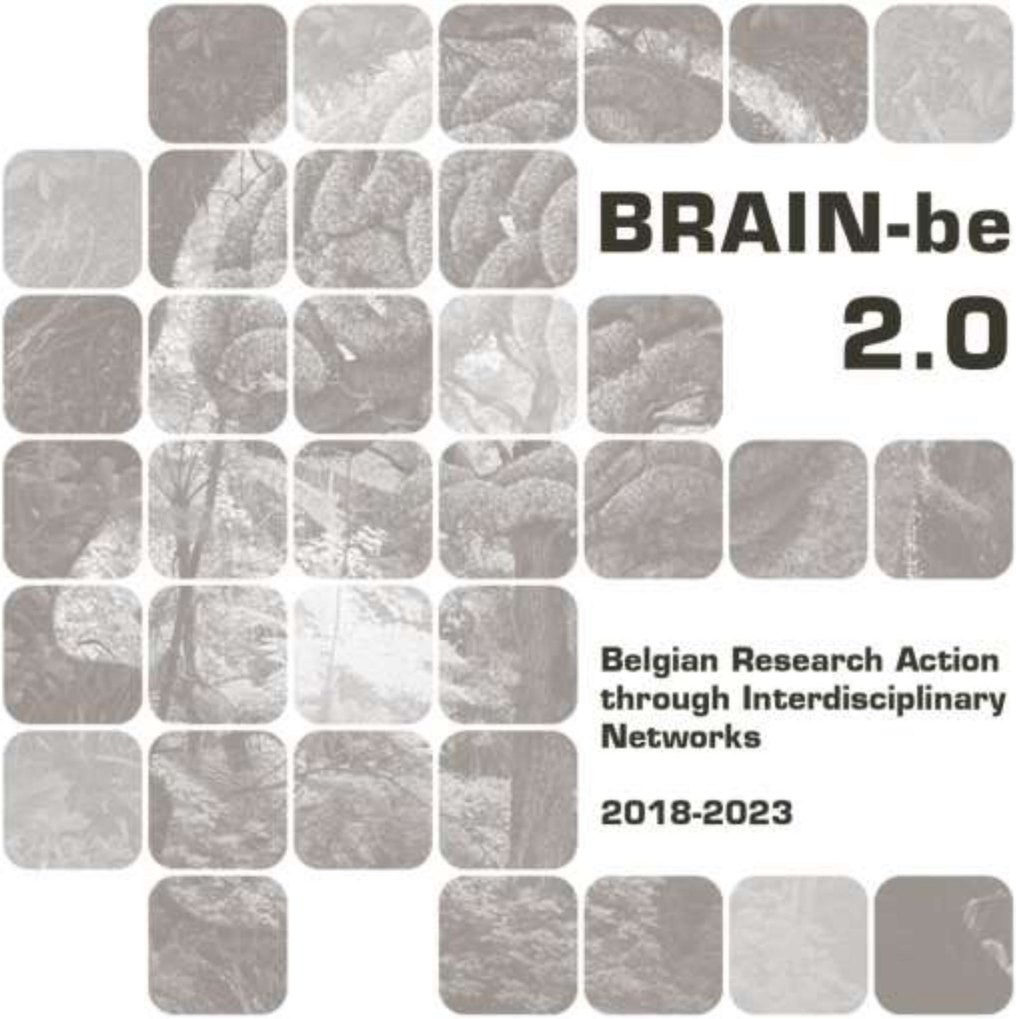

BELSHAKE

Earthquake ground-motion database and modeling in Belgium

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Pillar 1: Challenges and knowledge of the living and non-living world

