Nat. Hazards Earth Syst. Sci., 21, 1–22, 2021
https://doi.org/10.5194/nhess-21-1-2021

Natural Hazards
and Earth System
Sciences
Open Access

Development of a ~~country-wide~~ seismic site-response zonation map for the Netherlands

Janneke van Ginkel[1,2], **Elmer Ruigrok**[2,3], **Jan Stafleu**[4], **and Rien Herber**[1]

[1]Energy and Sustainability Research Institute Groningen, University of Groningen,
Nijenborgh 6, 9747 AG Groningen, the Netherlands
[2]R&D Seismology and Acoustics, Royal Netherlands Meteorological Institute,
Utrechtseweg 297, 3731 GA De Bilt, the Netherlands
[3]Department of Earth Sciences, Utrecht University, Princetonlaan 8a, 3584 CB Utrecht, the Netherlands
[4]TNO – Geological Survey of the Netherlands, Princetonlaan 6, 3584 CB Utrecht, the Netherlands

Correspondence: Janneke van Ginkel (j.a.van.ginkel@rug.nl)

Received: 24 August 2021 – Discussion started: 26 August 2021
Accepted: 4 November 2021 – Published:

Abstract. Earthquake site response is an essential part of seismic hazard assessment, especially in densely populated areas. The shallow geology of the Netherlands consists of a very heterogeneous soft sediment cover, which has a strong effect on the amplitude of ground shaking. Even though the Netherlands is a low- to moderate-seismicity area, the seismic risk cannot be neglected, in particular, because shallow induced earthquakes occur. The aim of this study is to establish a nationwide site-response zonation by combining 3D lithostratigraphic models and earthquake and ambient vibration recordings.

As a first step, we constrain the parameters (velocity contrast and shear-wave velocity) that are indicative of ground motion amplification in the Groningen area. For this, we compare ambient vibration and earthquake recordings using the horizontal-to-vertical spectral ratio (HVSR) method, borehole empirical transfer functions (ETFs), and amplification factors (AFs). This enables us to define an empirical relationship between the amplification measured from earthquakes by using the ETF and AF and the amplification estimated from ambient vibrations by using the HVSR. With this, we show that the HVSR can be used as a first proxy for site response. Subsequently, HVSR curves throughout the Netherlands are estimated. The HVSR amplitude characteristics largely coincide with the in situ lithostratigraphic sequences and the presence of a strong velocity contrast in the near surface. Next, sediment profiles representing the Dutch shallow subsurface are categorised into five classes, where each class represents a level of expected amplification. The mean amplification for each class, and its variability, is quantified using 66 sites with measured earthquake amplification (ETF and AF) and 115 sites with HVSR curves.

The site-response (amplification) zonation map for the Netherlands is designed by transforming geological 3D grid cell models into the five classes, and an AF is assigned to most of the classes. This site-response assessment, presented on a nationwide scale, is important for a first identification of regions with increased seismic hazard potential, for example at locations with mining or geothermal energy activities.

1 Introduction

Site-response estimation is a key parameter for seismic hazard assessment and risk mitigation, since local lithostratigraphic conditions can strongly influence the level of ground motion amplification during an earthquake (e.g. Bard, 1998; Bonnefoy-Claudet et al., 2006b, 2009; Borcherdt, 1970; Bradley, 2012). In particular, near-surface low-velocity sediments overlying stiffer bedrock modify earthquake ground motions in terms of amplitude and frequency content, as for instance observed after the Mexico City earthquake in 1985 (Bard et al., 1988) as well as more recent ones (e.g. L'Aquila, Italy, 2009; Tokyo, Japan, 2011; Darfield, New Zealand, 2012). Site-response estimations require detailed geological and geotechnical information of the subsurface. This can be retrieved from in situ investigations; however, this is a costly procedure. Because of the time and costs involved, there is a lack of site-response investigations covering large areas, while the availability of detailed and uniform ground motion amplification maps is fundamental for preliminary estimates of damage on buildings (e.g. Falcone et al., 2021; Gallipoli et al., 2020; Bonnefoy-Claudet et al., 2009; Weatherill et al., 2020).

Empirical seismic site response is widely investigated by the use of microtremor horizontal-to-vertical spectral ratios (HVSRs; e.g. Fäh et al., 2001; Lachetl and Bard, 1994; Bonnefoy-Claudet et al., 2006a; Albarello and Lunedei, 2013; Molnar et al., 2018; Lunedei and Malischewsky, 2015). The HVSR is obtained by taking the ratio between the Fourier amplitude spectra of the horizontal and the vertical components of a seismic recording. When a shallow velocity contrast is present, the peak in the HVSR curve is closely related to the shear-wave resonance frequency for that site. However, the HVSR peak amplitude cannot be treated as the actual site amplification factor but rather serves as a qualitative estimate (Field and Jacob, 1995; Lachetl and Bard, 1994; Lermo and Chavez-Garcia, 1993).

