Paper No. 727. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

MICROZONATION OF THE CITY OF BASEL (SWITZERLAND) BASED ON NUMERICAL SIMULATIONS AND IN-SITU MEASUREMENTS

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ABSTRACT

During the past centuries, the city of Basel has suffered damage caused by earthquakes. One extraordinary event described in historical documents is the strong earthquake which occurred in 1356. This event was one of the strongest earthquakes in NW Europe. The 1356 event was obviously much stronger than the low-magnitude earthquakes observed in the area during this century. Even though the present seismicity in the Basel area is low, strong earthquakes have to be expected due to the city's geographical location close to the northern boundary of the African-European convergence zone, at the southern end of the Rhine Graben. A crucial step towards preparedness for future events and mitigation of earthquake risk involves a microzonation study of the city. The first results of this microzonation study are presented in this contribution. The study includes a detailed mapping of the geology of the area, and it includes also the measurement and interpretation of ambient noise data, and numerical modelling of expected ground motion during earthquakes. A first preliminary microzonation of the centre of Basel is presented, and it is discussed by comparing it to the historically reported damage of the 1356 earthquake.

KEYWORDS

microzonation; seismic ambient noise; microtremors; numerical modelling; strong ground motion; historical earthquakes; site effects.

GEOLOGICAL AND GEOTECHNICAL INVESTIGATIONS

The initial step of the microzonation includes the collection, validation and mapping of geotechnical and geological information in the area of interest. For urban areas, many borehole data are generally available to estimate the thickness of the unconsolidated soils, and the depth of the ground-water table. For the Basel area, data from about 3000 boreholes are analysed. The collected data are used for a classification of the local soil conditions, the definition of the physical parameters (e.g. wave velocities, density, thickness), and the selection of some test sites which are representative for the different classes. These investigations will result in a series of maps which describe the thickness of the unconsolidated sediments, the age and composition of the soils, the depth of the ground-water table, and the deep structure down to real bedrock. Measurements from Standard Penetration Tests (SPT) have been used to estimate shear-wave velocities of the different soils present in the Basel area (Fäh *et al.*, 1996).

