Original Article: Investigation of Network Models Finite difference Method

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ABSTRACT

Mathematical models can be described as a description of a system with mathematical language. This is done by introducing the system under study with a series of equations. Interpreter equations of the system are obtained based on the laws governing that system, boundary conditions, initial conditions and physical properties of the system under study. These models make it easier and faster to investigate the effect of various parameters on the system response. Once the mathematical model of a system is obtained, they can be solved analytically or numerically depending on the complexity of the equations. If the model presented is valid for a range of real numbers assigned to variables, it will be a continuous model, and if the model is valid for specific numbers in a range and for all real numbers in that range, it will be a model will be discrete. If the system does not respond to changes in time, the proposed model is called permanent. If the passage of time affects the response of the system, the proposed model is called a non-sustainable model.

Introduction

Flow simulation within porous media has attracted the attention of many researchers over the past three decades (1-3).

Various applications of this simulation can be seen in branches such as water engineering, environmental engineering, petroleum

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engineering and groundwater hydrology (4-6). Groundwater pumped from underground structures is the main source of many water source systems. The amount of water output of a spring is considered as the output of the groundwater system can be greatly affected by the amount of pumping that is done from the same area. Water can be injected into wells drilled for storage, and groundwater levels can be raised using the same technique. These issues are among the issues that can have an impact on groundwater management (7-9).

Classification of mathematical models

Mathematical models can be divided into the following:

1- Linear or nonlinear: All mathematical models are based on variables that represent the quantities studied in the system and operators that represent how the variables are related. If the operators of the mathematical model express a linear relation for the variables, the proposed mathematical model is called a linear model; otherwise, the proposed model is called a nonlinear model.

This means that a specific amount of knowledge can be assigned to each of these variables. In random models, these definite values are replaced by indefinite values, meaning that values are assigned to them using a probabilistic distribution.

The equation governing groundwater

A. Enclosed aquifer: Water inside the soil tends to move from a point with more energy to a point with less energy. According to Darcy's law, this motion depends on both the energy difference between the two points and the hydraulic conductivity of the path. This relationship is presented by Mr. Darcy as follows:

$$V = -K.grad(H)$$

Where V is the velocity, H is the hydraulic head and K is the hydraulic conductivity. To obtain the equation of water flow inside the porous medium, the equilibrium of a mass for the element is written as follows:

$$q_1 = -T_{x(i-1,j)}\Delta y_j \left(\frac{\partial h}{\partial x}\right)_1 \quad \text{(a)}$$

$$q_2 = -T_{x(i,j)}\Delta y_j \left(\frac{\partial h}{\partial x}\right)_2 \quad \text{(b)}$$

$$q_3 = -T_{y(i,j+1)}\Delta x_i \left(\frac{\partial h}{\partial y}\right)_3 \quad \text{(c)}$$

$$q_1 = -T_{y(i,j)}\Delta x_i \left(\frac{\partial h}{\partial y}\right)_4 \quad \text{(d)}$$

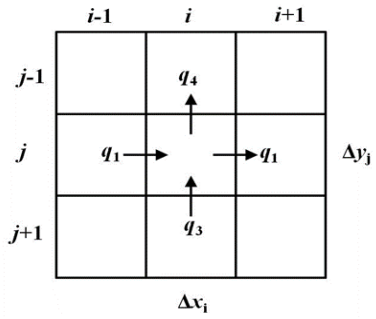

Figure 1: Two-dimensional element in a porous medium

Where T is the transfer coefficient. If the terms related to storage (S) and pumping (q) are considered:

$$-T_{x(i-1,j)}\Delta y_j\left(\frac{\partial h}{\partial x}\right)_1+T_{x(i,j)}\Delta y_j\left(\frac{\partial h}{\partial x}\right)_2-T_{y(i,j+1)}\Delta x_j\left(\frac{\partial h}{\partial y}\right)_3+T_{y(i,j)}\Delta x_i\left(\frac{\partial h}{\partial y}\right)_4=S_{i,j}\Delta x_i\Delta y_j\frac{\partial h}{\partial t}+q_{i,j}$$

