Assessing soil amplifications in Groningen, the Netherlands

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Abstract

Since the shallow part of the Dutch subsurface is practically always unconsolidated, the elastic waves generated by deeper (~3000 m) seated earthquakes will be subjected to transformation when arriving in these layers. Since, the number of induced seismic events has increased over recent decades, a better understanding of site response of the Dutch subsurface is required. Local site amplification can directly be measured due to the presence of sensors at multiple depth levels in the Groningen borehole network. Amplification factors from 73 local events have been calculated for each borehole location to quantify earthquake site response. Furthermore, horizontal-to-vertical spectral ratios (HVSR) from the ambient seismic field are calculated.

A relationship has been established between the composition of the upper Holocene sediments and the size of the amplitudes of HVSR and earthquake site response. Highest amplitudes are measured where the Holocene sediments are composed of clay, fine sands, silts and peat. We can conclude that HVSR from the ambient seismic field can be used as a first-order proxy to get an indication for wave amplification during a seismic event. This allows a first assessment on wave amplification at sites without sensors at multiple depth levels and without abundant local seismicity.

Introduction

Over the past few decades, increasing numbers of induced seismic events triggered the research on seismic wave amplification in soft sediments overlying the Groningen gas field in the Netherlands (Bommer et al., 2017b; Rodriguez-Marek et al., 2017). Although the magnitudes of the induced events are relatively small (maximum M=3.6 recorded to date), the damage to houses is locally significant. Site characterization is key for appropriate seismic hazard assessment and risk mitigation but it is often a challenge to obtain the correct subsurface properties.

The Netherlands are covered with thick (~1000 m) and very heterogeneous soft Cenozoic clastics. This sedimentary cover has a strong effect on seismic wave characteristics and the amplitude of ground movements at the Earth's surface. When the seismic velocity of the top layer is relatively low, the wave amplitude increases, resulting in stronger horizontal movement at the surface. Many studies have shown that soft sedimentary covers and variations in subsurface lithology can strongly influence the amplification of a seismic wave and hence the degree of damage on buildings (Bard et al., 1988; Bradley, 2012). Recent studies on the Groningen gas field show significant lateral variations in wave amplification and ground-movement during a local seismic event (Kruiver et al., 2017; Rodriguez-Marek et al., 2017).

Motivation

Detailed wave characterization in relation to the subsurface aims to support the design and re-enforcement measures for buildings in areas affected by induced or natural seismicity. Resonance frequencies of Dutch houses are in a range of about 1-4 Hz (Crowley et al., 2018), which is the frequency range at which maximum amplitude oscillation occurs. Therefore, we evaluate seismic wave amplification for this frequency band of 1-4 Hz.

This study is focused on approximately the upper 50 metres of soft sediments, where most of the wave amplification of the horizontal component (S-waves) is observed on borehole seismograms. There are three main factors that influence the amplitude development:

1. Towards the Earth's surface typically there is a reduction of seismic impedance (the material gets softer). As a consequence, the waves slow down and gain in amplitude
2. In soft sediments the wavefield experiences quite large inelastic losses, leading to a reduction of the amplitude.
3. Between an acoustic impedance contrast at depth and the free surface, the interference of multiple reverberations within the soft layer leads to a resonance pattern in which certain frequencies are amplified and others interfere destructively.

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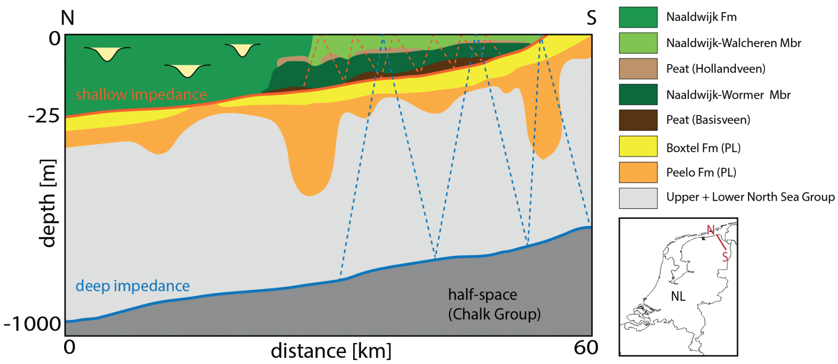

Figure 1 Schematic geological cross section of the soft sedimentary cover in the Groningen region. The Holocene and Pleistocene formations are represented in detail while the deeper part of the North Sea Group is grouped as one layer in light grey. The dashed lines demonstrate wave resonance between the free surface, a shallow (orange) and a deep (blue) acoustic impedance contrast.

