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iTOUGH2 ANALYSIS OF THE GROUND WATER LEVEL RESPONSE TO THE BAROMETRIC PRESSURE CHANGE (WELL YZ-5, KAMCHATKA)

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ABSTRACT

We performed iTOUGH2 inverse modeling using a two-dimensional, radial model (cylindrical symmetry around a monitoring well) applied to Jan. 25, 2007 - Feb. 20, 2008 observational data of the water level monitoring well YZ-5 (Kamchatka). Before the inversion, the systematic component related to hydrogeological basin recharge/discharge conditionswere removed, and water level was converted into well fluid pressures. The atmospheric pressure change was specified as time-dependent Dirichlet boundary conditions at the well head and earth surface. Reservoir permeabilities (on the order of 10^{-3} mD) were identified as the most sensitive parameters, while porosity and compressibility are less sensitive. Moreover, the barometric pressure change mostly propagates into an aquifer directly through the well head, with pressure propagation limited to about one meter around the well.

INTRODUCTION

It is usually assumed that barometric pressure change is immediately and fully transmitted through overlaying layers into the aquifer, increasing the sum of the effective stress and reference pressure, which balances the water level change in the monitoring well (Shestakov, 1979).

If this assumption is true, then it is possible to show that the change of the reference pressure (or well fluid pressure) δP is proportional to the atmospheric pressure change δP_{atm}:

$$\delta P = \delta P_{atm}/(1+4.75\ 10^{-10}/\ c_r) \quad (1)$$

where $4.75\ 10^{-10}$ is water compressibility, Pa^{-1}, and c_r is reservoir compressibility, Pa^{-1}.

Nevertheless, “existing theoretical understanding of pressure propagation in a low permeability formations are rather speculative, and further analysis need to apply to any specific observational data” (Shestakov, 1979), prompting additional investigation and analysis of this issue.

Input data used for this analysis include atmospheric pressure data and water level monitoring data of well UZ-5, collected by Kamchatka Branch Geophysical Survey of RAS. Enhanced statistical analyses of this data were already performed by Kopylova (2006).

iTOUGH2 inverse modeling capabilities significantly improve the efficiency of multi-parameter analysis of underground reservoirs hydrodynamics conditions (Finsterle, 2004; Kiryukhin et al., 2008). Inverse modeling analysis performed in this paper with iTOUGH2, a computer program that provides inverse modeling capabilities for the TOUGH2 suite of simulators; it solves the inverse problem by automatically calibrating a TOUGH2 model against observed data. This program may also simulate time-dependent Dirichlet boundary conditions on the earth surface and well head, where barometric pressure changes. Once the best estimate parameter set is identified, iTOUGH2 performs an extensive error analysis, which provides statistical information about residuals, estimation uncertainties, and the ability to discriminate among model alternatives. More information can be found at http://www-esd.lbl.gov/TOUGH2, and http://www-esd.lbl.gov/iTOUGH2.

CONCEPTUAL HYDROGEOLOGICAL MODEL AND OBSERVATIONAL DATA

Well UZ-5, located 20 km west from Petropavlovsk-Kamchatsky, Russia, is used as a monitoring well of the Kamchatka Branch Geophysical Survey of RAS in order to investigate earthquake and volcanic eruption precursors. This 1000 m deep well penetrates alluvial and volcanic avalanche deposits (0-270 m), quartz veined metamorphic sandstones and slates of Cretaceous age (270-1000 m) (Fig. 1).
Since May 2003, continuous water level monitoring conducted in well YZ-5 (Kedr-A2 water leveling device integrated with hand measurements, with an assumed total measurement error of 1 cm).

Barometric pressures were also recorded. All records are collected at the interval of 1 hr. Air temperature and precipitation data were also recorded. Data collected from Jan. 25, 2007 to Feb. 20, 2008 were used as input data in this analysis (Fig. 2). A more detailed sub-set of the observational data, obtained during the time interval of Dec. 1, 2007 to Dec. 31, 2007, when data were taken at 10 min sampling intervals, was also used for model calibration.

As mentioned above, water level data were converted into absolute fluid pressure in well in (Pa) for consistency with the primary variables used by TOUGH2. Well fluid pressure was calculated as the sum of water level change (Pa), atmospheric pressure change (Pa) and a constant value of 3,512,075 Pa, which corresponds to the pressure at the elevation of Layer 3 (see below). Fig.3 shows well fluid pressure after this conversion.

