Empirical Model for Induced Earthquakes in the Groningen Gas Field

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Abstract

The paper presents an empirical model for the field-wide prediction of frequency and strength of earthquakes induced by gas production from the Groningen gas field. It is based on a statistical analysis of 284 earthquakes, the total number of recorded earthquakes with a magnitude greater than 1,5 on the Richter scale until 01-01-2017.

The statistical analysis shows that the cumulative number of earthquakes correlates very well with the cumulative gas production. Mathematically the correlation can be described by a simple quadratic equation. By using this equation we can predict the average yearly earthquake frequency for a given production rate profile. The observed yearly frequencies deviate substantially from the predicted frequencies, indicating a sizeable inherent natural variability.

Another outcome of the analysis is that the strength distribution of the earthquakes recorded so far can be fairly well described by the well-known Gutenberg-Richter equation and that this distribution is time-invariant, confirming earlier results by KNMI investigators. Consequently, the observed increase in stronger earthquakes in the course of time can be simply attributed to an increase in yearly earthquake frequency.

Extrapolation of the quadratic equation results in a total number of earthquakes for the entire life cycle of the field in the order of 700. This leaves over 400 earthquakes for the remaining production period until the abandonment of the field. Extrapolation of the Gutenberg-Richter equation indicates a maximum earthquake strength of magnitude 4,4 on the Richter scale.

The main application of the empirical model is in forecasting future field-wide seismicity for given gas production scenarios. Example forecasts are presented that highlight the impact of production rate level on the development of seismicity in Groningen.

Introduction

The Groningen gas field is situated in the province of Groningen in the Netherlands and is one of the larger gas fields in Europe. Discovered in 1959, production from the field started in 1963 by conventional pressure depletion. NAM (Nederlandse Aaardolie Maatschappij BV), a joint venture of Shell and ExxonMobil, is the operator of the field. The gas-initially-in-place (GIIP) of the field is estimated at 2880 billion cubic meter[1]. The cumulative recovery from the field at 01-01-2017 is 75 per cent the GIIP.

The first earthquake in the field was recorded in 1991 in the village of Middelstum and had a strength of magnitude of 2,4 on the Richter scale. As of 01-01-2017 over 600 earthquakes with magnitude greater than 1 have been recorded over a large geographical area but concentrated in the center of the field near the town of Loppersum. The strongest earthquake with a

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[1] By convention Groningen gas volumes are expressed in gas volumes at normal conditions, viz. a temperature of 0˚C and a pressure of 1 bar

magnitude of 3,6 occurred in the summer of 2012 in the village of Huizinge. It was this event that triggered a massive effort to make the built environment in Groningen earthquake-proof so that the safety of the inhabitants of Groningen would be assured with the continued production from the field.

In this paper we present a statistical analysis of the historically observed earthquakes up to 01-01-2017. The main objective of the analysis is to establish and quantify trends in number and in strength of the earthquakes, if any. If successful the observed trends can be used for field-wide predictions of the future seismicity in Groningen. In the analysis we have restricted ourselves to earthquakes with a magnitude greater than 1,5 on the Richter scale. The reason for this cut-off is twofold. First, earthquakes with magnitudes less than 1,5 can be hardly felt at the surface and cause little if any damage to the built environment. Second, in the early days earthquakes with the lesser magnitudes may not have been picked up by KNMI's registration network operational at that time. However, there is no doubt that all earthquakes with magnitudes greater than 1,5 have been recorded since day one. Therefore, data on earthquakes with a magnitude greater than 1,5 constitute a statistically complete data set.

The outline of the paper is as follows. First we describe the available 'raw' data, the yearly recordings of the number of earthquakes and attendant strengths along with the yearly production data. We then take a closer look at possible trends in number of earthquakes and in strength of the earthquakes. Subsequently we estimate the total number of earthquakes and the strength distribution for the future earthquakes. Finally we present forecasts of the yearly earthquake frequencies for three different production scenarios, i.e. yearly production rates versus time, for the period from 2017 up to 2034.

Raw Data

Seismicity in Groningen is monitored through an extensive digital seismometer network operated by KNMI, the Royal Dutch Meteorological Institute. All data on seismic events in the Netherlands can be found in the KNMI earthquake database that can be accessed through KNMI's website (Ref. 1). A summary of the induced earthquakes for the Groningen gas field is also available at the website of NAM, which also provides data on gas production volumes since the start of production from the field in 1963 (Ref. 2).

