches to such a task is the kinematic modeling of strong ground motions, which is the main subject of this thesis. The simulations are usually performed once the main features of the seismic source, namely the activated fault and its mechanism, are known. Therefore, the simulations rely on input parameters from previous studies, such as location, determination of moment tensor, assignment of causative fault, low-frequency slip inversions constraining positions of main slip patches (so-called

asperities), etc. Specific problems of such preceding studies are not discussed here. On the other hand, the simulation results, after comparison with strong motion data (waveforms, intensities), can also contribute to determination or verification of some more detailed characteristics of the rupture process, such as spatial extent of the activated fault, direction of rupture propagation, etc.

Another, special, motivation of this thesis is the strong ground motion prediction for an unknown (future) earthquake. This problem has occurred during the work on EU project PRESAP ("Towards Practical, Real-time Estimation of Spatial Aftershock Probabilities: a Feasibility Study in Earthquake Hazard"), coordinated by J. McCloskey, Univ. of Ulster, during years 2000–2003. During the project the following procedure of prediction of strong aftershock occurrence was studied: After a strong earthquake, its fault plane solution is determined. The slip inversion is then performed. The resulting slip model is used to compute the redistribution of the static stress (namely Coulomb stress change) in the vicinity of the earthquake on oriented planes. The stress map is compared with the map of active geological faults and if there is found a correlation, it is characterized as an area where strong aftershocks are most likely to occur. It has been found that the procedure is scientifically feasible and it could be done in nearly real-time (with certain technological prerequisites). The next step, prediction of strong shaking due to the aftershocks, represents the second motivation of this thesis.

2.2 State of the art

As it is mentioned above, the strong motion records contain information about the seismic source. Unfortunately, such information is masked by propagation effects, which make the source model retrieval difficult and not yet resolved. For some far-field records it is possible to separate parts of the wavefield consisting predominantly of direct P or S waves. These phases carry information about the source in terms of the source time functions. After a correction for instrumental and propagation effects, it is commonly observed that their acceleration amplitude spectrum is characterized by ω^2 increase of amplitudes up to a so-called corner frequency, after which the spectrum is approximately constant (*Aki*, 1967). This is referred as the ω-squared model and it is understood to be a consequence of temporal and spatial finiteness of the seismic source.

In order to model the ω-squared source spectra in a simple way, *Brune* (1970) introduced the point source model of earthquakes. Later, it appeared to be unable to describe key features of ground motions due to large earthquakes such as their long duration and dependence of amplitudes on the azimuth to the observation point (source directivity). This resulted in the necessity of an extended-, or finite-fault, source representation.

One of the first finite-fault models was introduced in the paper by *Haskell* (1964). Its description can be found also in many textbooks on seismology. The fault is understood as a line characterized by unilateral rupture propagation at

constant velocity, uniform final slip and boxcar slip velocity function of constant duration. Under these assumptions, the model provides the desired ω-squared source spectrum. However, although it satisfies ω-squared spectral law and exhibits observed directivity effect, it is not sufficient. Problems are obvious when looking into the acceleration in time domain. The displacement is a convolution of two boxcars which yields a trapezoid function. Then, the acceleration consists only of four peaks, which is too simple. Although this problem can be overcome by convolution with a long-duration Green's function, the real broadband accelerograms are complicated even more, both in the time and the spectral domains.

The other problem of the Haskell model is its extrapolation to more general rupture (rectangular fault, etc.). *Bernard and Herrero* (1994) showed that if the observer is close to the rectangular Haskell model, it provides (instead of the ω-squared spectrum) an ω-cubed spectral decay. Such problem is one of the most important because the observations are characterized by the ω-squared spectral shape also in the near field. Moreover, this model is not acceptable even from the dynamic point of view (*Madariaga*, 1978).

