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# *"Influence of site effects in central Belgium on earthquake strong ground motions"*

*Final report of FNRS research project T.0116.14F*

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## Aim of the project

Investigations on strong ground motions generated by earthquakes provide evidence that the local geological structure of a site, especially the presence of soft sedimentary layers, modify the characteristics of seismic shaking at the surface. The felt experience or damage at a site is not merely the result of the energy released from the source but is often related to (de-)amplifications due to the local geology. In northern and central Belgium, the sedimentary cover above the London-Brabant Massif (L-BM; a basement massif extending from Belgium to the UK) increases in thickness from south to north because of the northwards dip of the top of the L-BM. These soft sediments could strongly influence the way how earthquakes are measured by seismometers at the surface and perceived by the local population. At the onset of this project we had only little knowledge on the complex mechanism at the origin of this site effect, on its regional extent and hence, on its consequences during future earthquakes. In this project we studied the transfrontier-felt macroseismic distributions of two recent moderate-magnitude earthquakes, i.e. the 2011 $M_L$ 4.3 Goch (DE) and the 2015 $M_L$ 4.2 Ramsgate (UK) events, of which the former was felt in Germany, The Netherlands and Belgium and the latter in UK, Belgium and France. To understand their impact on the NW European territory, a statistical analysis of earthquake macroseismic intensities combined with a geophysical study was performed. The goals of this multi-disciplinary project were:

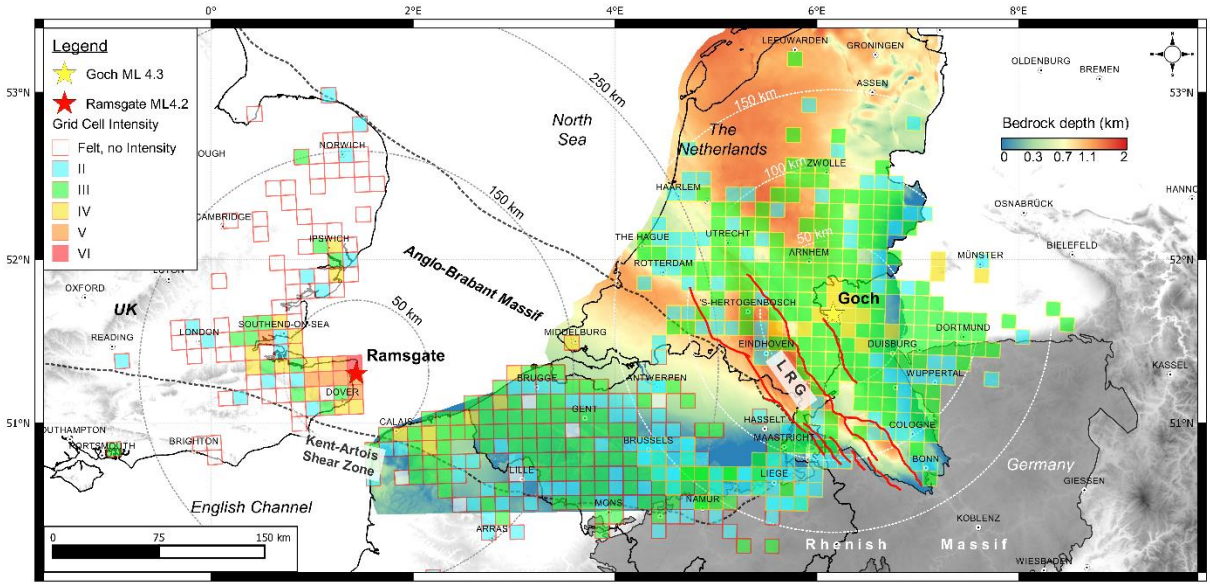
1. to develop a methodology to merge macroseismic intensities from different European seismological agencies to create transfrontier intensity maps of felt earthquakes;
2. to create a thickness map of sediments above the L-BM;
3. to evaluate the anelastic attenuation of seismic waves (Q-factor) in the L-BM and in its cover using the macroseismic distributions and the sediment thickness map.

