Seismic Hazard Screening (SHS): Area of Influence

Version 2.1

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Samenvatting

Introductie

Het Ministerie van Economische Zaken en Klimaat heeft EBN en TNO verzocht een nieuwe methode op te zetten om het risico op seismiciteit in te schatten voor geothermieprojecten in Nederland. Een van de eerste stappen in deze methodologie is het definiëren van het invloedsgebied (Area of Influence, AoI) van een geothermiesysteem. Deze AoI behelst het gebied rondom het geothermieproject dat zodanig beïnvloed wordt door het produceren en injecteren van water dat breuken die zich in dit gebied bevinden kunnen gaan schuiven. In voorliggend rapport is een methode opgesteld waarmee de grootte en vorm van dit gebied kan worden bepaald voor een specifiek project.

De nieuwe Seismic Hazard Screening (SHS) methode zal bestaan uit een aantal kernelementen. Dit rapport beschrijft het voorgestelde ontwikkelingsproces, de methode en de resultaten voor één van deze kernelementen: het definiëren van grote, relevante breukzones. Uiteindelijk wordt dit kernelement gecombineerd met andere kernelementen en door EBN en TNO-AGE samengevoegd tot één nieuwe SHS-methode. In dit samenvoegingsproces kunnen wijzigingen worden aangebracht in de methoden, drempelwaarden en/of resultaten ten opzichte van de afzonderlijke kernelement rapporten. De methoden, waarden en resultaten die in het huidige rapport worden beschreven, moeten daarom als voorlopig worden beschouwd.

Werkwijze

De methode voor het definiëren van de AoI is bepaald volgens de volgende stappen:

1 Het bepalen van de relevante parameters voor het risico op “shear failure” voor de injectie- en de productieput.
2 Het vergelijken van verschillende analytische methodes die gebruikt kunnen worden om de temperatuurverandering in het reservoir en de grootte van het thermisch beïnvloede gebied te bepalen. Op basis hiervan is de beste methode voor de uitwerking in deze studie gekozen.
3 Het bepalen van de drempelwaarden voor druk- en temperatuurverandering in het reservoir.
4 Het opzetten van een model dat de relevante effecten in het reservoir (druk/temperatuur) berekent voor een geothermieproject op het moment van thermische doorbraak.
5 Het berekenen van de grootte van het gebied rondom de putten waarbij deze drempelwaarden overschreden worden: de AoI.
6 Het opzetten van een geometrische routine om deze AoI te bepalen.

Bepaling methode

Op basis van de resultaten van de resultaten van de kern-element studie naar het breukreactivatie potentieel (PanTerra & IF-Technology, 2021) is geconcludeerd dat voor de injectieput de temperatuurverandering de relevante parameter is. Voor de productieput wordt extra rekening gehouden met de drukverlaging. Op basis van de vergelijking van de analytische methoden is bepaald dat de methode van Lauwerier (1955) geschikt wordt geacht om het temperatuurprofiel rondom de injectieput mee te berekenen. Deze methode geeft onder de meeste condities de grootste en dus meest conservatieve AoI en berekent een gedetailleerd temperatuurprofiel. Het moment van thermische doorbraak zal berekend worden op basis van Lippmann & Tsang (1980).

Invloedsgebied rondom de injectieput

Op basis van analyses in PanTerra & IF-Technology (2021) is geconcludeerd dat de grens van het thermische invloedsgebied rondom de injectieput bij een temperatuurdaling van 0^{o}C gelegd wordt. Dit is de meest conservatieve benadering met betrekking tot het invloedsgebied dat “shear failure” kan veroorzaken. Om het gebied rondom een put uit te rekenen waarvoor dit geldt is een model opgezet. Dit model is gerund voor verschillende zogenoemde “reality cases”. Op basis hiervan is geconstateerd dat de straal van het gebied rondom de injectieput gesimplificeerd kan worden tot de volgende relatie:

$$Straal\ AoI\ injectieput\ [m] = putafstand\ [m] * radius\ factor$$

Als conservatieve waarde kan 0.7 gebruikt worden. Deze waarde geldt bij een porositeit ≤30% en een debiet ≤1000 m3/h.

Invloedsgebied rondom de productieput

Uit PanTerra & IF-Technology (2021) volgt dat rondom de productieput een vaste straal van 300 m aangehouden kan worden. Dit is een conservatieve waarde waarvan verwacht wordt dat voor een conventioneel goethermisch project de invloed van de drukverlaging miniem wordt.

Tussenliggend gebied

Ook het gebied tussen de putten is onderdeel van de AoI: door de drukverlaging van de productieput trekt deze namelijk het geïnjecteerde water naar zich toe. Om deze gebieden mee te nemen in de AoI dienen raaklijnen getekend te worden langs de twee cirkels.

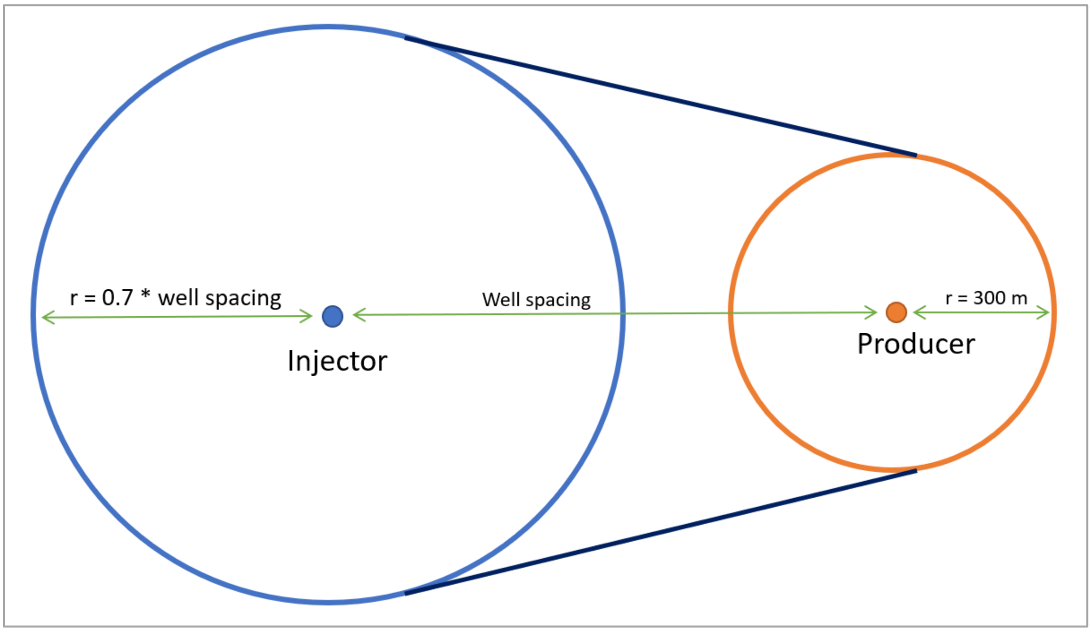


Figure 1-1 Voorbeeld van het construeren van de AoI.

Multiplets

Bij configuraties anders dan doublets kan de methodiek ook uitgevoerd worden. Dit kan door de werkwijze meerdere keren uit te voeren: één keer voor elke put. Alle cirkels en de gebieden tussen de cirkels samen vormen dan de AoI.

1 Introduction

The Ministry of Economic Affairs and Climate Policy has requested EBN and TNO to develop a new method to assess the seismicity risk for onshore geothermal projects in the Netherlands. One of the first steps in this method is to adequately define the Area of Influence (AoI) of a geothermal project. This area should comprise the area around the geothermal project (at reservoir level projected to the surface) in which faults and fractures might slip as a result of the production and injection of geothermal water. It will act as the starting point in further steps of the Seismic Hazard Screening (SHS).