Figure 1 displays the complete raw data set that we have used in our analysis. It comprises yearly gas production rates and yearly earthquake frequencies (= the number of earthquakes per year) with magnitudes greater than 1.5 recorded in the field from 1991, the year of the first earthquake in Middelstum, until 01-01-2017. The total number of earthquakes recorded in that period is 284. The stacked columns show the yearly frequencies in magnitude increments of 0,5, starting with a magnitude of 1.5. The line graph shows the annual production rate in billion cubic meter per year. The cumulative gas production from the field at 01-01-1991 amounted to 1240,19 billion cubic meter.
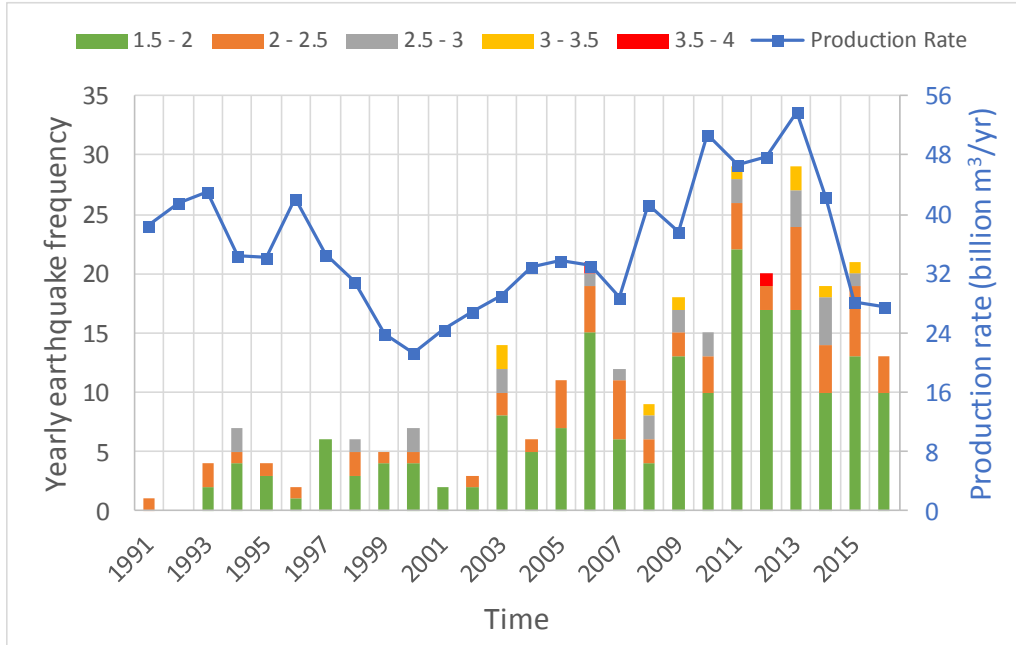
Figure 1 – Raw data set

The picture that emerges from Fig. 1 is rather confusing: production rates, earthquake frequencies and earthquake strengths seem to jump up and down without any clear trends. Seen from a distance, however, it looks like earthquake frequency and strength are increasing over time and thus with increasing depletion of the field.

Earthquake frequency

Let us first focus on the temporal trend in earthquake frequency. To this end we have re-arranged the time-series shown Fig. 1 in two ways. First we have replaced *time* by *cumulative gas production* as independent variable. Second, we have converted *yearly earthquake frequency* to *cumulative number of earthquakes*. By doing so we have reduced short-term fluctuations in both earthquake frequency and gas production rate. In addition, cumulative gas production is an excellent proxy for the average subsurface pressure of a gas reservoir; the average pressure of a gas reservoir declines with increasing production in a very predictable manner. As earthquakes are caused by changes in subsurface stress distribution induced by reservoir-pressure changes, we may expect a direct correlation between cumulative number of earthquakes and cumulative gas production. This is indeed the case as illustrated in Fig. 2, which shows a scatter plot of cumulative number of earthquakes with magnitude greater than 1,5 against cumulative gas production. It also shows a quadratic best fit through the observed cumulative number of earthquakes given by

$$N_q = a(G_p - G_{pr})^2 + b(G_p - G_{pr}) \qquad G_p \geq G_{pr} \qquad (1)$$

where N_q is the cumulative number of earthquakes, G_p is the cumulative gas production in billion cubic meter, G_{pr} is a reference cumulative gas production, and *a* and *b* are the coefficients

