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A shaky business: Natural gas extraction, earthquakes and house prices ☆

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The production of natural gas is strongly increasing around the world. Long-run negative external effects of extraction are understudied and often ignored in (social) cost-benefit analyses. One important example is that natural gas extraction leads to soil subsidence and subsequent induced earthquakes that may occur only after a couple of decades. We show that induced earthquakes that are noticeable to residents generate substantial non-monetary economic effects, as measured by their effects on house prices, also when house owners are fully compensated for damage to their houses. To address the issue that earthquakes do not occur randomly over space, we use temporal variation in the occurrence of noticeable earthquakes while controlling for the occurrence of earthquakes that cannot be felt by house owners. We find that earthquakes that are noticeable with peak ground velocities of above half a cm/s lead to price decreases of 1.9 percent. The total non-monetary costs of induced earthquakes for Groningen are about €170 million (about €600 per household). These results indicate that the non-monetary costs are in the same order of magnitude as the monetary damage costs.

1. Introduction

The production of natural gas has grown rapidly in recent years. For example, in the United States total shale gas production rose from 37 billion cubic metres in 2007 to 323 billion cubic meters in 2013, which is an increase of almost 900%. Recent developments in hydraulic fracturing ('fracking') and horizontal drilling have made the exploration of many gas reserves an economically viable alternative to the extraction of conventional fossil fuels (Vidic et al., 2013). Gas extraction imposes a substantial number of negative externalities on the surroundings, due to noise and air pollution, a reduction in aesthetic appeal of the environment, and ground water contamination. However, the long-term negative effects and the impacts on the local environment of gas extraction have hardly been studied.

In this paper, we focus on the effects of natural gas extraction, rather than shale gas extraction. One important issue is that natural gas extraction has an impact on seismic activity many years after the extraction has begun.[1] The physical

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[1] Although hydraulic fracturing uses different techniques compared to conventional extraction techniques (such as injection), shale gas extraction also seems to lead to increases in seismic activity (see Brodsky and Lajoie, 2013; Ellsworth, 2013; McGarr et al., 2015).

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0014-2921/

mechanism which explains the relationship between gas extraction and earthquakes is now well understood: Haak et al. (1993) and Segall et al. (1994), among others, have shown that there is a relation between natural gas extraction and earthquakes due to soil subsidence.[2] The areas that have experienced the largest soil subsidence are also the areas that are most frequently afflicted by earthquakes.

In the current study, we focus on the long-term (negative) effects of natural gas extraction for the Netherlands, where natural gas has been extracted for more than half a century. About a quarter of European natural gas reserves can be found in the northern parts of the Netherlands, and mainly in the province of Groningen. Natural gas is predominantly extracted by a regulated monopolist, the Dutch Petroleum Company (NAM). Only during the last two decades (so after three decades of extraction), an increasing number of earthquakes have been recorded.

We analyse the negative economic effects of these human-induced earthquakes, by looking at their effects on house prices. We believe that there are three main mechanisms by which earthquakes can affect real estate prices. The first mechanism is that past earthquakes have damaged properties. This mechanism may induce lower prices when households do not repair damage of houses hit by earthquakes, even after receiving compensation from the NAM. Particularly in the absence of future earthquakes, such behaviour is not rational, as the costs of the earthquake are sunk, so past earthquakes should not affect house prices per se.[3] In line with this assertion, Francke and Lee (2014a) show that houses in Groningen that have experienced damage due to earthquakes do not sell for lower prices. Second, one may expect historic earthquakes to signal an increased likelihood of damage by *future* earthquakes. In the Netherlands, however, due to compulsory compensation schemes provided by the NAM, households are compensated for any monetary costs as a result of earthquakes. So this second mechanism is also unlikely to impact house prices in Groningen.[4]

The third mechanism by which earthquakes impact property prices is that previous earthquakes may signal additional non-monetary costs of future earthquakes. These costs may relate to (fatal) injuries that may occur in the future, but essentially encompass all costs related to discomfort caused by an increasing number of earthquakes with an unknown magnitude occurring in the future. Hence, earthquakes arguably alter the expectations regarding future risk of damage of the property and even collapse of the property (see Beron et al., 1997; Naoi et al., 2009). In the current paper, we aim to identify this third mechanism and compare the non-monetary costs to past monetary costs. We use past earthquakes as a determinant of house prices, assuming that households use information on past earthquakes to predict the risk of future earthquakes.[5]

We have information on the location and magnitude of 717 earthquakes that occur in the province of Groningen since 1991. We also have access to a unique dataset with prices of housing transactions since 1996. We measure the incidence of noticeable earthquakes by focusing on earthquakes that generate vibrations implying peak ground velocities above half a cm/s, which corresponds to a probability of damage of about five percent. A connection of this measure to spatial price differences cannot be interpreted as a causal effect of earthquakes because one may argue that earthquakes do not occur randomly over space, for example because natural gas extraction is more likely to take place in areas that are less attractive (e.g. not in downtowns of cities). This is a relevant issue in this context, because the gas field in Groningen is below a rural area, where house prices tend to be lower. Using panel-data estimation techniques, we therefore use temporal variation in property prices and temporal variation in the occurrence of earthquakes that are noticeable by residents, to control for all time-invariant location attributes. In the regression analyses we also include a flexible function of earthquakes that cannot be felt by house owners and do not cause any damage. To include the latter as a control variable is useful, because noticeable earthquakes do *not* occur randomly over space and may therefore be correlated with changes in unobserved traits. By contrast, conditional on the cumulative number of weak earthquakes occurring, we show that the cumulative number of stronger noticeable earthquakes occur as good as randomly over space. Under the identifying assumption that, conditional on the occurrence of weak earthquakes, noticeable earthquakes occur randomly over space, this strategy identifies a causal effect of noticeable earthquakes on house prices.

The results indicate that earthquakes generating peak ground velocities above half a cm/s imply house price decreases of 1.9%. This estimate implies that the non-monetary costs are about € 3.5 thousand per property per noticeable earthquake. The total non-monetary costs of earthquakes for Groningen are about € 170 million, or € 600 per household. We then show that the annual non-monetary costs are in the same order of magnitude as the annual monetary costs due to damage of about € 12 million. These results are robust to a wide range of robustness checks and other identifying assumptions.

This is one of the first studies to look into the long-term negative effects of natural gas production. Our study is complementary to the studies by Muehlenbachs et al. (2012) and Gopalakrishnan and Klaiber (2014) who find that shale gas developments may reduce property values up to 25%, for example because of ground water contamination. By contrast, Delgado et al. (2014) do not find permanent price effects of shale gas explorations and conclude that there may be long-term

[2] More specifically, soil subsidence is the surface expression of reservoir compaction at depth. The compaction changes the stress regime at depth and causes the earthquakes.

[3] In the case of extreme damage (or restrictions to borrowing), one may observe that households do not repair damage to their houses, but extreme damage has not occurred during the period, at least not in the sample analysed.

[4] Compensation through insurance companies does not occur in the Netherlands, because damage of earthquakes is not insurable.

[5] This leaves the option open that households are irrational (e.g. overestimate earthquake risk) or have imperfect information on future earthquakes. This might lead to adjustments of price effects of earthquakes in the future.

costs that are not apparent at this point in time.[6] In contrast to shale gas extraction, natural gas extraction is less likely to contaminate groundwater; thus we identify the price effect of earthquakes.

The paper also relates to a number of studies that investigate the economic effects of earthquake risk. Brookshire et al. (1985) and Nakagawa et al. (2007) for example show that areas with a high earthquake risk command significantly lower house prices. Beron et al. (1997) show that this price discount became smaller after a large earthquake, which made them conclude that people initially overestimated the risk of earthquakes. By contrast, Naoi et al. (2009) show for Japan that the price discount of locating within an earthquake-prone area become significantly larger after an earthquake has occurred. Our paper is different in at least three aspects. We do not investigate the impacts of a single earthquake, but of many earthquakes. Previous studies focus on natural earthquakes, whereas we focus on earthquakes that are induced by human activities. Furthermore, because damage costs due to earthquakes are fully compensated in the Netherlands, we measure non-monetary costs of earthquakes, rather than the total costs. The latter is relevant for countries such as the Netherlands and the United States where it is debated (also in court) whether gas extraction companies have to compensate for non-monetary effects of earthquakes.[7] The paper also contributes to a small but growing literature on the external effects of energy production (see e.g. Davis, 2011, for the external effects of power plants; Sims and Dent, 2005, for the effects of power lines on house prices; Bohlen and Lewis, 2009, for the effects of hydropower; Gamble and Downing, 1982, and Gawande and Jenkins-Smith, 2001, for the effects of nuclear power plants and nuclear waste transport respectively; and Lang et al., 2014, and Dröes and Koster, 2014, for the economic effects of wind turbines).

This paper proceeds as follows. In Section 2 we discuss the regional context, introduce the datasets used, and discuss the econometric framework and identification strategy. Section 3 presents the results, subjects these results to a wide range of robustness checks, and discusses the quantitative implications by means of a counterfactual analysis. In Section 4 we draw conclusions.

2. Data and econometric framework

2.1. Natural gas extraction and earthquakes

Our analysis focuses on Groningen, which is a province in the north of the Netherlands with about 580 thousand inhabitants. In the Netherlands, there are several, mainly onshore, gas fields. The largest natural gas field in the Netherlands is located in the centre of the province of Groningen. This gas field is about 900 square kilometres and is located at a depth of three kilometres. It contains about 25% of natural gas reserves in Europe. Also other smaller gas fields are currently producing natural gas. Although there are some minor operators, the gas is extracted predominantly by one company, the Dutch Petroleum Company (NAM). This is a joint venture between two large oil and gas companies, Shell and ExxonMobil, which pays the national state for extraction.[8] The yearly benefits for the national government of natural gas extraction are about € 10 to € 15 billion, about 1.5% of Dutch GDP (Vlek and Geers, 2014).

