USING DIFFERENTIAL RECHARGE IN ORDER TO AVOID SALT WATER INTRUSION

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ABSTRACT

Saltwater intrusion control systems perform an effective piezometric action especially when they are made up by a recharging barrier.

This system can undergo a crisis along the coasts due to natural or anthropic factors, for example the tides and the waterways presence, able to skew the piezometry and thus making ineffective the barrier systems.

As in most of the cases, this problem appears when the discharges that can be extracted or injected are very small: in many cases, the salt water intrusion goes on, particularly in most permeable layers.

We would like to determine on the basis of recent experiences within which limits it is possible to obviate to the drawbacks deriving from this factor.

1 OPTIMAL RECHARGE THEORY

1.1 FACTORS WHICH AFFECT THE EXTENSION OF MARINE INTRUSION

With regard to confined aquifers, J. Bear has suggested the following relationship among the distance L from the sea at which the saline intrusion front propagates, the conductivity K of the aquifer and the unitary discharge q (m^2/s):

$$L = KB^2/2qG \tag{1.1}$$

In this relationship G represents the ratio between the fresh water density and the density difference between fresh water and salt water, which Ghyben and Herzberg set on average equal to 40.

If we apply Darcy relationship, which says that the unitary discharge q (confined aquifer discharge divided by the width of the flow section) is equal to the product of the hydraulic gradient J times the aquifer thickness B, times the hydraulic conductivity K, the previous relationship can be simplified in this way:

$$L = B/2GJ \tag{1.2}$$

If $G = 40$, it is possible writing:

$$L = B/80J \tag{1.3}$$

Thus the distance of the marine intrusion front from the sea basically depends on the hydraulic gradient (the higher J is, the lower the distance L is) and on the aquifer thickness, whose dependence with L is directly proportional. Since aquifer thickness and hydraulic gradient represent the factors which actually influence the intrusion extension towards the inland and the piezometric head basically controls the interface depth, it seems to be possible to keep the stability of the saline wedge advance front and its depth operating on these factors.

One of the most widespread method used in order to prevent the saline wedge extension towards inland and to deepen the fresh water - salt water interface is to recharge the aquifer by means of wells, in which a moderate raising occurs, propagating up to the interface, which in this way undergoes a lowering.

In the case of stratified soils and heterogeneous alluvial sediments, in which different conductivity layers follow one another vertically, a recharge cone occurs in the well with a different extent according to the depth and the aquifer trasmissivity. The recharge effectiveness varies thus according to the vertical series of the aquifer trasmissivity; as a matter of fact, this study deals with the discharge optimization problem of recharge barriers in coastal environments. It is thus seen to be useful to lay out the criteria to be followed in order to obtain, for the same injected discharge, the maximum performance in lowering the interface.

In order to better understand the optimal recharge theory it would be very interesting to compare the effects on piezometry caused by the recharge performed with the traditional techniques with the ones obtained recharging only the most suitable layers. The following chapter gives precisely the description of this comparison, carried out with the aid of Feflow software (Wasy GmbH).

2 MODEL TESTS

2.1 ANALYSIS AND COMPARISON OF THE REMEDIAL TECHNIQUES

To avoid the salt water intrusion, a differential recharge method has been tested, on the basis of numerical modelling. Three cases have been tested:

1. Recharging the whole aquifer system, consisting of two aquifers, with the same flow rate;
2. Recharging with different flow rate the aquifers, according to their hydraulic conductivity

This comparison takes place developing the model first of all with the traditional techniques and afterwards with the ones resulting from the selective recharge.

2.2 MODEL DESCRIPTION

The heterogeneous model has been implemented in Feflow (Diersch, 1996) which allows to evaluate precisely the salinity distributions with depth in the studied site.

By example, let's make the hypothesis that there are two aquifers in a specific zone and the uppermost one has a trasmissivity T1 much lower than the one, named T2, of the deepest aquifer. The two layers are divided by a clayey level which represents the aquiclude within the model.

The hydrogeological system lies near to the coast and the saline wedge moves forward in the deepest aquifer. Therefore it turns out necessary to limit the wedge advance by means of a barrier of injecting wells.

A common and wrong habit tends to reclaim injecting in the uppermost aquifer but this operation is not giving any benefit since the water injected is likely to disperse in the uppermost strata of the aquifer.

In order to make the barrier as effective as possible, the injection needs to take place as deeply as possible and in the most transmissive layer. The injection in depth makes the water disperse less and the higher permeability allows water to contrast more easily the wedge.

2.3 THREE LAYERS MODEL

The density-dependent model, shaped as a parallelepiped, represents, starting from the soil surface with increasing depth, at first a less transmissive aquifer, then a clayey level and in the end an aquifer more transmissive than the first one.

