How significant is vertical ground motion from low magnitude earthquakes?

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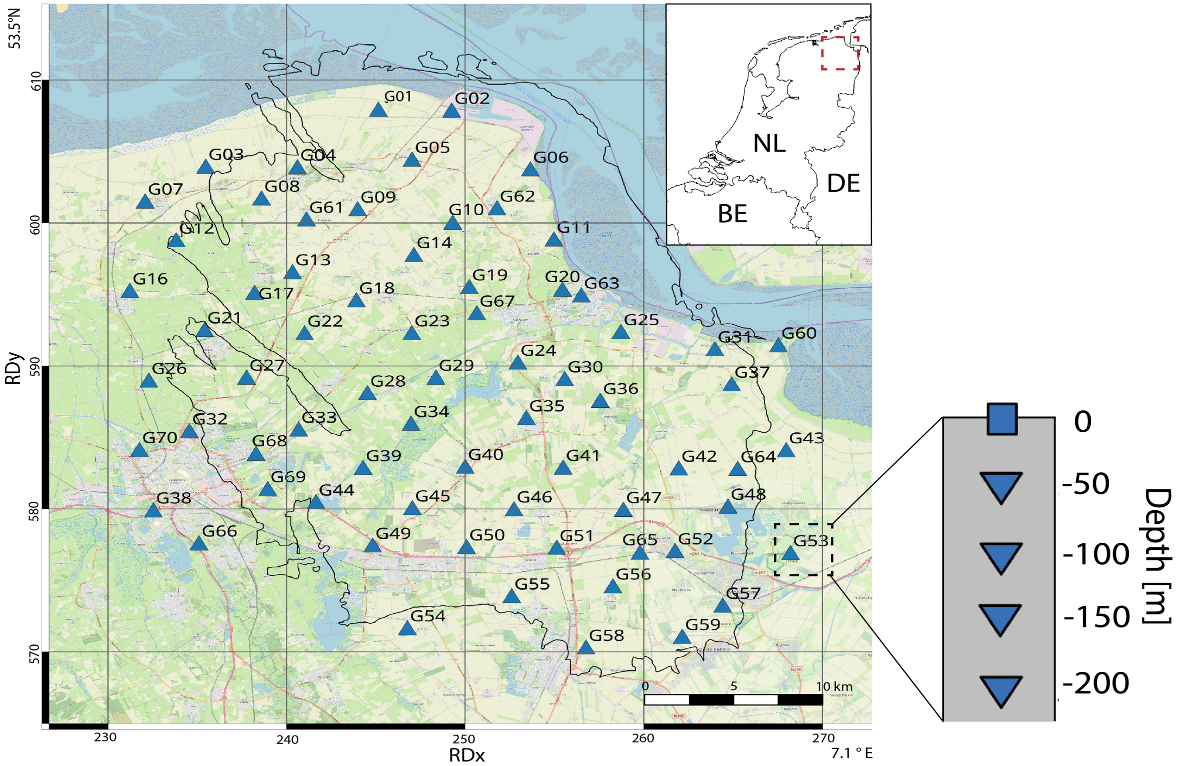
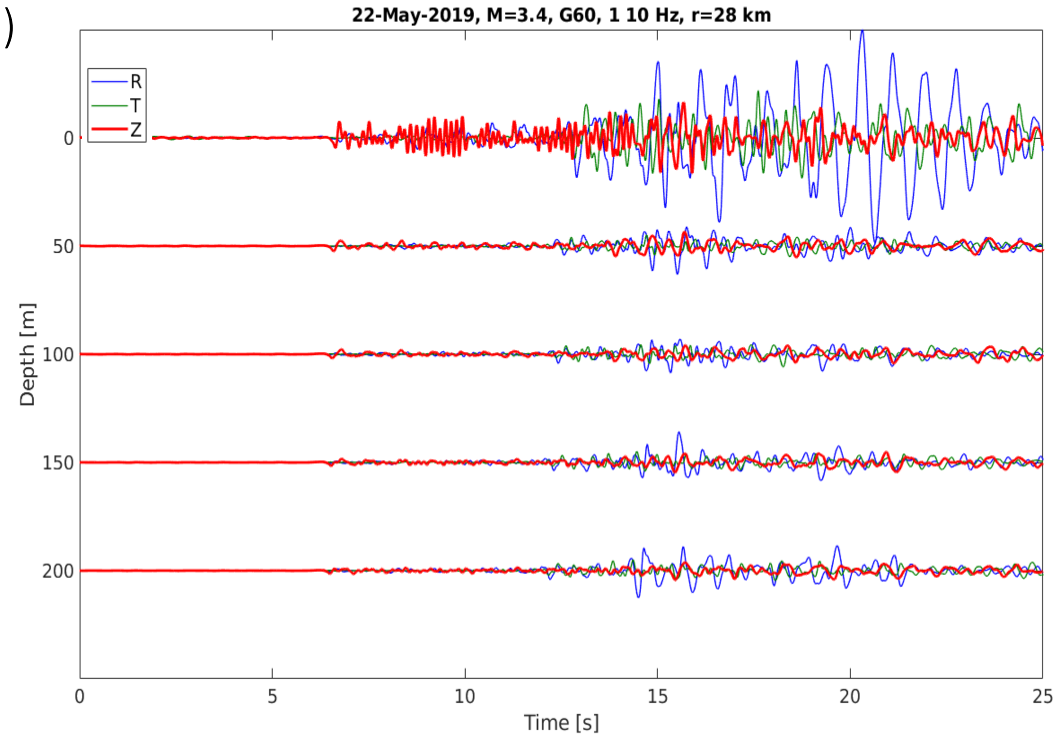
Groningen borehole network

a)



b)



The Groningen borehole network (Fig. a, KNMI) has recorded since early 2015 multiple induced seismic events and forms a great data set to study pressure wave propagation through the near-surface. The Groningen network installed on top of the Groningen gas field consists of 70 stations and each station is equipped with three-component, 4.5 Hz seismometers at 50 m depth intervals (50, 100, 150, 200 m) and an accelerometer at the surface. The stations are continuously recording. We use the three-component data set of earthquake recordings (19) from local events with magnitude two or higher. Seismic events exceeding this magnitude are recorded in the entire network and therefore useful for assessing site response.

