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Natural Gas Extraction, Earthquakes and House Prices

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Natural Gas Extraction, Earthquakes and House Prices[*]

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SUMMARY — 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 1.2 percent. The total non-monetary costs of induced earthquakes for Groningen are about € 150 million, about € 500 per household. The results also indicate that the non-monetary costs of are in the same order of magnitude as the monetary damage costs.

JEL-code — Q54, Q32, R30, R33
Keywords — natural gas extraction, earthquakes, house prices, hedonic price analysis.

I. Introduction

The production of natural gas has grown rapidly in recent years. For example, in the United States the total shale gas production rose from 37 billion cubic meters in 2007 to 323 billion cubic meters in 2013, an increase of almost 900 percent. Recent developments in hydraulic fracturing ('fracking') and horizontal drilling have made many gas reserves an economically

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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. The long-term negative effects and the impacts on the local environment of gas extraction have been hardly studied.

In this paper, we focus on the effects of natural gas, 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 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 plagued most frequently by earthquakes.

In the current study, we focus on the long-term (negative) effects of natural gas extraction for the Netherlands, where natural gas is 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, 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 long-run negative economic effects of these human-induced earthquakes, by looking at their effects on house prices. We believe that there are three main mechanisms how earthquakes affect real estate prices. The first mechanism is that past earthquakes have damaged properties which have not been repaired. This mechanism may be observed in the data when households do not repair damage of houses hit by earthquakes. 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]

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

[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 analysed.

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

The third mechanism of how 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 of an increasing number of earthquakes with an unknown magnitude occurring in the future. So, earthquakes arguably alter the expectations regarding future risk on damage of the property and even collapse of the property (see Beron et al., 1997; Naoi et al., 2009). In the current paper, we likely identify this third mechanism and compare the non-monetary costs to past monetary costs. We use past earthquakes as a determinant of house prices, which assumes that households use information on past earthquakes to predict the incidence of future earthquakes.

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 house prices of housing transactions since 1996. Using panel-data estimation techniques, we compare price changes between areas that differ in the number and magnitude of earthquakes. We measure the incidence of noticeable earthquakes by focusing on earthquakes that generate vibrations that lead to peak ground velocities above half a cm/s, which corresponds to a probability of damage of about five percent. This approach can be criticised, because one may argue that earthquakes may 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). Specifically, the gas field in Groningen is below a rural area, where house prices tend to be lower. We therefore only 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. 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 is relevant, because earthquakes generally are *not* randomly distributed over space. However, conditional on weak earthquakes occurring at a given location, we show that stronger noticeable earthquakes occur as good as random over space. This identification strategy then should identify a causal effect of noticeable earthquakes on house prices.

The results indicate that earthquakes generating peak ground velocities above half a cm/s imply price decreases of 1.2 percent of the house price. Vibrations with a lower intensity do not imply price discounts in our data. This estimate implies that the average non-monetary costs of a noticeable earthquake are about € 3 thousand per property per earthquake that generate peak ground velocities above half a cm/s. The total non-monetary costs of induced earthquakes for Groningen are about € 150 million, or € 500 per household. We continue to show that the annual non-monetary costs are in the same order of magnitude as the past monetary costs due to damage: the baseline estimate suggests that the total annual non-monetary costs are around € 10 million. The results are robust to a wide range of robustness checks and other identifying assumptions.

This is one of the first studies that looks into the long-term negative effects of natural gas production. Our study is complementary to the study by Muehlenbachs et al. (2012) and

Gopalakrishnan and Klaiber (2014) who find that shale gas developments may reduce property values up to 25 percent, for example because of ground water contamination. In contrast, Delgado et al. (2014) do not find permanent price effects of shale gas explorations and conclude that there may be long-term costs that are not apparent at this point in time.[5] In contrast to shale gas extraction, natural gas extraction does not contaminate groundwater so we identify the effect of noticeable earthquakes only.

The paper also relates to a number of studies that investigate the effects of earthquake risk. Brookshire et al. (1985) and Nakagawa (2007) for example show that areas with a high earthquake risk command significantly lower 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 on earthquakes. In contrast, Naoi et al. (2009) show for Japan that the price discount of locating within an earthquake-prone area became 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 humans. Furthermore, because any damage costs due to earthquakes are fully compensated, we measure non-monetary costs of earthquakes, rather than the combination of both. The latter is relevant for countries such as the Netherlands and the United States where gas extraction companies (usually) do not compensate for non-monetary effects of earthquakes.[6]

The paper furthermore 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 II we discuss the regional context, introduce the datasets used and discuss the econometric framework and identification strategy. Section III presents the results, subject these results to a wide range of robustness checks, and discuss

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[5] 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 the northern parts of Groningen on house prices and 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.

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

the quantitative implications by means of a counterfactual analysis. In Section IV, we draw some conclusions.

II. Data and econometric framework

A. 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 contain about 25 percent of natural gas reserves in Europe. Also other smaller gas fields are currently producing natural gas. Although there are some other minor operators, the gas is extracted predominantly by one company, the Dutch Petroleum Company (NAM), which is a joint venture between two large oil and gas companies: Shell and ExxonMobil, and which pay the national state for extraction.[7] The yearly benefits for the national government of natural gas extraction are about € 10 to € 15 billion, about 1.5 percent 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 percent of the Dutch households used natural gas for cooking and heating.[8] As was unknown at that time, the extraction of natural gas also has its (long-term) consequences, such as soil subsidence and earthquakes. The unexpected increase in 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 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 induced 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.[9] The main explanation is the combination of soil conditions present in Groningen and the shallow depth at which the extraction-induced earthquakes are triggered, between 2000 and 3000 metres (Wassing et al., 2010). We observe a strong correlation between the cumulative number of earthquakes until 2014 and number of damage claims per household in

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

[8] 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

[9] 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 ($\rho = 0.722$). If we only focus on earthquakes with a magnitude above two, the correlation is almost identical.[10]

