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TNO report

TNO-034-UT-2009-00171/B

Effects of differential pressures across the central Bergermeer fault

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No. of copies	5
Number of pages	13
Number of appendices	0
Customer	TAQA Energy BV
Projectname	TAQA Bergermeer seismicity
Projectnumber	034.82130

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1 Introduction

During the operation of the Bergermeer field as a Gas Storage facility, the aim of the operator, TAQA Energy BV, is to maintain a negligible differential pressure across the, during depletion seismically active, central fault of the field. However, during depletion the largest differential pressure across the central fault has been 20 bars, with the western compartment maintaining a higher pressure compared to the eastern compartment. This pressure difference has been adopted as the limiting differential pressure during the seasonal storage operation.

Pressure differences across the fault can increase the stresses on the fault and may promote induced seismicity. The aim of this study is to investigate the geomechanical response of reservoir and fault to differential pressures across the Bergermeer central fault and it's impact on seismic hazard and provide the operator with answers to the following questions:

- What is the influence of a differential pressure on the geomechanical behaviour of the central fault?
- What are the risks of a further increase in the pressure difference across the fault?
- What is the highest safe pressure difference across the fault in case the pressure in the eastern block is lower than the pressure in the western block (injection)?
- What is the highest safe pressure difference across the fault in case the pressure in the eastern block exceeds the pressure in the western block (production)?

A short description of the method used to analyse the impact of the differential pressures across the central fault and the results of the analysis are presented. In chapter 3 of the report the main conclusions are presented and the above questions are addressed.

2 Geomechanical analysis

2.1 Method

In order to investigate the response of the fault to differential pressures, the DIANA cross section constructed for the Bergermeer Seismicity Study (TNO report 2008-U-R1071/B) is used. The state-of-stress and temperature field at the end of the injection period computed in the Bergermeer Seismicity Study is used as input data for the current study. Geomechanical parameters of reference scenario 1 (TNO report 2008-U-R1071/B) are used. Relative shear displacements and corresponding potential earthquake magnitudes calculated when pressure differences are introduced can be compared with displacements and potential magnitudes calculated for the reference scenario (negligible pressure difference).

High pressures in the western block at the end of injection
The effect of a relatively high pressure in the western compartment as compared to the eastern block is studied. In the analysis, the pressure in the eastern block is fixed at an average value of approximately 133 bars (i.e. lowest compartment pressure in the eastern block at the end of the injection stage, in the reference scenario). The pressures at the western block are taken from this stage and increased to an average value of 150 bars, 170 bars and 180 bars. Relative shear displacements and stress paths are analysed and compared with the relative shear displacements and stress path at the end of the injection stage in the reference scenario of the former analysis, which has been described in TNO report 2008-U-R1071/B. The maximum pressure difference across the fault in the reference scenario, at the end of injection is approximately 3 bar (June 2013, see **Table 1**).

Low pressures in the western block at the end of production
Next the effect of a relatively high pressure at the end of production in the eastern block as compared to the western block is analysed. The pressures in the eastern block will be fixed at an average value of approximately 88 bars (approximately highest compartment pressure at the end of the production stage in the eastern block in the reference scenario). The pressures in the western compartment will be taken from this stage and decreased to approximately 80 bars, 60 bars and 40 bars. Again, relative shear displacements and stress paths will be analysed and compared with the relative shear displacements and stress path at the end of the production stage in the reference scenario of the former analysis (TNO report 2008-U-R1071/B). The maximum pressure difference across the fault in the reference scenario, at the end of production is approximately 8 bar (September 2013, see **Table 1**).

2.2 Results

High pressures in the western block at the end of the injection period

In the reference scenario (TNO report 2008-U-R1071/B) some plastic fault slip was observed on the central fault of the reservoir, just above and below the juxtaposition of the reservoir rocks (see **Figure 1** for location of fault slip in reference scenario).