And if T is constant:

$$-T_x\frac{\left(\frac{\partial h}{\partial x}\right)_1-\left(\frac{\partial h}{\partial x}\right)_2}{\Delta x_i}-T_y\frac{\left(\frac{\partial h}{\partial y}\right)_3-\left(\frac{\partial h}{\partial y}\right)_4}{\Delta y_j}=S_{i,j}\frac{\partial h}{\partial t}+\frac{q_{i,j}}{\Delta x_i\Delta y_j}$$

By tilting Δx and Δy to zero, is written as follows:

$$T_x\frac{\partial^2 h}{\partial x^2}+T_y\frac{\partial^2 h}{\partial y^2}=S\frac{\partial h}{\partial t}+w$$

And if the soil is the same:

$$T\left(\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial x^2}\right)=S\frac{\partial h}{\partial t}+w$$

Under stable conditions and without a spring or well, equation 2-6, which is the heat equation, will be converted to the following equation:

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=0$$

The above equation, known as the Laplace equation, is the most widely used equation in the fields of engineering and science. Although it is not difficult to obtain the general solution of the Laplace equation, and the private solution of the Laplace equation for some particular boundary conditions can be obtained by analytical methods, what makes solving this equation very difficult in real conditions is the existence of boundary conditions are geometrically very complex.

B. Free Aquifer: The equation governing the free aquifer is obtained using two hypotheses known as the Dupuit-Forchheimer hypothesis.

The first assumption is that the free aquifer head is independent of height and the second assumption is that the discharge is a function of the slope of the aquifer water level.

According to these hypotheses:

$$q_x=-K\left(H-\xi\right)\frac{\partial H}{\partial X}$$

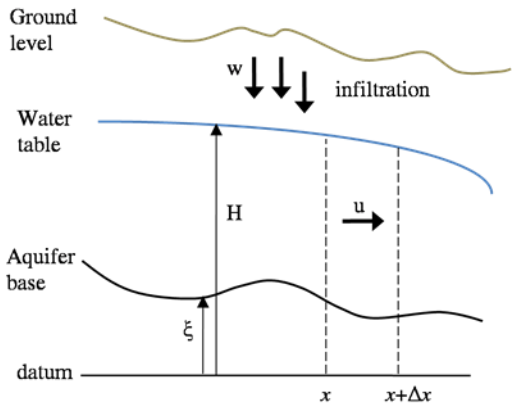

Figure 2: Non-enclosed aquifer

The correlation equation for the element will be written as follows:

$$S_y \frac{\Delta H}{\Delta T}\Delta x + q_{x+\Delta x} - q_x = w\Delta x \rightarrow$$

$$S_y \frac{\partial H}{\partial T} + \frac{\partial q}{\partial x} = w$$

The following equation will be obtained:

$$S_y \frac{\partial H}{\partial t} = \frac{\partial}{\partial x}\left(K\left(H-\xi\right)\frac{\partial H}{\partial x}\right) + w$$

The two-dimensional equation of groundwater movement in the free aquifer is also written as follows:

$$S_y \frac{\partial H}{\partial t} = \frac{\partial}{\partial x}\left(K\left(H-\xi\right)\frac{\partial H}{\partial x}\right) + w$$

Equation cannot be solved by conventional methods due to its nonlinearity. This equation is written in the steady state as follows:

$$\frac{\partial}{\partial x}\left(K\left(H-\xi\right)\frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(K\left(H-\xi\right)\frac{\partial H}{\partial y}\right) + w = 0$$

And assuming that ξ is constant:

$$K\frac{\partial}{\partial x}\left(\frac{1}{2}\frac{\partial H^2}{\partial x}\right) + K\frac{\partial}{\partial y}\left(\frac{1}{2}\frac{\partial H^2}{\partial y}\right) + w = 0 \rightarrow$$

$$\frac{\partial H^2}{\partial x^2} + \frac{\partial H^2}{\partial y^2} + \frac{2w}{K} = 0$$

This means that the equation governing the free aquifer is form $\nabla^2\left(H^2\right) + \frac{2w}{K} = 0$.

Physical models

Physical models can be considered as imitations of what actually exists. In constructing such models, it is not necessary to know the mathematical relations governing everything that is modeled, although knowing the governing relations can be of great help in constructing a physical model. The importance of these models becomes apparent when the governing mathematical relations are not known or the parameters in the problem are unknown. By using different experiments on the physical model and using the obtained results, a better understanding of the governing relationships and the number of parameters can be achieved.

