Are Love- and Rayleigh seismic waves detectable in Groningen?

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Summary

This note discusses seismically induced surface-waves and their relevance for induced seismicity in Groningen.

First, a general theoretical introduction of seismically induced body and surface waves in given, followed by a discussion of surface waves with other causes than seismicity. The second section explains why scientists are interested in seismically induced surface waves.

The final section addresses the relevance of surface waves for Groningen. A close look at the data collected for both the Hellum (M_L = 3.6) and Huizinge (M_L = 3.1) earthquakes shows that no surface waves were generated by these two earthquakes. Next the accelerometer records from regional earthquakes ($M_L \geq$ 4.0) earthquake were reviewed. This showed that neither the Weeze (M_L = 4.5) earthquake in Germany nor the Kerkrade (M_L = 4.0) generated surface waves within distances comparable to the extent of the Groningen field region. This lack of surface waves seen for these earthquakes is in line with the theory outlined in the first section of this note.

Larger earthquakes are required to generate surface waves. The earthquake in the Aegean Sea (M_L = 6.3) on 12th June 2017, generated surface waves which were recorded all over Europe. In Groningen, the amplitude of these waves would have been in the order of 10's of microns with a period of approximately 0.04 Hz and a wavelength of approximately 90 km (comparable to the distance from Groningen to Zwolle).

Seismic waves introduction

An earthquake is a sudden slip on a fault which occurs when the shear stress on the fault exceeds the fault frictional strength. When an earthquake occurs, two types of waves are generated and radiate spherically outwards from the fault surface that had slipped. The two types of waves are the primary, pressure waves or P-waves, and secondary, shear waves or S-waves. These are known as body waves because they travel through solid bodies, planet Earth including (figure 1). When body waves propagate through and reach a free surface, a new type of waves called surface waves are generated.

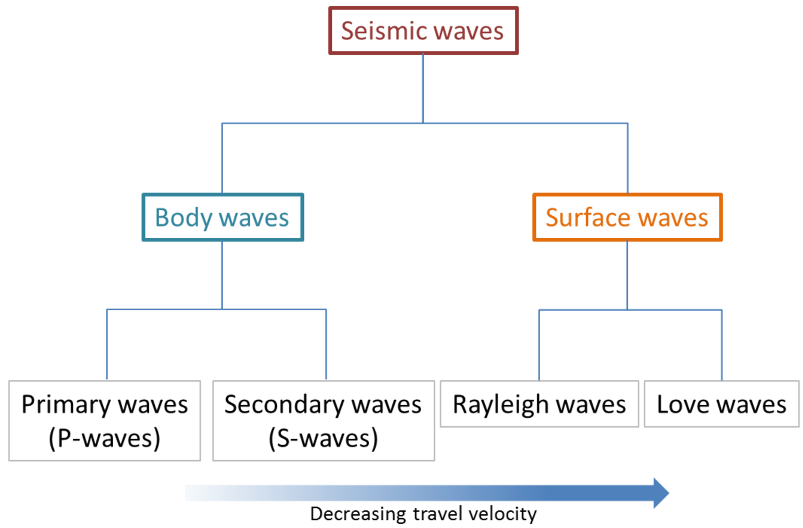


Figure 1. *A schematic depicting the types of waves generated by an earthquake. All earthquakes generate body waves (P and S), however surface waves are generated under special circumstances discussed later.*

The travel velocity of the body waves is as suggested by their respective names: P waves are the fastest and thus arrive first at the recording stations, followed by the S waves. Surface waves travel at a fraction of the S wave speed and are therefore recognizable in seismograms as the last arrival (figure 2). The surface waves tend to have the largest amplitudes because they attenuate at a different rate than the body waves due to different geometric spreading (from propagating along a surface versus through a solid body).

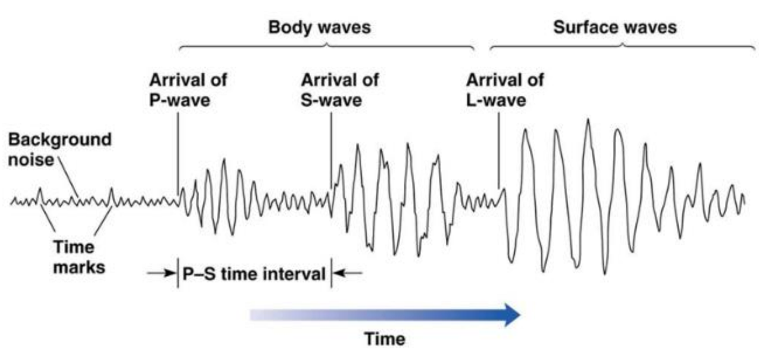


Figure 2. *A generic example of a seismogram showing time delay and relative amplitudes between P, S, and surface waves respectively. Local earthquake recordings usually exhibit the P and S wave arrivals and no surface wave arrivals.*

The particle motion excited by each set of waves is as follows: P-waves compress and dilatate the medium in the direction of motion or the longitudinal direction (figure 3, inset b); S-wave motion is pure shear, polarized perpendicular to the propagation direction (figure 3, inset c). S-wave particle motion can be divided into two components: the motion within a vertical plane through the propagation vector (SV-waves; illustrated in figure 3, inset c), and the horizontal motion in the direction perpendicular to this plane (SH-waves; particle motion is perpendicular to the motion shown in figure 3, inset c). Rayleigh waves move the ground particles in an elliptical motion, much like the ocean waves, and Love waves excite horizontal motion, like that of the SH waves.

Body waves

Primary waves (P-waves or pressure waves)

- They are the fastest waves (travelling at speeds twice that of S-waves) and are the first to be recorded during an earthquake.
- They travel through solid, liquid and gaseous materials.
- They are similar to sound waves in that they are longitudinal waves, with the particle movement in the same direction as the wave propagation (figure 3, inset a).

Secondary waves (S-waves or shear waves):

- They arrive at the surface with some time-lag after the primary waves.
- They are slower than the primary waves and can only travel through solid materials.
- They are transverse waves, causing of particle movement in directions perpendicular to the wave propagation direction (figure 3, inset c).
- S waves are polarized into SH and SV waves with particle motion in the horizontal and vertical planes, respectively.

