Mapping the local seismic hazard in the urban area of Brussels, Belgium

TOON PETERMANS[1], XAVIER DEVLEESCHOUWER[2], FRANCK POURIEL[3] & PHILIPPE ROSSET[4]

[1] *Royal Observatory of Belgium. (e-mail: toon.petermans@oma.be)*
[2] *Geological Survey of Belgium. (e-mail: Xavier.Devleeschouwer@naturalsciences.be)*
[3] *Geological Survey of Belgium. (e-mail: frank.pouriel@naturalsciences.be)*
[4] *Royal Observatory of Belgium. (e-mail: philippe.rosset@oma.be)*

Abstract: Several regional earthquakes have been strongly felt and caused damages in and around Brussels during history. For example the magnitude 6-6.5 Verviers earthquake in 1692, which is the strongest experienced in Belgium was felt as far as Kent in UK and caused severe damage in Belgian territory including Brussels. The well-documented 1938 Nukerke-Zulzich earthquake of magnitude 5.0 gives a good insight into the potential damage in the city of Brussels for a regional event. Although the built environment of the city has been changed over time, the deteriorated state of many of the ancient buildings increases the risk.

The urban area of Brussels lies on Tertiary soft sediments (sands and clays) resting on an old Palaeozoic basement. Previous studies have shown that the thickness of such soft sediments could largely influence the site response in case of an important regional earthquake.

Our project aims at mapping the seismic response of a pilot zone of Brussels for different earthquake scenarios. A simple but robust methodology is applied. Methods using ambient noise vibrations are coupled with 1D modelling to identify risky zones in terms of resonance frequency and amplification patterns.

A detailed knowledge of ground conditions is essential to compute and analyse the site response. This is currently done in Brussels at the 1/5000 scale by means of 2D and 3D GIS models of the underground geology. The geological model allows checking the nature, the thickness and the depth of each geological layer underneath any area of the city.

Maps featuring the local seismic hazard are proposed by combining geological data, field measurements and numerical modelling results into a GIS-based tool.

Résumé: En Belgique, plusieurs séismes régionaux ont été fortement ressentis et ont causé d'important dommages durant les derniers siècles. Le tremblement de terre le plus fort (magnitude estimée entre 6 et 6.5) date de 1692 et est localisé à proximité de Verviers. Il fut ressenti jusqu'au Kent en Grande Bretagne et provoqua d'important dommages à Bruxelles et dans tout le pays. Le séisme plus récent de Nukerke-Zulzich en 1938 permit de par son étude détaillée de mieux cerner le potentiel de dommages dans la région de Bruxelles en cas de séisme régional fort. Il est a noter que la conjonction de mouvements du sol modérés et d'un bâti ancien est susceptible d'augmenter fortement le risque sismique dans la ville. En effet, la zone urbaine de Bruxelles est construite sur des sédiments peu consolidés du tertiaire (sables et argiles) reposant sur un socle rocheux Paléozoïque qui pourraient fortement modifier les ondes sismiques en cas de séisme régional comme l'attestent de nombreuses études dans le monde.

Le présent projet a pour objectif de cartographier la réponse sismique d'une zone pilote de Bruxelles pour différents scénarios de séismes. Une méthodologie simple mais robuste est appliquée. Elle combine une méthode utilisant les enregistrements de bruit sismique et une méthode de simulation mono-dimensionnelle afin d'identifier les zones à « risque » en terme de fréquence de résonance et d'amplification des ondes sismiques. Une connaissance détaillée de la géologie locale est nécessaire pour, à la fois analyser les résultats de la méthode utilisant les enregistrements de bruit sismique et pour simuler le comportement sismique 1D des sites. Ce travail est en cours à Bruxelles à l'échelle du 1/5000 au moyen de modèles géologiques en 2D et 3D du sous-sol. Ils permettent de mieux connaître la nature, l'épaisseur et la profondeur des couches géologiques rencontrées jusqu'au socle Paléozoïque en tout point de la ville.

Une cartographie spécifique de l'aléa sismique local est envisagée en combinant les données géologiques, les résultats des enregistrements de terrain et de la simulation numérique au sein d'un outil SIG.

Keywords: geological hazard, seismic response, earthquakes, geology of cities, soil-structure interaction, site investigation.

INTRODUCTION

In the recent past, a lot of effort has been done to better constrain the seismic hazard in moderate seismic activity intra-plate regions like NW-Europe. Generally, this research is based on three majors branches of the seismology: paleoseismology (i.e. the study of faults and earthquake related structures), historical research (i.e. the study of earthquakes and damage reports in historical documents), and the instrumental analysis of recorded earthquakes, which started in the beginning of the 20th century. For a good comprehension of the seismic hazard in moderate seismic activity regions, these three branches are unmistakable, as we could underestimate the seismic hazard only regarding the instrumental recordings on a timescale of only 100 years. From ongoing paleoseismological investigation conducted by the Royal Observatory of Belgium (ROB) on the western border fault system of the Roer Graben in Belgium (Camelbeeck & Meghraoui 1996 1998; Vanneste et al. 2001), we known that in the last 100 000 years several large earthquakes have occurred with estimated magnitudes between 6 and 7. The last large earthquake in the Belgian territory, which is believed to have caused surface ground failure, is the 1692 Verviers earthquake. However, the seismic hazard at local scale is not only defined by the seismic source, its distance and its return period, but also by the so-called "site effects". These are the effect of local geologic and topographic conditions on seismic waves. Especially the geologic conditions are important in this study because many great cities, like Brussels, are built on favourable places where seismic waves will be amplified. These places are often alluvial valleys where there is a great impedance contrast between the younger soft sediments and the bedrock underneath. Higher is the impedance contrast, higher is the amplification. However, very thick alluvial deposits of several hundreds of meters will considerably cause damping of the seismic signal. There are many examples of destructive earthquakes in the past where greatest damages were not only located in the epicentral area, but also struck large cities on soft soil sediments (San Francisco, Kobe, Izmit…). The most well known is the magnitude 8.1 Michoacan, Mexico earthquake in 1985, where the centre of Mexico city, situated at 350 km away of the epicentre and lying on loose lake deposits, was heavily damaged and caused more than 10 000 casualties. Also more locally, The 1983 Liège earthquake (M_l = 4.9) has provoked considerable damages, which are partly accounted to site effects (Jongmans 1990).

For this study, we will focus on the urban area of Brussels. As the seismic risk is the convolution of the seismic hazard with the vulnerability, an urban area as Brussels with some deteriorated built environments at several places, could suffer heavy damages in case of important regional earthquakes. The vulnerability in urban area is of course more important than in rural area, because of the higher population and building density. Moreover, the presence of higher buildings in urban area can cause extra damages by amplifying the ground motion when the own-frequency or the harmonics of the building is close to the fundamental frequency of the ground shaking. Vice versa, the ground shaking can cause specific more damage to these buildings, because they are often in the same frequency range as the resonance frequency of the soft sediment layer, which acts as a sort of frequency filter for the seismic wave train.

The main objective of this project is combining geological data, field measurements and numerical modelling to provide maps featuring the local seismic hazard in a pilot zone of the Brussels city. This will be integrated in a GIS-based tool that will calculate automatically at any place the seismic hazard in terms of amplification and resonance frequency of a given seismic record. From now, the work is still in progress and there are not yet final hazard maps available. We will present first results deduced from field surveys and numerical modelling as well as the ongoing work dedicated to the 3D geological model of the Brussels area.

