

THREE DIMENSIONAL FINITE-DIFFERENCE MODELING OF STRONG GROUND-MOTION SITE EFFECTS DUE TO THE FINITE-EXTENT SOURCE - 1356 BASEL EARTHQUAKE, UPPER RHINE GRABEN

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SUMMARY

Simulation of the historical 1356 Basel earthquake was computed by using a hybrid technique that combines finite-extent source, path and site effects. The fault plane is placed at the southern part of the city, at the location of the fault of the concerned earthquake. Different source scenarios have been modeled and the amplifications with respect to a bedrock site are given. The hybrid-method synthetic seismograms at the site, accurate in frequency band 0-2.2 Hz, were computed by the finite difference method. The results are compared with results obtained from 2D modeling.

INTRODUCTION

The Basel earthquake of October 18, 1356 (I_0 =IX, M=6.9) is considered to be one of the most disastrous historical European events. The Basel area - Upper Rhine Graben - belongs today to seismically modest regions. Reducing the seismic risk by anti-seismic design needs the knowledge of the strong ground motion. The lack of the real data is effectively estimated by hybrid numerical modeling combining finite-extent source modeling with finite differences (FD) used for the site-effects computation.

The 3D FD site-effects modeling is computed for the recently established P and S-wave velocities structure of the Basel area (Kind [1]), including the topography. The finite-extent source features (kinematic and dynamic modeling) are combined with site effects. The topmost part of the finite-extent source is 3.5 km under the free surface. Several rupture histories are tested because the 1356 Basel earthquake source features are not well determined. The macroseismic information of the Basel area as well as recently established 2D computations serve as a comparison to the results.

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DIGITAL GEOLOGICAL MODEL OF THE UPPER RHINE GRABEN IN THE BASEL AREA

Digital models

Numerical methods need a digital model describing the material parameters of a geological structure. Since real structures might be very complex, the computations often need a proper averaging or smoothing of the material properties. The reasons for the smoothing might be numerical (e.g., averaging parameters in FD grid) or a fundamental restriction of the method (ray tracing in the smooth media).

Structure of Basel area

The following examples used the velocity model for the Basel area, compiled by Kind [1]. The model was prepared in the form of a 3D function a = a(X), where a is a parameter vector (a = (lambda, mu, rho, Qp, Qs, ...)) for each position vector X = (x, y, z) and x, y, z are the coordinates (in km) of the Swiss coordinate system. This function was programmed in FORTRAN 90:

1 – As a Fortran function called inside a given subroutine;

2 - As a separate program in .exe and .F90 forms that reads the spatial vectors (x,y,z) from a file on a disk and writes out the parameters vector represented by one line in the output file.

The main geologic feature of the Basel City area is the dominance of soft sediments to the west of the master contrast fault (Figure 1). The 3D digital-model for the Basel area is based on the knowledge of 6 main interfaces and the topography. Between the main interfaces, sub-layers are defined. The sub-layers always copy the topography above. The interfaces are defined on a regular grid with grid step equal to 50m. The values of the material parameters between the grid points are bi-linearly interpolated. Although they are defined for the whole 20km x 18km area, the level of accuracy is affected by a limited knowledge of the structure. In some parts of the model, the interfaces are simply extrapolated.



Figure 1: Representative cross-section of the geology in Basel. The dominant seismic S-wave velocity contrast is indicated as a line between MEL and UPM. The table represents the stratigraphic units represented by the abbreviations (Kind [1]).

In order to compute amplification effects with respect to bedrock site, a reference structure has to be defined. The bedrock model corresponds to the one proposed by Fäh et al. [2] and applied by Kind [1]

and Kind et al. [3,4]. This reference bedrock model is given in Table 1. The source is the same for the 3D model and the reference bedrock structure. The reference model contains the same topography in the same as way as the 3D model.

Depth	Rho	Vp	Qp	Vs	Qs
0.01	2.30	3.00	50.00	1.00	25.
0.02	2.30	3.10	50.00	1.40	25.
0.03	2.30	3.15	50.00	1.80	25.
0.14	2.40	3.20	50.00	1.85	25.
0.26	2.40	3.30	50.00	1.91	25.
0.38	2.40	3.40	50.00	1.97	25.
0.50	2.40	3.40	50.00	1.97	25.
0.90	2.50	3.40	50.00	2.00	25.
1.00	2.55	4.20	75.00	2.40	35.
10.0	2.65	5.20	125.0	2.80	50.