Several lobby and interest groups have been formed (e.g. 'Groninger Bodem Beweging' (GBB) and 'Schokkend Groningen') that represent the residents in the affected areas. These residents argue that in addition to the monetary costs that are compensated, residents 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 living comfort has 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 the number of earthquakes. This correlation is even more pronounced if we only focus on earthquakes with $M_L > 2$ ($\rho = 0.919$). The issue also received substantial attention in the Dutch press. As an illustration: the 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 future in the region. The secretary of state of economic affairs Henk Kamp also decided to reduce the extraction of natural gas with about 25 percent and to invest about € 1.2 billion (about 0.5 percent of the cumulative benefits of Dutch natural gas extraction) in the region into making buildings earthquake-proof (Department of Economic Affairs, 2013; 2014a; 2014b).[11]

B. 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 epicentre is certain 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 Figure 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 also other cities like Hoogezand-Sappemeer and Delfzijl have suffered from earthquakes more recently.[12]

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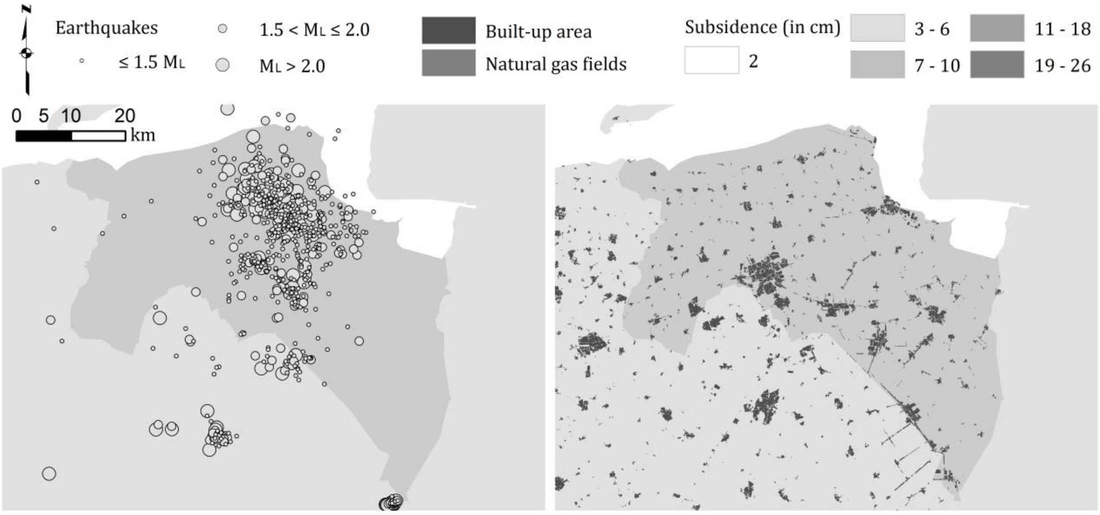
[10] We note that natural earthquakes with $M_L < 2$ are not noticeable by people and are only recorded by seismographs (Richter, 1958). Somewhat stronger earthquakes are only felt when they occur close to the earth's surface.

[11] In the Netherlands, the occurrence of (natural) earthquakes is uncommon, so newly built houses are not intended to be earthquake proof.

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



A. EARTHQUAKES

B. BUILT-UP AREA

C. NATURAL GAS FIELDS

D. SOIL SUBSIDENCE IN 2008

FIGURE 1 — MAPS OF THE PROVINCE OF GRONINGEN

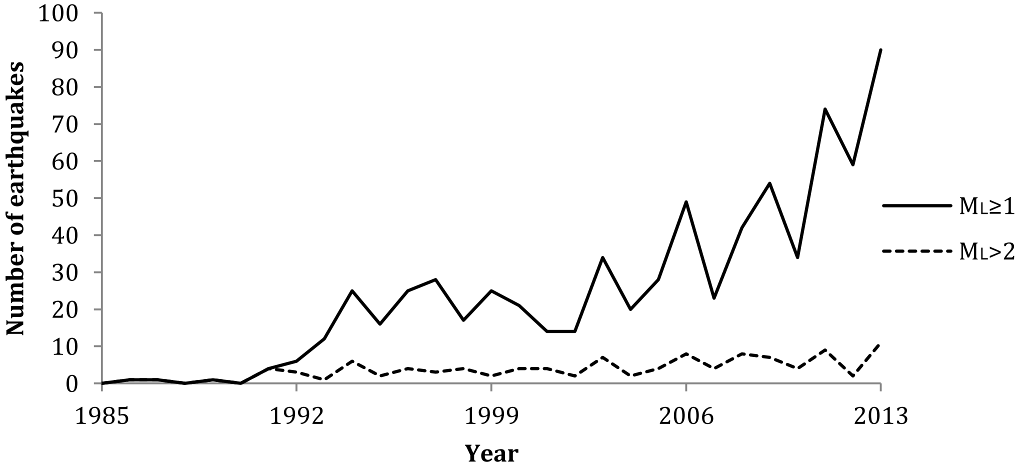


FIGURE 2 — EARTHQUAKES IN GRONINGEN

Panel D, Figure 1, shows 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 (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, 717 earthquakes have been recorded with a magnitude of at least one. The strongest earthquake was 3.6 M_L in Huizinge in 2012.[13] Figure 2 displays the number of earthquakes over time. It can be seen that after 2002, the number of earthquakes is increasing substantially (see Wassing et al., 2010). However, the large majority of earthquakes are rather weak. The number of earthquakes with $M_L > 2$ is around six per year since 2005. The year 2013 was an exception with 11 earthquakes with $M_L > 2$. In Appendix A.1, Figure 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 using an attenuation function that has been estimated for earthquakes occurring in the Netherlands (Dost and Haak, 2002; Dost et al., 2004).[14] 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:

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

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 assume that they occur at a depth of two kilometres ($s_{ijt} = 2$), as in Dost et al. (2004). A survey undertaken by the NAM confirmed the depth of two kilometres (with an error of 0.2 kilometres).[15] In Figure 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 kilometres of the epicentral location. When an earthquake with $M_L = 2.2$ occurs exactly below the location of

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[13] 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

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

[15] We checked whether changing s_{ijt} (e.g. to three kilometres) leads to different results, which is not the case (see Appendix A.4).

a house then $v_{it} \approx ½$ cm/s. In our study period, 45 earthquakes had an magnitude above 2.2, so generated peak ground velocities above half a cm/s. Because the cut-off value of the PGV of half a cm/s is arbitrary, in the sensitivity analysis we will also test whether earthquakes with lower v_{it} have any price effect (see Section III.B).