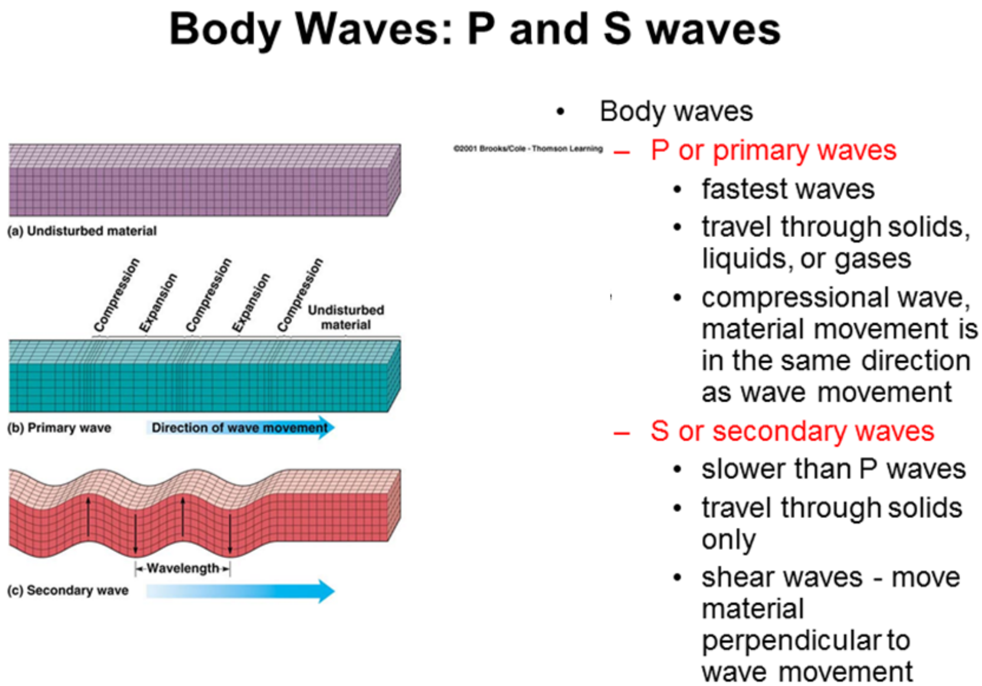


Figure 3. *A schematic of the type of ground motion experienced during propagation of the P and S waves. Seismic strain represented in this figure is highly exaggerated for enhanced clarity.*

Surface waves

There are two types of surface waves: Love and Rayleigh waves. Love waves (L waves in the title of figure 4) are generated by continual reflection off the Earth's free surface and the subsequent interference of the down-going SH waves with those turned back toward the surface. In other words, Love waves are formed through the constructive interference of the higher order SH surface multiples. In contrast to the Rayleigh waves, Love waves show no vertical motion. The particle motion is polarized in the horizontal plane and perpendicular to the direction of propagation (figure 4, inset b). Consequently, Love waves are best displayed on horizontal component seismograms.

The Rayleigh waves (R waves in the title of figure 4), are generated by a more complex interaction of the P and SV waves with a free surface. The particle motion caused by Rayleigh waves is of a rolling nature, similar to the ocean waves: as the wave propagates from left to right, particles follow a counterclockwise rotational orbit in the vertical plane (figure 4, inset a). At the Earth's surface, the amplitude in the vertical and horizontal directions are related roughly as 3:2. Hence, Rayleigh waves are usually best seen on vertical component seismograms. Amplitudes of Rayleigh waves decrease exponentially with increasing depth. For example, at a depth equal to one wavelength, the vertical and horizontal amplitudes fall to 0.19 and 0.11 of their free-surface values, respectively. The velocity of the Rayleigh waves is between 0.87 and 0.96 times the S-wave velocity thus Rayleigh waves arrive behind S waves.

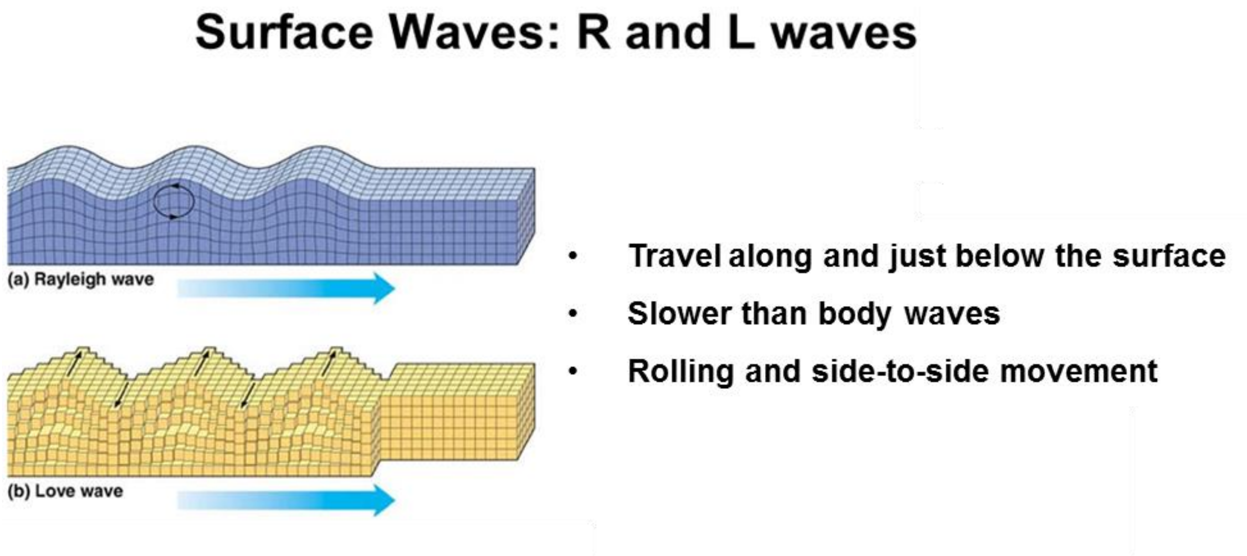


Figure 4. A cartoon representation of the type of ground motions experienced during propagation of Love and Rayleigh waves. Seismic strain in the schematic is highly exaggerated for enhanced clarity, in comparison to actual seismic strain in the Earth.

Because surface waves travel at a fraction of the S-wave velocity, some time is needed for the surface waves to differentiate behind the S-wave arrival (figure 5, inset). In fact, this time difference in the arrival between the surface wave and S-wave allows for a first rough estimate of whether an earthquake is local, regional, or teleseismic (i.e the epicenter-to-measuring stations distance is over ~1,000 km). This rough classification is of great help in choosing the proper approach, criteria and tools for further more detailed seismogram analysis, source location, and magnitude determination.

