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Scientific Notebook No. 183: Finite Element Simulaton of Slip on Bare Mountain Fault-- Effects on Seismicity Assessment for the Proposed Yucca Mountain Repository Sites (02/19/1996 through 07/15/1999)

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Goodluck OFOEGBU

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Contents

Page

Initial Entry 1
Description of Technical Procedure 2
Description of Model 9
Alternative Model for Main Fault Based
on INTER3 Elements 26
Alternative Material Model for Antithetic Faults 37
Normal and Shear Stresses on Faults 38
Orientation Definition for Jointed-Material
Model - - - - 39
Case 01 40
Mesh Modification to Eliminate Sharp Corner 45
Shear Strength of Detachment Fault 50
Case 02 52 GW
Case 03 57
Case 04 61
Case 05 66
Computation of Down-Dip Displacement 67
Displacement Vectors 79
Modeling Approach Based on Prescribed Fault
Displacement on Main Fault 81
Implementation of Prescribed Main-Fault
Displacement 83
Case 06 87
Case 07 95
Analysis Cases with Slip at Initial State 102
Alternative Model: All Faults as Slender
Isotropic Solids 110
Fault Slip Induced By Application of External
Shear Force 132
Determination of Down-Dip Rupture length 142
Determination of Rupture Area 143
Results for Analysis Cases sc01, sc02, 144
and sc03 144

Initial Entry: Feb. 19. 1996

FINITE ELEMENT SIMULATION OF SLIP ON BARE MOUNTAIN FAULT: EFFECTS ON SEISMICITY ASSESSMENT FOR PROPOSED YUCCA MOUNTAIN REPOSITORY SITE

Project Number 20-5708-471: Structural Deformation and Seismicity

Investigators: Goodluck I Ofoegbu and Kevin Smart

Collaborators: David A Ferrill

The objective of this project is to simulate fault slip on the Bare Mountain Fault to examine the following:

1. The distribution of fault displacement along the fault; specifically, the relationship between the magnitudes of fault displacement at depth and at the ground surface.
2. The distribution of ground-motion amplitudes within the hangingwall and footwall of the fault; specifically, to determine whether the magnitudes of acceleration on the ground surface and at depth are consistent with assumptions commonly made in the development of ground-motion attenuation curves.
3. The possibility that slip on the Bare Mountain Fault might trigger slip on Yucca Mountain faults, and how the potential for triggered slip may vary with the assumed geometry of the Yucca Mountain faults.

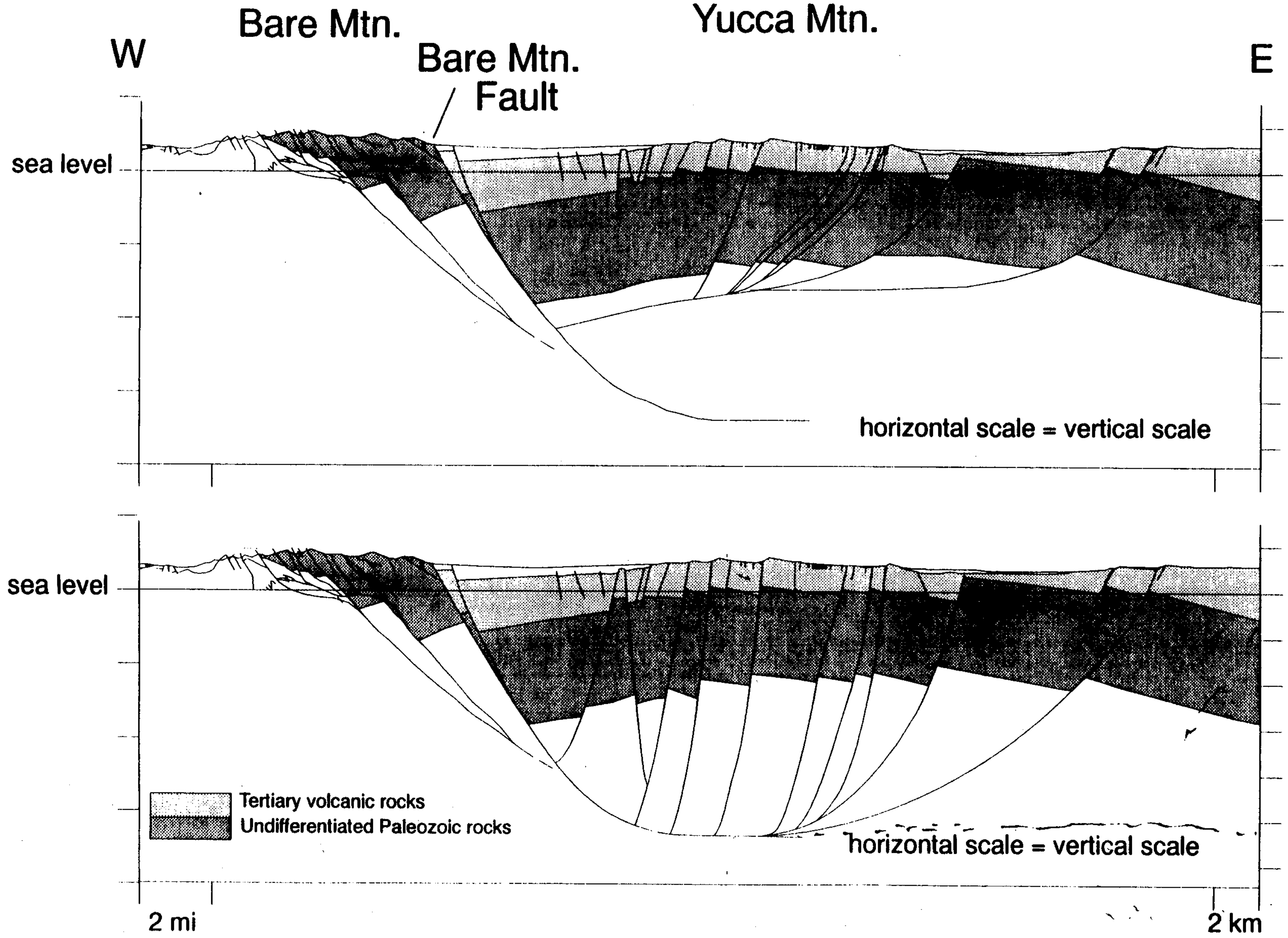
Specimen signatures and initials of participants.

Name	Signature	Initials
Goodluck I Ofoegbu	[signature]	GIO
Kevin Smart	Kevin J. Smart	KJS

All analyses (finite-element modeling) will be conducted using ABAQUS Version 5.5 on Silicon Graphics Work Station. Some post-processing of calculated results will be conducted ~~us~~ GIO on SUN WorkStation using C-codes described in this notebook.

[signature]

ALTERNATIVE MODELS FOR YUCCA MOUNTAIN FAULTS

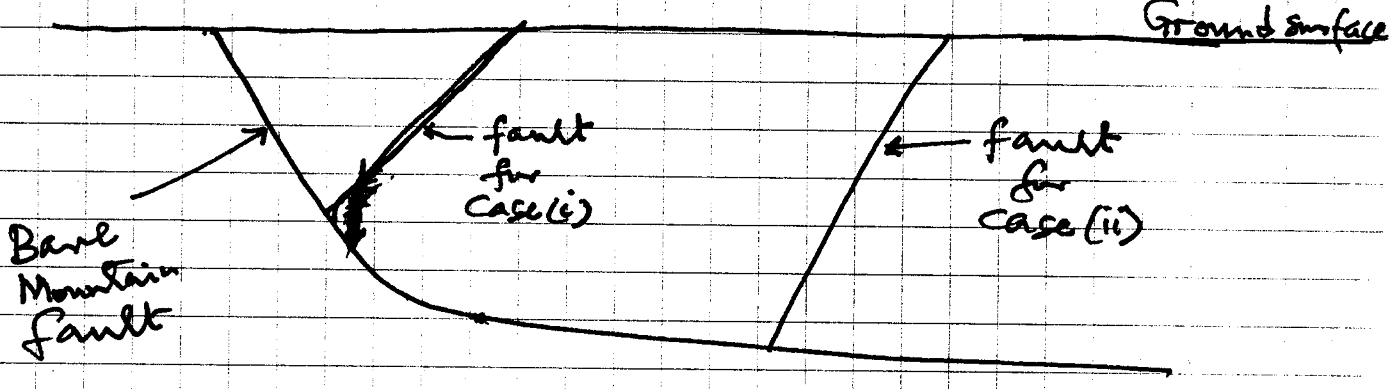


Use a simplified geometrical model of the Bare Mtn Fault to study the following:

① How slip on Bare Mtn Faults affects antithetic faults:

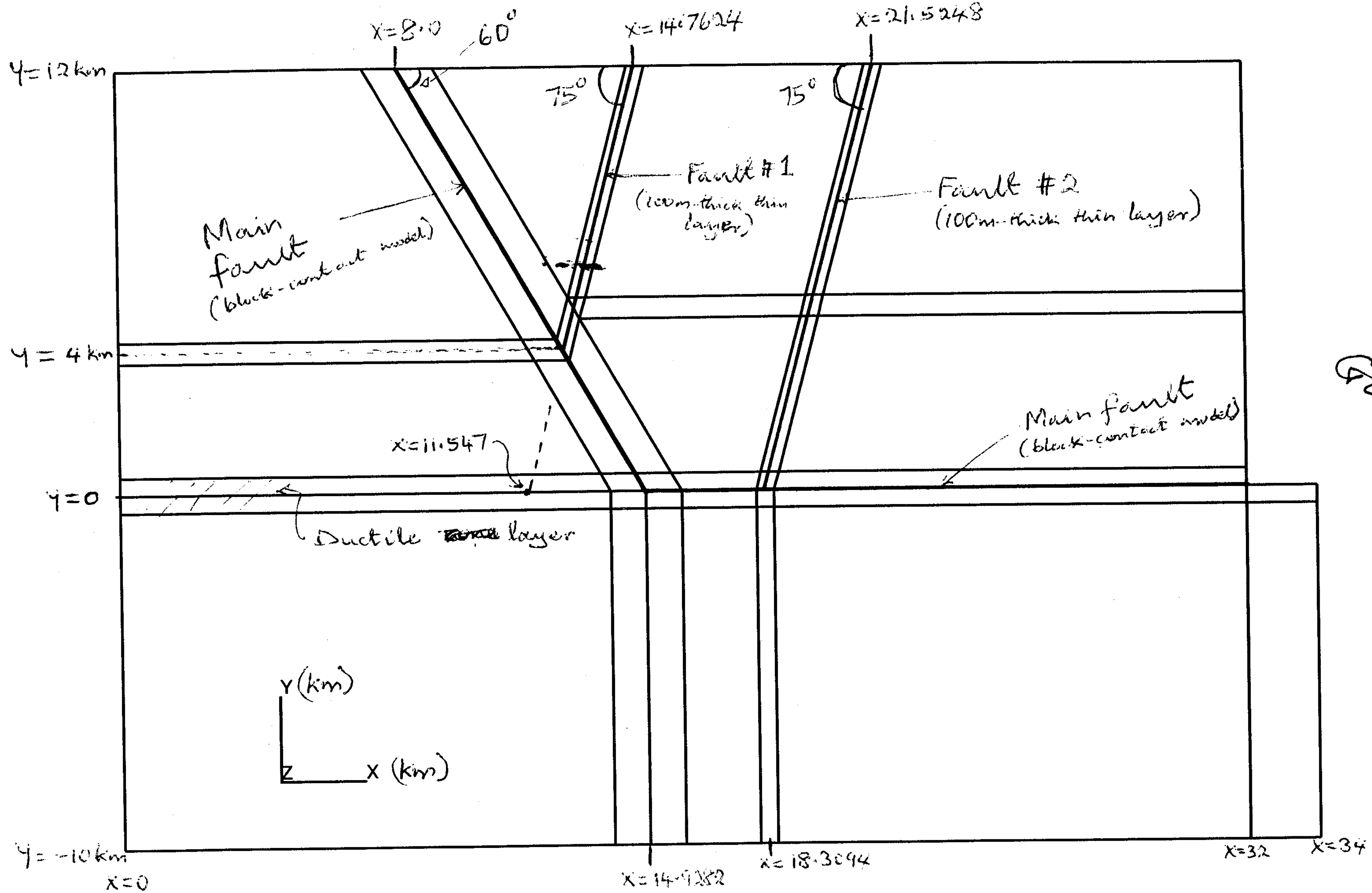
(i) intersecting the steep segment

(ii) intersecting the low-angle segment.



② Feasibility of simulating low-angle detachment as a ductile layer (brittle-ductile transition).

③ Feasibility of modeling listric fault as a block-contact while the antithetic faults are modeled as thin solids (thin weak zones).

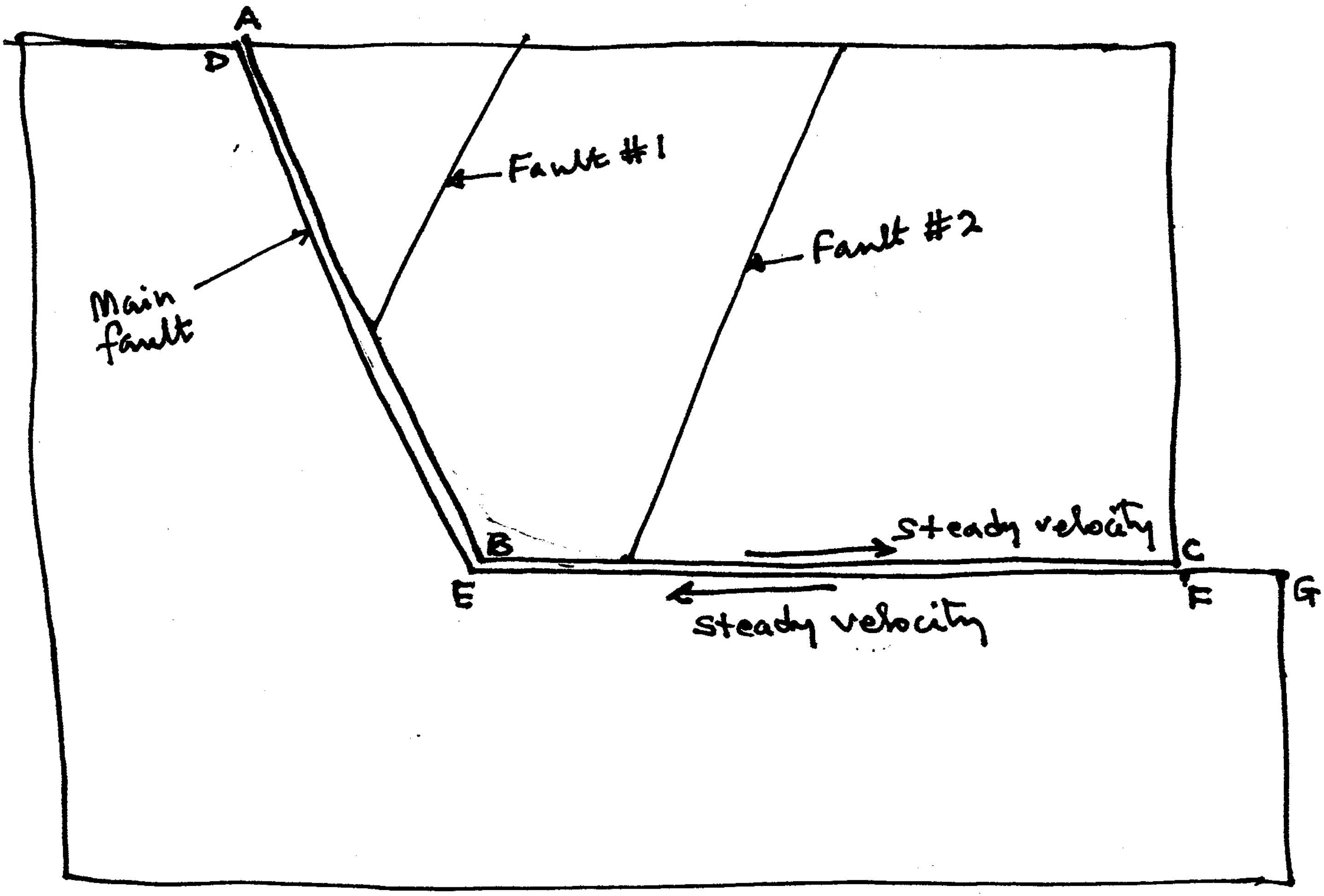


X=8.0
60°
X=14.7624
X=21.5248
Y=12 km
75°
75°
Fault #1
(100m-thick thin layer)
Fault #2
(100m-thick thin layer)
Main fault
(block-contact model)
Y = 4 km
X=11.547
Main fault
(block-contact model)
Y=0
Ductile layer
Y(km)
Z
X (km)
Y= -10km
X=0
X=14.9282
X=18.3094
X=32
X=34

GW

Fault Models

Main Fault



Main fault modeled as two inter-acting surfaces

ABC hangingwall surface

DEFG footwall surface

It was initially intended to assign smaller friction and dilation angles ~~angle and to~~ to the low-angle detachment than the steep segment of the fault,

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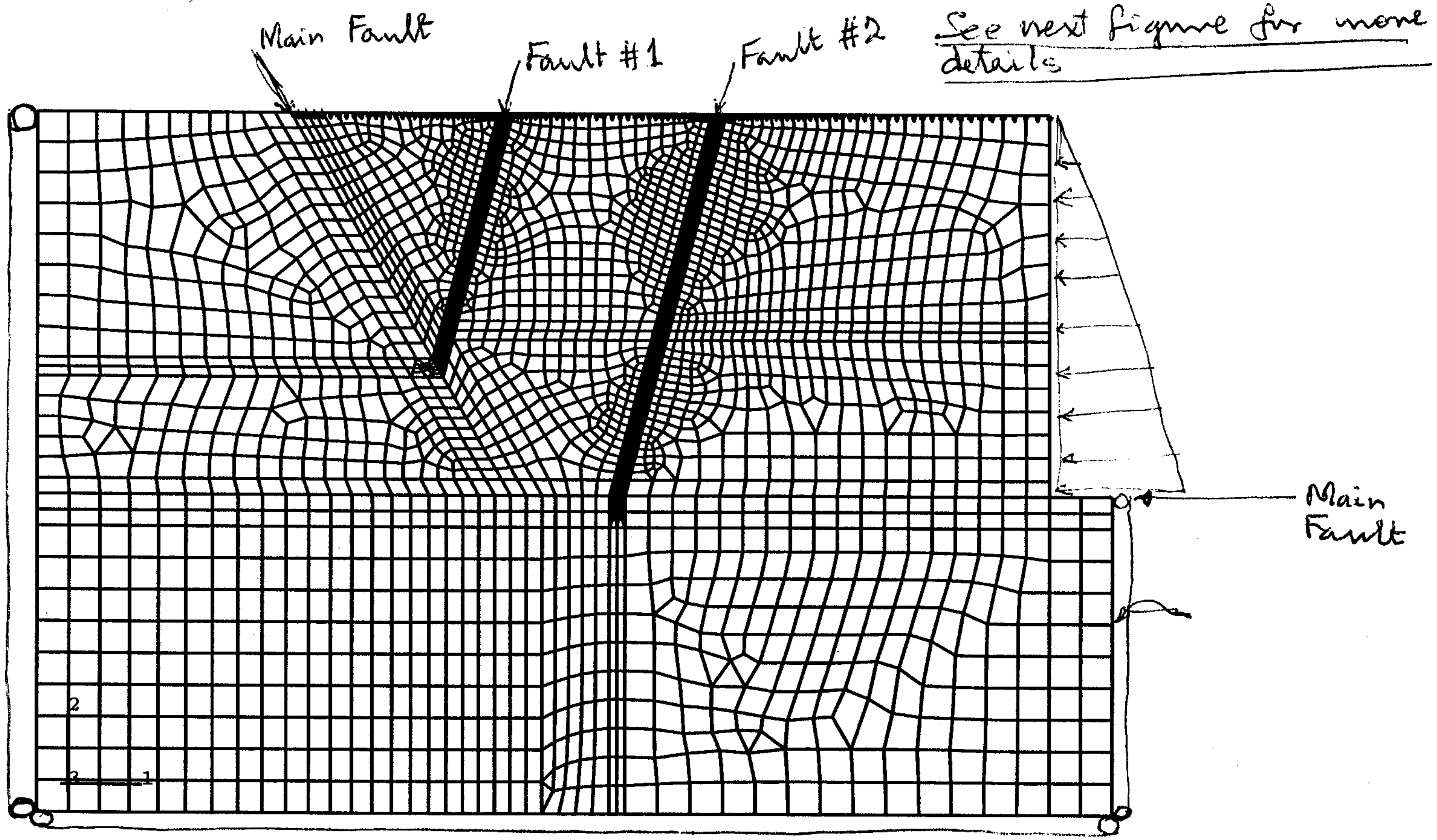
OK

but this could not be done because it required definition of two intersecting slave surfaces that interact with the same master surface, which ABAQUS does not encourage (It issues a warning message that convergence problems may occur.

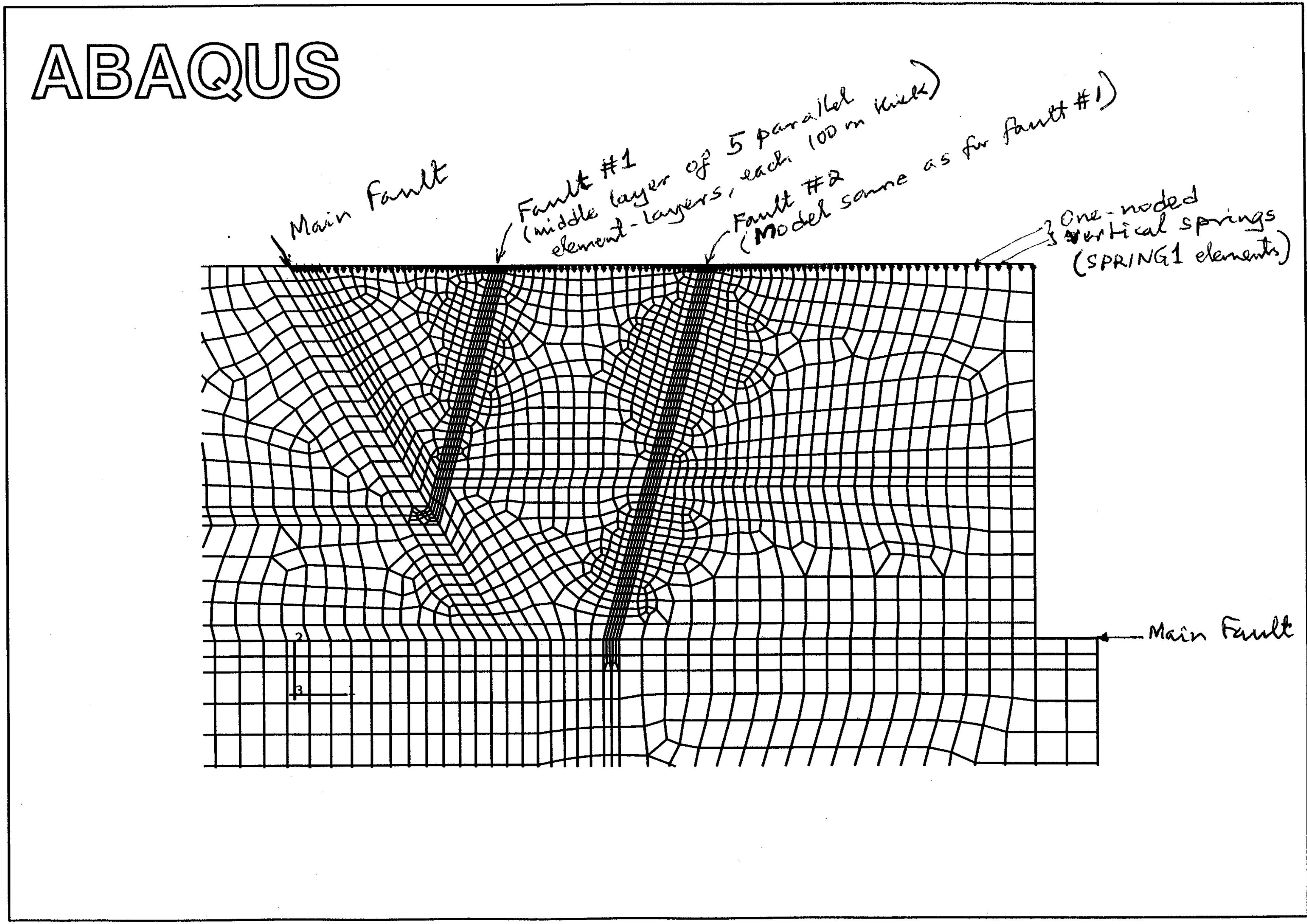
#10 ~~Steady-state flow in the ductile zone~~

& Steady-state slip on the low-angle detachment will be simulated by applying constant +x velocity on BC and -x velocity on EF.

ABAQUS



Main Fault
Fault #1
Fault #2
See next figure for more details
2
3
1
Main Fault


ABAQUS
Main Fault
Fault #1
(middle layer of 5 parallel element-layers, each 100 m thick)
Fault #2
(Model same as for fault #1)
One-noded vertical springs
(SPRING1 elements)
Main Fault
2
3
1

GAO

1 Description of Model

The finite element model is described using anotated excerpts from the ABAQUS input file.

1.1 Node Sets for Boundary Conditions and Results Processing

```
**
** Node set FIXLEFT represents all nodes at x=0
** x-displacement held at zero at these nodes
**
*NSET, NSET=FIXLEFT
   5900,   5901,   5926,   5939,   5959,   5970,   5986,   5997,
   6001,   6003,   6013,   6017,   6023,   6024,   6028,   6030,
   6032,   6066,   6083,   6116,   6133,   6417,   6467,   6487,
   6565,   6585,   6663,   6683,   6916,   6917,   6918,   6919,
   6920,   6921,   6922,   6923,   6924,   6925,   6926,   6927,
   6928,   6929,   6930,   6931,   6932,   6933,   8916,   8917,
   8919,   8920,   8922,   8923,   8926,   8928,   8930
**
** Node set FIXBASE represents all nodes at y=-10000 m
** y-displacement held at zero at these nodes
**
*NSET, NSET=FIXBASE
   6933,   6943,   6962,   6972,   6991,   7001,   7020,   7030,
   7049,   7059,   7078,   7088,   7107,   7117,   7136,   7146,
   7165,   7175,   7194,   7204,   7223,   7233,   7252,   7262,
   7281,   7291,   7310,   7320,   7339,   7349,   7368,   7378,
   7397,   7407,   7426,   7436,   7455,   7465,   7484,   7513,
   7532,   7542,   7561,   7590,   7609,   7619,   7638,   7730,
   7769,   7790,   7801,   7822,   7855,   7856,   7877,   7889,
   7909,   7921,   7941,   7953,   7973,   7985,   8005,   8017,
   8037,   8049,   8050,   8052,   8053,   8055,   8056,   8058,
   8059,   8061,   8062,   8064,   8065,   8069,   8373,   8392,
   8402,   8421,   8458,   8478,   8493,   8520,   8541,   8552,
   8573,
**
** Node set FIXRIGHT represents all nodes at x=34000 m
** x-displacement held at zero at these nodes
**
*NSET, NSET=FIXRIGHT
   5595,   5598,   5603,   6909,   6914,   8404,   8405,   8406,
   8407,   8408,   8409,   8410,   8411,   8412,   8413,   8414,
   8415,   8416,   8417,   8418,   8419,   8420,   8421
**
** Node set NDF1HW represents all nodes on the hangingwall side of Fault #1
** Node set NDF1FW represents all nodes on the footwall side of Fault #1
```

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```
** Fault-parallel displacements on these nodes will be used to compute
** the magnitude of fault displacement on Fault #1
**
*NSET, NSET=NDF1HW
     167,     168,     169,     170,     171,     172,     173,     174,
     175,     176,     177,     178,     179,     180,     181,     182,
     183,     184,     185,     186,     187,     188,     189,     190,
     191,     192,     193,     194,     195,     196,     197,     198,
     199,     200,     201,     202,     203,     204,     205,     206,
     207,     208,     209,     210,     211,     212,     213,     214,
     215,     216,     217,     218,     219,     220,     221,     489,
     490,     491,     492,     523,     524,     525,      526
**
*NSET, NSET=NDF1FW
     250,     251,     252,     253,     254,     255,     256,     257,
     258,     259,     260,     261,     262,     263,     264,     265,
     266,     267,     268,     269,     270,     271,     272,     273,
     274,     275,     276,     277,     278,     279,     280,     281,
     282,     283,     284,     285,     286,     287,     288,     289,
     290,     291,     292,     293,     294,     295,     296,     297,
     298,     299,     300,     301,     302,     303,     304,     483,
     484,     485,     486,     517,     518,     519,      520
**
** Node set NDF2HW represents all nodes on the hangingwall side of Fault #2
** Node set NDF2FW represents all nodes on the footwall side of Fault #2
** Fault-parallel displacements on these nodes will be used to compute
** the magnitude of fault displacement on Fault #2
**
*NSET, NSET=NDF2FW
    1092,    1093,    1094,    1095,    1096,    1097,    1098,    1099,
    1100,    1101,    1102,    1103,    1104,    1105,    1106,    1107,
    1108,    1109,    1110,    1111,    1112,    1113,    1114,    1115,
    1116,    1117,    1118,    1119,    1120,    1121,    1122,    1123,
    1124,    1125,    1126,    1127,    1128,    1129,    1130,    1131,
    1132,    1133,    1134,    1135,    1136,    1137,    1138,    1139,
    1140,    1141,    1142,    1143,    1144,    1145,    1146,    1331,
    1332,    1333,    1334,    1509,    1510,    1511,    1512,    1513,
    1514,    1515,    1516,    1517,    1518,    1519,    1520,    1521,
    1522,    1523,    1524,    1525,    1526,    1527,    1528,    1529,
    1530,    1531,    1532,    1533,    1534,    1535,    1536,    1537,
    1538,    1539,    1540,    1541,    1542,    1543,    1544,    4956,
    4965
**
*NSET, NSET=NDF2HW
    1009,    1010,    1011,    1012,    1013,    1014,    1015,    1016,
    1017,    1018,    1019,    1020,    1021,    1022,    1023,    1024,
```

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      1025,     1026,     1027,     1028,     1029,     1030,     1031,     1032,
      1033,     1034,     1035,     1036,     1037,     1038,     1039,     1040,
      1041,     1042,     1043,     1044,     1045,     1046,     1047,     1048,
      1049,     1050,     1051,     1052,     1053,     1054,     1055,     1056,
      1057,     1058,     1059,     1060,     1061,     1062,     1063,     1325,
      1326,     1327,     1328,     1455,     1456,     1457,     1458,     1459,
      1460,     1461,     1462,     1463,     1464,     1465,     1466,     1467,
      1468,     1469,     1470,     1471,     1472,     1473,     1474,     1475,
      1476,     1477,     1478,     1479,     1480,     1481,     1482,     1483,
      1484,     1485,     1486,     1487,     1488,     1489,     1490,     4955,
      4963
**
** Node set NDHWLEFT represents hangingwall side of the main-fault steep
** segment, excluding Node 4909 which lies at base of the fault.
** The fault-parallel displacement at these
** nodes (including Node 4909) and on Node set NDFOLEFT will be used
** to compute fault displacement on the main fault.
** Also, prescribed fault-parallel displacements may be applied on
** Node set NDHWLEFT
**
*NSET, NSET=NDHWLEFT
      508,      510,      514,      516,      520,      522,      526,      528,
      532,      534,      538,      731,      732,      733,      734,      735,
      736,      737,      738,      739,      740,      741,      742,      743,
      744,      745,      746,      747,      748,      749,      750,      751,
      752,      753,      754,      755,      756,      757,      758,      759,
      760,      761,      762,      765,      770,      773,      778,      781,
      786,      789,      794,      797,      802,      805,      810,      813,
      818,      821,      826,      829,      834,      837,      842,      4906
**
** Node set NDHWBASE represents the base of the main-fault hangingwall
** Prescribed +ve x-velocity will be applied at these nodes
** along with prescribed -ve x-velocity on Node set NDFOBASE
** to simulate steady-state flow in the ductile zone
**
*NSET, NSET=NDHWBASE
      4909,     4910,     4911,     4912,     4913,     4932,     4933,     4934,
      4935,     4936,     4937,     4938,     4939,     4940,     4941,     4960,
      4961,     4962,     4963,     4964,     4965,     4966,     4967,     4968,
      4969,     5027,     5028,     5029,     5030,     5031,     5032,     5033,
      5034,     5035,     5036,     5037,     5038,     5039,     5040,     5041,
      5042,     5043,     5044,     5045,     5046,     5047,     5048,     5049,
      5050,     5051,     5052,     5053,     5054,     5055,     5056,     5057,
      5058,     5059,     5060,     5061,     5062
**
** Node set NDFOLEFT represents the footwall side of the main-fault steep
```

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```
** segment. The fault-parallel displacement on these nodes will be used to
** calculate fault displacement on the main fault, as was explained earlier
**
*NSET, NSET=NDFOLEFT
    5063,    5065,    5066,    5068,    5072,    5082,    5090,    5096,
    5104,    5110,    5118,    5155,    5157,    5160,    5162,    5165,
    5167,    5170,    5172,    5175,    5177,    5180,    5182,    5185,
    5187,    5190,    5192,    5195,    5197,    5200,    5202,    5205,
    5207,    5210,    5212,    5215,    5217,    5220,    5222,    5225,
    5227,    5230,    5232,    5325,    5330,    5333,    5338,    5341,
    5346,    5349,    5354,    5357,    5362,    5365,    5370,    5373,
    5378,    5381,    5386,    5389,    5394,    5397,    5402,    5410,
    5415,
**
** Node set NDFOBASE represents the footwall side of the main-fault
** horizontal segment. Prescribed x-velocity will be applied at these nodes
** as was explained earlier.
**
*NSET, NSET=NDFOBASE
    5432,    5434,    5437,    5439,    5445,    5447,    5450,    5452,
    5455,    5457,    5460,    5462,    5465,    5467,    5473,    5475,
    5478,    5480,    5483,    5485,    5488,    5490,    5493,    5495,
    5499,    5500,    5501,    5502,    5503,    5504,    5505,    5506,
    5507,    5508,    5509,    5510,    5511,    5512,    5513,    5514,
    5515,    5516,    5517,    5518,    5519,    5520,    5521,    5522,
    5523,    5524,    5525,    5526,    5527,    5528,    5529,    5530,
    5531,    5532,    5533,     5534
**
** Node set NDTOP represents the top of the model.
** Ground-surface displacement will be monitored at these nodes.
**
*NSET, NSET=NDTOP
       1,      56,      84,     139,     167,     222,     250,     305,
     333,     388,     416,     570,     586,     618,     634,     666,
     682,     714,     730,     762,     843,     898,     926,     981,
    1009,    1064,    1092,    1147,    1175,    1230,    1258,    1713,
    1743,    1744,    1782,    1783,    1829,    1830,    1843,    1844,
    1846,    1847,    1893,    1894,    1933,    1934,    1962,    1963,
    1986,    1987,    2004,    2005,    2022,    2035,    2042,    2051,
    2056,    2061,    2065,    2070,    2072,    2073,    2077,    2084,
    2100,    2111,    2133,    2146,    2172,    2192,    2234,    2259,
    2309,    2335,    2382,    2383,    2405,    2406,    2408,    2409,
    2411,    2412,    2414,    2415,    2417,    2418,    2420,    2421,
    2423,    2424,    2426,    2427,    2429,    3356,    3377,    3392,
    3416,    3436,    3471,    3513,    3544,    3581,    3582,    3591,
    3633,    3657,    3694,    3716,    3744,    3763,    3764,    3769,
```

Cno GLO


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3793,   3808,   3827,   3842,   3860,   3876,   3893,   3910,
3925,   3940,   3956,   3970,   3971,   3974,   3992,   4005,
4022,   4036,   4037,   4041,   4042,   4044,   4045,   4047,
4049,   5232,   5233,   5234,   5316,   5317,   5735,   5764,
5779,   5803,   5817,   5841,   5854,   5874,   5885,   5886,
5888,   5889,   5891,   5892,   5894,   5895,   5897,   5898,
5900,   5902
```

1.2 Element Sets for Specification of Material-Property Zones

```
**
** Element set F1CORE represents Fault #1 as 100 m thick solid
** that will be assigned properties appropriate for a fault zone
**
*ELSET, ELSET=F1CORE
   55,     56,     57,     58,     59,     60,     61,     62,
   63,     64,     65,     66,     67,     68,     69,     70,
   71,     72,     73,     74,     75,     76,     77,     78,
   79,     80,     81,    140,    141,    150,    151
**
** Element set F2CORE represents Fault #2 as 100 m thick solid
** that will be assigned properties appropriate for a fault zone
**
*ELSET, ELSET=F2CORE
  294,    295,    296,    297,    298,    299,    300,    301,
  302,    303,    304,    305,    306,    307,    308,    309,
  310,    311,    312,    313,    314,    315,    316,    317,
  318,    319,    320,    379,    380,    421,    422,    423,
  424,    425,    426,    427,    428,    429,    430,    431,
  432,    433,    434,    435,    436,    437,    438,   1595
**
** Element set F1ZONE represents a 200 m thick transition zone on
** either side of Fault #1. It may be assigned properties same as
** or different from the main body of the hangingwall
**
*ELSET, ELSET=F1ZONE
    1,      2,      3,      4,      5,      6,      7,      8,
    9,     10,     11,     12,     13,     14,     15,     16,
   17,     18,     19,     20,     21,     22,     23,     24,
   25,     26,     27,     28,     29,     30,     31,     32,
   33,     34,     35,     36,     37,     38,     39,     40,
   41,     42,     43,     44,     45,     46,     47,     48,
   49,     50,     51,     52,     53,     54,     82,     83,
   84,     85,     86,     87,     88,     89,     90,     91,
   92,     93,     94,     95,     96,     97,     98,     99,
  100,    101,    102,    103,    104,    105,    106,    107,
```

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     108,     109,     110,     111,     112,     113,     114,     115,
     116,     117,     118,     119,     120,     121,     122,     123,
     124,     125,     126,     127,     128,     129,     130,     131,
     132,     133,     134,     135,     136,     137,     138,     139,
     142,     143,     144,     145,     146,     147,     148,     149,
     152,     153,     154,      155
**
** Element set F2ZONE represents a 200 m thick transition zone on
** either side of Fault #2. It may be assigned properties same as
** or different from the main body of the hangingwall
**
*ELSET, ELSET=F2ZONE
     240,     241,     242,     243,     244,     245,     246,     247,
     248,     249,     250,     251,     252,     253,     254,     255,
     256,     257,     258,     259,     260,     261,     262,     263,
     264,     265,     266,     267,     268,     269,     270,     271,
     272,     273,     274,     275,     276,     277,     278,     279,
     280,     281,     282,     283,     284,     285,     286,     287,
     288,     289,     290,     291,     292,     293,     321,     322,
     323,     324,     325,     326,     327,     328,     329,     330,
     331,     332,     333,     334,     335,     336,     337,     338,
     339,     340,     341,     342,     343,     344,     345,     346,
     347,     348,     349,     350,     351,     352,     353,     354,
     355,     356,     357,     358,     359,     360,     361,     362,
     363,     364,     365,     366,     367,     368,     369,     370,
     371,     372,     373,     374,     375,     376,     377,     378,
     381,     382,     383,     384,     385,     386,     387,     388,
     389,     390,     391,     392,     393,     394,     395,     396,
     397,     398,     399,     400,     401,     402,     403,     404,
     405,     406,     407,     408,     409,     410,     411,     412,
     413,     414,     415,     416,     417,     418,     419,     420,
     439,     440,     441,     442,     443,     444,     445,     446,
     447,     448,     449,     450,     451,     452,     453,     454,
     455,     456,     457,     458,     459,     460,     461,     462,
     463,     464,     465,     466,     467,     468,     469,     470,
     471,     472,     473,      474
**
** Element set FOHWZONE represents a 500 m thick transition zone
** on the main-fault hangingwall. It may be assigned properties same as
** or different from the main body of the hangingwall
**
*ELSET, ELSET=FOHWZONE
     156,     157,     158,     159,     160,     161,     162,     163,
     164,     165,     166,     167,     168,     169,     170,     171,
     172,     173,     174,     175,     176,     177,     178,     179,
     180,     181,     182,     183,     184,     185,     186,     187,
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    188,     189,     190,     191,     192,     193,     194,     195,
    196,     197,     198,     199,     200,     201,     202,     203,
    204,     205,     206,     207,     208,     209,     210,     211,
    212,     213,     214,     215,     216,     217,     218,     219,
    220,     221,     222,     223,     224,     225,     226,     227,
    228,     229,     230,     231,     232,     233,     234,     235,
    236,     237,     238,     239
**
** Element set HWDUCTIL represents a 500 m thick ductile zone at the
** base of the hangingwall
**
*ELSET, ELSET=HWDUCTIL
    1586,    1587,    1588,    1589,    1590,    1591,    1592,    1593,
    1594,    1596,    1597,    1598,    1599,    1600,    1601,    1602,
    1603,    1604,    1605,    1606,    1607,    1608,    1609,    1610,
    1611,    1612,    1613,    1614,    1615
**
** Element set HWALL represents the main body of the hangingwall
** It will be assigned linear-elastic properties
**
*ELSET, ELSET=HWALL
     475,     476,     477,     478,     479,     480,     481,     482,
     483,     484,     485,     486,     487,     488,     489,     490,
     491,     492,     493,     494,     495,     496,     497,     498,
     499,     500,     501,     502,     503,     504,     505,     506,
     507,     508,     509,     510,     511,     512,     513,     514,
     515,     516,     517,     518,     519,     520,     521,     522,
     523,     524,     525,     526,     527,     528,     529,     530,
     531,     532,     533,     534,     535,     536,     537,     538,
     539,     540,     541,     542,     543,     544,     545,     546,
     547,     548,     549,     550,     551,     552,     553,     554,
     555,     556,     557,     558,     559,     560,     561,     562,
     563,     564,     565,     566,     567,     568,     569,     570,
     571,     572,     573,     574,     575,     576,     577,     578,
     579,     580,     581,     582,     583,     584,     585,     586,
     587,     588,     589,     590,     591,     592,     593,     594,
     595,     596,     597,     598,     599,     600,     601,     602,
     603,     604,     605,     606,     607,     608,     609,     610,
     611,     612,     613,     614,     615,     616,     617,     618,
     619,     620,     621,     622,     623,     624,     625,     626,
     627,     628,     629,     630,     631,     632,     633,     634,
     635,     636,     637,     638,     639,     640,     641,     642,
     643,     644,     645,     646,     647,     648,     649,     650,
     651,     652,     653,     654,     655,     656,     657,     658,
     659,     660,     661,     662,     663,     664,     665,     666,
     667,     668,     669,     670,     671,     672,     673,     674,
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GW

