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Meteorological Institute
*Ministry of Infrastructure
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PGV levels and location uncertainty for the Hooghalen 01-10-2023 event

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Introduction

The Hooghalen event on 01-10-2023:19:55:06.29 with a local magnitude of 1.89 was detected by the KNMI network (*KNMI*, 1993) and located near-real time with the Hypocenter method (*Lienert et al.*, 1986). This fast solution uses an average 1D model for the north of the Netherlands (*Kraaijpoel and Dost*, 2013). In this report, an updated epicenter and its uncertainty is derived. Moreover, peak-ground velocity (PGV) levels are extracted from the recordings. These are used, together with a ground motion prediction equation, to find out where PGV levels of 2 mm/s and higher may have occurred.

Epicenter

The epicenter is improved by using a best-fitting traveltime versus distance model based on a database of local P-wave traveltime picks. This data-driven model incorporates actual underburden velocities and only well pickable phase arrivals. An error estimate is derived from the spread in picking times from the best-fitting model. This error incorporates both the local variations of the velocity field as well as picking errors. These errors are propagated further into the epicentral probability density function (PDF). This results into an updated epicenter and its 95% confidence region. Details of the method are described in *Ruigrok et al.* (2023).

Fig. 1 shows the seismic sensors where manual P-wave picks are available. A grid search is performed for a region around the Hypocenter solution, as indicated by the red boxes in the figure. In the first step, equal differential time (EDT, *Zhou*, 1994) residuals are computed. That is, for each grid point and for each station combination, the traveltime differences are forward modelled and tabulated. From these values, the observed traveltime differences are subtracted to obtain the EDT residuals. In the second step, the PDF is derived from the EDT residuals, using a L1 norm (*Tarantola*, 2005). Fig. 2 shows the 95% confidence area of the resulting PDF. The locations with the maximum probability is assigned to be the updated epicenter.

The following list contains the new epicenter for the Hooghalen 01-10-2023 event, both in wgs84 coordinates and in the Dutch national triangulation system (RD). The line that surrounds the 95% confidence zone is by approximation an ellipse. The parameters of this ellipse (major axis, minor axis and orientation) are listed, together with the standard deviations describing the epicentral PDF in the direction with the largest uncertainty σ_1 and the perpendicular direction with the smallest uncertainty σ_2.

Epicenter in wgs84 [deg]: 6.5698, 52.9402
Epicenter in RD [m]: 234500, 551000
Ellipse major and minor axes [m]: 889, 823
σ_1 and σ_2 [m]: 182, 168
Orientation of the major axis [deg]: 76

The waveform data used in the above analysis is publicly available and can be obtained through:

GUI: `http://rdsa.knmi.nl/dataportal/`

FDSN webservices: `http://rdsa.knmi.nl/fdsnws/dataselect/1/`

PGV levels

For induced events outside Groningen, the protocol as established in *Ruigrok and Dost* (2020) is used to compute PGV[1] contours. From the spatial distribution of PGV, contours are extracted for the P50, P90 and P99 probabilities. The P50 is the average field, which thus has a 50% probability of exceedance. The P90 is the 90th percentile, which PGV field has a 10% probability of exceedance. The P99 has a 1% probability of exceedance.

The PGV field is a combination of a model and local recordings. The model BMR2 (*Ruigrok and Dost*, 2020) is used. This is a ground motion prediction equation that provides the PGV level and its variability as a function of magnitude, epicentral distance and depth of the event. The model has been calibrated with PGV recordings from induced events in the Netherlands. Recordings at the Earth's surface from one specific event are used to estimate how much stronger, or weaker, this event is with respect to the average event in the database. This yields the so-called event term, which is used to adapt the model with a distance-independent shift up, or downwards. Still, uncertainty exists of the actual PGV that materialized at a certain location. This so-called within-event variability is caused, e.g., by the radiation pattern of the source and variations in near-surface amplification. At and nearby places where the PGV has been recorded, the uncertainty of the PGV is reduced by blending the model with the actually measured PGV. If the combined field reaches levels of 2 mm/s and higher, PGV contours are extracted and shown on a map.