One of the physical models that has been used in various researches is the sand box model. Sandboxes are models that put some of the actual porous medium in question into aquarium-like boxes and perform tests such as hydraulic conductivity, etc. on the sandbox. Illman et al. to understand which of the most common methods used to obtain hydraulic conductivity (8-10). It is better to perform various experiments on the heterogeneous sand box model and conclude that the use of the sand box will give very good results if the hydraulic guidance and the forcing function are well modeled. In a study by Yilung et al. on a sandbox model, the hydraulic conductivity coefficient

was obtained by three methods. The methods used were: 1- Using a fixed head 2- Using Neumann interpretation method on a radial analytical model and 3- Numerical fitting and among these three methods, the first method gave better values than the other two methods. In another study to find out if injecting edible oil into the porous medium could be a good option for studying anaerobic treatment. A sand box with dimensions of 1.2 (m) × 1.8 (m) × 0.98 (m) was used and the distribution of volatiles in the surface, middle and bottom layers was obtained within 5 to 7 weeks after injection (11-13)

The results obtained from this model were in good agreement with the observed real results and the results showed the possibility of modeling the porous medium with sandbox and contaminants with edible oil. In another study by Illman et al., 24 wells were drilled into a sand box to obtain a hydraulic conductivity, and by reading the head when water was injected at various points and obtaining an effective hydraulic coefficient. (14). Bryant and colleagues used spherical bullets of irregularly distributed size to model the porous medium. And considering that the distribution of cavities as well as their size was quite clear, they obtained the permeability of the proposed model theoretically. By comparing the results of these calculations with the results obtained on a laboratory sample of sand stone, they reached a very close agreement. Afzali used a ball model to investigate the turbulent flow of water in gravelly environments. His model was made of bullets with the same diameter and regular distribution. Faulkner et al. also used glass pellets to model the Karst porous medium and concluded that the proposed experimental model is a very good representation of groundwater movement, contamination, and mass transfer between the matrix domain and conduit. In a laboratory experiment using a sandbox, Berg et al. simulated what was happening in a real aquifer by lowering the water level with a pump and using hydraulic tomography to determine the hydraulic conductivity and specific storage capacity. Using these data in predictive models, they concluded that the distribution of hydraulic conductivity obtained using hydraulic tomography largely approximates the results obtained from the models.

Numerical methods

Because all natural groundwater aquifers have geometrically irregular boundary conditions, and most of these porous media are heterogeneous and heterogeneous, their analytical solution is almost impossible (15). This, as well as the dramatic advancement of computers over the past few decades, has led to the ubiquity and popularity of numerical methods such as the finite difference method and the finite element method over analytical methods. Unlike analytical methods, which obtain the answer to a problem as a continuous function of place and time, such as u = u (x, t), numerical methods determine the answer only at specific points in time and space, and to obtain the desired information in Points other than the marked points should use interpolation.

In using different numerical methods, it should be noted that due to the advantages and disadvantages of each of these methods and also the structural differences of these methods, the best method can never be determined, although due to the simplicity and convenience of some methods compared to other methods. A more appropriate option can be provided that reduces the volume of calculations and thus the computation time. Knowledge of most of the existing numerical methods can be considered as the transformation of the governing differential equations into a system of algebraic equations. Now, if these differential equations are linear, the resulting equations will also be linear, and as a result, the governing differential equations can be converted to a matrix. Major differences of numerical methods can be found in the coefficients of the formed matrix.

Finite difference method

The first step in the finite difference method is to draw grids perpendicular to each other on the desired domain. This network can have equal and equal or inequal distances in the direction of horizontal and vertical lines. In general, when more accuracy is desired, line spacing can be considered closer to each other, and when high

accuracy is not required, these distances can be considered farther apart. The most widely used equation in physics and engineering is the Laplace equation, which is a special case of the Poisson equation. These two equations are written as follows:

$$\nabla^2 u = f(x,y) \qquad \nabla^2 u = 0$$

If the Taylor expansion of the u function is written:

$$u(x+\Delta x, y) = u(x,y) + \frac{\partial u}{\partial x}\Delta x + \frac{\partial^2 u}{\partial x^2}\frac{\Delta x^2}{2!} + \dots$$

$$u(x-\Delta x, y) = u(x,y) - \frac{\partial u}{\partial x}\Delta x + \frac{\partial^2 u}{\partial x^2}\frac{\Delta x^2}{2!} - \dots$$