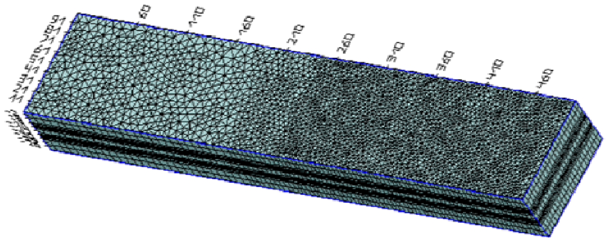

Figure 1 – Three dimensional model

2.3.1 Domain discretization

The vertical discretization is rather marked: there are actually 20 slices over a depth of 29 m. The clay bed is at a depth between 12 and 17.5 m.

The 20 slices, grouped together in three, represent the three hydrogeological units according to the following intervals:

1. the less transmissive aquifer with $T_1 = 1 \cdot 10^{-5}\, m^2/s$ is between the first and the 8th slice;
2. the clayey stratum with $T_A = 3 \cdot 10^{-8}\, m^2/s$ is between the 9th and the 12th slice;
3. the most transmissive aquifer with $T_2 = 1 \cdot 10^{-2}\, m^2/s$ is between the 13 rd and the 20th slice.

Figure 2 shows the horizontal discretization: the mesh is made up of 100320 triangular prismatic elements, each of them having 6 nodes. In order to have a valid mesh, no element can be obtuse and all of them must satisfy Delaunay criterion. This criterion says that the triangular face of each element must be circumscribable in a circle [1][2].
The length along the x axis is 500 m and the width along the y axis is 100 m.

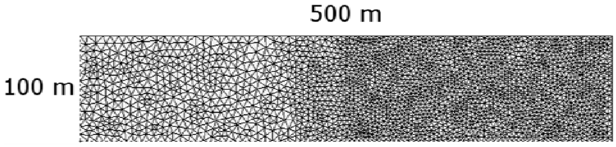

Figure 1 – Plant view of the mesh

2.3.2 Boundary and initial conditions

The following boundary conditions have been assigned to all the slices:

- longitudinal dispersivity α_L is equal to 16 m: α_L is a measure of the porous media heterogeneity at a microscopic scale, due to the meatuses and solid matrix presence;
- transversal dispersivity α_T is equal to 1.6 m: α_T is of a order of magnitude 10 or 20 times smaller than α_L;
- the ratio $\frac{\rho_s - \rho_d}{\rho_d}$, named *density ratio*, is equal to 0.03 where:
    - ρ_s is the saltwater density, equal to 1030 kg/m^3;
    - ρ_d is the freshwater density, equal to 1000 kg/m^3.
- a head loss of $i = 5‰$, with a head of $h = 2.5\ m$ at the left side of the model and $h = 0\ m$ at the right side of the model, in order to set up a flux which goes from the left to right of the model;
- the boundary condition *Well* in the uppermost aquifer (from the 1st slice to the 8th) and in the deepest one (from the 13th slice to the 20th) with a total discharge equal to $Q = 6.56\ L/s$.

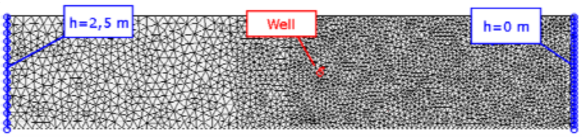

Figure 2 – Boundary conditions *Head* and *Well*. The first one is applied to all the slices, the second one is applied to all of them except those from the 9th to the 12th.

- the salinity initial condition equal to 2500 mg/L on all the slices of the model.

2.3.3 Simulations results

The scientific literature demonstrates that the saltwater intrusion can be avoided injecting fresh water in a series of wells. We have simulated the effects of the freshwater injection by means of the previously described model, with the aim of highlighting that providing a different inflow rate in the wells, according to the changes of permeability , can improve the effects of injection.
Therefore, have been carried out two simulations:

1. the fresh water has been injected by means of two wells, either having the screen slots in the more transmissive aquifer, the other in the less transmissive; the flow rate of two injection wells are the same

2. the fresh water has been injected with a flow rate proportional to transmissivity of the aquifer.

The injection well is identified with the letter **a** (Figure 3) and it is set on the crossing of the two sections along which the model is going to be studied.