## Results

### 1. Macroseismic intensity analysis of transfrontier-felt earthquakes

When an earthquake is felt, people can report their perception in online questionnaires, e.g. the questionnaire of the ROB and the Erdbebenstation Bensberg (DE). The felt distribution allows to investigate the ground motion intensity over the area where the earthquake was perceived. This effective crowdsourcing tool allows to reveal locations where the shaking effect was stronger or weaker. In Europe, however, the collection of testimonies is strongly fragmented across numerous seismological institutes which complicates the creation of reliable transfrontier-felt earthquake intensity maps. To map the impact of the Goch and Ramsgate earthquakes, first the testimonies of 6 different institutes (ROB-BNS, KNMI, BGS, NRW-GD, EMSC and USGS) were requested and processed. As the quality of response location was very diverse, a geocoding algorithm was developed to automatically convert street addresses into their geographical coordinates. After geocoding, the felt area was structured in equally-sized 100 $km^2$ grid cells and an average intensity was calculated for each grid cell using the merged dataset of all individual intensities of all institutes. This methodology was first tested on the macroseismic data of the 2008-2010 seismic swarm in the L-BM (Van Noten *et al.* 2015, Consentino 2016) and afterwards on the Goch and Ramsgate earthquakes. The resulting grid cell intensity map of both the Ramsgate and Goch earthquakes (see figure) shows a pronounced non-concentric felt distribution suggesting that source, path and local site effects strongly affects the propagation of seismic waves towards the surface. Contrary to northern Belgium, where hardly anyone felt the Goch event, many reports were submitted from central Belgium, (e.g. Brussels, Liège), despite the fact that these locations are at a larger epicentral distance. Similarly, the

Ramsgate event was less far perceived in the UK than on the European continent (up to 300 km). This suggests that the local geology affects the way how people perceived these and other past earthquakes.




**Grid cell intensity distributions of the 2011 Goch earthquake (red) and 2015 Ramsgate (yellow) earthquakes illustrated on a bedrock depth map of northern Belgium, The Netherlands and western Germany. Note the absence of felt responses in NE Belgium (between Antwerp and Hasselt), SW of Eindhoven (NL) and SW of Cologne due to thick sedimentary cover. Bedrock depth in the UK is not shown. LRG = Lower Rhine Graben. Source: Van Noten *et al.* (in review).**

## 2. Mapping the thickness of the sedimentary cover

To investigate influence of the thickness of soft sediments on the (de-)amplification of seismic waves, a sediment thickness map was created for the European continent. For northern Belgium and The Netherlands open source numerical data were openly available (DOV for Flanders and Dinoloket, TNO, for NL) but were extended after digitising bedrock depth maps of Legrand (1968) for central Belgium and Hager and Prüfert (1988) for western Germany. In central Belgium, the bedrock depth of the Legrand map was improved during an ULB Ma thesis project (Molron, 2015) during which the fundamental frequency of soil was calculated from H/V spectral ratio analysis of ambient noise measured above 175 boreholes. Several non-linear (powerlaw) regressions between the fundamental frequency of soil and sediment thickness could be developed which are now applicable for different regions where bedrock depth is unknown. Applying these powerlaws on additional H/V measurements allowed to improve the uncertainty in the sediment thickness map. To properly illustrate the geophysical results, a new 3D visualization tool applicable for Google Earth was developed and published in EOS (Van Noten, 2016).

## 3. Anelastic attenuation of seismic waves (Q-factor)

The analysis of the sedimentary cover and the intensity distribution shows that the intensity of shaking of the Goch earthquake was stronger (ground motion amplification) where the depth of the L-BM is less than 200 meters (see figure) and that the events were not felt at places with a thick sedimentary cover where seismic waves are de-amplified. The far-field felt effect of the Ramsgate earthquake demonstrates a very low anelastic attenuation (high Q factor) along-strike of the L-BM in a WNW-ESE direction. In a perpendicular orientation, seismic waves are stronger attenuated (low Q) because of (i) the increasing sedimentary thickness (lower Q) in northern Belgium and (ii) different crustal properties in adjacent rheologically different units at the border between the L-BM and the Kent-Artois shear zone in the south.

## Conclusions and perspectives

This study (published in Van Noten *et al.*, in review) provided a promising intensity grid cell methodology for European seismological agencies to share macroseismic intensity datasets of transfrontier-felt earthquakes anonymously. We also demonstrated the strong influence of the bedrock

depth on earthquake perception for people living in NW Europe. We moreover discovered that the Q factor in the Brabant Massif is significantly higher than in neighbouring tectonic regions. This is a new aspect that we didn't foresee to find. These findings will therefore be used in future ground -motion modelling efforts as more appropriate Q factor parameters can now be implemented.

## Outreach

### *Peer-reviewed publications:*

1. **Van Noten, K.**, Lecocq, T., Hinzen, K.-G., Sira, C. & **Camelbeeck, T.** ***in review*** *(2016).* Path and site effects deduced from transfrontier internet macroseismic data of two recent M4 earthquakes in NW Europe. *Solid Earth Discussions.* doi:10.5194/se-2016-150
2. **Van Noten, K. 2016.** Visualizing Cross-Sectional Data in a Real-World Context. *EOS, Transactions AGU* **97**, 16-19. doi:10.1029/2016EO044499
3. **Van Noten, K.**, Lecocq, T., Shah, A. & **Camelbeeck, T. 2015.** Seismotectonic significance of the 2008-2010 Walloon Brabant seismic swarm in the Brabant Massif (Belgium). *Tectonophysics* **656**, 20-38. doi:10.1016/j.tecto.2015.05.026