The new Seismic Hazard Screening (SHS) method will consist of a number of key-elements. This report describes the suggested development process, method and results for one of these key elements: the definition of relevant major faults. Eventually, this key-element will be combined with other key-elements and merged into a single, new SHS method by EBN and TNO-AGE. In this merging process, changes may be made to the methods, values and results as described in the individual key-element reports. The methods, values and results described in the current report should therefore be regarded as preliminary.

One of the other key-elements referred to is the fault reactivation potential. This has been addressed in PanTerra & IF-Technology (2021) with the development of a screening tool for fault reactivation under changes in temperature and pressure change as a result of operation of a geothermal doublet.

The reported work has been carried out as a “development of a simple, geometrical routine to establish the AoI of a geothermal system”, within a programme of studies that was carried out under supervision of TNO-AGE and EBN. The results of the work packages will be combined into the new Seismic Hazard Screening methodology. One of the other work packages that is referred to in this report is in the fault reactivation potential study, in which a tool was developed for indicative calculations on the fault reactivation potential created by changes in temperature and pressure as a result of geothermal production and injection.

In the current seismic hazard assessment methodology (IF Technology & Q-con, 2016) the AoI is not assessed and risks are related to a fixed distance with respect to the geothermal wells. However, the AoI is not constant in size, and depends on both the reservoir properties and the operational settings. Therefore, in order to get a better understanding of the area influenced by a specific geothermal project, it was proposed by TNO and EBN in 2021 (Mijnlieff & Jaarsma, 2021) to capture the region of changed stress in the subsurface in an adequate manner. A simple routine that can be used to define the AoI of a geothermal system at thermal breakthrough is presented in this report.

1.1 WORKFLOW

The development of a routine to define the AoI of a geothermal project has been carried out along the following steps:

1. Determining the relevant parameters for determining the risk on shear failure for both the injection well and the production well.
2. Comparison of various analytical methods that can be used to determine the temperature change and the thermally affected area in a geothermal reservoir, and selecting a method to be used in this study.
3. Determining the threshold values for pressure and temperature change in the reservoir for fault reactivation (see WP09).

4 Setting up a model that calculates the relevant effects (pressure/temperature) of a geothermal project in the reservoir at the moment of thermal breakthrough.
5 Calculate the AoI around the wells in the geothermal system which experience the threshold values for pressure and temperature changes.
6 Provide a geometrical routine that creates the above AoI.

2 Analytical methods

2.1 INTRODUCTION

All geomechanical models consider five types of assumptions, namely i) geometrical assumptions, ii) constitutive relationships (which includes mechanical failure), includes failure criteria), iii) initial and boundary conditions, iv) loading conditions, and v) an operational evaluation metric . Geometrical assumptions comprise the layering and structure of the subsurface, the location and trajectories of wells, the location and orientation of faults and the orientation and spacing of fracture networks. For geothermal operations, constitutive relationships comprise mechanical behaviour (I.e. linear-elasticity theory described by Young's modulus and Poisson's ratio), thermal behaviour (specified by the thermal capacity and conductivity) and hydraulic behaviour (porosity, permeability, fluid viscosity, etc) and the coupling between these physical processes specified by parameters such as the thermal expansion, and fluid and bulk compressibility. The initial conditions include in-situ stress, pore pressure and temperature profiles as a function of depth, whereas loading conditions are typically expressed as temporal changes in any of these conditions in the wellbore and/or reservoir. It is imperative that the size of any model is chosen such that appropriate boundaries can be imposed for the evaluation of the coupled mechanical, hydraulic and thermal behaviour (e.g no displacement, zero heat flux, and no mass flow boundary conditions). Finally, an (operational) evaluation metric should be defined that discriminates between an acceptable and a not acceptable outcome of the geomechanical evaluation. This is often a strain- or deformation-related metric (e.g. a maximum compaction strain, maximum subsidence, fracture size, size of a slip patch etc). In this study an appropriate metric is determined for the “Area of Influence” (AoI). For instance, the evaluation metric can be expressed in terms of the (change in) temperature or pore pressure.

In this chapter, alternative modelling approaches are discussed in terms of the five types of modelling assumptions. Alternative evaluation metrics to define the AoI are discussed. The selected metric to define the AoI for geothermal operations in a level 1 screening motivated and associated limitations are given.

2.2 PRESSURE/TEMPERATURE

The results of the key-element study regarding fault reactivation potential (PanTerra & IF-Technology, 2021) have shown that, regarding the injector, pressure changes outside of the cold water front are not big enough to result in the reactivation of faults. The leading parameter in the area around the injection well is therefore the temperature change in the reservoir. Regarding the producer it is the other way around: since the temperature does not change for this well, the focus is on the pressure change. More on this in chapter 3.2 - Threshold values.

2.3 EVALUATION OF METHODS

First, the assumptions that most modelling approaches have in common are described. This set of assumptions is referred to as the default modelling approach. Subsequently, additional modelling features and associated assumptions relative to this default modelling approach are given for different methods.

Most analytical approaches consider (as default):

Geometry:	A horizontal, axi-symmetric reservoir with infinite radial extent and constant height at unspecified depth. An unspecified depth implies that an infinite (full-)space is assumed without free surface where boundary

conditions can be applied (referred to as an infinite half-space). The injection well is considered in the thermo-hydraulic model (the production well is ignored).

Formation properties: Isotropic and homogenous hydraulic and thermal convection-diffusion properties in the reservoir. No hydraulic or thermal diffusion into the cap rock or basement is taken into account, and also no poro-elastic stress response is considered.
Initial conditions: Constant temperature and pressure over the reservoir height
Loading conditions: Injection of an incompressible fluid at constant flow rate as a line source over the entire reservoir interval.

In chronological order, the differences relative to the default modelling approach are given for Lauwerier (1955), Lippman & Tsang (1980), Koning (1988) and Brigham (2000).

Lauwerier (1955), presented by Prats (1986)
Geometry: As in default modelling approach.
Formation properties: One-dimensional vertical heat conduction in cap rock and basement are taken into account, without hydraulic diffusion. Also considering discontinuities in fluid mobility (while ignoring one-dimensional vertical heat conduction in cap rock and basement) and providing a poro-elastic stress solution.
Initial conditions: Normal in-situ stress regime, with the smallest principal stress in horizontal direction, causing a vertical fracture to occur.

Loading conditions: Unrestricted flow between wellbore and reservoir.

Evaluation metric: Tensile failure defines fracture initiation to determine fracture initiation pressure in the wellbore.

Lippman & Tsang (1980)
Geometry: Production and injection wells are considered.
Formation properties: As in default modelling approach.
Initial conditions: As in default modelling approach.
Loading conditions: Flow rate in production and injection wells are the same.
Evaluation metric: Time to thermal break-through.

Koning (1988) (Koning, 1988)
Formation properties: As Lauwerier (1955), while also considering discontinuities in fluid mobility (while ignoring one-dimensional vertical heat conduction in cap rock and basement) and providing a poro-elastic stress solution.
Loading conditions: Unrestricted flow between wellbore and reservoir.
Initial conditions: Normal in-situ stress regime, with the smallest principal stress in horizontal direction, causing vertical fractures to occur.
Evaluation metric: Tensile failure defines fracture initiation to determine fracture initiation pressure in the wellbore.

Brigham (2000)
Geometry: Production and injection wells are considered.
Formation properties: As in default modelling approach.

Initial conditions: As in default modelling approach.
Loading conditions: Flow rate in production and injection wells are the same.
Evaluation metric: Well distance at given field life.

All modelling approaches assume horizontal and axi-symmetric hydraulic and thermal conduction-diffusion in an isotropic and homogenous reservoir. The main feature of Lauwerier is the additional heat (cold) loss to the cap rock and basement. Lippman & Tsang (1980) and Brigham (2000) consider the impact of a single production well by assuming similar pressure and temperature contours around the production well compared to the injection well.