HISTORICAL AND RECENT SEISMICITY

Seismic hazard assessment requires a reliable earthquake database for Belgium and surrounding regions to formulate general hypothesis on the expected ground motion. The implication of historians, searching in archives for original sources of earthquakes, (e.g., Alexandre 1997, Melville et al 1996) improved the knowledge of seismic activity in northwest Europe from 1350 onwards. Together with the ongoing paleoseismologic investigation (Camelbeeck et al. 1996 1998, Vanneste et al. 2001) it tends to demonstrate that, large earthquakes could occur in the near future and cause a lot of damages. The two recent earthquakes affecting Belgium, the 1983 M_s 4.6 Liège earthquake and the 1992 M_s 5.4 Roermond earthquake have demonstrated that low to moderate seismic events induced already important direct losses, which are estimated to have been up to 100 millions euros for the latter.

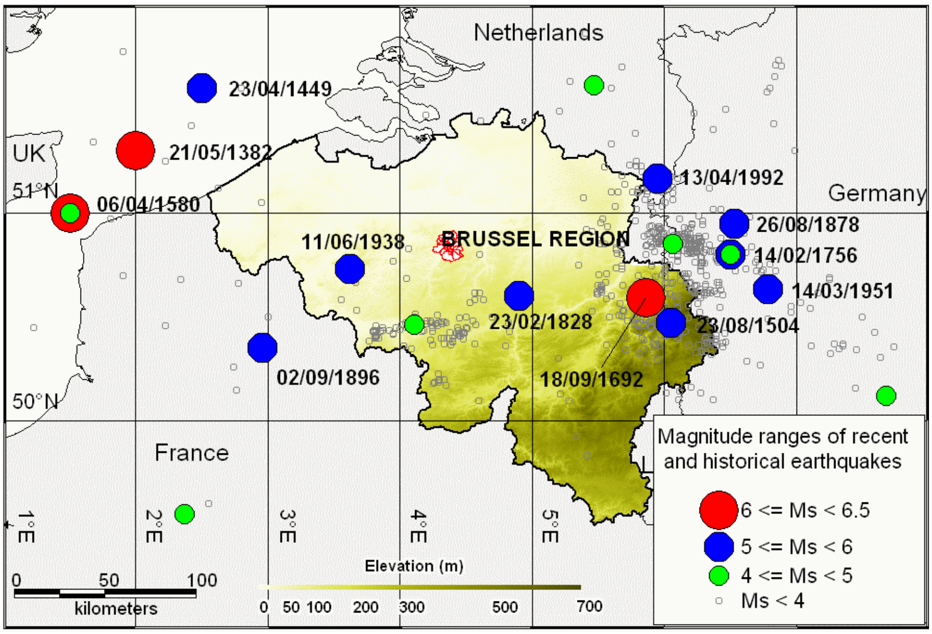

Figure 1. Historical and recent seismicity in and around Belgium.

Two regions in Belgium show considerably higher seismic activity, i.e. the Lower Rhine Embayment in the east of the territory and surroundings comprising the Liège-Verviers area, and the Hainaut zone in the west around the city of Mons (Figure 1). Historical seismicity suggests also that the southern North See, which is now relatively stable, has suffered from severe historical earthquakes in 1382 and 1580 with estimated magnitude of 6.0. On the regional seismic hazard map of Belgian (Leynaud et al. 2000), which was calculated for a return period of 475 years, according to the Eurocode 8 criteria (probability of 90 % of non-exceeding for 50 years), the highest peak ground acceleration zones corresponds to the three above-mentioned seismic zones. The urban area of Brussels is situated within 120 km of each of these regional seismic hazard zones and has a corresponding peak ground acceleration value around 0.5 m/s² (NAD, 2000).

In the past, several earthquakes were felt in Brussels and some of them caused damages (Table 1). For the 1756 Düren earthquake and 1828 Jauche earthquake, some sources indicate that the earthquakes were felt especially in the upside town.

Table 1. Important earthquakes felt in Brussels area. For some earthquakes, the intensity (I) conform to the EMS 98 scale (Grünthal 1998) was appointed for Brussels area.

Date	Location	Magnitude (M_s)	Comment
1382-05-21	North Sea	6.0	Felt
1580-04-06	Strait of Dover	6.0	Chimneys fell down
1692-09-18	Verviers	6.3	Damaging; I = VI-VII
1755-12-27	Aachen	5.2	Felt; I = V
1756-02-18	Düren	5.7	Felt, some chimneys fell down
1828-02-23	Jauche area	5.1	Felt, especially in the upside town
1896-09-02	Valley of the Scarpe	5.0	Felt in the upside town
1921-05-19	Geraardsbergen	4.0*	Felt
1938-06-11	Zulzich-Nukerke	5.0	Many chimneys fell down; I = VI
1983-11-08	Liège	4.7	Felt
1992-04-13	Roermond	5.4	Felt, local minor damage I= IV-V
2002-07-11	Eschweiler-Alsdorf	4.6*	Felt

* The magnitude is M_l (Local Magnitude) instead of M_s (Surface Wave Magnitude).

1692 Verviers earthquake

The September 18, 1692 earthquake, which occurred in the northern part of the Belgian Ardennes is the seismic event with the strongest known impact (importance of the destructions, number of deaths, felt area, etc.) in North-West Europe. Its magnitude has been estimated to be between 6.0 and 6.5 (Camelbeeck et al 2000). It caused moderate to severe damages in Brussels region, 100 km of the epicentre, but also further up to the coastal region of Kent, UK, and was felt at least more than 550 km further in Oxford and Bath, UK. There are not so many documents with reported damages in Brussels, but they all indicate fall of many chimneys, roof tiles, and pieces of plaster. The intensity for Brussels according, to the EMS 98 scale, is considered between VI and VII, which means that the earthquake in Brussels was slightly damaging to damaging.

1938 Zulzich-Nukerke earthquake

The 5.0 M_s Zulzich-Nukerke earthquake gives well inside of potential damages for a moderate seismic event. The earthquake with epicentre close to the town of Oudenaarde caused damages, according to at least intensity VI, along a WNW-ESE axis from the western border of Flanders up to the province of Liège, which is more than 175 km further. The elongated form of the epicentral zone is likely affected by the Paleozoic London-Brabant geostructural block, where the seismic waves are less attenuated (Nguyen et al. 2002).

The Brussels area is 50 km east of the epicentre. Officially, more than 1000 chimneys around Brussels were destroyed or partly damaged and several houses suffered from serious cracks in walls or fallen ornaments on the facade. At that time there was a call on the public radio to send any information to the Royal Observatory of Belgium concerning the earthquake. We reread all the letters coming from the Brussels area (Brussels and its 19 municipalities) and mapped where damage on chimneys occurred as shown on Figure 2. Especially for the city of Brussels (bold limit on the map) we had a fire report at our disposal with more than 100 localities where the fire brigades intervened for the damage on chimneys. In total 141 damaged structures could be located for the city of Brussels and 285 for the whole Brussels area. Although this is only a fifth of the total damages and the density of the inhabitation is not even, the damage map can be indicative for some site effects.

Only looking at Brussels city, two distinctive areas with an important density of the damaged structures are determined. The first one is in the east uptown around square Ambiorix and Shuman and the second is downtown in the middle of the pentagon of Brussels centre around the Anneessens quarter. Other areas as in the uptown southeastern part do not seem to have suffered much damage, likely because of the improved building environment of large federal buildings and parks. The greater damages around Anneessens can be contributed to the fact that the Paleozoic basement has there locally a wedge-shaped form of 20 m in height (see isohypse in Figure 2). Consequently, there might be an amplification of the seismic signal due to the densification of reflecting seismic waves.