All accelerometer recordings at distances smaller than 40 km are evaluated, which yields 40 recordings with a signal-to-noise ratio larger or equal to 6 dB. The nearest and furthest accepted stations are at 1.90 and 38.43 km epicentral distance, respectively. Table 1 lists the PGV values. Fig. 3 shows these recorded PGV values as function of epicentral distance, together with the event-term shifted BMR2 model for M=1.89. The epicenter of the Hooghalen maps to the western edge of the Eleveld gasfield 2. As hypocenter depth, the gas water contact is taken, which is at approximately 3.3 km depth.

Using the 40 recordings results in an event term of 0.0820. This is the average difference between modeled and recorded PGV levels (expressed in natural log). With the event term quantified, the remaining model variability is the within-event variability $\phi = 0.536$. This remaining variability is implemented to yield the confidence regions as plotted in Fig. 3. This figure shows that the P99 field reaches 2 mm/s and 3 mm/s within 2.6 km and 1.2 km epicentral distance, respectively.

The modeled PGV fields (Fig. 3) are locally corrected with the recorded PGV levels (Table 2). For the P99 field, an area remains where the 2 mm/s threshold level is exceeded, but not

[1] In this report, as PGV measure we use 'PGVrot', which is defined as $max(\sqrt{u_E^2(t) + u_N^2(t)})$, where $u_E(t)$ and $u_N(t)$ are the particle-velocity recording on the East and North component, respectively.

the 3 mm/s level. The 2 mm/s contour for P99 is shown in Fig. 4. The gridded version of this contour is available as kml file.

Station name	**Epicentral distance [km]**	**PGV [mm/s]**
ELE	1.90	0.767
ASS1	4.26	0.310
ASS2	8.24	0.076
VRS	10.91	0.101
N020	16.62	0.018
DR030	18.16	0.023
DON	17.92	0.018
ZDL	17.82	0.058
DVR	20.08	0.011
N010	20.86	0.028
VDM20	23.85	0.022
WPS	24.38	0.007
G540	24.03	0.014
G660	26.63	0.010
VNDM0	26.51	0.012
FDKD	28.15	0.009
WSVN	28.27	0.065
G490	28.39	0.039
ODBK	29.22	0.015
G380	28.99	0.019
G550	29.19	0.018
G440	30.34	0.018
COE3	30.52	0.013
BFB2	30.46	0.029
FR040	31.09	0.009
UTRP	31.14	0.009
HOEV	31.42	0.014
G390	33.34	0.011
G510	33.39	0.017
G590	34.12	0.009
G460	34.22	0.009
G720	34.58	0.009
BRTL	35.16	0.019
SNB	34.98	0.009
G400	35.51	0.015
ODHP	37.06	0.008
FR060	37.20	0.018
G340	37.11	0.020
G470	37.79	0.012
G280	38.43	0.041

Table 1: Recorded PGVs

Discussion and Conclusions

The epicenter of the M1.9 Hooghalen event maps to the southwestern edge of the Eleveld gasfield (Fig. 2), where a bounding fault exists. This fault and other faults in the gasfield have been re-activated before. The Eleveld M2.6 event on 25-04-1991 has been one of the first induced events detected in the Netherlands. Since then there have been 44 other events within a distance of 5 km from the current event. Most of these events have epicenters that map on top of the Eleveld gas field.

For the Hooghalen 01-10-2023 event, the highest recorded PGV is 0.767 mm/s at station ELE. A ground-motion prediction equation and the measured PGV values have been used to compute the PGV field that has a 1% chance of exceedance. This P99 PGV field reaches levels between 2 and 3 mm/s near the epicenter (Fig. 4).