It has long been recognized by many investigators (*Hartzell and Helmberger*, 1982, *Hartzell and Heaton*, 1986, *Beroza and Mikumo*, 1996, and many others) that the degree of earthquake source complexity is higher than that provided by the Haskell model (namely, e.g., the spatial complexity of earthquake slip, rise time and rupture time). For example, in the slip inversions of past earthquakes, relatively complex final slip distributions have been revealed. Typically, they consist of several (1-3) asperities.

Relatively large number of kinematic strong ground motion finite-extent models considering more advanced rupture propagation have been proposed to obtain desired ω-squared source time function. A summary and comparison of some of them is given by *Hartzell et al.* (1999). Let us distinguish the models into *integral* and *composite*, according to the source representation. Their range of applicability is discussed later.

In the *integral* approach (*Kostrov and Das*, 1988, *Spudich and Archuleta*, 1987, *Brokešová*, 1993, *Bernard et al.*, 1996), the source process is described by a relatively simple spatial-temporal distribution of slip function over the fault. Strong ground motions generated by such source model are calculated according to the representation theorem by evaluating the well-known surface representation integral along the fault. Numerically, the fault is discretized and the representation integral is substituted by a sum, so that the finite extent source is represented as a coherent superposition of point sources distributed regularly along the fault with the spacing small enough to avoid numerical problems in the integral evaluation. It is clear that this procedure could require much numerical effort for high frequencies due to the necessity of dense discretization. Note that the Haskell model belongs among these approaches although it is too simple as it is discussed above.

The idea of *composite* models (*Hartzell*, 1978, *Irikura and Kamae*, 1994, *Zeng et al.*, 1994, *Frankel*, 1991, 1995, *Beresnev and Atkinson*, 1997, *Burjánek*, 2002) is based on assumption that the modeled event can be seen as a discrete sequence of individually-rupturing subevents that are treated in point-source approximation (Brune, 1970). The source time function of each subsource is characterized by its spectral shape, corner frequency, seismic moment, etc. Contributions of subevents are summed in order to get proper seismic moment and spectral shape of the source function corresponding to the whole fault. This approach is often used together with the empirical Green's function (EGF) method, but synthetic Green's function can be used as well.

To synthesize final strong ground motions, one has to calculate Green's functions to involve effects due to the wave propagation phenomena. For simple 1D structure models, the Green's functions can be obtained by applying, e.g., discrete wavenumber method (*Bouchon*, 1981). However, when interest is concentrated in high frequencies, this method can easily become numerically too expensive. On the contrary, in high-frequency range and even for more complex (2D, 3D) models, the ray method (*Červený*, 2001, *Brokešová*, 1993) can be applied with advantage, provided that the model is smooth. Let us note that even in 2D models, due to the finiteness and arbitrary orientation of the fault as well as general station distribution (not respecting plane of the symmetry of the model), calculations of 3D rays are, in principle, unavoidable. The term '2.5D modeling' is used for 3D ray computation in 2D structure (*Brokesová*, 1990, 1992, 1993). An important disadvantage of the ray method is that it cannot provide complete wavefield – e.g., surface waves are completely missing in ray synthetics. Thus, the applicability is limited to near-source region or time windows not containing the surface waves. In this thesis both the discrete wavenumber and ray methods are used.

Note that the strong ground motion modeling is very complicated problem since one does not know the source and structural models in such a detail to be able to compute deterministically the seismograms up to relatively high frequencies. Therefore, one has to make a number of simplifications. In this thesis, the propagation effects are treated in relatively simple way, while the source effects are of main concern. In this way, one is able to model seismograms that are not affected by the site effects significantly. Moreover, due to complexities of the real path effect, the simulations can be subjected to comparison just with dominant part of the observed record, usually main pulses composed of strongest phases. Furthermore, the real and synthetic seismograms cannot be compared "point by point" because of the stochastic character of the waveforms. They can be compared in terms of peak value, duration, the envelope, etc., or just "by eye". The modeling results can be also supported by macroseismic data (intensities).

2.3 Thesis overview

The presented thesis comprises of the following papers:

P1: Gallovič, F., Brokešová, J. (2004a). On strong ground motion synthesis with k^{-2} slip distributions, *J. Seismology 8*, 211–224.