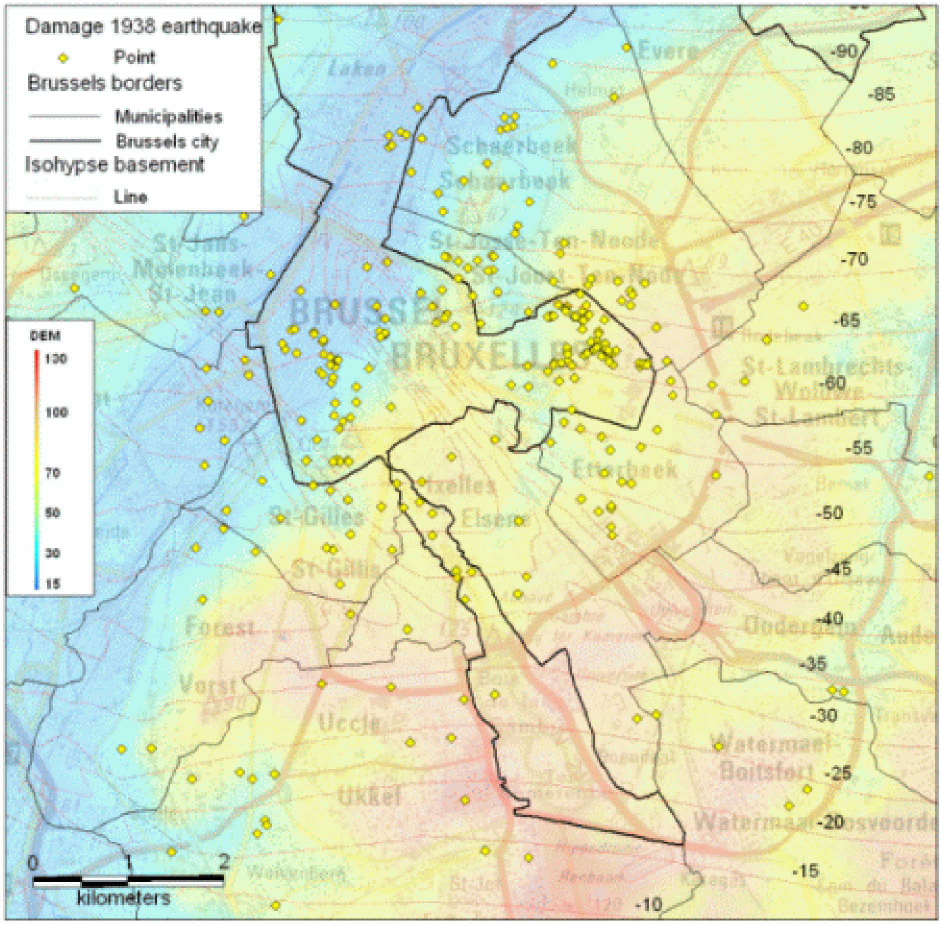

Figure 2. Damages distribution in the Brussels area after the 1938 earthquake. The geographic map is overlain by the Digital Elevation Model (DEM). The red dotted line indicates the isohypses of the Paleozoic basement.

GEOLOGICAL SETTING

A good knowledge of the shallow deposits is of prime importance for the estimation of the ground response affected by seismic waves. The geological data of Brussels are currently reinterpreted at the Geological Survey of Belgium (GSB) at a scale of 1/5000 in the framework of Brussels Urban Geology program (Devleeschouwer and Pouriel, 2004). It concerns the developments of 2D and 3D GIS geological model of the Brussels subsurface using Arc View tools. The area of Brussels and more particularly the historical heart of the city are recut by the Senne valley following a SW-NE axis. The altitude difference between the top of the hills and the valleys can reach more than 80 meters. A large plain, gently inclined towards the north and formed by the alluvial deposits of the Senne river, lies at an altitude ranging between 19 m in the south to 13 m in the north. Geologically is located in the central part of the Lower Paleozoic London-Brabant Massif that constitutes the seating for Tertiary and Quaternary deposits. These deposits have a variable thickness of less than 30 m in the southern part to more than 150 m in the northern part of Brussels at the higher located areas.

The Quaternary deposits comprise the modern Holocene alluvium in the central Senne valley with a thickness of more than 10 m and the Pleistocene deposits covering the whole area. On the top of the hills and along the hillsides these deposits are very thin. Additionally, anthropogenic backfills up to several meters are present almost everywhere. The Tertiary strata have a sub-tabular structure, inclining 0.5 % to the south. Marine Miocene and Upper Eocene sand formations (Formation of Maldegem, Lede and Brussel) have been partly preserved from the erosion and constitute now the top of the hills in east of the Senne valley. The Formation of Brussel is characteristic for channel structures up to 70 m thick, whereas its thickness is normally 30-35 m. The Gent and Tielt Formations (especially fine sand with clay) constitute the western parts of the hills. Underneath we find the continuous Lower Eocene Kortrijk Formation (60 m) and Upper Eocene Hannut Formation (30 m) with alternating sand and clayey members. The Cretaceous deposits are wedging out in the south against the Paleozoic bedrock, which consists in quartzite and slate of Early Cambrian age. A geological profile crossing the Senne river is shown in the Figure 3.

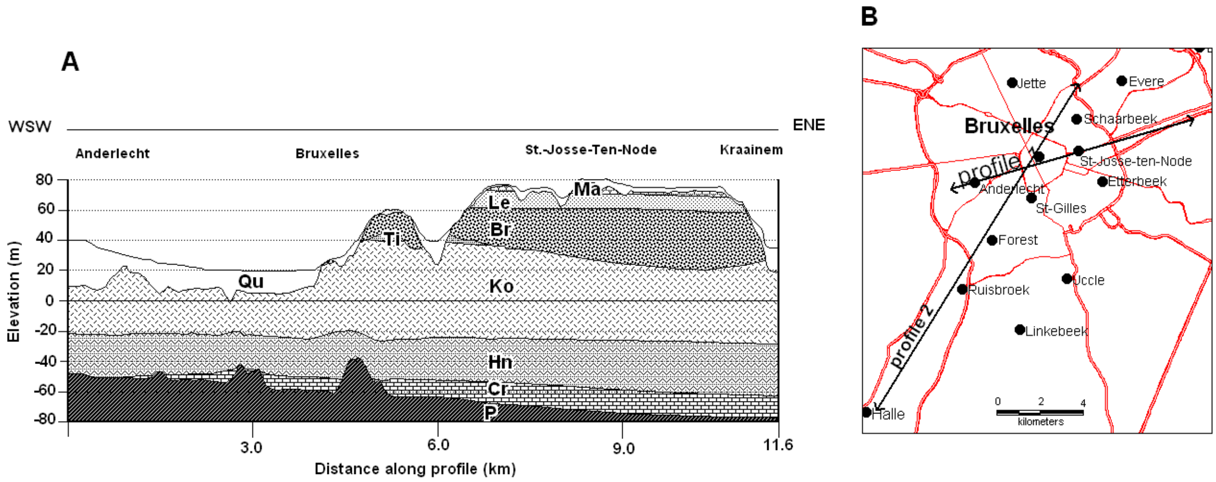

Figure 3 A: EW geological profile 1 (after Buffel & Matthijs 2002) through Brussels city with indication of the formations (P = Paleozoic; Cr = Cretaceous; Hn = Hannut; Ko = Kortrijk; Br = Brussel; Ti = Tielt; Le = Lede; Ma = Maldegem; Qu = Quaternary). **B:** map locating the two geological profiles presented in this paper.