Besides the above points, there is the free-surface effect: at the Earth's surface the upgoing and free-surface reflected down going waves are recorded at the same time, leading to an amplitude gain of a factor of 2.

Due to the data density, Groningen is an excellent case study to quantify amplifications at a local scale. Sensors are available at different depth levels and there is abundant local seismicity. For 69 sites we compare earthquake wave amplification with wave resonance of the ambient seismic field (persistent vibrations of seismic waves excited by many different noise sources). The goal is to find a suitable proxy for wave-amplification at sites where it cannot directly be recorded. For the Groningen region, a refined ground motion model has already been developed (e.g. Bommer et al., 2017). The methods developed and findings can be extrapolated to sites with potential seismic hazard were no ground motion model is available.

Geological setting

The Cenozoic sediments named the North Sea Group (NSG) cover almost the complete Dutch shallow subsurface. In this study, we focus on the upper 50 metres of unconsolidated sediments, which is composed of Pleistocene sands overlain by a very heterogeneous Holocene formation (Figure 1). The Holocene formation can be subdivided into several members. The Wormer and Walcheren Members mainly consist of marine clays, silt and fine sand. Two thin peat layers (Basisveen and Hollandveen) subdivide these two members. In the northern part of Groningen, the Naaldwijk Formation mainly consists of sandy channel systems (Meijles, 2015; Wong et al., 2007).

Seismic waves resonate between the free surface and an acoustic impedance contrast in the subsurface. In previous site response studies (Kruiver et al., 2017; Rodriguez-Marek et al., 2017; Spica et al., 2018), the top of the Cretaceous limestones (Chalk Group) is used as reference horizon and is characterized as the deep impedance contrast (blue line in Figure 1) with the NSG clastics. Secondly, a shallow impedance contrast (orange line in Figure 1) occurs between very unconsolidated Holocene soft sediments and underlying more compacted Pleistocene (peri) glacial sands. Soil resonance in this top Holocene layer is highly relevant since Dutch buildings have their maximal period of oscillation in the same frequency range.

Data

For this case study, we used 69 boreholes of the Groningen network, further referred to as G-network (Dost et al., 2017). Each borehole is equipped with an accelerometer at the surface and 4.5 Hz geophones at 50, 100, 150- and 200-metre depth (Figure 2). In addition, several sensors across the Netherlands are used. The data is available via the data portal from the Royal Netherlands Meteorological Institute (KNMI, 1993). All seismometers are continuously recording, picking up both local seismic events and the ambient seismic field. For this study we use 73 local seismic events in Groningen with magnitude > 1.5, recorded with the G-network during a period from 2014 to April 2019. From each borehole in the G-network, a lithological interpretation based on gamma ray logs is available.

Amplification factors from earthquakes

In order to quantify the seismic wave amplification in the upper 50 m, amplification factors are calculated between the surface accelerometer and the geophone at 50 m depth. Figure 3 shows a borehole seismogram for an M=3.4 event, for which significantly higher S-wave amplitudes are measured at the surface accelerometer, compared to those at the 50-m geophone.

For each site we calculated the amplification factor (AF) of the S-waves recorded at the surface accelerometer and at 50-m depth geophone for the frequency band 1-4 Hz. Vector summation of the two S-waves (E and N component) is applied to calculate a maximum averaged amplitude. The amplitude at the surface was divided by a factor of 2 in order to remove the effect of free surface amplification and then divided by the amplitude at 50-m depth (Figure 3). Next, the local AF is obtained by repeating the above procedure for all available M>1.5 events and averaging the

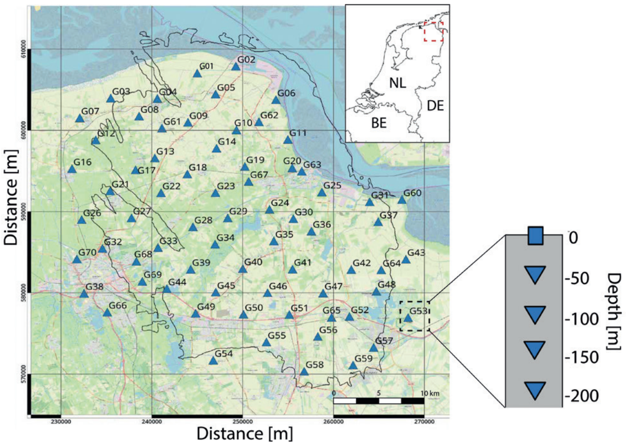

Figure 2 Map of the Groningen network, showing the 69 boreholes that are used for this study.