The discovery of these large gas reserves in Europe was unique in 1962 (gas and oil exploration in the North Sea quickly followed after this discovery), but only ten years after the discovery 75% of the Dutch households used natural gas for cooking and heating.[9] As was unknown at that time, the extraction of natural gas also has (long-term) negative consequences, such as soil subsidence and earthquakes. The unexpected occurrence of earthquakes in an area without natural earthquakes has caused substantial local turmoil. If one believes that local residents only care about monetary damage to their houses, then this turmoil may come as a surprise as homeowners are in principle fully compensated by the NAM for (monetary) costs of damage due to earthquakes induced by natural gas extraction. There have been 19,233 damage claims related to earthquakes in the period up to July 2014. This number is surprisingly high given that these earthquakes have been rather minor ($M_L < 4$). Nevertheless, this is already a good indicator that induced earthquakes may cause damage to properties, whereas minor non-induced (natural) earthquakes of similar magnitude are usually quite harmless.[10] The main explanation is the combination of soil conditions present in Groningen and the shallow depth of 3000 metres at which the extraction-induced earthquakes are triggered. We observe a strong correlation between the cumulative number of earthquakes until 2014 and number of damage claims per household in

[6] Recent reports, commissioned by the department of economic affairs, by Francke and Lee (2013, 2014b, 2014c) also study the economic effects of induced earthquakes in Groningen on house prices and house price trends. They make a distinction between 'treated' areas and 'control' areas that are comparable in terms of socio-economic and demographic characteristics. They do not find any price (trend) differences between treated and control areas. However, this may be due the definition of the treatment variable, which is in the report defined as municipalities that have received an earthquake of at least 2.4 M_L once during the study period. We show that there is spatial and temporal variation in the treatment within treated areas and even within municipalities. The approach pursued in the reports may therefore lead to a bias towards zero of the effect of earthquakes, due to potential measurement error. Furthermore, one may argue that the study does not accurately account for unobserved trends that are correlated with the location of earthquakes.

[7] Only very recently (since February 2014), the NAM provides (limited) compensation for decreases in house prices due to non-monetary costs of earthquakes, although there is an ongoing debate on what the amount of compensation should be.

[8] In Europe, all minerals below ground are owned by the national state, in contrast to for example the United States.

[9] Accidentally, the finding of this gas field induced a strong increase in public revenues causing a downturn in economic activity. This phenomenon, currently labelled as the 'Dutch disease', is described as the relationship between the increase in the economic development of natural resources and a decline in the revenues in the manufacturing and agricultural sectors.

[10] The US Geological Survey (2013) argues that earthquakes with a magnitude below four on the Richter scale should in principle not cause damage to properties.

municipalities in 2014 ($\rho = 0.722$).[11] If we only focus on earthquakes with a magnitude above two, the correlation is almost identical.[12]

Several lobby and interest groups have been formed (e.g. 'Groninger Bodem Beweging and 'Schokkend Groningen') that represent the residents in the affected areas. These residents argue that in addition to the monetary costs that are compensated, they dislike the uncertainty related to the increase in number of earthquakes and the risk associated with (fatal) personal injuries (Vlek and Geers, 2014). In newspapers, residents argue that their living comfort and quality of life have been strongly reduced, and they are afraid that their houses become unsaleable (for which we will show there is little evidence).

Not surprisingly, there is a strong correlation of 0.744 between interest group membership and number of earthquakes. This correlation is even more pronounced if we focus on earthquakes with $M_L > 2$ ($\rho = 0.919$). The issue also received substantial attention in the Dutch press. As an illustration: a major press releases on the topic 'earthquakes in Groningen' increased from 10 in 1998 to 192 in 2010. Especially the strongest earthquake of 3.6 M_L in Huizinge caused so much turmoil that the national government decided to finance additional research to the incidence and risk of stronger earthquakes in the region. In January 2014, the secretary of state of economic affairs Henk Kamp also decided to reduce the extraction of natural gas with about 25% and to invest about € 1.2 billion (about 0.5% of the cumulative benefits of Dutch natural gas extraction) in the region in order to make buildings earthquake-proof, renovate non-residential buildings and improve quality of life (Department of Economic Affairs, 2013, 2014a, 2014b).[13]

2.2. Geological data

We use data on earthquakes from the Royal Netherlands Meteorological Institute (KNMI), which has collected data on earthquakes since 1986 using a fine network of seismographs. The location of the earthquake's epicentre can be determined up to a hundred metres. In addition to the epicentre, we know the magnitude in Richter scale, which is, as is well known, a logarithmic scale.

In Fig. 1 we present a number of maps. In panel A, we display the spatial distribution of earthquakes. Earthquakes with $M_L > 2$ tend to occur in the centre of the main natural gas field (see panel C). Panel B shows the distribution of economic activities in the province. The main city in the province is the city of Groningen with about 200 thousand inhabitants. Although most earthquakes occur in rural areas, the city of Groningen and other cities such as Hoogezand-Sappemeer and Delfzijl have suffered from earthquakes more recently.[14] Panel D, Fig. 1, shows that soil subsidence is most severe in the centre of the main natural gas field (up to 26 centimetres), which is also the area that has received the highest number of earthquakes (Panel A).

About 30 years after the extraction of natural gas fields, the first recorded earthquake in Groningen occurred in Middelstum on December 5, 1991 with a magnitude of 2.4 on the Richter scale. Overall, 579 earthquakes have been recorded in Groningen with a magnitude of at least one. The strongest earthquake was 3.6 M_L in Huizinge in 2012.[15] Fig. 2 displays the number of earthquakes over time. It can be seen that after 2002, the number of earthquakes has been increasing substantially (see Wassing et al., 2010). However, the large majority of earthquakes are rather weak. The number of earthquakes with $M_L > 2.5$ is around 1.5 per year since 2003. The year 2013 was an exception with 5 earthquakes with $M_L > 2.5$. In Appendix A.1, Fig. A1, we display the cumulative distribution of earthquakes' magnitudes, which is approximately a power-law distribution as indicated by Richter (1958).

In the econometric analysis we determine the *intensity* of each earthquake for each property, by using information on the magnitude M_L at the epicentre of the earthquake and by using an attenuation function that has been estimated for earthquakes occurring in the Netherlands (Dost and Haak, 2002; Dost et al., 2004).[16] We then determine the peak ground velocity (PGV) of an earthquake occurring at location j, which is felt at a certain location i in year t, denoted by v_{it}. We use the peak ground velocity as a measure of earthquake intensity because the PGV provides the highest correlation with damage (Wu et al., 2004). The relationship between the magnitude of an earthquake and the intensity of an earthquake at a certain location is given by:

$$\log_{10} v_{it} = -1.53 + 0.74 M_{Ljt} - 1.33 \log_{10} r_{ijt} - 0.00139 r_{ijt}, \tag{1}$$

with v_{it} in cm/s. r_{ijt} is the hypocentral distance, which is given by $r_{ijt} = \sqrt{d_{ijt}^2 + s_{ijt}^2}$, where d_{ijt} is the distance in kilometres between location i and the epicentral location j and s_{ijt} is the source depth of the earthquake. Because we lack detailed information on the exact depth of the earthquakes, we set the depth of earthquakes to three kilometres ($s_{ijt} = 3$), which is also used in recent studies by the KNMI.

[11] To estimate this correlation, we use the cumulative municipal earthquake density in 2014 and the number of claims per household in 2014.

[12] We note that natural earthquakes with $M_L < 2$ are not noticeable by people and are only recorded by seismographs (Richter, 1958). Somewhat stronger earthquakes are only felt when they occur close to the earth's surface.

[13] In the Netherlands, the occurrence of natural earthquakes is uncommon, so houses are not built to be earthquake proof.

[14] As rural areas in the Netherlands are quite densely populated, we have a substantial number of house price observations.

[15] We also have some information on earthquakes with $M_L < 1$, but these earthquakes are not consistently measured in the study period. Because these earthquakes cannot be felt by house owners, we exclude this information. Including these earthquakes will not affect our results in any way

[16] The attenuation of an earthquake depends on the depth of the earthquake as well as the type of soil and is therefore region-specific.

