Unveiling the effects of soil composition on surface motion during seismic events

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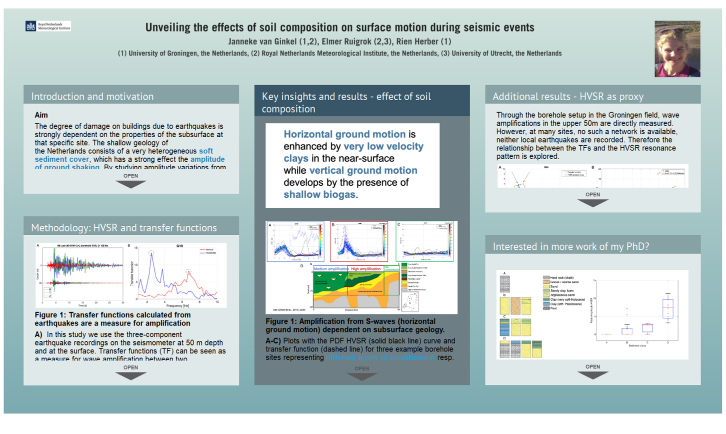
Abstract

The degree of damage on buildings due to earthquakes is strongly dependent on the properties of the subsurface at that specific site. The shallow geology of the Netherlands consists of an heterogeneous soft sediment cover, which has a strong effect on seismic wave propagation characteristics and in particular the amplitude of ground shaking. Where seismic velocities are lower, seismic wave amplitudes are higher. By studying local velocity and amplitude variations from seismic waves, we can obtain constraints on the seismic hazard. Gas extraction in the Groningen field, in the northern part of the Netherlands, is regularly causing shallow (3 km), low magnitude (Mw max= 3.6), induced earthquakes. This region forms an excellent study area due to the presence of a permanent borehole network and detailed subsurface knowledge. The earthquake wavefield consists of shear and compressional waves. Whereas a lot of research has been carried out on the shallow behaviour of the shear waves, this project includes the characterisation of the compressional waves in the shallow subsurface. In this way, ground motions in the vertical direction can be determined in order to support the re-enforcement design for buildings in the areas affected by induced seismicity. The Groningen borehole network is continuously measuring since 2015 and besides earthquakes, it records a wealth of background signals, which is usually called 'noise'. This noise contains low-energetic elastic waves which also resonate within the sedimentary layers. The local earthquake recordings are used to assess how the shallow unconsolidated subsurface geology influences the amplification of compressional waves, amplification can directly be measured because there are geophones on multiple depth levels. For compressional waves we observe a strong relationship between locations with high amplitudes and the presence of peat in the subsurface. Peat is generating biogas, resulting in a partly gas-saturated soil, hence very low seismic velocities. The noise resonance and earthquake amplification patterns are well-matched. Therefore, the learnings from the densely sampled Groningen region are of interest for other areas in the Netherlands with risk of seismicity since the noise resonance can be used as a first proxy to assess wave amplification.

Effects of sediment composition on surface motion during seismic events



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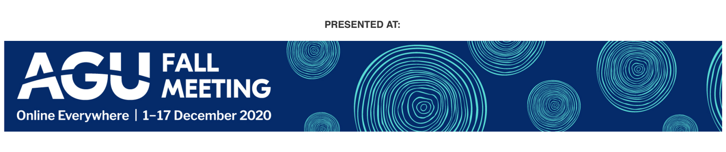


INTRODUCTION AND MOTIVATION

Aim

The degree of damage on buildings due to earthquakes is strongly dependent on the properties of the subsurface at that specific site. The shallow geology of the Netherlands consists of a very heterogeneous **soft sediment cover**, which has a strong effect the **amplitude of ground shaking**. By studying amplitude variations from seismic waves, we can obtain constraints on the seismic hazard.

The Groningen area is used to define a relationship between **wave amplification in horizontal an vertical direction** and the subsurface geology. These learnings can be extrapolated to other areas with risk of seismicity.

