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Leakage Detection and Characterization through Pressure Monitoring

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Abstract

Geological storage of carbon dioxide provides the possibility of maintaining access to fossil energy while reducing emissions of carbon dioxide to the atmosphere. One of the essential concerns in geologic storage is the risk of CO_2 leakage from the storage formations. CO_2 may leak through various pathways in the cap-rock overlying the storage aquifer. Characterization of the CO_2 leakage pathways from the storage formations into overlying formations is required.
We present a flow and pressure test to locate and characterize the leaks. The flow test is based on the injection (or production) of water into (or from) a storage aquifer at a constant rate. The pressure is measured at one or several monitoring wells in an aquifer overlying the storage aquifer, which is separated by an aquitard. The objective of the test is to locate and characterize any leakage through the separating aquitard. We present an inverse procedure to obtain the leakage pathway transmissibility and location, based on the pressure measurements in the presence of noise. A single monitoring well allows good determination of the leak magnitude but provides limited constraints on location. Adding a second monitoring well provides two-dimensional location of the leak location in the presence of noise/uncertainty in pressure measurements. It seems plausible that the use of multiple monitoring wells could enable cost-effective and sensitive detection of leakage over a large area. Unlike seismic imaging which only detects leakage when CO_2 penetrates the leak, these methods are able to test for leaks before CO_2 injection, or during injection but before the CO_2 plume reaches the leak.

Keywords: Pressure monitoring; leakage characterization; inverse problem

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1. Introduction

CO_2 storage in deep saline aquifers is a promising solution to control CO_2 emissions to the atmosphere. One of the key challenges in geologic storage is the risk of CO_2 leakage from the storage formations. CO_2 can leak to the surface and/or subsurface formations. Leakage to surface could pose health risks to humans, animals, and vegetation. The consequences of leakage to subsurface include reducing the efficiency of CO_2 trapping in target formation, small seismic events, adverse impacts on hydrocarbon recovery operations, and pollution of potable water aquifers. Current subsurface leakage detection methods are either based on spatial subsurface sampling (e.g. fluid and rock analysis in the observation wells) or geophysical measurements (e.g. seismic and electric resistance tomography). While the latter can capture *large* features (e.g. leakage from major fractures and faults) the former provides information on the leakage on a *small* length scale around the sampling point. Flow based systems have the potential

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for bridging the large gap in scale that exists between these two methods. A method for quantifying leakage through poorly sealed boreholes is presented in [1]. A nonreactive tracer is injected into an upper aquifer while the lower aquifer (separated from the upper aquifer by an aquitard) is pumped. Concentrations of the recovered tracer are used to obtain the leakage rate associated with the pumping. In this work we suggest a flow and pressure test to detect and characterize the leakage pathway based on the pressure data measured in an upper aquifer. Such a test can cover much larger areas of cap rock than a test that depends on movement of a physical tracer. This method might be applied to test for leakage pathways before CO_2 injection begins allowing better choices for locations of injection wells. Alternatively, modified versions of this test could be used during CO_2 injection.

In its simplest form the test consider water injection at a constant rate through a single well in the target aquifer. The pressure change due to leakage will be observed at a single monitoring well in an upper aquifer. Side and plan views of the test configuration are shown in Figure 1. We investigate the capability of obtaining the location and the transmissibility of the leak based on the pressure measurement. We refer to this problem as the leakage problem in the following.

The leakage problem is an inverse problem in the sense that the location and characteristics of the leak can be obtained from pressure measurements at the monitoring well(s). The leak parameters are found through history matching of the measured pressure data. Detailed analysis on the solution of the leakage inverse problem is given in [2, 3]. In this paper a summary of the main results given in [2, 3] are presented.

In the following we first present an overview of the forward model where a relationship between the leakage parameters and the pressure change in the upper aquifer is given. Next the corresponding inverse problem is presented. The stability of the solution is analysed based on the sensitivity coefficients and presented in terms of the confidence region. Finally, we investigate the benefits of adding additional monitoring wells.

