A phenomenological relationship between reservoir pressure and tremor rates in Groningen

May 2016

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Contents

Nederlands

Deze rapportage is een verslag van onderzoek dat is uitgevoerd in het kader een onderzoeksproject door het CBS in opdracht van Staatstoezicht op de Mijnen (SodM) sinds 2014. Dit onderzoek is ten behoeve van een statistische onderbouwing van het meet- en regelprotocol voor optimale gasexploitatie in de provincie Groningen, met in het bijzonder de aandacht gericht op de relatie tussen de gasdruk in het reservoir, die in de tijd varieert vanwege de gas productie bij de diverse clusters, en de aardbevingen in Groningen.

Uit de analyse blijkt dat er een duidelijke correlatie is in de zin dat voorafgaand aan aardbevingen er op de locatie van die aardbeving een signaal is te zien in de gasdruk in het reservoir. De jaarlijkse modulatie van gasextractie is duidelijk zichtbaar, hetgeen niet het geval is wanneer dezelfde analyse op een verzameling van willekeurige tijdstippen en locaties wordt uitgevoerd. Nauwkeurige analyse van de modulatie maakt aannemelijk dat de waarschijnlijkheid voor het optreden van aardbevingen op een bepaalde locatie binnen enkele weken reageert op veranderingen in de lokale gasdruk veranderingen in het reservoir op die locatie. Er zijn echter ook aanwijzingen voor een invloed die op een veel langere tijdschaal van meerdere jaren werkzaam is.

English

This report is a continuation of research, commenced in 2014, which is part of a research project being carried out by Statistics Netherlands and commissioned by State Supervision of Mines (SodM). This research is part of the underpinning of the statistical methods employed to support the protocol for measurement and control of the production of natural gas in the province of Groningen. In this research the particular focus is on the relationship between reservoir gas pressure variations and the earth tremors in Groningen.

From the analysis it is clear that there is a correlation, in the sense that prior to earthquakes there is an enhanced signal in the reservoir gas pressure at the location of the earthquake. The annual modulation of gas extraction is clearly visible, which is not the case if the same analysis is applied to a collection of random locations and times. A closer analysis of that modulation shows that it is plausible that the probability for a tremor to occur at any given location reacts within a few weeks to changes in local reservoir gas pressure. However there are also indications that some influence from the gas extraction is acting over much longer timescales of several years.

1 Introduction

For some decades earthquakes of modest magnitudes have occurred in and around the Groningen gas field. It is recognized that tremors can be induced by the production of gas from a field eg. (Wetmiller, 1986); (Grasso, J. and Wittlinger, G., 1990); (Bourne, S.J., Oates, J., van Elk, J., Doornhof, D., 2014). An extensive study program is in place to improve the understanding of the risk and hazard due to gas production-induced earthquakes in the Groningen field (Nederlandse Aardolie Maatschappij BV, 2013). A protocol is being established with the aim of mitigating these risks and hazards by adjusting the production strategy in time and space. Also the NAM is active

in improving safety of housing through structural strengthening of buildings. In order for this to be effective it is necessary first to understand whether tremor frequency and ground subsidence can be influenced at all by adjusting production. If so, it needs to be established how quickly the system reacts to production adjustments. Even if causality can be demonstrated, and the reaction time scale shown to be sufficiently short, implementation of the regulation protocol with adaptive control of production will require regular measurement of the effects on subsidence and earthquakes to provide the necessary feedback for production control.

Figure 1.1   The locations of all tremors within the zone in Groningen relevant to this analysis, recorded after 1 January 1995. The red squares are locations of the production clusters, some of which are identified by name. The production field is also shown in dark gray, overplotted on a map of the region.
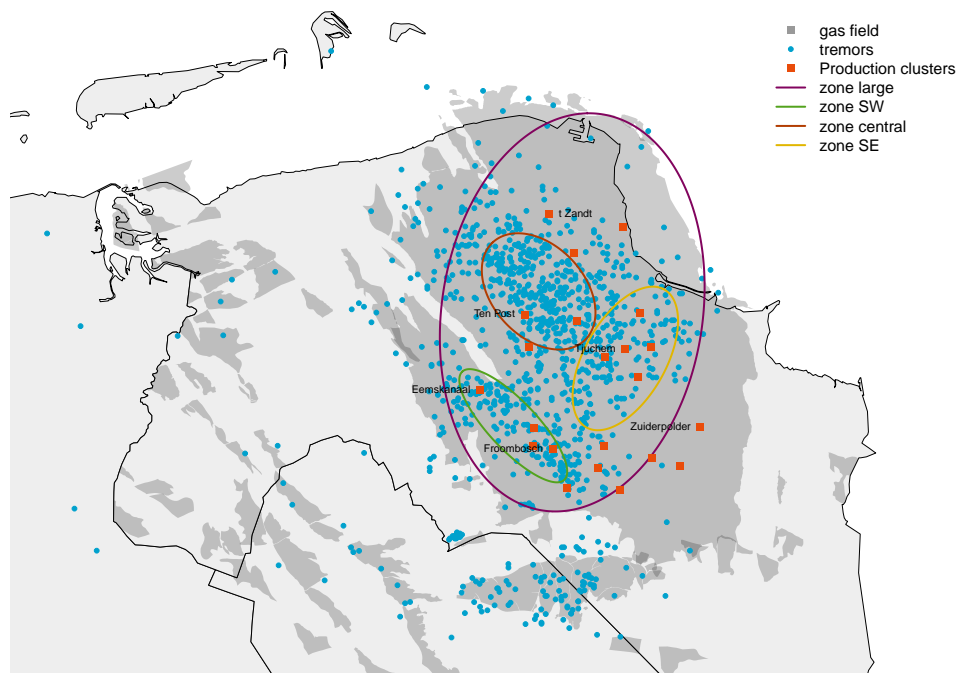
The causality relationship between gas production and eartquakes is difficult to establish unequivocally, purely on the basis of time series analyses. For instance, a constant rate of gas extraction might lead to a likelihood of tremors that increases with time through the compaction of the reservoir layer, cf. (Bourne, S.J., Oates, J., van Elk, J., Doornhof, D., 2014), but a correlation analysis would not necessarily provide any evidence of this. Because in practice the rate of production does vary periodically throughout the year, as well as incidentally for operational reasons, it becomes possible to pursue a correlation analysis between variations in tremor incidence and production variations. Preliminary results on a correlation analysis between ground subsidence and production variations (Pijpers, F.P. and D.J. van der Laan, 2015b) provide some support for the feasibility of this approach. There is no doubt that the extraction of natural gas strongly influences the balance of forces in the reservoir layers, eg. (Mulders, 2003). However, every tremor is the realisation of a stochastic process, for which the balance of forces in part determines the probability distribution function of that process. Because of this stochasticity there is an intrinsic decorrelation between variations in gas production and variations in tremor incidence frequency. Conversely, even if a correlation can be established between gas production and tremor incidence, it will depend on the exact nature of that correlation whether causality can be considered proven or likely.