of the quadratic equation. We have taken G_{pr} = 1240,19 billion cubic meter, the cumulative production at 01-01-1991, the very first day of the year of the first earthquake in Groningen. The coefficients a and b are equal to 3,2148E-04 and 7,6150E-03, respectively. The coefficient of determination (R^2) of the best fit is 0,9987 (1 is perfect). The coefficients a and b are both positive, consistent with a monotonically increasing upward-bending curve. An upward-bending trend means that at a constant production rate the earthquake frequency keeps increasing.
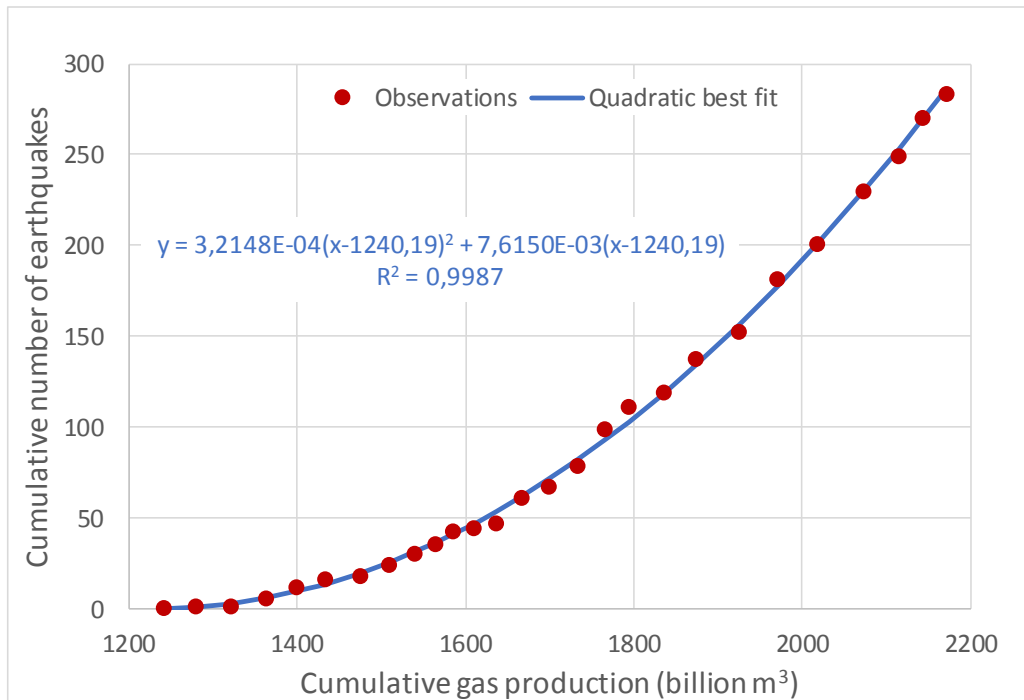

Figure 2 – Cumulative number of earthquakes versus cumulative gas production.

Having established a mathematical relationship between cumulative number of earthquakes and cumulative gas production, we can now predict earthquake frequency as a function of time for a given arbitrary production rate profile, i.e. production rate versus time. Suppose the production profile is available as a time table. First, we construct a time table for the cumulative production. Next, for each cumulative production entry in the table we calculate the cumulative number of earthquakes by means of Eqn 1. This yields a time table for the cumulative number of earthquakes from which we can directly determine the earthquake frequency. As the predicted earthquake frequencies are based on a best-fit equation for cumulative number of earthquakes as a function of cumulative gas production, the predicted frequencies should be considered *average* frequencies.

Fig. 3 shows a scatter plot of the actually observed yearly earthquake frequencies against the predicted yearly frequencies for the historical yearly production profile (see Fig. 1). Also shown is a solid straight line through the origin with a slope of unity. In the case of a perfect prediction all data points would fall on the straight line. Here the prediction is definitely not perfect but the data points do cluster around the straight line. The standard deviation of the predicted

earthquake frequency is equal to 4,3 earthquakes per year. The dashed lines parallel to the unit-slope line represent plus and minus two standard deviations. All 26 observed yearly frequencies except one (= 96 per cent) fall within two standard deviations of the predicted frequencies.
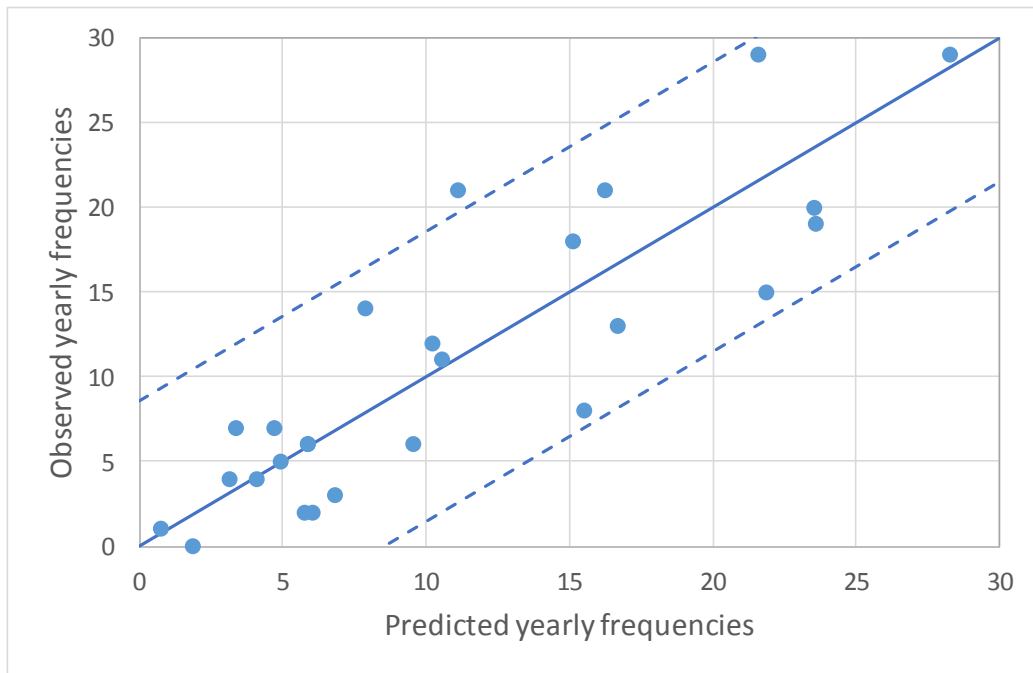
Figure 3 – Observed versus predicted yearly frequencies