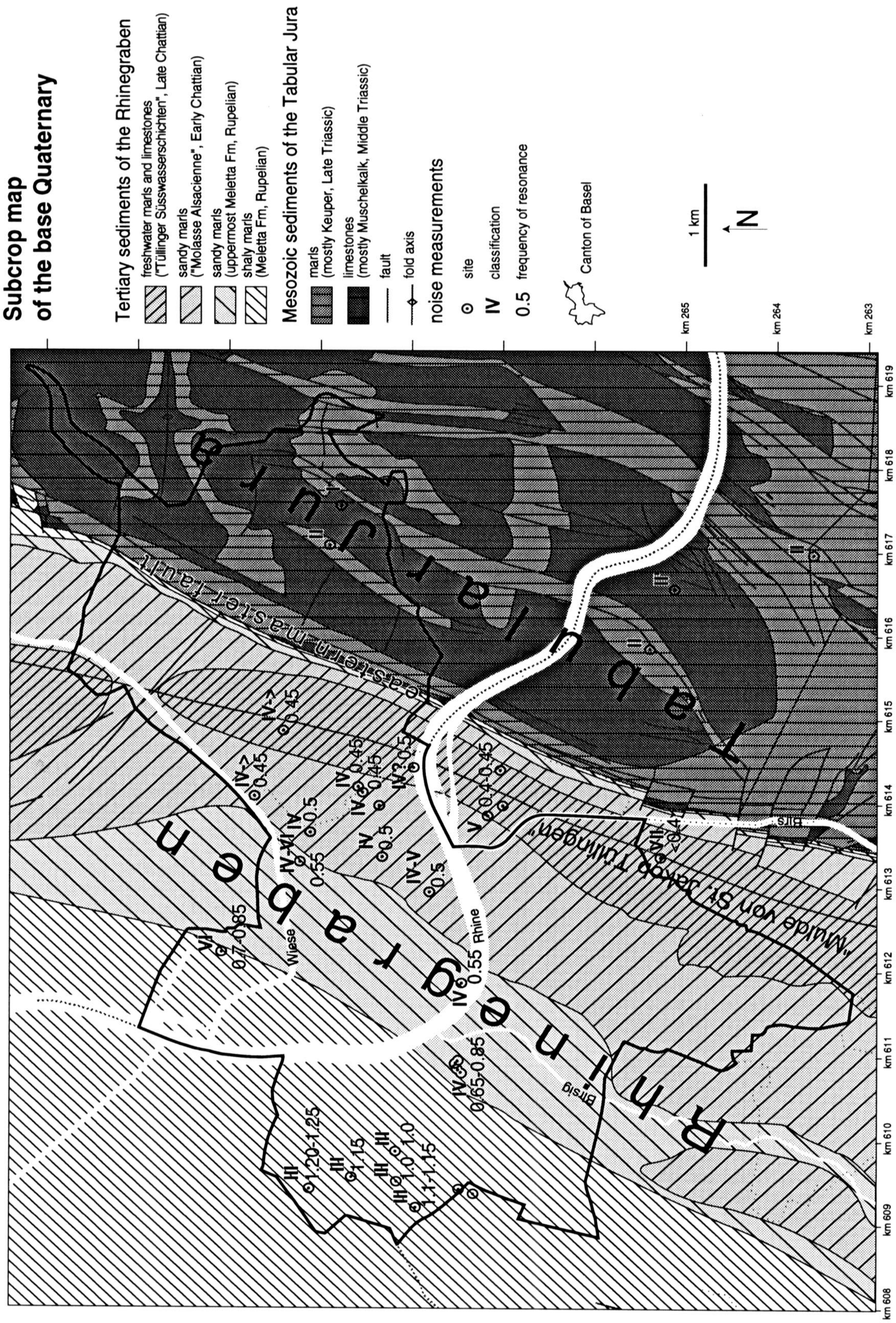

Fig. 1. Subcrop map of the base of the Quaternary. The sites where ambient noise measurements have been carried out are classified with Roman numbers according to the type of polarisation spectrum observed at the site. The measured fundamental frequency of resonance is given for sites within the Rhinegraben.

A general overview of the geology in the Basel area is given in Fig. 1. The city of Basel is located at the eastern master fault of the southern Rhinegraben. The throw at the border fault of the Rhinegraben is about 1400m. Within the Rhinegraben (on the downthrown side) the Mesozoic strata (Triassic to Jurassic) are overlain by 500 to 1000 m of Tertiary sediments. They form an asymmetric syncline with its axis parallel to the fault zone forming the "Mulde von St. Jakob - Tüllingen" (Fischer *et al.* 1971, Gürler *et al.* 1987). These Tertiary layers are known only by very few outcrops and deep reaching wells. Fig. 1 shows a subcrop map of the base of the Quaternary. The following Tertiary formations can be distinguished: The Meletta (Rupelian, max. 350 m thick) are mostly argillaceous marls. At its transition to the "Molasse Alsacienne" (Early Chattian) they become more sandy. The "Molasse Alsacienne" with a maximum thickness of 300 m is an intercalation of sandy layers and argillaceous marls. The topmost "Tüllinger Süsswasserschichten" (Late Chattian, max. 200 m thick) are calcareous to argillaceous marls with interlayering freshwater carbonates. At their base gypsum is frequent. The carbonates are found predominantly in the northern part, whereas the marly facies is more developed to the south. Above the Tertiary sediments 5 to 40 metres of Pleistocene and Holocene gravels were deposited, mostly by the Rhine but also by smaller rivers like the Birs and the Wiese. The composition of these gravels is well known throughout the town by about 3000 shallow wells, that were drilled for construction and groundwater purposes (Noack, 1993). With the help of this dense dataset we were able to compile a map with regions where sand-rich gravel predominates, regions with gravel with little to no sand, and areas with a significant amount of conglomerates. The thickness of the gravels was reconstructed by the subtraction of the contour map of the base Quaternary from a detailed digital elevation model. To the east, on the shoulder of the Rhinegraben, the Mesozoic sediments (Triassic, in some smaller grabens also Lower Jurassic (e.g. Laubscher 1982)) are overlain directly by some 5 to 50 m of Pleistocene and Holocene gravels.

