Seismic exceedance rates for an induced seismicity case in the UK considering the temporal variability of the seismicity

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Abstract: The temporal variability of the seismicity is a phenomenon that occurs in aftershock sequences or induced seismicity applications, the former being the most devastating from the structural damages and/or human losses point of view, while the latter present lower seismicity levels mainly due to the operation and monitoring of these type of applications. This study addresses the problem of time-dependency in the seismic hazard assessment focusing on a case study of induced seismicity in the United Kingdom where hydraulic fracturing operations were carried out to extract gas in the Preston New Road (PNR) site. The analysis was carried out using an operational time unit linked to the injection scheme of these types of applications called sleeve to estimate the seismic exceedance rates per case by using a ground motion prediction model developed for the site. The results show that the use of this *sleeve* time unit allows seeing the evolution of the seismicity levels over time, which is related to the maximum magnitude, the number of events and the cumulative volume injected in each stage.

Keywords: Induced seismicity, time-dependent, sleeve unit time, seismicity rates

1. Introduction

In the United Kingdom, induced seismicity is a subject that has been studied several years ago but only a few projects of this type were carried out in the last decade. One specific type of these projects is hydraulic fracture (HF) stimulation, which is widely used in the commercial production of hydrocarbons and in developing engineered geothermal systems worldwide (Igonin et al. 2019; Langenbruch et al. 2020). The HF is a technique to extract petroleum resources from impermeable host rocks through a high-pressure fluid injection causing fractures that result in induced earthquakes (Schultz et al. 2020). In the UK, only three wells have been hydraulic fractured (HF) within the Carboniferous Bowland Shale formation, a reservoir with properties comparable to the major producing shales reservoir in North America (Kettlety et al. 2021; Clarke et al. 2018; Verdon 2014). All of these three operational sites ended up in events felted by the population and created a controversy about this kind of activity in the country. The first well drilled was the Preese Hall well, stimulated in 2011 and generated a local magnitude of ML 2.3, which caused an intervention by the government leaving, as a result, the implementation of a traffic light system (TLS) to mitigate the risk and extended to other sites (Oil and Gas Authority 2018). The effectiveness of this method is a subject that is still in the debate between the private and academia (Clarke et al. 2019; Verdon and Bommer 2021; Baisch, Koch, and

Muntendam-Bos 2019). The idea behind the TLS is to minimize the number of events felt by the public and to avoid structural and/or non-structural damages. In 2018 two horizontal wells at the Preston New Road site, approximately 4 km to the south of the Press Hall site, aimed to extract shale gas by HF and started operations with the eyes of the general public on it due to previous experience but it ended up in an event of ML 1.5 and the operations stopped. Later on, after a period of calm in 2019, the operations started again reaching an event of ML 2.9 leaving as a result of the indefinite interruption of the project until today. With all of this in mind, the purpose of this document is to study the seismicity variations in time for the HF at the Preston New Road site and introduce them into the estimation of the seismic hazard at the site.

2. Dataset

The dataset used in this study corresponds to the shale gas extraction site in Preston New Road (PNR), North West England, where hydraulic fracturing (HF) operations were carried out in two different periods, between 15 October to 17 December 2018 (hereinafter PNR-1z), and later on between 15 August to 02 October of 2019 (hereinafter PNR-2) (Cuadrilla Resources 2019b, 2019a). To monitor the operation an array of sensors, including broadband seismometers and geophones were installed at the surface and downhole of the site, for the company in charge of the operation, Cuadrilla Resources Ltd (CRL), in collaboration with the British Geological Survey (BGS) and the University of Liverpool (Clarke et al. 2019). During the first period of operation (PNR-z1), the events recorded were between $-0.8 \leq ML \leq 1.5$ and between $-1.7 \leq ML \leq 2.9$ for the second period (PNR-2), crossing several times all the flags of the TLS system imposed in the UK and having, as a result, the temporary and permanent suspension of the operation at the site. Both wells (PNR-1z and PNR-2) ran through the natural gas-bearing Carboniferous formation of the Lower Bowland shale at a depth of approximately 2.3 km (Clarke et al. 2018). In the case of the PNR-z1 well, a sliding-sleeve completion method was used, with 41 individual sleeves numbered ascending from toe to the heel of the well, and a hydraulic fracture plan up to 765 m3 of fluid per sleeve was set (Baptie et al. 2020). However, a total number of 16 sleeves were hydraulically fractured with a total of about 4,600 m3 of fluid injected and an average volume for each fracture of 234 m3 with a maximum of 431 m3 (Mancini et al. 2021). On the other hand, the PNR-2 well followed the same sleeve method performed up to 7 possible hydraulic fracture stages. Fig 1 presents the spatial and temporal distribution of both datasets, PNR-z1, and PNR-2, with a color scheme according to each sleeve for both cases as well as the cumulative volume injected.

