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Simulation of a Novel Groundwater Lowering Technique using Arbitrary Lagrangian-Eulerian Method

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Abstract: A novel method for groundwater lowering, which can be applied at construction sites, for aquifer remediation measures or in open mining, is proposed. In contrast to conventional techniques, dewatering is achieved without water conveyance. In this paper the physical concept of the new technology, referred as single borehole pump & inject, is modeled using COMSOL Multiphysics. Two and three dimensional models are developed respectively and potential equation derived from Darcy's law is solved. The dynamics of hydraulic head changes in unconfined aquifer is modeled using arbitrary Lagrangian-Eulerian (*ale*) moving mesh method. Numerical results from the model show the same trends as measured data from field experiments.

Keywords: Groundwater lowering, pump and inject, *ale*, Darcy's law

1. Introduction

Groundwater is extracted not only for water supply, but also for the land use demand. Large scale groundwater extraction is widely used in dewatering business especially at underground mining, urban construction and flood control sites.

The conventional approach to dewatering is to pump water out to the surface from one or more pumping wells to decrease the groundwater table in the vicinity of the pumping wells (Cashman 2002, Powers 2007). The pumped water is normally re-injected into the ground at a distant location or discharged directly into a nearby surface water body. The high pumping rate in boreholes and inadequate groundwater recharge are the principle reasons for environmental problems, e.g. land subsidence, groundwater and/or surface water contamination.

Düsensauginfiltration (DSI), literally translated as 'Nozzel-Suction-Infiltration', is an alternative dewatering method introduced by W. Wils (2010). Unlike the state-of-the-art installations, water is not withdrawn above the ground but injected back into the deeper part of the aquifer. Hence, groundwater lowering is achieved and the water contamination is prevented by avoiding unnecessary groundwater extraction.

The challenge of modeling such systems is to define the complicated physical boundary conditions in fluid dynamics and to provide insight into the system's behaviour. Using COMSOL Multiphysics we have constructed 2D and 3D steady-state models which couple the groundwater flow with the moving boundary and moving mesh mode, as the model region is identical with the saturated part of the aquifer that changes due to drawdown. We also analyzed the parameter sensitivity through a simplified approach for steady-state in a 2D vertical-cross-section.

Ongoing field experiments accompany the model work. These are performed at Plötzin in Brandenburg and Korschenbroich in North Rhine-Westphalia in Germany within the framework of DSI-project funded by Deutsche Bundesstifung Umwelt (DBU).

2. Principle

The concept of DSI method is visualized in the sketch in Figure 1. Groundwater is pumped at the upper part (light green color region) of the borehole. Similar to classic pumping, hydraulic pressure around the pumping region declines and consequently creates drawdown at the borehole and its surrounding. The pumped water is injected at the same rate deeper in the borehole (light orange color region). Near the injection position the pore water pressure rises forming a hydraulic barrier for the flowing groundwater.

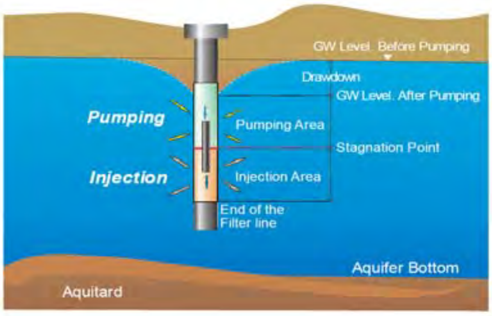

Figure 1. Sketch of the single borehole pump & inject concept

The increased pressure is more effective in horizontal directions rather than upwards to the drawdown region. This will be shown by numerical models described herein.

In addition some packers are used to separate the pumping and infiltration part of the borehole. A stagnation location appears at the borehole, where packers are installed. The location of the stagnation location may also be affected by disturbed conditions in the direct vicinity of the borehole due to drilling, i.e. the skin zone.

3. Governing Equations

In the model we solve the groundwater flow equations, which are derived from empirical Darcy's law and the principle of fluid mass conservation:

$$\nabla\left(\rho\cdot\mathbf{u}\right)=0 \qquad\qquad \mathbf{u}=-\frac{k}{\mu}\nabla p \qquad\qquad (1)$$

The system is analyzed at steady state. ρ denotes fluid density, μ the viscosity, k the permeability and p pressure. From p as main dependent variable we calculate the velocity vector $\mathbf{u}$ and hydraulic head h.