BRAIN-be 2.0

Belgian Research Action through Interdisciplinary Networks

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BOTTOM-UP PROJECT

BELSHAKE

Earthquake ground-motion database and modeling in Belgium

Contract - B2/202/P1

SUMMARY

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SUMMARY

1.1. Context

Belgium, and NW Europe in general, is situated in a stable continental or intraplate region, characterized by low to moderate seismic activity. Nevertheless, damaging earthquakes have occurred here too. The most important ones during the 20th century are the 1938 Zulzeke-Nukerke (magnitude $M = 5.0$), the 1983 Liège ($M = 4.6$) and the 1992 Roermond (NL) earthquakes ($M = 5.3$). Historical records indicate that larger earthquakes have occurred in the past, such as the 1580 earthquake in the English Channel ($M \cong 6.0$) and the 1692 Verviers earthquake ($M \cong 6.3$). This evidence shows that damaging earthquakes, although infrequent, do occur in our region, and hence that seismic hazard is not negligible. European seismic hazard maps depict Belgium as a region with elevated hazard compared to adjacent areas in France, the United Kingdom (UK), Germany and The Netherlands. Seismic hazard assessments (SHAs) provide essential input for engineers to design earthquake-resistant buildings and infrastructure. Examples include country-wide hazard maps in support of the European building code Eurocode 8 and site-specific SHAs for critical infrastructure such as nuclear facilities, SEVESO classified industries, etc. A crucial component of SHA are ground-motion models (GMMs), which relate earthquake ground motion to magnitude, epicentral distance, and possibly other source, path and site properties. Strong variations in ground motion are observed between different regions of the world, mainly due to different crustal attenuation characteristics. However, very few GMMs are available for intraplate areas and none specifically for Belgium. Consequently, SHAs in Belgium so far had to rely on GMMs developed for other parts of the world. Although the selection of GMMs has grown more sophisticated over the years, their validity for our regions has not been tested and their weighting remains subjective. Considering that in probabilistic SHA, the ground motion branch of the logic tree is one of the main contributors to uncertainty, there is clearly a need for ground-motion data from lower-seismicity regions.

Earthquake ground-motion databases are fundamental resources for the development of GMMs. In the past two decades, several international efforts have collected strong-motion data, such as the Next Generation Attenuation (NGA) project in the United States, and the follow-up projects NGA-West and NGA-East, the KiK-net database in Japan, the ITACA database in Italy, the RESORCE database for Europe and the Middle East, and the worldwide Engineering Strong Motion database. These databases predominantly contain data from the most active regions of the world, where earthquakes are more abundant. A large number of GMMs have been derived from these databases. In contrast, intraplate areas, where seismicity is much lower, are much less represented. Although the vast majority of recorded data in these regions concern weak-motion records from earthquakes with magnitudes lower than the magnitude range relevant for SHA ($M \geq \sim 4.5$), recent successful projects to compile ground-motion databases in France, Switzerland and Australia have demonstrated that it is not only feasible, but also valuable, to conduct similar studies for Belgium.

1.2. Objectives

The above considerations provided the rationale to launch a dedicated project, BELSHAKE, which intends to bridge a gap in know-how and in data collection in the field of earthquake ground-motion with respect to the international seismological community. The currently available seismic data in Belgium are mainly used to detect and locate regional earthquakes, and to determine their main source characteristics (e.g., focal depth, local magnitude, focal mechanism), but a systematic inventory of these data for the purpose of ground-motion modelling has not been undertaken yet.

The main objectives of the project are twofold: (1) to build a database of recorded earthquake ground motion in Belgium and adjacent regions, and (2) to develop the capacity to model ground motion due to earthquakes in Belgium based on this database. This will allow to evaluate the validity of existing GMMs in Belgium and ultimately to develop a model specifically for our country. The used methodology is well-established, but has not, or only in part, been applied in the Belgian context. Thus, both the topic and the methodology are situated within the international state-of-the-art.

1.3. Results

The most important result of the BELSHAKE project is the development of a new earthquake ground-motion database for Belgium and surrounding regions, i.e. the BELSHAKE database. This database is based on digital waveform data starting from 1985 and currently contains $\sim$6400 records from 327 tectonic and 17 induced earthquakes with $M \geq 2$. Considerable efforts were undertaken to ensure that both the waveform data, the metadata and the derived intensity measures (IMs) adhere to the best practices set by international ground-motion databases. All waveforms have been visually inspected, and problems were either corrected or flagged. A main challenge we encountered concerns the reconstruction of missing instrument response information for older records. This information is required to convert recorded ground motion to physical units and to correct for instrument characteristics. We applied different methods and evaluated their validity in different ways. Records for which instrument response was found to be unreliable, were flagged in the database, preventing them to be used in subsequent steps. All reliable records were processed using a semi-automated, uniform workflow. The processing steps and the order in which they are applied have been adapted with slight variations from the schemes in established ground-motion databases. Subsequently, up to 109 intensity measures were computed from the processed data, for more than 120,000 record-component-window combinations. We also determined moment magnitudes from the waveform data for 294 events in the database and confirmed their reliability by comparing the results of different methods and comparing with values in other seismic catalogs. Finally, we performed various consistency checks to ensure the quality and reliability of IMs, including evaluation of different component ratios, residual analysis with respect to a generic GMM, comparison of co-located stations, and comparison with common events in the French RESIF/EPOS-France database. Anomalous IMs were analysed, and problematic values were either corrected or removed. The final residuals show no discernible trend with distance or magnitude, and vary in a narrow range that is similar to or even smaller than that in the database for France. The BELSHAKE database has already proven its value, as it allowed a recalibration of the Belgian local magnitude scale in parallel to this project. This in turn provided new insights in geometrical spreading and path duration, which are important results for the project as well.