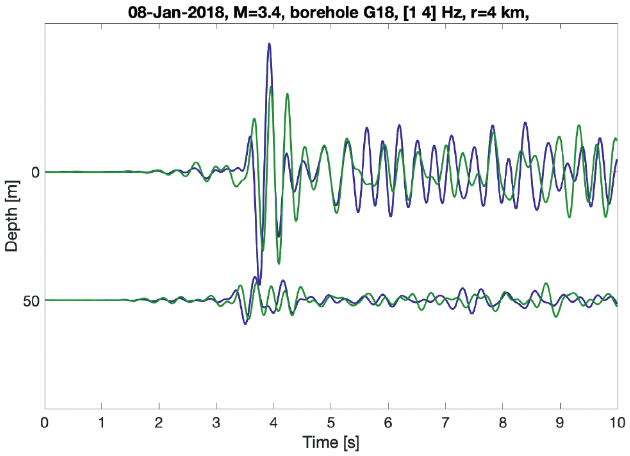

Figure 3 Seismogram of the Zeerijp earthquake in January 2018, M3.4. This borehole is 4 km away from the epicentre. The surface accelerometer shows higher amplitudes for the S-waves (on east and north components) than amplitudes measured at the 50-m depth geophone, plotted for the frequency band 1-4 Hz.

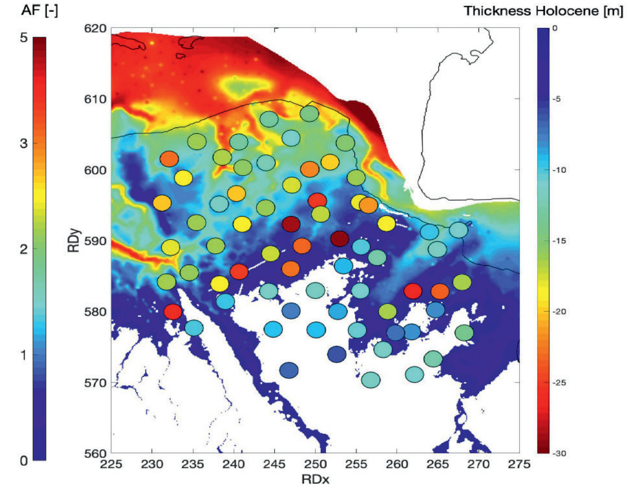

Figure 4 Amplification factors (coloured circles) for all boreholes in the G-network plotted on top of the Holocene thickness map.

values. These calculations are performed at all 69 borehole sites and each local AF is plotted on top of a Holocene thickness map in Figure 4. Lowest AFs are computed in the southern part of the area, where the Holocene is absent. The middle part of the area contains the highest AFs, while in the northern area, the AFs are moderate.

In many site response studies, a hard-rock reference site is used to model amplification factors of soft sediments (Perron et al., 2018). However, the absence of a hard-rock reference site forces us to compare the amplification factors between each site and consider them as relative values.

HVSR from the ambient seismic field

Calculating the horizontal-to-vertical spectral ratio (HVSR) of the ambient seismic field is a widely used approach to measure site characteristics. Many experiments have shown the relationship between the HVSR peak frequency and the fundamental resonance frequency of a site e.g. (Fäh et al., 2001; Scherbaum et al., 2003; Arai and Tokimatsu, 2004; Parolai et al., 2004; Bonnefoy-Claudet et al., 2006). A peak in an HVSR curve occurs at a frequency at which seismic waves resonate between strong impedance contrasts, thus amplifying the ground motion during a seismic event. Commonly, the ambient seismic field consists of surface waves, and for the frequencies between 1-4 Hz, the surface waves are sensitive to shallow lithological variations.

Since we focus on the upper 50 m of the subsurface, HVSR curves from the surface accelerometer are calculated. By averaging the power spectral densities (PSD; McNamara & Buland, 2004) of the two horizontal components and dividing them by the PSD of the vertical component, for each 24 hours an H/V ratio is computed (Albarello and Lunedei, 2013). Subsequently, a distribution is made from 30 daily H/V ratios, where for each frequency a range of amplitudes and their probability of occurrence is plotted (Figure 5). With this method we are able to interpret the HVSR peaks that are stable and use the mean (black line in Figure 5) of the probabilities for further analysis.