Lippman & Tsang focus on the time to break-through, whereas Brigham provides the well distance for given field life. An important limitation of Lippman & Tsang and Brigham compared to Lauwerier is the assumption of a thermal front, which is specified by the radial distance from the injection well. The temperature change is assumed negligible further away from the injection well, and constant within thermally affected zone. Lauwerier provides a continuous temperature and temperature gradient as a function of the radial distance to the injection well.

Koning (1988) also evaluates the stress distribution around the injection well as a results of a cold injectant. This is essential when evaluating potential fracturing conditions - as Koning does - but also when considering induced seismicity that may occur along geological faults.

2.4 COMPARISON OF MODELS

The comparison of analytical methods is focussed on a comparison between Lauwerier (1955) and Brigham (2000) as far as the thermo-hydraulic modelling is concerned. This is possible, because Koning (1988) is following Lauwerier and the approach by Lippman & Tsang is identical to Brigham. In this study, the expressions given by Prats (1986) are used instead of Lauwerier, because some inconsistencies in Lauwerier (1955) are resolved. These two analytical methods have been compared to DoubletCalc 2D, a numerical method by TNO (TNO, DoubletCalc 2D 1.0 User Manual, 2015), and the so-called “Franse methode” (TNO, Bepaling begrenzing Winningsvergunning Aardwarmte, 2014). This is done by running a model in DoubletCalc 2D, and, using the same input, calculating the radius of the thermal front using the analytical methods Lauwerier. This has been done for several scenarios (Models) in which one or two input parameters are changed to see the impact on the radius of the thermal front. The varied input data and the corresponding results are given in Table 2-1. The other input parameters, kept constant in this analysis, are given in Chapter 6: Appendix 1.

A comparison of the various approaches shows that the radius of the thermal front is the largest when using Lauwerier (1955). The thermal front assumption by Brigham (and also Lippman & Tsang) consistently yields a smaller area of thermal influence, despite the fact that Lauwerier accounts for thermal diffusion in vertical direction. However, Lauwerier’s approach does not incorporate the production well, which may cause an under-estimation of the thermally affected zone. In extreme cases, with strong thermal breakthrough, the thermal radius might exceed the well spacing, as shown by model 6 in Table 2-1.

Table 2-1 Calculated radius of influence for various reservoir models and using various calculation methods after 30 years of operation.

Parameter	Unit	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Description		Base case	Very thin reservoir	Very high flow rate	High flow, thin res.	Large ΔT	Small well spacing
Thickness	[m]	100	70	100	70	100	100

Well spacing	[m]	1500	1500	1500	1500	1500	500
Temp. aquifer	[˚C]	80	80	80	80	100	80
Temp. injection	[˚C]	30	30	30	30	10	30
Well rate	[m³/h]	250	250	500	400	250	250
Radius of the thermal front (injector): ΔT= 0 ˚C							
DoubletCalc 2D (numerical)	[m]	580	680	780	820	600	550
Lauwerier (analytical)	[m]	612	730	791	925	612	612*
Brigham (analytical)	[m]	530	633	750	801	530	-
”Franse methode”	[m]	750	750	750	750	750	250

* Note that the well spacing is smaller than the area of influence: this means that thermal breakthrough has taken place.

2.5 PREFERRED METHOD

In order to calculate the size of the temperature front, Lauwerier (1955) is the preferred method for further calculations, because i) it provides the largest Area of Influence in most conditions, and ii) it provides a temperature profile rather than a piston-like thermal front, while also vertical thermal conduction is taken into account. The method by Lippmann & Tsang, which is similar to Brigham, is used to calculate the time of thermal breakthrough.

3 Model development

3.1 WORKFLOW

The goal of this project is to set up a simple geometrical routine that captures the area of influence (AoI) i.r.t. seismic activity around a geothermal project at the moment of thermal breakthrough. In order to come to a geometrical routine to determine the AoI, a series of models has been run to calculate the size of this AoI based on local reservoir properties and operational settings. The radius around the injection well has been determined based on the change in temperature, and the radius around the production well has been determined based on the change in pressure. The method consists of several steps:

1. Determining the threshold values for pressure and temperature change in the reservoir. This will be used to define the outline of the Area of Influence.
2. Calculate the timing of thermal breakthrough for a geothermal project.
3. Calculate the relevant effects (pressure/temperature) along a radial axis for a geothermal project in the reservoir at the moment of thermal breakthrough.
4. Derive the radius around a well that experiences the threshold values (Area of Influence, AoI). This is the geometrical shape covering the AoI.
5. Sensitivity runs for several reality cases and extreme cases.

This results in a geometrical shape which restricts the area within which fault reactivation is possible as a result of the geothermal system.

3.2 THRESHOLD VALUES

For the purpose of a seismic hazard screening, it is most important that the AoI reflects the area within which perturbations as a result of the geothermal operations are significant enough to potentially cause fault reactivation (and hence, induced seismicity).

3.2.1 Injector

The pressure and temperature changes required to cause shear failure have been determined in WP09. This study showed that for the injection well, the temperature effect that can result in fault slip stretches out further than the pressure effect. Therefore, it is decided that for determination of the AoI of a geothermal project, it is sufficient to consider the temperature effect. A depth-dependent relationship has been set up that calculates the ΔT required in order for a fault to slip. This “threshold” is defined as follows:

$$|A_T \Delta T| < \ 0.08533 \ \times \sigma_v' \qquad (1)$$

where A_T is the thermo-elastic constant, ΔT (= $T_{\text{reservoir}} - T_{\text{injection}}$) is the cooling and σ_v' is the initial vertical effective stress. Equation (1) is a special case of equation (5) in the WP09 report for the (conservative limit) case of a dimensionless fault offset equal to one, zero fault cohesion, (static) fault friction factor equal to 0.6, dip angle of 60° and ratio between initial horizontal and vertical effective stress equal to 0.45.

Using flow modelling, the area where the value of ΔT equals this formula can be determined, providing an area of influence based on fault slip. However, it was concluded that the calculated fault slip criteria is not appropriate to reflect the area of influence. Modelling of the temperature differential is subject to parametrization which would require a stochastic approach. This stochastic approach would then need to be treated conservatively resulting in a significantly larger

AoI than a deterministic approach. The safety margin applied on ΔT can be expected to reflect an AoI near-similar to the completely cooled down area. The conclusion taken from relation (1) is therefore that a ΔT = 0˚C border is a conservative estimate of the AoI and it is not necessary to consider the effect of pressure or poro-elastic stress outside the temperature influenced zone. For this reason it was decided the AoI will be at the edge of the cooled down area, where ΔT = 0 ºC.

3.2.2 Producer

The area around the producer is influenced by a negative change in pressure. The possibility of shear failure is regarded as low because 1) due to the limited extent of the pressure distortion the resulting poro-elastic stress change is minor and 2) the decrease in pressure has less impact on the normal stress as it effectively "shuts" the fault. Similarly to section 3.2.1 a "threshold" was determined for the pressure increase. See WP09 for detailed explanation. The formula is as follows:

$$\frac{|A_p \Delta p|}{\sigma_v'} < 0.4084 \qquad (2)$$

where the poro-elastic constant A_p = 0.7 and σ_v'-gradient is 0.116 bar/m. The resulting ΔP vs depth is given in Figure 3-1. For comparison, the maximum expected pressure decrease at the producer is given on the basis of the injection pressure of 0.135 bar/m (reflecting the injection protocol by SodM & TNO-AGE, 2013). This is well below the pressure threshold defined by (2), which indicates the pressure increase resulting in shear failure will not be reached for a conventional geothermal project. This is under the (conservative) assumption that the pressure decrease on the producing side is similar to the increase at the injector site. In reality, the lower viscosity at the producer will result in a smaller differential pressure, and the contrast would be even higher.