INTERPRETATION OF AMBIENT SEISMIC NOISE

In-situ measurements allow to restrict the large parameter space of the soil properties. In urban areas, it is generally not possible to carry out measurements with controlled-source seismic methods. For this reason we focus on ambient seismic noise, or microtremor measurements. One of the cheapest techniques is based on a polarization analysis of the microtremor wavefield. The procedure has the potential to make site period predictions more reliable, and in the case of existing borehole data, it allows estimates of average shear-wave velocities of the unconsolidated sediments. This method is applied for different sites in Basel (Fig. 1), accompanied by numerical experiments for the interpretation of the results. Figure 2 shows a comparison between a measured polarisation spectrum and the result of a numerical experiment. The measured polarisation spectrum (Fig. 2a) is computed from about 500 samples of noise data, each with 20s duration, and recorded at one site from 8 pm to 7 am. For each sample, the polarisation is computed. The polarisation is defined as the ratio between the Fourier spectrum of the vertical component of motion and the ones's from the horizontal components. All polarisations from the 500 samples are plotted in the same figure which results in the polarisation spectrum shown in Fig. 2a. The solid line represents the maximum polarisation observed in the 500 samples, only taking into account samples in which signal-energy in the considered frequency band is larger than the average signal-energy. The modal summation method (Panza, 1985) is used for the interpretation of the observed polarisation spectrum. Figure 2b shows the polarisation of all normal modes that exist in the chosen structure. The set of normal modes is complete for given phase velocity and frequency bands. The structure in this example is composed of an average crustal model for the Basel area (Fäh *et al.*, 1996) overlaid by a layer of unconsolidated sediments (h=30m, vp=1650 m/s, vs=500 m/s). The numerical experiment is designed in the way that we excite all normal modes, that can be excited with about 300 different sources located close to or at the free surface. The signals from the different sources are combined and analysed in the same manner as it is done for the observed noise data. A result of such a numerical experiment is shown in Fig. 2c. As long as the real structure at the site can be approximated by one layer of soft soils over bedrock, the numerical experiments are successful in the interpretation of measured polarisation spectra. For structures with strong velocity gradients or with several layers that have different velocities, the interpretion of the polarisation spectra is not unique.

Polarisation spectra can be used to identify thick layers of unconsolidated sediments. The fundamental period of resonance, which can be recognized as a minimum in a polarisation spectrum, and the knowledge of the thickness of the sediments from borehole-data can be used to estimate average shear-wave velocities. We can expect that sites with similar polarisation spectra will exhibit similar amplification effects during earthquakes, as long as enough time samples are used for the calculation of the polarization spectrum in order to reduce possible effects from the noise sources. In Fig. 1, sites with similar polarisation spectra are shown with the same Roman numbers. It is noticed that at least three major zones can be distinguished (Type II, III and IV spectra). The zone with type III spectra corresponds to an area where sediments with an average shear-wave velocity of the order of 500 to 600 m/s reach a thickness of about 100-150m . The sediments of this zone are composed of a surficial layer of Pleistocene gravel, underlain by argillaceous marls of Tertiary age (Meletta Fm). At the transition to the more sandy Molasse Alsacienne the Tertiary sediments become stiffer and the average shear-wave velocity is increasing. The thickness of the Tertiary sediments is increasing in the "Mulde of St.Jakob - Tüllingen", which is well seen by the decreasing fundamental-frequency of resonance (Fig. 1). In this zone with type IV spectra, the site effects are mainly controlled by the surficial layers of gravel. To the north of the zone with type IV spectra, the Tertiary sediments are stiffer (Type IV-> spectra), whereas to the south the stiffness is decreasing (Type V spectra). Type II spectra are observed outside the Rhinegraben. There is a layer of gravel, which in some parts overlays a thin layer of marls with low shear-wave velocities. The fundamental frequency of resonance is above 2 Hz.

