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Induced seismicity: a global phenomenon with special relevance to the Dutch subsurface

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Human-induced seismicity, in particular associated with oil and gas operations, has been observed for almost a century. One of the first documented examples was in the Goose Creek Field in Texas, where subsidence of an area following the contours of the oil field was accompanied by surface faulting and small earthquakes (Pratt & Johnson, 1926). The steady growth of the usage of the subsurface in the past decades, also in populated areas, combined with an extended capability to monitor smaller seismic events than before, has led to an increased number of reported induced events.

As a consequence, human-induced seismicity has gained increased interest worldwide from a scientific, political and societal perspective. It is not always evident whether events are human induced or natural, especially when induced seismic events are also releasing tectonic stress. In these cases, human activities trigger natural seismic events that would have occurred at a later date (Dahm et al., 2013). This is often referred to as 'triggered seismicity' (e.g. McGarr et al., 2002; Shapiro et al., 2013; Dahm et al., 2015). Criteria have been developed to distinguish between human-induced seismicity and natural seismicity, based on the seismic history of the region and on the temporal, spatial and depth relationship between the event and subsurface activities (e.g. Davis & Frohlich, 1993).

Subsurface engineering activities associated with induced seismicity include water impoundment, mining, changes in subsurface fluid and/or gas pressure due to operations related to hydrocarbon extraction, hydraulic fracturing for shale gas exploitation, wastewater injection, hydrocarbon storage operations, CO_2 geological sequestration and hydraulic stimulation of and/or production/injection in geothermal fields. These activities alter the stress field in the shallow crust, inducing or triggering earthquakes, through the following (combination of) mechanisms, depending on the situation (after Grigoli et al., 2017). In the case of fluid injection, the pore pressure increase reduces the effective normal stress through the Terzaghi effective stress principle, leading to fault reactivation when the failure criterion is exceeded. This requires a relatively high permeability pathway, such that injected fluids migrate into the fault. When mass, volume or temperature changes occur due to subsurface operations, these changes alter the shear and/or normal stress acting on a fault, which then may fail. And last, for hydraulic fracturing processes, small seismic events can occur when the fluid pressure exceeds the minimum principal stress, where new tensile fractures are created in previously unfractured rock. An additional mechanism for fault reactivation is when the fault strength itself is affected by changes in fluid properties (i.e. mechanical–chemical interactions, see for example Pluymakers et al, 2014; Pluymakers & Niemeijer, 2015).

Though human-induced earthquakes are generally smaller in magnitude than natural earthquakes, they can have large consequences, especially when they occur in densely populated areas. The Netherlands is one of the most densely populated countries worldwide, with a rising number of geothermal plays and several hydrocarbon plays – including the largest onshore gas field of Europe, the Groningen field. Induced seismicity in the area of the Groningen field has led to the planned termination of active production in 2023, which is just over 10 years after the 2012 magnitude 3.6 Huizinge event.

The continued seismicity and planned termination of Groningen gas production have made induced seismicity in the Netherlands a hot topic, for all kinds of subsurface engineering activities. This thematic collection of eight papers comes 5 years after the previous special issue which focused specifically on Groningen. In this collection, you will find an overview of all recorded occurrences of induced seismicity in the Netherlands (Muntendam-Bos et al., 2022). Activities for which seismicity has been observed include gas extraction, underground gas storage, geothermal heat extraction, salt solution mining and post-mining water ingress, with relatively low magnitudes up to 3.6. However, events exceeding magnitude 1.5–2.0 may be felt by the Dutch public, due to the soft topsoils in combination with shallow hypocentres (Muntendam-Bos et al., 2022). For public perception as well as political decision making, it is indeed the ground motion model that is critical in determining the site response and associated seismic hazard. Kruiver et al. (2022) present a sophisticated Ground Motion Model utilising field-based measurements of soil shear wave velocity (V_s) profiles in the soil. Their results show that the regional V_s profiles used in the current ground motion model capture spatial variability and represent reliable input for site-response calculations.