P2: Gallovič, F., Brokešová, J. (2004b). The k^{-2} rupture model parametric study: example of the 1999 Athens earthquake, *Studia geoph. et geod. 48*, 589–613.

P3: Gallovič, F., Brokešová, J. (2006a). Hybrid *k*-squared Source Model for Strong Ground Motion Simulations: an Introduction, *submitted to Phys. Earth Planet. Interiors*.

P4: Gallovič, F., Brokešová, J. (2006b). Probabilistic Aftershock Hazard Assessment: Numerical Testing of Certain Methodological Features, *submitted to J. Seismology*.

Papers **P1-2** are already published and **P3-4** have been submitted for publication. The thesis is supplemented by an appendix, a copy of paper

Gallovič, F., Burjánek, J. (2006), Directivity in Strong Ground Motion Modeling Methods, *submitted to Annali di Geofisica*,

which is a logical subject of the thesis. However, it is not a part of the thesis since the author has just 50% share of authorship.

3 Strong ground motion simulation models and their applications

One of the aims of this thesis is to propose a realistic kinematic model of a finite-extent fault suitable for strong ground motion prediction and, possibly, source inversions. On the one hand, the model should intrinsically account for significant and important effects, which can be modeled in determinist way (e.g., constructive interference of seismic waves in the direction of rupture propagation), and, on the other hand, be able to reproduce correctly stochastic nature of high-frequency radiation. In this thesis the model is applied to simulate recorded data during major events and to predict strong ground motions, especially for aftershocks of large earthquakes.

The integral *k*-squared rupture model, introduced by *Bernard and Herrero* (1994), represents the starting point of this thesis. The authors propose a kinematic self-similar stochastic final slip distribution. At wave numbers $k < k_c =$

$1/L$ (L being the length of the line fault), the slip amplitude spectrum is constant. For wave numbers $k > k_c$, the amplitudes decay as k^{-2} (hence the model is called as k-squared). Note that such shape of slip amplitude spectra is independently supported also by statistical analysis of slip inversion results (*Mai and Beroza*, 2002; *Somerville et al.*, 1999). At low wave numbers, the phase spectrum is assumed such that the slip is concentrated in the center of the fault. At higher wave numbers, the phase is random.

Bernard and Herrero (1994) showed that a simple line fault with k-squared slip distribution in Fraunhoffer's approximation with rupture propagating unilaterally at constant velocity radiates the ω-squared source spectrum, provided the slip is instantaneous (i.e. the slip velocity function is δ-pulse). If more general slip velocity function with a certain finite duration (rise time), e.g., a boxcar, is used, it acts as a low-pass filter. The source acceleration spectrum starts to decay after the frequency corresponding to the reciprocal of the rise time, i.e. this leads to undesired ω-cubed source spectrum. To preserve the ω-squared source spectrum, *Bernard et al.* (1996) proposed the boxcar with a k-dependent rise time. More specifically, the rise time is maximal and constant for wave numbers lower than $1/L_0$, while for wave numbers higher it is proportional to $1/k$. In this way, The rupture propagates at constant velocity in a slip pulse of width L_0. Slip inhomogeneities of shorter characteristic dimensions rupture in time proportional to their spatial wavelength. This results in non-uniform shape of slip rate functions over the fault.

The integral k-squared rupture model has already been used for past as well as future earthquakes in wide frequency range (e.g, *Berge-Thierry et al.*, 2001; *Zollo et al.*, 1997; *Emolo and Zollo*, 2001). All these authors emphasize the importance of considering complex source processes for estimating strong ground motion in the near-source region.

3.1 Generalization of the integral k-squared source model

In paper **P1**, a simple analytical expression for kinematic strong motion synthesis for a 2D fault model buried in a general medium, including the k-dependent rise time, is proposed. In the same paper, the above described source model is generalized in several aspects in order to provide more flexible tool for simulating a variety of earthquakes.