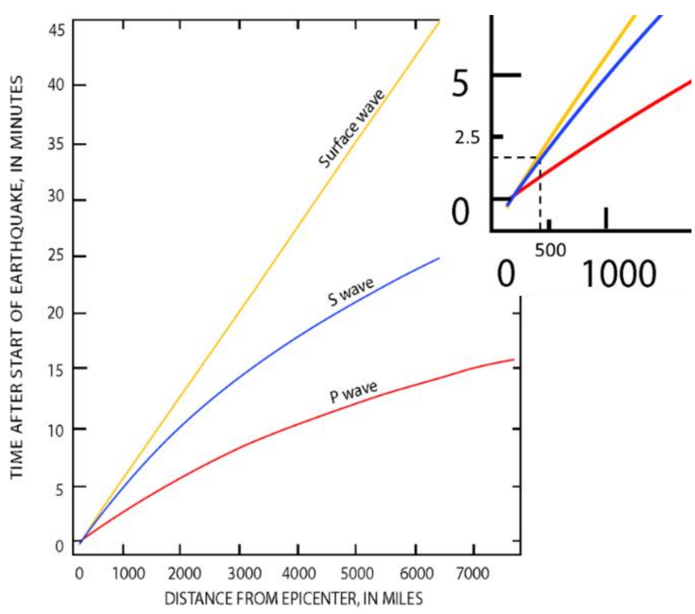


Figure 5. A simplified travel-time curve showing the expected arrivals of P, S and surface waves at a range of distances from the epicenter. The inset shows a zoom-in into the near-field region to highlight the approximate epicentral distance and time needed for the emergence of the surface wave out of the S wave arrival. Source: www.iris.edu

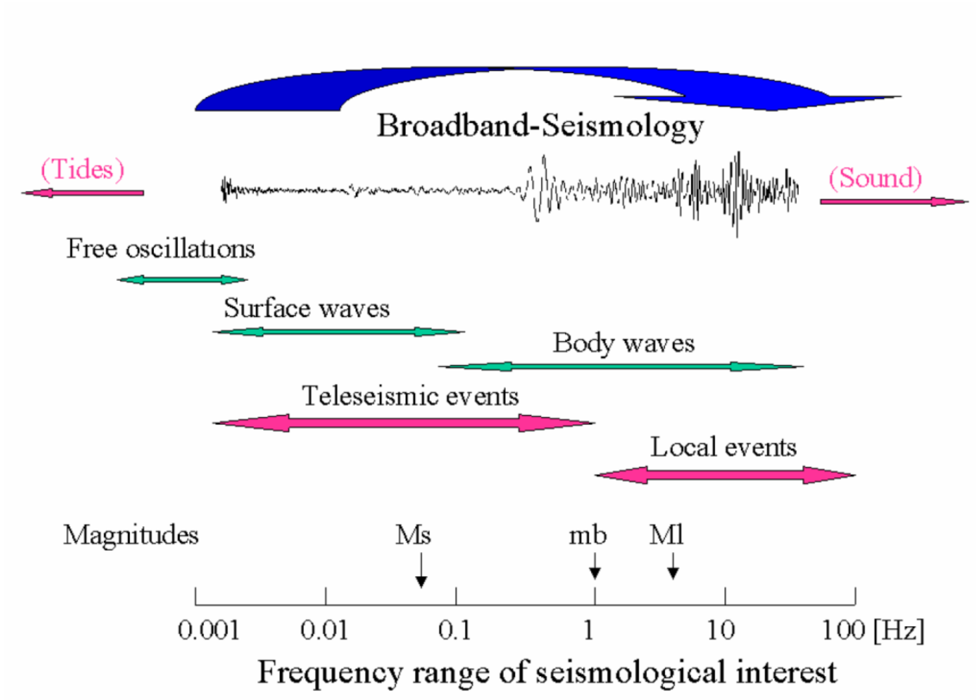


Figure 6. *General range of frequencies for a range of earthquakes. Surface waves recorded on seismograms contain lower frequency energy than earthquakes observed in the Groningen field (>1 Hz).*

The frequency content of earthquakes is directly dependent on the magnitude. The larger the fault that caused the earthquake, the greater the earthquake magnitude and the lower the frequency content of the radiated waves. Conversely, the smaller the earthquake, the higher its frequency content and, as will be outlined in the following text, the less powerful Rayleigh and Love wave generation.

Natural causes of surface vibrations

A seismometer placed in the ground will continually record the local ambient noise wavefield -a persistent "background" signal that exists due to a multitude of causes. This background signal is termed seismic noise, and mostly consists of surface waves. The sources of these vibrations can be natural or man-made. Natural sources include rivers, wind, ocean wave interactions with the seafloor, storm surf crashing against the shore, etc. In the Groningen field, seismic noise measured in the Loppersum area by a seismic station shows background noise consisting of mainly surface waves with amplitudes on the order of several microns (figure 7). Roughly three different types of source mechanisms can be distinguished. At the very low frequencies (green box highlighting low frequencies in figure 7), the noise comes from distant sources such as constant waves in the North Sea and the Atlantic Ocean. These surface waves have small amplitudes but because they always exist, when averaged over time they have a considerable power. At slightly higher frequencies (outlined by the red box), the surface waves are generated under the influence of waves induced by storms in the North Sea. At the highest frequencies (outlined by the blue box), the strongest source of noise is the traffic in the area. This can be seen in the figure as the yellow and green striping. Bright yellow indicates high noise power and green means low noise power, i.e. quiet periods.

The green bands coincide with nighttime, while the yellow bands coincide with daytime showing the interesting acoustic effect of human activities on the environment.

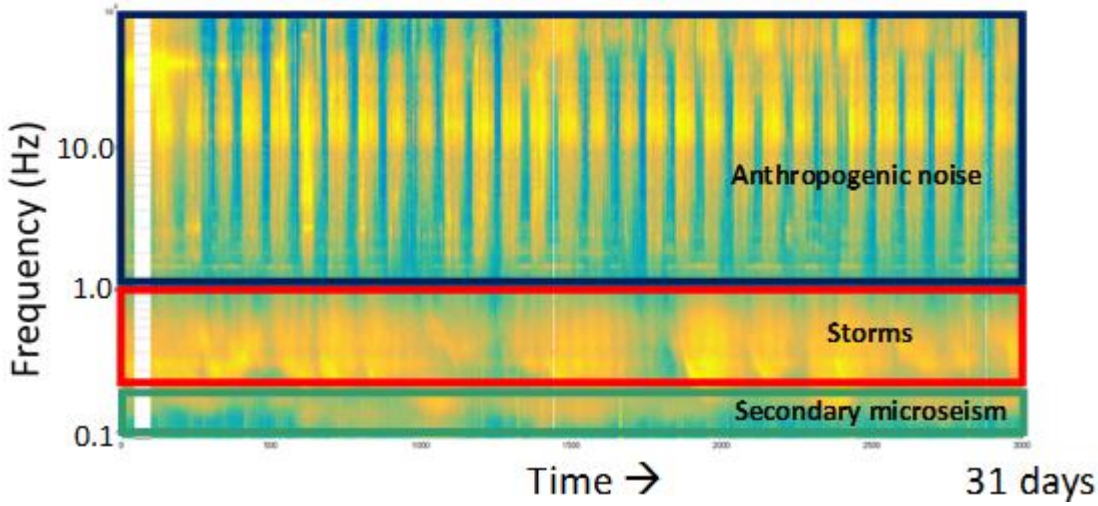


Figure 7. *Seismic noise power measured by a station in Loppersum, plotted as a function of frequency and time.*