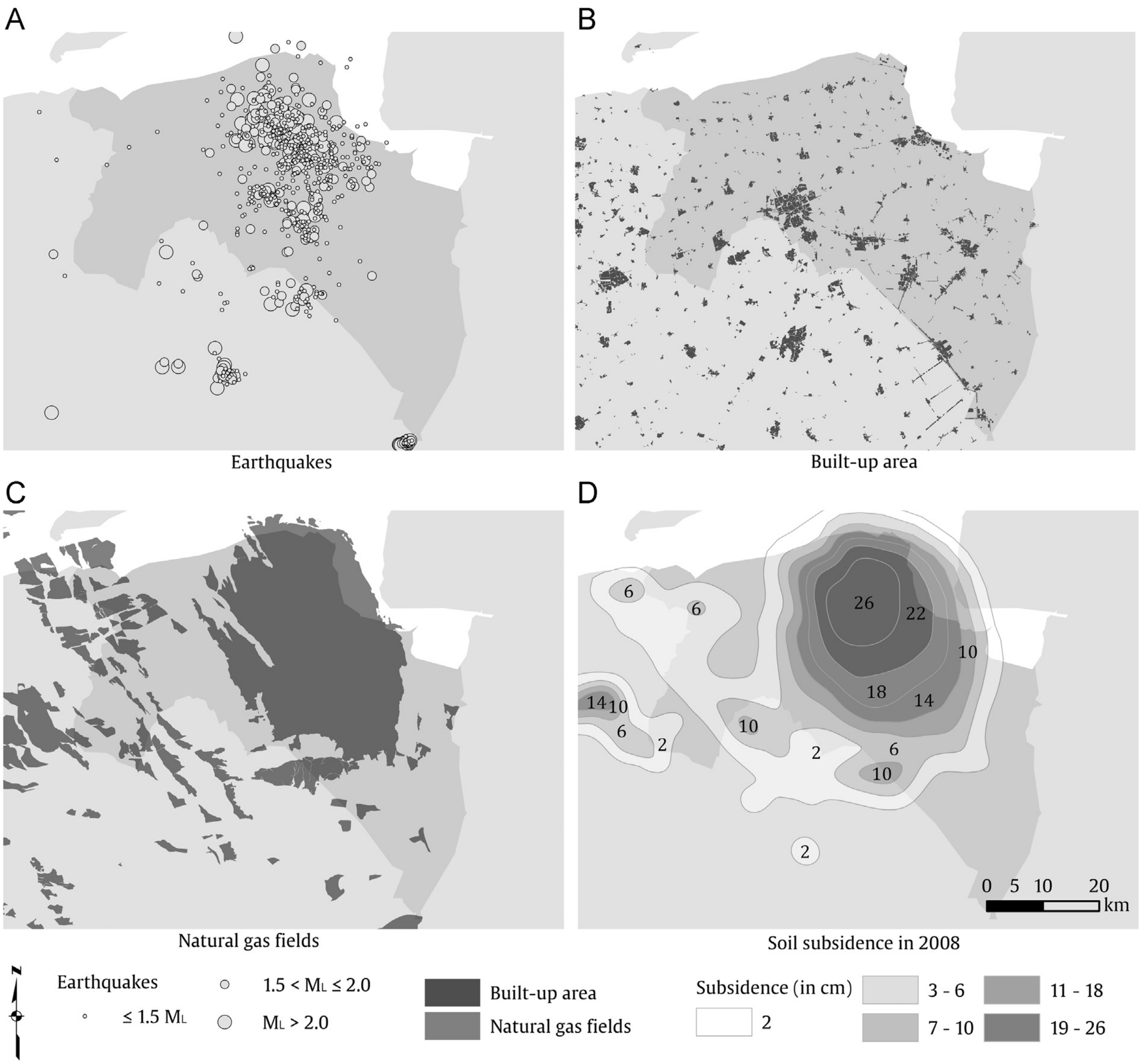

Fig. 1. Maps of the province of Groningen.

In Fig. A2, Appendix A.1, we plot the attenuation function for earthquakes with different magnitudes. For example, the largest earthquake with $M_L = 3.6$ generates peak ground velocities above a half until 11.5 km of the epicentral location. When an earthquake with $M_L = 2.5$. Because the cut-off value of the PGV of half a cm/s occurs exactly below the location of a house then $v_{it} \approx ½$ cm/s. In our study period, 21 earthquakes had an magnitude above 2.5 is arbitrary, in the sensitivity analysis we will also test whether earthquakes with lower v_{it} have any price effect (see Section 3.2).

For each observation we then calculate the number of earthquakes:

$$e_{it} = \sum_{t=1991}^{t} 1(v_{it} > ½). \tag{2}$$

where we refer to e_{it} as the number of *noticeable* earthquakes until year t. So, we focus on earthquakes generating peak ground velocities of at least half a cm/s, which corresponds roughly to a damage probability of about five percent (Van Kanten-Roos et al., 2011). Figure A3 shows the spatial distribution of e_{it} , which seems to coincide with the general pattern of earthquakes.

We note that e_{it} must have (some) measurement error, because the attenuation function (1) has been estimated. Because measurement error due to estimating the attenuation function is likely completely random, it is plausible that our estimates of the effect of noticeable earthquakes on house prices are biased towards zero, and therefore conservative. We investigate this issue in the sensitivity analysis (Section 3.2), e.g. by estimating errors-in-variables regressions.

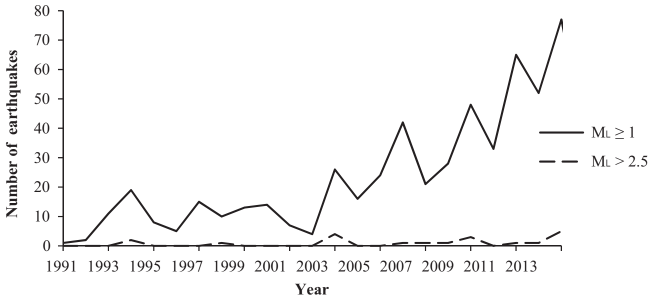

Fig. 2. Earthquakes in Groningen.

Table 1
Descriptive statistics.

	(1) Mean	(2) sd	(3) Min	(4) Max
House price (*in € per* m^2)	1365	519.6	500	5000
Number of earthquakes ($PGV > ½$ cm$/s$)	0.0716	0.410	0	7
Weak earthquakes ($1 < M_L \leq 1.5$) ($< 1km$)	0.103	0.435	0	10
Soil subsidence (*in cm*)	8.016	6.329	0	26
Distance to natural gas field (in km)	1.518	1.656	0	7.236
Size of property (in m^2)	113.0	36.51	30	250
Number of rooms	4.271	1.260	0	24
House type —apartment	0.282	0.450	0	1
House type—terraced	0.233	0.423	0	1
House type—semi-detached	0.260	0.439	0	1
House type—detached	0.225	0.417	0	1
Garage	0.394	0.489	0	1
Garden	0.622	0.485	0	1
Central heating	0.866	0.341	0	1
Listed building	0.00683	0.0823	0	1
Construction year < 1945	0.326	0.469	0	1
Construction year 1945–1959	0.0695	0.254	0	1
Construction year 1960–1970	0.169	0.374	0	1
Construction year 1971–1980	0.176	0.381	0	1
Construction year 1981–1990	0.105	0.306	0	1
Construction year 1991–2000	0.111	0.314	0	1
Construction year > 2000	0.0441	0.205	0	1
Population density	4031	3378	0	14,382
Share young people ($< 15 years$)	0.155	0.0620	0	0.370
Share elderly people ($\geq 65 years$)	0.144	0.0861	0	0.840
Share foreigners	0.0515	0.0519	0	0.620
Average household size	2.266	0.549	0	4.300
Land use—residential	0.470	0.232	0	0.989
Land use—industrial/commercial	0.119	0.130	0	0.823
Land use—infrastructure	0.0581	0.0379	0	0.265
Land use—open space	0.317	0.265	0	0.992
Land use—water	0.0364	0.0517	0	0.688

Note: The number of observations is 81,872.

2.3. Real estate data

Our analysis is based upon a house transactions dataset from the Dutch Association of Real Estate Agents (NVM) for the province of Groningen. It contains information on about half of all transactions between 1996 and 2013. The dataset provides information on the transaction price and a wide range of housing attributes, such as the size, house type and whether the property has a garden or a garage.

We also gather data on neighbourhood attributes from Statistics Netherlands.[17] We have information on the population density, share of young and elderly people, share of foreigners, and average household size.[18] Some parts of Groningen are

[17] The average distance to the centroid of a neighbourhood is about 0.4 km, so these areas are rather small. We have observations in 549 neighbourhoods in Groningen.

[18] We have data for the years 1995, 1997, 1999, 2001 and 2003–2013. For missing years, we match transactions to the nearest preceding year for which we have neighbourhood information.

considered as deprived and have low population growth. We expect that these neighbourhood attributes capture most of these negative neighbourhood effects on house prices. We furthermore add data on land use at the neighbourhood level.[19] More specifically, we have information on the share of residential land, commercial land, share of land used for infrastructure, open space and water at the neighbourhood level.

Table 1 reports descriptive statistics. The average house price per square metre is € 1365. We focus on the effect of noticeable earthquakes. Because we have relatively few observations that have experienced high PGV*s*, we group all earthquakes with PGVs > ½ cm/s. 3241 observations (4.0%) have experienced at least one earthquake that generates PGVs above half a cm/s. The share of these observations is much higher in 2013 (10.0%) than in 1996 (0.3%). Many properties are in areas that experienced soil subsidence with an average of 8 centimetres (the soil subsidence data are available for the year 2008 only). Most of our observations are close to or above a natural gas field: 36% are above a natural gas field and for the other observations the average distance to a natural gas field is 2.36 km. Because a large share of the observations is outside urban areas, we have a high number of semi-detached and detached properties, which usually have only two floors. A relatively high share of observations, about one third, refer to properties that are constructed before the Second World War (as population growth in Groningen has been low due to outmigration to other provinces over the last century). The number of observations of houses constructed after 2000, when the number of earthquakes started to increase, is only 4%, so we essentially analyse the prices of houses that have been built ignoring the possibility of future earthquakes. The latter is relevant, because making a house earthquake proof is expensive after it has been constructed. The population density in Groningen is about 20% lower than the national average, whereas the share of open space (0.32) is about one third higher than the national average (0.24). The share of foreigners is much lower in Groningen and about 50% of the national average.

2.4. Empirical framework

We aim to estimate the causal effect of earthquakes on house prices. Because residents get compensation for monetary costs related to damage, we are able to identify non-monetary price effects of induced earthquakes. We use past earthquakes as a determinant of house prices, implying that we assume that households use information on past earthquakes to predict the incidence of future earthquakes. Let p_{it} denote the log house price per square meter in postcode i in year t. The basic equation to be estimated yields:

$$p_{it} = \alpha e_{it} + \beta x_{it} + \theta_t + \epsilon_{it}, \tag{3}$$

where α, β and θ_t are parameters to be estimated, x_{it} are housing attributes, θ_t are year fixed effects to control for annual price effects, and ϵ_{it} is an identically and independently error term.