Concerning the k^{-2} slip distribution, corner wave number k_c (defined in the previous section) is generalized to $k_c = K/L$ (note that $K = 1$ corresponds to the model by *Bernard and Herrero*, 1994). It is shown that the K-parameter controls the smoothness/roughness of the slip distribution. In paper **P1**, current indirect observations (inverted slip models) are discussed and it is concluded that the preferred value of K is around 1. To model realistic k^{-2} slip distributions for a rectangular (2D) fault with $K = 1$ consisting of asperities, so-called hybrid slip is suggested. It is a combination of deterministic part at long scales (e.g.,

asperities) and stochastic part at the remaining scales, see **P1**.

The restriction to a boxcar slip velocity function (with k-dependent rise time), discussed in *Bernard et al.* (1996), is relaxed. It is found that the desired ω-squared source spectrum can be generated by any slip velocity function with k-dependent rise time. Thus, the spectral decay at frequencies higher than the corner frequency is given only by the decay of the slip distribution spectrum, regardless of the type of slip velocity function. In this way, more realistic slip velocity functions can be considered.

The rupture model described in paper **P1** involves a number of free parameters (fault dimensions, slip roughness, maximum rise time, slip velocity function), thus providing a flexible tool for simulating a variety of earthquakes. Therefore, the paper **P1** concerns also an analytical study of the influence of the kinematic parameters on the radiated wave field but just for a simple line fault in Fraunhoffer's approximation in homogeneous medium.

Finally, it is shown numerically on an example of the 1999 Athens earthquake that the integral k-squared model provides ω-squared source spectrum even in a vicinity of a 2D normal fault buried in 1D structure. Next section provides more details concerning the application of the discussed source model to this earthquake.

3.2 Application of the generalized integral k-squared source model to the 1999 Athens earthquake

The goal of paper **P2** is to apply the integral k-squared model to the 1999 Athens earthquake of $M_w = 5.9$ (*Tselentis and Zahradník*, 2000) and to provide a parametric study regarding sensitivity of spatial distribution of acceleration (PGA maps) on individual model parameters (see above). Note that in **P2** a 2D rupture model with radial rupture propagation is studied, so it is not straightforward to compare the results obtained in this study with that obtained in **P1** for a unilateral rupture propagation along a line fault.

The main earthquake parameters determined by previous studies are fixed: namely location of the epicentre, hypocentral depth, scalar seismic moment, focal mechanism and the position of the nucleation point on the fault. Rupture velocity is set to 80% of the S-wave velocity at the nucleation point depth. The values of the remaining parameters of the integral k-squared rupture model (fault dimensions, slip pulse width, K-parameter and the type of the slip velocity function) are varied in the parametric study.

Green's functions are calculated by the ray method assuming relatively simple 1D structural model, consisting of 5 homogeneous layers above a halfspace (for details see **P2**). The direct S wave is assumed to represent the most important part of the wave field in terms of PGA for the particular source and structural model. Therefore, only direct S waves are taken into account.

The parametric study shows significant directional dependence of mean PGA's with a distinct localized maximum to the east from the epicenter. Due to the relative simplicity of the structural model considered, this is attributed to the effect of source directivity. In the Athens earthquake model, the rupture propagates from the nucleation point situated in the left bottom corner of the fault in all directions, so that it includes not only the strike direction but also the up-dip direction. Consequently, the location of the highest PGAs cannot be easily interpreted as a manifestation of the forward directivity known from the line fault studies. Moreover, the location of the spot is strongly influenced by the radiation pattern.

More detailed analysis of the results reveals that the directivity effect is more pronounced for the case of instantaneous rise time than in the case of the other slip velocity functions considered. The slip pulse width changes mainly the maximum PGA values, not the location of the PGA maximum. The same can be stated about K and the slip velocity functions. The fault dimensions affect both the PGA maximum values (depending mainly on the corresponding mean slip) as well as the location of the maximum on the map. However, its relative location with respect to the fault remains the same. The overall look of the PGA map changes significantly when an asperity on the fault is taken into account, more specifically one observes that spot of PGA maximum is split into two parts. From the calculations performed it seams that the mean slip on the asperity influences mainly the PGA values while retaining the shape of the maps unchanged (similarly to mean slip over the whole fault, see above).

