Groundwater models as civil engineering tools

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Abstract The building of groundwater flow models has become a matter of practice for many hydrologists. Originally these models were mostly regional models used for large and long-term projects, such as groundwater recharge studies for water supply companies, artificial storage and recovery, and environmental impact assessments. Nowadays numerical models are increasingly used to simulate short-term and small-scale projects, such as construction dewatering, dumping-grounds, groundwater remediation and urban hydrology. Basically, models for such small-scale projects do not differ much from models for regional projects. However, it is the limited size of the area of interest, the distribution and quality of the available data, and the influence of local heterogeneities that may produce particular problems. The small-scale groundwater systems simulated in civil engineering groundwater models are sensitive to local details in hydraulic properties and boundary conditions. Generally speaking, the finite-element method is more suitable for solving these civil engineering problems than the finite-difference method. Irregular finite-element grids allow for much more flexibility of internal and external boundaries, but a smart generator is required to create a well-organized, advantageous finite-element grid.
Key words numerical modelling; finite elements; small-scale model; civil engineering

INTRODUCTION

Numerical models are increasingly employed to solve groundwater flow problems. This used to be specialists territory, but nowadays there are several software packages that can be used to analyse groundwater flow problems in a quick and easy way. Building a computer model has become a routine for many hydrologists. Groundwater models are often regional models, and used for large or long-term projects, such as groundwater recharge studies for water supply companies, artificial storage and recovery, and environmental impact assessments. In the past, the effects of short-term and small-scale projects were solely calculated using analytical formulas. But gradually, numerical modelling has gained ground and more and more the effects of short-term and small-scale projects, such as construction dewatering, dumping-grounds, groundwater remediation and urban hydrology, are calculated using the finite-difference and the finite-element techniques. In many cases finite-element models show a more realistic spatial discretization than finite-difference models. In the Netherlands a lot of experience has been gained using this numerical modelling method. In general, a model for a small-scale project does not differ much from a model for a regional project. However, it is the difference in scale that manifests itself in the limited size of the area of interest, the distribution and quality of the available data, and the influence of local heterogeneities within the radius of influence that produces particular problems for small-scale models.

ANALYTICAL AND NUMERICAL MODELS

Although field experience is very valuable in practice, groundwater flow calculations are often desired or required at the initial phase of a civil engineering project. This may be essential for the design of the planned activities or for the comparison of different scenarios, e.g. for impact and risk assessments. When doing geohydrological calculations one is typically interested in:

- Finding suitable locations and required rates or capacities of pumping and injection wells;
- Determining the radius of influence and expected changes in groundwater levels and potentiometric heads;
- Determining the time characteristic of flow systems, especially in phreatic layers;
- Calculating flow velocities, pathlines and the transport of contaminants.

A major disadvantage of analytical models, i.e. the mathematical description of groundwater flow for a specific situation by means of exact formulas, is that they can only be applied to (or developed for) situations where the subsoil is highly schematised. Such schematisations are generally restricted to single homogeneous and isotropic aquifers of infinite extent, with straight boundaries, rectangular strips, perfectly circular excavations, and sudden drawdowns (Bruggeman, 1999). Furthermore, solutions are based on superposition and only one cause of groundwater flow can be calculated at a time. Due to the many assumptions made, the outcome of an analytical model can often only be considered a rough estimate of the possible effects of the planned activities. Therefore complicated flow problems are not easily solved with analytical methods. Analytical solutions for transient (dynamic) problems are even more troublesome to compute, because they often require look-up tables or graphs, or the evaluation of integrals or infinite series of complex functions.

Numerical models (based on finite differences or finite elements) don't have these restrictions and therefore can be used favourably to solve complicated groundwater flow problems. Of course numerical models have their limitations too: special codes are required for specific problems, such as density-dependent flow and coupled saturated unsaturated flow. The accuracy of the results of numerical models mainly depends on the availability of information about the hydraulic properties of the subsoil. Both finite-difference and finite-element methods divide the model area into a large number of small cells or elements, and solve the water balance equation for each of these smaller parts. Therefore, one of the steps of a numerical modelling procedure is the spatial discretization of the model area. The size of these cells or elements should be relatively small in all areas where the hydraulic properties are known in detail, where strong spatial variations in groundwater flow occur or are anticipated, and where accurate model results are required.