2. The Forward Problem

An analytical model to obtain the pressure change at the monitoring aquifer in response to the leakage from the storage aquifer has been developed in an earlier work [4]. Initially, we consider only two aquifers (storage and monitoring) which are separated by an impermeable aquitard. We consider a single-phase 1-D radial flow system in both aquifers. Leakage occurs in vertical direction through a single leakage pathway. The aquifers are considered as infinite and the injection (production) rate to be constant over the injection (production) period. The Cartesian coordinate system with the centre at the injection well is used for assigning the location of the leak and monitoring well(s). The ordinate of the monitoring well is considered zero with the abscissa of L which is the monitor-injector distance (see nomenclature below for a complete list of symbols). The leak is located at (x_l, y_l). Defining dimensionless coordinates $x_{lD}=x_l/r_w$, $y_{lD}=y_l/r_w$, $x_{mD}=x_m/r_w$, and $y_{mD}=y_m/r_w$ the following relationship between the coordiantes and the leak-monitor distance(ρ_D) and leak-injector distance (R_D) can be obtained:

$$\rho_D = \sqrt{\left(x_{lD} - x_{mD}\right)^2 + \left(y_{lD} - y_{mD}\right)^2} \quad \text{and} \qquad R_D = \sqrt{x_{lD}^{\ 2} + y_{lD}^{\ 2}}$$

Based on the exact analytical solution, the dimensionless pressure response at the monitoring well (assumed to be completed throughout the depth of the the monitoring aquifer) to leakage can be obtained by:

$$\overline{P}_{mD} = \frac{\overline{q}_{lD}(s) K_0\left(\sqrt{\frac{s}{\eta_D}}\rho_D\right)}{T_D r_{lD}\sqrt{\frac{s}{\eta_D}} K_1\left(\sqrt{\frac{s}{\eta_D}} r_{lD}\right)} \qquad \text{Equation 1}$$

$$\overline{q}_{lD} = \frac{\dfrac{K_0\left(\sqrt{s} R_D\right)}{s^{3/2} K_1\left(\sqrt{s}\right)}}{\dfrac{K_0(\sqrt{s} r_{lD})}{r_{lD}\sqrt{s} K_1(\sqrt{s} r_{lD})} + \dfrac{K_0\left(\sqrt{\frac{s}{\eta_D}} r_{lD}\right)}{T_D r_{lD}\sqrt{\frac{s}{\eta_D}} K_1\left(\sqrt{\frac{s}{\eta_D}} r_{lD}\right)} + \dfrac{1}{\alpha}} \qquad \text{Equation 2}$$

where:

$$R_D = \frac{R}{r_w}, \qquad \rho_D = \frac{\rho}{r_w}, \qquad L_D = \frac{L}{r_w}, \qquad r_{lD} = \frac{r_l}{r_w}, \qquad T_D = \frac{k_m h_m}{k_s h_s}, \qquad \eta_D = \frac{\eta_m}{\eta_s}, \alpha = \frac{r_l^2 k_l}{2k_s h_s h_l},$$

$$P_{mD} = \frac{2\pi k_s h_s}{q\mu B}\left(P_{m0} - P_m\right), \; t_D = \frac{\eta_s t}{r_w^2}, \qquad q_{lD} = \frac{q_l}{q}$$

The bar sign on P_{mD} and q_{lD} shows that these equations are given in Laplace domain with the Laplace transform variable s. Since Laplace inversion to obtain the close-form solution is not possible, we use a numerical Stehfest algorithm [5] for inversion to time domain.