Note that paper **P2** is mainly methodical with the emphasis to directivity effect. Therefore, it is preferred to compare (although roughly) the results with intensities having better azimuthal coverage than few strong motion records obtained from stations lying in the city of Athens only. It is concluded that the source effect (especially directivity) could considerably contribute to the location of maximum intensities observed. However, since the relation between intensities and PGAs is very uncertain, the parametric study of the rupture model cannot constrain the details of the model: for example, whether the rupture fault was without asperity but larger than $7.5 \times 6 \text{km}^2$, or whether there were more asperities on relatively large fault and so on. For this a slip inversion of local/regional data is needed. However, an appropriate study by *Roumelioti et al.* (2003), favoring the asperity model, appeared after the publication of paper **P2** (see later).

3.3 Problems of the integral k-squared source model

In the study by *Gallovič and Burjánek* (2006), see Appendix, integral k-squared source modeling technique and composite model with fractal subevent size distribution (FSSD, *Burjánek*, 2002) are compared with respect to high-frequency directivity inherent to the methods. PGAs are simulated for a set of virtual receivers distributed radially around epicenter of the 1999 Athens earthquake,

which is chosen as a representative for unilateral earthquake. The results are compared with Greek empirical PGA attenuation relation (*Skarlatoudis et al.*, 2003), especially with the observed scatter. While the composite approach provides variations in PGA by a factor of less then 10, the k-squared model by a factor of about 100. The large scatter in k-squared model is attributed to strong high-frequency directivity effect, not present in the FSSD model (see more detailed explanation in *Gallovič and Burjánek*, 2006).

The PGA attenuation relations are obtained by regression of data under the assumption of their log-normal distribution. Many PGA attenuation relations provide the data uncertainty (in terms of standard deviation σ) ranging from about one half to double of the mean value (*Si and Midorikawa*, 1999, *Ambraseys et al.*, 2005, etc.). Then, assuming $\pm 2\sigma$ scatter in the log-normal data distribution, the maximum total variation corresponds to a factor of about 16. From this point of view, the scatter provided by the k-squared model seems to be larger than what is suggested by the observations. The standard deviation of empirical attenuation relations is considered to represent robust information for calibration and possible rejection of strong motion prediction methods. However, the data set has to be sufficiently large including large number of observations close (< 30 km) to the faults, which is not always satisfied.

Nevertheless, there are other studies suggesting weak or no high-frequency directivity. For example, *Somerville et al.* (1997) showed on empirical data that the amplification due to directivity vanishes for high-frequency ground motions. *Boatwright and Boore* (1982) analyzed ground accelerations radiated by the 1980 Livermore valley earthquakes and suggest that the total variation of PGA should not exceed a factor of 10. However, the high-frequency directivity is still under debate since these observations are still questionable and very sporadic.

In order to decrease the scatter, the integral k-squared method is supplemented by a formal high-frequency spectral modification (suggested by *Bernard and Herrero*, 1994) that eliminates the directivity due to the rupture propagation. The formal nature of the modification comes from unclear physical reasons for small high-frequency directivity. A possible explanation is incoherency at the source as discussed further. Note also that the spectral modification needs as an input the angle between station azimuth and direction of rupture propagation, which is not always easy to define (e.g., in the case of non-unilateral propagation). This is a drawback of the spectral modification, which limits its applicability.

To conclude, the composite FSSD model provides the PGA scatter in agreement with uncertainty of attenuation relations. Since PGA is mainly affected by high-frequency spectral content, we presume that the composite model represents a suitable description of the rupture process for high frequency radiation. On the other hand, the composite approach is supplemented by a spectral correction at low frequencies in order to fit the seismic moment. From this point of view, the kinematic description is more suitable for low-frequency calculation (see further). This stimulates to introduce a hybrid model that would combine the integral a

composite source representations.