SITE EFFECTS

It is commonly accepted in earthquake engineering that shallow soft soil deposits can have a major influence in ground motion amplification and it is necessary to include such effects in earthquake scenarios. In the same context, the fundamental resonant frequency of the soft soil is an important parameter in these studies as the vulnerability of buildings and infrastructures is directly connected with their own resonance frequency. Site effects can largely be attributed to the impedance contrast when seismic waves are passing the limit from hard rock to unconsolidated low velocity and low-density sediments. Due to conservation of energy, the amplitude of the refracted seismic waves will increase. Secondly, the refracted waves will be trapped in the unconsolidated layer and the reflected waves will travel up and down amplifying the signal until damping will attenuate the seismic waves. Very thick unconsolidated deposits will have greater attenuation and consequently lower amplification factors at surface.

For this study, we use two methods to estimate the local ground response in terms of fundamental resonance frequency and its amplification of the soft soil, namely ambient noise recordings and numerical analysis of the ground response (Rosset P. et al. 2005a, 2005b).

Ambient noise recordings

Method

Ambient noise is the low amplitude ground motion coming from artificial surface sources as traffic and human activities, but also from wind-structure interactions and longer period oceanic waves and currents. There are different methods to use ambient noise, but the most usefully is the H/V method. It is a rather cheap method (single 3-component seismometer and 1 acquisition system) and it is relatively easy to set up in urban area and not time-consuming. Nogoshi and Igarashi introduced the method in Japan in 1971, but it was further developed by Nakamura in 1989. The method consists in calculating at one single site the Fourier spectra of the seismic signal of the three components and dividing the horizontal spectrum by the spectrum of the vertical component. Nakamura claimed that the obtained spectral ratio curve exhibits a peak that is correlated with the fundamental resonance frequency of the site. The theoretical background is not yet fully understood, but comparisons with other techniques have proven the validity and efficiency for the fundamental mode of resonance (Bard 1999). On the other hand, the amplitude of the H/V peak is not useful because it is highly sensitive to many parameters as Poisson ratio and source-receiver distance (Lachet & Bard 1994). Furthermore, the H/V spectrum provides valuable information about the soft sediment characteristics as the resonance frequency F_0 is directly related to the thickness (H) and the shear wave velocity (V_s) through a simple linear relation $F_0 = V_s/4H$ when considering a single horizontal homogeneous soft soil layer.

For the measurements in Brussels area, we use 3-components 5 sec. seismometer from Lennartz (LE-3D/5s) coupled with a 24-bit Cityshark II acquisition system from LEAS. The measurements have duration of 10 minutes each at a sampling rate of 100 Hz. Direct sources of noise (footsteps, cars) and the nearness of high buildings were as much as possible avoided for site location. A wind cap around the seismometer was used in windy conditions. Afterwards the data were analyzed by user-friendly software SPCRATIO (Rosset 2002) to calculate the H/V ratios. The program SPCRATIO is runs under a Matlab environment and calculates the Fourier spectra and the final H/V ratio with automatic detection of the maximum peak amplitude and its corresponding frequency. First, the user can choose a portion of the signal for analysing and the program detrends and segments the chosen signal portion into windows (in our case one-minute-windows and an overlap of 30 seconds between windows). The time windows are Fourier transformed using tapering windows before transformation and the obtained spectra are smoothed using the average method weighted with a Parzen Window. Finally, the average of all the H/V ratios for each window and its standard deviation are calculated.

Results for Brussels

A total of 140 measurements were carried out in Brussels area, of which 32 turned out to be insufficient to determine precisely the resonance frequency. The reason for this was mostly the continuous disturbance of the measurement due to near traffic and underground transport. But sometimes we cannot exclude the fact that complex geology, in terms of anomalies in the Paleozoic basement, can give rise to less clear H/V peaks. We envisaged two scales of investigation, namely a global resonance frequency map of the Brussels area (Figure 4 left) with a grid of 1 to 1.5 km and a microzonation map around St-Gilles just south of Brussels city with measurements every 100 to 200 m (Figure 4 right).

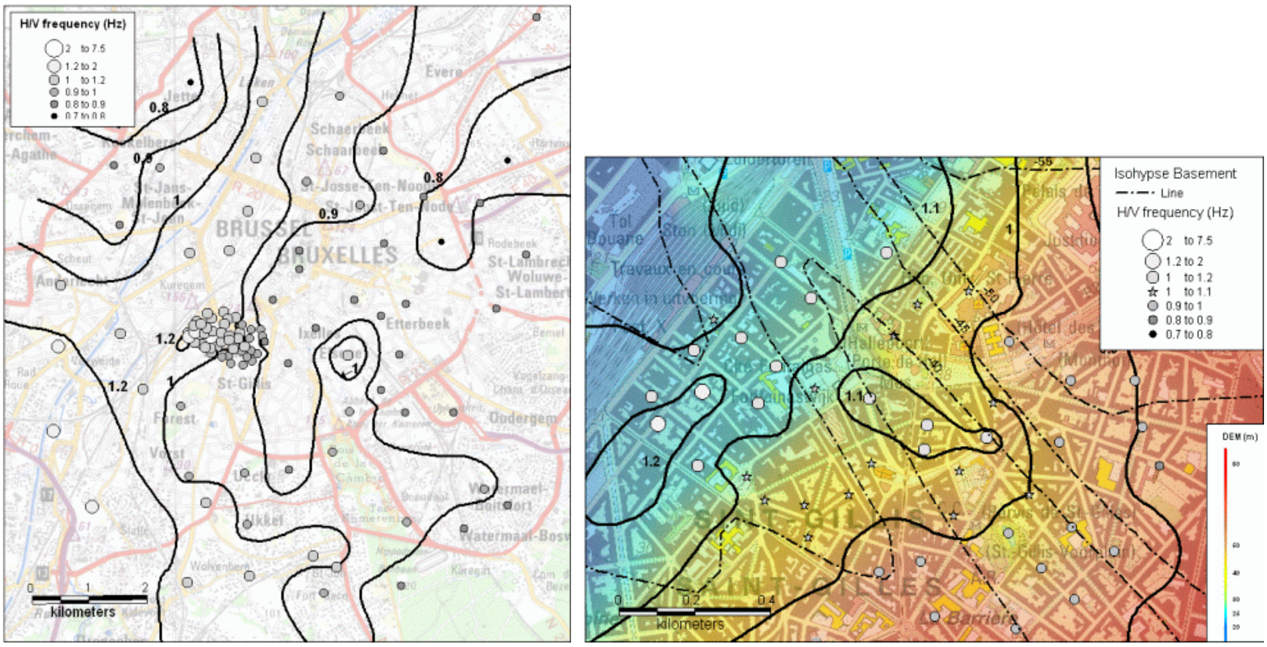

Figure 4. Left: H/V frequency contour map of Brussels on a 1/100000 geographic map with H/V sites indicated. The area with dense H/V sites is St.-Gilles. The central valley of the Senne has the highest H/V frequency values.
Right: H/V frequency microzonation contour map of St-Gilles on a 1/10000 geographic map overlain by the DEM and the isohypse contour map of the Paleozoic basement (Buffel et al. 2002) with indication of the H/V sites. one notice the good correlation between the H/V contours on the one hand and the DEM and isohypse map on the other hand.