The borehole seismogram of the station G60 (Fig. b) does show major amplification in upper 50m for both horizontal (R, T) and vertical (Z) components. This amplification in the upper 50 m is observed to greater or lesser extent in multiple seismograms across the Groningen network (van Ginkel et al., 2019). In the following slides we present several approaches to assess the amplification behaviour of pressure waves, recorded on the vertical component.

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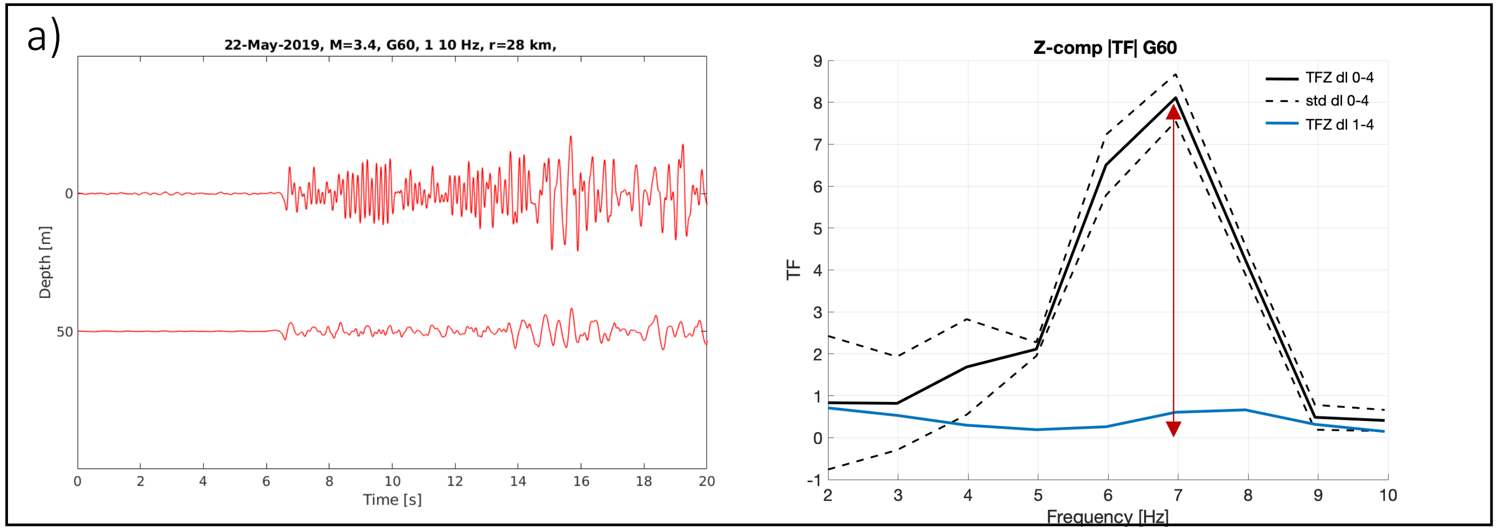
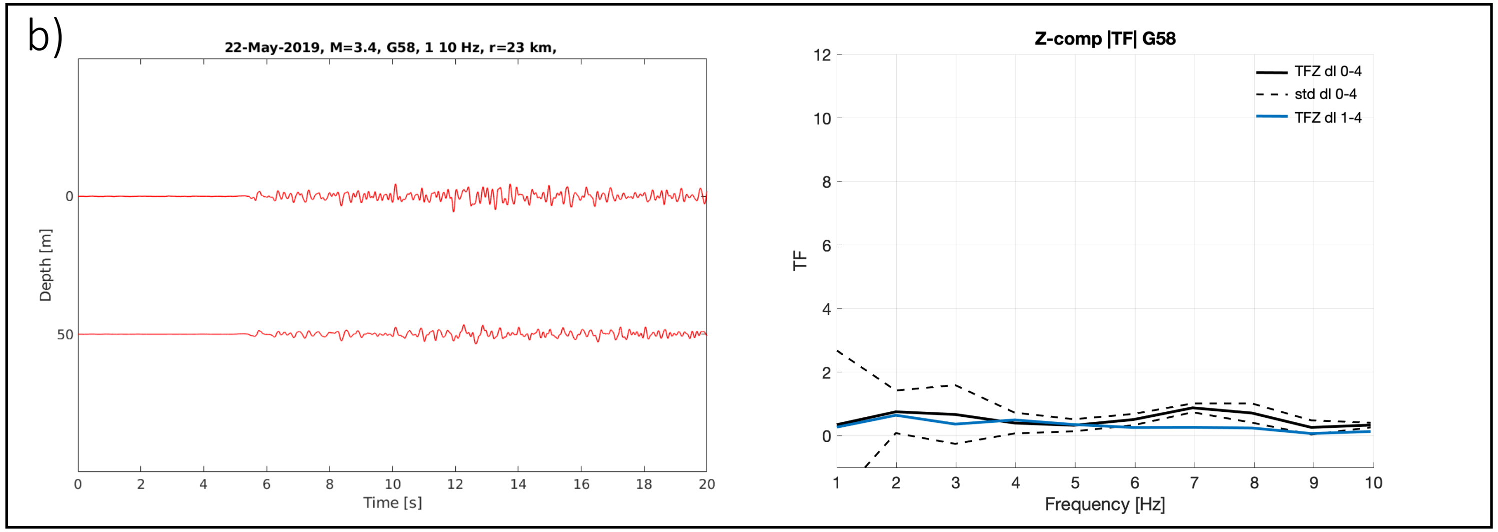
Transfer functions (1)





Transfer functions (TF) can be used to investigate pure vertical wave amplification, independent of shear wave propagation characteristics. We aim to compare the amplification of vertical motion between the surface and 50m depth seismometer from all locations. Examples are shown in Fig. a and b. Transfer functions are closely related to the level of wave amplification and are frequency dependent. The transfer function is defined as:

$$TF_{(m,n)} = \frac{U_m}{U_n}$$

Where U_m represents the total recording in the frequency domain at the layer of interest and U_n is the reference horizon. Thereafter, the final TF (solid black line) is calculated by averaging the TFs from each event and uncertainties are captured in the standard deviation (dashed line). TFs between 50 m and 200m are plotted in blue to illustrate that in this deeper interval, no amplification evolves. The red arrow depicts the peak value (amplitude) for the transfer function.