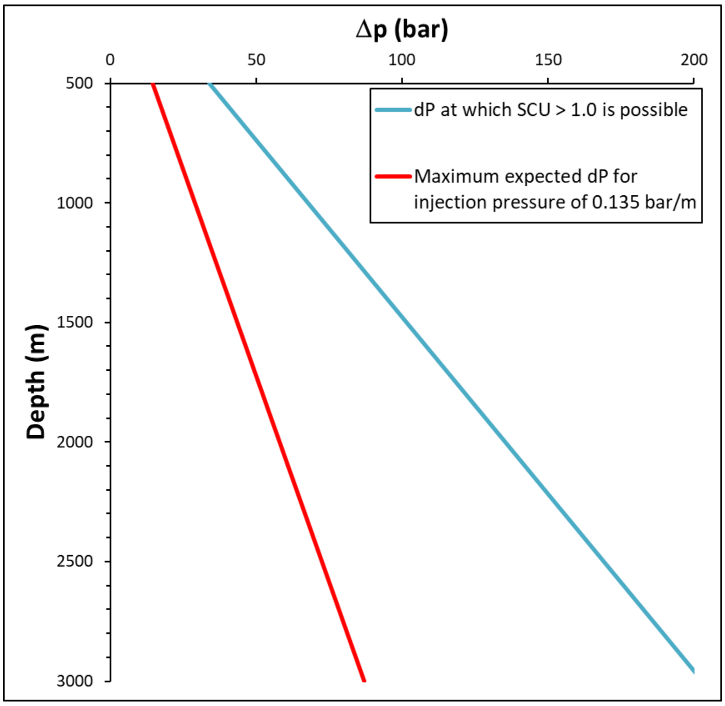


Figure 3-1 Differential pressure (blue) at which equation (2) yields "SCU" > 1.0 which here represents shear failure (See PanTerra & IF-Technology, (2021) for more thorough explanation).

3.3 PRESSURE DISTURBANCE DUE TO SHUT-IN

Diffusion of pore pressure causing post-injection seismicity and expansion of a seismic cloud after shut-in have been reported in other geothermal projects, e.g. in the Upper Rhine Graben and Pohang (TNO, 2019). It should be noted that these projects are not matrix-permeability systems. The impact of pressure disturbances within the reservoir as a result of water hammer following shut-in is expected to be limited. Typical water hammer effects can be sometimes severe within the wellbore and very near-wellbore area (van den Hoek, 2020) but such pulses do not penetrate deeply into the reservoir. This is illustrated for one pressure pulse with the amplitude of the stable borehole drawdown in Figure 3-2. This figure shows the pressures in response to one water hammer pulse of 10 seconds (this is the typical duration of a water hammer pulse, see van den Hoek, 2020). As can be seen, the maximum of the pulse quickly drops with increasing distance from the wellbore: at a distance of about 10 times the wellbore radius (typically 1 m), the maximum achieved is less than one percent of the drawdown.

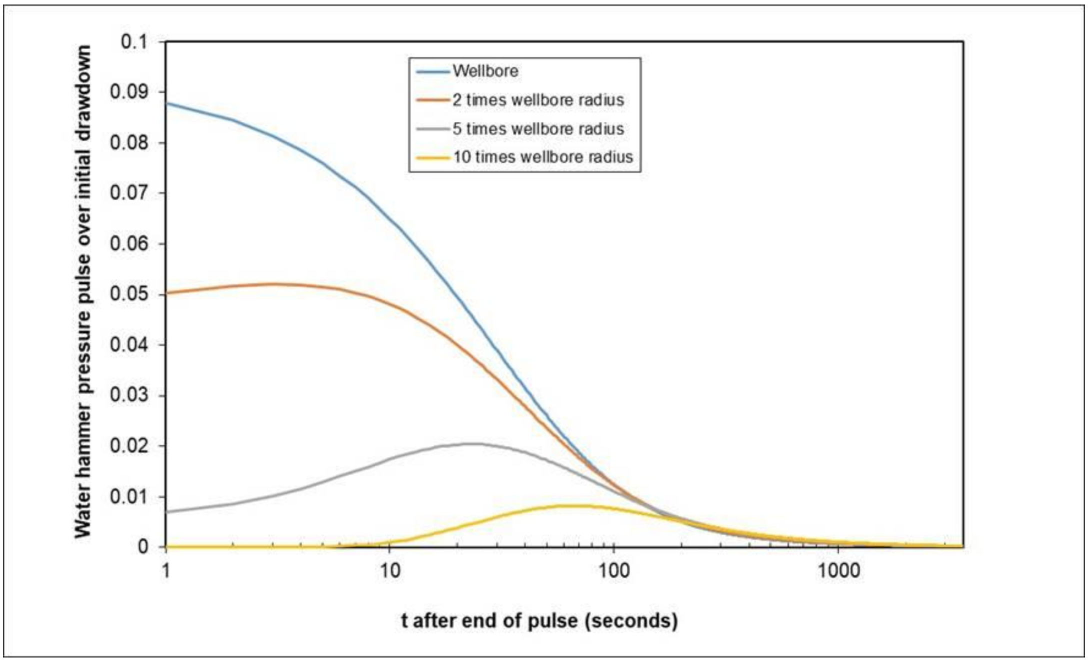


Figure 3-2 Pressure response to one water hammer pulse of 10 seconds (typical duration of a water hammer pulse). See text for explanation.

On the basis of the above it can be concluded that the differential pressure at the producer is not expected to cause significant differential pressure impacting fault reactivation for non-critically stressed faults. The area around the producer, however, should be appropriately buffered to limit the potential effect of the “hammer” as well as the largest differential pressure. Figure 3-3 presents the pressure profile expected for the case studies in Zuid-Holland, Noord-Holland and Centraal Nederland, and a theoretical case with 100 bar BHP at the injection well. The pressure profile is similarly constructed as in TNO’s DoubletCalc 1.4.3 (TNO, 2014). The largest differential pressure, as expected, is in the very-near vicinity of the well (0-5 m). The larger part of the logarithmic profile is already dissipated within the first 100 m. At 300 m, all pressure profiles indicate a pressure differential of 10 bar or lower. For this reason, the AoI of the producer is determined at a fixed radius of 300 m.

