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TNO report

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Injection Related Induced Seismicity and its relevance to Nitrogen Injection: Main findings, recommendations and general guidelines.

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1 Introduction

Pressure maintenance by injection of nitrogen into a reservoir is considered as one of the potential options to mitigate induced seismicity during gas production. As seismicity in producing gas reservoirs is a consequence of stress changes caused by the decline in pore pressures and ongoing (differential) compaction of the reservoir rocks, it is expected that seismicity and the seismic hazard can be reduced by decreasing these stress changes and the compaction by maintaining the pore pressure in the reservoir rocks. In recent years, however, numerous field cases of injection-related induced seismicity have been published in literature. Hence, the question can be raised whether injection of nitrogen itself can have an adverse effect on the seismic hazard and can cause an unwanted increase in seismicity. NAM requested TNO to perform a generic study to estimate the potential for induced seismicity caused by the injection of nitrogen in a producing gas reservoir and to specify general operational guidelines for nitrogen injection to reduce the potential of injection-related seismicity. This generic study consisted of the following three main parts:

1. Literature study on injection-related induced seismicity worldwide (reported in [1]),
2. Description and analysis of field cases of injection in The Netherlands (reported in [2]),
3. Geomechanical modelling of the effects of (nitrogen) injection on fault stability in a reservoir, representative for a typical Rotliegend reservoir in the northern part of The Netherlands (reported in [3]).

For more detailed descriptions of the results of these parts of the study we refer the reader to the specific project reports [1]-[3]. The current document presents the last part of the study, being a synthesis of the main findings from the three main parts of the study. Based on these findings, we formulate general operational guidelines for nitrogen injection in depleted Rotliegend gas reservoirs and recommendations for possible follow-up work.

2 Main findings

A large number of analogue field cases of injection-induced seismicity which have been related to waste water disposal, secondary oil and gas recovery, underground gas storage, geothermal projects and hydraulic stimulation for shale gas production were studied in literature. Analysis of these field cases indicates that in most cases the main underlying mechanism of induced seismicity is pore pressure diffusion (in reservoir and along fault planes) and the increase of pore pressures above virgin reservoir pressures, which results in the reactivation of critically stressed faults and related seismicity. Since the main purpose of nitrogen injection into a seismically active depleting gas reservoir is the mitigation of seismicity by pressure maintenance, pore pressures are not likely to increase above virgin reservoir pressures. Still, the mechanism of pore pressure increase in the faults is of relevance to nitrogen injection into a seismically active producing reservoir, as faults in the reservoir are expected to be critically stressed below original reservoir pressures. Literature study also shows that due to pore pressures diffusing downwards, deeper fault segments outside the reservoir can be reactivated. Other potential mechanisms which are (less frequently) mentioned in literature and which can be of relevance to nitrogen injection-induced seismicity are the

- adverse effect of thermal stresses caused by injection of fluids below ambient reservoir temperatures,
- irreversibility of stress paths during production and injection, and
- stress transfer caused e.g. by fault slip and differential (de)compaction in the reservoir.

2.1 Pore pressure diffusion into faults

In case of nitrogen injection into a depleted reservoir, pore pressures can only diffuse into the faults outside the reservoir when such faults are also depleted. Local increases of pore pressures in faults within a high permeability reservoir (like the Rotliegend sandstone reservoirs) due to injection into or close to these faults are not expected to occur, as pore pressures will quickly dissipate into the surrounding rocks. When deformation of the reservoir rocks is dominated by poro-elastic processes and differential pressures over the faults are small, stress paths on faults within the permeable reservoir are largely reversible during production and injection. Geomechanical modelling shows that for those conditions fault segments within the permeable reservoir rocks which were reactivated (and potentially seismically active) during first-time depletion will re-stabilize during injection. When nitrogen is injected into or close to a fault segment hydraulically connected to the reservoir but embedded in low-permeability rocks, pore pressures within these fault segments can locally be raised above pore pressures of the surrounding, less permeable strata. Geomechanical modelling shows that, although fault segments in permeable reservoir rocks stabilize during injection, fault segments which are already critically stressed during first-time depletion and are embedded in less permeable rocks remain critically stressed during the injection phase. However, fault movements which occur on the fault segments in less permeable rocks during the injection phase are very small compared to the fault movements during the depletion phase. Moreover, for faults critically stressed during the depletion phase, the total slip lengths decrease during the injection phase. Hence, under the assumption that total slip lengths can be used as a proxy for induced seismicity, it can be concluded that in a reservoir where poro-elastic processes dominate and where faults are already critically stressed during the depletion phase, the mechanism of pore pressure diffusion during injection does not cause an increase of induced seismicity potential.