As with the CBS reports from the previous phases of this project, starting point for the analysis of

the statistics of tremors is the catalog of tremors as reported by the Royal Netherlands Meteorological Institute (KNMI) based on their processing of the network of seismometers that they manage. Further selections from that catalog are made as necessary, for instance in order to filter out tremors that have occurred outside of the zone of interest, or tremors from an epoch when the seismometer network was less sensitive and may suffer from more serious completeness issues. The selection/filtering criteria are chosen to be consistent with those of the previous Statistics Netherlands reports, (Pijpers, 2014b), (Pijpers, F.P., 2015a), (Pijpers, F.P., 2015c): tremors before 1995 are excluded and the spatial region of interest is the same as in those reports (see fig. 1.1).

The gas pressure inside the reservoir can be modelled, by making use of detailed geophysical mapping of the reservoir and its material properties, that together determine the diffusive flow of gas through the reservoir, induced by the gas production at the various clusters. In a previous report (Pijpers, F.P., 2015b), the gas flow induced by the gas production was modelled using a very simplified model of the flow, which did not take any variation of these material properties into account. Much better models are available however, in the form of the reservoir modelling tool MoReS (Por, G.J., Boerrigter, P., Maas, J.G., de Vries, A., 1989). In collaboration with TNO the MoReS code has been used to provide the starting point for an improved analysis. The reservoir gas pressure as a function of time at the required locations, ie. the locations of tremors and of a reference set of points, has been determined. These time series data are then combined in a way very similar to what is described in (Pijpers, F.P., 2015b) but without having to take recourse to the very simplified flow model used in that report. The time resolution that MoReS can provide is very high, but for the purposes of the present analysis it is considered sufficient to use weekly sampling points, which corresponds to the time resolution used in the previous report. The pressure data used are weighted vertical averages inside the reservoir. The horizontal resolution of the numerical grid of MoReS varies, but is everywhere sufficient for the present analysis, since spatial uncertainties of less than about $500\ m$ are irrelevant given the uncertainty in localisation of tremors. While therefore better modelling, and thus more accurate pressures, are available, there will nevertheless still be a contribution to noise due to the uncertainty of localisation of tremors and also due to the spread in the localisation of the clusters in the reservoir.

2 Background

2.1 Propagation of the signal of gas extraction

It is clear that the locations of tremors do not coincide with the locations of the wells. If the gas extraction at the wells is to have an influence at other locations, a signal has to pass from the well to those other locations. A signal occurs as gas diffuses through the reservoir layer, to replace the gas extracted at the well, or cluster of wells. A diffusive model for the signal of gas extraction has been used for instance by (Baranova, V., Mustaqeem, A., Bell, S., 1999) (their eq. 5) to model induced seismicity by hydrocarbon production in western Canada. A more general description can be found in (Russell, T.F. and Wheeler, M.F., 1983). A controlling parameter for such diffusion is the diffusivity in the medium which is determined by material properties of both the medium and the material diffusing through it: the permeability of the medium and its porosity, the viscosity of the diffusing gas and its compressibility. None of these properties are constant throughout the region, and the system of larger and smaller faults also play an

important role in channelling or obstructing flow. For a description of the detailed modelling of the flow and pressure in the reservoir layers using MoReS the reader is referred to (Por, G.J., Boerrigter, P., Maas, J.G., de Vries, A., 1989) .

2.2 The local gas pressure history for tremors

In order to assess whether there is any kind of statistical correlation between the gas pressure throughout the Groningen field and the generation of tremors it is of interest to reconstruct the history of the gas pressure at the location of tremors in the period leading up to the time of the tremor. It is assumed that the occurrence of tremors is not a fully deterministic process, but rather that an identical set of circumstances gives an identical finite likelihood for a tremor to occur. A single event is then of limited value in terms of the information that it carries. Therefore one would wish to combine the history of every relevant tremor to find the typical local gas pressure history for tremor events. The time at which the tremor occurs is set to 0, and the local pressure or local relative pressure variation is determined for all selected tremors using the MoReS code, for a range of time values counting back from that tremor time. This is done for all selected tremors after which straightforward averaging of the time histories for every (selected) tremor achieves the goal of obtaining the typical history of local gas pressure, and relative pressure variation before tremors as a function of 'look-back' time.