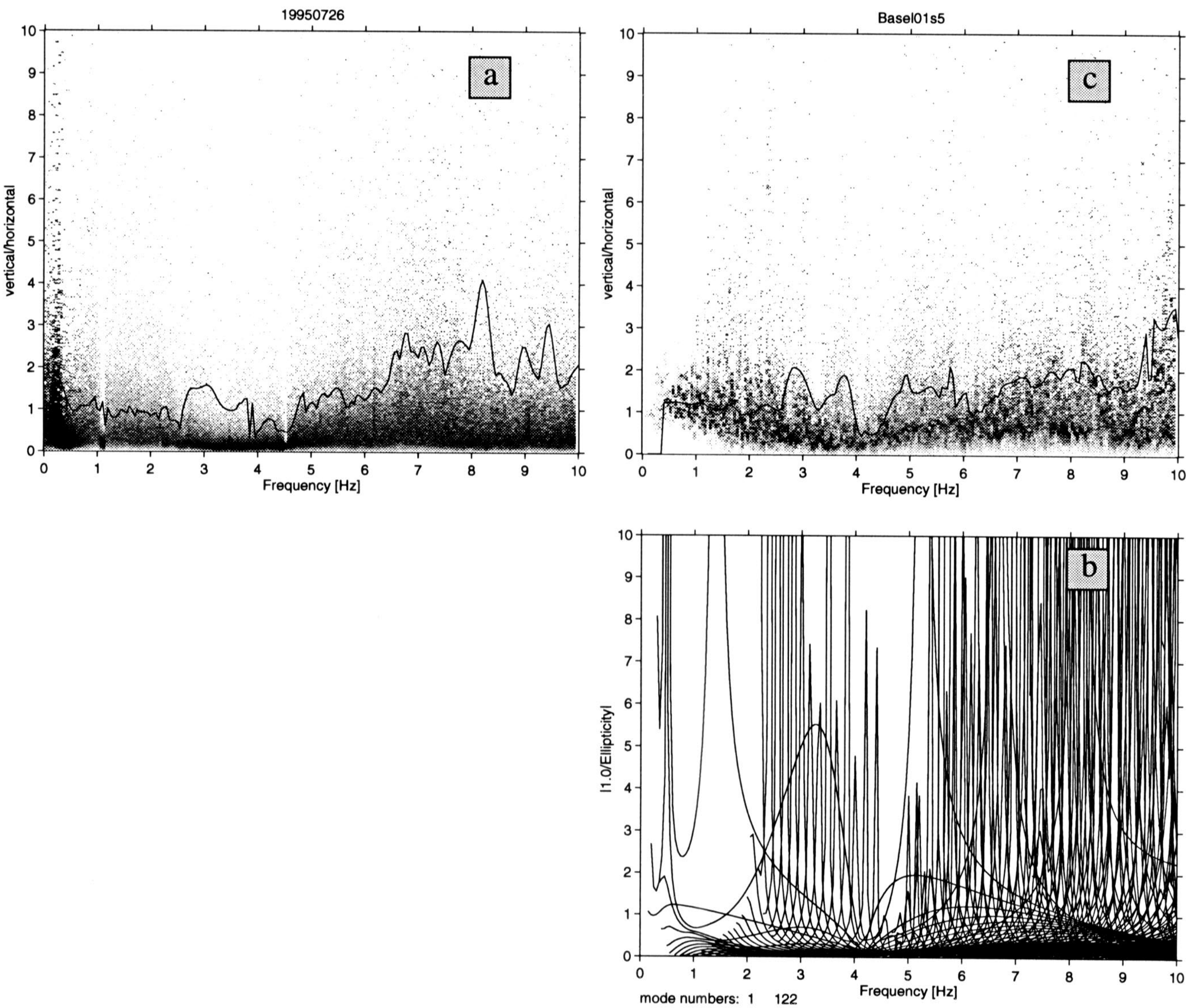

Fig. 2. Comparison between (a) an observed polarisation spectrum at a site with a type II spectrum and (c) a polarisation spectrum computed from synthetic noise. The theoretical polarisation properties for all modes that exist in the considered structural model are shown in (b).