3.4   Introducing hybrid k-squared source model and its applications

Generally, the integral model was applied successfully in a low-frequency band in both forward and inverse problems, e.g., in inversions for slip velocities of past earthquakes (e.g., *Hartzell and Heaton*, 1986, *Wald et al.*, 1996, *Asano et al.*, 2005). Therefore, such a model is acceptable at large scales where the faulting process is assumed to be deterministic. Therefore, it is considered to be a suitable description of finite-extent seismic source at low frequencies. At small scales, the rupture process is presumably non-linear and incoherent process due to a heterogeneous small-scale distribution of dynamic and geometric rupture parameters. As such, the rupture is expected to behave chaotically, requiring stochastic description. Although one assumes relatively complicated k-squared source model, it is likely too simple to represent actual source behavior because it contains the stochastic component in the slip distribution only. Such simplification of the stochastic nature of the rupture process in the k-squared source model is demonstrated by the large scatter in PGA (as discussed above). On the other hand, the composite approach provides possibly better description of such faulting style for adequate modeling of high-frequency earthquake source radiation (*Hartzell*, 1978, *Irikura and Kamae*, 1994, *Zeng et al.*, 1994, *Frankel*, 1995, *Beresnev and Atkinson*, 1997). However, this model usually leads to incorrect spectral amplitudes in low-frequency band (when compared to the integral model), see above.

Therefore, in paper **P3** a new, hybrid, kinematic finite-extent source model is proposed. It is applicable for both large and small scales, combining both integral and composite source descriptions. The faulting process is decomposed into slipping on individual, formal, overlapping subsources of various sizes, distributed randomly along the fault. The properties of the subsources are such that they provide k-squared slip distribution – similarly to the integral model explained above. Although such a decomposition is inherent to the composite approaches, in the proposed hybrid model the same set of subsources is used both in the integral (low-frequency) and composite (high-frequency) calculations. More specifically, at low frequencies one employs the representation theorem assuming the k-squared slip distribution (obtained by composing subsources slip contributions) and, at high frequencies, the composite approach, based on the summation of ground motion contributions from the subsources treated as individual point sources, is used. In the cross-over frequency range we apply weighted averaging of the real and imaginary parts of the integral and composite parts of the spectrum.

Note that in paper **P3** the hybrid combination is not treated as a technical

problem only but it also includes discussion about faulting mechanism that could underlay such a hybrid model. The source is assumed to behave as follows: At large scales, the subsources (of all dimensions) act so that the slipping is equivalent to the integral k-squared model discussed above. Final slip at a point on the fault is given by the sum of slip contributions from individual subsources overlaying the point. The generated wave field is then the same as it would be in the integral k-squared model where the contributions from different source points along the fault sum coherently. At small scales, the subsources behavior is assumed to be chaotic. Therefore, the subsources are assumed to radiate, effectively, isotropic high-frequency wavefield. In this way, the subsources act as individual point subevents and they are equivalent to randomly distributed point sources (as in the composite approach). Note that due to the random subsources positions, their wave-field contributions sum incoherently. Finally, the cross-over filtering can be seen to simulate smooth transition between deterministic and chaotic style of faulting. For more detailed explanation of the hybrid model and its numerical implementation see **P3**.

Paper **P3** involves also two applications on numerical examples. First, the hybrid model is applied to the 1999 Athens earthquake and it is shown that it predicts directivity in correspondence with observation (attenuation relations) in terms of PGA scatter (on the contrary to the integral k-squared source model as discussed in Sec. 3.3). Note that the slip (subsources) distribution of the Athens earthquake model is different in this application than in papers **P1** and **P2**. In this case the asperities are constrained by the result of slip inversion by *Roumelioti et al.* (2003), which was not available when publishing papers **P1** and **P2**. The inverted slip model is characterized by two asperities (stronger and weaker). Both of them are located to the east from the hypocenter, the stronger one being situated down-dip from the hypocenter while the weaker one up-dip (see Fig. 5 in **P3**). In this way, the directivity effect shifts highest PGA values to the east of the epicenter (Fig. 8 in **P3**) as in the study **P2**. This holds both for the integral k-squared and the hybrid techniques (Fig. 16 in **P2**) because the composite (high-frequency) part of the hybrid simulation modifies mainly the synthetics in the direction opposite to the rupture propagation.