For each observation we then calculate the number of earthquakes:

$$(2) \qquad e_{it} = \sum_{\underline{t}=1991}^{t} 1\left(v_{i\underline{t}} > ½\right).$$

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. This error is, however, likely to be small because we focus on the incidence of earthquakes using a certain threshold, which reduces the measurement error. We investigate this issue further in the sensitivity analysis (Section III.B), e.g. by estimating errors-in-variables regressions.

C. 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.[16] We have information on the population density, share of young and elderly people, share foreigners, and average household size.[17] Some parts of Groningen are 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

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[16] The average distance to the centroid of a neighbourhood is about 0.4 kilometres, so these areas are rather small.

[17] 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.

TABLE 1 — DESCRIPTIVE STATISTICS

	(1) mean	(2) sd	(3) min	(4) max
House price (*in € per m*^{2})	1,365	519.6	500	5,000
Number of earthquakes ($PGV > ½\ cm/s$)	0.104	0.545	0	11
Weak earthquakes ($1 < M_L \leq 1.5$) ($< 1\ km$)	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	4,031	3,378	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.

neighbourhood level.[18] 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 meter is € 1,365. 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

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[18] 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.

cm/s. 4,125 observations (5.0 percent) have experienced at least one earthquake that generates PGVs above half a cm/s. The share is of course much higher in 2013 (11.2 percent), while it was about 1 percent in 1996. 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 (the distance to a gas field is on average 1.5 kilometres). 36 percent of the observations are above a natural gas field and for the remaining observations the average distance to a natural gas field is 2.36 kilometres. 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.[19] A relatively high share of the 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 percent, so we analyse the prices of a stock 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 percent lower than the national average. Also, the share of open space (0.32) is higher than the national average (0.24). The share of foreigners is much lower in Groningen and about 50 percent of the national average.

D. Empirical framework

We aim to estimate the causal effect of earthquakes on house prices. Because residents can get compensation for monetary costs related to damage, we should be able to identify non-monetary price effects of induced earthquakes. We use past earthquakes as a determinant of house prices, which assumes 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 relatively attractive (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-

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[19] Note that in this area, there are essentially no high-rise residential buildings.

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. 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. Because noticeable earthquakes are rare, 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 number of weak earthquakes with $1 < M_L \leq 1.5$, are indeed *not* statistically significantly concentrated in space. We therefore control for the total number of 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.[20] When we also control for neighbourhood attributes z_{it}, this leads to the following specification:

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

where $\Omega(\cdot) = \sum_{r=1}^{5} \delta_r n_{it}^r$, where δ_r are parameters so be estimates, so $\Omega(\cdot)$ 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:

$$n_{it} = \sum_{\underline{t}=1991}^{t} 1\big(d_{ij\underline{t}} < 1\big) \cdot 1\big(1 < M_{Ljt} \leq 1.5\big). \tag{5}$$

Equation (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 non-noticeable earthquakes.[21]

III. Results

A. 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.[22]

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

[21] 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.

[22] 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.

TABLE 2 — BASELINE RESULTS

(dependent variable: the logarithm of house price per m^2)

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	OLS	OLS	OLS	OLS	OLS
Number of earthquakes	-0.0318***	-0.0224***	-0.0219***	-0.0168***	-0.0117***	-0.0123***
($PGV >$ ½ cm/s)	(0.00416)	(0.00377)	(0.00328)	(0.00351)	(0.00301)	(0.00295)
Size of property *(log)*			-0.460***	-0.460***	-0.460***	-0.460***
			(0.00757)	(0.00755)	(0.00762)	(0.00763)
Number of rooms			0.0232***	0.0232***	0.0237***	0.0237***
			(0.000992)	(0.000987)	(0.000966)	(0.000966)
House type – terraced			0.0895***	0.0895***	0.0902***	0.0902***
			(0.00582)	(0.00582)	(0.00586)	(0.00585)
House type – semi-detached			0.148***	0.148***	0.148***	0.148***
			(0.00632)	(0.00630)	(0.00632)	(0.00631)
House type – detached			0.356***	0.356***	0.353***	0.353***
			(0.00832)	(0.00832)	(0.00837)	(0.00836)
Garage			0.109***	0.109***	0.107***	0.107***
			(0.00263)	(0.00263)	(0.00261)	(0.00261)
Garden			0.00433	0.00440	0.000764	0.000768
			(0.00490)	(0.00489)	(0.00468)	(0.00468)
Central heating			0.122***	0.122***	0.117***	0.117***
			(0.00354)	(0.00354)	(0.00356)	(0.00356)
Listed building			0.100***	0.0998***	0.0994***	0.0995***
			(0.0127)	(0.0127)	(0.0128)	(0.0128)
Population density *(log)*					-0.0117***	-0.0117***
					(0.00227)	(0.00227)
Share young people (<15 years)					0.201**	0.202**
					(0.0806)	(0.0806)
Share elderly people (≥65 years)					-0.532***	-0.531***
					(0.0544)	(0.0543)
Share foreigner					0.180***	0.179***
					(0.0538)	(0.0537)
Average household size					-0.153***	-0.152***
					(0.00998)	(0.00997)
Land use – industrial/commercial					0.117***	0.117***
					(0.0263)	(0.0263)
Land use – infrastructure					0.129	0.127
					(0.156)	(0.156)
Land use – open space					0.131***	0.131***
					(0.0205)	(0.0205)
Land use – water					0.182***	0.181***
					(0.0623)	(0.0624)
Number of weak earthquakes				-0.0173***	-0.00862***	
($1 < M_L \leq 1.5$), ($< 1\ km$)				(0.00383)	(0.00313)	
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 (3,733)	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. *, **, ***, 10%, 5%, 1% significance, respectively.