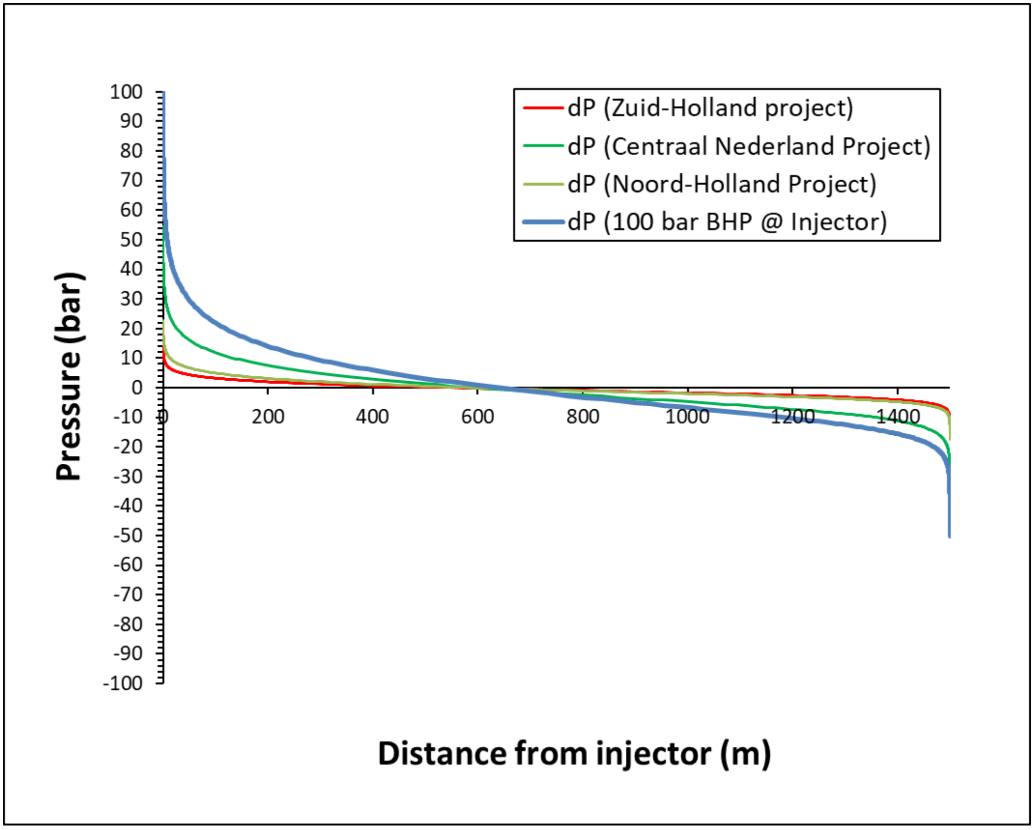


Figure 3-3 Logarithmic pressure profile between injector and producer

3.4 THERMAL BREAKTHROUGH

The moment of thermal breakthrough is calculated using the analytical method by Lippmann & Tsang (1980) (chapter 2). This method is based on flow equations, depending on reservoir and fluid properties. It states that, when the injected and produced volumes are equal, the system will approach a steady state flow. Thereafter, the pressures and flow velocities in this region stay constant.

For each project, the largest AoI is assumed to be achieved at the moment of thermal breakthrough. At the moment of thermal breakthrough, the cold water has been advected to the producer, and the shape of the cold front is therefore not circular, as the shape calculated by Lauwerier, but more in the shape of a drop. This results in a decrease of the production temperature. An illustration of such a shape is given in Figure 3-4. This temperature map has been calculated using DoubletCalc 2D. Figure 3-4 illustrates that the size of the thermal front is smaller than would have been calculated assuming a radial temperature distribution. The impact of a non-radially shaped thermal front around the injector has been properly captured by Lippmann & Tsang.

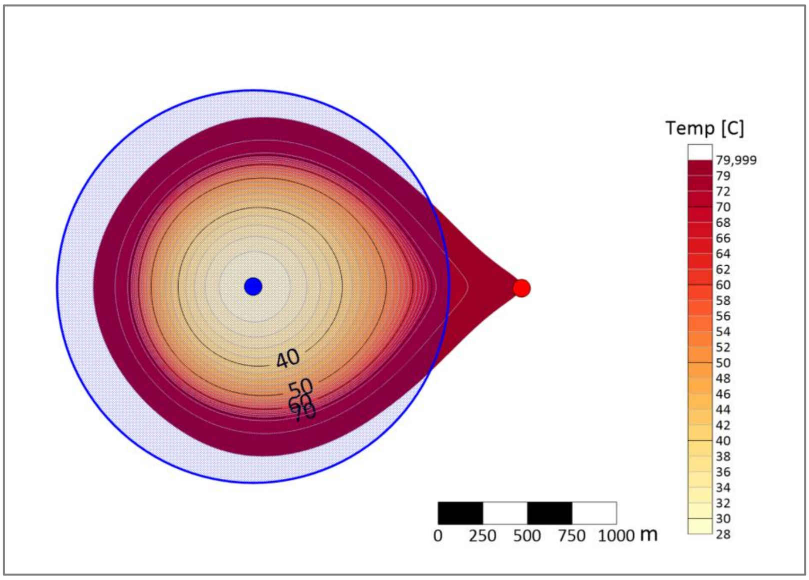


Figure 3-4 A top-view temperature map for a geothermal doublet experiencing thermal breakthrough. The radius of the cooled down area is app. 900 m. The AoI calculated using Lauwerier is given in blue (radius =1050 m). This figure illustrates the differences in shape of the cooled down area using a numerical model and the analytical method by Lauwerier.

3.5 TEMPERATURE PROFILE

The temperature profile at the moment of thermal breakthrough has been calculated using a modification to a radial reservoir of Lauwerier, (1955), as presented by Prats (1986). This method shows the temperature change in a reservoir that is cooled down by an injection well after a certain time period. The method is 2D radial and assumes a homogeneous reservoir, resulting in a circular area of influence. An example of a calculated temperature profile is given in Figure 3-5. The input matches the input used for Figure 3-4. For comparison, the temperature profiles for the DoubletCalc 2D results are given as well: one along the line between the two wells, and one from the injection well into the Western direction.

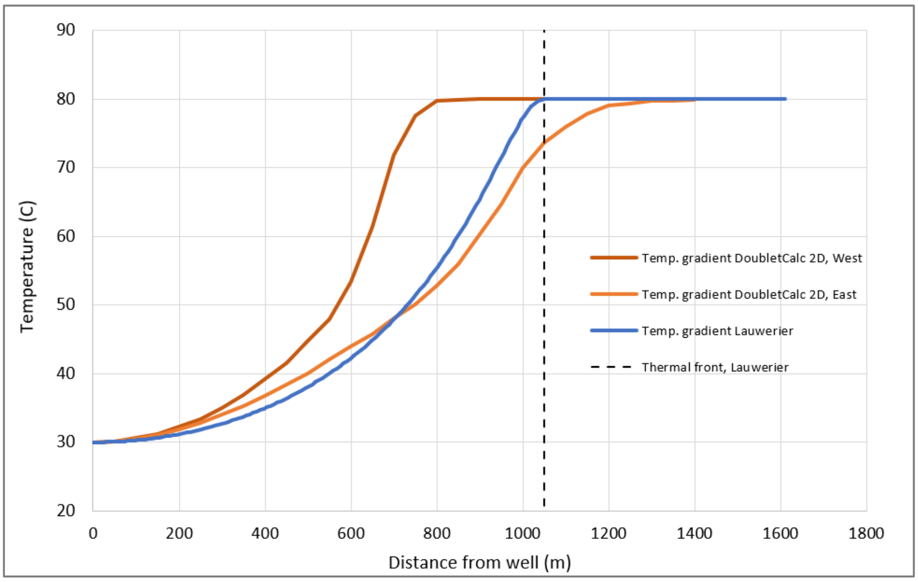


Figure 3-5 Example of several temperature profiles calculated using the analytical method by Lauwerier and the numerical method DoubletCalc 2D (one from the injector in Eastern direction, and one the Western direction, for the well configuration

as presented in figure 3-4).The dotted line is the radius of the area of influence, calculated using Lauwerier: ΔT=0ºC at a distance of 1050 m from the injection well.

3.6 TEMPERATURE MODELLING

3.6.1 Assumptions

Model build-up

A radial symmetric layer cake model is assumed (Figure 3-6), in which all layers are homogeneous and isotropic in the horizontal direction. Heat transport in the horizontal direction in the reservoir is calculated as advective transport (due to pressure movements). Heat transport to the cap and the base is calculated as conductive transport (due to differences in temperatures).

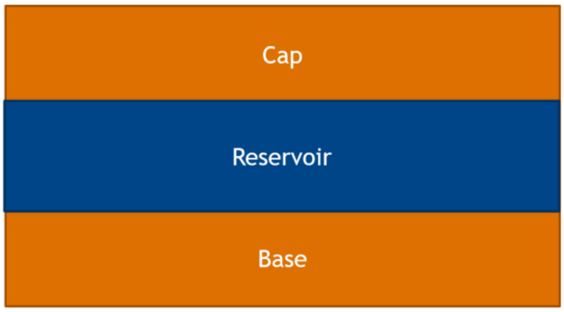


Figure 3-6 Schematic overview of the model structure.