Human causes of surface vibrations

As indicated earlier, the vibrations generated by engineering procedures that occur at, or close to the Earth's surface, often induce surface waves. Examples of these types of activities include road traffic, pile driving, quarry blasts, seismic acquisition with active sources including vibroseis trucks, accelerated weight drops, and dynamite explosions, or even windmills. Since these engineering processes are superficial, most of the energy is transmitted as the surface waves and guided in the low velocity surface layers (Jongmans and Demanet, 1992). The surface wave energy caused by these is proportional to the size of the source that caused it and is attenuated within a fairly short distance (100's of meters to a few km depending on the size of the source). For example, a shallow quarry blast was detected up to 350m away from the "epicenter" and caused ground motions of up to 1.3 mm/s (figure 8).

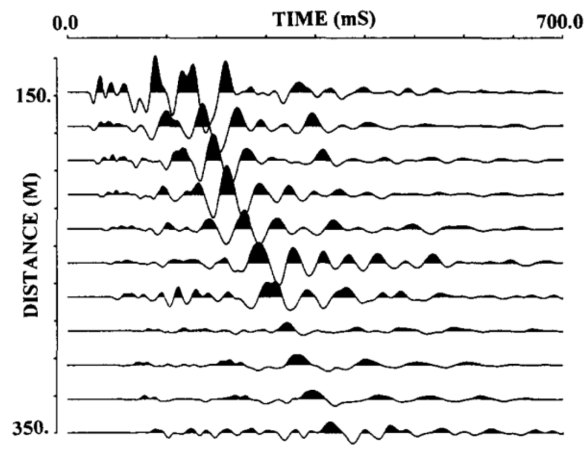


Figure 8. *Seismic records of a shallow limestone quarry blast recorded between distances of 150m to 350m on the vertical component accelerograms. The signal is dominated by surface Rayleigh waves with maximum ground velocity of 1.35 mm/s (from Jongmans and Demanet, 1992).*

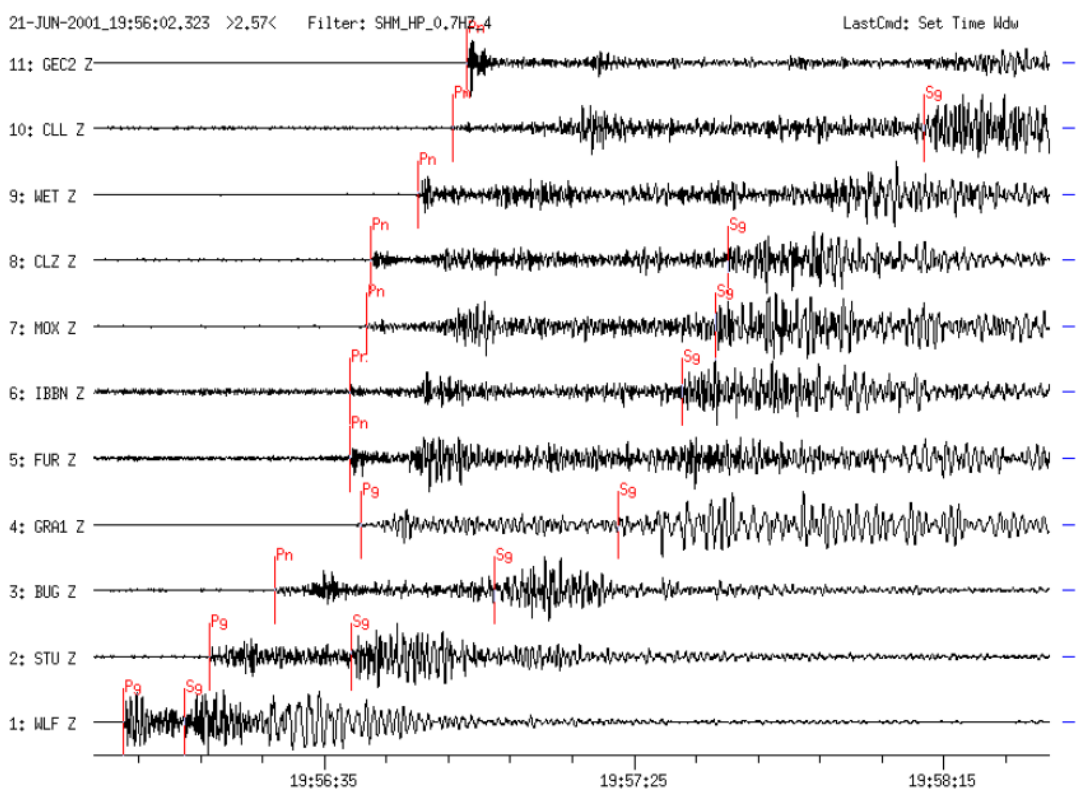


Figure 9. *Example of a shallow mine-collapse, measuring at a magnitude 3.7 located at the French-German border. Traces show generation of surface waves (long-period waves arriving approximately 10-15 seconds after the Sg marker on the WLF trace). The closest station WLF (bottom trace) is at 80 km epicentral distance, while the farthest trace is recorded at GEC2, 501 km away. Note the amplitude of the surface wave at short epicentral distance (WLF station) is equal to or smaller than the S wave (borrowed from Bormann et al. textbook, Potsdam Uni release).*

Why study surface waves?

Due to their dispersive nature (different frequency waves travel at different velocities), surface waves carry a lot of information about the medium they propagate in. Surface waves generated by earthquakes provide abundant information on the structure of the Earth's crust and upper mantle. In the case of industrial-made ground roll due to the processes like pile driving, active seismic acquisition, etc. the vibrations can be used to estimate dynamic characteristics of surficial soils such as soil shear characteristics, attenuation factors, and shear wave velocity estimation.

As already discussed, in contrast to the body waves, the velocity of surface waves is frequency dependent and thus surface waves are dispersed: different frequency waves travels at different velocities. Accordingly, depending on the crustal structure along the propagation path, the duration of Love and Rayleigh wave trains increases with distance. At relatively short epicentral distances (within a few tens to a few hundred kilometers, depending on the source characteristics), earthquake-generated surface waves are obscured by the S wave arrivals and therefore provide little information. But, at teleseismic distances (epicenter-to measuring stations distance over ~1,000 km) surface waves are prominent in their late arrival (following the S wave), their long-periods and large amplitudes relative to other arrivals in the seismogram (see figure 2, and figure 5, inset).