Table 1: Pressure distribution (in bars) around Bergermeer's central fault both at the top and bottom of the reservoir blocks in the reference scenario (memo TAQA, d.d. ..). The pressure difference in the last column presents the difference between the top of block II (western block) and the bottom of block I (eastern block) , hence the reservoir segments that touch in the DIANA model.

		Block II		Block I		pressure diff
Month	year	top	Bottom	top	Bottom	right-left
AUG	2009	19,97	47,59	10,26	22,47	2,5051
MAY	2010	20,61	49,55	16,27	27,56	6,95
NOV	2010	40,66	68,06	45,56	55,95	15,29
MAY	2011	36,57	64,92	45,02	55,37	18,80
NOV	2011	67,80	95,15	72,57	82,65	14,85
MAY	2012	62,52	90,58	71,83	81,94	19,43
DEC	2012	84,90	112,24	88,69	98,91	14,01
APR	2013	98,00	126,37	108,50	118,92	20,93
JUN	2013	141,24	168,34	133,65	143,89	2,65
SEP	2013	97,53	123,77	78,73	89,66	7,87-

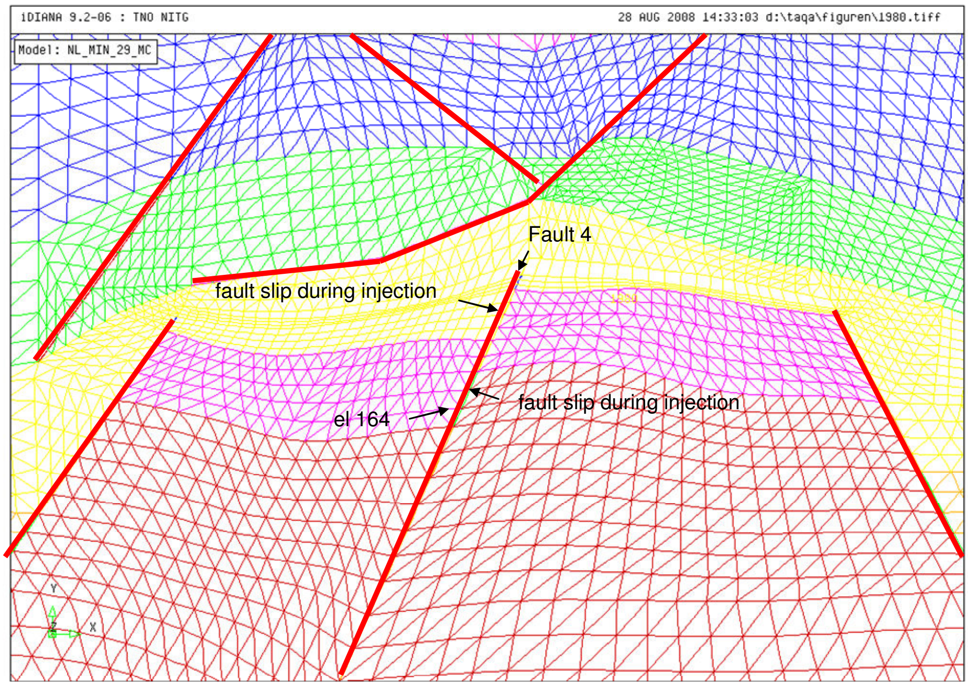


Figure 1: Location of maximum fault slip during injection, on central fault intersecting the reservoir. Reservoir rocks are indicated in pink colours. Also indicated the location of fault element 164. From: TNO report 2008-U-R1071/B.