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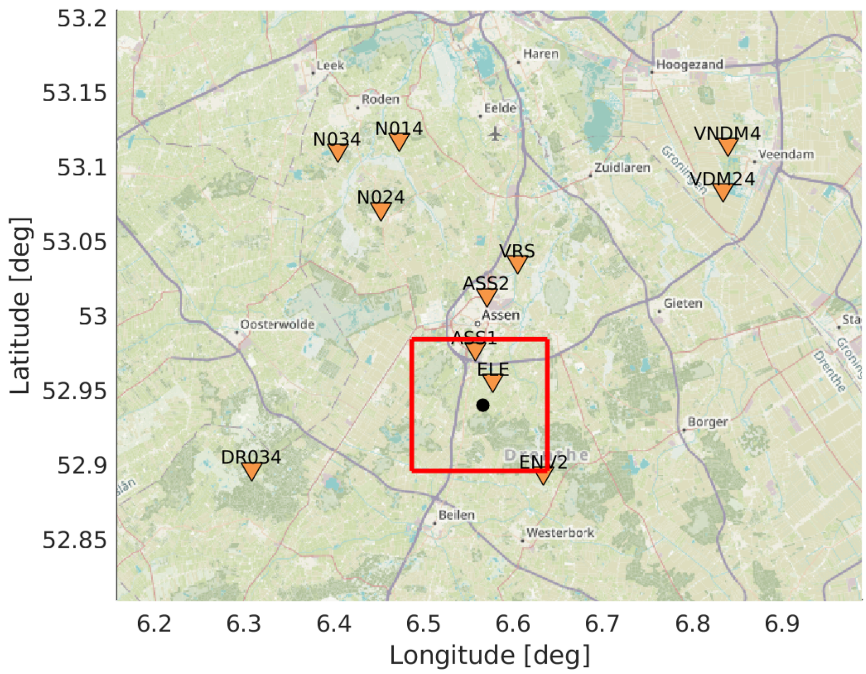

Figure 1: Overview map with locations of stations (orange triangles) where P-wave onsets were picked, the fast Hypocenter solution (black dot) and the boundary line of the area in which a grid search is done (red box). Background map is from www.openstreetmap.org.

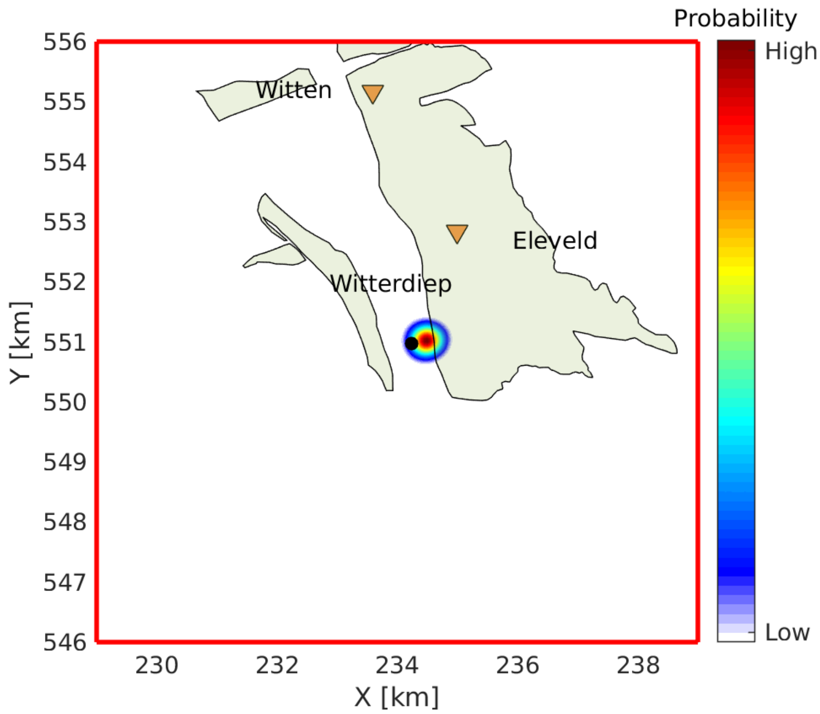

Figure 2: Map showing hydrocarbon fields (green-filled polygons), the fast Hypocenter solution (black dot) and the epicentral probability density function (PDF) using time-differences and an optimized model. The 95% confidence area of the PDF is shown, with probabilities expressed in percentage per grid point. The field polygons are from www.nlog.nl, using the March 2020 update.