Due to their nature of propagation mentioned above, surface waves contain a great deal of information about the structure of the earth's crust and mantle and are predominantly used in earthquake seismology in global crustal velocities studies. Because surface waves carry information of the wave velocity at a variety of different frequencies, they offer a direct constraint on the velocity vs. depth profile everywhere along the source-receiver path. Comprehensive studies of the surface waves phase velocities can be used to invert for maps of phase velocity for both Rayleigh and Love waves. The structure seen in these maps is related to Earth's lateral velocity variations; the depth dependence in this heterogeneity is constrained by the results at different periods. Inverting surface wave phase velocity observations is currently one of the best ways to resolve three-dimensional velocity variations in the upper few hundred kilometers of the mantle.

Damaging surface waves at short epicentral distances?

Surface waves generated by earthquakes and recorded by accelerometers contain lower frequency energy than the body waves, generally in the range below 0.1 Hz (figure 6). To place that in the context of the local Groningen seismicity, all historic earthquakes observed in the Groningen field are smaller than M3.6 and transmit majority of the radiated energy in the frequency range well above 1 Hz, in the form of P and S waves (see figures 11 and 12). Frequency content of an earthquake is determined by the size of the ruptured fault: the smaller the fault size, the smaller the magnitude and the higher the frequency content; conversely, the larger the earthquake, the lower the frequency of the generated waves.

As previously mentioned, the amplitude of the surface wave decays roughly exponentially with depth. Although surface waves travel along the surface of the Earth, they radiate energy downwards. This allows for a computation of the surface wave amplitude decay with depth (figure 10). Rayleigh waves of higher frequencies decay much faster with depth than the Rayleigh waves of lower frequency (i.e. longer period). Conversely, higher frequency waves generated by the relatively small Groningen field earthquakes at the depth of the gas reservoir (roughly located at 3 km) do not radiate Rayleigh waves detectable at the surface. Surface waves with frequencies of 0.5Hz do not sample depths deeper than ~1.5 km.

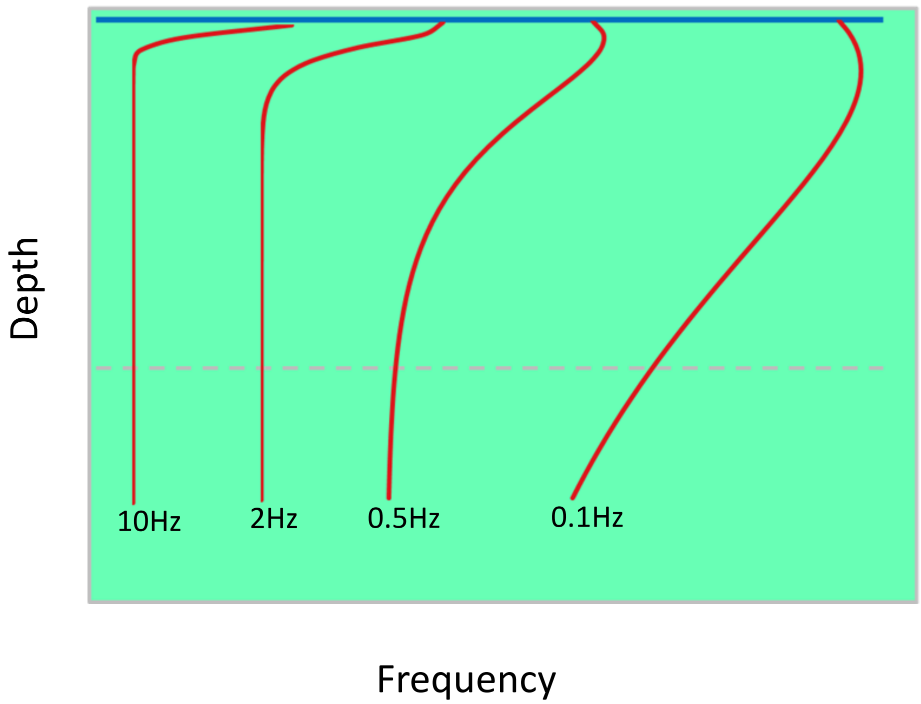


***Figure 10**. Amplitude decay of surface Rayleigh waves as a function of depth for increasingly lower frequencies.*

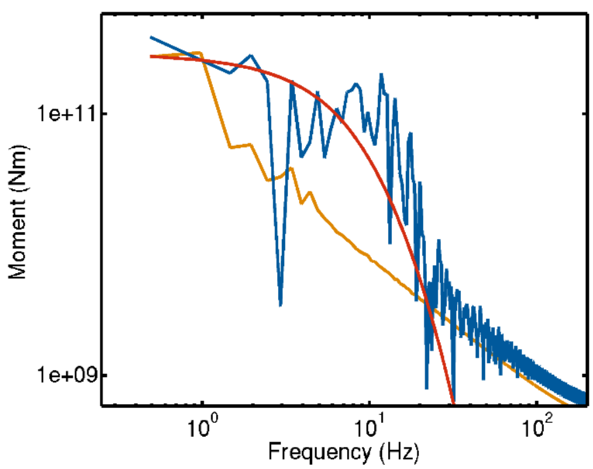
Wave theory shows that frequencies below 0.5Hz could start to generate waves capable of propagating through the overburden and to the surface, however Groningen field earthquake spectra are obliterated by noise below approximately 1Hz (Dost & Kraaijpoel, 2013). Consequently, local induced earthquakes are of small enough magnitude that they do not excite low frequencies needed to generate Rayleigh waves that could travel from the reservoir depth and be detectable at the surface.

Besides a certain magnitude requirement to yield low frequency waves, a key prerequisite for the generation of powerful surface waves is the specific geometry of local geology. Classic work by Bard and Bouchon (1980) shows the importance of non-planar subsurface interfaces as well as a sedimentary basin depth comparable to the wavelength of the incident SH waves to generate Love waves that may develop larger amplitudes than the SH waves they originate from. The shallow subsurface in the Groningen field does not include non-planar surfaces of this nature (long, inclined surface traversing the basin; Barn and Bouchon, 1980), nor is there a basin-edge to create an opportunity for the incident surface wave reflection and a potential subsequent positive interference. The shallowest, sufficiently high velocity contrast interface is the base of the North Sea group at approximately 800 m depth across the Groningen gas field (Kruiver et al., 2017). Assuming the dominant frequency of the largest local event thus far, the 2012 Huizinge M3.6 to be ~2Hz (conservative approximation, Dost and Kraaijpoel, 2013) and the average VS of the shallowest 800m to be ~400 m/s (Kruiver et al., 2017) implies wavelengths of less than ~200 meters. Notwithstanding the previous calculation that shows why typical Groningen earthquakes cannot generate surface waves, this back-of the envelope calculation further substantiates the impossibility of the generation of damaging surface waves due to a lack of a high velocity contrast at such shallow depth (~200m).

