S/N # 598

SCIENTIFIC NOTEBOOK

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by

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EVALUATION OF ABAQUS AS A COMPLIANCE DETERMINATION COMPUTER CODE (CNWRA 95-016)

Southwest Research Institute
Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

TASK 2.3 PROBLEM SET 4:
FRACTURE FLOW ANALYSES

EVALUATION OF COMPUTER CODE ABAQUS FOR COMPLIANCE DETERMINATION—PHASE II PROBLEM SETS

1 DESCRIPTION OF PROBLEM SETS

PROBLEM SET 4: LEAK-OFF FROM PARTIALLY FILLED FRACTURE

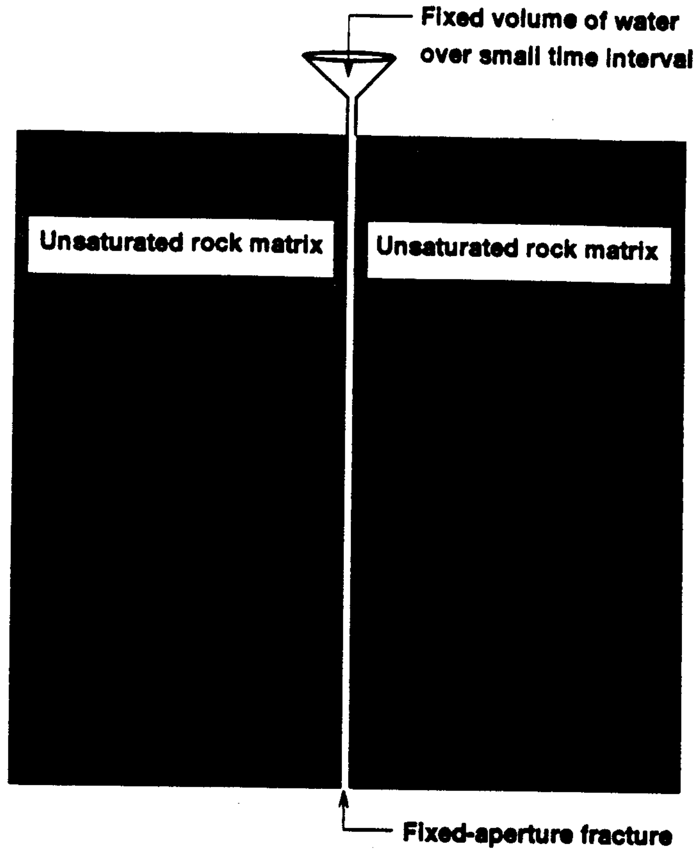
This problem set examines the capabilities of ABAQUS in modeling moisture flow through unsaturated fractured rock. A fixed volume of water Q_o is introduced at the top of a vertical fracture in unsaturated rock; and the advance of water in the fracture and absorption into the rock matrix are monitored. The geometry of the problem is illustrated in Figure 4-1. Fracture flow and matrix imbibition will be monitored in terms of the following:

(i) Leading edge of water in the fracture, as a function of time.
(ii) Trailing edge of water in the fracture, as a function of time.
(iii) Maximum travel distance in the fracture, as a function of the volume Q_o.
(iv) Location of the wetting front in the rock matrix.

This problem will be solved using ABAQUS, V-TOUGH, and PORFLO for the two groups of material parameters used in Problem Set 1 (*Transient Infiltration*), which are listed in Table 4-1. The properties of water will be set as follows: density, ρ=1,000 kg·m^{-3}; dynamic viscosity, η=10^{5} Pa·s. The value of gravitational acceleration will be set to 10 m·s^{-2}.

Table 4-1. Material and model parameter specifications for Problem Set 4

Material and Model Parameters	Value for Topopah Spring Welded Tuff	Value for Higher Permeability Material
Initial pressure head in rock matrix (m)	−1,000	−2.5
Initial saturation in rock matrix	0.274	0.288
Saturated hydraulic conductivity (m·s^{-1})	6.693×10^{-12}	1.625×10^{-5}
Porosity	0.0925	0.3
Gardner permeability parameter, α (m^{-1})	0.0177	7.3
Residual saturation, S_r	0.0724	0.1833
van Genuchten parameter, β (m^{-1})	0.0072	2.9227
van Genuchten parameter, n	1.7664	2.0304


Fixed volume of water
over small time interval
Unsaturated rock matrix
Unsaturated rock matrix
Fixed-aperture fracture

Input Files

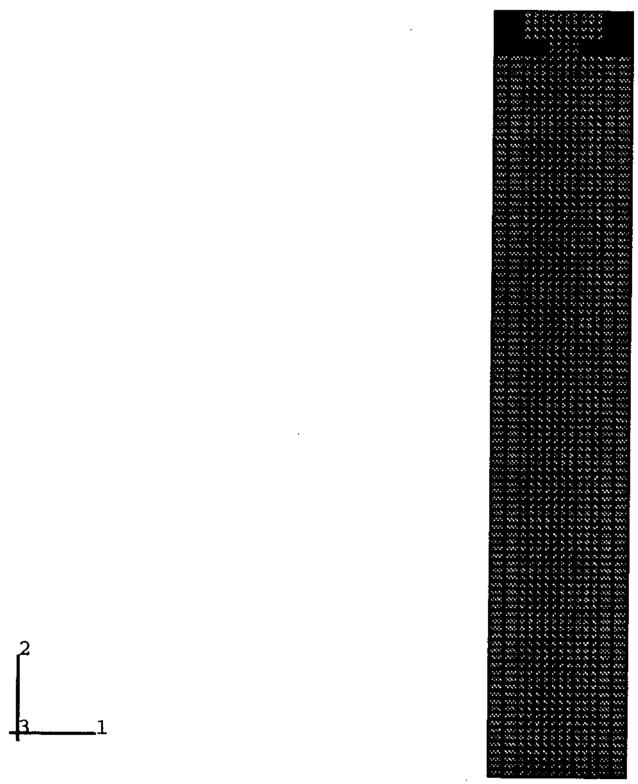
df902.inp — Model as described previously

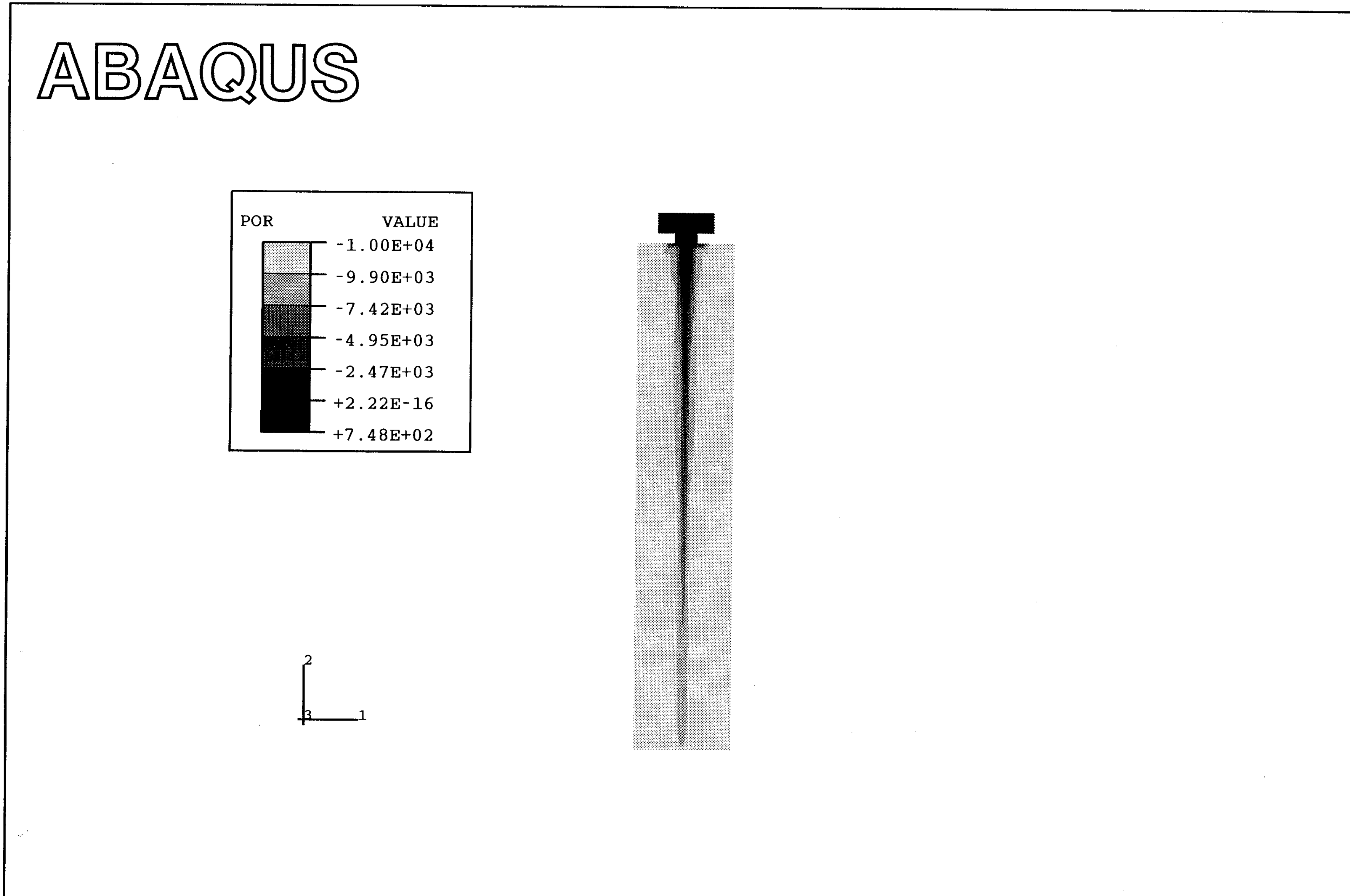
df903.inp — Fracture-wall rock modeled as fracture-zone 1 material (See attached Moisture-retention curves).

Sorption, exsorption and relative-permeability input data generated using C code SorptionInput.c, which is based on the van Genuchten moisture-retention law, ~~the~~ (GW) and Mualem-van Genuchten ~~perm~~ or (GW) Gardener permeability (GW) functions. The Gardener function was not used ~~of~~ for this problem set.

```
#include <stdio.h>
#include <math.h>
#include <stdlib.h>

main()
{
  float porosity,satPerm,unitWeight;
  float beta,n,m,lambda,rsat,rDrainSat,alpha;
  double *ph,*imbibSat,*drainSat,*relPerm,sat,se,term1;
  int i,numPoints,maxNumPoints;

  maxNumPoints = 121;
  ph = (double *)malloc(maxNumPoints*sizeof(double));
  imbibSat = (double *)malloc(maxNumPoints*sizeof(double));
  drainSat = (double *)malloc(maxNumPoints*sizeof(double));
  relPerm = (double *)malloc(maxNumPoints*sizeof(double));
  if (!ph || !imbibSat || !drainSat || !relPerm){
    printf("\n        Memory allocation error\n");
    return;
  }

/*
  This codes prepares sorption, exsorption, and relative-permeability
  input data for ABAQUS analyses, for six different materials. It is
  currently setup for fracture-zone 2 material. The code can be setup
  for any of the six materials identified by removing/inserting
  comment markers as necessary
*/

/*  Higher permeability material (Material 2) */
/*
  lambda = 0.0;
  unitWeight = 10.0;
  porosity = 0.3;
  satPerm = 1.625e-5;
  rsat = 0.055/porosity;
  rDrainSat = 0.065/porosity;
  beta = 2.9227;
  alpha = 7.3;
  n = 2.0304;
  m = 1.0 - 1.0/n;
  numPoints = 40;

  ph[0] = -5.5;
  ph[1] = -5.0;
  for (i=2; i<11; i++) ph[i] = ph[i-1] + 0.5;
  for (i=11; i<30; i++) ph[i] = ph[i-1] + 0.025;
  for (i=30; i<39; i++) ph[i] = ph[i-1] + 0.0025;
  ph[39] = 0.0;
*/

/*  Topopah Spring Welded */
/*
  lambda = 0.0;
  satPerm = 6.693e-12;
  unitWeight = 10.0;
  porosity = 0.0925;
  rsat = 0.0067/porosity;
  rDrainSat = 0.0077/porosity;
  beta = 0.0072;
  alpha = 0.0177;
  n = 1.7664;
  m = 1.0 - 1.0/n;
  numPoints = 34;

  ph[0] = -2000.0;
  ph[1] = -1000.0;
  for (i=2; i<11; i++) ph[i] = ph[i-1] + 100.0;
  for (i=11; i<20; i++) ph[i] = ph[i-1] + 10.0;
  for (i=20; i<29; i++) ph[i] = ph[i-1] + 1.0;
  for (i=29; i<34; i++) ph[i] = ph[i-1] + 0.2;
*/

/* Fracture zone 1    */
/*
  lambda = 0.0;
  unitWeight = 10.0;
  satPerm = 6.06e-4;
  porosity = 0.09255;
  rsat = 0.274087;
  rDrainSat = 0.284087;
  beta = 1.0;
  alpha = 0.1;
  n = 5.0;
  m = 1.0 - 1.0/n;
  numPoints = 77;

  ph[0] = -2000.0;
  ph[1] = -1000.0;
  ph[2] = -100.0;
  for (i=3; i<22; i++) ph[i] = ph[i-1] + 5.0;
  for (i=22; i<71; i++) ph[i] = ph[i-1] + 0.1;
  for (i=71; i<76; i++) ph[i] = ph[i-1] + 0.01;
  ph[77] = 0.0;
*/

/* Fracture zone 2   */

  lambda = 0.0;
  unitWeight = 10.0;
  satPerm = 6.06e-4;
  porosity = 0.0925;
  rsat = 0.274087;
  rDrainSat = 0.284087;
  beta = 0.1;
  alpha = 0.1;
  n = 4.0;
  m = 1.0 - 1.0/n;
  numPoints = 77;

  ph[0] = -2000.0;
  ph[1] = -1000.0;
  ph[2] = -100.0;
  for (i=3; i<22; i++) ph[i] = ph[i-1] + 5.0;
  for (i=22; i<71; i++) ph[i] = ph[i-1] + 0.1;
  for (i=71; i<76; i++) ph[i] = ph[i-1] + 0.01;
  ph[77] = 0.0;

/* Fracture zone  3 in Material 2 */
/*
  lambda = 0.0;
```

ABAQUS





df902, after 6000 s

Post-processing for pore-pressure history

The files

df9021pHist.dat
df9022pHist.dat

df9031pHist.dat
df9032pHist.dat

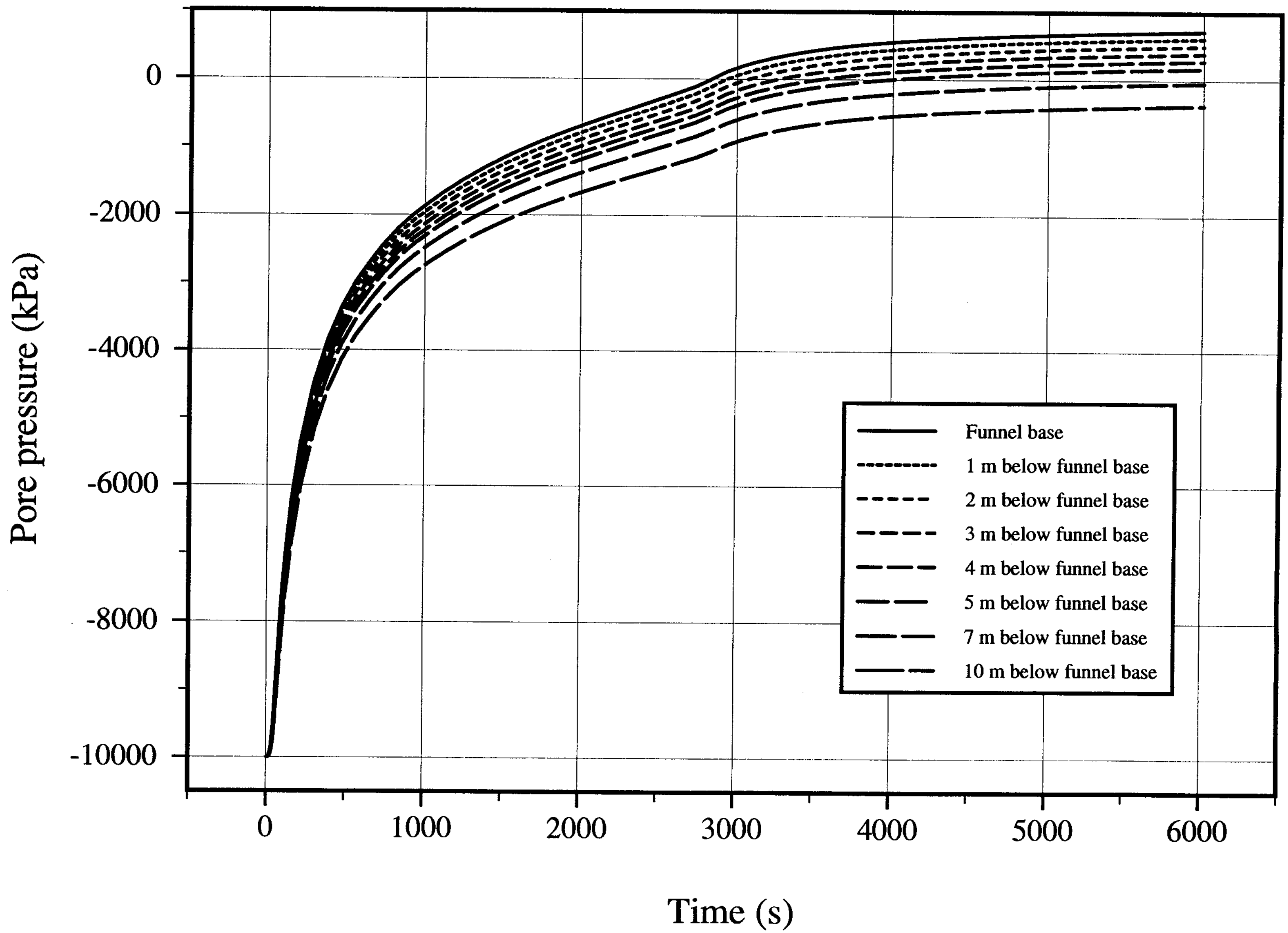
were obtained using ABAQUS commands "READ CURVE" and "PRINT CURVE" in ABAQUS/POST sessions on jobs df902 and ~~df903~~ df903. (GTO)

Run the XPLOT batch files

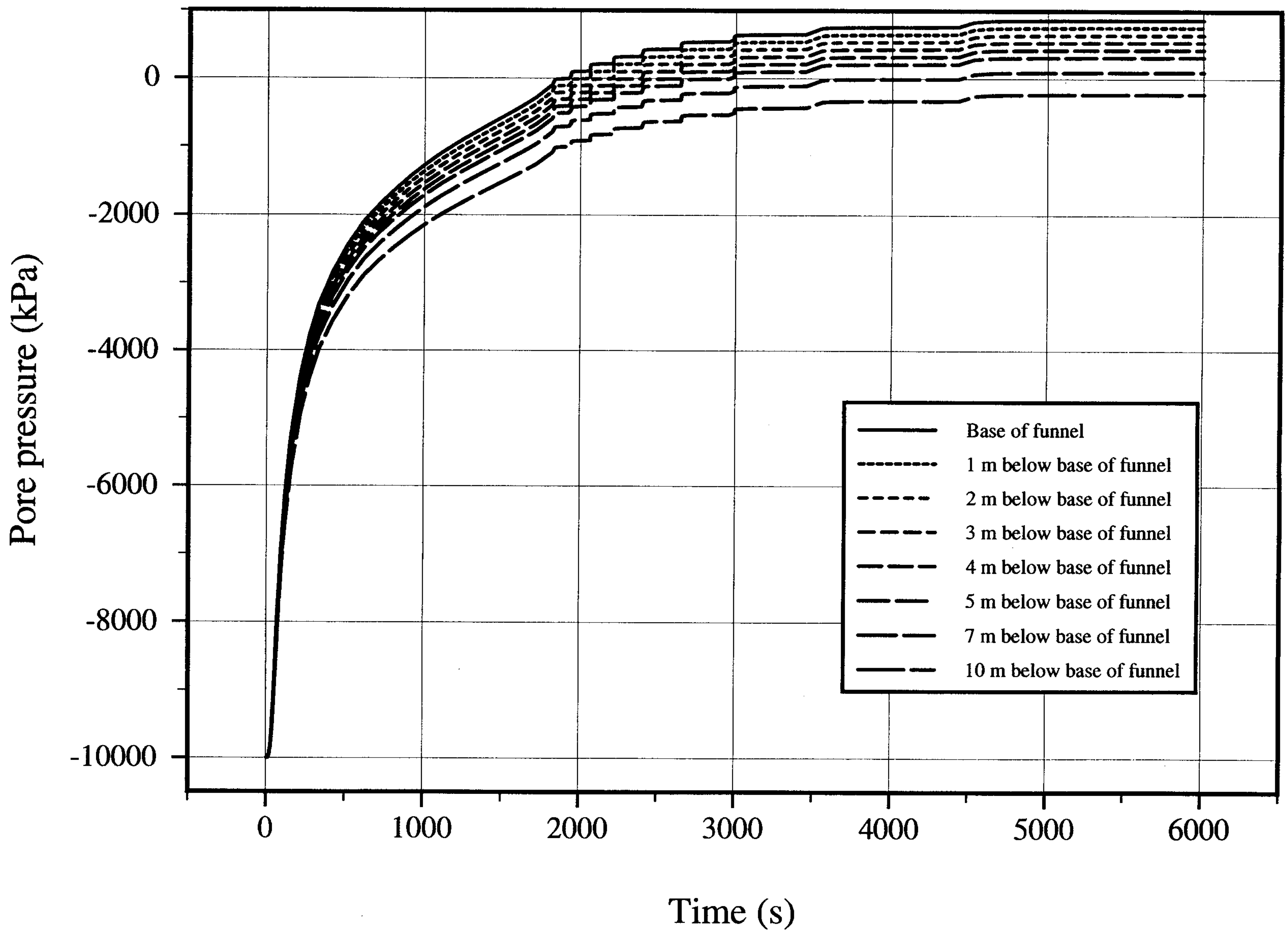
df902pHist.xpb and
df903pHist.xpb

to obtain the pore-pressure history plots shown in the next two pages.

Pore Pressure History on Fracture Wall (df902 model)



Pore Pressure History on Fracture Wall (df903 model)



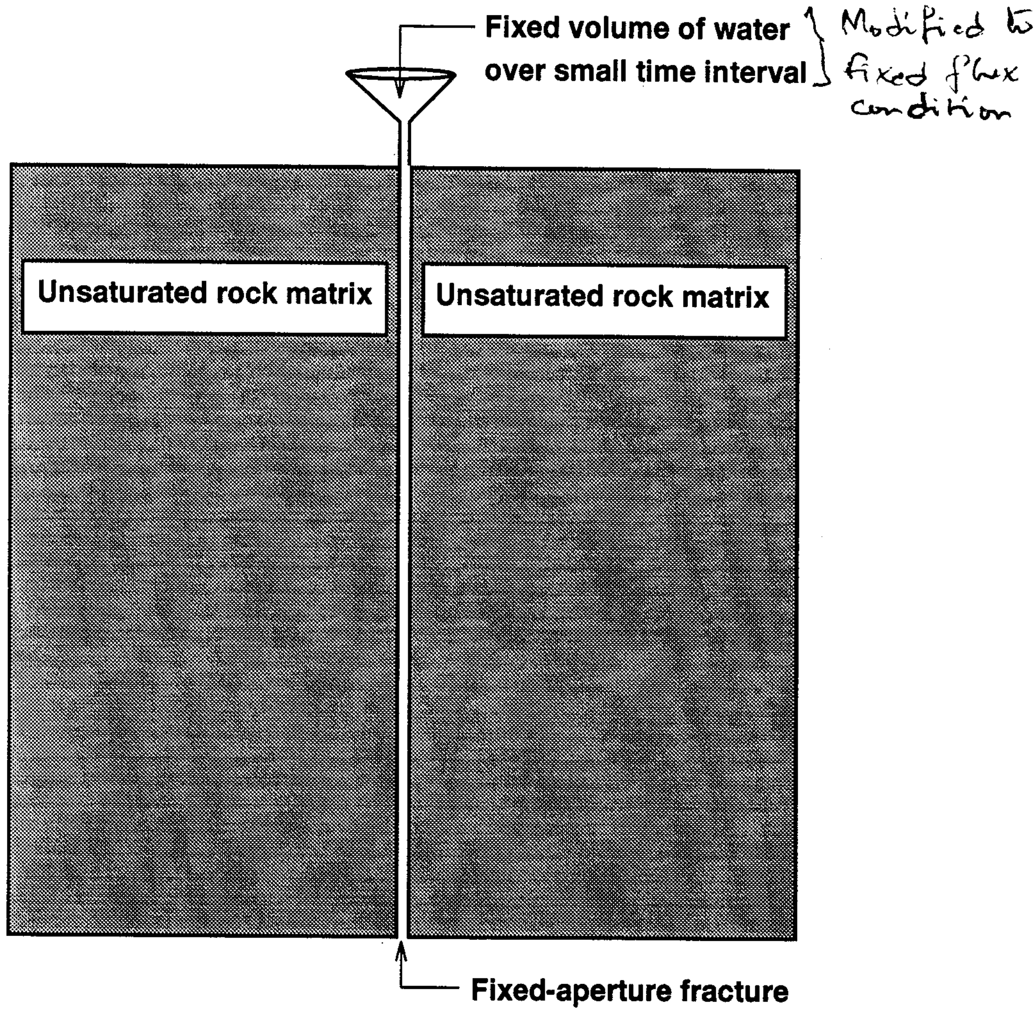

Fixed volume of water
over small time interval
Modified to
fixed flux
condition
Unsaturated rock matrix
Unsaturated rock matrix
Fixed-aperture fracture

Figure 1

Model

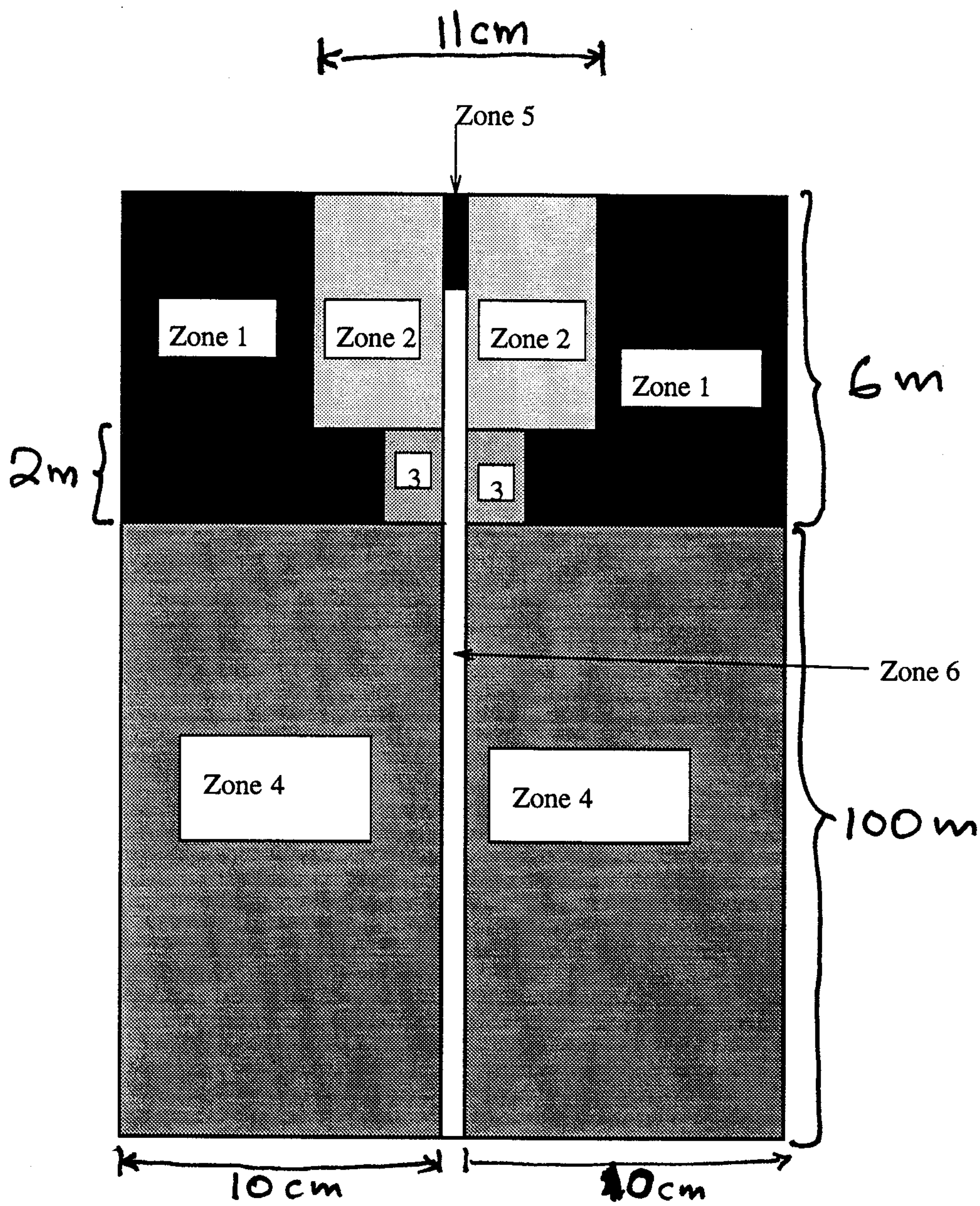


Figure 2

See next page for explanation

GW
5

Zone 1: Non-conducting elements (SEALZONE)

Zone 2: High-conductivity high-porosity elements (FUNNEL ZONE)

Zone 3: Low-conductivity elements (BUFFER ZONE)

Zone 4: Study zone (

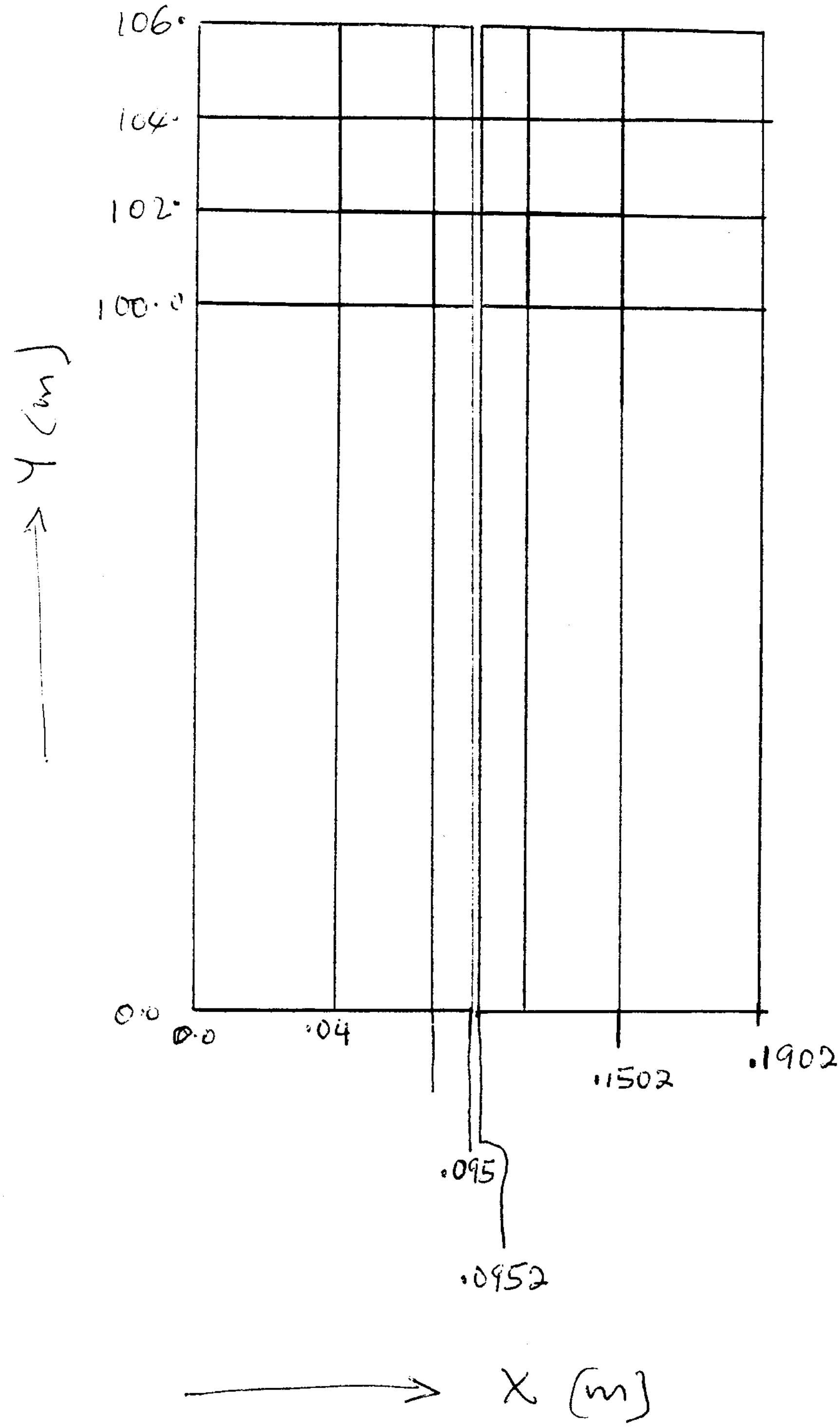
Zone 5: Same as Zone 1

Zone 6: Fractures

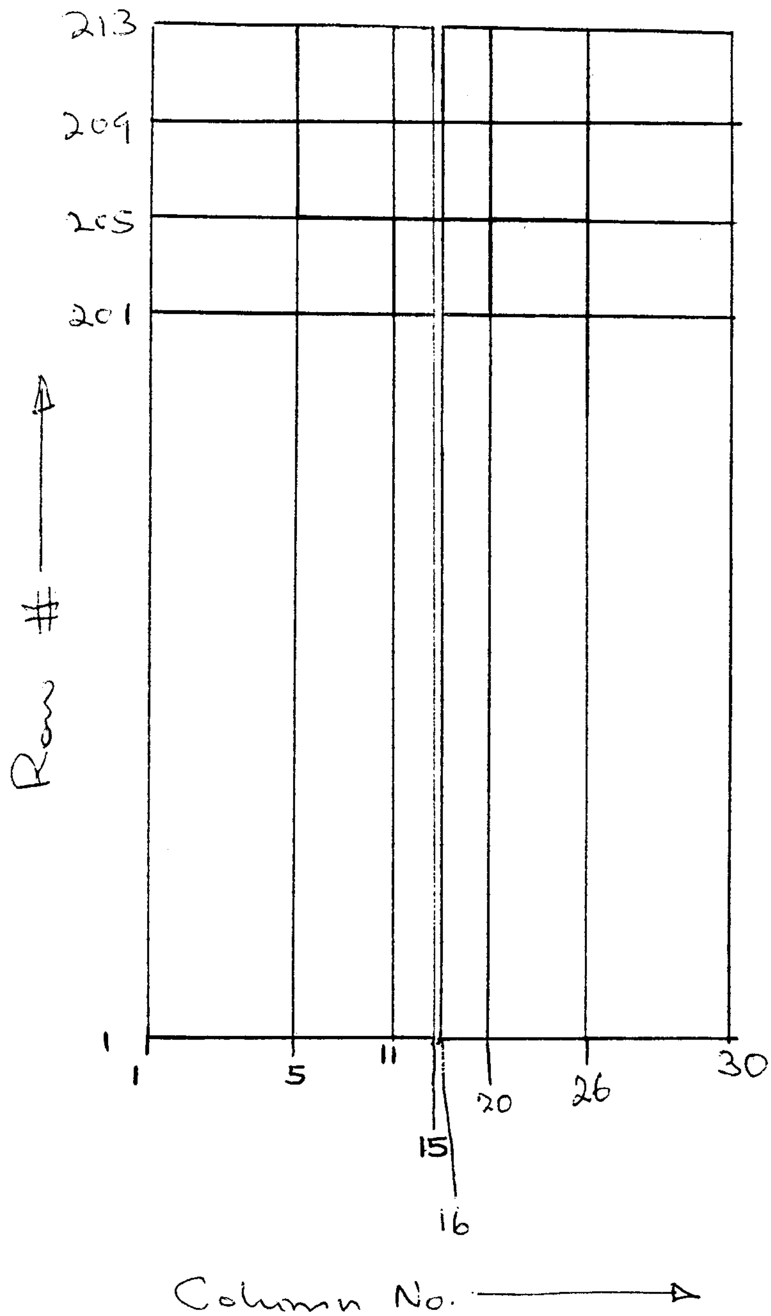
Changes

Assign BUFFER ZONE same ~~properties~~ as FUNNEL ZONE, but introduce a zero-thickness seal ~~between~~ BUFFER ZONE and STUDY ZONE

Coordinates (Model 2)

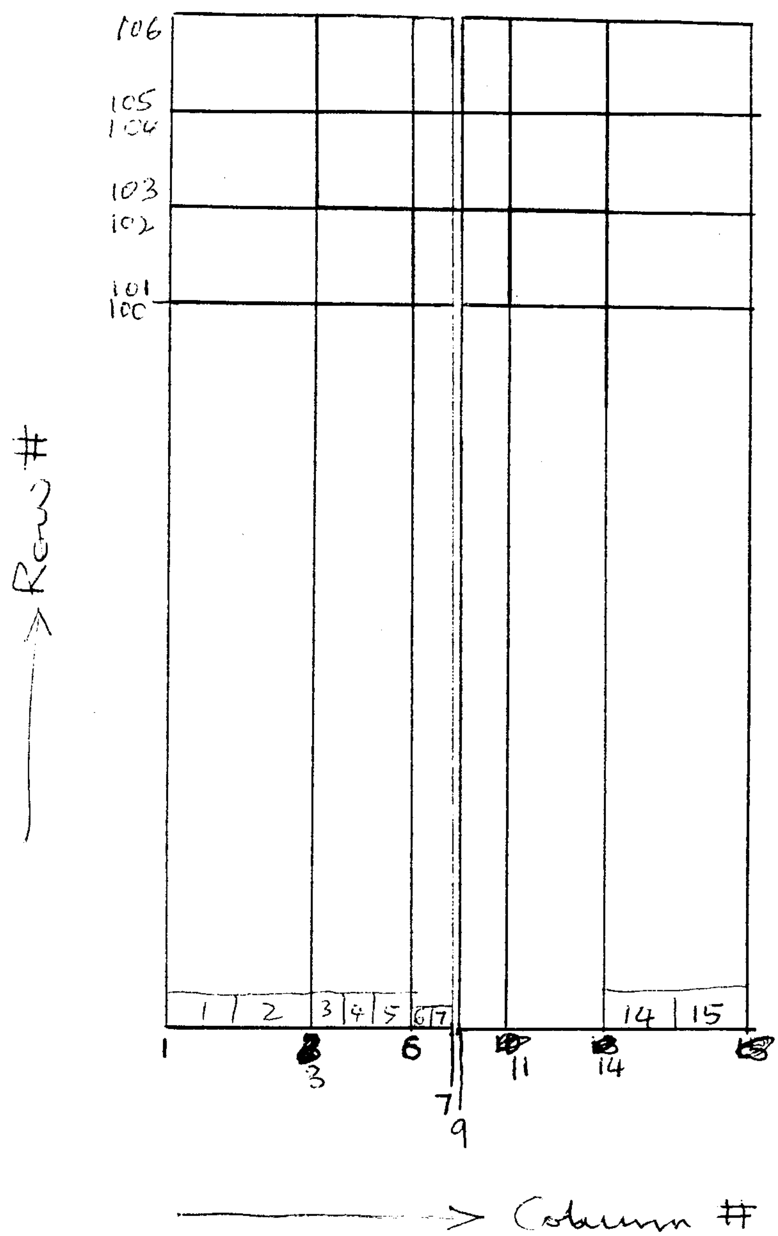


Node Numbers (Model 2)



Node = 30* (Row-1) + Column

Element Numbers (Model 2)



Element = 15 * (Row - 1) + Column

Unit of pressure kPa

~~don~~
Viscosity of water $\underline{10^{-6}}$ kPa.s

ρ_w = 1000 kg/m³ = ~~1.0 (10³~~ GW
= $\underline{1.0}$ (10^3 kg/m³)

~~Saturated unit w~~ GW

$\gamma_w = \rho_w g$ = ~~1.0 x 10~~ GW 1.0 (10^3 kg/m³) x 10 $\frac{m}{s^2}$
= $\underline{10 \text{ kN/m}^3}$

rock density = 2000 kg/m³ = $\underline{2.0}$ (10^3 kg/m³)

Saturated conductivity

Study zone	6.693×10^{-12} m/s
buffer zone	6.693×10^{-14} m/s
funnel zone	6.693×10^{-4} (GW) m/s
fracture	~~0.33~~ ~~3.33 x 10~~ 3.33×10^{-2} (GW) m/s

Initial void ratio 0.102 ~

≡ porosity of 0.0925

Tangential Permeability

$$q = -k_t \frac{\partial P}{\partial t}$$ — t = tangential coordinate

q = tangential flux ($L^2 T^{-1}$)

$\partial P / \partial t$ = tangential pressure gradient ($F L^{-3}$)

$$k_t = \frac{e^3}{12\mu} \quad (L^5 F^{-1} T^{-1})$$

μ = dynamic viscosity of water

~~$= 10^{3}$ Pa·s = 100 kPa·s~~

$= 10^{-3}$ Pa·s = 10^{-6} kPa·s

e = 0.2 mm = 2×10^{-4} m

$$k_t = \frac{(2\times10^{-4})^3}{12 \times 10^{-6}} = ~~6.667 \times 10^{-15}~~ \text{(GW)}$$

$$= 6.667 \times 10^{-7} \quad (m^5\, kN^{-1}\, s^{-1})$$

equivalent hydraulic conductivity

$$= \frac{\gamma_w e^2}{12\mu} = \frac{10 \frac{kPa}{m} \times (2\times10^{-4}\, m)^2}{12 \times 10^{-6}\, kPa \cdot s} \text{ (GW)}$$

$$= 3.33 \times 10^{-2} \text{ m/s}$$

NODE SETS

ALLNODES	Every node
FZNODES	Funnel zone nodes
BZNODES	(GW) ~~BUFF~~ Buffer zone nodes
UZLEFT	Study zone left boundary
UZBASE	Study zone bottom "
UZRIGHT	Study zone right "
UZNODES	Study zone nodes

ELEMENT SETS

STUDYZON	Study zone
SEALZONE	Non-conducting seal
BUFFERZO	Buffer zone
FUNNELZO	Funnel zone
FZTOP	Top of funnel zone (flux boundary applied on side 3 of these elements)
FRACTURE	Fracture elements (conducting)
FRACPLUG	Non-conducting fracture elements

Pore pressure history monitored at node set PMONITOR

```
*NSET, NSET=PMONITOR, GEN
15, 6015, 60
```

The pore-pressure history at following nodes were eventually plotted

Node	Depth below funnel base (m)
6015	0.0
5955	1.0
5895	2.0
5835	3.0
5775	4.0
5715	5.0
5595	7.0
5415	10.0

Thin-solid Model

V_f = fracture volume

V_p = pore volume in equivalent solid

n = porosity of solid

~~w_f = width of fracture (fracture~~ G10

e = fracture aperture

t = thickness of thin solid

w = model width

L = model height

$$V_p = V_f$$

$$\Rightarrow nwtL = ewL$$

$$\Rightarrow t = \frac{e}{n}$$

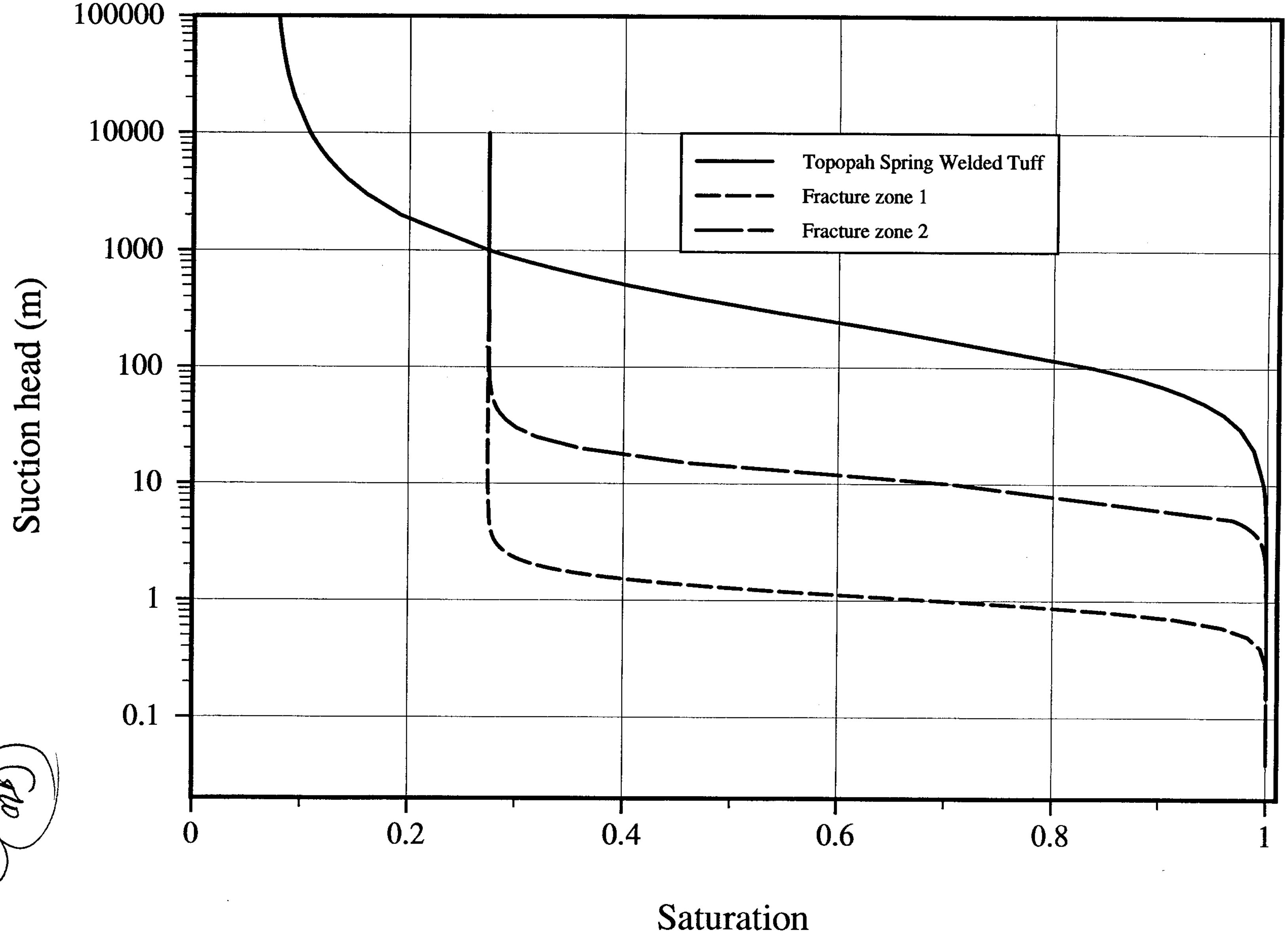
$$e = 2 \times 10^{-4} \text{ m}$$

$$n = 0.0925$$

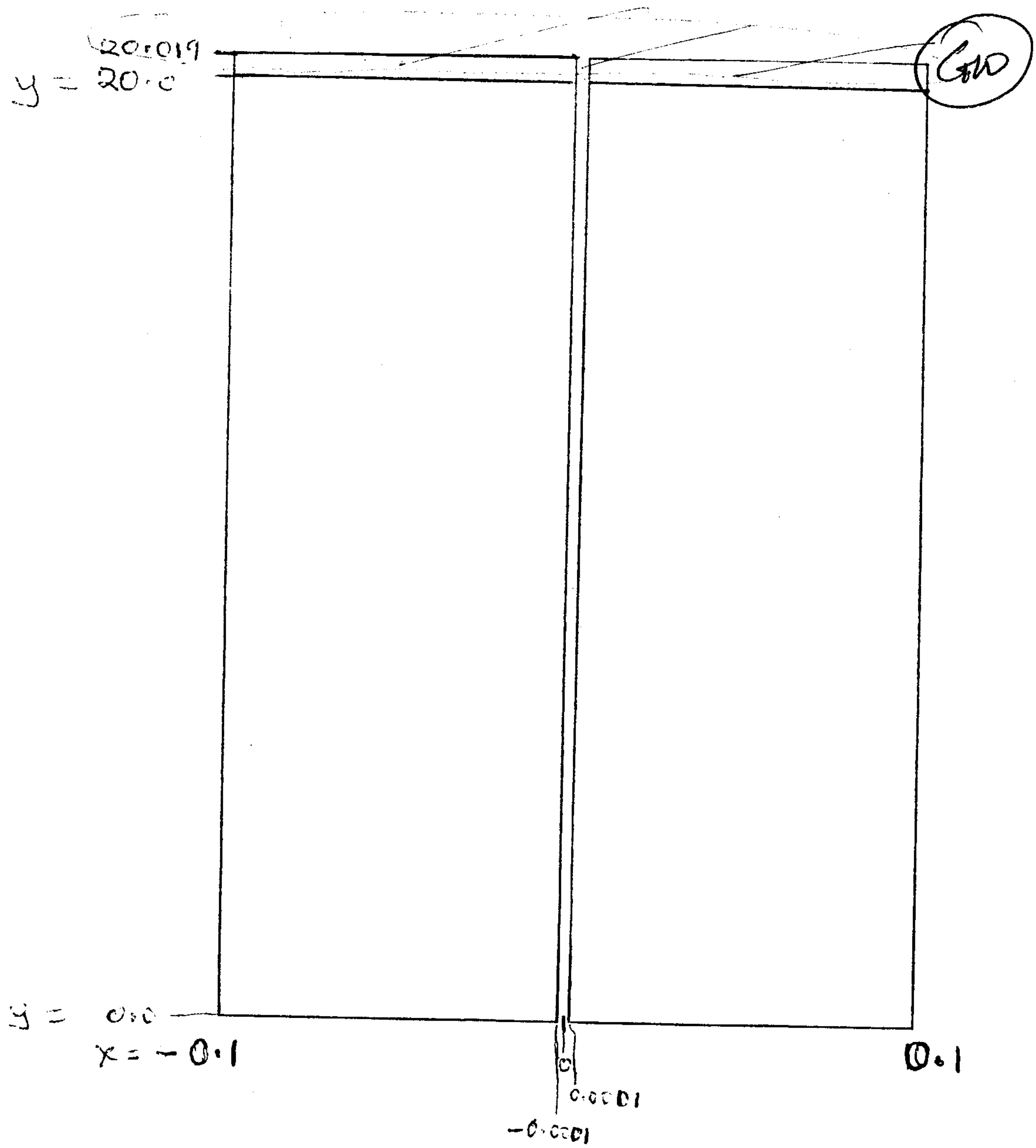
$$t = \frac{2 \times 10^{-4}}{0.0925} = 2.2 \times 10^{-3} \text{ m}$$