4. Use of COMSOL Multiphysics

COMSOL Multiphysics 4.2 was used to set up the models. The main objectives of modeling are 1) to evaluate the groundwater flow parameters by comparing the numerical results with measured data from the experiments and 2) to predict the tendency of the system accurately when parameters are varied.

Two modules, Darcy's Law (*dl*) and Moving Mesh (*ale*), were used in the model. Darcy's module uses pressure p as dependent variable and determines the hydraulic head in time and space. In order to compute the deformation of the unconfined aquifer, arbitrary Lagrangian-Eulerian (*ale*) module was applied. Parameters were evaluated mainly through 2D model. A 3D model provides a better representation of more complex situations, in which it is possible to take inhomogeneities and ambient groundwater flow into account. The 3D model was set up by applying the calibrated parameters from the 2D model.

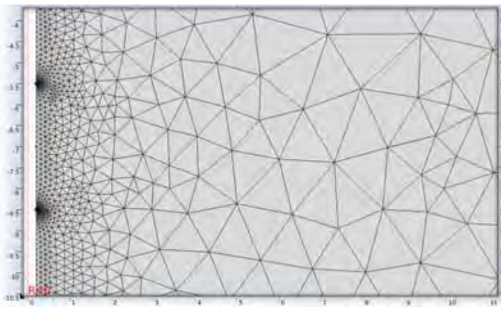

Figure 2. Finite element mesh of 2D model region with the well at the left side of the vertical cross-section; refined in the vicinity of pumping and infiltration points.

4.1 Geometry and Meshing

The axisymmetric 2D vertical-cross-section model used radial coordinates around the well.

The 3D geometry was built by extruding a *xy*-work plane. The borehole was implemented as a hole (circle) in the middle of the work plane and extruded together. To implement different flux boundary conditions (see details below), the work plane was extruded four times in different scale respectively, yielding a system with 5 layers. Eventually, the borehole appears as a cylinder in the middle of aquifer domain.

Triangular (2D) and tetrahedron (3D) finer meshes were used by default. Further meshing was made with a drastic refinement in the vicinity of the borehole especially near the pumping and infiltration positions (see Figure 2 for the 2D case).

4.2 Boundary Conditions

The model region concerns the saturated part of the aquifer, which has the groundwater table as upper (free) boundary and the aquifer base, i.e. aquitard, as lower boundary. The boundaries as well as the model domain are shown in Figure 3.

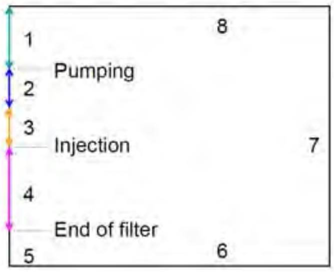

Figure 3. 2D vertical-cross-section geometry with labeled boundaries

Boundary 8 is a free boundary which will change from the fixed position, shown in Figure 3. Boundary 1 shrinks correspondingly. In the *dl*-mode we took no-flow as boundary condition at the groundwater table, i.e. it was assumed that there is no groundwater recharge. The atmospheric condition was required at the free surface directly (expressed by a Dirichlet condition) in the *ale* mode (details see below).

At the aquifer base (boundary 6) and from the end of the filter to the bottom of the aquifer (boundary 5), we required no-flow boundary.

Zero hydraulic pressure condition across the model edges was specified at outer boundary (7) for pressure constrains.

The borehole itself was divided into four parts (boundary 1~4) and different mass flux conditions were applied for pumping and infiltration activities respectively.

- Above the pump location (1)
- Between pump location and stagnation point (2)
- Between stagnation point and infiltration level (3)
- Between infiltration level and the base of aquifer (4)

The mass flux conditions were differentiated according to the specified radial velocity in equation (2)

$$v_r = \frac{\theta Q_{well}}{2\pi r_b H}\log\left(\frac{z-z_s}{H}\right) \qquad (2)$$

Radial velocity v_r was given by this logarithmic distribution at both upper and lower side of pumping and infiltration points, as function of variable depth z. The influencing parameters were the pumping/infiltration rate Q_{well}, pumping or infiltration depth z_s, region length H, and the water distribution factor θ. For θ = 0.5 equal distribution of water flux above and below the pumping or infiltration positions were obtained.