Figure 4 shows the predicted and observed yearly frequency profiles in real time. The shaded zone around the predicted profile indicates the uncertainty of the predictions, which is taken at plus or minus two standard deviations. The variation in predicted frequency arises from the variation in yearly production rate. As we can see the observed frequencies may deviate substantially from the predicted ones. This deviation can be attributed largely to the inherent natural variability of the induced earthquakes. Because of the large natural variability, the observed frequency in a single year does not mean much on its own. In much the same way as the observed average temperature on a summer day is not representative of the average summer temperature. We further observe that in 2013 the upward trend in earthquake frequency has been effectively reversed. This is a direct consequence of the increasingly lower maximum-allowable production rates imposed by the Dutch government: from 53,87 billion cubic meter/year in 2013 down to 42,41, 28,10 and 27,95 billion cubic meter/year in 2014, 2015 and 2016, respectively. Lower production rates imply a lower decline rate of the subsurface reservoir pressure, resulting in a reduction in earthquake frequency.
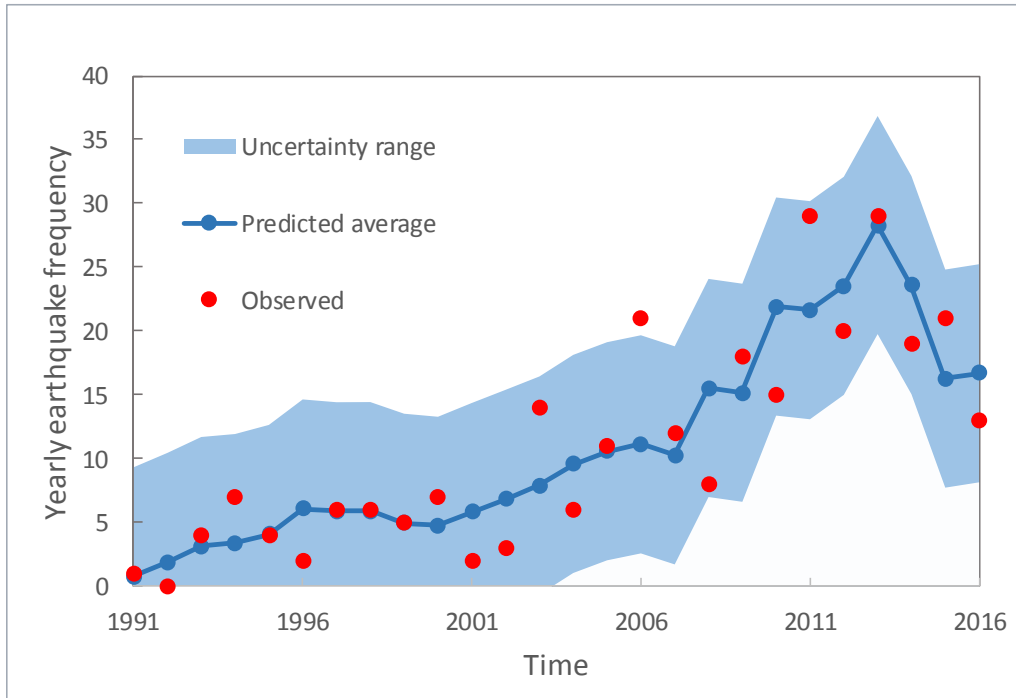
Figure 4 – Observed versus predicted yearly frequency in real time

Strength of Earthquakes

Let us now take a look at possible trends in the strength of the observed earthquakes. Traditionally, the strength distribution of earthquakes in earthquake areas is displayed in a Gutenberg-Richter plot (Ref. 3), which shows the logarithm of the cumulative number of earthquakes larger than a certain magnitude on the Richter scale as a function of the magnitude. In many earthquake areas the data points fall on a straight line with a negative slope close to unity. This means that the number of earthquakes becomes increasingly fewer by a constant factor 10 for each unit increase in magnitude. Thus, there are 10 times more earthquakes of magnitude 3 than 4, 100 times more earthquakes of magnitude 2 than 4, and 1000 times more earthquakes of magnitude 1 than 4. Although originally proposed for tectonic earthquakes, the Gutenberg-Richter equation also applies reasonably well to the induced earthquakes in the Groningen field (Ref. 4).