Most of the H/V measurements show very clear peak with amplitudes between 15 and 25, which could be correlated with a clear impedance contrast between the Paleozoic basement and the overlying unconsolidated sediments. With the 108 good H/V measurements, we created a resonance contour map, using the natural neighbour interpolation method in Vertical Mapper, an extension of the GIS MapInfo. The lowest H/V frequencies, ranging from 0.7 to 0.9 Hz, can be found in the elevated areas especially in the north of Brussels. This is evident because of the negative correlation of the thickness of the soft sediment with the H/V frequency ($F_0 = V_s/4H$). In the Senne valley, the frequencies are ranging from 0.9 Hz in the north to more than 2.0 Hz in the south. The geological SW-NE profile along the Senne valley of the Figure 5 is compared with the H/V fundamental frequencies and some H/V spectra at several sites . Some measurements (e.g. B03 and B04) were carried out in the south of the Brussels area to have an idea of the resonance frequency for thinner unconsolidated layers. There is a very strong correlation between the geology in terms of thickness and the H/V frequencies. Only measurement F08 has a remarkably higher H/V frequency of 1.18 Hz than measurement F07 southwards (1.05 Hz). This anomaly can be accounted to a bulge of the basement just at that point (Figure 5). It is clear from the profile that H/V measurements can be very useful and accurate in mapping the isohypses of the basement, at least as the geophysical properties of the subsoil are known, and can predict very small variations in the shape of the basement. A same anomaly can be observed in St. Gilles, where several H/V sites exhibit abnormal high frequency peaks up to 1.35 Hz (middle contour of 1.1 Hz at Figure 4 right) whereas hundred meters further it drops again to 1.05 Hz. The highest peaks have broader more indistinct peak spectrum, so we did not include them for the interpolation. On the isohypse map of the Paleozoic basement of Brussels, we can correlate this anomaly with a bulge of 20 m in the Paleozoic. This local complexity of the shape of the basement gives probably also rise to less distinctive H/V peaks.

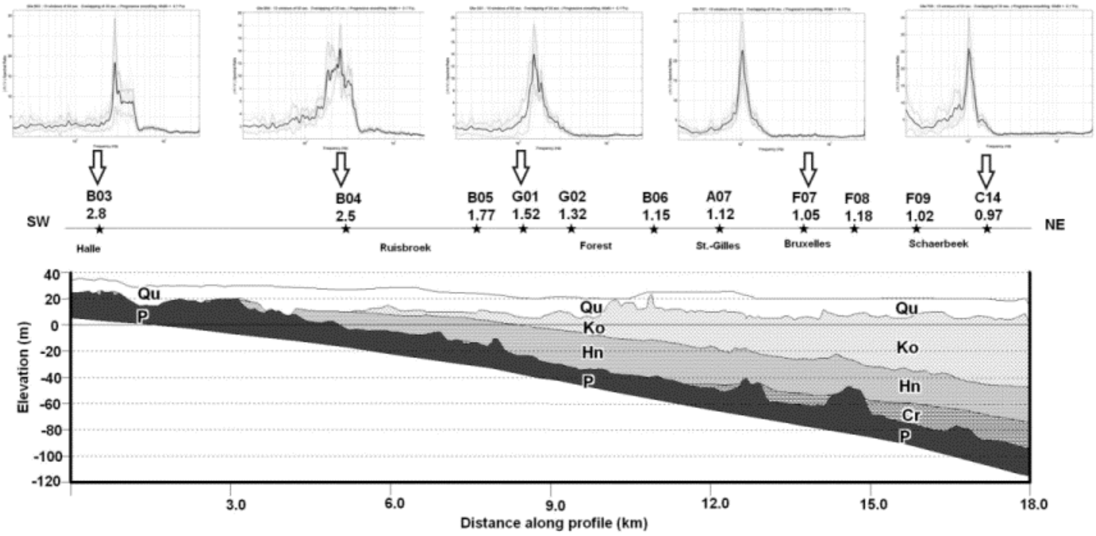

Figure 5. Geological SW-NE profile 2 (see Figure 3B for location) with indication on top of the H/V frequencies (Hz) and some H/V spectra of several sites close to the profile. Abbreviated names of the different geological formations are briefly explained in geological setting.

The main fundamental frequency domain of the Brussels area is between 0.75 Hz and 1.30 Hz. For vulnerability purposes, a simple rule can be used to estimate the fundamental resonance frequency of a building, namely 10 dividing to the number of floors. This means for the Brussels area that in case of earthquake, buildings with 8 to 14 floors have a higher vulnerability as the ground shaking will be in the same frequency domain than the fundamental resonance frequency of the building. The figure 6 shows an H/V spectrum with two peaks for a site near St.-Gilles, which was located at 30 m of a building with 11 floors. From the comparison with neighbouring sites, it was clear that the second H/V peak of 1.07 Hz must be the resonance frequency of the subsoil. Due to the windy conditions that day, we believe that the first peak (0.83 Hz) exhibit the resonance frequency of the high building. This seems to be confirmed by the fact that the same distinctive peak can be found in the Fourier spectra for the three components, while this is never the case for the H/V fundamental frequency of the subsoil.

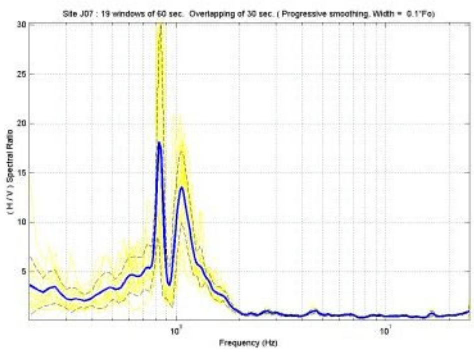

Figure 6. H/V spectrum of a site near St.-Gilles with two peaks. The first peak at 0.83 Hz represents the resonance frequency of a building of 11 floors; the second peak at 1.07 Hz represents the resonance frequency of the subsoil.

Numerical analysis of ground response

Method

The numerical analysis of the ground response is a useful tool to retrieve the frequencies as well as the amplitudes of the subsoil seismic response. A good knowledge of the geophysical parameters of the unconsolidated sediments is required. In urban area, there is mostly plenty of information available coming from boreholes and Cone Penetration Tests of infrastructure works. The Brussels Urban Geology (BUG) program (Devleeschouwer et al. 2004) provides us with up-to-date 3D geological models, which we will implement in the future for calculation routines in GIS-environment for seismic hazard scenarios.

A one-dimensional simulation approach is used, considering the multiple reflection theory of S-waves in horizontal infinite layered deposits, which is almost the case in Brussels. This means that the base of the soil column is excited by an incident shear wave, mostly vertical and the wave train will propagate up and down in the soil column. Each layer has its specific dynamic characteristics, namely the shear wave velocity, the density and the damping (as Q-factor) and also its thickness. The calculations are performed with own software (Rosset 2005a) based on the reflectivity method by Kennett (1983). A simplified Monte-Carlo approach is included for the uncertainties of the layer characteristics. This implicates that the result of one site is the mean calculated ground response of a set of hundreds of random values for the 4 parameters. The ultimate result is also called the transfer function of the site.

Results for Brussels

The ground model used here was a single layer over a half-space due to the lack of information for the shear velocity, and the Q-factor for all the geological layers. It was developed from 20 H/V sites, which were less than 150 m from a site of a borehole that penetrated the Palaeozoic basement. The mean shear velocity for the sediment column was estimated using the formula $F_0 = V_s/4H$. The shear velocity in our calculation is thus dependent of the thickness of the sediment layer.

