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Groningen explosion database

Elmer Ruigrok[1,2*], Jordi Domingo-Ballesta[1], Gert-Jan van den Hazel[1], Bernard Dost[1] and Läslo Evers[1,3] present a database of explosion waveforms recorded over the Groningen province in the Netherlands. They explain the database's use for sensor orientation, deep crustal imaging and near-surface tomography.

Introduction

In the Netherlands a seismic network is in place to monitor both induced and natural seismicity. Most natural seismicity occurs in the south, over an extensional tectonic regime that can be seen as an extension of the Rhine Graben. Most induced seismic activity occurs in the north of the country and is primarily related to gas extraction and reactivation of existing faults at reservoir level (Spetzler and Dost, 2017; Willacy et al., 2019). In Groningen, in the north east of the Netherlands, an especially dense network is in place. The network is operated by the Royal Netherlands Meteorological Institute (KNMI). Both event data and continuous recordings are publicly available (KNMI, 1993). In the Nineties, a seismic network has been installed to monitor seismicity from the Groningen field and a string of surrounding gas fields (Dost et al., 2017). Since 2014 this network has been expanded with a dedicated network to monitor seismicity from the Groningen field (the G-network, Figure 1), and two gas storage plants (the N- and GK- networks, Figure 1). The area has soft soil and high seismic noise conditions. As a remedy, most of the seismic sensors have been installed in boreholes - in a set-up shown on Figure 1(c). This set-up yields a seismic power reduction up till about 30 dB in the relevant bandwidth (Ruigrok and Dost, 2019).

Besides induced seismicity and natural seismicity, these networks pick up arrivals from all kinds of other seismic sources: sonic booms, explosions, piling works, etc. Events that are detected at multiple stations are analysed. All non-earthquake events end up at a separate list. A subset of the non-earthquake sources are the controlled explosions. These events are compiled into the Groningen explosion database. In Groningen and surroundings, KNMI has detected three types of explosions (Figure 2):

1. Most of the onshore explosions are part of seismic surveys. Buried dynamite charges are used to illuminate subsurface targets as part of seismic acquisition. In recent years, a survey was done to improve the model for the unconsolidated sediments, which make up about the first 800 metres of the subsurface below Groningen. Seismic characteristics of these sediments are relevant for assessing the seismic wave amplification in the near surface, which is one ingredient of the seismic hazard model for the region (Rodriguez Marek et al., 2017; Bommer et al., 2017).
2. In the Dutch subsurface, remnants from the Second World War ordnance are still present. Some of the explosives that were released from bombers did not detonate when hitting

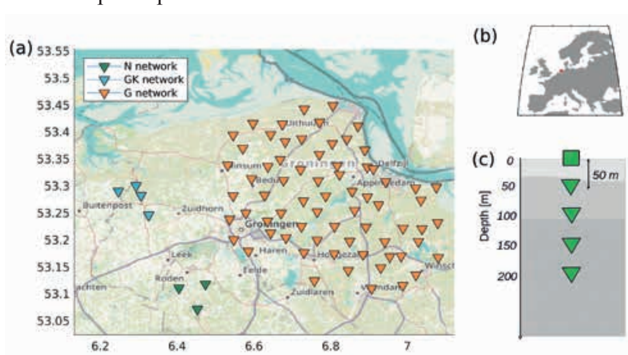

Figure 1 (a) Three networks of seismic stations that have been installed in the Groningen area since 2014: the Groningen (G), the Norg (N) and the Grijpskerk (GK) networks. The typical station spacing in each network is a few kilometres. (b) the location of the province of Groningen (Netherlands) within Europe shown in red. (c) All stations have a uniform set-up: a three-component accelerometer at the Earth's surface (square) and three-component geophones (triangles) at 50, 100, 150 and 200 m depth. Background map on (a) is from www.openstreetmaps.org.