Faults with little to no offset, which are embedded in low-permeability rocks and which are not yet critically stressed during the depletion phase show a different response during the injection phase. Fault segments bounded by the low-permeability rocks (such as the Ten Boer clay) show an increase in shear capacity utilization during injection. Although in the modelled scenario of a fault dip of 75^0 failure was not reached during injection, injection can possibly initiate a first reactivation and slip on fault segments with more critical orientations. The latter scenario is recommended to be subject of further analysis.

2.2 Thermal stresses

In a number of literature cases, seismicity could be related to thermal stressing caused by the cooling of the rocks due to injection of fluids at temperatures below ambient reservoir temperatures. This mechanism also plays a role when large amounts of nitrogen are injected into the reservoir at injection temperatures below ambient reservoir temperatures. Geomechanical modelling shows that temperature effects can have a significant impact on fault stability. For the case of nitrogen injected at temperatures of 10 ^{0}C for a period of 20 years, models show that the seismicity potential of the faults within a distance of 500 m of the injection well will increase. These temperature effects and their negative impact on fault stability can be reduced by heating the nitrogen close to reservoir temperatures.

2.3 Stress path irreversibility

A further mechanism mentioned in literature which leads to an increase of the seismicity potential of faults is the difference in reservoir stress path during reservoir production and re-pressurization. This difference results from a significant amount of plastic deformation during first-time depletion of a reservoir, which cannot be recovered during injection and first-time re-pressurization of a reservoir. Geomechanical modelling shows that fault slip displacements and lengths of slip patches increase during injection when large differences in reservoir stress paths during production and re-pressurization occur. When fault slip displacement and total fault slip length are used as indicative estimates for the induced seismicity potential of the faults, it is concluded that stress path irreversibility due to plasticity in the production phase can have an adverse effect on the seismicity potential of the faults during injection. Literature data indicate that some amount of plastic deformation in reservoir sandstones is expected during first-time reservoir depletion. Study of the Dutch injection field cases on the other hand shows that only very limited seismicity was observed during first-time re-pressurization for Underground Gas Storage (UGS) operations in the depleted Norg, Grijpskerk and Bergermeer Rotliegend fields. For all these three fields faults were already critically stressed and therefore seismically active during the production phase. Pressure fluctuations in the UGS operations in these fields are much larger than anticipated for nitrogen injection (aiming at pressure maintenance). The absence of significant seismicity in these three fields during the re-pressurization phases of the UGS operations can be interpreted as an indication that, for Rotliegend sandstone reservoirs, the effect at reservoir scale of differences in stress path coefficients during production and injection on fault stability is limited.

2.4 Differential pressure evolution and effects of stress arching

Geomechanical modelling results show that the effects of differential pore pressures (resulting from simultaneous production and injection), related differential compaction and stress arching on fault stability are negligible. Though differences in pore pressures can evolve in a producing reservoir in which pore pressures are maintained by local injection, pressure gradients are generally expected to be small, and related stress arching effects are very small, in case of injection for pressure maintenance. The effect of differential pore pressures caused by a dispersed production and injection on fault stability is therefore expected to be negligible.