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ONE- AND TWO-DIMENSIONAL MODELLING

The collected data-base is used to conduct different parameter studies through theoretical computations which allow a definition of the variability of ground motion, and the expected amplification effects on different soils. The modelling techniques are based on methodologies, which take into account the seismic source, the propagation path, and the local soil conditions. The methods and their possibilities are described in Fäh and Suhadolc (1994), and in Fäh and Panza (1994).

One-dimensional modelling with the mode-summation method is used to quantify the influence of 72 different seismic sources on the amplification effects at specific test sites with respect to bedrock. Since the material properties of the different soils are known only within some limiting values, a sensitivity study for the wave-velocities is also performed. This testing of the site effects regarding sensitivity to the earthquake characteristics (azimuth, depth, source mechanisms) and soil properties are to be used for microzonation studies, since a zonation should be insensitive to all unknown parameters of the source and the path. In Table 1, a typical velocity profile for a site in Basel is given. For each numerical simulation, we have computed the relative spectral amplification with respect to bedrock. From the spectral amplification obtained with the 72 seismic sources, we then computed the average and the maximum spectral amplification for a certain structural model. The maximum and average spectral amplification for the three velocity models in Table 1 are given in Fig. 3. The amplifications are large at the fundamental frequency of the soil column. This shows the importance to determine the fundamental frequency of resonance with in-situ measurements. For the different velocity models it is noticed, that the lower the velocities the more the low-frequency part of the spectrum is affected, and the higher are the amplification effects.

Two-dimensional modelling is applied to estimate the influence of lateral heterogeneities on ground motion. Due to the fact that two-dimensional modelling is time consuming, only a limited number of cross-sections and seismic sources can be studied. Figure 4 shows an example of the numerical simulation of the effects at the northern border of the sedimentary basin in the Basel area, caused by the Wutöschingen earthquake of December 30, 1992. It should be mentioned, that synthetic signals obtained from numerical modelling can explain the shape, the duration and the frequency content of the strong motion records observed in the Basel area during this earthquake (Fäh *et al.*, 1996).

Table 1: Low/average/high seismic wave velocities for the gravels at a test site. The structure underneath corresponds to an average crustal model for the Basel area (Fäh *et al.*, 1996).

depth [m]	thickness [m]	density [g/cm^{-3}]	v_p[km/s]	v_s [km/s]	Q_β
1.50	1.50	1.80	0.52 / 0.52 / 0.52	0.10 / 0.15 / 0.20	20
4.50	3.00	1.90	0.60 / 0.75 / 0.92	0.29 / 0.36 / 0.44	20
10.00	5.50	2.00	0.52 / 0.61 / 0.76	0.20 / 0.25 / 0.31	20
16.00	6.00	2.00	0.69 / 0.86 / 1.05	0.28 / 0.35 / 0.43	20
20.00	4.00	2.00	1.65 / 1.65 / 1.65	0.28 / 0.35 / 0.43	20
21.00	1.00	2.00	1.65 / 1.65 / 1.65	0.36 / 0.45 / 0.55	20
24.00	3.00	2.30	1.65 / 3.00 / 3.00	0.45 / 1.00 / 1.00	20

The spatial variation of the site response can be studied by computing relative peak ground acceleration PGA(2D)/PGA(bedrock) and relative Arias Intensities W(2D)/W(bedrock) along the cross-section of interest (Fig. 4), also taking into account the variability of ground motion induced by higher and lower shear wave velocities relative to an average velocity model of the sediments. The velocities of the crustal structure are kept constant. The Arias Intensity W is defined as follows:

$$W = \frac{\pi}{2g} \lim_{t \to \infty} \int_0^t \left(\ddot{x}^2(\tau) \right) d\tau$$

where x is the displacement time-series, and g is the constant of gravity. The PGA is only affected by the soft sediments in the sedimentary basin; the lateral variability of the structure has only minor effects on the PGA. For the model with low velocities, the maximum PGA is about 1.3-1.5 times the PGA on bedrock. The relative Arias Intensity depends strongly on the duration of the seismic ground motion. At lateral heterogeneities such as the transition from bedrock to soft sediments, local surface can be exited which can significantly increase the duration of the ground motion. Local resonance effects and focusing of waves due to subsurface topography can also contribute to the amplification of the seismic waves. This is well seen in Fig. 4, where a significant variability and increase of the Arias Intensity is observed inside the sedimentary basin. Lateral changes of the soft sediments should therefore be accounted for in seismic microzonation studies.