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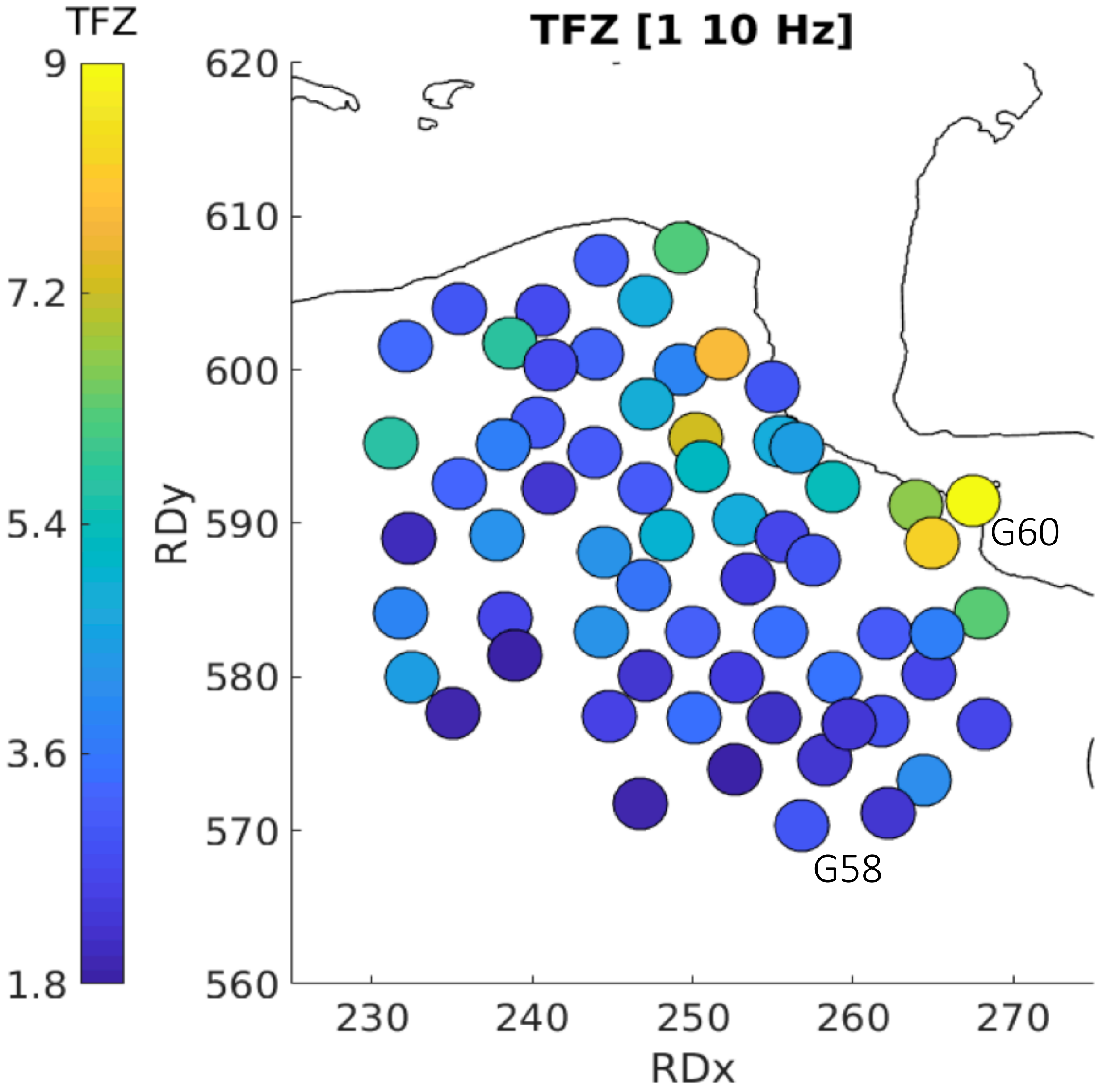
Transfer functions (2)