3. The Inverse Problem

In the leakage inverse problem considered here the transient pressure measurements at a monitoring well are given. The pressure measurements are given at times t_i, where i=1,2,...,I. In dimensionless form the leak will be parameterized by three parameters: x_{lD}, and y_{lD}, and α. x_{lD} and y_{lD} parameters correspond to the leak location while the leakage coefficient (α) correspond to the leak transmissibility. These parameters are to be estimated by minimization of the chi-square function. When noise distribution is the same for all the measurments the chi-square objective function will be reduced to ordinary least-square:

$$f(\boldsymbol{x}) = \left(\boldsymbol{Y} - \boldsymbol{P}_{mD}(\boldsymbol{x})\right)^T \left(\boldsymbol{Y} - \boldsymbol{P}_{mD}(\boldsymbol{x})\right) \qquad \text{Equation 3}$$

where $\boldsymbol{x}^T = \begin{bmatrix} x_{lD} & y_{lD} & \alpha \end{bmatrix}$

In this paper, a *scalar* is written as a plain letter and a *vector* as a ***bold*** letter. A matrix is shown by a bracketed bold letter. In the above equations $\boldsymbol{Y}$, $\boldsymbol{P}_{mD}$ and $\boldsymbol{x}$ are the measured dimensionless pressure, calculated dimensionless pressure and parameter column vectors, respectively.

The inverse problem is investigated by using base case described in Table 1. Water is to be injected in the 100 mD permeable and 30 m thick target storage aquifer. The pressure will be monitored at an upper aquifer with 25 mD permeability and 10 m thickness. The aquifers are separated by a 4 m thick cap-rock. We consider 100 days test duration over which 2400 measurements (sampling frequency=1/hr) have been taken with equal time interval. The true leakage parameters for the base case are: x_{lD}=460, y_{lD}=196, α=4.17e-5.

4. Sensitivity coefficients

The sensitivity matrix [$\boldsymbol{J}$] can be utilized to study the parameters inter-dependence and their relative impact on the pressure response. The elements of the sensitivity matrix are known as sensitivity coefficients $J_{ij} = \frac{\partial P_{mD,i}}{\partial x_j}$.

The columns of the Jacobian matrix are the sensitivities with respect to each parameter. Relatively linear dependent columns of the Jacobian matrix represent (almost) parallel curves which make the inverse problem ill-conditioned and leads to unstable solution. Therefore, it is desirable to have a sensitivity matrix which is comprised of linearly independent columns. The linear independence allows independent evaluation of the parameters. For the leakage problem the parameters and the sensitivity coefficients are different by orders of magnitude. The sensitivity coefficient can be normalized to provide information on relative importance of the parameters as well as linear dependence [6]. The relative sensitivity coefficient for the i'th measurement with respect j'th parameter can be defined as: $x_j \frac{\partial P_{mD,i}}{\partial x_j}$

Comparison of the magnitude of these relative sensitivity coefficients gives a good indication of the relative importance of different parameters. The magnitude of relative sensitivity coefficients is shown in Figure 2. The relative sensitivity coefficient to parameter α is considerably larger making the estimation of leakage coefficient much easier than the leak coordinates. The abscissa of the location affects the pressure the least. Note that all the sensitivities look very similar in shape and almost linearly dependent. This causes ill-posing of the leakage problem and makes independent evaluation of the parameters troublesome.

Further investigations based on the correlation, Hessian, and covariance matrices are performed the details of which is given in [2]. Considering the base case properties it was shown that the leakage inverse problem may be very ill-conditioned and non-convex. For such a problem, obtaining the true parameters may be difficult, especially in the presence of noise. The noise highly depends on the environment of the pressure measurement and the pressure gauge in use. The characteristics of the error of the pressure data considering the present pressure transducer technology and environmental sources of error are discussed in [7]. Current pressure quartz gauges are able to measure pressure changes lower than 0.01 psi (≈ 70 Pa) under favourable conditions. As such, synthetic pressure data for the base case are generated considering 70 Pa normally distributed noise. The 95% confidence interval (where there is 95% chance for the true parameters to lie within) is evaluated based on the covariance matrix. Two dimensional projections of the confidence interval are shown in Figure 3 for each pair of parameters. There is a 95% chance that the true parameters lie within the intervals of x_{lD} Є {-300.6, 919.0}, y_{lD} Є {-84.2, 332.9} and α Є {3.684e-5, 4.488e-5}. The confidence interval shows that the location parameters vary over a very wide range making placement of the leak very difficult. However, the leak transmissibility can be evaluated within a narrower confidence interval.