2.2 mm solid of 0.0925 porosity

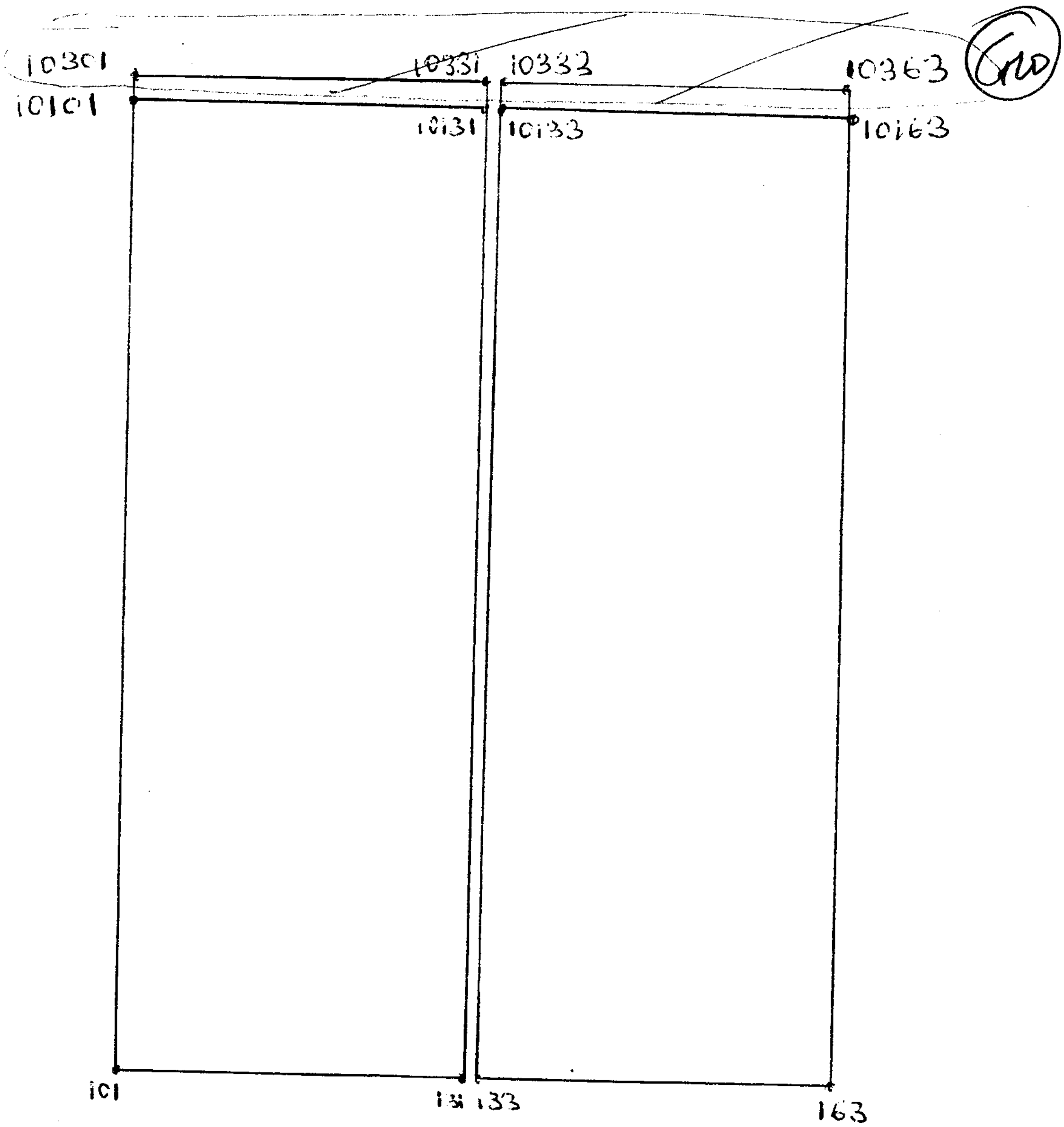
$\equiv$ 0.2 mm fracture

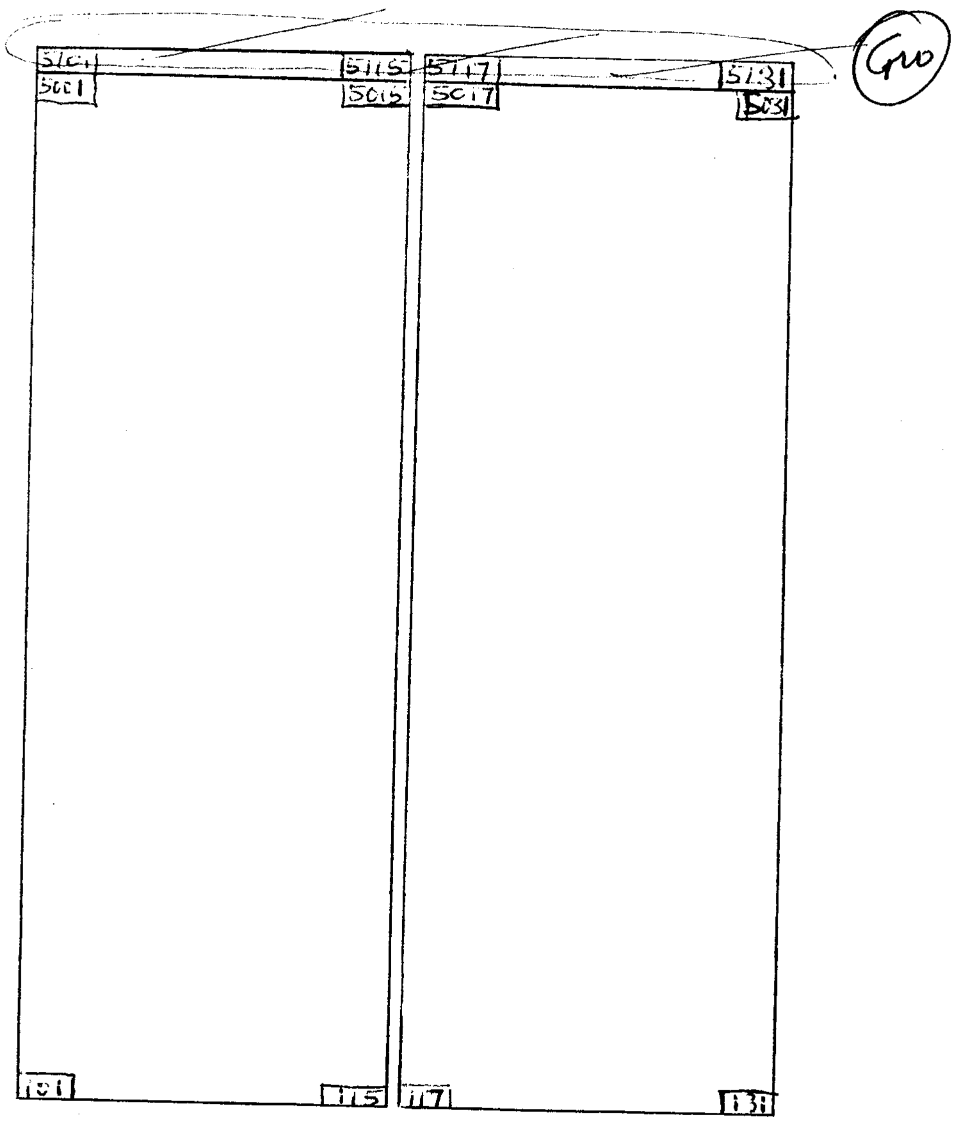

Topopah Spring Welded Tuff
Fracture zone 1
Fracture zone 2
Suction head (m)
100000
10000
1000
100
10
1
0.1
0
0.2
0.4
0.6
0.8
1
Saturation

Coordinates



Node Numbers




5115
5117
5131
5015
5017
5031
115
117

Pore-pressure history saved at following nodes

Distance from Fracture Top (m)	Node Number
0.00	~~10331~~ 10131
0.98	8331
1.93	7131
2.98	6131
4.04	5331
~~5.00~~ 4.99	4731
6.94	3731
10.04	2531
15.10	1131
18.92	331

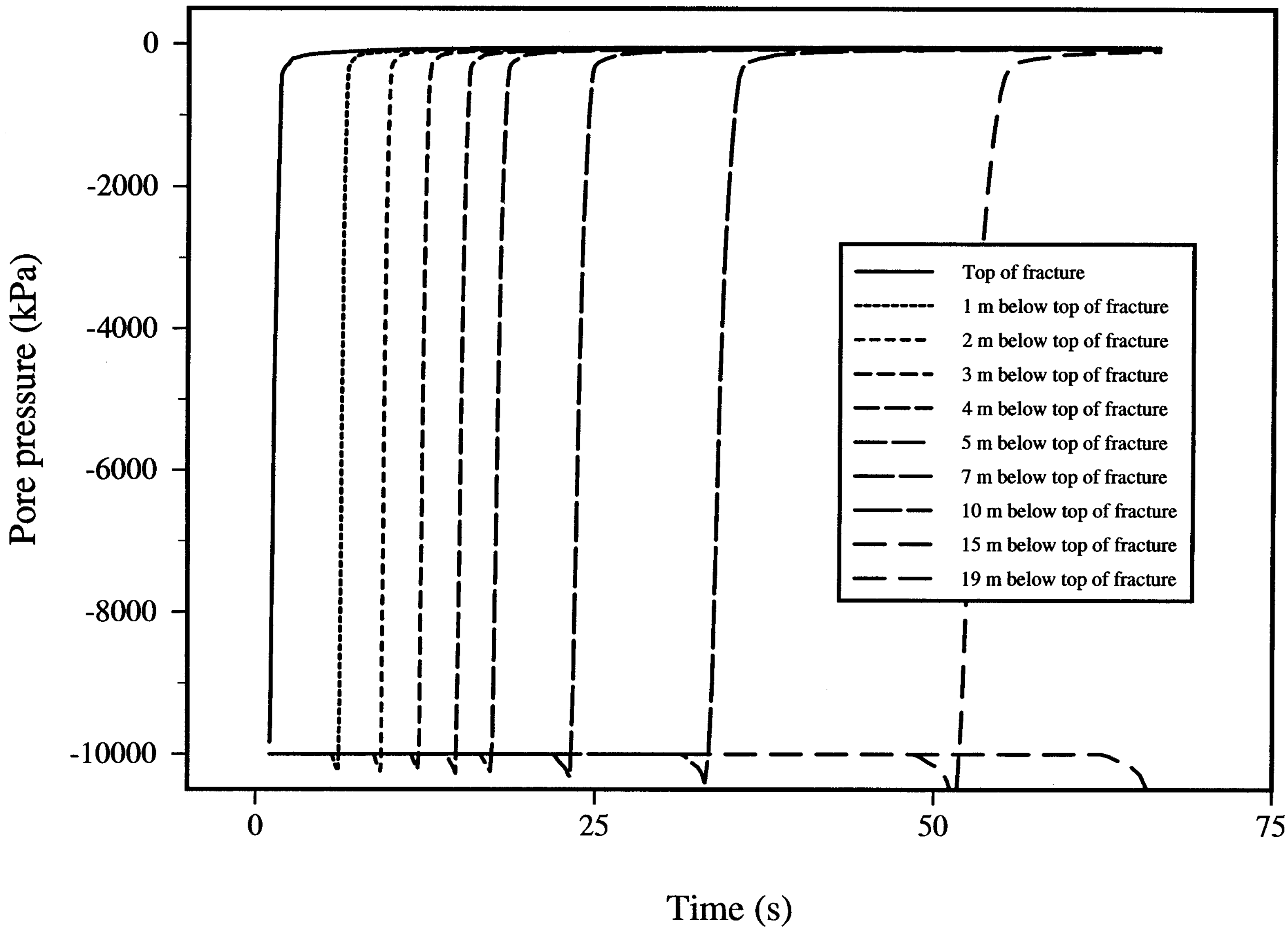
Saturation history saved at centroid of following elements in model C20

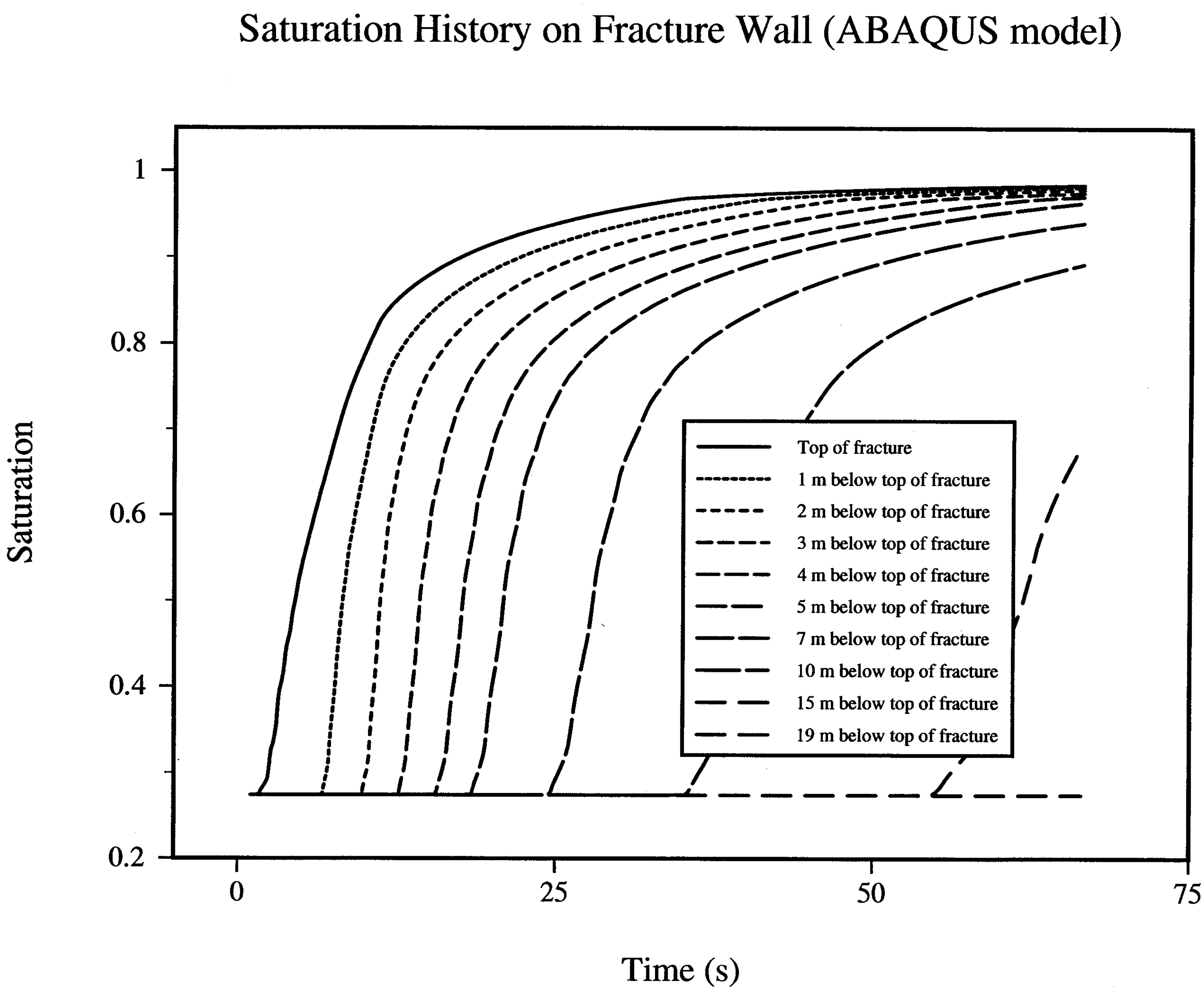
Distance from Fracture top (m)	Element Number
0.05	5016
1.05	4116
2.03	3516
3.11	3016
4.19	2616
5.17	2316
7.17	1816
10.35	1216
~~4.46~~ 15.54 (GW)	516
~~0.54~~ 19.46 (GW)	116

Input Files

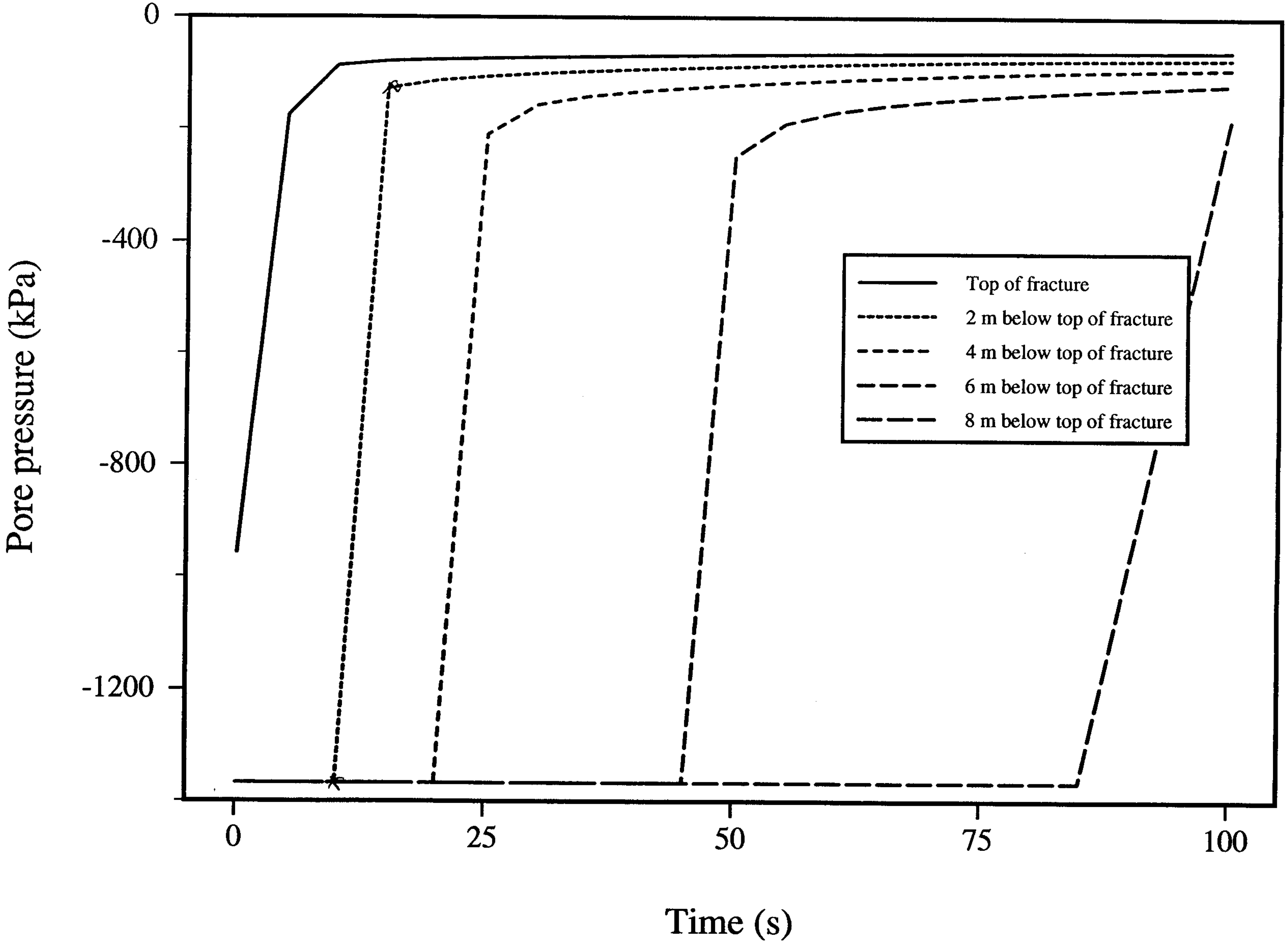
C23.inp	Fracture-zone 1 properties with orthotropic conductivity
C24.inp	Fracture-zone 1 properties with isotropic conductivity

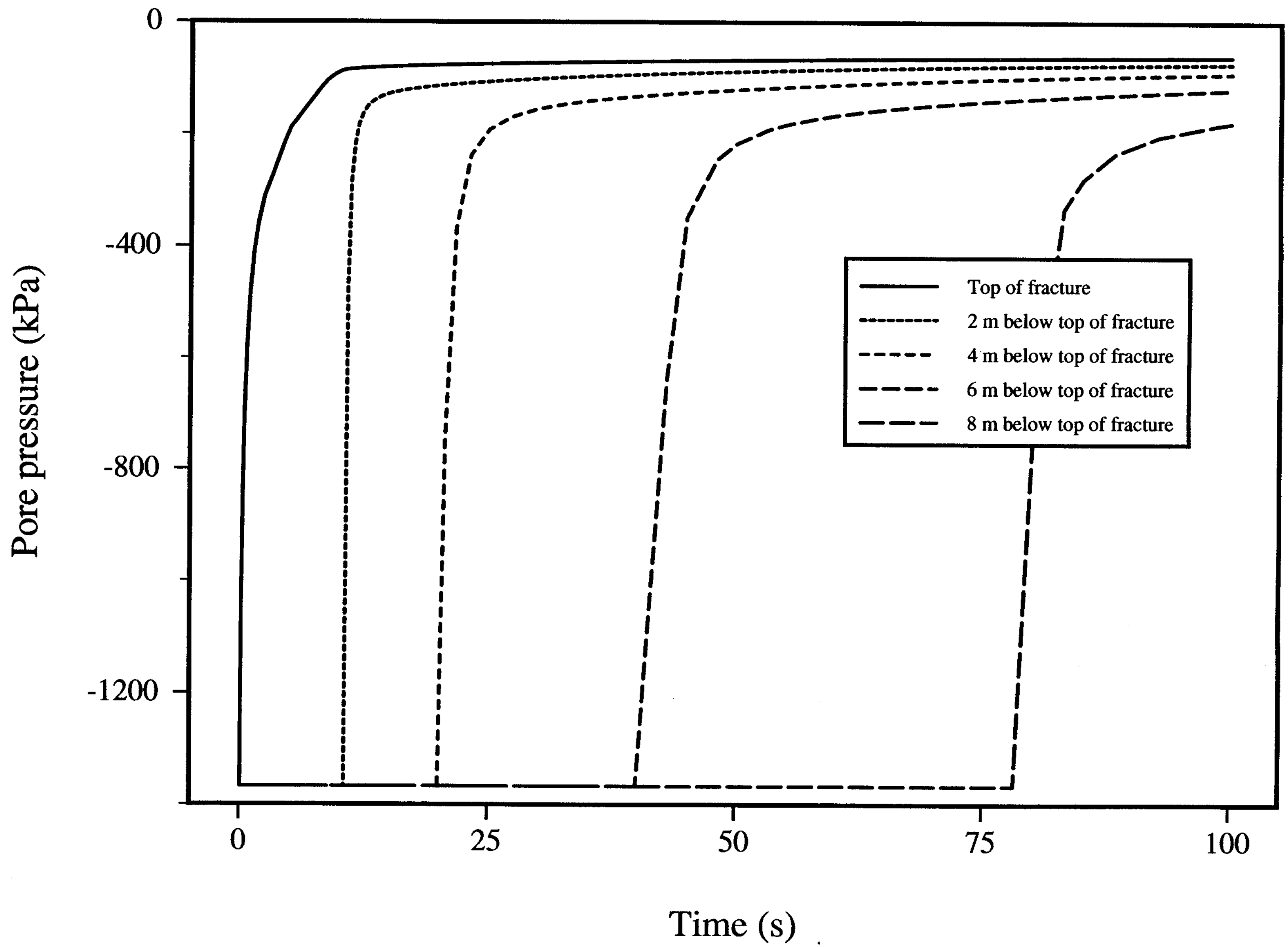
Pore Pressure History on Fracture Wall (ABAQUS model)




Saturation History on Fracture Wall (ABAQUS model)
Saturation
Time (s)
1
0.8
0.6
0.4
0.2
0
25
50
75
Top of fracture
1 m below top of fracture
2 m below top of fracture
3 m below top of fracture
4 m below top of fracture
5 m below top of fracture
7 m below top of fracture
10 m below top of fracture
15 m below top of fracture
19 m below top of fracture

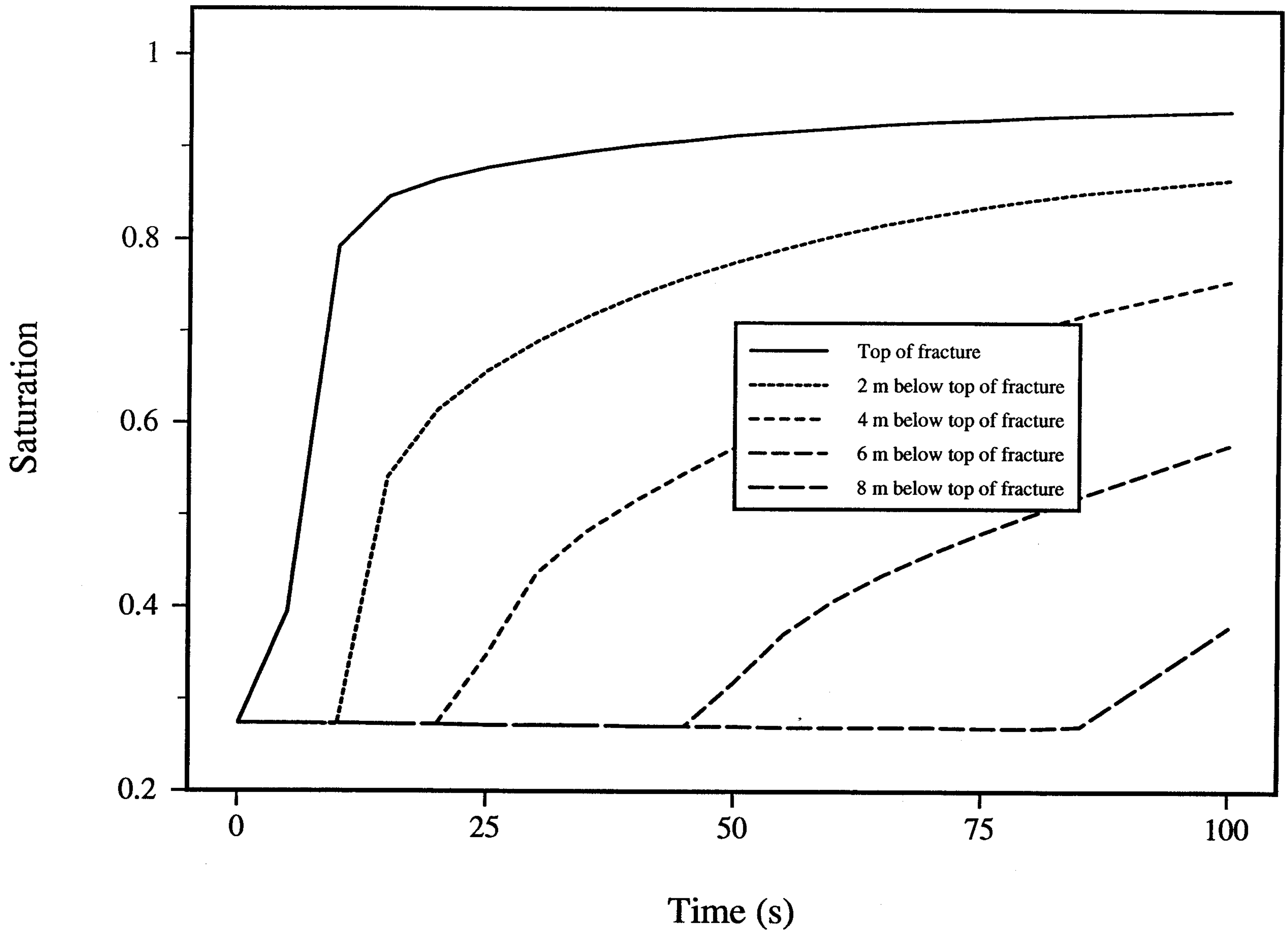
Pore Pressure History on Fracture Wall (CTOUGH model)

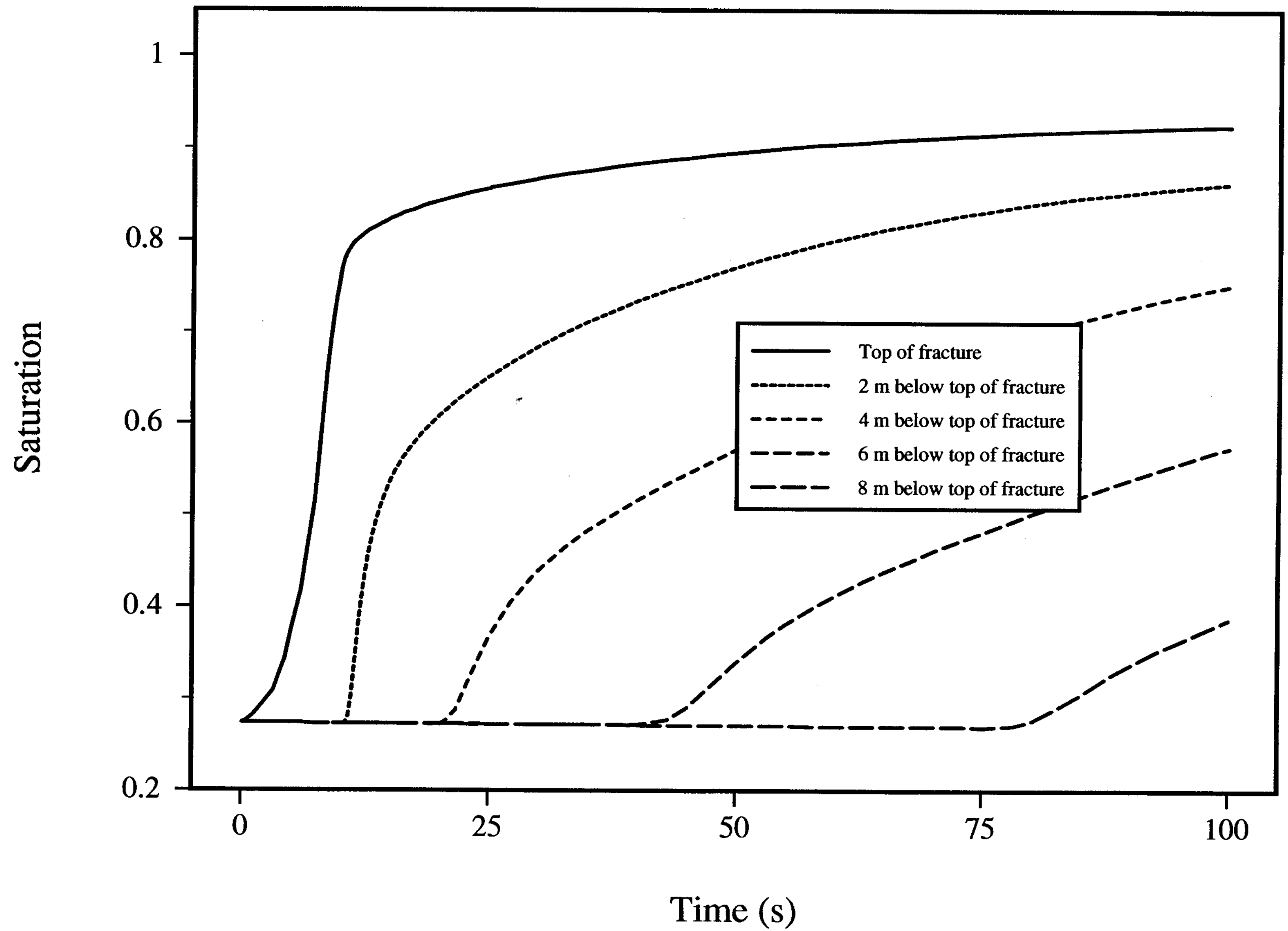




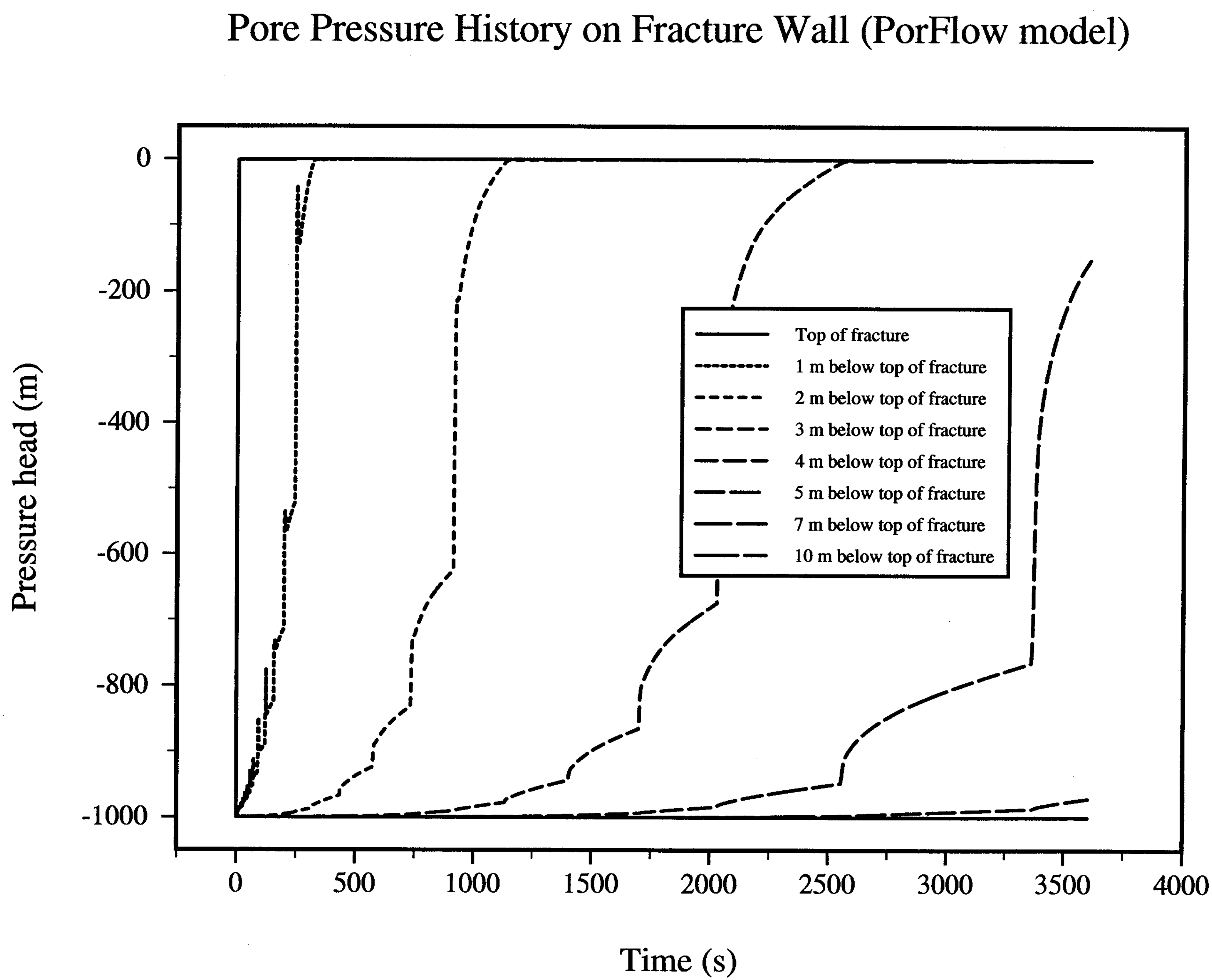
0
-400
-800
-1200
Pore pressure (kPa)
0
25
50
75
100
Time (s)
Top of fracture
2 m below top of fracture
4 m below top of fracture
6 m below top of fracture
8 m below top of fracture

Saturation History on Fracture Wall (CTOUGH model)



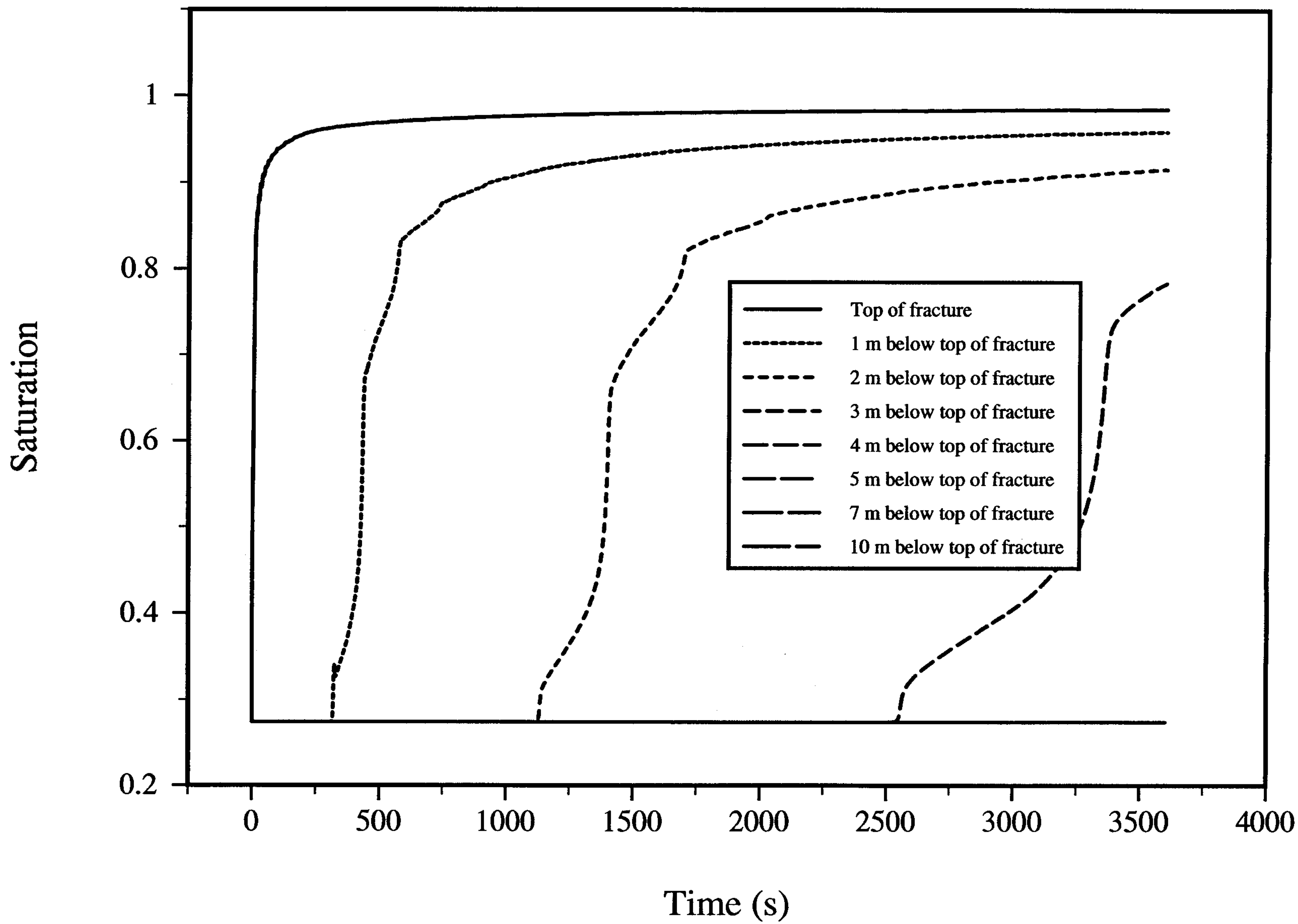


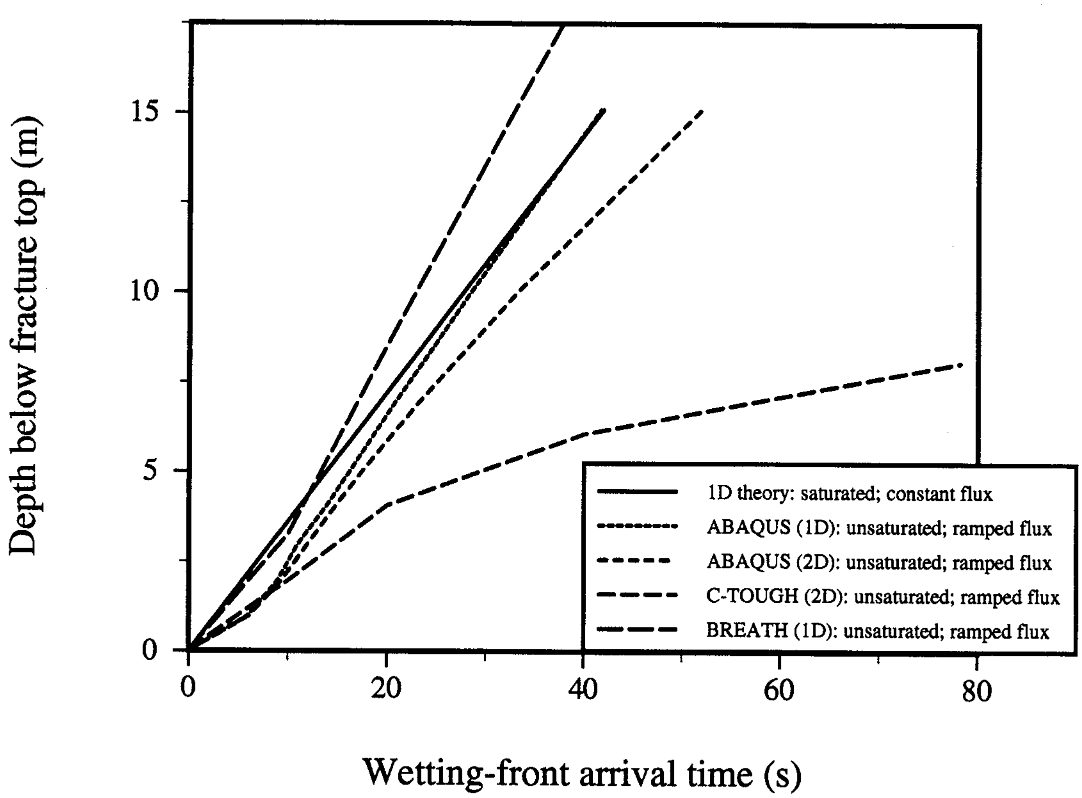
Saturation
Time (s)
1
0.8
0.6
0.4
0.2
0
25
50
75
100
Top of fracture
2 m below top of fracture
4 m below top of fracture
6 m below top of fracture
8 m below top of fracture



Pore Pressure History on Fracture Wall (PorFlow model)
0
-200
-400
-600
-800
-1000
Pressure head (m)
0
500
1000
1500
2000
2500
3000
3500
4000
Time (s)
Top of fracture
1 m below top of fracture
2 m below top of fracture
3 m below top of fracture
4 m below top of fracture
5 m below top of fracture
7 m below top of fracture
10 m below top of fracture

Saturation History on Fracture Wall (PorFlow model)





15
10
5
0
0
20
40
60
80
Depth below fracture top (m)
Wetting-front arrival time (s)
1D theory: saturated; constant flux
ABAQUS (1D): unsaturated; ramped flux
ABAQUS (2D): unsaturated; ramped flux
C-TOUGH (2D): unsaturated; ramped flux
BREATH (1D): unsaturated; ramped flux

C23   1D: saturated constant flux

Depth (m)	Ta-ABAQUS (s)	Ta-THEORY (s)
0.98	6.08	2.72
1.93	9.24	5.36
2.98	12.00	8.27
4.04	14.78	11.21
4.99	17.40	13.85
6.94	23.24	19.26
10.04	33.37	27.86
15.10	51.89	41.91

For 1D Saturated case.

Constant Flux of 3.33×10^{-2} m/s

$$V = \frac{3.33 \times 10^{-2}}{0.0925} \text{ m/s} = 0.360 \text{ m/s}$$

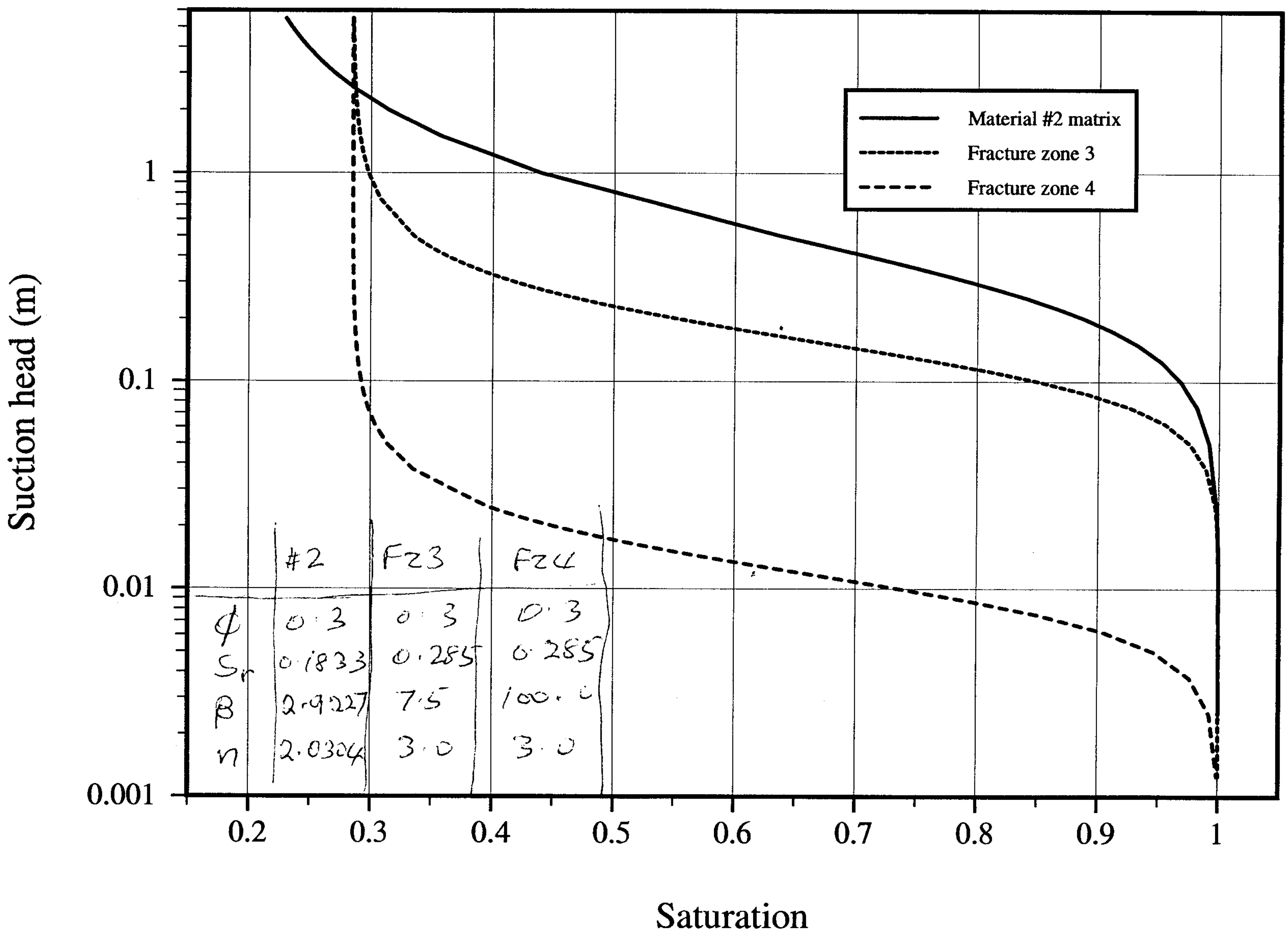
Depth	Arrival Time (s)
0.98	2.72
1.93	5.36
⋮	
15.10	41.9

Case C24 (Isotropic Permeability for Fracture Zone)

Node	~~Depth~~ (m)	Arrival Time (s)
10131	0.0	—
8331	0.98	6.085
7131	1.93 ~~0.98~~ (GW)	9.24
6131	2.98	12.00
5331	4.04	14.69
4731	4.99	17.46
3731	6.94	23.24
2531	10.04	33.41
1131	15.10	51.82
331	18.92	—

Case of

Material #2


Material #2 matrix
Fracture zone 3
Fracture zone 4
Suction head (m)
Saturation
1
0.1
0.01
0.001
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
#2 Fz3 Fz4
φ 0.3 0.3 0.3
Sr 0.1833 0.285 0.285
β 2.9227 7.5 100.0
n 2.0304 3.0 3.0

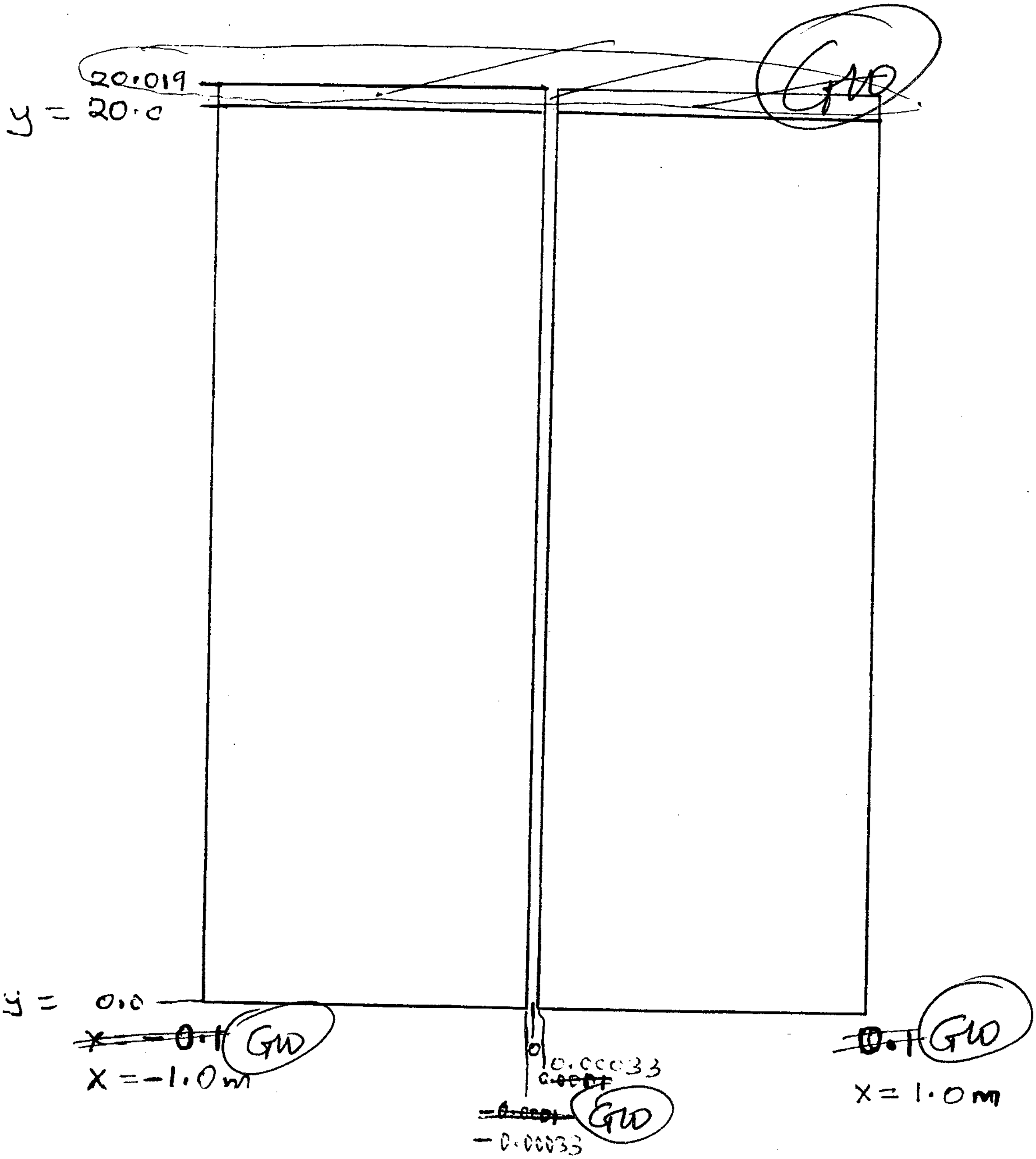
Equivalent thickness of thin solid

For Material 2 Simulations

$$t = \frac{2 \times 10^{-4}}{0.3} = 6.66 \times 10^{-4}$$

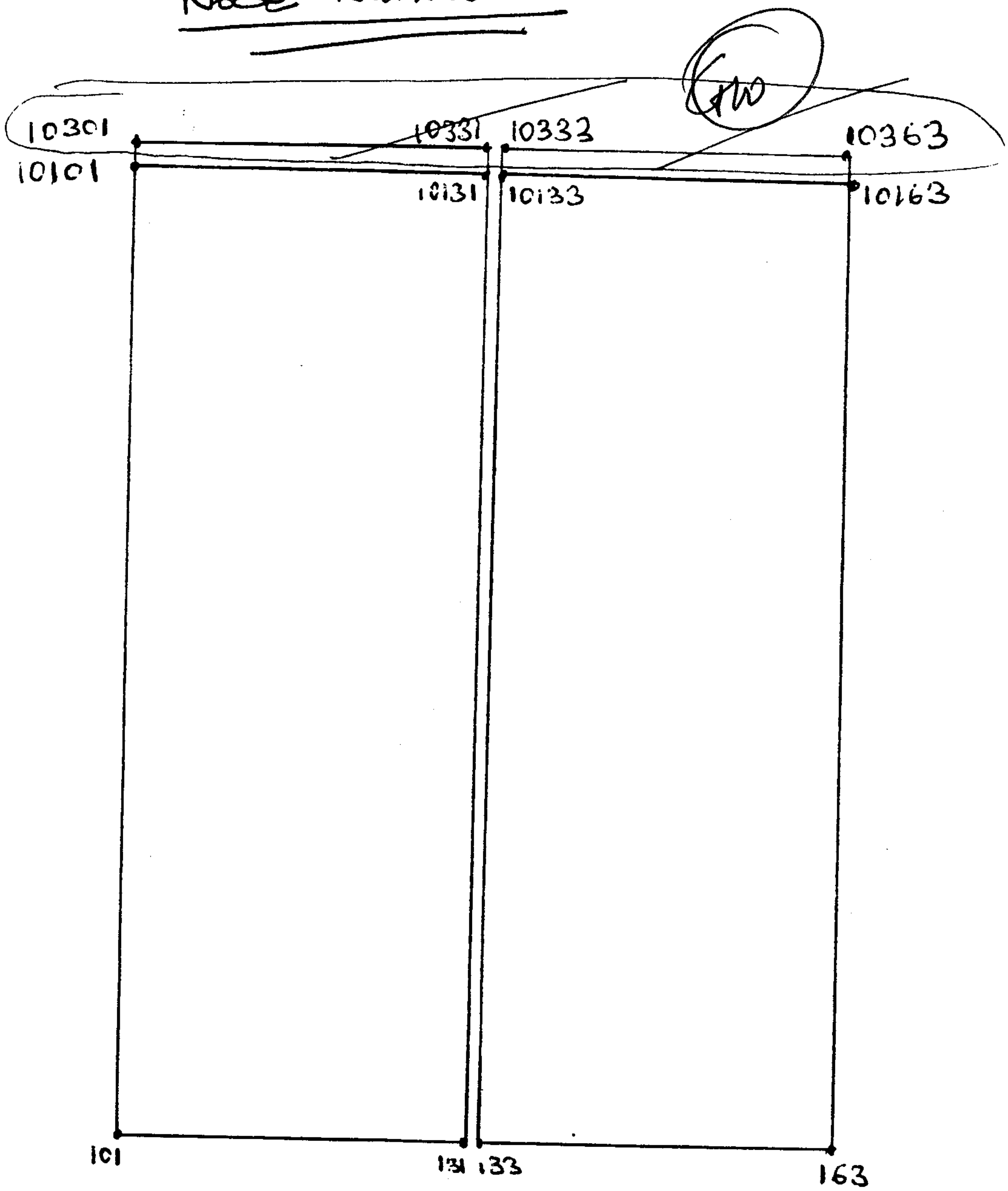
$$t/2 = 3.33 \times 10^{-4}$$

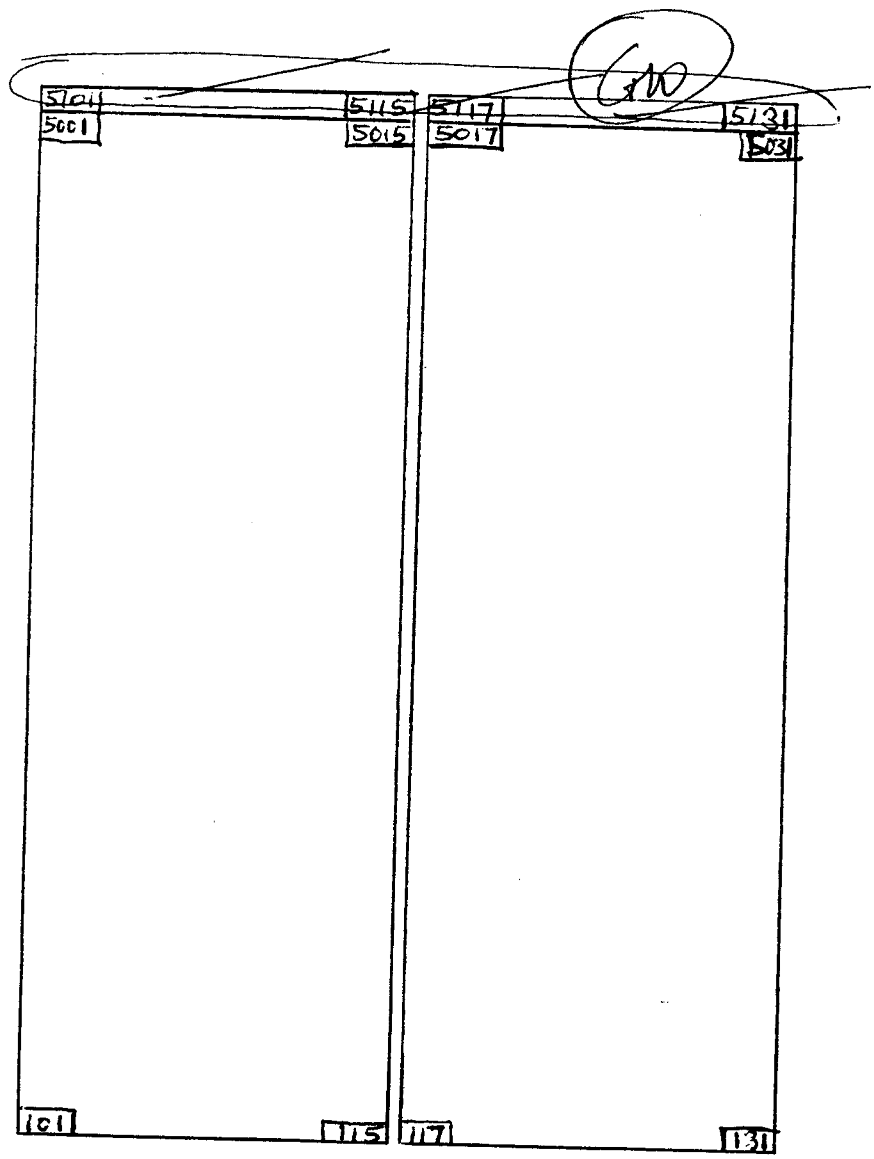
Coordinates



Same FE mesh as used for C20 series, except for the change in horizontal coordinates indicated.