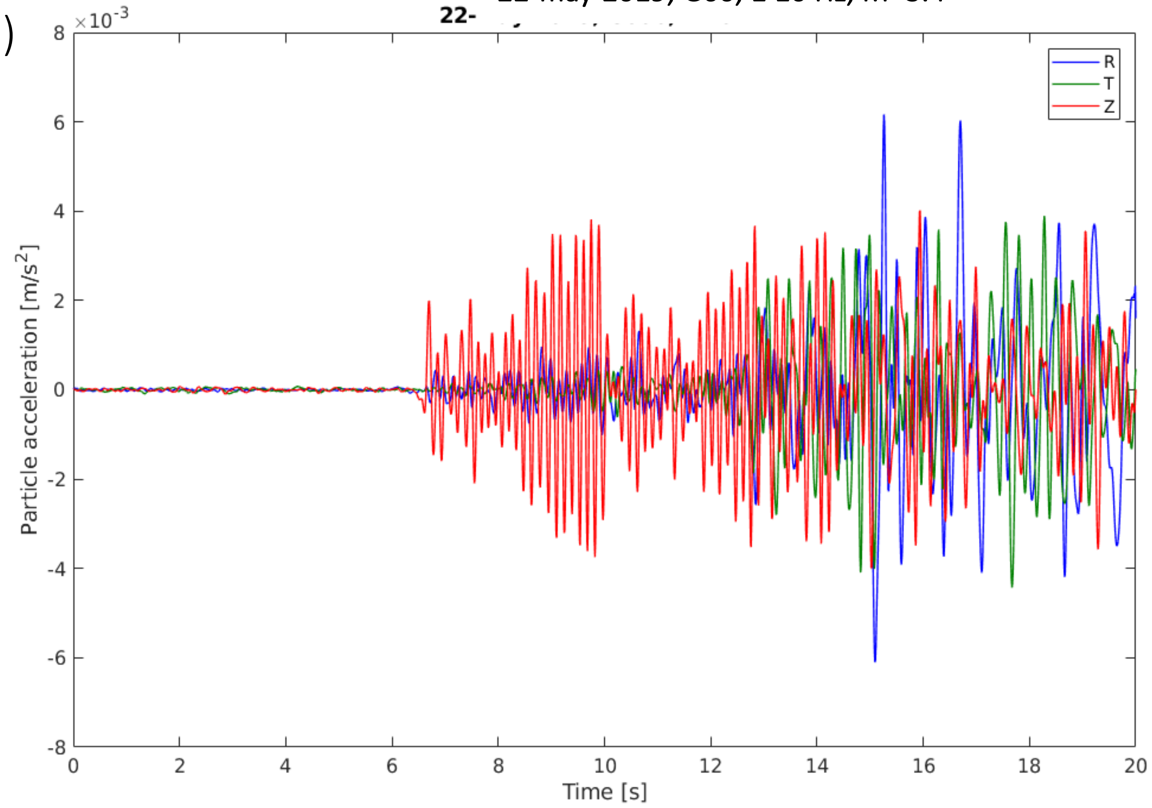


The peak value of the TF (amplitude) is analysed for each location and plotted spatially. The example TFs from locations G58 and G60 are highlighted in the figure.

The distribution of amplitude spectra shows highest values in the eastern section of the region.

VH factor (1)

a)



In case of absence of a borehole network, we investigate how surface seismometers can be used to assess ground motion in the vertical direction.

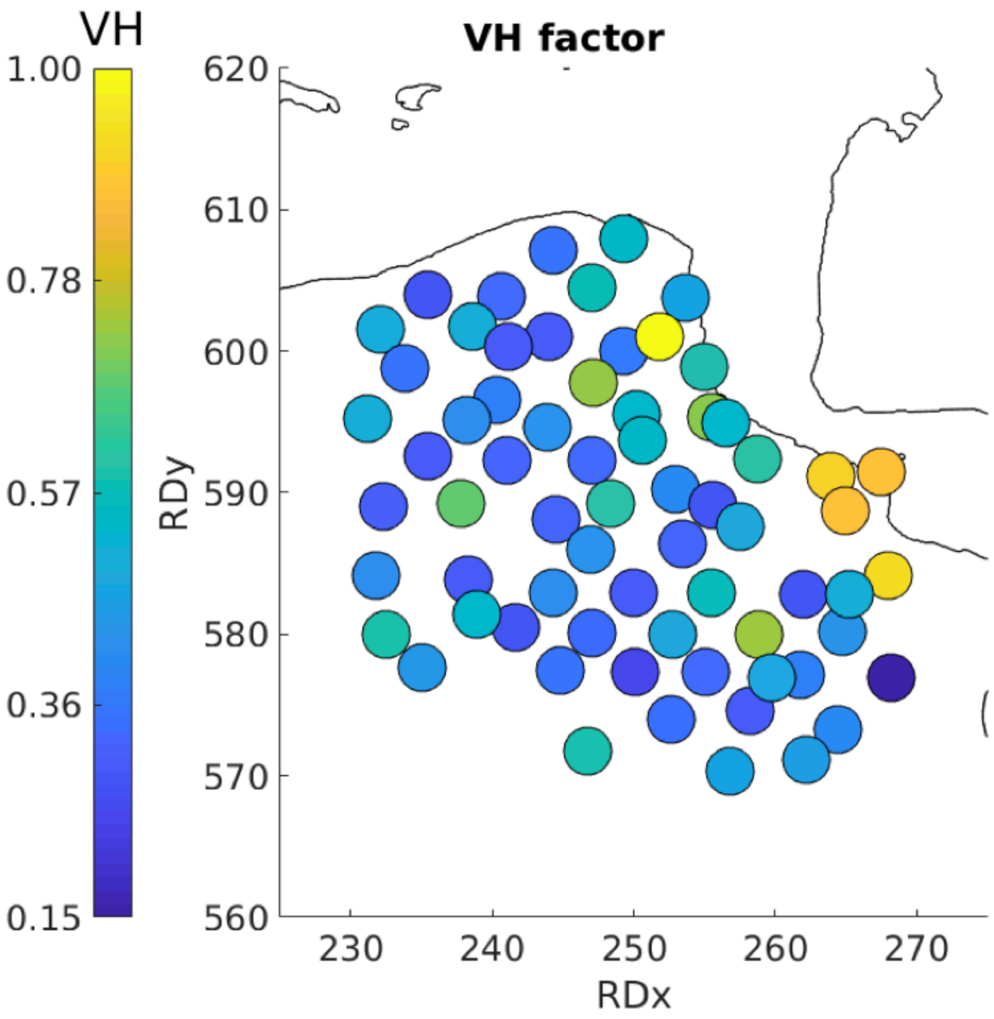
A possible proxy for vertical ground-motion amplification can be established by calculating the VH factor for each site with a seismometer located at the surface. The main aim of estimating the VH factor is to translate the hazard map of horizontal ground motion into a hazard map for vertical ground motion. Kramer et al., 1996 defines peak horizontal acceleration (vector sum of R-and T-component) and peak vertical acceleration (Z) simply by the largest absolute value obtained from the accelerogram of that component (Fig. a). Here, the VH factor is calculated for each local seismic event with magnitude larger than 2, across a frequency band of 1-10 Hz:

$$VH = \frac{Z_{\max(0)}}{\sqrt{E^2_{\max(0)} + N^2_{\max(0)}}}$$

In the VH factor is a strong influence of the source radiation pattern. However, by averaging over many sources, we aim to reduce this source influence and focus on the site effect.