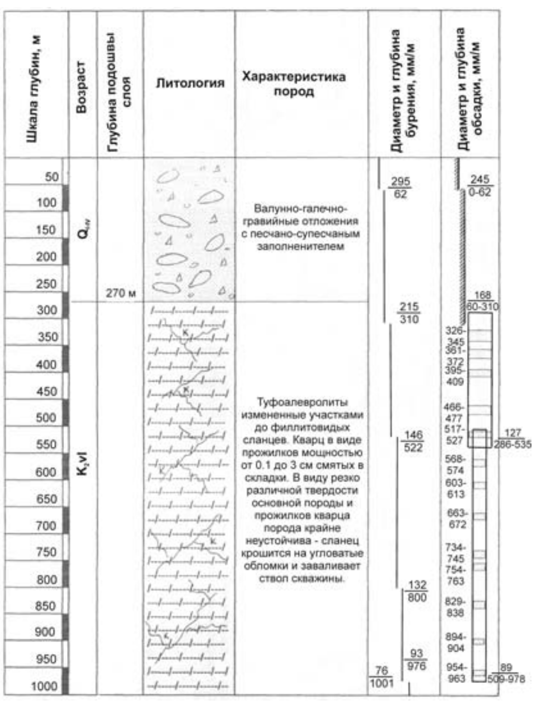

Figure 1: Lithologic column and casing of the well YZ-5.

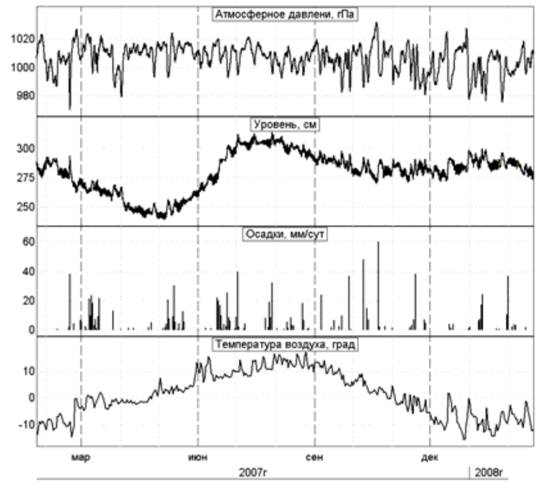

Figure 2: Well UZ-5 observational data collected from Jan. 25, 2007 to Feb. 20, 2008. From upper to lower graphs: barometric pressure (hPa), water level (cm), precipitation (mm/day), air temperature (°C).

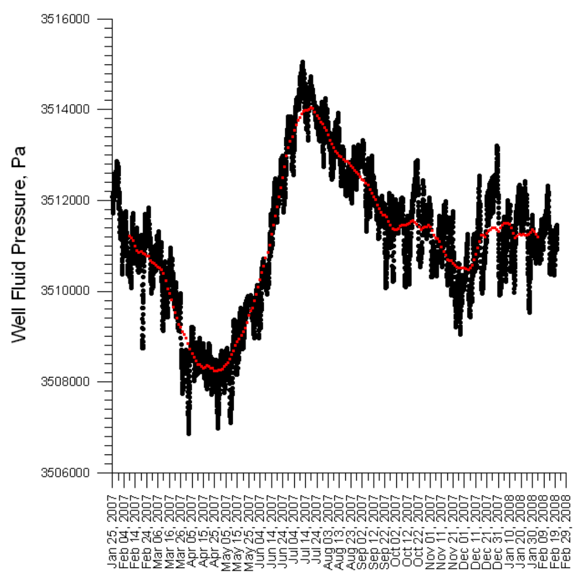

Figure 3: Well fluid pressure, converted from original water level data (Fig. 2). The systematic component, estimated as the moving average approximation, is shown by the dotted red line.

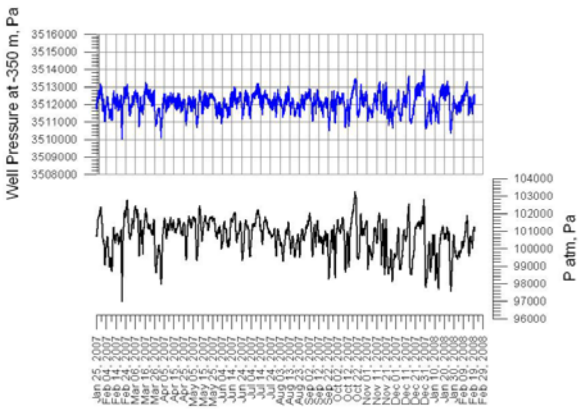

Figure 4: Well fluid pressure (upper graph) and atmospheric pressure (lower graph) used as observational data for model calibration.