An important model in probabilistic estimation of seismic hazard is the Gutenberg–Richter law, which describes the relative occurrence of small to large earthquakes in a statistical population, where the slope is the b-value. A larger b-value indicates a relative scarcity of large events and vice versa. For the Groningen field, Kraaijpoel et al. (2022) performed a statistical analysis on spatio-temporal patterns in the magnitude distribution of induced earthquakes, testing which reservoir properties can be possible *b*-value predictors. This shows that statistically, the reservoir thickness is a strong predictor for spatial b-value variations in the Groningen field. However, a direct causal relation is not evident. For these types of analyses and subsequent extraction of parameters, it is important to know if events are correlated or not. For this reason, Trampert et al. (2022) reanalysed the Groningen event catalogue, with a specific emphasis on the scale invariance of events. The distributions of seismic moments and interevent times show a scale-invariant power law behaviour over several decades. This scale invariance implies that the dominant slopes in seismic moment and inter-event time distributions are related to the time evolution of the elastic energy loading in the system (Trampert et al., 2022).

To estimate future seismic hazard and risk due to subsurface activities, it is important to correctly model the relation between the induced subsurface perturbations and the occurrence of seismicity. For this, accurate source models are needed – capable of not only retrospectively model the existing seismic catalogue but also to properly predict the development of future seismicity. Kühn et al. (2022) provide a good overview of existing literature on the most important model approaches for Groningen seismogenic models, with all their achievements and limitations. Modelling of seismicity after termination of production is a challenge for all seismicity models because delayed processes and mechanisms play a crucial role. For instance, a clear seismicity decrease followed by the significant production reduction in 2014, but larger earthquakes of magnitudes $M \geq 3.0$ and clusters of events continued to occur (Muntendam-Bos, 2020; Kühn et al., 2022). To fully incorporate the physics of the Groningen field, not only the seismic processes need to be considered but also aseismic processes. Jansen & Meulenbroek (2022) consider slip patch development under initially aseismic conditions using semi-analytical modelling techniques. Their findings include approximate expressions for the induced seismic moment per unit strike length and a description of the effect of coupling between slip patches.

It is also important to see if lessons learnt from induced seismicity in the extremely well studied and monitored Groningen field can be applied to other places in the Netherlands. A relatively new but rapidly increasing application of subsurface use, not only in the Netherlands but also worldwide, is geothermal energy. In the Netherlands, there are currently 28 functioning doublets at 1.5–3 km depth, delivering six petajoules yearly. Current forecasts include an increase to 200 petajoules or ~700 doublets by 2050 (Stichting Platform Geothermie et al., 2018; Rijksoverheid, 2019).

In the Netherlands, there is one recorded incident in the tectonically active Roer Valley Graben where induced seismicity has led to termination of the geothermal operations: Vörös & Baisch (2022) provide a report on the characteristics of the largest M1.7 earthquake, which triggered the red light of the traffic light system used, and compare the findings with the seismic hazard assessment conducted prior to the earthquake. In this case, the geomechanical analysis indicates that fault activation was caused by the thermo-elastic stresses due to the re-injection of cold water close to the Tegelen fault. Thermo-elastic stresses are also inferred by Buijze et al. (2023) to be the most prominent difference in seismic hazard for geothermal plays. Buijze et al. review the main differences and similarities in geological and petrophysical characteristics between hydrocarbon and geothermal plays in the Netherlands. They provide insights into and constraints on the factors that could play a role for fault reactivation and induced seismicity and how these might differ for hydrocarbon production and geothermal operations (Buijze et al., 2023).

It is clear from the papers published in this special issue as well as many other scientific contributions on induced seismicity over recent years that the topic continues to be of great scientific interest. Not only because of its direct societal relevance and link to the energy transition but also because induced seismic events occur in geological systems that are relatively well constrained and typically intensely monitored. Research into induced seismicity will surely continue with the aim to better define the hazard and set the boundary conditions for safe utilisation of the subsurface.

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