2.5 Concluding remarks

In general, geomechanical modelling shows that when plastic deformation during first-time depletion of the field is expected to be limited (i.e. predominantly poro-elastic reservoir deformation during depletion) and thermal effects are sufficiently mitigated, injection and pressure maintenance has a positive effect on fault stability, as the total slip lengths decrease during injection. In such a case injection for pressure maintenance is expected to be an efficient strategy for mitigating seismicity. On the other hand, when plastic deformation is expected to strongly affect the stress paths during first-time depletion and/or thermal effects are not sufficiently mitigated, nitrogen injection can cause an unwanted increase of the induced seismicity potential of a field.

3 General guidelines and recommendations

In a number of publications mitigation options for injection-induced seismicity are proposed. In [4] and [5] the importance is emphasized of avoiding injection into or close to permeable active faults. As concluded in our study, reactivation of permeable active faults within the reservoir rocks itself is not very likely but the stability of fault segments in low permeable rocks which are depleted during production can locally be adversely affected when injection occurs in close vicinity of these faults. Large pressure increases should therefore be avoided in areas where faults are expected to extend upwards or downwards into less permeable layers which are potentially depleted during production.

Temperature effects can be reduced by injecting nitrogen at temperatures close to ambient reservoir temperatures. Additional field-specific research is recommended to determine and optimize the specific injection temperatures to mitigate seismicity due to temperature effects. Such research will have to involve dynamic reservoir models which take into account the effects of compression and expansion (so-called Joule-Thomson effect) of the gas on the spatial and temporal evolution of temperatures and pressures around the injection well.

The adverse effects of stress path irreversibility due to plastic deformation of the reservoir rocks during first-time depletion on fault stability and seismicity potential are less easily mitigated than temperature effects. When stress path irreversibility due to plastic deformation in the depletion phase is anticipated, large build-up of pore pressures is to be avoided in regions in which most plasticity and related stress path irreversibility during production and injection is expected (e.g. in regions of less consolidated, high porosity rocks). At this stage, too little data on stress paths during production and injection is available to conclude whether significant stress path irreversibility is expected in Rotliegend gas reservoirs. The absence of significant seismicity during the re-pressurization phases of the UGS operations in three Rotliegend reservoirs seems to indicate that at reservoir-scale the effect of differences in stress path coefficients during production and injection on fault stability is limited. However, we emphasize that differences between individual fields can be very large and mechanisms of fault reactivation are in most cases still poorly understood, which means we should not over-interpret observations from analogue injection field cases. More data on material and reservoir-scale behavior during re-pressurization from experimental work and data from field observations and field tests are needed to assess the potential of injection-induced seismicity due to stress-path irreversibility.

As the general aim of nitrogen injection is to mitigate seismicity caused by ongoing production, nitrogen injection should result in pressure maintenance at the location of faults seismically active during the production phase. However, to avoid injection-induced seismicity on such faults which are already critically stressed due to production, significant increases in pressures at these fault locations should be avoided. This applies especially for those areas where faults are expected to be embedded into less permeable rocks (like the Ten Boer clay and other clay layers which are expected to be depleted during the production phase) and for areas in which much plastic deformation during the production phase is expected (e.g. high porosity areas, which can be related to high compaction areas). A general ‘safe’ distance between the injection wells and faults cannot be specified and has to be determined based on field-specific data. Furthermore, it has to be noted that in literature a number of injection-induced seismicity cases related to the reactivation of previously undetected faults have been described. As in general faults with no or little offset will not be detected from seismic data, injection close to such faults cannot always be avoided.

Other measures which may be considered for mitigation concern:

- pumping at lower pressures for longer injection periods and slowly building up the injection pressures, and as well injection into a sufficient number of wells, in order to avoid strong local pressure build up near the injection wells.
- installation of (seismic) real-time monitoring to facilitate monitoring of the pressure evolution and related seismic response of the reservoir.

Before implementation of nitrogen injection at full reservoir scale, a field test may be considered as to give first insights in the reservoir’s evolution of pressures and related seismic response.

4 References

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