In *ale* mode, the whole domain is free to deform. At boundary 2 to 7, zero displacement in horizontal and vertical directions was enforced. In the borehole above the pump (boundary 1), mesh is free to deform vertically and zero displacement was applied in horizontal direction. At the groundwater table (boundary 8), the boundary condition forced the total pressure to match the atmospheric pressure, which is expressed by the condition:

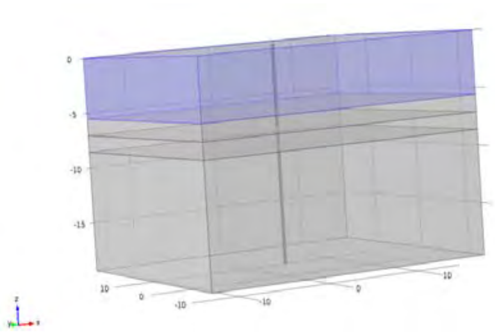

Figure 4. 3D model set-up.

$$z = h \qquad (3)$$

where z denotes the vertical coordinate and h hydraulic head. At boundary (1) we required vertical deformation only. The boundary term (given by eq. 2) also has to be modified in order to account for the shrinking of the pumping region above the pump position.

In the 3D model, the same mass flux boundary conditions were applied respectively for all surrounding sides of the borehole. Although the model consists of four different domains, the continuity between domains was not necessary to set up additionally. Setting domain by extruded work-plane automatically provides continuity between the connected domain boundaries (see Figure 4).

4.3 Input Parameters

Following parameters (see table 1) were used in the model to demonstrate the concept. The pumping and infiltration rates are given according to one of the field tests. Typical values for hydraulic conductivity and porosity for sandy aquifer are used. The aquifer material as well as aquifer depth are determined through the direct push test in the field. The reference model data were oriented at Plötzin site.

Table 1: Input parameter values for model set-up

Parameters		
Name	*Value*	*Unit*
Hydraulic conductivity	$1.5 \cdot 10^{-3}$	m/s
Pumping rate	22	m^3/h
Infiltration rate	22	m^3/h
Porosity	0.25	–

In the result analysis, we used parameter sweep to vary the pumping and infiltration rate to predict the drawdown changes.

5. Results and Discussion

5.1 2D & 3D Model Result

Figure 5 illustrates a typical result obtained with 2D model concerning the vertical cross section for a single borehole (in the figure on the left). The velocity field (arrows), equal-potential contour field (filled line), and the hydraulic head profiles are calculated by the model.

As it is shown in the result, hydraulic head is lowered at the upper part of the borehole (indicated with blue color), and consequently drawdown is created. The result displays around -1 meter as the lowered hydraulic head. However, the actual water displacement was only 0.04m (see Figure 7) according to the calculation. The enlarged drawdown here is created due to the scale factor (70 is used in the deformation) in COMSOL. For the velocity arrows and the contours, the same deformation scale factor is applied. At the lower part of the borehole, the increase of the potential hydraulic head is displayed with dark red color. Furthermore, the velocity field in the diagram indicates also the groundwater flow directions.

Comparison between field experiments and the model results shows that the fundamentals of the DSI-technique are understood already. The quantitative values are still not accurate enough because not all the aquifer parameters i.e. well skin zone, anisotropy factor, water distribution factor θ, were calibrated in the model. However, qualitatively, in terms of understanding and capturing the physics of the system, the result is promising. It proves that drawdown is feasible within the aquifer, even if water is injected in the lower part.

In case of monitoring multi DSI boreholes, in order to consider the horizontal inhomogeneity (right and left side of the borehole) factors of aquifer, three dimensional models were required. In figure 6, we demonstrate an example view of the 3D model result.