Obtaining this averaged local pressure history for tremors is not yet sufficient for the purposes of the analysis. If instead of using locations and times of the selected tremors, one would pick an equal number of randomly chosen locations and times, a local pressure history could be obtained by applying the same technique of co-adding of gas pressure histories. Since by definition such a randomly chosen set of locations and times is not special, it is only the differences between the histories of true tremors and artificial 'events' that is of interest. If the co-added pressure history of true tremors is statistically indistinguishable from the co-added pressure history of random locations and times, no causality between gas pressure and tremors can be demonstrated.

The analysis thus requires that a set of locations and times be set up, which can be used to build a local history of gas pressure in the same way that it is done for the true set of selected tremors. It might not be appropriate however to generate such a set using a completely uniform distribution over space or time. It is clear from fig. 1.1 that the spatial distribution of tremors is not uniform, and it is known that the distribution over time also is not completely uniform. It is desirable to mimic at least some aspects of the real distribution over space and time in the distribution for the set of articificial events. To this end the number of tremors in $2.5 \ km \times 2.5 \ km$ grid squares is counted. For the artificial events the number of events in each of these squares is reproduced, but random $(x, y)-$coordinates uniformly distributed within each grid square are generated. Similarly, for the timing of these artifical events, the full time range since 1995 is sectioned into intervals of length $300 \ d$ and the number of true events in each of these sections counted. The number of artificial events must match this true number but the actual timing within each subinterval is generated from a uniform distribution. In the following sections the plots are shown for a single realisation of random events.

3 Comparison of histories

In the following sections, several different selection criteria are applied to the catalog of earthquakes in the Groningen field. In section 3.1 all earthquake data are used, in section 3.2 only those tremors are included with magnitudes $M > 1$ for which the catalog is likely to be complete in terms of detection, and in section 3.3 tremors with $M > 1.5$ which are most likely be well-localised as well as complete in the catalog. Finally, in section 3.4 the set with $M > 1$ an additional analysis is presented where the aim is to distinguish whether it is the timing or the location of the tremors that is most important in determining the characteristics. Both the gas pressure and local relative variations in gas pressure are considered in all sections.

3.1 All tremors

In the manner as described in section 2 in the first instance all tremors are selected having occurred within the relevant region and also having occurred after Jan. 1 1995, as indicated in fig. 1.1. For comparison the set of random events is shown in fig. 3.1. A total of 786 tremors (cq. events) is involved. The local gas pressure history for each tremor, and also for each artificial

Figure 3.1 On the right: the locations of artificial events set up as described in section 2.2, for comparison when selecting all true tremors after 1995. The indicated scales are in km. On the left are the true events in the same coordinate system
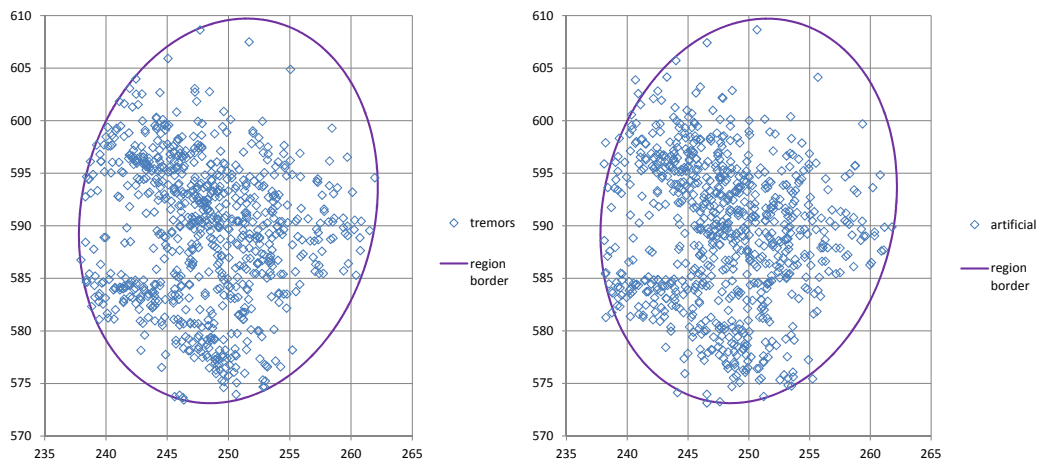
Figure 3.2 The co-added histories of gas pressure at locations of tremors (black line) and at the set of artificial events (red dashed), as a function of time (in weeks). The left panel shows the number of events over which the average is taken in the co-adding. On the right the reservoir pressure is shown
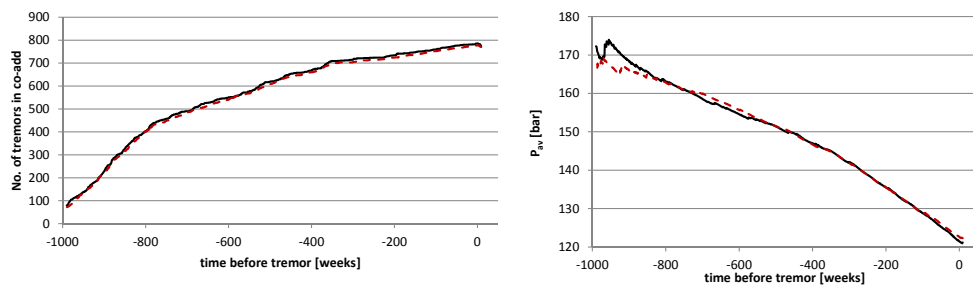
event, is constructed using MoReS, and then co-added to obtain the mean history as a function of look-back time. Fig. 3.2 shows the pressure history both for the true tremors and for the artifical events for a (typical) realisation. While the detection timing of the tremors is very precise, the localisation is not always as good. For this reason it is not necessary to use a finer temporal resolution than a week which is also the time unit shown.