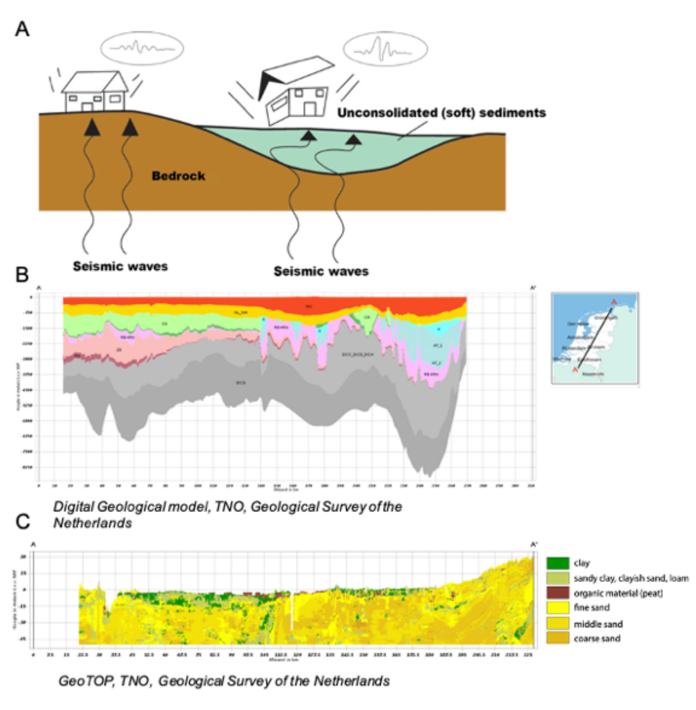


Figure 1: In the Netherlands, earthquake waves are amplified by a soft sediment layer at the surface

A) Cartoon that illustrates the effect of a soft sediment layer compared to bedrock on the propagation behaviour of seismic waves.

B) The Netherlands is completely covered with sediments (red layer).

C) Across the Netherlands, the top layer of soft sediments are very heteogeneous in composition and stiffness, therefore the **level of amplification** is different per location. This is called the **site effect**. The upper 50 m of the sediment layer is composed of very soft Holocene shallow marine clays and peat, overlying in some areas more compacted Pleistocene (peri)glacial sands.

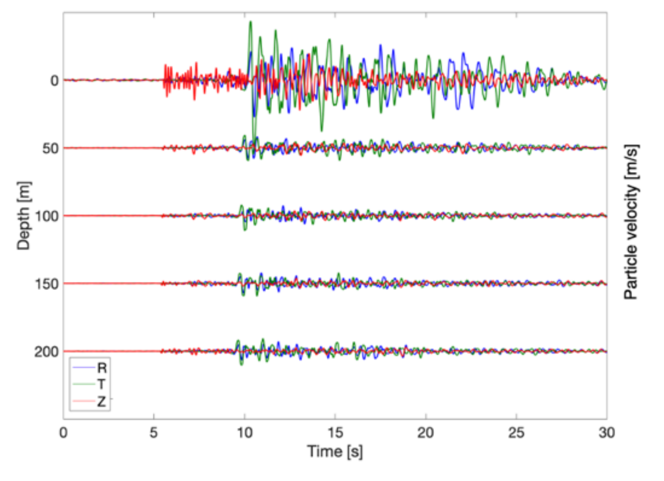


Figure 2: Borehole seismogram for station Groningen G60 for the Zeerijp earthquake (M=3.4)

The red line represents the recordings on the vertical component (compressional waves, P-waves) of the seismometers, while the blue and green lines represent resp. the radial and transverse component (shear waves, S-waves) processed for the frequency range 1-10 Hz. We focus on this frequencies since in general local structures resonate in this range.

This figure illustrates that earthquake wave **amplification mostly takes place in the upper 50m** of the subsurface, and that both P-and S-waves are amplified.