VH factor (2)

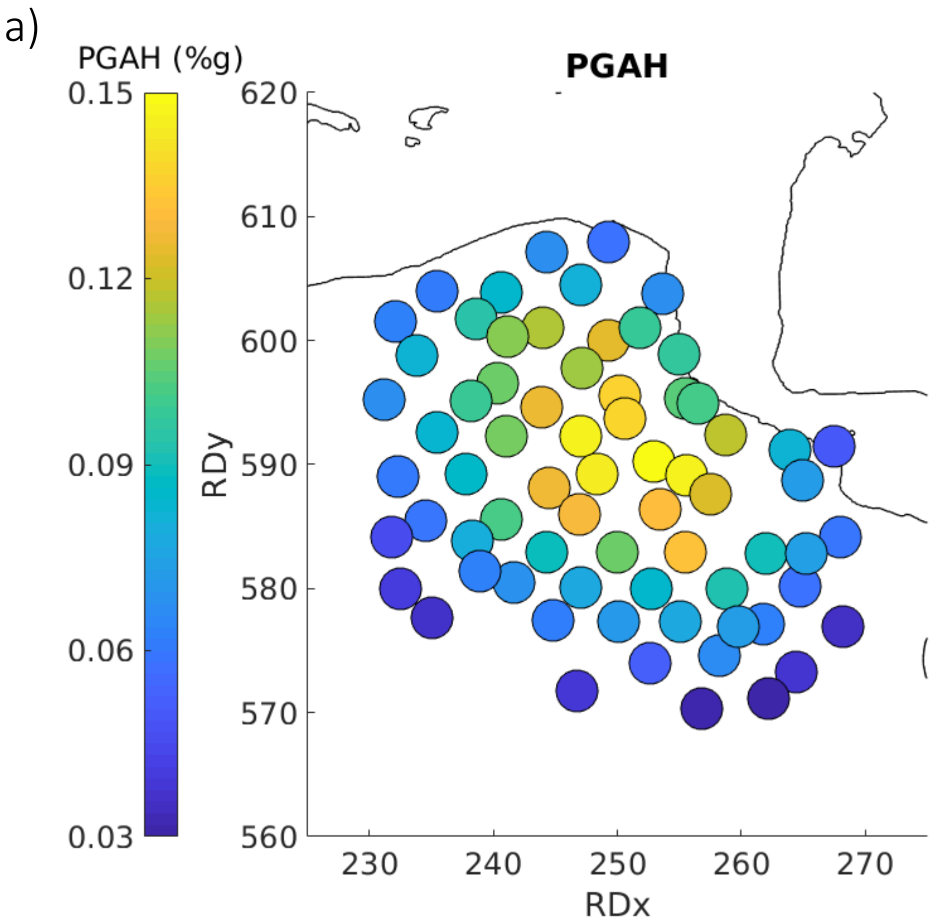
a)

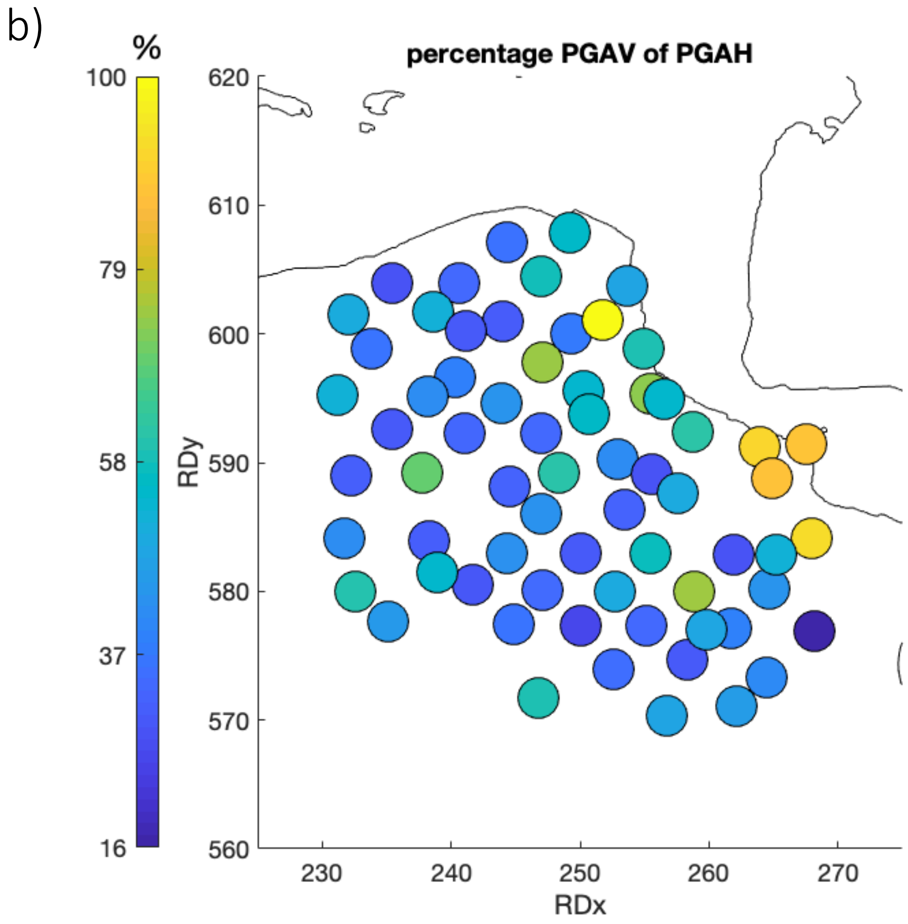


From 19 local events, for all accelerometers in the Groningen network, the VH factor is calculated, averaged and plotted in Fig. a. Here we observe an increase in VH factor towards the east and a diversity in values, ranging from 0.15 to 1.0. Here, the diversity in VH factors illustrates the interest in assessment of amplification per site instead on using a standard factor of 2/3 of horizontal PGA.

The main aim of estimating the VH factor is to translate the hazard map of horizontal ground motion into a hazard map for vertical ground motion.

Peak vertical acceleration





Based on the ground motion prediction equations for Groningen (Bommer et al., 2017) horizontal peak ground accelerations (PGAH) for a return period of 475 years are established and plotted for each location of the Groningen network in Fig. a. For each location, the PGAH can be converted to a vertical peak ground acceleration (PGAV) by multiplying the PGAH with the VH factor. For all locations, the PGAV is lower than the PGA, except site G62. Figure b shows PGAV as percentage of PGAH, illustrating highest accelerations in the eastern part of the region.