Table 1: The 1D vertical profile used as reference model. The abbreviations depth, Rho, Vp, Qp, Vs, Qs are the depth (km) of the top of next layer, density (g/cm³), P-wave velocity (km/s), P-wave quality factor, S-wave velocity (km/s), S-wave quality factor.

RESPONSE SPECTRA

Analysis of the results is accommodated to the engineering needs by the use of the pseudo-accelerationresponse spectra (PSA) of synthetic signal for the receivers placed at the free surface. For all cases, the attenuation was 5% of critical damping. PSA were computed for 50 frequencies, regularly distributed between 0.1 Hz and 2.2 Hz on log scale. To represent the variability and differences of the damage potential within the studied area, the spectral amplification was computed as the PSA ratio between the results obtained with the 3D model and the reference bedrock structure. This ratio quantifies the amplification effects at a specific site, and it can be compared with results obtained by Kind [1] from twodimensional modeling with SH wave propagation.

FUNDAMENTAL FREQUENCIES

Fundamental frequencies of resonance of soft sediments can be obtained from H/V spectral ratios of recorded ambient vibrations. This has been done by Kind [1] for the Basel areas (Figure 2, left part). The spectral ratio between the recordings on the horizontal and the vertical components exhibits a large peak at fundamental frequency of resonance f_0 , as long as the S-wave velocity contrast between the sediments and the bedrock is larger than 2.5 to 3. A large number of time windows in the measured signal has been used to compute an average H/V spectral ratio. In case of known thickness of the soft sediments from borehole information or seismic measurements, H/V spectral ratios can be used to estimate the average shear wave velocity V_S with the simple formula:

$V_s=f_0*4h$

where h is the thickness of the soft sediments. By knowing the fundamental frequency of resonance, we also qualitatively know the expected amplification as function of frequency: The expected amplification is large at the fundamental frequency of resonance and significant for the frequency range above, but absent in the frequency range below $f_0/2$. The fundamental frequency of resonance should therefore be visible in the synthetic ground motion. The frequencies corresponding to the maximum PSA amplitude in a particular point at the free surface are therefore plotted in Figure 2 (right part). The incident wave is a plane S-wave with vertical incidence.



Figure 2: Comparison of measured fundamental frequencies (left panel, Kind [1], coordinates in km) and frequencies corresponding to the computed maximum of pseudo-acceleration response spectra (right panel, coordinates in m). The lines denote as follows: red - Basel-city limits, dashed black - the surface trace of the Rhine Graben master fault, grey - rivers, thick grey - the Rhine river, the dark-grey lines are the faults. The coordinates are in meters (the Swiss coordinate system).

We used the total horizontal component of the incident S-wave synthetics for evaluation the PSA. The qualitative agreement in Figure 2 is very good. The frequencies do not exactly correspond in those parts where fundamental frequencies above 1Hz dominate. This is evident around the most-western part of the city limits and especially at the south-eastern border of the city, outside the Rhine Graben. The incident wavefield is evidently suffering from an insufficient frequency content of the computed signal at frequencies above 1Hz. The fundamental frequency and the frequency of the maximum PSA follow the main geologic features that are given in the cross-section in the Figure 1.

HYBRID STRONG GROUND MOTION SIMULATION

Hybrid method

The hybrid approach (Opršal and Zahradník [5], Opršal et al. [6]) combines computational methods in two successive steps. The 1st step uses FD, ray, discrete wavenumber method (or, in principle, any convenient 3D method) to compute the particle motion on a formal box that envelopes local site of interest. Results from the 1st step are used as input data through a special 'permeable' boundary algorithm in the 2nd step, computed by FD. This hybrid technique evaluates separately the source, path and site effects needing less computer memory and time than all-in-one methods (e.g., direct FD computation). For more details on the method, see Opršal et al. [7].

Finite-extent sources (1st step)

The $M_w = 6.9$ Basel earthquake (Fäh et al. [8]) is one of the strongest European earthquakes but the knowledge of its source mechanism is very poor. The error in the magnitude estimate is +/- 0.5 units. The knowledge of the intensities that could be a good lead to the rough estimation of the source characteristics are also characterized by a large level of uncertainty.