More information is required to enable leakage characterization within acceptable limit. Different strategies to maximize the information that can be obtained in order to characterize the leak are presented and evaluated in [3]. Increasing the number of monitoring wells was found to be most promising the results of which are reviewed in the following section.

5. Multiple Monitors

The influence of obtaining pressure data from more than one monitoring well is investigated for the base case. The goal is the investigation of how increasing the number of wells adds to the information. The multi-monitor configuration is shown in Figure 4. The capability of obtaining the leakage parameters based on the pressure data at monitoring well #1 is investigated above. It is assumed that complimentary data from up to four extra monitoring wells are available and are taken over the same time span with the same time spacing. The monitoring points are spatially located 5 meters apart on a line perpendicular to the original injector-monitor connecting line. Such a line may correspond to the trajectory of a horizontal well drilled perpendicular to the line connecting the injector to the first monitoring point. It seems likely that locating the monitoring wells on some kind of grid would be substantially more effective than locating about a single line.

Stabilization of the problem due to the addition of data from the extra monitoring points is investigated using the determinant of the information matrix at the true parameters (Figure 5). The determinant of the information matrix ($[\boldsymbol{J}]^T[\boldsymbol{J}]$) is a helpful indication of the level of information added through different practices. A larger determinant implies availability of more information on the parameters to be estimated. [8, 9]

The determinant is increased by almost 5 orders of magnitude, as a result of integrating the pressure data from 5 monitoring wells. The most significant improvement comes by increasing the number of wells from 1 to 2, which results in an increase of the determinant by 4 orders of magnitude.

The confidence interval can be used to illustrate the improvement resulting from increasing the number of monitoring wells. Two dimensional projections of the 95% confidence interval considering five monitring wells are shown in figure below. There is a 95% chance that the true parameters lie within the intervals of x_{lD} Є {454.0, 479.2}, y_{lD} Є {183.3, 197.9} and α Є {4.124e-5, 4.178e-5}. Compared to the single monitoring case, significant improvement is gained. The confidence intervals for parameters x_{lD}, y_{lD} and α are reduced by 98, 97 and 93 percent, respectively, when considering 5 monitoring wells compared to the single monitoring well case. Considering only 2 monitoring wells, the confidence interval reductions for x_{lD}, y_{lD} and α are 96, 90 and 87 percent, respectively, compared to the single monitoring case.

6. Conclusions

A pressure and flow test to characterize the leak through a cap-rock is presented. Water is injected at a constant rate in the target aquifer and the pressure is monitored in an upper aquifer at a monitoring well. The pressure response due to leakage through a pathway in an otherwise sealing cap-rock is analyzed to locate and characterize the leak. The leak is characterized by determination of the leak transmissibility and its location. Considering a single monitoring well the leakage characterization inverse problem may be very ill-posed and unstable. The instability roots in almost linearly dependent sensitivities to the leakage parameters. Applying to a base case, it is found that the leakage location lie within a very wide confidence interval making it very difficult to locate the leak in practice.

To enable the leakage characterization more information are obtained through increasing the number of monitoring wells. Increasing the number of monitoring wells was found to provide very useful information on the leak parameters. The time delay in sensing the leak for different monitoring wells improves the parameter estimation considerably.