The econometric problem of the above equation is that earthquakes may occur by chance in attractive areas (e.g. areas with beautiful views) or non-attractive areas (e.g. rural areas with few amenities). This may imply a correlation between e_{it} and ϵ_{it}. To partly solve for this, we include postcode area fixed effects η_i. In the Netherlands, postcode areas encompass about half a street (on average 15 households), which is comparable to a census block in the United States. These fixed effects essentially deal with all unobserved time-invariant spatial attributes and we identify the effects of earthquakes on house prices using temporal variation (Van Ommeren and Wentink, 2012).

Given these fixed effects, it might still be the case that the occurrence of earthquakes is correlated to unobserved price trends, so earthquakes are correlated to time-varying spatial attributes. For example, changes in drilling activities may be correlated to the occurrence of noticeable earthquakes.[20] In Appendix A.2, using the point-pattern methodology proposed by Duranton and Overman (2005), we show that noticeable earthquakes generating PGVs > ½ cm/s are indeed much more concentrated than one would expect if earthquakes would occur randomly over space. It is plausible that *conditional* on the number of weak earthquakes, noticeable earthquakes occur as good as random over space. In Appendix A.2 we test this idea and illustrate that noticeable earthquakes, conditional on the cumulative number of weak earthquakes with $1 < M_L \leq 1.5$, are indeed *not* statistically significantly concentrated in space. For an individual earthquake to be spatially random, a sufficient (but not necessary) condition is that the cumulative spatial distribution of earthquakes is random.

In the regression analysis, we therefore control for the change in the cumulative number of weak earthquakes in the vicinity of the property (within one kilometre), which mitigates the possibility that unobserved price trends are correlated with the incidence of noticeable earthquakes.[21] Hence, the key identifying assumption is that noticeable earthquakes occur randomly over space, conditional on changes in the occurrence of weak earthquakes, so that noticeable earthquakes are uncorrelated to time-varying unobservables. When we also control for neighbourhood attributes z_{it}, this leads to the following specification:

$$p_{it} = \alpha e_{it} + \beta x_{it} + \gamma z_{it} + \eta_i + \theta_t + \Omega(n_{it}) + \epsilon_{it}, \tag{4}$$

[19] The land use data are from the years 1996, 2000, 2003, 2006, 2008 and 2010. For the missing years, we match the observations to the nearest preceding year for which we have neighbourhood information.

[20] In the sensitivity analysis we will show that price trends are uncorrelated to drilling activities.

[21] In the sensitivity analysis we also estimate models where we include region × year fixed effects to further control for unobserved price trends.

where $\Omega(\bullet) = \sum_{r=1}^{5} \delta_r n_{it}^r$, where δ_r are parameters to be estimated, so $\Omega(\bullet)$ is a flexible fifth-order polynomial function of the number of non-noticeable earthquakes within a given distance of the property. n_{it} is then given by:

$$n_{it} = \sum_{t=1991}^{t} 1\left(d_{ijt} < 1\right) \cdot 1\left(1 < M_{Ljt} \le 1.5\right). \tag{5}$$

Eq. (4) identifies the effect of noticeable earthquakes as captured by e_{it}, where the incidence of noticeable earthquakes can be considered random, as we compare price changes between areas that have experienced the same number of weak earthquakes.[22]

3. Results

3.1. Baseline regressions

In Table 2 we report the main regression results. We cluster standard errors at the neighbourhood level to account for potential spatial autocorrelation of the error term.[23] Column (1) reports the results of a naïve regression of the logarithm of house price on the number of earthquakes and year fixed effects. The results indicate that house prices are at least 4.2% lower in areas that experienced an earthquake that cause PGVs > ½ cm/s. We do not interpret this as a causal effect, as noticeable earthquakes do not occur randomly over space, e.g. because earthquakes occur in rural areas that have lower house prices. Column (2) includes postcode area fixed effects to control for all time-invariant spatial attributes. The results indicate that an earthquake that generates vibrations with a peak ground velocity above half a cm/s reduces house prices with 3.2%. The results are virtually identical once we include 15 housing attributes in the regression (column (3)). In column (4) we address the issue that earthquakes may occur non-randomly over space, by controlling for the number of weak earthquakes within a kilometre of the property with a magnitude between 1 and 1.5. In this way, we control for earthquakes that cannot be felt by households. The effect of noticeable earthquakes then is similar, but somewhat lower (in absolute value), compared to the previous specification. We observe that the additional control variable, the number of weak earthquakes, has a negative price effect, which might indicate that there is some negative price trend that is correlated with the location of earthquakes. It might also indicate that earthquakes generating lower peak ground velocities have a negative price effect. We will test for this in the next subsection.

In column (5), we control for a host of observable neighbourhood attributes. It is shown that the effect of noticeable earthquakes is similar to previous specifications (1.8% per noticeable earthquake). Neighbourhood attributes have a statistically significant effect on house prices and generally have the expected signs.[24] Areas with positive increases in population densities seem to encounter small price decreases: doubling population density is associated with a decrease in prices of 0.8%. Neighbourhoods with an increasing share of elderly people experience price decreases. In general, we also observe that an increase in the share of commercial land increases the price, possibly due to a better access to shops, jobs and amenities. Increases in the amount of open space and water are also associated with positive price increases.

In column (6), which we consider the preferred specification, we include a flexible function of the number of weak earthquakes within one kilometre of the property. The results indicate that a noticeable earthquake generating PGVs above half a cm/s leads to a similar price decrease of 1.9%. So, summarising, the results indicate a price discount of 1.9–3.2% per noticeable earthquake.

3.2. Robustness

In this subsection we subject these results to a number of sensitivity checks. Again, we consider the specification in column (6), Table 2 as the baseline specification. Tables 3 and 4 report the results.

We first investigate whether weaker earthquakes have any price effect and whether within the category of noticeable earthquakes we find that the strongest earthquakes have the most pronounced effect. It is shown in column (1) , Table 3, that lower peak ground velocities do not lead to price discounts. On the contrary, lower peak ground velocities seem to have a positive price effect, which is in line with our argument that weaker earthquakes are not randomly distributed across space. Higher PGVs seem to have a similar negative price effect. The effect seems smaller than when ½ cm/s ≤ ¾ cm/s, but the effects are not statistically significantly different from each other.

[22] As the cut-off value of one kilometre is arbitrary, we show in Appendix A.4 that the results hold if we choose other cut-off values.

[23] We may cluster standard errors over space (at the neighbourhood or municipality level) to account for spatial correlation, or over time (at the postcode level) to account for serial correlation. Because the neighbourhood attributes we include later only vary at the neighbourhood level, clustering at the neighbourhood level seems the most appropriate. In Appendix A.3 we discuss this issue in more detail and show robustness of our results to different levels of clustering. We also test for spatial autocorrelation in the error term by estimating Moran's I.

[24] We note that these variables are potentially endogenous. For example, higher prices imply that it is more attractive to construct houses, leading to a higher population density. Although we do not claim causal effects of the neighbourhood controls, it is reasonable to interpret the neighbourhood attributes as proxies for difficult-to-capture demographic trends.

Table 2
Baseline results. (dependant variable: the logarithm of house price per m^2).

	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS
Number of earthquakes ($PGV > ½$ cm/s)	−0.0421***	−0.0315***	−0.0305***	−0.0247***	−0.0183***	−0.0191***
	(0.0103)	(0.00808)	(0.00644)	(0.00719)	(0.00603)	(0.00608)
Size of property (*log*)			−0.459***	−0.460***	−0.460***	−0.460***
			(0.0152)	(0.0152)	(0.0154)	(0.0154)
Number of rooms			0.0232***	0.0232***	0.0237***	0.0237***
			(0.00129)	(0.00128)	(0.00126)	(0.00126)
House type—terraced			0.0894***	0.0894***	0.0901***	0.0901***
			(0.0103)	(0.0103)	(0.0103)	(0.0103)
House type—semi-detached			0.148***	0.148***	0.148***	0.148***
			(0.0119)	(0.0119)	(0.0120)	(0.0120)
House type—detached			0.356***	0.356***	0.353***	0.353***
			(0.0162)	(0.0162)	(0.0164)	(0.0164)
Garage			0.109***	0.109***	0.107***	0.107***
			(0.00354)	(0.00353)	(0.00344)	(0.00343)
Garden			0.00436	0.00441	0.000763	0.000768
			(0.00790)	(0.00789)	(0.00754)	(0.00754)
Central heating			0.122***	0.122***	0.117***	0.117***
			(0.00433)	(0.00433)	(0.00461)	(0.00461)
Listed building			0.100***	0.0997***	0.0994***	0.0995***
			(0.0195)	(0.0195)	(0.0188)	(0.0188)
Population density (*log*)					−0.0118***	−0.0118***
					(0.00356)	(0.00355)
Share young people (< 15 years)					0.00198	0.00199
					(0.00141)	(0.00141)
Share elderly people (≥ 65 years)					−0.00532***	−0.00531***
					(0.000877)	(0.000877)
Share foreigner					0.00179**	0.00178**
					(0.000832)	(0.000832)
Average household size					−0.153***	−0.153***
					(0.0161)	(0.0161)
Land use—industrial/commercial					0.117**	0.117**
					(0.0491)	(0.0491)
Land use— infrastructure					0.125	0.124
					(0.336)	(0.336)
Land use—open space					0.131***	0.130***
					(0.0371)	(0.0370)
Land use—water					0.181**	0.180**
					(0.0907)	(0.0909)
Number of weak earthquakes ($1 < M_L \leq 1.5$), (< 1 km)				−0.0177***	−0.00870**	
				(0.00479)	(0.00397)	
Number of weak earthquakes, $\Omega(n_{it})$	No	No	No	No	No	Yes
Construction year dummies (6)	No	No	Yes	Yes	Yes	Yes
Year fixed effects (18)	Yes	Yes	Yes	Yes	Yes	Yes
Postcode area fixed effects (3733)	No	Yes	Yes	Yes	Yes	Yes
Observations	81,872	81,872	81,872	81,872	81,872	81,872
R-squared	0.453	0.731	0.812	0.812	0.818	0.818

Notes: we cluster standard errors at the neighbourhood level. Standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

One may argue that local trends may be correlated to the number of earthquakes. Although we think that a flexible function of the number of weak earthquakes in vicinity should properly control for this, in column (2) we include region × year fixed effects to control for variation in price trends between the different regions within Groningen.[25] The results indicate a negative price effect of noticeable earthquakes of 2.0%, so the effect is essentially the same compared to the baseline estimate.