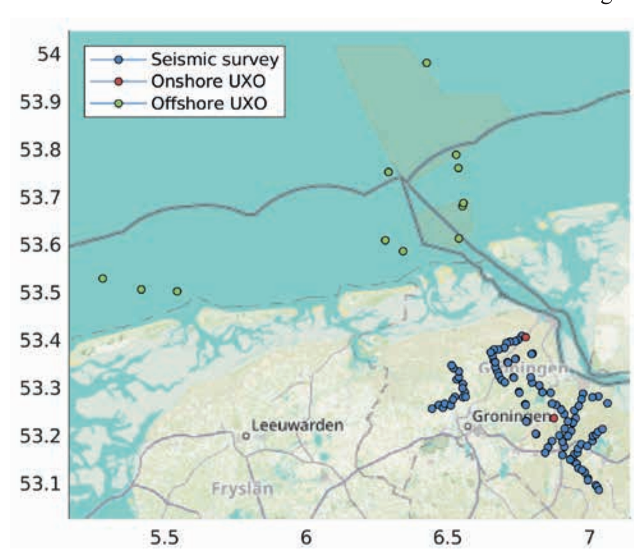

Figure 2 Controlled explosions in the Groningen region with confirmed locations. Blue dots denote charges that are used for seismic surveys (<2 kg dynamite). Red dots denote controlled explosions of aerial bombs (both are 125 kg). Green dots denote controlled explosions of Second World War ordnance that was found on the sea bottom (with charges up till 750 kg). Background map is from www.openstreetmaps.org.

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the Dutch soft soil. These unexploded ordnance (UXO) are actively sought prior to construction works, if there are indications that there have been bombings in the area. Also they are found by chance, e.g., by farmers ploughing their fields. A division of the Dutch army (EOD) is mobilized whenever an UXO is found. What follows is a controlled explosion by adding an additional explosive charge. The controlled explosion is typically done at the spot where the UXO is found. When this yields potential damage, the UXO is first moved to a place with more favourable near-surface and infrastructure conditions.

3. Also on the sea bottom, a large amount of UXOs exist, in both Dutch and German territorial waters close to Groningen. For example, sea mines that were not cleaned up, torpedoes and aircraft bombs that missed their target and lodged in the sea bed and ammunition that was dumped at sea. In recent years, many offshore construction works have taken place. Electricity cables have been placed to connect the Dutch grid with the Norwegian grid (NorNed) and with the Danish grid (COBRA). Wind turbine parks have been constructed north of Groningen (e.g., Riffgat, Riffgrund and Gemini) and many new offshore wind farms are under construction or on the drawing board. Prior to all this activity on the sea bed, geophysical surveys are carried out to find UXOs (e.g., van der Baan, 2019). When found, also these UXOs are typically detonated at, or close to, the place where they are found. Figure 2 shows locations of controlled detonations.

For the KNMI, these explosions are part of the ambient field. Nevertheless, they have found their way in various work flows. Their accurate location makes them suitable for different kinds of studies. We will show how the explosions are distinguished from local earthquakes. Moreover, we will exemplify the use of 'ambient' explosions for sensor orientation, deep crustal imaging and near-surface tomography.

Event differentiation

The explosions can quite easily be distinguished from induced seismicity. The explosions take place at or just below the Earth's surface, whereas the induced events take place at or near the gas reservoir which is at about 3 km deep (de Jager and Visser, 2017). As a consequence, the shotgathers are different. Figure 3 shows the responses for two types of explosions and an induced event. The following differences exist:

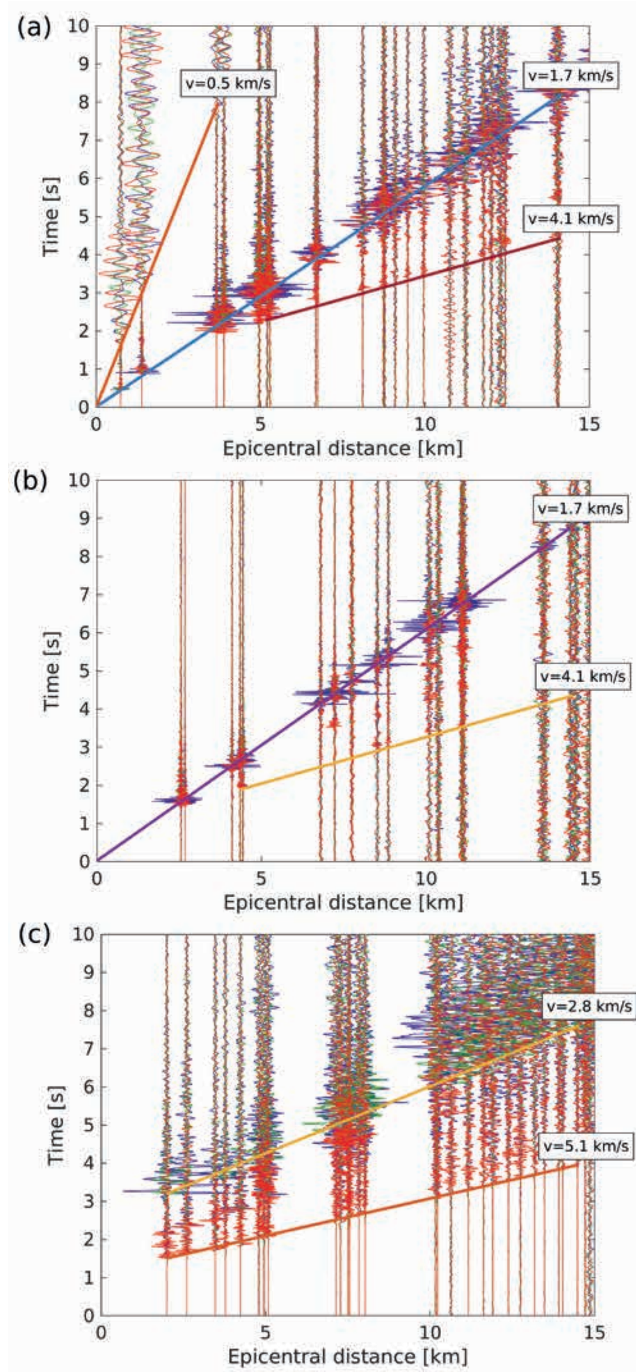

Figure 3 Shotgathers for three types of events in the Groningen area: (a) detonation of an aerial bomb at Zijldijk on 18-04-2018, (b) seismic survey detonation at Scheemda on 13-04-2017 and (c) an induced earthquake below Appingedam on 08-08-2018. The three colours show recordings over three orthogonal components: radial (direction away from the source, as shown on the blue seismograms), transverse (the horizontal component perpendicular to the radial direction, as shown with the green seismograms) and vertical (red). The straight lines fit the most prominent arrivals. The slope of the lines correspond to the indicated velocities. Recordings are shown for the 50-m depth level, bandpass filtered between 2 and 45 Hz.

1. The explosions generate clear surface waves. In Figure 3a and 3b arrivals can be seen that go through the origin. For the local earthquake (Figure 3c) such waves are not generated.
2. The explosions yield a first arrival with a velocity of about 4 km/s. This is a refraction over the Chalk group, the first consolidated lithology below the loose sediments. The induced events, on the other hand, yield a first arrival of about 5 km/s, corresponding to P-wave velocities of deeper strata.
3. The induced earthquakes yield strong S-waves. The first S-wave arrival comes in with a velocity of about 2.8 km/s (Figure 3c). The explosions, on the other hand, generate no or only modest S-waves, or a mix of S- and surface waves, with very low velocities typical for unconsolidated sediments (0.5 km/s, Figure 3a).
4. The induced events show a rich distribution of different arrivals with considerable amplitudes. The explosions, on the other hand, are more impulsive and show only a few distinct arrivals.

The UXO detonation (Figure 3a) generates waves with a velocity of 0.5 km/s. These are a typical S-wave velocities for near-surface sediments in the Groningen area (Hofman et al., 2017; Noorlandt et al., 2018). Polarizations can be seen that are not purely in the vertical-radial plane. Probably a mixture of direct S, Rayleigh and Love waves is induced. For the seismic survey detonation (Figure 3b) no surface or S-waves can be distinguished. The source is buried at 16 m depth and has only a small fraction of the explosive content of the UXO detonation. Any surface wave that might be generated is likely to be attenuated below the detection threshold within a few kilometres.

Both the UXO and the seismic-survey detonations (Figure 3a and 3b, respectively) yield a strong surface wave with a velocity of 1.7 km/s. This surface wave has typical P-wave velocities for water-saturated unconsolidated sediments (Hofman et al., 2017). It is polarized in the radial-vertical plane; note that this arrival maps the radial component (blue seismograms) and vertical component (red seismograms). Due to the large thickness of the unconsolidated sediments (about 800 m) and a large impedance contrast with the underlying chalk, a large frequency band of seismic waves remains trapped in these sediments and interferes into shingled guided waves (Roth et al., 1998).