The total gas pressure has clearly decreased over the past decades, which is the dominant trend that is visible in the righthand panel Fig. 3.2. At negative times before -500 weeks the number of tremors for which histories are available starts dropping off, and especially before -700 weeks this drop-off is quite steep (lefthand panel of Fig 3.2). This influences negatively the statistical reliability of the history for very early times, so that in subsequent analysis the focus lies on the time range of $[-500, 0]$ weeks. To enable a focus on variations on timescales of a year, it is convenient to subtract for each point in the pressure time series a moving average of the pressure in the individual time series and co-add relative pressure variations. The time series, for each location, of the relative pressure variation is calculated using:

$$\left(\frac{\Delta P}{P}\right)_i \equiv -\left(P_i - \frac{1}{M+1}\sum_{j=0}^{M} P_{i-j}\right)/P_i \tag{1}$$

in which each P_i is the reservoir pressure at time t_i. Here the length of the window is taken to be 12 weeks ie. $M = 11$. These time series are then co-added so that a single time series as a function of time before tremor is obtained. Note the minus sign in the above definition. It is chosen so that the fractional pressure variation is positive, which happens because the window in the moving average has as the index i as its last measurement and the trend in the pressure is downwards.

Figure 3.3   The co-added histories of relative gas pressure variation at locations of tremors (black line) and at the set of artificial events (red dashed), as a function of time (in weeks).
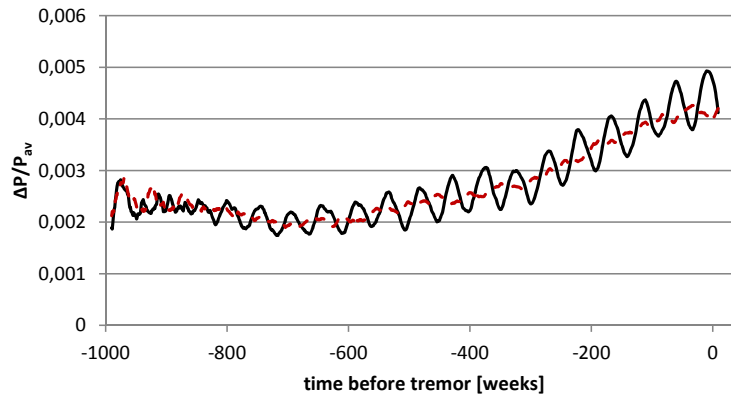

By comparing these histories of reservoir gas pressure it is clear that the co-added pressure history for tremors show a periodic signal, which is absent from the artificial events. By taking the ratio of the two co-added pressure histories the common behaviour can be removed so that it is possible to focus on the differences between these histories. fig. 3.4 shows this ratio, where it is seen that the periodic signal persists.

Although there is an annual modulation of gas production, the different time delays between an arbitrary location in the field and each cluster would be expected to 'wash out' such a signal, especially after co-adding the histories for a large number of events as indeed is seen in the

Figure 3.4   The ratio of the co-added histories of the pressure (left panel) of true tremors and artificial events, as a function of time before tremor (in weeks), ie. the ratio of the histories shown in the right panel of fig. 3.2. The right panel shows the ratio of the relative pressure variations, ie. of the histories shown in fig. 3.3
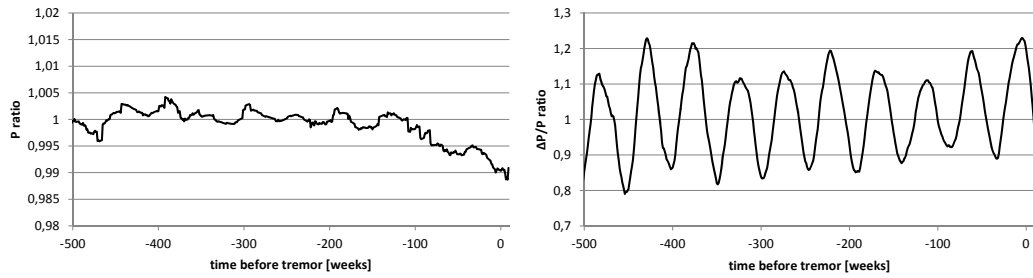
Figure 3.5   Left panel: the ratio of the pressure P as a function of look-back time for the tremors and the artificial events (blue, identical to lefthand panel of fig 3.4) and a fit (red). Right panel: the Fourier amplitude of the ratio of the two histories of pressure (blue) and the Fourier amplitude of the fit (red).
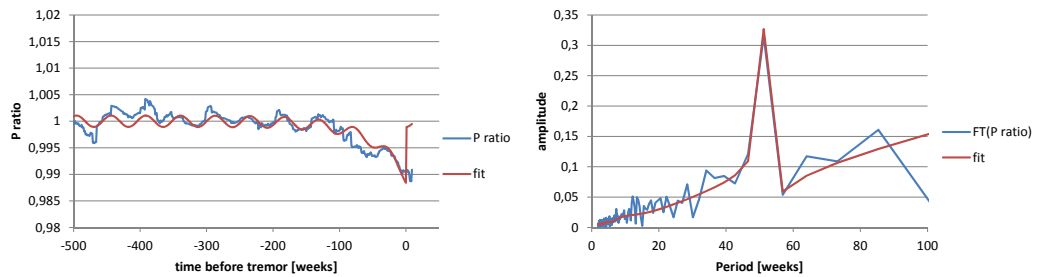
history for the reference set. Also, it is clear that the ratio of the history of true tremors and the reference set has values well below 1 and increases slowly to 1 towards negative times, ie. 2 or 3 years before tremors occur. In the righthand panel of Fig. 3.4 the ratio has been taken of $\Delta P/P$ for the true tremors and for the reference set of artificial events. Using $\Delta P/P$ has the advantage of removing the general downward trend in pressure, so that the annual modulation is particularly clear. Also, in a previous report (Pijpers, F.P., 2015b) a quantity was presented and analysed that is closely related to this relative pressure variation.