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 3.2 percent 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 2.2 percent. 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, so 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, so 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 the previous specifications (1.2 percent per noticeable earthquake). Neighbourhood attributes also have a statistically significant effect on house prices and generally have the expected signs.[23] Areas with increasing population densities seem to face very small price decreases: doubling population density is associated with a decrease in prices of 0.8 percent. Neighbourhoods with a higher share of young people seem to be more attractive, while areas with a high share of elderly people experience lower prices. In general, we also observe that having more commercial land close to the property increases the price, possibly due to a better access to shops, jobs and amenities. Open space and water also are associated with positive price increases, compared to residential land.

In column (6), which we consider as the preferred specification, we include a flexible function of the number of weak earthquakes within one kilometre of the property. The results again indicate that a noticeable earthquake generating PGVs above half a cm/s leads to a price decrease of 1.2 percent. So, summarising, the results indicate a price discount of 1.2-2.2 percent in areas that have experienced noticeable earthquakes.

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[23] 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.

B. 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. Table 3 reports the results.

We first investigate whether weaker earthquakes have any price effects and whether within the category of noticeable earthquakes we find that the strongest earthquakes have the strongest effect. It is shown in column (1) 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 might relate to the fact that these weaker earthquakes are not randomly distributed across space. Higher PGVs seem to have a similar negative price effect. The effect seems smaller than when $\frac{1}{2}\text{ cm/s} < \text{PGV} \leq \frac{3}{4}\text{ cm/s}$, but the effects are not statistically significantly different from each other.

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.[24] The results indicate a negative price effect of noticeable earthquakes of 1.2 percent.

It has been argued that the impact of earthquakes is highly dependent on soil type. Different 'weak' soil types, such as clay and peat, may amplify the oscillations of earthquakes (Wassing and Dost, 2012). We then 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.[25] The results in column (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 (p-value $= 0.107$). The estimated effect in peat areas is imprecise due to a low number of observations, but seems to be somewhat stronger, in line with expectations.

In column (4) we test whether the impact is different for properties inside and outside built-up areas, as defined by Statistics Netherlands. About 9 percent 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. This might be because the risks in built-up areas are higher, e.g. because properties are located close to each other and because buildings tend to be taller.

It is plausible that historic/old buildings are less resistant to earthquakes, which may increase the risk on (fatal) injuries and discomfort. In column (5) we therefore test whether

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

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

TABLE 3 — SENSITIVITY ANALYSIS

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS
	Include weaker earthquakes	Region×year fixed effects	Soil-type specific effects	Built-up areas	Historic buildings only	Property fixed effects	Time-varying effects	Include Drenthe and Friesland	Days on the market	Transaction/ asking price ratio
Number of earthquakes ($PGV > ½\ cm/s$)		-0.0117*** (0.00349)			-0.0158*** (0.00426)	-0.0191* (0.0104)		-0.00756*** (0.00234)	3.666 (2.470)	0.00114 (0.000927)
Number of earthquakes ($PGV > ¾\ cm/s$)	-0.0192*** (0.00576)									
Number of earthquakes ($½\ cm/s < PGV \leq ¾\ cm/s$)	-0.0226*** (0.00543)									
Number of earthquakes ($¼\ cm/s < PGV \leq ½\ cm/s$)	0.00911*** (0.00220)									
Number of earthquakes ($PGV > ½\ cm/s$) × soil type – clay			-0.0179*** (0.00488)							
Number of earthquakes ($PGV > 1$) ($PGV > ½\ cm/s$) × soil type – peat			-0.0215 (0.0237)							
Number of earthquakes ($PGV > 1$) ($PGV > ½\ cm/s$) × soil type – sand			-0.00977*** (0.00307)							
Number of earthquakes ($PGV > ½\ cm/s$) × inside built-up area				-0.0191*** (0.00330)						
Number of earthquakes $PGV > ½\ cm/s$) × outside built-up area				0.00321 (0.00422)						
Number of earthquakes $PGV > ½\ cm/s$) × ($1996 \leq$ year ≤ 2001)							0.00605 (0.00884)			
Number of earthquakes $PGV > ½\ cm/s$) × ($2002 \leq$ year ≤ 2007)							-0.00867** (0.00410)			
Number of earthquakes $PGV > ½\ cm/s$) × ($2008 \leq$ year ≤ 2013)							-0.0119*** (0.00302)			
Number of weak earthquakes, $\Omega(n_{it})$	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Housing attributes (15)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Neighbourhood attributes (9)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects (18)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region×year fixed effects (475)	Yes	Yes	No	No	No	No	No	No	No	No
Province×year fixed effects (54)	No	No	No	No	No	No	No	Yes	No	No
Postcode area fixed effects (3,733)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Property fixed effects (69,193)	No	No	No	No	No	Yes	No	No	No	No
Observations	81,872	81,872	81,872	81,872	26,692	81,872	81,872	230,520	80,868	81,661
R-squared	0.818	0.824	0.818	0.818	0.800	0.990	0.818	0.803	0.271	0.265

Notes: We cluster standard errors at the neighbourhood level. Standard errors are in parentheses. *, **, ***, 10%, 5%, 1% significance, respectively.

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 (1.6 percent) is about 30 percent higher compared to the baseline specification.

In all the specifications we control for postcode area fixed effects that encompass about half a street, which 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 the price discount 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 this strongly reduces the degrees of freedom. We then only identify the effect based on properties that are sold at least twice. Column (6) indicates that earthquakes that generate PGVs $>$ ½ cm/s have a negative effect on house prices of 1.9 percent. This effect is higher compared to the baseline specification, but the coefficient is somewhat imprecisely estimated due to large number of fixed effects and therefore not statistically significantly different from the baseline specification.

In column (6) 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 0.9 percent between 2002 and 2007 and then somewhat higher (1.2 percent) 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 is being extracted. Also there, soil subsidence and earthquakes have been recorded (see Figure 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 (7) that the coefficient is somewhat lower (−0.8 percent), but still is highly statistically significant.[26]

In the last two specifications in Table 3, 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 (9) 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 houses are

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[26] It appears that we have too little identifying variation to identify province-specific effects of earthquakes.