Layer properties

The properties of the cap are similar to those of the base. The “locked” input parameters used in the calculations are given in Table 3-1. They are named “locked” because they are kept constant in the various analyses: the values are taken from literature and chosen such that the resulting AoI will be the largest (conservative values).

Table 3-1 Locked input.

Parameter	Unit	Value	Source
Used for calculating thermal breakthrough			
Heat capacity water	[MJ/m³/K]	4.0	Based on empirical formula from DoubletCalc 2D
Specific heat capacity reservoir rock (matrix)	[MJ/m³/K]	2.7	Value for Slochteren, calculated from Verweij (2003). Conservative i.r.t. thermal breakthrough.
Used for calculating the thermal radius			
Heat capacity water	[MJ/m³/K]	4.0	Based on empirical formula from DoubletCalc 2D
Specific heat capacity reservoir	[MJ/m³/K]	2.1	Koning (1988). Conservative for AoI.
Specific heat capacity cap/base	[MJ/m³/K]	2.1	Koning (1988). Conservative for AoI.
Thermal diffusivity cap and base	[m²/s]	1*10^-6	Conservative value.

3.6.2 Input

The variable input is shown in Table 3-2. It consists of reservoir properties and operational settings.

Table 3-2 Variable model input.

Parameter	Unit	Remarks
Reservoir properties		
Reservoir thickness	[m]	Net thickness
Depth top reservoir	[mTVD]	Top reservoir at location of the injector
Reservoir porosity	[-]	In order to correctly calculate the radius of the AoI, the maximum porosity is 30%
Temperature reservoir	[°C]	Temperature at the top of the reservoir
Operational settings		
Flow rate	[m^3/h]	Flow rate for the injector. Note: in case of a multiplet, the flow rate matches the specific injector of interest.
Well spacing	[m]	The distance between the two wells at reservoir level.
Temperature of the injection water	[°C]	The temperature of the injected water. This influence the temperature profile within the area of influence, but it does not influence the radius of the thermal front. This value is usually between 15 and 35°C.
Equivalent running hours	[hr]	The number of hours the system will be operational each year. The default value is 8760 hours.

3.7 VERIFICATION THROUGH NUMERICAL SIMULATION

The results of the analytical Lauwerier model have been benchmarked against reservoir simulations. Results are shown in Figure 3-7. Qualitatively, the agreement is very good.

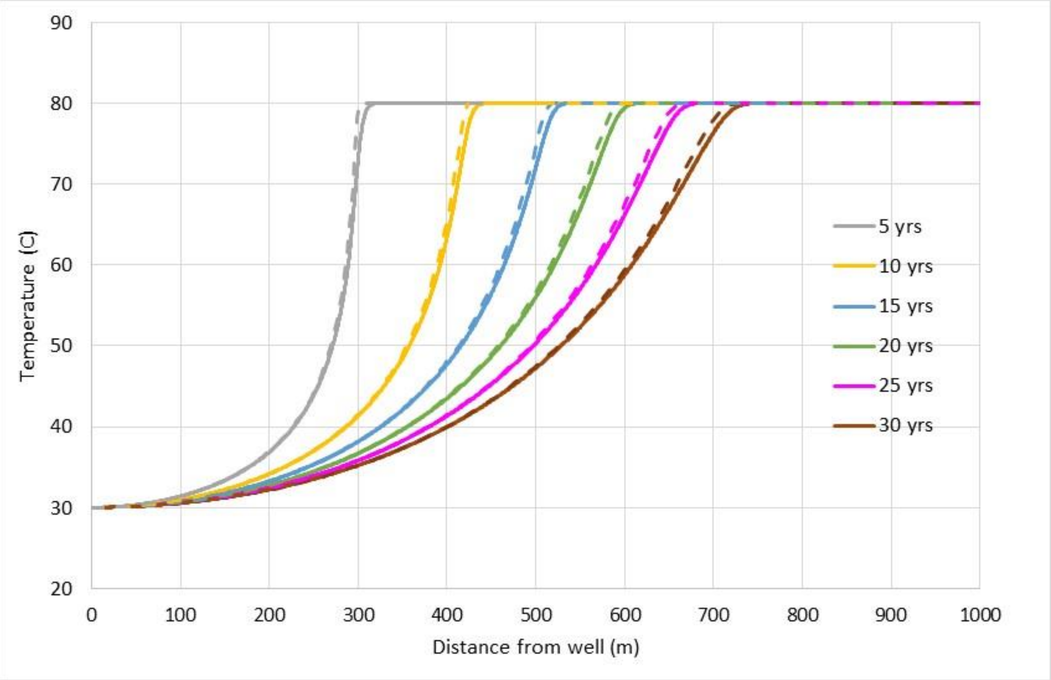
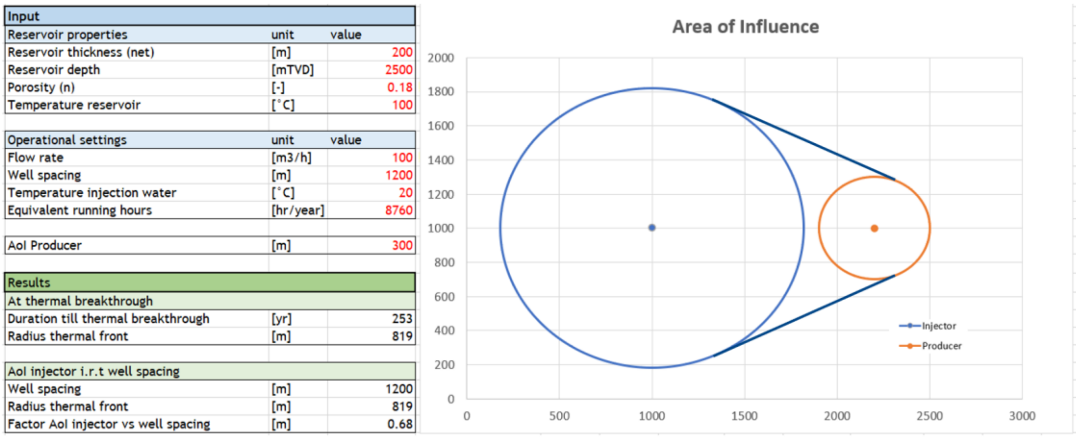


Figure 3-7 Results of the numerical simulations for various time period. Dashed lines correspond to the temperature profiles as calculated with Lauwerier.

3.8 MODEL SCENARIOS

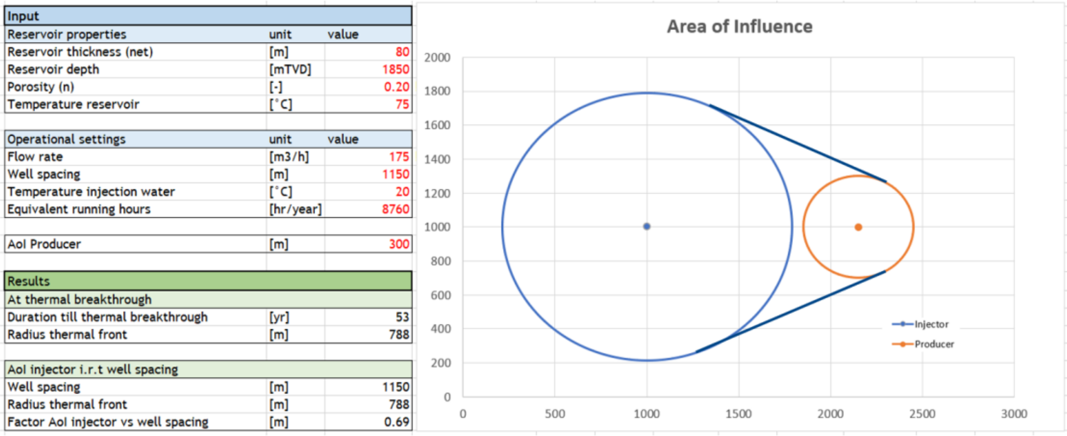
Several reality checks have been carried out: the model has been run for several case studies, to determine the size of the AoI with respect to the position of the wells. The presented cases are a project in the province of Noord-Holland (Figure 3-8), a project in central Netherlands ("Centraal Nederland") (Figure 3-9) and one in the province of Zuid-Holland (Figure 3-10). For each of the projects a doublet is assumed. In case the project is a multiplet, the flow rate injected in one of the injectors is chosen as the model flow rate. The AoI around the injector is calculated for the moment of thermal breakthrough, based on the input in red. The AoI around the producer has the previously determined constant radius of 300 m.