3. Seismicity Rates

To estimate the seismicity rates we studied independently each dataset (PNR-z1 and PNR-2) using a *sleeve unit time* which is reported in the seismic catalog. This unit time is established by the operator of the HF site and it depends on technical decisions taken every day, due to the monitoring of the seismicity, the injection rates, the pressure in the well, etc. For that reason, each *sleeve unit time* has different lengths but in all of them plenty (i.e. more than a thousand events per sleeve with $-3 < M < 2$) of events were registered by the monitoring array from which we can compute the seismicity rates. There are some issues related to the conversion from local magnitude (M_L) to moment magnitude (M_w) because of the different arrays deployed to monitor the seismicity operated by two separated companies. Several authors have addressed this problem (Baptie et al. 2020; Suroyo and Edwards 2020; Edwards et al. 2021, 2015; Cuadrilla Resources 2019b, 2019a) which for obvious reasons will have a big impact on the seismicity rates and then on the seismic hazard assessment. In this study, we followed the approach proposed by Baptie et al. (2020) for the PNR datasets adjusting the moment magnitude estimates in the downhole through the surface local magnitude. Then, a Poissonian distribution per sleeve was made to obtain the seismic parameters (a and b values) following the Gutenberg-Richter (GR) distribution.

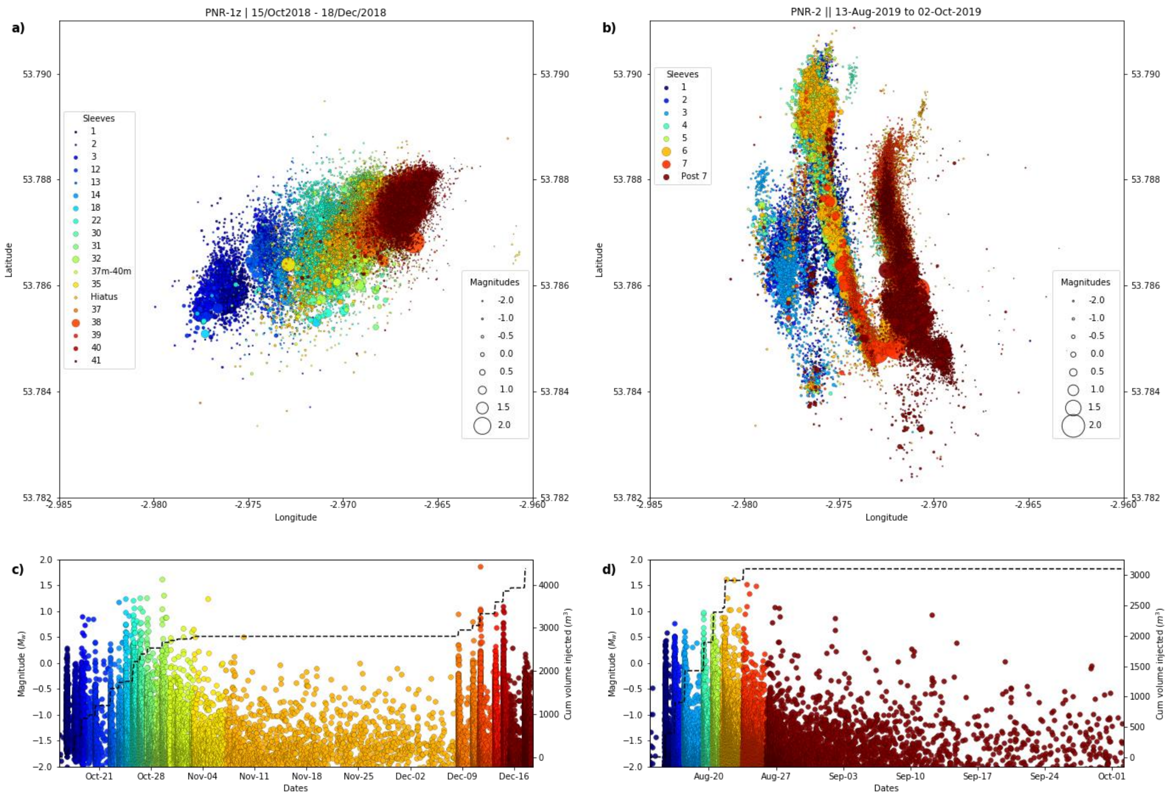

Fig. 1. Spatial and temporal distribution of the datasets PNR-z1 and PNR-2. Top: a), b) spatial distribution. Bottom: c), d) temporal distribution. Left: PNR-z1 (2018). Right: PNR-2 (2019). Dotted line: cumulative volume injected (m^3). Colors: sleeves.