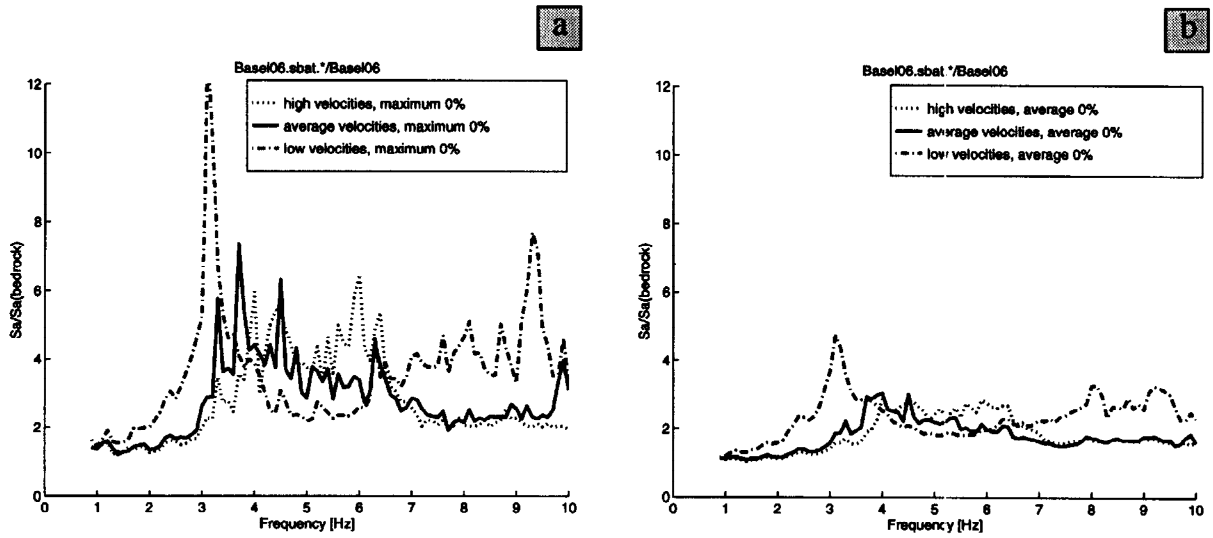

Fig. 3. (a) Maximum and (b) average spectral amplifications with respect to bedrock, for the models given in Table 1.

A QUALITATIVE SEISMIC MICROZONATION

The results obtained from numerical simulations, in-situ measurements, and geotechnical site characterization are summarized and are used for a qualitative microzonation of a test area in the centre of Basel. The area is divided into small cells of 25m×25 m each. For each cell, local soil conditions are rated by a scheme that assigns to the different soil properties a certain integer number from 0 to 4. The following properties have been rated: deep sediments (0-4, from microtremor measurements), the age of the surficial sediments (0-4, from geology), the composition of soils (0-3, from borehole informations), the thickness of Pleistocene and Holocene gravels (0-3, from borehole informations), the distance from lateral heterogeneities (0-4, from geology and numerical results), the depth of the ground water table (0-4, from borehole data). The numbers are summed for each cell. The result is a map in which each cell is characterized by a number from 0 to 18. High numbers indicate an increased hazard and low numbers a reduced hazard with respect to the regional value (Fig. 5). Preliminary results for the centre of Basel are given in Fig. 5 , and a detailed description of the rating scheme is given in Fäh *et al.* (1996).