675,	676,	677,	678,	679,	680,	681,	682,
683,	684,	685,	686,	687,	688,	689,	690,
691,	692,	693,	694,	695,	696,	697,	698,
699,	700,	701,	702,	703,	704,	705,	706,
707,	708,	709,	710,	711,	712,	713,	714,
715,	716,	717,	718,	719,	720,	721,	722,
723,	724,	725,	726,	727,	728,	729,	730,
731,	732,	733,	734,	735,	736,	737,	738,
739,	740,	741,	742,	743,	744,	745,	746,
747,	748,	749,	750,	751,	752,	753,	754,
755,	756,	757,	758,	759,	760,	761,	762,
763,	764,	765,	766,	767,	768,	769,	770,
771,	772,	773,	774,	775,	776,	777,	778,
779,	780,	781,	782,	783,	784,	785,	786,
787,	788,	789,	790,	791,	792,	793,	794,
795,	796,	797,	798,	799,	800,	801,	802,
803,	804,	805,	806,	807,	808,	809,	810,
811,	812,	813,	814,	815,	816,	817,	818,
819,	820,	821,	822,	823,	824,	825,	826,
827,	828,	829,	830,	831,	832,	833,	834,
835,	836,	837,	838,	839,	840,	841,	842,
843,	844,	845,	846,	847,	848,	849,	850,
851,	852,	853,	854,	855,	856,	857,	858,
859,	860,	861,	862,	863,	864,	865,	866,
867,	868,	869,	870,	871,	872,	873,	874,
875,	876,	877,	878,	879,	880,	881,	882,
883,	884,	885,	886,	887,	888,	889,	890,
891,	892,	893,	894,	895,	896,	897,	898,
899,	900,	901,	902,	903,	904,	905,	906,
907,	908,	909,	910,	911,	912,	913,	914,
915,	916,	917,	918,	919,	920,	921,	922,
923,	924,	925,	926,	927,	928,	929,	930,
931,	932,	933,	934,	935,	936,	937,	938,
939,	940,	941,	942,	943,	944,	945,	946,
947,	948,	949,	950,	951,	952,	953,	954,
955,	956,	957,	958,	959,	960,	961,	962,
963,	964,	965,	966,	967,	968,	969,	970,
971,	972,	973,	974,	975,	976,	977,	978,
979,	980,	981,	982,	983,	984,	985,	986,
987,	988,	989,	990,	991,	992,	993,	994,
995,	996,	997,	998,	999,	1000,	1001,	1002,
1003,	1004,	1005,	1006,	1007,	1008,	1009,	1010,
1011,	1012,	1013,	1014,	1015,	1016,	1017,	1018,
1019,	1020,	1021,	1022,	1023,	1024,	1025,	1026,
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1035,	1036,	1037,	1038,	1039,	1040,	1041,	1042,

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1067,	1068,	1069,	1070,	1071,	1072,	1073,	1074,
1075,	1076,	1077,	1078,	1079,	1080,	1081,	1082,
1083,	1084,	1085,	1086,	1087,	1088,	1089,	1090,
1091,	1092,	1093,	1094,	1095,	1096,	1097,	1098,
1099,	1100,	1101,	1102,	1103,	1104,	1105,	1106,
1107,	1108,	1109,	1110,	1111,	1112,	1113,	1114,
1115,	1116,	1117,	1118,	1119,	1120,	1121,	1122,
1123,	1124,	1125,	1126,	1127,	1128,	1129,	1130,
1131,	1132,	1133,	1134,	1135,	1136,	1137,	1138,
1139,	1140,	1141,	1142,	1143,	1144,	1145,	1146,
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1163,	1164,	1165,	1166,	1167,	1168,	1169,	1170,
1171,	1172,	1173,	1174,	1175,	1176,	1177,	1178,
1179,	1180,	1181,	1182,	1183,	1184,	1185,	1186,
1187,	1188,	1189,	1190,	1191,	1192,	1193,	1194,
1195,	1196,	1197,	1198,	1199,	1200,	1201,	1202,
1203,	1204,	1205,	1206,	1207,	1208,	1209,	1210,
1211,	1212,	1213,	1214,	1215,	1216,	1217,	1218,
1219,	1220,	1221,	1222,	1223,	1224,	1225,	1226,
1227,	1228,	1229,	1230,	1231,	1232,	1233,	1234,
1235,	1236,	1237,	1238,	1239,	1240,	1241,	1242,
1243,	1244,	1245,	1246,	1247,	1248,	1249,	1250,
1251,	1252,	1253,	1254,	1255,	1256,	1257,	1258,
1259,	1260,	1261,	1262,	1263,	1264,	1265,	1266,
1267,	1268,	1269,	1270,	1271,	1272,	1273,	1274,
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1299,	1300,	1301,	1302,	1303,	1304,	1305,	1306,
1307,	1308,	1309,	1310,	1311,	1312,	1313,	1314,
1315,	1316,	1317,	1318,	1319,	1320,	1321,	1322,
1323,	1324,	1325,	1326,	1327,	1328,	1329,	1330,
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1347,	1348,	1349,	1350,	1351,	1352,	1353,	1354,
1355,	1356,	1357,	1358,	1359,	1360,	1361,	1362,
1363,	1364,	1365,	1366,	1367,	1368,	1369,	1370,
1371,	1372,	1373,	1374,	1375,	1376,	1377,	1378,
1379,	1380,	1381,	1382,	1383,	1384,	1385,	1386,
1387,	1388,	1389,	1390,	1391,	1392,	1393,	1394,
1395,	1396,	1397,	1398,	1399,	1400,	1401,	1402,
1403,	1404,	1405,	1406,	1407,	1408,	1409,	1410,

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    1411,     1412,     1413,     1414,     1415,     1416,     1417,     1418,
    1419,     1420,     1421,     1422,     1423,     1424,     1425,     1426,
    1427,     1428,     1429,     1430,     1431,     1432,     1433,     1434,
    1435,     1436,     1437,     1438,     1439,     1440,     1441,     1442,
    1443,     1444,     1445,     1446,     1447,     1448,     1449,     1450,
    1451,     1452,     1453,     1454,     1455,     1456,     1457,     1458,
    1459,     1460,     1461,     1462,     1463,     1464,     1465,     1466,
    1467,     1468,     1469,     1470,     1471,     1472,     1473,     1474,
    1475,     1476,     1477,     1478,     1479,     1480,     1481,     1482,
    1483,     1484,     1485,     1486,     1487,     1488,     1489,     1490,
    1491,     1492,     1493,     1494,     1495,     1496,     1497,     1498,
    1499,     1500,     1501,     1502,     1503,     1504,     1505,     1506,
    1507,     1508,     1509,     1510,     1511,     1512,     1513,     1514,
    1515,     1516,     1517,     1518,     1519,     1520,     1521,     1522,
    1523,     1524,     1525,     1526,     1527,     1528,     1529,     1530,
    1531,     1532,     1533,     1534,     1535,     1536,     1537,     1538,
    1539,     1540,     1541,     1542,     1543,     1544,     1545,     1546,
    1547,     1548,     1549,     1550,     1551,     1552,     1553,     1554,
    1555,     1556,     1557,     1558,     1559,     1560,     1561,     1562,
    1563,     1564,     1565,     1566,     1567,     1568,     1569,     1570,
    1571,     1572,     1573,     1574,     1575,     1576,     1577,     1578,
    1579,     1580,     1581,     1582,     1583,     1584,      1585
**
** Element set FOFWZONE represents a 500 m thick transition zone
** on the main-fault footwall. It may be assigned properties same as
** or different from the main body of the footwall
**
*ELSET, ELSET=FOFWZONE
    1616,     1617,     1618,     1619,     1620,     1621,     1622,     1623,
    1624,     1625,     1626,     1627,     1628,     1629,     1630,     1631,
    1637,     1638,     1639,     1640,     1641,     1642,     1643,     1644,
    1645,     1646,     1647,     1648,     1649,     1650,     1651,     1652,
    1653,     1654,     1655,     1656,     1657,     1658,     1659,     1660,
    1661,     1662,     1663,     1664,     1665,     1666,     1667,     1668,
    1669,     1670,     1671,     1672,     1673,     1674,     1675,     1676,
    1677,     1678,     1679,     1680,     1681,     1682,     1683,     1684,
    1685,     1686,     1687,     1688,     1689,      1690
**
** Element set FWDUCTIL represents a 500 m thick ductile zone at the
** base of the main fault on the footwall side
**
*ELSET, ELSET=FWDUCTIL
    1691,     1692,     1693,     1694,     1695,     1696,     1697,     1698,
    1699,     1700,     1701,     1702,     1703,     1704,     1705,     1706,
    1707,     1708,     1709,     1710,     1711,     1712,     1713,     1714,
    1715,     1716,     1717,     1718,     1719,     1720,     1721,     1722,
```

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    1723,    1724,    1725,    1726
**
** Element set FWALL represents the main body of the footwall
** It will be assigned linear-elastic properties
**
*ELSET, ELSET=FWALL
    1727,    1728,    1729,    1730,    1731,    1732,    1733,    1734,
    1735,    1736,    1737,    1738,    1739,    1740,    1741,    1742,
    1743,    1744,    1745,    1746,    1747,    1748,    1749,    1750,
    1751,    1752,    1753,    1754,    1755,    1756,    1757,    1758,
    1759,    1760,    1761,    1762,    1763,    1764,    1765,    1766,
    1767,    1768,    1769,    1770,    1771,    1772,    1773,    1774,
    1775,    1776,    1777,    1778,    1779,    1780,    1781,    1782,
    1783,    1784,    1785,    1786,    1787,    1788,    1789,    1790,
    1791,    1792,    1793,    1794,    1795,    1796,    1797,    1798,
    1799,    1800,    1801,    1802,    1803,    1804,    1805,    1806,
    1807,    1808,    1809,    1810,    1811,    1812,    1813,    1814,
    1815,    1816,    1817,    1818,    1819,    1820,    1821,    1822,
    1823,    1824,    1825,    1826,    1827,    1828,    1829,    1830,
    1831,    1832,    1833,    1834,    1835,    1836,    1837,    1838,
    1839,    1840,    1841,    1842,    1843,    1844,    1845,    1846,
    1847,    1848,    1849,    1850,    1851,    1852,    1853,    1854,
    1855,    1856,    1857,    1858,    1859,    1860,    1861,    1862,
    1863,    1864,    1865,    1866,    1867,    1868,    1869,    1870,
    1871,    1872,    1873,    1874,    1875,    1876,    1877,    1878,
    1879,    1880,    1881,    1882,    1883,    1884,    1956,    1957,
    1958,    1959,    1960,    1961,    1962,    1963,    1964,    1965,
    1966,    1967,    1968,    1969,    1970,    1971,    1972,    1973,
    1974,    1975,    1976,    1977,    1978,    1979,    1980,    1981,
    1982,    1983,    1984,    1985,    1986,    1987,    1988,    1989,
    1990,    1991,    1992,    1993,    1994,    1995,    1996,    1997,
    1998,    1999,    2000,    2001,    2002,    2003,    2004,    2005,
    2006,    2007,    2008,    2009,    2010,    2011,    2012,    2013,
    2014,    2015,    2016,    2017,    2018,    2019,    2020,    2021,
    2022,    2023,    2024,    2025,    2026,    2027,    2028,    2029,
    2030,    2031,    2032,    2033,    2034,    2035,    2036,    2037,
    2038,    2039,    2040,    2041,    2042,    2043,    2044,    2045,
    2046,    2047,    2048,    2049,    2050,    2051,    2052,    2053,
    2054,    2055,    2056,    2057,    2058,    2059,    2060,    2061,
    2062,    2063,    2064,    2065,    2066,    2067,    2068,    2069,
    2070,    2071,    2072,    2073,    2074,    2075,    2076,    2077,
    2078,    2079,    2080,    2081,    2082,    2083,    2084,    2085,
    2086,    2087,    2088,    2089,    2090,    2091,    2092,    2093,
    2094,    2095,    2096,    2097,    2098,    2099,    2100,    2101,
    2102,    2103,    2104,    2105,    2106,    2107,    2108,    2109,
    2110,    2111,    2112,    2113,    2114,    2115,    2116,    2117,
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6720

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2222, 2223, 2224, 2225, 2226, 2227, 2228, 2229,
2230, 2231, 2232, 2233, 2234, 2235, 2236, 2237,
2238, 2239, 2240, 2241, 2242, 2243, 2244, 2245,
2246, 2247, 2248, 2249, 2250, 2251, 2252, 2253,
2254, 2255, 2256, 2281, 2282, 2283, 2284, 2285,
2286, 2287, 2288, 2289, 2290, 2291, 2292, 2293,
2294, 2295, 2296, 2297, 2298, 2299, 2300, 2301,
2302, 2303, 2304, 2305, 2306, 2307, 2308, 2309,
2310, 2311, 2312, 2313, 2314, 2315, 2316, 2317,
2318, 2319, 2320, 2321, 2322, 2323, 2324, 2325,
2326, 2327, 2328, 2329, 2330, 2331, 2332, 2333,
2334, 2335, 2336, 2337, 2338, 2339, 2340, 2341,
2342, 2343, 2344, 2345, 2346, 2347, 2348, 2349,
2350, 2351, 2352, 2353, 2354, 2355, 2356, 2357,
2358, 2359, 2360, 2361, 2362, 2363, 2364, 2365,
2366, 2367, 2368, 2369, 2370, 2371, 2372, 2373,
2374, 2375, 2376, 2377, 2378, 2379, 2380, 2381,
2382, 2383, 2384, 2385, 2386, 2387, 2388, 2389,
2390, 2391, 2392, 2393, 2394, 2395, 2396, 2397,
2398, 2399, 2400, 2401, 2402, 2403, 2404, 2405,
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2497, 2498, 2499, 2500, 2501, 2502, 2503, 2504,
2505, 2506, 2507, 2508, 2509, 2510, 2511, 2512,

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2569,  2570,  2571,  2572,  2573,  2574,  2576,  2577,
2578,  2579,  2580,  2581,  2582,  2583,  2584,  2586,
2587,  2588,  2589,  2590,  2591,  2592,  2593,  2594,
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2619,  2620,  2621,  2622,  2623,  2624,   2625
```

1.3 Displacement-Based Boundary Conditions

```
***
*** X-displacement held at zero at nodes FIXLEFT and FIXRIGHT
*** Y-displacement held at zero at nodes FIXBASE
***
*BOUNDARY
FIXLEFT,1
FIXRIGHT,1
FIXBASE,2
***
*** Prescribed horizontal velocity applied to Node set NDHWBASE and
*** NDFOBASE to simulate steady-state flow along the horizontal segment of
*** the main fault. Nonzero prescribed velocities or displacements
*** are applied within analysis-step definitions
***
```

1.4 Pressure Boundary Conditions

```
***
*** Horizontal pressure on exterior boundary of hangingwall
*** along the vertical line x=32000 m;
*** based on unit weight of 0.025 MPa/m
*** and horizontal-to-vertical stress ratio of 0.25
***
*DLOAD,AMPLITUDE=NOCHANGE
    1076, P4,     37.8464
    1077, P3,     2.91127
    1124, P4,     32.0239
    1125, P4,     26.2014
    1126, P4,     20.3789
```

GO GO


```
    1127, P4,     14.5563
    1128, P3,     8.73379
    1390, P3,     41.6819
    1391, P3,     43.5304
    1410, P1,     46.7397
    1411, P1,     51.3097
    1412, P1,     55.8798
    1413, P1,     60.4499
    1414, P1,     65.0199
    1415, P2,       69.59
    1615, P3,     73.4375
***
*** Vertical pressure on footwall bench
*** on horizontal line at y=0, x>32000 m;
*** based on unit weight of 0.025 MPa/m
***
*DLOAD,AMPLITUDE=NOCHANGE
    1725, P4,        300.
    1726, P4,        300.
```

1.5 Initial Stress State

```
***
*** Initial stress state based on unit weight,
*** i.e., vertical stress gradient, of 0.025 MPa/m
*** and horizontal-to-vertical stress ratio of 0.25
***
*INITIAL CONDITIONS,TYPE=STRESS,GEOSTATIC
F1CORE,0.0,12000.0,-300.0,0.0,0.25,0.25
F2CORE,0.0,12000.0,-300.0,0.0,0.25,0.25
F1ZONE,0.0,12000.0,-300.0,0.0,0.25,0.25
F2ZONE,0.0,12000.0,-300.0,0.0,0.25,0.25
FOHWZONE,0.0,12000.0,-300.0,0.0,0.25,0.25
HWDUCTIL,0.0,12000.0,-300.0,0.0,0.25,0.25
HWALL,0.0,12000.0,-300.0,0.0,0.25,0.25
FOFWZONE,0.0,12000.0,-300.0,0.0,0.25,0.25
FWDUCTIL,0.0,12000.0,-300.0,0.0,0.25,0.25
FWALL,0.0,12000.0,-300.0,0.0,0.25,0.25
```

1.6 Body Forces

```
***
*** Body forces: Vertical downward body force due to gravity
*** based on unit weigth 0.025 MN per cubic metre
***
*DLOAD,AMPLITUDE=NOCHANGE
```

GRD


```
F1CORE,BY,-2.5E-2
F2CORE,BY,-2.5E-2
F1ZONE,BY,-2.5E-2
F2ZONE,BY,-2.5E-2
FOHWZONE,BY,-2.5E-2
HWDUCTIL,BY,-2.5E-2
HWALL,BY,-2.5E-2
FOFWZONE,BY,-2.5E-2
FWDUCTIL,BY,-2.5E-2
FWALL,BY,-2.5E-2
```

1.7 Material Properties for Solid Elements

```
***
*** Three sets of solid material properties are assigned:
***
***    (1) Elastic Drucker-Prager material (RUBBLE)
***        for the two fault zones F1CORE and F2CORE.
***        Each fault zone is 100 m thick.
***
***    (2) Viscoelastic Drucker-Prager material (SILIPOTI)
***        for a 1000-m thick layer centered at the horizontal detachment
***        fault at a 12000 m depth (Y=0):
***        element sets HWDUCTIL and FWDUCTIL
***
***    (3) Linear-elastic material (LEROCK) for the rest of the rock body
***
***        SILIPOTI materials are temporarily assigned LEROCK properties;
***        steady-state flow along the detachment fault will be simulated
***        by applying prescribed horizontal relative velocity along
***        the fault, using Node sets NDHWBASE and NDFOBASE
***
*SOLID SECTION,ELSET=F1CORE,MATERIAL=RUBBLE
*SOLID SECTION,ELSET=F2CORE,MATERIAL=RUBBLE
*SOLID SECTION,ELSET=HWDUCTIL,MATERIAL=LEROCK
*SOLID SECTION,ELSET=FWDUCTIL,MATERIAL=LEROCK
*SOLID SECTION,ELSET=F1ZONE,MATERIAL=LEROCK
*SOLID SECTION,ELSET=F2ZONE,MATERIAL=LEROCK
*SOLID SECTION,ELSET=FOHWZONE,MATERIAL=LEROCK
*SOLID SECTION,ELSET=FOFWZONE,MATERIAL=LEROCK
*SOLID SECTION,ELSET=HWALL,MATERIAL=LEROCK
*SOLID SECTION,ELSET=FWALL,MATERIAL=LEROCK
***
*MATERIAL, NAME=LEROCK
*DENSITY
2.5E-3
```

ℳ


```
*ELASTIC
3.25E4,0.25
*MATERIAL,NAME=RUBBLE
*DENSITY
2.5E-3
*ELASTIC
3.25E4,0.25
*DRUCKER PRAGER,SHEAR CRITERION=LINEAR
50.0,0.78,30.0
*DRUCKER PRAGER HARDENING,TYPE=COMPRESSION
2.0,0.0
```

1.8 Model and Property Definition for Main Fault

```
***
*** Main fault modeled using the interacting-surfaces model in ABAQUS:
*** FOMASTER represents the footwall surface, and FOSLAVE the hangingwall
*** surface, of the main fault
***
*** Surface Definitions
***
*ELSET,ELSET=S1MASTER,GEN
1639,1654,1
*ELSET,ELSET=S3MASTER,GEN
1672,1692,2
*ELSET,ELSET=S4MASTER,GEN
1616,1620,1
1695,1726,1
*ELSET,ELSET=S2SLAVE,GEN
221,239,2
1586,1615,1
*ELSET,ELSET=S3SLAVE,GEN
147,155,2
204,219,1
*SURFACE DEFINITION,NAME=FOMASTER
S1MASTER,S1
S3MASTER,S3
S4MASTER,S4
*SURFACE DEFINITION,NAME=FOSLAVE
1586,S1
S2SLAVE,S2
S3SLAVE,S3
***
*** Contact definitions
***
*CONTACT PAIR,INTERACTION=FMAIN
```

```
FOSLAVE,FOMASTER
***
*** Interface properties based on Coulomb law; no slip in elastic states;
*** 40-degree friction angle on steep segment (FBRITTLE);
***
*SURFACE INTERACTION,NAME=FMAIN
1.0
*FRICTION,LAGRANGE
0.8391
```

(AW)

2 Alternative Model for Main Fault Based on INTER3 Elements

The interacting-surfaces model applied to the main fault as was described earlier was not successful. ABAQUS reported numerical difficulties consisting of initial overclosure or nonclosure of the two surfaces. Furthermore, the surfaces chattered during an attempt at initial static equilibrium; as a result, equilibrium was not achieved.

An alternative model for the main fault using INTER3 elements is described below. The node-connectivity data for the elements was developed using the node sets NDHWLEFT, NDHWBASE, NDF0LEFT, and NDF0BASE and the C codes reproduced below.

2.1 Node Sorting in Down-Dip Order

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

typedef struct Point {
  int node;
  float x,y;
  struct Point *next;
};

main()
{

/*
  This code sorts nodal points on a surface in a user-chosen order.
  It reads nodal data from a file created using ABAQUS/Post function
  PRINT NODES. The user-chosen order is defined in function IsBelow.
*/

   char buf[121];
   int node;
   float x,y;
   struct Point *FirstPoint,*LastPoint,*currentPoint;

   FirstPoint = LastPoint = NULL;
   while (gets(buf))
     if (sscanf(buf,"%d %f %f",&node,&x,&y) == 3){
       currentPoint = (struct Point *)malloc(sizeof(struct Point));
       if (!currentPoint){
         printf("\t***\tMemory allocation failure\t***\n");
         return;
       }
       currentPoint->node = node;
       currentPoint->x = x;
```

GAD


```
      currentPoint->y = y;
      StorePoint(currentPoint,&FirstPoint,&LastPoint);
    }

  PrintPoints(FirstPoint);
}

StorePoint(current,first,last)
  struct Point *current,**first,**last;
{
  struct Point *old,*p;

  p = *first;

  if (!*last){          /* current is the very first item in the list */
    current->next = NULL;
    *last = current;
    *first = current;
    return;
  }

  old = NULL;
  while (p){
    if (IsBelow(current,p)){
      old = p;
      p = p->next;
    }
    else{
      if (old) {      /* insert current at this point in the list */
        old->next = current;
        current->next = p;
        return;
      }
      current->next = p;    /* current becomes new first element */
      *first = current;
      return;
    }
  }

  (*last)->next = current;  /* current becomes new last element */
  current->next = NULL;
  *last = current;
}

PrintPoints(first)
  struct Point *first;
```

GAO


```
{

  if (!first){
    printf("\t***\tNothing to print\t***\n");
    return;
  }

  printf("%10s%12s%12s\n","Node","xcoord (m)","ycoord (m)");

  while (first){
    printf("%10d%12.5E%12.5E\n",first->node,first->x,first->y);
    first = first->next;
  }
}
int IsBelow(current,p)
  struct Point *current,*p;
{
  int below,notBelow;
  float delta,yTol;

/*
   This code module determines whether first-named POINT is down-dip (below)
   or up-dip of second-named POINT
*/

  below = 1;
  notBelow = 0;
  yTol = 0.05;

  delta = current->y - p->y;
  if (delta < -yTol)
    return(below);

  if (delta > yTol)
    return(notBelow);

  delta = current->x - p->x;
  if (delta > 0.0)
    return(below);

  return(notBelow);
}
```

2.2 Sorted Nodes: Footwall Surface of Main Fault

```
Node  xcoord (m)  ycoord (m)
```

GAO

5232	8.00000E+03	1.20000E+04
5230	8.13900E+03	1.17590E+04
5227	8.27800E+03	1.15190E+04
5225	8.41700E+03	1.12780E+04
5222	8.55600E+03	1.10370E+04
5220	8.69500E+03	1.07960E+04
5217	8.83400E+03	1.05550E+04
5215	8.97300E+03	1.03150E+04
5212	9.11200E+03	1.00740E+04
5210	9.25100E+03	9.83300E+03
5207	9.39000E+03	9.59200E+03
5205	9.52900E+03	9.35200E+03
5202	9.66800E+03	9.11100E+03
5200	9.80700E+03	8.87000E+03
5197	9.94600E+03	8.62900E+03
5195	1.00850E+04	8.38900E+03
5192	1.02240E+04	8.14800E+03
5190	1.03630E+04	7.90700E+03
5187	1.05020E+04	7.66600E+03
5185	1.06410E+04	7.42600E+03
5182	1.07800E+04	7.18500E+03
5180	1.09190E+04	6.94400E+03
5177	1.10580E+04	6.70300E+03
5175	1.11970E+04	6.46300E+03
5172	1.13360E+04	6.22200E+03
5170	1.14750E+04	5.98100E+03
5167	1.16140E+04	5.74000E+03
5165	1.17530E+04	5.50000E+03
5162	1.18920E+04	5.25900E+03
5160	1.20310E+04	5.01800E+03
5157	1.21700E+04	4.77700E+03
5155	1.23090E+04	4.53700E+03
5118	1.24480E+04	4.29600E+03
5110	1.24820E+04	4.23700E+03
5104	1.25160E+04	4.17700E+03
5096	1.25510E+04	4.11800E+03
5090	1.25850E+04	4.05900E+03
5082	1.26190E+04	4.00000E+03
5072	1.26530E+04	3.94100E+03
5068	1.26870E+04	3.88200E+03
5066	1.27210E+04	3.82300E+03
5065	1.27550E+04	3.76300E+03
5063	1.27900E+04	3.70400E+03
5325	1.28820E+04	3.54400E+03
5330	1.29750E+04	3.38400E+03
5333	1.30670E+04	3.22400E+03

5338	1.31600E+04	3.06300E+03
5341	1.32520E+04	2.90300E+03
5346	1.33450E+04	2.74300E+03
5349	1.34370E+04	2.58300E+03
5354	1.35300E+04	2.42300E+03
5357	1.36220E+04	2.26200E+03
5362	1.37150E+04	2.10200E+03
5365	1.38070E+04	1.94200E+03
5370	1.39000E+04	1.78200E+03
5373	1.39920E+04	1.62100E+03
5378	1.40850E+04	1.46100E+03
5381	1.41770E+04	1.30100E+03
5386	1.42700E+04	1.14100E+03
5389	1.43620E+04	9.80600E+02
5394	1.44550E+04	8.20400E+02
5397	1.45470E+04	6.60200E+02
5402	1.46400E+04	5.00000E+02
5410	1.47840E+04	2.50000E+02
5415	1.49280E+04	0.00000E+00
5432	1.51780E+04	0.00000E+00
5434	1.54280E+04	0.00000E+00
5437	1.56780E+04	0.00000E+00
5439	1.59280E+04	0.00000E+00
5445	1.61410E+04	0.00000E+00
5447	1.63540E+04	0.00000E+00
5450	1.65680E+04	0.00000E+00
5452	1.67810E+04	0.00000E+00
5455	1.69940E+04	0.00000E+00
5457	1.72070E+04	0.00000E+00
5460	1.74200E+04	0.00000E+00
5462	1.76330E+04	0.00000E+00
5465	1.78460E+04	0.00000E+00
5467	1.80590E+04	0.00000E+00
5473	1.81090E+04	0.00000E+00
5475	1.81590E+04	0.00000E+00
5478	1.82090E+04	0.00000E+00
5480	1.82590E+04	0.00000E+00
5483	1.83090E+04	0.00000E+00
5485	1.83590E+04	0.00000E+00
5488	1.84090E+04	0.00000E+00
5490	1.84590E+04	0.00000E+00
5493	1.85090E+04	0.00000E+00
5495	1.85590E+04	0.00000E+00
5499	1.89330E+04	0.00000E+00
5500	1.93060E+04	0.00000E+00
5501	1.96790E+04	0.00000E+00

Gro


```
5502 2.00530E+04 0.00000E+00
5503 2.04260E+04 0.00000E+00
5504 2.08000E+04 0.00000E+00
5505 2.11730E+04 0.00000E+00
5506 2.15460E+04 0.00000E+00
5507 2.19200E+04 0.00000E+00
5508 2.22930E+04 0.00000E+00
5509 2.26660E+04 0.00000E+00
5510 2.30400E+04 0.00000E+00
5511 2.34130E+04 0.00000E+00
5512 2.37860E+04 0.00000E+00
5513 2.41600E+04 0.00000E+00
5514 2.45330E+04 0.00000E+00
5515 2.49060E+04 0.00000E+00
5516 2.52800E+04 0.00000E+00
5517 2.56530E+04 0.00000E+00
5518 2.60260E+04 0.00000E+00
5519 2.64000E+04 0.00000E+00
5520 2.67730E+04 0.00000E+00
5521 2.71460E+04 0.00000E+00
5522 2.75200E+04 0.00000E+00
5523 2.78930E+04 0.00000E+00
5524 2.82670E+04 0.00000E+00
5525 2.86400E+04 0.00000E+00
5526 2.90130E+04 0.00000E+00
5527 2.93870E+04 0.00000E+00
5528 2.97600E+04 0.00000E+00
5529 3.01330E+04 0.00000E+00
5530 3.05070E+04 0.00000E+00
5531 3.08800E+04 0.00000E+00
5532 3.12530E+04 0.00000E+00
5533 3.16270E+04 0.00000E+00
5534 3.20000E+04 0.00000E+00
```

2.3 Sorted Nodes: Hangingwall Surface of Main Fault

```
Node  xcoord (m)  ycoord (m)
 762 8.00000E+03 1.20000E+04
 761 8.13900E+03 1.17590E+04
 760 8.27800E+03 1.15190E+04
 759 8.41700E+03 1.12780E+04
 758 8.55600E+03 1.10370E+04
 757 8.69500E+03 1.07960E+04
 756 8.83400E+03 1.05550E+04
 755 8.97300E+03 1.03150E+04
 754 9.11200E+03 1.00740E+04
```

753	9.25100E+03	9.83300E+03
752	9.39000E+03	9.59200E+03
751	9.52900E+03	9.35200E+03
750	9.66800E+03	9.11100E+03
749	9.80700E+03	8.87000E+03
748	9.94600E+03	8.62900E+03
747	1.00850E+04	8.38900E+03
746	1.02240E+04	8.14800E+03
745	1.03630E+04	7.90700E+03
744	1.05020E+04	7.66600E+03
743	1.06410E+04	7.42600E+03
742	1.07800E+04	7.18500E+03
741	1.09190E+04	6.94400E+03
740	1.10580E+04	6.70300E+03
739	1.11970E+04	6.46300E+03
738	1.13360E+04	6.22200E+03
737	1.14750E+04	5.98100E+03
736	1.16140E+04	5.74000E+03
735	1.17530E+04	5.50000E+03
734	1.18920E+04	5.25900E+03
733	1.20310E+04	5.01800E+03
732	1.21700E+04	4.77700E+03
731	1.23090E+04	4.53700E+03
538	1.24480E+04	4.29600E+03
534	1.24820E+04	4.23700E+03
532	1.25160E+04	4.17700E+03
528	1.25510E+04	4.11800E+03
526	1.25850E+04	4.05900E+03
522	1.26190E+04	4.00000E+03
520	1.26530E+04	3.94100E+03
516	1.26870E+04	3.88200E+03
514	1.27210E+04	3.82300E+03
510	1.27550E+04	3.76300E+03
508	1.27900E+04	3.70400E+03
765	1.28820E+04	3.54400E+03
770	1.29750E+04	3.38400E+03
773	1.30670E+04	3.22400E+03
778	1.31600E+04	3.06300E+03
781	1.32520E+04	2.90300E+03
786	1.33450E+04	2.74300E+03
789	1.34370E+04	2.58300E+03
794	1.35300E+04	2.42300E+03
797	1.36220E+04	2.26200E+03
802	1.37150E+04	2.10200E+03
805	1.38070E+04	1.94200E+03
810	1.39000E+04	1.78200E+03

813	1.39920E+04	1.62100E+03
818	1.40850E+04	1.46100E+03
821	1.41770E+04	1.30100E+03
826	1.42700E+04	1.14100E+03
829	1.43620E+04	9.80600E+02
834	1.44550E+04	8.20400E+02
837	1.45470E+04	6.60200E+02
842	1.46400E+04	5.00000E+02
4906	1.47840E+04	2.50000E+02
4909	1.49280E+04	0.00000E+00
4910	1.51780E+04	0.00000E+00
4911	1.54280E+04	0.00000E+00
4912	1.56780E+04	0.00000E+00
4913	1.59280E+04	0.00000E+00
4932	1.61410E+04	0.00000E+00
4933	1.63540E+04	0.00000E+00
4934	1.65680E+04	0.00000E+00
4935	1.67810E+04	0.00000E+00
4936	1.69940E+04	0.00000E+00
4937	1.72070E+04	0.00000E+00
4938	1.74200E+04	0.00000E+00
4939	1.76330E+04	0.00000E+00
4940	1.78460E+04	0.00000E+00
4941	1.80590E+04	0.00000E+00
4960	1.81090E+04	0.00000E+00
4961	1.81590E+04	0.00000E+00
4962	1.82090E+04	0.00000E+00
4963	1.82590E+04	0.00000E+00
4964	1.83090E+04	0.00000E+00
4965	1.83590E+04	0.00000E+00
4966	1.84090E+04	0.00000E+00
4967	1.84590E+04	0.00000E+00
4968	1.85090E+04	0.00000E+00
4969	1.85590E+04	0.00000E+00
5027	1.89330E+04	0.00000E+00
5028	1.93060E+04	0.00000E+00
5029	1.96790E+04	0.00000E+00
5030	2.00530E+04	0.00000E+00
5031	2.04260E+04	0.00000E+00
5032	2.08000E+04	0.00000E+00
5033	2.11730E+04	0.00000E+00
5034	2.15460E+04	0.00000E+00
5035	2.19200E+04	0.00000E+00
5036	2.22930E+04	0.00000E+00
5037	2.26660E+04	0.00000E+00
5038	2.30400E+04	0.00000E+00

```
5039 2.34130E+04 0.00000E+00
5040 2.37860E+04 0.00000E+00
5041 2.41600E+04 0.00000E+00
5042 2.45330E+04 0.00000E+00
5043 2.49060E+04 0.00000E+00
5044 2.52800E+04 0.00000E+00
5045 2.56530E+04 0.00000E+00
5046 2.60260E+04 0.00000E+00
5047 2.64000E+04 0.00000E+00
5048 2.67730E+04 0.00000E+00
5049 2.71460E+04 0.00000E+00
5050 2.75200E+04 0.00000E+00
5051 2.78930E+04 0.00000E+00
5052 2.82670E+04 0.00000E+00
5053 2.86400E+04 0.00000E+00
5054 2.90130E+04 0.00000E+00
5055 2.93870E+04 0.00000E+00
5056 2.97600E+04 0.00000E+00
5057 3.01330E+04 0.00000E+00
5058 3.05070E+04 0.00000E+00
5059 3.08800E+04 0.00000E+00
5060 3.12530E+04 0.00000E+00
5061 3.16270E+04 0.00000E+00
5062 3.20000E+04 0.00000E+00
```

2.4 Generate Connectivity Data for INTER3 Elements

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

main()
{
  char buf[121];
  char fwfilename[]="fmainFw.nodes";
  char hwfilename[]="fmainHw.nodes";
  int i,node,*hwNodes,*fwNodes,numNodes;
  int element,lastElem;
  float x,y;
  FILE *Fin;

/*
  This code developes element-connectivity definitions for
  ABAQUS INTER3 elements using nodal data read from two files;
  one file contains the nodal data for the base of the elements
  and the other contains the data for the top;
  there are numNodes nodes defined in each file.
```

```
*/

  numNodes = 125;
  lastElem = 6000;

  fwNodes = (int *)malloc(numNodes*sizeof(int));
  hwNodes = (int *)malloc(numNodes*sizeof(int));
  if (!fwNodes || !hwNodes)
    DumpAndQuit("Memory allocation failure");

/* Read element-base nodes */

  Fin = fopen(fwfilename,"r");
  if (!Fin){
    sprintf(buf,"Unable to open file %s",fwfilename);
    DumpAndQuit(buf);
  }

  i = 0;
  while (fgets(buf,80,Fin))
    if (sscanf(buf,"%d %f %f",&node,&x,&y) == 3){
      fwNodes[i] = node;
      if (++i == numNodes) break;
    }

  fclose(Fin);
  if (i < numNodes){
    sprintf(buf,"Only %d of %d nodes found in %s",i,numNodes,fwfilename);
    DumpAndQuit(buf);
  }

/* Read element-top nodes */

  Fin = fopen(hwfilename,"r");
  if (!Fin){
    sprintf(buf,"Unable to open file %s",hwfilename);
    DumpAndQuit(buf);
  }

  i = 0;
  while (fgets(buf,80,Fin))
    if (sscanf(buf,"%d %f %f",&node,&x,&y) == 3){
      hwNodes[i] = node;
      if (++i == numNodes) break;
    }
```

GTO


```
  fclose(Fin);
  if (i < numNodes){
    sprintf(buf,"Only %d of %d nodes found in %s",i,numNodes,hwfilename);
    DumpAndQuit(buf);
  }

/* Generate and write element-connectivity data */

  element = lastElem + 1;
  node = 0;
  printf("*ELEMENT,TYPE=INTER3,ELSET=FMAIN\n");

  while (node < numNodes-1){
    printf("%d,%d,%d,%d,%d,%d,%d\n",
      element++,
      fwNodes[node],
      fwNodes[node+1],
      fwNodes[node+2],
      hwNodes[node],
      hwNodes[node+1],
      hwNodes[node+2]        );
    node += 2;
  }
}

DumpAndQuit(s)
char *s;
{
  printf("\n *** %s ***\n\n",s);
  exit(0);
}
```

2.5 Element Property Definitions for INTER3 Elements

The elements are divided into two sets: set FBRITTLE represents main-fault segments in brittle rock, and FDUCTILE represents segments in ductile rock.

```
*ELEMENT,TYPE=INTER3,ELSET=FBRITTLE
6001,5232,5230,5227,762,761,760
6002,5227,5225,5222,760,759,758
6003,5222,5220,5217,758,757,756
6004,5217,5215,5212,756,755,754
6005,5212,5210,5207,754,753,752
6006,5207,5205,5202,752,751,750
6007,5202,5200,5197,750,749,748
6008,5197,5195,5192,748,747,746
```

GUD


```
6009,5192,5190,5187,746,745,744
6010,5187,5185,5182,744,743,742
6011,5182,5180,5177,742,741,740
6012,5177,5175,5172,740,739,738
6013,5172,5170,5167,738,737,736
6014,5167,5165,5162,736,735,734
6015,5162,5160,5157,734,733,732
6016,5157,5155,5118,732,731,538
6017,5118,5110,5104,538,534,532
6018,5104,5096,5090,532,528,526
6019,5090,5082,5072,526,522,520
6020,5072,5068,5066,520,516,514
6021,5066,5065,5063,514,510,508
6022,5063,5325,5330,508,765,770
6023,5330,5333,5338,770,773,778
6024,5338,5341,5346,778,781,786
6025,5346,5349,5354,786,789,794
6026,5354,5357,5362,794,797,802
6027,5362,5365,5370,802,805,810
6028,5370,5373,5378,810,813,818
6029,5378,5381,5386,818,821,826
6030,5386,5389,5394,826,829,834
6031,5394,5397,5402,834,837,842
6032,5402,5410,5415,842,4906,4909
*ELEMENT,TYPE=INTER3,ELSET=FDUCTILE
6033,5415,5432,5434,4909,4910,4911
6034,5434,5437,5439,4911,4912,4913
6035,5439,5445,5447,4913,4932,4933
6036,5447,5450,5452,4933,4934,4935
6037,5452,5455,5457,4935,4936,4937
6038,5457,5460,5462,4937,4938,4939
6039,5462,5465,5467,4939,4940,4941
6040,5467,5473,5475,4941,4960,4961
6041,5475,5478,5480,4961,4962,4963
6042,5480,5483,5485,4963,4964,4965
6043,5485,5488,5490,4965,4966,4967
6044,5490,5493,5495,4967,4968,4969
6045,5495,5499,5500,4969,5027,5028
6046,5500,5501,5502,5028,5029,5030
6047,5502,5503,5504,5030,5031,5032
6048,5504,5505,5506,5032,5033,5034
6049,5506,5507,5508,5034,5035,5036
6050,5508,5509,5510,5036,5037,5038
6051,5510,5511,5512,5038,5039,5040
6052,5512,5513,5514,5040,5041,5042
6053,5514,5515,5516,5042,5043,5044
```

CRO


```
6054,5516,5517,5518,5044,5045,5046
6055,5518,5519,5520,5046,5047,5048
6056,5520,5521,5522,5048,5049,5050
6057,5522,5523,5524,5050,5051,5052
6058,5524,5525,5526,5052,5053,5054
6059,5526,5527,5528,5054,5055,5056
6060,5528,5529,5530,5056,5057,5058
6061,5530,5531,5532,5058,5059,5060
6062,5532,5533,5534,5060,5061,5062
```

2.6 Material Property Definitions for INTER3 Elements

```
***
*** Material properties for INTER3 (main-fault) elements:
*** Element set FBRITTLE represents fault segments in the brittle zone;
*** Element set FDUCTILE represents those in ductile zone
***
*INTERFACE,ELSET=FBRITTLE
*FRICTION,LAGRANGE
0.8391
*INTERFACE,ELSET=FDUCTILE
*FRICTION,TAUMAX=10.0
0.8391
```

Cr+P

3 Alternative Material Model for AntiThetic Faults

The isotropic material model based on the Drucker-Prager yield criterion was found to be inappropriate for modeling Faults #1 and #2, because yielding occured near the base of the two faults under the initial stress state. The strength parameters (Drucker-Prager friction angle of 50°, dilation angle of 30°, and unconfined compressive strength of 5 MPa) should prevent slip on 75°-dipping planes under the applied initial stress state. On the other hand, because the strength criterion is isotropic, slip may occur in any direction for which the slip criterion is satisfied under the existing stress state. Such slip condition was satisfied near the base of Faults #1 and #2; as a result, the faults (fault zones) yielded as was observed.