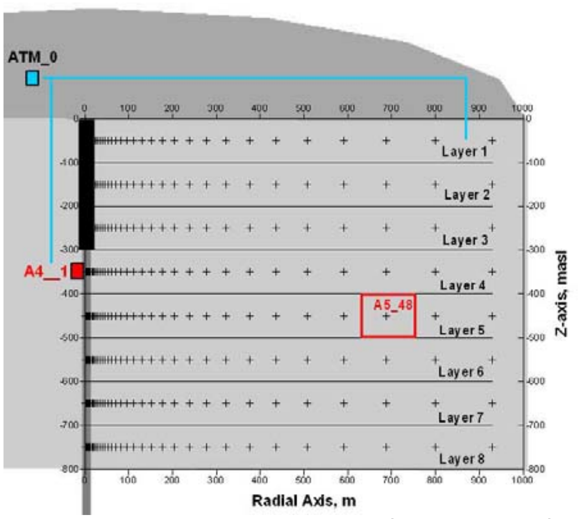

Figure 5: Vertical cross-section of the right half of the RZ2DL numerical grid well-reservoir system: reservoir element centers are shown by crosses, element A5_48 is shown as an example of grid element naming convention ('5' corresponds to Layer number, '48' is the element number in radial grid sequence), ATM_0 is the element, where time dependent boundary atmospheric pressures are specified, A4__1 is the element representing the well.

It is clearly from Figs. 2 and 3 that seasonal systematic changes of the water level (fluid pressure) took place in well YZ-5: level drawdown from January 2007 until May 2007 (winter recharge shortage period), then June-July 2007 level build up (spring flood time), and also second water level build up (probably related to autumn floods events). Since we have no exact knowledge on the hydrogeological basin and recharge/discharge conditions, it was assumed that the well fluid pressure may be split into a systematic component and a more high frequency residual component. The systematic component was estimated using Grapher-3 as a running average approximation with a window width of 721, which corresponds to one month of the observational time(Fig. 3). The more high frequency residual component assumed to be caused by the atmospheric pressure change. Fig. 4 shows well fluid pressure and atmospheric pressure change used as observational data for model calibration.

NUMERICAL GRID GENERATION AND MODEL PARAMETRIZATION

The TOUGH2 mesh maker was used to generate a radially symmetric two-dimensional grid (RZ2DL) (Fig. 5). The numerical model represents a well-reservoir system as a cylindrical space with an outer radius of 1000 m and a height of 1000 m, and a well located in the vertical axis position. The model cylinder, representing the reservoir, is divided into eight 100 m thick layers, each layer consisting of the fifty radially incremented elements starting from well radius of 0.073 m; the total number of the elements used is 400. The well, represented by a single element, A4__1, which belongs to the fourth layer positioned at 350 m depth, is characterized by the average well radius of 0.073 m and lumped well volume of 13.39 m^3; it is connected to element A4__2 of the reservoir with the interaction area of 45.87 m^2. An inactive element ATM_0 is used to specify change of the atmospheric pressure. This element is connected to the well element A4__1 and to all elements of the reservoir upper layer A1_**.

Three domains are specified in the model: POMED, includes the three uppermost layers of the reservoir, corresponding to the alluvial and volcanic avalanche deposits; BASE1 represents five layers of the reservoir basement, corresponding to quartz veined metamorphic sandstones and slates of Cretaceous age; and WELL1, which is the well domain (element A4__1).

LONG TERM INVERSE MODELING

iTOUGH2 inverse modeling is used to match the calculated and observed data of the well fluid pressure change during the time interval Jan. 25, 2007 to Feb. 20, 2008.

The following parameters are to be estimated: reservoir porosity ϕ_r, reservoir permeability k_r, reservoir compressibility c_r and well permeability k_w.