The depth-dependent polarization of guided waves is akin to the polarization of Rayleigh waves. This distinguishes the guided waves from direct P-waves. On Figure 4 it is shown that both a low-frequency arrival from a distant offshore explosion, and a local onshore explosion, have very similar polarization. The guided wave has near-vertical polarization at the Earth's surface. At 150 m depth, the polarization is near horizontal. At depths shallower than 150 m, the particle motion is retrograde, at depths of 150 m or more, the motion is prograde.

In the Groningen area, a very detailed P-wave velocity model is available down to reservoir depth (Romijn, 2017). The model has been derived from surface seismic data and well logs. Lateral heterogeneity in the upper few hundred metres, however, is not well resolved with a typical surface-seismic study. We are setting up a guided-wave tomography to cover this part of the velocity model. Many source-receiver paths are available (Figures 1 and 2). The offshore explosions (Figure 2) are used to further expand the model to the Wadden Sea and North Sea. The model will be used for the location of future near-surface events.

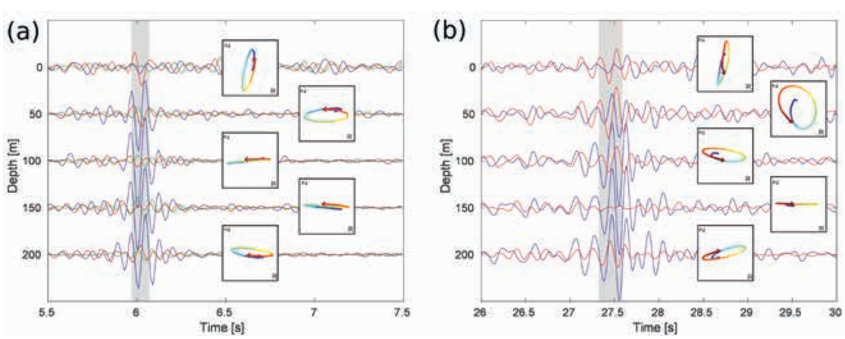

Figure 4 Two-component responses are shown – vertical (red) and radial (blue)– from (a) an onshore explosion and (b) an offshore explosion recorded at station G36. In the insets, for each depth level, the particle motions (in m/s) are shown for a time window around the guided wave as depicted in grey. (a) Onshore explosion is 10 km from the station, arrivals are bandpass-filtered between 4 and 15 Hz. The arrival has a peak frequency of 12 Hz. (b) Offshore explosion is 46 km from the station, arrivals are bandpass filtered between 2 and 15 Hz. The arrival has a peak frequency of 4 Hz.