Groningen Earthquakes

The frequency spectrum analysis of what can reasonably be termed an average Groningen earthquake, a magnitude 1.6 Zuidbroek event, gives a general guideline for the frequency content of this type of an event (figure 11).

These observations show that for a typical Groningen earthquake record the weak amplitude background seismic noise is the only signal at low frequencies below approximately 1 Hz, the frequency range where Rayleigh (and Love) waves exist. If local Rayleigh (or Love) waves were being generated, their signal would unambiguously be dominating that of the noise.



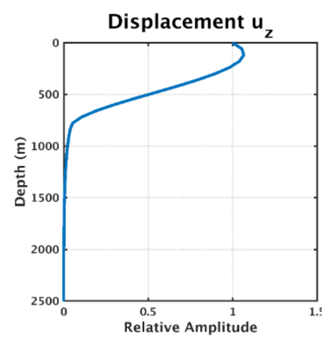


Figure 11. *Left: Amplitude spectrum of a local M1.6 earthquake (Zuidbroek) measured at a station in Wittewierum, blue line. Yellow line shows the spectrum of the background seismic noise, while the red line represents the modeled source spectrum. Right: Theoretical Rayleigh wave displacement as a function of depth at 0.6Hz calculated for the simplified Groningen velocity model. It is evident that the Rayleigh wave displacement diminishes within several hundred-meter depth. Rayleigh-wave amplitude of a higher frequency wave diminishes even more rapidly. This graph also shows that a seismic source at any depth greater than ~1,000m will not produce Rayleigh waves detectable at the surface.*

Hellum Earthquake Example

One of the largest earthquakes in the Groningen field that has been recorded by the enhanced shallow borehole network is the M3.1 Hellum event. The epicenter of the Hellum event was south of the Loppersum area but it was well recorded by the network. The earthquake record show lack of existence of surface waves, and the spectral analysis supports the rationale of surface wave generation and propagation laid out above: a magnitude 3.1 event generates bulk of its energy between 2.0 and 12Hz and is therefore severely limited in the Rayleigh wave generation and propagation distance (figure 12 B).

Although Hellum earthquake is orders of magnitude larger than the M1.6 Zuidbroek event analyzed above, it does not generate virtually any energy below ~1.5Hz and thus cannot succeed in producing detectable surface waves.

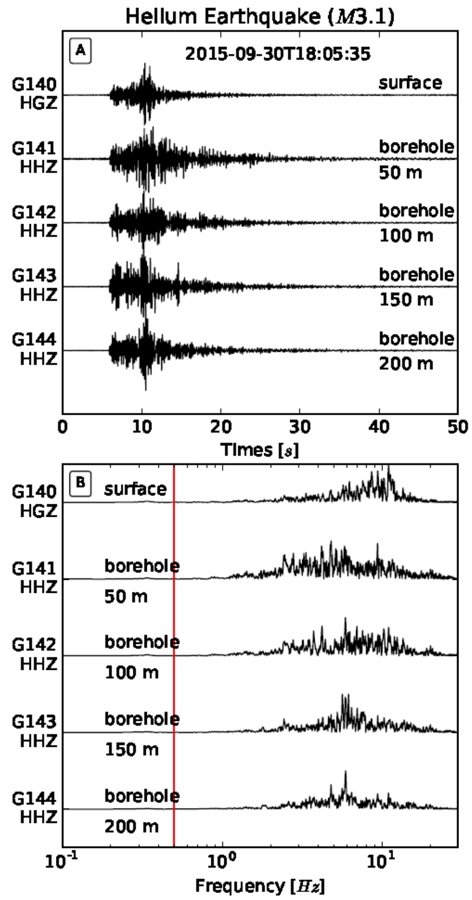


Figure 12. *Hellum M3.1 event analysis: top figure shows waveforms recorded at the surface and 4 depth level of the 200 meter shallow borehole on the station G14. Data shown is the vertical component recording, bandpass filtered between 1 and 20Hz. Bottom figure shows the power spectra of the unfiltered earthquake records. The spectra are completely flat below about 1Hz. Red line is set at 0.5Hz.*

Huizinge Earthquake Example

The Huizinge event is the largest magnitude earthquake in the Groningen induced-seismicity catalog. The event occurred on August 16, 2012 near the town of Huizinge, Groningen, and was recorded by the KNMI borehole network, the regional accelerometer network, and all additional seismic stations in the south of the Netherlands (Dost and Kraaijpoel 2013). The moment magnitude was calculated at M_w=3.6 ± 0.1 and the depth is determined to be 3 km, the approximate depth of the reservoir. The waveform recordings from the regional network show maximum peak ground acceleration values of up to 85 cm/s^2 and peak ground velocity values of up to 3.45 cm/s (Dost and Kraaijpoel, 2013). The waveform analysis of the regional network recordings reveals that a multiple S-wave phases were recorded (figures 13 and 14), with an absence of any surface wave arrivals.