The multi-parameter inverse modeling used 941 equally spaced (10 hr interval) calibration points based on observational data. Inversion results can be summarized as follows:

1. The model matches the observed well fluid pressure change reasonably well; the standard deviation (root mean squared residuals) is 302 Pa, mean (mean of residuals = bias) is 69 Pa (Fig. 6);

2. Reservoir permeability k_r and well permeability k_w are found to be the most sensitive model parameters; reservoir porosity ϕ_r and reservoir compressibility c_r are less sensitive; nevertheless, all four parameters can be estimated (Table 1);

3. Reservoir permeability k_r and well permeability k_w have a strong correlation coefficient of 0.993, reservoir porosity ϕ_r and reservoir compressibility c_r are 60-150 times less sensitive compared to permeabilities, hence uncertainty of these estimates is rather large (Table 1);

4. There is no significant effect of the barometric pressure transmission through overlaying layers into the aquifer; the most atmospheric pressure change is transmitted directly through the well. Spatial analysis of the barometric wave propagation in the well-reservoir system after more than 1 year of modeling time shows that Layer 2 elements are not effected at all by barometric pressure changes, and the horizontal propagation along Layer 4 is limited to about 0.9 m.

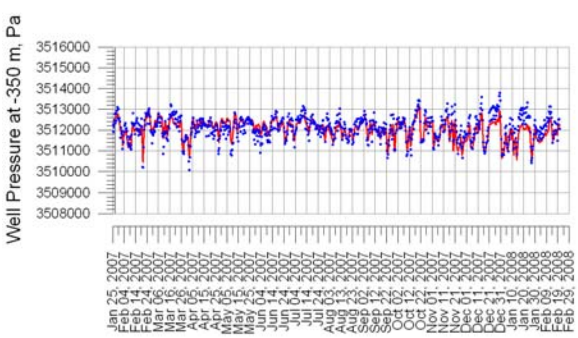

Figure 6: Match of long-term data: modeled well pressure (red lines), observational data (blue dots).

Table 1: iTOUGH2 parameter estimates and their uncertainties for inversion of long-term data.

Estimated parameter	Value	95% confidence interval
Reservoir permeability k_r, mD	1.14×10^{-3}	0.55×10^{-3} – 2.40×10^{-3}
Well permeability k_w, mD	14.9	7.6 –33.0
Reservoir porosity ϕ_r	0.110	0.050–0.170
Reservoir compressibility c_r, Pa^{-1}	1.7×10^{-4}	0.4×10^{-4} – 6.8×10^{-4}

SHORT TERM INVERSE MODELING

iTOUGH2 inverse modeling was also applied to a more detailed sub-set of observational data, obtained during the time interval from Dec. 1, 2007 to Dec. 31, 2007, when more frequent records were obtained (data sampling each 10 min.). It was done to check the possibility to estimate compressibility-porosity parameters based on higher time resolution observational data.

The multi-parameter inversion was based on 447 equally spaced (100 min interval) calibration points. The following results were obtained:

1. The model matched observational well fluid pressure changes very well: standard deviation (root mean squared residuals) is 202 Pa, the mean of the residuals is 29 Pa (Fig. 7);

2. Reservoir permeability k_r and well permeability k_w are found to be the most sensitive model parameters; reservoir porosity ϕ_r and reservoir compressibility c_r are less sensitive; nevertheless all four parameters can be estimated (Table 2);

3. Reservoir permeability k_r and well permeability k_w have a strong correlation coefficient of 0.977, reservoir porosity ϕ_r and reservoir compressibility c_r are 15-30 times less sensitive compared to permeabilities, hence, the uncertainty of the estimates is rather large (Table 2);

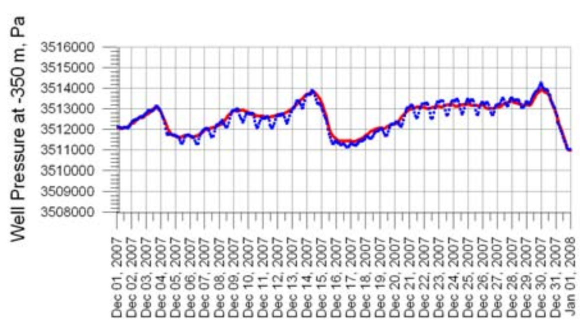

Figure 7: Match of short-term inverse modeling data: modeled well pressure (red lines), observational data (blue dots).

Table 2 iTOUGH2 parameters estimates and their uncertainties for short term inverse modeling.