3. Hazard Curves

To compute the seismic hazard curves, we used the ground motion prediction model (GMPM) proposed by Edwards et al. (2021) which was developed for the same site and used the same dataset. This GMPM is based on two other GMPMs proposed for induced seismicity applications in other parts of the world, but filling the gaps with the levels of magnitudes presented in the Preston New Road site.

The seismic source model was developed using the seismicity parameters (a, b values) per sleeve, with its relative location in space, through a point source model. In other words, we are moving in space and time taking into account the variation of the seismicity along each well (PNR-z1 and PNR-2); both datasets were considered independently. Using the GMPM by Edwards et al. (2021) we estimated the hazard curves per sleeve but considered a daily exceedance rate. Fig 2 shows the hazard curves at the intensity level of PGA per sleeve, the color scheme follows the same pattern as Fig 1 for both datasets. These curves represent the hazard levels expressed in daily exceedance rates that could happen for a certain level of PGA. Since each sleeve was treated independently, each curve also shows the seismicity levels at a specific time. As it can be seen, the evolution of the hazard levels increases when higher magnitudes occur and decreases when we have periods of lower magnitudes due to the relaxation of the injection rates (i.e. PNR-z1: Hiatus, PNR-2: Post 7).

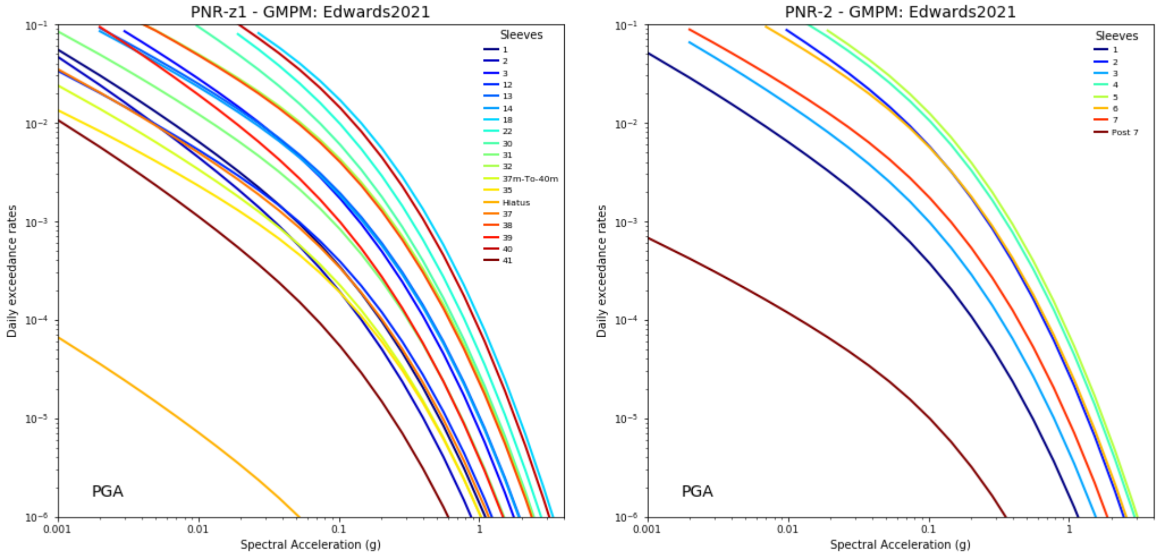

Fig. 2. Hazard curves for a daily exceedance rate at the intensity level of PGA. The color scheme follows the same pattern as Fig 1. Left: PNR-z1. Right: PNR-2.