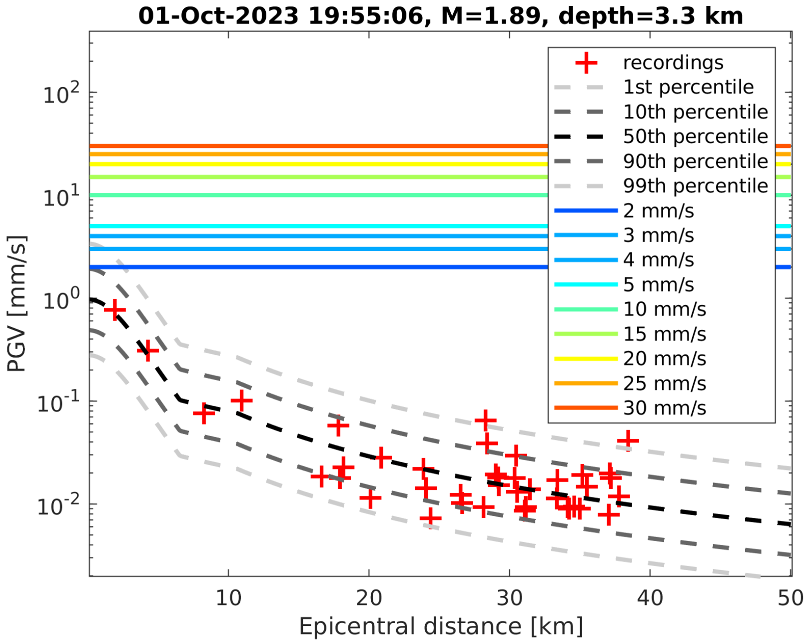

Figure 3: BMR2 model and confidence regions for this model (dashed lines), PGV thresholds (coloured lines) and measured PGV values for the Hooghalen event (red crosses). Both the model and the recordings are expressed in PGVrot.

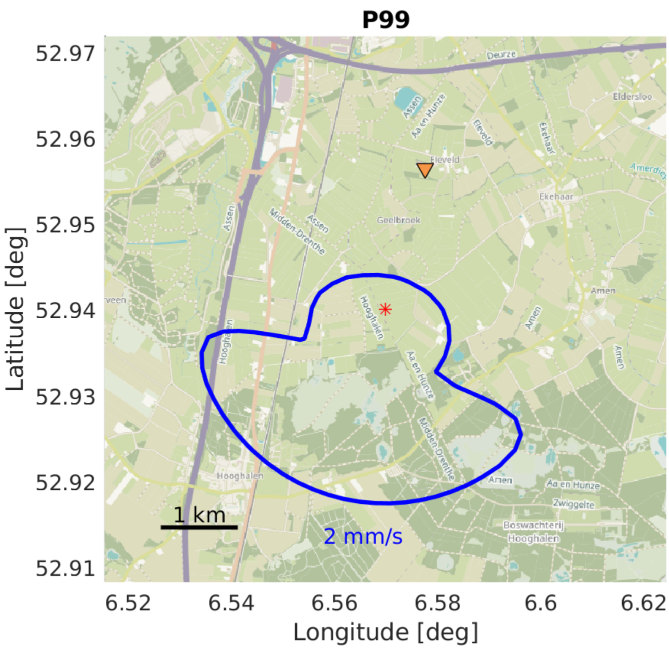

Figure 4: The bounding line of the 2 mm/s PGV threshold region for the P99 model (blue line), and the updated epicenter (red star), together with the nearest accelerometer (ELE, orange triangle).

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