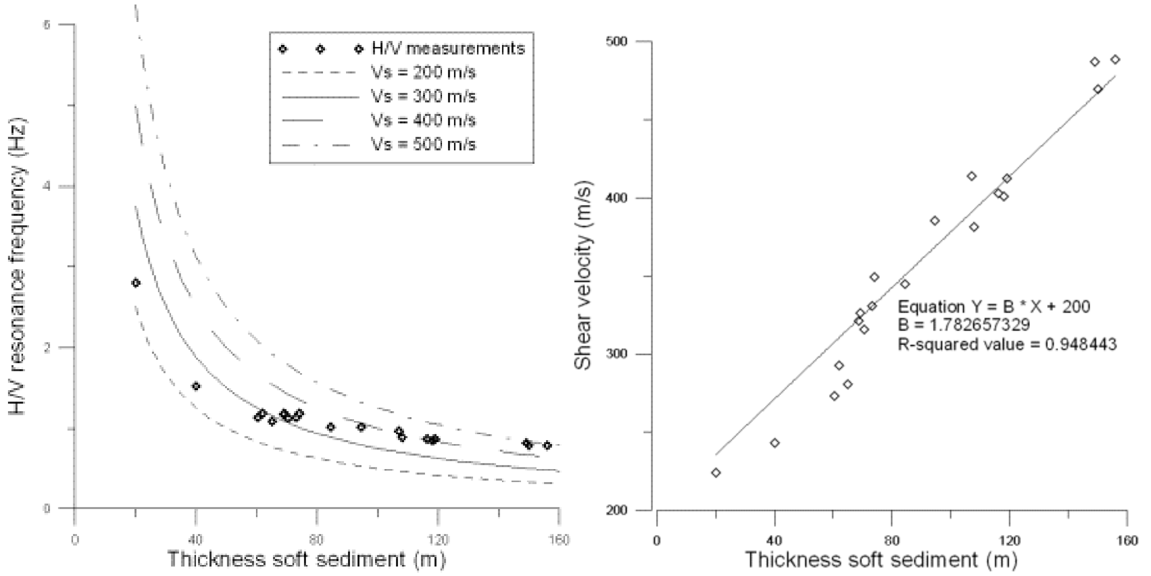

Figure 7. Left: Diagram showing the relationship between the thickness, the resonance frequency and the theoretical shear wave velocity for 20 H/V sites. **Right:** Linear regression analysis between the thickness and the shear wave velocity of 20 selected H/V sites.

Table 2: Geophysical characteristics of 20 H/V sites. F_0 is the fundamental resonance frequency obtained with the H/V method; H is the thickness of the sediment layer, V_s is the shear wave velocity of the total sediment layer derived from the formula $V_s = 4HF_0$; V_s reg. is the shear velocity derived from the regression line in figure 7 right;   is the mean density of the sediment layer; Q is the quality factor for the damping; F_0 1D is the fundamental resonance frequency obtained by the 1D numerical analysis; A 1D is the amplitude of F_0 1D; Amp is the amplification of the ground response for a seismic scenario with an existing earthquake signal scaled to 0.05 g.

Measurement	F_0 H/V (m/s)	H (m)	Vs H/V (m/s)	Vs reg. (m/s)	(kg/m³)	Q	F_0 1D Hz	A 1D	Amp
C12	0.78	156	489	478	1800	40	0.78	5.38	2.79
B11	0.78	150	470	467	1800	40	0.78	5.49	2.84
C13	0.82	149	487	466	1800	40	0.81	5.56	2.90
C08	0.87	119	413	412	1800	40	0.85	5.89	2.97
B09	0.85	118	401	410	1800	40	0.85	6.05	3.04
C10	0.87	116	403	407	1800	40	0.85	6.10	3.02
B08	0.88	108	381	393	1800	40	0.85	6.07	3.03
C14	0.97	107	414	391	1800	40	0.95	6.04	2.77
A11	1.02	95	386	368	1800	40	1.00	6.28	2.62
D02	1.02	85	345	351	1800	40	1.03	6.46	2.65
F08	1.18	74	349	332	1800	40	1.17	6.35	2.16
C03	1.13	73	331	330	1800	40	1.15	6.62	2.25
A07	1.12	71	316	326	1800	40	1.12	6.84	2.35
H13	1.18	69	326	323	1800	40	1.17	6.88	2.12
C01	1.17	69	322	322	1800	40	1.15	6.98	2.25
A08	1.08	65	281	316	1800	40	1.10	6.98	2.47
A09	1.18	62	293	311	1800	40	1.15	7.28	2.28
H15	1.13	60	273	308	1800	40	1.15	7.09	2.34
G01	1.52	40	243	271	1800	40	1.49	7.18	3.46
B03	2.80	20	224	236	1800	40	2.78	6.96	4.57

The diagrams prove that it is not useful to use a fixed V_s value in a 1-layer model for the 20 selected H/V sites (Figure 7 right). Moreover, there exists an excellent linear correlation between the thickness of the soft sediment and the calculated shear velocity with equation $V_s = 1.78\ H + 200$ and with a high R squared value of 0.95. A numerical comparison between the shear velocity obtained with the H/V measurement (V_s H/V) and the one from the regression analysis (V_s reg.) for the 20 selected sites is proposed in Table 2. The biggest difference is only 35 m/s for measurement A08 and H15. In a first phase we will consider a model where the density is constant at 1800 kg/m³ and also the quality factor at 40. The results obtained after the numerical analysis are shown in table 2 under F_0 1D and A 1D, respectively the fundamental resonance frequency and its amplitude. The calculated fundamental frequencies are almost exactly the same as the measured ones, which pleads for this simple model. On the other hand, the amplitudes, which are ranging from 5.4 to 7.2, are 3 to 5 times lower than the ones obtained with the H/V method. The sites with a thin sediment layer have the highest amplitudes. This contradicts the fact that some earthquakes where better felt at the higher elevated areas in Brussels region. The topographic site-effect can play a role in amplifying the seismic signal in elevated ridge-shaped areas, which is not included in the numerical modelling. Furthermore, the Q-factor will have also its influence in the calculations. If we consider that damping is also thickness dependent with lower Q-factors for less thick soft sediment layers, than the spectral amplitudes of the transfer function will become lower. For example, measurement G01 would have amplitude of 6.06, instead of 7.18, when the Q value is lowered to 10. This possible relationship will be further investigated in the future.