The low frequency (0.4 Hz) peak of the HVSR (black arrow in Figure 5) is related to resonance between the free surface and the deep impedance contrast; of top Chalk and the NSG. This peak is considered to be the first higher mode. The fundamental mode at lower frequencies is not well expressed due to a lack of instrument sensitivity at frequencies lower than 0.2 Hz. The low frequency peak of the HVSR PDF is relatively stable, reflecting a stable source. The low frequency ambient seismic field (0.1 to 1.0 Hz) is primarily generated by ocean-wave solid-Earth interaction at the Atlantic Ocean and North Sea.

On the other hand, when moving to higher frequencies, the HVSR probabilities become lower. The sources of the ambient seismic field at higher frequencies are mainly of less stable anthropogenic origin (e.g. traffic, wind turbines), hence the probability of the HVSR curves is lower in this domain. The peak frequency of this high-frequency (HF) peak is related to resonance in the very shallow subsurface (<50 m depth).

Comprehension of this HF peak is crucial to determine the soil fundamental frequency for site effect evaluations. Many studies have shown that the HVSR amplitudes cannot directly be related to actual soil amplification factors (Albarello and Lunedei, 2013; Bard 1999; Bonnefoy-Claudet et al., 2006), the main underlying reason being that a large part of the noise field is composed of surface waves, which have notches in their H/V

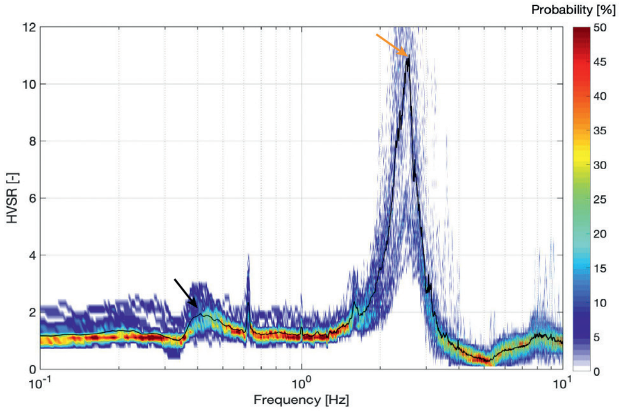

Figure 5 Probability Density Function (PDF) of the HVSR from the ambient seismic field for accelerometer G230. The black arrow points to the peak of the first harmonic from wave resonance between the free surface and the deep impedance contrast. The orange arrow indicates the peak that arises due to resonance between the free surface and the shallow impedance contrast.

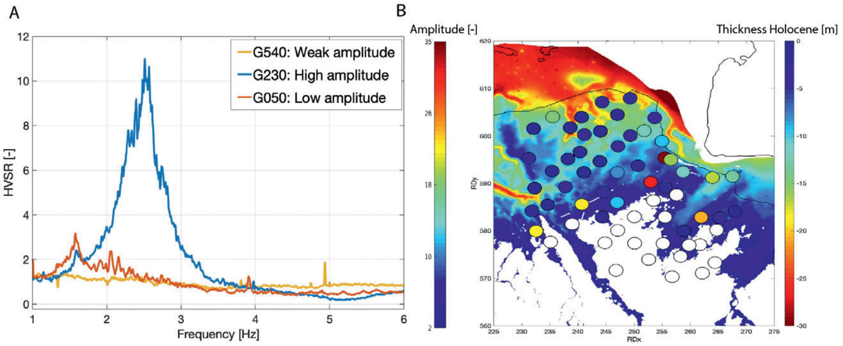

Figure 6 A) Three examples of HVSR curves representing each amplitude regime of high amplitudes (HVSR >5), low amplitudes (2<HVSR <5) and weak amplitudes (HVSR <2). B) For all accelerometers on the G-network, the relative size of the amplitude for the secondary peak are plotted (bubbles) on top of the Holocene thickness map.

ratio. The H/V amplitude that is actually measured is especially a function of the relative contribution of body waves and surface waves in the noise field. Only when steeply impinging body waves are recorded can the H/V ratio be directly be linked to absolute amplification factors. In this study, we do not quantify the height of the HF peak as an absolute value but use the maximum HVSR as a relative size for amplification of the horizontal component at each site in the G-network. The underlying assumption is that at all sites a similar mixture of surface and body waves are recorded.