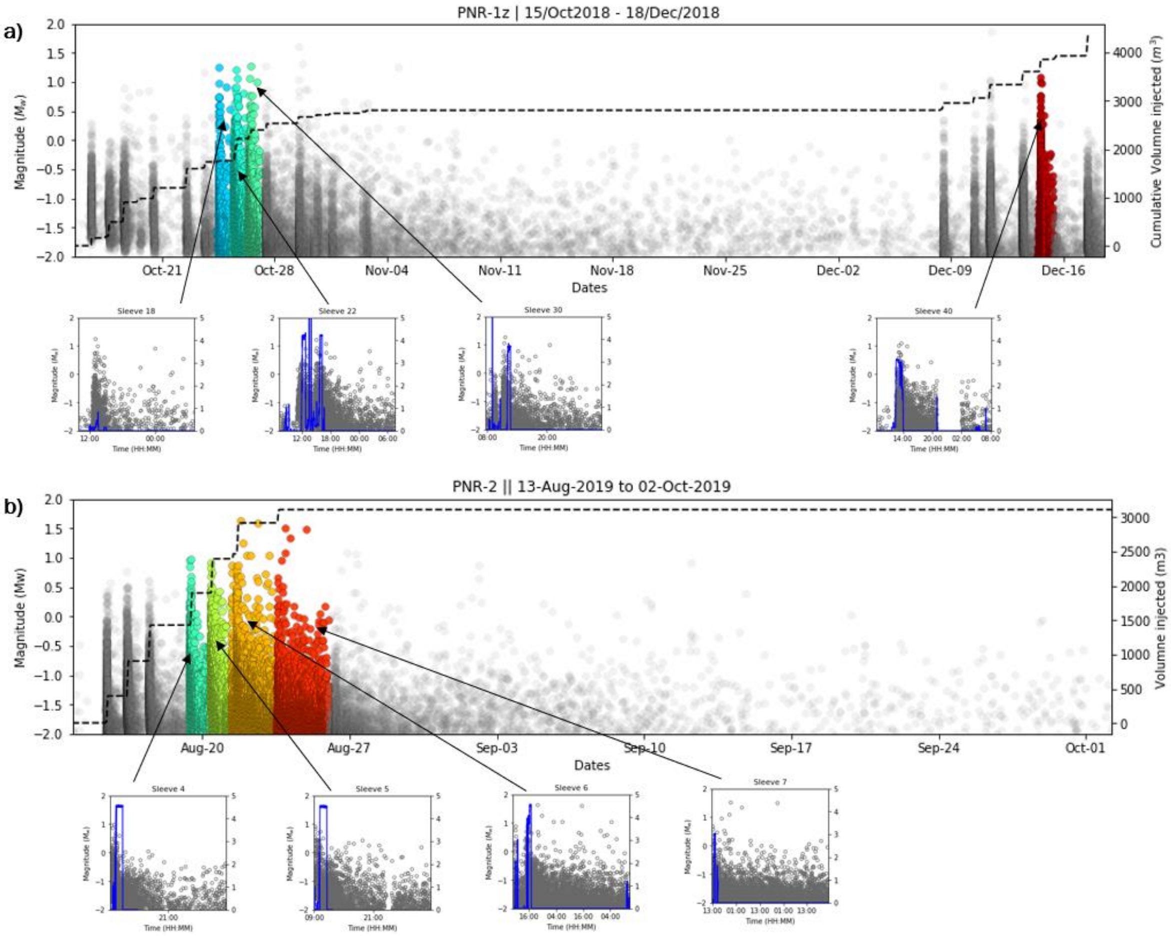

Fig. 3. Localization of the maximum hazard curves shown in Fig 2. **a)** PNR-z1, seismicity, and injection rates of sleeves 18, 22, 30, and 40. b) PNR-2, seismicity, and injection rates of sleeves 4, 5, 6, and 7.

Fig 3, shows the localization of the sleeves with higher hazard levels according to Fig 2 for both datasets. For PNR-z1 the maximum hazard curves occur at sleeves 18, 22, 30, and 40, and those correspond to the ones with the highest magnitudes but also when the cumulative injected volume almost reach the peak until the operations were stopped because of the traffic light system; sleeves 18, 22, and 30 in the beginning phase of the dataset and sleeve 40 in the ending phase. Similarly, PNR-2 presents its maximum hazard curves at sleeves 4, 5, 6, and 7 which are just before the stopped signal for this dataset. Then, if we look in terms of maximum hazard level, both datasets reach similar values of daily exceedance rates for their corresponding maximum; this could be related to the maximum magnitude established at each sleeve and it is something that needs more focus in further research.

4. Conclusions

In this study, we compute daily exceedance rates for an induced seismicity case in the United Kingdom, where hydraulic fracturing operations were carried out to extract gas at the Preston New Road (PNR) site in the United Kingdom. The aim was to include the variation in time of the seismicity through a *sleeve unit time*, which is attached to a technical decision made by the operator of the site. The results show that modeling each sleeve independently could be an alternative approach to see the variation and evolution of the seismic hazard levels at the site during the hydraulic fracturing operations. Because the *sleeve unit time* is not constant, we decided to compute daily exceedance rates that could be estimated for other intensity measures such as PGV or macroseismic intensities and identify threshold levels to help the regulators and the companies to understand better this type of seismicity.

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