Given that there appears to be a modulation of the signal, it is useful to perform a Fourier transform of this ratio time series. The Fourier transform is generally complex valued, unless a time series is symmetric around 0 which is not the case here cf. (Bracewell, 1965). In Fig. 3.5 on the left the data are reproduced from the top panel of Fig. 3.4 together with a fitting function of the form:

$$\begin{aligned} f(t) &= A + B\exp\left(\alpha t\right) + C\cos\left(2\pi t/P + \phi\right) \quad \forall t < 0 \\ f(t) &= 1 \quad \forall t \geq 0 \end{aligned} \tag{2}$$

with the time t measured in units of weeks. For the fit shown the values of the various constants are:

$$A = 1, \; B = -0.0105, \; C = -0.00107, \; \alpha = 0.02, \; P = 1yr, \; \phi = 0 \tag{3}$$

The Fourier amplitude (complex modulus) for this ratio of the pressure time histories is shown in Fig. 3.5 on the right together with the Fourier amplitude of the same fitting function. In the Fourier amplitude there is a peak, at a period of 1 year. This implies that the timing of tremors correlates with the minima and maxima in the history of the gas pressure, which has an annual modulation. The peak in the Fourier domain is superposed on a slope, which arises from the

structure in the time domain on long time scales: with the underlying trend in pressure ratio increasing slowly to 1 towards earlier times. The value for the parameter α corresponds to an e-folding time scale of 50 weeks. This is not a formal best fit in the sense that an e-folding time of 65 weeks (and all values in between) would also still provide an adequate fit.

Figure 3.6   Left panel : the ratio of $\Delta P/P$ as a function of look-back time for the tremors and the artificial events (blue) and a fit (red) which jumps discontinuously to 1 at $t = 0$. Right panel: the Fourier amplitude of the ratio of the two histories (blue) and the Fourier amplitude of the fit (red).
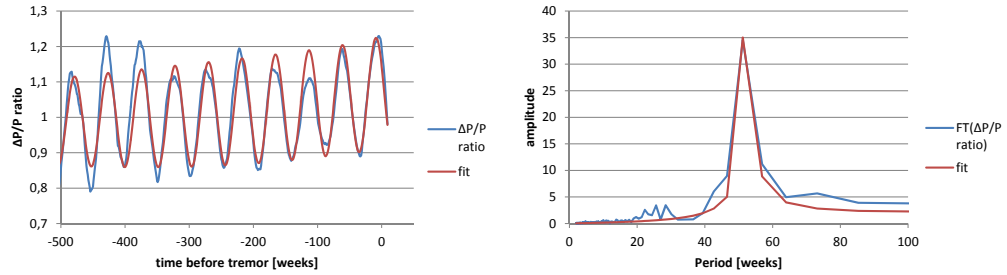
In the same way that the ratio of the pressure histories for the co-added real events and co-added artificial events can be determined, the ratio of the relative pressure variations $\left(\frac{\Delta P}{P}\right)_{real} / \left(\frac{\Delta P}{P}\right)_{artif.}$ can be determined as well. This ratio is shown in Fig. 3.6 in the lefthand panel, with its Fourier Transform in the righthand panel. Here the annual modulation is very clear. A fit is also shown, with its Fourier transform in the panel on the right. This fit has the form:

$$g(t) = A + B \exp\left(\alpha_1 t\right) + C\left[\exp\left(\alpha_2 t\right) + D\alpha_3^2 t^2 \exp(\alpha_3 t)\right] \cos\left(2\pi t/P + \phi\right) \tag{4}$$

For the fit shown the values of the various constants are:

$$A = 0.9684, \ B = 0.1, \ C = 0.016, \ D = 0,3262$$

$$\alpha_1 = 0.0033, \ \alpha_2 = 0.001 \ \alpha_3 = 0.005 \ P = 1yr, \ \phi = 2\pi\left(\frac{9}{52}\right) \tag{5}$$

There is range around the given value of the parameter ϕ that would also produce an acceptable fit. This value indicates that there is a delay time of about 9 weeks between the occurrence of a tremor and the most recent peak in the ratio $\left(\frac{\Delta P}{P}\right)_{real} / \left(\frac{\Delta P}{P}\right)_{artif.}$ at the tremor location.

While not absolute proof, this gives a strong indication that the likelihood for a tremor to occur reacts causally to gas production in the sense that locations of true tremors have a local pressure that is distinctly below the pressure for random locations for some two year leading up to the time at which a tremor occurs. In addition the annual modulation, caused by the annual pattern of gas extraction, is clearly visible. By focussing on the relative pressure variations around the trend, this modulation is even more apparent, and it appears that there is a small lag of around nine weeks between the fiirst maximum in the pressure variation and the occurrence of a tremor. A purely periodic signal in the gas pressure history of true tremors could still have been a coincidence in the sense that a speculative natural effect might produce an annual variation in tremor likelihood. This speculative process unrelated to gas production would then introduce a spurious correlation simply because it has an annual variation as does the gas production rate. However, the pressure history for the co-added set of randomly chosen locations and times does not show the periodic variation whereas the true events do. It is difficult to envisage a process extraneous to gas extraction that would produce this effect.