Estimated parameter	Value	95% confidence interval
Reservoir permeability k_r, mD	0.39×10^{-3}	0.27×10^{-3} – 0.55×10^{-3}
Well permeability k_w, mD	8.4	6.1–11.8
Reservoir porosity ϕ_r	0. 087	0. 083–0.091
Reservoir compressibility c_r, Pa^{-1}	5.2×10^{-6}	3.7×10^{-6} – 7.5×10^{-6}

DISCUSSION

The inversion of short-term, high-frequency data yields more certain and reliable parameter estimates compared to the inversion of long-term data. Nevertheless, long-term monitoring data are needed to refine observational data and extract the seasonal component. The 95% confidence intervals of the three parameters (reservoir permeability k_r, well permeability k_w, and reservoir porosity ϕ_r) estimated with short- and long-term data overlapped (Table 1 and 2), suggesting robustness. Compressibility is the least sensitive model parameter and thus has a large uncertainty.

The term and value of "barometric efficiency" (BE = $\delta P / \delta P_{atm}$) is often used for reservoir compressibility estimations, based on qn expressions similar to equation (1). Nevertheless, this is not valid for the cases analyzed above. As shown by inverse modeling, the value of barometric efficiency is mostly related with well-reservoir system permeability, since compressibility is the least sensitive model parameter and the volume influenced by barometric pressure change is limited to one meter around the perforated well interval.

As an example, Fig. 8 shows the best-fit modeling case with BE= 0.58; the value of BE increases to 0.93 if permeability is increased by two orders of magnitude, and decreases to 0.02 with a permeability decrease of two orders of magnitude.

On the other hand, a four-order-of-magnitude compressibility change produces a BE range from 0.58 to 0.65 only (Fig.9).

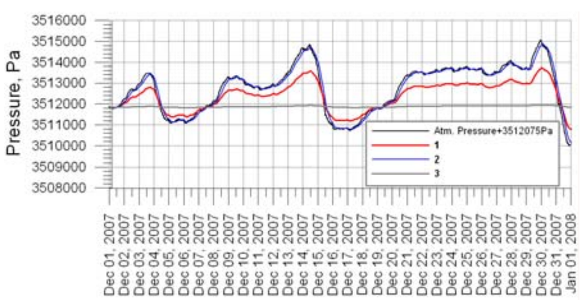

Figure 8: Model sensitivity to permeability change: observed barometric pressure change +3512075 Pa; 1 - short-term inverse modeling (best fit); 2 – calculated pressure with two-orders-of-magnitude permeability increase; 3 – calculated pressure with two-orders-of-magnitude permeability decrease.

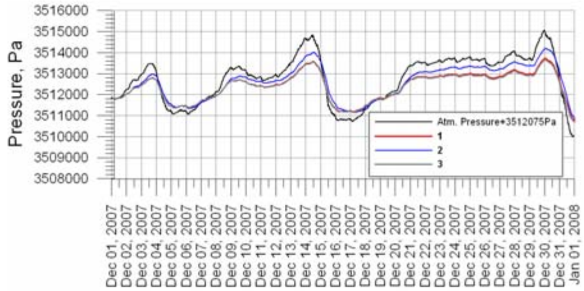

Figure 9: Model sensitivity to compressibility change: observed barometric pressure change +3512075 Pa; 2 – calculated pressure with two-orders-of-magnitude compressibility decrease; 3 – calculated pressure with two-orders-of-magnitude compressibility increase.

CONCLUSIONS

1. More than one year of water level records in Well YZ-5 show a systematic component, which is related to hydrogeological basin recharge/discharge conditions. Before the inversion, this systematic component was removed, and water level was converted into well fluid pressure.

2. iTOUGH2 inverse modeling was used to match the well fluid pressure change during the time interval bewteen Jan. 25, 2007 and Feb. 20, 2008 as well as a more detailed sub-set of data between Dec.1, 2007 and Dec. 31, 2007. The model uses atmospheric pressure change as time-dependent Dirichlet boundary conditions at the well head and the earth surface. Four parameters (well and reservoir permeabilities, porosity and compressibility) were estimated. The most sensitive model parameters are well and reservoir permeabilities, with mean values estimated as 8-15 mD and 0.4×10^{-3} - 1.1×10^{-3} mD, respectively. Reservoir porosity and reservoir compressibility are less sensitive; they are estimated as 0.087-0.110 and 5.2×10^{-6} - 1.7×10^{-4} Pa^{-1}, respectively. The relatively large compressibility values may caused by drilling mud sealing of the fracture system adjacent to the well. The modeling shows that atmospheric pressure propagation into the reservoir is limited to about one meter around the perforated well interval, mainly transmitted through the well head rather than the formation.

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