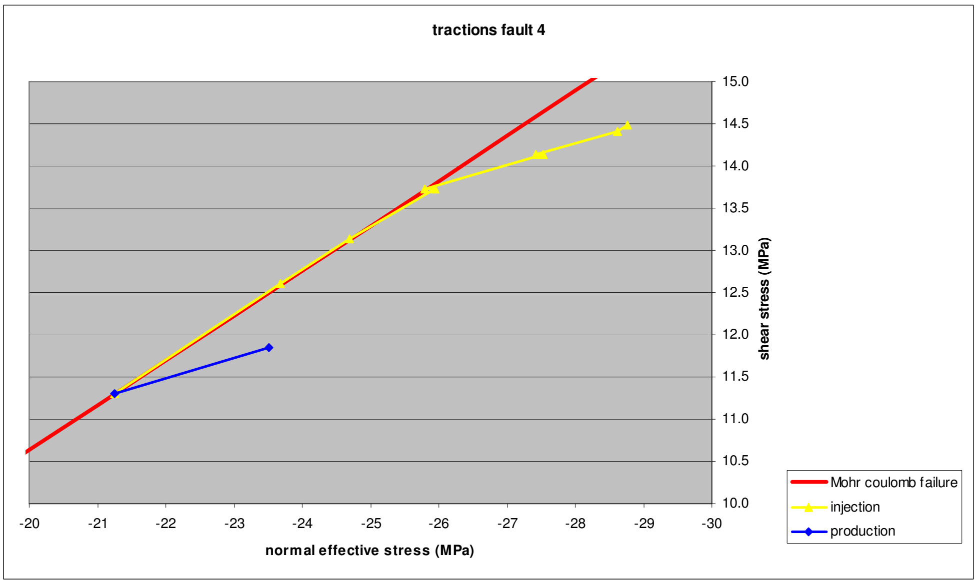


Figure 2: Stress path during injection and production in fault element 164 below the juxtaposition of reservoir rocks. From TNO-report 2008-U-R1071/B.

As can be seen from **Figure 2** the stress path coincides with the Mohr Coulomb failure surface during injection (the stress path touches the MC failure surface in november 2011 and May 2012 during the end stage of cushion gas injection). Relative shear displacements between the start of injection and end of injection are given in **Figure 3** (green curve for reference scenario). Relative shear displacements for the reference scenario amount up to 4mm for the fault area below the juxtaposition of reservoir rocks. The modelled relative shear movement for the reference scenario corresponds to a seismic event with a magnitude M=2.6. From the stress paths given in **Figure 4** it can be seen that for higher pressures of 150, 170 and 180 bars in the western block at the end of injection, also fault slip is expected. The amount of relative shear displacement increases when the pressure in the western block at the end of injection is increased (see **Figure 3**). The effects of the pressure increase is most pronounced in the fault area below the juxtaposition of reservoir rocks (see **Figure 3**). For a pressure increase up to 150, 170 and 180 bars relative shear displacements increase from approximately 4mm to 6.5mm to 8.5mm resp. In terms of seismic hazard, the modelled relative shear displacements correspond with events of resp. maximum magnitudes of M=2.6, M=2.8 and M=2.9 (see **Table 2**).

Table 2: Mean displacement (δ_{mean}) and maximum displacement (δ_{max}) over the fault width for different pressures in the western reservoir compartment from DIANA and their maximum seismic magnitude for the internal fault in the reservoir.

Pressures	δ_{max} (cm)	M	δ_{mean} (cm)	M	fault width (m)
Reference injection	0.4	2.6	0.1	2.6	100
150 bar	0.4	2.5	0.1	2.6	100
170 bar	0.7	2.8	0.2	2.7	150
180 bar	0.8	2.9	0.2	2.7	150
Reference production	<0.1	none	<0.1	none	100
40 bar	0.3	2.6	<0.1	2.5	150
60 bar	0.1	2.3	<0.1	2.3	150
80 bar	<0.1	2.2	<0.1	2.2	250