Figure 5 shows the Gutenberg-Richter plot for all of the induced earthquakes up to 01-01-2017, 284 in total. Here we have plotted the normalized cumulative frequency against magnitude for magnitudes larger than 1,5 up to 4 in magnitude intervals of 0,5. By definition, the normalized cumulative frequency for a magnitude of 1,5 is equal to unity. As we can see the cumulative frequencies indeed plot reasonably well on a straight line. We have fitted the data points by the exponential equation

$$F = ae^{-bM}, \tag{2}$$

where F and M denote cumulative frequency and magnitude, respectively, and a and b are constant coefficients. The best fit gives a = 31,26 and b = 2,295. The coefficient of determination of the best fit is 0,9846. The coefficient b corresponds to a negative logarithmic slope of 0,997 (=2,295/ln10), indeed close to unity. The last data point in Fig. 5 lies slightly below the best-fit straight line, which indicates that the Gutenberg-Richter plot might bend down at the higher magnitudes, which is not uncommon in these plots.
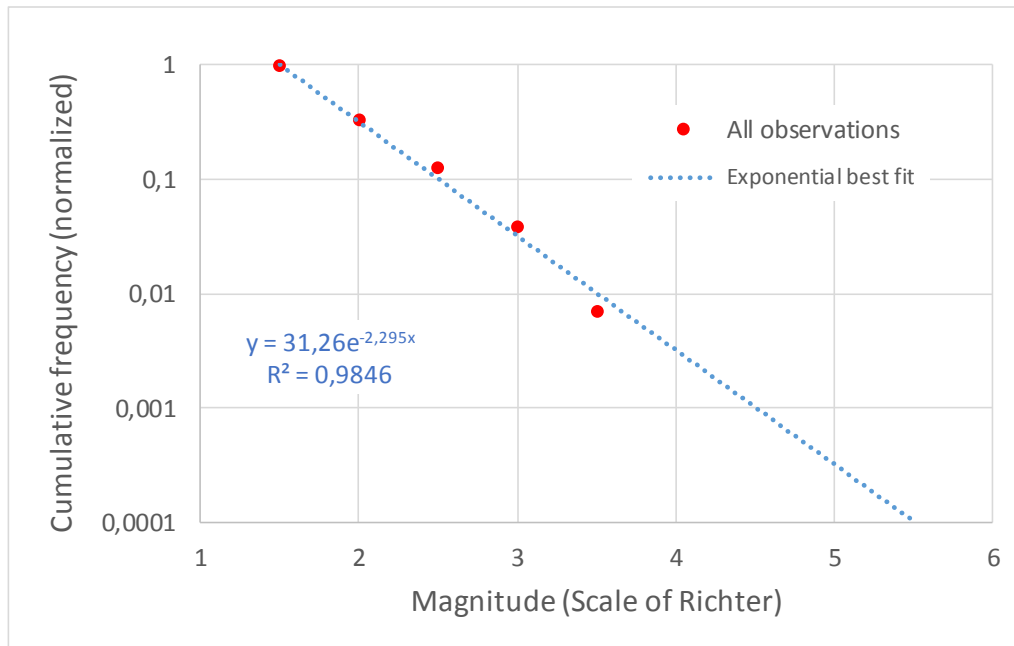

Figure 5 – Gutenberg-Richter plot for all Groningen earthquakes with magnitude > 1,5

