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Techniques of Water-Resources Investigations of the United States Geological Survey

Chapter A3

# A MODULAR FINITE-ELEMENT MODEL (MODFE) FOR AREAL AND AXISYMMETRIC GROUND-WATER-FLOW PROBLEMS, PART 1: MODEL DESCRIPTION AND USER'S MANUAL

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Book 6

MODELING TECHNIQUES

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# APPENDICES

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## Definition of Input and Output Files

All Input Types are arranged in one file called MODFE.DAT, which is defined and opened by a Fortran statement in the main program. Fortran-unit number 50 is assigned to this file by the "OPEN" statement. The user can change the name of the file in the "OPEN" statement or delete the statement from the program and open the input file by commands to the operating system of the computer. The Fortran-unit number for input (50) is represented in MODFE by the program variable IIN. To change the Fortran-unit number, the user must change the program statements in subroutines INITB or INITCG where the value of IIN is assigned.

Output from MODFE is placed in a file called MODFE.OUT, which is defined and opened by a Fortran statement in the main program. Model output is written to MODFE.OUT by using Fortran-unit number 60. Like the input file, the user can change the name of the output file on the "OPEN" statement, or delete the statement from the program and open the output file by commands to the operating system of the computer. The Fortran-unit number is represented in MODFE by the program variable IOUT, which is assigned the value of 60 in subroutines INITB and INITCG.

Two temporary-storage files are used by MODFE during simulation. These files are used to store terms that form coefficients to the finite-element equations prior to solution (on Fortran unit 55) and to store element areas and incidences (on Fortran unit 56). The Fortran-unit numbers are represented by program variables ITA (=55) and ITB (=56), and are assigned values in subroutines INITB and INITCG. The files are opened by statements in the main program, which can be deleted and replaced by commands to the operating system, if desired.

## Examples of Model Input

Examples of input to MODFE that correspond to four, simplified aquifer problems are presented in this section. Output corresponding to these simulations are given in the following section. Structures of the main programs that were used for these simulations are listed in the section "Program Structures and Lists of Main Programs," in Torak (1993).

The first example input corresponds to a simulation of nonsteady-state flow in a confined aquifer (table 7). The finite-element mesh consists of two elements and four nodes (fig. 38). Three stress periods are simulated in which values for areally distributed stress and specified-heads are changed at the beginning of the second and third stress periods. Areally distributed recharge is applied during the second stress period only, and nodes 2 and 3 are specified-head boundaries. Note that the indicators for changing stresses or boundary conditions (Input-Type 17A) are set to zero for the first stress period, and the appropriate indicators are set to 1 for stress-periods 2 and 3. The aquifer problem was solved by using the linear version of MODFE termed LMFE1.

The two-element, four-node mesh from the first example (fig. 38) is used in the second example to demonstrate inputs for nonlinear conditions. A surficial (unconfined) aquifer contains a discharge well at node 1, two specified-head boundaries at nodes 2 and 3, and a nonlinear head-dependent (Cauchy-type) boundary along the element side defined by nodes 1 and 4 (table 8). The controlling head, $H_r$, to the nonlinear boundary condition is changed on the second and third stress periods. Because the aquifer is surficial, values for TOP, Input-Type 12C, represent the altitude of land surface. Also, conversion between confined and unconfined conditions cannot occur; thus, the specific yield (= 0.1) is input for the program variable STR (Input-Type 10) in addition to its input for SY (Input-Type 12D). The nonlinear version of MODFE termed NLMFE8 that uses the iterative, conjugate-gradient (MICCG) method is used for this simulation.

The third example demonstrates input for a steady-state, water-table simulation by using the finite-element mesh shown in figure 38. The aquifer problem contains a nonlinear point sink at node 1, nonlinear steady vertical leakage in both elements, and specified-head boundaries at nodes 2 and 3 (table 9). The nonlinear steady vertical leakage is of the discharge-only type, which is indicated by the input of a negative value for the leakage coefficient, program variable VNCF, as Input-Type 15B. The MICCG method is used to solve the finite-element equations. Inputs that control water-table iterations are made as Input-Type 2B. Note that the closure tolerance (TOL) for MICCG iterations is 0.1 (Input-Type 2A) and the tolerance for water-table iterations (TOLSW) is 0.0001 (Input-Type 2B). By specifying TOL greater than TOLSW, an acceptable solution of hydraulic head is obtained with less computational work than if-