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Nomenclature

f	Least square objective function
h	Thickness, m
I	number of measurements
k	Permeability, m^2
L	Monitor-injector distance, m
P	Pressure, Pa
q	Volumetric flow rate, m^3/s
R	Leak-injector distance, m
r	Radius, m
T	Transmissivity = permeability × thickness, m^3
t	Time, s
x	Abscissa of the location in Cartesian coordinate, m
y	Ordinate of the location in Cartesian coordinate, m
α	Leakage coefficient
γ	Euler constant=0.5772…
η	Aquifer diffusivity coefficient = permeability / (porosity × fluid viscosity × total compressibility) , m^2/s
μ	Viscosity, Pa.s
ρ	Leak-monitor distance, m

Vectors and matrices:

$[\boldsymbol{J}]$	Jacobian matrix	$\boldsymbol{x}$	Parameters vector
$\boldsymbol{P}$	Calculated pressure vector	$\boldsymbol{Y}$	Dimensionless measured pressure vector

Subscripts:		Superscripts:	
D	Dimensionless	T	Transpose
i	Measurement at i'th time	prime: ’	Shows the second set of leak locations
l	Leakage		
m	Monitoring well/aquifer		
s	Storage aquifer		
w	Well		
0	initial		

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Table 1. Descriptions of the base case

k_l, leak permeability (m^2)	150e-15
R, leak-injector distance (m)	50
ρ, leak-monitoring distance (m)	35
h_l, leakage interval (m)	24
r_l, leak radius(m)	0.2
monitoring aquifer compressibility (1/Pa)	1e-9
μ, brine viscosity (Pa.s)	0.5e-3
monitoring aquifer porosity(fraction)	0.1
k_m, monitoring aquifer permeability(m^2)	25e-15
h_m, monitoring aquifer thickness(m)	10
Storage aquifer compressibility (1/Pa)	1 e-9
Storage aquifer porosity (fraction)	0.1
k_s, Storage aquifer permeability (m^2)	100e-15
h_s, Storage aquifer thickness(m)	30
q, injection rate into the storage aquifer (m^3/s)	0.01
r_w, injection well radius(m)	0.1
L, monitor-injector distance (m)	75