If there would be a strong correlation between the location of drilling activities and noticeable earthquakes, our results may be driven by negative externalities of drilling activities, rather than the negative effects of earthquakes. Because the locations of drilling activities are essentially time-invariant during the period investigated by us, the mainpotential negative effects are captured by postcode fixed effects.[26] To test whether the willingness to pay for these negative externalities may

[25] These are defined by the first two numbers of the postcode. We then have seven different regions in the province of Groningen.

[26] Furthermore, the cross-sectional correlation between the log distance to the nearest drilling activity and the number of noticeable earthquakes is very low ($\rho = 0.022$).

Table 3
Sensitivity analysis part I.

	(1) OLS Include weaker earthquakes	(2) OLS Region×year fixed effects	(3) OLS Distance to drilling activities	(4) OLS Soil-type specific effects	(5) OLS Built-up areas	(6) OLS Historic buildings only
Number of earthquakes ($PGV > ½\ cm/s$)		−0.0198*** (0.00748)	−0.0172** (0.00702)			−0.0225*** (0.00681)
Number of earthquakes ($PGV > ¾\ cm/s$)	−0.0213** (0.00845)					
Number of earthquakes ($½\ cm/s < PGV \leq ¾\ cm/s$)	−0.0336*** (0.00981)					
Number of earthquakes ($¼\ cm/s < PGV \leq ½\ cm/s$)	0.0112*** (0.00394)					
Number of earthquakes ($PGV > ½\ cm/s$) × soil type – clay				−0.0251*** (0.00826)		
Number of earthquakes ($PGV > 1$) ($PGV > ½\ cm/s$) × soil type – peat				−0.0284 (0.0348)		
Number of earthquakes ($PGV > 1$) ($PGV > ½\ cm/s$) × soil type – sand				−0.0158** (0.00727)		
Number of earthquakes ($PGV > ½\ cm/s$) × inside built-up area					−0.0276*** (0.00653)	
Number of earthquakes $PGV > ½\ cm/s$) × outside built-up area					0.00217 (0.00693)	
Number of earthquakes $PGV > ½\ cm/s$) × (1996≤year≤2001)						
Number of earthquakes $PGV > ½\ cm/s$) × (2002≤year≤2007)						
Number of earthquakes $PGV > ½\ cm/s$) × (2008≤year≤2013)						
Number of weak earthquakes, $\Omega(n_{it})$	Yes	Yes	Yes	Yes	Yes	Yes
Distance to drilling, $\Psi(\log(a_i)\tilde{n}t)$	No	No	Yes	No	No	No
Housing attributes (15)	Yes	Yes	Yes	Yes	Yes	Yes
Neighbourhood attributes (9)	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects (18)	Yes	Yes	Yes	Yes	Yes	Yes
Region×year fixed effects (475)	Yes	Yes	No	No	No	No
Postcode area fixed effects (3,733)	Yes	Yes	Yes	Yes	Yes	Yes
Observations	81,872	81,872	81,872	81,872	81,872	26,692
R-squared	0.818	0.824	0.820	0.818	0.818	0.800

Note: We cluster standard errors at the neighbourhood level. Standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Table 4
Sensitivity analysis part II

	(1) OLS Property fixed effects	(2) OLS Include data from 1985	(3) OLS 'Long'-differences	(4) OLS Time-varying effects	(5) OLS Include Drenthe and Friesland	(6) OLS Days on the market	(7) OLS Transaction/ asking price ratio
Number of earthquakes ($PGV > ½\ cm/s$)	−0.0230 (0.0178)	−0.0249*** (0.00664)	−0.0423** (0.0183)		−0.0103* (0.00540)	2.801 (3.304)	0.00174 (0.00144)
Number of earthquakes ($PGV > ¾\ cm/s$)							
Number of earthquakes ($½\ cm/s < PGV \leq ¾\ cm/s$)							
Number of earthquakes ($¼\ cm/s < PGV \leq ½\ cm/s$)							
Number of earthquakes ($PGV > ½\ cm/s$) × soil type – clay							
Number of earthquakes ($PGV > 1$) ($PGV > ½\ cm/s$) × soil type – peat							
Number of earthquakes ($PGV > 1$) ($PGV > ½\ cm/s$) × soil type – sand							
Number of earthquakes ($PGV > ½\ cm/s$) × inside built-up area							
Number of earthquakes $PGV > ½\ cm/s$) × outside built-up area							
Number of earthquakes $PGV > ½\ cm/s$) × (1996≤year≤2001)				0.00298 (0.0118)			
Number of earthquakes $PGV > ½\ cm/s$) × (2002≤year≤2007)				−0.0167** (0.00746)			
Number of earthquakes $PGV > ½\ cm/s$) × (2008≤year≤2013)				−0.0189*** (0.00620)			
Number of weak earthquakes, $\Omega\ (n_{it})$	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Housing attributes (15)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Neighbourhood attributes (9)	Yes	No	No	Yes	Yes	Yes	Yes
Year fixed effects (18)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province×year fixed effects (54)	No	No	No	No	Yes	No	No
Postcode area fixed effects (3,733)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Property fixed effects (69,193)	No	Yes	Yes	No	No	No	No
Observations	81,872	91,316	6,930	81,872	230,520	80,868	81,661
R-squared	0.990	0.843	0.929	0.818	0.803	0.271	0.265

Note: We cluster standard errors at the neighbourhood level. Standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Table 5
Accounting for measurement error (dependent variable: the logarithm of house price per m^2).

	(1) Errors-in-variables EIVREG	(2) ≥ 2 earthquakes OLS	(3) ≥ 3 earthquakes OLS
Number of earthquakes ($PGV > ½$ cm/s)	−0.0685***		
	(0.0224)		
Dummy ≥ 2 earthquakes ($PGV > ½$ cm/s)		−0.0502***	
		(0.0159)	
Dummy ≥ 4 earthquakes ($PGV > ½$ cm/s)			−0.0629***
			(0.0233)
Number of weak earthquakes, $\Omega(n_{it})$	Yes	Yes	Yes
Housing attributes (15)	Yes	Yes	Yes
Neighbourhood attributes (9)	Yes	Yes	Yes
Year fixed effects (18)	Yes	Yes	Yes
Postcode area fixed effects (3736)	Yes	Yes	Yes
Reliability	0.382		
Observations	81,872	80,047	79,572
R-squared	0.734	0.820	0.821

Notes: In column (2), we exclude observations which experienced one earthquake with PGVs > ½ cm/s. In column (3) we exclude observations we exclude observations which experienced one, two or three earthquakes with PGVs > ½ cm/s. We use cluster-bootstrapped standard errors in column (1) (500 replications). We cluster standard errors at the neighbourhood level in all specifications. Standard errors are in parentheses.*** p < 0.01, ** p < 0.05, * p < 0.10.

Table 6
Counterfactual analysis.

	(1) $\hat{\alpha} = -0.0191$	(2) $\hat{\alpha} = -0.0103$	(3) $\hat{\alpha} = -0.0629$
Average effect per property per earthquake (*in €*)	−€ 3,437.59	−€ 1,863.80	−€ 11,344.78
Average effect per earthquake $M_L > 2.5$ (*in €*)	−€ 8,037,961.00	−€ 4,358,028.50	−€ 26,526,954.00
Total effect of earthquakes (*in €*)	−€ 168,800,000.00	−€ 91,518,600.00	−€ 557,100,000.00

Note: the total number of owner-occupied properties in Groningen is estimated to be 76,164. We assume that only earthquakes that generate PGVs > § cm/s have a price effect. All results are in 2013 prices.

differ over time, we include a fifth-order polynomial function of the interactions of log distance to the nearest drilling activity and the year of observation, so:

$$\Psi\left(z_i, t-\underline{t}\right) = \sum_{r=1}^{5} \zeta_r \log(z_i)\left(t-\underline{t}\right)^r, \tag{6}$$

where z_i is the distance to the nearest drilling activity, $\underline{t} = 1995$ and ζr are parameters to be estimated. The results in column (3), Table 3, indicate that a stronger earthquake imply a price discount of 1.7%, which is very similar to the baseline specification.

It has been argued that the impact of earthquakes depends strongly on soil type. Different ‘weak’ soil types, such as clay and peat, may amplify the oscillations of earthquakes (Wassing and Dost, 2012). We therefore use data on soil types from Statistics Netherlands. For larger built-up areas, our data provide no information on soil types, so for these observations we impute the soil type by using the nearest soil type, including clay, peat and sand.[27] The results in column (4), Table 3, indicate that the impact of earthquakes is not statistically significantly different between different types of soils, although there is weak evidence that the impact in clay areas is larger than in sandy areas. The estimated effect in peat areas is imprecise due to a low number of observations, but seems to be somewhat stronger.