To find out whether the strength distribution has changed over time we have divided the total dataset into two roughly equal subsets: the first half from 1991 to 2010 with 138 earthquakes and the second half from 2010 to 2017 with 146 earthquakes. Fig. 6 shows the Gutenberg-Richter plots for both subsets along with the exponential best-fit. For all practical purposes the two subsets show identical distributions. Hence the strength distribution may be considered time-invariant, confirming earlier results of Dost and Kraaijpoel (Ref. 4). In other words, there is no observational evidence that the earthquakes become stronger (or weaker) in time. It is true that up to 2013 the number of stronger earthquakes increased but this is merely due to the increase in yearly frequencies and not to a change in the strength distribution.
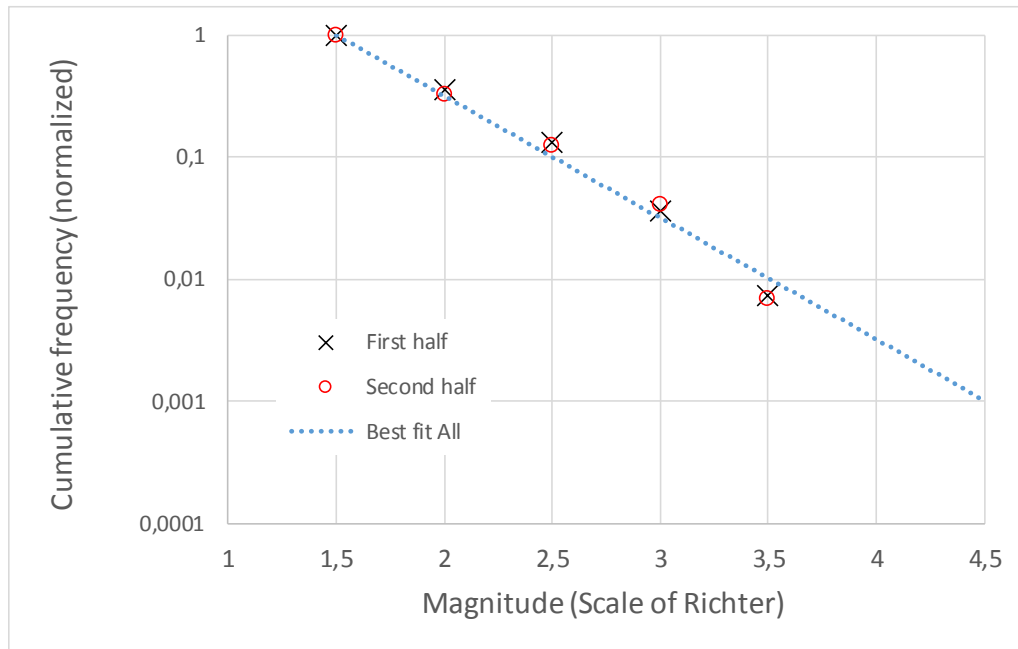
Figure 6 – Gutenberg-Richter plot for first-half and second-half subsets

Ultimate number of earthquakes

Assuming that the empirical relation Eqn (1) also holds in the future, we may estimate the ultimate number of earthquakes at abandonment of the field. At this point it is technically no longer possible to continue production because the subsurface pressure of the gas reservoir has become too low to sustain the flow of gas to the surface. The ultimate cumulative gas production at abandonment can be accurately estimated given the advanced depletion state of the field. The ultimate number of earthquakes then follows directly from Eqn (1). It is a fixed number, regardless of the applied gas production rates; it is only determined by the abandonment pressure of the field and thus by the ultimate cumulative gas production. Yearly production level does affect the number of yearly earthquakes, but it has no bearing on the ultimate number of earthquakes. A lower/higher production rate simply means that the total number of earthquakes is spread out over a longer/shorter time period.

The gas-initially-in-place (GIIP) of the Groningen field is estimated at 2880 billion cubic meter. Assuming a recovery factor of 95%, we then calculate a cumulative gas production at abandonment of 0,95 x 2880 = 2736 billion cubic meter. Insertion of this number into Eqn (1) yields a total of 730 earthquakes. This is the total number of earthquakes during the entire lifecycle of the Groningen gas field.

Now that we have a figure for the ultimate number of earthquakes, we can also estimate the maximum strength of an earthquake under Groningen conditions, provided the observed Gutenberg-Richter strength distribution as given by Eqn (2) also applies to future earthquakes. Let us assume that there is just one earthquake with the maximum magnitude. As there are 730 earthquakes in total, the normalized frequency of this maximum earthquake is 1/730 =

0,000137. Extrapolation of the cumulative frequency distribution Eqn (2) down to a frequency of 0,000137 gives a maximum magnitude of 4,4. The extrapolation assumes that the fitted straight line in the Gutenberg-Richter plot (see Fig. 5) remains straight beyond the so far maximum observed magnitude of 3,6 and thus ignores the possible downward bend in the plot. Hence the maximum magnitude of 4,4 should be considered a pessimistic estimate. In passing we note that the 4,4 estimate compares favorably with the most likely value of the range of maximum magnitudes that arose from an expert workshop aimed at estimating the maximum magnitude of induced earthquakes in Groningen (Ref. 5).