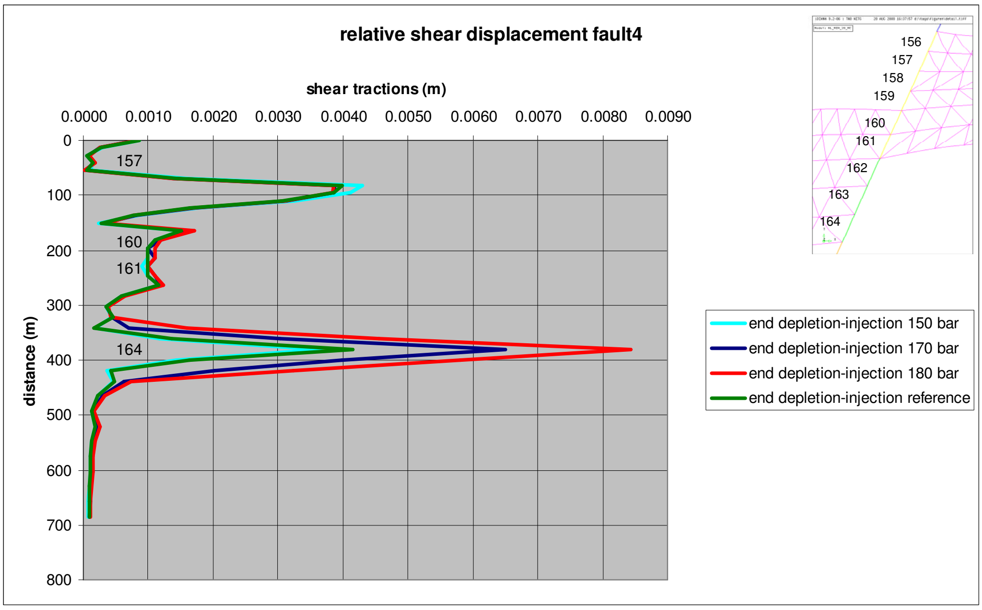


Figure 3: Relative shear displacements during injection up to pressures of 150, 170 and 180 bars in the western block. For comparison, also relative shear displacements in the reference scenario are presented (green curve).