In column (5) we test whether the impact is different for properties inside and outside built-up areas, as defined by Statistics Netherlands. About 9% of the observations is located outside built-up areas, including villages, towns and cities. The results indicate that only in built-up areas earthquakes lead to a price discount, while the effect is essentially zero outside these areas, suggesting that the risks in built-up areas are higher, e.g. because buildings are taller and located closer to each other.

It is plausible that historic/old buildings are less resistant to earthquakes, which may increase the risk of (fatal) injuries and discomfort. In column (6), Table 3, we therefore test whether the impact of earthquakes is different for historic buildings, by only selection properties that are constructed before 1945. Indeed, it is shown that the impact (2.3%) is about 15% higher compared to the baseline specification.

[27] In Fig. A4, Appendix A.1, we display a map with the main soil types for the province of Groningen.

In all specifications we control for postcode area fixed effects that encompass about half a street. This should control for all time-invariant attributes of locations. However, we also may test whether the inclusion of 69,193 property fixed effects may impact the results. Such a specification is preferred when there are substantial differences in price discounts between houses within the same area or when the type of housing sold over time strongly changes (e.g. those that are more damaged by earthquakes are less likely to be sold). Note that including property fixed effects strongly reduces the degrees of freedom: we then identify the effect based on properties that are sold at least twice. Column (1), Table 4, indicates that noticeable earthquakes have a negative effect on house prices of 2.3%. This effect is higher compared to the baseline specification, but the coefficient is imprecisely estimated due to large number of fixed effects and is therefore not statistically significant at conventional levels (p-value = 0.197).

In the analysis we select transactions that took place from 1996 onwards, because neighbourhood attributes are only available since 1996. In column (2), Table 4, we also include data from 1985 onwards. This increases the number of observations with 12%, but we cannot control for changes in neighbourhood attributes. The results indicate that the impact of noticeable earthquakes is somewhat stronger (2.5%). We also have estimated a long-differences specification where we only include observations before earthquakes start to occur (so before December 1991) and after the strong earthquake in Huizinge, which caused a lot of attention in the media. The results in column (3) highlight that our initial estimate may then be somewhat conservative: the price effect of noticeable earthquakes is 4.2%.

In column (4) we test whether the effect of earthquakes on house prices is stable over time. Because the incidence and magnitude of earthquakes are increasing over time, and because house prices incorporate forward-looking behaviour, price effects may increase over time. The results indicate that in the first six years, the effect is not statistically significantly different from zero, which is not too surprising given the low number of noticeable earthquakes and the absence of attention from the press. The effect is 1.7% between 2002 and 2007 and then somewhat higher (1.9%) between 2008 and 2013, which is in line with the idea that induced earthquakes receive much more attention in the last years.

We also have information on house prices from other provinces in the Netherlands. In particular, in the adjacent provinces of Drenthe and Friesland some natural gas has been extracted. Also there, soil subsidence and earthquakes have been recorded (see Fig. 1). We therefore also estimate the same model where we include these provinces. To control for province-specific price trends, we include 54 province × year fixed effects. It is shown in column (5) that the coefficient is somewhat lower (−1.0%).[28]

In the last two specifications in Table 4, we consider two alternative housing market indicators that may have been affected by earthquakes. First, we consider the effect on days on the market. Homeowners have claimed that their properties are unsaleable due to the earthquakes. However, column (6) does not support this assertion: earthquakes do not seem to lead to longer (or shorter) selling times. Arguably, days on the market may be an imperfect measure to capture 'saleability' of properties, when a substantial proportion of affected houses are never transacted, but this seems unlikely. In column (7), Table 4, we choose as dependent variable the ratio of the transaction price to the first advertised asking price. The results indicate that there is no significant effect of earthquakes on this particular ratio.

We have argued above that the way in which we calculate the number of earthquakes must imply some measurement error, because Eq. (1) has been estimated, so the peak ground velocity is observed with measurement error. Because measurement error of estimating the attenuation function is probably approximately random, this suggests that our estimates are biased towards zero. Here, we aim to quantify the *upper bound* of this bias. Table 5 reports results where we investigate this issue in more detail.

We account for measurement error in our estimation procedure by calculating the reliability of the predicted peak ground velocity dummy using data of Dost et al. (2004) on 57 actual measurements of the PGV of 22 earthquakes occurring in the Netherlands between 1997 and 2002. The measure of reliability is given by:

$$\lambda = \frac{\sigma^2_{\tilde{e}^*}}{\sigma^2_{\tilde{e}^*} + \sigma^2_{\tilde{\xi}}}, \tag{7}$$

given that $\tilde{e}^*_{it} = \tilde{e}_{it} + \tilde{\xi}_{it}$, where $\tilde{e}^*_{it}$ is a demeaned dummy variable that equals one when the observed PGV > ½ cm/s, $\tilde{e}_{it}$ is a demeaned dummy variable when the predicted PGV > ½ cm/s using Eq. (1). We demean the values by postcode areas, which is essentially the same as including postcode area fixed effects. The reliability is then 0.382.[29] We then estimate an errors-in-variables regression given this minimum reliability measure. Column (1) shows that the effect of an earthquake that generates PGVs above half a cm/s is maximally 6.9%.

This effect is most likely a strong overestimate because the reliability measure ignores that a non-negligible share of the properties is affected by more than one earthquake with PGVs > ½ cm/s (2.8% of observations). We therefore create a dummy that indicates whether observations experienced at least two earthquakes with PGVs > ½ cm/s. We interpret this effect then as the upper bound effect of having received *at least one earthquake*. Column (2) reports results when we exclude observations that experienced one earthquake with PGVs > ½ cm/s. The effect is then 5.0%. We determine the (ultimate) upper bound of the effect by focusing on observations that experienced at least three earthquakes with PGVs > ½ cm/s. It is

[28] We have too little identifying variation to identify province-specific effects of earthquakes.

[29] Note that the reliability of $\tilde{e}_{it}$ exceeds that of $\tilde{v}_{it}$ because for low values of $\tilde{v}_{it}$ and high values, the measurement error of $\tilde{e}_{it}$ is essentially zero, because there is an almost zero probability given these values that the dummy variable takes on a different value due to measurement error.

then very unlikely that these observations did not experience any earthquake with PGVs > ½ cm/s. Again, we exclude observations with one or two earthquakes. The results in column (3) indicate then that the ultimate upper bound of the effect of a noticeable earthquake is 6.3%.

In the Appendix A we undertake some additional sensitivity checks. First, we analyse whether the results are robust to the threshold distance chosen to count the number of weak earthquakes in the vicinity of the house (see Eq. (5)). The results reported in Appendix A.4 show that the impact of peak ground velocities above half a cm/s may decrease somewhat if we increase the buffer size up to five kilometres. We also show that the results are robust to the assumption of the earthquake depth (which we set to three kilometres). One may also question the particular attenuation function we use to determine the intensity of earthquakes (see Eq. (1)). In Appendix A.5, as an alternative, we rely on a cross-sectional identification strategy and use the soil subsidence as an indicator of earthquake intensity. The results show that earthquakes again have considerable negative price effects.

3.3. *Counterfactual analysis*

To understand the quantitative implications of our results for the owner-occupied housing market, we conduct a counterfactual analysis on the estimated total non-monetary costs of induced earthquakes. Given that we have to make some additional assumptions, these results should be interpreted with caution. First, we estimate the benefits and costs in 2013 prices, by deflating house prices, investments and subsidies by the consumer price index, obtained from Statistics Netherlands. We assume that the estimated price effect is constant across the study period. Second, our transactions data refer to about 50% of owner-occupied housing stock, so we assume that our results are representative for the whole stock of 176 thousand owner-occupied properties in the province of Groningen. Third, about 35% of the properties in the province refer to rental properties. It is plausible that the effects on renters are smaller than for owners (as owners tend to be richer). In addition, most of these rental properties are rent-controlled, so future costs to most renters are usually zero. For these reasons, we ignore the effect of earthquakes on inhabitants of the rental properties in the analysis, so the total effects are best interpreted as lower bound estimates.

Table 6 reports the results for three different estimates. Column (1) reports the results when we take the baseline estimate of -0.0191 (see column (6), Table 2). Column (5) in Table 4 provides the results for the lower bound estimate of the effect of earthquakes and column (3) in Table 5 provides the upper-bound of the effect of earthquakes. We first calculate the average effect per property that has experienced an earthquake that generates peak ground velocities above half a cm/s. It is shown that the average non-monetary costs are € 3.4 thousand per property per earthquake. The lower and upper bound estimates suggest that the costs are in between € 1.9 and € 11.3 thousand. Next, we calculate the average total non-monetary costs per earthquake with $M_L > 2.5$ (because weaker earthquakes do not generate PGVs above a half cm/s). The costs per noticeable earthquake are € 8.0 million. Taking into account the range of the estimated effect, the total effect of an earthquake is between € 4.3 and € 26.5 million.

We then calculate the total non-monetary costs of earthquakes in our study period for the province of Groningen. These costs appear to be € 169 million (and between € 92 and € 557 million for the range of the estimated effect), or about € 600 per household. We compare this total estimate of the non-monetary costs to the total amount paid by the NAM to compensate for damage due to earthquakes. It appears that the NAM has paid about € 50 million to house owners based on 19,343 damage claims in the province of Groningen (which is about € 2500 per claim on average). 4567 of these claims occurred in 2013, so given that the average size of the claim is constant across the study period, the total monetary damage costs for that year were € 11.9 million. It seems not unreasonable to assume that the *annual* future monetary damage costs are roughly of the same value. Our estimates imply that the *annual* non-monetary costs are about € 8.4 million, given an interest rate of 5%. Hence, the annual monetary costs of induced earthquakes are in the same order of magnitude. It is interesting to compare these estimates to the recently announced public investment in this region in order to compensate inhabitants: compared to the public investments of about € 1.2 billion euros in the next years, implying annual investments of € 60 million. The total annual costs of earthquakes then seem to be an order of magnitude smaller.