TABLE 4 — ACCOUNTING FOR MEASUREMENT ERROR

(dependent variable: the logarithm of house price per m^2)

	(1) Errors-in-variables EIVREG	(2) ≥2 earthquakes OLS	(3) ≥4 earthquakes OLS
Number of earthquakes ($PGV > ½\ cm/s$)	-0.0502*** (0.0127)		
Dummy ≥2 earthquakes ($PGV > ½\ cm/s$)		-0.0276** (0.0109)	
Dummy ≥4 earthquakes ($PGV > ½\ cm/s$)			-0.0382* (0.0203)
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 (3,736)	Yes	Yes	Yes
Reliability	0.382		
Observations	81,872	79,976	78,180
R-squared	0.734	0.820	0.823

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. *, **, ***, 10%, 5%, 1% significance, respectively.

never transacted, but this is unlikely. In column (10) 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 equation (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 4 reports results where we investigate this issue in more detail.

We may 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:

$$\lambda = \frac{\sigma^2_{\tilde{e}^*}}{\sigma^2_{\tilde{e}^*} + \sigma^2_{\tilde{\xi}}}, \tag{6}$$

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 equation (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.[27] We then estimate an errors-in-variables regression given this minimum reliability measure. Column (1) shows that the effect of an earthquake that generate PGVs above half a cm/s is maximally 5.0 percent.

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 percent of observations). We then 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 *at least one earthquake*. Column (2) reports the results where we exclude observations that experienced one earthquake with PGVs $>$ ½ cm/s. The effect is then 2.8 percent. We determine the (ultimate) upper bound of the effect by focusing on observations that experienced at least four earthquakes with PGVs $>$ ½ cm/s. It is then very unlikely that these observations did not experience any earthquake with PGVs $>$ ½ cm/s. Again, we exclude observations with one, two or three earthquakes. The results in column (3) indicate then that the ultimate upper bound of the effect of a noticeable earthquake is 3.8 percent.

In the Appendix 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 equation (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, but are still in line with our main conclusions. We also show that the results are robust to the assumption of the earthquake depth (which we set to two kilometres in this research).

One may also question the particular attenuation function (see equation (1)) we use to determine the intensity of earthquakes. In Appendix A.5, as an alternative, we count the number of earthquakes with $M_L > 2.2$ (which corresponds to earthquakes that generate peak ground velocities above half a cm/s) within one kilometre and half a kilometre of the property. The results show that earthquakes again have considerable negative price effects. We note that the estimates are not always very precise, but in line with the baseline estimates.

C. 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

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[27] 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.

TABLE 5 — COUNTERFACTUAL ANALYSIS

	(1)	(2)	(3)
	$\hat{\alpha} = -0.0123$	$\hat{\alpha} = -0.00756$	$\hat{\alpha} = -0.0382$
Average effect per property per earthquake *(in €)*	-€ 2,220.55	-€ 1,362.38	-€ 6,882.46
Average effect per earthquake $M_L > 2.2$ *(in €)*	-€ 3,240,348.50	-€ 1,988,069.10	-€ 10,043,276.00
Total effect of earthquakes *(in €)*	-€ 145,800,000.00	-€ 89,463,112.00	-€ 451,900,000.00

Note: the total number of owner-occupied properties in Groningen is estimated to be 76,164. We assume that only earthquakes that generate PGVs $>$ ½ cm/s have a price effect. All results are in 2013 prices.

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 percent 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 percent 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 exclude 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 5 reports the results for three different estimates. Column (1) reports the results when we take the baseline estimate of -0.0123 (see column (6), Table 2). Column (8) in Table 3 provides the results for the lower bound estimate of the effect of earthquakes and column (3) in Table 4 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 about € 2.2 thousand per property per earthquake. The lower and upper bound estimates suggest that the costs are in between € 1.4 and € 6.9 thousand. Next, we calculate the average total non-monetary costs per earthquake with $M_L > 2.2$ (because weaker earthquakes do not generate PGVs above a half cm/s). The costs per noticeable earthquake are € 3.2 million. Taking into account the range of the estimated effect, the total effect of an earthquake is between € 2 and € 10 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 € 145 million (and between € 89 and € 452 million for the range of the estimated effect), or about € 500 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 € 2,500 per claim on average). 4,567 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 € 7.2 million, given an interest rate of 5 percent. Hence, the annual monetary costs of induced earthquakes are in the same order of magnitude, albeit somewhat higher. It is interesting to compare these estimates to the 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.

IV. Conclusions

The extraction of natural gas has unforeseen negative long-run effects. Natural gas extraction 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 on (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 costs due to induced 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 1.2 percent. We show that this estimate implies that the costs per earthquake per property may exceed € 2 thousand. The total non-monetary costs due to earthquakes in Groningen are about € 150 million, or about € 500 per household, which is substantial. The non-monetary costs due to induced earthquakes are the same order of magnitude as the monetary (damage) costs of earthquakes. One of the policy consequences of this analysis is that the external costs of induced earthquakes should be internalised, e.g. by introducing a fee for gas extraction.

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Appendix

A.1 Other descriptive statistics

In this section of the Appendix, we present three figures. In Figure 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 $M_L = 1$.