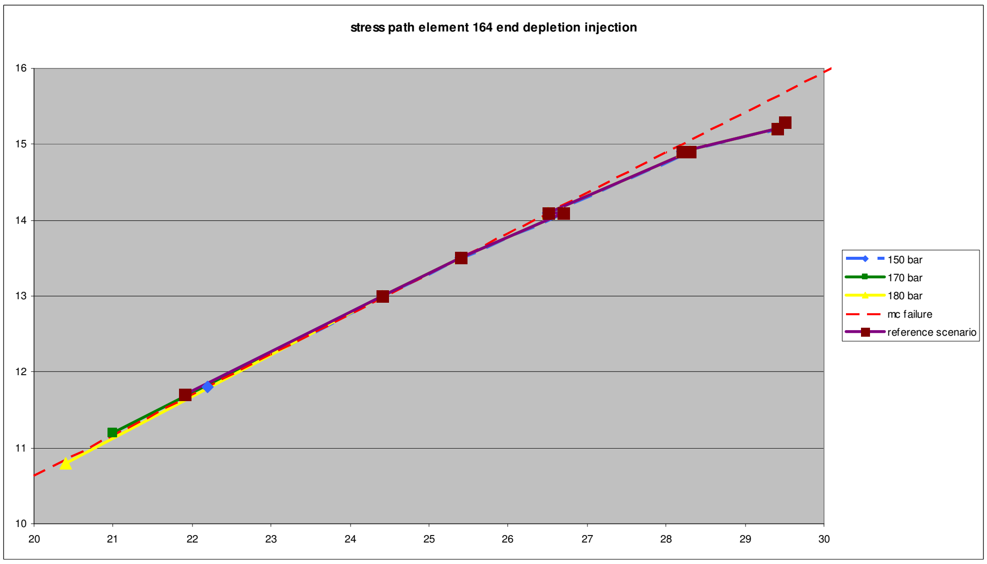
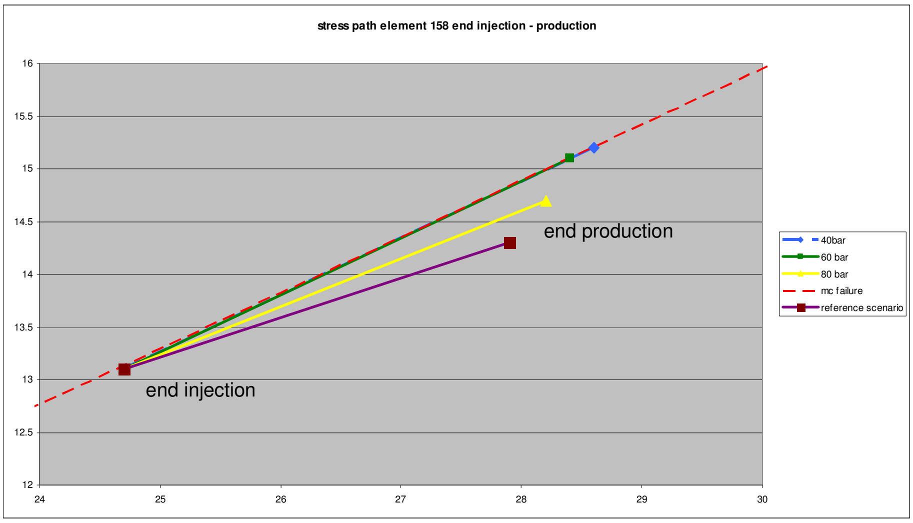
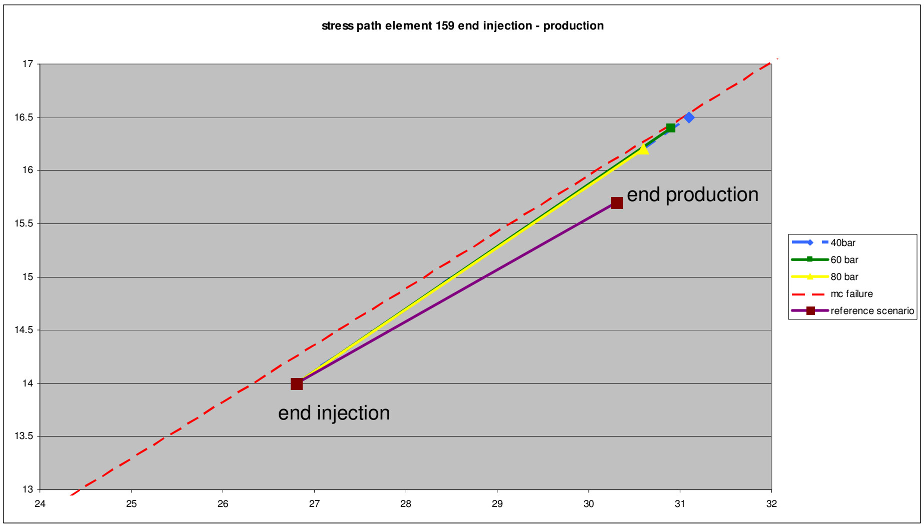


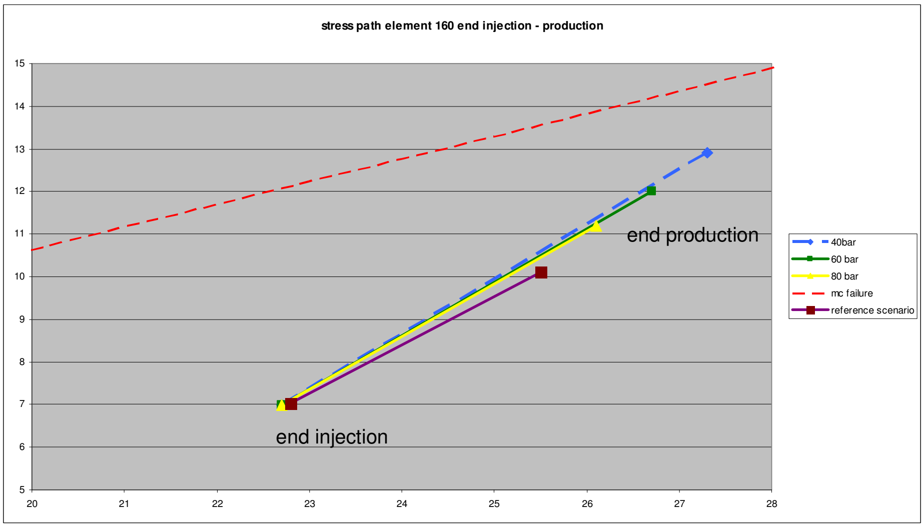
Figure 4: Stress path in fault element 164 for pressures of 150, 170 and 180 bars in the western block. Also presented is the stress path for the reference scenario.