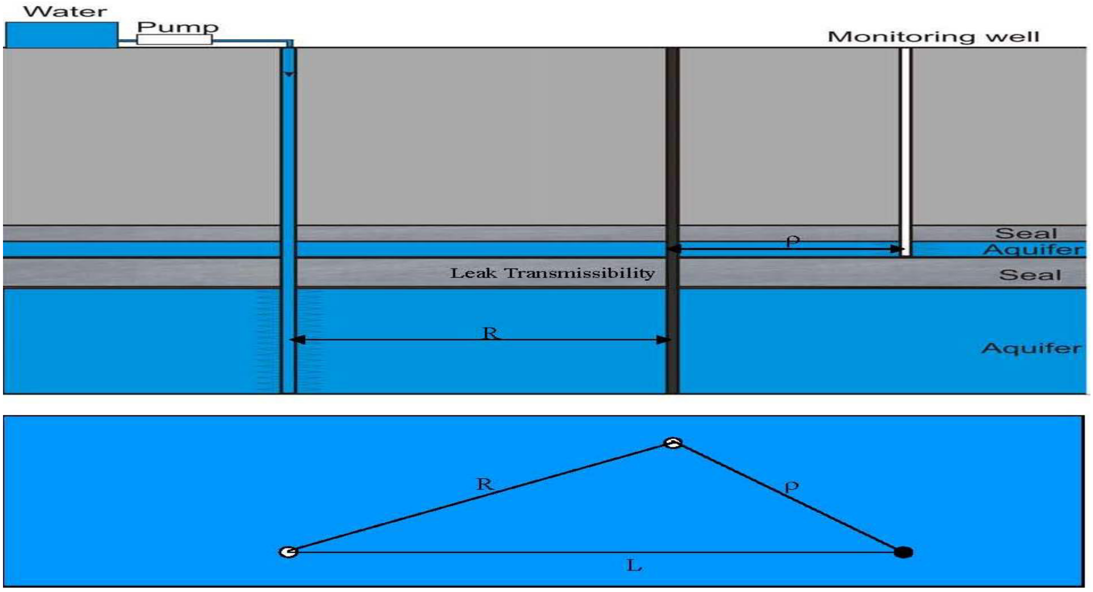

Figure 1. The side and plan views of the leakage test configuration

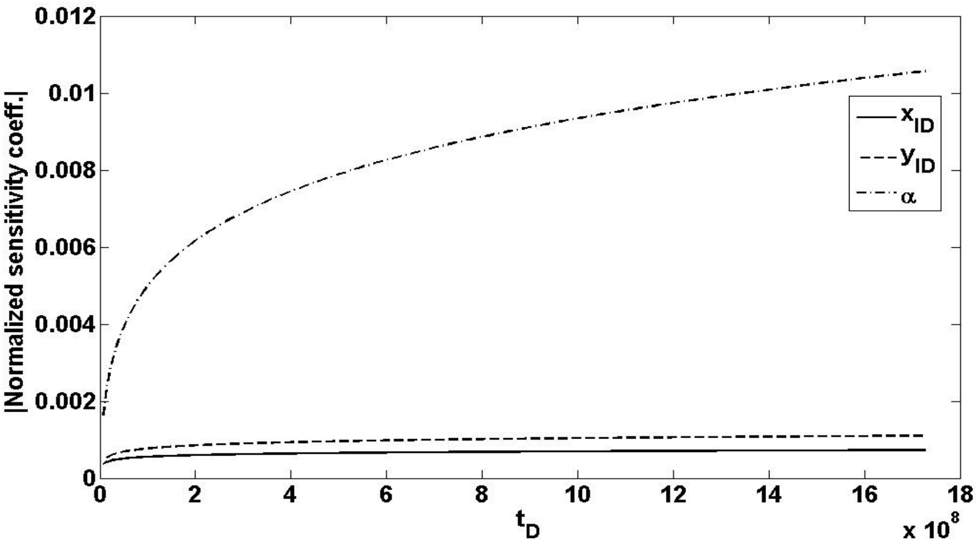

Figure 2. Relative sensitivity coefficients for the base case

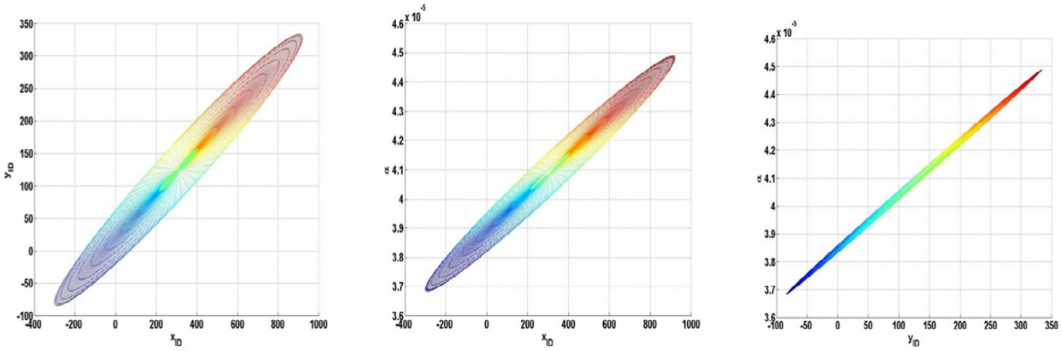

Figure 3. 2D projections of the joint 95% confidence region

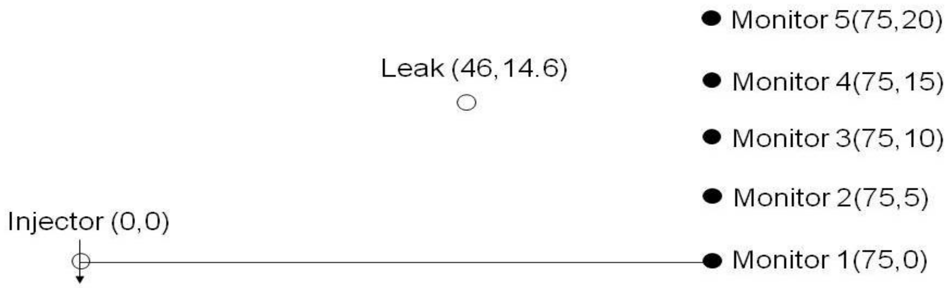