4. Conclusions

The extraction of natural gas has unforeseen negative long-term effects because it may lead to soil subsidence and subsequent earthquakes. These induced earthquakes impose negative effects on the built environment in the form of monetary costs (e.g. damage) and non-monetary costs (e.g. reduction in living comfort, risk of (fatal) injuries). In this paper we estimate the non-monetary costs of earthquakes for Groningen, the Netherlands. Because the monopolist that extracts the natural gas compensates house owners for monetary damage costs due to earthquakes, we are able to identify the non-monetary costs of earthquakes. We show that, despite this compensation, noticeable earthquakes that generate peak ground velocities above half a cm/s have a negative effect on house prices of about 1.9%. We show that this estimate implies that the costs of an earthquake are about € 3.5 thousand per property. The total non-monetary costs due to earthquakes in Groningen are about € 170 million, or about € 600 per household, which is substantial. The annual non-monetary costs (about € 10 million) due to induced earthquakes are in the same order of magnitude as the monetary (damage) costs of earthquakes.

In principle, external costs of induced earthquakes should be internalised. This might be done by introducing a Pigouvian tax incorporating these damages, which would internalise social costs and improve the efficiency of drilling and gas production.

Appendix A

Other descriptive statistics

In this section of the Appendix A, we present three figures. In Fig. A1 we present the cumulative distribution of earthquakes' magnitudes. An earthquake with $M_L = 2$ is about four times less likely to occur than an earthquake with $M_L = 1$. Furthermore, an earthquake with $M_L = 3$ is 16 times less likely to occur than an earthquake with $M_L = 1$.

In Fig. A2 we display the earthquake attenuation function based on Dost et al. (2004). Itis shown that only earthquakes with $M_L > 2.5$ generate peak ground velocities above a half cm/s. In particular stronger earthquakes generate larger peak ground velocities that can be felt relatively far away from the epicentral location.

In Fig. A3 we report the estimated number of earthquakes with a peak ground velocity above half a cm/s in 2013. The municipalities of Loppersum and Ten Boer are the most affected. Also a small area in the southern part of Groningen seems to be affected. This is because of some rather strong earthquakes in a sparsely populated area in Drenthe, where also some natural gas has been extracted.

In Fig. A4 we display a soil type map for the Groningen area. The data are from Statistics Netherlands, which provide information on nine soil types. For the urban areas we impute information on soil types by calculating for each point in the urban area the distanceto the nearest soil type for which we have information. We then group soil types into three main categories: clay, peat and sand. Light clay, heavy clay, light sabulous clay, heavy sabulous clay and loam are grouped into the category ‘clay’; moerig and sand into ‘sand’; and we consider ‘peat’ as a distinct category. The map shows that the middle of the province of Groningen is characterised by clay soils. Only a small share of the province has peat soils.

Do earthquakes occur randomly over space?

Our identification strategy should identify a causal effect of earthquakes on house prices if the locations of earthquakes are randomly distributed over space, and are therefore uncorrelated to unobserved locational traits. Hence, for an earthquake to be spatially random, a sufficient (but not necessary) condition is that the cumulative spatial distribution of earthquakes is random. However, if earthquakes are concentrated in space, then there might be correlation of unobserved location attributes with the location of earthquakes (e.g. effects related to drilling activities). To measure whether the

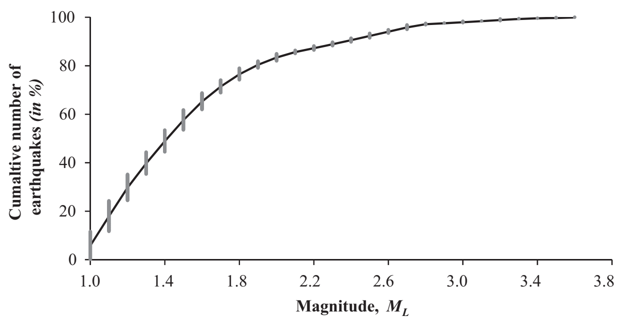

Fig. A1. Cumulative distribution of earthquakes.

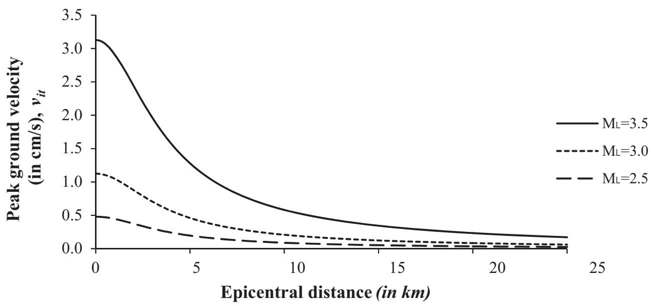

Fig. A2. Earthquake's local magnitude using an attenuation function.

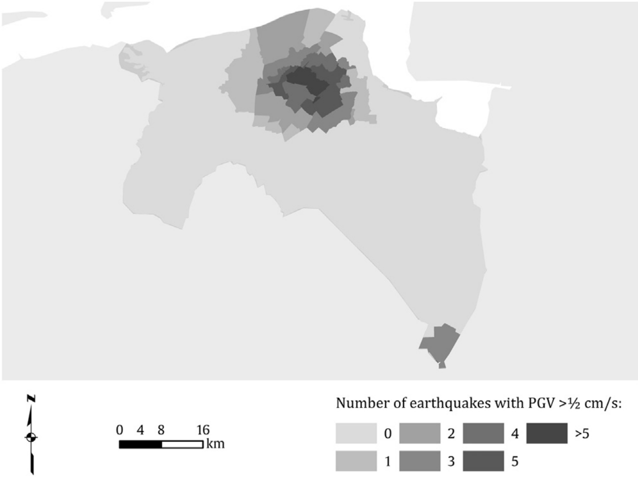

Fig. A3. Map of number of earthquakes with PGVs > ½ cm/s in 2013 since 1991.

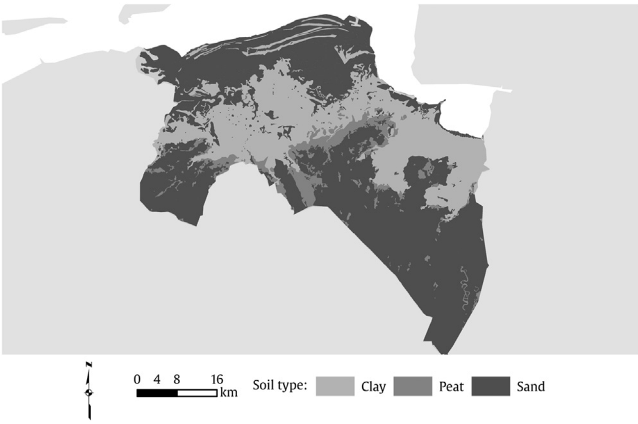

Fig. A4. Map of soil types in Groningen.

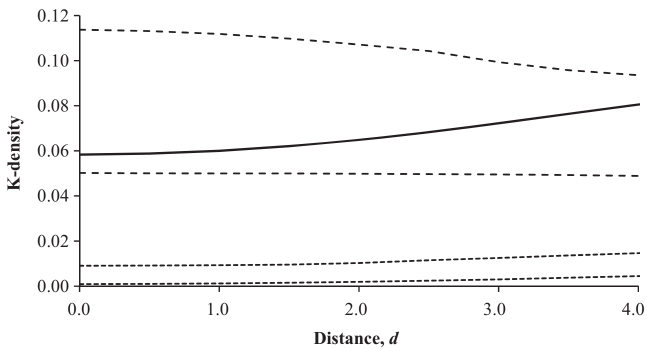

Fig. A5. Kernel densities for the spatial distribution of earthquakes with $M_L > 2.5$. *Note:* The black line represent the kernel density for a given distance, the dotted lines are the 5% global confidence bands with randomly generated locations, the dashed lines represent the 5% global confidence bands when we draw random locations from the set of weak earthquakes. We note that local confidence bands are very similar to global confidence intervals, so we do not display them here. We run 500 simulations to construct the confidence bands.

cumulative spatial distribution of earthquakes is (statistically significantly) clustered in space, we use the point-pattern methodology proposed by Duranton and Overman (2005) and estimate kernel densities for the location pattern of earthquakes. This measure is invariant to spatial scale and aggregation and provides an indication of statistical significance. We briefly discuss the procedure. For more details, we refer to Duranton and Overman (2005; 2008).

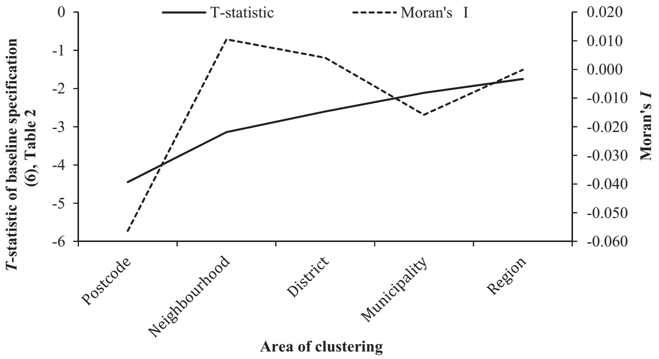

Fig. A6. *T*-statistics and Moran's *I* for different levels of clustering.

Table A1
Results: inclusion of weak earthquakes. (dependent variable: the logarithm of house price per m^2).