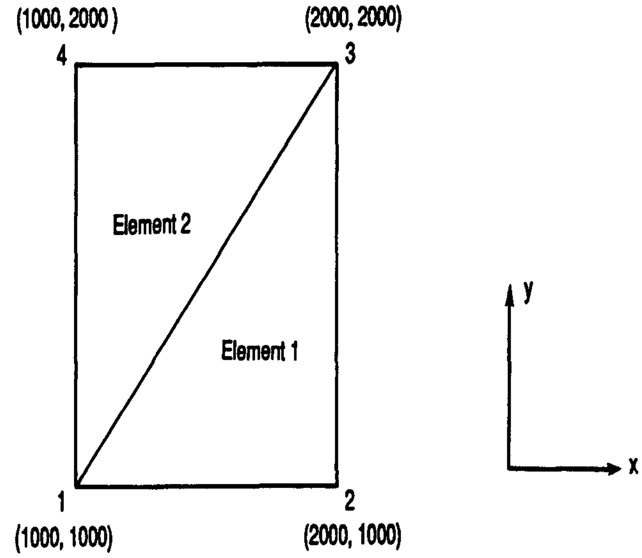


Figure 38.—Two-element, four-node, finite-element mesh used in examples of input to MODular Finite-Element model (MODFE).

TOLSW were greater than TOL (see section "Stopping Criteria" in Cooley (1992) for details). The computational features of two versions of MODFE, NSSFE3 and NSSFE5, are combined to solve the aquifer problem given as example 3.

The fourth example (table 10) lists the input that was used in Cooley (1992) to obtain computed values of hydraulic head which are compared with the analytical solution for conversion between confined and unconfined conditions (Moench and Prickett, 1972). Problem specifications and details of the finite-element discretization in space and time are given by Cooley (1992). In general, the aquifer problem is solved by using 68 triangular elements, 52 nodes, and 44 time steps. A head-dependent (Cauchy-type) boundary is placed at a distance of 32,000 meters from the pumped well to provide inflow to the simulated region from an aquifer that is assumed to be infinite in areal extent. The nonlinear version of MODFE termed NLMFE8 is used to simulate this aquifer problem.

Table 7.—Data input and descriptions for first example problem

| Input Type | Description | Input |
|---|---|---|
| 1: | TITLE | *** EXAMPLE 1. -- TWO-ELEMENT, FOUR-NODE PROBLEM SOLVED WITH LMFE1. |
| 1: | TITLE | *** CONTAINS THREE STRESS PERIODS WITH CHANGES TO SPECIFIED HEADS |
| 1: | TITLE | *** AND AREALLY DISTRIBUTED STRESSES ON EACH STRESS PERIOD. |
| 2: | Problem Specifications | 2 4 1 3 1 0 1 1 2 4 2 |
| 3: | IRAD IUNIT ISTD | 0 1 0 |
| 4: | TITLE | ** 1 MAP UNIT = 1000 FIELD UNITS (FT); TIME IN SECONDS ** |
| 4: | SCALE | 1000. |
| 5: | Suppress Printout | 0 0 0 0 0 0 0 |
| 6: | I XG(I) YG(I) H(I) HR(I) | 1 1. 1. 100. 0. |
| 6: | I XG(I) YG(I) H(I) HR(I) | 2 2. 1. 100. 0. |
| 6: | I XG(I) YG(I) H(I) HR(I) | 3 2. 2. 100. 0. |
| 6: | I XG(I) YG(I) H(I) HR(I) | 4 1. 2. 100. 0. |
| 8A: | KZ NOS IZIN | 1 1 1 |
| 8B: | ALPHZ QBNZ | 0. .002 |
| 8B: | J KQB(J) LQB(J) HK(J) HL(J) | 1 1 4 0. 0. |
| 9: | J HB | 2 90. |
| 9: | J HB | 3 90. |
| 10: | Hydraulic Properties | 1 2 1E-3 1E-3 0. 0. .001 0. |
| 11: | IEL ND(I) I=1,4 | 1 1 2 3 0 |
| 11: | IEL ND(I) I=5,8 | 2 1 3 4 0 |
| 17A: | Stress-Period Indicators | 1 0 0 0 0 0 0 0 0 |
| 17B: | DELT(1) | 5000. |
| 17A: | Stress-Period Indicators | 1 0 1 0 0 1 0 0 0 |
| 17B: | DELT(1) | 2000. |
| 19A: | N NQCH | 1 0 |
| 19B: | L NBE NO QOLD QNEW | 1 1 2 0.0 1.E-6 |
| 22A: | N NHCH | 2 0 |
| 22B: | J HB | 2 110. |
| 22B: | J HB | 3 110. |
| 17A: | Stress-Period Indicators | 1 0 1 0 0 1 0 0 0 |
| 17B: | DELT(1) | 3000. |
| 19A: | N NQCH | 1 0 |
| 19B: | L NBE NO QOLD QNEW | 1 1 2 1.E-6 0.0 |
| 22A: | N NHCH | 2 0 |
| 22B: | J HB | 2 100. |
| 22B: | J HB | 3 100. |