In the same figure, an interpretation of the historically reported damage of the earthquake of 1356 is given. For this event, historical documents report that the city of Basel was almost completely destroyed, and that nearly all medieval fortified castles collapsed within a 30 km radius of Basel (for a review, see Mayer-Rosa and Cadiot, 1979). Wechsler (1987) analysed the damage in Basel from historical documents that describe expenditure for the repair of damaged buildings. A summary of the reported damage is shown in Fig. 5 (Fäh *et al.*, 1996). It is obvious that mostly reports from buildings such as churches and monasteries exist, and that a present day validation of the damage in 1356 is rather uncertain. Moreover, local soil conditions in the city have changed due to human activity. For example, the moats of the city which have been filled during the last century can be well identified in the microzonation map, but they were not existent in 1356. Nevertheless, the comparison between the damage distribution and the preliminary microzonation map shows acceptable agreement at many sites, for example in the valley of the river Birsig, at the site of the churches Münster, St.Ulrich, St. Martin, and St. Leonhard.

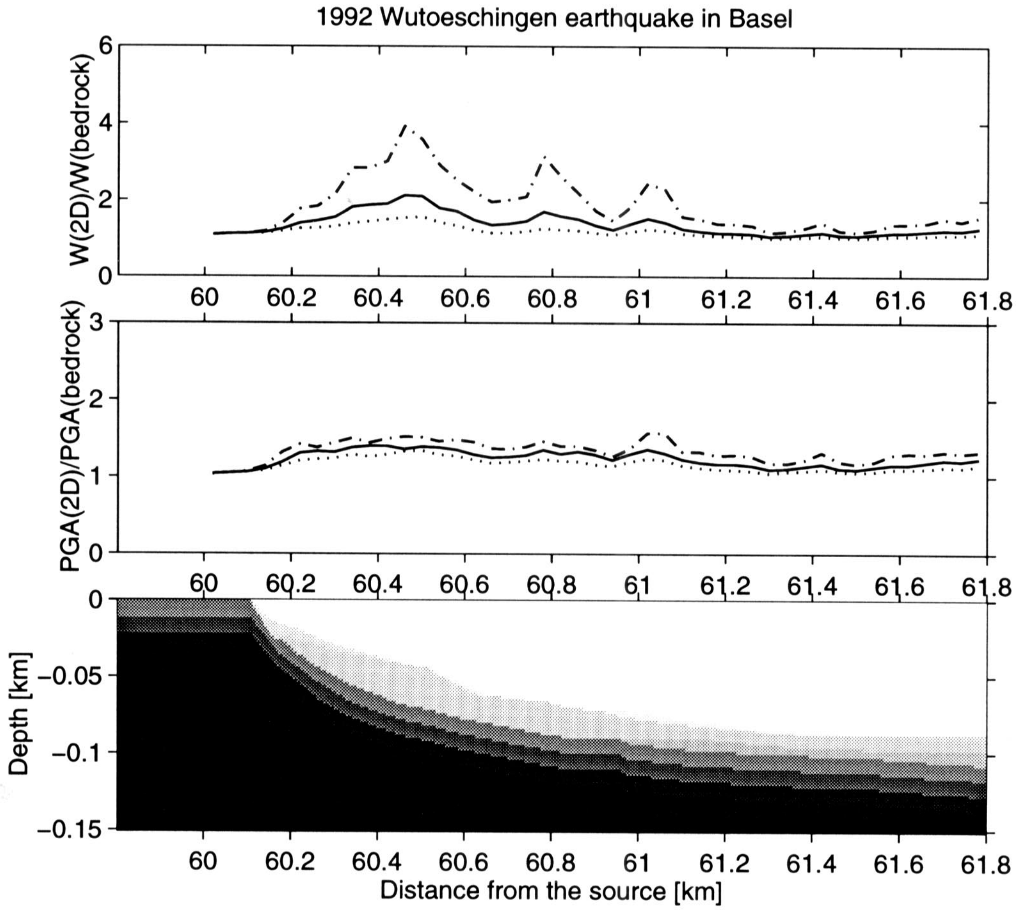

Fig. 4. Relative Arias Intensities W(2D)/W(bedrock) and relative peak ground acceleration PGA(2D)/PGA(bedrock) along a two-dimensional cross-section (dash-dotted lines: low velocities; solid line: average velocities; dotted lines: high velocities).