For the issues being investigated in the current modeling exercise, it is necessary to restrict slip to fault-parallel directions. As a result, an alternative material model based on the JOINTED-MATERIAL model in ABAQUS, was selected for Faults #1 and #2. Under such a model, the solid elements that represent the faults are modeled as laminated solids with weakness planes oriented parallel to the fault planes. The weakness planes behave like Mohr-Coulomb surfaces, with a friction angle, dilation angle, and cohesion. Therefore, the model is similar to the one applied to the main fault, except that the main-fault model does not account for cohesion.

The model parameters are given in the input-file excerpt reproduced below.

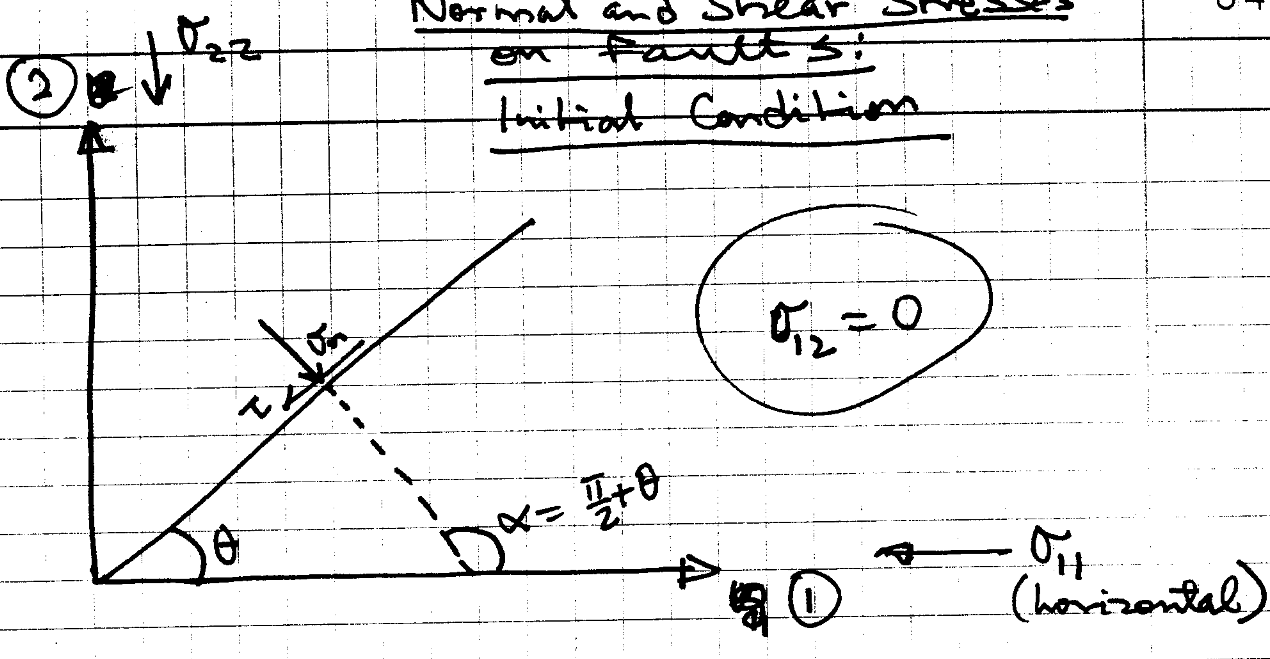
```
***
*** The two antithetic faults (Faults \#1 and \#2) are modeled as
*** laminated solids using the JOINTED MATERIAL model
***
*** Define orientation for the jointed material model
***
*ORIENTATION,NAME=ANFAULTS
-100.0,26.7949,0.0,-100.0,-373.2051,0.0
***
*** Material Definition for the faults
*** One weakness direction (coincident with fault attitude)
*** with friction and dilation angles of 38 and 19 degrees,respectively
*** and cohesive strength of 5 MPa
***
*MATERIAL,NAME=RUBBLE
*DENSITY
2.5E-3
*ELASTIC
3.25E4,0.25
*JOINTED MATERIAL,JOINT DIRECTION=ANFAULTS
38.0,19.0,5.0
*JOINTED MATERIAL,SHEAR RETENTION
0.1
```

March 11 1996

GLD

046

Normal and Shear Stresses ~~on Faults:~~ Initial Condition



$\sigma_{12} = 0$

$$\sigma_n = \sigma_{11}\cos^2\alpha + \sigma_{22}\sin^2\alpha$$

$$\tau = \tfrac{1}{2}(\sigma_{22}-\sigma_{11})\sin 2\alpha$$

$$\sigma_{22} = \gamma d = 25d \text{ MPa} \quad (d \text{ in km})$$

$$\sigma_{11} = k\sigma_{22} = 0.25 \times 25d = 6.25d \text{ MPa}$$

$$\sigma_n = 25d\,(0.25\cos^2\alpha + \sin^2\alpha)$$

$$\tau = -12.5d\,(1-0.25)\sin 2\alpha$$

$$= -9.375d\sin 2\alpha$$

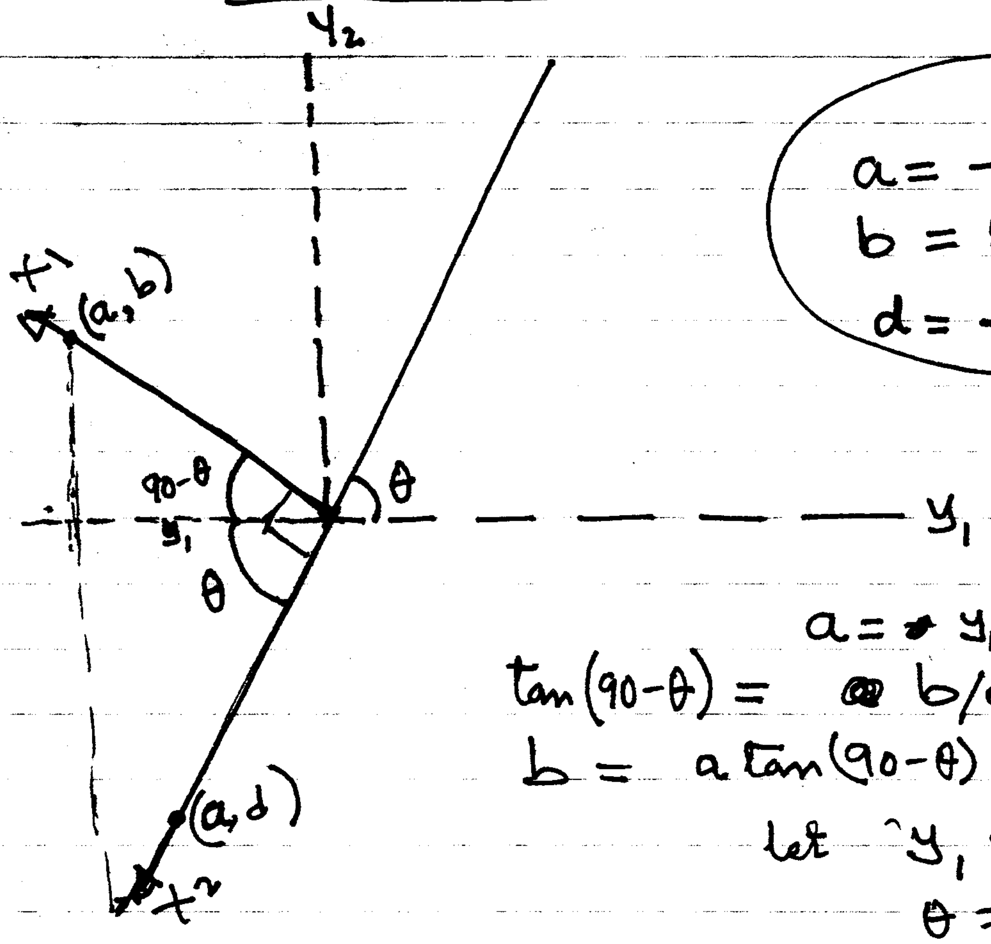
for $\theta = 60^\circ$, $\alpha = 150^\circ$ $\quad$ $\sigma_n = 10.9375$ MPa/km

$\tau = 8.119$ MPa/km

for $\theta = 75^\circ$, $\alpha = 165^\circ$ $\quad$ $\sigma_n = 7.506$ MPa/km

$\tau = 4.6875$ MPa/km

Orientation Definition for Jointed-Material Model



$a = -100$ m
$b = 26.7949$ m
$d = -373.2051$

$$a = y_1$$

$$\tan(90-\theta) = b/a$$

$$b = a\tan(90-\theta) = -y_1 \tan(90-\theta)$$

let $y_1 = 100$
$\theta = 75$

$$a = -100 \text{ m}$$

$$b = 100 \tan 15^\circ = 26.7949$$

$$d = a \tan\theta$$
$$= 100 \tan 75$$
$$= 373.2051$$

GW

047

Case 01

Base Model M04Base.inp.

① ~~App~~ Establish initial equilibrium state using base model

② Apply perturbation (as described below) using file C01.inp

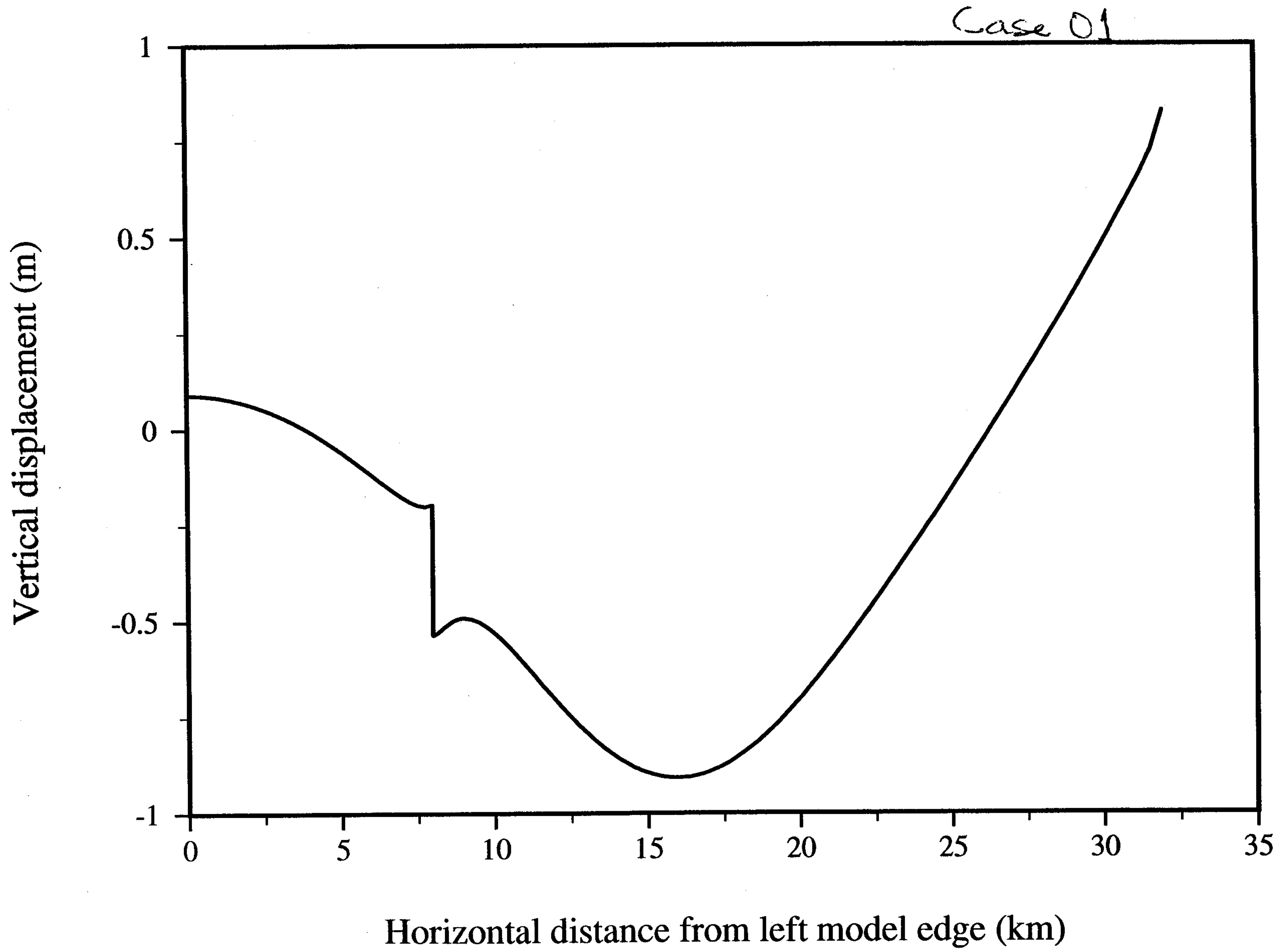
Perturbation

① 0.005 m/yr steady velocity (x-direction) on node set NDHWBASE

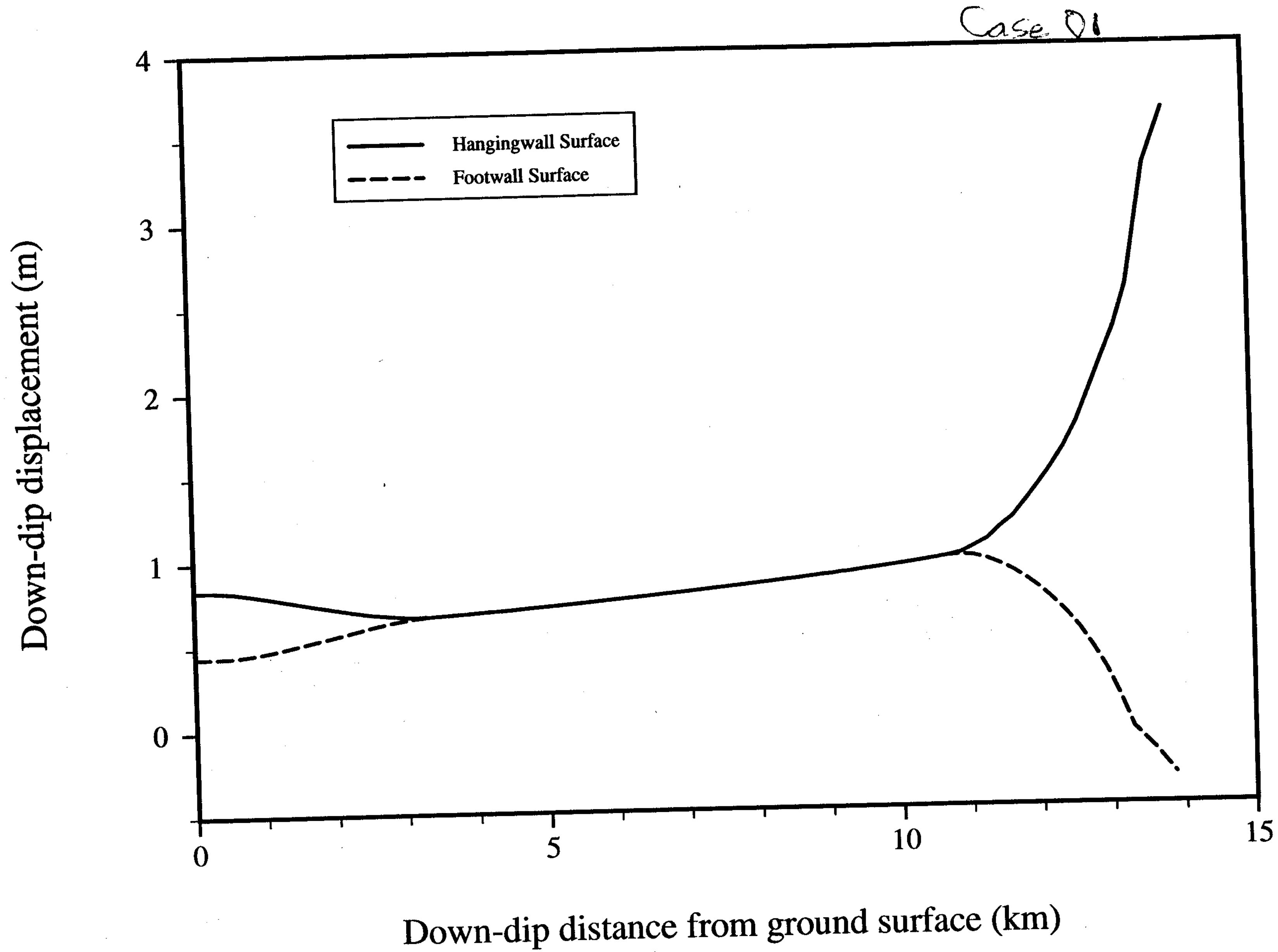
② -0.005 m/yr steady velocity (x-direction) on node set NDFOBASE

Velocity applied for ~~a~~ 500 yrs.

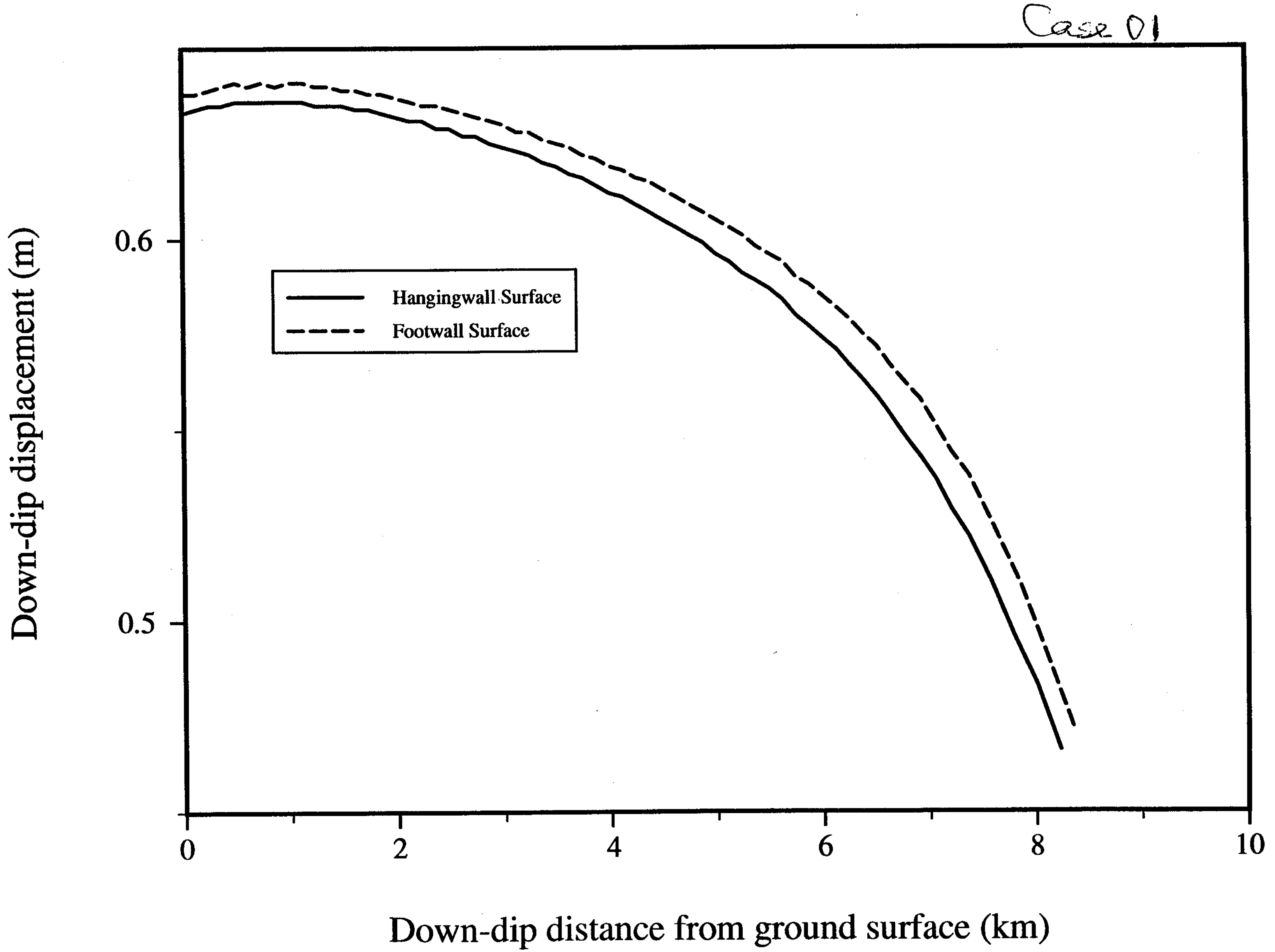
Ground Surface Profile



Surface Displacements on Main Fault

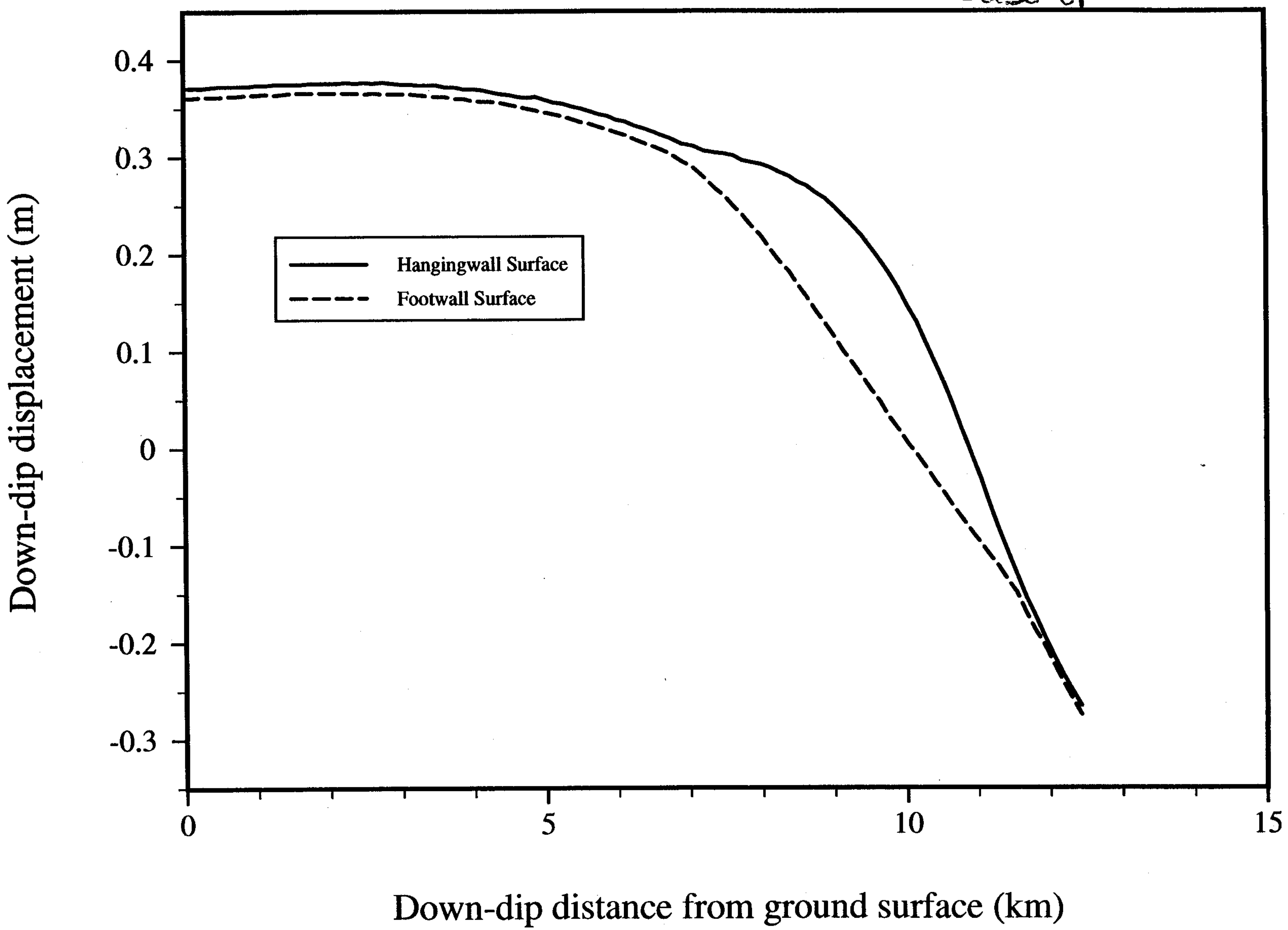


Surface Displacements on Fault #1



Surface Displacements on Fault #2

Case 01



CR10

GW

045

March 15

Decision made to modify the FE mesh slightly to eliminate (round) the sharp angle at the intersection of steep and low-angle segments of main fault.

GWD

042

Modified Nodal Coordinates

Node	X	Y
4909	1.4928E4	125.0
4906	1.4784E4	312.5
4910	1.5178E4	62.5
5410	(same as 4906)	
5415	(same as 4909)	
5432	(same as 4910)	
5414	1.46781E4	62.5
5423	1.49282E4	-187.5

New Node

9001	1503375E4	312.5

Modified Element

El. Num	Type	Incidences
1586	CPE6	840, 842, 4909, 841, 4906, 9001

New Element

4001	CPE6	840, 4909, 4911, 9001, 4910, 4907

Element 1586 and 4001 belong to Element Set HWDUCTIL

GW

Other Changes

Change the node-set classification of the following nodes

Node	Move from Node Set	Add to Node Set
4909	NDHWBASE	NDHWLEFT
4910	NDHWBASE	NDHWLEFT
5415	NDF0BASE	NDF0LEFT
5432	NDF0BASE	NDF0LEFT

Recall ① +x steady velocity applied at node set NDHWBASE

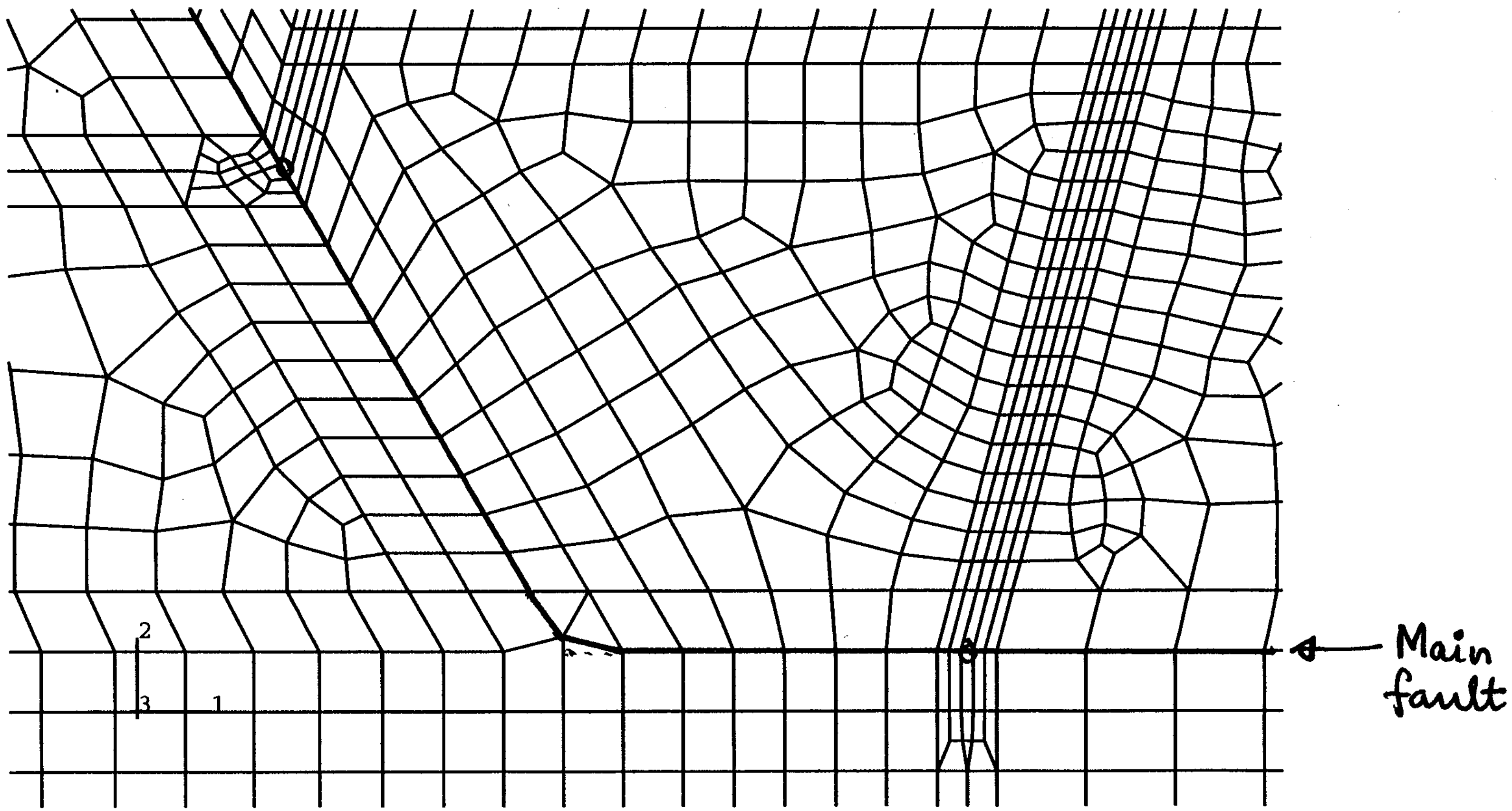
② −x steady velocity applied at node set ~~NDHW~~ NDF0BASE

③ Node sets NDHWLEFT and NDF0LEFT used to compute fault displacement on main fault.

ABAQUS

Portion of Modified Mesh

from input file m05Base.inp



BNO

051

Shear Strength of Detachment Fault

Shear strength of detachment given by the equation

$$\tau - \tau_{max} = 0$$

τ = shear stress

τ_{max} = constant shear strength.

Refer to attached excerpt (next page) from Engelder's textbook and paper by Bruhn and Schultz (1996) — JGR, 101(B2): 3401-3412 — for support of the applied shear-strength model.

τ_{max} = 100 MPa (based on the value of τ on 60°-dipping plane — dip of high-angle segment of main fault — at 12-km depth).

Shear-strength model implemented as

$$\tau = \mu\sigma_{max} \quad \text{for } \tau < \tau_{max}$$

$$\tau = \tau_{max} \quad \text{otherwise.}$$

Case 02

Base model: m05Base.inp

Analysis model: c02.inp

① Establish initial equilibrium state using base model.

② Apply perturbation as described below using analysis model

Perturbation

① 0.005 m/yr steady velocity in X-direction on node set NDHWBASE

② -0.005 m/yr steady velocity in x-direction on node set NDFOBASE

Apply velocity for 500 yrs.

Fault displacement on main-fault steep segment, based on Case 02, plotted on next page. Slip occurred over a fault length of about ~~25~~ 2.5 km (depth of about 2 km) at the top, ~~and length of about~~ and at the base of the fault.

Case 03

Case 03 differs from Case 02 in the perturbation step, which was run as follows:

~~① Appt~~

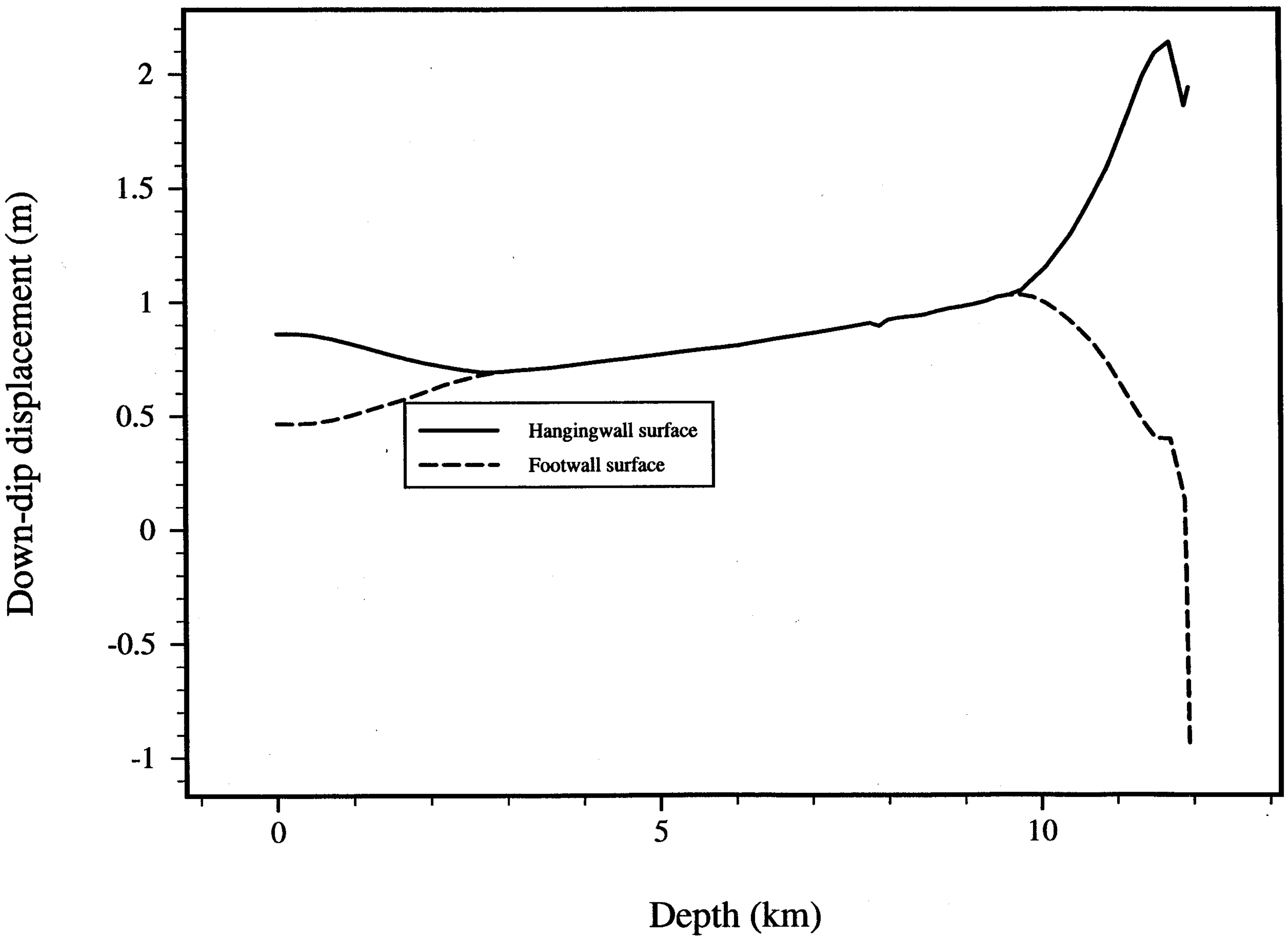
Perturbation of Case 03

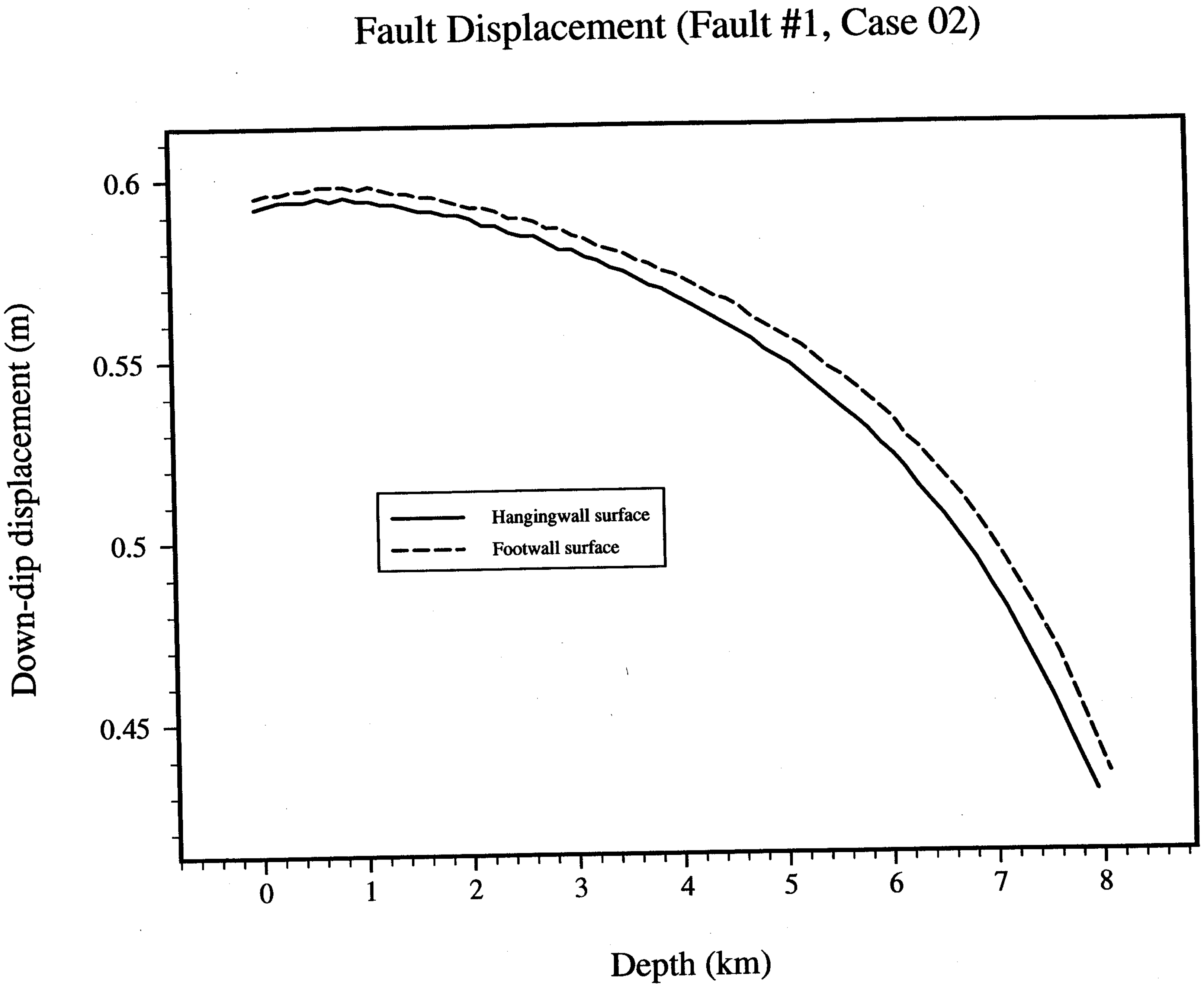
① 5 m x-displacement on node set NDHWBASE

② −5 m x-displacement on NDF0BASE

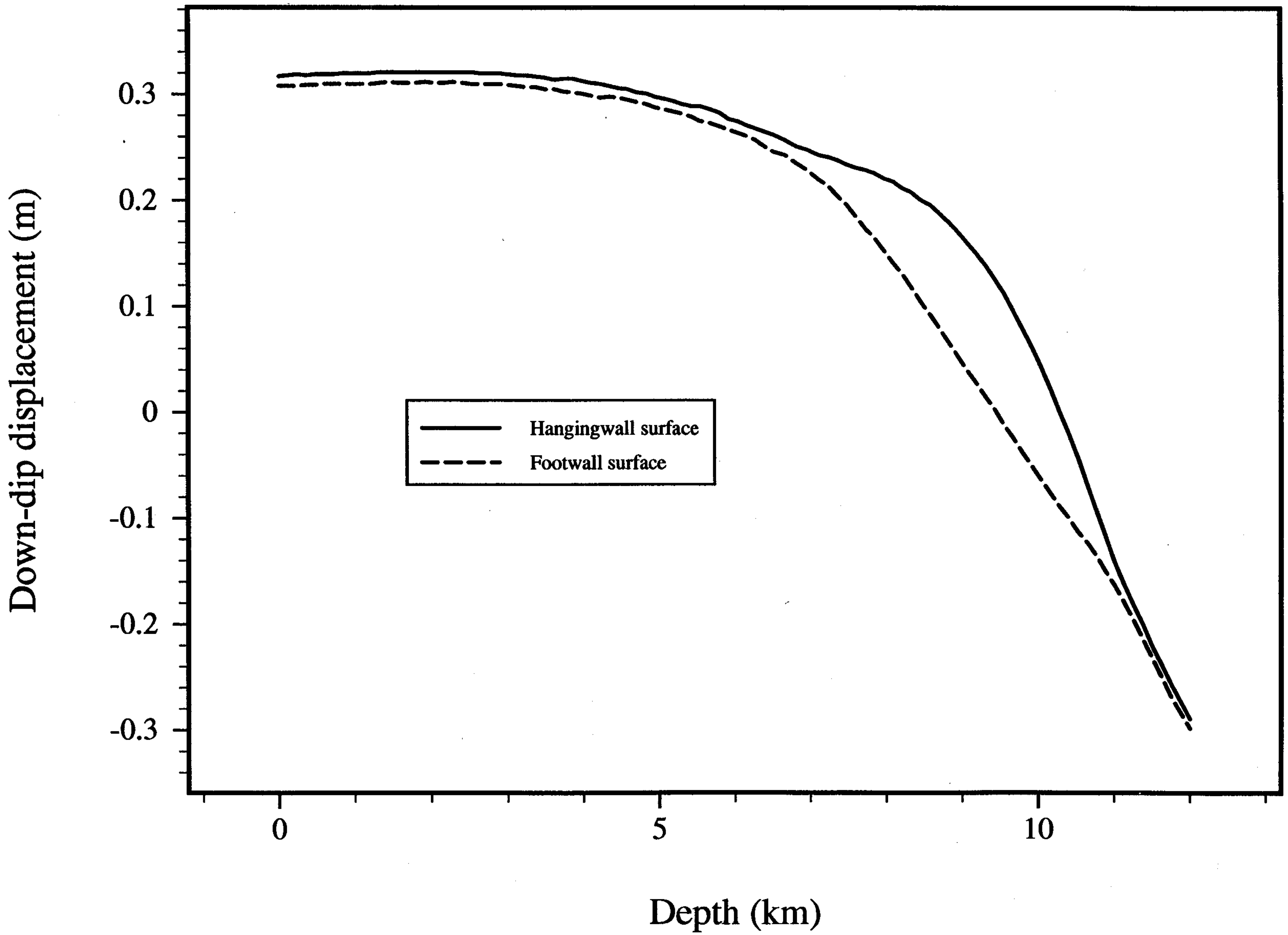
Results of Cases 02 and 03 are similar except that Fault #2 slipped in Case 02 but not in Case 03.