The mathematical background of the finite-difference and finite-element method is fundamentally different, but for the modeller the difference is only reflected by the way the model area can be discretized. Finite-difference models are usually based on a simple pattern of rectangular cells, created by dividing a rectangular model area by two series of lines parallel to the sides (e.g. Modflow). Finite-element models allow for a more flexible spatial discretization based on e.g. topography, geology and groundwater flow, since they often use irregularly shaped triangles (e.g. MicroFEM, Triwaco).

Finite-element models allow boundaries to be shaped along specific geological lines (faults, limits of aquifers) or hydrological boundaries (groundwater divides, pathlines, head contours). With a triangular grid all possible shapes and positions that may be important (rivers, impermeable layers, sheetpile walls, pumping wells and piezometers) can be positioned exactly (Fig. 1). The refining of a grid near the centre of a model does not affect the node spacing at the model boundaries. However, for the design of an irregularly shaped element grid it is advised to use a grid generator that builds a complete grid with a minimum amount of input data. A gradual transition from larger to smaller elements that avoids triangles with obtuse angles is important for the numerical accuracy of the calculations.

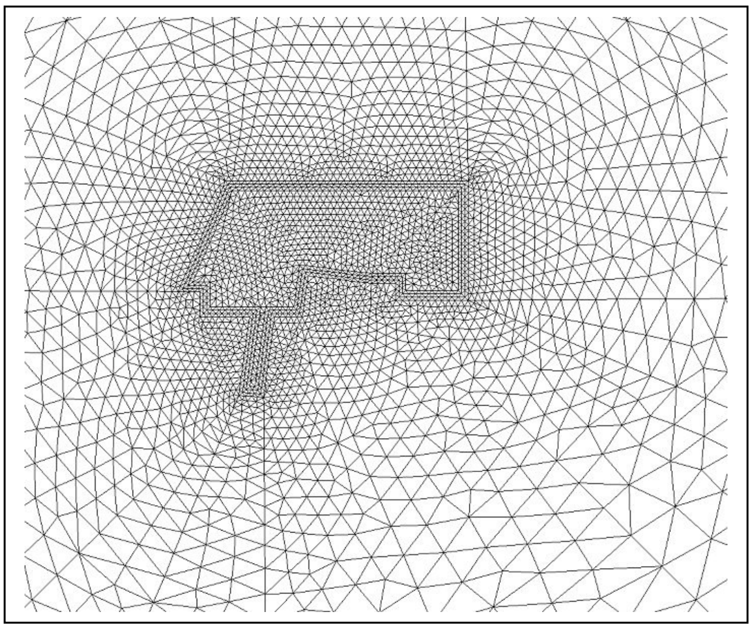

Fig. 1 Part of a finite-element grid for a construction dewatering.

MODELLING FOR CIVIL ENGINEERS

It is obvious that the characteristics of any numerical model completely depend on its purpose and on the geological and hydrological situation. However, the scale used and the details required in a civil engineering model result in a different approach to the consecutive steps of designing the model. Some of these differences will now be explained.

The scale of the planned activity is often of the order of a few tens (e.g. excavation dewatering) or hundreds of metres (e.g. a pipeline, quarry or dumping ground) (Fig. 2). Since most planned activities are near ground (water) level and dewatering is usually a short-term activity, the radius of influence is often restricted. On the one side this is convenient, because the size of the model can be limited, but on the other side, due to the used scale, even the smallest detail in information can be of significant importance. This implies that detailed information of the (variation of) hydraulic properties of both