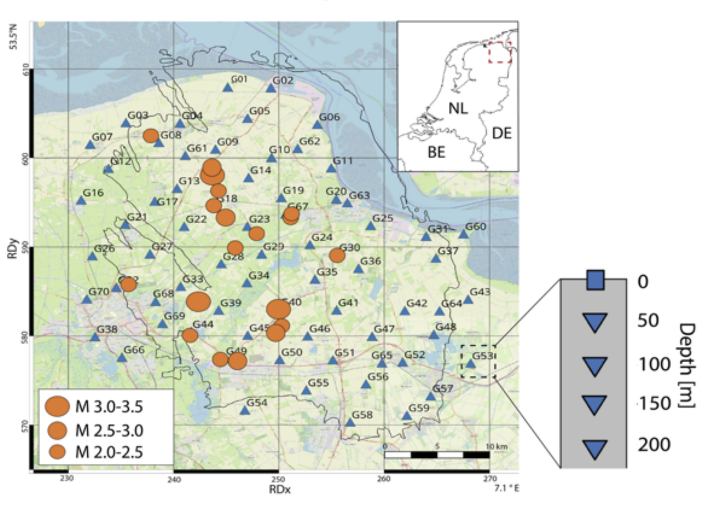


Figure 3: Groningen borehole network (G-network) in the northeast of the Netherlands.

This network is used for our studies. The triangles represent the surface location of each borehole site in the network. Each borehole contains an accelerometer at the surface and four 4.5Hz geophones at depth with a 50 m depth spacing. The orange circles represent the local earthquakes with magnitude 2 or higher, recorded in the G-network since 2015. Coordinates are shown within the Dutch National Triangulation Grid (RD).

METHODOLOGY: HVSR AND TRANSFER FUNCTIONS

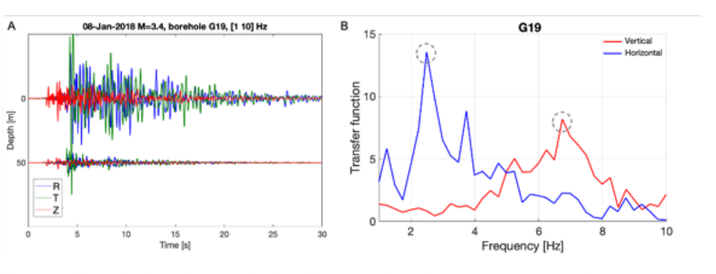


Figure 1: Transfer functions calculated from earthquakes are a measure for amplification

A) In this study we use the three-component earthquake recordings on the seismometer at 50 m depth and at the surface.

B) Transfer functions (TF) can be seen as a measure for wave amplification between two seismometers at a certain depth level. Example of the TFs calculated on the horizontal (blue) and vertical (red) component at borehole G19. The grey circles illustrate the peak amplitude for each transfer function. **These peak amplitudes are further used to make a link with the subsurface geology**.

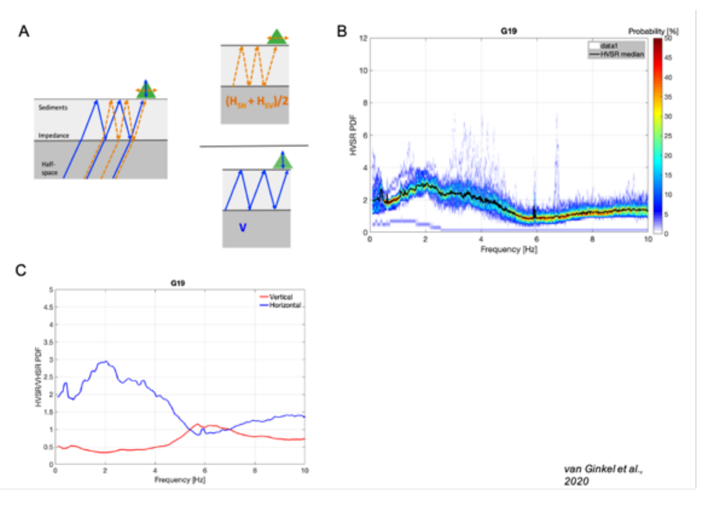


Figure 2: From microtremors, HVSR curves estimate the site effect because of resonance in the sediment layer.