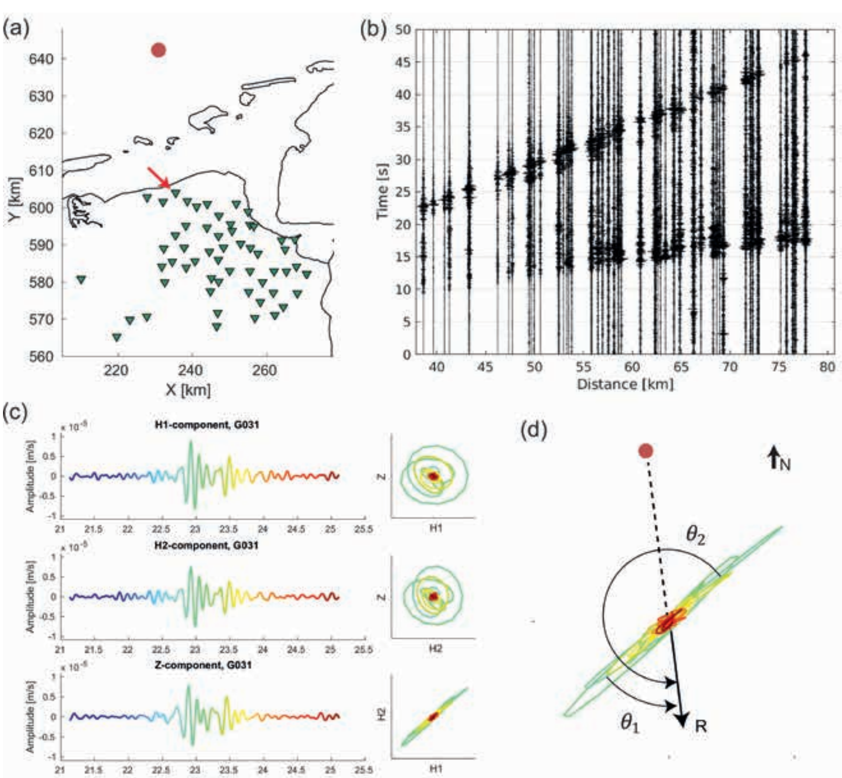

Figure 5 Illustration of estimating the orientation of horizontal components with an offshore explosion. (a) Location of the offshore UXO (red dot) and the sensors that recorded the explosion (green triangles); (b) is the resulting vertical-component shotgather for sensors at 200 m depth. (c) seismograms for the three components (left) and hodograms (right) at the station that is highlighted in (a). The particle polarization in the horizontal plane (spanned by components H1 and H2) should direct towards or away from the source (the radial direction R). This is achieved by (d) rotating the horizontal components anti-clockwise with either θ_1 or θ_2.

Sensor orientation

Geophones in the three seismic networks (Figure 2) are three-component sensors with a corner frequency of 4.5 Hz. The orientation of the horizontal components is unknown at the moment of installation. The geophones are integrated in a 200m-long line. This line is lowered in a temporary borehole, which is filled up as soon as the lowest geophone reaches target depth. During the lowering, it is unknown how the geophones turn around their vertical axis.

The estimation of the horizontal-component orientation amounts to finding the angle θ that, after anti-clockwise rotation over θ, maps one of the horizontal components to north and the other to east. For estimating the orientation, the operator of the Groningen gas field (NAM) commissioned check shots. When these were not yet available, we started to work with alternative estimates using local seismicity and explosions.

Figure 5 illustrates how one orientation-angle estimate is obtained from an explosion. The location and the response of a large offshore UXO is shown. It was well recorded on all sensors that were active in the Groningen region by the time. The second clear arrival is the guided wave. A time window around this guided wave is taken (Figure 5c) and the polarization is utilized. The horizontal components are labelled H1 and H2 to indicate that they are not oriented east (E) and north (N). The particle polarization in the horizontal plane is shown in more detail on Figure 5(d). This polarization should be away from the source (i.e., in the radial direction) or towards the source. The particle motion becomes polarized in the radial direction when the orientation of the sensor is anti-clockwise rotated (in the horizontal plane) over angle θ_1 or θ_2 (= θ_1+180 deg). The 180 deg ambiguity is removed by using, among others, teleseismic arrivals and well-calibrated broadband reference stations.

Eventually, for almost every sensor, a mean orientation angle was estimated from multiple check shots. For the same sensor, the orientation angle was estimated using abundant local seismicity. A third estimate was obtained from a large suite of explosions (Figure 2). These three mean estimates and their standard deviations were combined into a weighted mean orientation and its weighted standard deviation. In general, small (< 5 deg) uncertainty remains after combining findings from the different data attributes. The resulting angles were added to the station metadata, which is available through the KNMI waveform distribution website. All seismic and acoustic data can be found using http://rdsa.knmi.nl/ as a starting point.

The estimated orientations are used in different studies. For example, for determination of the moment tensor of the induced events, the P- and S-wave polarization are important constraints. Also for event location, the availability of sensor orientation angles is important. Picking of the first S-wave is done on the transverse component, which is the direction perpendicular to the radial component. On this component there are (almost) no issues with P-S conversions that arrive prior to the direct S-wave.

Crustal model

For the upper 3 km of the crust in Groningen, a detailed model is available. This model has recently been extended to larger depths, by reprocessing the surface-seismic data. A carbonate platform from the lower Carboniferous, at depths of 5 to 7 km, can still be recognized on the newly migrated reflection data (Kortekaas and Jaarsma, 2017). Also, a low-resolution S-wave model is available extending to the upper mantle (Yudistra et al., 2018), showing that the Moho is at about 33 km depth below Groningen. However, P-wave velocities below 4 km depth, and details on the structure below 7 km depth, are not known. We use the explosions to find an improved (P-wave) crustal model. We do this by first combining the responses from different explosions into a so-called supergather.