Figure 4. Problem modification by adding more monitoring locations

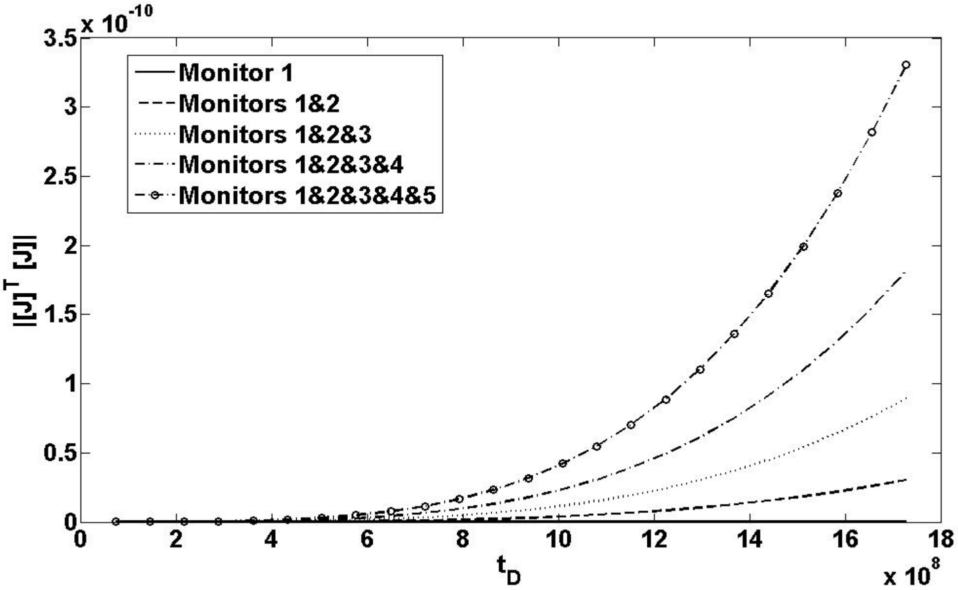

Figure 5. Determinant of the information matrix for multi-monitor problem

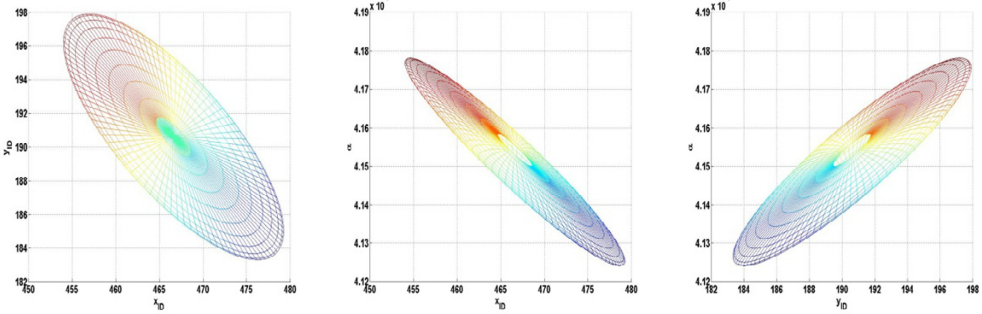

Figure 6. Projections of the 95% confidence interval for the best-fit parameters considering 5 monitoring wells