Node Numbers




5101
5115
5117
5131
5001
5015
5017
5031
101
115
117
131

Nodes Monitored for Pore-Pressure History

Node Number	Y-coordinate (m)	Depth below fracture tip (m)
10131	20	0.0
9731	19.8	0.2
9131	19.5	0.5
8531	19.2	0.2
8131	18.9	1.1
7731	18.6	1.4
7331	18.2	1.8
6931	17.9	2.1
6531	17.5	2.5
6131	17.0	3.0

Elements Monitored for Saturation History

Elem No	Y coordinate at Centroid (m)	Distance of centroid from fracture top (m)
5016 ~~501~~ (GWD)	19.96	0.04
4816 ~~480~~ (GWD)	19.75	0.25
4516 ~~450~~ (GWD)	19.45	0.55
4216 ~~420~~ (GWD)	19.15	0.85
4016	18.80	1.20
3816	18.50	1.50
3616	18.15	1.85
3416	17.80	2.20
3216	17.35	2.65
3016	16.90	3.10

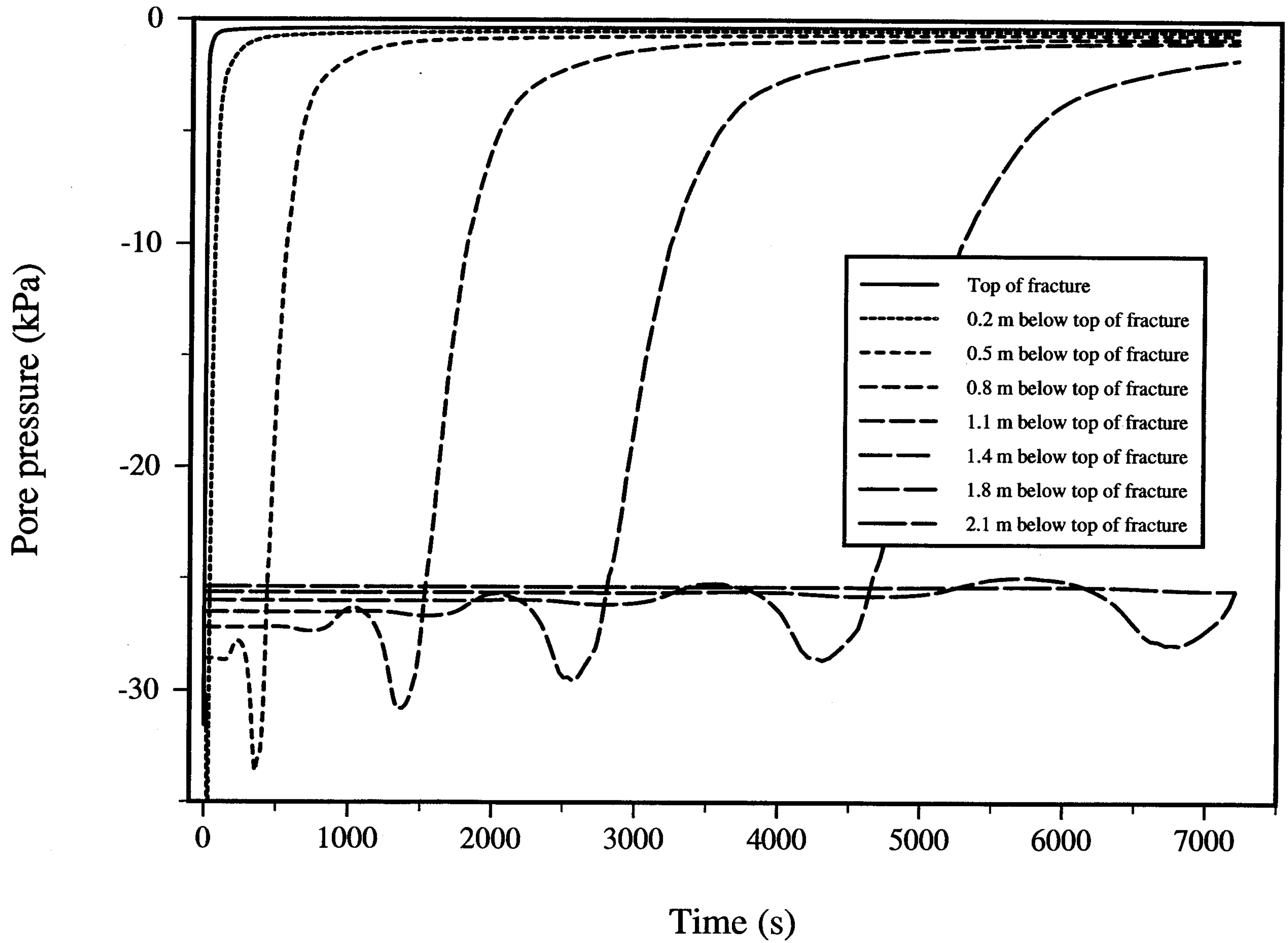
Input Files

C31 Fracture-zone 3 properties with orthotropic conductivity

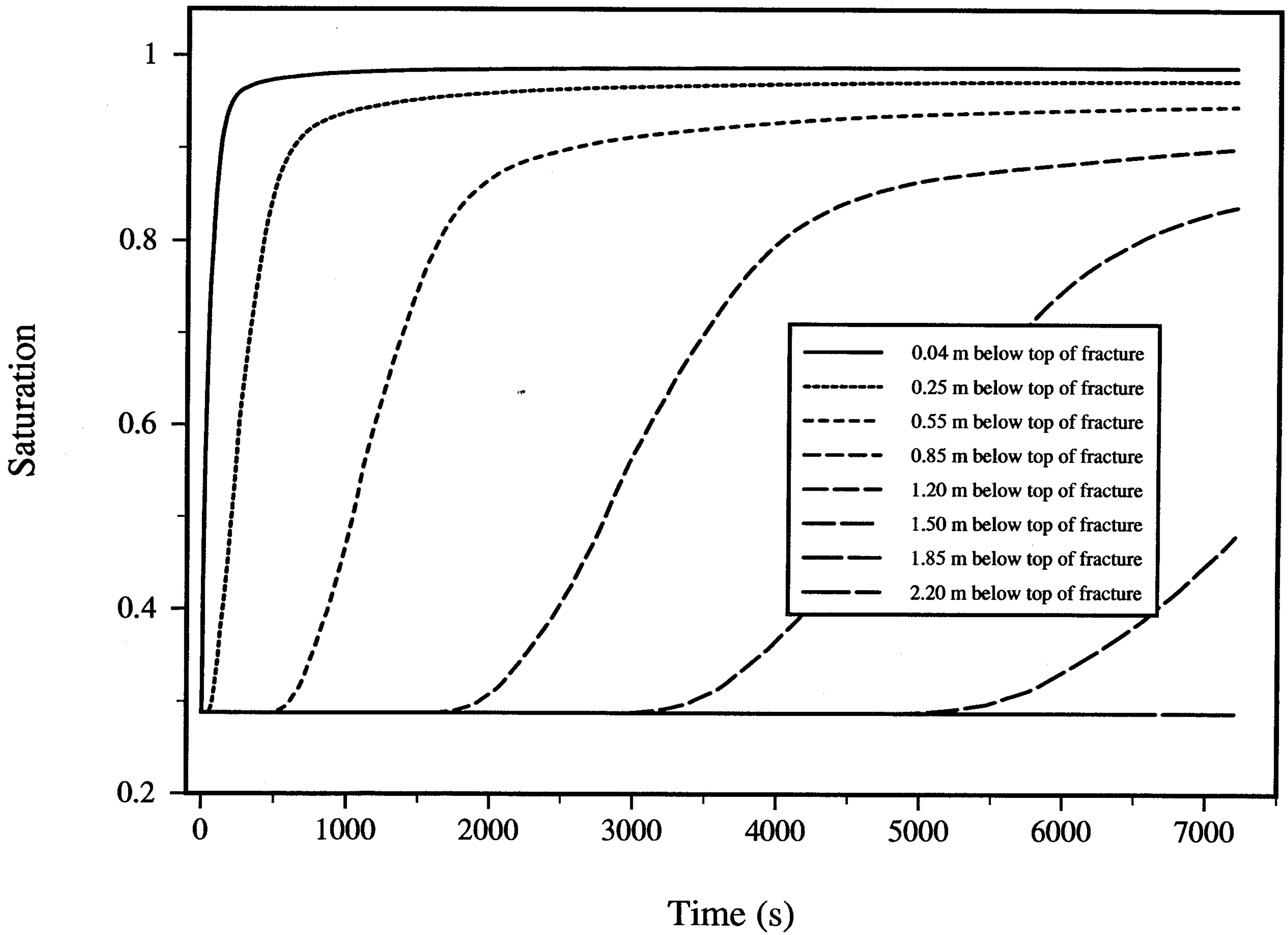
C32 Fracture-zone 3 properties with isotropic conductivity

C41 Fracture-zone 4 properties with orthotropic conductivity.

Pore Pressure History on Fracture Wall (ABAQUS model c31)



Saturation History on Fracture Wall (ABAQUS model c31)



Wettingfront Arrival Times

Run ABAQUS command file C30.jnl & during an ABAQUS/Post session, ~~on the as follows:~~ (GWO)

Example

```
abaqus post restart=c41
*results, file = c41
*input, file=c30.jnl
*end
```

Then using vi text editor, split the file abaqus.rpt into two or more tables.

Compile the c code wFrontArrival.c and process the ~~sq~~ tables one at a time as follows

Example

```
cc wFrontArrival.c
a.out < file1
a.out < file2
     etc
```

for all the ~~files~~ (GWO) result files

The output of wFrontArrival.c goes to the screen, and may be re-directed to a file.

Example for case C41

```
Cross-over time at node      10131 is   7.925e+00 seconds
Cross-over time at node       9731 is   1.442e+02 seconds
Cross-over time at node       9131 is   8.514e+02 seconds
Cross-over time at node       8531 is   2.344e+03 seconds
Cross-over time at node       8131 is   4.233e+03 seconds
Cross-over time at node       7731 is   7.022e+03 seconds
```

Extract the information from this file to set up a table, such as the following:

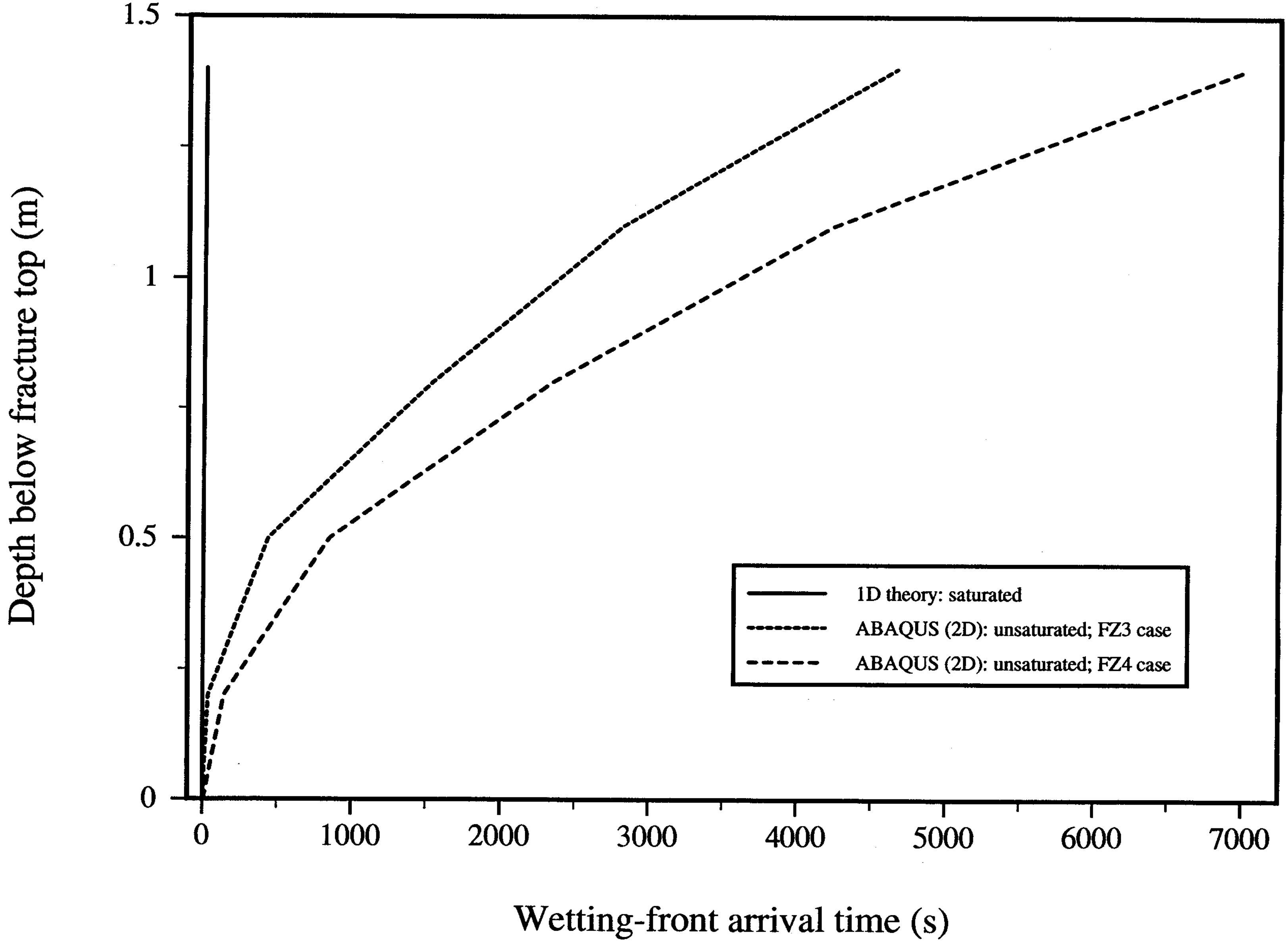
Node	Depth (m)	Front-arrival time for case C41 (s)
10131	0.0	7.9
9731	0.2	144.2
9131	0.5	851.4
8531	0.8	2344
8131	1.1	4233
7731	1.4	7022
7331	1.8	—
6931	2.1	—

Node Number	Depth (m)	Arrival Time (s) Case C31	Arrival Time (s) Case C32
10131	0.0	1.634	1.634
9731	0.2	38.13	38.13
9131	0.5	438.9	438.9
8531	0.8	1541	1541
8131	1.1	2814	2814
7731	1.4	4659	4659
7331	1.8	—	—
6931	2.1	—	—

Depth	Theoretical Arrival Time (s) (1D — Sat case)
0.0	0.0
0.2	1.80
0.5	4.50
0.8	7.21
1.1	9.91
1.4	12.6

$V = \frac{3.33 \times 10^{-2}}{0.3}$ m/s

$= 0.11$ m/s



1.5
1
0.5
0
Depth below fracture top (m)
0
1000
2000
3000
4000
5000
6000
7000
Wetting-front arrival time (s)
1D theory: saturated
ABAQUS (2D): unsaturated; FZ3 case
ABAQUS (2D): unsaturated; FZ4 case

CYLINDRICAL HEAT SOURCE
IN INFINITE MEDIUM
(TASK 2.3 PROBLEM 5)

PROBLEM SET 5: CYLINDRICAL HEAT SOURCE IN INFINITE MEDIA

The purpose of this problem set is to evaluate the modeling of coupled thermal-hydrological problems in ABAQUS. The problems examine changes in temperature and pore-water pressure and saturation around a cylindrical heat source buried in an infinite rock mass. The rock mass is homogeneous and isotropic. Water flows through pore channels only; there is no flow through fractures.

The problem will be solved for both the saturated and unsaturated rock masses, using ABAQUS, V-TOUGH, and PORFLO. The saturated case will also be solved analytically, using the solution obtained by Booker and Savidou (1985). A FORTRAN code of the Booker-Savidou solution, which was developed by T.S. Nguyen of the Atomic Energy Control Board, Canada, was obtained through the DECOVALEX secratariate. This code will be used if it is found to reproduce satisfactorily the responses calculated by Booker and Savidou (1985); otherwise, use of the analytical solution will be dropped from the study.

The thermal output of the heater will be specified in a way to maintain below-boiling conditions in the rock mass, because ABAQUS has no provisions for modeling the vaporization and condensation of water.

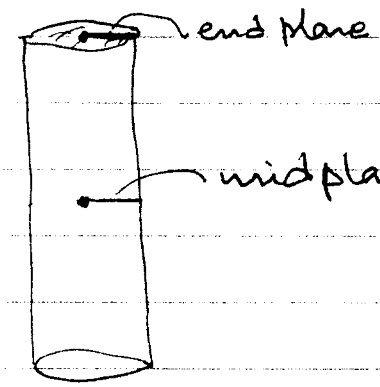
Analytical Solution

AECB Canada Code

Source file: MyBookerSolution.f

Input file: BoSa.inp

Output files BosaEnd.out — end plane
BosaMid.out — mid plane



~~Outs~~ C-codes TempHist.c and plHist.c used to extract temperature and pore-pressure data from the .out files, for XPLOT plotting.

AECB Code

Compile with f77 -e (to accept 132-column source)

```
C*** THERMAL CONSOLIDATION AROUND A VOLUMETRIC HEAT SOURCE
C*** BASED ON BOOKER SOLUTION (1985)
C*** THE VOLUME IS DEFINED BY FUNCTION SUBROUTINES Y1,Y2,Z1,Z2
C*** INTEGRATION IS PERFORMED BY GAUSSIAN QUADRATURE
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 NU,LAM,M,KAP,MV,KT,KH
      Character Fname*10,Fname2*10,TITLE*80
      DIMENSION XP(500),YP(500),ZP(500),TIME(500),ZG(256),WG(265)
      COMMON/SPACE/XF,YF,ZF,T
      COMMON KAP
      COMMON C
      COMMON LAM,G
      COMMON Y,Z
      EXTERNAL FTEMP,FPRES,FSXX,FSZZ,Y1,Y2,Z1,Z2
C****OPEN INPUT,OUTPUT FILES
      Write(6,102)
102   Format('Name of the data file? '/)
      Read(5,*)Fname
      Open(51,file=Fname)
      write(6,103)
103   format('name of output file?'/)
       Read(5,*)Fname2
      open(52,File=Fname2)
C****ENTER INPUT DATA
       READ(51,*)TITLE
      READ(51,*)X1,X2
      READ(51,*)E,NU,AS,AW
      READ(51,*)RHOS,RHOW,POR
      READ(51,*)CS,CW,KT,KH,GRAV
      READ(51,*)QV
      READ(51,100)NGAUS,NT,NP
100    FORMAT(3I5)
       READ(51,*)(XP(I),YP(I),ZP(I),I=1,NP)
      READ(51,*)(TIME(I),I=1,NT)
C****ECHO INPUT DATA
       WRITE(52,*)TITLE
       WRITE(52,200)
      WRITE(52,201)E,NU,AS,AW
      WRITE(52,202)RHOS,RHOW,POR
      WRITE(52,203)CS,CW,KT,KH,GRAV
      WRITE(52,204)QV
      WRITE(52,205)NGAUS,X1,X2
200    FORMAT(//'INPUT DATA'/10('-'))

201    FORMAT('E=',E15.6/'NU=',E15.6/'AS=',E15.6/'AW=',E15.6)
202    FORMAT('RHOS=',E15.6/'RHOW=',E15.6/'POROSITY='E15.6)
203    FORMAT('CS=',E15.6/'CW=',E15.6/'KT=',E15.6/'KH=',E15.6/
     * 'GRAVITY=',E15.6)
204    FORMAT('HEAT GENERATION RATE',E15.6)
205    FORMAT('NUMBER OF GAUSSIAN INTEGRATION POINTS',I5/
     * 'LIMITS OF VOLUMETRIC SOURCE  X1=',E15.6,'X2=',E15.6)
C****CALCULATE SECONDARY PARAMETERS
      LAM=NU*E/(1.+NU)/(1.-2.*NU)
      G=E/2./(1.+NU)
      BP=(LAM+0.666666666666667*G)*AS
      AU=AS*(1-POR)+AW*POR
      M=POR*RHOW*CW+(1.-POR)*RHOS*CS
      KAP=KT/M
      MV=1./(LAM+2.*G)
      C=KH/MV/RHOW/GRAV
      X=AU/MV-BP
      XX=X/AU/(1.-C/KAP)
      Y=MV*(XX+BP/AU)
      Z=MV*XX
      PI=3.141592654
      FACT=QV/4./PI/KT
       WRITE(52,400)LAM,G,KAP,C,AU,BP,X,Y,Z
400   FORMAT(//'CALCULATED PARAMETERS'/21('-')/'LAMBDA',E15.6/'G',E15.6/
     *'THERMAL DIFFUSIVITY ',E15.6/'CONSOLIDATION COEFFICIENT',E15.6/
     * 'AU',E15.6/'BP',E15.6/'X',E15.6/'Y',E15.6/'Z',E15.6//)
C****CALCULATE TEMPERATURE,PORE PRESSURE AND STRESSES AT DIFFERENT TIMES AND POI
NTS
      CALL DGAUSS(ZG,WG,NGAUS)
      DO IT=1,NT
        T=TIME(IT)
        WRITE(52,300)T
        DO I=1,NP
          XF=XP(I)
          YF=YP(I)
          ZF=ZP(I)
             TEMP=QUAD3D(FTEMP,X1,X2,Y1,Y2,Z1,Z2,ZG,WG,NGAUS)*FACT
             PRES=QUAD3D(FPRES,X1,X2,Y1,Y2,Z1,Z2,ZG,WG,NGAUS)
             PRES=PRES*FACT*X/(1.-C/KAP)
             SXX=QUAD3D(FSXX,X1,X2,Y1,Y2,Z1,Z2,ZG,WG,NGAUS)
             SZZ=QUAD3D(FSZZ,X1,X2,Y1,Y2,Z1,Z2,ZG,WG,NGAUS)
             SXX=BP*TEMP +AU*FACT*SXX
             SZZ=BP*TEMP +AU*FACT*SZZ
             WRITE(52,301)XF,YF,ZF,TEMP,PRES,SXX,SZZ
        END DO
      END DO
300    FORMAT('TIME=',E15.6/11X,'X',11X,'Y',11X,'Z',8X,'TEMP',
     * 7X,'PRESS',9X,'SXX',9X,'SZZ')
301    FORMAT(7E12.4)
      STOP
      END

      REAL*8 FUNCTION FTEMP(XS,YS,ZS)
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 KAP
      COMMON/SPACE/XF,YF,ZF,T
      COMMON KAP
      R=((XF-XS)**2+(YF-YS)**2+(ZF-ZS)**2)**0.5
      FTEMP=F(KAP,T,R)/R
      RETURN
      END

      REAL*8 FUNCTION FPRES(XS,YS,ZS)
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 KAP
      COMMON/SPACE/XF,YF,ZF,T
      COMMON KAP
      COMMON C
      R=((XF-XS)**2+(YF-YS)**2+(ZF-ZS)**2)**0.5
      FPRES=(F(KAP,T,R)-F(C,T,R))/R
      RETURN
      END

      REAL*8 FUNCTION FSXX(XS,YS,ZS)
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 KAP,LAM,KAPT
      COMMON/SPACE/XF,YF,ZF,T
```

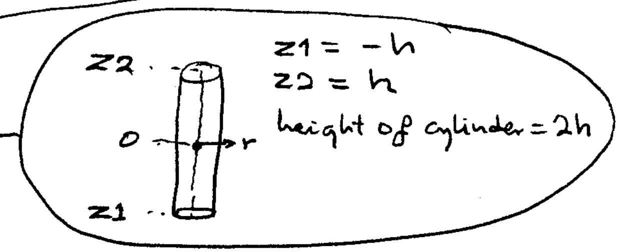
E = Young's modulus
NU = Poisson's ratio
AS = Volumetric thermal expansivity for solid
AW = Volumetric thermal expansivity for water
RHOS = Density of solid
RHOW = Density of water
POR = Porosity
Heat generation rate (QV)
CS = specific heat of solid (per unit mass)
CW = specific heat of water (per unit mass)
KT = Thermal conductivity
KH = Hydraulic conductivity
GRAV = acceleration due to gravity

X/[ln(1 - C/K)]

```
      COMMON KAP
      COMMON C
      COMMON LAM,G
      COMMON Y,Z
       XR=XF-XS
      YR=YF-YS
      ZR=ZF-ZS
      Pi=3.141592654
      E=2.718281828
      R2=XR**2+YR**2+ZR**2
      R=(XR**2+YR**2+ZR**2)**0.5
      GSTAR=Y*GF(KAP,T,R)-Z*GF(C,T,R)
      DGSDR= Y*(-2*kap*t/r**3 + Sqrt(kap*t)/(E**(r**2/(4*kap*t))*Sqrt(Pi)*r**2)
     -
     -  Sqrt(kap*t)/(2*E**(r**2/(4*kap*t))*kap*Sqrt(Pi)*t) +
     -  Sqrt(kap*t/(Pi*r**2))/(E**(r**2/(4*kap*t))*r) +
     -  r*Sqrt(kap*t/(Pi*r**2))/(2*E**(r**2/(4*kap*t))*kap*t) +
     -  2*kap*t*Erfc(r/(2*Sqrt(kap*t)))/r**3)
     -  -Z*(-2*c*t/r**3 + Sqrt(c*t)/(E**(r**2/(4*c*t))*Sqrt(Pi)*r**2) -
     -  Sqrt(c*t)/(2*E**(r**2/(4*c*t))*c*Sqrt(Pi)*t) +
     -  Sqrt(c*t/(Pi*r**2))/(E**(r**2/(4*c*t))*r) +
     -  r*Sqrt(c*t/(Pi*r**2))/(2*E**(r**2/(4*c*t))*c*t) +
     -  2*c*t*Erfc(r/(2*Sqrt(c*t)))/r**3)
       DUX=(1.-XR**2/R2)*GSTAR/R+XR**2/R2*DGSDR
      DUY=(1.-YR**2/R2)*GSTAR/R+YR**2/R2*DGSDR
      DUZ=(1.-ZR**2/R2)*GSTAR/R+ZR**2/R2*DGSDR
      EV=-(DUX+DUY+DUZ)
      FSXX=LAM*EV - (2.0) * G * DUX
      RETURN
      END

      REAL*8 FUNCTION FSZZ(XS,YS,ZS)
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 KAP,LAM,KAPT
      COMMON/SPACE/XF,YF,ZF,T
      COMMON KAP
      COMMON C
      COMMON LAM,G
      COMMON Y,Z
       XR=XF-XS
      YR=YF-YS
      ZR=ZF-ZS
      Pi=3.141592654
      E=2.718281828
      R2=XR**2+YR**2+ZR**2
      R=(XR**2+YR**2+ZR**2)**0.5
      GSTAR=Y*GF(KAP,T,R)-Z*GF(C,T,R)
      DGSDR= Y*(-2*kap*t/r**3 + Sqrt(kap*t)/(E**(r**2/(4*kap*t))*Sqrt(Pi)*r**2)
     -
     -  Sqrt(kap*t)/(2*E**(r**2/(4*kap*t))*kap*Sqrt(Pi)*t) +
     -  Sqrt(kap*t/(Pi*r**2))/(E**(r**2/(4*kap*t))*r) +
     -  r*Sqrt(kap*t/(Pi*r**2))/(2*E**(r**2/(4*kap*t))*kap*t) +
     -  2*kap*t*Erfc(r/(2*Sqrt(kap*t)))/r**3)
     -  -Z*(-2*c*t/r**3 + Sqrt(c*t)/(E**(r**2/(4*c*t))*Sqrt(Pi)*r**2) -
     -  Sqrt(c*t)/(2*E**(r**2/(4*c*t))*c*Sqrt(Pi)*t) +
     -  Sqrt(c*t/(Pi*r**2))/(E**(r**2/(4*c*t))*r) +
     -  r*Sqrt(c*t/(Pi*r**2))/(2*E**(r**2/(4*c*t))*c*t) +
     -  2*c*t*Erfc(r/(2*Sqrt(c*t)))/r**3)
       DUX=(1.-XR**2/R2)*GSTAR/R+XR**2/R2*DGSDR
      DUY=(1.-YR**2/R2)*GSTAR/R+YR**2/R2*DGSDR
      DUZ=(1.-ZR**2/R2)*GSTAR/R+ZR**2/R2*DGSDR
```

```
      EV=-(DUX+DUY+DUZ)
       FSZZ=LAM*EV - (2.0) * G * DUZ
      RETURN
      END

      REAL*8 FUNCTION F(C,T,R)
      IMPLICIT REAL*8(A-H,O-Z)
      F=ERFC(R/2./(C*T)**0.5)
      RETURN
      END

      REAL*8 FUNCTION GF(C,T,R)
      IMPLICIT REAL*8(A-H,O-Z)
      A=C*T/R**2
      GF=A+(0.5-A)*F(C,T,R) - (A/3.1415926)**0.5*DEXP(-R**2/4./C/T)
      RETURN
      END

      REAL*8 FUNCTION Y1(X)
      IMPLICIT REAL*8 (A-H,O-Z)
      Y1=-(0.32**2-x**2)**0.5
      RETURN
      END

      REAL*8 FUNCTION Y2(X)
      IMPLICIT REAL*8 (A-H,O-Z)
      Y2=(0.32**2-x**2)**0.5
      RETURN
      END

      REAL*8 FUNCTION Z1(X,Y)
      IMPLICIT REAL*8 (A-H,O-Z)
      Z1=-1.125  0.5
      RETURN
      END

      REAL*8 FUNCTION Z2(X,Y)
      IMPLICIT REAL*8 (A-H,O-Z)
      Z2=1.125  0.5
      RETURN
      END

      REAL*8 FUNCTION QUAD3D(FXYZ,X1,X2,Y1,Y2,Z1,Z2,ZG,WG,N)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION ZG(256),WG(256)
      SS=0.
      XM=0.5*(X1+X2)
      XR=0.5*(X2-X1)
      DO IX=1,N
        X=ZG(IX)*XR+XM
        YL=Y1(X)
        YH=Y2(X)
        YM=0.5*(YL+YH)
        YR=0.5*(YH-YL)
        SY=0.
        DO IY=1,N
          Y=YM+YR*ZG(IY)
          ZL=Z1(X,Y)
          ZH=Z2(X,Y)
          ZM=0.5*(ZL+ZH)
```

radius of cylinder 0.25



```
            ZR=0.5*(ZH-ZL)
            SZ=0.
            DO IZ=1,N
              Z=ZM+ZR*ZG(IZ)
              FF=FXYZ(X,Y,Z)
              SZ=SZ+WG(IX)*WG(IY)*WG(IZ)*FF
            END DO
            SZ=SZ*ZR
            SY=SY+SZ
          END DO
          SY=SY*YR
          SS=SS+SY
        END DO
        SS=SS*XR
        QUAD3D=SS
        RETURN
        END


        SUBROUTINE DGAUSS(Z,W,N)
C
C         COMPUTE THE FIRST  N  ROOTS AND WEIGHT FACTORS TO THE
C      GAUSS-LEGENDRE QUADRATURE INTEGRATION SCHEME
C         FOR THE SOLUTION OF INTEGRALS OF THE FORM
C
C                 INTEGRAL OF  F(Z)*DZ = SUM OF  W(I)*F(Z(I))
C                                          AS  I = 1,... N
C                INTEGRATED FROM  A TO B
C
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION W(256),Z(256)

C         Z          ROOTS OF THE LEGENDRE POLYNOMIALS P(N+1)(Z)
C
C         W          WEIGHT FACTORS FOR THE GAUSS-LEGENDRE QUADRATURE
C
C         N          NUMBER OF INTEGRATION POINTS
C      N CAN ONLY HAVE THE VALUE OF EITHER 4,5,6,10,15,20,60,104,256
C
C
C
C
C      THE ROOTS AND WEIGHT FACTORS FOR THE NORMALIZED INTEGRAL ARE TAKEN
C      FROM :
C         APPLIED NUMERICAL METHODS
C         BY : B. CARNAHAN, H.A. LUTHER AND J.O. WILKES
C              JOHN WILEY AND SONS, INC.    , 1969
      CONTINUE
C       AND IN ADDITION :
C              GAUSSIAN QUADRATURE FORMULAS
C       BY : A.H. STROUD AND DON SECREST
C         PRINTICE-HALL, INC.   1966
C
C
C
C         PROGRAMME WAS WRITTEN BY :  MICHAEL J. UNGS  JULY, 1976
C
C
C
C              NORMALIZED ROOTS AND WEIGHTS
C
      IF(N.NE.4) GO TO 50
      Z(1)=.3399810435848562D0
      Z(3)=.8611363115940525D0
      W(1)=.6521451548625461D0
      W(3)=.3478548451374538D0
      GO TO 10000
50    IF(N.NE.5) GO TO 60
      Z(1)=0.
      Z(2)=.5384693101056830D0
      Z(4)=.9061798459386639D0
      W(1)=.5688888888888888D0
      W(2)=.4786286704993664D0
      W(4)=.2369268850561890D0
      GO TO 10000
60    IF(N.NE.6) GO TO 100
      Z(1)=.2386191860831969D0
      Z(3)=.6612093864662645D0
      Z(5)=.9324695142031520D0
      W(1)=.4679139345726910D0
      W(3)=.3607615730481386D0
      W(5)=.1713244923791703D0
      GO TO 10000
100   IF(N.NE.10) GO TO 150
      Z(1)=.148874338981631D0
      Z(3)=.433395394129247D0
      Z(5)=.679409568299024D0
      Z(7)=.865063366688985D0
      Z(9)=.973906528517172D0
      W(1)=.295524224714753D0
      W(3)=.269266719309996D0
      W(5)=.219086362515982D0
      W(7)=.149451349150581D0
      W(9)=.066671344308688D0
      GO TO 10000
150     IF(N.NE.15) GO TO 200
      Z(1)=0.
      Z(2)=.201194093997435D0
      Z(4)=.394151347077563D0
      Z(6)=.570972172608539D0
      Z(8)=.724417731360170D0
      Z(10)=.848206583410427D0
      Z(12)=.937273392400706D0
      Z(14)=.987992518020485D0
      W(1)=.202578241925561D0
      W(2)=.198431485327111D0
      W(4)=.186161000115562D0
      W(6)=.166269205816994D0
       W(8)=.139570677926154D0
      W(10)=.107159220467172D0
      W(12)=.070366047488108D0
      W(14)= .030753241996117D0
      GO TO 10000
200    IF(N.NE.20) GO TO 600
      Z(1)=.7652652113349733D-01
      Z(3)=.2277858511416450D0
      Z(5)=.3737060887154195D0
      Z(7)=.5108670019508270D0
      Z(9)=.6360536807265150D0
      Z(11)=.7463319064601507D0
      Z(13)=.8391169718222188D0
```

```
      Z(15)=.9122344282513259D0
      Z(17)= .9639719272779137D0
      Z(19)=.9931285991850949D0
      W(1)=.1527533871307258D0
      W(3)=.1491729864726037D0
      W(5)=.1420961093183820D0
      W(7)=.1316886384491766D0
      W(9)=.1181945319615184D0
      W(11)=.1019301198172404D0
      W(13)=.8327674157670474D-01
      W(15)=.6267204833410906D-01
      W(17)=.4060142980038694D-01
      W(19)=.1761400713915211D-01
      GO TO 10000
600    IF(N.NE.60) GO TO 1040
      Z(1)=.2595977230124779D-01
      Z(3)=.7780933394953656D-01
      Z(5)=.1294491353969450D0
      Z(7)=.1807399648734254D0
      Z(9)=.2315435513760293D0
      Z(11)=.2817229374232616D0
      Z(13)=.3311428482684481D0
      Z(15)=.3796700565767979D0
      Z(17)=.4271737415830783D0
      Z(19)=.4735258417617071D0
      Z(21)=.5186014000585697D0
      Z(23)=.5622789007539445D0
      Z(25)=.6044405970485103D0
      Z(27)=.6449728284894770D0
      Z(29)=.6837663273813554D0
      Z(31)=.7207165133557303D0
      Z(33)=.7557237753065856D0
      Z(35)=.7886937399322640D0
      Z(37)=.8195375261621457D0
      Z(39)=.8481719847859296D0
      Z(41)=.8745199226468983D0
      Z(43)=.8985103108100459D0
      Z(45)=.9200784761776275D0
      Z(47)=.9391662761164232D0
      Z(49)=.9557222558399961D0
      Z(51)=.9697017887650527D0
      Z(53)=.9810672017525981D0
      Z(55)=.9897878952222217D0
      Z(57)=.9958405251188381D0
      Z(59)=.9992101232274360D0
      W(1)=.5190787763122063D-01
      W(3)=.5176794317491018D-01
      W(5)=.5148845150098093D-01
      W(7)=.5107015606985562D-01
      W(9)=.5051418453250937D-01
      W(11)=.4982203569055018D-01
      W(13)=.4899557545575683D-01
      W(15)=.4803703181997118D-01
      W(17)=.4694898884891220D-01
      W(19)=.4573437971611448D-01
      W(21)=.4439647879578711D-01
      W(23)=.4293889283593564D-01
      W(25)=.4136555123558475D-01
      W(27)=.3968069545238079D-01
      W(29)=.3788886756924344D-01
      W(31)=.3599489805108450D-01
      W(33)=.3400389272494642D-01
      W(35)=.3192121901929632D-01
      W(37)=.2975249150078894D-01
      W(39)=.2750355674992479D-01
      W(41)=.2518047762152124D-01
      W(43)=.2278951694399781D-01
      W(45)=.2033712072945728D-01
      W(47)=.1782990101420772D-01
      W(49)=.1527461859678479D-01
      W(51)=.1267816647681596D-01
      W(53)=.1004755718228798D-01
      W(55)=.7389931163345455D-02
      W(57)=.4712729926953568D-02
      W(59)=.2026811968873758D-02
      GO TO 10000
1040   IF(N.NE.104) GO TO 2560
      Z(1)=.1503080570420580D-01
      Z(3)=.4507883345537786D-01
      Z(5)=.7508612251067031D-01
      Z(7)=.1050255546478664D0
      Z(9)=.1348700729684854D0
      Z(11)=.1645927063496751D0
      Z(13)=.1941665938185881D0
      Z(15)=.2235650088272125D0
      Z(17)=.2527613834057209D0
      Z(19)=.2817293321725080D0
      Z(21)=.3104426761792209D0
      Z(23)=.3388754665692306D0
      Z(25)=.3670020080281650D0
      Z(27)=.3947968820053119D0
      Z(29)=.4222349696849036D0
      Z(31)=.4492914746865266D0
      Z(33)=.4759419454741398D0
      Z(35)=.5021622974534502D0
      Z(37)=.5279288347376772D0
      Z(39)=.5532182715620344D0
      Z(41)=.5780077533275774D0
      Z(43)=.6022748772554004D0
      Z(45)=.6259977126325152D0
      Z(47)=.6491548206311185D0
      Z(49)=.6717252736833362D0
      Z(51)=.6936886743939371D0
      Z(53)=.7150251739739257D0
      Z(55)=.7357154901783585D0
      Z(57)=.7557409247321753D0
      Z(59)=.7750833802283033D0
      Z(61)=.7937253764827685D0
      Z(63)=.8116500663320458D0
      Z(65)=.8288412508583829D0
      Z(67)=.8452833940293626D0
      Z(69)=.8609616367385050D0
      Z(71)=.8758618102342710D0
      Z(73)=.8899704489254118D0
      Z(75)=.9032748025512220D0
      Z(77)=.9157628477059157D0
      Z(79)=.9274232987070864D0
      Z(81)=.9382456177991042D0
      Z(83)=.9482200246834838D0
      Z(85)=.9573375053700733D0
      Z(87)=.9655898203461570D0
      Z(89)=.9729695120673583D0
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      Z(91)=.9794699117905919D0
      Z(93)=.9850851458144620D0
      Z(95)=.9898101413367193D0
      Z(97)=.9936406326897030D0
      Z(99)=.9965731714060389D0
      Z(101)=.9986051626519773D0
      Z(103)=.9997352218760882D0
       W(  1) =     .3005934726091462D-01
       W(  3) =     .3003218199259360D-01
       W(  5) =     .2997787600578057D-01
       W(  7) =     .2989647837794739D-01
       W(  9) =     .2978806266985645D-01
       W( 11) =     .2965272685908227D-01
       W( 13) =     .2949059325146727D-01
       W( 15) =     .2930180837059142D-01
       W( 17) =     .2908654282535595D-01
       W( 19) =     .2884499115580069D-01
       W( 21) =     .2857737165729427D-01
       W( 23) =     .2828392618325631D-01
       W( 25) =     .2796491992658968D-01
       W( 27) =     .2762064118002044D-01
       W( 29) =     .2725140107556215D-01
       W( 31) =     .2685753330333987D-01
       W( 33) =     .2643939381002810D-01
       W( 35) =     .2599736047717519D-01
       W( 37) =     .2553183277970497D-01
       W( 39) =     .2504323142490426D-01
       W( 41) =     .2453199797222264D-01
       W( 43) =     .2399859443422820D-01
       W( 45) =     .2344350285908004D-01
       W( 47) =     .2286722489489493D-01
       W( 49) =     .2227028133640237D-01
       W( 51) =     .2165321165429792D-01
       W( 53) =     .2101657350772073D-01
       W( 55) =     .2036094224029680D-01
       W( 57) =     .1968691036020432D-01
       W( 59) =     .1899508700473277D-01
       W( 61) =     .1828609738982209D-01
       W( 63) =     .1756058224508301D-01
       W( 65) =     .1681919723481482D-01
       W( 67) =     .1606261236555251D-01
       W( 69) =     .1529151138069267D-01
       W( 71) =     .1450659114276789D-01
       W( 73) =     .1370856100396590D-01
       W( 75).=     .1289814216552733D-01
       W( 77) =     .1207606702671645D-01
       W( 79) =     .1124307852416543D-01
       W( 81) =     .1039992946259468D-01
       W( 83) =     .9547381838326911D-02
       W( 85) =     .8686206157923711D-02
       W( 87) =     .7817180756425343D-02
       W( 89) =     .6941091125180975D-02
       W( 91) =     .6058729274750651D-02
       W( 93) =     .5170893207327752D-02
       W( 95) =     .4278386752472274D-02
       W( 97) =     .3382020818687030D-02
       W( 99) =     .2482621802176784D-02
       W(101) =     .1581095291194842D-02
       W(103) =     .6794761824845529D-03
      GO TO 10000
 2560  IF(N.NE.256) GO TO 3000
      Z(1)=.6123912375189529D-02
      Z(3)=.1837081847881366D-01
      Z(5)=.3061496877997902D-01
      Z(7)=.4285452653637909D-01
      Z(9)=.5508765569463398D-01
      Z(11)=.6731252116571640D-01
      Z(13)=.7952728910023296D-01
      Z(15)=.9173012716351955D-01
      Z(17)=.1039192048105094D0
      Z(19)=.1160926935603328D0
      Z(21)=.1282487672706070D0
      Z(23)=.1403856024113758D0
      Z(25)=.1525013783386563D0
      Z(27)=.1645942775675538D0
      Z(29)=.1766624860449019D0
      Z(31)=.1887041934213888D0
      Z(33)=.2007175933231266D0
      Z(35)=.2127008836226259D0
      Z(37)=.2246522667091319D0
      Z(39)=.2365699497582840D0
      Z(41)=.2484521450010566D0
      Z(43)=.2602970699919425D0
      Z(45)=.2721029478763366D0
      Z(47)=.2838680076570817D0
      Z(49)=.2955904844601356D0
      Z(51)=.3072686197993190D0
      Z(53)=.3189006618401062D0
      Z(55)=.3304848656624169D0
      Z(57)=.3420194935223716D0
      Z(59)=.3535028151129699D0
      Z(61)=.3649331078236540D0
      Z(63)=.3763086569987163D0
      Z(65)=.3876277561945155D0
      Z(67)=.3988887074354591D0
      Z(69)=.4100898214687165D0
      Z(71)=.4212294180176238D0
      Z(73)=.4323058260337413D0
      Z(75)=.4433173839475273D0
      Z(77)=.4542624399175899D0
      Z(79)=.4651393520784793D0
      Z(81)=.4759464887869833D0
      Z(83)=.4866822288668903D0
      Z(85)=.4973449618521814D0
      Z(87)=.5079330882286160D0
      Z(89)=.5184450196736744D0
      Z(91)=.5288791792948222D0
      Z(93)=.5392340018660591D0
      Z(95)=.5495079340627185D0
      Z(97)=.5596994346944811D0
      Z(99)=.5698069749365687D0
      Z(101)=.5798290385590829D0
      Z(103)=.5897641221544543D0
      Z(105)=.5996107353629683D0
      Z(107)=.6093674010963339D0
      Z(109)=.6190326557592612D0
      Z(111)=.6286050494690149D0
      Z(113)=.6380831462729113D0
      Z(115)=.6474655243637248D0
      Z(117)=.6567507762929732D0
      Z(119)=.6659375091820485D0
      Z(121)=.6750243449311627D0
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Z(123)=.6840099204260759D0
Z(125)=.6928928877425769D0
Z(127)=.7016719143486851D0
Z(129)=.7103456833045433D0
Z(131)=.7189128934599714D0
Z(133)=.7273722596496521D0
Z(135)=.7357225128859178D0
Z(137)=.7439624005491115D0
Z(139)=.7520906865754920D0
Z(141)=.7601061516426554D0
Z(143)=.7680075933524456D0
Z(145)=.7757938264113257D0
Z(147)=.7834636828081838D0
Z(149)=.7910160119895459D0
Z(151)=.7984496810321707D0
Z(153)=.8057635748129986D0
Z(155)=.8129565961764315D0
Z(157)=.8200276660989170D0
Z(159)=.8269757238508125D0
Z(161)=.8337997271555048D0
Z(163)=.8404986523457627D0
Z(165)=.8470714945172962D0
Z(167)=.8535172676795029D0
Z(169)=.8598350049033763D0
Z(171)=.8660237584665545D0
Z(173)=.8720825999954882D0
Z(175)=.8780106206047065D0
Z(177)=.8838069310331582D0
Z(179)=.8894706617776108D0
Z(181)=.8950009632230845D0
Z(183)=.9003970057703035D0
Z(185)=.9056579799601446D0
Z(187)=.9107830965950650D0
Z(189)=.9157715868574903D0
Z(191)=.9206227024251464D0
Z(193)=.9253357155833162D0
Z(195)=.9299099193340056D0
Z(197)=.9343446275020030D0
Z(199)=.9386391748378148D0
Z(201)=.9427929171174624D0
Z(203)=.9468052312391274D0
Z(205)=.9506755153166282D0
Z(207)=.9544031887697162D0
Z(209)=.9579876924111781D0
Z(211)=.9614284885307321D0
Z(213)=.9647250609757064D0
Z(215)=.9678769152284894D0
Z(217)=.9708835784807430D0
Z(219)=.9737445997043704D0
Z(221)=.9764595497192341D0
Z(223)=.9790280212576220D0
Z(225)=.9814496290254644D0
Z(227)=.9837240097603154D0
Z(229)=.9858508222861259D0
Z(231)=.9878297475648606D0
Z(233)=.9896604887450652D0
Z(235)=.9913427712075830D0
Z(237)=.9928763426088221D0
Z(239)=.9942609729224096D0
Z(241)=.9954964544810963D0
Z(243)=.9965826020233815D0
Z(245)=.9975192527567208D0
Z(247)=.9983062664730064D0
Z(249)=.9989435258434088D0
Z(251)=.9994309374662614D0
Z(253)=.9997684374092631D0
Z(255)=.9999560500189922D0
W(1)=.1224767164028975D-01
W(3)=.1224583436974792D-01
W(5)=.1224216010427280D-01
W(7)=.1223664939504015D-01
W(9)=.1222930306871027D-01
W(11)=.1222012222730396D-01
W(13)=.1220910824803724D-01
W(15)=.1219626278311471D-01
W(17)=.1218158775948177D-01
W(19)=.1216508537853550D-01
W(21)=.1214675811579445D-01
W(23)=.1212660872052732D-01
W(25)=.1210464021534046D-01
W(27)=.1208085589572454D-01
W(29)=.1205525932956014D-01
W(31)=.1202785435658257D-01
W(33)=.1199864508780581D-01
W(35)=.1196763590490589D-01
W(37)=.1193483145956356D-01
W(39)=.1190023667276648D-01
W(41)=.1186385673407107D-01
W(43)=.1182569710082397D-01
W(45)=.1178576349734342D-01
W(47)=.1174406191406055D-01
W(49)=.1170059860662074D-01
W(51)=.1165538009494524D-01
W(53)=.1160841316225310D-01
W(55)=.1155970485404363D-01
W(57)=.1150926247703949D-01
W(59)=.1145709359809063D-01
W(61)=.1140320604303918D-01
W(63)=.1134760789554549D-01
W(65)=.1129030749587550D-01
W(67)=.1123131343964966D-01
W(69)=.1117063457655344D-01
W(71)=.1110828000900984D-01
W(73)=.1104425909081390D-01
W(75)=.1097858142572957D-01
W(77)=.1091125686604903D-01
W(79)=.1084229551111479D-01
W(81)=.1077170770580462D-01
W(83)=.1069950403897978D-01
W(85)=.1062569534189656D-01
W(87)=.1055029268658148D-01
W(89)=.1047330738417040D-01
W(91)=.1039475098321172D-01
W(93)=.1031463526793401D-01
W(95)=.1023297225647821D-01
W(97)=.1014977419909486D-01
W(99)=.1006505357630638D-01
W(101)=.9978823097034910D-02
W(103)=.9891095696695828D-02
W(105)=.9801884535257327D-02
W(107)=.9711202995266279D-02
W(109)=.9619064679840727D-02
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      W(111)=.9525483410629284D-02
      W(113)=.9430473225737752D-02
      W(115)=.9334048377623269D-02
      W(117)=.9236223330956302D-02
      W(119)=.9137012760450806D-02
      W(121)=.9036431548662873D-02
      W(123)=.8934494783758207D-02
      W(125)=.8831217757248750D-02
      W(127)=.8726615961698807D-02
      W(129)=.8620705088401014D-02
      W(131)=.8513501025022490D-02
      W(133)=.8405019853221535D-02
      W(135)=.8295277846235225D-02
      W(137)=.8184291466438269D-02
      W(139)=.8072077362873499D-02
      W(141)=.7958652368754348D-02
      W(143)=.7844033498939711D-02
      W(145)=.7728237947381555D-02
      W(147)=.7611283084545659D-02
      W(149)=.7493186454805883D-02
      W(151)=.7373965773812346D-02
      W(153)=.7253638925833913D-02
      W(155)=.7132223961075390D-02
      W(157)=.7009739092969822D-02
      W(159)=.6886202695446320D-02
      W(161)=.6761633300173798D-02
      W(163)=.6636049593781065D-02
      W(165)=.6509470415053660D-02
      W(167)=.6381914752107880D-02
      W(169)=.6253401739542401D-02
      W(171)=.6123950655567932D-02
      W(173)=.5993580919115338D-02
      W(175)=.5862312086922653D-02
      W(177)=.5730163850601437D-02
      W(179)=.5597156033682910D-02
      W(181)=.5463308588644310D-02
      W(183)=.5328641593915930D-02
      W(185)=.5193175250869280D-02
      W(187)=.5056929880786842D-02
      W(189)=.4919925921813865D-02
      W(191)=.4782183925892691D-02
      W(193)=.4643724555680060D-02
      W(195)=.4504568581447897D-02
      W(197)=.4364736877968056D-02
      W(199)=.4224250421381536D-02
      W(201)=.4083130286052668D-02
      W(203)=.3941397641408833D-02
      W(205)=.3799073748766257D-02
      W(207)=.3656179958142502D-02
      W(209)=.3512737705056307D-02
      W(211)=.3368768507315551D-02
      W(213)=.3224293961794198D-02
      W(215)=.3079335741199337D-02
      W(217)=.2933915590829716D-02
      W(219)=.2788055325327706D-02
      W(221)=.2641776825427490D-02
      W(223)=.2495102034703706D-02
      W(225)=.2348052956327312D-02
      W(227)=.2200651649839910D-02
      W(229)=.2052920227966143D-02
      W(231)=.1904880853499718D-02
      W(233)=.1756555736330729D-02
      W(235)=.1607967130749327D-02
      W(237)=.1459137333310733D-02
      W(239)=.1310088681902504D-02
      W(241)=.1160843557567724D-02
      W(243)=.1011424393208440D-02
      W(245)=.8618537014200890D-03
      W(247)=.7121541634733206D-03
      W(249)=.5623489540314098D-03
      W(251)=.4124632544261763D-03
      W(253)=.2625349442964459D-03
      W(255)=.1127890178222721D-03
      GO TO 10000
3000   CONTINUE
      WRITE(8,4000)N
4000  FORMAT(/////,40X,'*****  ERROR FLAG FROM SUBROUTINE DGAUSS *****',
     2//,20X,'SUBROUTINE  DGAUSS  DOES NOT CONTAIN THE  N= ', I3,
     $' ROOTS AND WEIGHT FACTORS',
     3                    /, 20X,'FOR THE GAUSS-LEGENDRE QUADRADURE INTEG
     4RATION SCHEME, THEY MUST BE ADDED ',/, 30X,'PROGRAM SHALL END AFTE
     5R FORMAT 4000  IN SUBROUTINE  DGAUSS')
      STOP
10000   CONTINUE
C
C             CONSTRUCT THE REMAINING COEFFICIENTS FROM THE GIVEN ONES
C
      N0=0
      NF=N/2
      IF(Z(1).EQ.0.) N0=1
      NJ=N0
      DO 10100 J=1,NF
      NJ=NJ+2
      Z(NJ)=-Z(NJ-1)
10100  W(NJ)=W(NJ-1)
       RETURN
       END

      REAL*8 FUNCTION ERFC(X)
      REAL*8 X
      DOUBLE PRECISION DX, DEXP, DVAL
      DOUBLE PRECISION P(5), Q(5), R(3), S(3)
      DATA P / 0.564201376674554810D0,
     #         4.028389617759693D0,
     #         13.06138566338851D0,
     #         22.40039515948224D0,
     #         18.3983860429584D0 /
      DATA Q / 7.140837197994081 9D0,
     #         23.640303763581146D0,
     #         43.36458705913165D0,
     #         43.16075727248846D0,
     #         18.3983859792919D0 /
      DATA R / 0.5641895901974089 4D0,
     #         0.329589904886677D0,
     #         0.6141050178508D0 /
      DATA S / 0.5841849230414610 9D0,
     #         1.588352759869 69D0,
     #         0.2953483221592D0 /
C
      IF ( X .GE. 9.307 )  GOTO 200
      IF ( X .LE. -3.75 )  GOTO 300
      DX = ABS(X)
```

```
      IF ( DX .GE. 8.0D0 )  GOTO 100
C
      DVAL = DEXP(-DX*DX)*((((P(1)*DX + P(2))*DX + P(3))*DX +
     # P(4))*DX + P(5))/(((((DX + Q(1))*DX + Q(2))*DX + Q(3))*DX +
     # Q(4))*DX + Q(5))
      IF ( X .LT. 0.0 )  DVAL = 2.0D0 - DVAL
      ERFC = DVAL
      RETURN
C
  100 CONTINUE
      DVAL = DEXP(-DX*DX)*((R(1)*DX + R(2))*DX + R(3))/
     # (((DX + S(1))*DX + S(2))*DX + S(3))
      ERFC = DVAL
      RETURN
C
  200 CONTINUE
      ERFC = 0.0
      RETURN
C
  300 CONTINUE
      ERFC = 2.0
      RETURN
      END
```

```
THERMAL CONSOLIDATION AROUND A CYLINDRICAL SOURCE-buffer material properties
-0.32 0.32
1.E8 0.25 0.5E-4 0.4E-3
2700. 1000. 0.3
710. 418. 1.6 5.e-13 9.81
411.
20    7    3
0.32  0.  0.
0.64  0.  0.
0.   0. 1.125
8640.
86400.
432000.
864000.
4320000.
8640000.
43200000.
```