a.



b.



c.

Figure 5: Stress path during production for a) fault element 158 b) fault element 159 and c) fault element 160.

Low pressures in the western block at the end of production

In the reference scenario (TNO report 2008-U-R1071/B) no plastic fault slip was observed on the central fault of the reservoir during production. However, from **Figure 5**b it can be observed that during production on the juxtaposition of reservoir rocks (fault element 160) the stress path in the reference scenario converges on the Mohr Coulomb failure line. As pressures in the western reservoir compartment are decreased to 80, 60 and 40 bars, the risk of seismicity during production increases. **Figure 5**a, b and c show the stress paths from the end of injection towards the end of production for the reference scenario and for a pressure decline to 80, 60 and 40 bars in the western block. For a pressure decline to 60 and 40 bars the stress state at the end of production lies on the Mohr Coulomb failure line in fault elements 158 and 159 (see **Figure 5**a and b, see **Figure 3** for location of fault elements). For a pressure decline to 80 bars the stress state at the end of production lies on the Mohr Coulomb failure line in fault element 159. **Figure 6** shows the relative shear displacements on the central fault for the reference scenario and pressure declines to 80, 60 and 40 bars. The increase of the relative shear displacements is mainly observed on the fault area above the juxtaposition of reservoir rocks. Relative shear displacements for 80 bars are less than 1 mm, maximum relative shear displacements for 60 bars are 1.3mm and maximum relative shear displacements for 40 bars are approximately 3 mm. The modelled shear displacements for 80, 60 and 40 bars correspond to seismic events of resp. maximum magnitudes of M=2.2, M=2.3 and M=2.6 (**Table 2**).

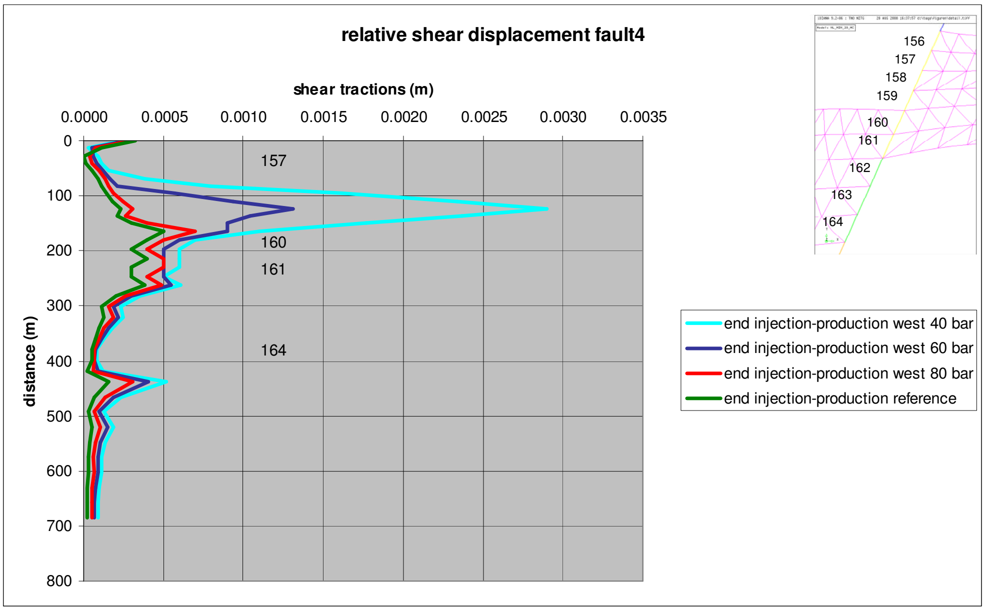


Figure 6: Relative shear displacements on central fault for pressures of 40, 60 and 80 bars in the western block during production. Reference scenario also shown.