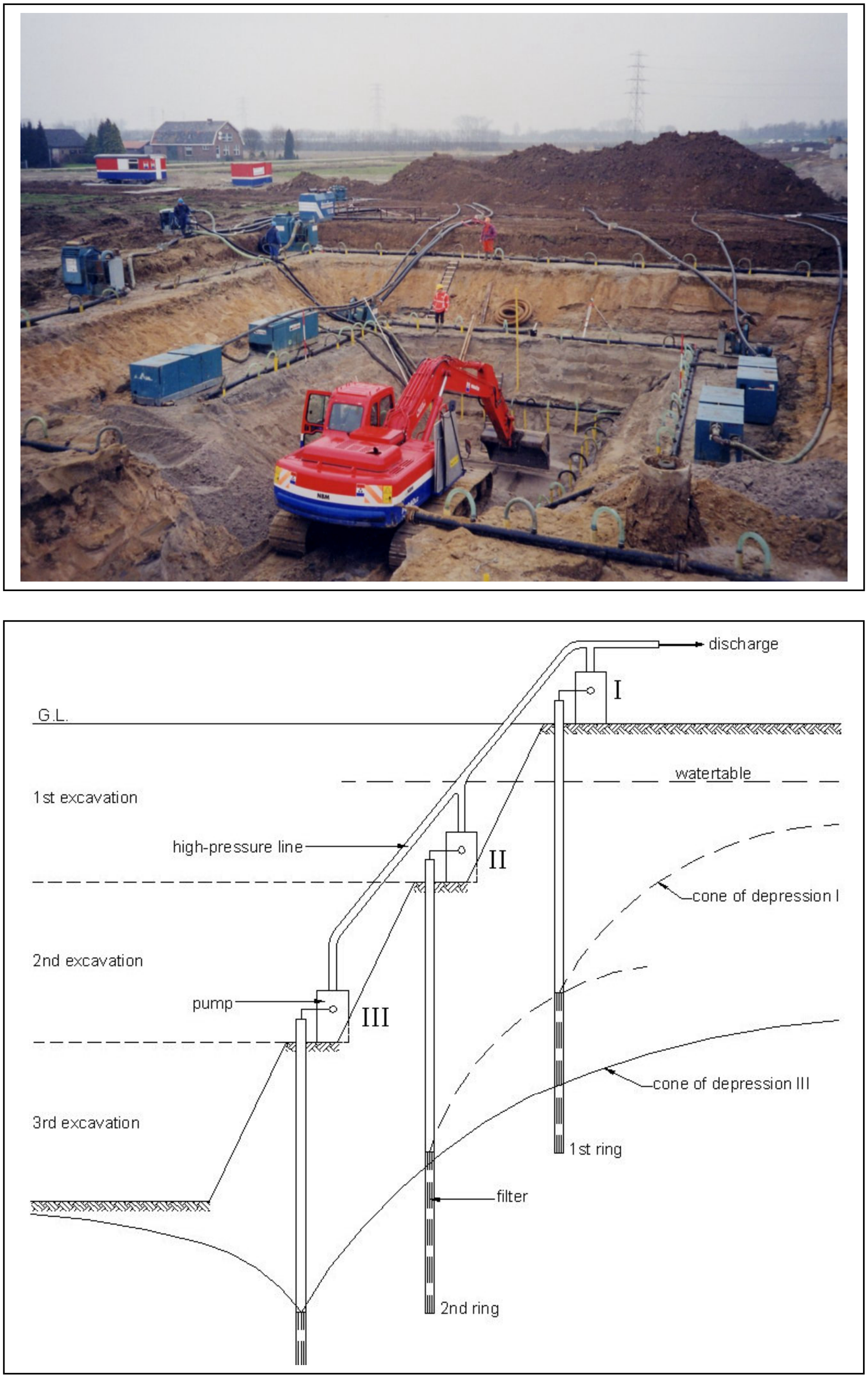

Fig. 2 Excavation dewatering.

permeable and less permeable layers may be essential for the schematisation of the local subsurface. A detailed mapping and modelling of the local presence or absence of (thin) less permeable layers, for example, will certainly make a lot of difference in the resulting groundwater flow. On this very local scale, small hydrological objects such as ditches, trenches and drains, and also foundations and leaky sewers, play their part in the flow system. In this respect the important advantage of the finite-element method is that lithological boundaries (e.g. the local presence of clay, peat and sand layers, raised surfaces) and the position of whatever affects groundwater flow (e.g. river shores, dikes, polders, drains, sheet piles and wells) can be positioned in the model with the necessary accuracy. In general this requires small elements for the whole area of interest.

The small system scale also affects the geohydrological schematisation. A regional less permeable (clay) layer at a depth of a few tens of meters can often be used as an impervious base, but the full sequence of all overlying layers has to be schematized with sufficient detail. Also partially penetrating wells, sheet piles and horizontal drains can be modelled accurately when an appropriate vertical discretization is used. The Dupuit or quasi 3-D modelling approach is no restriction to build a fully 3D numerical model, because each aquifer can be divided into several sub-layers (Leake & Mock, 1997).

The size of a civil engineering groundwater model can be chosen smaller than a regional model, because the area of interest is smaller (Fig. 3) and because short-term activities with a limited radius of influence allow close by model boundaries. This does not generally imply that the size of civil engineering models is small. The distance between the activity and the model boundaries highly depends on the overall hydraulic properties. Up to what distance can changes in groundwater level and potentiometric head be expected? Is the aquifer confined or phreatic? What is the order of magnitude of the transmissivities and vertical hydraulic resistances? To avoid inaccuracies and miscalculations, the model boundaries are better chosen at a safe distance.