Sample output file

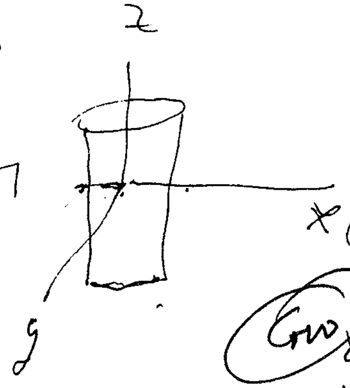
THERMAL CONSOLIDATION AROUND A CYLINDRICAL SOURCE-buffer material properties

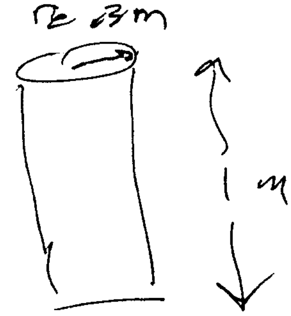
$y_1 = -\sqrt{(.3)^2 - x^2}$

$y_2 = +\sqrt{(.3)^2 - x^2}$

$z_1 = -0.5$

$z_2 = 0.5$





(Give) x1 = -0.3 x2 = 0.3

y = f(x) $y = \sqrt{(0.3)^2 - x^2}$

DATA

= 0.100000E+09

J= 0.250000E+00

AS= 0.500000E-04

AW= 0.400000E-03

IOS= 0.270000E+04

RHOW= 0.100000E+04

POROSITY= 0.300000E+00

= 0.710000E+03

= 0.418000E+03

KT= 0.160000E+01

= 0.500000E-12

AVITY= 0.981000E+01

HEAT GENERATION RATE 0.411000E+03

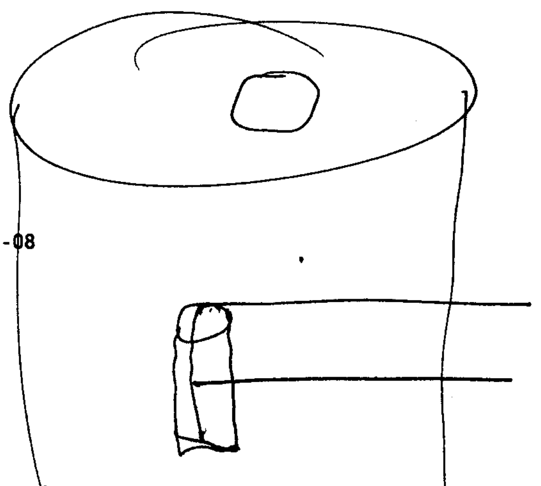
NUMBER OF GAUSSIAN INTEGRATION POINTS 20

MITS OF VOLUMETRIC SOURCE X1= -0.320000E+00X2= 0.320000E+00

r = 0.32 m

Subroutine Y1 & Y2

0.5



LCULATED PARAMETERS

LAMBDA 0.400000E+08

0.400000E+08

HERMAL DIFFUSIVITY 0.109044E-05

CONSOLIDATION COEFFICIENT 0.611621E-08

A 0.155000E-03

0.333333E+04

.. 0.152667E+05

Y 0.100463E+01

0.825418E+00

TIME= 0.864000E+04

X	Y	Z	TEMP	PRESS	SXX	SZZ
0.3200E+00	0.0000E+00	0.0000E+00	0.9185E+00	0.1410E+05	-0.3861E+04	-0.1911E+04
0.6400E+00	0.0000E+00	0.0000E+00	0.3369E-02	0.5173E+02	0.4007E+04	-0.7923E+03
0.0000E+00	0.0000E+00	0.1125E+01	0.1174E+01	0.1803E+05	-0.1064E+05	-0.3544E+04

ME= 0.864000E+05

X	Y	Z	TEMP	PRESS	SXX	SZZ
0.3200E+00	0.0000E+00	0.0000E+00	0.6944E+01	0.1066E+06	-0.4350E+05	-0.2909E+05
0.6400E+00	0.0000E+00	0.0000E+00	0.1548E+01	0.2377E+05	0.1007E+05	-0.1226E+05
0.0000E+00	0.0000E+00	0.1125E+01	0.6085E+01	0.9264E+05	-0.5425E+05	-0.1885E+05

TIME= 0.432000E+06

X	Y	Z	TEMP	PRESS	SXX	SZZ
0.3200E+00	0.0000E+00	0.0000E+00	0.1480E+02	0.2246E+06	-0.9972E+05	-0.7490E+05
0.6400E+00	0.0000E+00	0.0000E+00	0.7029E+01	0.1079E+06	-0.2220E+05	-0.4787E+05
0.0000E+00	0.0000E+00	0.1125E+01	0.1102E+02	0.1643E+06	-0.9365E+05	-0.3747E+05

ME= 0.864000E+06

X	Y	Z	TEMP	PRESS	SXX	SZZ
0.3200E+00	0.0000E+00	0.0000E+00	0.1769E+02	0.2643E+06	-0.1186E+06	-0.9229E+05
0.6400E+00	0.0000E+00	0.0000E+00	0.9594E+01	0.1473E+06	-0.4043E+05	-0.6519E+05
0000E+00	0.0000E+00	0.1125E+01	0.1313E+02	0.1915E+06	-0.1069E+06	-0.4707E+05

0.432000E+07

X	Y	Z	TEMP	PRESS	SXX	SZZ
0.3200E+00	0.0000E+00	0.0000E+00	0.2207E+02	0.2995E+06	-0.1347E+06	-0.1099E+06
0.6400E+00	0.0000E+00	0.0000E+00	0.1379E+02	0.2098E+06	-0.7495E+05	-0.9230E+05

```
 0.0000E+00  0.0000E+00  0.1125E+01  0.1694E+02  0.2163E+06 -0.1128E+06 -0.5972E+05
TIME=    0.864000E+07
          X           Y           Z        TEMP       PRESS         SXX         SZZ
 0.3200E+00  0.0000E+00  0.0000E+00  0.2317E+02  0.2851E+06 -0.1257E+06 -0.1048E+06
    400E+00  0.0000E+00  0.0000E+00  0.1488E+02  0.2193E+06 -0.8356E+05 -0.9574E+05
     00E+00  0.0000E+00  0.1125E+01  0.1799E+02  0.2073E+06 -0.1036E+06 -0.5817E+05
IME=    0.432000E+08
          X           Y           Z        TEMP       PRESS         SXX         SZZ
 0.3200E+00  0.0000E+00  0.0000E+00  0.2466E+02  0.1942E+06 -0.7165E+05 -0.6234E+05
 0.6400E+00  0.0000E+00  0.0000E+00  0.1636E+02  0.1780E+06 -0.6712E+05 -0.7267E+05
 0.0000E+00  0.0000E+00  0.1125E+01  0.1946E+02  0.1575E+06 -0.6720E+05 -0.4153E+05
```

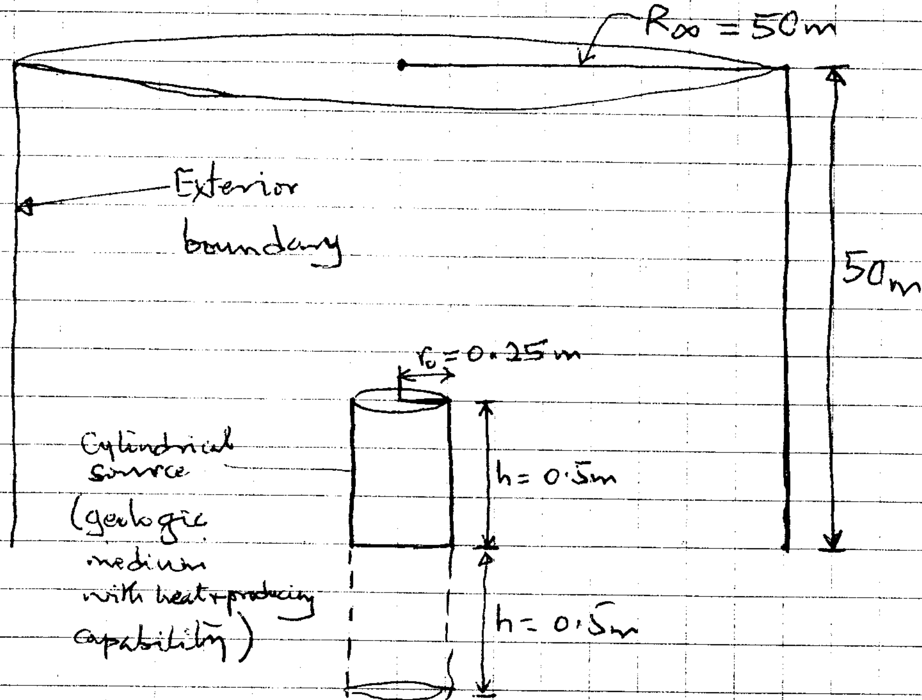
```
 THERMAL CONSOLIDATION AROUND A CYLINDRICAL SOURCE-buffer material properties


INPUT DATA
----------
E=   0.100000E+09
NU=    0.250000E+00
AS=    0.500000E-04
AW=    0.400000E-03
RHOS=    0.270000E+04
RHOW=    0.100000E+04
POROSITY=    0.300000E+00
CS=    0.710000E+03
CW=    0.418000E+03
KT=    0.160000E+01
KH=    0.500000E-12
GRAVITY=    0.981000E+01
HEAT GENERATION RATE    0.411000E+03
NUMBER OF GAUSSIAN INTEGRATION POINTS   20
LIMITS OF VOLUMETRIC SOURCE  X1=  -0.320000E+00X2=    0.320000E+00


CALCULATED PARAMETERS
---------------------
LAMBDA   0.400000E+08
G   0.400000E+08
THERMAL DIFFUSIVITY    0.109044E-05
CONSOLIDATION COEFFICIENT    0.611621E-08
AU   0.155000E-03
BP   0.333333E+04
X   0.152667E+05
Y   0.100463E+01
Z   0.825418E+00


TIME=    0.864000E+04
           X            Y            Z         TEMP        PRESS          SXX
 SZZ
  0.3200E+00  0.0000E+00  0.0000E+00  0.9185E+00  0.1410E+05 -0.3861E+04 -0.1911
E+04
  0.6400E+00  0.0000E+00  0.0000E+00  0.3369E-02  0.5173E+02  0.4007E+04 -0.7923
E+03
  0.0000E+00  0.0000E+00  0.1125E+01  0.1174E+01  0.1803E+05 -0.1064E+05 -0.3544
E+04
TIME=    0.864000E+05
           X            Y            Z         TEMP        PRESS          SXX
 SZZ
  0.3200E+00  0.0000E+00  0.0000E+00  0.6944E+01  0.1066E+06 -0.4350E+05 -0.2909
E+05
  0.6400E+00  0.0000E+00  0.0000E+00  0.1548E+01  0.2377E+05  0.1007E+05 -0.1226
E+05
  0.0000E+00  0.0000E+00  0.1125E+01  0.6085E+01  0.9264E+05 -0.5425E+05 -0.1885
E+05
TIME=    0.432000E+06
           X            Y            Z         TEMP        PRESS          SXX
 SZZ
  0.3200E+00  0.0000E+00  0.0000E+00  0.1480E+02  0.2246E+06 -0.9972E+05 -0.7490
E+05
  0.6400E+00  0.0000E+00  0.0000E+00  0.7029E+01  0.1079E+06 -0.2220E+05 -0.4787
E+05
  0.0000E+00  0.0000E+00  0.1125E+01  0.1102E+02  0.1643E+06 -0.9365E+05 -0.3747
E+05
TIME=    0.864000E+06
           X            Y            Z         TEMP        PRESS          SXX
 SZZ
  0.3200E+00  0.0000E+00  0.0000E+00  0.1769E+02  0.2643E+06 -0.1186E+06 -0.9229
E+05
  0.6400E+00  0.0000E+00  0.0000E+00  0.9594E+01  0.1473E+06 -0.4043E+05 -0.6519
E+05
  0.0000E+00  0.0000E+00  0.1125E+01  0.1313E+02  0.1915E+06 -0.1069E+06 -0.4707
E+05
TIME=    0.432000E+07
           X            Y            Z         TEMP        PRESS          SXX
 SZZ
  0.3200E+00  0.0000E+00  0.0000E+00  0.2207E+02  0.2995E+06 -0.1347E+06 -0.1099
E+06
  0.6400E+00  0.0000E+00  0.0000E+00  0.1379E+02  0.2098E+06 -0.7495E+05 -0.9230
E+05
  0.0000E+00  0.0000E+00  0.1125E+01  0.1694E+02  0.2163E+06 -0.1128E+06 -0.5972
E+05
TIME=    0.864000E+07
           X            Y            Z         TEMP        PRESS          SXX
 SZZ
  0.3200E+00  0.0000E+00  0.0000E+00  0.2317E+02  0.2851E+06 -0.1257E+06 -0.1048
E+06
  0.6400E+00  0.0000E+00  0.0000E+00  0.1488E+02  0.2193E+06 -0.8356E+05 -0.9574
E+05
  0.0000E+00  0.0000E+00  0.1125E+01  0.1799E+02  0.2073E+06 -0.1036E+06 -0.5817
E+05
TIME=    0.432000E+08
           X            Y            Z         TEMP        PRESS          SXX
 SZZ
  0.3200E+00  0.0000E+00  0.0000E+00  0.2466E+02  0.1942E+06 -0.7165E+05 -0.6234
E+05
  0.6400E+00  0.0000E+00  0.0000E+00  0.1636E+02  0.1780E+06 -0.6712E+05 -0.7267
E+05
  0.0000E+00  0.0000E+00  0.1125E+01  0.1946E+02  0.1575E+06 -0.6720E+05 -0.4153
E+05
```

Problem 8: Cylindrical Heat Source in Infinite Medium



Material ~~pr~~ Parameters

Mechanical

Young's modulus = 10^8 Pa

Poisson's ratio = 0.4

Density of solid particles ρ_s = 2700 kg/m^3

Density of water ρ_w = 1000 kg/m^3

GW ~~Bulk d~~ Porosity = 0.3

Bulk density ρ_b = 2190 kg/m^3

Dry density ρ_d = 1890 kg/m^3

Gravitational acceleration = 10 m/s^2

Thermal properties

Volumetric expansivity of solid particles = $5 \times 10^{-5}\ K^{-1}$

Volumetric expansivity of water = $5.5 \times 10^{-4}\ K^{-1}$

Specific heat of solid particles = 710 J/(kg.K)

Specific heat of water = 4189.3 J/(kg.K)

Bulk specific heat = 2.599×10^{6} J/(m^3.K)

= 1187.0 J/(kg.K)

Thermal conductivity (bulk) = 1.6 J/(m.s.K)

Hydrological Properties

Saturated Hydraulic Conductivity = 1.017×10^{-10} m/s

Van Genuchten β = 2.9227

van Genchten n = 2.0304

Residual saturation = 0.055/0.3 ≈ 0.1833

Initial Conditions

Temperature 25°C

Pore pressure: 0.0, -3.75 kPa

Heat source

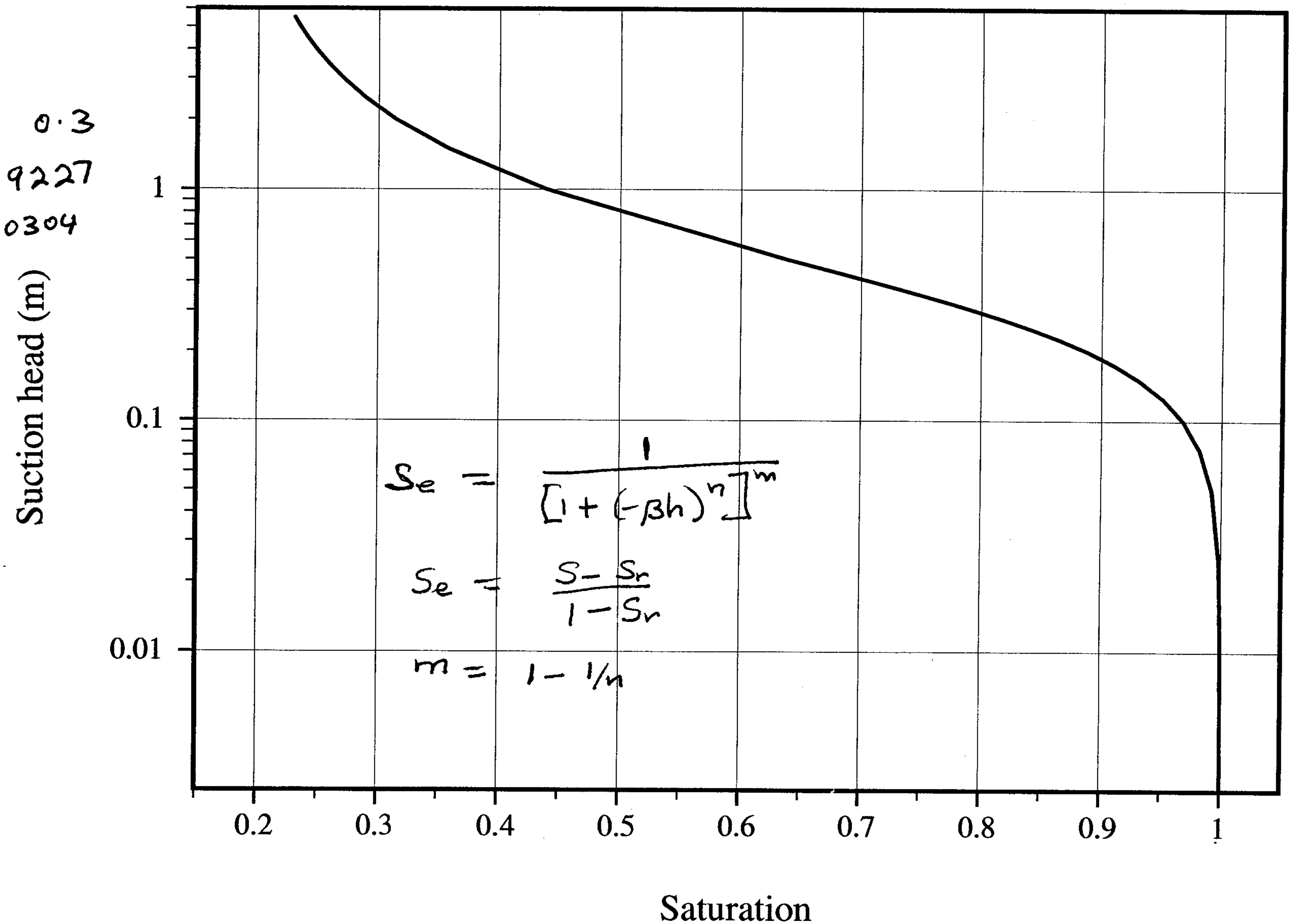
600 J/(m^3.s)

~~Monitor~~ GW

Calculate the history of ~~pore~~ pressure, temperature and saturation, at $r = 0, 0.25, 0.5$ and 1.25 m on the planes $z = 0$ (midplane) and $z = 0.5$ (end plane).

~~Higher Permeability Material~~

Porosity 0.3
$\beta = 2.9227$
$n = 2.0304$



$$S_e = \frac{1}{[1+(-\beta h)^n]^m}$$

$$S_e = \frac{S - S_r}{1 - S_r}$$

$$m = 1 - 1/n$$

Input Files

(1) t5.inp — Heat flow analysis

~~t5m1.inp Thermo-Mechanical-Hydraulic~~ (G12)

(2) t5m1.inp — Thermoconsolidation analysis: Saturated case.

(3) t5m2.inp — Thermoconsolidation analysis Unsaturated case, with $P_o = -3.75$ kPa, $S_o = 0.741$.

(4) t5m3.inp — Thermoconsolidation analysis Saturated case, with K_{sat} specified as a function of temperature.

t5 job must be completed before running (G12) any of the thermoconsolidation jobs. The latter require the file t5.fil

```
*HEADING
Problem 5: Effect of buried cylindrical heat source:
Analysis with fine mesh (element characteristic size of 0.05 m)
Length in m; energy in J; mass in kg; time in s;
Heat flow analysis.
*PREPRINT, MODEL=NO, HISTORY=NO, ECHO=NO
**
*** Nodal data
**
*NODE
101,0.0,0.0
141,2.5,0.0
161,5.0,0.0
181,50.0,0.0
*NSET,NSET=N25
141
*NSET,NSET=N50
161
*NSET,NSET=N500
181
*NGEN,NSET=BASE
101,141,1
*NFILL,BIAS=0.875,TWOSTEP,NSET=BASE
N25,N50,20,1
*NFILL,BIAS=0.75,TWOSTEP,NSET=BASE
N50,N500,20,1
*NCOPY,OLD SET=BASE,CHANGE NUMBER=4000,SHIFT,NEW SET=HL25
0.0,2.5,0.0
0.0,0.0,0.0,0.0,0.0,1.0,0.0
*NCOPY,OLD SET=BASE,CHANGE NUMBER=6000,SHIFT,NEW SET=HL50
0.0,5.0,0.0
0.0,0.0,0.0,0.0,0.0,1.0,0.0
*NCOPY,OLD SET=BASE,CHANGE NUMBER=8000,SHIFT,NEW SET=TOP
0.0,50.0,0.0
0.0,0.0,0.0,0.0,0.0,1.0,0.0
*NFILL,NSET=ALLNODES
BASE,HL25,40,100
*NFILL,BIAS=0.875,TWOSTEP,NSET=ALLNODES
HL25,HL50,20,100
*NFILL,BIAS=0.75,TWOSTEP,NSET=ALLNODES
HL50,TOP,20,100
***
*** Element connectivity
***
*ELEMENT, TYPE=DCAX8
101,101,103,303,301,102,203,302,201
*ELGEN,ELSET=ALLELEME
101,40,2,1,40,200,100
***
*** The following node and element sets are used to apply boundary conditions
*** Node sets BASE and TOP have already been defined
***
*NSET,NSET=LEFT,GEN
101,8101,100
*NSET,NSET=PPTOP,GEN
8101,8181,2
*NSET,NSET=RIGHT,GEN
181,8181,100
*NSET,NSET=PPRIGHT,GEN
181,8181,200
*ELSET,ELSET=BASE,GEN
101,140,1
*ELSET,ELSET=LEFT,GEN
101,4001,100
*ELSET,ELSET=HEATER,GEN
101,401,100
102,402,100
***
*** The following node and element sets will be used to monitor changes
***
*NSET,NSET=MONITOR
101,105,109,121
901,905,909,921
*ELSET,ELSET=MONITOR
101,102,103,104,105,110,111
401,402,403,404,405,410,411
501,502,503,504,505,510,511
***
*** Element and material properties
***
*SOLID SECTION,ELSET=ALLELEME,MATERIAL=LEPROCK
*MATERIAL, NAME=LEPROCK
**
*DENSITY
2190.0
*SPECIFIC HEAT
1187.0
*CONDUCTIVITY
1.6
***
*** Initial temperature set to 25 Celcius at all nodes
***
*INITIAL CONDITIONS,TYPE=TEMPERATURE
ALLNODES,25.0
***
*** Kinematic constraints
***
*WAVEFRONT MINIMIZATION,SUPPRESS
***
*** The following amplitude defines constant conditions
***
*AMPLITUDE,NAME=NOCHANGE
0.0,1.0,1.0E15,1.0
***
*** Step 1: Analysis to 8.64E7 s (1000 d)
***
*STEP,INC=5000
*HEAT TRANSFER,DELTMX=1.0
1.0,8.64E7
***
*** Apply volumetric heat generation (element set HEATER)
*** Apply zero heat flux (symmetry conditions) on base and left boundary surface
s
***
*DFLUX,AMPLITUDE=NOCHANGE
HEATER,BF,600.0
BASE,S1,0.0
LEFT,S4,0.0
***
*** Zero-perturbation conditions on right and top boundary surfaces
***
```

```
*BOUNDARY,AMPLITUDE=NOCHANGE
RIGHT,11, ,25.0
TOP,11, ,25.0
*NODE PRINT,FREQUENCY=0
*EL PRINT,FREQUENCY=0
*RESTART, WRITE, FREQ=0
*NODE FILE,NSET=ALLNODES,FREQ=1
NT
*END STEP
```

```
*HEADING
Problem 5: Effect of buried cylindrical heat source:
Analysis with fine mesh (element characteristic size of 0.05 m)
Length in m; mass in (1000 kg); stress in kPa; time in s;
Thermoconsolidation analysis with external temperature input;
Temperature data in t5.fil;
*PREPRINT, MODEL=NO, HISTORY=NO, ECHO=NO
**
*** Nodal data
**
*NODE
101,0.0,0.0
141,2.5,0.0
161,5.0,0.0
181,50.0,0.0
*NSET,NSET=N25
141
*NSET,NSET=N50
161
*NSET,NSET=N500
181
*NGEN,NSET=BASE
101,141,1
*NFILL,BIAS=0.875,TWOSTEP,NSET=BASE
N25,N50,20,1
*NFILL,BIAS=0.75,TWOSTEP,NSET=BASE
N50,N500,20,1
*NCOPY,OLD SET=BASE,CHANGE NUMBER=4000,SHIFT,NEW SET=HL25
0.0,2.5,0.0
0.0,0.0,0.0,0.0,0.0,1.0,0.0
*NCOPY,OLD SET=BASE,CHANGE NUMBER=6000,SHIFT,NEW SET=HL50
0.0,5.0,0.0
0.0,0.0,0.0,0.0,0.0,1.0,0.0
*NCOPY,OLD SET=BASE,CHANGE NUMBER=8000,SHIFT,NEW SET=TOP
0.0,50.0,0.0
0.0,0.0,0.0,0.0,0.0,1.0,0.0
*NFILL,NSET=ALLNODES
BASE,HL25,40,100
*NFILL,BIAS=0.875,TWOSTEP,NSET=ALLNODES
HL25,HL50,20,100
*NFILL,BIAS=0.75,TWOSTEP,NSET=ALLNODES
HL50,TOP,20,100
***
*** Element connectivity
***
*ELEMENT, TYPE=CAX8RP
101,101,103,303,301,102,203,302,201
*ELGEN,ELSET=ALLELEME
101,40,2,1,40,200,100
***
*** The following node and element sets are used to apply boundary conditions
*** Node sets BASE and TOP have already been defined
***
*NSET,NSET=LEFT,GEN
101,8101,100
*NSET,NSET=PPTOP,GEN
8101,8181,2
*NSET,NSET=RIGHT,GEN
181,8181,100
*NSET,NSET=PPRIGHT,GEN
181,8181,200
*ELSET,ELSET=BASE,GEN
101,140,1
*ELSET,ELSET=LEFT,GEN
101,4001,100
*ELSET,ELSET=HEATER,GEN
101,401,100
102,402,100
***
*** The following node and element sets will be used to monitor changes
***
*NSET,NSET=MONITOR
101,105,109,121
901,905,909,921
*ELSET,ELSET=MONITOR
101,102,103,104,105,110,111
401,402,403,404,405,410,411
501,502,503,504,505,510,511
***
*** Element and material properties
***
*SOLID SECTION,ELSET=ALLELEME,MATERIAL=LEPROCK
*MATERIAL, NAME=LEPROCK
**
*DENSITY
1.89
*ELASTIC
1.0E5,0.4
*EXPANSION
1.6667E-5
*EXPANSION,PORE FLUID
1.8333E-4
*SORPTION,LAW=TABULAR
-5.50000E+01,2.29940E-01
-5.00000E+01,2.34730E-01
-4.50000E+01,2.40594E-01
-4.00000E+01,2.47935E-01
-3.50000E+01,2.57386E-01
-3.00000E+01,2.69991E-01
-2.50000E+01,2.87616E-01
-2.00000E+01,3.13917E-01
-1.50000E+01,3.57096E-01
-1.00000E+01,4.39453E-01
-5.00000E+00,6.38781E-01
-4.75000E+00,6.55252E-01
-4.50000E+00,6.72605E-01
-4.25000E+00,6.90862E-01
-4.00000E+00,7.10033E-01
-3.75000E+00,7.30110E-01
-3.50000E+00,7.51063E-01
-3.25000E+00,7.72831E-01
-3.00000E+00,7.95309E-01
-2.75000E+00,8.18347E-01
-2.50000E+00,8.41729E-01
-2.25000E+00,8.65171E-01
-2.00000E+00,8.88309E-01
-1.75000E+00,9.10697E-01
-1.50000E+00,9.31813E-01
-1.25000E+00,9.51077E-01
-1.00000E+00,9.67876E-01
-7.50000E-01,9.81617E-01
```

```
-5.00000E-01,9.91777E-01
-2.50000E-01,9.97964E-01
-2.25000E-01,9.98355E-01
-2.00000E-01,9.98704E-01
-1.75000E-01,9.99011E-01
-1.50000E-01,9.99277E-01
-1.25000E-01,9.99500E-01
-1.00000E-01,9.99682E-01
-7.50000E-02,9.99823E-01
-5.00000E-02,9.99922E-01
-2.50000E-02,9.99981E-01
0.00000E+00,1.00000E+00
*SORPTION,TYPE=EXSORPTION
-5.50000E+01,2.61371E-01
-5.00000E+01,2.65965E-01
-4.50000E+01,2.71590E-01
-4.00000E+01,2.78632E-01
-3.50000E+01,2.87697E-01
-3.00000E+01,2.99787E-01
-2.50000E+01,3.16693E-01
-2.00000E+01,3.41921E-01
-1.50000E+01,3.83337E-01
-1.00000E+01,4.62333E-01
-5.00000E+00,6.53525E-01
-4.75000E+00,6.69324E-01
-4.50000E+00,6.85968E-01
-4.25000E+00,7.03480E-01
-4.00000E+00,7.21868E-01
-3.75000E+00,7.41126E-01
-3.50000E+00,7.61224E-01
-3.25000E+00,7.82103E-01
-3.00000E+00,8.03664E-01
-2.75000E+00,8.25761E-01
-2.50000E+00,8.48189E-01
-2.25000E+00,8.70674E-01
-2.00000E+00,8.92868E-01
-1.75000E+00,9.14342E-01
-1.50000E+00,9.34597E-01
-1.25000E+00,9.53073E-01
-1.00000E+00,9.69187E-01
-7.50000E-01,9.82368E-01
-5.00000E-01,9.92112E-01
-2.50000E-01,9.98047E-01
-2.25000E-01,9.98422E-01
-2.00000E-01,9.98757E-01
-1.75000E-01,9.99052E-01
-1.50000E-01,9.99306E-01
-1.25000E-01,9.99521E-01
-1.00000E-01,9.99695E-01
-7.50000E-02,9.99830E-01
-5.00000E-02,9.99925E-01
-2.50000E-02,9.99982E-01
0.00000E+00,1.00000E+00
*PERMEABILITY,SPECIFIC=10.0
1.01700E-10,0.4286
*PERMEABILITY,SPECIFIC=10.0,TYPE=SATURATION
3.24043E-06,2.29940E-01
4.76644E-06,2.34730E-01
7.30021E-06,2.40594E-01
1.17521E-05,2.47935E-01
2.01481E-05,2.57386E-01
3.74947E-05,2.69991E-01
7.79805E-05,2.87616E-01
1.90124E-04,3.13917E-01
5.92208E-04,3.57096E-01
2.81066E-03,4.39453E-01
3.08230E-02,6.38781E-01
3.59961E-02,6.55252E-01
4.22110E-02,6.72605E-01
4.97045E-02,6.90862E-01
5.87707E-02,7.10033E-01
6.97736E-02,7.30110E-01
8.31623E-02,7.51063E-01
9.94884E-02,7.72831E-01
1.19423E-01,7.95309E-01
1.43772E-01,8.18347E-01
1.73492E-01,8.41729E-01
2.09684E-01,8.65171E-01
2.53587E-01,8.88309E-01
3.06526E-01,9.10697E-01
3.69842E-01,9.31813E-01
4.44759E-01,9.51077E-01
5.32217E-01,9.67876E-01
6.32651E-01,9.81617E-01
7.45722E-01,9.91777E-01
8.69905E-01,9.97964E-01
8.82817E-01,9.98355E-01
8.95797E-01,9.98704E-01
9.08837E-01,9.99011E-01
9.21928E-01,9.99277E-01
9.35057E-01,9.99500E-01
9.48207E-01,9.99682E-01
9.61356E-01,9.99823E-01
9.74464E-01,9.99922E-01
9.87456E-01,9.99981E-01
1.00000E+00,1.00000E+00
***
*** Initial temperature set to 25 Celcius at all nodes
***
*INITIAL CONDITIONS,TYPE=TEMPERATURE
ALLNODES,25.0
*INITIAL CONDITIONS,TYPE=PORE PRESSURE
ALLNODES,-0.025
*INITIAL CONDITIONS,TYPE=SATURATION
ALLNODES,0.999981
*INITIAL CONDITIONS,TYPE=RATIO
ALLNODES,0.4286
*INITIAL CONDITIONS,TYPE=STRESS
ALLELEME,-0.025,-0.025,-0.025,0.0
***
*** Kinematic constraints
***
*BOUNDARY
BASE,2
TOP,2
LEFT,1
RIGHT,1
*WAVEFRONT MINIMIZATION,SUPPRESS
***
*** The following amplitude defines constant conditions
***
*AMPLITUDE,NAME=NOCHANGE
```

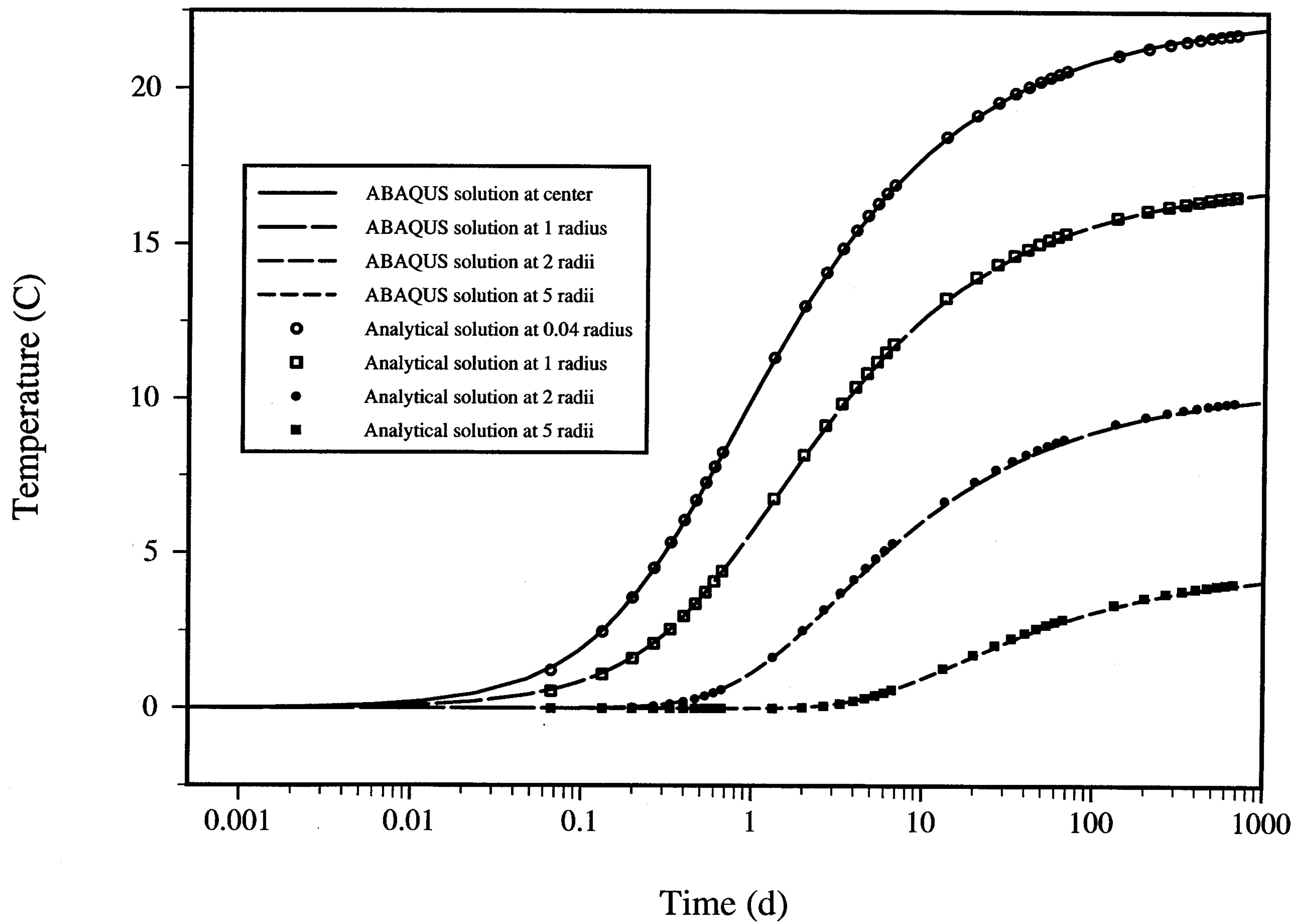
```
0.0,1.0,1.0E15,1.0
***
*** Step 1: Analysis to 8.64E7 s (1000 d)
***
*STEP,INC=5000
*SOILS,CONSOLIDATION,UTOL=2.5
1.0,8.64E7
**
** Impermeable boundaries (midplane and axial symmetry conditions)
**
*DFLOW,AMPLITUDE=NOCHANGE
BASE,S1,0.0
LEFT,S4,0.0
***
*** Zero-perturbation conditions on right and top boundary surfaces
***
*BOUNDARY,AMPLITUDE=NOCHANGE
PPRIGHT,8, ,-0.025
PPTOP,8, ,-0.025
*TEMPERATURE,FILE=t5,BSTEP=1,ESTEP=1
*RESTART, WRITE, FREQ=1,OVERLAY
*NODE PRINT,FREQUENCY=0
*EL PRINT,FREQUENCY=0
*NODE FILE,NSET=MONITOR,FREQ=1
POR
****EL FILE,ELSET=MONITOR,FREQ=1,POSITION=AVERAGE
***SAT
*END STEP
```

```
*HEADING
Problem 5: Effect of buried cylindrical heat source:
Analysis with fine mesh (element characteristic size of 0.05 m)
Length in m; mass in (1000 kg); stress in kPa; time in s;
Thermoconsolidation analysis with external temperature input;
Temperature data in t5.fil;
Case of unsaturated medium, initial pore pressure of -3.75 kPa.
*PREPRINT, MODEL=NO, HISTORY=NO, ECHO=NO
**
*** Nodal data
**
*NODE
101,0.0,0.0
141,2.5,0.0
161,5.0,0.0
181,50.0,0.0
*NSET,NSET=N25
141
*NSET,NSET=N50
161
*NSET,NSET=N500
181
*NGEN,NSET=BASE
101,141,1
*NFILL,BIAS=0.875,TWOSTEP,NSET=BASE
N25,N50,20,1
*NFILL,BIAS=0.75,TWOSTEP,NSET=BASE
N50,N500,20,1
*NCOPY,OLD SET=BASE,CHANGE NUMBER=4000,SHIFT,NEW SET=HL25
0.0,2.5,0.0
0.0,0.0,0.0,0.0,0.0,1.0,0.0
*NCOPY,OLD SET=BASE,CHANGE NUMBER=6000,SHIFT,NEW SET=HL50
0.0,5.0,0.0
0.0,0.0,0.0,0.0,0.0,1.0,0.0
*NCOPY,OLD SET=BASE,CHANGE NUMBER=8000,SHIFT,NEW SET=TOP
0.0,50.0,0.0
0.0,0.0,0.0,0.0,0.0,1.0,0.0
*NFILL,NSET=ALLNODES
BASE,HL25,40,100
*NFILL,BIAS=0.875,TWOSTEP,NSET=ALLNODES
HL25,HL50,20,100
*NFILL,BIAS=0.75,TWOSTEP,NSET=ALLNODES
HL50,TOP,20,100
***
*** Element connectivity
***
*ELEMENT, TYPE=CAX8RP
101,101,103,303,301,102,203,302,201
*ELGEN,ELSET=ALLELEME
101,40,2,1,40,200,100
***
*** The following node and element sets are used to apply boundary conditions
*** Node sets BASE and TOP have already been defined
***
*NSET,NSET=LEFT,GEN
101,8101,100
*NSET,NSET=PPTOP,GEN
8101,8181,2
*NSET,NSET=RIGHT,GEN
181,8181,100
*NSET,NSET=PPRIGHT,GEN
181,8181,200
*ELSET,ELSET=BASE,GEN
101,140,1
*ELSET,ELSET=LEFT,GEN
101,4001,100
*ELSET,ELSET=HEATER,GEN
101,401,100
102,402,100
***
*** The following node and element sets will be used to monitor changes
***
*NSET,NSET=MONITOR
101,105,109,121
901,905,909,921
*ELSET,ELSET=MONITOR
101,102,103,104,105,110,111
401,402,403,404,405,410,411
501,502,503,504,505,510,511
***
*** Element and material properties
***
*SOLID SECTION,ELSET=ALLELEME,MATERIAL=LEPROCK
*MATERIAL, NAME=LEPROCK
**
*DENSITY
1.89
*ELASTIC
1.0E5,0.4
*EXPANSION
1.6667E-5
*EXPANSION,PORE FLUID
1.8333E-4
*SORPTION,LAW=TABULAR
-5.50000E+01,2.29940E-01
-5.00000E+01,2.34730E-01
-4.50000E+01,2.40594E-01
-4.00000E+01,2.47935E-01
-3.50000E+01,2.57386E-01
-3.00000E+01,2.69991E-01
-2.50000E+01,2.87616E-01
-2.00000E+01,3.13917E-01
-1.50000E+01,3.57096E-01
-1.00000E+01,4.39453E-01
-5.00000E+00,6.38781E-01
-4.75000E+00,6.55252E-01
-4.50000E+00,6.72605E-01
-4.25000E+00,6.90862E-01
-4.00000E+00,7.10033E-01
-3.75000E+00,7.30110E-01
-3.50000E+00,7.51063E-01
-3.25000E+00,7.72831E-01
-3.00000E+00,7.95309E-01
-2.75000E+00,8.18347E-01
-2.50000E+00,8.41729E-01
-2.25000E+00,8.65171E-01
-2.00000E+00,8.88309E-01
-1.75000E+00,9.10697E-01
-1.50000E+00,9.31813E-01
-1.25000E+00,9.51077E-01
-1.00000E+00,9.67876E-01
```

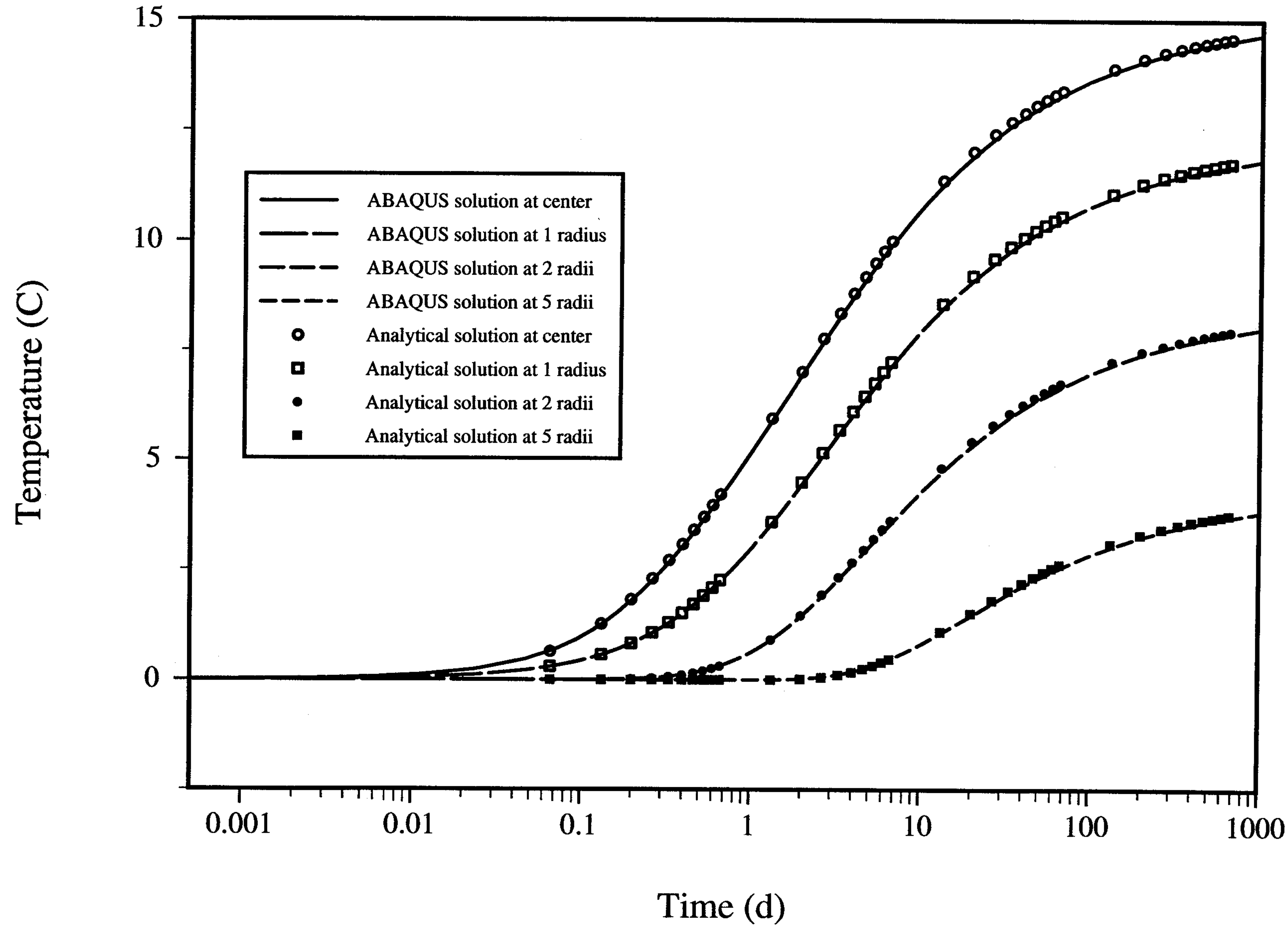
```
-7.50000E-01,9.81617E-01
-5.00000E-01,9.91777E-01
-2.50000E-01,9.97964E-01
-2.25000E-01,9.98355E-01
-2.00000E-01,9.98704E-01
-1.75000E-01,9.99011E-01
-1.50000E-01,9.99277E-01
-1.25000E-01,9.99500E-01
-1.00000E-01,9.99682E-01
-7.50000E-02,9.99823E-01
-5.00000E-02,9.99922E-01
-2.50000E-02,9.99981E-01
0.00000E+00,1.00000E+00
*SORPTION,TYPE=EXSORPTION
-5.50000E+01,2.61371E-01
-5.00000E+01,2.65965E-01
-4.50000E+01,2.71590E-01
-4.00000E+01,2.78632E-01
-3.50000E+01,2.87697E-01
-3.00000E+01,2.99787E-01
-2.50000E+01,3.16693E-01
-2.00000E+01,3.41921E-01
-1.50000E+01,3.83337E-01
-1.00000E+01,4.62333E-01
-5.00000E+00,6.53525E-01
-4.75000E+00,6.69324E-01
-4.50000E+00,6.85968E-01
-4.25000E+00,7.03480E-01
-4.00000E+00,7.21868E-01
-3.75000E+00,7.41126E-01
-3.50000E+00,7.61224E-01
-3.25000E+00,7.82103E-01
-3.00000E+00,8.03664E-01
-2.75000E+00,8.25761E-01
-2.50000E+00,8.48189E-01
-2.25000E+00,8.70674E-01
-2.00000E+00,8.92868E-01
-1.75000E+00,9.14342E-01
-1.50000E+00,9.34597E-01
-1.25000E+00,9.53073E-01
-1.00000E+00,9.69187E-01
-7.50000E-01,9.82368E-01
-5.00000E-01,9.92112E-01
-2.50000E-01,9.98047E-01
-2.25000E-01,9.98422E-01
-2.00000E-01,9.98757E-01
-1.75000E-01,9.99052E-01
-1.50000E-01,9.99306E-01
-1.25000E-01,9.99521E-01
-1.00000E-01,9.99695E-01
-7.50000E-02,9.99830E-01
-5.00000E-02,9.99925E-01
-2.50000E-02,9.99982E-01
0.00000E+00,1.00000E+00
*PERMEABILITY,SPECIFIC=10.0
1.01700E-10,0.4286
*PERMEABILITY,SPECIFIC=10.0,TYPE=SATURATION
3.24043E-06,2.29940E-01
4.76644E-06,2.34730E-01
7.30021E-06,2.40594E-01
1.17521E-05,2.47935E-01
2.01481E-05,2.57386E-01
3.74947E-05,2.69991E-01
7.79805E-05,2.87616E-01
1.90124E-04,3.13917E-01
5.92208E-04,3.57096E-01
2.81066E-03,4.39453E-01
3.08230E-02,6.38781E-01
3.59961E-02,6.55252E-01
4.22110E-02,6.72605E-01
4.97045E-02,6.90862E-01
5.87707E-02,7.10033E-01
6.97736E-02,7.30110E-01
8.31623E-02,7.51063E-01
9.94884E-02,7.72831E-01
1.19423E-01,7.95309E-01
1.43772E-01,8.18347E-01
1.73492E-01,8.41729E-01
2.09684E-01,8.65171E-01
2.53587E-01,8.88309E-01
3.06526E-01,9.10697E-01
3.69842E-01,9.31813E-01
4.44759E-01,9.51077E-01
5.32217E-01,9.67876E-01
6.32651E-01,9.81617E-01
7.45722E-01,9.91777E-01
8.69905E-01,9.97964E-01
8.82817E-01,9.98355E-01
8.95797E-01,9.98704E-01
9.08837E-01,9.99011E-01
9.21928E-01,9.99277E-01
9.35057E-01,9.99500E-01
9.48207E-01,9.99682E-01
9.61356E-01,9.99823E-01
9.74464E-01,9.99922E-01
9.87456E-01,9.99981E-01
1.00000E+00,1.00000E+00
***
*** Initial temperature set to 25 Celcius at all nodes
***
*INITIAL CONDITIONS,TYPE=TEMPERATURE
ALLNODES,25.0
*INITIAL CONDITIONS,TYPE=PORE PRESSURE
ALLNODES,-3.75
*INITIAL CONDITIONS,TYPE=SATURATION
ALLNODES,0.741126
*INITIAL CONDITIONS,TYPE=RATIO
ALLNODES,0.4286
*INITIAL CONDITIONS,TYPE=STRESS
ALLELEME,-3.75,-3.75,-3.75,0.0
***
*** Kinematic constraints
***
*BOUNDARY
BASE,2
TOP,2
LEFT,1
RIGHT,1
*WAVEFRONT MINIMIZATION,SUPPRESS
***
*** The following amplitude defines constant conditions
***
```