Fault Displacement (Main Fault, Case 02)

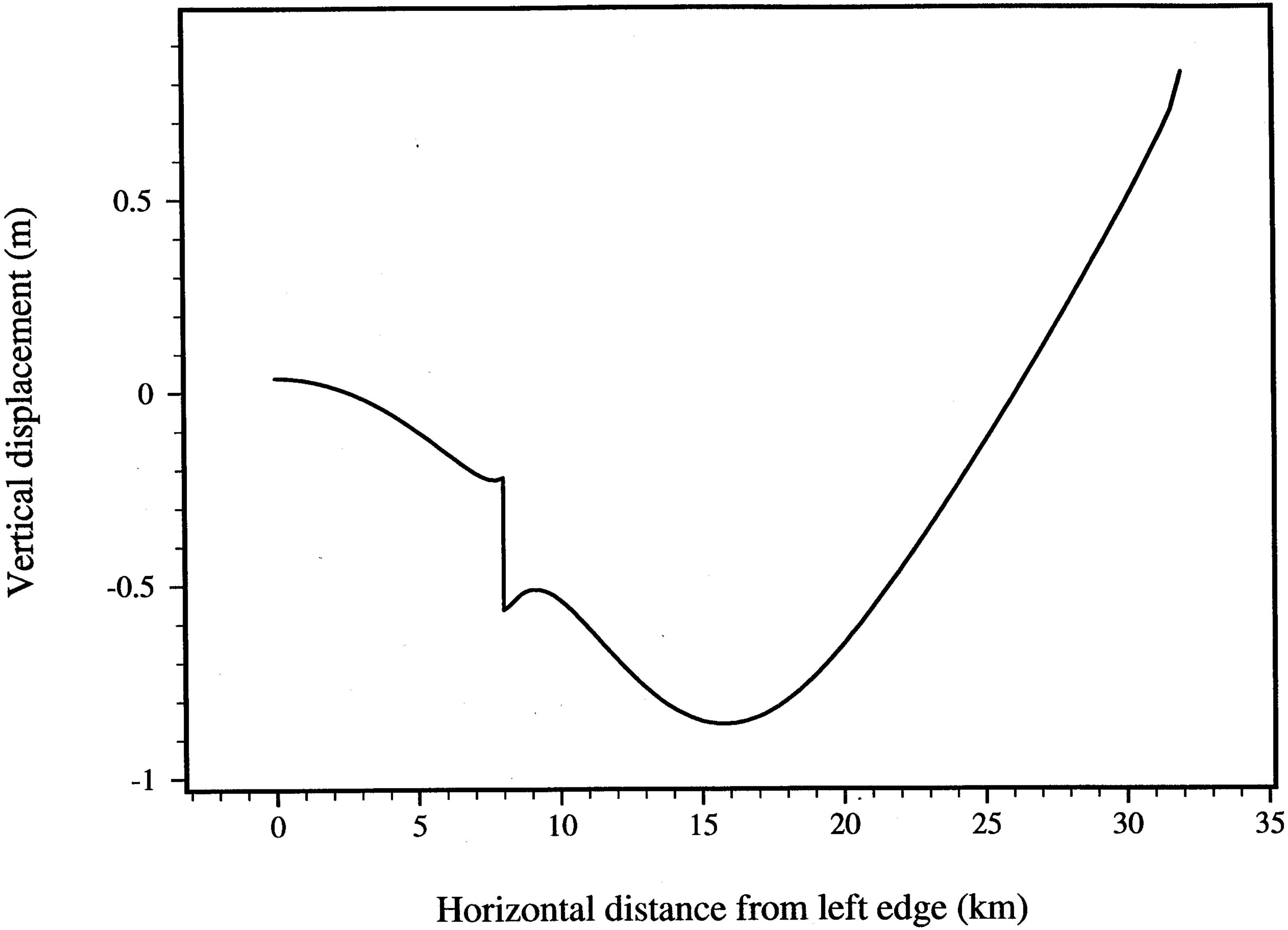



Fault Displacement (Fault #1, Case 02)
Down-dip displacement (m)
0.6
0.55
0.5
0.45
0
1
2
3
4
5
6
7
8
Depth (km)
Hangingwall surface
Footwall surface

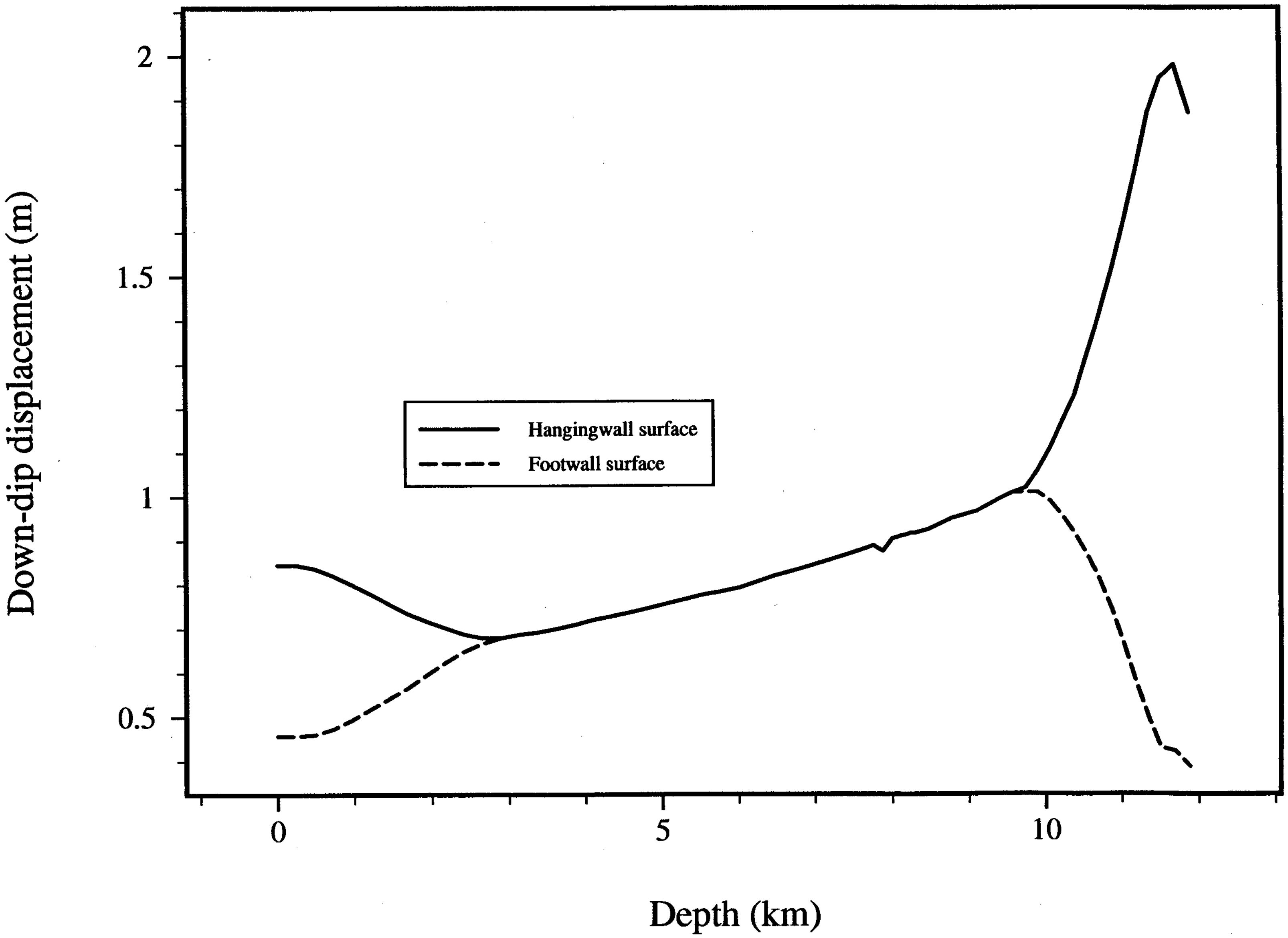
Fault Displacement (Fault #2, Case 02)

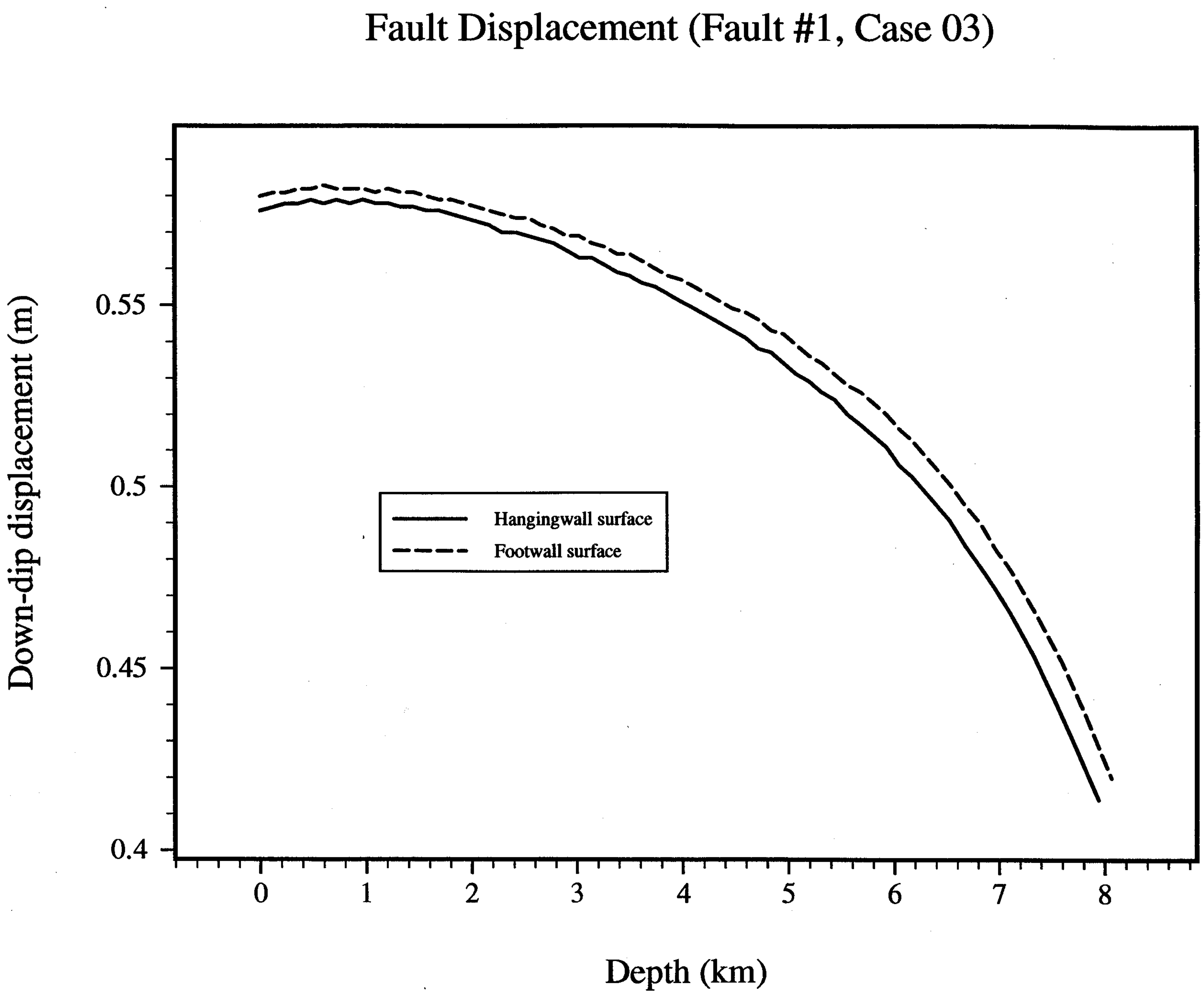


Ground Surface Profile (Case 02)



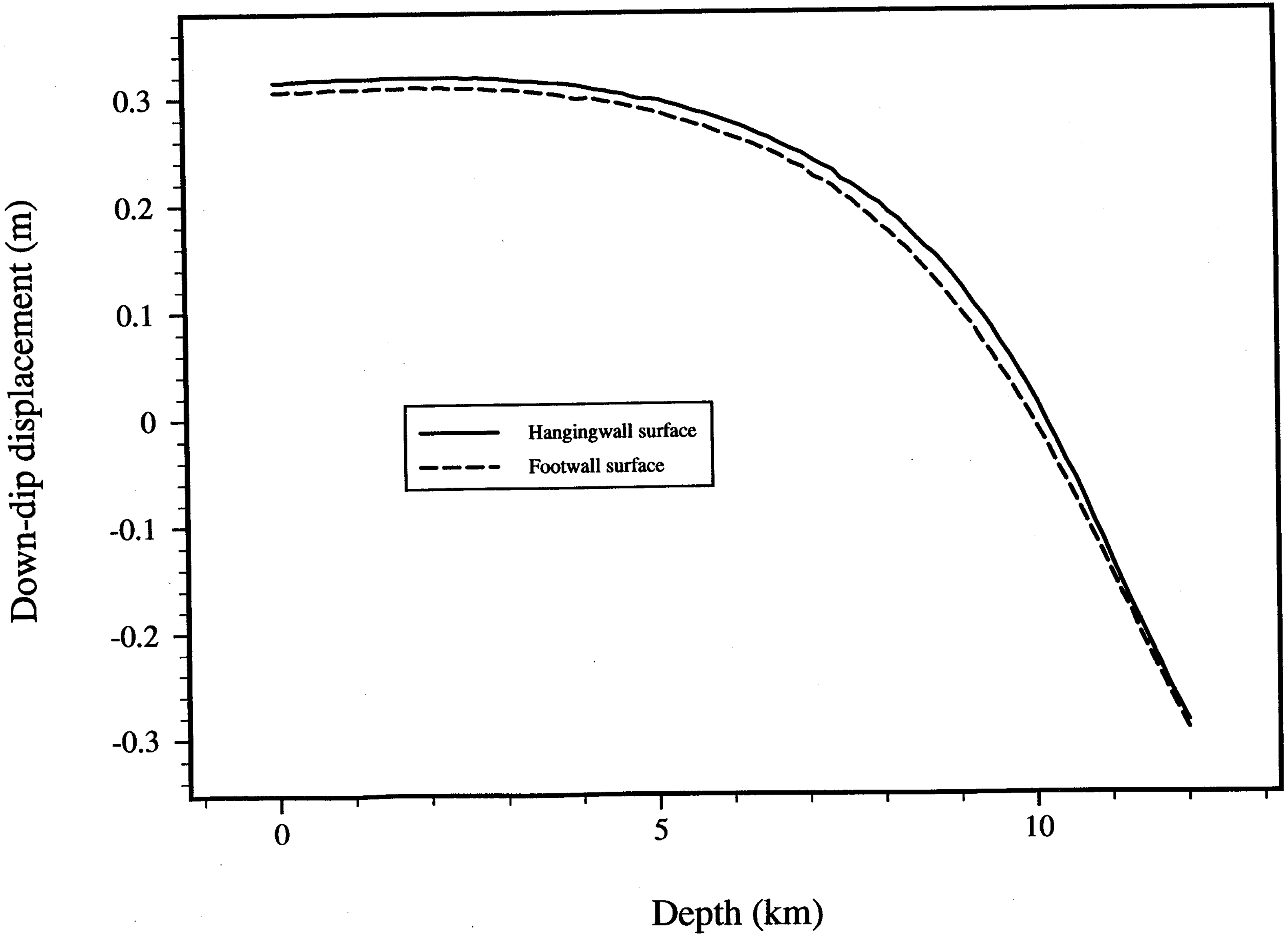
Fault Displacement (Main Fault, Case 03)



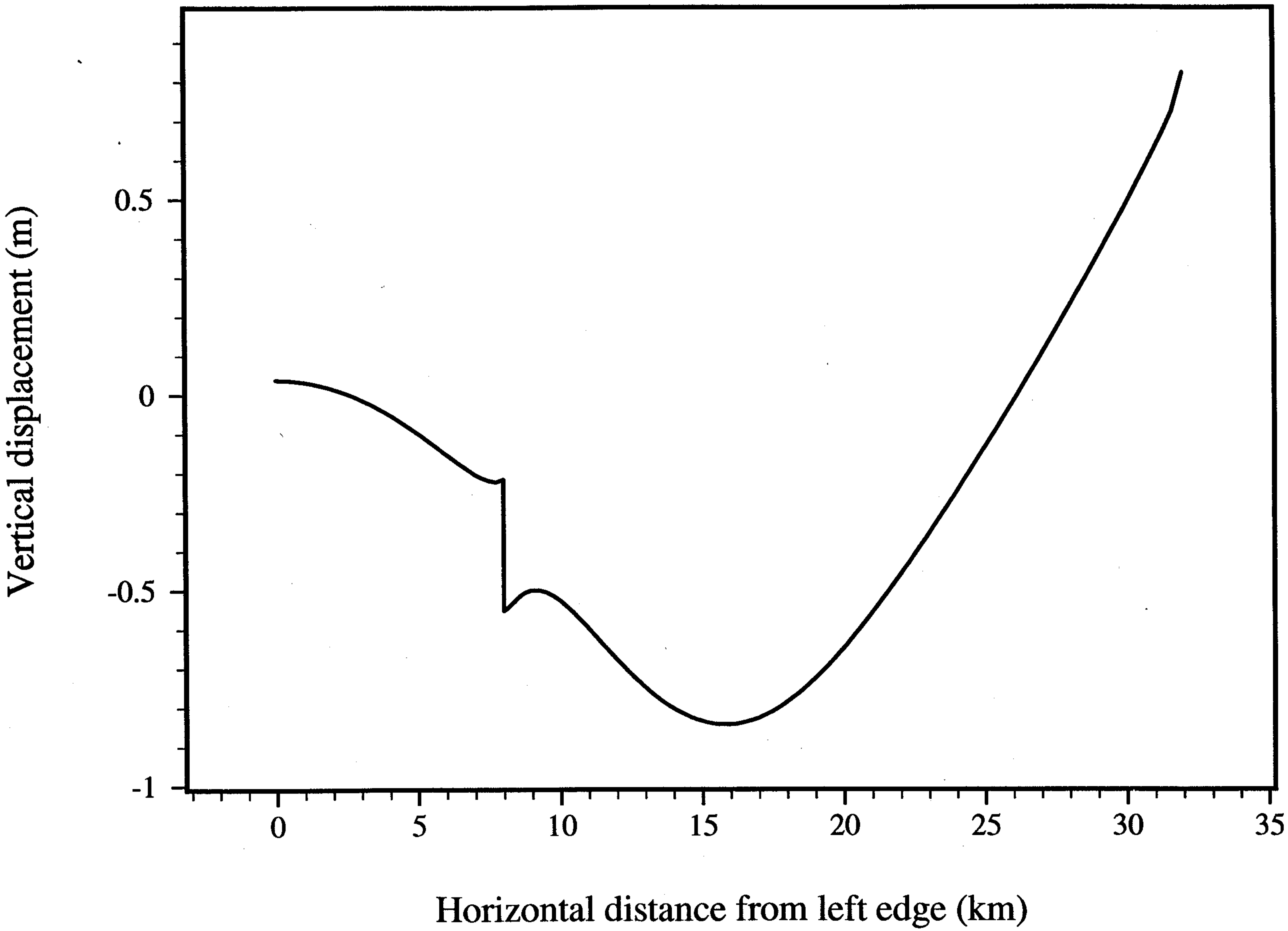


Fault Displacement (Fault #1, Case 03)
Down-dip displacement (m)
0.55
0.5
0.45
0.4
0
1
2
3
4
5
6
7
8
Depth (km)
Hangingwall surface
Footwall surface

Fault Displacement (Fault #2, Case 03)



Ground Surface Profile (Case 03)



QUO

Case 04

Base Model: m05Base.inp

Analysis Step: C04.inp

Procedure

Establish initial equilibrium using base model. Then perturb equilibrium as following in the analysis step:

① 12.5 m x-displacement on ~~ND~~HWBASE

② −12.5 m x-displacement on NDFOBASE

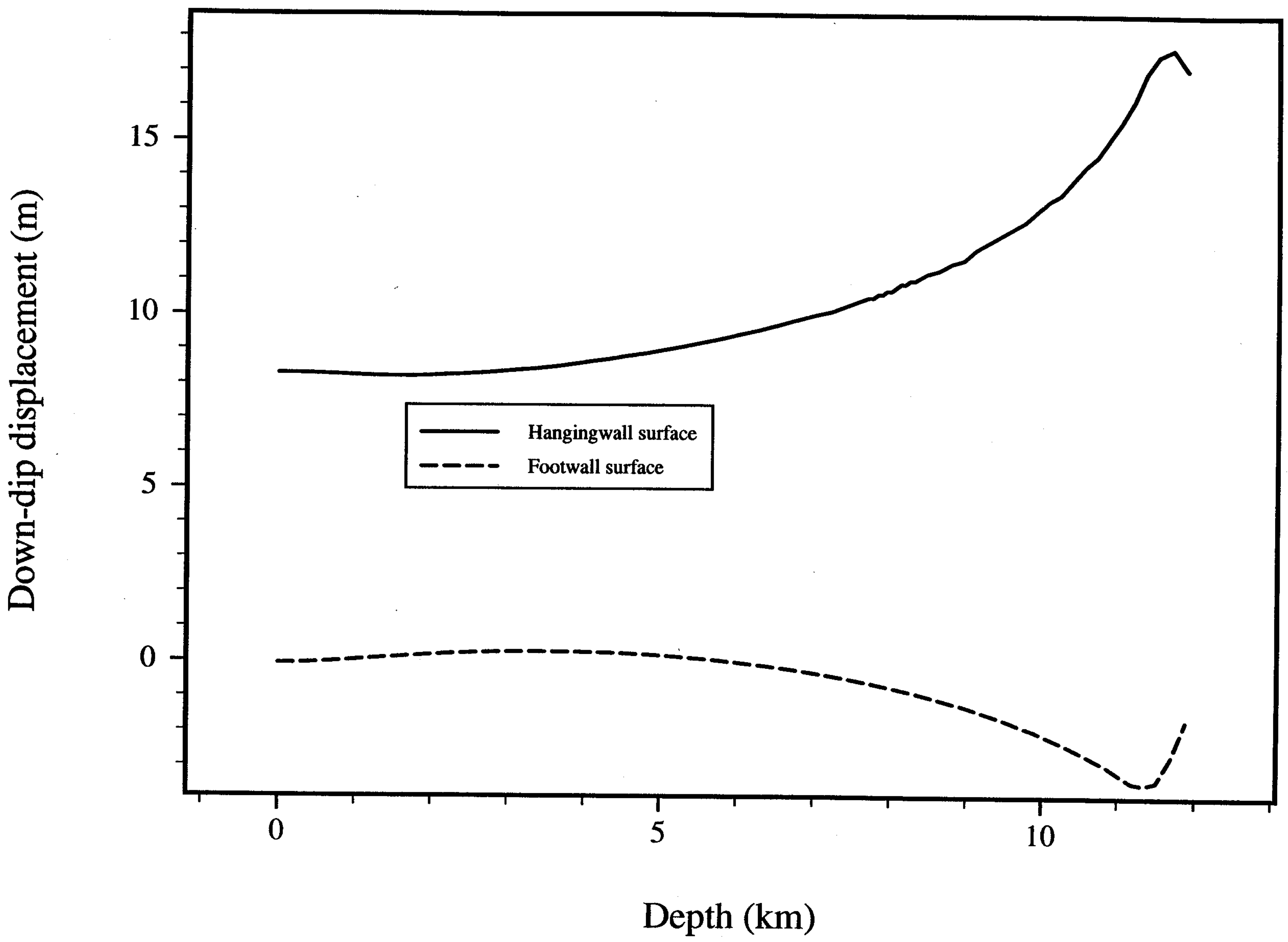
which gives 25-m fault displacement on the detachment fault, partitioned 50/50 b/w hangingwall and footwall.

Results show:

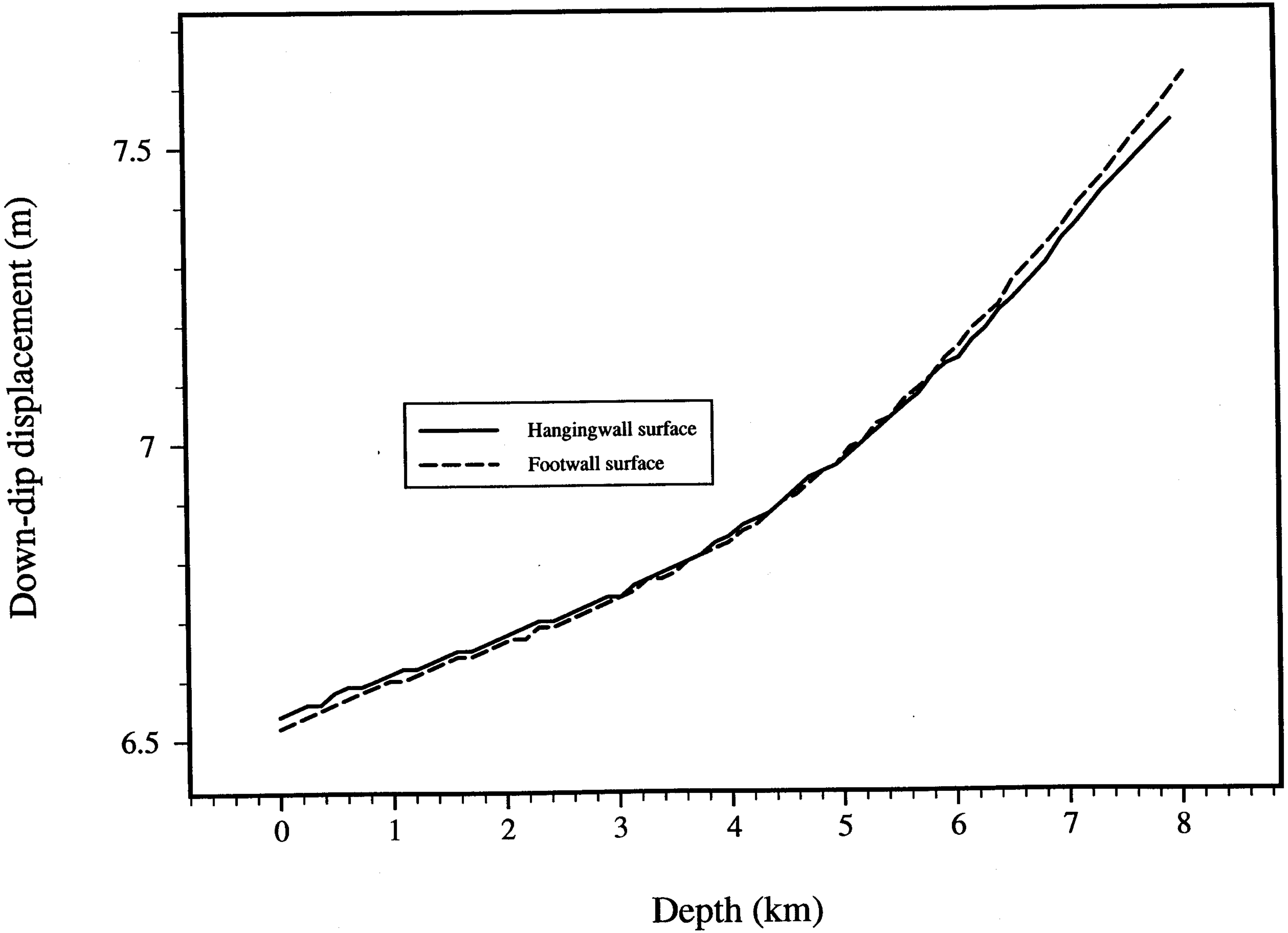
① Slip along entire length of main fault, & varying from 8 m at the ground surface to 21 m at the base.

② No noticeable slip on Faults #1 and #2

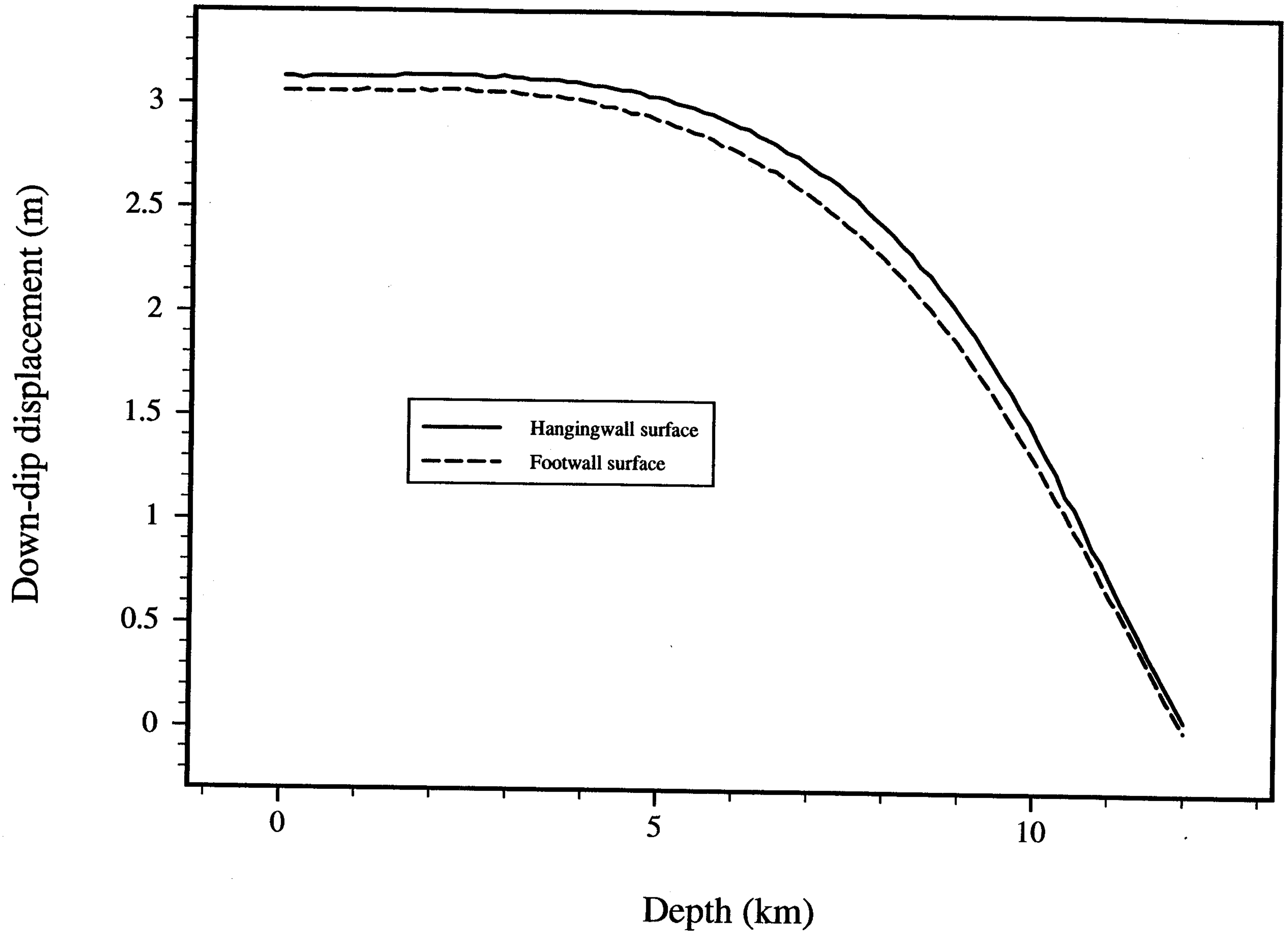
Fault Displacement (Main Fault, Case 04)



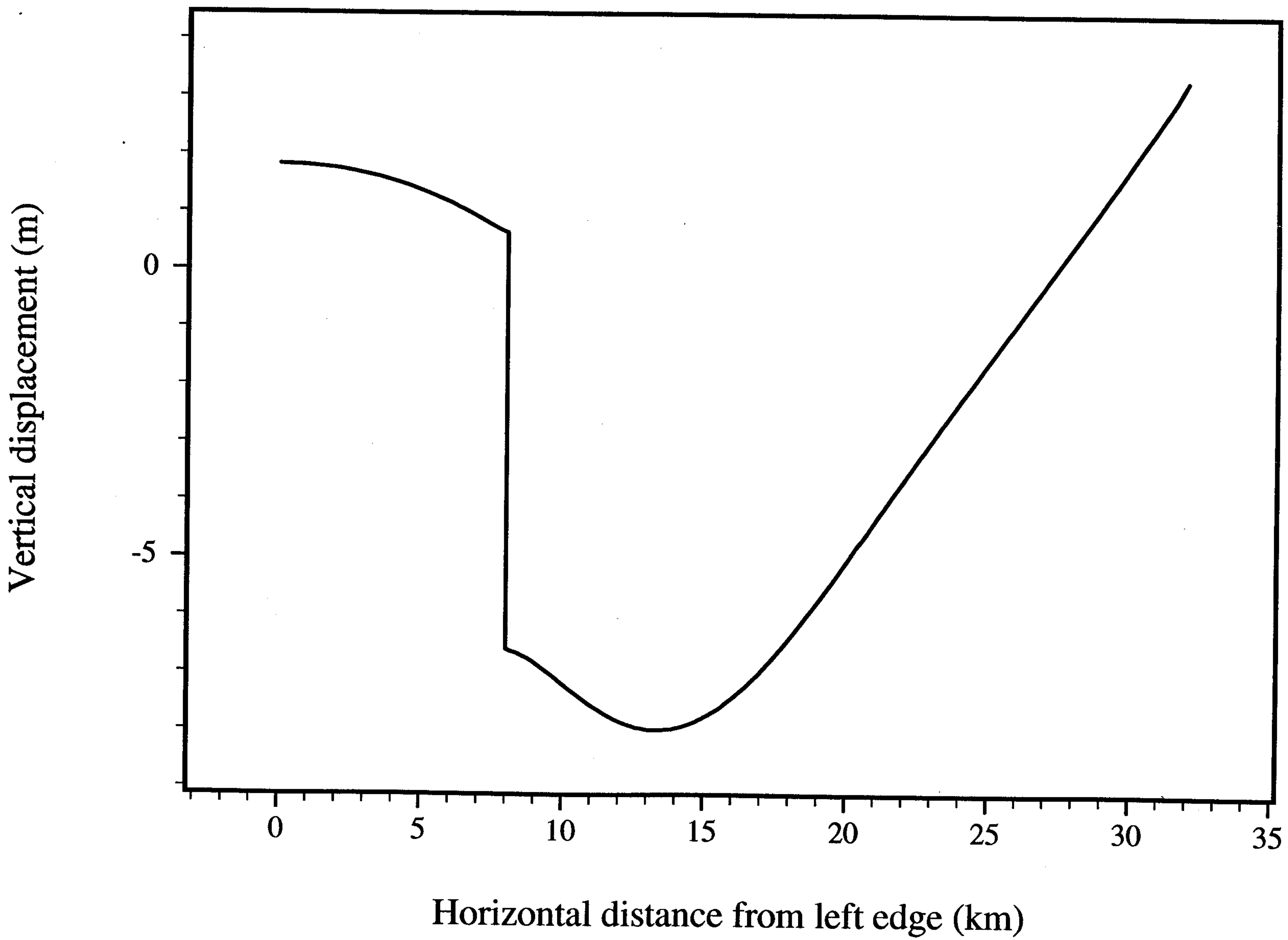
Fault Displacement (Fault #1, Case 04)



Fault Displacement (Fault #2, Case 04)



Ground Surface Profile (Case 04)



055

Case C05

Base Model: m05Base.inp

Analysis Model: C05.inp

Initial static equilibrium established using m05Base.inp. Thereafter, a relative velocity of 1 cm/yr is applied between the footwall and hangingwall of the detachment fault for 1000 yrs. The velocity is partitioned 50/50 b/w hangingwall and footwall. Displacement history is recorded on the footwall and hanging wall of the three faults (except the detachment) at fault-length intervals of about 1 km from the ground surface.

Q/B

4 Computation of Down-Dip Displacement

The magnitude of down-dip displacement on a fault surface was computed using the ABAQUS-calculated x- and y-displacements (u_x and u_y, respectively) at nodes on the surface. The computations were done using the following transformation:

$$u_{fs} = u_x \cos\theta + u_y \sin\theta \tag{1}$$

where θ is the inclination of the fault surface, counterclockwise from the positive x-axis.

The results of the computations for the hangingwall and footwall surfaces of a given fault were stored in separate files. Each of the files is a 5-column table with the following parameters:

1. Node number;
2. depth from ground surface in km;
3. down-dip fault length (km) from ground surface;
4. inclination of surface at the node (i.e., angle θ); and
5. down-dip displacement of the node, relative to its position at the initial state, i.e., $-u_{fs}$ in Equation (1).

Each of the files is assigned a name such as cNNFFSSdisp.dat, where NN is a two-digit analysis-case number, FF is the fault number (i.e., f0, f1, or f2), and SS is the fault surface (either hw for hangingwall or fw for footwall).

4.1 C Code for Computation of Down-Dip Displacement

The computations were done using the following C code, stored in file "FaultSurfaceDisp.c". To use the code, compile it using a unix C compiler and run it using the following command

progName NUM

where NUM is the fault number (0, 1, or 2).