The Netherlands experiences tectonically related seismic activity in the southern part of the country, with magnitudes up to 5.8 measured so far (Camelbeeck and Van Eck, 1994; Houtgast and Van Balen, 2000; Paulssen et al., 1992). Additionally, gas extraction in the northern part of the Netherlands regularly causes shallow (3 km), low-magnitude ($M_\mathrm{w} \leq 3.6$ thus far) induced earthquakes (Dost et al., 2017). Over the last decades, an increasing number of these induced seismic events have stimulated the research on earthquake site response in the Netherlands. Various studies (van Ginkel et al., 2019; Kruiver et al., 2017a, b; Bommer et al., 2017; Noorlandt et al., 2018) undertaken in the Groningen area (northeastern part of the Netherlands) concluded that the heterogeneous unconsolidated sediments are responsible for significant amplification of seismic waves over a range of frequencies pertinent to engineering interest. Although the local earthquake magnitudes are relatively small, the damage to the houses can be significant. Hence multiple studies (e.g. Rodriguez-Marek et al., 2017; Bommer et al., 2017; Kruiver et al., 2017a; Noorlandt et al., 2018) were performed on ground motion modelling including the site amplification factor for the Groningen region.

Groningen forms an excellent study area due to the presence of the permanently operating borehole seismic network (G-network). Local earthquake recordings over the Groningen borehole show that the largest amplification develops in the top 50 m of the sedimentary cover (van Ginkel et al., 2019), although the entire sediment layer has a thickness of around 800 m in this region. Furthermore, van Ginkel et al. (2019) showed the existence of a correlation between the spatial distribution of microtremor horizontal-to vertical spectral ratio (HVSR) peak amplitudes and the measured earthquake amplification. This observation is in accordance with those of Pilz et al. (2009), Perron et al. (2018), and Panzera et al. (2021), who show a comparison of site-response techniques using earthquake data and ambient seismic noise analysis.

The aim of this work is to design a site-response zonation map for the Netherlands, which is both detailed and spatially extensive. Rather than using ground motion prediction equations with generic site amplification factors conditioned on $V_{\mathrm{s}30}$, we propose a novel approach for the development of a nationwide zonation of amplification factors. To this end, we combine multiple seismological records, geophysical data, and detailed 3D lithostratigraphic models in order to estimate and interpret site response. We first select the Groningen borehole network where detailed information on subsurface lithology, numerous earthquake ground motion recordings, and ambient seismic noise recordings is available since their deployment in 2015. From this, we extract empirical relationships between seismic wave amplification and different lithostratigraphic conditions, building upon the proxies defined in van Ginkel et al. (2019).

Next, the ambient vibration measurements of the seismic network across the Netherlands are used, necessary to calibrate the amplification (via HVSR) with the local lithostratigraphic conditions. By combining the detailed 3D geological subsurface models GeoTOP (Stafleu et al., 2011, 2021) and NL3D (Van der Meulen et al., 2013), with a derived classification scheme, a zonation map for the Netherlands is constructed.

The presented site-response zonation map for the Netherlands is especially designed for seismically quiet regions where tectonic seismicity is absent, but with a potential risk of induced seismicity, for example due to mining or geothermal energy activity (Majer et al., 2007; Mena et al., 2013; Mignan et al., 2015). As a result, this map can be implemented in seismic hazard analysis.

2 Geological setting and regional seismicity

The Netherlands is positioned at the southeastern margin of the Cenozoic North Sea basin. The onshore basin infill is characterised by Paleogene, Neogene, and Quaternary sediments reaching a maximum thickness of ~ 1800 m. Minimum onshore thicknesses are reached along the basin flanks in the eastern and southern Netherlands and locally at uplifted blocks like the Peel Block. The main tectonic feature of the country is the Roer Valley Graben, bounded by the Peel Boundary Fault in the northeast and the Rijen, Veldhoven, and Feldbiss faults in the south and southwest (Fig. 1).

The Paleogene and Neogene sediments are dominated by marine clays and sands that were primarily deposited in shallow marine environments. The Quaternary sediments, reaching a maximum onshore thickness of ~ 600 m, reflect a transition from shallow marine to fluvio-deltaic and fluvial depositional environments in the early Quaternary to a complex alternation of shallow marine, estuarine, and fluvial

Table 1. ~~Comparison between the Eurocode 8 ground type classification and the sediment classification (NL classification) we present in this paper.~~ The V_{s10} and velocity contrast (VC) values assigned to each class are based on the amplification relationships presented in Sect. 4 and Appendix A. For class V there are no empirical data available relating V_{s10} and VC with A_0 (HVSR peak amplitude), hence not determined (n.d).