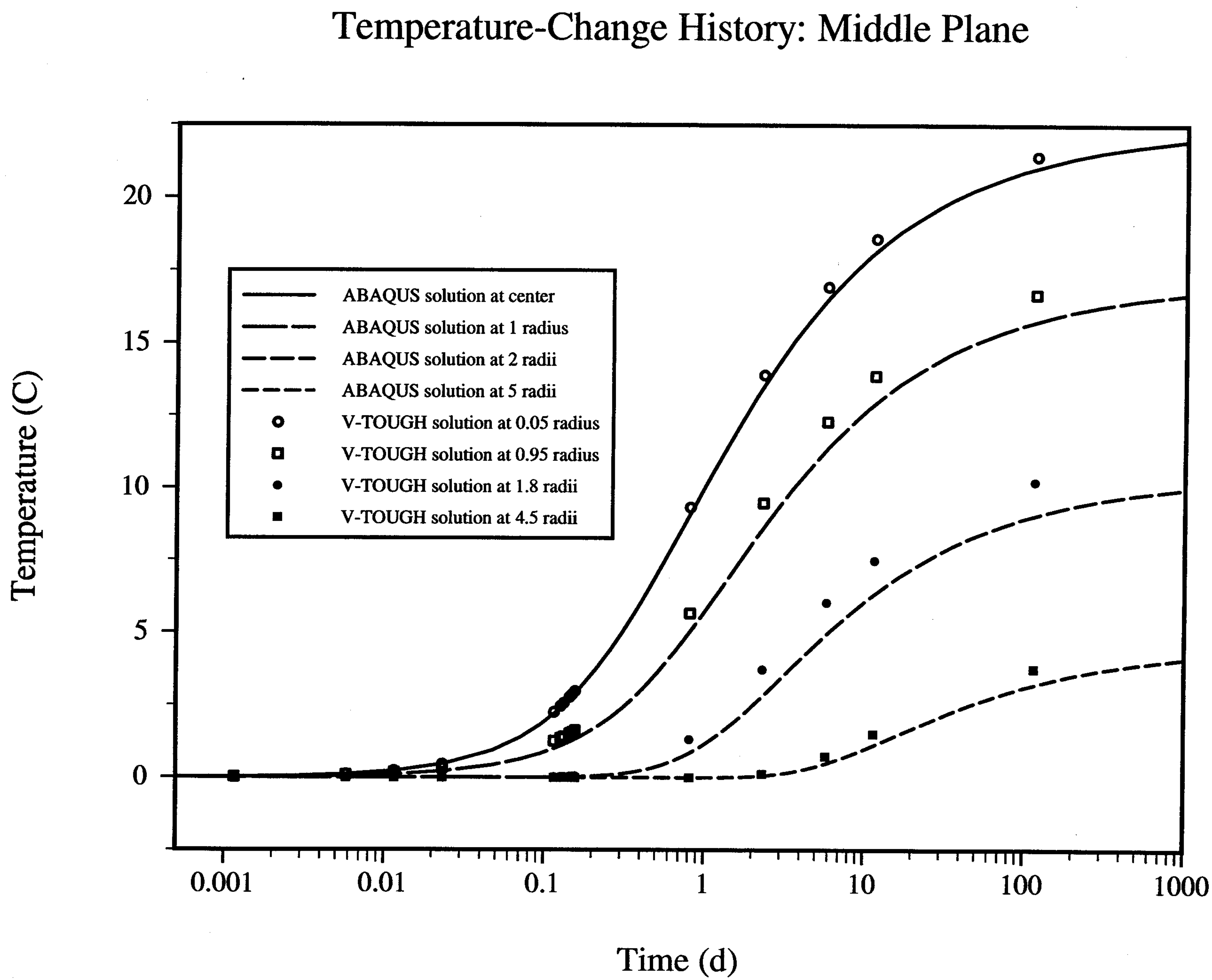
```
*AMPLITUDE,NAME=NOCHANGE
0.0,1.0,1.0E15,1.0
***
*** Step 1: Analysis to 8.64E7 s (1000 d)
***
*STEP,INC=5000
*SOILS,CONSOLIDATION,UTOL=2.5
1.0,8.64E7
**
** Impermeable boundaries (midplane and axial symmetry conditions)
**
*DFLOW,AMPLITUDE=NOCHANGE
BASE,S1,0.0
LEFT,S4,0.0
***
*** Zero-perturbation conditions on right and top boundary surfaces
***
*BOUNDARY,AMPLITUDE=NOCHANGE
PPRIGHT,8, ,-3.75
PPTOP,8, ,-3.75
*TEMPERATURE,FILE=t5,BSTEP=1,ESTEP=1
*RESTART, WRITE, FREQ=1,OVERLAY
*NODE PRINT,FREQUENCY=0
*EL PRINT,FREQUENCY=0
*NODE FILE,NSET=MONITOR,FREQ=1
POR
*EL FILE,ELSET=MONITOR,FREQ=1,POSITION=AVERAGE
SAT
*END STEP
```

Temperature-Change History: Middle Plane



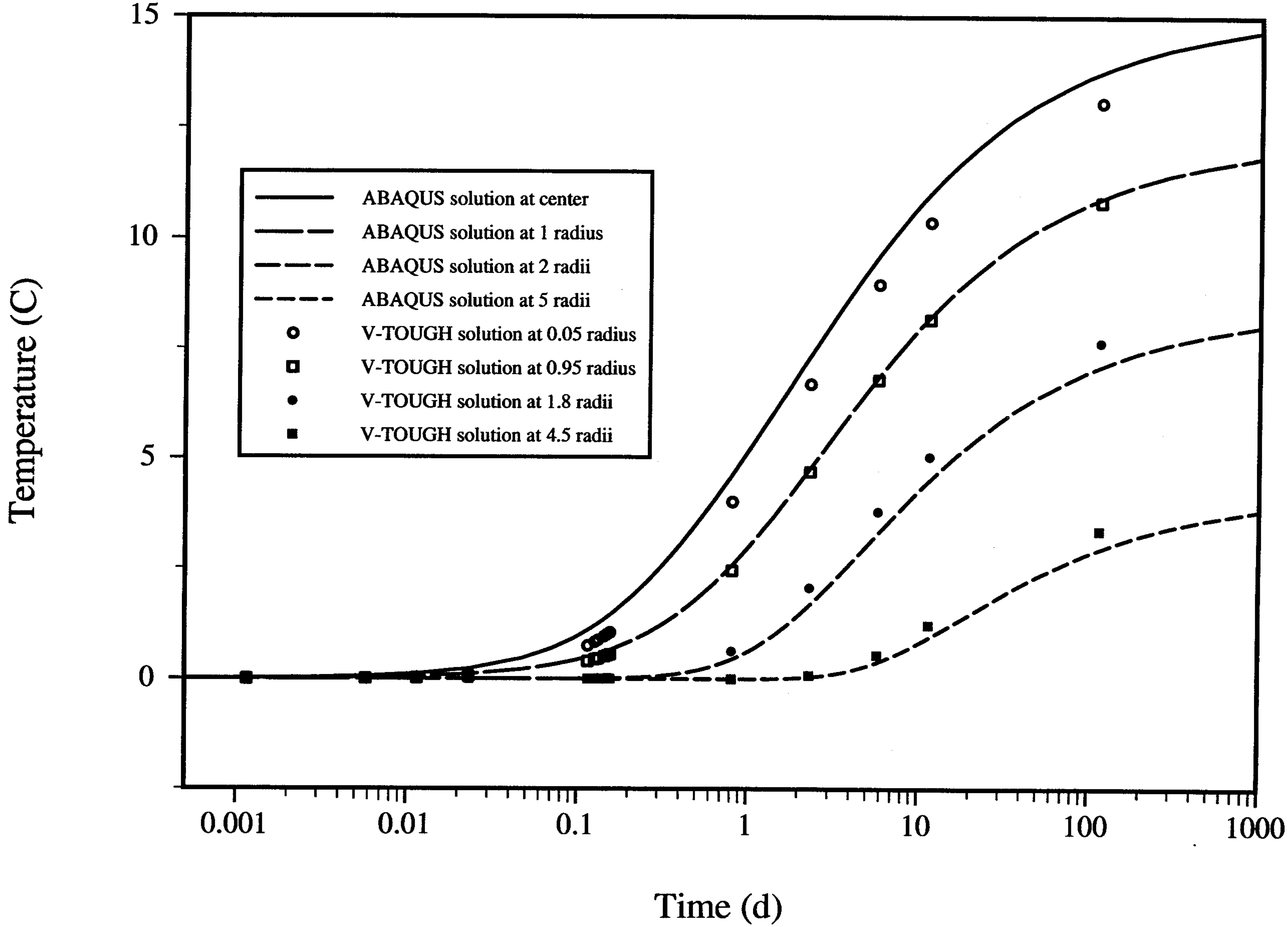
Temperature-Change History: End Plane



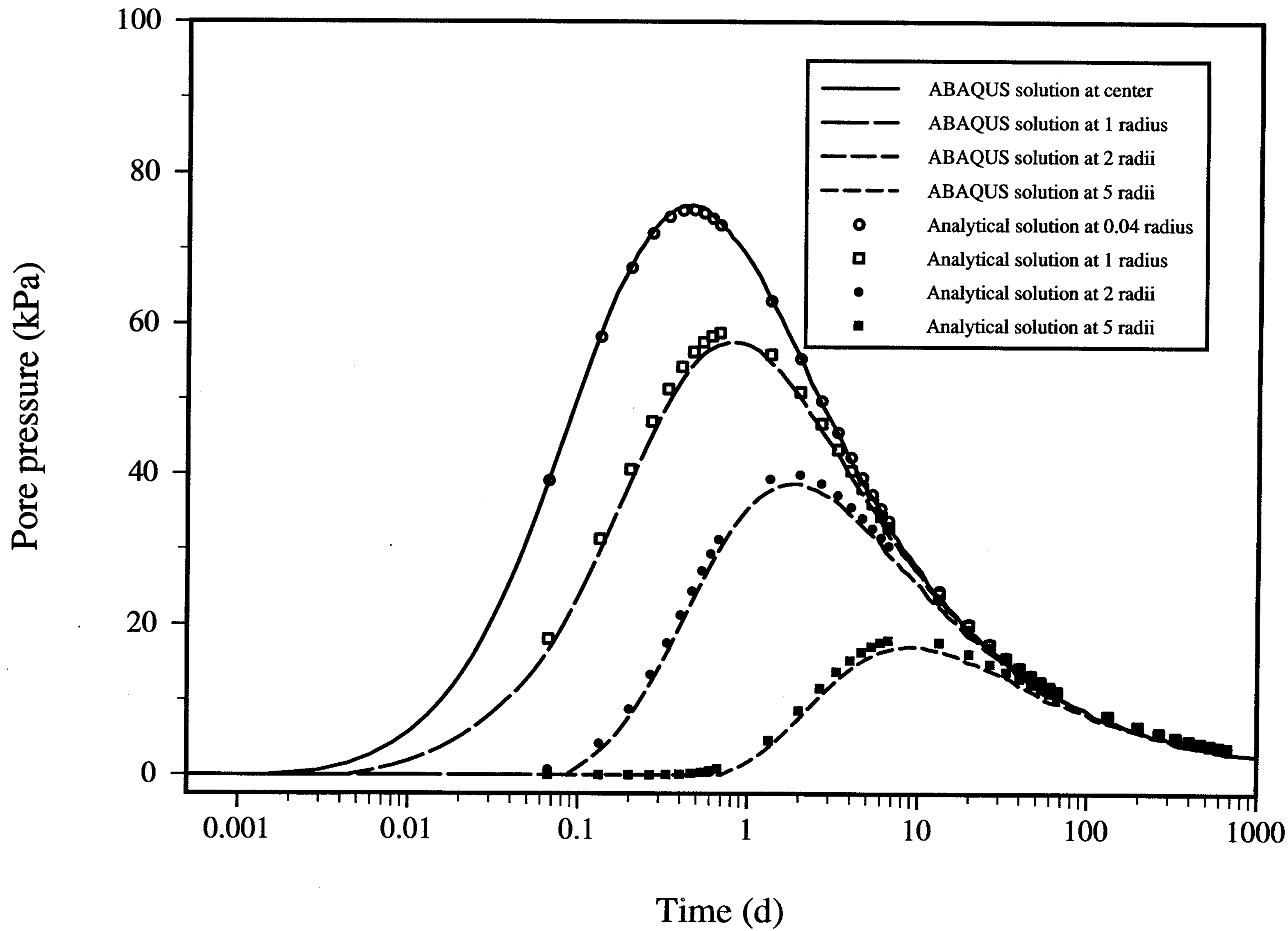


Temperature-Change History: Middle Plane
Temperature (C)
Time (d)
0
5
10
15
20
0.001
0.01
0.1
1
10
100
1000
ABAQUS solution at center
ABAQUS solution at 1 radius
ABAQUS solution at 2 radii
ABAQUS solution at 5 radii
V-TOUGH solution at 0.05 radius
V-TOUGH solution at 0.95 radius
V-TOUGH solution at 1.8 radii
V-TOUGH solution at 4.5 radii

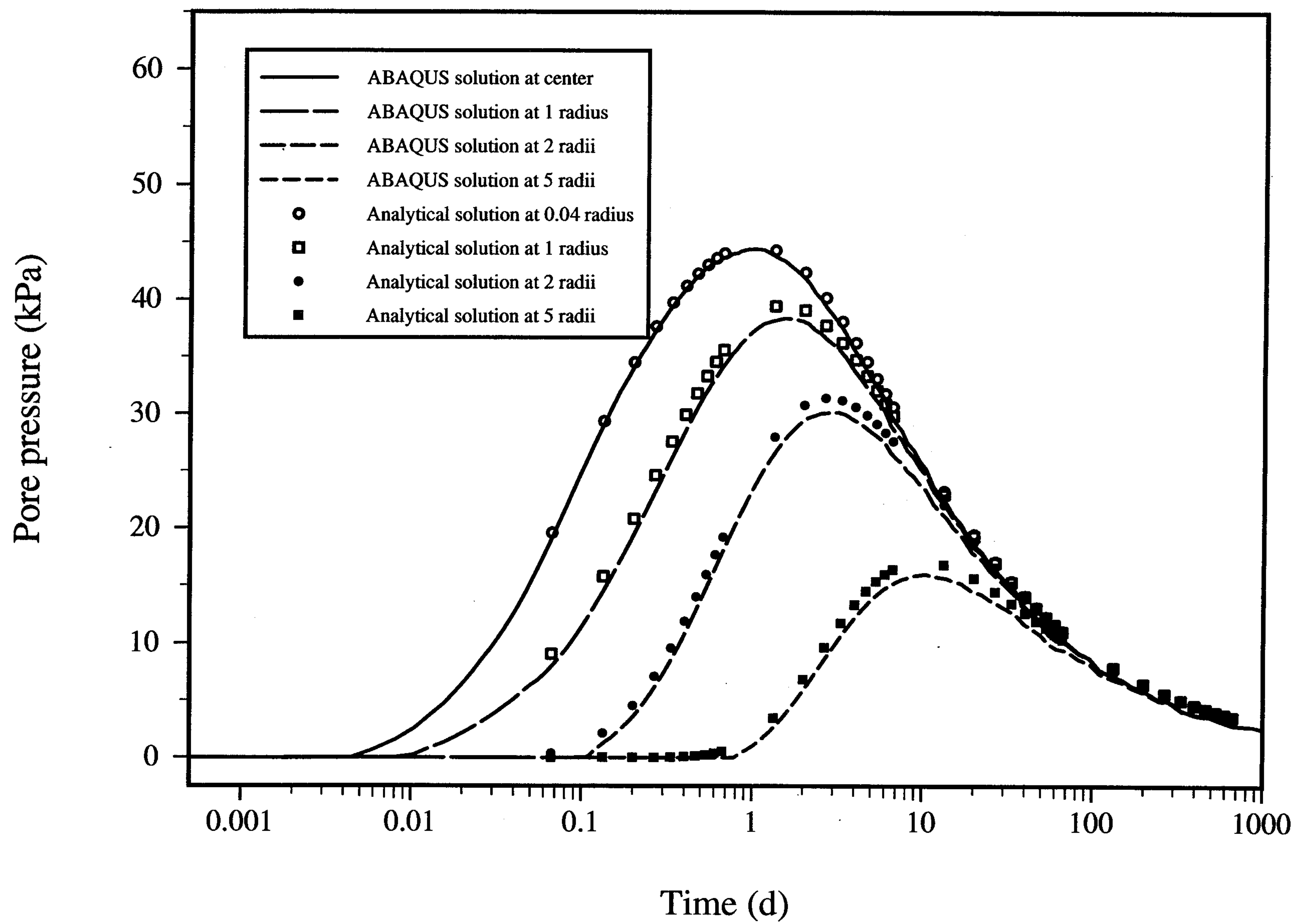
Temperature-Change History: End Plane



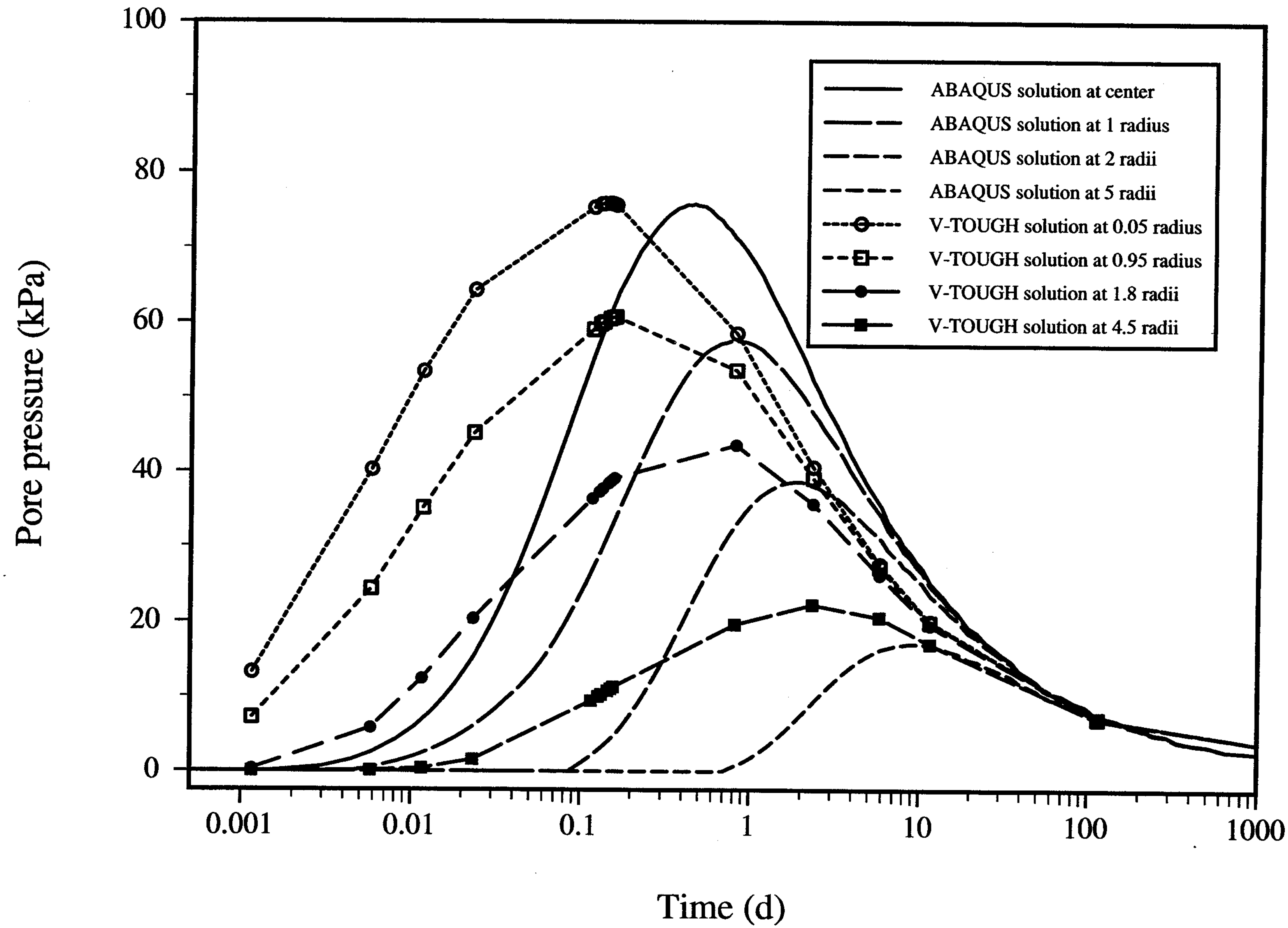
Pore-Pressure History: Middle Plane



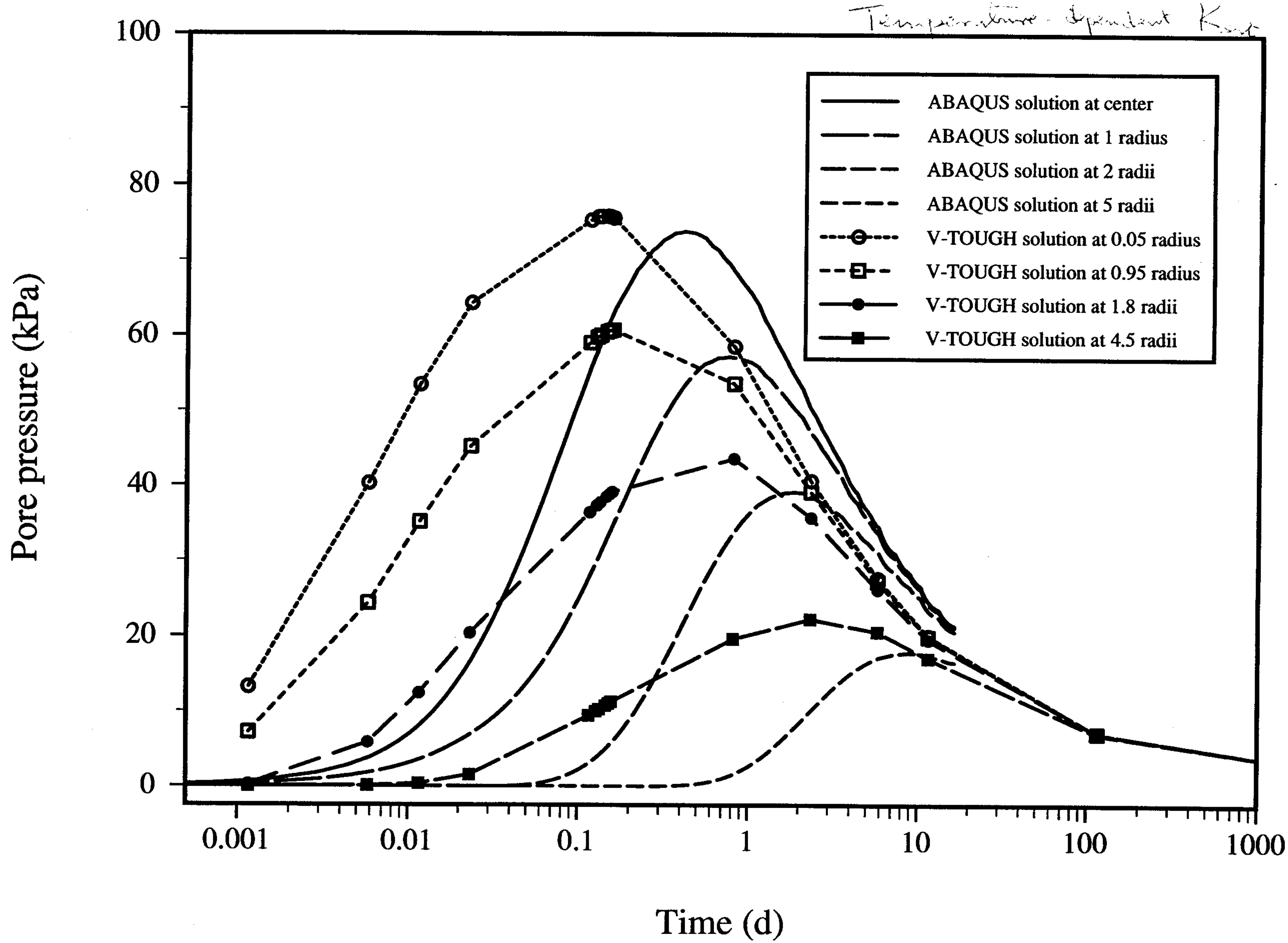
Pore-Pressure History: End Plane



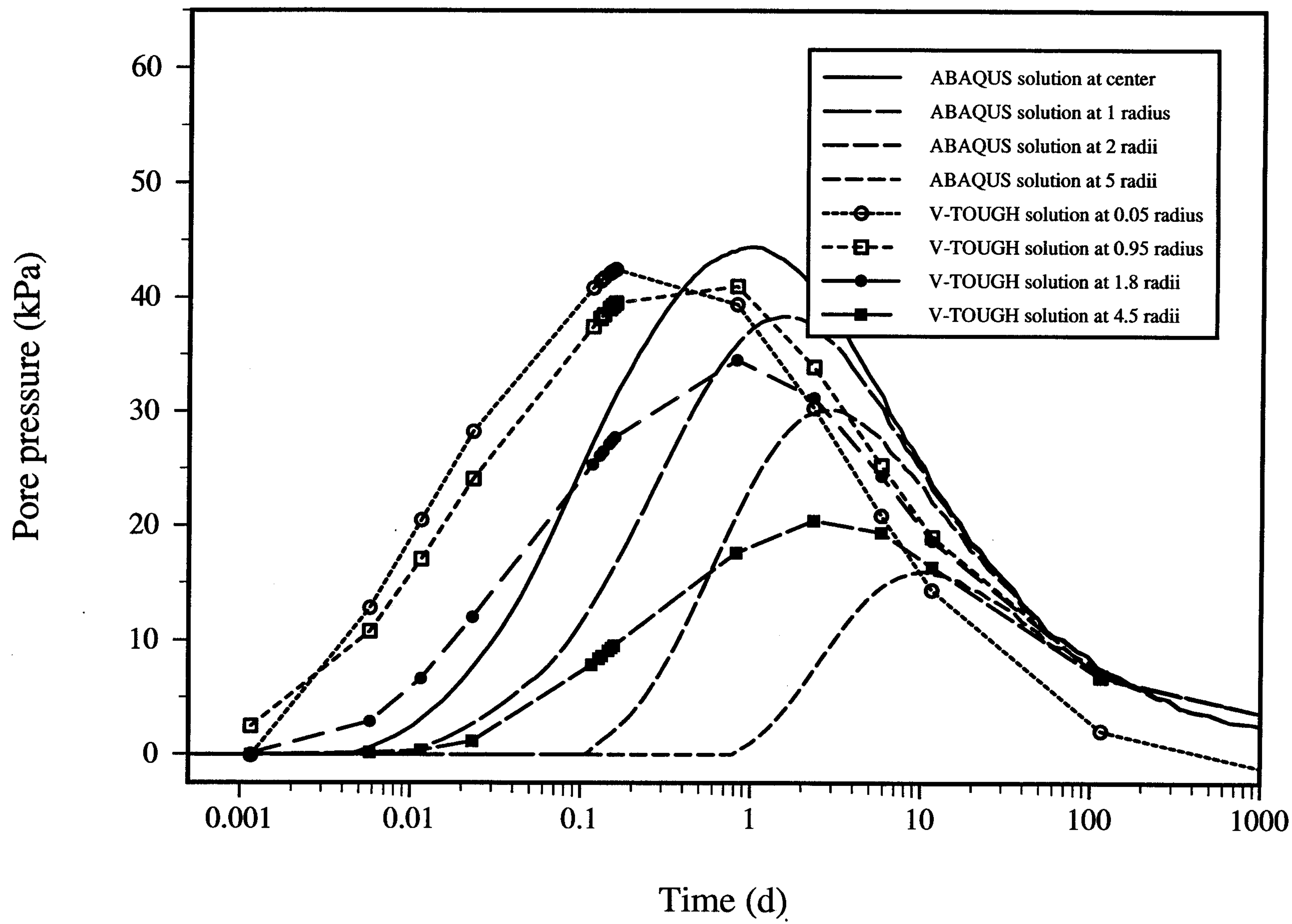
Pore-Pressure History: Middle Plane



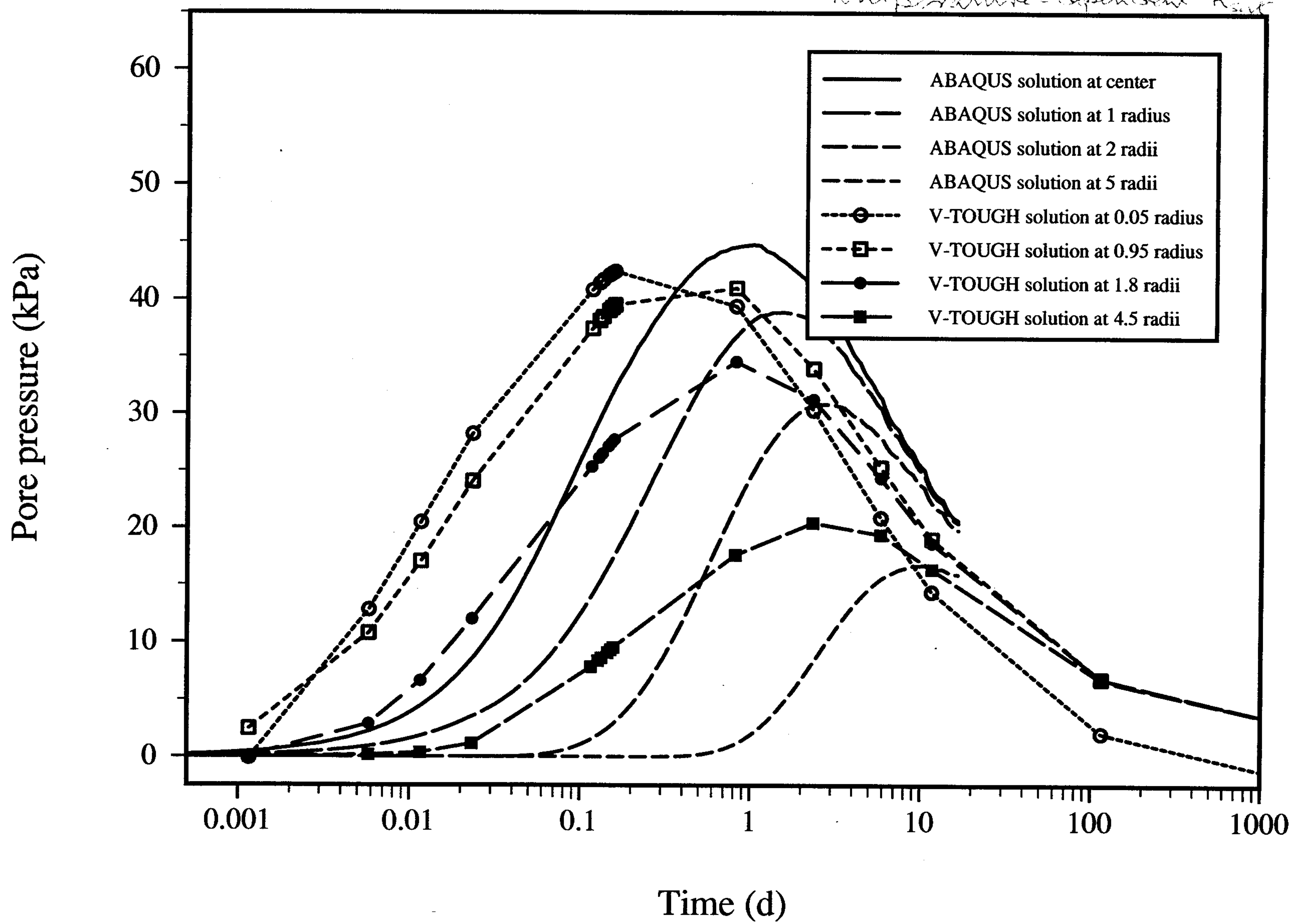
Pore-Pressure History: Middle Plane



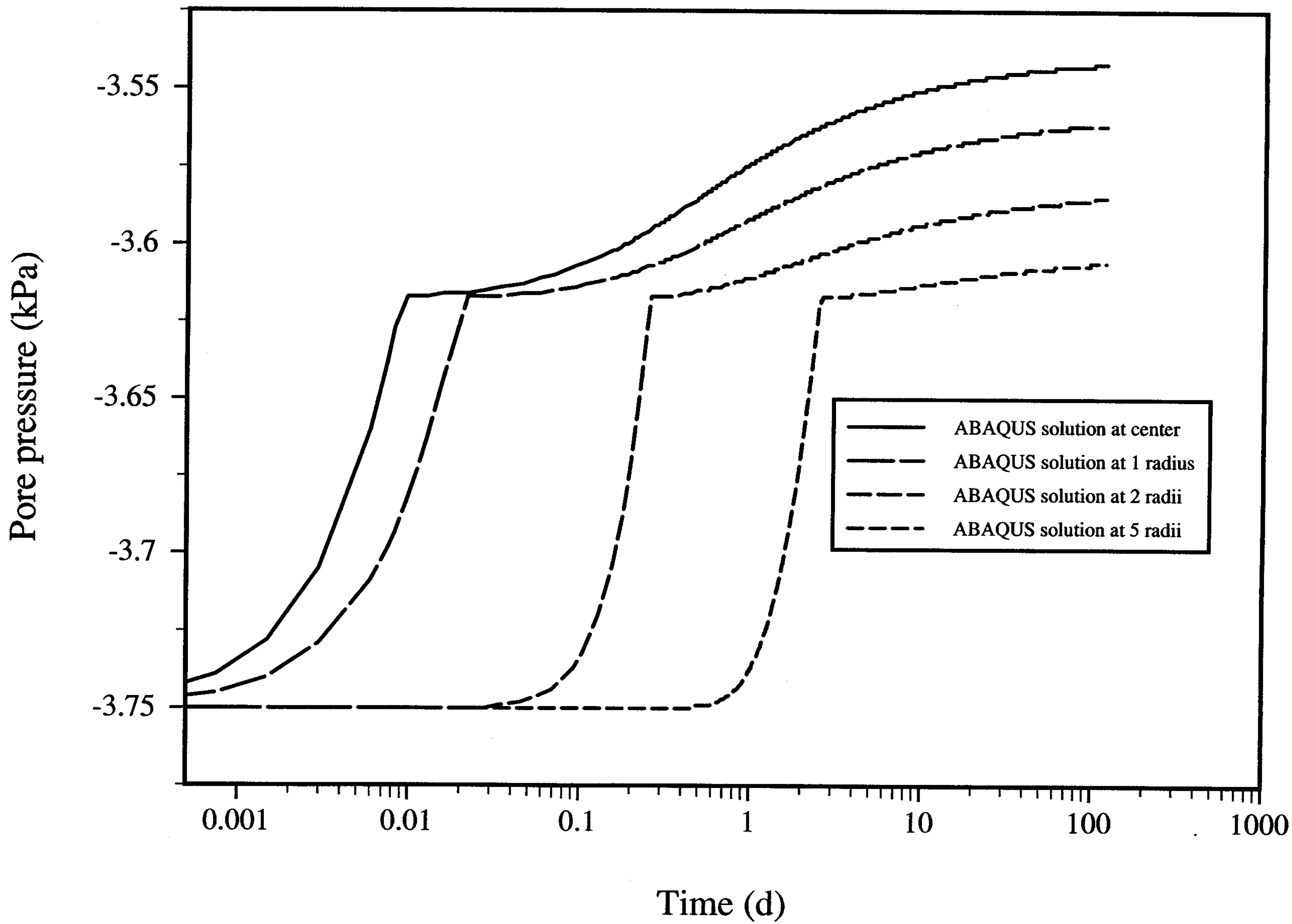
Pore-Pressure History: End Plane



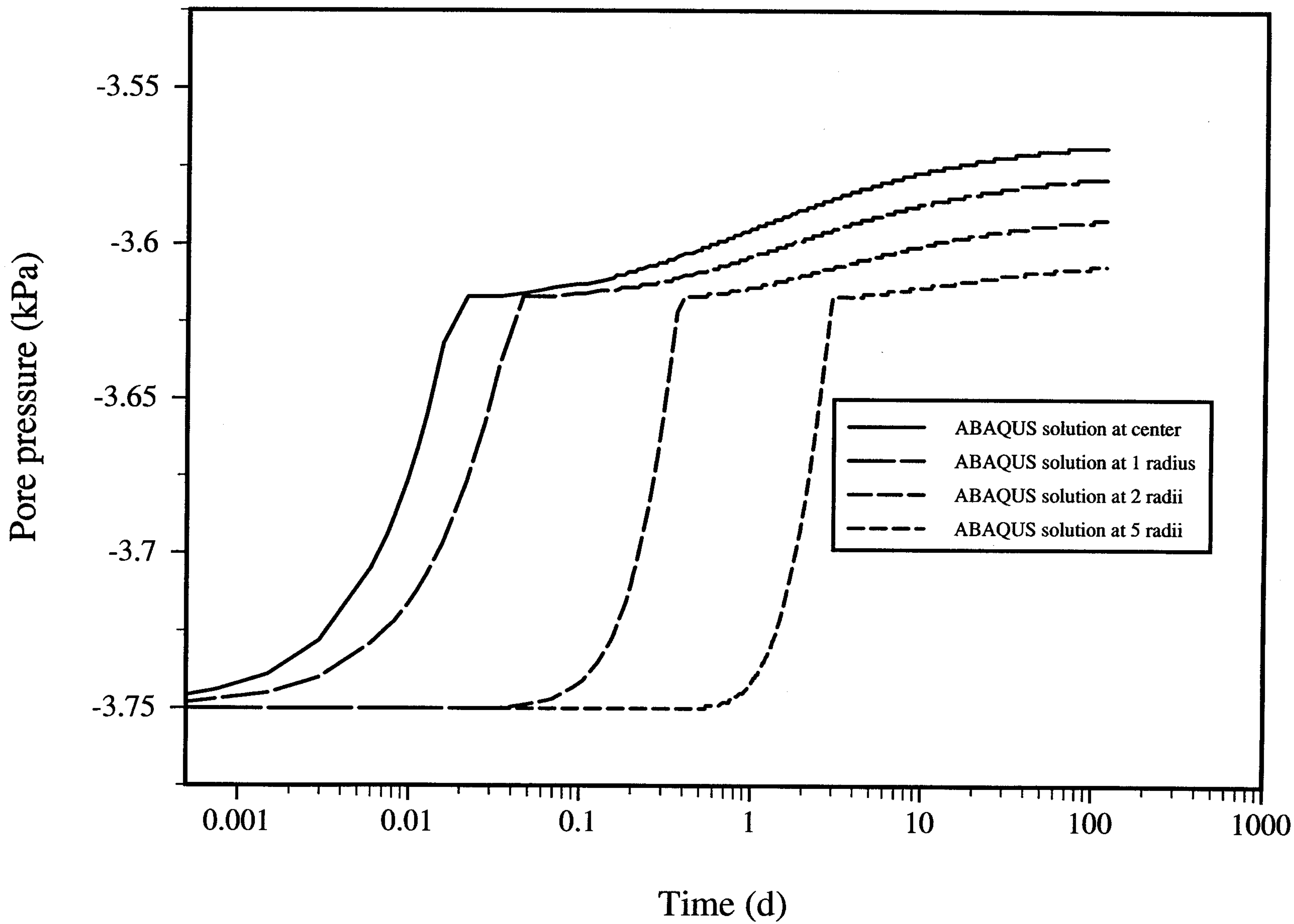
Pore-Pressure History: End Plane



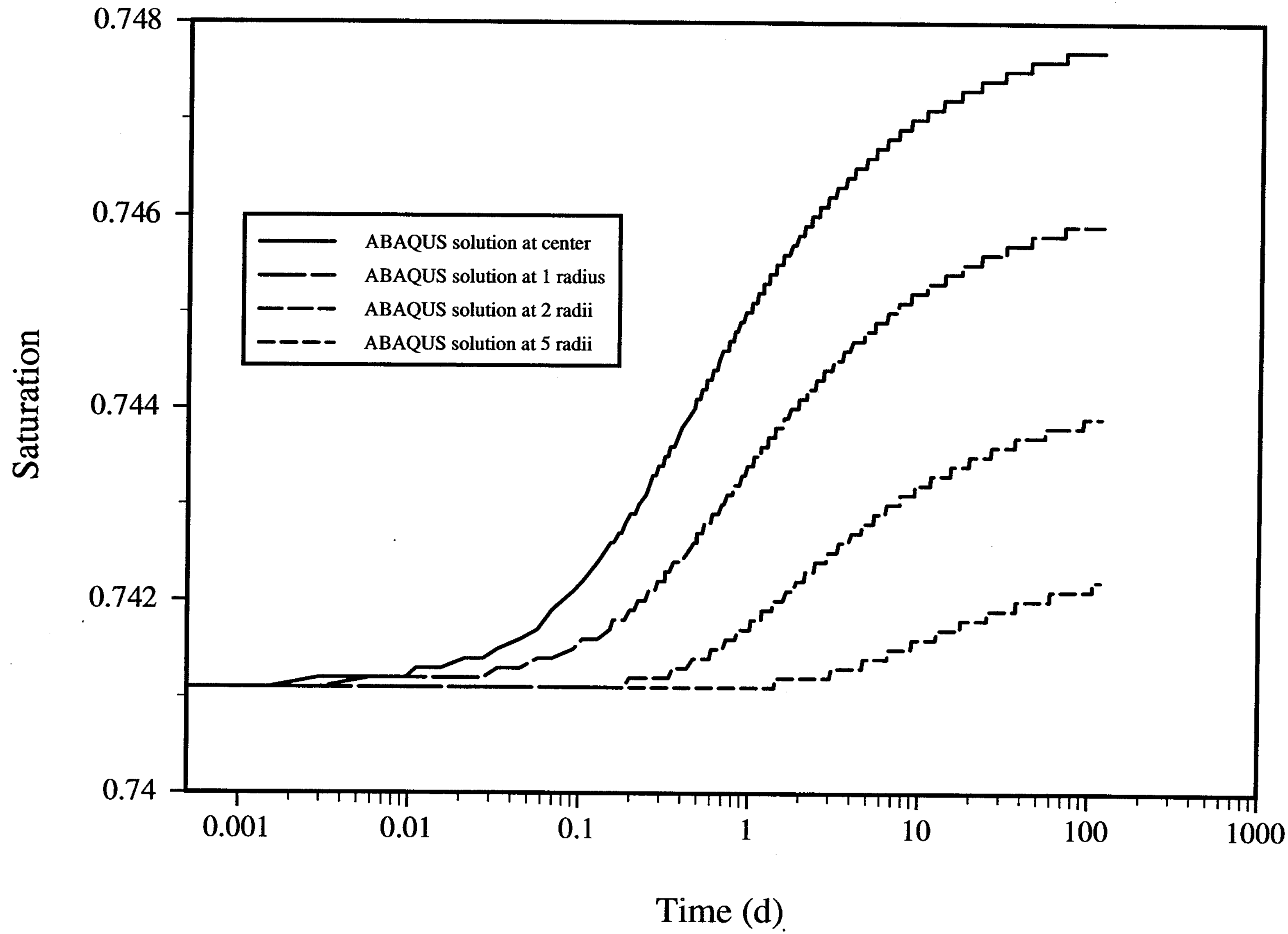
Pore Pressure History: Middle Plane



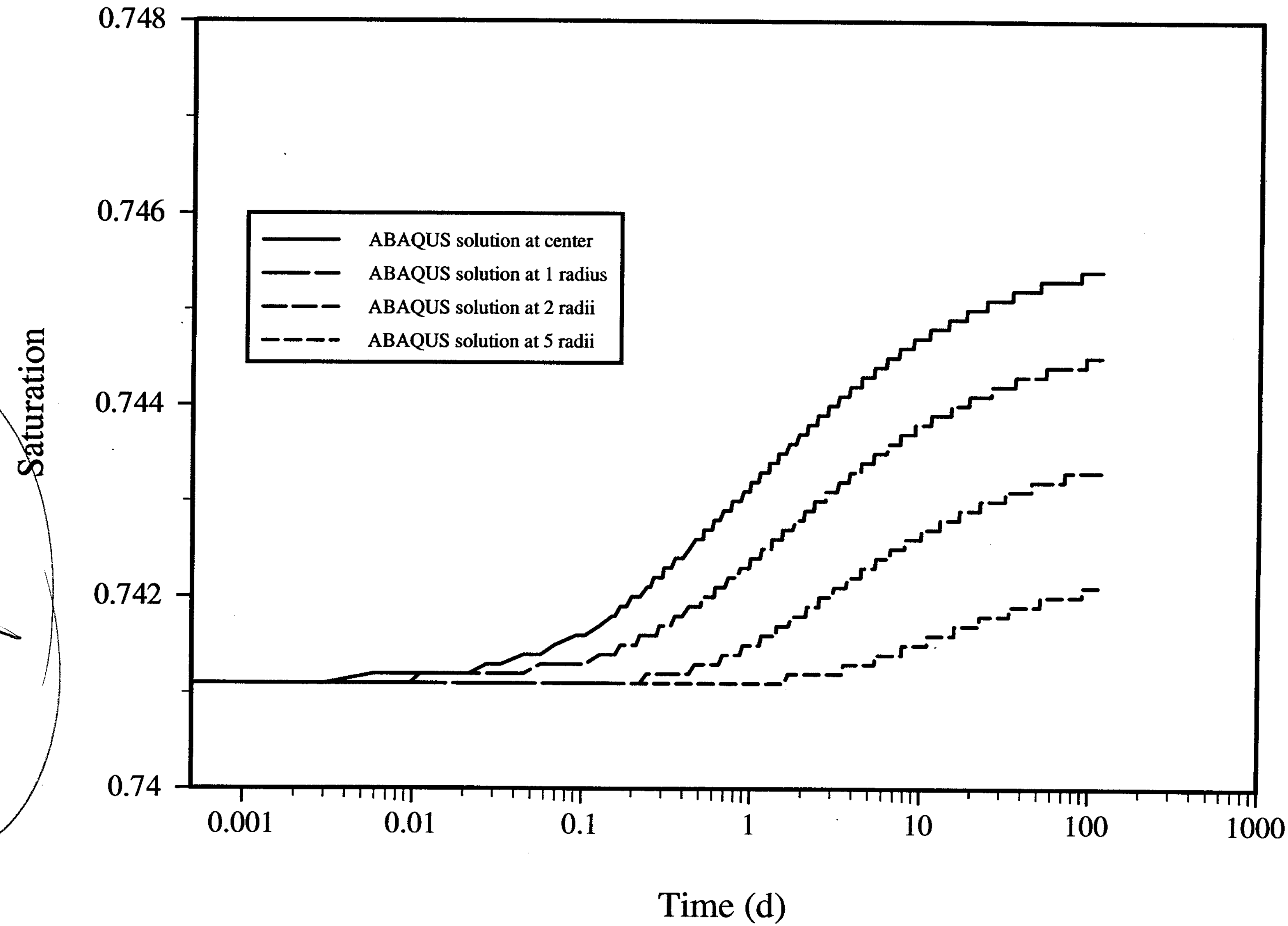
Pore Pressure History: End Plane



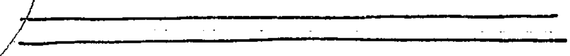
Saturation History: Middle Plane



Saturation History: End Plane



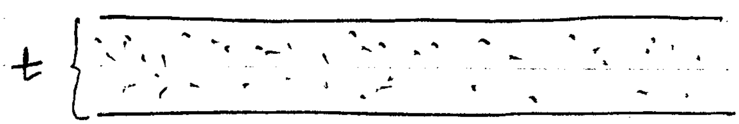
Effect of Mechanical Deformation on Fracture Permeability



aperture: e

Length: L

pore volume, $V_{vf} = eL$ per unit width



Equivalent thin solid

porosity $= \phi$

thickness $= t$

Length $= L$

pore volume $V_{vs} = \phi L t$

$$V_{vs} = V_{vf} \implies \phi L t = eL$$

$$\boxed{\implies \phi t = e}$$

Pore volume = fracture volume

$$= Lwe$$

ΔV_v = change in pore volume

$$\Delta V_v = Lw\Delta e \quad \text{(GWO)} \quad \text{- - - - - [1]}$$

for no change in L or w.

$$\frac{\Delta V_v}{V_v} = \frac{Lw\Delta e}{Lwe} = \frac{\Delta e}{{}^{o}e}$$

$$\Delta e = {}^{o}e \frac{\Delta V_v}{V_v} \quad \text{- - - - - (2)}$$

$\dfrac{\Delta V_v}{V_v}$ = Inelastic volumetric strain increment $\Delta \varepsilon_v^N$

$$\therefore \quad \Delta e = {}^{o}e \Delta \varepsilon_v^N \qquad e = {}^{o}e + \Delta e$$

$$\text{or} \quad e = {}^{o}e(1 + \Delta \varepsilon_v^N) \quad \text{- - - - (3)}$$

${}^{o}e$ = (GWO) ~~pre~~ value of aperture at end of last increment

e = value of aperture at end of current increment.

$\Delta \varepsilon_v^N$ = current incremental inelastic volumetric strain.