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

typedef struct Point {
  int node;
  float x,y,ux,uy,td,theta;
  struct Point *next;
};

main(argc, argv)
```

GtW


```
  int argc;
  char* argv[];
{

/*
  This code sorts nodal points on a fault surface in a down-dip order;
  calculates down-dip displacement at the nodes using values of x- and
  y-displacements at the nodal points; and calculates down-dip distance
  from the ground surface using nodal point x and y coordinates.
  It reads nodal data from a file created using ABAQUS/Post function
  PRINT NODES. Slope of fault segments calculated based on assumption
  that each set of three consecutive nodal points lie on a straight line

*/

  char buf[121];
  int node,fnum;
  float x,y,ux,uy,angle,pi;
  struct Point *FirstPoint,*LastPoint,*currentPoint;

/* Process command-line argument to determine fault dip */

  if (argc < 2)
    DumpAndQuit("Usage: ProgramName faultNumber");

  fnum = atoi(argv[1]);
  if (fnum<0 || fnum>2){
    sprintf(buf,"Fault number %d is not valid",fnum);
    DumpAndQuit(buf);
  }
  pi = 4.0*atan(1.0);
  if (fnum > 0)
    angle = 75.0*pi/180.0;

/*
  Read input file for nodal point data
  Setup storage and store nodal data in a linked list
  sorted in down-dip order
*/

  FirstPoint = LastPoint = NULL;
  while (gets(buf))
    if (sscanf(buf,"%d %f %f %f %f",&node,&x,&y,&ux,&uy) == 5){
      currentPoint = (struct Point *)malloc(sizeof(struct Point));
      if (!currentPoint)
        DumpAndQuit("Memory allocation failure");
```

Ch6


```
      currentPoint->node = node;
      currentPoint->x = x;
      currentPoint->y = y;
      currentPoint->ux = ux;
      currentPoint->uy = uy;
      if (fnum > 0) currentPoint->theta = angle;
      StorePoint(currentPoint,&FirstPoint,&LastPoint);
    }

/*
  Calculate slope of fault segment at each nodal point;
  calculate down-dip distance at each point;
  then print out the nodal point data in down-dip order
*/

  if (fnum==0) FaultSlopeAtPoint(FirstPoint);
  DownDipDistance(FirstPoint);
  PrintPoints(FirstPoint);
}

StorePoint(current,first,last)
  struct Point *current,**first,**last;
{
  struct Point *old,*p;

  p = *first;

  if (!*last){          /* current is the very first item in the list */
    current->next = NULL;
    *last = current;
    *first = current;
    return;
  }

  old = NULL;
  while (p){
    if (IsBelow(current,p)){
      old = p;
      p = p->next;
    }
    else{
      if (old) {      /* insert current at this point in the list */
        old->next = current;
        current->next = p;
        return;
      }
```

GHO


```
      current->next = p;    /* current becomes new first element */
      *first = current;
      return;
    }
  }

  (*last)->next = current;  /* current becomes new last element */
  current->next = NULL;
  *last = current;
}

PrintPoints(first)
  struct Point *first;
{

  float y0,angle,pi,ca,sa;

  if (!first)
    DumpAndQuit("Empty list submitted for printing");

  printf("%10s%12s%12s%12s%12s\n",
    "Node","Depth-km","fLen-km","Dip","fDisp-m");

  pi = 4.0*atan(1.0);
  y0 = first->y;

  while (first){
    ca = cos(first->theta);
    sa = sin(first->theta);
    printf("%10d%12.2f%12.2f%12.2f%12.2E\n",
      first->node,
      1.0e-3*(y0 - first->y),
      1.0e-3*first->td,
      (180.0/pi)*first->theta,
      -(ca*first->ux + sa*first->uy)
    );
    first = first->next;
  }
}
int IsBelow(current,p)
  struct Point *current,*p;
{
  int below,notBelow;
  float delta,yTol;

  /*
```

QAQ


```
    This code module determines whether first-named Point
    is down-dip (below) or up-dip of second-named Point.
    It will not work for horizontal surfaces.
*/

  below = 1;
  notBelow = 0;
  yTol = 0.05;

  delta = current->y - p->y;
  if (delta < -yTol)
    return(below);

  return(notBelow);
}

DownDipDistance(first)
  struct Point *first;
{
  float x0,y0,x1,y1,td;

/*
   This code module computes the down-dip distance of Points
   along a fault surface
*/

  if (!first)
    DumpAndQuit("Empty list submitted for distance calculation");

  x0 = first->x;
  y0 = first->y;
  td = 0;

  while (first){
    x1 = first->x;
    y1 = first->y;
    td += sqrt((x1-x0)*(x1-x0) + (y1-y0)*(y1-y0));
    first->td = td;
    x0 = x1;
    y0 = y1;
    first = first->next;
  }
}

FaultSlopeAtPoint(first)
  struct Point *first;
```

Gtto


```
{
  float angle;
  struct Point *pFirst,*pMid,*pEnd;

/*
  Calculate slope of fault segments at nodal points, consecutive sets of
  three rectilinear Points in down-dip order
*/

  if (!first)
    DumpAndQuit("Empty list submitted for slope calculation");

/*
  Process first segment (set of 3 nodes). Issue error message if
  there are less than 3 nodes in the list.
*/

  pFirst = first;
  pMid = pFirst->next;
  if (!pMid)
    DumpAndQuit("Only one node in list submitted for slope calculation");
  pEnd = pMid->next;
  if (!pEnd)
    DumpAndQuit("Only two nodes in list submitted for slope calculation");
  angle = atan2((pFirst->y - pEnd->y),(pFirst->x - pEnd->x));
  pFirst->theta = pMid->theta = angle;
  pEnd->theta = !(pEnd->next) ? angle : angle/2.0;

 /* Process the rest of the segments */

  pFirst = pEnd;
  while (pFirst){
    pMid = pFirst->next;
    if (!pMid) break;   /* Previous segment is the last one */

    pEnd = pMid->next;
    if (!pEnd){     /* Midnode of current segment is the last node */

      angle = atan2((pFirst->y - pMid->y),(pFirst->x - pMid->x));
      pFirst->theta += angle/2.0;
      pMid->theta = angle;
    }
    else{  /* This segment has three nodes; there may be another segment */

      angle = atan2((pFirst->y - pEnd->y),(pFirst->x - pEnd->x));
      pFirst->theta += angle/2.0;
```

GtO


```
      pMid->theta = angle;
      pEnd->theta = !(pEnd->next) ? angle : angle/2.0;
    }
    pFirst = pEnd;
  }
}

DumpAndQuit(s)
char *s;
{
  printf("\n *** %s ***\n\n",s);
  exit(0);
}
```

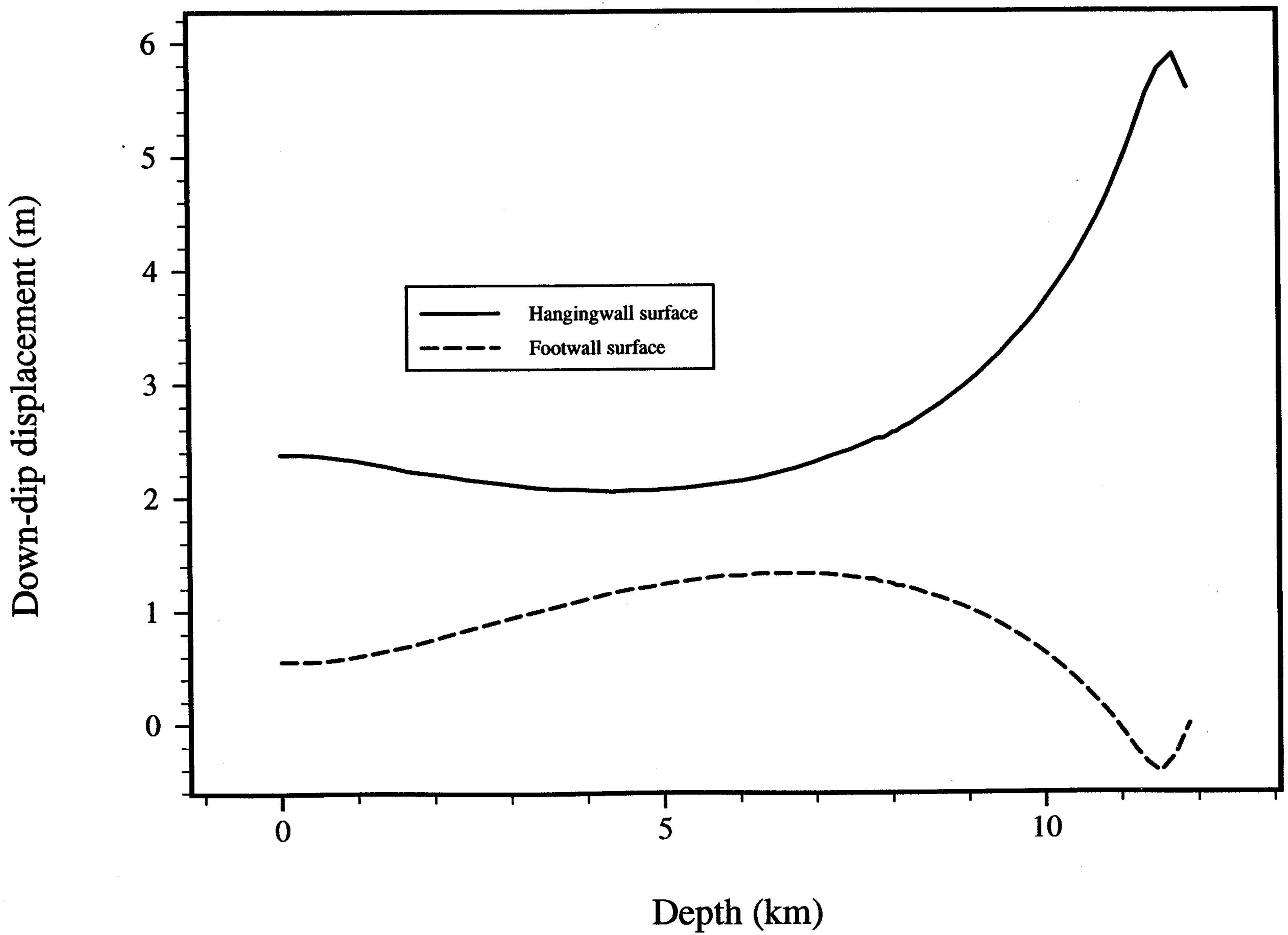
4.2 Typical Output From FaultSurfaceDisp.c Code

The following data from file c05f0fwdisp.dat is a typical output from the code reproduced above. The information in such files were used to produce the plots of down-dip displacement given in this notebook.

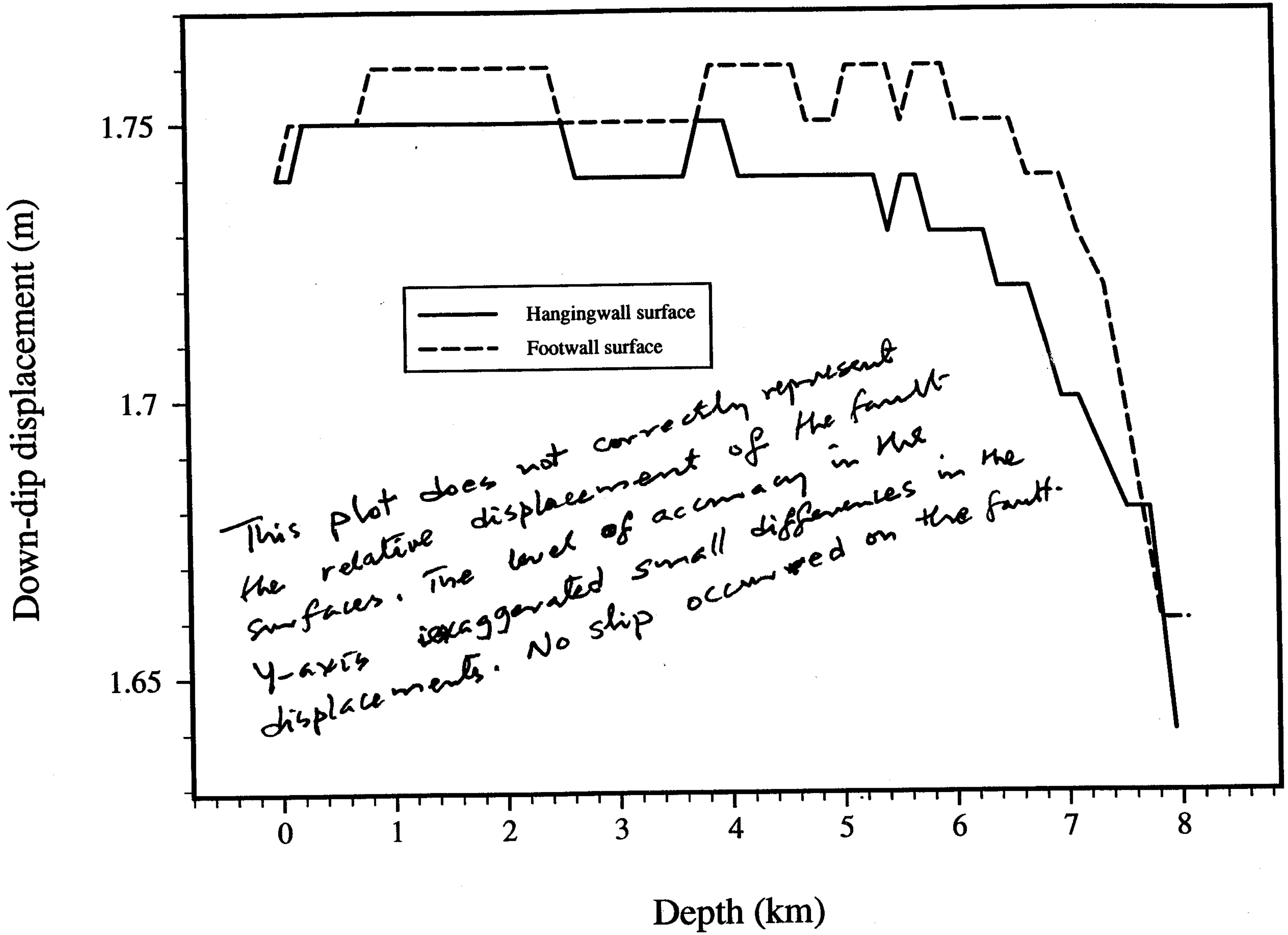
Node	Depth-km	fLen-km	Dip	fDisp-m
5232	0.00	0.00	120.08	5.56E-01
5230	0.24	0.28	120.08	5.54E-01
5227	0.48	0.55	120.08	5.56E-01
5225	0.72	0.83	120.08	5.72E-01
5222	0.96	1.11	120.08	5.96E-01
5220	1.20	1.39	120.08	6.27E-01
5217	1.44	1.66	119.82	6.60E-01
5215	1.69	1.95	119.57	6.96E-01
5212	1.93	2.23	119.88	7.41E-01
5210	2.17	2.50	120.18	7.88E-01
5207	2.41	2.78	120.10	8.32E-01
5205	2.65	3.06	120.03	8.75E-01
5202	2.89	3.34	120.00	9.18E-01
5200	3.13	3.61	119.97	9.61E-01
5197	3.37	3.89	119.82	1.00E+00
5195	3.61	4.17	119.67	1.04E+00
5192	3.85	4.45	119.91	1.08E+00
5190	4.09	4.72	120.15	1.12E+00
5187	4.33	5.00	120.18	1.16E+00
5185	4.57	5.28	120.20	1.19E+00
5182	4.82	5.56	120.18	1.21E+00
5180	5.06	5.84	120.15	1.24E+00
5177	5.30	6.12	120.18	1.26E+00
5175	5.54	6.40	120.20	1.28E+00
5172	5.78	6.67	119.73	1.30E+00

5170	6.02	6.95	119.26	1.30E+00
5167	6.26	7.23	119.73	1.32E+00
5165	6.50	7.50	120.20	1.32E+00
5162	6.74	7.78	120.18	1.32E+00
5160	6.98	8.06	120.15	1.32E+00
5157	7.22	8.34	120.18	1.31E+00
5155	7.46	8.62	120.20	1.29E+00
5118	7.70	8.90	120.34	1.27E+00
5110	7.76	8.96	120.47	1.27E+00
5104	7.82	9.04	118.71	1.25E+00
5096	7.88	9.10	116.95	1.24E+00
5090	7.94	9.17	118.81	1.24E+00
5082	8.00	9.24	120.68	1.23E+00
5072	8.06	9.31	120.68	1.21E+00
5068	8.12	9.38	120.68	1.21E+00
5066	8.18	9.44	120.57	1.20E+00
5065	8.24	9.51	120.47	1.19E+00
5063	8.30	9.58	119.91	1.18E+00
5325	8.46	9.76	119.36	1.14E+00
5330	8.62	9.95	119.99	1.11E+00
5333	8.78	10.14	120.62	1.07E+00
5338	8.94	10.32	119.99	1.03E+00
5341	9.10	10.50	119.36	9.82E-01
5346	9.26	10.69	120.03	9.31E-01
5349	9.42	10.88	120.70	8.75E-01
5354	9.58	11.06	119.99	8.12E-01
5357	9.74	11.25	119.28	7.43E-01
5362	9.90	11.43	119.99	6.69E-01
5365	10.06	11.62	120.70	5.87E-01
5370	10.22	11.80	119.99	4.99E-01
5373	10.38	11.99	119.28	4.03E-01
5378	10.54	12.17	119.99	2.99E-01
5381	10.70	12.36	120.70	1.86E-01
5386	10.86	12.54	119.99	6.89E-02
5389	11.02	12.72	119.28	-7.67E-02
5394	11.18	12.91	119.99	-2.30E-01
5397	11.34	13.10	120.70	-3.57E-01
5402	11.50	13.28	124.21	-4.35E-01
5410	11.69	13.52	127.72	-2.89E-01
5415	11.88	13.76	127.72	-6.75E-03

Fault Displacement (Main Fault, Case 05)



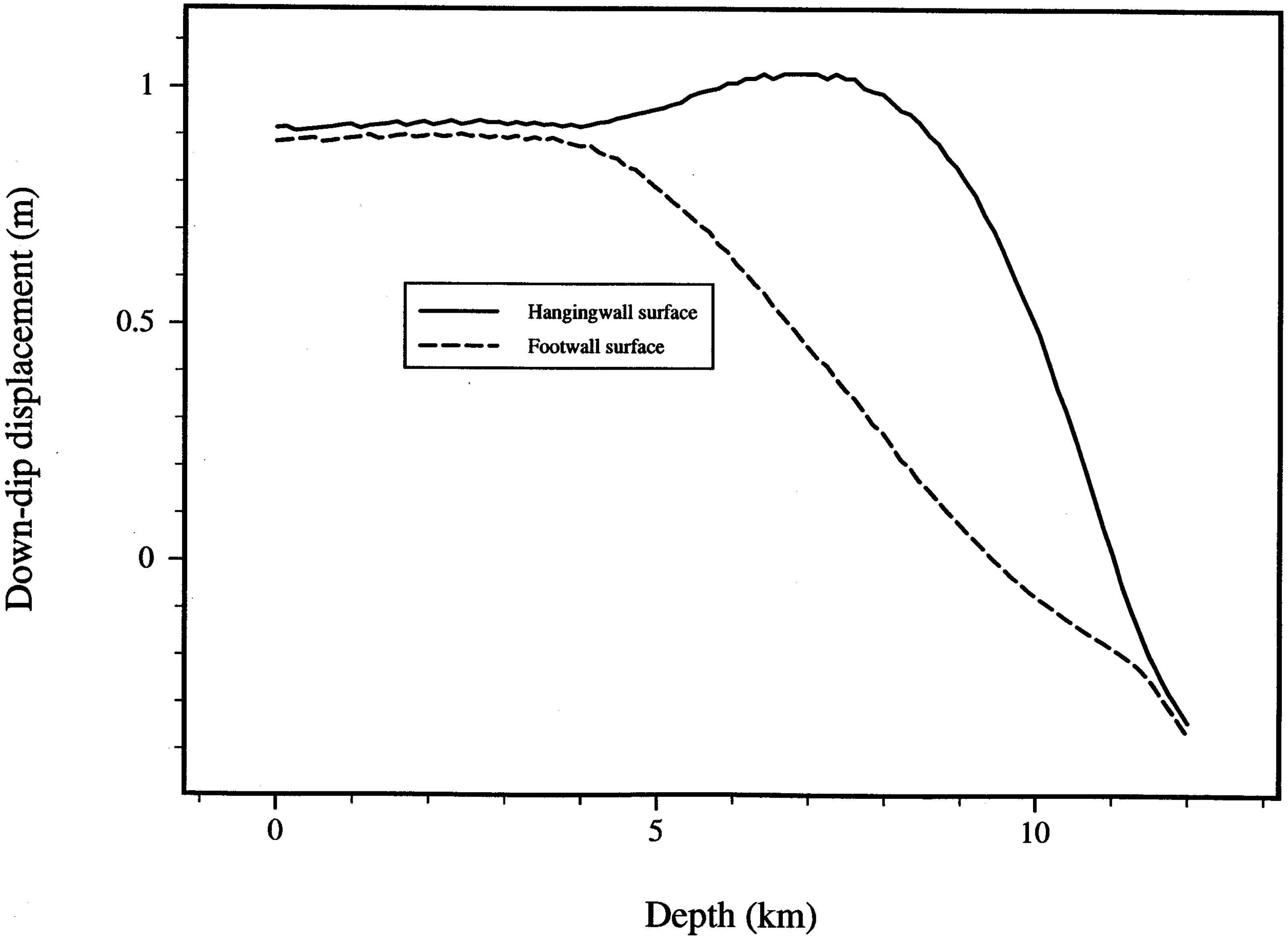
Fault Displacement (Fault #1, Case 05)



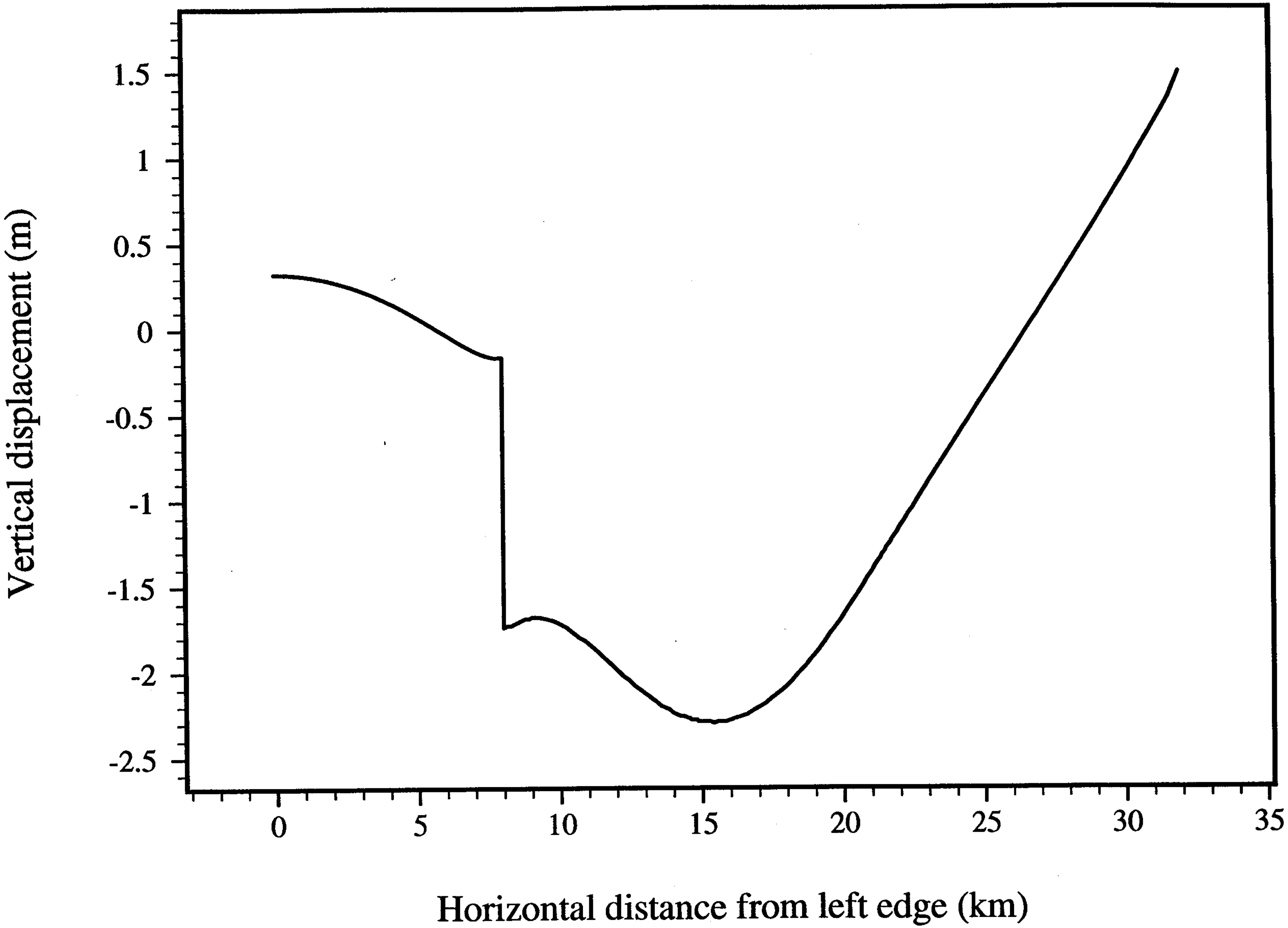
This plot does not correctly represent the relative displacement of the fault surfaces. The level of accuracy in the y-axis ~~ex~~ exaggerated small differences in the displacements. No slip occurred on the fault.

CAD

Fault Displacement (Fault #2, Case 05)



Ground Surface Profile (Case 05)



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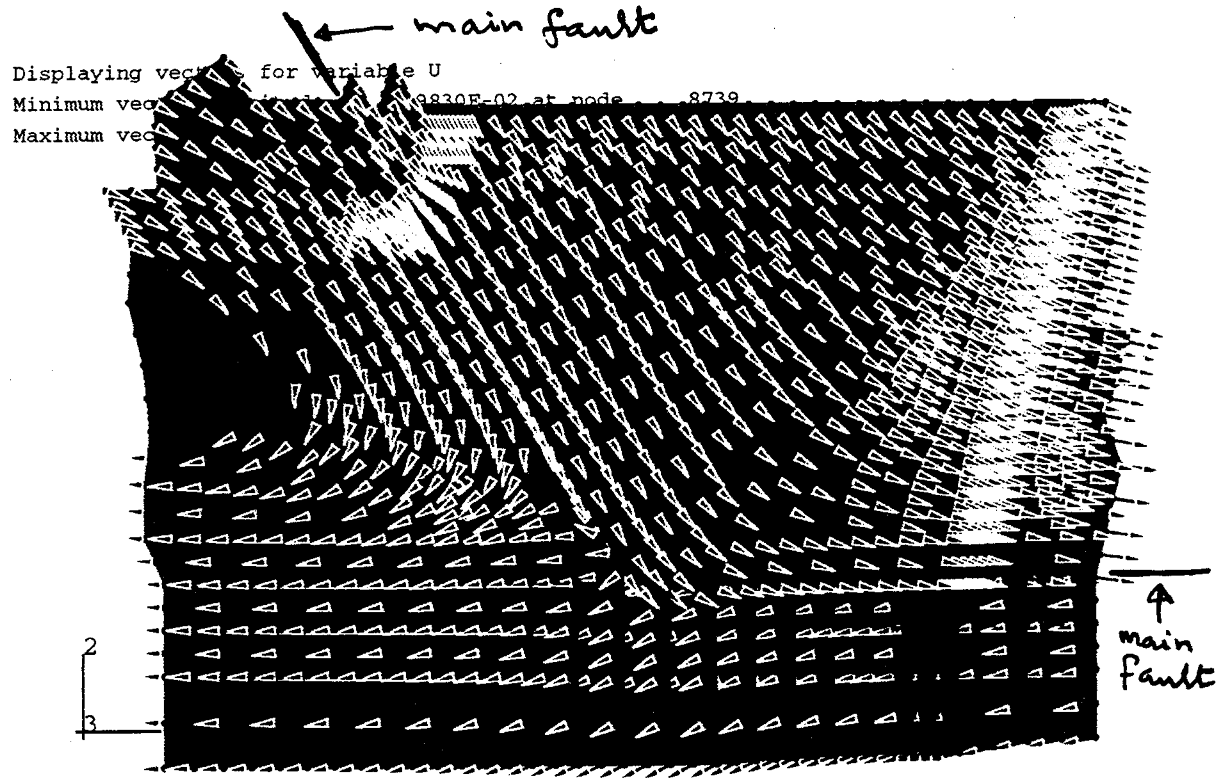
Displacement Vectors

A plot of displacement vectors, shown below for Case c05 (after 1000 yrs of 1 cm/yr relative velocity on the detachment fault) suggests that something may be wrong



with the modeling approach. The vectors show that resultant downward and eastward displacement occured in both the hangingwall and footwall of the main fault, except near the high-to-low-angle transition,

where the resultant footwall displacements are ~~to the~~ westward and upward. The displacement pattern depicted by the vectors is not ~~consistent~~ in agrement with the pattern expected for normal faulting.

Expected pattern

Calculated pattern.

The calculated displacement pattern suggests that the magnitude of displacements caused by elastic down-drag prior to fault slip overwhelmed ~~was not fully~~ the ~~sam~~ displacement pattern caused by fault slip. This result suggests that it may be incorrect to apply ~~Such a result suggests that it may be incorrect~~ prescribed fault displacements on the detachment ~~to induce~~ fault.

GW

Modeling Approach Using Prescribed Fault Displacements Applied on Steep Segment of Main Fault

Prescribed fault displacement of magnitude D_f will be applied over a ~~down-dip~~ up-dip fault length L_p (perturbed length) measured from Nodes 5402 (footwall) and 842 (hangingwall).

The displacement will ~~be~~ applied ~~in~~ rapidly (at an instant), and the response will be determined through both static and dynamic analysis (to see which analysis gives ~~better~~ more consistent results). The magnitude of L_p will be varied.

The applied D_f will be partitioned b/w footwall and hanging ~~wall~~ wall by a factor f, as follows:

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u_f = ~~Foo~~ prescribed footwall displacement

u_h = prescribed hangingwall displacement

D_f = prescribed fault displacement (positive number) ~~over up-dip length Lp~~

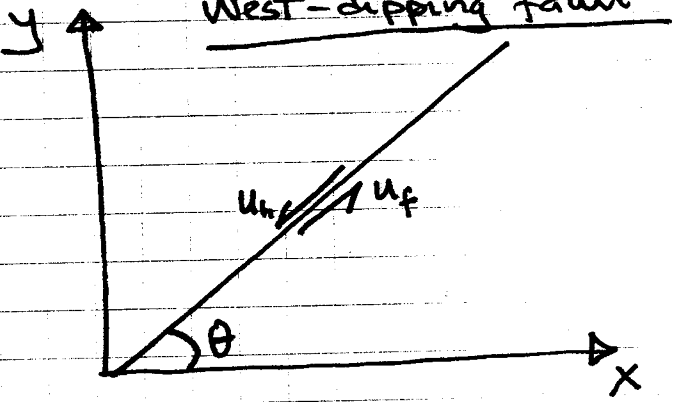
f = partitioning factor ~~f2p~~

$$u_f = f D_f$$
$$u_h = (f-1) D_f$$
$$(0 \le f \le 1)$$

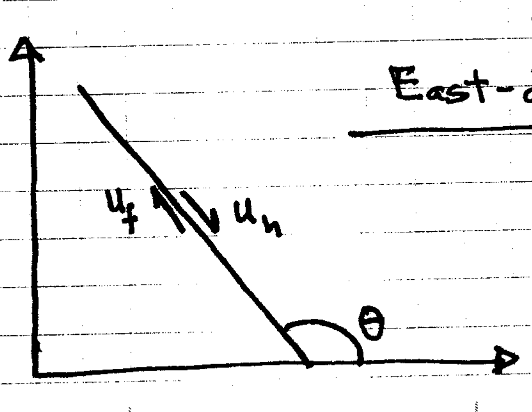
If the inclination of the fault is θ, both u_f and u_h have x- and y-components as follows

$$u_{fx} = f D_f \cos\theta$$
$$u_{fy} = f D_f \sin\theta$$
$$u_{hx} = (f-1) D_f \cos\theta$$
$$u_{hy} = (f-1) D_f \sin\theta$$

West-dipping fault



East-dipping fault



5 Implementation of Prescribed Main-Fault Displacement

The nodal displacements equivalent to a prescribed displacement on the main fault are computed using the code in file "preDisp.c", reproduced subsequently in this section. The prescribed fault displacement is defined in terms of the magnitude of fault displacement (D_f), the footwall partition coefficient (fraction of D_f applied to the footwall), f, and the first and last nodes on the footwall and hangingwall surfaces that demarcate the fault-surface segments over which the prescribed displacement should be applied. These nodes are determined from one of the files cNNFFSSdisp.dat (which were described earlier in these notes).

5.1 C Code for Implementation of Prescribed Main-Fault Displacement

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

main()
{

/*
  This code prepares ABAQUS input block to implement a prescribed fault
  displacement on the steep segment of the main fault. The node numbers
  and local fault inclination at the nodes where the displacements are
  applied are read from two files (output of code FaultSurfaceDisp.c).
  The following inputs are required:

  fwFile                  Name of footwall file
  hwFile                  Name of hangingwall file
  nfFirst                 Topmost footwall node for prescribed displacement
  nfLast   (5402)         Deepest footwall node for prescribed displacement
  nhFirst                 Topmost hangingwall node for prescribed displacement
  nhLast   (842)          Deepest hangingwall node for prescribed displacement
  pfDisp                  prescribed fault displacement (m)
  fpf                     footwall partition factor

  Values of nfFirst and nhFirst depend on the up-dip fault length over which
  the prescribed displacement is to be applied. Both are determined through
  examination of the two files fwFile and hwFile.

*/

  char buf[81],
       *fwFile = "c05f0fwdisp.dat",
       *hwFile = "c05f0hwdisp.dat";
  int node,nfFirst,nfLast,nhFirst,nhLast;
  float depth,flen,dip,disp;
```

```
  float pfDisp,fpf;
  FILE *Fin;

  nfFirst = 5378;
  nfLast = 5402;
  nhFirst = 818;
  nhLast = 842;
  pfDisp = 2.0;
  fpf = 0.5;

/* Footwall */

  Fin = fopen(fwFile,"r");
  if (!Fin) DumpAndQuit("Unable to open footwall file");

  printf("*BOUNDARY,AMPLITUDE=NOCHANGE\n");
  while (fgets(buf,80,Fin))
    if (sscanf(buf,"%d %f %f %f %f",&node,&depth,&flen,&dip,&disp) == 5){
      if (node == nfFirst)
        do{
          ComputeAndPrint(node,dip,pfDisp,fpf);
          fgets(buf,80,Fin);
          if (sscanf(buf,"%d %f %f %f %f",&node,&depth,&flen,&dip,&disp) != 5)
            DumpAndQuit("Invalid input line encountered in footwall file");
          if (node == nfLast) ComputeAndPrint(node,dip,pfDisp,fpf);
        } while (node != nfLast);

      if (node == nfLast) break;
    }
  fclose(Fin);

/* Hangingwall */

  Fin = fopen(hwFile,"r");
  if (!Fin) DumpAndQuit("Unable to open hangingwall file");

  printf("*BOUNDARY,AMPLITUDE=NOCHANGE\n");
  while (fgets(buf,80,Fin))
    if (sscanf(buf,"%d %f %f %f %f",&node,&depth,&flen,&dip,&disp) == 5){
      if (node == nhFirst)
        do{
          ComputeAndPrint(node,dip,pfDisp,(fpf-1.0));
          fgets(buf,80,Fin);
          if (sscanf(buf,"%d %f %f %f %f",&node,&depth,&flen,&dip,&disp) != 5)
            DumpAndQuit("Invalid input line encountered in hangingwall file");
          if (node == nhLast) ComputeAndPrint(node,dip,pfDisp,(fpf-1.0));
```

```
      } while (node != nhLast);

    if (node == nhLast) break;
  }
  fclose(Fin);

}

ComputeAndPrint(node,dip,pfDisp,factor)
  int node;
  float dip,pfDisp,factor;
{
  float pi,theta,ux,uy;

  pi = 4.0*atan(1.0);
  theta = (pi/180.0)*dip;
  ux = factor*pfDisp*cos(theta);
  uy = factor*pfDisp*sin(theta);
  printf("%d,1, ,%.3f\n",node,ux);
  printf("%d,2, ,%.3f\n",node,uy);
}

DumpAndQuit(s)
char *s;
{
  printf("\n *** %s ***\n\n",s);
  exit(0);
}
```

5.2 Input Block to Implement Prescribed Main-Fault Displacement

A typical input block (output from code reproduced above) to implement a prescribed fault displacement on steep segment of main fault ($D_f = 2$ m and $f = 0.5$) is reproduced below.

```
*BOUNDARY,AMPLITUDE=NOCHANGE
5378,1, ,-0.500
5378,2, ,0.866
5381,1, ,-0.511
5381,2, ,0.860
5386,1, ,-0.500
5386,2, ,0.866
5389,1, ,-0.489
5389,2, ,0.872
5394,1, ,-0.500
5394,2, ,0.866
5397,1, ,-0.511
```

```
5397,2, ,0.860
5402,1, ,-0.562
5402,2, ,0.827
*BOUNDARY,AMPLITUDE=NOCHANGE
818,1, ,0.500
818,2, ,-0.866
821,1, ,0.511
821,2, ,-0.860
826,1, ,0.500
826,2, ,-0.866
829,1, ,0.489
829,2, ,-0.872
834,1, ,0.500
834,2, ,-0.866
837,1, ,0.511
837,2, ,-0.860
842,1, ,0.562
842,2, ,-0.827
```

Analysis Case 06

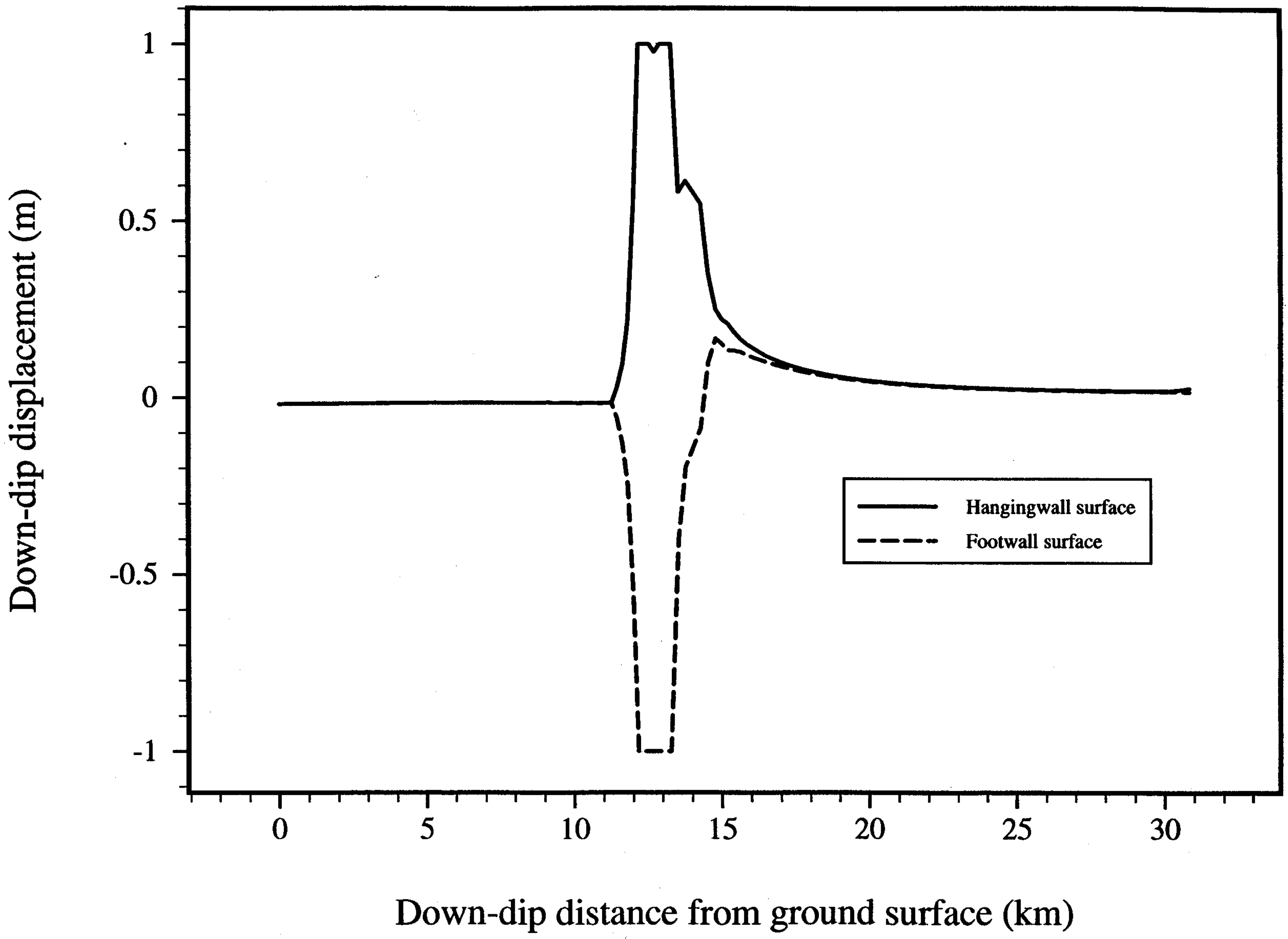
Initial equilibrium state established using static analysis defined in m05Base.inp

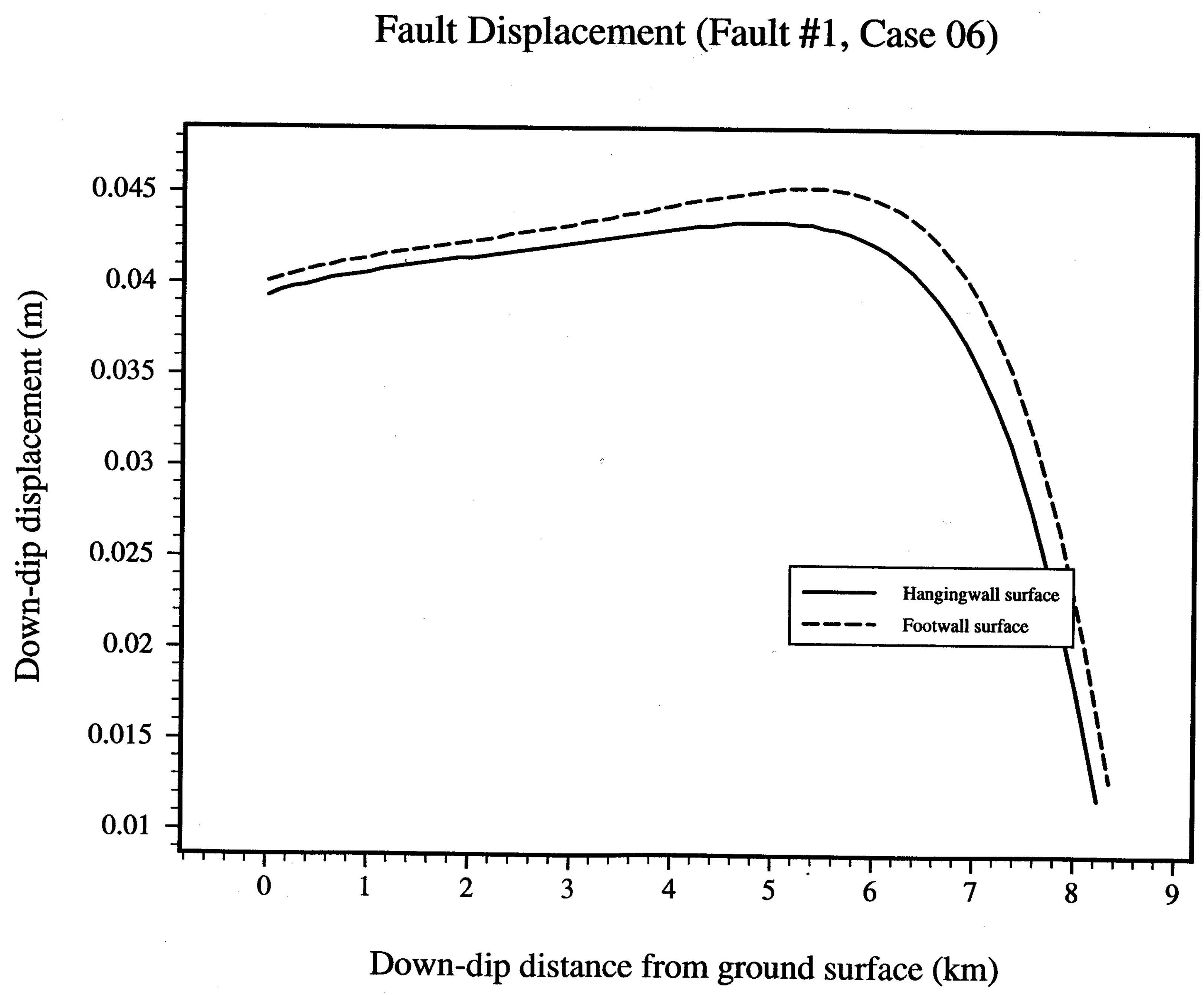
Induced Fault Slip

2 m applied over 1.11 Km, partitioned 50/50 between footwall and hangingwall. Nodal displacements equivalent to the prescribed fault displacement were computed using code in "preDisp.c".