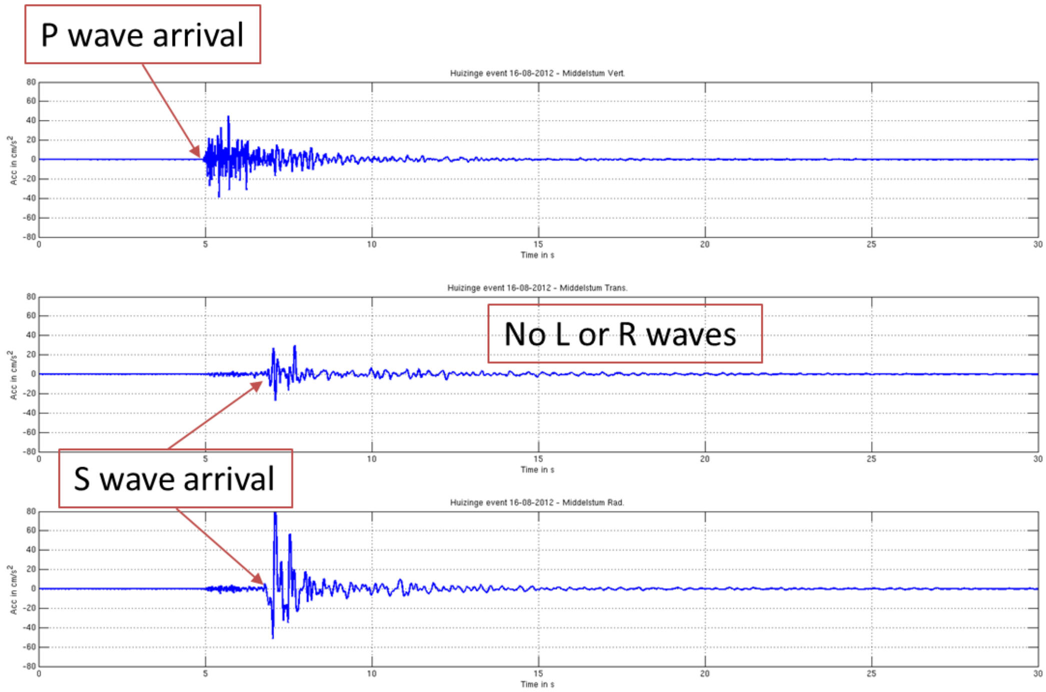


Figure 13. *The 2012 Huizinge event 3-component accelerometer recorded by the Middelstum station, displayed over 30 seconds duration shows a double-peaked S wave arrival and no evidence of subsequent surface wave arrival. Components displayed are vertical, horizontal 1, and horizontal 2 from top to bottom of the figure respectively.*

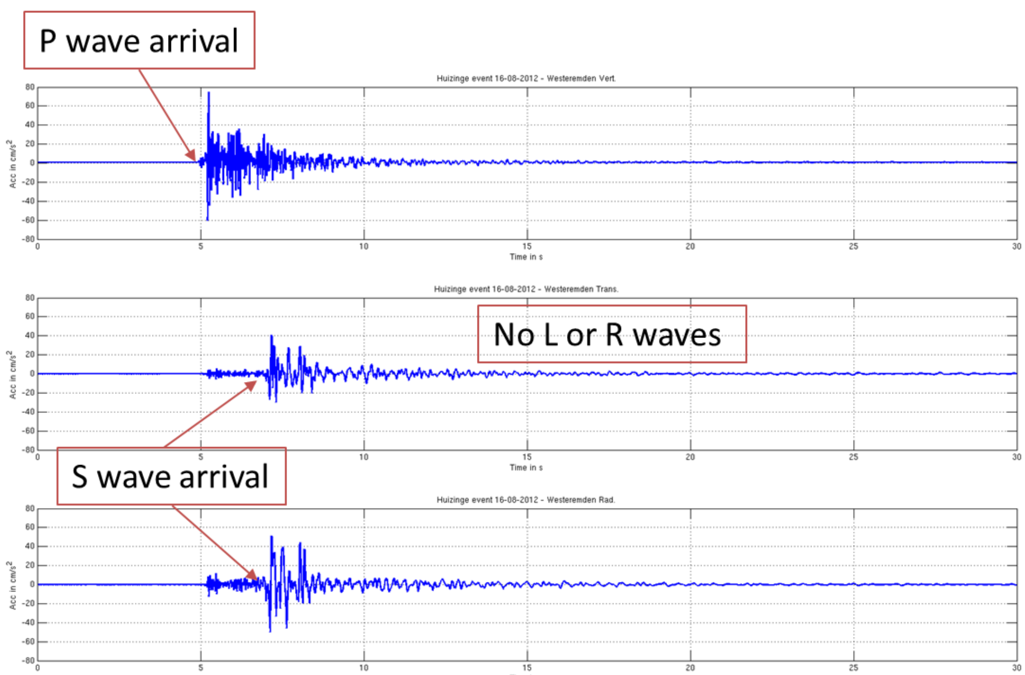


Figure 14. *The Huizinge event 3-component seismogram as recorded by the Westeremden accelerometer. There is a notable double-peaked S-wave arrival and an absence of any surface waves in the recordings.*

Examples of regional M≥4 earthquakes

We review several M≥4 events in Germany and the Netherlands, specifically focusing on the whether the data shows surface waves arrival at local stations. One of the largest events observed in the general region is magnitude M4.5 Weeze earthquake in Germany that occurred on 09/08/2011 at 19:02:51. The earthquake occurred around 180 km away from the Groningen stations but was recorded by the ZLV staggered borehole set of stations. A close examination of the waveforms reveals that the highest amplitude arrivals are the S waves, in other words, no noticeable surface waves were generated. As already discussed, for the generation of notable surface waves it is required that the magnitude of the quake be large enough to excite waves of the appropriate periods (generally <1 sec periods; figure 6).