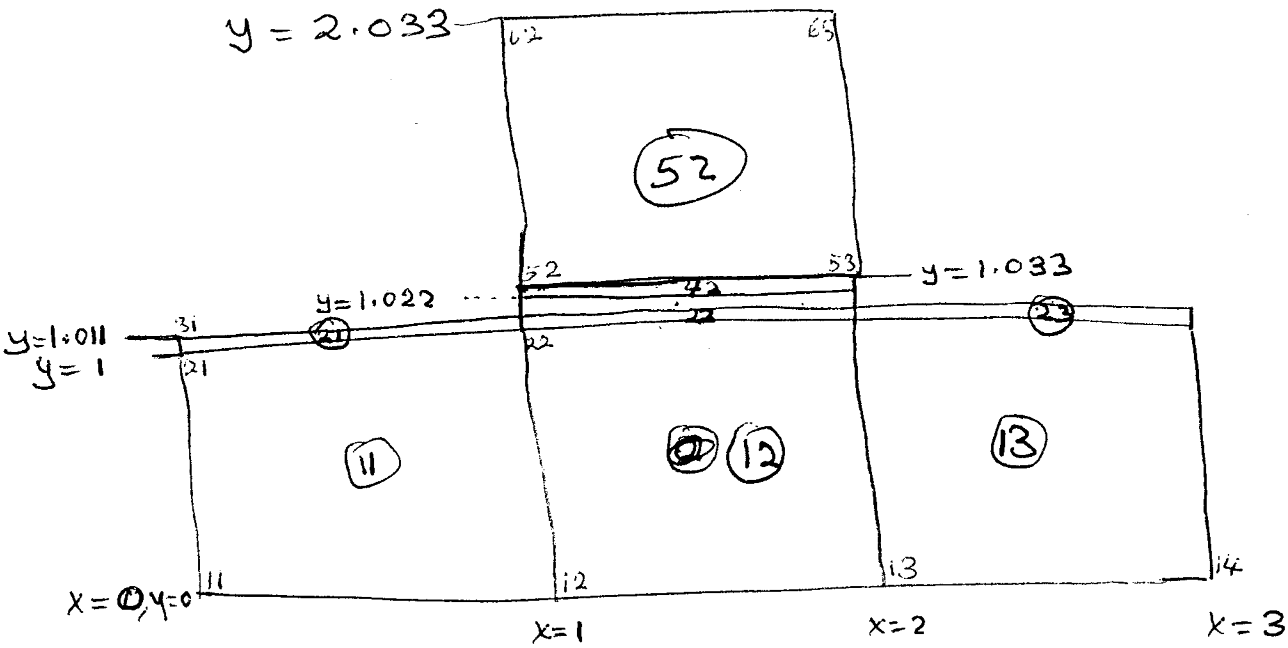
Fracture Permeability

$$K_f = \frac{\gamma_w \cdot e^2}{12\mu} = \frac{k\gamma_w}{\mu}$$

$$\Longrightarrow \quad k = \frac{e^2}{12}$$

= fracture permeability in L^2 units.

```
      SUBROUTINE UVARM(UVAR,DIRECT,T,TIME,DTIME,CMNAME,ORNAME,
     1           NUVARM,NOEL,NPT,LAYER,KSPT,KSTEP,KINC,NDI,NSHR)
C
      INCLUDE 'ABA_PARAM.INC'
      CHARACTER*8 CMNAME,ORNAME,FLGRAY(15)
      DIMENSION UVAR(NUVARM),DIRECT(3,3),T(3,3),TIME(2)
      DIMENSION ARRAY(15),JARRAY(15)
C
C     This code computes changes in equivalent fracture aperture
C     and permeability using values of inelastic strain
C     supplied by ABAQUS. The results are stored in the vector UVAR,
C     and can be obtained from ABAQUS as variable UVARMn,
C     where n is defined as follows
C
C     Number n            Variable UVARMn
C     ========            ===============
C        1                Inelastic volumetric strain
C        2                Equivalent fracture aperture
C        3                Fracture permeability (L^2 units)
C
C     The parameter NLGEOM must be specified in the STEP command in the
C     input file; also, the command "USER OUTPUT VARIABLES" must be
C     invoked in the material definition, with the number of user
C     output variables set to 3. The initial equivalent aperture
C     (AINIT) need to be specified for each element; it may have to be
C     specified through a file if its values vary
C
      TTOL = 1.0D-12
      AINIT = 1.0D-4
C
C     If total time is zero, initialize UVAR vector and return.
C
      IF (TIME(2) .LT. TTOL) THEN
        UVAR(1) = 0.0
        UVAR(2) = AINIT
        UVAR(3) = AINIT*AINIT/12.0
        RETURN
      END IF
C
C     Save value UVAR vector at end of last increment
C
      VSLAST = UVAR(1)
      ALAST = UVAR(2)
C
C     Call utility subroutine to get current inelastic strain;
C     then calculate inelastic volumetric strain.
C     The parameter NLGEOM must be specified on the STEP command;
C
      CALL GETVRM('IE',ARRAY,JARRAY,FLGRAY,JRCD)
      IF (JRCD) THEN
        WRITE(6,1000)
        RETURN
      END IF
C
      VSN = 0.0
      DO 20 I=1,NDI
   20 VSN = VSN + ARRAY(I)
C
      UVAR(1) = VSN
      DVSN = VSN - VSLAST
      A = ALAST*(1.0 + DVSN)
      UVAR(2) = A
      UVAR(3) = A*A/12.0
      RETURN
C
C----67--1---------2---------3---------4---------5---------6---------7-*
 1000 FORMAT(/,10X,'UNSUCCESSFUL CALL FOR IE FROM UVARM')
      END
```


y = 2.033
62
63
52
52
53
y = 1.033
y = 1.022
42
22
23
y=1.011
y = 1
31
21
21
22
11
12
13
11
12
13
14
x = 0, y = 0
x=1
x=2
x = 3

Strain-Dependent Dilation

ϕ = friction angle (Mohr-Coulomb model)

β = Drucker-Prager equivalent friction angle

α = Dilation angle (Mohr-Coulomb model)

ψ = Drucker-Prager equivalent dilation angle

u = shear displacement

v = normal displacement

Source

Laboratory Characterization of Rock Joints.
by Hsiung et al (1994) - NUREG/CR-6178
CNWRA 93-013

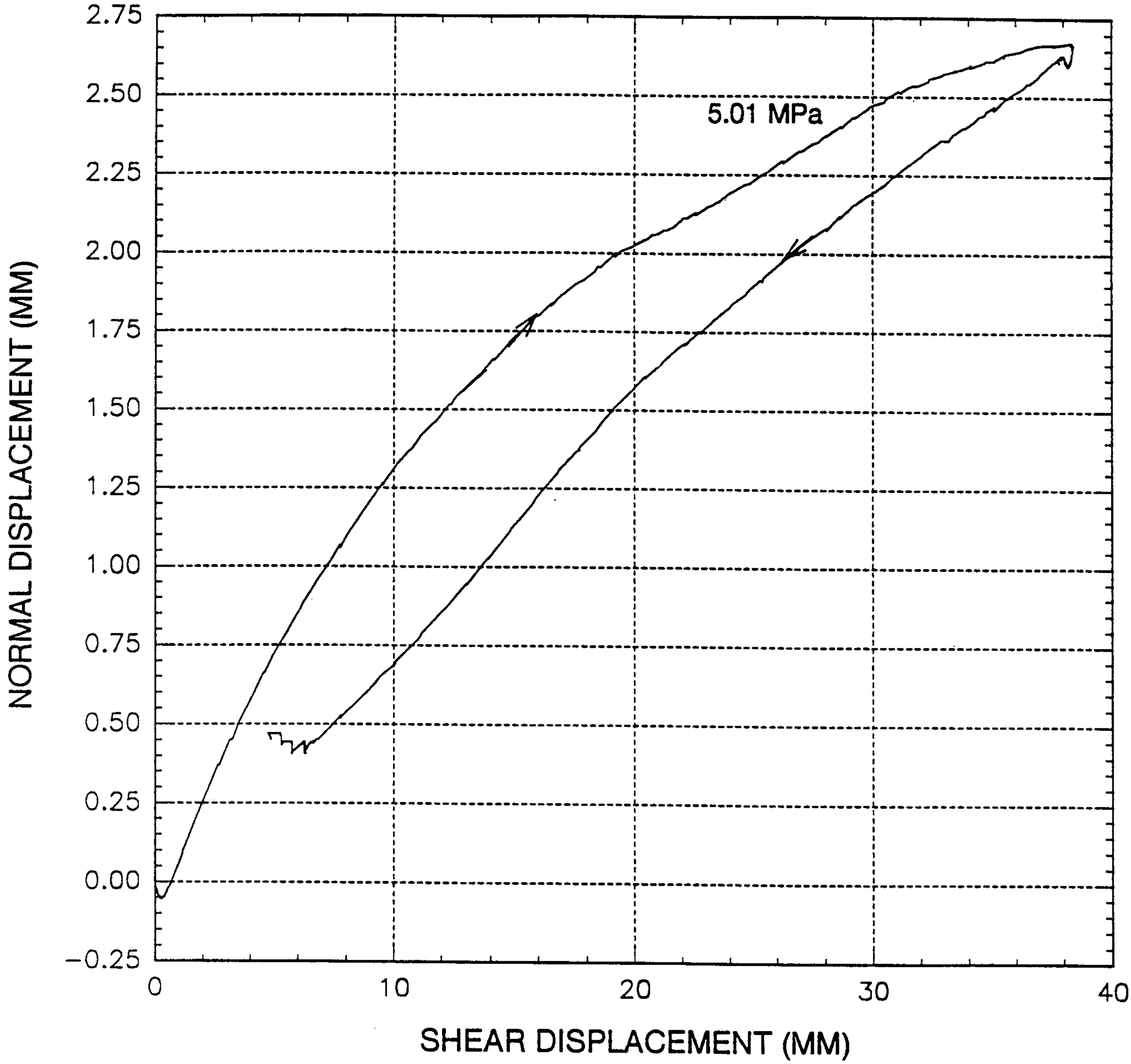


Figure 5-5. Normal displacement (dilation) response for test no. 7 under applied normal stress of 5.01 MPa

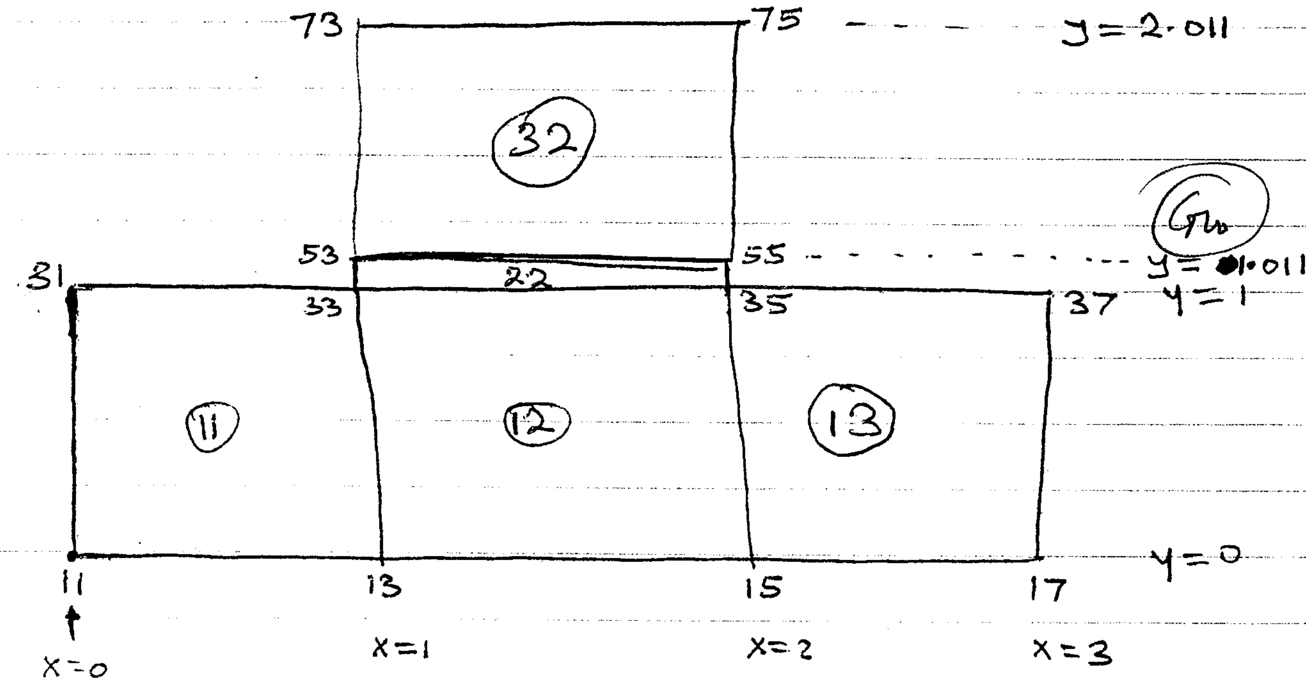
u (mm)	v (mm)	dv/du	$\alpha = \tan^{-1}(dv/du)$	α/ϕ
0.0	0.0	–	–	
5.0	0.75	0.15	8.53°	0.1[illegible]
10.0	1.30 (GW)	0.11	6.28°	0.14
15.0	1.75	0.09	5.14°	0.11
20.0	2.05	0.06	3.43°	0.07
(GW) 30.0	2.45	0.04	2.29	0.05
40.0	2.70	0.025	1.43	0.0[illegible]

$$\phi = \tan^{-1}(4.75/5.01) = 43.5^\circ$$

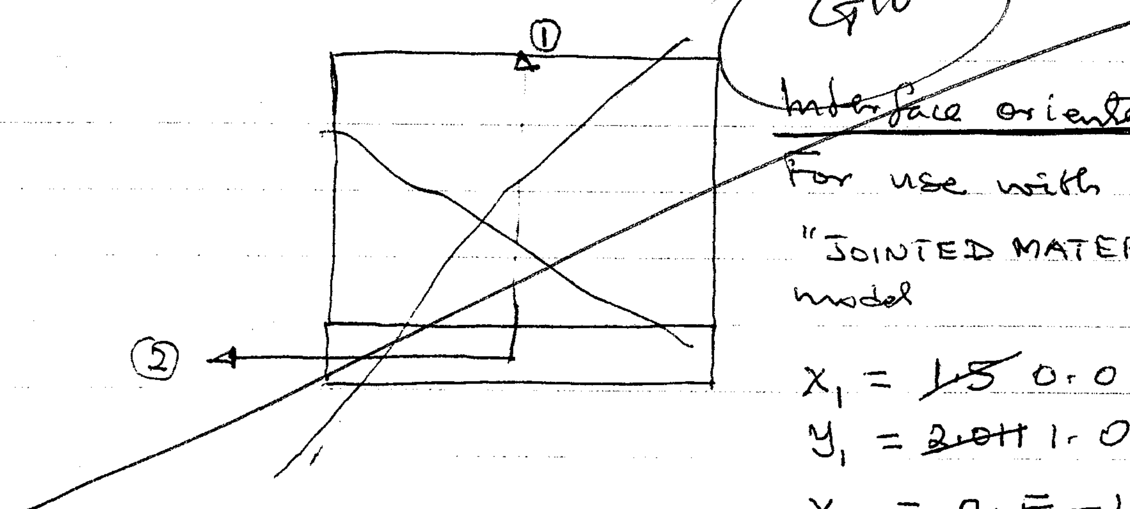
$$\beta = \tan^{-1}(\sqrt{3}\sin\phi) = 50^\circ$$

u (lab) (mm)	u (model) (mm)	ψ	
0.0	0.0	9.8	10
5.0	5.0	9.8	10
10.0	10.0	7.2	7
15.0	15.0	5.9	6
20.0	20.0	3.95	4
30.0	30.0	2.65	3
40.0	40.0	1.65	2

Model Based on Quadratic Elements



Gro



~~Interface~~ orientation

For use with "JOINTED MATERIAL" model

x_1 = ~~1.5~~ 0.0

y_1 = ~~2.011~~ 1.0

x_2 = ~~0.5~~ −1.0

y_2 = ~~1.0055~~ 0.0

$\beta = 50^\circ$

$\phi = 48.6^\circ$ for $\psi/\beta = 1$ $C = 0.19$

$\phi = 43.5^\circ$ for $\psi/\beta = 0$ $C = 0.21$

} 0.2

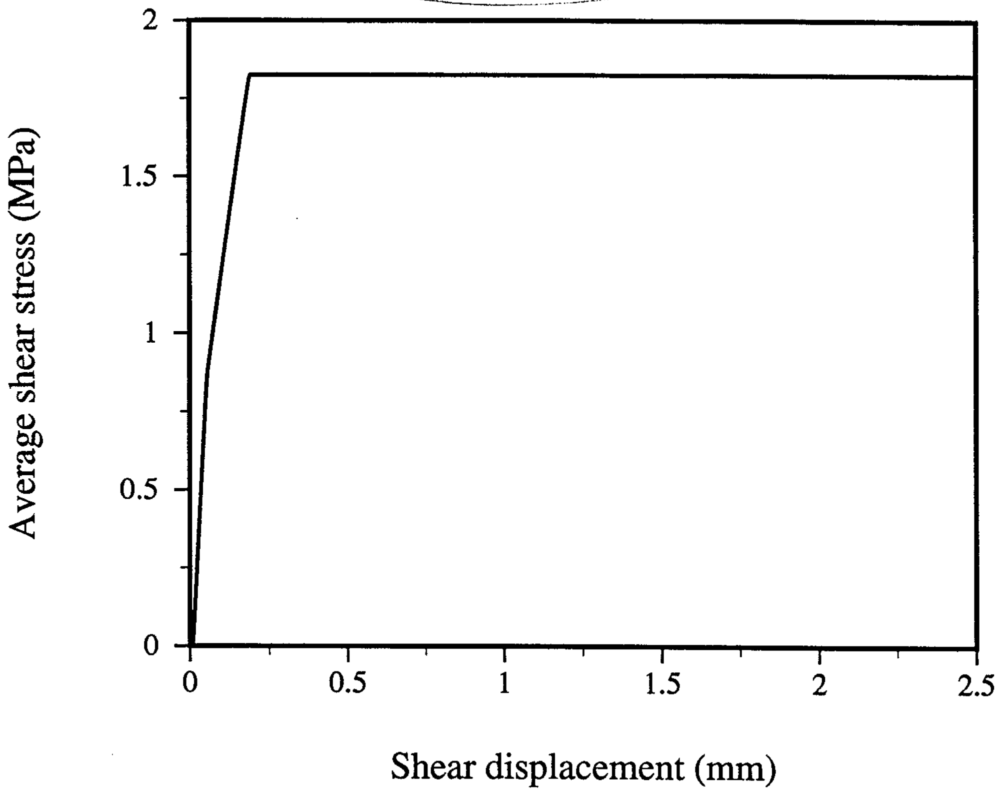
$$C = \frac{q_u}{2\tan(45+\phi/2)}$$

$\phi = 47.6$ $C = 0.2$

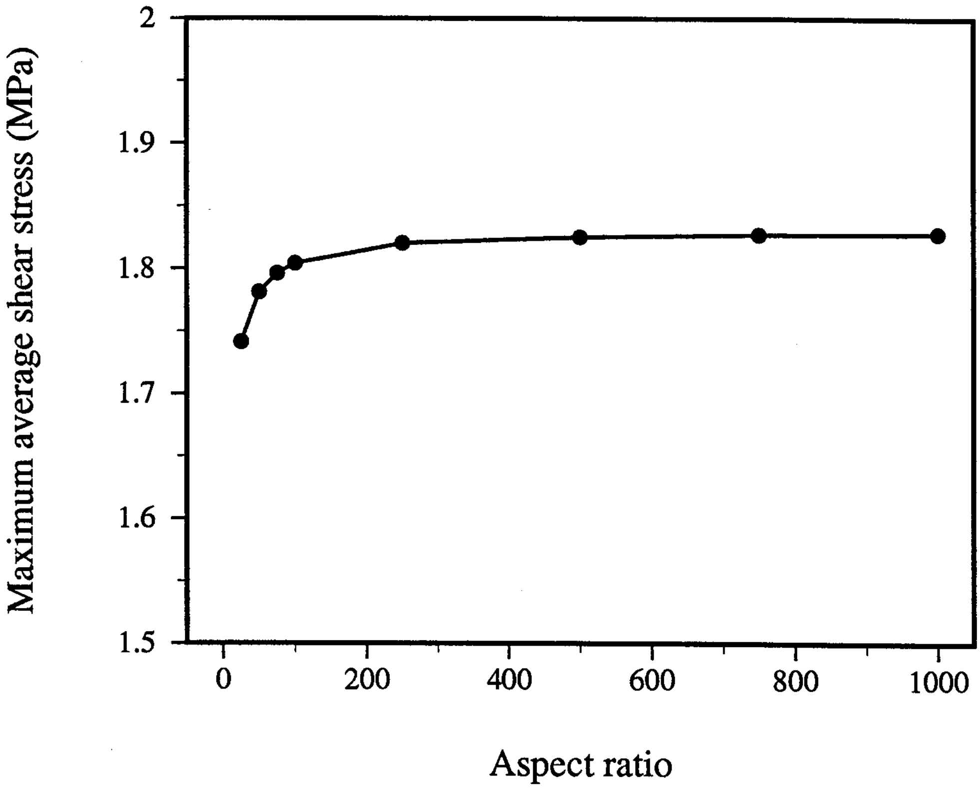
$\tau = 2.39$ MPa

Aspect Ratio (Ar)	t (mm)	Shear displacement (mm)	Plastic Volumetric Strain	Max avg shear stress (τ_{10}) ~~Max shear stress~~ MPa
25	40	40	0.351	1.741
50	20	20	0.350	1.781
75	13.33	13.33	0.350	1.796
100	10	10	0.350	1.804
250	4.0	4.0	0.352	1.820
500	2.0	2.0	0.355	1.825
750	1.33	1.333	0.358	1.827
1000	1.0	1.0	0.362	1.828

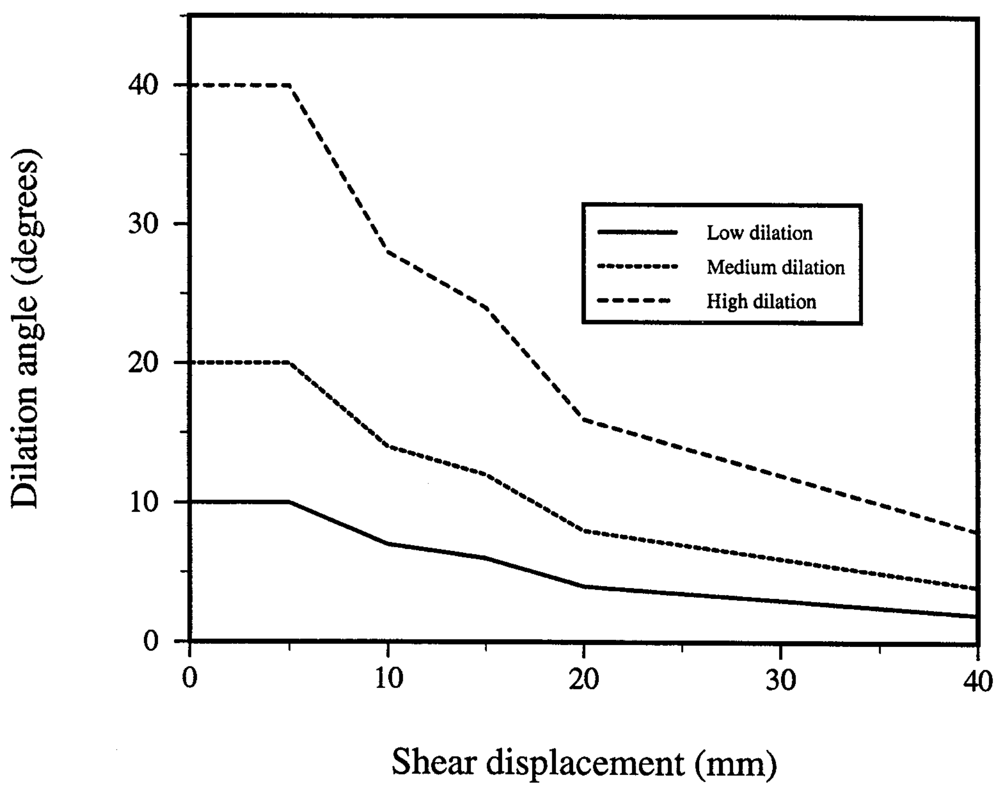
mhs30500.ps


Average shear stress (MPa)
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
Shear displacement (mm)

mhtaumax.ps

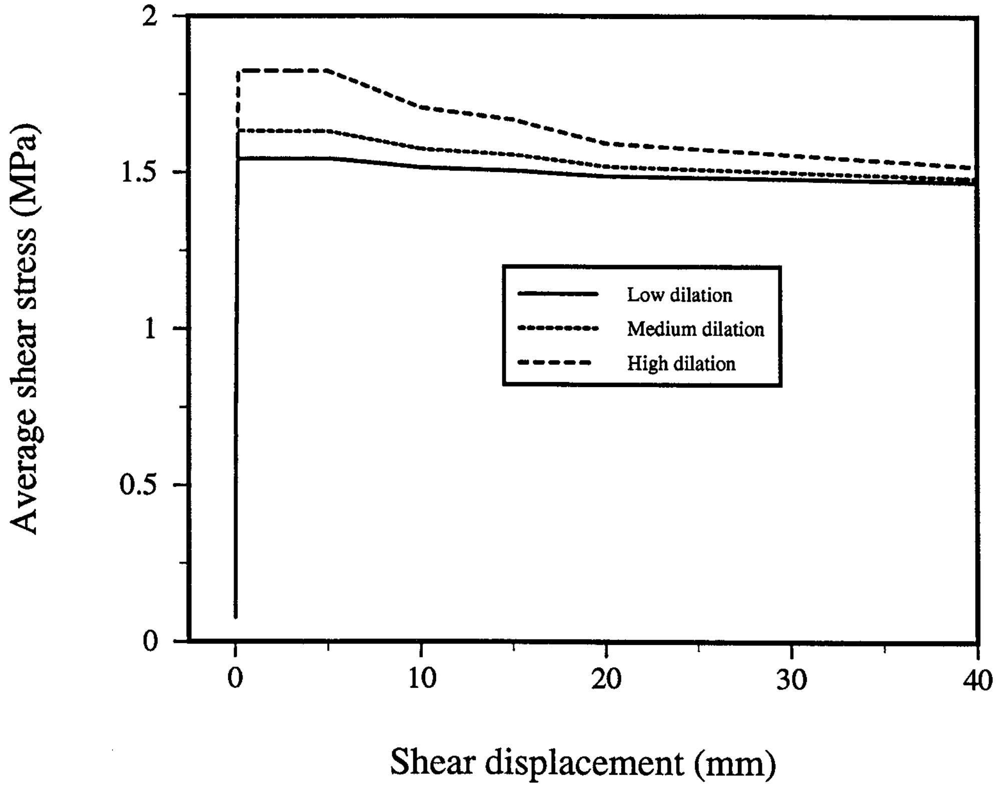

Maximum average shear stress (MPa)
2
1.9
1.8
1.7
1.6
1.5
0
200
400
600
800
1000
Aspect ratio

mhdilang.ps



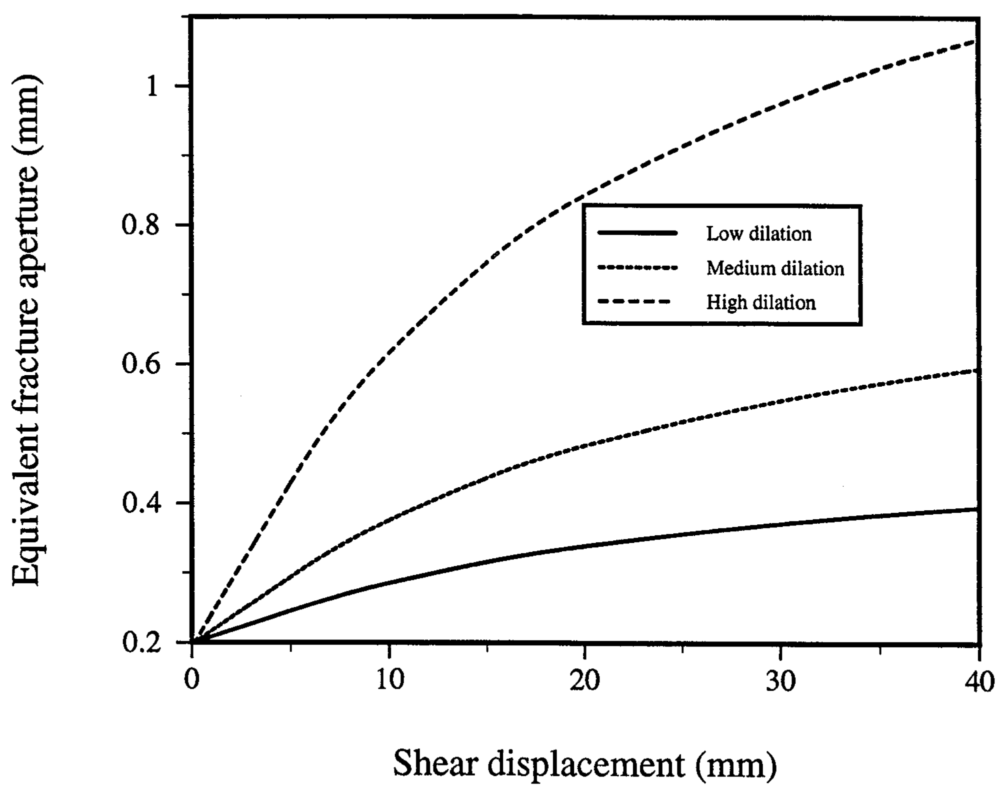
Dilation angle (degrees)
40
30
20
10
0
0
10
20
30
40
Shear displacement (mm)
Low dilation
Medium dilation
High dilation

mhshstrs.ps



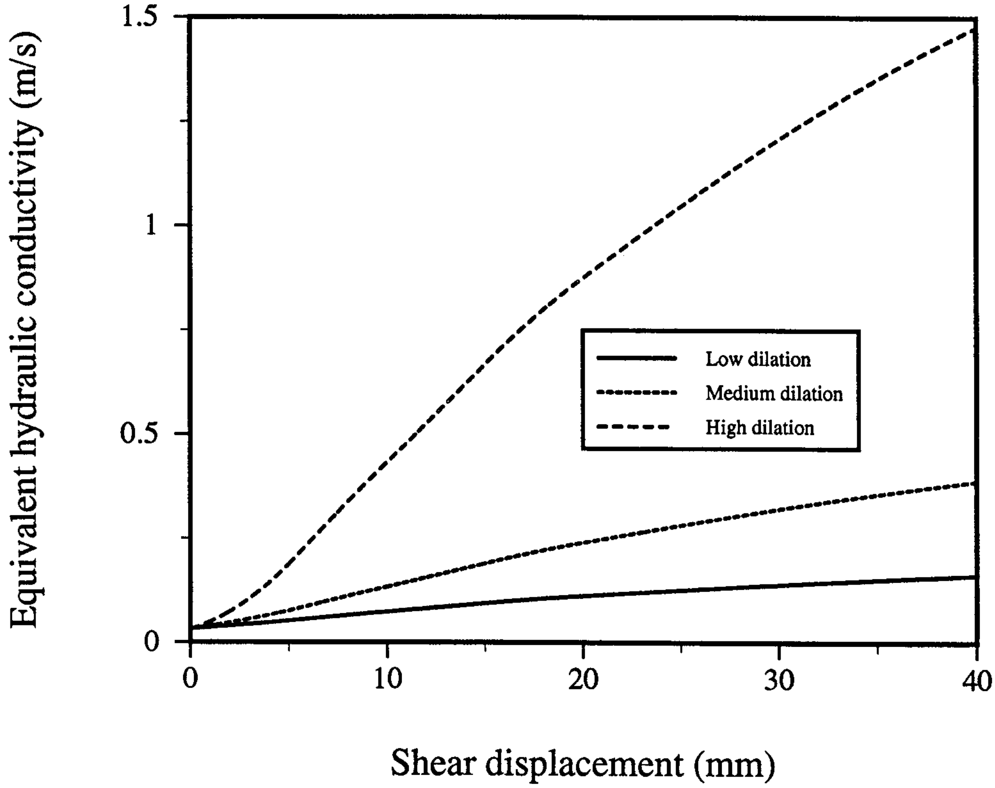
Average shear stress (MPa)
2
1.5
1
0.5
0
0
10
20
30
40
Shear displacement (mm)
Low dilation
Medium dilation
High dilation

mhafrac.ps



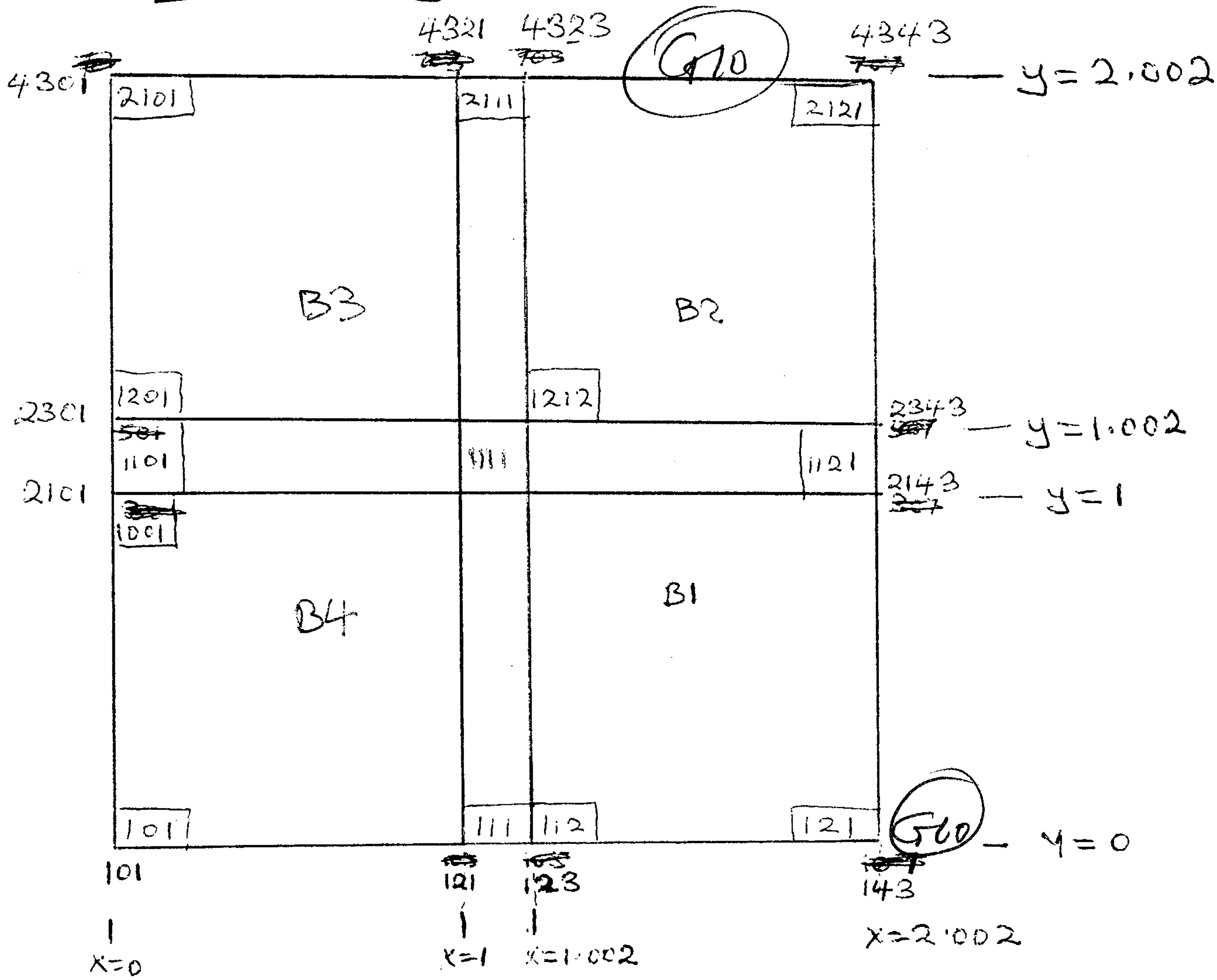
Equivalent fracture aperture (mm)
1
0.8
0.6
0.4
0.2
0
10
20
30
40
Shear displacement (mm)
Low dilation
Medium dilation
High dilation

mhksat.ps


Equivalent hydraulic conductivity (m/s)
1.5
1
0.5
0
0
10
20
30
40
Shear displacement (mm)
Low dilation
Medium dilation
High dilation

Case of Intersecting Fractures

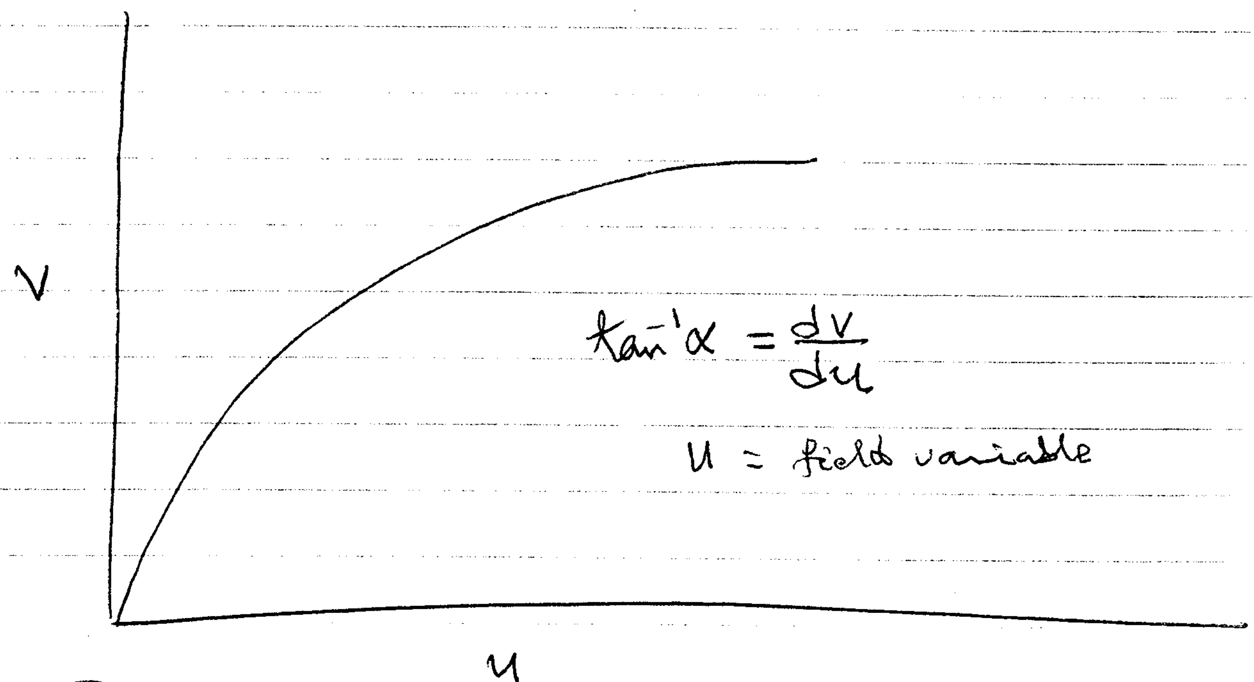
Two Orthogonal Fractures



Thin solid elements:

① Drucker-Prager

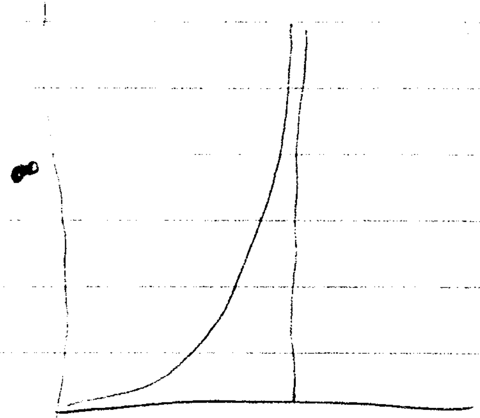
— Dilation ~~&~~ shear-induced strain-dependent dilation use lab V vs U data



② GW DP—Cap

— Normal deformation response

— Effects of R and α on permeability.



Conversion of joint pressure-vs-aperture relationship to pressure-vs-volumetric strain function

e = aperture

e_0 = initial aperture

$\Delta\varepsilon_v^N$ = inelastic volumetric strain

L = length of joint

W = width of joint

$$\Delta\varepsilon_v^N = \frac{\Delta V_v}{V_v} = \frac{LW\Delta e}{LWe_0} = \frac{\Delta e}{e_0}$$

$$\Longrightarrow \quad \Delta e = e_0 \Delta\varepsilon_v^N$$

$$e = e_0 + \Delta e$$

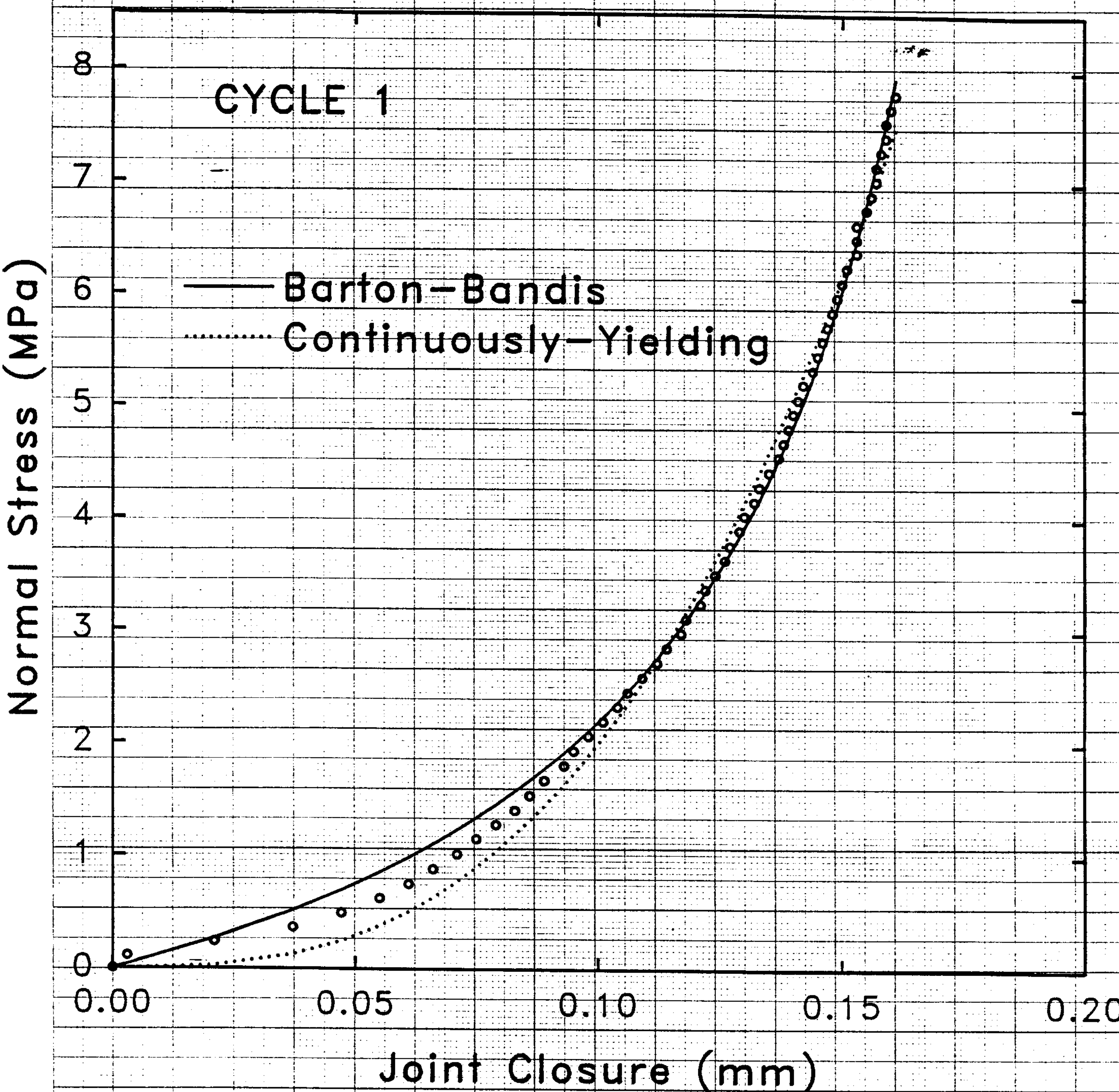
$$e = e_0 + e_0\Delta\varepsilon_v^N = e_0(1 + \Delta\varepsilon_v^N)$$

$$\Longrightarrow \quad e = e_0(1 + \Delta\varepsilon_v^N)$$

and
$$\Delta\varepsilon_v^N = \frac{e}{e_0} - 1$$

e_0 = aperture at end of last increment

e = aperture at end of current increment


CYCLE 1
Barton-Bandis
Continuously-Yielding
Normal Stress (MPa)
0
1
2
3
4
5
6
7
8
0.00
0.05
0.10
0.15
0.20
Joint Closure (mm)

P (MPa)	c (mm)	e mm	$\Delta\varepsilon_v^N$	ε_v^N
~~0.0~~ GW				
0.0	0.0	1.0	0.0	0.0
1.0	0.0625	0.9375	−0.0625	−0.0625
2.0	0.10	0.9	−0.04	−0.1025
3.0	0.1188	0.8812	−0.0209	−0.1234
4.0	0.1313	0.8687	−0.0142	−0.1376
5.0	0.1438	0.8562	−0.0144	−0.1520
8.0	0.1625	0.8375	−0.0218	−0.1738

G10 foreglen
Pages 95-116

TASK 2.3: PROBLEM 8 HEATED DRIFT WITH OPEN FRACTURE

G. Ofoegbu

PROBLEM SET 8: HEATED DRIFT WITH OPEN FRACTURE

The purpose of this problem set is to evaluate the modeling of the normal stiffness of rock discontinuities in ABAQUS. The results of Problem Set 3 indicated substantial differences in the values of fracture-surface normal stress calculated using ABAQUS and UDEC. It is believed that the differences are caused by the different methods used by the two codes to model the normal stiffness of discontinuities. This issue is important for two reasons, namely, (i) the normal stiffness of a rock fracture has a strong effect on aperture changes, which are important for the prediction of mechanical-effect-dependent fluid flow through fractures; and (ii) fracture-surface shear resistance depends on the normal stress, which depends on the normal stiffness. Therefore, this problem was developed to evaluate all the provisions available in ABAQUS for modeling fracture opening and closure under the influence of normal stress.

The geometry of the problem is illustrated in Figure 8-1. It consists of a horizontal circular drift intersected at its crown and floor by a single vertical fracture. The drift is located in the interior of a horizontal drift-array that consists of drifts located at the same horizontal center-to-center distance from each other. The fracture is initially open, and its aperture cannot decrease below a specified minimum value. The values of *in situ* principal compressive stress are 10 MPa vertical, and 2 MPa horizontal.

The sequence of events to be modeled consists of drift excavation under constant (initial) temperature, followed by drift heating, which will be accomplished by applying a specified temperature history to the drift wall.

The problem will be solved in two and three dimensions using ABAQUS, UDEC, and 3DEC. The purpose of the three-dimensional (3D) solution is to evaluate the ABAQUS 3D-interface elements. To facilitate the comparison of the 3D and two-dimensional (2D) solutions, the geometry of the problem and the magnitude and orientation of the *in situ* principal stresses will be the same for the 3D and 2D models. In that case, the 3D-calculated responses for the middle vertical plane normal to the drift axis should be the same as those calculated using the 2D model.

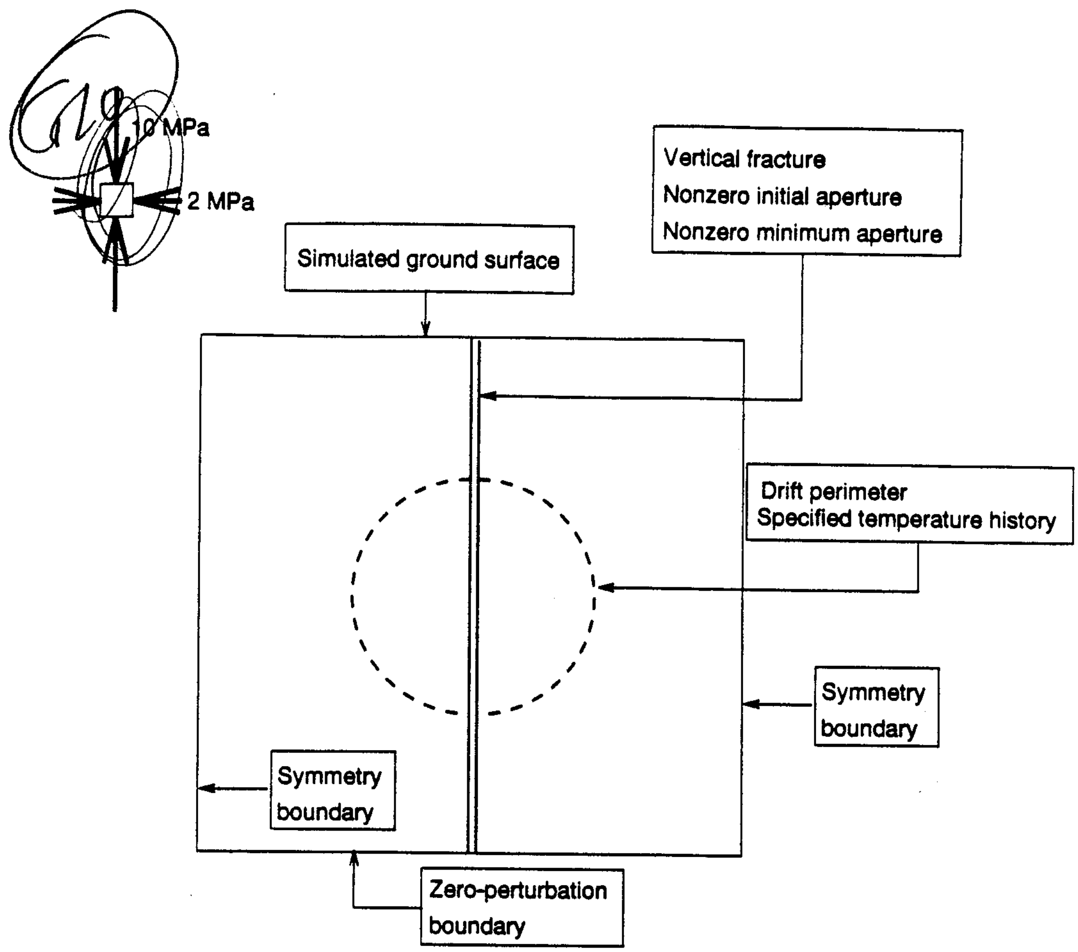


Figure 8-1. Problem geometry for Problem Set 8

5 m diameter
22.5 m center-to-center

Initial aperture = 1 mm
Minimum aperture = 0.1 mm

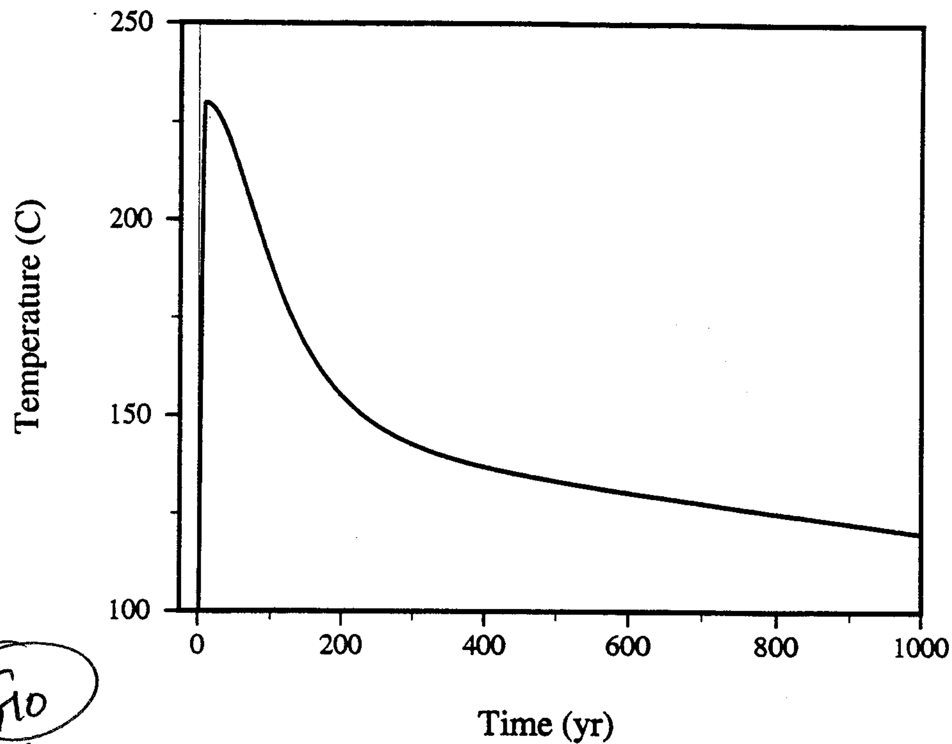


Figure 4-3. Temperature history applied to the drift wall to simulate the thermal history of emplaced waste

Table 4-1. Material property specifications for Problem Set 3

Property, symbol, and unit	Value
Young's modulus, E (MPa)	3.27×10^4
Poisson's ratio, ν	0.25
Friction angle for fracture surfaces, ϕ	40°
Cohesion for fracture surfaces (MPa)	0.0
Coefficient of linear expansion, α (K^{-1})	8.5×10^{-6}
Thermal conductivity, k_θ ($MJ\ m^{-1} \cdot s^{-1} \cdot K^{-1}$)	2.1×10^{-6}
Specific heat capacity, C_v ($MJ \cdot m^{-3} \cdot K^{-1}$)	2.2
Density, ρ ($10^6\ kg \cdot m^{-3}$)	2.24×10^{-3}

4.2 BOUNDARY CONDITIONS

The boundaries of the problem domain can be classified into *internal* and *external* boundaries. The internal boundaries are the drift wall (represented by curve ABC in Figure 4-2), and the symmetry planes (represented in the same figure by the horizontal line AD and vertical line CF) that were established

Material Parameters

Thermal conductivity

$$K_\theta = 2.1 \times 10^{-6} \ MJ\ m^{-1}.s^{-1}.K^{-1}$$

$$= 2.1 \times 10^{-6} \ MJ\ m^{-1}.d^{-1}.K^{-1}.\ 8.64E4\ (s^{-1}d$$

$$= 0.1814\ MJ.m^{-1}.d^{-1}.K^{-1}$$

Fracture-element conductance

$$K = K_\theta / e$$

e = fracture aperture

e	~~R~~ (GRO) K $(MJ.m^{-2}.d^{-1}.K^{-1})$
~~1×10^{-4} m~~	~~1814.4~~ (GRO)
1×10^{-3} m	181.44
~~1×10^{-4} m~~ (GRO)	~~1814.4~~
1×10^{-5} m	18144.0
1×10^{-6} m	181440.0

~~Specific heat~~ GM

=

Density = 2.24 ~~kg~~ $\times 10^3$ kg/m³

Specific heat =

$$2.2 \frac{MJ}{m^3 \cdot K} \times \frac{1}{2.24 \times 10^3} \frac{m^3}{kg}$$

$$= 9.821 \times 10^{-4} \; MJ/(kg \cdot K)$$

Initial Temperature 25°C everywhere.

Boundary Conditions

① No temperature change on the ground surface and at depth of 1000 m below drift centerline.

② Prescribed temperature history on driftwall

③ No heat flux normal to vertical boundaries

Mechanical Properties

Young's modulus 3.27×10^4 MPa

Poisson's ratio 0.25

Thermal expansivity (linear) 8.5×10^{-6} K^{-1}

Fractures

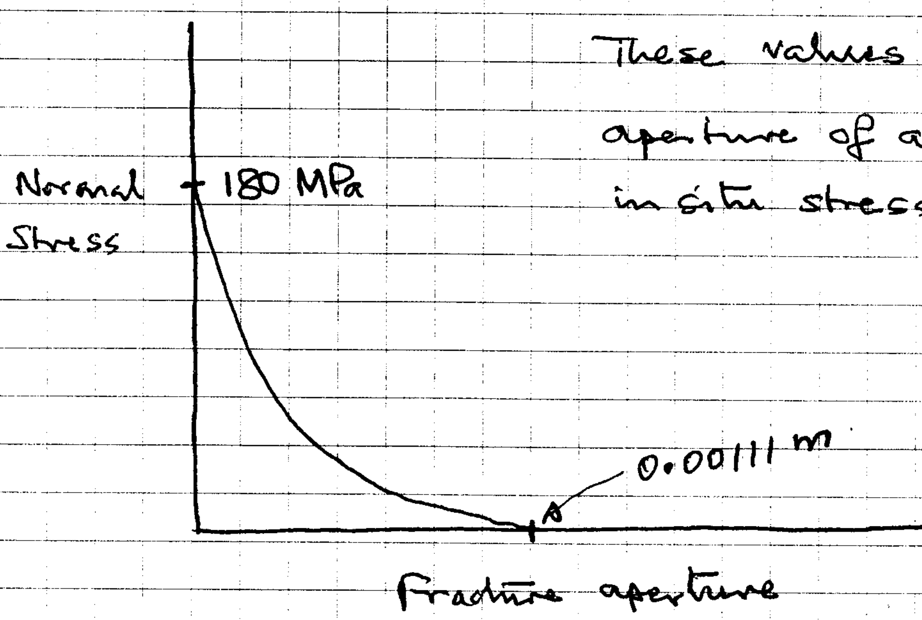
(Chg) Coefficient of friction 0.8391

No slip allowed under elastic states

(i.e. infite elastic shear stiffness)

Normal Stiffness:

Use "SURFACE BEHAVIOR, SOFTENED" command with following values



These values ~~were~~ allow an initial aperture of about 1 mm under the in situ stress state.

Initial Stress: Vertical gradient:

$\sigma_v = 0.0$ at 300 m above drift centerline (ground surface)

$\sigma_v = -2.5$ MPa at 200 m above drift centerline.

These values correspond to a vertical gradient of 0.025 MPa/m.

$\sigma_h = 0.2\sigma_v$ at every depth.

σ_v = vertical stress.
σ_h = horizontal stress.

Boundary conditions

Free surfaces: ground surface
drift wall

Zero normal ~~dis~~ (GW) - displacement:
(i) horizontal boundary at 1000 m below centerline.

(ii) Two vertical boundaries.

General Procedure for 2D Problem

① Using a coarse mesh, set up an all-inclusive model (Global Model) with boundaries at the ground surface and at depth of 1000 m below drift centerline.