As a second example, the hybrid model is applied to the 1997 Kagoshima earthquake. Basic properties of the adopted source and structural models are set according to *Horikawa* (2001). Simulated peak values (PGA and PGV) are compared to the observed ones. The agreement is satisfactory at most of the considered stations. The discrepancies could be addressed to significant site-effects not included in the modeling. At stations which are not affected by strong site effects, the model relatively well reproduces the complexity of measured waveforms in terms of envelope, duration, polarity, spectral amplitudes, their decay etc.

To summarize, the hybrid combination of the integral and composite approaches is numerically efficient, keeping advantages of both the approaches while

minimizing their problems. Contrary to the integral k-squared approach, the chaotic small-scale behavior is involved in the hybrid model (resulting in more realistic directivity effect). In contrast to the composite approach, the hybrid model is better constrained for low-frequency calculation, e.g., for slip inversions, because, for example, no artificial low-frequency filtering is necessary.

Another application for the hybrid k-squared can be the prediction of strong ground motions. From the discussion in Sec. 2.1 it follows that the main concern is the prediction for aftershocks of large earthquakes as their spatial-temporal prediction seems to be mostly feasible (in terms of probabilities).

3.5   Probabilistic aftershock hazard assessment

The task of strong ground motion prediction for aftershocks is an "multi-source" problem. After a mainshock, a number of faults can be activated due to stress transfers. Those can be then able to produce aftershocks of various magnitudes. Moreover, the seismogenic zone could comprise activated blind faults, also being able to produce earthquakes. In all these cases one can ask how to combine strong-ground motion prediction maps for all the activated faults, including all possible earthquake scenarios and magnitudes to a single map, which could then be easily understood by, e.g., authorities and decision makers. Note that the prediction maps have to be combined in probabilistic sense since we are not able to predict the aftershock occurrence in terms of position and time exactly, deterministically.

For this task, *Wiemer* (2000) suggested so-called probabilistic aftershock hazard assessment (PAHA), which is based on classical probabilistic seismic hazard approach (PSHA, *Cornell*, 1968). PAHA has been recently applied in the STEP program (available online at `http://pasadena.wr.usgs.gov/step` since May 2005) for California (see *Gerstenberger et al.*, 2005). This program provides probabilities of strong shaking in California within the next 24 hours.

PAHA intrinsically combines two main features: 1) statistical description of aftershock occurrence and 2) probabilistic description of strong ground motion. The latter means the probability density function of a given strong motion characteristics under study as a function of earthquake magnitude and station location. It is used to translate the aftershock probabilities to probabilistic forecast of strong motion characteristics exceedence.

In paper **P4**, the basic equations used for PAHA are first recapitulated. Then, a simple hazard parametric study (utilizing attenuation relations) is presented. An example application of the PAHA for a given activated fault is presented for the A25 aftershock (M5.8) of the 1999 Izmit earthquake. The hybrid k-squared approach (see Sec. 3.4) is utilized to simulate PGVs, assuming a number of magnitudes and scenarios. The source dimensions are obtained from the empirical scaling relations (*Somerville et al.*, 1999). The simulations are compared with attenuation curves for strike-slip earthquakes. It is found that if the radiation pattern effect is taken into account in the whole frequency range, the PGVs

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exceed $\pm 2\sigma$ bounds of the attenuation curves. Therefore, random variations of focal mechanism ($\pm 90^o$ for strike, dip and rake) are prescribed to individual point sources in the composite part of the computation. This results in weak radiation pattern effect at high frequencies, and, therefore, in lower scatter of simulated PGVs in agreement with the $\pm 2\sigma$ bounds. Nevertheless, since the radiation pattern without any variations is taken into account in the integral part of the modeling, the PGV maps still exhibit "remanent" lobes. Further, the PGV maps are more prolate along the fault in both direction, which is due to directivity effect pronounced for some of the scenarios.