Table 8.—Data input and descriptions for second example problem

| Input Type | Description | Input |
|---|---|---|
| 1: | TITLE | *** EXAMPLE 2. -- TWO-ELEMENT, FOUR-NODE PROBLEM SIMULATING WATER-TABLE CONDI- |
| 1: | TITLE | *** TIONS. THREE STRESS PERIODS SHOW CHANGES TO CONTROLLING HEADS AT NONLIN- |
| 1: | TITLE | *** EAR CAUCHY-TYPE BOUNDARIES AND TIME-STEP SIZES. SOLUTION BY MICCG METHOD. |
| 2: | Problem Specifications | 1 4 3 3 1 1 0 0 2 4 10 |
| 2A: | TOL | 1.E-5 |
| 2C: | NBNC NLCZ NPNB | 1 1 0 |
| 3: | IRAD IUNIT ISTD | 0 1 0 |
| 4: | TITLE | ** 1 MAP UNIT = 1000 FIELD UNITS (FT); TIME IN SECONDS ** |
| 4: | SCALE | 1000. |
| 5: | Suppress Printout | 0 0 0 0 0 0 0 |
| 6: | I XG(I) YG(I) H(I) HR(I) | 1 1. 1. 100. 0. |
| 6: | I XG(I) YG(I) H(I) HR(I) | 2 2. 1. 100. 0. |
| 6: | I XG(I) YG(I) H(I) HR(I) | 3 2. 2. 100. 0. |
| 6: | I XG(I) YG(I) H(I) HR(I) | 4 1. 2. 100. 0. |
| 7: | I QWEL | 1 -.5 |
| 9: | J HB | 2 100. |
| 9: | J HB | 3 100. |
| 10: | Hydraulic Properties | 1 1 1E-5 1E-5 0. 0. .1 0. |
| 11: | IEL ND(I), I=1,4 | 1 1 2 3 4 |
| 12A: | IPTK IPTP | 0 0 |
| 12B: | THK(I) | 100. 100. 100. 100. |
| 12C: | TOP(I) | 101. 101. 101. 101. |
| 12D: | KZ NO SY | 1 1 .1 |
| 13A: | IPNC IPNP | 0 0 |
| 13B: | KZ NO IZIN | 1 1 0 |
| 13D: | Nonlinear-Boundary Side | 1 1 4 .0002 102. 102. 60. 60. |
| 17A: | Stress-Period Indicators | 3 0 0 0 0 0 0 0 0 |
| 17B: | DELT(I) | 600. 600. 600. |
| 17A: | Stress-Period Indicators | 3 0 0 0 0 0 0 0 1 |
| 17B: | DELT(I) | 200. 300. 500. |
| 24A: | N NGNCH | 1 0 |
| 24B: | J HRK(J) HRL(J) | 1 85. 85. |
| 17A: | Stress-Period Indicators | 1 0 0 0 0 0 0 0 1 |
| 17B: | DELT(I) | 200. |
| 24A: | N NGNCH | 1 0 |
| 24B: | J HRK(J) HRL(J) | 1 80. 80. |

