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Site amplification at the city scale in Basel (Switzerland) from geophysical site characterization and spectral modelling of recorded earthquakes

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ABSTRACT

Hazard assessment at the city scale requires a detailed characterization of the effect of surface geology on ground motion (site effects). Though this analysis is commonly achieved using geophysical site characterization and site response modelling, we propose here a complementary analysis based on amplification functions retrieved from Empirical Spectral Modelling (ESM) of earthquake recordings. We applied this method to the city of Basel (Switzerland) that benefits from a detailed microzonation and a dense Strong Motion Network with 21 modern free-field stations. We first verified the accuracy of ESM amplification functions for this region and used them to determine the bedrock interface at a site with a detailed velocity profile. While the interface between Upper and Lower Tertiary was, until now, considered responsible for the fundamental frequency of resonance in the Rhine Graben, we found that the bedrock interface in fact lies at the Mesozoic limestone. We also investigated the second peak of the H/V ratios that is clustered in a particular area of the basin where amplification is found to be different. We successfully used the ESM amplification functions to verify the microzonation of 2006 and would strongly advise the installation of strong motion stations where such studies are performed in the future. Outside the Rhine Graben, where shallow sediments are found, we propose an amplification functional form based on ESM and the fundamental frequency of resonance. Finally, we combined all our findings and generated amplification maps of the response spectrum at any period of interest for earthquake engineering. This map is proposed for a high resolution real-time implementation in ShakeMap and will be used for seismic loss assessment.

1. Introduction

The city of Basel is located at the south-eastern edge of the Upper Rhine Graben, at the border between France, Germany and Switzerland. Seismic hazard in the city of Basel is moderate, with uniform hazard spectra from the 2015 Swiss national seismic hazard maps of the Swiss Seismological Service (SED) indicating peak ground acceleration (PGA) at a rock horizon ($V_{s,30} = 1105$ m/s) of 0.1 g at a return period of 475 years, and 0.5 g at 10,000 years (SED, 2015a). It was struck in 1356 by the largest earthquake known to have occurred North of the Alps, with M_w ~6.6 according to recent studies (Fäh et al., 2009). The earthquake destroyed the city and caused damage in many villages nearby. The number of fatalities was probably limited, most likely due to the numerous foreshocks that made the inhabitants leave their houses. Two fatalities have been certified, although the real number is unknown (Fäh et al., 2009). Other historical events of magnitude 5 and above occurred in 1650 and 1721, causing slight damage to the city (Schwarz-Zanetti and Fäh, 2011; Gisler and Fäh, 2011). More recently, the 2006 $M_w = 3.2$ event induced by petrothermal activities caused widespread minor non-structural damage that led to about 9 M$ damage claims (Giardini, 2009). This is in stark contrast to a similar geothermal event that occurred in St. Gallen, Switzerland in 2013, which caused insignificant damage, as would be expected for this size of event (Edwards et al., 2015a). A key question therefore is whether amplification phenomena in Basel lead to high ground-motions.

The first qualitative microzonation study for the city was carried

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out by Fäh et al. (1997). It was followed in 2006 by a quantitative microzonation project (Fäh and Huggenberger, 2006) that was eventually implemented in the local building code (Fäh and Wenk, 2009). Apparent from the microzonation studies is significant amplification of earthquake ground motions, which varies according to the mechanical properties of the deposits: in the Rhine Graben, deep sedimentary layers with various degrees of consolidation have been deposited since the Tertiary, whereas outside the Graben, alluvial valleys are filled with unconsolidated Quaternary sediments. This geological complexity and the resulting site response motivated the development of site characterization techniques based on ambient vibrations (e.g. Kind et al., 2005; Havenith et al., 2007) and site response analyses based on numerical modelling (e.g. Oprsal et al., 2005).

We propose here an alternative, data-driven approach to assess the amplification of earthquake ground motions that should complement classical geophysical site characterization. Our study is motivated by the "Basel Risk Mitigation" project promoted by the Canton Basel-City between 2013 and 2015 with the goal of assessing the consequences of significant earthquakes on local school buildings, and as a pilot study for real-time loss assessment for the whole city (Michel and Fäh, 2016). Our approach is based on collecting observations of site amplification at permanent seismic stations with respect to a known reference rock profile, as detailed by Poggi et al. (2011) and Edwards et al. (2013). The main source of our data is the Swiss Strong Motion Network (SSMNet; Clinton et al., 2011; Michel et al., 2014) that was densified in the region throughout the development of this study.

In this paper, we present and discuss the amplification maps developed for the studied area. Our goal is to define the amplification of the 5% damped response spectrum in the range of the vibration frequencies of typical Swiss buildings, i.e., between 1 and 10 Hz. The amplification maps derived herein can be used as input to loss assessment studies through high-resolution earthquake scenarios and ShakeMaps (Wald et al., 1999; Worden et al., 2010; Cauzzi et al., 2015) for the Basel area.