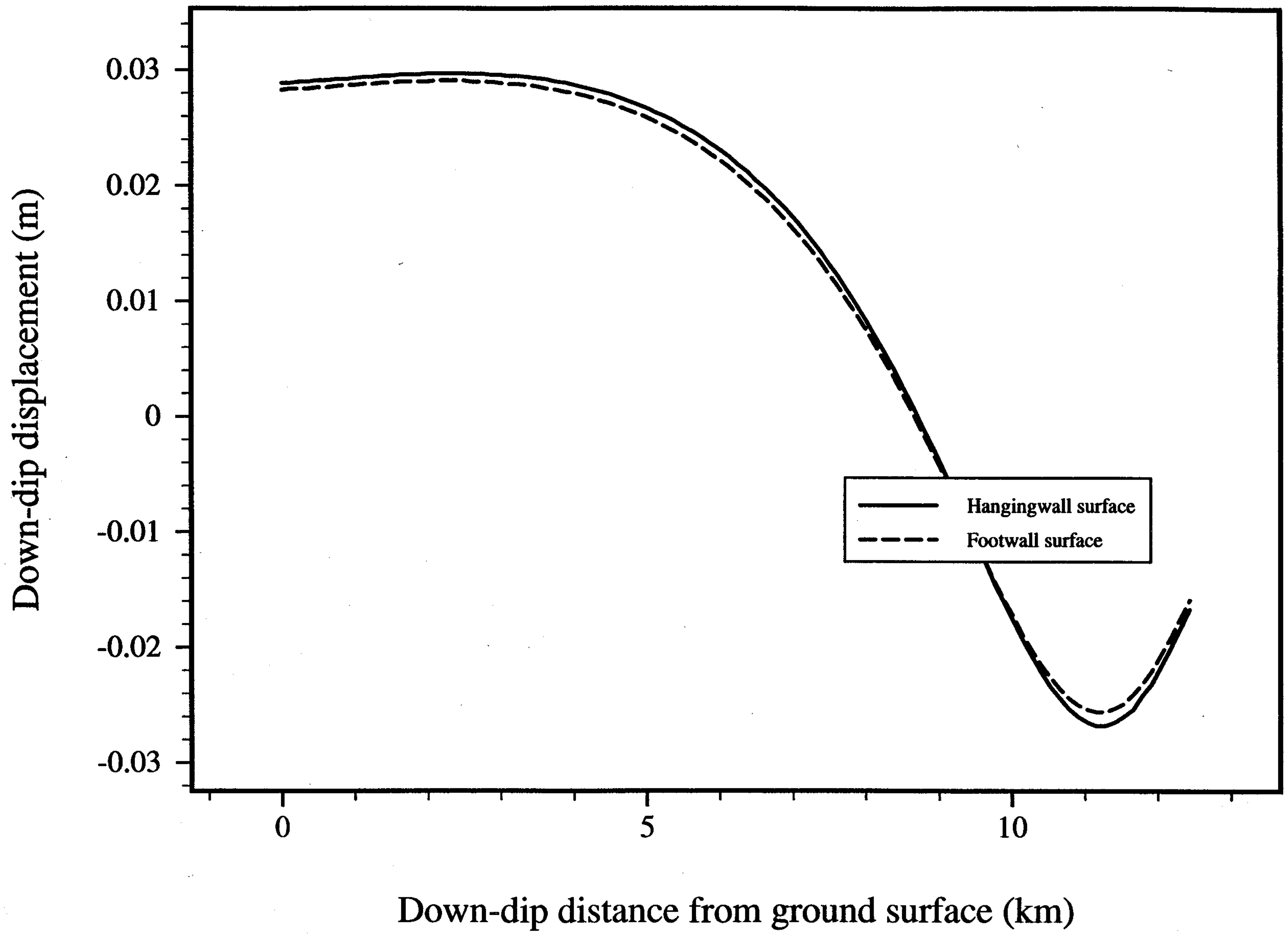
Perturbation step (induced fault displacement) implemented using static analysis defined in C06.inp (restart ~~of the~~ from m05Base.res).

Fault Displacement (Main Fault, Case 06)

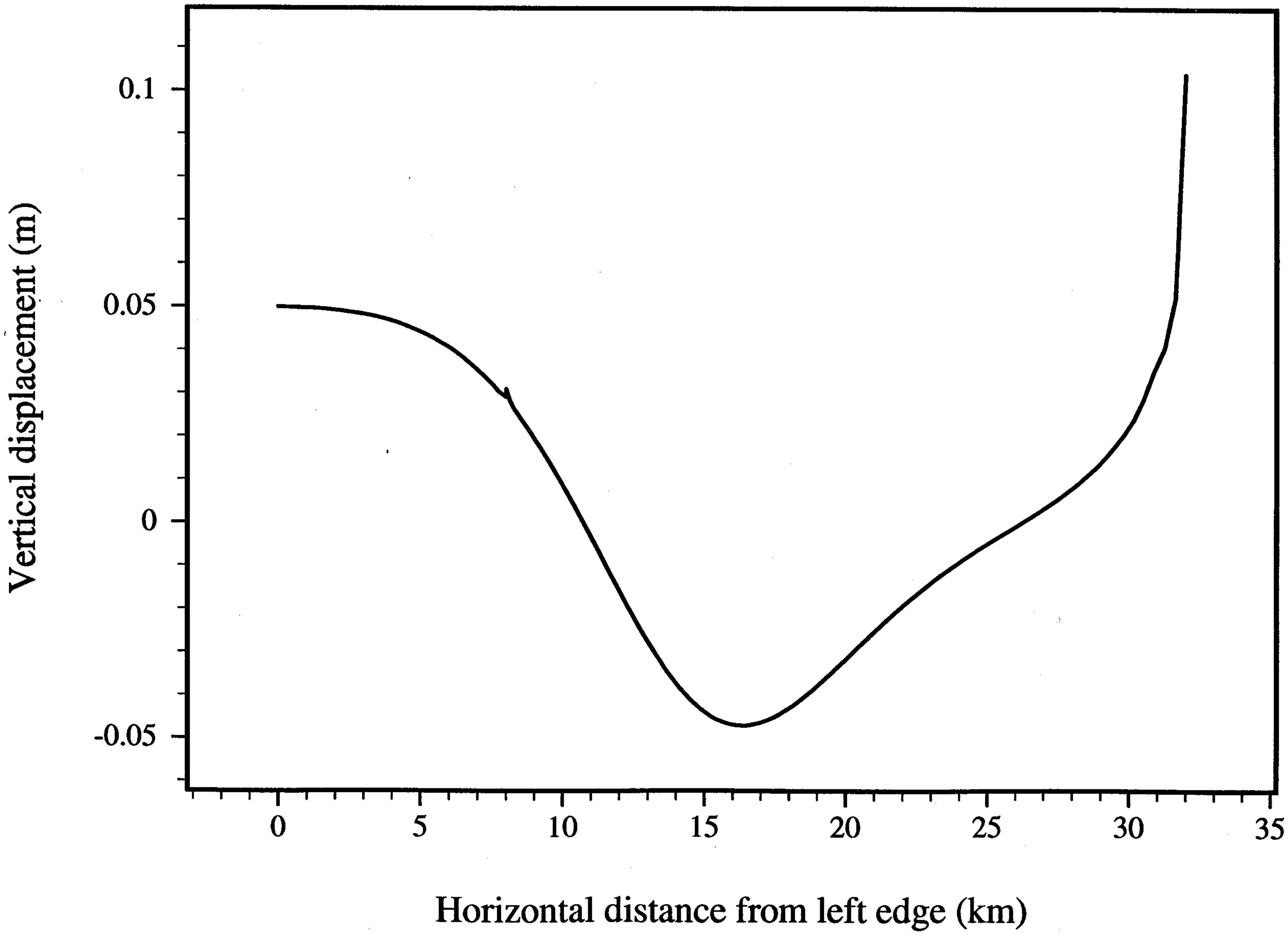



Fault Displacement (Fault #1, Case 06)
Down-dip displacement (m)
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0
1
2
3
4
5
6
7
8
9
Down-dip distance from ground surface (km)
Hangingwall surface
Footwall surface

Fault Displacement (Fault #2, Case 06)

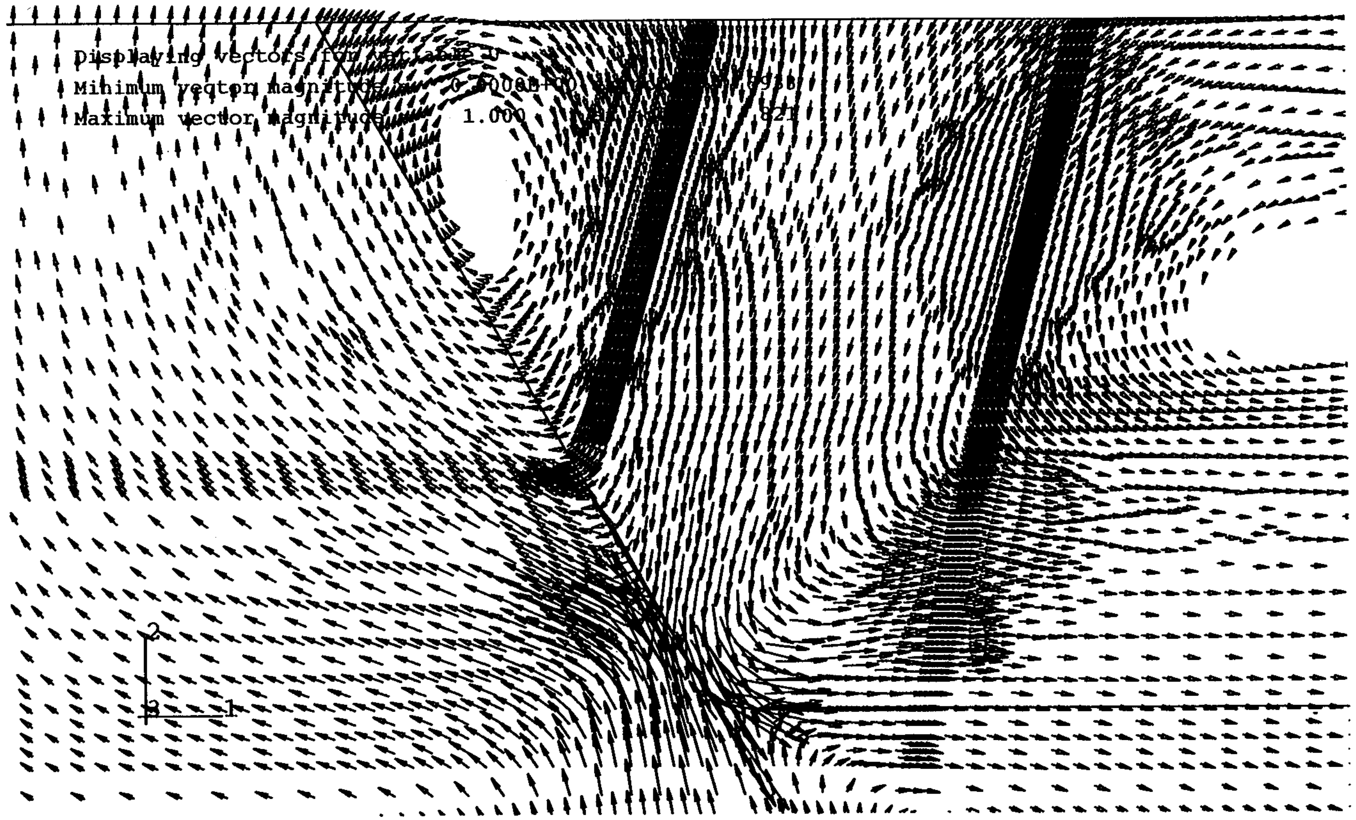


Ground Surface Profile (Case 06)



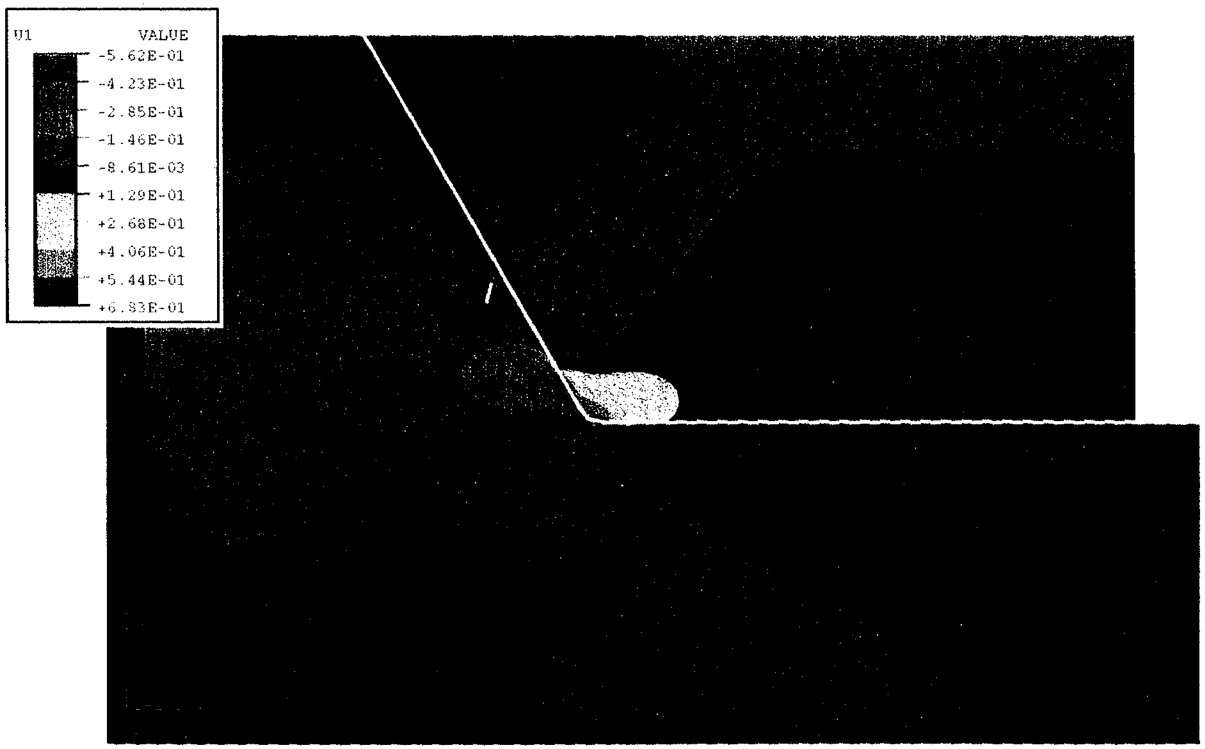
ABAQUS

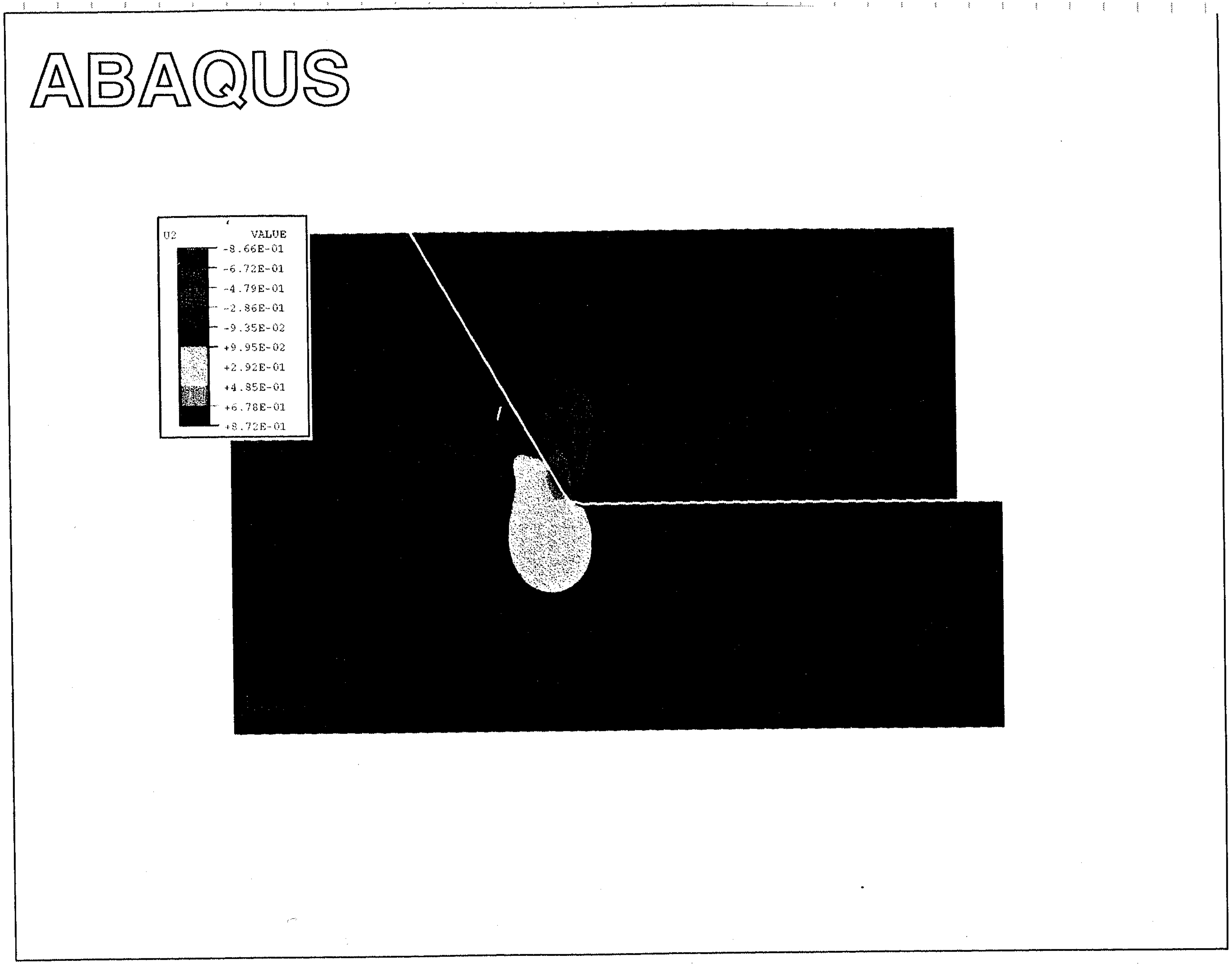
c06



C6

ABAQUS


U1
VALUE
-5.62E-01
-4.23E-01
-2.85E-01
-1.46E-01
-8.61E-03
+1.29E-01
+2.68E-01
+4.06E-01
+5.44E-01
+6.83E-01


ABAQUS
U2
VALUE
-8.66E-01
-6.72E-01
-4.79E-01
-2.86E-01
-9.35E-02
+9.95E-02
+2.92E-01
+4.85E-01
+6.78E-01
+8.72E-01

CAD

054

Case 07

Analysis Case 07 differs from Case 06 in the use of dynamic analysis for the perturbation step.

Initial equilibrium state established through static analysis defined in m07Base.inp (same as m05Base.inp, except that damping parameters are specified in m07Base but not in m05Base)

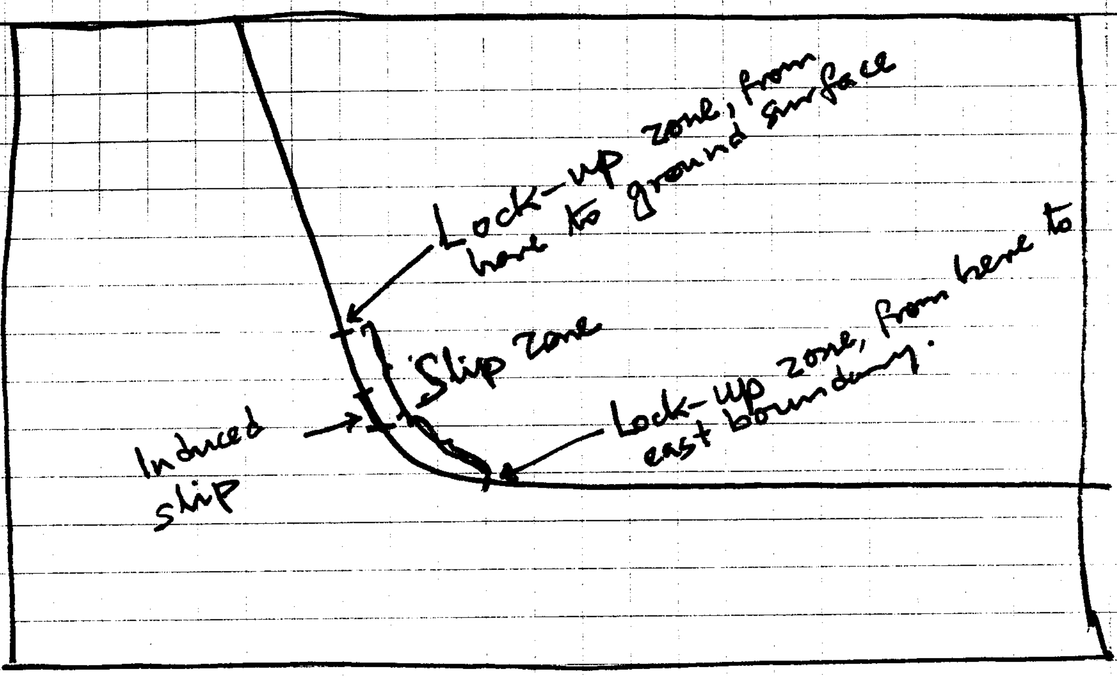
Dynamic analysis of induced fault slip is defined in c07.inp (a restart of m07Base).

Comparison of Cases 06 and 07

① Displacement vectors, in both cases, are consistent with the pattern of deformation expected near the main fault: downward-eastward in the hangingwall and upward-westward in the footwall.

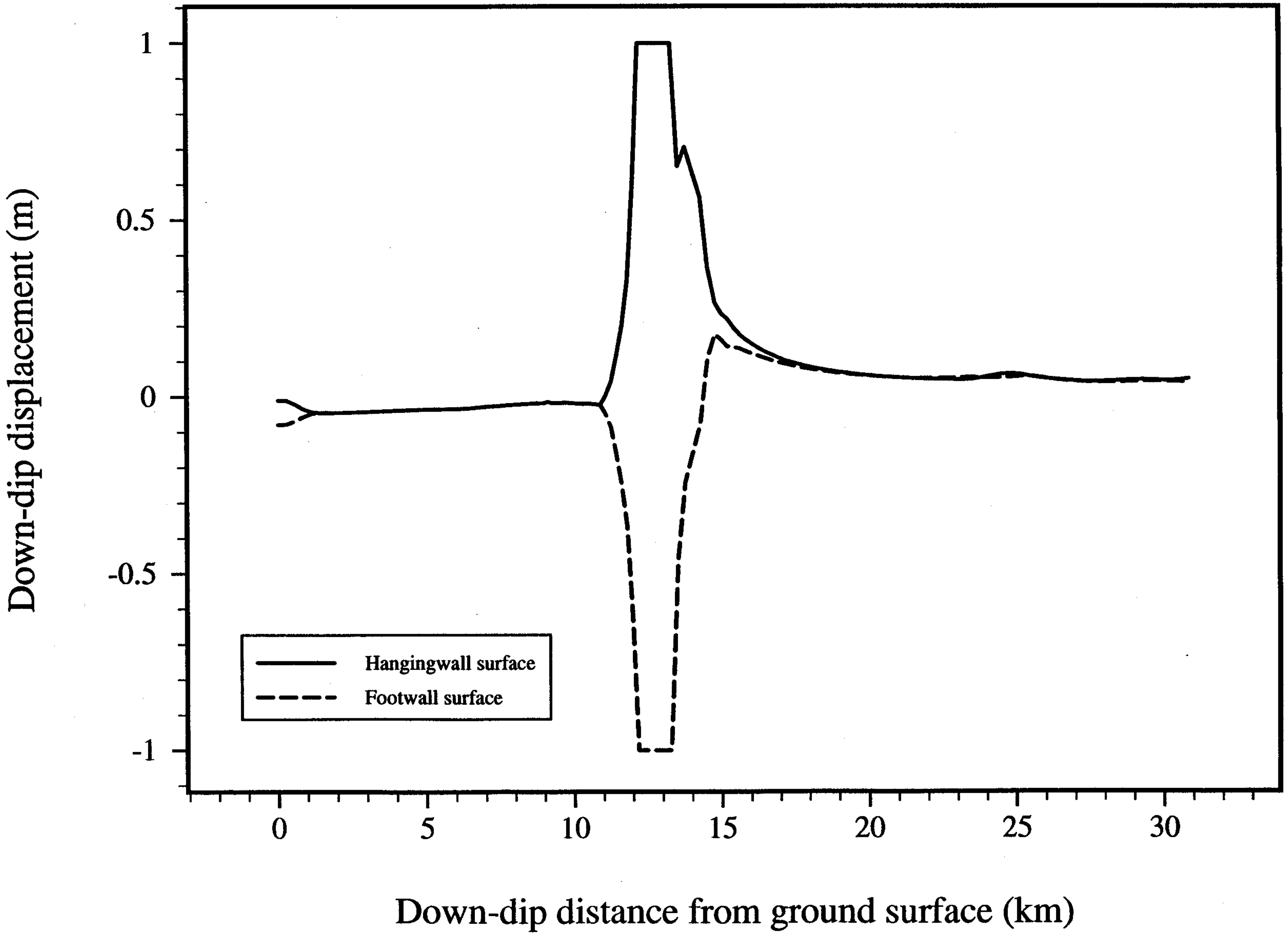
② The main fault slipped over a distance of about 5 km in both cases, ~~just above~~ ~~but remained~~ ~~"locked"~~ near the base of the high-angle segment; but remained locked elsewhere.

055

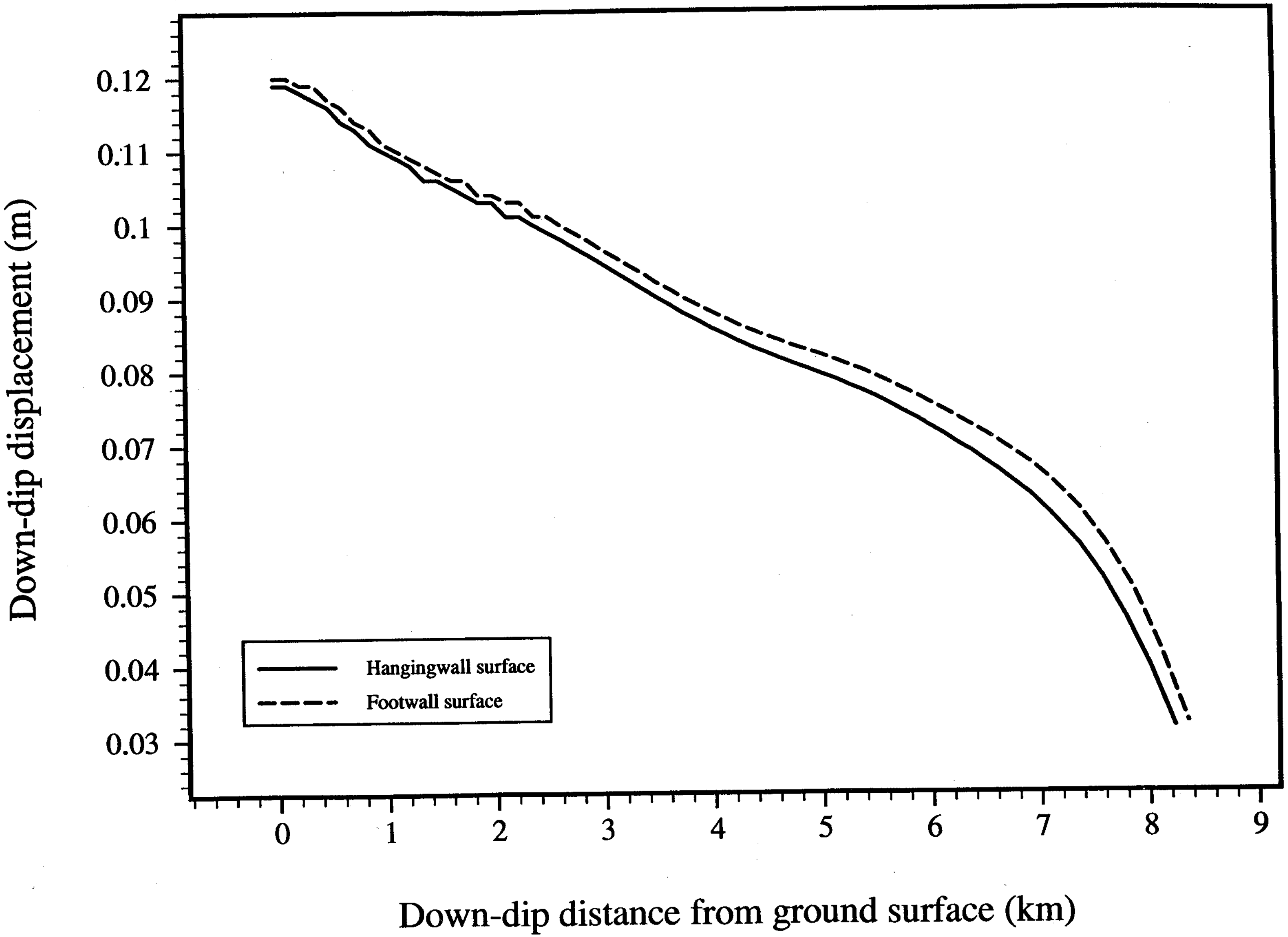


Using Wells and Coppersmith's empirical ~~rela~~ relationships, the induced fault displacement of ~~ab~~ 2m corresponds to an induced earthquake of about 7.2 moment magnitude. An earthquake of such magnitude should cause fault rupture up to the ground surface. The fact that fault ~~such~~ rupture did not propagate to the ground surface in the analyses (C06 and C07), suggests that the shear strength assigned to the faults may be too high.

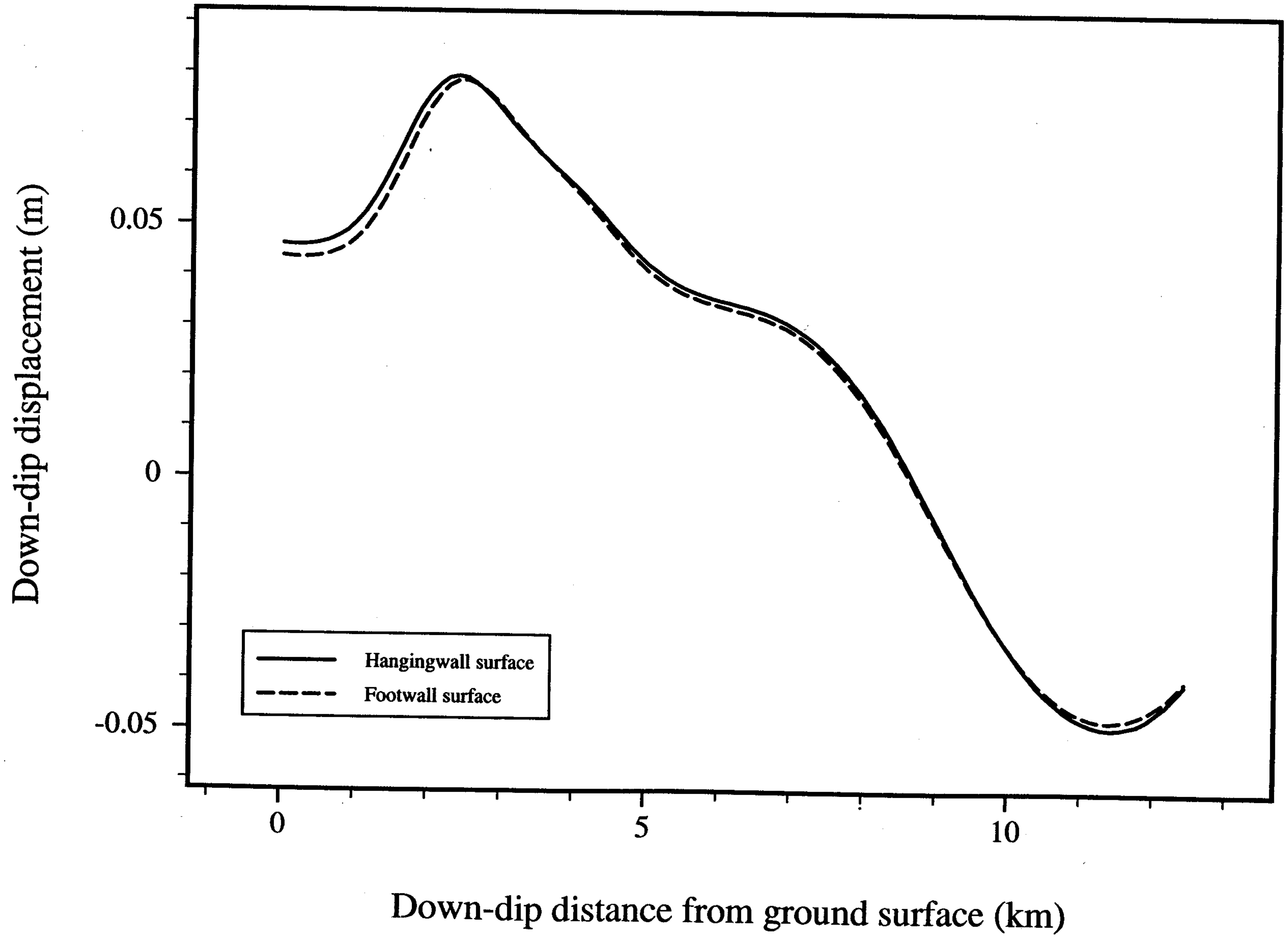
Fault Displacement (Main Fault, Case 07)



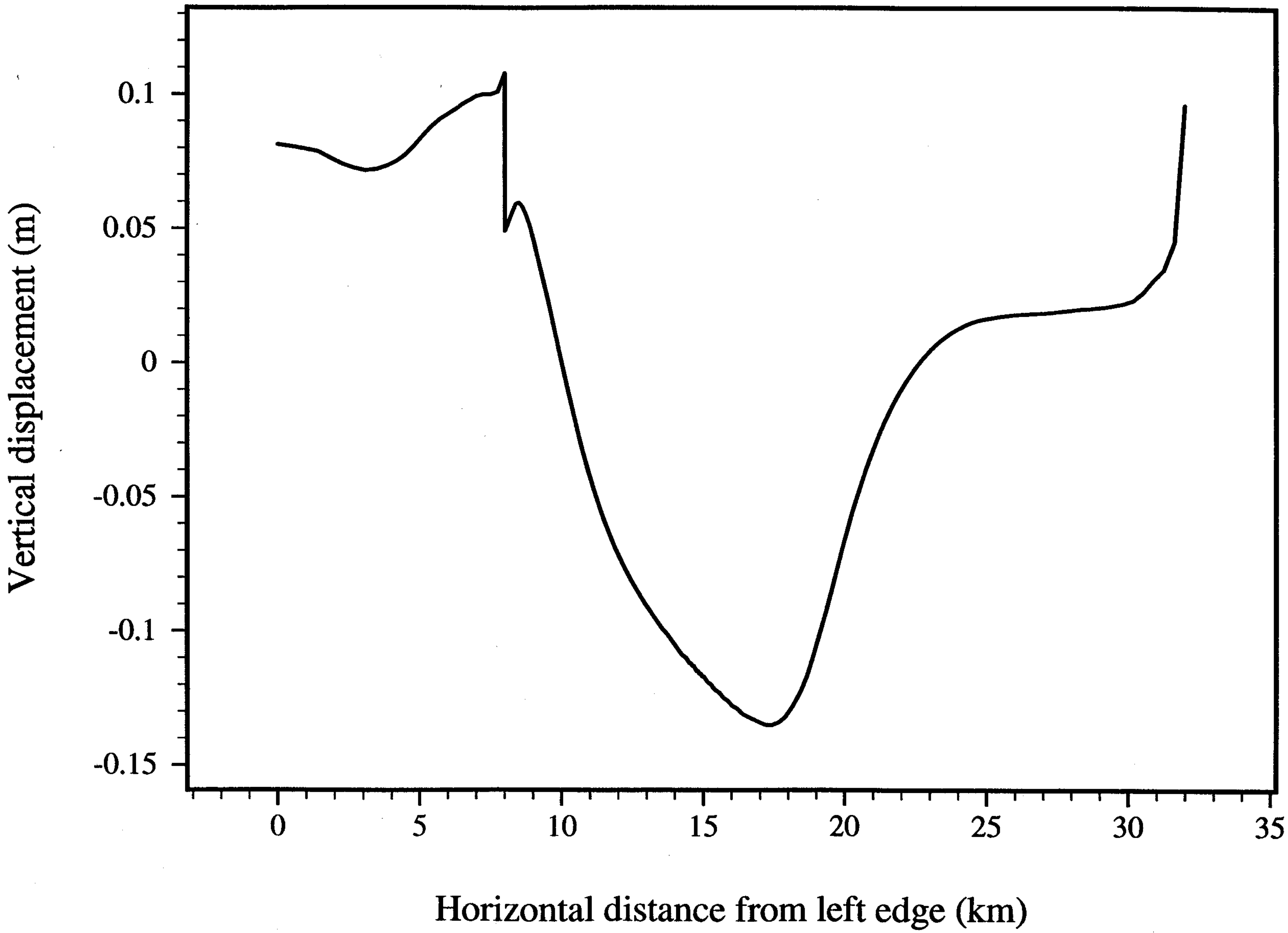
Fault Displacement (Fault #1, Case 07)



Fault Displacement (Fault #2, Case 07)

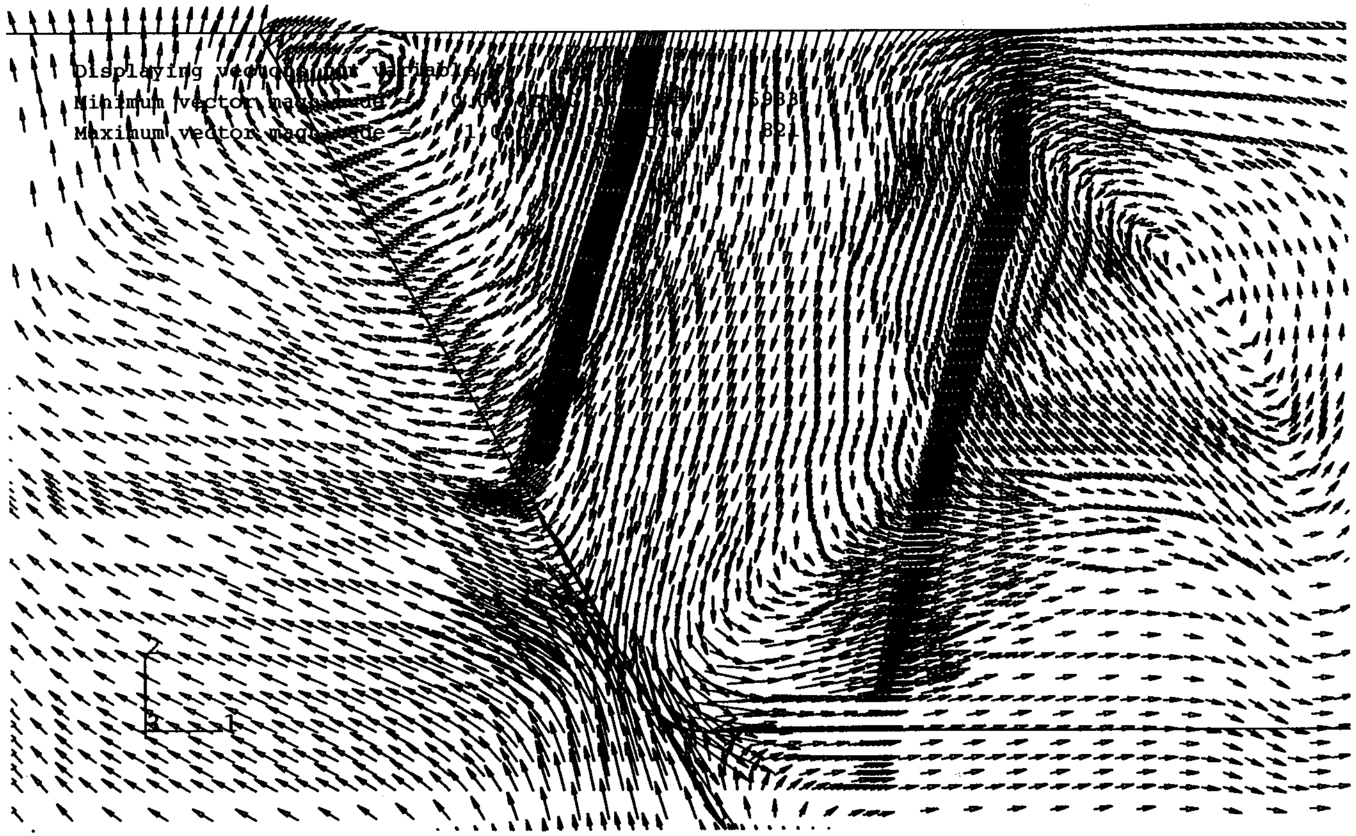


Ground Surface Profile (Case 07)



ABAQUS

C07



Displaying
Minimum vector magnitude =
Maximum vector magnitude =

Qto

6 Analysis Cases With Slip At Initial State

The shear-strength parameters for the faults were modified to satisfy the condition for incipient slip at the initial state, under the prescribed initial stress of $\sigma_v = 25$ MPa/km and $\sigma_h = 0.25\sigma_v$. The following parameters were assigned: For fault f0, $\phi = 37°$, $c = 0$, and maximum shear strength of the detachment is 80 MPa; for faults f1 and f2, $\phi = 32°$, $\varphi = 16°$, and $c = 2.5$ MPa; where ϕ is friction angle, φ is dilation angle, and c is cohesion.