Table 9.—Data input and descriptions for third example problem

| Input Type | Description | Input |
|---|---|---|
| 1: | TITLE | *** EXAMPLE 3. -- TWO-ELEMENT, FOUR-NODE MESH SIMULATING STEADY-STATE, |
| 1: | TITLE | *** NONLINEAR FLOW; WATER-TABLE CONDITIONS AND POINT AND AREALLY DISTRI- |
| 1: | TITLE | *** BUTED LEAKAGE FUNCTIONS. SOLVED BY COMBINING NONLINEAR SSCG MODELS. |
| 2: | Problem Specifications | 2 4 1 1 1 0 0 0 2 4 10 |
| 2A: | TOL | .1 |
| 2B: | NITSW TOLSW DSMX | 10 .0001 10. |
| 2C: | NBNC NLCZ NPNB | 0 0 1 |
| 2D: | NVNZ | 1 |
| 3: | IRAD IUNIT ISTD | 0 1 1 |
| 4: | TITLE | ** 1 MAP UNIT = 1000 FIELD UNITS (FT); TIME UNITS IN SECONDS** |
| 4: | SCALE | 1000. |
| 5: | Suppress Printout | 0 0 0 0 0 0 0 |
| 6: | I XG(I) YG(I) H(I) HR(I) | 1 1. 1. 100. 100. |
| 6: | I XG(I) YG(I) H(I) HR(I) | 2 2. 1. 100. 100. |
| 6: | I XG(I) YG(I) H(I) HR(I) | 3 2. 2. 100. 100. |
| 6: | I XG(I) YG(I) H(I) HR(I) | 4 1. 2. 100. 100. |
| 9: | J HB | 2 100. |
| 9: | J HB | 3 100. |
| 10: | Hydraulic Properties | 1 2 1E-5 1E-5 0. 0. 0. 0. |
| 11: | IEL ND(I), I=1,4 | 1 1 2 3 0 |
| 11: | IEL ND(I), I=5,8 | 2 1 3 4 0 |
| 12A: | IPTK IPTP | 0 0 |
| 12B: | THK(I) | 100. 100. 100. 100. |
| 12C: | TOP(I) | 101. 101. 101. 101. |
| 13A: | IPNC IPNP | 0 0 |
| 14: | I KP(I) GCP HZP | 1 4 .01 89. |
| 15A: | IPNV IPHS | 0 0 |
| 15B: | L NBE NO VNCF | 1 1 2-2.2018E-8 |
| 15C: | HS(I) | 90. 90. 90. 90. |

Table 10.—Data input and descriptions for fourth example problem

| Input Type Description | Input |
| --- | --- |
| 1: TITLE | MOENCH AND PRICKETT TEST PROBLEM |
| 1: TITLE | STORAGE CONVERSION |
| 1: TITLE | ********************************** |
| 2: Problem Specifications | 34 52 44 1 1 1 2 1 0 5 20 |
| 2A: TOL | .0001 |
| 2C: NBNC NLCZ NPNB | 0 0 0 |
| 3: IRAD IUNIT ISTD | 0 0 0 |
| 5: Suppress Printout | 0 0 0 0 0 0 0 |
| 6: I XG(I) YG(I) H(I) HR(I) | 1 0 0 0. 0. |
| | 2 122.60 -24.386 |
| . . . . . | 3 125 0 |
| . . . . . | 4 122.60 24.386 |
| . . . . . | 5 173.38 -34.488 |
| | 6 176.78 0 |
| | 7 173.38 34.488 |
| | 8 245.20 -48.773 |
| | 9 250 0 |
| | 10 245.20 48.773 |
| | 11 346.76 -68.974 |
| | 12 353.55 0 |
| | 13 346.76 68.974 |
| | 14 490.39 -97.545 |
| | 15 500 0 |
| | 16 490.39 97.545 |
| | 17 693.52 -137.95 |
| | 18 707.11 0 |
| | 19 693.52 137.95 |
| | 20 980.79 -195.09 |
| | 21 1000 0 |
| | 22 980.79 195.09 |
| | 23 1387.04 -275.90 |
| | 24 1414.21 0 |
| | 25 1387.04 275.90 |
| | 26 1961.57 -390.18 |
| | 27 2000 0 |
| | 28 1961.51 390.18 |
| | 29 2774.05 -551.79 |
| | 30 2828.4 0 |
| | 31 2774.05 551.79 |
| | 32 3923.14 -780.36 |
| | 33 4000 0 |
| | 34 3923.14 780.36 |
| | 35 5548.20 -1103.61 |
| | 36 5656.9 0 |
| | 37 5548.20 1103.61 |
| | 38 7846.28 -1560.72 |
| | 39 8000 0 |
| | 40 7846.28 1560.72 |
| | 41 11096.3 -2207.19 |
| | 42 11313.7 0 |
| | 43 11096.3 2207.19 |
| | 44 15692.6 -3121.45 |
| | 45 16000 0 |
| | 46 15692.6 3121.45 |
| | 47 22192.6 -4414.39 |
| . . . . . | 48 22627.4 0 |
| . . . . . | 49 22192.6 4414.39 |
| . . . . . | 50 31385.1 -6242.89 |
| | 51 32000 0 |
| 6: I XG(I) YG(I) H(I) HR(I) | 52 31385.1 6242.89 0. 0. |
| 7: I QWEL | 1-2099.4375 |