	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS
Number of earthquakes ($PGV >$ ½ cm/s)	-0.0200^{***}	-0.0178^{***}	-0.0170^{**}	-0.0156^{*}	-0.0107^{***}	-0.0123^{***}
	(0.00568)	(0.00669)	(0.00784)	(0.00821)	(0.00267)	(0.00295)
Number of weak earthquakes, $\Omega(n_{it})$	<500 m	<1500 m	<2500 m	<5000 m	<1000 m	<1000 m
Earthquake depth (in km)	3	3	3	3	1.5	2
Housing attributes (15)	Yes	Yes	Yes	Yes	Yes	Yes
Neighbourhood attributes (9)	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects (18)	Yes	Yes	Yes	Yes	Yes	Yes
Postcode area fixed effects (3736)	Yes	Yes	Yes	Yes	Yes	Yes
Observations	81,872	81,872	81,872	81,872	81,872	81,872
R-squared	0.818	0.818	0.818	0.818	0.818	0.818

Notes: We cluster standard errors at the neighbourhood level. Standard errors are in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.10$.

Table A2
Soil subsidence (dependent variable: the logarithm of house price per m^2).

	(1) OLS	(2) OLS	(3) OLS
Soil subsidence (*in cm*)	-0.00454^{***}	-0.00921^{***}	-0.00370
	(0.00106)	(0.00248)	(0.00262)
Number of weak earthquakes, $\Omega(n_{it})$	Yes	Yes	Yes
Housing attributes (15)	Yes	Yes	Yes
Neighbourhood attributes (9)	Yes	Yes	Yes
Year fixed effects (18)	Yes	Yes	Yes
Municipality fixed effects (25)	No	Yes	Yes
Neighbourhood fixed effects (549)	No	No	Yes
Observations	27,089	27,089	27,089
R-squared	0.335	0.539	0.633

Notes: We cluster standard errors at the neighbourhood level in all specifications. Standard errors are in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.10$.

Let $\hat{K}_t(d)$ denote the estimated kernel density at a given distance d, d_{ij} denotes the distance between earthquake i and j, where $i=1,\dots,I$ and n represents the number of earthquakes. Then:

$$\hat{K}(d)=\frac{1}{n(n-1)h}\sum_{i=1}^{I-1}\sum_{j=i+1}^{I}\Upsilon\left(\frac{d-d_{ij}}{h}\right), \tag{8}$$

where h is the bandwidth and we define:

$$\Upsilon(\bullet) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{d-d_{ij}}{h}\right)^2}, \tag{9}$$

so we use a Gaussian weighting function. An important parameter of the kernel density function is the bandwidth h. Following common practise, we set the bandwidth equal to Silverman's plug-in method (see Silverman, 1986).[30] We estimate $\hat{K}(d)$ for $d \le 4$ because the median distance between earthquakes with $M_L > 2.5$ in our region is about 6.5 kilometres.[31] To deal with the issue that distance d cannot be negative, we use the reflection method, as proposed by Silverman (1986). We aim to test whether the estimated concentration is statistically significantly different from randomness, so we have to define a counterfactual location pattern. We first assign earthquakes to randomly generated locations in the province of Groningen. Then, we test whether the location pattern of noticeable earthquakes differs significantly from the location pattern of weak earthquakes ($1 < M_L \le 1.5$). This test is in line with our identification strategy used, where we test the impact of noticeable earthquakes *conditional* on the location of weak earthquakes.

One may determine the five percent local confidence bands by ranking 500 simulations of the counterfactual location patterns in ascending order and choose the 5th and 95th percentiles to obtain the five percent lower and upper confidence interval. We are more interested in whether *global* concentration of earthquakes is different from randomness, so we determine global confidence intervals by treating each of the estimated density functions for each simulation as a single observation. Following Duranton and Overman (2005), we choose identical local confidence levels in such a way that the global confidence level is five percent. We conclude that earthquakes are significantly concentrated at the five percent level if they are *above* the 95 confidence band.

Fig. A5 reports the results. It is shown that conditional on a randomly generated set of locations, it is shown that these earthquakes are much more concentrated than if they would occur randomly over space. However, once we condition on the location of weak earthquakes ($1 < M_L \le 1.5$), we show that noticeable earthquakes are not statistically significantly concentrated anymore and well within the confidence bands.

Robustness – different levels of clustering

To estimate standard errors, one should control for serial correlation, otherwise standard errors may be too small (Bertrand et al., 2004). We may also cluster standard errors over space to account for spatial correlation. We cluster at the neighbourhood level, because the data on neighbourhood attributes are gathered at the neighbourhood level. However, we investigate whether clustering at higher levels of spatial aggregation will influence the conclusion that induced earthquakes have a significant impact on house prices. We also test whether there is spatial autocorrelation in the error term. If there is (substantial) spatial autocorrelation, one may be concerned about whether the standard errors are correctly estimated. One way to investigate whether there is spatial autocorrelation is to estimate Moran's I, which is given by:

$$I = \frac{n}{S_0} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \hat{\epsilon_i} \hat{\epsilon_j}}{\sum_{i=1}^{n} \epsilon_i^2}, \tag{10}$$

where $\hat{\epsilon}_i$ and $\hat{\epsilon}_j$ denote estimated residuals, w_{ij} is the spatial weight between i and j, n is the number of observations and $S_0 = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}$. Note that the average residual $\overline{\epsilon} = 0$. To determine the weights, we select observations in the same geographical area of the property (e.g. neighbourhood, district). The weight matrix is row-standardised, so $\frac{n}{S_0} = 1$ and $-1 \le I \le 1$.

In Fig. A6 we plot the T-statistic for the baseline estimate of noticeable earthquakes for different spatial levels of clustering. When we cluster at the postcode level, the number of clusters is large and the T-statistic is -4.45. We also observe that there is some *negative* spatial autocorrelation ($I = -0.0563$). Neighbourhood level clustering delivers a T-statistic of about -3.14. The spatial autocorrelation coefficient is then positive but close to zero ($I = 0.0105$). Hence, it is unlikely that we have a problem of spatial autocorrelation in the baseline estimates. When we cluster standard errors at the district level (a group of neighbourhoods), the number of clusters is 109 and the T-statistic is -2.60, so the estimate is still statistically significantly different from zero at the five percent level. Moran's I is then essentially zero ($I = 0.00405$). Once we cluster at higher levels of spatial aggregation, standard errors may not be correct because we would have too few clusters (see Angrist and Pischke, 2008). For example, when we cluster at the municipality level we only have 25 clusters, less than is usually recommended. Still, the estimate is statistically significantly different from zero at the five percent level (the corresponding T-statistic is -2.11). At the regional level, we have only seven clusters. The T-statistic is then -1.75, so the estimate is imprecise but still significantly different from zero at the ten percent level.

[30] More specifically, $h = 1.06\sigma_{d_{ij}} I^{-\frac{1}{5}}$, where $\sigma_{d_{ij}}$ is the standard deviation of the estimated bilateral distances between earthquakes.

[31] Information for larger distances is redundant: if earthquakes are concentrated at small distances, they are by construction dispersed at large distances (as there are too few earthquakes occurring far from each other).

Robustness – weak earthquakes and earthquake depth

To control for the non-random location pattern of earthquakes, we include a flexible function of the number of weak non-noticeable earthquakes within one kilometre of the property. This one kilometre cut-off value is of course arbitrary. Table A1 therefore reports results for other values. It is shown that the results are generally robust, although they become somewhat smaller in magnitude when we include the number of weak earthquakes within five kilometres (see column (4)). The effect is then 1.6% of an earthquake that generate PGVs > ½ cm/s.

There is much uncertainty about the exact depth of earthquakes. There is some evidence that earthquakes occur at a more shallow depth (see Dost et al., 2004). In column (5) we test when it is assumed that earthquakes occur at an implausibly low depth of 1.5 km, whether this would influence the results. It appears that the price decrease per noticeable earthquake is then 1.1%, which is somewhat lower. Column (6) shows that the price effect becomes 1.2% when we set the earthquake depth to 2 km.

Robustness – soil subsidence

To calculate the intensity of earthquakes, we use a measure of the peak ground velocity. Because this measure is estimated, the depth of earthquakes is uncertain and the epicentral location is only known up to a hundred metres, this may imply measurement error. In this part of the Appendix A, we therefore also consider an alternative way to measure the intensity of earthquakes. More specifically, we use data on subsidence of the soil. Recall that soil subsidence is the strongest in the centre of the Groningen natural gas field (up to 26 centimetres), which is also the area that has received the highest number of earthquakes (see Fig. 1d). Because we only have data on 2008 soil subsidence, we include transactions that took place between 2006 and 2010. Table A2 reports the results.

Because we do not have temporal variation in soil subsidence, our analysis relies on a cross-sectional identification strategy. We therefore cannot include postcode fixed effects, which would absorb all identifying variation. If we do not include location fixed effects (but control for neighbourhood and housing attributes), the results suggest that a ten cm downward shift of the soil leads to a decrease in price of 4.5% (see column (1)). Hence, this price effect is substantial if we take into account that the soil subsidence in the most heavily targeted areas was 26 cm. The results become even somewhat stronger if we control for municipality fixed effects in column (2), so that we analyse differences in soil subsidence within the municipality. We may even try to include neighbourhood fixed effects (see column (3)). Not surprisingly, the effect becomes imprecise and lower in magnitude, because part of the effect is absorbed in the neighbourhood fixed effects. Nevertheless, the point estimate suggests that a ten centimetre downward shift in the soil leads to a price decrease of 3.7% (p-value = 0.158). We think our initial identification strategy using changes in earthquakes is more convincing, but these result largely confirm these estimates.

Appendix B. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.euroecorev.2015.08.011

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