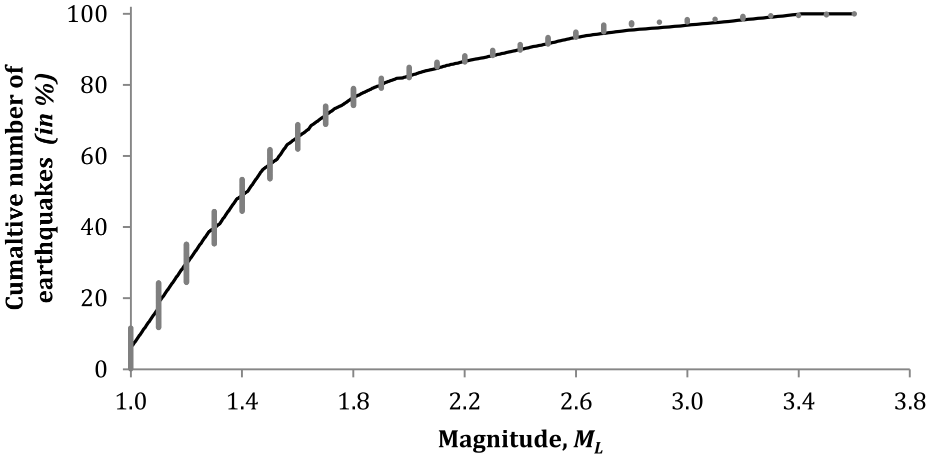


FIGURE A1 — CUMULATIVE DISTRIBUTION OF EARTHQUAKES

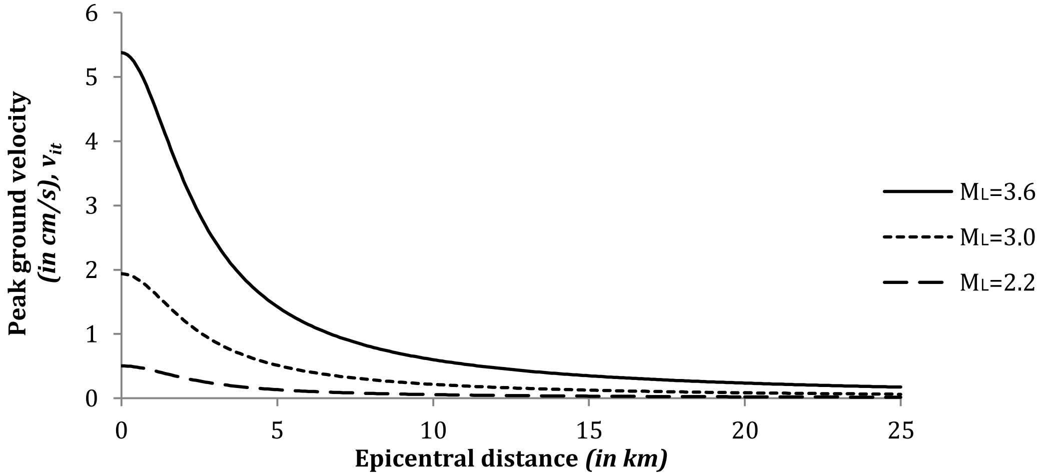


FIGURE A2 — EARTHQUAKE'S LOCAL MAGNITUDE USING AN ATTENUATION FUNCTION

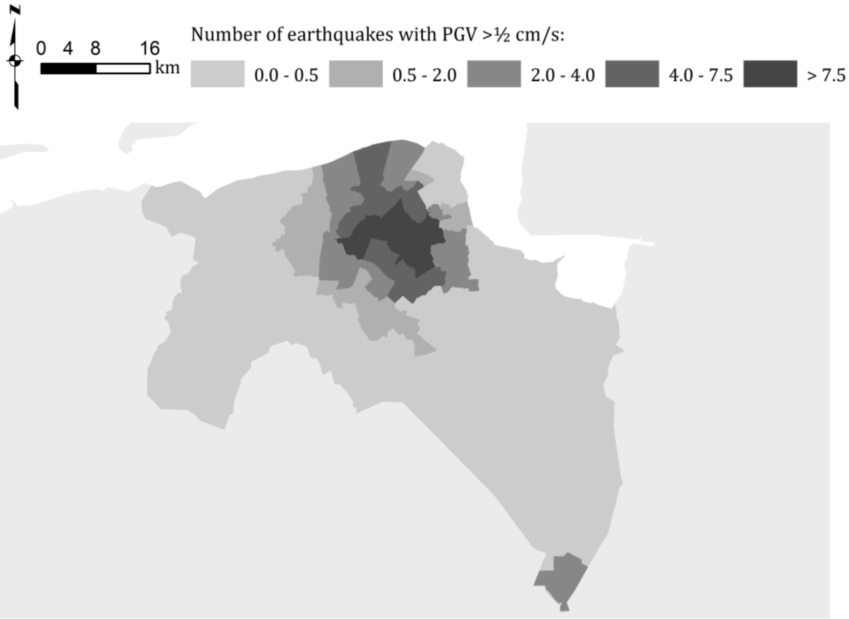


Figure A3 — Map of number of earthquakes with PGVs $>$ ½ cm/s in 2013 since 1991

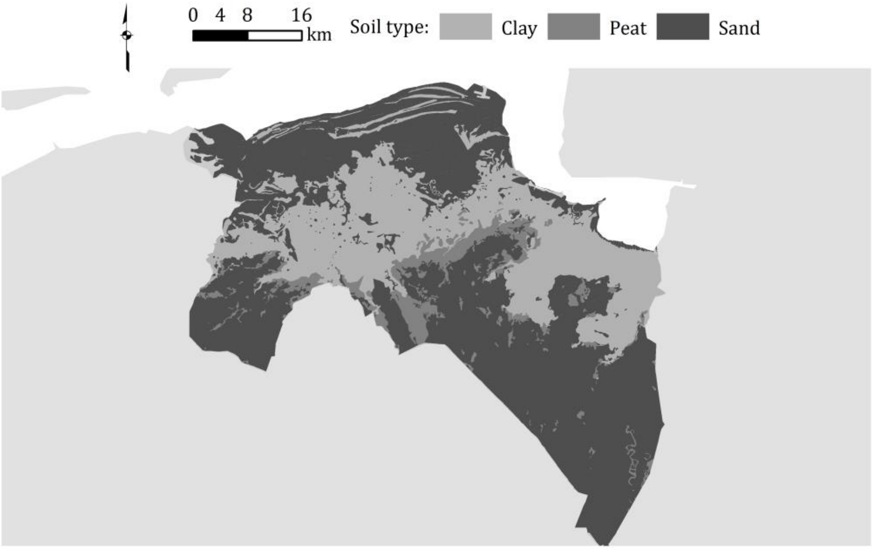


Figure A4 — Map of soil types in Groningen

In Figure A2 we display the earthquake attenuation function based on Dost et al. (2004). It is shown that only earthquakes with $M_L > 2.2$ 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 Figure 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 Figure 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 distance to 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.