Table 10.—Data input and descriptions for fourth example problem—Continued

| Input Type Description | Input |
|---|---|
| 8A: KZ NOS IZIN | 1 2 1 |
| 8B: ALPHZ QBNZ | .04558 0. |
| 8B: J KQB(J) LQB(J) HK(J) HL(J) | 1 50 51 0. 0. |
| 8B: J KQB(J) LQB(J) HK(J) HL(J) | 2 51 52 0. 0. |
| 10: Hydraulic Properties | 1 34 26.73 26.73 0 0 .0001 0 |
| 11: IEL ND(I), I=1,4 | 1 1 2 3 0 |
| | 2 1 3 4 0 |
| . . . | 3 5 6 3 2 |
| . . . | 4 3 6 7 4 |
| . . . | 5 8 9 6 5 |
| | 6 6 9 10 7 |
| | 7 11 12 9 8 |
| | 8 9 12 13 10 |
| | 9 14 15 12 11 |
| | 10 12 15 16 13 |
| | 11 17 18 15 14 |
| | 12 15 18 19 16 |
| | 13 20 21 18 17 |
| | 14 18 21 22 19 |
| | 15 23 24 21 20 |
| | 16 21 24 25 22 |
| | 17 26 27 24 23 |
| | 18 24 27 28 25 |
| | 19 29 30 27 26 |
| | 20 27 30 31 28 |
| | 21 32 33 30 29 |
| | 22 30 33 34 31 |
| | 23 35 36 33 32 |
| | 24 33 36 37 34 |
| | 25 38 39 36 35 |
| | 26 36 39 40 37 |
| | 27 41 42 39 38 |
| | 28 39 42 43 40 |
| | 29 44 45 42 41 |
| . . . | 30 42 45 46 43 |
| . . . | 31 47 48 45 44 |
| . . . | 32 45 48 49 46 |
| | 33 50 51 48 47 |
| 11: IEL ND(I), I=133,136 | 34 48 51 52 49 |
| 12A: IPTK IPTP | 0 0 |
| 12B: THK(I) | 100 100 100 100 100 100 100 100 |
| | 100 100 100 100 100 100 100 100 |
| . | 100 100 100 100 100 100 100 100 |
| . | 100 100 100 100 100 100 100 100 |
| . | 100 100 100 100 100 100 100 100 |
| | 100 100 100 100 100 100 100 100 |
| 12B: THK(I) | 100 100 100 100 |
| 12C: TOP(I) | -2 -2 -2 -2 -2 -2 -2 -2 |
| | -2 -2 -2 -2 -2 -2 -2 -2 |
| . | -2 -2 -2 -2 -2 -2 -2 -2 |
| . | -2 -2 -2 -2 -2 -2 -2 -2 |
| . | -2 -2 -2 -2 -2 -2 -2 -2 |
| | -2 -2 -2 -2 -2 -2 -2 -2 |
| 12C: TOP(I) | -2 -2 -2 -2 |
| 12D: KZ NO SY | 1 34 .1 |
| 13A: IPNC IPNP | 0 0 |
| 17A: Stress-Period Indicators | 44 0 0 0 0 0 0 0 0 |
| 17B: DELT(I) | .00005 .00005 .00005 .00005 .00007 .00011 .00014 .00018 |
| . | .0003 .0004 .0006 .0007 .0011 .0014 .0018 .003 |
| . | .004 .006 .007 .011 .014 .018 .03 .04 |
| . | .06 .07 .11 .14 .18 .3 .4 .6 |
| | .7 1.1 1.4 1.8 3 4 6 7 |
| 17B: DELT(I) | 11 14 18 30 |