The results are presented in the green table on the left in each of the figures and visualised to the right. The table shows the moment of thermal breakthrough for the input data, and presents the corresponding Area of Influence for the injector. In the lowermost three rows of the table, a comparison is made between the Area of Influence and the well spacing, resulting in a corresponding factor.



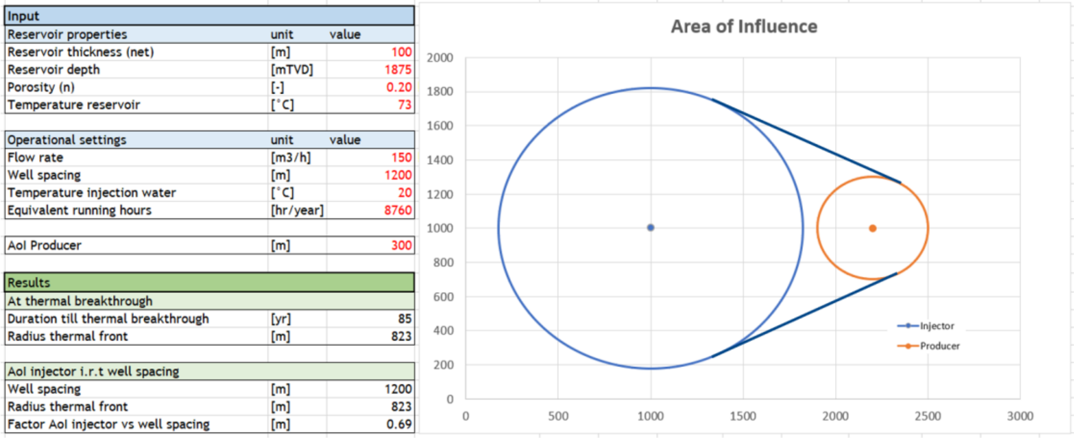
Input		
Reservoir properties	unit	value
Reservoir thickness (net)	[m]	200
Reservoir depth	[mTVD]	2500
Porosity (n)	[-]	0.18
Temperature reservoir	[°C]	100
Operational settings	unit	value
Flow rate	[m3/h]	100
Well spacing	[m]	1200
Temperature injection water	[°C]	20
Equivalent running hours	[hr/year]	8760
AoI Producer	[m]	300
Results		
At thermal breakthrough		
Duration till thermal breakthrough	[yr]	253
Radius thermal front	[m]	819
AoI injector i.r.t well spacing		
Well spacing	[m]	1200
Radius thermal front	[m]	819
Factor AoI injector vs well spacing	[m]	0.68

Figure 3-8 Reality check for a doublet at the Noord-Holland project.



Input		
Reservoir properties	unit	value
Reservoir thickness (net)	[m]	80
Reservoir depth	[mTVD]	1850
Porosity (n)	[-]	0.20
Temperature reservoir	[°C]	75
Operational settings	unit	value
Flow rate	[m3/h]	175
Well spacing	[m]	1150
Temperature injection water	[°C]	20
Equivalent running hours	[hr/year]	8760
AoI Producer	[m]	300
Results		
At thermal breakthrough		
Duration till thermal breakthrough	[yr]	53
Radius thermal front	[m]	788
AoI injector i.r.t well spacing		
Well spacing	[m]	1150
Radius thermal front	[m]	788
Factor AoI injector vs well spacing	[m]	0.69

Figure 3-9 Reality check for a doublet at the Centraal Nederland project.



Input		
Reservoir properties	unit	value
Reservoir thickness (net)	[m]	100
Reservoir depth	[mTVD]	1875
Porosity (n)	[-]	0.20
Temperature reservoir	[°C]	73
Operational settings	unit	value
Flow rate	[m3/h]	150
Well spacing	[m]	1200
Temperature injection water	[°C]	20
Equivalent running hours	[hr/year]	8760
AoI Producer	[m]	300
Results		
At thermal breakthrough		
Duration till thermal breakthrough	[yr]	85
Radius thermal front	[m]	823
AoI injector i.r.t well spacing		
Well spacing	[m]	1200
Radius thermal front	[m]	823
Factor AoI injector vs well spacing	[m]	0.69

Figure 3-10 Reality check for a doublet at the Zuid-Holland project.

3.9 SIMPLIFYING THE AOI AROUND THE INJECTOR

The cases clearly show that the radius of the AoI around the injector can be simplified based on the well spacing and a constant factor, which is named the “radius factor”:

$$Radius\ AoI\ injector\ [m] = well\ spacing\ [m] * radius\ factor$$

The factor depends the so called “locked” input (Table 3-1), and the variable input (Table 3-2). At first glance, the case studies already show minimal variation in the factor between 0.68 and 0.69 for differences in variable input. The main boundary condition of t = thermal breakthrough limits the impact of the reservoir and operational conditions. The properties that are the “locked” input (Table 3-1) mainly describe the thermal properties within the reservoir and cap and base. The thermal properties are chosen such that they create the largest radius possible. Low diffusion rates will offer a limited heat transfer and smaller heat capacities allow for less heat absorption. This combined effect will provide a high side estimate of the radius of the AoI.

A sensitivity analysis is provided for the variable input (Table 3-2). Out of these parameters, the only parameters that influence the factor are the porosity (strong effect) and the flow rate (minor effect). The other parameters also certainly have an effect on the size of the AoI, but since this study focusses on the moment of thermal breakthrough this effect is compensated by a shorter/longer lifetime. The “locked” input parameters are kept at constant value. Table 3-3 shows the minimum (0.65) and maximum (0.70) value for the radius factor, and the corresponding min. and max. porosity and flow rate values. Based on the cases and sensitivities it is concluded that the radial T = 0°C boundary does not exceed 0.7 times the well distance. This means that in a direction other than to the producer well, this is the maximum influence sphere. A radius factor of 0.7 is therefore considered appropriate for the area of influence of the injector.

Table 3-3 minimum and maximum radius factor and corresponding porosity and flow rate.

	Unit	Min	Max
Radius factor	[-]	0.65	0.70
Valid for:			
Porosity	[%]	5	30
Flow rate	[m³/h]	10	1000

3.10 CONSTRUCTING THE AOI

The Area of Influence can be constructed using the following workflow. The resulting shape is an area seen from top view. The shape is valid for the depth range covering the reservoir. It is a shape consisting of three components. The first is a radius around the injector, the second is a radius around the producer. The third covers the area between the two circles.

1) AoI Injector

The area of influence around the injector is related to the well spacing, and is described by the following formula (Paragraph 3.9):

$$Radius\ AoI\ injector\ [m] = well\ spacing\ [m] * radius\ factor$$

Based on the case studies and the sensitivity analysis it is concluded that a radius factor of 0.7 is most appropriate.

2) AoI Producer

The area of influence around the producer well is constant: a circle with a radius of 300 m.

3) Combining the two

The area between the two circles also belongs to the Area of Influence. This is done by drawing tangent lines along both circles: draw a line from the top of the smallest circle and let it tangent the upper side of the larger circle. Repeat for the lower side (dark blue in Figure 3-11).

Example

An example of a constructed AoI is given in Figure 3-11. Everything between the lines and within the circles belongs to the AoI.