Now, by omitting the higher terms and terms and adding the above two relations, we can write:

$$u(x+\Delta x, y) + u(x-\Delta x, y) = 2u(x,y) + \frac{\partial^2 u}{\partial x^2}\Delta x^2 + \dots \longrightarrow$$

$$\frac{\partial^2 u}{\partial x^2} = \frac{u(x+\Delta x, y) - 2u(x,y) + u(x-\Delta x, y)}{\Delta x^2}$$

And by repeating the same thing for the variable y:

$$\frac{\partial^2 u}{\partial x^2} = \frac{u(x, y+\Delta y) - 2u(x,y) + u(x, y-\Delta y)}{\Delta y^2}$$

By placing two equations 3-10 and 3-11 in the Laplace or Poisson equation, the following equation is obtained:

$$\frac{u(x+\Delta x, y) - 2u(x,y) + u(x-\Delta x, y)}{\Delta x^2} + \frac{u(x, y+\Delta y) - 2u(x,y) + u(x, y-\Delta y)}{\Delta y^2} = f(x,y)$$

And in a special case $\Delta x = \Delta y$:

$$-4u_{i,j} + u_{i+1,j} + u_{i-1,j} + u_{i,j+1} + u_{i,j-1} = f_{i,j}$$

If this formula is written for the rest of the points, a system of algebraic equations is obtained which can be written as a matrix:

$$[k]\{u\} = \{f\} + \{b\}$$

The vector (b)will be the effect of boundary conditions.

Finite volume method

This method was originally proposed to deal with the problems of the finite difference method and has gradually become one of the most common methods in solving problems. One of the biggest disadvantages of the finite difference method is that it has to be used for Cartesian knots, and therefore its application in problems where the boundaries are curved is very erroneous.

To solve the Poisson equation using the finite volume method, we can write:

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = f(x,y) \rightarrow \frac{\partial}{\partial x}\left(\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\partial u}{\partial y}\right) = f(x,y)$$

And according to the law of divergence:

$$\int_\Gamma \left(\frac{\partial u}{\partial x}\hat{n}_x + \frac{\partial u}{\partial y}\hat{n}_y\right) ds = \int_\Omega f(x,y)\, d\Omega$$

$$\sum_{CS}^{A,B,C,D,E}\left(\frac{\Delta u}{\Delta x}n_1 + \frac{\Delta u}{\Delta y}n_2\right)\Delta\Gamma = \sum_{CV} f\,\Delta\Omega$$

After the principal equation is raised using the law of divergence, the equation is written as follows using the finite difference method:

This integral can be written as follows:

$$(u_7 - u_1)S_{7,1} + (u_9 - u_1)S_{9,1} + (u_{11} - u_1)S_{11,1} + (u_2 - u_1)S_{2,1} + (u_5 - u_1)S_{5,1} = f_1\Omega_1$$

Where Ω_1 is the sum of all areas of control volumes that surround point one? For example, the value of $S_{7,1}$ in the above expression is equal to:

$$S_{7,1}=\left(\cos\theta\frac{\Delta\Gamma}{\Delta x}+\sin\theta\frac{\Delta\Gamma}{\Delta y}\right)_{7,1}^{a}+\left(\cos\theta\frac{\Delta\Gamma}{\Delta x}+\sin\theta\frac{\Delta\Gamma}{\Delta y}\right)_{7,1}^{b}=\frac{\Delta y_{7,1}\Delta y_b}{\Delta\Omega_{7,1}}+\frac{\Delta x_{7,1}\Delta x_b}{\Delta\Omega_{7,1}}$$

Finite element method

This method is divided into different sub-categories and the formulation of each of these methods is different. The most commonly used method for solving field problems such as the Laplace equation or heat is the Galerkin method, which belongs to the weighted residue method classification. Considering the Poisson equation and assuming that the approximate answer to this equation is u_e, we can write:

$$\frac{\partial^2 u^e}{\partial x^2}+\frac{\partial^2 u^e}{\partial y^2}\approx f(x,y)\rightarrow\frac{\partial^2 u^e}{\partial x^2}+\frac{\partial^2 u^e}{\partial y^2}-f(x,y)=R(x,y)$$

Where R (x, y) remains. The main purpose of the weighted residue method is to minimize R (x, y) in the sense that:

$$\int w(x,y)R(x,y)dxdy=0$$

Where w (x, y) is called the weight function. Another step used in the finite element method.