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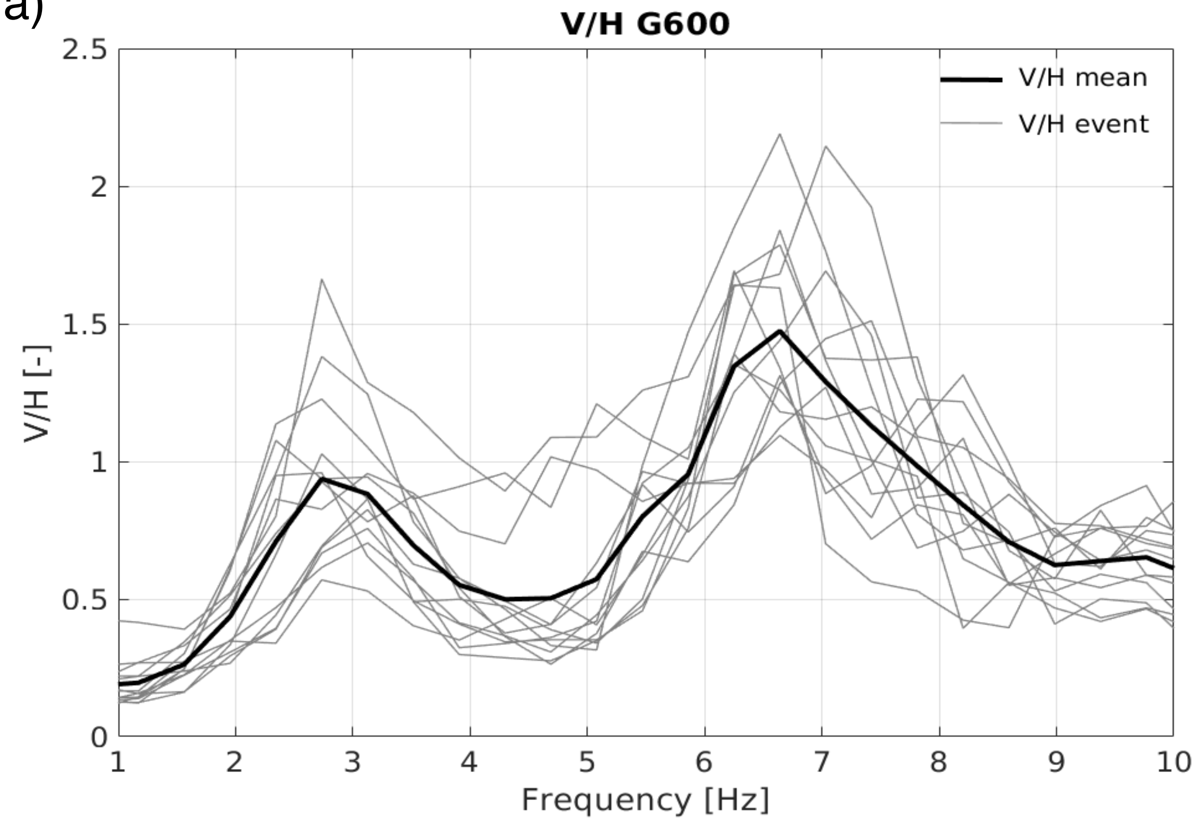
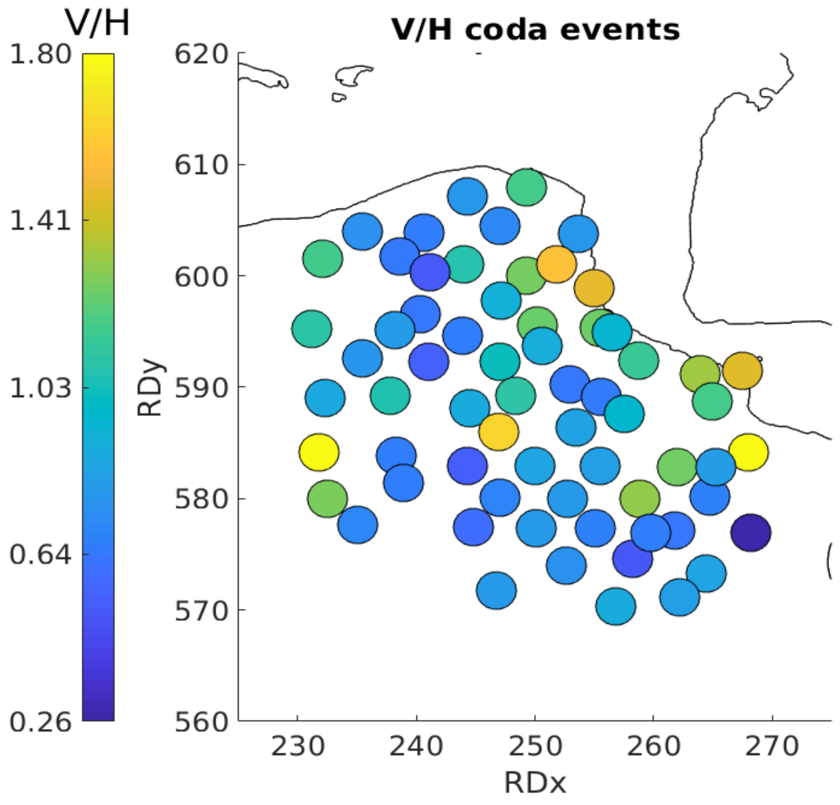
V/H spectral ratios

a)



b)



In addition to the VH factor, we briefly show the results of calculating V/H spectral ratios (VHSR), another approach to investigate vertical amplification with only a seismometer at the surface. The Groningen local seismic events have very short windows for the first P-and S-arrivals so no stable VHSR can be calculated from this part of the wave. Therefore, the coda window is chosen to calculate VHSR from. From each location, from the 19 local events, average VHSR are computed and peak amplitudes defined (Fig. a). Distributions of VHSR peak amplitude spectra for each location in the Groningen network are plotted in Fig. b.