The position of the source is considered to be located on the Rheinach fault south of the Basel (Meghraoui et al. [9]). For our simulations it will be the north-most point of the fault plane (Figure 3). The considered fault plane has a strike of 0° , and a dip of 75° . All of the source models presented have the source plane buried under the free surface with the hypocenter at approximately 12 km depth.



Figure 3: The topography of the computational model. The lines denote as follows: red - Basel-city limits, dashed black - the surface trace of the Rhine Graben master fault, grey - rivers, thick grey - the Rhine river, the white rectangle demarks the area shown in the spectral-amplification results. The brown patch S denotes a part of the finite-extent source, the dashed white line is the profile of the receivers placed at the free surface, the coordinates are in meters (the Swiss coordinate system).

The 1989 Loma-Prieta-like models (M1, M2)

The following two source models are $M_w = 6.9$ models with a final slip distribution equal to the Loma Prieta Earthquake (Figure 4). The W x L dimensions of the rupture zone are 35 km x 13 km, strike = 0° (along the N-S direction), and the dip is 75° . He whole rupture zone is buried so that the topmost part is 3.5 km under the free surface and its north most part is 9 km south of the Basel city limits (Figure 3). The final slip distributions of these Loma-Prieta-like source models (Figure 4) are computed based on the spatial random-field model for earthquake slip (Mai and Berosa, [10]). In order to generate a physically self-consistent rupture model, we deploy the pseudodynamic source characterization similar to the one firstly by Mai et al. [11], and then further developed by Guatteri et al. [12]. In purely kinematic source models, the rupture velocity and rise time are chosen without considering the underlying dynamics of earthquake rupture. In contrast, the pseudo-dynamic source model uses the static stress-drop corresponding to the final slip distribution to approximate the fracture energy on the rupture plane. This distribution of fracture energy is then used to calculate physically consistent distributions of rupture velocity and rise time. The final source model therefore comprises realistic spatial and temporal variations in the slip, rupture propagation and rise time (Figures 5,6). The hypocenter in this approach is a predefined parameter, but it exerts a large influence of the rupture propagation and the resulting rise-time distribution. The two presented models M1 and M2 differ in the position of the hypocenters (Figures 5,6). In this way it is possible to choose significant rupturing histories as 'towards to' (M1) and 'away from' (M2) the site of interest. Slight difference between the symmetry rise time and rupture time and thus also stress drop, fracture energy, crack resistance v_r/v_s (rupture to S-wave velocities ratio) is essential due to source dynamics. Ground motions are propagated to the observer location (as an input for the FD) is computed by DWFE method of Olson et al. [13] (using the COMPSYN code of Spudich and Xu). In this application we use the Kostrov approximation of local slip-velocity source-time function in frequency domain (Mai et al., [11]).



Figure 4: The final-slip distribution used for M1 and M2 rupture histories, Loma-Prieta-like earthquake. Hypocenters, H1 and H2 stars, are corresponding to the M1 and M2 rupture histories, respectively (see Figures 5, 6). Both H1 and H2 are situated 3km from the bottom part, and 6 km from the corresponding sides of the rupture zone. The dimensions of the fault are 13 km x 36 km, down-dip distance is measured from the intersection of the fault plane with flat free surface.



Figure 5: Rupture zone, model M1 with the Loma-Prieta-like features. Propagation of the rupture is 'towards Basel site' (Figures 3, 4). Coordinates are in km.



Figure 6: Rupture zone, model M2 with the Loma-Prieta-like features. Propagation of the rupture is 'away from Basel site' (Figures 3, 4). Coordinates are in km.

The 1999 Athens Earthquake model (M3)

The next model is the $M_w = 5.9$, 1999 Athens Earthquake model computed by PEXT method (Zahradník and Tselentis [14]). PEXT method models finite-extent source in which source complexities are represented by stochastic PErturbation and EXtrapolation of the low-frequency deterministic wavefield. The low-frequency part contains the near, intermediate and far-field terms, and also the effects of the free surface and 1D structure. For more details on the composite-source modeling actual method see Opršal et al. [7].