### *Supervised Theses:*

1. Bruno Cirilo Consent, 2016. *Analysing Earthquake sounds by macroseismic analysis of online 'Did You Feel It?' responses.* BSc Thesis Geology, Katholieke Universiteit Leuven, Supervisors: **K. Van Noten** (ROB), M. Sintubin (KULeuven)
2. Lauriane Meyer, 2015. *Applicability of continuous H/V spectral ratio analysis for volcano monitoring.* MSc Thesis Geology, Université Libre de Bruxelles, Supervisors: T. Lecocq, **K. Van Noten** (ROB).
3. Justine Molron, 2015. *Thickness estimation of sediments overlying the Brabant Massif by H/V spectral ratio analysis in central Belgium.* MSc Thesis Geology, Université Libre de Bruxelles. Supervisors: **K. Van Noten**, T. Lecocq (ROB).

### *Conference sessions convened:*

1. Hough, S.E., Bossu, R., Martin, S.S., **Van Noten, K**. 2016. Session S018: Macroseismic Data: Challenges, Opportunities, and Insights. American Geophysical Union Fall Meeting, 12-16 December 2016, San Francisco, USA.
2. **Van Noten, K**., Arroucau, P., Mordret, A., Lecocq, T., Farrugia, D. & Agius, M.R. 2016. Seismology for non-seismologists. European Geosciences Union GA, Short course 55, 17-22 April 2016, Vienna, Austria.

### *Presentations at international conferences:*

1. **Van Noten, K.**, Lecocq, T., Hinzen, K.-G., Sira, C. & **Camelbeeck, T.** 2016. *Transfrontier Macroseismic Data Exchange in Europe: Intensity Assessment of M4 Earthquakes by a Grid Cell Approach*. American Geophysical Union, AGU2016, 12-16 December 2016, San Francisco, USA.
2. Consentino, B.C., **Van Noten, K.**, Sintubin, M. 2016. *Macroseismic intensity assessment of the 2008-2010 Walloon Brabant Seismic Swarm (Belgium) by a grid cell* procedure. 48th Congresso Brazileiro de Geologia, 9-13 October 2016, Porto Alegre, Brazil.
3. **Van Noten, K.**, Lecocq, T., Hinzen, K.-G., Sira, C. & **Camelbeeck, T.** 2016. *Transfrontier Macroseismology in Europe*. ESC2016, 4-9 September 2016, Trieste, Italy.
4. **Van Noten, K.**, Lecocq, T., Hinzen, K.-G., Sira, C. & **Camelbeeck, T.** 2016. *Transfrontier macroseismic data exchange in NW Europe: examples of non-circular intensity distributions.* Geophysical Research Abstracts 18, EGU2016-4609, session SM3.3, 17-22 April 2016, Vienna, Austria.
5. **Van Noten, K.** & Lecocq, T. 2016. *Continuous H/V Spectral Ratio Analysis of Ambient Noise: a necessity to understand microzonation results obtained by mobile stations.* Geophysical Research Abstracts 18, EGU2016-4609, session SM2.2/NH4.13, 17-22 April 2016, Vienna, Austria.
6. **Van Noten, K.**, Lecocq, T. & **Camelbeeck, T.** 2016. *Macroseismic analysis of "Did You Feel It?" responses to ML > 3 earthquakes felt in and around Belgium.* 5th International Geologica Belgica Conference, January 2016, Mons, Belgium.
7. **Van Noten, K.** 2016. *Visualizing (geological) cross-sections vertically in Google Earth.* 5th International Geologica Belgica Conference, January 2016, Mons, Belgium.
8. **Van Noten, K.**, Lecocq, T., Meyer, L., Molron, J. & **Camelbeeck, T.** 2015. *Continuous H/V Spectral Ratio Analysis of Ambient Noise Recorded by Stationary Seismic Stations to Improve Microzonation Results Obtained by Mobile Stations*. American Geophysical Union, AGU2015-NS41B-1936, 14-18 December 2015, San Francisco, USA.
9. **Van Noten, K.**, Lecocq, T., Hinzen, K. & **Camelbeeck, T.** 2015. *Macroseismic analysis of "Did You Feel It?" responses to ML > 3 earthquakes felt in Belgium and its neighbouring countries*. Membach 20-40 Workshop: Earthquake activity and hazard in NW Europe. La Gileppe, Belgium. 15 October 2015.
10. Lecocq, T., Hinzen, K., **Van Noten, K.** & **Camelbeeck, T.** 2015. *Nearly 15 years of real-time transfrontier macroseismic data acquisition and mapping*. Membach 20-40 Workshop: Earthquake activity and hazard in NW Europe. La Gileppe, Belgium. 15 October 2015.
11. **Van Noten, K.**, Lecocq, T., Molron, J., **Camelbeeck, T.** & Van Camp, M. 2015. *Shear wave velocity estimation of cover sediments by seismic array measurements*. Geophysical Research Abstracts 17, EGU2015-7445, session SM4.1, 12-17 April 2015, Vienna.

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