Slip calculated at the initial state is subtracted from slip calculated at the end of a subsequent analysis step to obtain the induced/triggered slip for the analysis step. The following codes were modified for the new slip-calculation procedure:

1. FaultSurfaceDisp.c was modified to print out nodal displacements u_x and u_y.

2. preDisp.c, which converts prescribed fault displacements to equivalent u_x and u_y values, was modified to add initial-state displacements u_{xo} and u_{yo} to the prescribed fault displacement. This change was necessary because ABAQUS requires prescribed displacements to be given as the total displacement desired at the end of the analysis step in which the prescribed displacement is applied.

The value of fault displacement (i.e., fault slip) D_f induced/triggered in an analysis step is calculated using the fault-surface nodal displacements at the initial state and at the end of the analysis step. That is

$$D_f = (u_{h1} - u_{ho}) - (u_{f1} - u_{fo}) \tag{1}$$

where u stands for nodal displacement, subscripts h and f represent hangingwall and footwall, respectively, and subscripts o and 1 represent the initial state and end of analysis step 1, respectively.

6.1 C Code FaultDisp.c for Computation of Fault Displacement

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

main()
{

/*************************************************************
  Code to compute fault displacement (fault slip) on three faults:
  f0, f1, and f2. The code reads input from the following files:

  FileName                 Information Read From File
  ============             ==========================
  c08f0hwdisp.dat          Case 08 hangingwall surface disp for f0       (u0)
  c08f0fwdisp.dat          Case 08 footwall surface disp for f0          (u1)
  m08bf0hwdisp.dat         Initial-state hangingwall surface disp for f0 (u2)
  m08bf0fwdisp.dat         Initial-state footwall surface disp for f0    (u3)
```

```
  The character group f0 in the file names represent fault f0;
  similarly named sets of 4 files are also read for faults f1 and f2 by
  replacing f0 in the file names with f1 and f2, respectively.
  The character groups c08 and m08b in the file names represent
  analysis cases, and can be modified in the variable-name declarations
  below.

  Fault displacement for each fault is calculated as the sum

                    (u0 - u2) - (u1 - u3)

  which gives the value of fault slip that occured from the end of
  analysis case m08b to the end of case c08.

  The values of fault displacement are stored in three files
  named c__f_disp.dat, where c__ stands for c08 for the case illustrated
  and f_ is f0, f1, or f2.

  System Requirement:  Compile with acc on SUN OS (cc will not work)
*************************************************************/

  char buf[151],*fname;
  char *tail="disp.dat";
  char *fault[]={"f0","f1","f2"},
       *surface[]={"hw","fw"},
       *pcase[]={"c08","m08b"};
  int i,j,k,fnum,node[4];
  float depth[4],flen[4],dip[4],fsdisp[4],ux,uy;
  float fdisp;
  FILE *Fin[4],*Fout;

  fname = (char *)malloc(17*sizeof(char));
  if (!fname) DumpAndQuit("Memory allocation error");

  for (i=0; i<3; i++){
    sprintf(fname,"%s%sdisp.dat",pcase[0],fault[i]);
    Fout = fopen(fname,"w");
    if (!Fout){
      sprintf(buf,"Unable to open file %s",fname);
      DumpAndQuit(buf);
    }
    fnum = 0;
    for (j=0; j<2; j++)
      for (k=0; k<2; k++){
        sprintf(fname,"%s%s%s%s",pcase[j],fault[i],surface[k],tail);
```

```
        Fin[fnum] = fopen(fname,"r");
        if (!Fin[fnum]){
          sprintf(buf,"Unable to attach file %d to %s",fnum,fname);
          DumpAndQuit(buf);
        }
        fnum++;
      }

    for (j=0; j<4; j++)
      if (!fgets(buf,150,Fin[j]))
        DumpAndQuit("Empty input file encountered");

    fprintf(Fout,"%10s%12s%12s%12s%12s\n","Node","Depth-km","fLen-km",
      "Dip","fDisp-m");
    while (fgets(buf,150,Fin[0]))
      if (sscanf(buf,"%d %f %f %f %f %f %f",&node[0],&depth[0],&flen[0],
        &dip[0],&fsdisp[0],&ux,&uy) == 7){
        for (j=1; j<4; j++)
          if (!fgets(buf,150,Fin[j]) || sscanf(buf,"%d %f %f %f %f %f %f",
            &node[j],&depth[j],&flen[j],&dip[j],&fsdisp[j],&ux,&uy) != 7)
              DumpAndQuit("Invalid input line encountered");
        fdisp = (fsdisp[0]-fsdisp[2]) - (fsdisp[1]-fsdisp[3]);
        fprintf(Fout,"%10d%12.2f%12.2f%12.2f%12.2E\n",node[0],-depth[0],
          flen[0],dip[0],fdisp);
      }

    for (j=0; j<4; j++) fclose(Fin[j]);
    fclose(Fout);
  }
}

DumpAndQuit(s)
char *s;
{
  printf("\n *** %s ***\n\n",s);
  exit(0);
}
```

6.2 Results for An Analysis Case With Slip At Initial State

The results obtained for Case c08 are shown. The initial state for this case was obtained using m08Base.inp, and the perturbation step using c08.inp. A prescribed fault displacement of 2 m was applied over a 1-km distance at the base of fault f0 steep segments. The resulting fault-surface displacements are saved in files named m08bFFSSdisp.dat for the initial state or c08FFSSdisp.dat for the end of the perturbation step; where FF stands for f0, f1, or f2; and SS is hw for hangingwall or fw for footwall.

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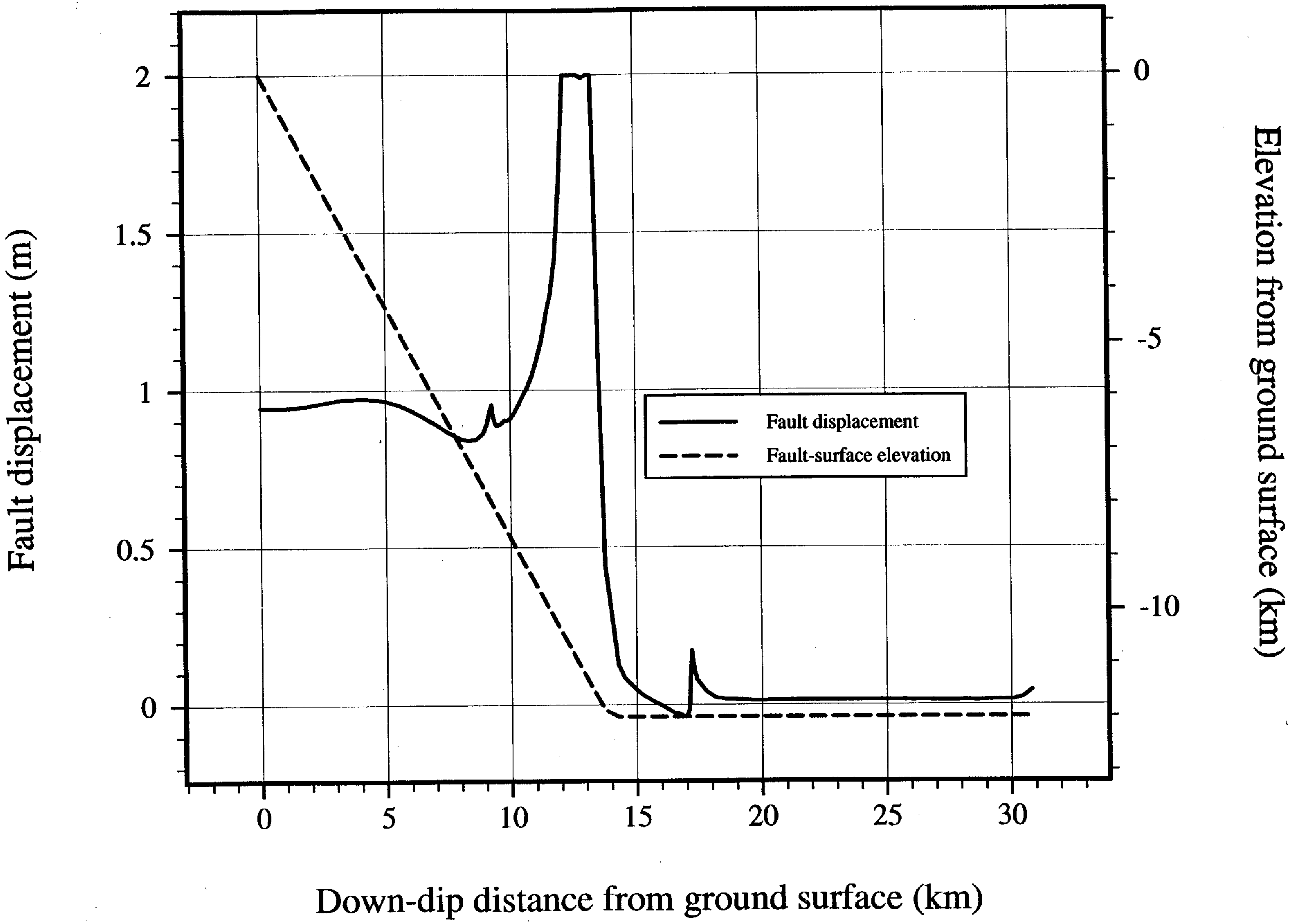
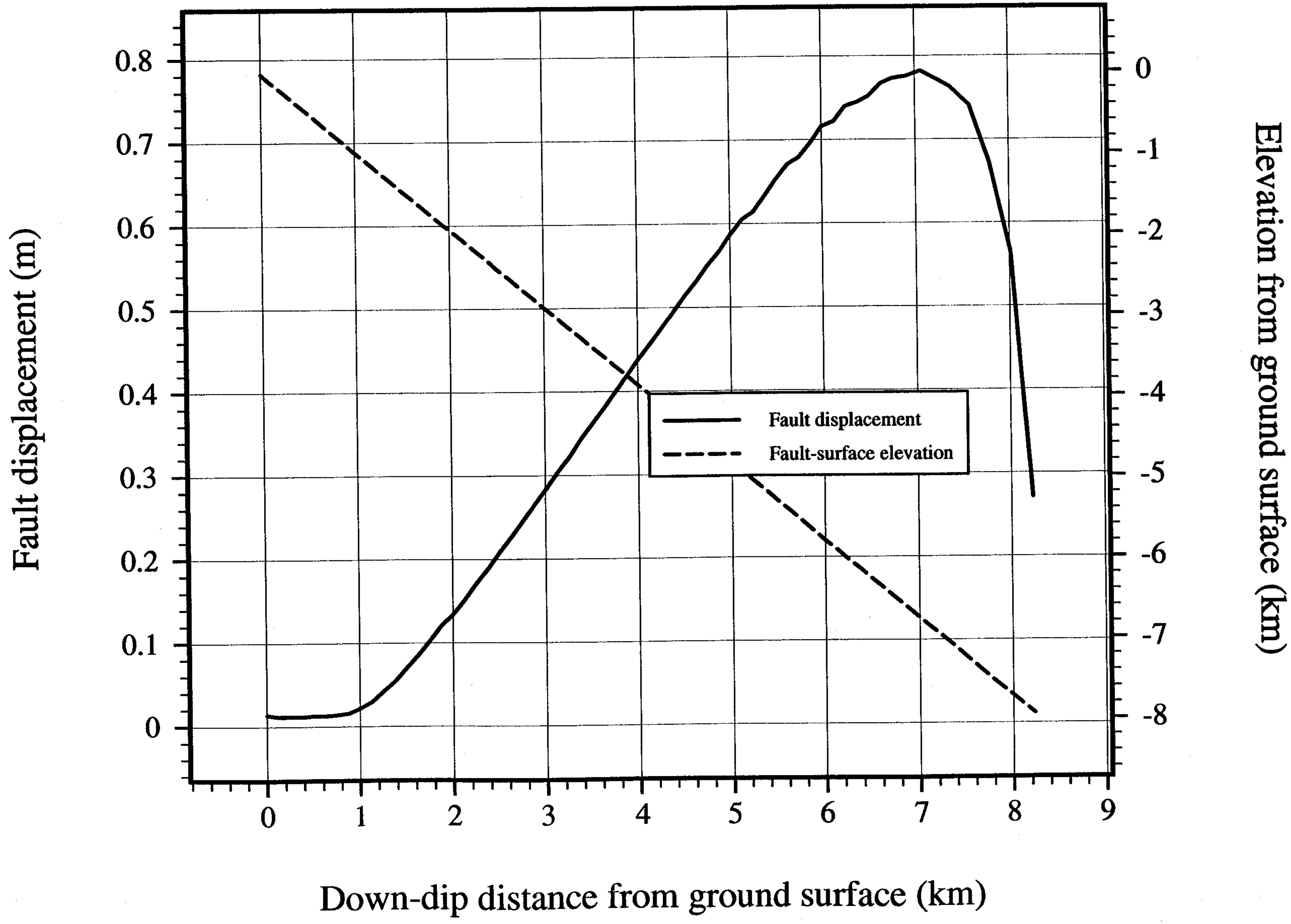
The results show that the induced 2-m slip caused triggered slip on all three faults, except on the low-angle detachment. Slip did not occur on the detachment because of the occurence of high normal stress and low shear stress on the horizontal detachment, since the applied block-contact fault model restricts slip to fault-parallel planes.

An attempt was made to generate slip on the detachment by applying a steady-state creep model to the rock above and below the detachment (element sets HWDUCTIL and FWDUCTIL). This approach was not successful because of numerical difficulties associated with the block-contact model. As a result, a decision was made to develop another finite element model, in which all faults will be modeled as slender isotropic solids. This model will be described in subsequent notes.

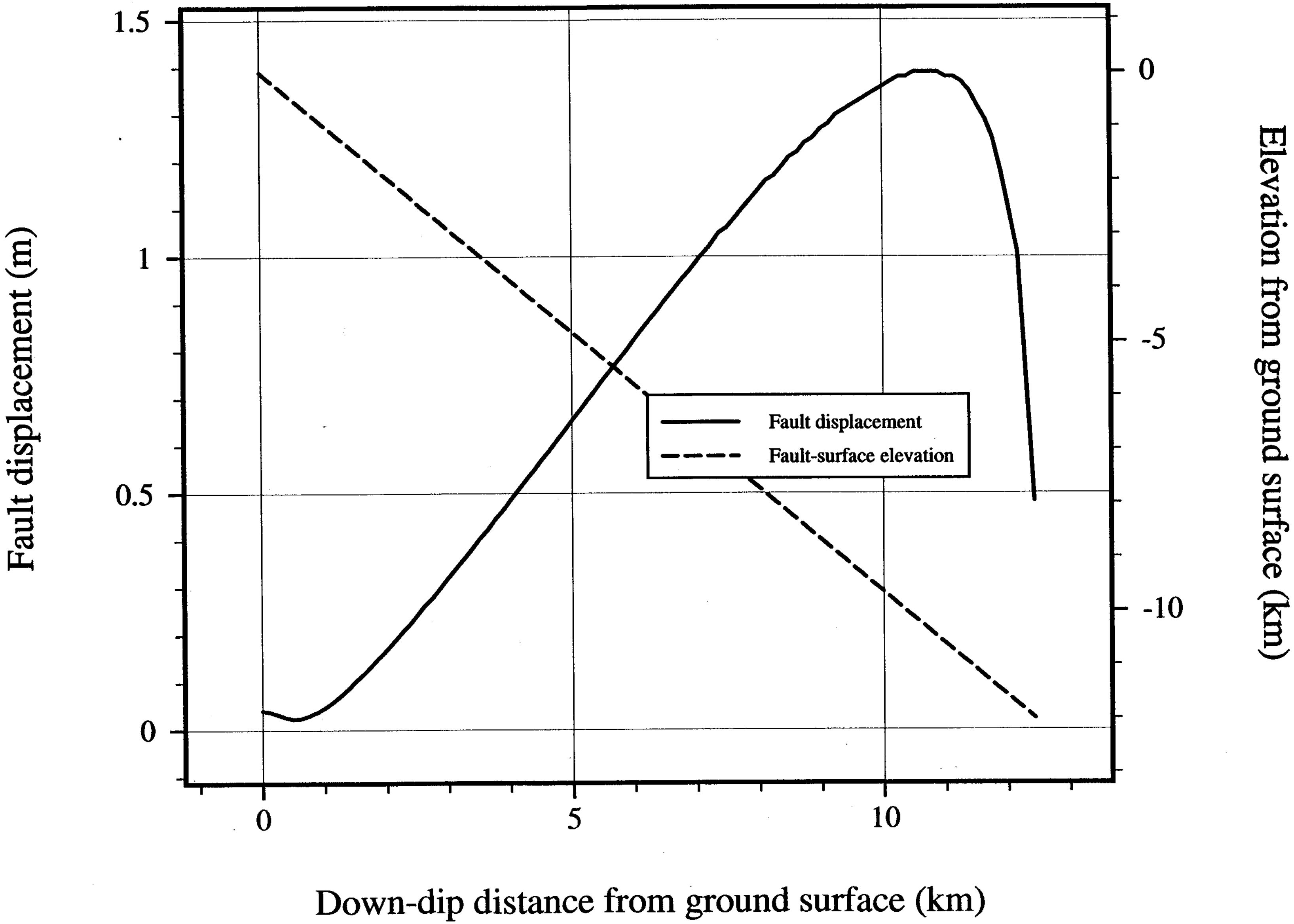
Main Fault, Case 08



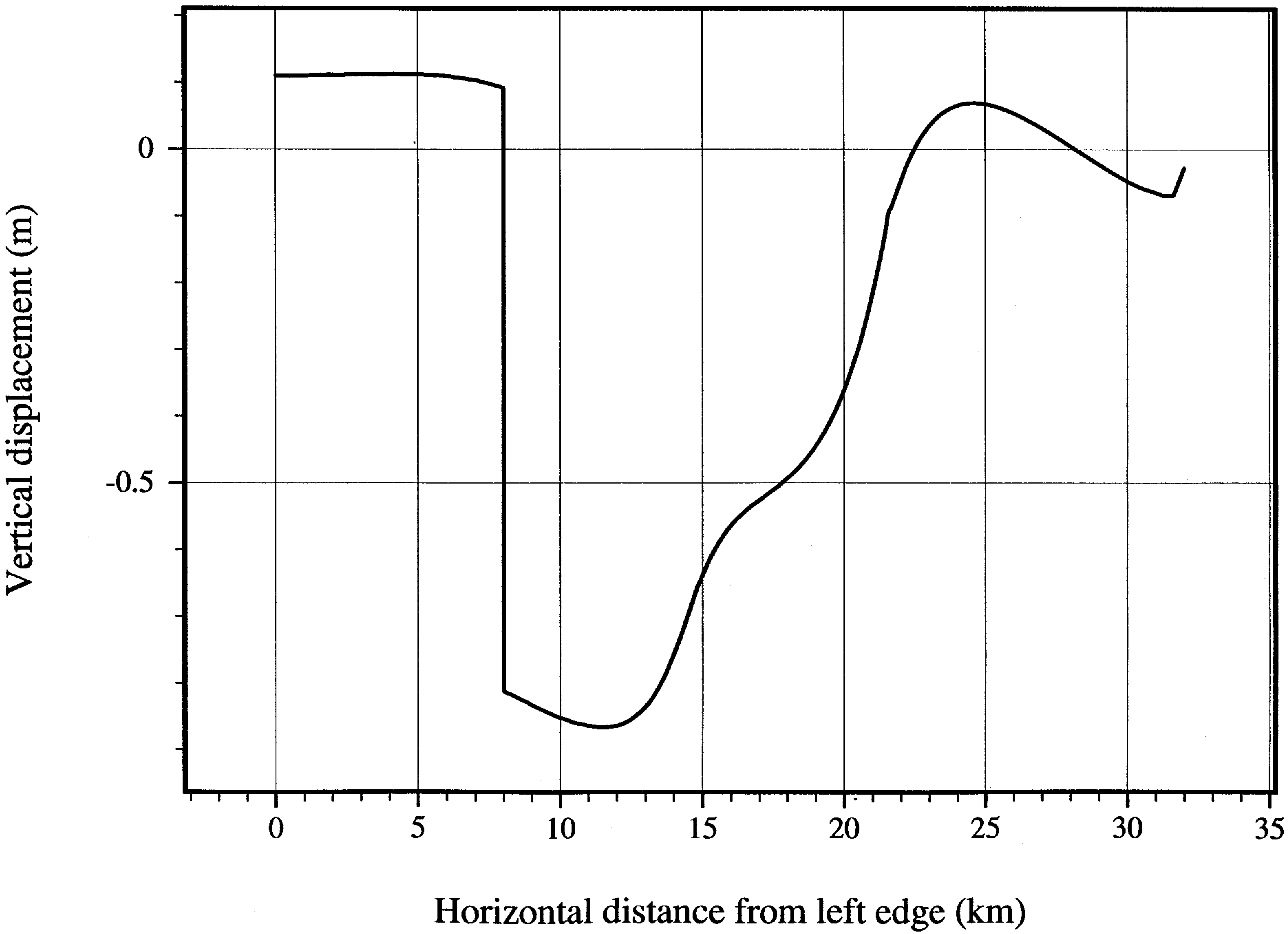
Fault #1, Case 08



Fault #2, Case 08



Ground Surface Profile (Case 08)



7 Alternative Model: All Faults as Slender Isotropic Solids

A new model was developed in which all three faults (F0, F1, and F2) are represented as slender isotropic solids. The mechanical behavior of the faults will be modeled as elastic-plastic, and a steady-state creep model may be applied to the detachment to simulate slow fault slip (if considered necessary). The following advantages are expected from modeling faults as isotropic solids:

1. Isotropic-solid models allow slip to develop in any direction within a fault zone (unlike block-contact models, which restrict slip to fault-parallel planes). As a result, problems such as fault locking that were observed with the block-contact model, especially along the detachment (e.g., see Case c08), are likely to be eliminated.
2. The isotropic-solid model is numerically more stable than the block-contact model.
3. A non-zero thickness for the fault zone, which is permitted under the solid model, will allow the placement of fictitious-beam elements along the hangingwall and footwall surfaces of the fault. Such elements are required for applying external shear stress on the fault. Beam elements cannot be placed on fault surfaces with the block-contact model because such elements require non-zero thickness. As a result, the only way to apply external shear stress on the fault is through nodal displacements or forces, and the magnitude of applied shear stress is difficult to control in both cases.

7.1 Geometrical Model

All three faults have the same orientations as in the previous model: F1 and F2 dip 75°W and F0 dips 60°E at the ground surface with a horizontal detachment at 12-km depth. Each of the faults is modeled as a 100-m thick solid. Because of the thickness, the hangingwall and footwall surfaces of the detachment are at $y = 50$ and $y = -50$ m, respectively. Both F1 and F2 are normal to F0 near their bases. The change in attitude of both faults at their intersection with F0 was made to facilitate finite-element discretization of the model.

7.2 Finite Element Model

Each fault is flanked by two fault-parallel element layers on the footwall and hangingwall sides. The mechanical behavior of the flanking elements can be set to that of either the fault or the surrounding rock. The following element and node sets were set up:

F0SSCORE Steep segments of fault F0

F0DSCORE Detachment segments of fault F0

F0ZONE Four fault-parallel element layers, two on each side of fault F0

F1CORE Fault F1

F1ZONE Four fault-parallel element layers, two on each side of fault F1

F2CORE Fault F2

F2ZONE Four fault-parallel element layers, two on each side of fault F2

HWALL The rest of the hangingwall of fault F0

FWALL Footwall of fault F0

NDLEFT All nodes along $x = 0$, i.e., left boundary of model. Zero x-displacement will be enforced on these nodes

NDBASE All nodes along $y = -10000$ m, i.e., base of model. Zero y-displacement will be enforced on these nodes

NDRIGHT All nodes along $x = 34000$ m, i.e., right boundary of F0 footwall. Zero x-displacement will be enforced on these nodes

NDTOP All nodes along top of model ($y = 12000$) m. Vertical displacement at these nodes will be plotted to produced the ground-surface profile

NDF0FW All nodes on footwall surface of fault F0

NDF0HW All nodes on hangingwall surface of fault F0

NDF1FW All nodes on footwall surface of fault F1

NDF1HW All nodes on hangingwall surface of fault F1

NDF2FW All nodes on footwall surface of fault F2

NDF2HW All nodes on hangingwall surface of fault F2

Node sets NDF0FW, NDF0HW, NDF1FW, NDF1HW, NDF2FW, and NDF2HW will be sorted in down-dip order using C code **FaultNodes.c**, and the values of x and y displacements (u_x and u_y, respectively) at these nodes will be used to compute fault displacement on each of the faults. The node sets NDF0FW and NDF0HW, sorted as explained above, will be used to set up beam elements on the footwall and hangingwall surfaces of fault F0. Such beam elements can be incorporated in the model when required.

7.3 Code FaultNodes.c

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

typedef struct Point {
  int node;
  float x,y,theta;
  struct Point *next;
};
```

Cato


```
main()
{

/*****************************************************************
  This code sorts nodal points on a surface in a user-chosen order,
  and calculates local slope of surface at each node using
  quadratic-element topology.
  It reads nodal data from a file created using ABAQUS/Post function
  PRINT NODES. The user-chosen order is defined in function IsBelow.
*****************************************************************/

  char buf[121];
  int node;
  float x,y;
  struct Point *FirstPoint,*LastPoint,*currentPoint;

  FirstPoint = LastPoint = NULL;
  while (gets(buf))
    if (sscanf(buf,"%d %f %f",&node,&x,&y) == 3){
      currentPoint = (struct Point *)malloc(sizeof(struct Point));
      if (!currentPoint){
        printf("\t***\tMemory allocation failure\t***\n");
        return;
      }
      currentPoint->node = node;
      currentPoint->x = x;
      currentPoint->y = y;
      StorePoint(currentPoint,&FirstPoint,&LastPoint);
    }

/*
  Calculate slope of fault segment at each nodal point;
  then print out the nodal point data in down-dip order
*/

  FaultSlopeAtPoint(FirstPoint);
  PrintPoints(FirstPoint);
}

StorePoint(current,first,last)
  struct Point *current,**first,**last;
{
  struct Point *old,*p;

  p = *first;
```

Gtw


```
  if (!*last){           /* current is the very first item in the list */
    current->next = NULL;
    *last = current;
    *first = current;
    return;
  }

  old = NULL;
  while (p){
    if (IsBelow(current,p)){
      old = p;
      p = p->next;
    }
    else{
      if (old) {      /* insert current at this point in the list */
        old->next = current;
        current->next = p;
        return;
      }
      current->next = p;    /* current becomes new first element */
      *first = current;
      return;
    }
  }

  (*last)->next = current;  /* current becomes new last element */
  current->next = NULL;
  *last = current;
}

PrintPoints(first)
  struct Point *first;
{
  float pi;

  pi = 4.0*atan(1.0);

  if (!first){
    printf("\t***\tNothing to print\t***\n");
    return;
  }

  printf("%10s%15s%15s%12s\n","Node","xcoord (m)","ycoord (m)","LocalSlope");

  while (first){
```

```
    printf("%10d%15.5E%15.5E%12.2f\n",first->node,first->x,first->y,
    (180.0/pi)*first->theta);
    first = first->next;
  }
}
int IsBelow(current,p)
  struct Point *current,*p;
{
  int below,notBelow;
  float delta,yTol;

/*
   This code module determines whether first-named POINT is down-dip (below)
   or up-dip of second-named POINT
*/

  below = 1;
  notBelow = 0;
  yTol = 0.05;

  delta = current->y - p->y;
  if (delta < -yTol)
    return(below);

  if (delta > yTol)
    return(notBelow);

  delta = current->x - p->x;
  if (delta > 0.0)
    return(below);

  return(notBelow);
}

FaultSlopeAtPoint(first)
  struct Point *first;
{
  float angle;
  struct Point *pFirst,*pMid,*pEnd;

/*
  Calculate slope of fault segments at nodal points, consecutive sets of
  three rectilinear Points in down-dip order
*/

  if (!first)
```

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```
    DumpAndQuit("Empty list submitted for slope calculation");

/*
  Process first segment (set of 3 nodes). Issue error message if
  there are less than 3 nodes in the list.
*/

  pFirst = first;
  pMid = pFirst->next;
  if (!pMid)
    DumpAndQuit("Only one node in list submitted for slope calculation");
  pEnd = pMid->next;
  if (!pEnd)
    DumpAndQuit("Only two nodes in list submitted for slope calculation");
  angle = atan2((pFirst->y - pEnd->y),(pFirst->x - pEnd->x));
  pFirst->theta = pMid->theta = angle;
  pEnd->theta = !(pEnd->next) ? angle : angle/2.0;

/* Process the rest of the segments */

  pFirst = pEnd;
  while (pFirst){
    pMid = pFirst->next;
    if (!pMid) break;   /* Previous segment is the last one */

    pEnd = pMid->next;
    if (!pEnd){     /* Midnode of current segment is the last node */

      angle = atan2((pFirst->y - pMid->y),(pFirst->x - pMid->x));
      pFirst->theta += angle/2.0;
      pMid->theta = angle;
    }
    else{  /* This segment has three nodes; there may be another segment */

      angle = atan2((pFirst->y - pEnd->y),(pFirst->x - pEnd->x));
      pFirst->theta += angle/2.0;
      pMid->theta = angle;
      pEnd->theta = !(pEnd->next) ? angle : angle/2.0;
    }
    pFirst = pEnd;
  }
}

DumpAndQuit(s)
char *s;
{
```

```
  printf("\n *** %s ***\n\n",s);
  exit(0);
}
```

7.4 Material Model

The material model is explained in the following excerpt from the ABAQUS input file (file m02Base.inp in directory BMountn/fz.test).

```
***
*** Three sets of solid material properties are assigned:
***
***     (1) Elastic Drucker-Prager material (RUBBLE)
***         for the fault zones F1CORE, F2CORE and FOSSCORE.
***         Each fault zone is 100 m thick.
***
***     (2) Viscoelastic Drucker-Prager material (SILIPOTI)
***         may be applied to the detachment fault.
***         (i.e., element set FODSCORE) in certain options.
***
***         SILIPOTI material is not defined in this file; so FODSCORE
***         elements are assigned RUBBLE properties
***
***     (3) Linear-elastic material (LEROCK) for the rest of the rock body,
***         i.e., element sets FWALL, HWALL, FOZONE, F1ZONE, and F2ZONE
***
*SOLID SECTION,ELSET=F1ZONE,MATERIAL=LEROCK
*SOLID SECTION,ELSET=F2ZONE,MATERIAL=LEROCK
*SOLID SECTION,ELSET=FOZONE,MATERIAL=LEROCK
*SOLID SECTION,ELSET=HWALL,MATERIAL=LEROCK
*SOLID SECTION,ELSET=FWALL,MATERIAL=LEROCK
*SOLID SECTION,ELSET=F1CORE,MATERIAL=RUBBLE
*SOLID SECTION,ELSET=F2CORE,MATERIAL=RUBBLE
*SOLID SECTION,ELSET=FOSSCORE,MATERIAL=RUBBLE
*SOLID SECTION,ELSET=FODSCORE,MATERIAL=RUBBLE
***
*MATERIAL, NAME=LEROCK
*DENSITY
2.5E-3
*ELASTIC
3.25E4,0.25
*MATERIAL,NAME=RUBBLE
*DENSITY
2.5E-3
*ELASTIC
```

```
3.25E4,0.25
*DRUCKER PRAGER,SHEAR CRITERION=LINEAR
50.0,0.78,30.0
***
*** Material RUBBLE is assigned compressive strength of 100 MPa in Step 1
*** and 5 MPa in Step 2 (value at end of Step 2 is the desired value), by
*** specifying compressive strength as function of a field variable that has
*** the same value as total time
***
*DRUCKER PRAGER HARDENING,TYPE=COMPRESSION,DEPEND=1
100.0,0.0, ,0.0
100.0,0.0, ,0.5
5.0,0.0, ,1.0
*DAMPING,ALPHA=0.025,BETA=0.025
```

7.5 Boundary and Initial Conditions

The initial stress state is set as vertical stress $\sigma_v = 25$ MPa/km depth, and horizontal stress $\sigma_h = 0.25\sigma_v$. Boundary conditions are zero-perturbation conditions set as follows: zero x-displacement on node sets NDLEFT and NDRIGHT, zero y-displacement on node set NDBASE, horizontal pressure of 6.25 MPa/km depth on right boundary of fault F0 hangingwall, and vertical pressure of 301.25 MPa on the top surface of horizontal bench at the right boundary of the footwall. The top of the model is a free surface.

7.6 Analysis Steps

Each analysis will be conducted in three steps: the first two steps establish the initial equilibrium state, and a chosen perturbation will be applied in the third step to induce fault slip.

7.6.1 Step One: Initial Equilibrium with Increased Shear Strength

The model is brought to initial static equilibrium under the influence of initial stress, gravitational body force, boundary pressures, and boundary displacements. Because the body forces and boundary pressure are applied as external forces whereas the initial stress is treated as pre-existing stress, it is important that all forces be applied instantaneously in order to establish equilibrium without deformation. On the other hand, because slip would occur on the faults under the specified material properties and initial stress, the numerical process may fail to converge if the forces are applied instantaneously. To deal with this problem the fault zones are assigned an initially high unconfined compressive strength (100 MPa) to preclude fault slip in analysis step 1 (during which all forces are applied instantaneously).

7.6.2 Step Two: Initial Equilibrium with Appropriate Shear Strength

During Step 2, the unconfined compressive strength of the fault zones is gradually reduced to the desired value (5 MPa) from the initial high value. The reduction is accomplished by specifying the

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unconfined compressive strength as a function of a field variable that has the value of total time. This enables fault slip at the initial state to be accomodated through incremental analysis.

7.6.3 Subsequent Analysis Steps

There will be at least one subsequent analysis step, during which a desired perturbation will be introduced to induce fault slip. Such analysis steps will be run as restart jobs on the restart files saved at the end of Step 2.

7.7 Monitored Responses

The aspects of response to be monitored are (i) fault displacement on F0, F1, and F2; (ii) vertical displacement at the ground surface; and (iii) ground acceleration at selected points on the ground surface and at depths of 200-500 m. Other aspects of response, such as stress change and slip rate may also be monitored.

7.7.1 Fault Displacement

Nodal displacements on the hangingwall and footwall surfaces of the three faults (extracted from node sets NDF0FW, NDF0HW, NDF1FW, NDF1HW, NDF2FW, and NDF2HW) will be processed using the C code FaultSurfaceDisp.c (see April 08 1996 entries), the output from which will be converted to fault displacement (fault slip) using the C code FaultDisp.c (see June 07 1996 entries).

7.7.2 Ground Surface Displacement

Displacement results for the ground surface are extracted from the node set NDTOP and processed using the C code GroundSurfaceDisp.c that is reproduced below.

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

typedef struct Point {
  int node;
  float x,y,ux,uy;
  struct Point *next;
};

main()
{

/***********************************************************************
  GroundSurfaceDisp.c

  This code sorts nodal points on the ground surface (and the associated
```

GTVO


```
  nodal displacements) in left-to-right order; It reads nodal data from
  a file created using ABAQUS/Post function PRINT NODES.
*************************************************************************/

  char buf[121];
  int node;
  float x,y,ux,uy;
  struct Point *FirstPoint,*LastPoint,*currentPoint;

/*
  Read input file for nodal point data
  Setup storage and store nodal data in a linked list
  sorted in left-to-right order
*/

  FirstPoint = LastPoint = NULL;
  while (gets(buf))
    if (sscanf(buf,"%d %f %f %f %f",&node,&x,&y,&ux,&uy) == 5){
      currentPoint = (struct Point *)malloc(sizeof(struct Point));
      if (!currentPoint)
        DumpAndQuit("Memory allocation failure");
      currentPoint->node = node;
      currentPoint->x = x;
      currentPoint->y = y;
      currentPoint->ux = ux;
      currentPoint->uy = uy;
      StorePoint(currentPoint,&FirstPoint,&LastPoint);
    }

  PrintPoints(FirstPoint);
}

StorePoint(current,first,last)
  struct Point *current,**first,**last;
{
  struct Point *old,*p;

  p = *first;

  if (!*last){          /* current is the very first item in the list */
    current->next = NULL;
    *last = current;
    *first = current;
    return;
  }
```

```
  old = NULL;
  while (p){
    if (IsBelow(current,p)){
      old = p;
      p = p->next;
    }
    else{
      if (old) {      /* insert current at this point in the list */
        old->next = current;
        current->next = p;
        return;
      }
      current->next = p;    /* current becomes new first element */
      *first = current;
      return;
    }
  }

  (*last)->next = current;  /* current becomes new last element */
  current->next = NULL;
  *last = current;
}

PrintPoints(first)
  struct Point *first;
{

  if (!first){
    printf("\t***\tNothing to print\t***\n");
    return;
  }

  printf("%10s%12s%12s%12s%12s\n","Node","x (km)","y (m)","xDisp (m)",
         "yDisp (m)");

  while (first){
    printf("%10d%12.2f%12.2f%12.2E%12.2E\n",first->node,1.0e-3*first->x,
      1.0e-3*first->y,first->ux,first->uy);
    first = first->next;
  }
}
int IsBelow(current,p)
  struct Point *current,*p;
{
  int below,notBelow;
  float delta,xTol;
```

```
/*
   This code module determines whether first-named Point is down-dip, i.e.,
   to the right, or up-dip (to the left) of second-named Point
*/

  below = 1;
  notBelow = 0;
  xTol = 0.05;

  delta = current->x - p->x;
  if (delta > xTol)
    return(below);

  return(notBelow);
}

DumpAndQuit(s)
char *s;
{
  printf("\n *** %s ***\n\n",s);
  exit(0);
}
```

7.7.3 Ground Acceleration

Ground acceleration will be monitored at the nodes shown in the following table. The ground surface is at y=12000 m.

Node	xcoord (m)	ycoord (m)	Depth (m)
6859	5.600E+02	1.200E+04	0.00
6860	5.750E+02	1.175E+04	250.00
6861	5.890E+02	1.150E+04	500.00
5486	6.294E+03	1.200E+04	0.00
5485	6.556E+03	1.200E+04	0.00
5493	6.436E+03	1.176E+04	240.00
5503	6.578E+03	1.152E+04	480.00
5504	6.234E+03	1.151E+04	490.00
2072	1.187E+04	1.200E+04	0.00
2091	1.187E+04	1.178E+04	220.00
2110	1.187E+04	1.156E+04	440.00
10957	1.825E+04	1.200E+04	0.00

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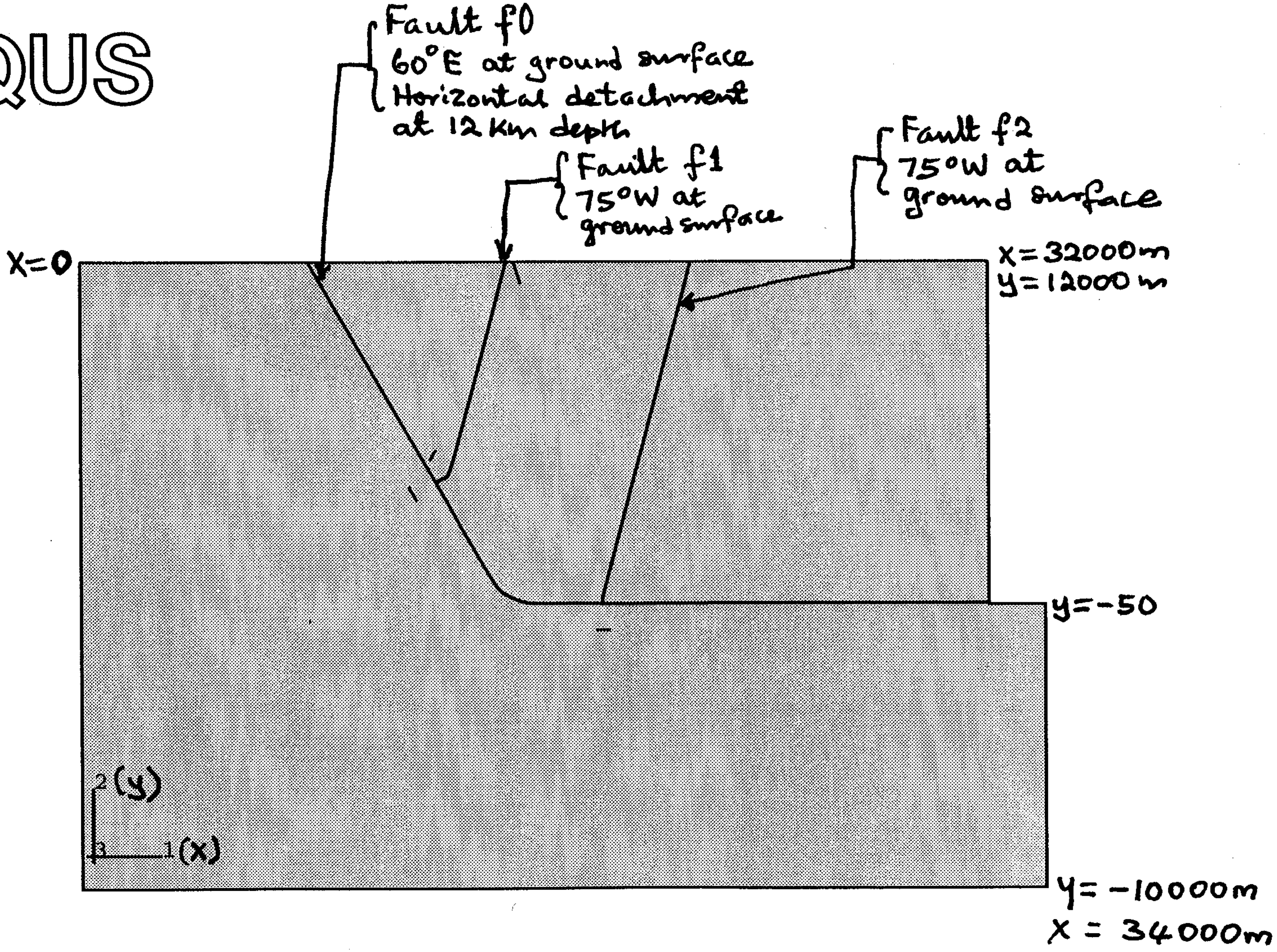
10974	1.822E+04	1.173E+04	270.00
10980	1.820E+04	1.147E+04	530.00
11019	1.838E+04	1.147E+04	530.00
3669	2.286E+04	1.200E+04	0.00
3687	2.285E+04	1.176E+04	240.00
3714	2.284E+04	1.151E+04	490.00
3657	2.533E+04	1.200E+04	0.00
3681	2.534E+04	1.175E+04	250.00
3702	2.534E+04	1.151E+04	490.00
3646	2.886E+04	1.200E+04	0.00
3645	2.925E+04	1.200E+04	0.00
3694	2.913E+04	1.171E+04	290.00
3731	2.902E+04	1.141E+04	590.00
3732	2.938E+04	1.137E+04	630.00

The locations of the nodes are shown in the attached figure (x=0 at the left boundary of the model).