A) This cartoon simply describes the theory behind the horizontal-to-vertical spectral ratio (HVSR) by Nakamura(1989). All kind of sources generate microtremors, unnoticeable for humans. Seismometers measure these microtremors and by dividing the horizontal component over the vertical, **resonance in the sedimentary layer** is estimated.

B) The seismometers are continuously recording the microtremors. By using one month of recordings and constructing probability functions thereof, we are able to derive stable HVSR curves.

C) Example of the HVSR (blue) calculated on the horizontal and VHSR (red) of the vertical component at borehole G19. A **peak in the curve implies resonance and wave amplification.**

KEY INSIGHTS AND RESULTS - EFFECT OF SOIL COMPOSITION

Horizontal ground motion is enhanced by **very low velocity clays** in the near-surface while **vertical ground motion** develops by the presence of **shallow biogas**.

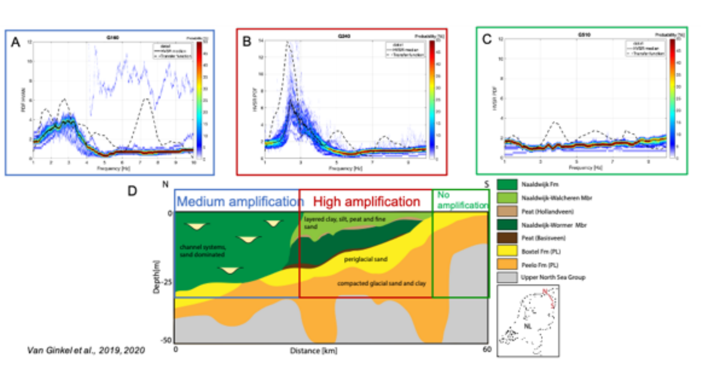


Figure 1: Amplification from S-waves (horizontal ground motion) dependent on subsurface geology.

A-C) Plots with the PDF HVSR (solid black line) curve and transfer function (dashed line) for three example borehole sites representing **different levels of amplification** resp. 'medium', 'high' and 'none'.

D) Schematic geological cross section of the upper 50m of the soft sedimentary cover in the Groningen region. The level of amplification estimated at the borehole locations is linked to the subsurface geology: in **clay and peat develop highest amplitudes.** At locations with stiff **(peri)glacial sands, there is no amplification**.

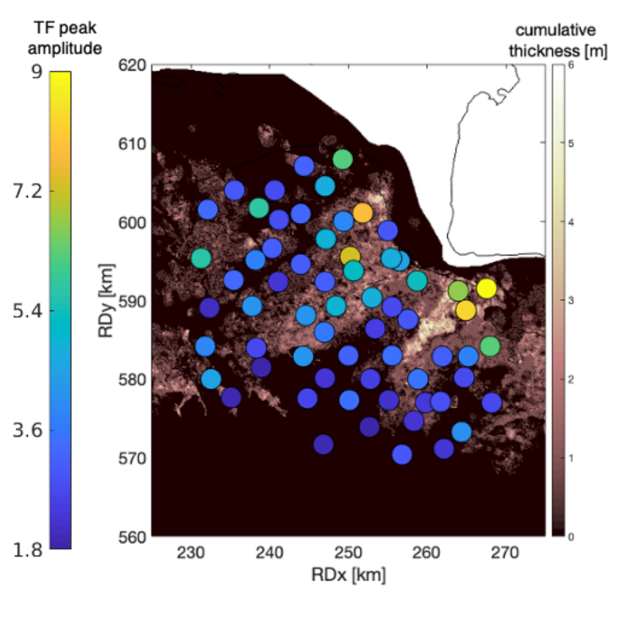


Figure 2: P-waves (vertical ground motion) are amplified at locations with peat in the shallow subsurface.