As of 01-01-2017 we have already seen 284 of the total of 730 earthquakes, a little over 40 per cent of the total. That means that for the remaining field life we may expect an additional 446 (730 -284) earthquakes, almost 60 per cent of the total. Figure 7 displays the magnitude distribution of the remaining 446 earthquakes, which follows straightforwardly from the empirical Gutenberg-Richter Eqn (2).
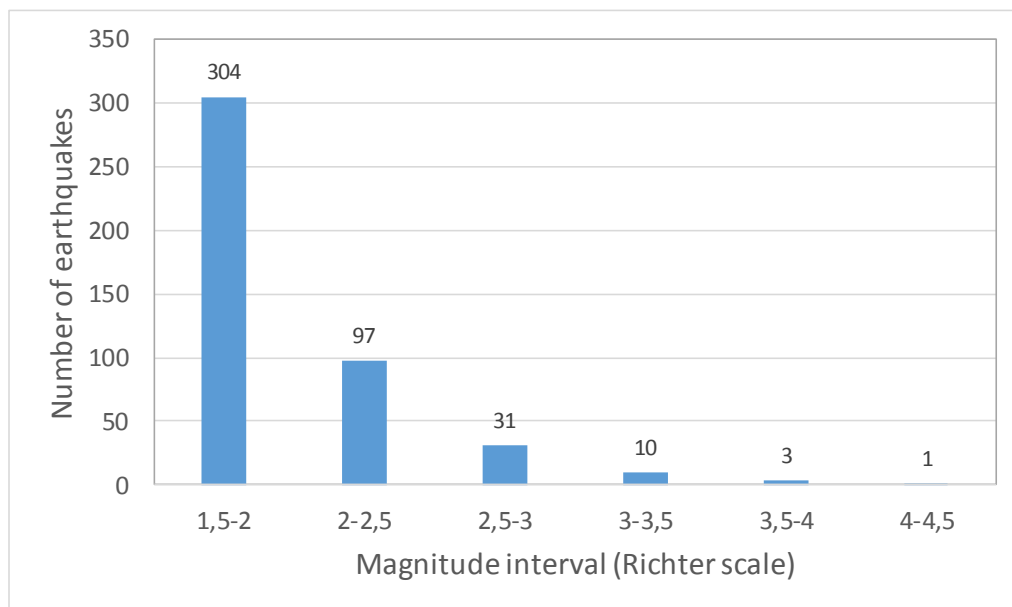

Figure 7 – Magnitude distribution of remaining earthquakes

Production scenarios

The main application of the empirical correlations is in forecasting the yearly earthquake frequency and associated strength distribution for a given future production scenario, i.e. annual production rate as a function of time. A common future production scenario consists of production at a constant plateau rate followed by a period of declining production rates, called tail period. During the plateau period the subsurface reservoir pressure is sufficiently high to enable production at the plateau rate. At a certain point, however, the reservoir pressure becomes too low for the plateau rate to be sustained. This point marks the end of the plateau period and the onset of the tail production period. During the tail period the field is producing

at maximum capacity but the capacity is steadily declining. The lower the plateau production rate, the lower is the pressure decline and thus the longer the plateau period takes.

As an example, we have elaborated the yearly earthquake frequency profiles for three different production scenarios with plateau production rates of 21, 27 and 33 billion cubic meter/year. They describe the continued production by pressure depletion from 2017 up to 2034 as discussed in the recent Winningsplan of NAM (Ref. 6). We have taken the yearly production rates of these production scenarios directly from the Winningsplan. NAM determined the length of the plateau period and the declining rates during the tail period by mathematical reservoir simulation. The plateau ends at 2028, 2023 and 2020 for the production scenarios of 21, 27 and 33 billion cubic meter/year, respectively.
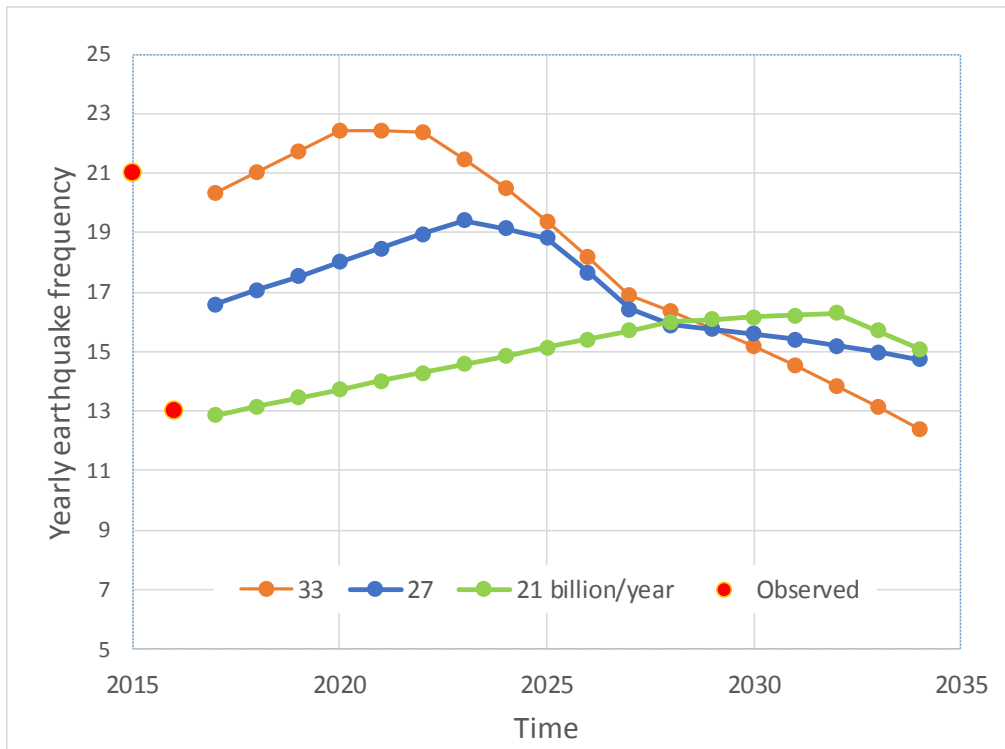