~~Eurocode 8~~			~~NL classification~~				
~~Ground type [m/s]~~	~~Description stratigraphy sediment class~~	~~V_{s30} description top 200 m~~			V_{s10} [m/s]	VC	A_0
~~A~~	~~Hard rock & rock~~	~~> 800~~	I	Hard rock	> 800	–	–
~~B~~	~~Soft rock & very dense soil~~	~~360–800~~	II	Stiff sediment	> 200	none or < 1.5	< 2
~~C~~	~~Stiff soil~~	~~180–360~~	III	Soft sediment on stiff sediment	100–200	1.5–2.0	2–4
~~D~~	~~Soft soil~~	~~< 180~~	IV	Very soft sediment on stiff sediment	< 100	> 2.0	> 4
~~E~~	~~Special soil~~	~~< 100~~	V	Shallow bedrock (< 100 m)	no data	no data	n.d.

Table 2. Amplification factors and standard deviations (σ) for the NL classification. σ_{AF} is the uncertainty when a local (HVSR) recording is available. σ GeoTOP and σ NL3D represent the additional uncertainty associated with the GeoTOP and NL3D models.

Class	AF_{NL}	σ_{AF}	σ GeoTOP	σ NL3D
II	1.94	0.30	–	–
III	2.4	0.28	0.32	0.34
IV	3.03	0.34	–	–

mation is not included in GeoTOP and NL3D. We therefore distinguish two types of uncertainty.

1. σ_{AF}. This is the variability that originates from the classification. Within the classification, a number of different sites are binned into the same class (Fig. 9), although in reality there is still a range of amplification behaviour. This variability is approximated with the outcome of the manual classification (Fig. 11a), which could be done in great detail.

2. σ_{mod}. The geological models are geostatistical models where not all grid cells contain individual lithological data. Hence, there is an uncertainty of the actual lithological succession at each grid cell. The total uncertainty σ_{tot} (derived from Fig. 11b and c) can be written as $\sqrt{\sigma_{AF}^2 + \sigma_{mod}^2}$. By additionally averaging over the classes (labelled with subscript $_i$), we find the model uncertainty σ_{mod}:

$$\sigma_{mod} = \frac{1}{n} \sum_{i=1}^{n} \sqrt{\sigma_{tot,i}{}^2 - \sigma_{AF,i}{}^2}. \tag{3}$$

Table 2 lists the mean AF values, the uncertainty in AF (σ_{AF}), and the uncertainty (σ) for the GeoTOP and NL3D models.

6.4 Site-response zonation map

The workflow presented in Fig. 10 results in a class category assigned to each grid cell of the GeoTOP and NL3D models. As a result, we present the national site-response zonation map (Fig. 12), where each class characterises a certain level of expected site-response amplification. Additionally, each class has an AF_{NL} assigned (Table 1). Figure 13 presents four zoom-in panels of the map, each depicting a region of particular interest.

Some areas show a large scatter in classes, which is derived from a large heterogeneity in the near surface as represented in the lithostratigraphic models. Typically, at these places there is large model uncertainty, for example in northeast North Holland (Fig. 13a). Here, the Holocene lithological successions are very heterogeneous in terms of clay, peat, and clayish sand. This region also exhibits discrepancies between the model's lithological successions and HVSR curve characteristics, for instance with seismometers J01 (Fig. 8) and J02. The geological model at these locations presents large portions of clayish sand, resulting in Class III, while the HVSR curves exhibit distinctive, high-amplitude peaks, demonstrating local conditions related to Class IV.

For larger sedimentary bodies, like the dune area, there is less model uncertainty. Dune sand is identified as Class II, and here, the HVSR of the seismometers (e.g. ALK2, Fig. 8) deficit CE2 any peak due to the absence of a velocity contrast in the near surface.

Figure 13b covers the "Randstad" region, the most densely urbanised part of the Netherlands, where the class is mainly determined as IV. Figure 13c shows the southeastern part. Most of the northern part of this region is Class II due to Pleistocene sands reaching the surface. Most of the southern part of this region falls into Class V since the bedrock occurs at a depth less than 100 m. A few places with bedrock outcrops fall into Class I.

Since Groningen has been studied in much detail, we also present the site-response zonation for this region (Fig. 13d) and discuss this in Sect. 7.

Please note the remarks at the end of the manuscript.