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On the origin of exponential growth in induced earthquakes in Groningen

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Abstract. The Groningen gas field shows exponential growth in earthquake event counts around a magnitude M1 with a doubling time of 6-9 years since 2001. This behavior is identified with dimensionless curvature in land subsidence, which has been evolving at a constant rate over the last few decades essentially uncorrelated to gas production. We demonstrate our mechanism by a tabletop crack formation experiment. The observed skewed distribution of event magnitudes is matched by that of maxima of event clusters with a normal distribution. It predicts about one event $<$ M5 per day in 2025, pointing to increasing stress to human living conditions.

Keywords: Induced earthquakes; crack formation; statistical forecasting

1. Introduction

Induced earthquakes are a modern phenomenon associated with exploitation of natural energy resources or injection of waste (Rayleigh *et al.* 1976, Nicholson and Wesson 1990, Frolich 2012, Evans *et al.* 2012) at generally moderate strengths (e.g., Ellsworth 2013). Recent studies in particular focus on the potential for a correlation between induced events and fracking and waste water injection (Keranen *et al.* 2014, Weingarten *et al.* 2015). Fig. 1 shows induced events in Groningen, The Netherlands, due to the exploitation of natural gas since 1959 (De Kam 2014).

Though moderate in magnitude, frequent events act as physical stressors to living conditions. As a relatively modern phenomenon, induced events pose some novel challenges for hazard analysis, beyond a mere extrapolation of the geophysical impact of natural earthquakes (Hough 2013). In

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Groningen, half of the inhabitants are now living with a feeling of anxiety or fear and wish to move out, in part, by the stochastic nature of earthquakes (Fonteyne *et al.* 2009, Grillon *et al.* 2004). It has led to ameliorating policies (e.g., De Waard (2014)), generally seeking reduction in earthquake activity by limiting gas production, whose short term impact is uncertain (Nicholson and Wesson 1990, Bakun *et al.* 2005, NAM 2013).

Groningen data on reservoir pressure, land subsidence and yearly production of natural gas cover an area of 900 km^2 (NAM 2013). Since 2001, earthquake event counts show exponential growth at seemingly 'clock-work' precision (Fig. 1), based on a logarithmic plot of event counts with remarkably good fit by a linear curve covering the year 2000 to the present. This observation applies to event counts with a choice of magnitude cut-off over a broad range $\mathrm{M}_c = 0-3$. Collectively, they represent an energy release $\dot{E} \simeq 3$GJ in over one hundred registered events per year with a doubling time of 6-9 years (see also Dost *et al.* (2013)). The Groningen field apparently shows a robust principle at work with unknown but possibly long-term implications by exponential growth in counts.

Fig. 2 shows NAM production levels in GNm^3 per year and land subsidence, associated with a decline in reservoir pressure to below 100 bar at present, down from about 150 bar in 2000 and 350 bar in 1959. The statistical correlation by Pearson coefficient between event counts in Fig. 1 to production is nill, indicative of no correlation (Fig. 2, lower left panel).

These earthquakes arise from stresses induced by a decline in well pressure (Hubbert and Rubey 1959), possibly at some distance away and delayed in time. Paradox Valley in Colorado (Ellsworth 2013) shows events at distances over ten kilometers with delays of a decade. The Salton Sea Geothermal Field shows, subsequent to initial exploitation, a correlation of seismicity with net extracted volume $\dot{V}$ (injected minus extracted volume) of about 10^6 m^3 per month at 1-2.5 km depth (Brodsky and Laipote 2013). Large area induced seismicity points to large scale deformations that may be measured in land subsidence.

Here, we propose a novel physical mechanism for exponential growth in event counts in induced earthquakes in response to dimensionless curvature of land subsidence, demonstrated by a table top experiment. Based on dimensionless variables, it is insensitive to details of geophysical composition. The skewed distribution in magnitudes is modeled by maxima of event clusters, that will be used for a statistical forecast on event count and maximal magnitude in the coming decade.

2. Exponential growth from curvature induced strain

Groningen land subsidence is $\dot{h} \simeq 0.5$ cm yr^{-1} (Fig. 2, right lower panel) with a delay in response to a reduction in volume V due to a gradual compactification in the reservoir associated with a steady decrease in reservoir pressure (NAM 2013). Compactification $\dot{V} \simeq 10^6$ m^{-3} per month is roughly similar to that in aforementioned Salton Sea Geothermal Field. It represents a mechanical energy input of $\dot{E}_0 \simeq 0.3$TJ per year, whereby $\dot{E}/\dot{E}_0 \simeq 10^{-2}$.

Subsidence gives rise to curvature-induced strain, inevitably leading to the build up of internal stresses. At critical values, materials fail by cracks or slip, described by the Mohr-Coulomb law (Coulomb 1776, Hubbert and Rubey 1959). Subsidence in Groningen is taken the shape of a shallow bowl of radius $r \simeq 15$ km (NAM (2013), Fig. 3). Relative to its radius of curvature R, the dimensionless curvature $\rho = r/R \simeq 4 \times 10^{-5}$ should be representative for large scale internal strain. For small perturbations in the absence of cracks and slides, internal stresses increase with strain induced