The parameters for the model are as follows: $M_w = 5.9$, L = 10 km, W = 8 km composite source of 5 x 5 = 25 sub-events, each sub-event has slip duration = 0.57 sec, slip 0.059 m, and slip velocity time history is the causal Brune impulse. The asperity, which has a dimension of 4.0 km x 4.8 km, has a slip contrast of 2.2. The nucleation point is assumed to be at the south most part of the model at depth of 10 km at southern bottom corner of the asperity. Thus the rupture propagates 'towards Basel area'. For the rest of the rupture area, a homogeneous slip is set to maintain the moment. Upper edge of the fault plane is at 8 km depth. Radial rupture propagates with velocity = 2.8 km/s with 10% perturbation. The average slip velocity follows (subevent slip / subevent duration) ~ 0.1 m/s and is the same for any M_w subevent due to self-similarity. Maximum slip velocity depends on the wavelet used as a source time function, in this case (Brune's wavelet) it is 0.24 m/s = (average slip velocity * 2.3).

The source model was verified against the strong-motion acceleration waveforms recorded in the central part of Athens (Kalogeras and Stavrakakis [15]; Ambraseys et al. [16]), for Figures see Opršal et al. [7]. The dominant frequencies of velocities were of about 0.6 Hz.

Finite differences (2nd step)

The 3D explicit FD method (Opršal and Zahradník [5]) is designed for topography models on irregular rectangular grids. The single-template approximation to the hyperbolic partial differential equation (PDE) is solved explicitly in the spatial and the time domain. The boundary conditions at the interfaces

(including the topographic free surface) are satisfied via a treatment of the material parameters. The medium is Hooke's isotropic inhomogeneous body, with a particle-velocity dependent term added to the PDE to approximate viscoelastic behavior of the medium.

The 2^{nd} step is a 2^{nd} order 3D FD method on irregular grids with topography. The FD method uses a single template everywhere in the model including the free surface (vacuum formalism). It is stable for complex models with high Vp/Vs contrasts and high (Vp/Vs)-ratio contrasts.

COMBINED SOURCE-PATH AND SITE EFFECTS AT BASEL AREA

The following results are compared for the three source models described above. Direct comparison between M1 and M2 may be done because the earthquake is of the same magnitude and the only difference is in the direction of rupture propagation. The directivity of the source plays a very important role for the frequency content and the amplitudes of the ground motion. Model M3 is for a smaller earthquake, thus the frequency content is shifted towards higher frequencies.

We first evaluate frequencies corresponding to the computed maxima of pseudo-acceleration response spectra in order to show a strong dependence of the ground motion from the combined effect of the source, path and site (Figure 7). The images of the experiments are not different from Figure 2. The common-frequency patches for models M1 and M2 show less scattered than that for model M3. It is caused by enhanced energy for frequencies above 1 Hz, and consequently more energy in the higher modes of the surface waves. Focusing effects are visible as orange linear patterns in model M3. These patterns are parallel to the strike of the Rhine Graben structure.



Figure 7: Frequencies corresponding to the computed maximum of the pseudo-acceleration response spectra. The lines denote as follows: red - Basel-city limits, dashed black - the surface trace of the Rhine Graben master fault, grey - rivers, thick grey - the Rhine river. Comparison is shown for M1, M2 and M3 source models. Coordinates are in meters (the Swiss coordinate system). See also Figure 2.

A comparison of the amplification in PSA for the models M1, M2 and M3 is shown at Figure 8. The frequency band 0-2.2 Hz is subdivided into 7 sub-bands in order to visualize the amplification as a function of frequency. The maximum and average values of amplifications are expressed for each sub-band and each source model. This helps to represent the variability and typical pattern of the amplification. For all the models it is characteristic that the maxima for the lowest frequencies are in the deep parts of the Rhinegraben (mainly M1). With increasing frequency they move to the north-western

part of the city area called the shoulder of Basel. The largest amplitudes are obtained for the M1 model. The maximum amplification is in general in the 0.9-1.1 and 1.1-1.3 Hz frequency bands.



Figure 8: Amplification in the pseudo acceleration response (damping 5%) for the M1, M2 and M3 finiteextent sources. The results are shown for a set of frequency bands corresponding to each of the rows. The left and right sides of each column correspond to the maximum and mean amplitudes in the frequency band. The red line denotes Basel-city limits; dashed black line the surface trace of the Rhine Graben master fault; grey lines are rivers, thick grey line is the Rhine River.

The synthetic accelerograms (EW component) and acceleration maxima (total horizontal component) for the M1, M2, and M3 source histories are shown in the appendix in Figure 12, and Figure 13, respectively. All receivers are on the free surface, in Figure 12, the receivers aligned on EW-direction profile (see also Figure 3). The time histories differ reasonably. The frequency content of the M1 and M3 models is higher due to rupture propagation 'towards' Basel site. Added to that the magnitude of the M3 source is smaller. The high-frequency oscillations appearing before the S-wave arrival in the synthetics of M1 are due to the dynamic process during rupturing.