Placing u^e with a set of functions called base functions and unknown coefficients that we are looking for is as follows: Reddy (2006):

$$u(x,y)\approx u^e(x,y)=\sum_{j=1}^{n}u_j\Psi_j(x,y)$$

Where $\Psi_j(x,y)$ the base and u_j functions of the coefficients are unknown. By applying the above relation in Poisson equation and placing u^e instead of u:

$$\int_\Omega\left\{w(x,y)\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial x}\right)+w(x,y)\frac{\partial}{\partial y}\left(\frac{\partial u}{\partial y}\right)-w(x,y)\,f(x,y)\right\}dxdy=0\rightarrow$$

$$\int_\Omega\left\{\frac{\partial}{\partial x}\left(w(x,y)\frac{\partial u}{\partial x}\right)-\frac{\partial w}{\partial x}\frac{\partial u}{\partial x}+\frac{\partial}{\partial y}\left(w(x,y)\frac{\partial u}{\partial y}\right)-\frac{\partial w}{\partial y}\frac{\partial u}{\partial y}-w(x,y)f(x,y)\right\}dxdy=0$$

According to the law of divergence can be written:

$$\int_\Omega\left\{\frac{\partial}{\partial y}\left(w(x,y)\frac{\partial u}{\partial y}\right)=\int_\Gamma w(x,y)\frac{\partial u}{\partial y}\hat{n}_y dS\right.$$

$$\int_\Omega\left\{\frac{\partial}{\partial x}\left(w(x,y)\frac{\partial u}{\partial x}\right)=\int_\Gamma w(x,y)\frac{\partial u}{\partial x}\hat{n}_x dS\right.$$

By placing the above two relations:

$$-\int_\Omega\left\{\frac{\partial w}{\partial x}\frac{\partial u}{\partial x}+\frac{\partial w}{\partial y}\frac{\partial u}{\partial y}+w(x,y)f(x,y)+\int_\Gamma w(x,y)\left(\frac{\partial u}{\partial x}\hat{n}_x+\frac{\partial u}{\partial y}\hat{n}_y\right)dS=0\right.$$

$$-\int_\Omega\left\{\frac{\partial w_i}{\partial x}\sum_{j=1}^{n}u_j\frac{\partial\Psi_j}{\partial x}+\frac{\partial w_i}{\partial y}\sum_{j=1}^{n}u_j\frac{\partial\Psi_j}{\partial y}+\Psi_i(x,y)f(x,y)dxdy\right\}$$

$$+\int_\Gamma\Psi_i(x,y)q_n dS=0$$

And if the following relations are assumed for simplification:

$$\int_\Omega\frac{\partial w_i}{\partial x}\frac{\partial w_j}{\partial x}+\frac{\partial w_i}{\partial y}\frac{\partial w_j}{\partial y}=k_{ij}$$

$$\int_{\Omega} \Psi_i(x,y) f(x,y) dxdy = f_i$$

$$\int_{\Omega} \Psi_i(x,y) q_n dS = Q_i$$

$$[k]\{u^e\} = -\{f\} + \{Q\}$$

The above equation shows that the Laplace problem is obtained as a system of algebraic equations.

The main advantage of the finite element method over the finite difference method is that it is easier to solve problems with irregular borders.

Conclusion

In the finite volume method, irregular quadrilateral grids can be used to better model curved and irregular borders. Another advantage of the finite volume method is that it is based on the integration of survival equations. Unlike the finite difference method, in which the principle of survival is satisfied only when the dimensions of the element tend to zero, in the finite volume method the principle of survival is established within all networks. Other advantages of this method include the ability to solve problems in which discontinuities are seen (such as the existence of two different sexes or two different coefficients).

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