In the second part of the project, we first analysed anelastic attenuation of seismic waves in Belgium through the high-frequency attenuation factor kappa (κ), which was determined for all records in the BELSHAKE database. Analysis of the κ-distance relationship using different fitting methods allowed decomposing whole-path κ values into site-specific (κ_0) and regional (kappa gradient κ_r) components in four crustal domains. Our results show that variations in κ_r are relatively small, with an overall average corresponding to an apparent (frequency-independent) Q factor around 1750, confirming that regional attenuation in Belgium is relatively low. Comparison of site-specific κ_0 values with V_{S30}, the average shear-wave velocity in the top 30 m, shows relatively constant values over a broad V_{S30} range for stations situated on bedrock. This indicates that bedrock with high V_{S30} in Belgium does not show the low κ_0 values typical of hard rock in e.g. Eastern North America. Subsequently, we evaluated the goodness-of-fit of more than 20 published GMMs with respect to observed data in the BELSHAKE database, using multiple statistical measures. Although no single model consistently outperforms all others, several models demonstrate good and stable performance across different measures. An interesting and unexpected finding is that low-attenuation versions of NGA-West GMMs for California, a plate boundary, match the data better than NGA-East GMMs for the intraplate region of Eastern North America, both in terms of absolute values and in spectral shape. Building on this result, we applied the relatively simple Referenced Empirical Approach to adjust some of the tested GMMs to the Belgian situation. Our analyses show that this method should be applied carefully. It should be limited to models requiring only minor adjustment and with spectral shapes that are not too different from those observed. It should also be verified that the residuals do not show any trend with magnitude to avoid bias for higher magnitudes relevant in SHA. Nevertheless, we identified three models that could be reliably adjusted. The most promising of those is a stochastic model developed for the UK, which shows the best fit to the BELSHAKE database. In addition, thanks to data international data exchange other researchers have determined factors to calibrate a pan-European GMM using a more sophisticated method, which was beyond the possibilities in the BELSHAKE project. Finally, we also implemented two methods, EGF and EXSIM, to simulate ground motion from higher-magnitude earthquakes. As a proof of concept, we simulated realistic ground motions for the largest earthquake in the database, the 1992 Roermond earthquake. This exercise benefited from other results obtained in the project, such as the path and site components of κ, V_{S30} values for Belgian seismic stations, along with the newly derived geometrical spreading and path duration models. Thus, we have paved the way for stochastic simulation of accelerograms for hypothetical high-magnitude earthquakes that are in agreement with the average source, path and site characteristics in and around Belgium.

1.4. Conclusions

Available seismic data in Belgium have so far been underexploited in terms of engineering seismological applications. In the BELSHAKE project, we established the first ground-motion database serving this purpose. Thanks to its quality-checked records, integrated instrument response information and comprehensive metadata, the BELSHAKE database is a high-quality resource for earthquake ground motion in Belgium, as attested by the small uncertainties on epicentral locations and magnitudes, and the low residuals. Although the magnitude coverage is relatively limited (mainly $M \leq 4$), it contains important information on source, path and site characteristics of ground motion in our regions. The database complements existing databases by increasing the coverage of low-seismicity zones and lower magnitudes. In addition, it will serve as a reference dataset for many other seismological applications. An example is the recalibration of the Belgian local magnitude scale performed alongside this project.

Using the BELSHAKE database, we have characterised both geometrical spreading and anelastic attenuation in Belgium in more detail than before. It also allowed evaluating which published GMMs show the best agreement with observations, and we managed to calibrate a few of these models. Thus, and for the first time, we developed GMMs specifically for Belgium based on local data. This will allow better informed and data-driven selection of GMMs in SHA. In parallel, we developed the capacity to simulate ground motion from higher-magnitude earthquakes. Together, these advances lay a solid foundation for further developments in ground-motion modelling in Belgium. Our results will be very useful for new SHAs in Belgium, such as will be needed for the revision of Eurocode 8, as well as for the prolongation of existing or the siting of new nuclear facilities.

1.5. Keywords

Earthquakes, ground-motion model, database, seismic hazard, seismic attenuation