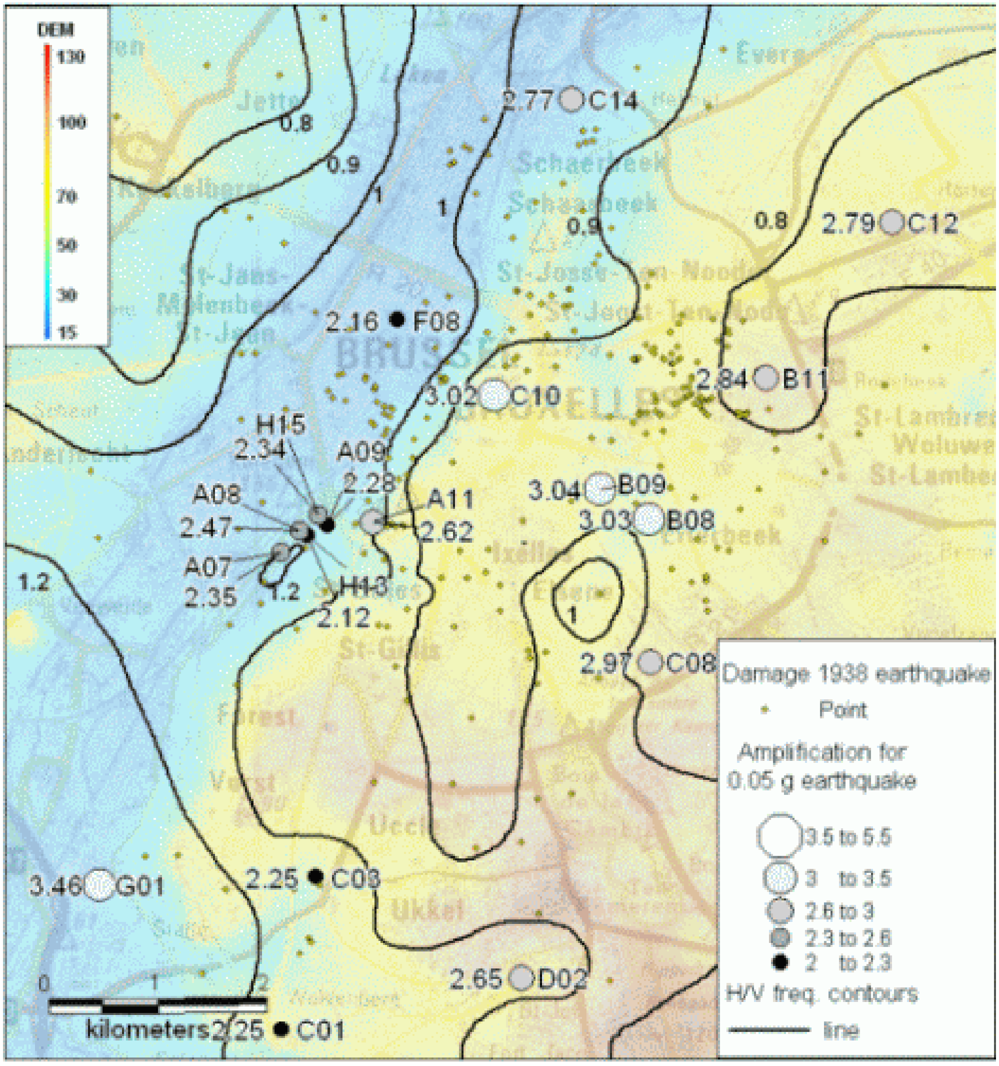

Figure 8. Resuming map with indication of the amplification factors for a 0.05 g seismic event. The 1938 Zulzich-Nukerke damage points and the H/V frequency contours are also plotted on the 1/100000 topographic map overlain by the DEM.

A better method to constrain the seismic hazard of site effects is to simulate real seismic scenarios by using existing seismic signals. This is done by convoluting the seismic signal with the transfer function of the site. The result is an amplification factor of the original seismic signal for the calculated ground response and thus a peak ground acceleration (PGA). The same software for calculating the transfer function was used (Rosset 2005b). The tool in the software for the convolution is also based on the reflectivity method from Kennett (1983) and is able to scale the used time series of a seismic signal. We used the seismic signal of the M_s 6.87 Campano Lucano earthquake in Italy on 23/11/1980. The seismic station was 32 km remote of the epicentre and the measured PGA on that site was 2.12 m/s². We scaled it to 0.5 m/s² g in accordance with the calculated PGA value for a return period of 475 years provided for zone I in the National Application Document of the Eurocode 8 regulations (NAD 2000) . In Table 2 the amplification factors for the 20 selected sites are given under "Amp" and a resuming map with the location and value of these points is provided in Figure 8. They are varying from 2.16 to 4.57, which correspond to a PGA of 1.08 m/s² and 2.29 m/s². There is a greater amplification for the sites where the fundamental resonance frequency is between 0.8 Hz and 0.9 Hz and higher than 1.25 Hz. It corresponds approximately to thickness of the soft sediments ranging from 110 m to 140 m and less than 50 m. However, we have to bring in that the characteristics of the seismic signal influence the amplification results and thus, other time series scaled to a same PGA will give rise to different amplification values. For example, the frequency spectrum of the used time series of the Campano Lucano earthquake exhibits peaks for frequencies 0.85 Hz and 2.5 Hz and this is reflected in the greater amplification values of the selected sites with approximately the same fundamental frequency.

The damage locations of the Zulzich-Nukerke 1938 earthquake are also plotted on Figure 8. There is not a good correlation between the damage locations on the one hand and the H/V contours and amplification values on the other hand. The damaged Anneessens quarter for example lies in a zone with relatively low amplification values. As already mentioned before, 2D geological structure can amplify the ground response, which is probably the case for the Anneessens quarter.

In general, it is relatively easy to provide qualitative maps of the fundamental resonance frequency of an area. For the Brussels area, the measured and calculated H/V frequencies corresponds almost perfectly, which indicates that our 1-layer 1D model with shear velocity dependency of the thickness of the soft soil layer works fine. On the other hand, it is far more difficult to provide seismic hazard maps with consistent amplification values, because the obtained results are more difficult to verify and the type of seismic signal will influence the ground response of the site.

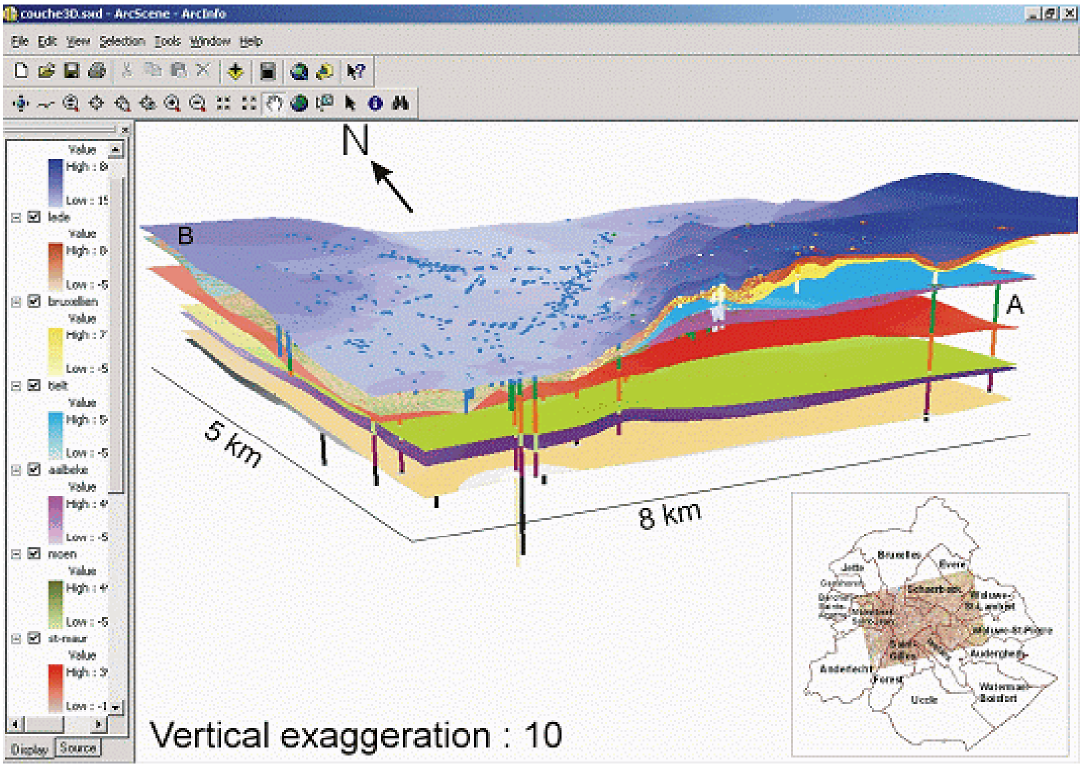

Figure 9. 3D geological model in the centre of Brussels based on 700 drill holes. The location of the 3D model is indicated on the bottom right map. A column shape of various colours, corresponding to different geological formations, represents each drill hole (A). The Inverse Distance Weighting interpolation method is used to create a 3D model of the underground by coloured layers. Each layer (B) defines the roof of one geological formation.