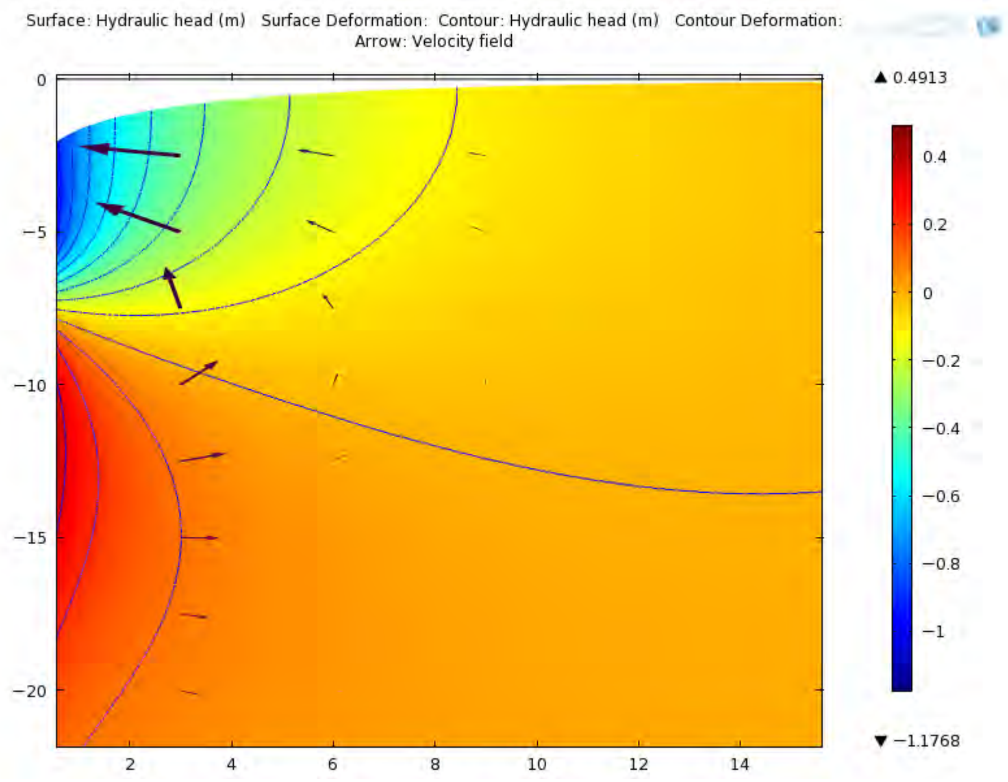

Figure 5. Example of 2D vertical-cross-section model output

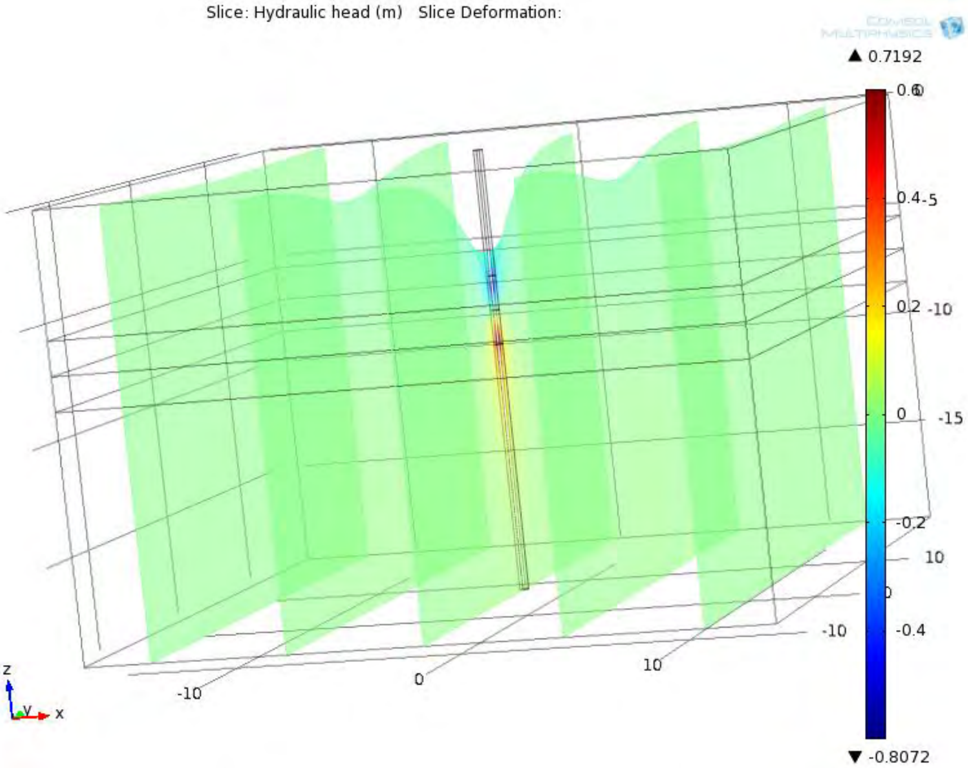

Figure 6. Example of the slice view of 3D model output with hydraulic head profile of the borehole.