Fig. 3 Small-scale civil engineering problems.

When using a finite-element model a large model area is no problem, because an additional number of large elements near the model boundaries hardly increases calculation times and file sizes. In case of doubt, a simple numerical or analytical model can help to assess the distance between the area of interest and the model boundaries. In many cases it may be a good choice to design a four-sided model with fixed head boundaries along head contours both upstream and downstream, and with no-flow boundaries along pathlines on the other two sides.

For transient models the stress periods and time steps can be chosen in the usual way. Due to the small spatial and temporal scales of civil engineering groundwater problems it may be necessary to pay attention to short term variations of the boundary conditions, like high rainfall events and high water surges or tides in rivers.

For the required detailed modelling of the area of interest all available information about the local subsoil and its surroundings must be used. The regional geological and hydrogeological information (mainly maps and reports) is supplemented with local data obtained from borehole logs, cone penetration tests and other field measurements. The hydrological situation is first identified at a regional scale, and then completed with local measurements of groundwater levels and potentiometric heads. Depending on the available spatial and temporal hydraulic data it may be useful to build and calibrate a model before the planned activities are started. This will establish the initial situation, augment the understanding of the local flow system, and help to select suitable field measurements that may improve the groundwater flow model.

Calibration based on the initial ‘natural’ groundwater flow will always produce a better model, leading to an increased accuracy of the predicted effects. The use of inverse modelling (parameter estimation) software (PEST, FemInvs) is highly recommended because it provides detailed information about the accuracy and correlation of the obtained parameter values (Hemker, 1997). This is important in areas, for example, where neither groundwater pumping nor seepage and infiltration contribute much to the total water balance. In those cases groundwater flow is mainly determined by the fixed heads on the model boundaries and less dependent on transmissivities and vertical hydraulic resistances. When the planned activities lead to an increase in horizontal and vertical flow in the area of interest, the model results will become increasingly dependent on the local hydraulic parameters. This implies that field measurements during the activities are important to improve the calibration. In all cases where sufficient information about the hydraulic properties is lacking, it is recommended to carry out pumping tests and, subsequently, evaluate the pumping test with the groundwater model.

Depending on the required results, the model can either be based on superposition, or the future flow system can be simulated. In case of superposition modelling the initial condition is a no-flow system (set all hydraulic heads to zero and remove recharge and wells) on which the planned draining and pumping activities are superposed. The computed model results represent the effects of the activities only. Analytical methods are always based on superposition. Theoretically, superposition can only be used when all hydraulic properties and boundary conditions remain constant. Varying transmissivities, hydraulic resistances and specific yields, due to a moving water table, can be taken into account when using numerical models. The same applies to drains, ditches or streams that fall dry. In the designing phase of the project, superposition models are generally used to calculate the changing groundwater levels and the radius of influence. The future situation can be obtained by combining the initial (natural) situation with the effects of the activities. Field measurement during the activities (e.g. observed heads as part of a monitoring plan) can then easily be compared with the computed results. Such models also allow the computation of flow velocities, pathlines and the advective transport of contaminants.

Numerical models are very useful to compare the possible outcomes of different plans and schemes. When the method of superposition is not allowed, the effects of any activity can still be determined by comparing the outcomes of the modelling results with and without intervention. The comparison of different model outcomes is also used to obtain insight in the credibility of the calculation results by varying one or more sensitive parameters within plausible limits.

CONCLUSIONS

The choice between analytical and numerical models is simple because a numerical model has more to offer in practically all respects. The major advantages are:

- The calculations are easier to perform.
- It is possible to model the subsoil and boundary conditions in more detail.
- The real (time) groundwater flow can be modelled and not just the (superposed) effects of some proposed activity.
- The results can be presented in various ways using export modules and GIS.

The choice between the finite-difference and finite-element method is less important, but finite-element grids are more efficient and have more possibilities to follow irregular shapes. However, a smart grid generator is required to create such superior finite-element grids. The small-scale groundwater systems simulated in civil engineering models are likely to be sensitive to local details in hydraulic properties and boundary conditions. This sensitivity can easily be assessed with the numerical groundwater flow models itself.

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