PERSPECTIVES

The study of the seismic hazard in the urban area in Brussels is still in progress. First integration of site response data to the 3D geological model shows the efficiency to combine geological and seismic information to figure out a new geological model (Rosset et al. 2005d). The second step of the project is the integration of the modelling process into a GIS-based 3D geological model at a 1:5000 scale. The current version of the 3D geological model is available through the BUG program, Brussels Urban Geology (Devleeschouwer & Pouriel 2004), which is largely detailed in a paper, also submitted at the IAEG2006 Congress (Devleeschouwer & Pouriel 2006). A perspective concerns the carrying out of the implementation of the database with the archives of the Geological Survey of Belgium (GSB) and also to integrate the cone penetration tests archives of the Ministry for the Equipment and Transport (MET) of the Walloon Region in order to improve the accuracy of the 3D geological model, which is illustrated on Figure 9. It is planned to link the geological models of the BUG program with tools in a GIS-environment in order to calculate automatically the transfer function (resonance frequency and amplitude) for any given site in Brussels area.

By using a multi-layered model, where every geological layer will have its own characteristics (shear velocity, density and quality factor), we will need to further improve our knowledge of the geotechnical parameters. The dense H/V measurements in St.-Gilles will contribute to verify the calculated empirical results with the experimental ones.

A second goal is to provide with amplification maps for the Brussels region for different seismic scenarios. These scenarios can be dependent on the characteristics of the seismic signal (the PGA, the length of the signal) but also on the angle of the incident seismic waves. The calculations of the seismic scenarios could then be integrated in the same intended GIS-environment at certain distinct locations by convoluting a given seismic signal with the transfer function of that location.

The final objective of the project is to reinforce the prevention strategy against major seismic event by producing useful maps indicating the more vulnerable zones in urban areas (Rosset et al., 2005c).

Corresponding author: M Toon Petermans, Royal Observatory of Belgium, Avenue Circulaire, 3, Brussels, 1180, Belgium. Tel: +32 2373 0314. Email: toon.petermans@oma.be.

REFERENCES

ALEXANDRE, P. 1997. Le tremblement de terre de 1692. *Feuillets de la cathédrale de Liège*, **28** (3) 2, 3-19.

BARD, P.-Y. 1999. Microtremor measurements: a tool for site estimation? *In: Proceedings of the Second International Symposium on the Effects of Surface geology on Seismic motion, 1-3 December 1998*, *Yokohama*, Balkema, Rotterdam, **3**, 1252-1279.

BUFFEL, P. & MATTHIJS, J. 2002. Geological map of Bruxelles-Nivelles n°31-39, 1/50.000-scale map, published by the Flemish Region and carried out jointly by the Geological Survey of Belgium and the Ministry of the Flemish Community.

CAMELBEECK, T. & MEGHRAOUI, M. 1996. Large earthquakes in northern Europe more likely than once thought. *EOS*, Transactions, American Geophysical Union, **77**, 405-409.

CAMELBEECK, T. & MEGHRAOUI, M. 1998. Geological and geophysical evidence for large palaeoearthquakes with surface faulting in the Roer Graben (Northwestern Europe), *Geophysical Journal International*, **132**, 347-362.

CAMELBEECK, T., ALEXANDRE, P., VANNESTE, K. & MEGHRAOUI, M. 2000. Long-term seismicity in regions of present day low seismic activity: the example of western Europe, *Soil Dynamics and earthquake engineering*, **20**, 405-414.

DEVLEESCHOUWER, X. & POURIEL, F. 2004. *The BUG program: a 2D and 3D modelling of the geology in the Brussels Region*. Internal Report, Geological Survey of Belgium, Brussels, 16 pp.

DEVLEESCHOUWER, X. & POURIEL, F. 2006. Brussels Urban Geology (BUG): a 2D and 3D model of the underground by means of GIS. *In: Proceedings of the 10th IAEG Congress, Nottingham**, United Kingdom,*** **submitted.**

GRÜNTHAL, G. 1998. European Macroseismic Scale 1998, *Cahiers du Centre Eur. De Géodyn. et de Séismologie*, **15**, 1-99.

JONGMANS, D. 1989. Les phénomènes d'amplification d'ondes sismiques dus à des structures géologiques. *Annales de la Société Géologique de Belgique,* **112**(2), 369-379.

KENNET, B. L. N. 1983. *Seismic wave propagation in stratified media*. Cambridge University Press, New-York, 342 pp.

LACHET, C. & BRARD, P.-Y. 1994. Numerical and theoretical investigations on the possibilities and limitations of the Nakamura's technique. *Journal of Physics of the Earth*, **42**, 377-397.

LEYNAUD, D., JONGMANS, D., TEERLYNCK, H. & CAMELBEECK, T. 2000. Seismic hazard assessment in Belgium, *Geologica Belgica,* **3** (1-2), 67-86.

MELVILLE C., LEVRET A., ALEXANDRE, P., LAMBERT, J., & VOGT, J. 1996. Historical seismicity of the Strait of Dover-Pas de Calais, *Terra Nova*, **8**, 626-647.

NAKAMURA, Y., 1989. A method for dynamic characteristics estimation of subsurface using microtremors on the ground surface, *Quat. Rep. Railway Tech. Res. Inst.*, **30**, 25-33.

NAD 2002. Eurocode 8: Conception et dimensionnement des structures pour la résistance au séisme - Partie 1-1 : Règles générales – Actions sismiques et exigences générales pour les structures. Document d'application belge. NBN-ENV 1998-1-1: 2002 NAD-E/N/F, Institut Belge de Normalisation (IBN), 17 pp.

NGUYEN, F., TEERLYNCK, H., VAN ROMPAEY, G., VAN CAMP, M., JONGMANS, D. & CAMELBEECK, T. 2004. Use of microtremor measurement for assessing site effects in Northern Belgium – interpretation of the observed intensity during the Ms=5.0 June 11, 1938 earthquake. *Journal of Seismology*, **8** (1), 41-56.

ROSSET, P. 2002. SPCRATIO User's Manual: "A tool to analyze ambient noise records". *Structural Engineering Series*, University McGill. Report No. 2002-01, 20 pp

ROSSET, P. 2005a. *Guidelines of used and developed tools for numerical analysis in one dimension.* Internal Report, Royal Observatory of Belgium, 28 pp.

ROSSET, P. 2005b. *Guidelines of used and developed tools for generation of synthetic time series*. Internal Report, Royal Observatory of Belgium, 10 pp.

ROSSET, P., BARSZEZ, A.-M., CAMELBEECK, T., QUINIF, Y., SABBE, A. & WILQUIN, H. 2005c. Mapping the local seismic hazard and its influence on built environment: case study in the Mons Basin (Hainaut, Belgium). *In: Proceedings from the Deuxième Journée des Géographes Belges, 9 November2005, Gent.* DCL Print & Sign, Zelzate, 305-311.

ROSSET, P., PETERMANS, T., DEVLEESCHOUWER, X., POURIEL, F. & CAMELBEECK, T. 2005d. Identifying the influence of the local geology in case of earthquake for urban planning: case study in Brussels. *In: Proceedings from the Deuxième Journée des Géographes Belges, 9 November2005, Gent.* DCL Print & Sign, Zelzate, 171-176.

VANNESTE, K., VERBEECK, K., CAMELBEECK, T., RENARDY, F., MEGHRAOUI, M., JONGMANS, D., PAULISSEN, E. & FRECHEN M. 2001. Surface rupturing history of the Bree fault escarpment, Roer Valley Graben : new trench evidence for at least six successive events during the last 150 to 185 kyr. *Journal of Seismology*, **5**, 329-359.