② Using the global model, compute the ~~displace~~ (GRO) histories of

(a) temperature

(b) vertical displacement

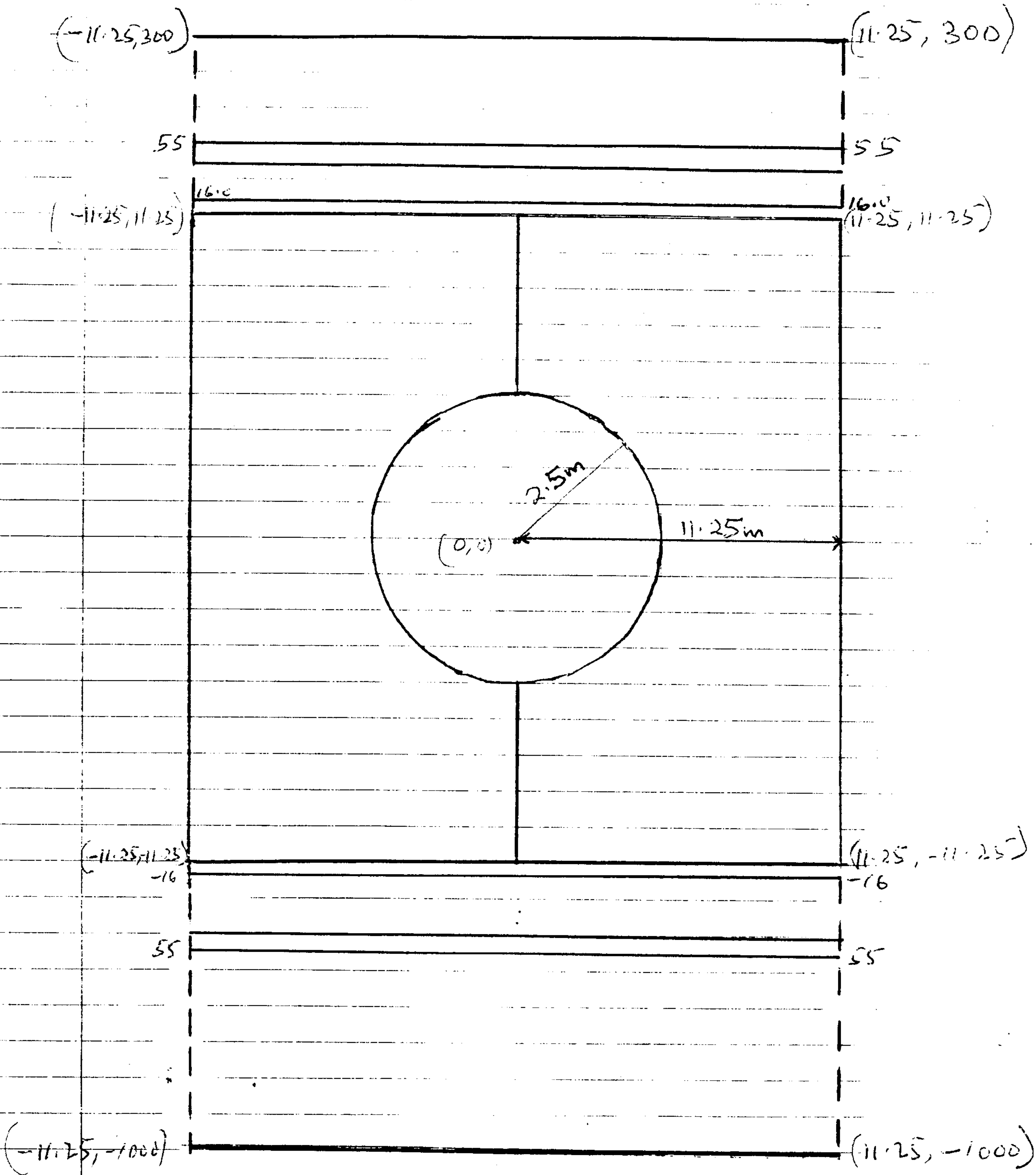
at ±50 m above drift centerline. ~~Store in~~ (GRO)

③ ~~Set up detailed (GRO) local model~~

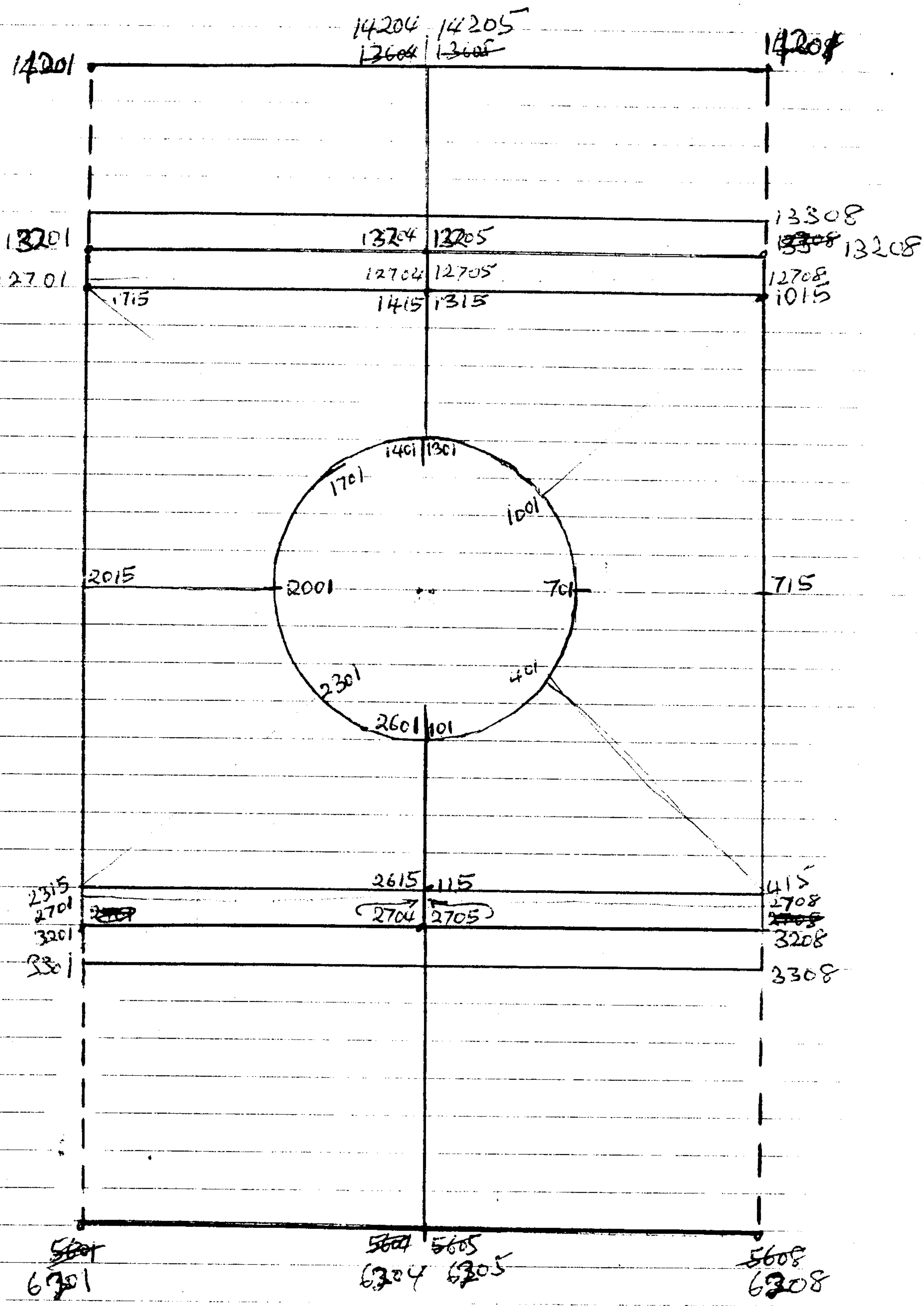
③ Using a fine mesh, set up detailed model of drift, with boundaries at ±50 m above drift centerline. ~~At~~ (GRO)

④ Analyze detailed model using the ABAQUS SUBMODEL utilities.

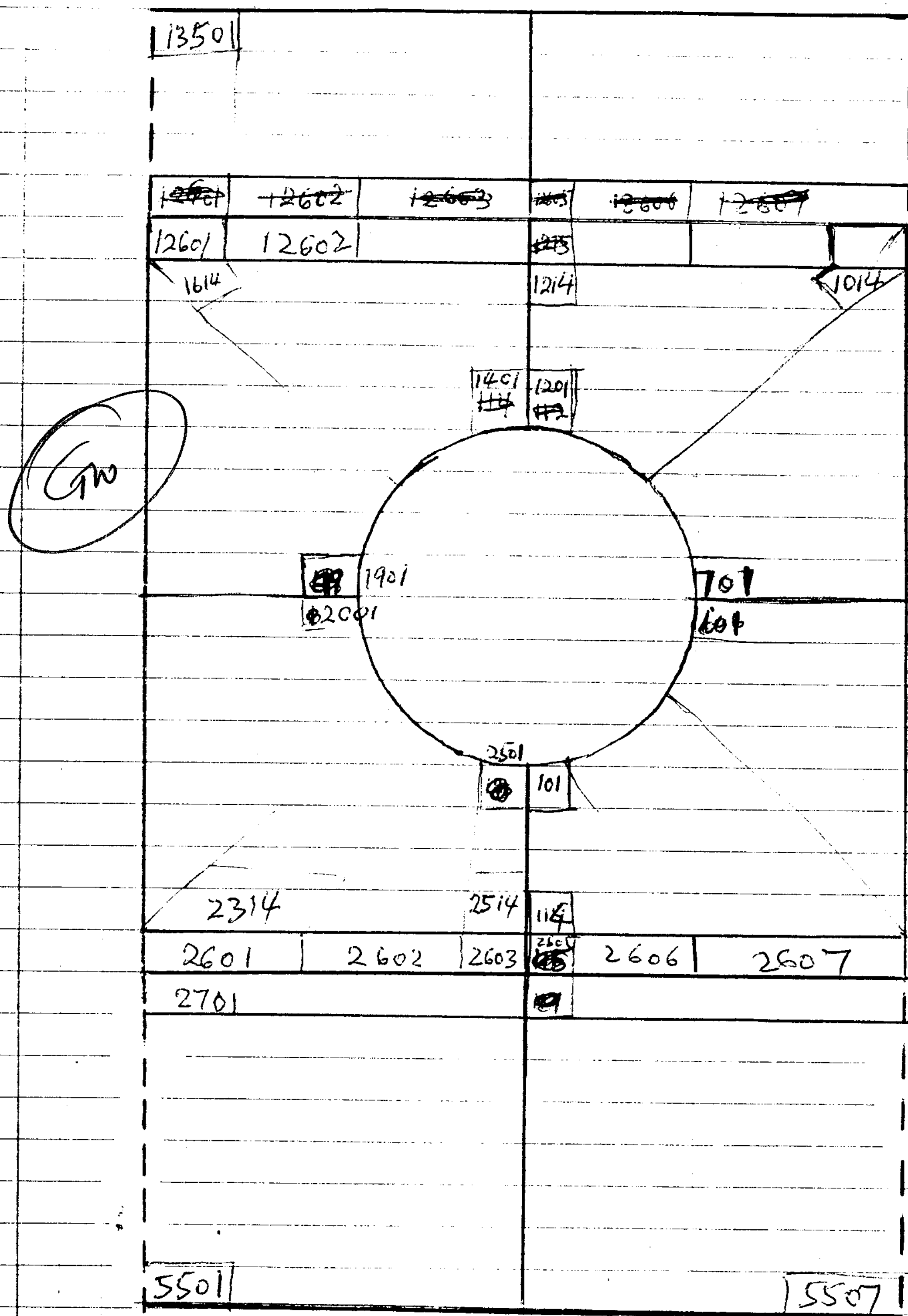
Global Model: Coordinates

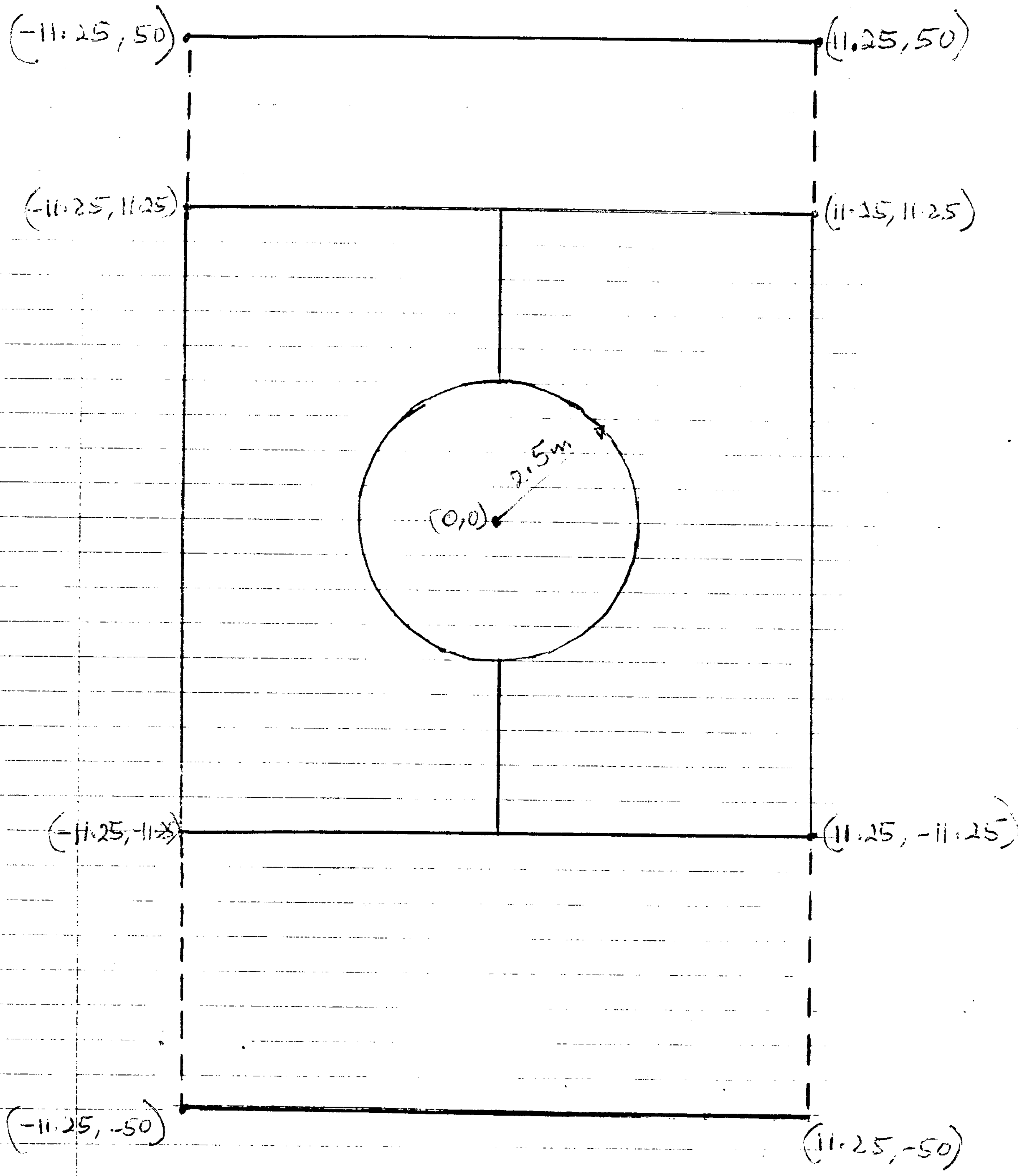


Global Model: Nodes

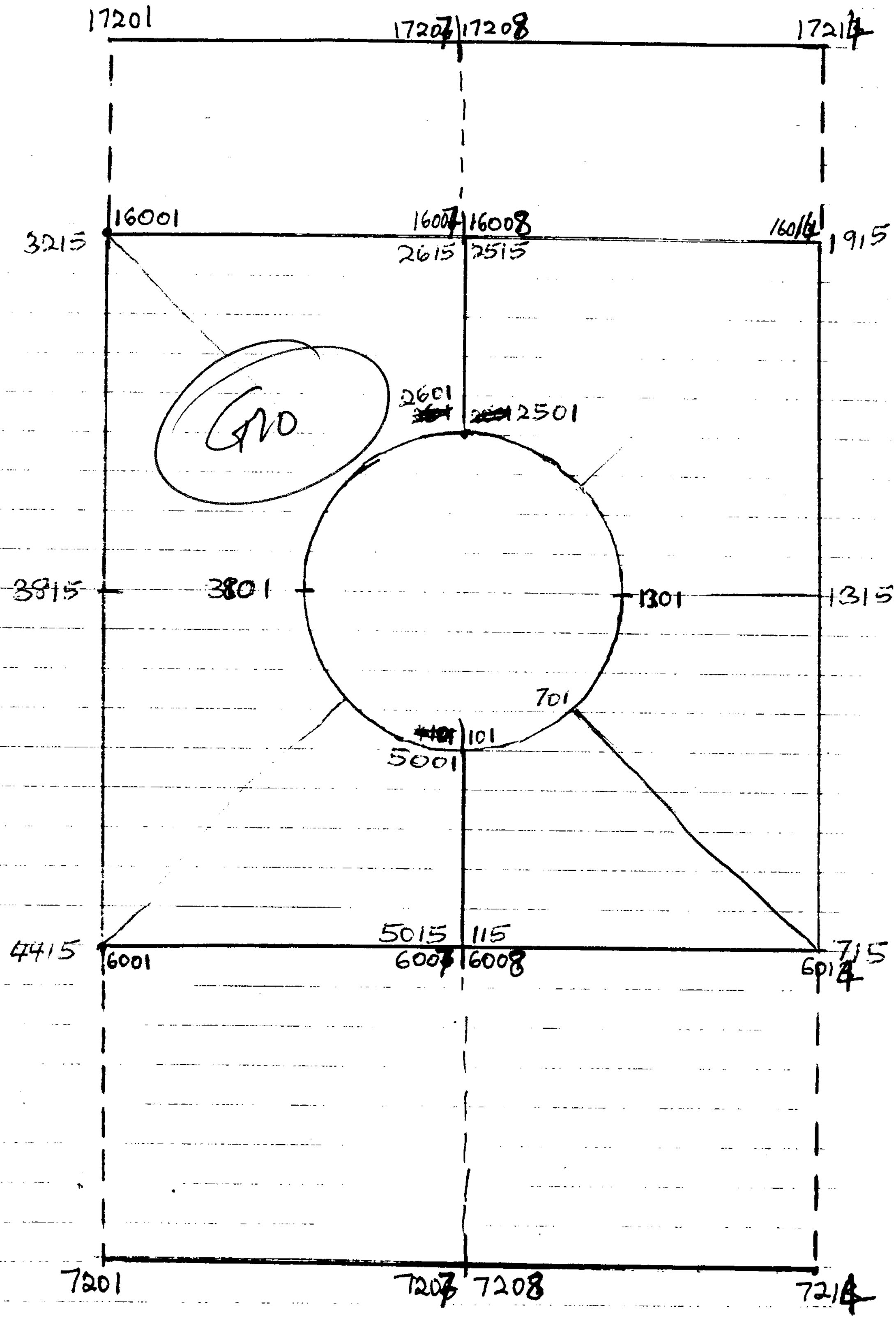


Global Model: Elements

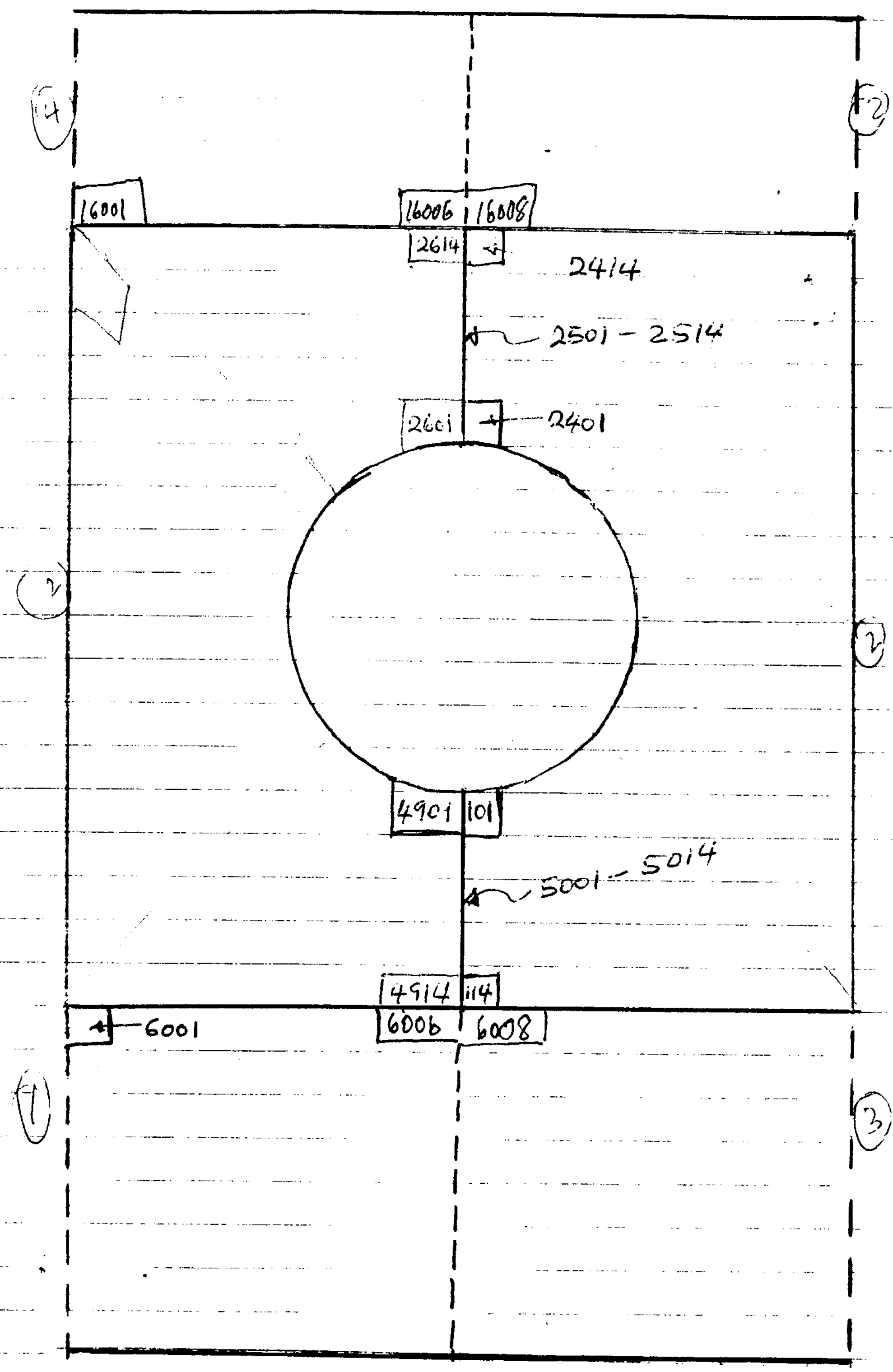



(-11.25, 50)
(11.25, 50)
(-11.25, 11.25)
(11.25, 11.25)
7.5m
(0,0)
(-11.25, -11.25)
(11.25, -11.25)
(-11.25, -50)
(11.25, -50)

Local Model: Nodes



Local Model: Elements



Thermal Analysis Steps

Step	Time at end of Step (Days)	Activity
1	1.0	Establish initial state and boundary conditions
2	3651	Apply prescribed drift-wall temperature history

Mechanical Analysis Steps

Step	Time at end of Step (days)	Activity
1	0.5	Establish initial state and boundary conditions, without drift
2	0.5	Excavate drift
3	3651	Apply temperature distribution computed in Step 2 of Thermal Analysis

Input Files

gmt.inp Thermal analysis: Global Model

gmm.inp Mechanical analysis: Global Model

smt.inp Thermal analysis: Local model
File gmt.fil must reside in same directory, and gmt must be introduced ~~at~~ as the corresponding global model

smm.inp Mechanical analysis: Local model
~~File smt.fil must~~ (GW)
File gmm.fil required, and ~~gg~~ gmm must be introduced as global model.

~~In addition, files~~ (GW)

Each thermal analysis must be completed before the corresponding mechanical analysis, and the .fil file from the ~~thermal~~ analysis must reside in the ~~at~~ same directory as the .inp file for the corresponding mechanical analysis.

Results Processing

On completion of mechanical analysis:

1. Run job in smpost.inp
2. Split file, smpost.dat, using vi text editor, into three files as follows:

   smoofrac.dat ~~Sm00Frac.dat~~ (GNO) : Pre-excavation

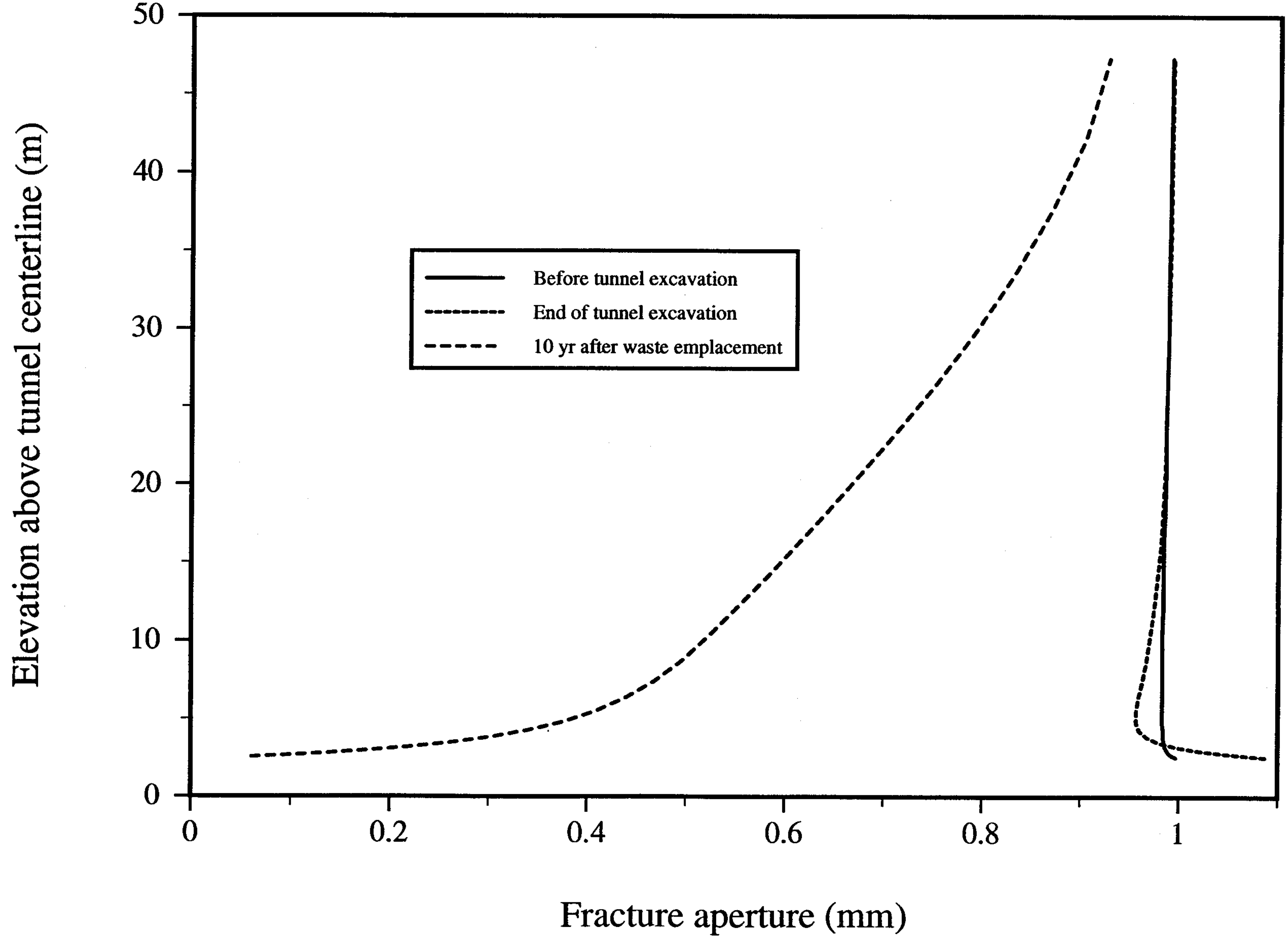
   sm01frac.dat ~~Sm01Frac.dat~~ (GNO) : End of excavation

   sm10fract.dat ~~Sm10Frac.dat~~ (GNO) 10 yrs following waste emplacement.
3. Compile c program ~~a~~ smFracAperture.c

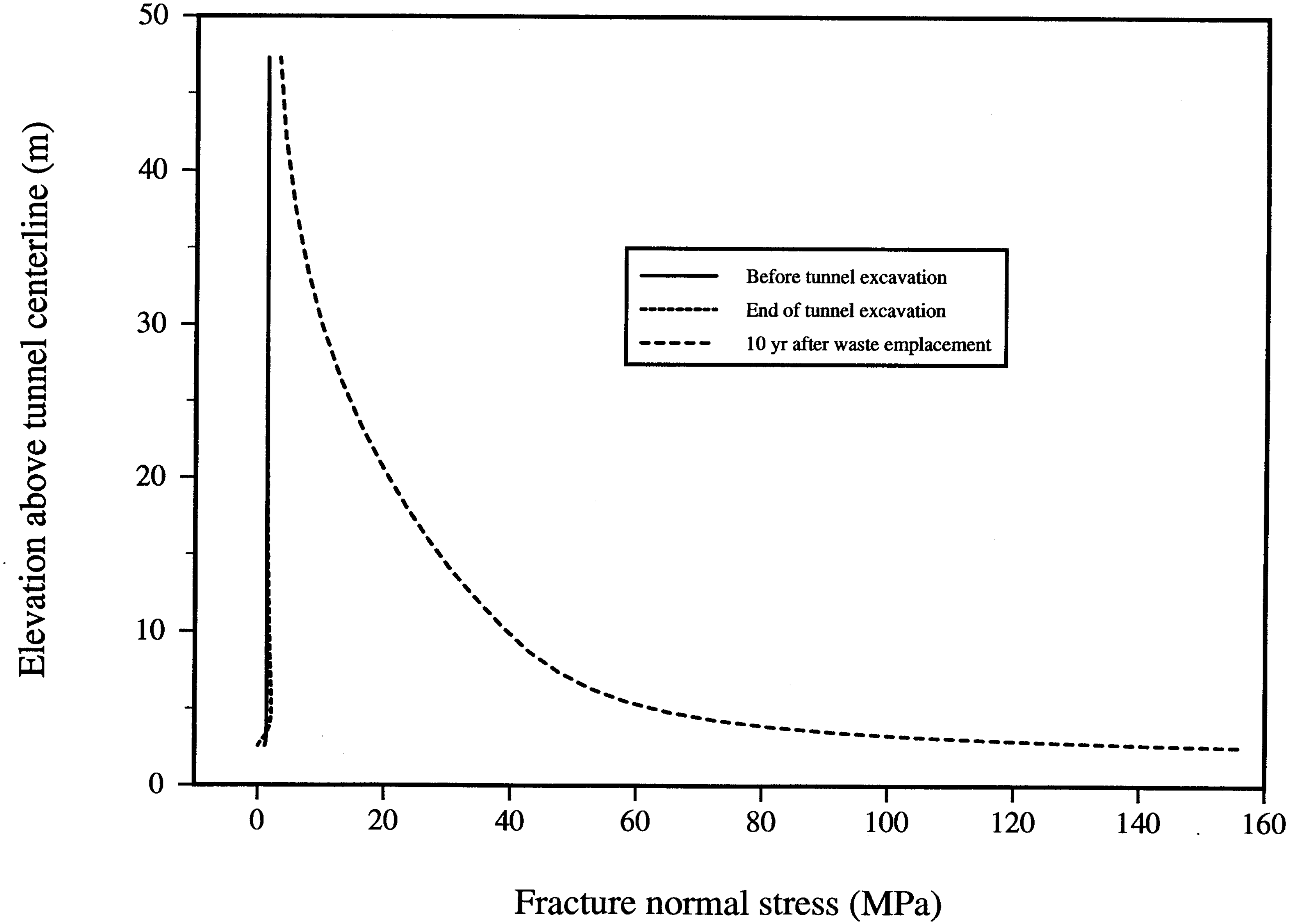
   Then execute (GNO) ~~~~ the a.out file and re-direct it's output to a ~~another~~ (GNO) file.
4. Compile and run c program smfracStress.c in the same way.

Follow Procedure (1) - (4) with "gm" substituted for "sm" in the file names, to obtain the results of the global model.

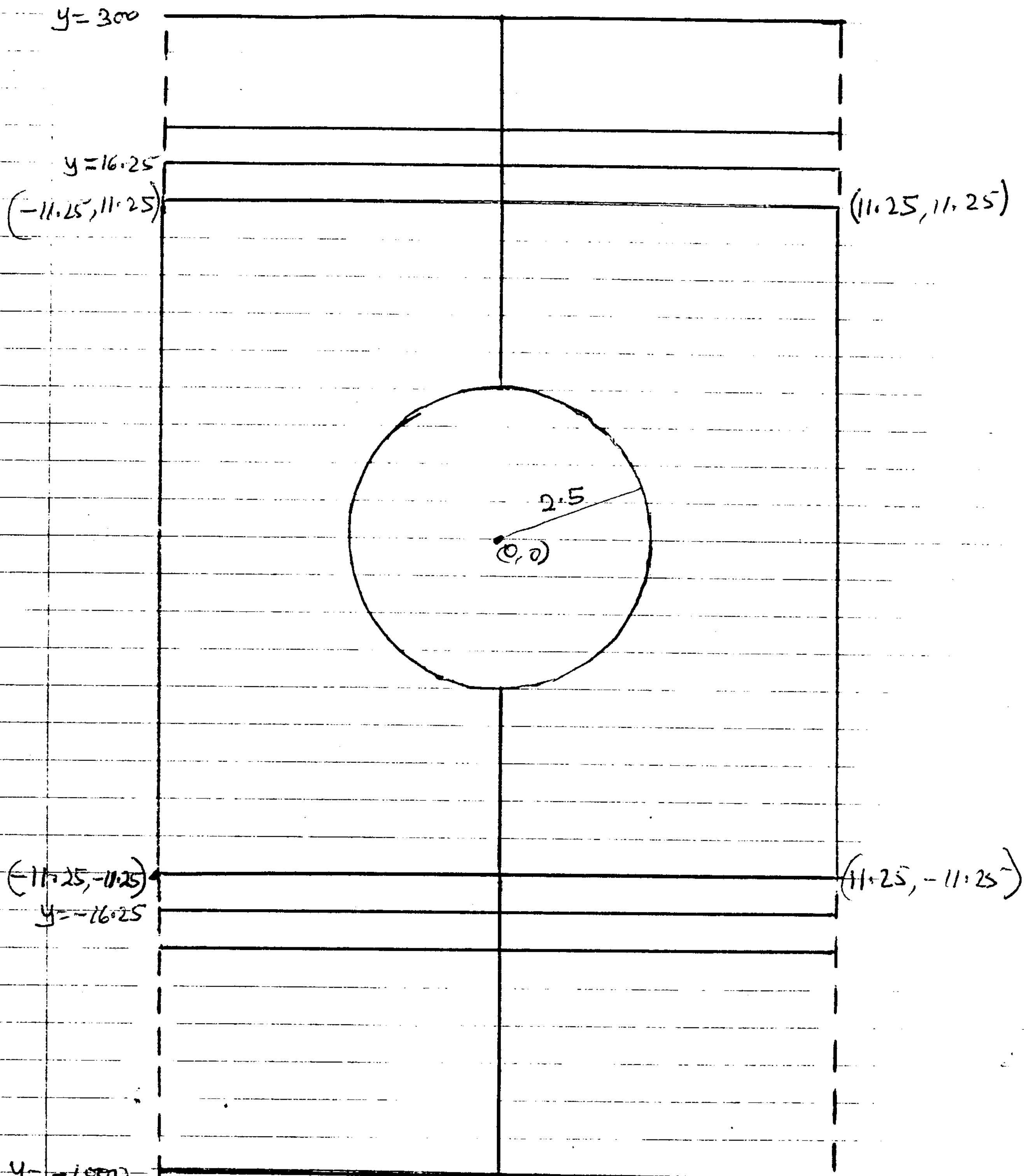
Fracture Aperture Profiles (ABAQUS 2D)



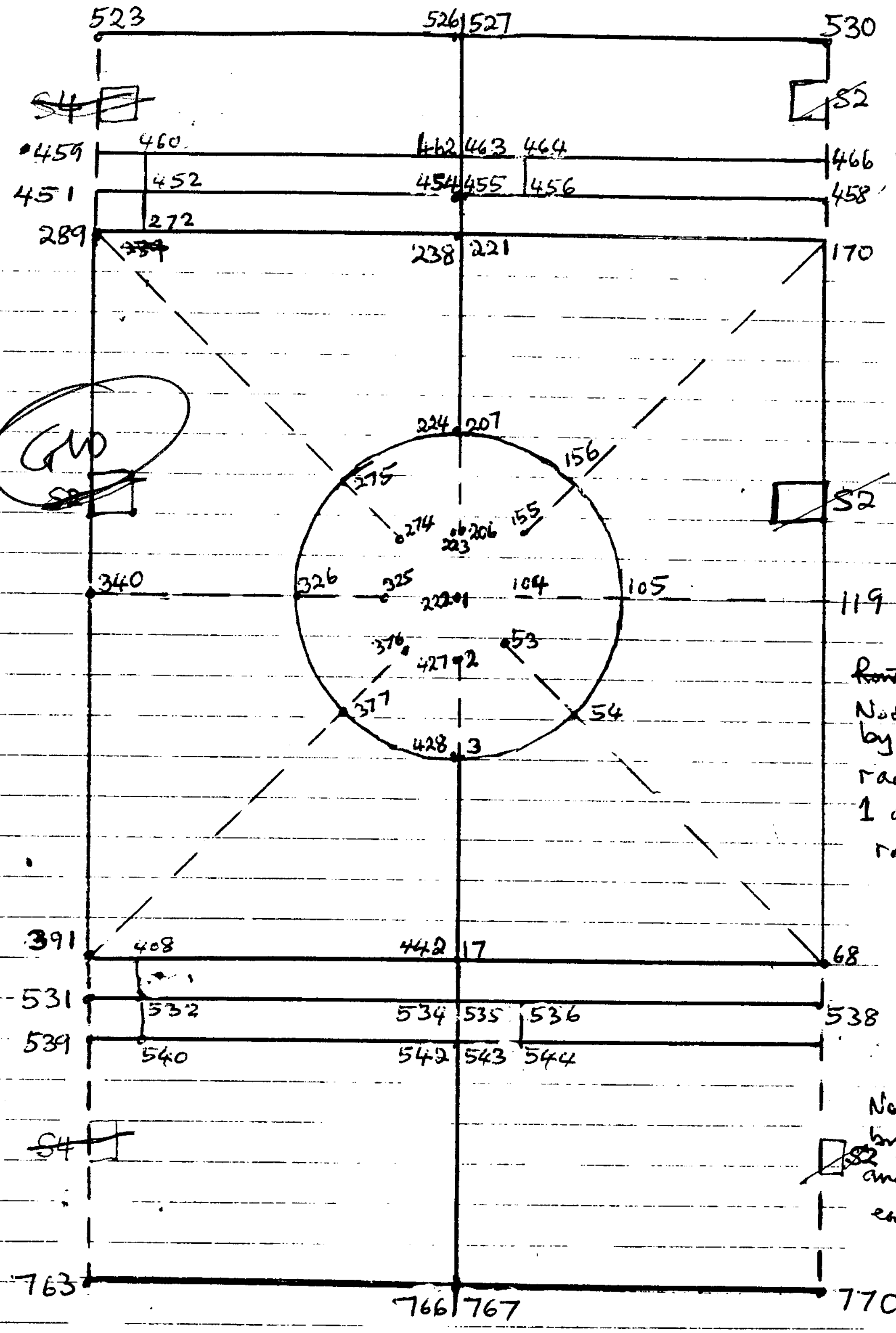
Fracture Normal-Stress Profiles (ABAQUS 2D)



3D MODEL


y=300
y=16.25
(-11.25,11.25)
(11.25,11.25)
2.5
(0,0)
(-11.25,-11.25)
(11.25,-11.25)
y=-16.25
y=-1000

Global Model; XY Plane at Z = 0; Node Numbers



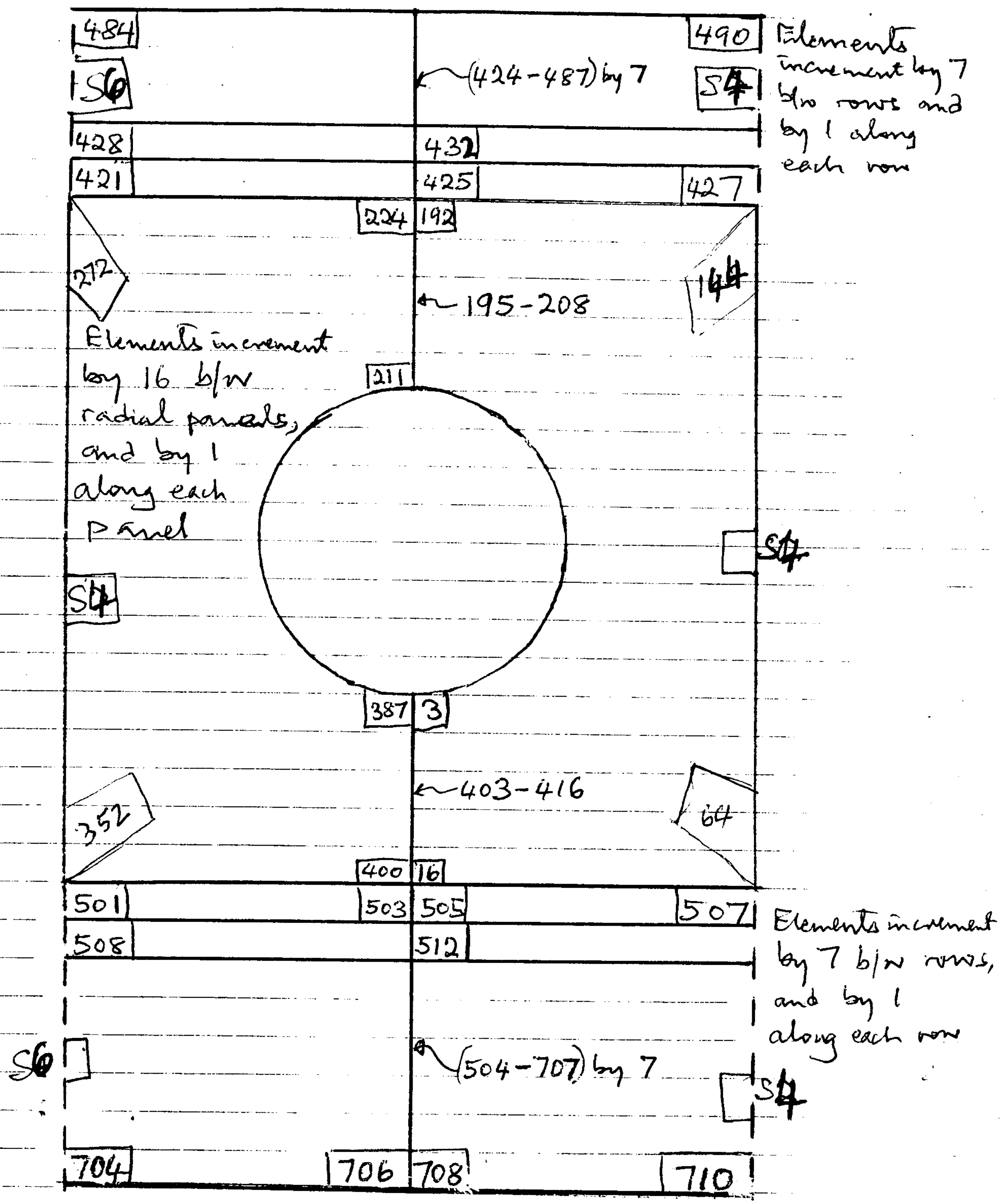
Nodes increment by 8 b/w rows, and by 1 along each row

~~Row to~~

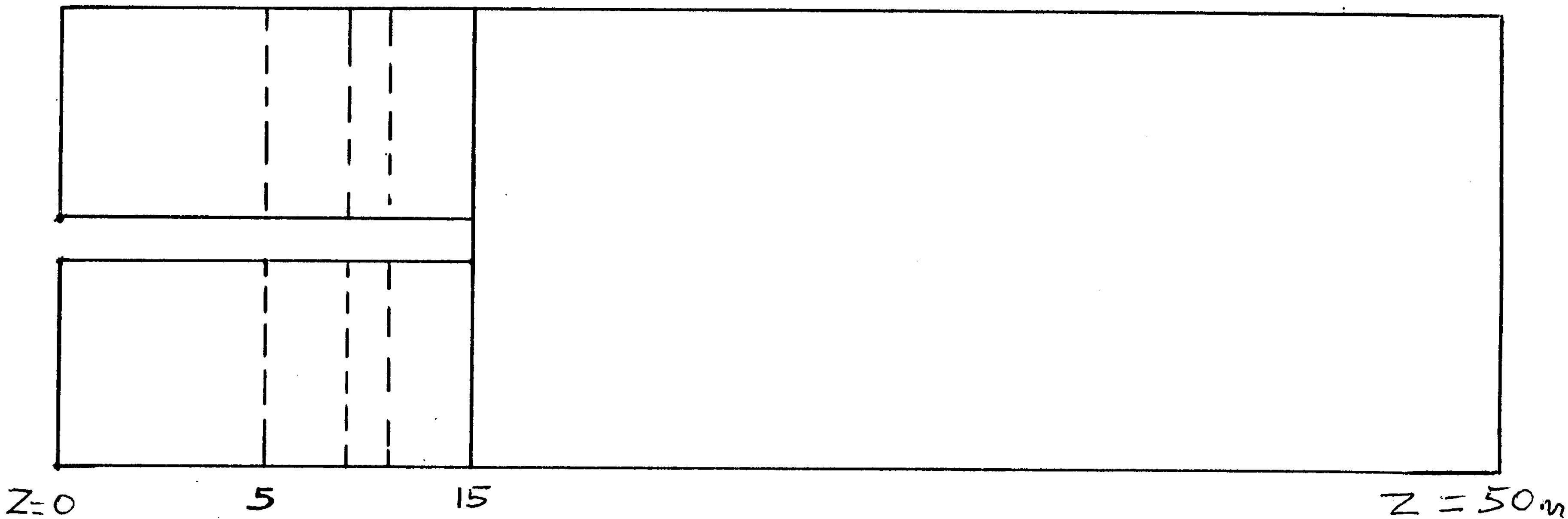
Nodes increment by 17 b/w radii, and by 1 along each radius.

Nodes increment by 8 b/w rows, and by 1 along each row

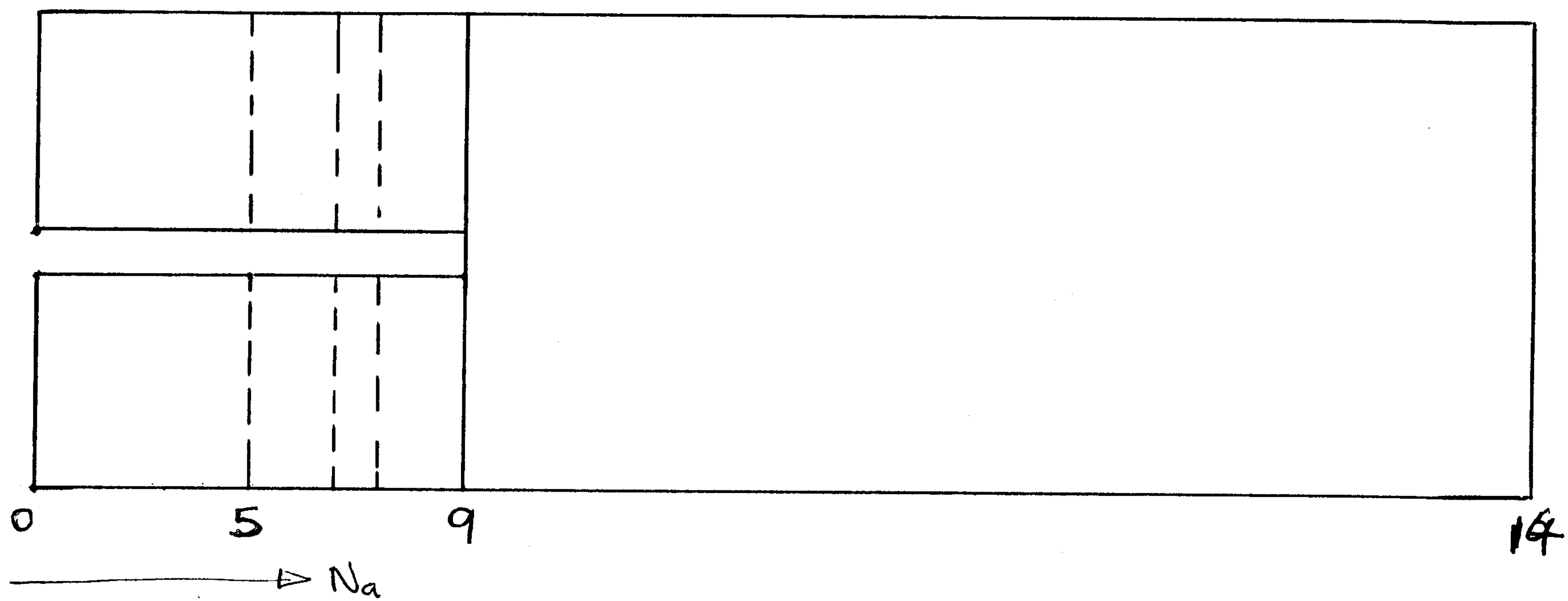
Global Model: XY Plane @ Z=0: Element Numbers



Global Model: Z-coordinates



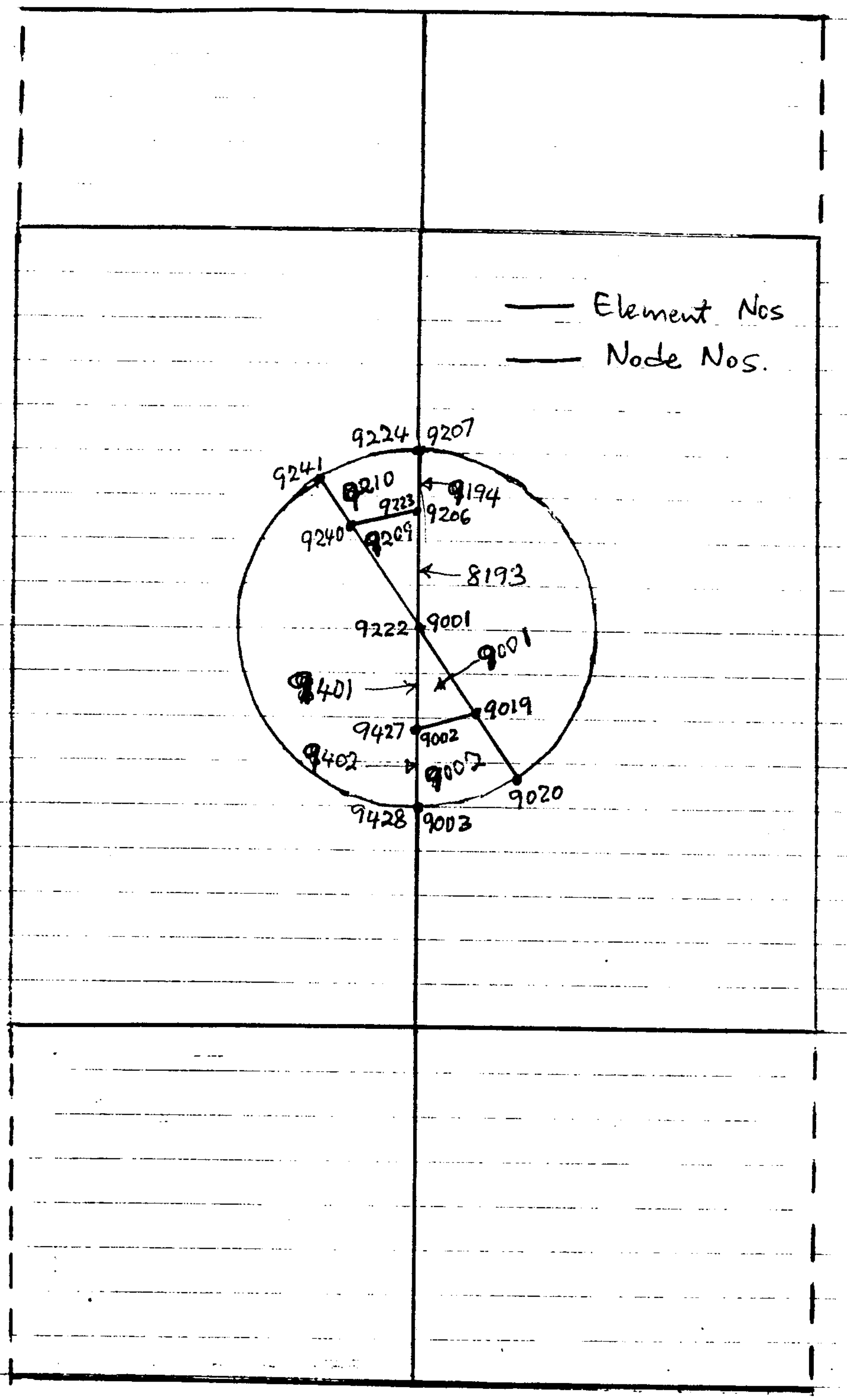
Global Model: Node Numbers Along Tunnel Axis



Node = $1000 N_a + N_{00}$

N_{00} = node numbers on Z=0 plane

Global Model: Additional Elements on Plane @ Z=15m



```
***
*** Prescribed temperature history applied at node set WPWALL
***
*NSET,NSET=WPWALL,GEN
3,428,17
1003,1428,17
2003,2428,17
3003,3428,17
4003,4428,17
5003,5428,17
***
*** Node set WALL required in mechanical analyses to specify boundary
*** conditions for the excavated surface: the nodes are fixed in Step 1
*** and released in Step 2 to simulate excavation
***
*NSET,NSET=WALL
WPWALL,
*NSET,NSET=WALL,GEN
6003,6428,17
7003,7428,17
8003,8428,17
9003,9428,17
***
*** Zero temperature-change applied at node set TOPNODES
***
*NSET,NSET=TOPNODES,GEN
523,530,1
1523,1530,1
2523,2530,1
3523,3530,1
4523,4530,1
5523,5530,1
6523,6530,1
7523,7530,1
8523,8530,1
9523,9530,1
10523,10530,1
11523,11530,1
12523,12530,1
13523,13530,1
14523,14530,1
***
*** Zero temperature-change and zero vertical displacement applied at
*** node set BASENODE
***
*NSET,NSET=BASENODE,GEN
763,770,1
1763,1770,1
2763,2770,1
3763,3770,1
4763,4770,1
5763,5770,1
6763,6770,1
7763,7770,1
8763,8770,1
9763,9770,1
10763,10770,1
11763,11770,1
12763,12770,1
13763,13770,1
14763,14770,1
***
*** Zero horizontal displacement applied at node set LEFTNODE
***
*NSET,NSET=LEFTNODE,GEN
289,391,17
1289,1391,17
2289,2391,17
3289,3391,17
4289,4391,17
5289,5391,17
6289,6391,17
7289,7391,17
8289,8391,17
9289,9391,17
10289,10391,17
11289,11391,17
12289,12391,17
13289,13391,17
14289,14391,17
459,523,8
1459,1523,8
2459,2523,8
3459,3523,8
4459,4523,8
5459,5523,8
6459,6523,8
7459,7523,8
8459,8523,8
9459,9523,8
10459,10523,8
11459,11523,8
12459,12523,8
13459,13523,8
14459,14523,8
531,763,8
1531,1763,8
2531,2763,8
3531,3763,8
4531,4763,8
5531,5763,8
6531,6763,8
7531,7763,8
8531,8763,8
9531,9763,8
10531,10763,8
11531,11763,8
12531,12763,8
13531,13763,8
14531,14763,8
***
*** Zero horizontal displacement applied at node set RIGHTNOD
***
*NSET,NSET=RIGHTNOD,GEN
68,170,17
1068,1170,17
2068,2170,17
3068,3170,17
4068,4170,17
5068,5170,17
6068,6170,17
```

```
7068,7170,17
8068,8170,17
9068,9170,17
10068,10170,17
11068,11170,17
12068,12170,17
13068,13170,17
14068,14170,17
458,530,8
1458,1530,8
2458,2530,8
3458,3530,8
4458,4530,8
5458,5530,8
6458,6530,8
7458,7530,8
8458,8530,8
9458,9530,8
10458,10530,8
11458,11530,8
12458,12530,8
13458,13530,8
14458,14530,8
538,770,8
1538,1770,8
2538,2770,8
3538,3770,8
4538,4770,8
5538,5770,8
6538,6770,8
7538,7770,8
8538,8770,8
9538,9770,8
10538,10770,8
11538,11770,8
12538,12770,8
13538,13770,8
14538,14770,8
***
*** Temperature and displacement histories will be saved at
*** node set SMBNODES, to provide information for internal definition
*** of the submodel boundary conditions
***
*NSET,NSET=SMBNODES
Z12P5NOD,Z15NODES,
*NSET,NSET=SMBNODES,GEN
475,490,1
1475,1490,1
2475,2490,1
3475,3490,1
4475,4490,1
5475,5490,1
6475,6490,1
7475,7490,1
8475,8490,1
9475,9490,1
10475,10490,1
11475,11490,1
12475,12490,1
13475,13490,1
14475,14490,1
571,586,1
1571,1586,1
2571,2586,1
3571,3586,1
4571,4586,1
5571,5586,1
6571,6586,1
7571,7586,1
8571,8586,1
9571,9586,1
10571,10586,1
11571,11586,1
12571,12586,1
13571,13586,1
14571,14586,1
***
*** Zero normal heat flux applied on face 4 of element set S4RIGHT
*** Face 4 of these elements collected into surface named RLVIEW for
*** longitudinal view of results
***
*ELSET,ELSET=S4RIGHT,GEN
64,144,16
1064,1144,16
2064,2144,16
3064,3144,16
4064,4144,16
5064,5144,16
6064,6144,16
7064,7144,16
8064,8144,16
9064,9144,16
10064,10144,16
11064,11144,16
12064,12144,16
13064,13144,16
427,490,7
1427,1490,7
2427,2490,7
3427,3490,7
4427,4490,7
5427,5490,7
6427,6490,7
7427,7490,7
8427,8490,7
9427,9490,7
10427,10490,7
11427,11490,7
12427,12490,7
13427,13490,7
507,710,7
1507,1710,7
2507,2710,7
3507,3710,7
4507,4710,7
5507,5710,7
6507,6710,7
7507,7710,7
8507,8710,7
9507,9710,7
10507,10710,7
11507,11710,7
```

```
12507,12710,7
13507,13710,7
***
*** Zero normal heat flux applied on face 4 of element set S4LEFT
***
*ELSET,ELSET=S4LEFT,GEN
272,352,16
1272,1352,16
2272,2352,16
3272,3352,16
4272,4352,16
5272,5352,16
6272,6352,16
7272,7352,16
8272,8352,16
9272,9352,16
10272,10352,16
11272,11352,16
12272,12352,16
13272,13352,16
***
*** Zero normal heat flux applied on face 6 of element set S6LEFT
***
*ELSET,ELSET=S6LEFT,GEN
421,484,7
1421,1484,7
2421,2484,7
3421,3484,7
4421,4484,7
5421,5484,7
6421,6484,7
7421,7484,7
8421,8484,7
9421,9484,7
10421,10484,7
11421,11484,7
12421,12484,7
13421,13484,7
501,704,7
1501,1704,7
2501,2704,7
3501,3704,7
4501,4704,7
5501,5704,7
6501,6704,7
7501,7704,7
8501,8704,7
9501,9704,7
10501,10704,7
11501,11704,7
12501,12704,7
13501,13704,7
```

(Same as for 2D model)

Thermal Analysis Steps

Step	Time at end of Step (Days)	Activity
1	1.0	Establish initial state and boundary conditions
2	3651	Apply prescribed drift-wall temperature history

Mechanical Analysis Steps

Step	Time at end of Step (days)	Activity
1	0.5	Establish initial state and boundary conditions, without drift
2	0.5	Excavate drift
3	3651	Apply temperature distribution computed in Step 2 of Thermal Analysis

Input Files

g3mt.inp — Thermal analysis

g3mm.inp — Mechanical analysis

~~(File g3mt.fil required)~~

Following files required in the same directory as g3mm.inp, in order to run the mechanical analysis

① g3mt.fil — contains temperature output from thermal analysis

② Sigini.f — FORTRAN code for the computation of initial stresses.