A.2 Are earthquakes occurring 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. However, if earthquakes are concentrated in space, this assumption would be harder to defend because then there might be correlation of unobserved location attributes with the location of earthquakes (e.g. effects related to drilling activities). To measure whether earthquakes are (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. The main advantages of this approach are that the measure is invariant to spatial scale and aggregation and provides an indication of statistical significance. Below, we briefly discuss the procedure. For more details, we refer to Duranton and Overman (2005; 2008).

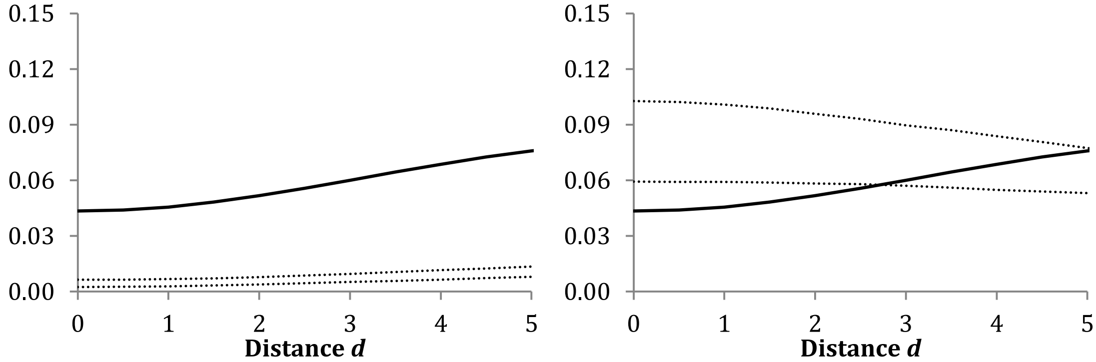
Let $\widehat{K}_t(d)$ denote the estimated kernel density at a given distance d, d_{ij} denotes the distance between earthquake i and j, where $i = 1, \ldots, I$ and n_i represents the number of earthquakes at a given location. Then:

$$\widehat{K}(d) = \frac{1}{h \sum_{i=1}^{I-1} \sum_{j=i+1}^{I} n_i n_j} \sum_{i=1}^{I-1} \sum_{j=i+1}^{I} n_i n_j \Upsilon\left(\frac{d - d_{ij}}{h}\right), \tag{7}$$

where h is the bandwidth and we define:

$$\Upsilon(\cdot) = \frac{1}{\sqrt{2\pi}} \mathrm{e}^{-\frac{1}{2}\left(\frac{d-d_{ij}}{h}\right)^2}, \tag{8}$$

so we use a Gaussian weighting function. An important parameter of the kernel density function is the bandwidth h. Following common practice, we set the bandwidth equal to



A. $M_L > 2.2$, RANDOM LOCATIONS B. $M_L > 2.2$, EARTHQUAKE LOCATIONS

FIGURE A5 — KERNEL DENSITIES FOR THE SPATIAL DISTRIBUTION OF EARTHQUAKES

Note: The black line represent the kernel density at a given distance, the dotted are the 5 percent global confidence bands. We note that local confidence bands are very similar to global confidence intervals, so we do not display them. We run 500 simulations to construct the confidence bands.

Silverman's plug-in method (see Silverman, 1986).[28] We estimate $\widehat{K}(d)$ for $d \leq 5$ because the median distance between earthquakes with $M_L > 2.2$ in our region is about 7.5 kilometres.[29] 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 ($1 < M_L \leq 1.5$). 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

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

[29] 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).

percent. We conclude that earthquakes are significantly concentrated at the five percent level if they are *above* the 95 confidence band.

Figure A5 reports the results. We first focus on the location pattern of noticeable earthquakes that generate PGVs above half a cm/s ($M_L > 2.2$) in Figure A5A. 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, which is in line with Figure 1A. However, once we condition on the location of weak earthquakes ($1 < M_L \leq 1.5$), we show in Figure A5B that noticeable earthquakes are not statistically significantly concentrated anymore. It seems that noticeable earthquakes are more dispersed until 2.5 kilometres than would be expected from the general location pattern of earthquakes. This is not a problem, because unobserved traits are thought to be correlated over space, so these are only correlated with geographically *concentrated* variables.

A.3 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, we may be concerned 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:

$$I = \frac{n}{S_0} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \hat{\epsilon}_i \hat{\epsilon}_j}{\sum_{i=1}^{n} \hat{\epsilon}_i^2}, \tag{9}$$

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 $\bar{\epsilon} = 0$. 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 $n/S_0 = 1$ and $-1 \leq I \leq 1$.

In Figure 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 -3.93. We also observe that there is some *negative* spatial autocorrelation ($I = -0.0563$). Neighbourhood level clustering delivers a T-statistic