The synthetics and the maxima-values show that the amplitudes of M1 and M2 differ by the factor of ~ 10, however, the ratio of the PSA values are 2 (for typical values in the middle of the Basel city). The reason is longer apparent duration of the M2 rupturing. By analogy, the acceleration-maxima amplitudes of M2 and M3 computations differs by a factor of ~ 3 but the corresponding PSA differ by a factor of 16. On the other hand, the M1 and M3 models have a very similar duration, and their maximum-acceleration ratio is ~ 30 which is about the same as the ratio between their PSA values.

Difference of the M2 model with respect to M1 and M3 is characterized by a different distribution of the acceleration-maxima amplitudes (Figure 13). Models M1 and M3 have few solid narrow peaks of about 2 times higher value then in the rest of the city area. Model M2 has very uniformly spread amplitudes of 80-90% of the maximum accelerations for approximately 50% of the city area. Models M2 and M3 have opposite pattern of the acceleration-maxima-values distribution at the part lying within the city limits west of Rhine Graben master fault (zones 1-5 of Figure 9), see Figure 13.

The 2D behavior of the wave propagation in the Basel city area was previously studied by Kind [1]. The Basel city was subdivided into 5 zones by considering ranges of the fundamental frequency of resonance of the sediments. PSA was then computed for 5 individual sections of surface receivers (Figure 9, upper left panel). For each of the sections a series of 2D simulations was performed assuming different source positions and mechanisms. Amplifications obtained for one zone were collected and the result is shown in Figure 9.

The 3D behavior was studied similarly. The 5 spatial zones were kept unchanged. The computations were performed for all free-surface receivers located in the 3D model. Relatively high density (100 surface receivers / km^2) assures a few hundred points for the analysis even for the small zone defined by (1.1-1.3) Hz fundamental frequency. This analysis was performed independently for the three models (See Figure 10). The comparison of averaged/enveloped M1, M2, M3-source simulations to the 2D-analysis results of Kind [1] is shown at Figure 11.

An overall feature of the 3D vs 2D results is the lower amplification for the 3D case. As to the amplitudes, the 3D-results maxima over a particular domain are comparable to the 2D averaged results. This might be due to the source positions in the modeling. While Kind [1] assumes the source location in the east and west of the city, our location is to the south. This hypothesis has to be further tested by placing the sources in the 3D modeling also to the east and west of the site.

The different zones in the Basel area can be characterized as follows:

- 1. Zone 1 (0.4-0.6) Hz; 2397 receivers: Pronounced amplification for (0.4-0.7) Hz band with splitting (maxima envelope) into two peaks is the same as observed in the 2D modeling. The pronounced peak at 1.6 Hz is missing in the 3D modeling. A peak is present at 1.8-2.2 Hz for M3, increased values of amplification are features for M1 and M2 models.
- 2. Zone 2 (0.6-0.73) Hz; 682 receivers: As in Zone 1, the fit at the fundamental frequency is very good with a small shift to (0.7-0.9) Hz for model M1. The peak at 2.5 Hz is not present in 3D results because of the frequency content of the input signal.
- 3. Zone 3 (0.73-0.9) Hz; 651 receivers: The fundamental frequency is clearly shifted from (0.7-1.0) Hz (2D) to 0.8-1.2 Hz. Peak at 2.5 Hz is clearly indicated.
- 4. Zone 4 (0.9-1.1) Hz; 491 receivers: Shift of the fundamental frequency is from 0.7 Hz-1 Hz (2D) to (1.1-1.3) Hz (M1, and M2). Another peak at 2 Hz is not present in the 2D result.
- 5. Zone 5 (1.1-1.3) Hz; 199 receivers: The fundamental frequency is about the same, again as in zone 4, a new peak is present at ~2.2 Hz.

The 3D and 2D features are most different in the zones with (0.9-1.1) Hz and (1.1-1.3) Hz fundamental frequency. The difference is the lack of the amplification peaks above 1Hz in the 3D case, the shifting of the fundamental frequencies to higher values, and the presence of other peaks at (2.0-2.2)Hz. These peaks

are missing in the 2D cases. The fundamental-frequency peaks are sharper for 3D case but this fact may be due to one position of the source plane. On the other hand the envelopes of the M1, M2 and M3 models are very close to the results of Kind [1] at zones 3, 4, and 5 (see Figure 11).