Mean PGVs and their variances are retrieved from the simulations for all magnitudes considered and they are used for the PAHA analysis. Such PAHA maps are then compared with those obtained by the use of attenuation relations. The main difference between the maps is that the one obtained by the use of simulations is affected by the remanent radiation pattern lobes and directivity (prolongation along the fault strike).

4   Conclusions and Outlooks

The strong ground motion modeling is studied with a focus on the source effects. The classical integral k-squared model is generalized and applied to the 1999 Athens earthquake. Problems of this model are revealed concerning strong (perhaps overestimated) directivity effect, affecting mainly antidirective stations. Therefore, a hybrid model combining the integral k-squared model at low frequencies and composite model at high frequencies is proposed. Such a model then provides the directivity effect in terms of PGA variations in agreement with observation (attenuation relations). The model is successfully applied to the 1997 Kagoshima earthquake, showing that, despite the neglected site-effects, the model relatively well reproduces the complexity of measured waveforms. Finally, this model is applied to the problem of probabilistic prediction of strong ground shaking for aftershocks of large earthquake, namely to the example of A25 aftershock (M5.8) of the 1999 Izmit earthquake.

One of the advantages of the hybrid k-squared source modeling technique is its ability to be combined with different techniques for Green's function computations in both frequency ranges. The model can be combined with finite difference (or finite element, etc.) method in order to account for propagation effects, e.g., due to basins. This would allow us to study mixed source-propagation effects. Such a work has been already started by the participation in the "Numerical Benchmark of 3D Ground Motion Simulation In the Valley of Grenoble, French Alps" in cooperation with Dept. of Physics of the Earth and Planets, Comenius University in Bratislava, Slovakia.

The hybrid k-squared source model has recently found practical use in the modeling of past Italian earthquakes and in deterministic and probabilistic strong

ground motion prediction. The work is being done in the frame of S3 project ("Scenari di scuotimento e di danno atteso in aree di interesse prioritario e/o strategico"), in cooperation with Istituto Nazionale di Geofisica e Vulcanologia, Milan, Italy (F. Pacor) and Universitá Federico II, Naples, Italy (A. Emolo, A. Zollo, V. Convertito).

In future work, the assumption made in the case of the k-squared source model that directivity vanishes at high frequencies has to be proved or disproved. This must be done by comparison of simulations with data recorded close to unilateral ruptures, such as the 2004 Parkfield earthquake (*Bakun et al.*, 2005).

Another important and relatively open problem is the choice of the cross-over transition zone in the hybrid k-squared model. This zone represents the frequency range where the source representation changes from deterministic (integral) to chaotic (composite). Up to now, this cross-over zone has been fixed for all stations under study. However, one could expect that due to the incoherency introduced by the propagation effects, the transition frequency range likely depends on the source distance. Such a relation is left for further studies.

Concerning the probabilistic prediction of hazard due to large aftershocks, an interesting problem is its combination with physical models of remote aftershock triggering, associated with, e.g., Coulomb stress changes. Such combination would extend the method employed in STEP program because the aftershock statistics would not be constrained just by the geometrical vicinity of the mainshock but also by co-seismic stress changes.

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6 References

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P2: Gallovič, F., Brokešová, J. (2004b). The k^{-2} rupture model parametric study: example of the 1999 Athens earthquake, *Studia geoph. et geod. 48*, 589–613.

P3: Gallovič, F., Brokešová, J. (2006a). Hybrid *k*-squared Source Model for Strong Ground Motion Simulations: an Introduction, *submitted to Phys. Earth Planet. Interiors.*

P4: Gallovič, F., Brokešová, J. (2006b). Probabilistic Aftershock Hazard Assessment: Numerical Testing of Certain Methodological Features, *submitted to J. Seismology.*

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7 Included papers and Appendix

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