Figure 8 – Forecast of yearly earthquake frequency for 33, 27 and 21 billion cubic meter/year

Figure 8 shows the average earthquake frequency as a function of time for the three production scenarios. As a reference we have also included the observed frequencies in 2015 and 2016 with the associated yearly production rates of 28,10 and 27,95 billion cubic meter, respectively. Initially, the field can be produced at the constant plateau rate in all three cases. Production rate level has a marked effect on earthquake frequency in the plateau period. A larger plateau production rate gives rise to a stronger pressure-decline rate and this leads to a higher earthquake frequency. In addition, the frequency during the plateau period increases linearly with time and with a slope proportional to the plateau production rate. This increase is a direct consequence of the quadratic term in Eqn (1). The earthquake frequency begins to drop the moment the field enters the tail production phase. By and large, the magnitude of and the

trends in earthquake frequencies shown in Fig. 8 are in fair agreement with the results of the NAM predictions (Ref.6). NAM's predictions are based on a seismic model with reservoir compaction as the driver for the induced earthquakes.

As for the strength of the future earthquakes, we may assume that the strength distribution, taken over a sufficiently long period, is time invariant as we have observed in the past. The distribution of the earthquakes in any one year, however, may deviate substantially from the long-term distribution. The yearly distribution can be pictured as resulting from the random sampling from a vase filled with earthquakes with a known strength distribution. In the beginning of the forecast period the vase contains 446 earthquakes, of which 1 with a magnitude between 4 and 4,5, 3 between 3,5 and 4, 10 between 3 and 3,5, 31 between 2,5 and 3, 97 between 2 and 2,5 and 304 between 1,5 and 2. Each year we randomly draw a number of earthquakes from the vase depending on the production rate in that year. As the yearly number is very small compared with the total number of earthquakes, at least initially, the sampling is strongly biased leading to significant year-to-year variations in strength distribution.

The strongest earthquake with a magnitude of 4,4 can happen, in theory, at any time during the remaining production period. The probability that this happens in a given year is equal to the frequency of the 4,4 earthquake (=0,000137) times the yearly earthquake frequency in that year and thus depends on the yearly production rate. This yearly frequency in 2017 for a production rate of 33, 27 and 21 billion cubic meter/year is 20, 17 and 13, respectively. Hence the probability of a 4,4 earthquake happening in 2017 at a production rate of 33, 27 and 21 billion cubic meter/year is 4,5, 3,8 and 2,9 per cent/year, respectively.

Conclusions

1. The observed cumulative number of earthquakes with a magnitude greater than 1,5 correlates very well with cumulative gas production and can be very well described mathematically by a quadratic equation.
2. The quadratic equation can be used to predict the average yearly earthquake frequency for a given production rate profile. Observed yearly frequencies deviate substantially from the predicted frequencies, indicating a sizeable inherent natural variability.
3. The strength distribution of the earthquakes is fairly well described by the Gutenberg-Richter equation for cumulative frequency as a function of magnitude. For all practical purposes this distribution is time-invariant.
4. The observed increase in stronger earthquakes in the course of time can be attributed to an increase in yearly earthquake frequency.
5. The ultimate number of earthquakes with a magnitude greater than 1,5 over the entire life cycle of the field is of the order of 700. This number is not affected by yearly production rate: a lower/higher production rate simply means that the total number of earthquakes is spread out over a longer/shorter time period.
6. Up to 01-01-2017 roughly 300 earthquakes with a magnitude greater than 1,5 have been recorded, leaving 400 earthquakes for the remaining production period.

7. The magnitude of the strongest future earthquake is estimated at 4,4 on the Richter scale.
8. Example forecasts are presented that highlight how yearly production rate affects the development of seismicity in Groningen.

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