3.2 Tremors with magnitudes $M > 1$

Although the catalog provided by the KNMI contains data for a large number of tremors with magnitudes $M < 1$ it is likely that many such tremors have not been picked up by the seismic network, so that the catalog is not complete. It is therefore necessary to assess whether the lack of completeness affects the results of the analysis. The same steps as described in section 3.1 are therefore executed for a smaller set with 540 tremors, for which the magnitude $M \geq 1$. A selection of the same number of artificial comparison events is made, in order to ensure that the comparison is between as similar as possible sets of events.

Figure 3.7   The co-added histories of relative gas pressure variation at locations of tremors with $M \geq 1$ (black line) and at the set of artificial events (red dashed), as a function of time (in weeks).
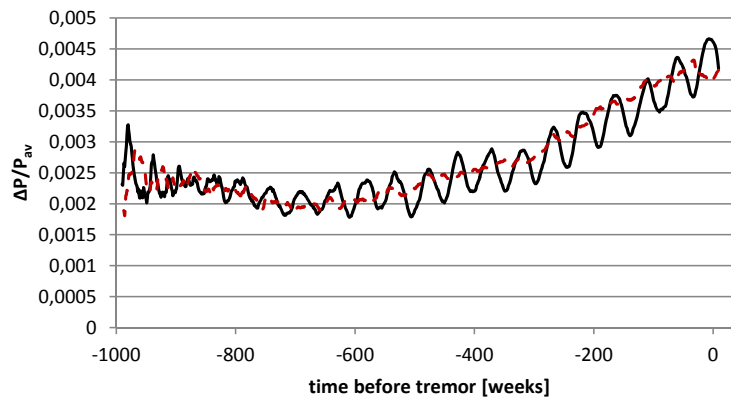
Figure 3.8   Left panel : the ratio of $\Delta P/P$ as a function of look-back time for the tremors and the artificial events (blue) and a fit (red). Right panel: the Fourier amplitude of the ratio of the two histories (blue) and the Fourier amplitude of the fit (red). Only tremors with a magnitude $M \geq 1$ are used.
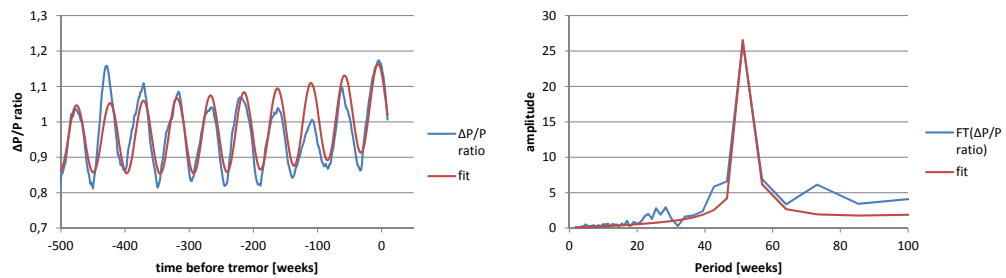

Fig. 3.7 shows the relative pressure variation history both for the true tremors and for the artificial events. In fig. 3.8, the left-hand panel shows the ratio of the relative pressure histories using only tremors with $M \geq 1$, and the panel on the right shows its Fourier transform. In both panels also fitting functions are shown wioth the same form as in the previous section. A periodic signal is still visible in the relative pressure variation history. In the left panel of fig. 3.8, the ratio of the two is shown. While there is more variation in the amplitude of the annual modulation, compared to the full set of tremors used in the previous section, it is still present. The amplitude of the Fourier transform (right panel of fig. 3.8) shows that the (average) amplitude of the periodic signal, with the 1 year period, is now smaller than it is if no selection on magnitude is applied. Further of interest is that the parameter ϕ of the fit, expressing the delay time between the most recent maximum in this ratio and the tremor, is slightly smaller: it corrsponds to a delay of 6 weeks rather than 9 weeks.

3.3 Tremors with magnitudes $M \geq 1.5$

While it is likely that the completeness of the KNMI catalog for tremor magnitudes $M > 1$ is good, there are nevertheless some reservations concerning the accurate spatial localisation of tremors with magnitudes between $M = 1$ and $M = 1.5$. For this reason it is useful also to consider the same analysis as described in the previous sections but selecting only tremors that have $M > 1.5$; numbering 231. For comparison, once again comparison sets of artifical events have been generated as well.