Another reason for the differences in amplitudes and the shapes of the PSA curves is the fact that the reference model is not a 1D model. In fact, it is a 3D model where the interfaces copy the free surface above. Therefore it may have some influence on the wavefields.

For the future research, an integer Fortran 90 function for the five frequency/spatial zones has been prepared. It returns an integer value (number of zone, '0' for position out of the 5 zones) to a position vector X = (x, y); x, y, being the coordinates (in km) of the Swiss coordinate system.



Figure 9: Left panel - Amplification zonation along the individual sections for the City of Basel (Kind [1]). Five frequency ranges are differentiated, their spatial extent is indicated in the sketch with the frequency increasing from the south east to the north west. For each section and frequency range a dashed line shows the maximum amplification from all scenarios and from all points with a fundamental frequency within the specific range. At each point of a section the average amplification over all scenarios is determined and the envelope of these curves from the same points is shown as continuous line. Right panel - The same frequency ranges as in the left panel are considered. The dashed line indicates overall maximum amplification from all scenarios, while the continuous line shows the envelope of the average amplification curves, selecting classes of points by the fundamental frequencies. (From Kind [1])



Figure 10: Amplification zonation for particular zones covering the City of Basel and its vicinity, and the 3 source model histories used in the 3D modeling. The spatial extent of five (fundamental-) frequency zones (Kind [1], see also Figure 9) with the frequency increasing from the south east to the north west are indicated by colors. For each frequency/spatial zone a dashed line shows the maximum amplification from all points inside the spatial/frequency range. By analogy, the solid line corresponds to the average amplification over all corresponding-range points. The curves are determined for each event separately.



Figure 11: Comparison of the amplification zonations for particular zones covering the City of Basel. The spatial extent of five (fundamental-) frequency zones (Kind [1], see also Figure 9) with the frequency increasing from the south east to the north west are indicated by colors. The thick lines correspond to the 3 source model histories used in the 3D modeling, the thin lines are obtained by Kind [1]. For each frequency/spatial zone the red lines show the maximum amplification from all points inside the spatial/frequency range. By analogy, the blue lines denote the average amplification over all corresponding-range points.

CONCLUSION

The simulation of the 1356 Basel earthquake for two propagation characteristics (towards and away from Basel city), combined with the site effects results in maximum horizontal PGA = 1,6g and 0.12g, respectively. Another M_w =5.9 earthquake with propagation towards to the city results in maximum horizontal PGA = 0.08g. The local structure has an important impact on the amplitudes, frequency content, and duration of the strong ground motion synthetics. This is well indicated on the response spectra reaching the 4.5g and 2.5g for the M=6.9 earthquake. Shifting the rupture zone up so that it penetrates also the topmost sedimentary layers (probably in 1D reference model) smoothes a strongly pronounced asperity responsible for high amplitudes of the ground motion but does not really result in reasonably smalled PGA and PSA values.

We recognized zones in the city where we expect strong amplification in specific frequency band. The comparison with 2D computation showed good correspondence (Fäh et al. [17]). As an addition to this experiment, 3D strong ground motion scenario case including two $M_w = 6.5$ and one $M_w = 5.9$ histories for 3 significant positions of the fault plane is presented by Opršal et al. [18].

APPENDIX



Figure 12: Example of the synthetic accelerograms (EW component) for various M1, M2, and M3 source histories. The receivers are on the free surface EW-direction profile (denoted by thick vertical lines, E-W direction corresponds to upward direction here) as shown in Figure 3. The blue vertical lines depict the maximum amplitudes (denoted by a value) recorded on the corresponding profiles.



Figure 13: Maxima of total horizontal acceleration recorded on the free surface. The lines denote as follows: red - Basel-city limits, dashed black - the surface trace of the Rhine Graben master fault, grey - rivers, thick grey - the Rhine river. Comparison is shown for M1, M2 and M3 source models. Coordinates are in meters (the Swiss coordinate system). See also Figure 3.