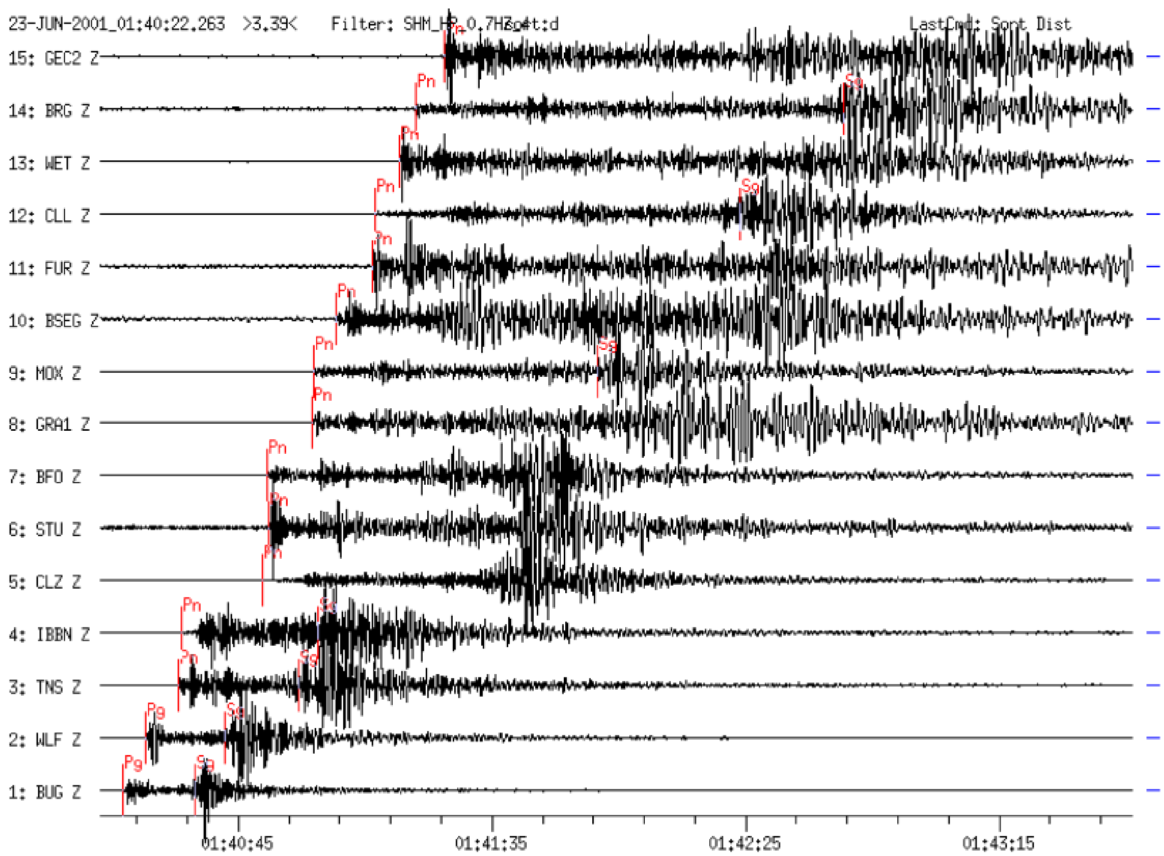


Figure 15. *An example of a M4.0 Kerkrade, Netherlands earthquake recorded at the 15 broadband stations of the German regional seismic network. The seismograms displayed are the vertical component, a direction sensitive to the Rayleigh waves, and the epicentral distance ranges from 112km (BUG station) to 600 km (GEC2 station). The waveforms in the above figure have been normalized for clarity of display, otherwise the arrivals at the more distant stations would be impossible to discern. Data is high-passed at 0.7Hz.*

Looking at the M4.0 Kerkrade earthquake example in the Netherlands (figure 15), there are no clear surface waves generated at distances of 112km (station BUG, lowest trace), which is already greater than the Groningen field size and the general surrounding area that experiences shaking due to the local induced events. These data also represent a nice example of the variability of waveforms and relative phase amplitudes of local/regional earthquakes with respect to different azimuths and epicentral distances. For example, note the S-to-P wave arrival time increase with the increase in the epicentral distance.

Teleseismic surface waves

A valuable recent example illustrating the uneventful passage of teleseismic surface waves is the recent Aegean Sea earthquake, an M6.3 event that occurred on Jun 12th, 2017. This earthquake was of large enough magnitude to be detected by highly sensitive seismometers across the globe capable of measuring sub-micron ground motions. In Europe, the earthquake arrival was detected by stations in Germany, Spain, the UK and Russia. The recoded Rayleigh wave, best displayed on the vertical component (figure 16, right) shows amplitude records at seismic stations across Europe and the Near East to be on the order of 10's of microns with a period of approximately 0.04 Hz. Given the average European crustal velocities of ~3.5 km/s (Verbeke et al., 2012), these Rayleigh waves had wavelengths of approximately 90 km. Keeping in mind the Rayleigh wave amplitudes of a few microns and the wavelengths comparable to the distance from Groningen to Zwolle, it is very clear that these types of infinitesimal ground motions are only recordable with highly sensitive seismometers.

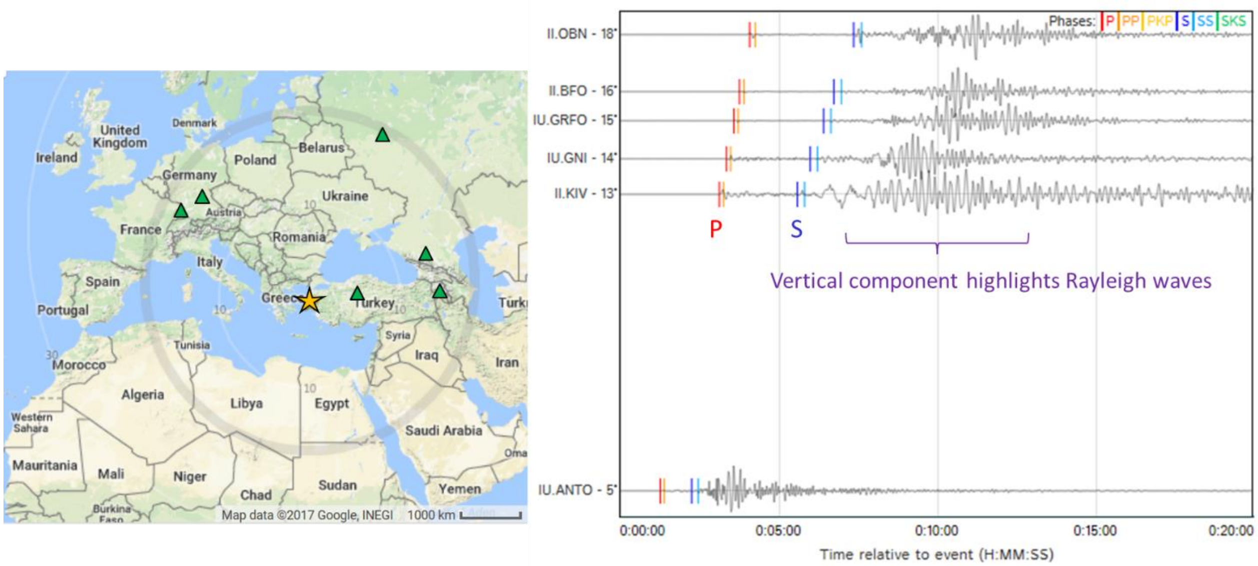


Figure 16. *Map of Aegean Sea M6.3 earthquake (epicenter shown by the yellow star) on June 12 2017, and the location of the seismic stations that recorded it (green triangles). Left: waveforms recorded throughout Europe, vertical component shown to highlight Rayleigh waves (courtesy of USGS). Stations codes: ANTO-Ankara, Turkey; KIV-Kislovodsk, Russia; GNI-Garni, Armenia; GRFO-Grafenberg, Germany; BFO-Black Forest Observatory, Schiltach, Germany; OBN-Obninsk Russia. There were no stations in the Netherlands listed in this worldwide database.*

Conclusions

In general, surface waves are generated through a complex interaction of the incoming S-wave arrivals with the earth's free surface. Seismic surface waves are routinely observed on seismograms from distant, teleseismic earthquakes. In many cases, they are the strongest arrivals on the record although the amplitudes are of the order microns. On the other hand, damaging surface waves are generated by large, local earthquakes that can output long-period energy (generally less than half a second period). A substantial fault size and therefore large magnitude earthquake is needed to generate this kind of energy. The following are the key factors preventing the local Groningen field induced-seismic events from generating significant surface waves: (1) the magnitude of the events is not of sufficient size for the generation of long period surface waves; and (2) the earthquakes are too deep: they occur at reservoir depth resulting in the complete attenuation of the dominant wavelength before it reaches the surface. The complexity of the subsurface in Groningen involves strong contrasts in velocity between the slow sediment layers and faster sedimentary rock, surface waves amplitudes decay rapidly with depth. Furthermore, the surface waves that are observed in Groningen are mainly related to background seismic noise.

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