Based on the HVSR curve characteristics, three regimes of relative amplitudes can be distinguished. High amplitude peaks are defined with an HVSR larger than 5, medium amplitude peaks with an HVSR between 2 and 5, and weak amplitude when HVSR is less than 2. Three examples of HVSR curves representing each regime are plotted in Figure 6a. For the accelerometers at all borehole sites in Groningen, the relative size of the HVSR peak amplitudes in the frequency range 1-4 Hz are plotted on top of a map with Holocene thicknesses, which vary from 0 to 25 m. A relationship has been found between the absence of Holocene sediments and HVSR curves with a weak peak amplitude (white circles in Figure 6b). Furthermore, the highest amplitudes are observed in the central part of the network, where the Holocene layer is relatively thin (<7 m).

Comparison of the HVSR, AF and subsurface composition

So far, we have demonstrated that the AFs calculated from local seismic events (Figure 4) and amplitudes derived from HVSR curves (Figure 6b), do not show significant amplification at sites where the Holocene is absent. Apparently, no impedance contrast is present to cause significant S-wave amplification. The remaining sites display a wide spread of amplifications and in the following section, we present a relationship between the size of the amplification and the subsurface composition, and of the size of the HVSR and the subsurface composition.

The lithology in each borehole in the G-network has been described based on gamma ray logs (Doornenbal et al., 2015). We further simplify the lithology into the three types of soil for the upper 50 m; sand, clay or mixture are distinguished and assigned to each borehole. Peat cannot be conclusively distinguished as lithology from the gamma ray logs. The AF and HVSR amplitude maximum are calculated for each borehole and compared with the soil type in Figure 7. In general, the AFs show a relationship with the soil type: low AF's are measured in sand-prone soils, while high AFs can be linked to a clay-rich soil composition. A similar picture emerges for the HVSR amplitudes: generally lower in sand-prone soils, generally higher in clay.

An impedance contrast is expected between the Holocene formations and the (peri)glacial Pleistocene sands, which are more compacted due to ice sheet loading. The Holocene sediments can be subdivided into several lithostratigraphic formations and members. In general, the sandy channel systems of the Naaldwijk Formation are present in the northern part of the area where lower HVSR amplitudes and AFs are measured. Towards the south, the Naaldwijk-Wormer and Naaldwijk-Walcheren Members are alternating with two peat layers. Here the soil is more heterogeneous and clay-rich, resulting in the highest measured amplification for both the HVSR maxima and AFs. Figure 8 summarizes the relationship between the degree of amplification and the subsurface composition.

The analysis of the Groningen data indicates that HVSR noise can be used as a first-order proxy for amplification. With the HVSR approach we are able to distinguish between sites with

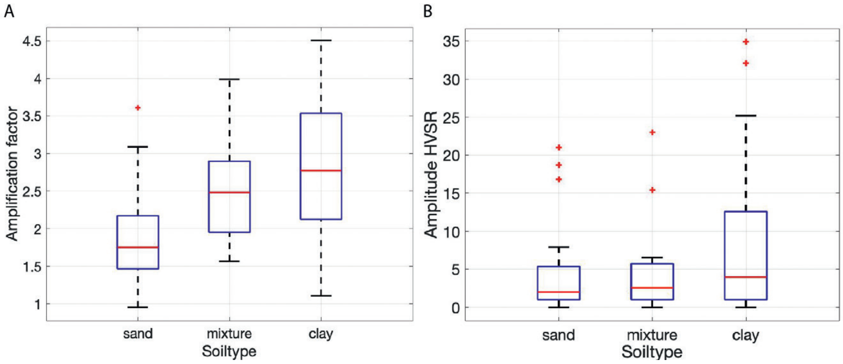

Figure 7 For each borehole, an amplification factor and HVSR amplitude maximum is calculated, and a soil type is assigned. The boxplot shows the data distribution the red central mark indicates the median; the bottom and top edges of the box indicate resp. the 25th and 75th percentiles. The whiskers extend to the most extreme data points and the outliers (1.5x away from the interquartile range) are plotted individually as red crosses. A) Amplification factors calculated from local seismic events, assigned to a soil type. B) The maximum amplitude from HVSR curves, assigned to a soil type.