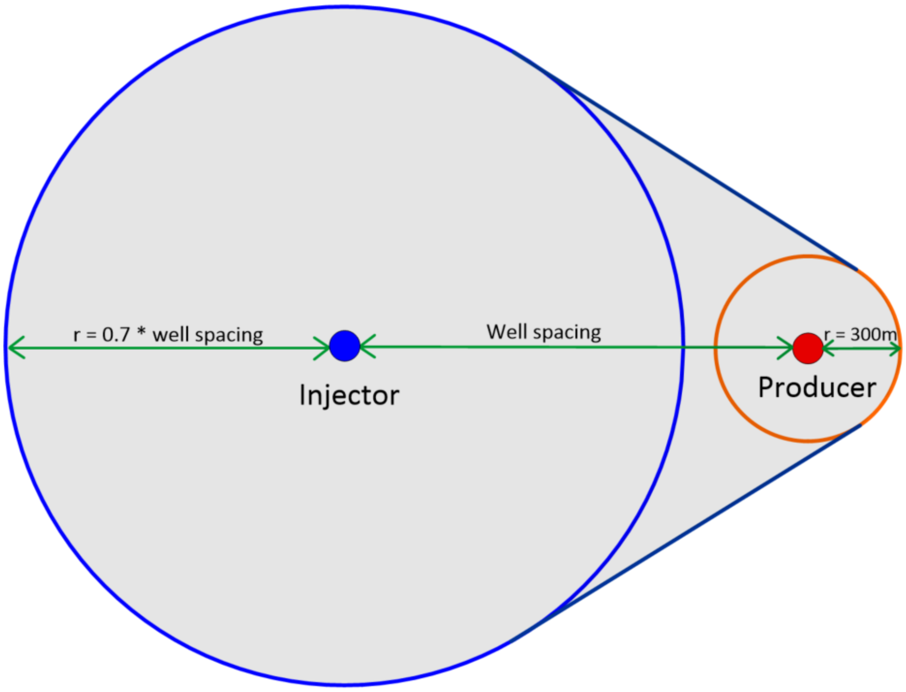


Figure 3-11 Example of the construction of the Area of Influence for a hypothetical project with a well spacing of 1500 m..

3.11 MULTIPLETS

The current model is based on a geothermal doublet systems and focuses on the influence of the injector. In case of a multiplet (triplet, double doublet, etc.) the routine can be used as well, by simply applying it multiple times: once for each well.

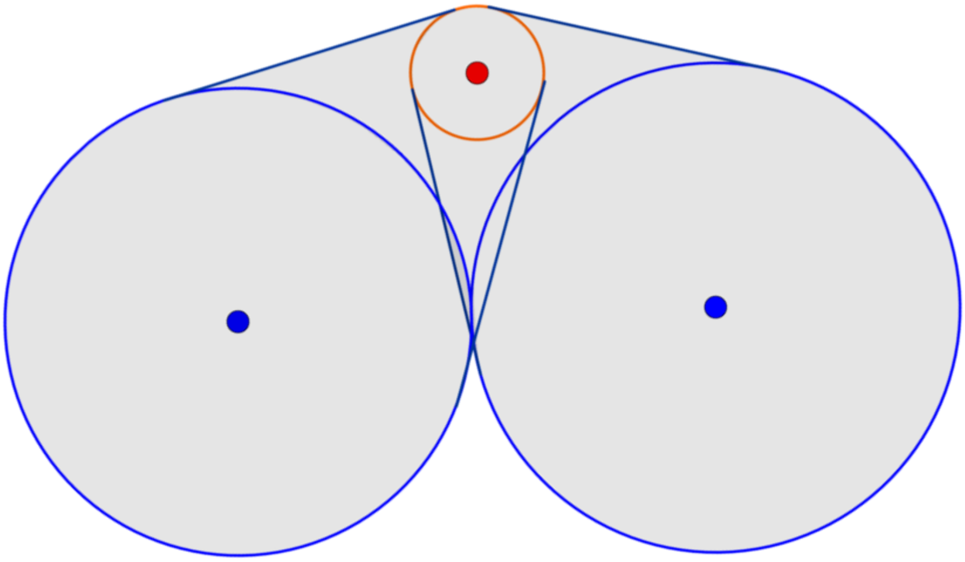


Figure 3-12 Schematic view of a triplet system (two injectors, one producer) and their corresponding AoI. The total AoI is the total area covered by the different shapes.

3.12 SENSITIVITY

The calculation method for the Area of Influence is valid in case both the porosity and the flow rate fall within the range given in Table 3-4.

Table 3-4 The min. and max. values for which the AoI construction method is valid

	Unit	Min	Max
Porosity	[%]	5	30
Flow rate	[m^3/h]	10	1000

4 Conclusion

This report proposes a simple, geometrical solution to determine the size and shape of an area of influence (AoI) around a geothermal project with respect to the risk of induced seismicity. This AoI reflects the area within which perturbations as a result of the geothermal operation are significant enough to potentially cause fault reactivation (and hence, induced seismicity). It is defined for the moment of thermal breakthrough, in line with the method for determining the shape of a production license. The workflow consists of three parts: Construction of the area around the injector, of the area around the producer, and of the area in between. Everything within the constructed circles and lines is considered part of the AoI.

Area around the Injector

Based on the results of the fault-reactivation potential study (PanTerra & IF-Technology, 2021), it is concluded that a temperature change of 0 °C will not result in fault slip. This is a conservative value. Pressure changes outside of the cold water front are not big enough to result in fault slip. The leading parameter in the determination of the AoI around the injection well is therefore the temperature change.

To calculate the radius of the area around the injection well with a temperature change of more than 0 °C a model has been set up. The model uses the analytical method by Lauwerier (1955) to calculate the temperature profile of a reservoir as a result of the geothermal project at the time of thermal breakthrough. This method is the preferred method because i) it provides the largest Area of Influence in most conditions, and ii) it provides a temperature profile rather than a piston-like thermal front, while also vertical thermal conduction is taken into account. The method by Lippmann & Tsang, which is similar to Brigham, is used to calculate the time of thermal breakthrough.

The model has been run for several reality cases, and a sensitivity analysis has been conducted. Based on this it is concluded that the AoI around the injection well can be simplified using the following relation:

$$Radius\ AoI\ injector\ [m] = well\ spacing\ [m] * radius\ factor$$

Based on the case study it is concluded that a radius factor of 0.7 is most appropriate. It is valid for a reservoir porosity of 30% or less, and a flow rate of 1000 m3/h or less.

Area around the Producer

The area of influence around the producer well is based on the pressure change. A constant zone is defined: a circle with a radius of 300 m. This has been determined based on the fault reactivation potential study, and is considered to be a conservative radius. This is a conservative value for which it is expected that the pressure differential has decreased drastically (<10 bar) for expected geothermal settings. Results from the fault reactivation potential study show that for a regular geothermal setting the pressure differential will not reach shear failure conditions. The value of 300 m is used as the pressure differential has severely lowered (<10 bar) over this distance for a regular geothermal setting as demonstrated using reality cases.

Area between the Producer and the Injector

The area between the two circles also belongs to the Area of Influence. This is done by drawing tangent lines along both circles.

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6 Appendix 1

Tabel 6.1 Input data for the model comparison in paragraph 3.6. Note that these values are used for comparison purposes only: this input data has been kept constant, while other input data has been varied for the different models.

Parameter	Unit	Value
Reservoir depth	[mTVD]	2000
Porosity (n)	[-]	0.17
Specific heat capacity water	[MJ/m^{3}K]	3.9
Specific heat capacity reservoir rock	[MJ/m^{3}K]	1.0
Specific heat capacity cap/base	[MJ/m^{3}K]	1.4
Alfa (diffusivity) cap and base	[m^2/s]	0.000001
Lifetime of doublet	[yr]	30
Equivalent running hours	[hr/year]	6000