To assess vertical ground motion, transfer functions are calculated from recordings of P-wave arrivals on the vertical component. This figure shows the peak amplitude of each transfer function plotted against the cumulative thickness of the peat layers. P-wave velocities drop significantly when the subsurface is **partly saturated with gas**, generated by Holocene peat. At these **sites with low velocities, highest peak amplitudes** are measured. Mainly the eastern part of Groningen is experiencing amplification in vertical directions where large industrial facilities and pipeline infrastructure nearby the city of Delfzijl are located.

ADDITIONAL RESULTS - HVSR AS PROXY

Through the borehole setup in the Groningen field, wave amplifications in the upper 50m are directly measured. However, at many sites, no such a network is available, neither local earthquakes are recorded. Therefore the relationship between the TFs and the HVSR resonance pattern is explored.

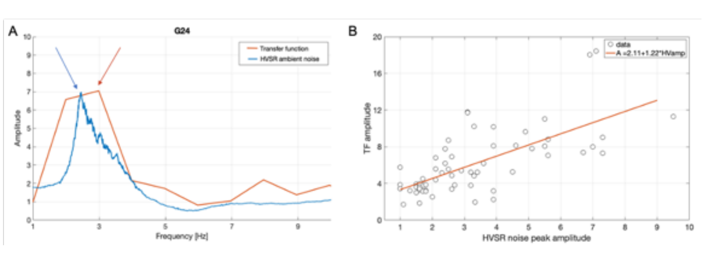


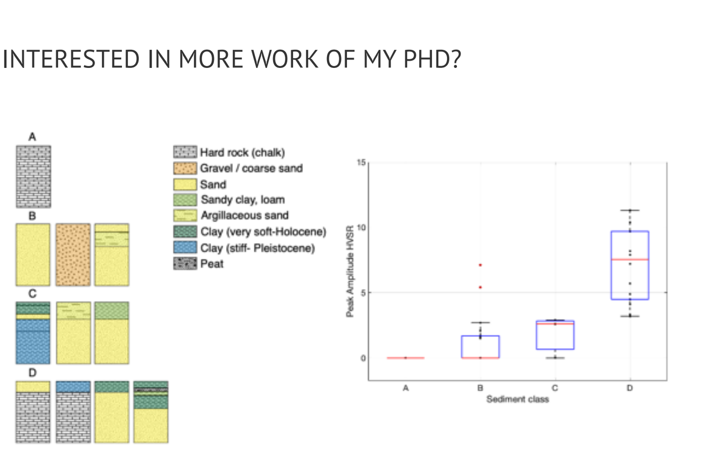
Figure 1: Relationship between the peak amplitudes of the transfer functions and HVSR

A) The curve characteristics and the peak amplitudes, as indicated with the arrows, of the transfer function (red) and the HVSR (blue) are comparable.

B) At all borehole locations in the Groningen network, the peak ampllitudes derived from the TFs and HVSRs are plotted together with a fitting function.

Based on the good correlation between the TFs and the HVSR we can conclude that the **HVSR can be used as proxy for seismic wave amplification** in this sedimentary setting. In general, the HVSR underestimates the level of amplification as measured with the TFs.

INTERESTED IN MORE WORK OF MY PHD?



The learnings from the Groningen Laboratory are applied in other sites across the Netherlands with (a potential of) seismic hazard. To asses amplification at sites with limited data, we construct an amplification classification based on subsurface geology.

Unfortunately, at the time of this live session, I have already presented my further work in the session: S005: Seismology Contributions: Earthquake Ground Motions and Engineering Seismology I, on Monday December 7, 10:30 - 11:30 PST. The oral talk is pre-recorded and you can watch it here.

Link to session S005

[VIDEO] https://www.youtube.com/embed/vh1L7pAwelk?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

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REFERENCES

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