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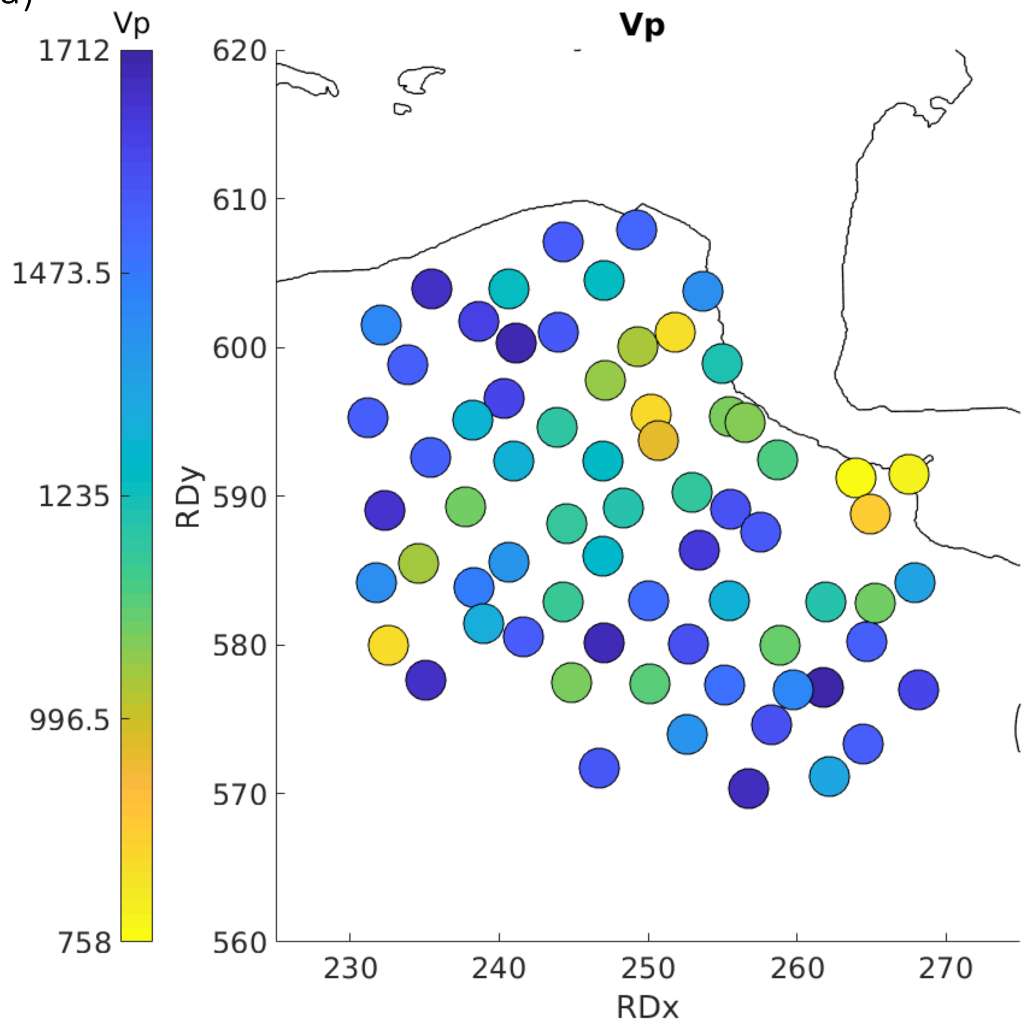
Relationship with seismic velocity

a)



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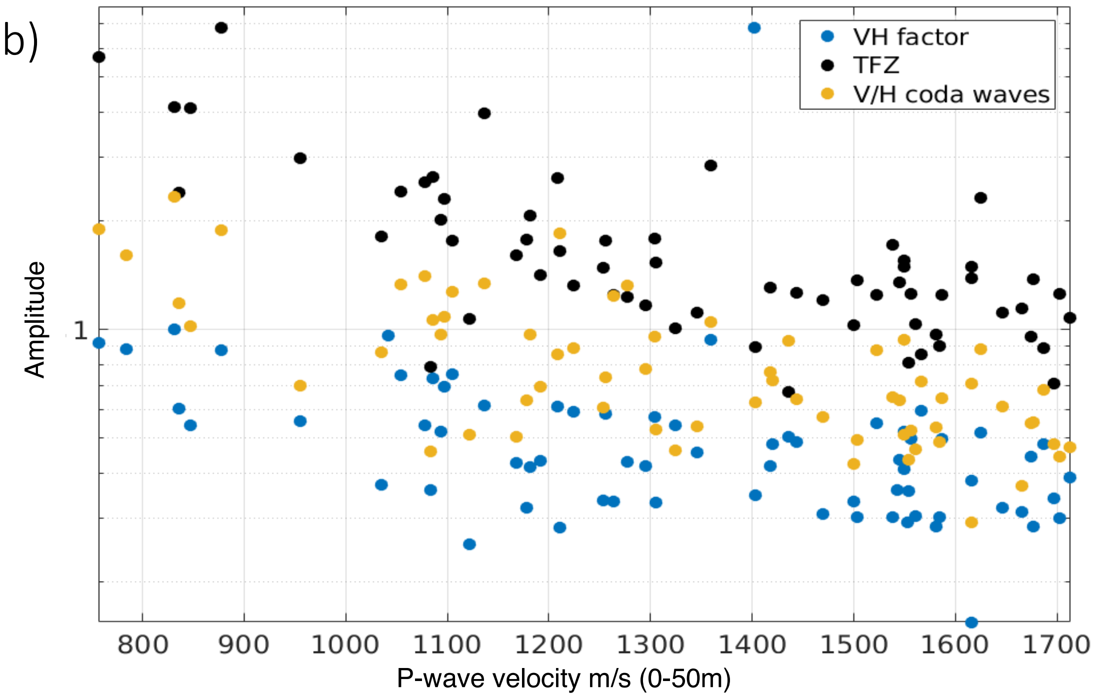
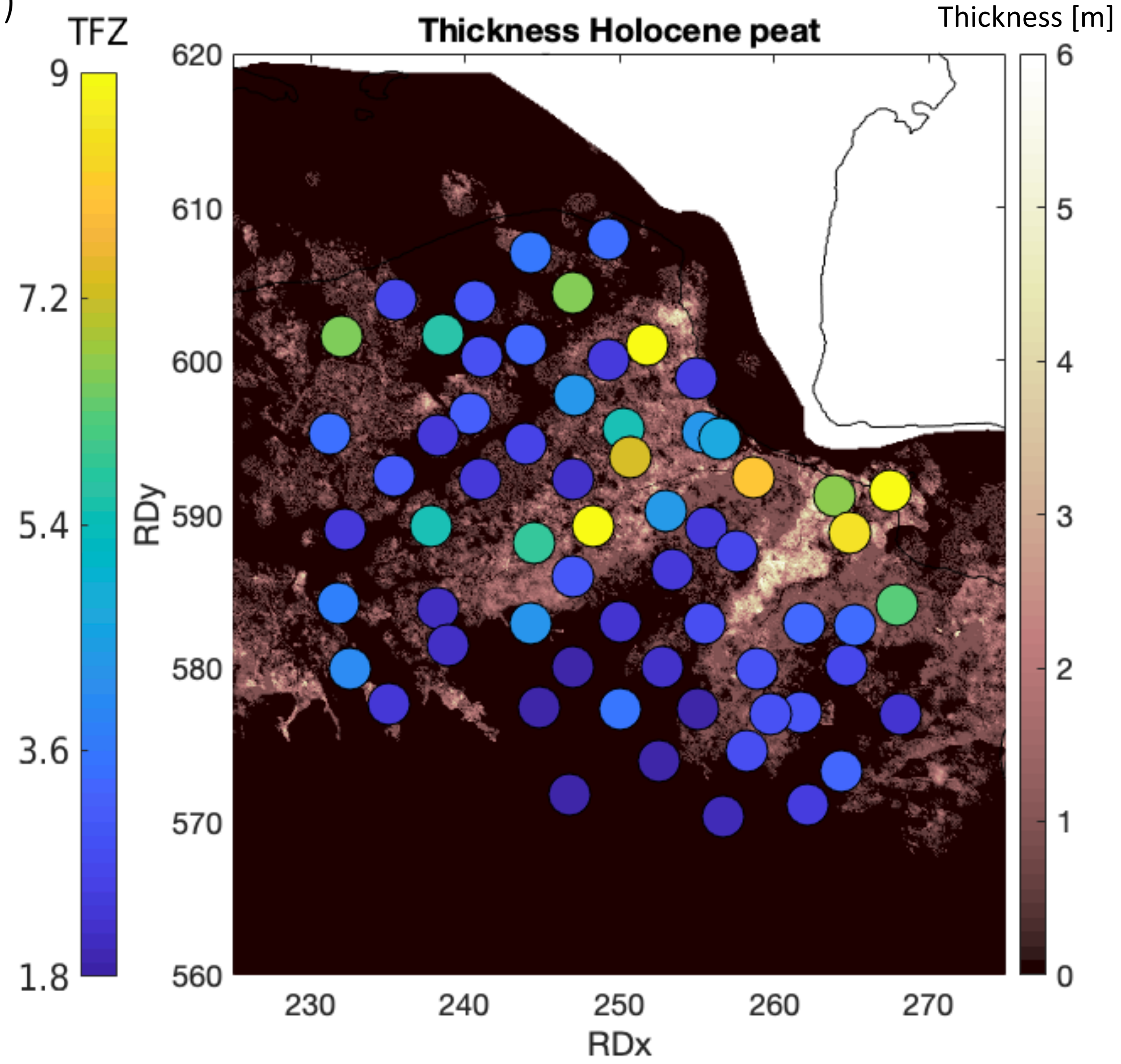