The different explosion types have large differences in explosive yield, which is expressed in TNT equivalent. The seismic survey explosions have less than 2 kg TNT. Clear arrivals are recorded up to a distance of 10 to 15 km (Figure 3b). Because many of the shots are in the vicinity of KNMI stations, there are many good records available at short range. To cover the distance range between 15 and 25 km, the onshore UXOs are very suitable. They are also close to KNMI stations, but have significantly larger explosive contents, yielding clear arrivals at 15 km distance and beyond (Figure 3a). The offshore detonations have yields up to a few hundred kg TNT. They induce waves that are recorded over the entire NE Netherlands KNMI network (Figure 5b). More importantly, waves are registered that made it all the way to the lower crust and upper mantle.

Figure 6 shows a merging of shotgathers due to both onshore and offshore explosions. Two prominent arrivals are the guided wave through the soft sediments (hightlighted with purple) and a refraction over the upper mantle (hightlighted with dark green). We use this and similar gathers to invert for a 1D crustal model, which is continuing work. The new model will shed more light on

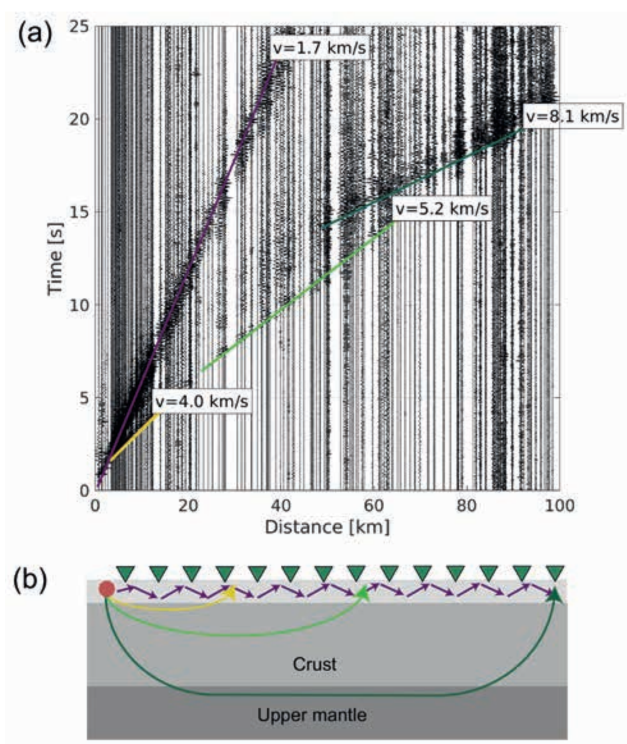

Figure 6 (a) A merger of six explosions into a supergather, with velocities shown for a few arrivals. (b) Simplified crustal model with raypaths for the highlighted arrivals in (a): guided waves through the unconsolidated sediments (purple), refracting waves over soft consolidated sediments (yellow), diving and refracting waves over hard consolidated sediments (light green) and a refraction over the upper mantle (dark green). Diving waves over the mid- and deep-crustal crystalline rock are not interpreted.

the crustal history in the Groningen region. Moreover, the velocity model has a direct application in locating regional earthquakes.

Conclusions

Seismologists use earthquakes, commissioned explosions and ambient seismic noise for subsurface studies. At the KNMI network we also measure 'ambient' explosions. These are explosions that occur near the network, but which are not commissioned for the purpose of usage within this network. The ambient explosions include signals from nearby seismic surveys, and the detonation of remnants of war, also called unexploded ordnance (UXO). In this study we have shown that their data, as recorded over the permanent seismic network, is useful for different studies. The impulsive nature of the explosions yields clear seismic arrivals carrying information of subsurface properties. When exact location and timing is known, the explosions are useful for sensor and velocity-model calibration. The UXOs typically have explosive content that goes far beyond what is permissible for seismic surveys. This results in a rich distribution of diving and refracted arrivals all the way down to the upper mantle. This allows construction of a profile of the entire crust.

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