3 Conclusions and recommendations

The aim of this study is to model the geomechanical response of reservoir and fault to differential pressures across the Bergermeer central fault and it's impact on seismic hazard. In order to investigate the influence of a pressure difference across the central fault, pressure differences are introduced by increasing pressures in the western block during injection and lowering the pressures in the western block during production. Relative shear displacements and stress paths are analysed and magnitudes of potential earthquakes are quantified. Results are then compared with the relative shear displacements, stress paths and potential earthquake magnitudes during injection and production, calculated for the reference scenario (described in TNO report 2008-U-R1071/B).

- What is the influence of a differential pressure on the geomechanical behaviour of the central fault?

In all modelled cases an increase of the differential pressures across the central fault causes an increase of the maximum plastic fault slip along the central fault.

- What are the risks of a further increase in the pressure difference across the fault?

For the reference scenario (negligible pressure difference) a magnitude of M=2.6 was calculated for the first period of injection and no induced seismicity was predicted for the production stage (one cycle only).

When pressure differences are introduced across the central fault, seismicity may occur during both injection *and* production. It is not possible to quantify the frequency of seismic events. For pressure differences across the central fault, modelled relative shear displacements correspond to magnitudes between M=2.2 and M=2.9. Hence, in terms of the magnitude of the events that can be expected, the impact of an increase of differential pressures across the central fault is relatively small. For comparison, the range of magnitudes due to the uncertainty in geomechanical parameters calculated in the former study (assuming a negligible pressure difference across the central fault) is M=2.4 – 2.7.

- What is the highest safe pressure difference across the fault in case the pressure in the eastern block is lower than the pressure in the western block (injection)?

Fault slip is already observed in the reference scenario, in which the pressure difference across the fault is negligible, which means we cannot define a highest safe pressure difference.

Fault slip increases with increasing pressures in the western reservoir compartment at the end of the injection stage. Fault slip increases from 4mm for the reference scenario (negligible pressure difference over the central fault) to 8.5mm for a maximum pressure of 180 bar in the western reservoir block. Taking into account the dimensions of the central fault, a maximum fault slip of 4mm (reference scenario) corresponds to a seismic event of magnitude M=2.6; a fault slip of 8.5 mm corresponds to a seismic event of magnitude M=2.9.

- What is the highest safe pressure difference across the fault in case the pressure in the eastern block exceeds the pressure in the western block?

In the reference scenario, no significant pressure difference exists across the central fault. Though no fault slip is predicted in the reference scenario during production, the stress state during production converges to the Mohr Coulomb failure line. In the reference scenario only one injection-production cycle was modelled. We cannot exclude the possibility of fault slip during subsequent cycles of production, hence we can not conclude maintaining a negligible pressure difference during production is 'safe'.

Fault slip in the models does occur when pressures in the western reservoir compartment are decreased during production and pressure differences are introduced. The models show that even a small decrease of pressures in the western block (up to 80 bars) results in fault slip along the central fault. Maximum calculated fault slip for 80, 60 and 40 bars, resp., are less then 1mm, 1.3mm and appr. 3 mm. These modelled fault slips correspond to seismic events of magnitudes between M=2.2 and M=2.6.

4 References

Muntendam-Bos, A.G., B.B.T. Wassing, C.R. Geel, M. Louh, K. van Thienen-Visser, Bergermeer Seismicity study, 2008, TNO report 2008-U-R1071/B.

5 Signature

Utrecht, January 2009 TNO Built Environment and Geosciences

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