The evaluation of local amplification patterns for seismic waves is essential for seismic microzonation. It is the continuation of larger-scale seismic hazard assessment and mapping. Seismic microzonation is an interdisciplinary effort between geology, seismology and engineering seismology. It combines theoretical predictions of local ground motions by means of advanced numerical modelling techniques, field measurements for the estimation of local soil properties, and the validation of historical earthquakes in order to verify and enhance the proposed microzonation. The proposed microzonation of the centre of Basel will provide an important mean for pre-disaster orientation for planers and risk managers, and it is the basic input for an accurate risk assessment.

ACKNOWLEDGEMENTS

We would like to thank Dieter Mayer-Rosa, Lukas Hauber and Jost Studer for their contribution to this work, and the city of Basel for the financial support. This research was supported by the Swiss National Science Foundation under Grant No. 4031-034231.

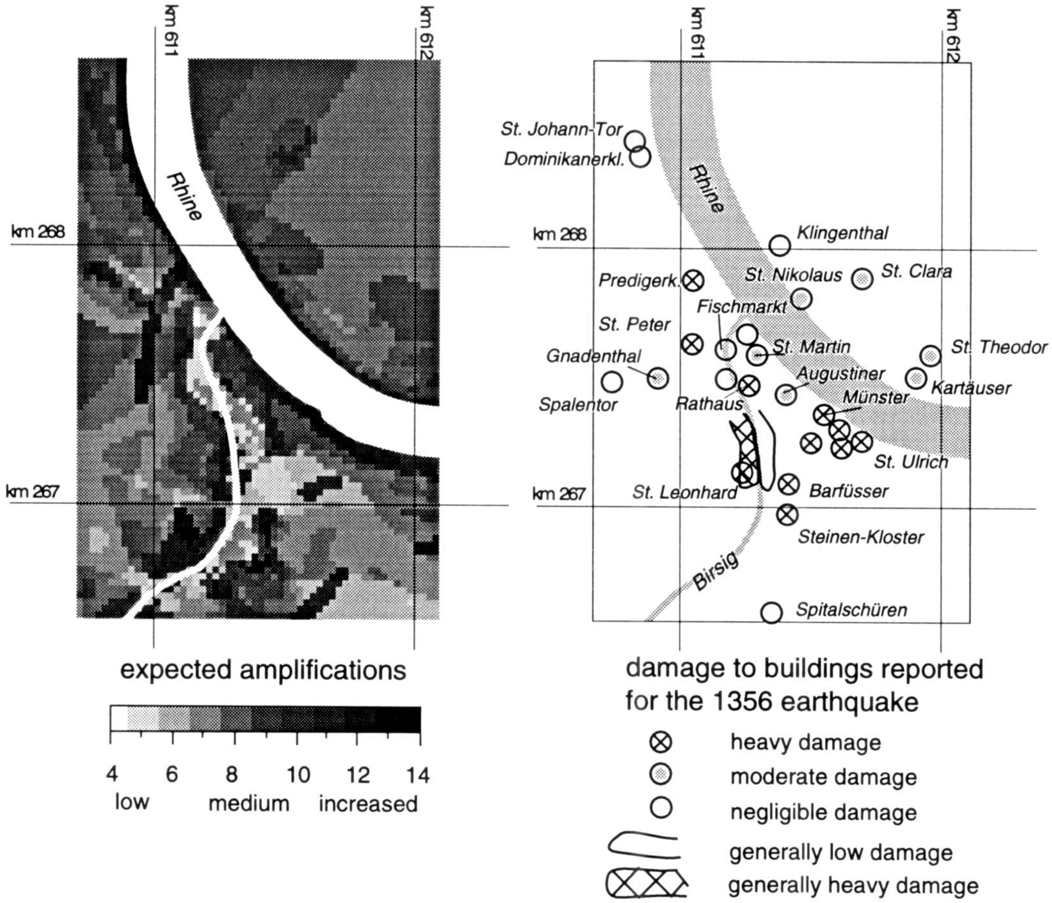

Fig. 5. Comparison between the preliminary microzonation map of the centre of Basel and the damage reported for the 1356 earthquake.

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