To view a transverse section

~~To get a transverse view~~

*DETAIL, ELSET=ALLELEMENTS, MAX=(11.25, Y_{max}, Z_{max}), MIN=(-11.25, Y_{min}, Z_{min})

Suggested: ① $Y_{min} = -50$

$Y_{max} = 50$

Then set Z_{min} and Z_{max} to include only one Z-layer of elements.

② Use ELSET=BODY to exclude fracture elements from the DETAIL.

To view a longitudinal section along tunnel axis

*DETAIL, ELSET=BODY, MAX=(0, Y_{max}, 50), MIN=(-0.25, Y_{min},

*VIEW, VIEWPOINT=(-1,0,0), UP=(0,1,0)

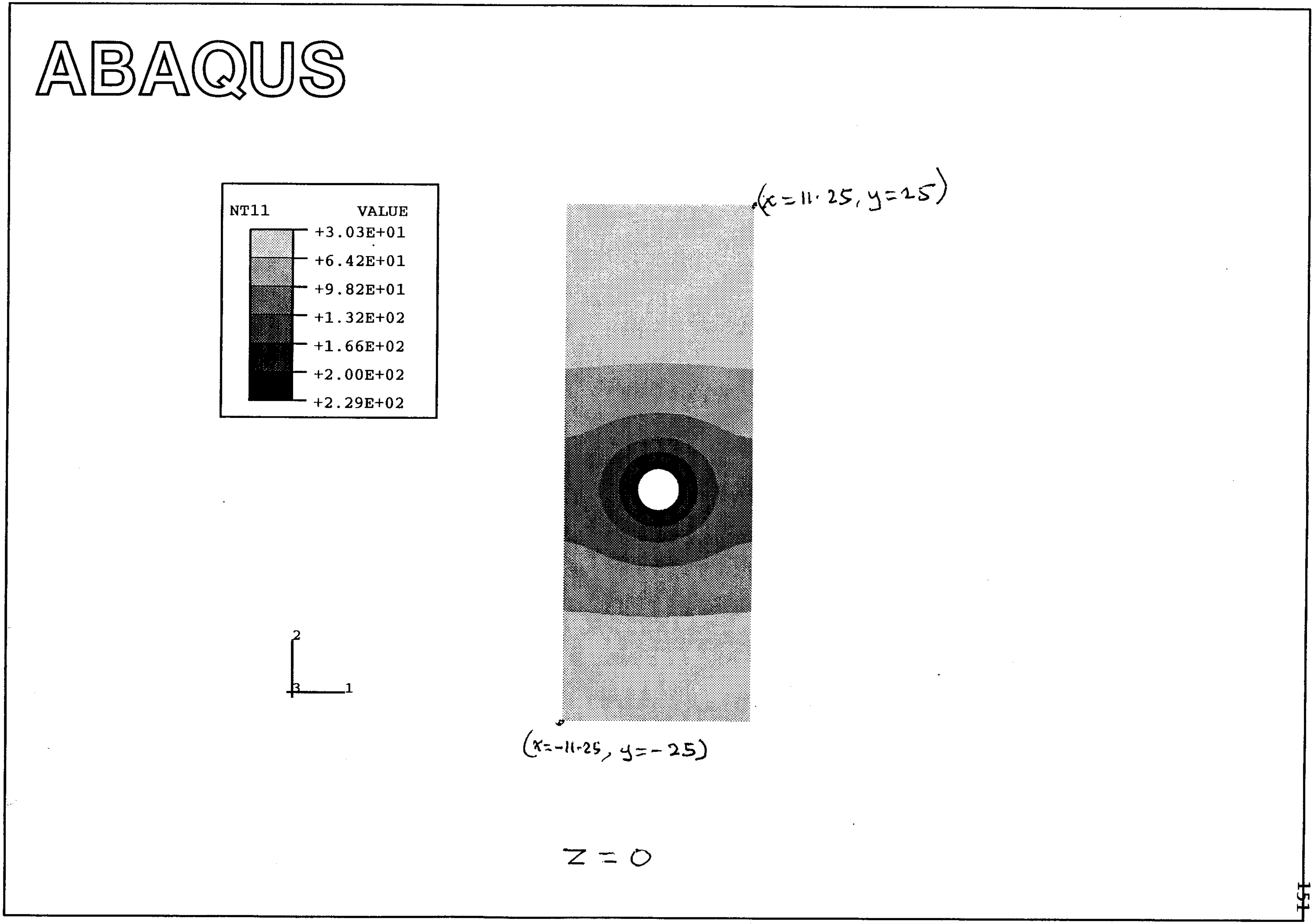
Suggestion ① Y_{min}=-25, Y_{max}=25

② Set ELSET=ALLELEMENTS to include fracture elements.

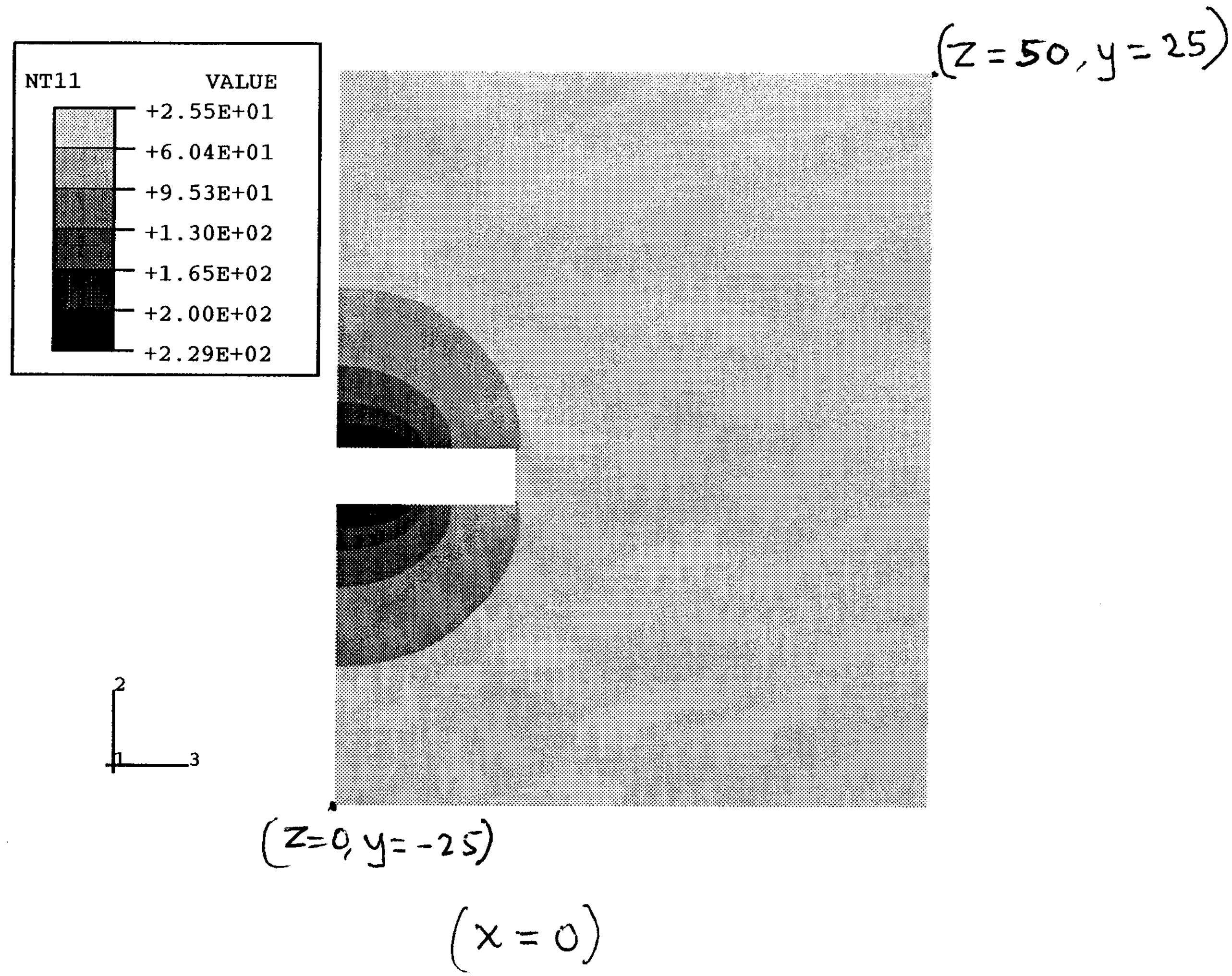
To view longitudinal section along X=11.25

*DETAIL, ELSET=~~[struck out]~~ S4RIGHT, (GW) MAX = (11.5, y_{max}, 50),
MIN = (0, y_{min}, 0).

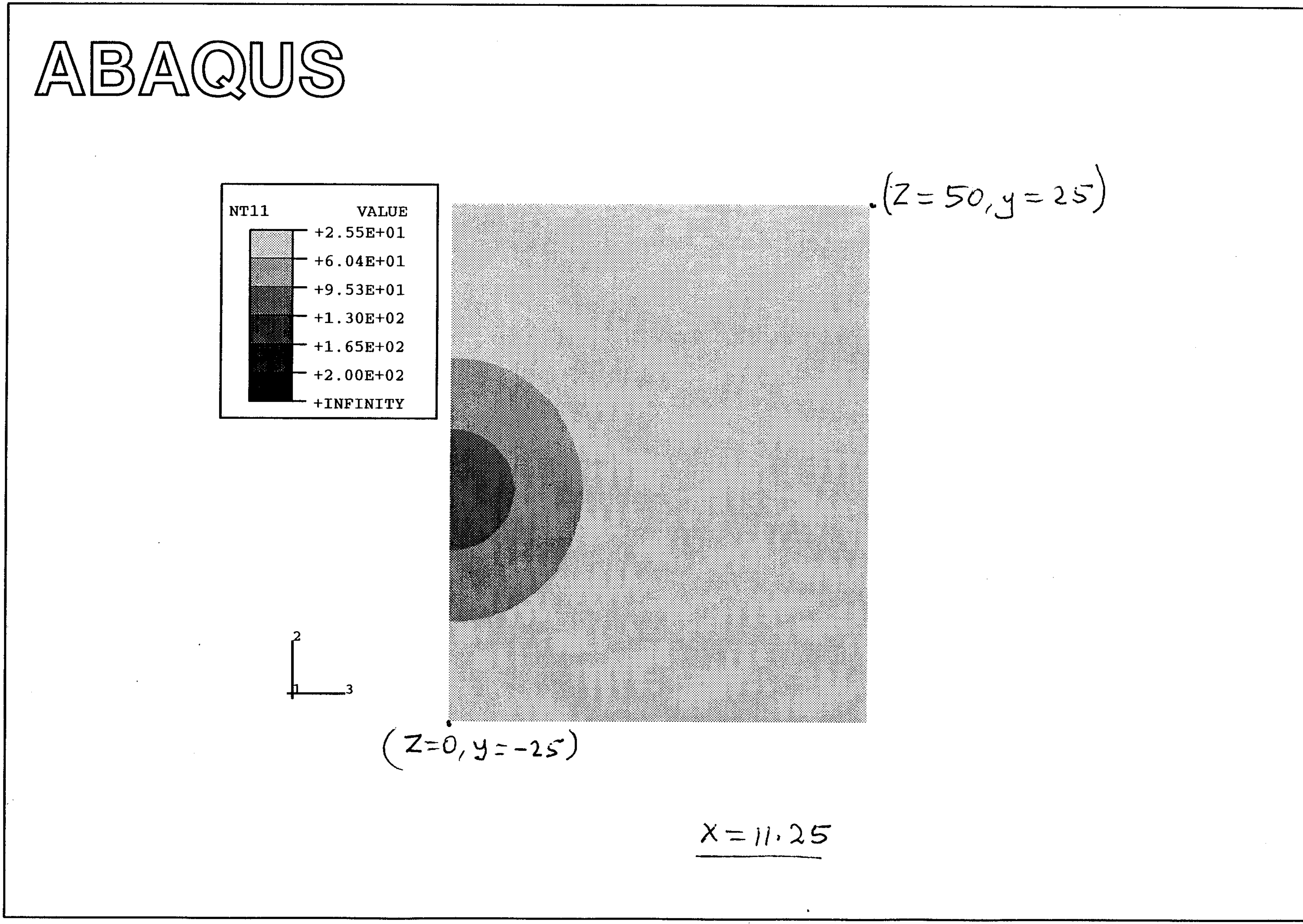
The next three contour
plots are produced by
running the ~~jnl~~ ABAQUS command
file tContours.jnl from a POST
session on g3mt.res


ABAQUS
NT11
VALUE
+3.03E+01
+6.42E+01
+9.82E+01
+1.32E+02
+1.66E+02
+2.00E+02
+2.29E+02
(x=11.25, y=25)
(x=-11.25, y=-25)
2
3
1
Z = 0

ABAQUS



NT11 VALUE
+2.55E+01
+6.04E+01
+9.53E+01
+1.30E+02
+1.65E+02
+2.00E+02
+2.29E+02
(z = 50, y = 25)
(z=0, y= -25)
(x = 0)
2
1
3


ABAQUS
NT11
VALUE
+2.55E+01
+6.04E+01
+9.53E+01
+1.30E+02
+1.65E+02
+2.00E+02
+INFINITY
2
1
3
(Z = 50, y = 25)
(Z=0, y=-25)
X = 11.25

May 08 '95

~~File estimate~~ (initials)

(1) File-size estimates by ABAQUS indicate that the mechanical analysis model requires about 594 MB of disk space for the temporary and restart files.

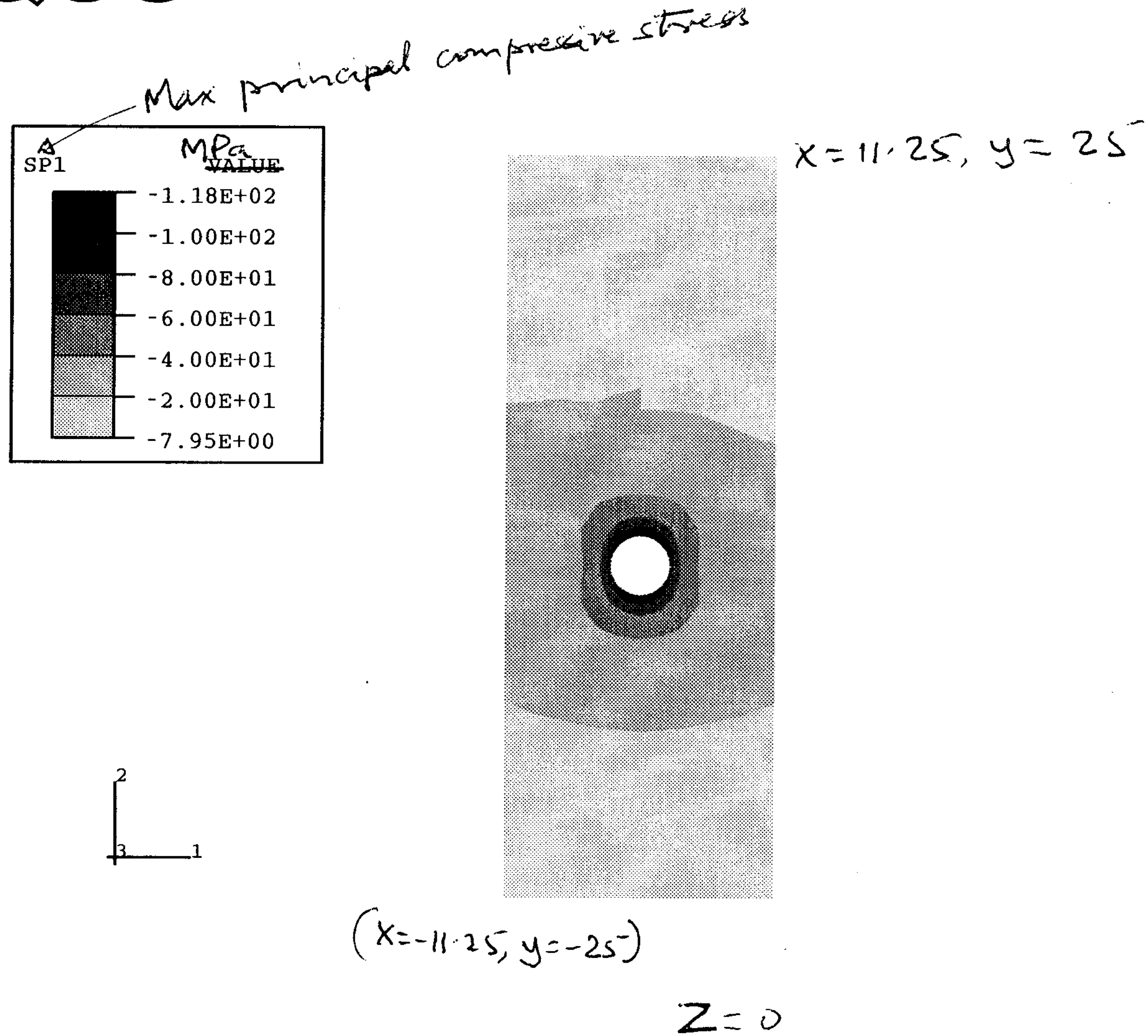
My partition ~~of~~ on the Performer has 548 Mb.

∴ 2 Z-layers were removed (the number of element layers between Z=15 and Z=50 m was reduced from 5 to 2).

(2) Mech-analysis model failed to converge in Step 1, because of frictional-contact chattering. "*FRICTION" command was disabled ~~deleted~~ to correct the ~~problem in~~ problem. This is okay, because there is no shear stress on the fracture surface in this problem

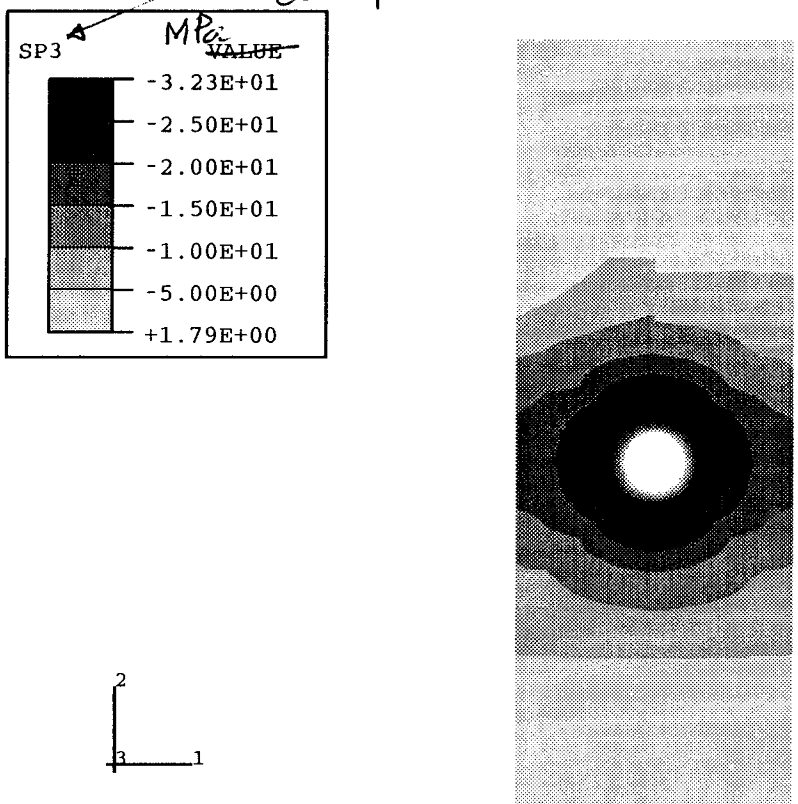
The next 6 contour plots
can be obtained by running the
file sContours.jnl from within an ABAQUS
Post session on g3mm.res

ABAQUS


Max principal compressive stress
SP1
MPa
VALUE
-1.18E+02
-1.00E+02
-8.00E+01
-6.00E+01
-4.00E+01
-2.00E+01
-7.95E+00
x = 11.25, y = 25
(x = -11.25, y = -25)
Z = 0
2
3
1

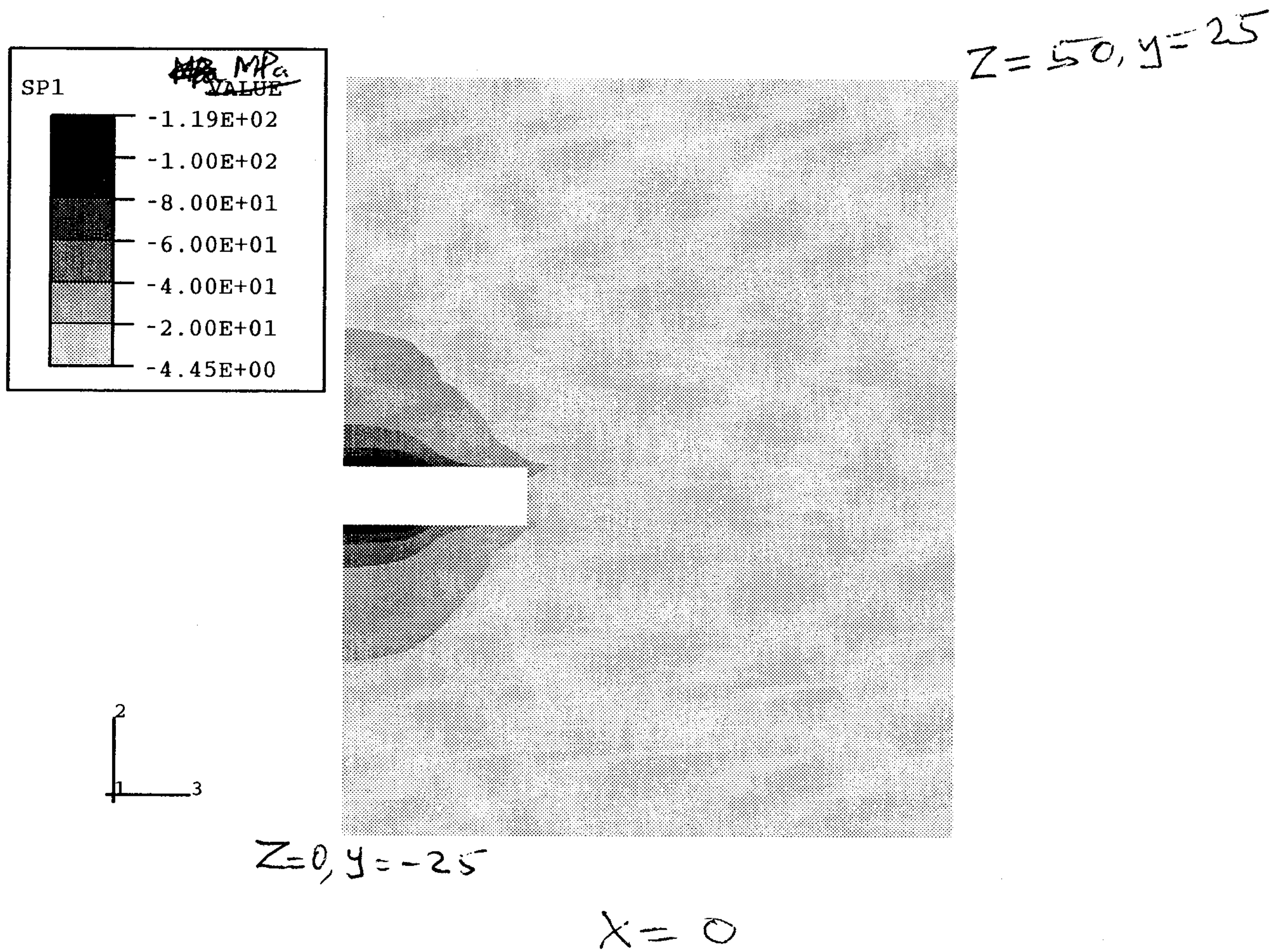
ABAQUS

Minimum principal compressive stress



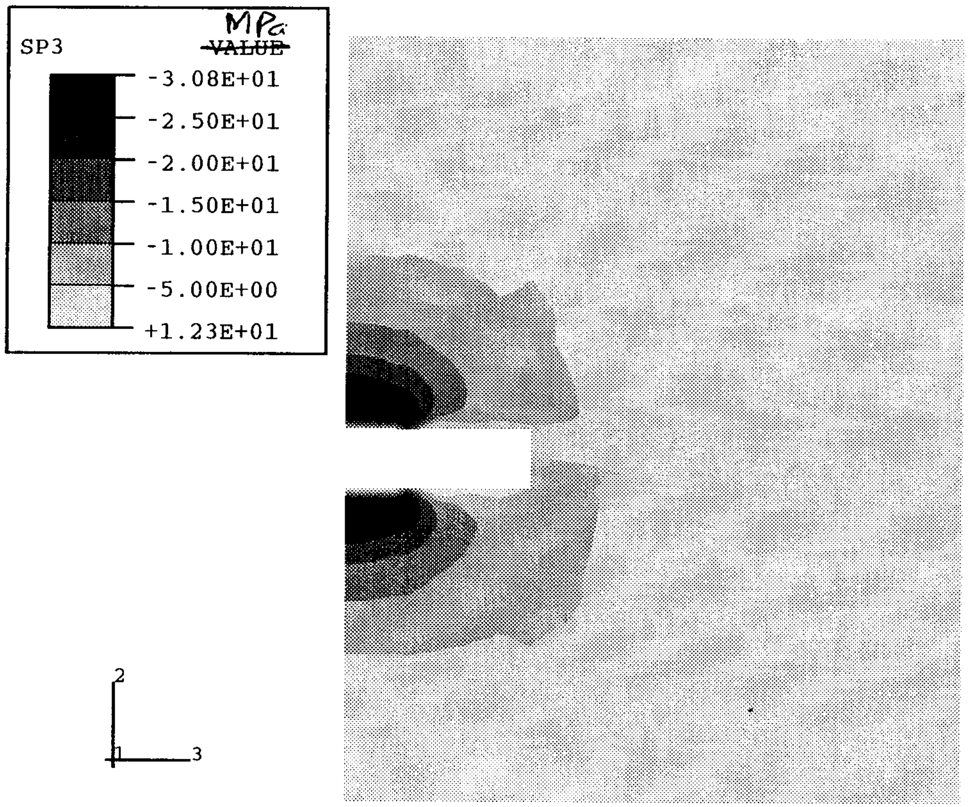
Same section as on previous page

ABAQUS



SP1
MPa
VALUE
-1.19E+02
-1.00E+02
-8.00E+01
-6.00E+01
-4.00E+01
-2.00E+01
-4.45E+00
Z=50, y=25
2
1
3
Z=0, y=-25
x=0

ABAQUS

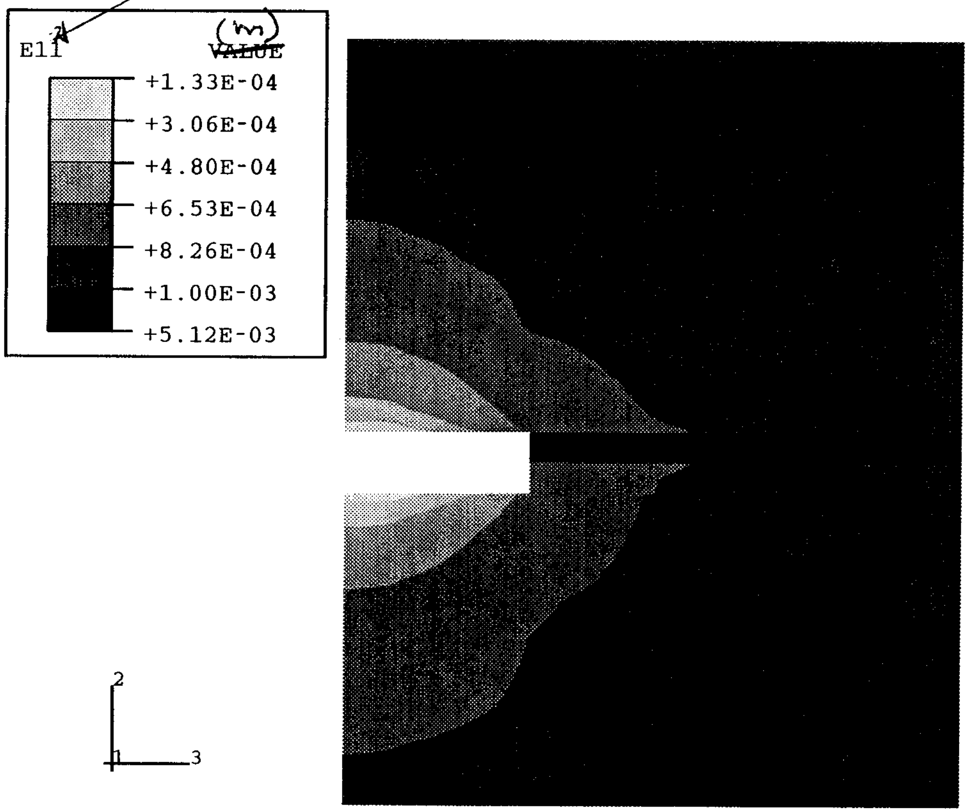


Same section as on previous page

ABAQUS

fracture Aperture

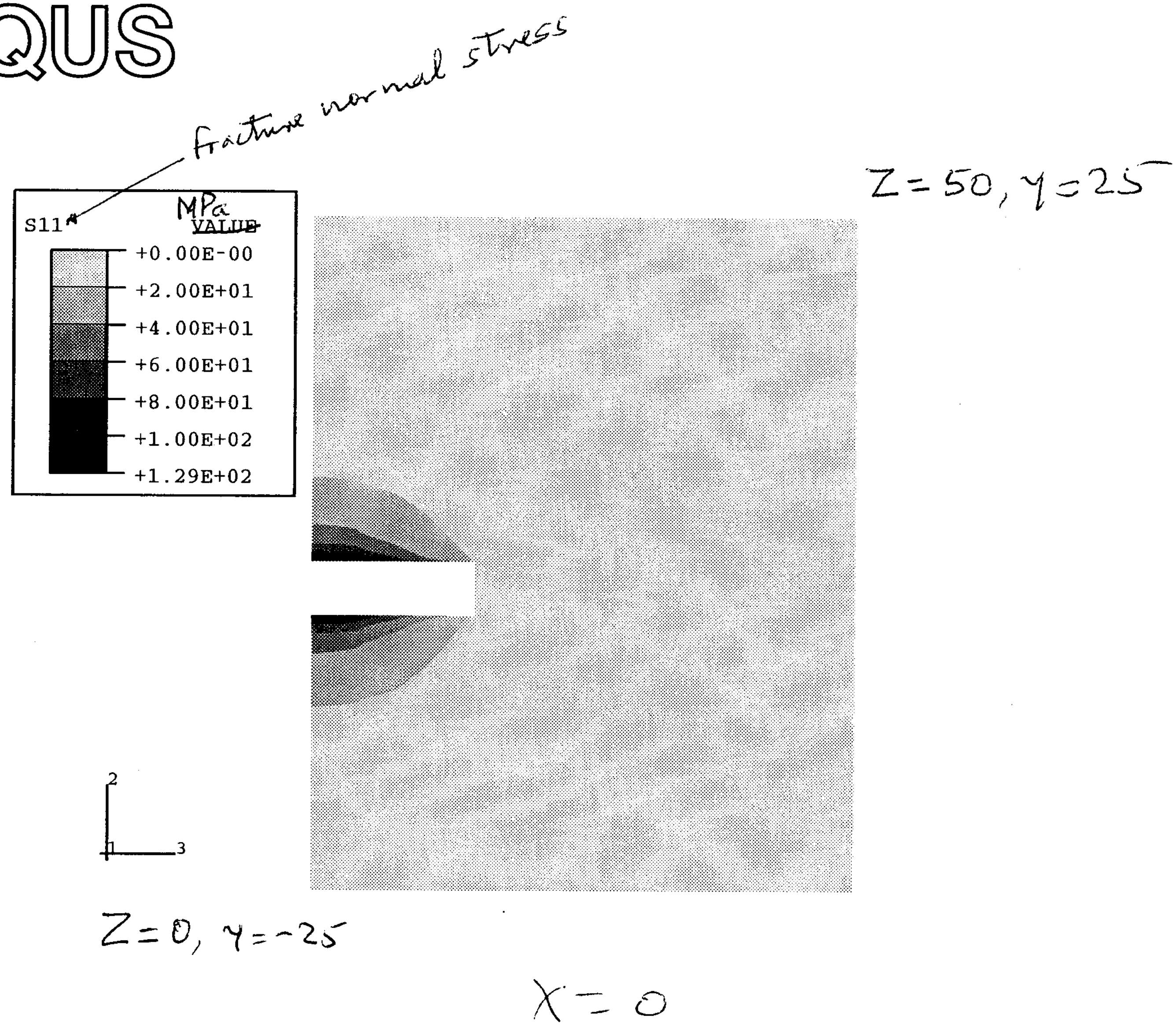
Z=50, y=25



Z=0, y=-25

X=0

ABAQUS



fracture normal stress
S11
MPa
VALUE
+0.00E-00
+2.00E+01
+4.00E+01
+6.00E+01
+8.00E+01
+1.00E+02
+1.29E+02
Z=50, Y=25
2
1
3
Z=0, Y=-25
X=0

① Run job fspost.inp on g3mm.res to obtain printout of fracture aperture and normal stress for fracture elements above tunnel axis and closest to z=0.

② Split fspost.dat into 3 files ~~files~~ (described below) using vi editor.

gm3400Frac.dat ~~file~~ - - - Step1 results

gm3401Frac.dat ~~file~~ - - - Step2 results

gm3410frac.dat ~~file~~ - - - Step3 results

③ Compile and run the C code FracStress.c and redirect its output ~~and FracAperture.c~~ to an external file (e.g. FracStress.dat)

~~④ This C code~~

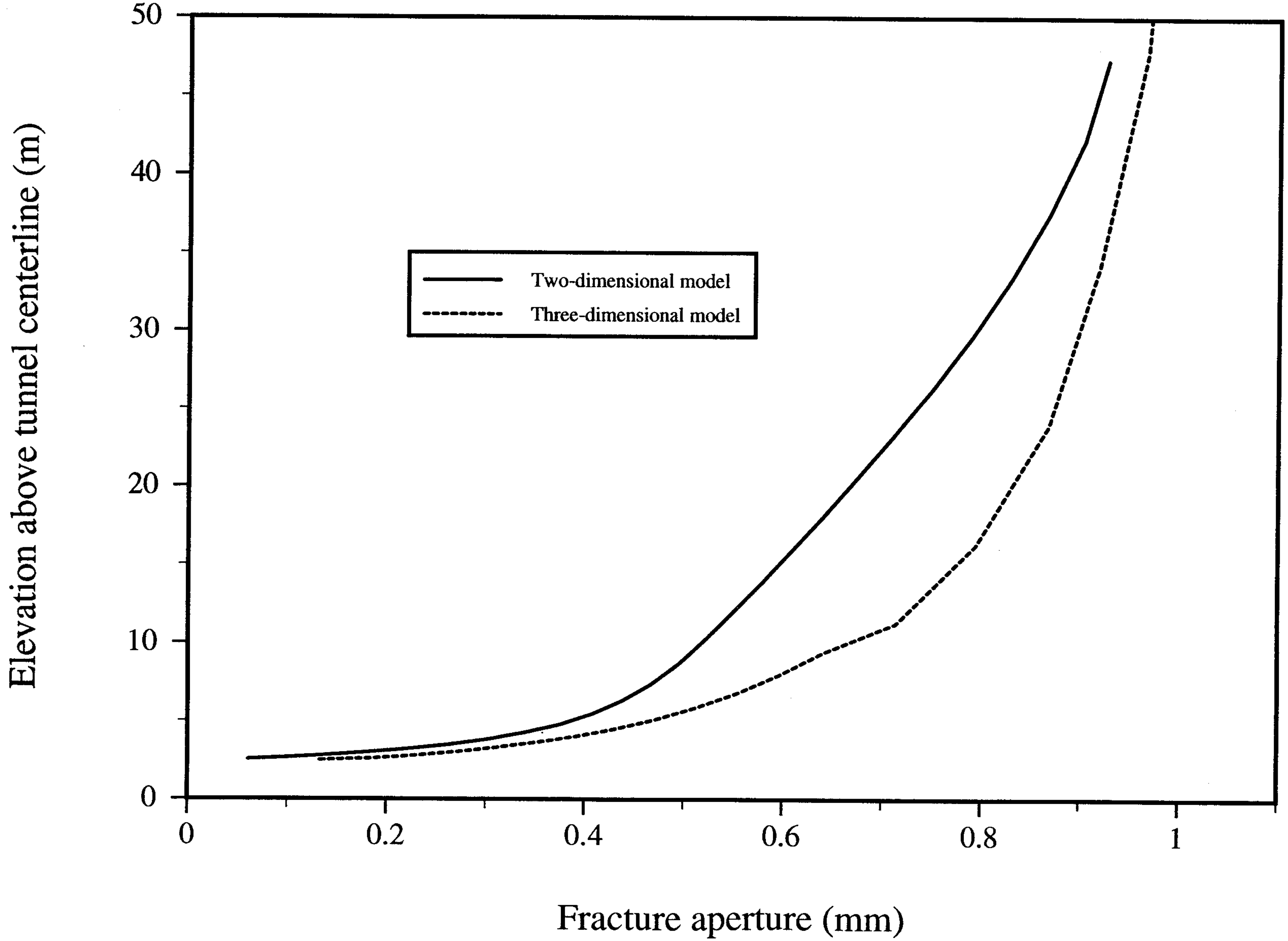
④ Do the same for the code fracAperture.c

⑤ The results tabulated in the files obtained in steps 3 and 4 can be plotted using xplot, as follows:

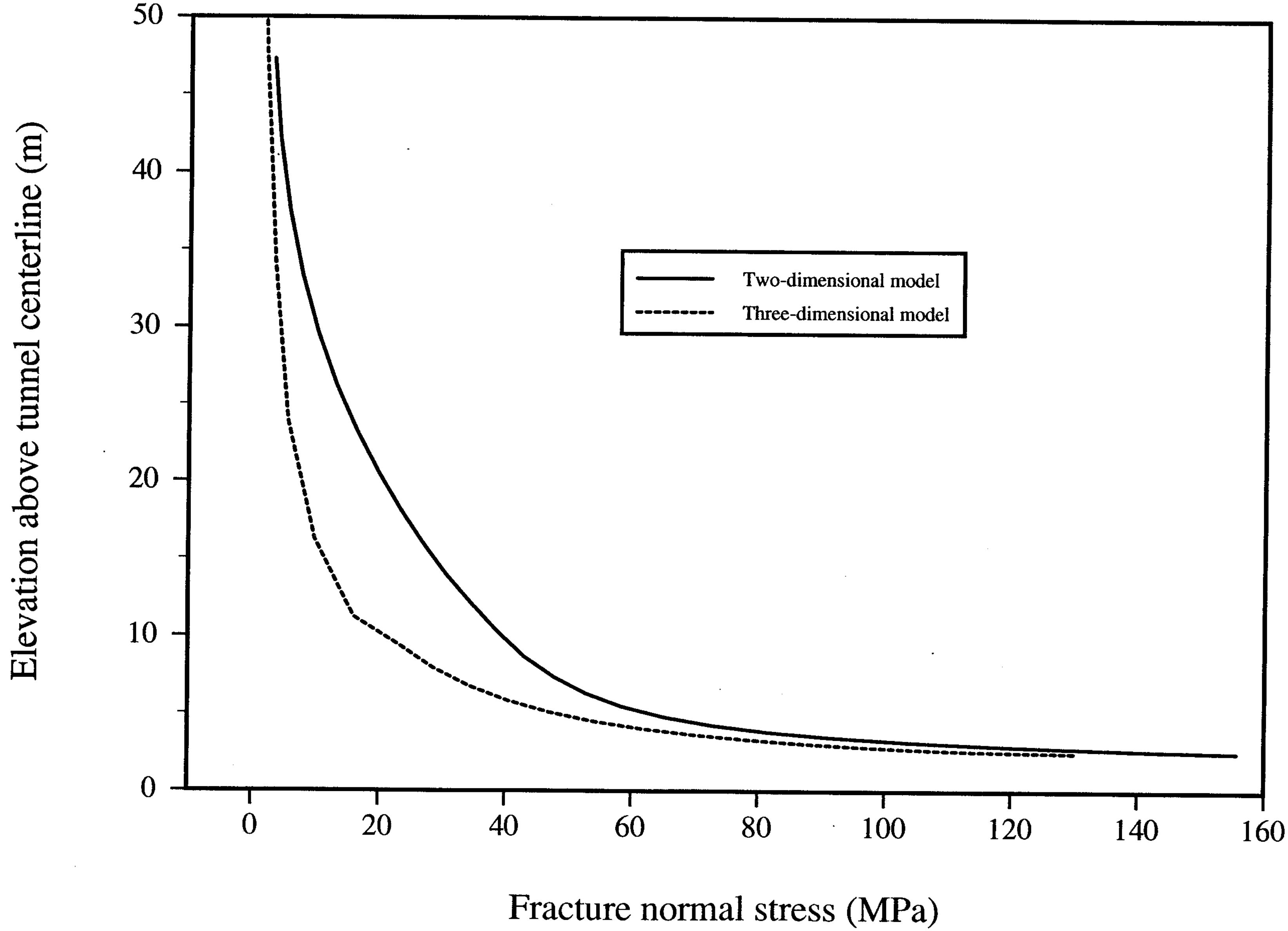
GWO ~~XPLOT~~ XPLOT Batch File	Results plotted
FracAperture.xpb	Fracture aperture profiles
FracStress.xpb	Fracture normal-stress profiles
ApertureCompare.xpb	Comparison of aperture profiles ~~based on~~ from (GWO) 2D and 3D models.
FStrsCompare.xpb (GWO)	Comparison of stress profiles from 2D and 3D models

Plots are shown in next 4 pages

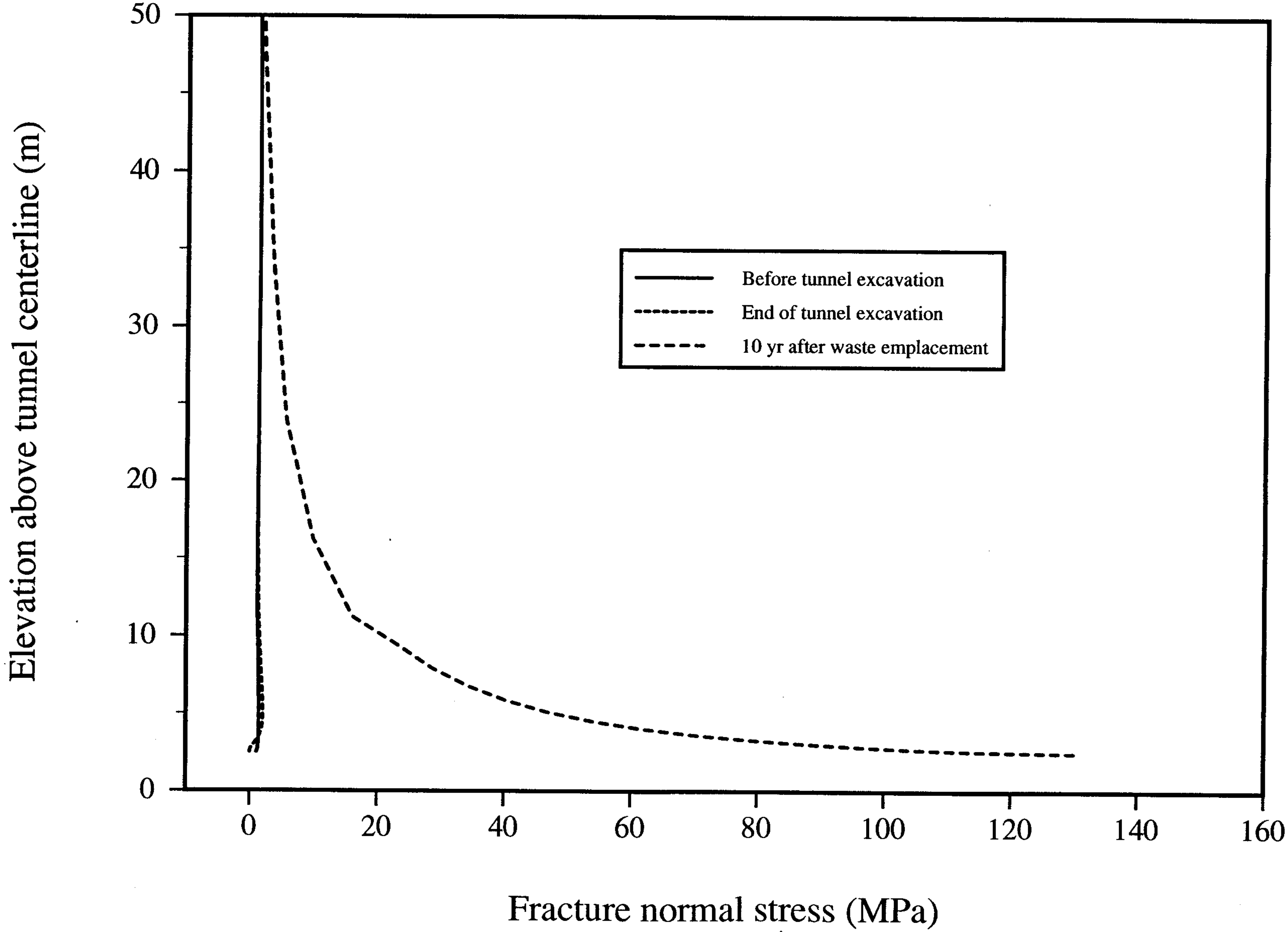
MidPlane Fracture Aperture Profiles



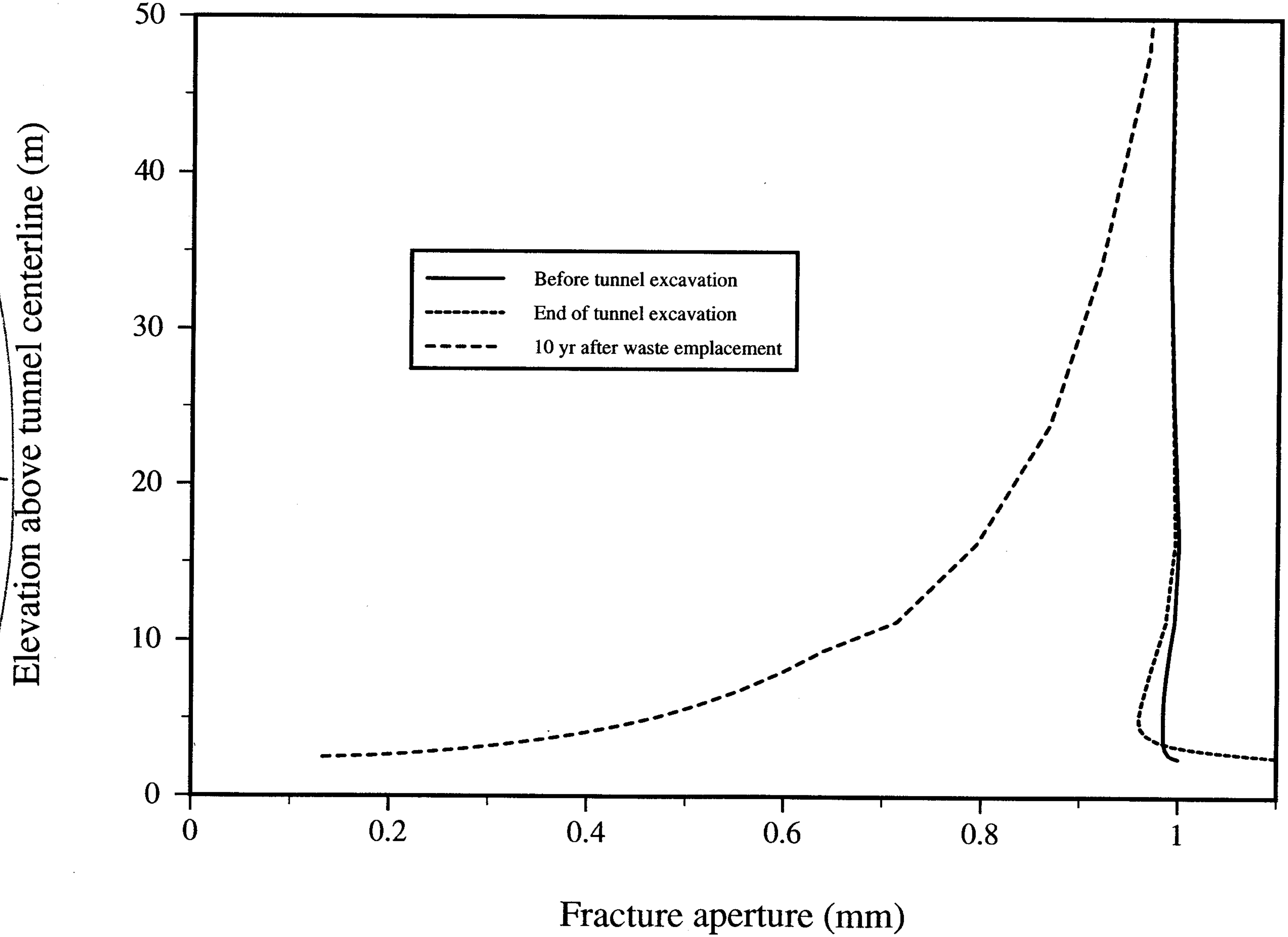
MidPlane Fracture Normal-Stress Profiles



MidPlane Fracture Normal-Stress Profiles (ABAQUS 3D)



MidPlane Fracture Aperture Profiles (ABAQUS 3D)



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