In this paper, the Basel context is first presented including the geology, the existing microzonation studies and the SSMNet with its recent modernization and extension, completed by the installation of temporary stations within this project. We recall how the spectral modelling technique of Edwards et al. (2013) is implemented on the whole Swiss Network to retrieve information on the Fourier site amplification from recorded events. We validate this approach in Basel and propose a method to compute the site amplification for the response spectrum. Two results concerning the interpretation of the observed site amplification are presented: the interpretation of the bedrock depth and the secondary peaks in the Rhine Graben. Further, a verification of the 2006 microzonation is presented. Finally, we propose a method to combine the available data with the site characterization information to derive an amplification map for a prototype implementation in a high-resolution ShakeMap.

2. The Basel area

2.1. Geology

The area of Basel (Fig. 1) comprises two major distinct geological domains, namely the Rhine Graben and the Jura mountains. The Rhine Graben opened during the Oligocene and Miocene ages (starting 35 Myrs ago) and has been filled with thick marine and freshwater sediments since that time (Fig. 2). East of the master fault of the Graben, the Tabular Jura is made of Mesozoic rock, carved by the Rhine and smaller rivers, generally overlaid by Quaternary sediments of variable (but generally limited to 35 m in most areas) thickness. In the South, the Graben extends to the folded Jura with a gradually decreasing thickness. Defining the Eastern and Southern boundaries between these two geologic features is not straightforward. They can be defined based on tectonic considerations (e.g. the location of the main Eastern fault – although this is not well defined), sedimentary considerations (e.g., presence of Tertiary sediments deposited during the extension of the Graben), or engineering seismology considerations (e.g., a jump in the resonance frequency as used in Fäh et al., 2006). In this project, we used a simplified representation of the main geological units based on the available geological maps and the 2006 microzonation map, as shown in Fig. 1.

Outside the Rhine Graben, the Quaternary sediments exceed 35 m thickness only for small areas of the Rhine valley (e.g. at station SMZW) and of the Ergolz valley (GeORG project team, 2013). According to Fäh et al. (2006), three main types of sediments can be found in this area: Pleistocene sediments are mostly made of alluvial terraces of the main rivers and are in general compact; Loess sediments, which are very soft, can be found on top of hills and were formed by wind transport; Holocene sediments are in general unconsolidated alluvial sediments (gravel and sand).

In the Rhine Graben, the Quaternary sediments are also rarely thicker than 35 m (GeORG project team, 2013). Loess hills in the South-West were distinguished from the rest of the Rhine Graben as explained in section 4.2. The Tertiary deposits (Fig. 2) are mostly marls of lacustrine origin with various degrees of consolidation filling the basin with a thickness of 50–1000 m in Basel (GeORG project team, 2013). They are particularly deep in the "Mulde von St-Jakob-Tüllingen" (Fig. 2), along the Eastern limit of the Graben until Reinach in the South as well as West of the Allschwil fault.

The upper Tertiary (Oligocene age) is made of various sediment types with freshwater origin superimposing seawater sediments mostly made of mudstone, both poorly consolidated (GeORG project team, 2013). The lower Tertiary is mostly constituted by a thick consolidated marl layer (formerly called Sannoisian marl).

The upper Mesozoic layers in the graben are made of massive limestone of Oxfordian age. The Lower Tertiary has been considered as the geophysical bedrock since the first studies on Basel (Fäh et al., 1997). However, we show in section 4.1 that the geophysical bedrock could be located at the top of the Mesozoic units.

2.2. Microzonation studies

Fäh et al. (1997) first proposed a qualitative microzonation of the city of Basel. They collected geological and geotechnical data, used SPT (Standard Penetration Test) to estimate the shear-wave velocity (Vs) and used the Horizontal-to-Vertical (H/V) Spectral Ratios at about 20 measurements points in the city to compute the dominant frequencies of the site response. They interpreted the fundamental frequency as the resonance of the Upper Tertiary and Quaternary layers, based on the transition between soft sediments and harder rock observed in deep boreholes. They proposed a qualitative microzonation, mostly relying on the Quaternary geology (14 criteria out of 20). This microzonation strategy was implemented in the whole city and related to amplification of earthquake ground motions in terms of EMS-98 (Grünthal, 1998) macroseismic intensity in Fäh et al. (2001). Kind (2002) further developed the use of single station measurements (255 measurement points) and introduced ambient vibration array measurements to estimate the Vs profiles at 5 sites (Kind et al., 2005). Further 2D numerical modelling was performed, and the Rhine Graben was split into five zones of assumed similar amplification. Steimen et al. (2003) studied 2D resonance in the Rhine Graben using observation and modelling and concluded that no 2D resonance was occurring in Basel but that 2D geometry was playing a