In the example, we show five vertical slices. The same colors (blue for low hydraulic head, red for high hydraulic head) are used here to have consistency with 2D result. The lowered groundwater table is displayed by deformed geometry with the scale factor of 150.

5.2 Parameter Variation

Using COMSOL Multiphysics, parameter variations can easily be done using *parametric sweep* as solver options. We performed an extensive study with the focus on the infiltration rates while keeping the pumping rates constant. This enables the comparison with the classical pumping test (where infiltration is zero).

Figure 7 shows the variation of the infiltration rates. The hydraulic head changes along the groundwater table (boundary 8 in Figure 3) are displayed for different infiltration rates. Here, the pumping rate is given as a constant value, 22m^3/h (around 0.006m^3/s). To compare the drawdown of DSI system with the classic pumping test, infiltration rate is varied from zero to 0.006m^3/s, which is the same with the pumping rate, with the interval of 0.001m^3/s (result is shown at the top of figure 7). Hydraulic head is lowered to -0.16m (blue curve in figure) under the classic pumping test condition. Higher hydraulic head is observed with increasing infiltration rates. When the same pumping and infiltration rates are applied (dark green curve), it results -0.8m hydraulic head.

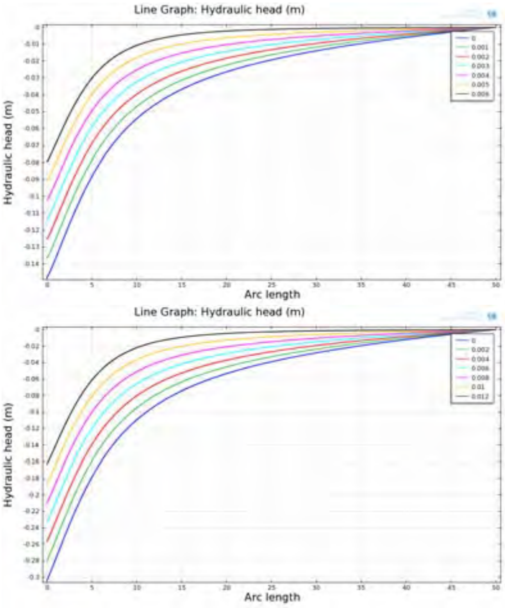

Figure 7. Decreased drawdown with the increasing infiltration rate: (Top: 0 ~ 22 m^3/h, Bottom: 0~ 44 m^3/h).

Our results indicate that compared with the state-of-the-art pumping test (only pumping), half of the drawdown is obtained by using the DSI-technique with equal pumping and infiltration rates.

The discussed result above lead us to another parameter variation study. If the pumping and infiltration rates are doubled (44m^3/h around 0.12 m^3/s), do we reach the hydraulic head of -0.16m? A positive answer is obtained by the second parameter sweep result, shown at the bottom of figure 7. The same drawdown (dark green in the bottom figure) is observed when the pumping and infiltration rates are both increased to 44 m^3/h. Moreover, double drawdown (-0.3m) is achieved with the conventional dewatering method.

However, the limitation of the infiltration rate in reality has to be considered. The infiltration requires an overpressure while the pump has a limited power, bounding the pumping or infiltration rates.

6. Conclusions

In the paper, we demonstrated a novel dewatering method and studied the applicability of the concept through modeling COMSOL Multiphysics models. The model results show that the DSI method is promising. The advantage of the DSI method, concerning the environmental and economical benefits, guarantees its optimistic future in dewatering industry.

However, the method also has its limitations. First, it can be only applied for permeable aquifers (sand, gravel as the main material). Moreover, high pumping and infiltration rates might create a water flow shortcut in the direct vicinity of the borehole. Also, a dynamic and long term study, considering the temporal or long time seasonal changes in groundwater recharge, has to be performed.

All in all, COMSOL Multiphysics is a helpful tool to understand the presented physics. We were able to compute the hydraulic head changes as well as the velocity fields of the system.

More systematic investigation on specific sites, including the field test and model simulation, will be arranged in the future. The influencing parameters will be intensively evaluated through sensitivity tests for the field test. We plan to use the inter connection of COMSOL with MATLAB to have a detail analysis of the parameters.

7. References

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7. Acknowledgements

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