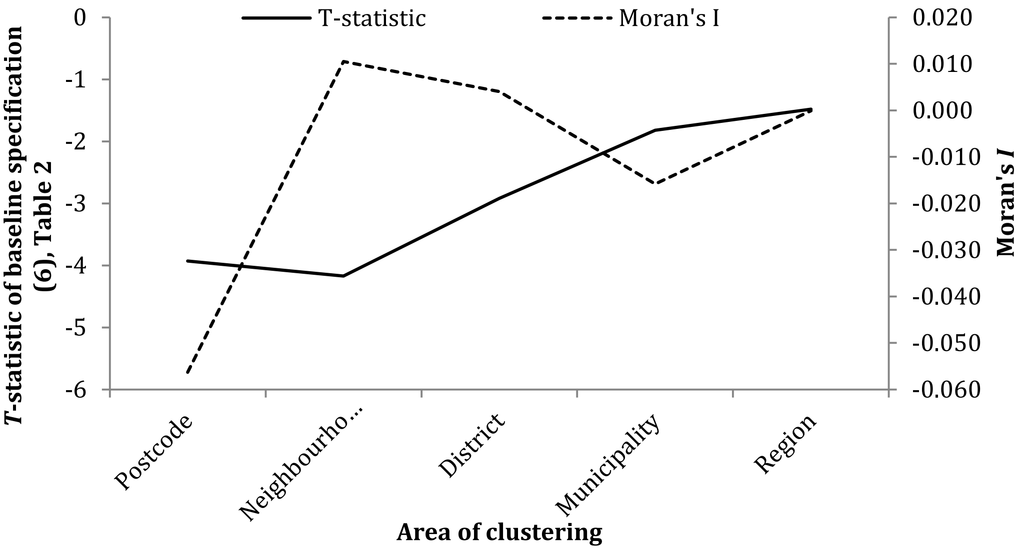

FIGURE A6 — T-STATISTICS AND MORAN'S I FOR DIFFERENT LEVELS OF CLUSTERING

of about -4.17. 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 the standard errors at the district level (a group of neighbourhoods), the number of clusters is 398 and the T-statistic is -2.92 so the estimate is still statistically significantly different from zero at the one 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 ten percent level (the corresponding T-statistic is -1.82). At the regional level, we have only seven clusters. The T-statistic is then -1.48, so the estimate is imprecise but still significantly different from zero at the twenty percent level.

A.4 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 0.7 percent of an earthquake that generate PGVs $>$ ½ cm/s, and similar to the lower bound estimate assumed in the counterfactual analysis.

TABLE A1 — RESULTS: INCLUSION OF WEAK EARTHQUAKES
(dependent variable: the logarithm of house price per m²)

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	OLS	OLS	OLS	OLS	OLS
Number of earthquakes ($PGV > ½\ cm/s$)	-0.0133*** (0.00277)	-0.0108*** (0.00321)	-0.00892** (0.00359)	-0.00687* (0.00364)	-0.0107*** (0.00267)	-0.0191*** (0.00392)
Number of weak earthquakes, $\Omega(n_{it})$	<500m	<1500m	<2500m	<5000m	<1000m	<1000m
Earthquake depth *(in km)*	2	2	2	2	1.5	3
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 (3,736)	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. *, **, ***, 10%, 5%, 1% significance, respectively.

There is much uncertainty about the exact depth of earthquakes. Until now, we used measurements by the NAM for Roswinkel, which is a different area, so the assumption of an earthquake depth of $s_{ijt} = 2$ may be incorrect. In column (5) we test whether when earthquakes would occur more shallow (at a depth of 1.5 kilometres) this will influence the results. It appears that the price decrease per noticeable earthquake is then 1.1 percent, which is very similar. The KNMI, however, often assumes that earthquakes occur at a depth of three kilometres. Column (6) shows that the price effect then becomes somewhat higher (1.9 percent), which is not surprising given that a higher value of s_{ijt} implies that we concentrate on stronger earthquakes.

A.5 Robustness – buffers

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 exact location is known up to a hundred metres, this may imply measurement error. In this part of the Appendix, we therefore also consider an alternative way to measure the intensity of an earthquake. More specifically, we calculate the number of earthquakes above a certain magnitude M_L within a given radius of the property. Table A2 reports the results.

In column (1) we count the number of earthquakes with $M_L > 2.2$ within one kilometre of the property. We choose an initial cut-off value of 2.2 because that corresponds to earthquakes that generate peak ground velocities above half a cm/s. If we control for housing and neighbourhood attributes and include year and postcode area fixed effects, the results

TABLE A2 — RESULTS: NUMBER OF NOTICEABLE EARTHQUAKES WITHIN A CERTAIN RADIUS
(dependent variable: the logarithm of house price per m²)

	(1)	(2)	(3)	(4)	(5)	(6)
	OLS	OLS	OLS	OLS	OLS	OLS
Number of earthquakes ($M_L > 2.2$), ($< 1\ km$)	-0.0157	-0.00936	-0.00626			
	(0.0140)	(0.0141)	(0.0143)			
Number of earthquakes ($1.5 < M_L \leq 2.2$), ($< 1\ km$)			-0.0101*			
			(0.00583)			
Number of earthquakes ($M_L > 2.2$), ($< 0.5\ km$)				-0.0461**	-0.0416*	-0.0411*
				(0.0228)	(0.0224)	(0.0223)
Number of earthquakes ($1.5 < M_L \leq 2.2$), ($< 0.5\ km$)						-0.00931
						(0.0116)
Number of weak earthquakes, $\Omega(n_{it})$	No	<1000m	<1000m	No	<500m	<500m
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 (3,733)	No	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. *, **, ***, 10%, 5%, 1% significance, respectively.

indicate that a noticeable earthquake within one kilometre of the property decreases house prices with 1.57 percent. However, this approach seems less efficient, as the p-value is only 0.261. In column (2) we also control for the number of weak earthquakes. The point estimate is slightly lower, but similar (-0.9 percent). The results are hardly affected when we also control for earthquakes with $1.5 < M_L \leq 2.2$. The point estimate of these potentially noticeable earthquakes is statistically significant at the ten percent level, albeit not statistically significantly different from the impact of the number of earthquakes with $M_L > 2.2$.

The problem of the above analysis might be that we introduce additional measurement error, as earthquakes that are just above 2.2 M_L occur more frequently than stronger earthquakes (see Figure A1), but probably generate no peak ground velocities beyond a few hundred metres. It is therefore preferable to take a smaller radius in which we count the number of earthquakes with $M_L > 2.2$. We therefore also count the number of noticeable earthquakes ($M_L > 2.2$) within 500 meters of the property. In column (4) we show that the impact of an earthquake is stronger (-4.6 percent), which is somewhat higher than the baseline estimate. This result is very similar if we control for the number of weak earthquakes within 500 meters. If we control for the number of potentially noticeable earthquakes ($1.5 < M_L \leq 2.2$), the coefficient is almost identical to the previous specification. The coefficient of the latter type of earthquakes is now smaller and not statistically significantly different from zero.