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REFERENCES

- 1. Kind, F., "Development of Microzonation Methods: Application to Basel, Switzerland". PhD Thesis Nr. 14548, ETH Zuerich, 2002.
- 2. Fäh, D., Rüttener, E., Noack, T., Kruspan, P. "Microzonation of the city of Basel." Journal of Seismology, 1997, 1, 87-102.
- 3. Kind, F., Fäh, D., Zechner, E., Huggenberger, P., Giardini, D., "Seismic zonation from a 3D seismic velocity reference model of the area of Basel, Switzerland." Bull. Seismol. Soc. Am., submitted.
- 4. Kind, F., Fäh, D., Giardini, D., "Array measurements of S-wave velocities from ambient vibrations." Geophysical Journal Int., submitted.
- 5. Opršal, I., Zahradník, J. "Elastic finite-difference method for irregular grids." Geophysics, 1999, 64, 240-250.
- 6. Opršal, I., Brokešová, J., Fäh, D., Giardini, D. "3D Hybrid Ray-FD and DWN-FD Seismic Modeling For Simple Models Containing Complex Local Structures." Stud. Geophys. Geod., 2002., 46, 711-730.
- 7. Opršal, I., Zahradník, J., Serpetsidaki, A., Tselenits, G.-A. "3D hybrid simulation of the source and site effects during the 1999 Athens earthquake, Proc. of 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada, August 1-6, 2004, Paper No. 3337.
- Fäh, D., Giardini, D., Bay, F., Bernardi, F., Braunmiller, J., Deichmann, N., Furrer, M., Gantner, L., Gisler, M., Isenegger, D., Jimenez, M., J., Kästli, P., Koglin, R., Masciadri, V., Rutz, M., Scheidegger, C., Schibler, R., Schorlemmer, D., Schwarz-Zanetti, G., Steimen, S., Sellami, S., Wiemer, S., Wössner, J. "Earthquake Catalogue Of Switzerland (ECOS) And The Related Macroseismic Database". Eclogae geol. Helv., 2003, 96, 219-236.
- 9. Meghraoui, M., Delouis, B., Ferry, M., Giardini, D., Huggenberger, P., Spottke, I., Granet, M. "Active Normal Faulting in the Upper Rhine Graben and Paleoseismic Identification of the 1356 Basel Earthquake." Science, 2001, 293, 2070-2073.
- 10. Mai, P., M., Beroza, G., C. "A spatial random field model to characterize complexity in earthquake slip." J. Geophys. Res., 2002, 107 (B11), 2308, doi:10.1029/2001JB000588.
- 11. Mai, P., M., Guatteri, M., Beroza, G., C. "A stochastic-dynamic earthquake source model for strong motion prediction: earthquake scenarios on the Hayward-Rodgers-Creek fault system." Eos Transactions, American Geophysical Union, 2001, 82, 869.
- 12. Guatteri, M, Mai, P., M., Beroza, G., C. "A pseudo-dynamic approximation to dynamic rupture models for strong ground motion prediction, submitted to BSSA, 2004.
- 13. Olson, A., H., Orcutt, J., A., Frazier, G., A. "The discrete wavenumber finite element method of synthetic seismograms." Geophys. J. R. Astr. Soc., 1984, 77, 421-460.
- 14. Zahradník, J., Tselentis, G.-A., "Modeling strong-motion accelerograms by PEXT method, application to the Athens 1999 earthquake." Proc. of XXVIII Gen. Ass. of Europ. Seismol. Comm, 1-6 Sep. 2002, Genoa (CD-ROM), or <u>http://seis30.karlov.mff.cuni.cz/</u>.
- 15. Kalogeras, I., Stavrakakis, G. "Processing of the strong-motion data from the September 7th, 1999 Athens earthquake." Geodynamic Institute, National Observatory of Athens, 1999.
- 16. Ambraseys, N., Smit, P., Berardi, R., Rinaldis, D., Cotton, F., C. Berge-Thierry "Dissemination of European Strong-Mottion Data." CD-ROM collection, 2000. European Council, Environment and Climate Research Programme.
- 17. Fäh, D., Kind, F., Lang, K., Giardini, D., 2001. Earthquake scenarios for the city of Basel. Soil Dynamics and Earthquake Engineering 21, 405-413.
- 18. Opršal, I., Fäh, D., Giardini, D., Mai, M. "Deterministic earthquake scenario for the Basel area Simulating strong motion and site effects for Basel." (in prep., see http://geo.mff.cuni.cz/ -> people -> Ivo Oprsal).