Figure 3.9 **The co-added histories of relative gas pressure variation at locations of tremors (black line) and at the set of artificial events (red dashed), as a function of time (in weeks).**
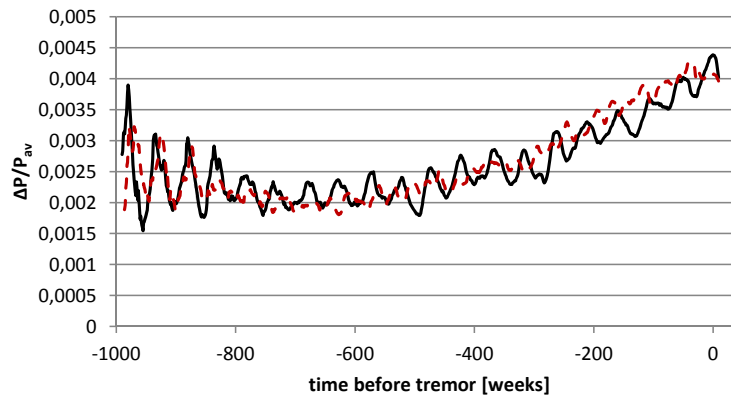
Figure 3.10 **Left panel : the ratio of $\Delta P/P$ as a function of look-back time for the tremors and the artificial events (blue) and a fit (red). Right panel: the Fourier amplitude of the ratio of the two histories (blue) and the Fourier amplitude of the fit (red). Only tremors with a magnitude $M \geq 1.5$ are used.**
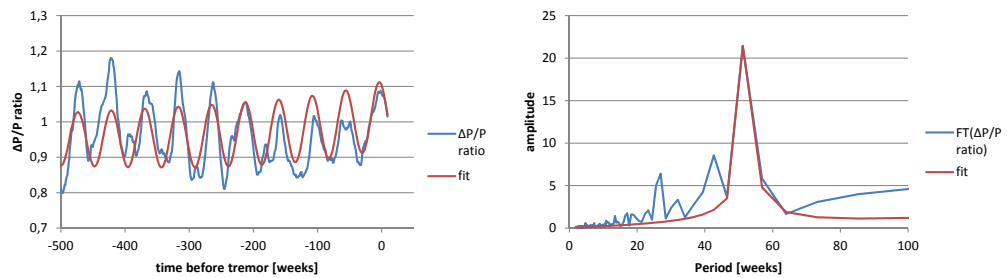
It is evident that the number of events with magnitude $M \geq 1.5$ is rather smaller than could be used in the previous 2 sections. A periodic signal is still identifiable in the history itself (fig. 3.9) but is less clean. It can also be seen in the ratio with the history for the artificial events (fig. 3.10). A Fourier transform of the ratio of histories (see fig. 3.9) reveals that the annual modulation is clearly present but with a slightly smaller amplitude than before. The parameter ϕ now corresponds to a delay time of 4 weeks, but the uncertainty is large enough that it is not clear whether this is significantly different from the value obtained for the set with tremors with $M \geq 1$.

3.4 Spatial effects

In the analysis up to this point the reference sets used, against which the pressure history of gas pressure before true tremors is compared, are random both in space and in time. It is of interest to understand to what extent spatial correlation or temporal correlation of true events plays a role. This can be done by using as reference set events for which the time is chosen at random as described before, but to use the spatial locations for the actual events in the catalog. Conversely one can assign random locations, but keep the timing of the true events.

Figure 3.11   Left panel: the histories of the relative pressure variations for true events (black) and events at random locations, but using the timing of true events (red dashed). Right panel: the histories of the relative pressure variations for true events (black) and events with identical locations but random times. In all cases a set of 540 true events with $M > 1$ is used.
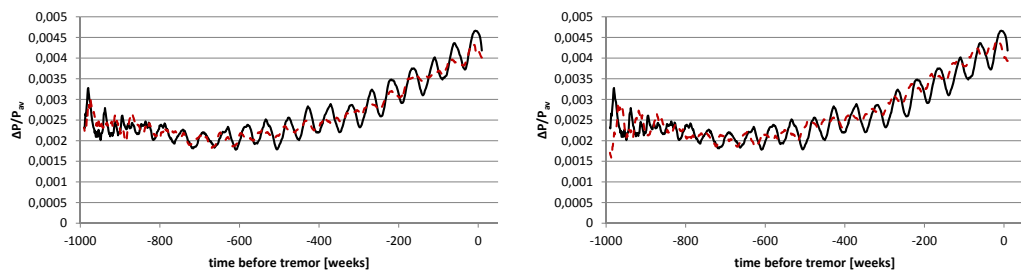

Fig. 3.11 shows the results for the two different options with the selections of 540 events in the KNMI catalog with $M > 1$ as in section 3.2. The history of the true events is identical to that already shown in section 3.2. While

Figure 3.12   The ratio of the histories of pressure (top panels) and relative pressure variations (bottom panels) at locations of tremors, with as references sets the random locations but true event times (lefthand panels), and true locations with random times (righthand panels). The set of 540 events with $M > 1$ is used in all cases.
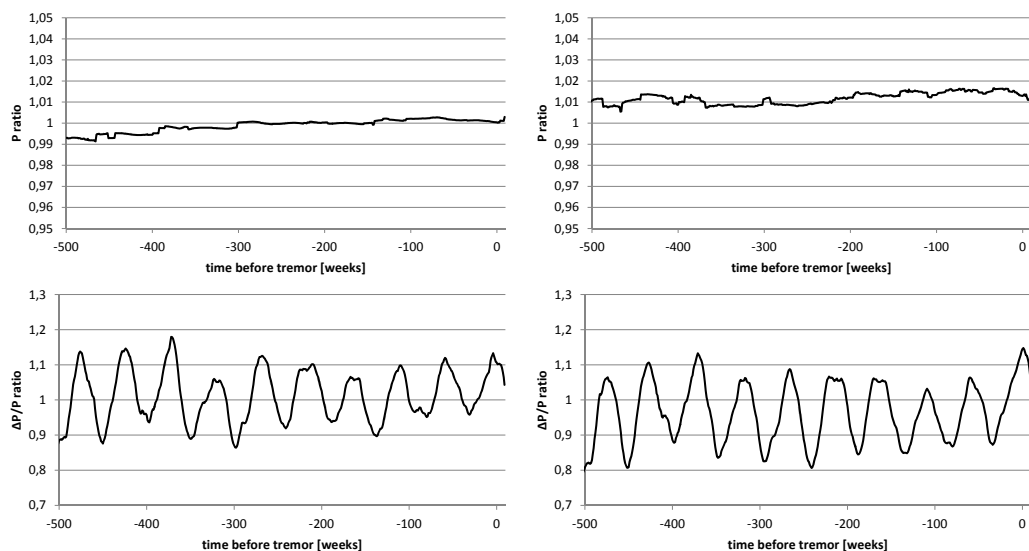

Fig. 3.12 shows the results for the ratios of the pressures (top panels) and relative pressure variations (bottom panels), both for the case of using a reference set keeping the timing of the true tremors with random locations (lefthand panels) and vice versa (righthand panels).