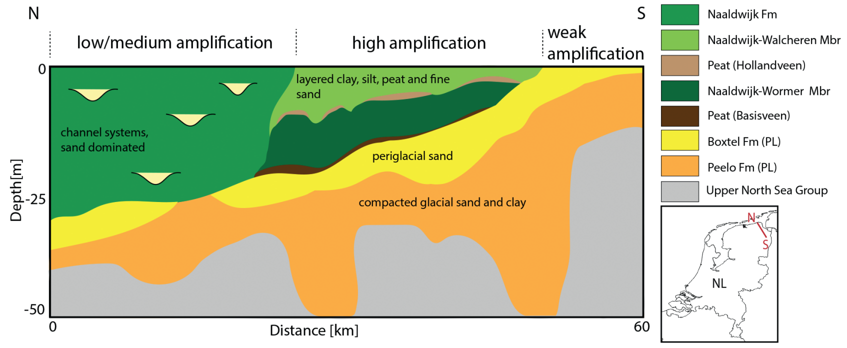

Figure 8 Schematic cross-section of the Holocene and upper Pleistocene Formations for the northeast of the Netherlands. Three amplitude regimes are defined and correlate with different compositions of the shallow subsurface.

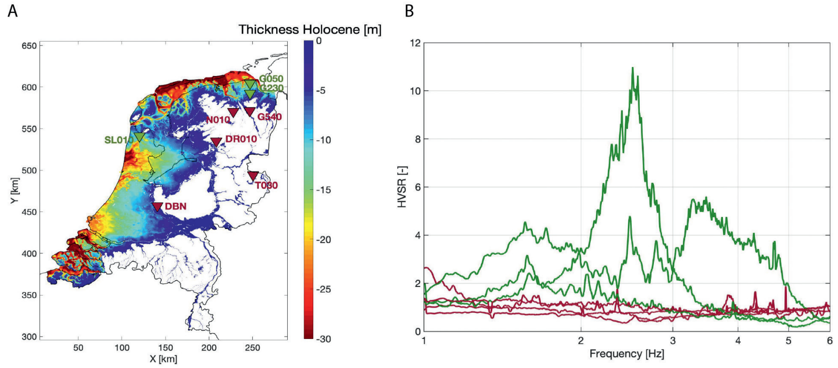

Figure 9 To compare HVSR curves, ambient seismic field data is used from accelerometers at various sites. A) Holocene thickness map with locations of the accelerometers, indicated with triangles. B) HVSR curves of the accelerometers in A; the green curves are sites where Holocene is present and show relatively high amplitudes. At sites were the Holocene is absent, no amplitudes are measured (red curves).

very low HVSRs (<2), intermediate and sites with large HF peaks in HVSR (>5). Therefore, for any potential hazardous site, the presence of relatively high amplitudes can be a first measure for wave amplification during a seismic event. However, with this method the actual amount of amplification cannot be quantified.

Amplification across the Netherlands

With the knowledge of the relationship between subsurface composition and amplitudes from the Groningen network, other sites can also be evaluated using a similar approach. HVSR curves with high amplitude maxima, recorded at accelerometer seismic sensor at the surface, can be a first indication for wave amplification during a seismic event. Subsequently, further research can be done to quantify the actual amplification. To test the HVSR first-order proxy, we have calculated HVSR curves for several sites across the Netherlands (Figure 9). Higher HF peaks are observed at sites where the Holocene sediments are present (green curves in Figure 9b). These peaks are absent in various sites where Pleistocene sediments outcrop (red curves). However, actual amplification of a seismic event could be less or more due to non-linearity of soil behaviour and local variations in Holocene sediment composition.

Conclusions

In this article we explored the possibility of comparing the amplification functions of local seismic events with the relative amplitudes of horizontal-to-vertical spectral ratios (HVSR) derived from the ambient seismic field. We computed amplification factors (AF) for the top 50 m at sites of the Groningen seismic network. For the amplification factors and HVSRs we found a relationship with the presence or absence of the Holocene sediments. For both methods, the highest amplitudes are measured in the heterogeneous and clay-rich part of the Holocene deposits. However, finding a more detailed lithological proxy for local amplification variations remains a challenge.

Significant amplification is observed in both the AFs and HVSR curves, calculated for the frequency band 1-4 Hz. We choose this frequency band because this is corresponding to the resonance frequency for most Dutch buildings. This knowledge on amplification of the horizontal component in this frequency band can be applied to building design for response to a seismic event.

The analysis on the Groningen data implies that HVSR can be used as first-order proxy for amplification for other sites with risk of seismicity. For sites outside Groningen we found significant HVSR values only for sites where the Holocene is present.

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