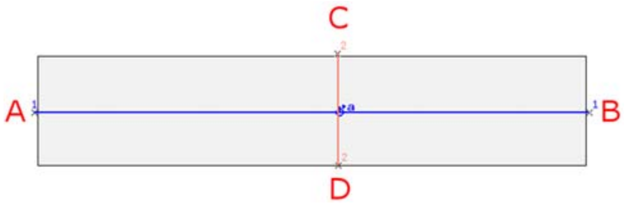

Figure 3 – Model top view with the two sections A-B and C-D

1. Injection at the same flow rate causes, according to Dupuit's formula, a piezometric rise bounded by a quasi parabolic outline. The shape of this "recharge zone" is identical to capture zone of a pumping well. The ratio of front width of two wells is the inverse of the ratio between the transmissivities. The same results are obtained from the simulations, injecting freshwater in a well which has the screens located in both aquifers with different transmissivity. We have inferred that in aquifers stratified with different transmissivities, often the recharge can not avoid the salt water intrusion, where the transmissivity is higher.
2. Injection of a flow rate proportional to transmissivities, generates a "recharge zone" of a same shape and width. In these conditions, the simulations demonstrates that occurrence of salt water intrusion in more permeables aquifer sections disappears. Therefore, the differential recharge, i.e. the using freshwater flow rates proportional to transmissivities at different depth, can be a good solution in many cases of vertically heterogeneous aquifers.

3 DISCUSSION OF RESULTS

The simulations improve the hypothesis that the differential recharge can have good effects effects on the freshwater maintenance along the coasts, avoiding the saltwater intrusion in more permeable parts of the aquifer.
For this reason, we have take into account the criteria for evaluating, the "recharge zone" limits considering the transmissivity vertical changes; the differential recharge implies the calculation of outlines of recharge zone for different depth. This calculations is the same used for the wells "capture zone", and several methods have been proposed. The difficulties arise from the fact that the saltwater intrusion has an extent of many hundred of meters; therefore number of recharge wells are required , generating an hydraulic recharge barrier.

For the calculation of recharge barrier limits, analytical methods has been presented by Shan (1999), Christ and Goltz (2004), and a new model for lot of wells has been developed (Colombo et al., 2012, in press). This model considers not only a number of wells N≥2, but also the possibility to locate the wells everywhere in the complex plain (x, y). To use this models, any simplifications are necessary: the aquifer must be homogeneous, isotropic, confined, with an uniform B thickness and constant Darcy velocity J. The flow is steady-state. The complex potential w (Javandel and Tsang, 1984), by the linearity of Laplace equation, can be expressed as the superimposition of effects of a system formed by N injection or pumping wells and the groundwater.

To obtain the formulation of the capture curve function, it needs at first to evaluate the function of the flow in the stagnation point, corresponding to velocity equal to 0.
Another successful method consists of numerical modelling of the recharge zone by means of Feflow (Diersch, 1996).

These methods allow to trace successful the limits of the recharge barrier, even in hydrogeological complex conditions, as the scientific literature demonstrates; therefore we believe that the differential recharge can be carried out without remarkable difficulties.

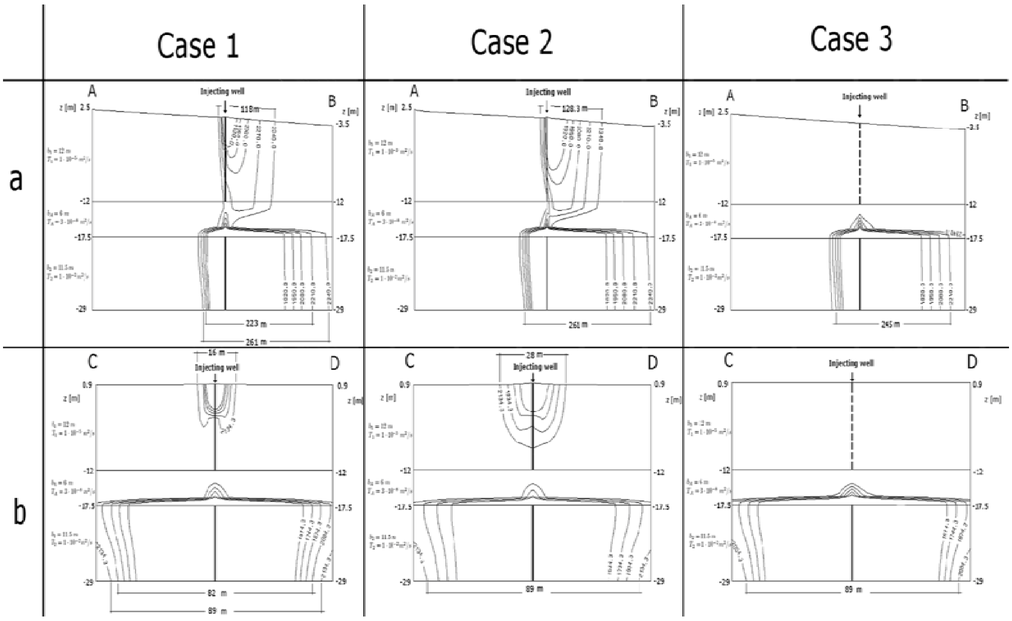

Figure 5 – Effects of differential recharge in two layered aquifer with different transmissivity. Between the aquifers, is located a thin aquiclude. The simulations demonstrates the possibility of generate large extension changes of injected freshwater in salty aquifers, by means of employing different flow rates in the aquifers.

4 REFERENCES

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