In both cases the ratios of the relative pressure variations are clearly distinct between the true

events and the reference set, so that the annual modulation is seen. For the reference set with the true event locations and random timing the amplitude of the modulation is slightly larger than for the reference set with random event locations and the timing of the true events. The history of the ratio of the pressure itself for the reference set with random event locations and the timing of the true events is very close to 1 throughtout and does not show a signature of an annual modulation even though the relative pressure variations do. For the reference set with the true event locations and random timing the pressure ratio history is clearly different from 1.

From the combination of these sets of simulations it appears that both the location and the timing contribute to the modulation effect seen in the history of the ratio of relative pressure variation between true events and the reference set. In a previous report (Pijpers, F.P., 2015b) it appeared that it is mostly the locations that are characteristic of tremors. This is not confirmed here, when using the more sophisticated gas pressure modelling of MoReS. It is not unlikely that the better modelling used here has restored the signal that is destroyed when using the more basic flow model of the previous report.

4 Conclusions

There is a strong indication that the likelihood for tremors to occur reacts causally to gas production in the sense that increased production leads to an increased tremor likelihood within a time period of 5 to 10 weeks of the maximum in the relative pressure variation arriving at a tremor generating site such as a fault or fracture.

In the reports (Pijpers, 2014b), (Pijpers, F.P., 2015a), and (Pijpers, F.P., 2015c) it is demonstrated that a strong reduction in gas production at a number of clusters in the beginning of January 2014 was followed during that year by a reduction in frequency of tremors in the vicinity of those clusters, which is consistent with the time scale reported now. In work of (Pijpers, 2014a), (Pijpers, F.P. and D.J. van der Laan, 2015a), (Pijpers, F.P. and D.J. van der Laan, 2015b) a rapid response of the subsidence to production variations with a delay of about 9 weeks has been seen. Thus it would appear that production variations once propagated to the location of faults or fractures are followed by subsidence and the generation of tremors on very similar timescales.

Absolute proof of causality requires the ability to exclude or identify the influence of all other possible factors that could affect the likelihood of tremors. In the case at hand an, as yet unidentified, external process that might explain the timing of tremors instead of the gas pressure would need to introduce an annual modulation which in addition would have to be phased just right for the gas production variations propagated to tremor sites to coincidentally line up in the period leading up to tremors, as well as phasing these to increase just before tremors. Although such a process might exist, currently the data and this analysis do not give any reason to reject a hypothesis of causality through reservoir pressure variations induced by production. It is not unusual in such a case to apply Occam's razor and select, at least as working hypothesis, the most parsimonious attribution of causality ie. to the gas production itself.

The analysis of section 3.4 shows that the spatial distribution of tremor sites appears to play an important role in the correlation with the gas production, as well as the timing. A previous result of (Pijpers, F.P., 2015b) which suggested that the location was more important than the timing is

not confirmed. This behaviour is nevertheless still consistent with eg. the discussion in (Bourne, S.J., Oates, J., van Elk, J., Doornhof, D., 2014), where it is the interaction of reservoir compaction, because of pressure depletion, with pre-existing faults and fractures that generates tremors. The locations of those pre-existing faults or fractures is then the relevant spatial characteristic of the tremors that is found in the analysis presented here. The timing is important because it plays a role in 'lining up' in time gas pressure variations at the fracture locations. It would be of interest to map out the full pattern of the relative gas pressure variations within the reservoir, and overlay this on maps of the pre-existing faults and fractures to assess whether higher incidence of tremors is spatially correlated or co-located with areas where these faults coincide with higher amplitudes of the signal. If so, this could provide a mapping tool that could be of assistance in assessing regionally differentiated hazard. Evidently this is limited by the spatial resolution and sensitivity with which faults can be mapped.

There are two time scales over which enhanced production appears to have an effect on tremor incidence. In general tremors show a history of enhanced signal for some two years beforehand, on which the annual modulation is superposed. This is shorter than the time scale previously reported (Pijpers, F.P., 2015b), probably because the approximations of the previous report used a uniform diffusivity, which would have the effect of retaining time coherence that in reality does not occur because it is destroyed by the variations in diffusivity that the reservoir layer in reality has. Within the context of critical systems, cf. (Main, 1995), one may hypothesize that the pressure depletion over long time scales has put the system of faults into a (nearly) critical state. The additional short term effect of production variations in this critical systems context might be that they act to push the system temporarily but repeatedly to a critical state and act as a trigger for tremor avalanches. There is some indication that larger magnitude tremors are associated with slightly shorter reaction times to pressure variations, but this requires further investigation.

One could hypothesize that a reduction in the amplitude of the annual modulation of production levels would have the effect of reducing the tremor rate relatively quickly but possibly by only modest amounts. In this case obtaining a more sustained further reduction in tremor incidence could then require longer term reduction in production, the effect of which on tremor incidence might only be noticeable after a few years.

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