The amplitude distribution discussed in previous slides shows a consistent pattern of increased amplitudes in the eastern region. Amplification is constrained by seismic velocities, hence the comparison is created between amplitude and seismic velocity distribution. Despite the extensive data set available for shear wave velocities in the shallow subsurface, for the pressure wave velocities, only average velocities for the upper 50 m are available for each borehole location (Hofman et al., 2017, Fig. a). Low seismic velocities correspond to locations with highest amplitude spectra (Fig. b). Although the main aim of estimating the VH factor is to translate the hazard map of horizontal ground motion into a hazard map for vertical ground motion, we observe a clear correlation with amplification, hence the VH factor is also plotted in this figure.

Relationship with subsurface

a)



Map based on GeoTOP v1.3 by TNO – Geological Survey of the Netherlands

The transfer functions indicate amplification in the upper 50 m and therefore the soil composition in this interval is examined. The locations of extremely low P-wave velocities correspond to the locations with highest amplitudes measured. Subsequently these locations are compared to cumulative thickness maps of the existing lithologies in the upper 50 m of the Groningen subsurface and best match is observed between TF amplitudes and the cumulative thickness of peat (Fig. a).

Although the thickness of the peat is relatively small (less than 1 and up to 5 m) in the upper 50 m, apparently it has a significant influence on pressure wave characteristics. Pressure waves are, in contrast to shear waves, highly dependent on the bulk modulus, and subsequently dependent on the level of saturation. In Groningen, the water table is fluctuating slightly through the year but can be considered as relative stable and up to the surface. However, already a very small amount of gas changes the stiffness of a medium since gas compresses much easier than water. Therefore in a gas-saturated medium the pressure wave velocities are significant lower. Peat generates biogenic gas, and is overlain by a non-porous clay layer, trapping the gas. This has a strong influence on the amount of saturation of the soil hence on pressure wave velocities and amplification.

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Is it significant?

Conclusions

- Across the Groningen network, vertical PGAs are smaller than the horizontal PGAs. However, we observe quite a range in vertical PGA, indicating site-dependent behaviour of the pressure waves.
- For the selected frequency range of 1-10 Hz, the amplitude spectra of the transfer function estimates and VHSR revealing similar maximum amplitudes at sites were the P-wave velocities are extremely low. However, per site, their mutual amplification values are different since different parts of the waveform are used (full waveform, maximum amplitude and coda window).
- In case of a borehole seismic network, transfer functions would describe amplification most appropriate. However, in many cases only a surface seismometer is available for analysis. In this case, VH factor and VHSR can be used as proxy on vertical wave amplification.
- The peak amplitude values for vertical ground motion presented in this study tend to exceed the rule of thumb value of being 2/3 of horizontal motion, especially when soil is not fully saturated with water but with small amounts of gas, generated by the shallow peat layer.
- Finally, we conclude that each site should be assessed individually for site response in vertical direction. Furthermore, detailed geological classification and additional focus on level of saturation and presence of gas is required to assess vertical ground motion.

References

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