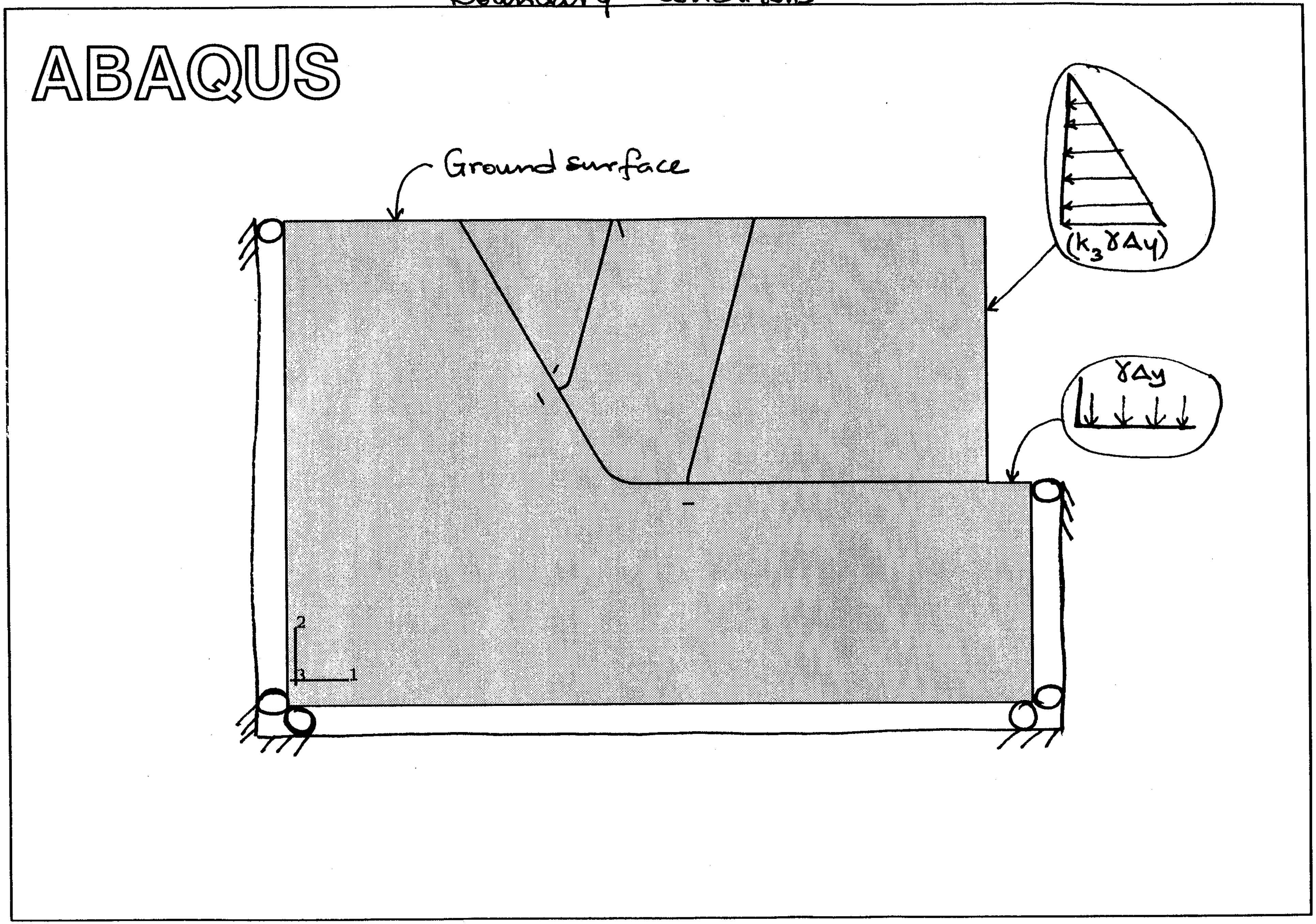
Geometry

ABAQUS

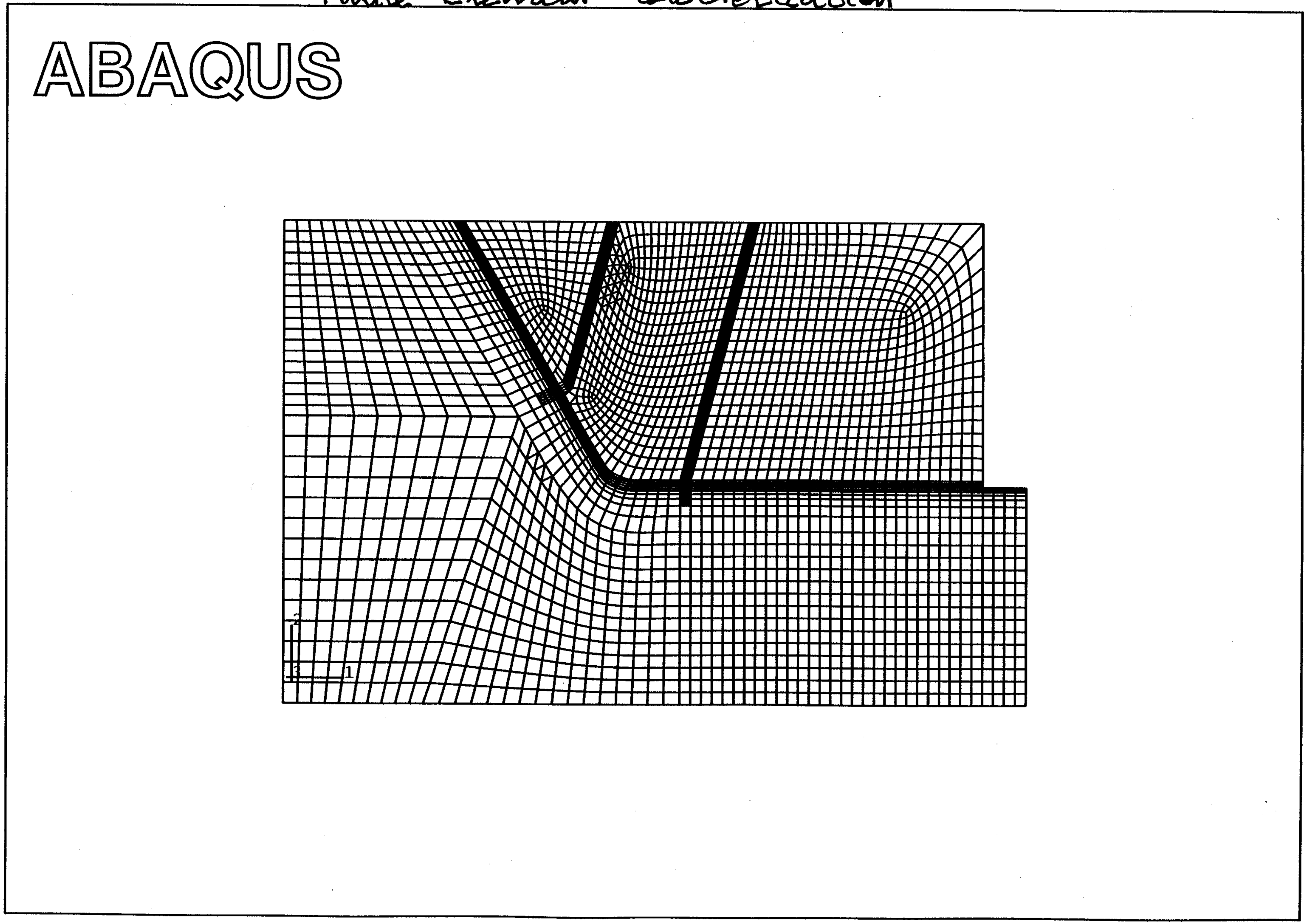


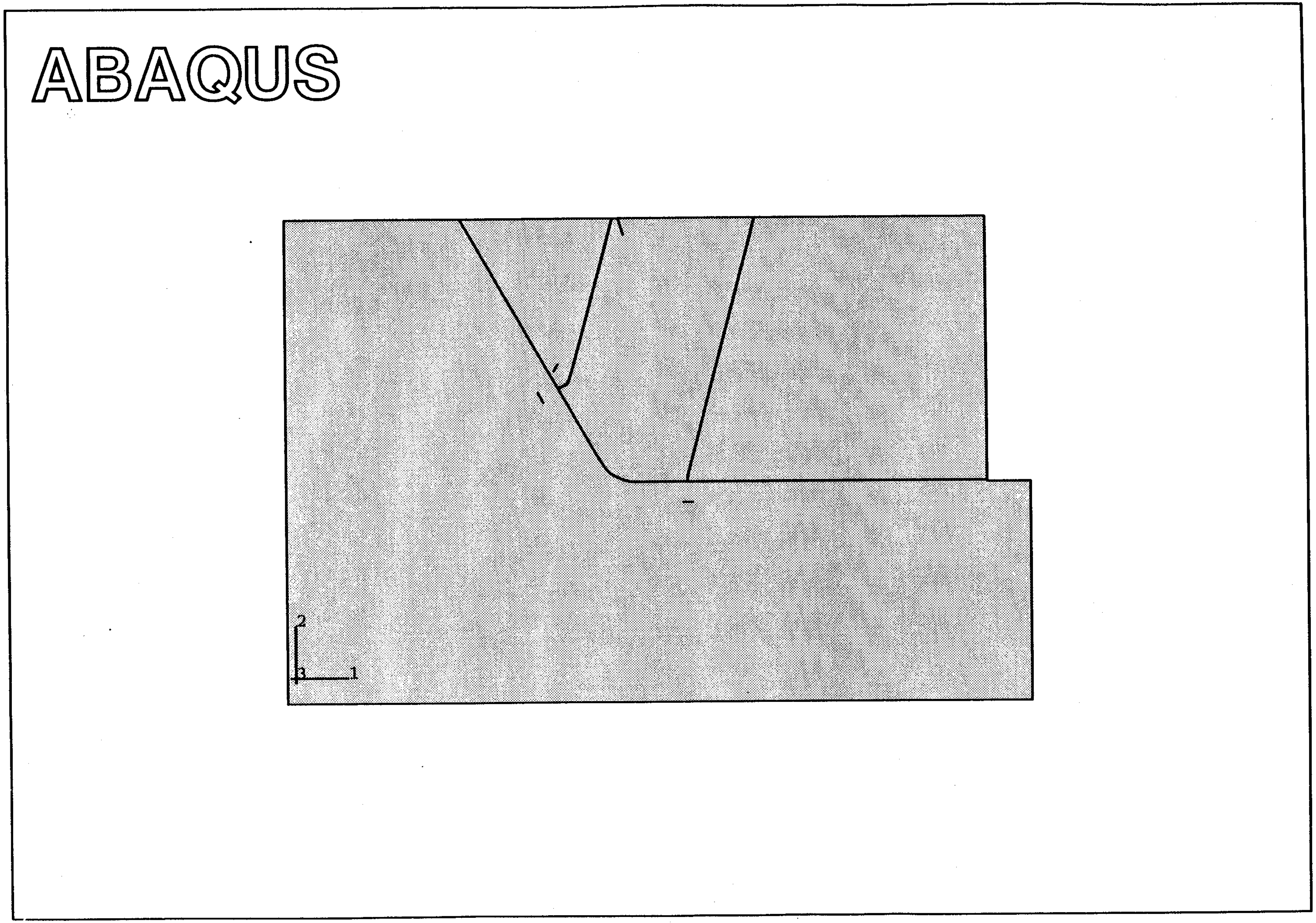
Each fault modeled as 100-m thick isotropic, elastic-plastic solid.

Boundary Conditions

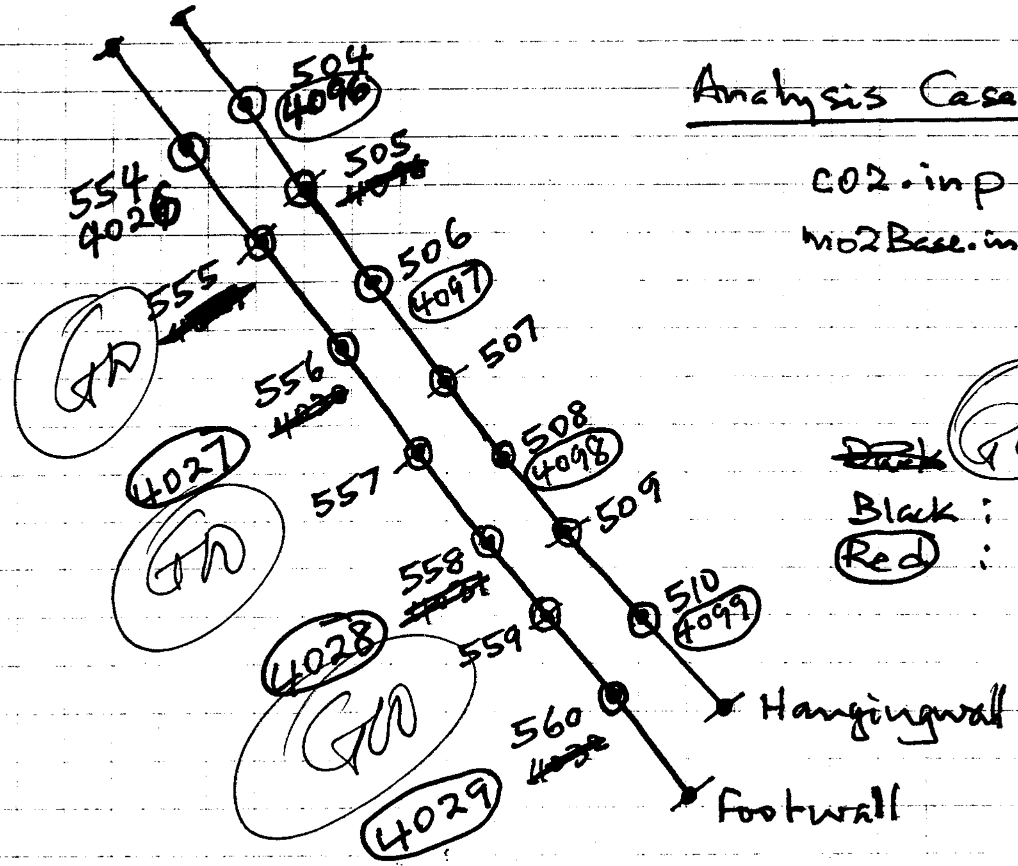


Finite Element Discretization




ABAQUS
2
3
1

GLO



Analysis Case C02

C02.inp — Dynamic perturbation

mo2Base.inp — Initial static equilibrium

~~Black~~ GLO

Black : Node numbers

Red : Fictitious beam element numbers.

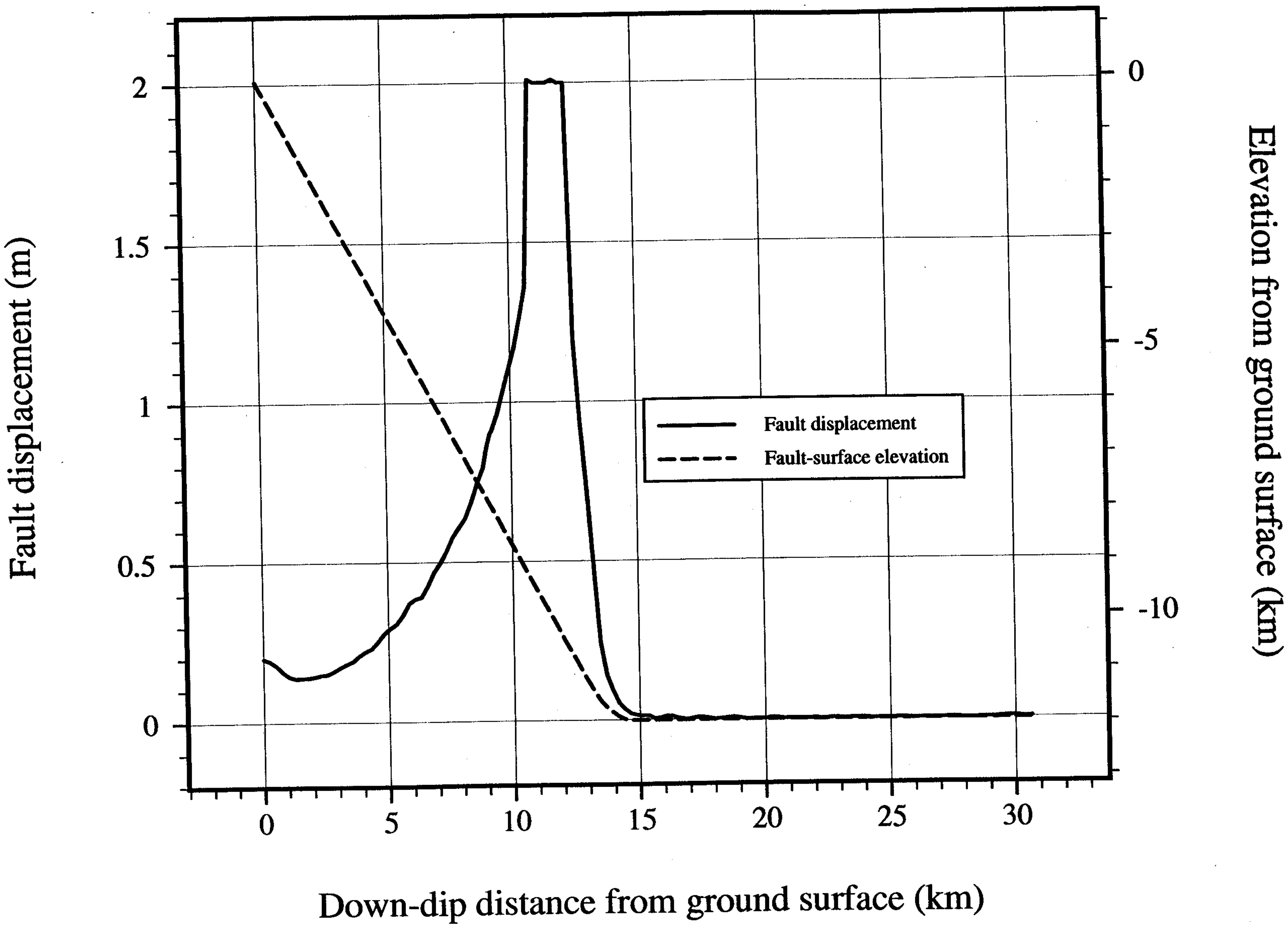
Induced fault displacement applied at the nodes shown above on the footwall and hangingwall of fault F0.

Fault Length

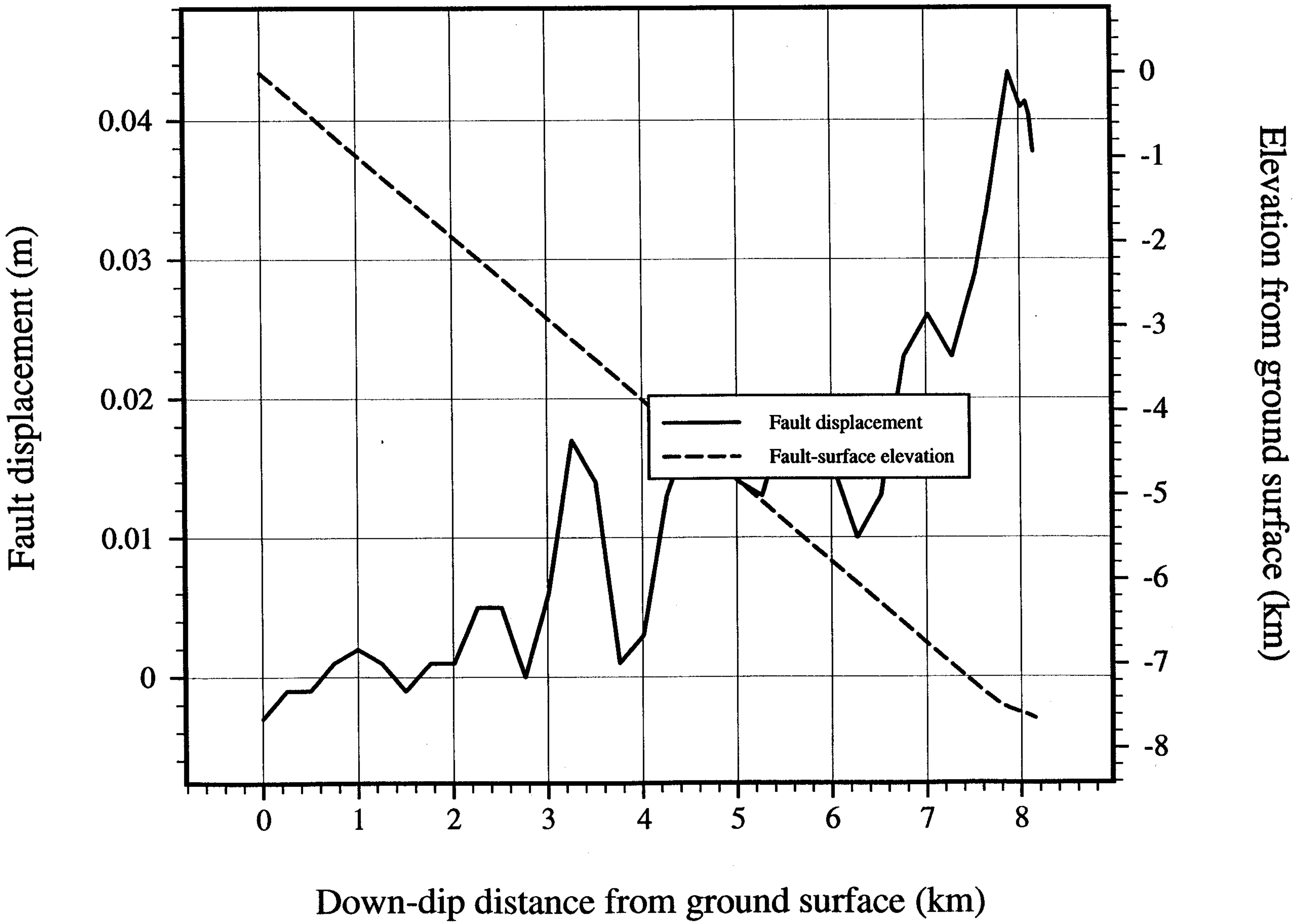
Node 554 — Node 560 : 1.43 km

Node 504 — Node 510 : 1.42 km

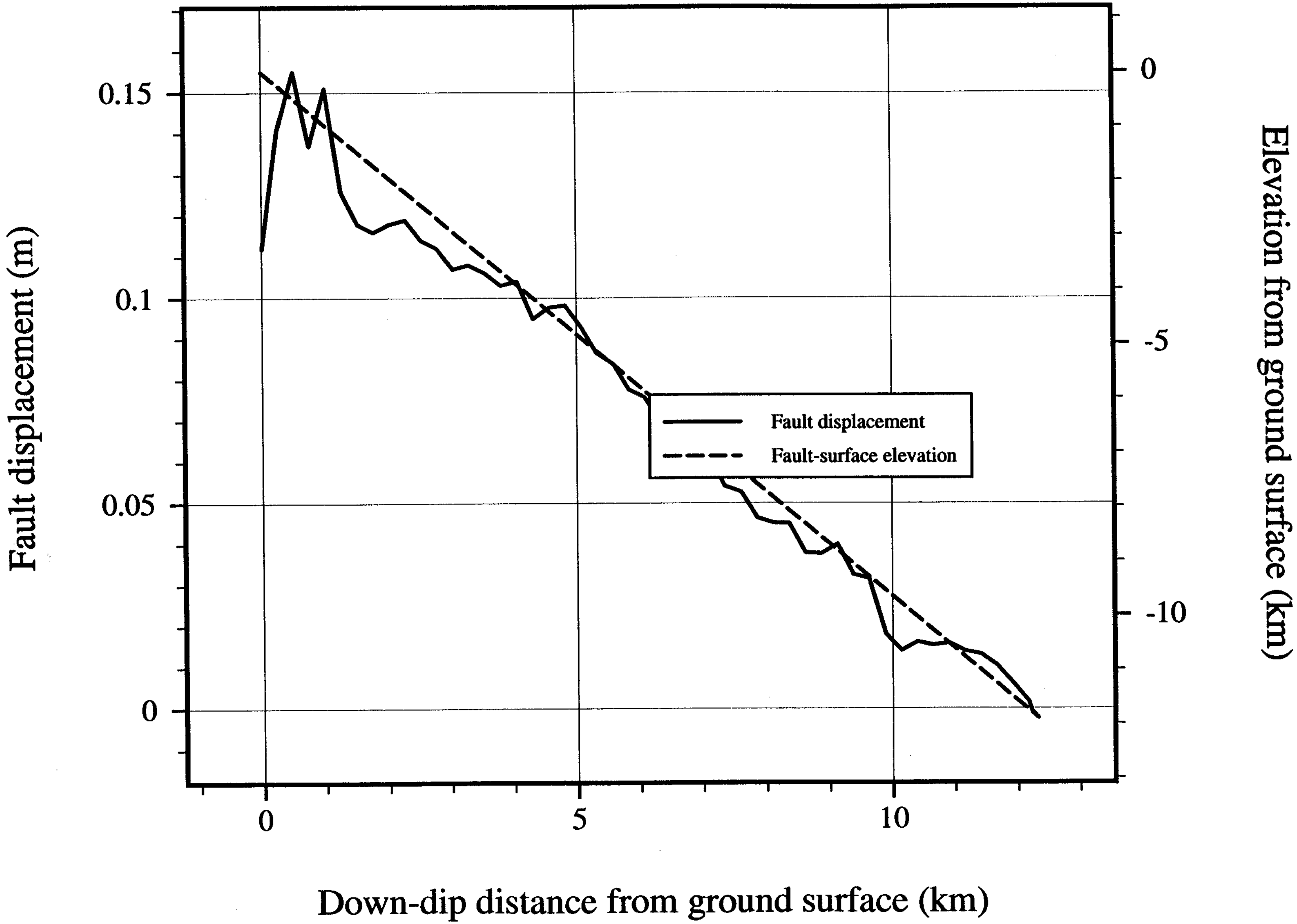
Main Fault, Case 02



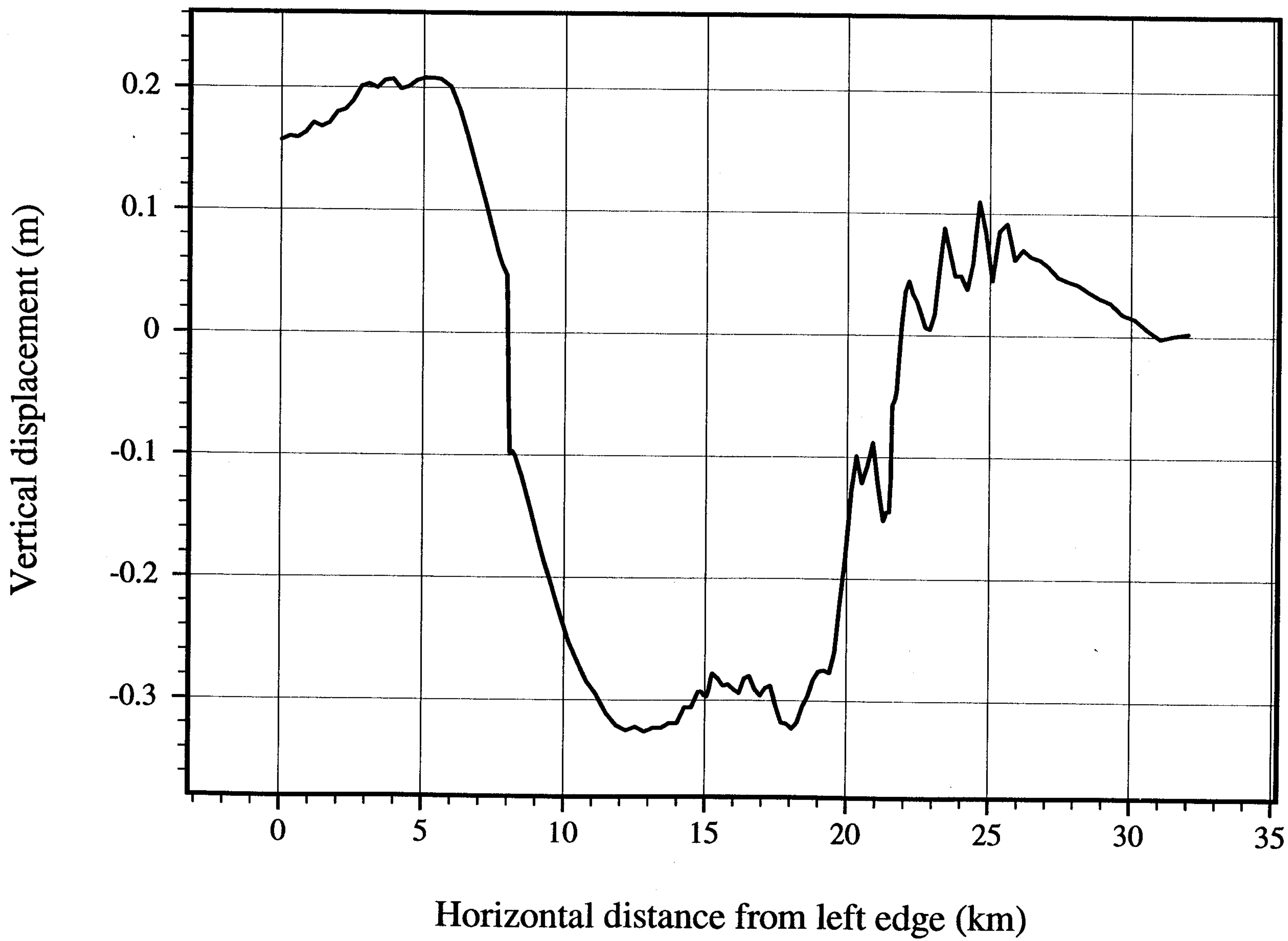
Fault #1, Case 02



Fault #2, Case 02



Ground Surface Profile (Case 02)



8 Fault Slip Induced By Application of External Shear Force

In this procedure, external shear forces are applied on selected segments of fault F0 through the application of axial forces on fictitious-beam elements placed on the hangingwall and footwall surfaces of the fault. The beams are referred to as fictious because they do not represent physical components of the modeled domain. As a result they are assigned small values of elastic stiffness and density, as will be discussed subsequently, such that their contributions to the mass and stiffness of the domain are negligible.

8.1 Definition of Fictitious-Beam Elements

The nodal data for the beam elements were generated from the node sets NDF0FW and NDF0HW using the following C code.

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

main()
{
  char buf[121];
  char *fwfilename="ndf0fw.sorted";
  char *hwfilename="ndf0hw.sorted";
  int i,node,*hwNodes,*fwNodes,numNodes;
  int element,lastElem;
  float x,y,dip;
  FILE *Fp;

/****************************************************************
  B22Elems.c

  This code developes element-connectivity definitions for
  ABAQUS B22 elements on two (adjacent) fault surfaces
  using nodal data read from two files;
  one file contains the nodal data for the footwall surface
  and the other contains the data for the hangingwall surface;
  there are numNodes nodes defined in each file. The nodes are
  already sorted in the order they appear on each surface.
****************************************************************/

  numNodes = 143;
  lastElem = 4000;

  fwNodes = (int *)malloc(numNodes*sizeof(int));
  hwNodes = (int *)malloc(numNodes*sizeof(int));
  if (!fwNodes || !hwNodes)
    DumpAndQuit("Memory allocation failure");
```

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```
/* Read footwall-surface nodes */

  Fp = fopen(fwfilename,"r");
  if (!Fp){
    sprintf(buf,"Unable to open file %s",fwfilename);
    DumpAndQuit(buf);
  }

  i = 0;
  while (fgets(buf,80,Fp))
    if (sscanf(buf,"%d %f %f %f",&node,&x,&y,&dip) == 4){
      fwNodes[i] = node;
      if (++i == numNodes) break;
    }

  fclose(Fp);
  if (i < numNodes){
    sprintf(buf,"Only %d of %d nodes found in %s",i,numNodes,fwfilename);
    DumpAndQuit(buf);
  }

/* Read hangingwall-surface nodes */

  Fp = fopen(hwfilename,"r");
  if (!Fp){
    sprintf(buf,"Unable to open file %s",hwfilename);
    DumpAndQuit(buf);
  }

  i = 0;
  while (fgets(buf,80,Fp))
    if (sscanf(buf,"%d %f %f %f",&node,&x,&y,&dip) == 4){
      hwNodes[i] = node;
      if (++i == numNodes) break;
    }

  fclose(Fp);
  if (i < numNodes){
    sprintf(buf,"Only %d of %d nodes found in %s",i,numNodes,hwfilename);
    DumpAndQuit(buf);
  }

/* Footwall-surface elements */

  element = lastElem + 1;
```

```
  node = 0;
  printf("*ELEMENT,TYPE=B22,ELSET=FWBEAMS\n");

  while (node < numNodes-1){
    printf("%d,%d,%d,%d\n",
      element,
      fwNodes[node],
      fwNodes[node+1],
      fwNodes[node+2]    );
    ++element;
    node += 2;
  }

/* Hangingwall-surface elements */

  node = 0;
  printf("*ELEMENT,TYPE=B22,ELSET=HWBEAMS\n");

  while (node < numNodes-1){
    printf("%d,%d,%d,%d\n",
      element,
      hwNodes[node],
      hwNodes[node+1],
      hwNodes[node+2]    );
    ++element;
    node += 2;
  }

}

DumpAndQuit(s)
char *s;
{
  printf("\n *** %s ***\n\n",s);
  exit(0);
}
```

8.2 Properties of Fictitious-Beam Elements

The beam elements were assigned a solid rectangular cross section with a thickness (normal to model) and depth (normal to fault surface) of 1 m. The beam material was assigned a linear-elastic material model with Young's modulus of 0.0325 MPa (=10^{-6} times the Young's modulus of rock) and density of 0.0025 kg/m^3 (also 10^{-6} times the density of rock). The properties were assigned through the following excerpt from the ABAQUS input file.

Gro


```
***
*** Fictitious beams are assigned solid-rectangular section with depth
*** and thickness of 1.0 m, respectively. They are assigned isotropic,
*** linear-elastic material property, with values of density and Young's
*** modulus equal to 10^-6 times the respective values for rock. As a
*** result of the assigned material density and stiffness, the beams
*** are not expected to affect the stiffness and mass matrices for the
*** system.
***
*BEAM SECTION,ELSET=FWBEAMS,MATERIAL=FICTBEAM,SECTION=RECT
1.0,1.0
*BEAM SECTION,ELSET=HWBEAMS,MATERIAL=FICTBEAM,SECTION=RECT
1.0,1.0
*MATERIAL,NAME=FICTBEAM
*ELASTIC
3.25E-2,0.25
*DENSITY
2.5E-9
```

8.3 Applied Axial Forces on Fictitious-Beam Elements

Axial forces will be applied on the fictitious-beam elements on the hangingwall and footwall surfaces of fault F0 to transmit shear stresses into the fault elements. Each quadrilateral element of fault F0 is sandwiched between two fictitious-beam elements, and the magnitude of axial force to be applied to the beam elements was calculated based on the stress conditions at the centroid of the quadrilateral. The vertical and horizontal stresses, σ_v and σ_h, respectively, at the quadrilateral centroid were calculated as γd and $k_3\gamma d$, respectively, where $\gamma = 25$ MPa/km, $k_3 = 0.25$, and d is the depth (km) of the quadrilateral centroid. The shear stress required to cause slip at the centroid of the fault element was calculated as $\tau = \mu\sigma_n$, where $\mu = \tan 37°$ is the friction coefficient applied to the fault zone, and

$$\sigma_n = \sigma_h \cos^2\alpha + \sigma_v \sin^2\alpha \qquad \text{where} \qquad \alpha = \frac{\pi}{2} + \theta \tag{1}$$

and θ is the dip of the fault evaluated at the centroid of the quadrilateral element.

The axial force (MN/m) to be applied to the beam elements are calculated as $f_s\tau$ for the footwall-surface beam and $-f_s\tau$ for the hangingwall-surface beam, where f_s is a scale factor that varies linearly from 0.0 at time t_o, through 1.25 at time $t_o + 0.25$ s, to 0.95 at time $t_o + 0.5$ s, and remains constant at 0.95 thereafter, where t_o is time at the beginning of the load-application analysis step.

8.4 Computation of Equivalent Beam Forces

The scale factor f_s is applied through the amplitude reference LOADHIST defined in the ABAQUS input file as follows.

```
***
```

```
*** The following amplitude definition applies a time-varying multiplication
*** factor to externally applied fault shear stress (applied through axial
*** beam loading).
***
*AMPLITUDE,NAME=LOADHIST,TIME=STEP TIME,DEF=TABULAR
0.0,0.0,0.25,1.25,0.5,0.95,5.0,0.95
```

The x- and y-components of the beam axial forces (without the f_s factor) were computed using the C code reproduced below.

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

float LimEquilShearStress(float y1,float y2,float y3,float y4,float dip,
  float unitWeight,float k3Ratio);
int EquivalentBeamLoad(float tau,float dirFactor,float dip,
  float* fx,float* fy);

main()
{

/***************************************************************
  FaultShearLoading.c

  Code to calculate equivalent beam loads to apply specified
  magnitudes of shear stress on quadrilateral fault-zone elements.
  Each quadrilateral element is represented by a pair of beam elements,
  one on the hangingwall surface and the other on the footwall surface
  of the quadrilateral. The connectivity data for the beam elements
  is developed using nodal data read from two files;
  one file contains the nodal data for the footwall surface
  and the other contains the data for the hangingwall surface;
  there are numNodes nodes defined in each file. The nodes are
  already sorted in down-dip order.

  The vertical and horizontal stresses at the centroid of each
  quadrilateral are calculated using specified rock unitWeight and
  k3Ratio, and are transformed to obtain the normal stress on the
  fault at the quadrilateral centroid. The limit-equilibrium shear
  stress under the computed normal stress is calculated based on
  a specified Mohr-Coulomb failure criterion. The magnitude of beam
  axial loading (force per unit length) statically equivalent to a
  specified shear stress at the quadrilateral centroid is numerically
  equal to the shear stress.

  System Requirement:      Compile with acc on SUN OS
```

```
                          cc will not work

  Author:       G.I. Ofoegbu
  Date:         June 21 1996
  Revised:      June 24 1996

***************************************************************/

  char buf[121];
  char *fwfilename="ndf0fw.sorted";
  char *hwfilename="ndf0hw.sorted";
  int i,node,*hwNodes,*fwNodes,numNodes;
  int lastElem,numQuadElems,fwElnum,hwElnum;
  float x,y,dip,y1,y2,y3,y4;
  float *fwDip,*hwDip,*yhw,*yfw;
  float tau,fx,fy,unitWeight,k3Ratio;
  FILE *Fin,*FhOut,*FfOut;

  numNodes = 143;
  lastElem = 4000;
  numQuadElems = 71;
  unitWeight = 0.025;
  k3Ratio = 0.25;

  fwNodes = (int *)malloc(numNodes*sizeof(int));
  hwNodes = (int *)malloc(numNodes*sizeof(int));
  hwDip = (float *)malloc(numNodes*sizeof(float));
  fwDip = (float *)malloc(numNodes*sizeof(float));
  yhw = (float *)malloc(numNodes*sizeof(float));
  yfw = (float *)malloc(numNodes*sizeof(float));
  if (!fwNodes || !hwNodes || !hwDip || !fwDip || !yhw || !yfw)
    DumpAndQuit("Memory allocation failure");

  FfOut = fopen("B22fwLoad.def","w");
  FhOut = fopen("B22hwLoad.def","w");
  if (!FfOut || !FhOut)
    DumpAndQuit("Unable to open output file");

/* Read footwall-surface nodes */

  Fin = fopen(fwfilename,"r");
  if (!Fin){
    sprintf(buf,"Unable to open file %s",fwfilename);
    DumpAndQuit(buf);
  }
```

```
  i = 0;
  while (fgets(buf,80,Fin))
    if (sscanf(buf,"%d %f %f %f",&node,&x,&y,&dip) == 4){
      fwNodes[i] = node;
      fwDip[i] = dip;
      yfw[i] = y;
      if (++i == numNodes) break;
    }

  fclose(Fin);
  if (i < numNodes){
    sprintf(buf,"Only %d of %d nodes found in %s",i,numNodes,fwfilename);
    DumpAndQuit(buf);
  }

/* Read hangingwall-surface nodes */

  Fin = fopen(hwfilename,"r");
  if (!Fin){
    sprintf(buf,"Unable to open file %s",hwfilename);
    DumpAndQuit(buf);
  }

  i = 0;
  while (fgets(buf,80,Fin))
    if (sscanf(buf,"%d %f %f %f",&node,&x,&y,&dip) == 4){
      hwNodes[i] = node;
      hwDip[i] = dip;
      yhw[i] = y;
      if (++i == numNodes) break;
    }

  fclose(Fin);
  if (i < numNodes){
    sprintf(buf,"Only %d of %d nodes found in %s",i,numNodes,hwfilename);
    DumpAndQuit(buf);
  }

  fwElnum = lastElem + 1;
  hwElnum = numQuadElems + fwElnum;
  node = 0;
  fprintf(FfOut,"*DLOAD,AMPLITUDE=LOADHIST\n");
  fprintf(FhOut,"*DLOAD,AMPLITUDE=LOADHIST\n");

  while (node < numNodes-1){
                  /* Extract y-coordinate of quadrilateral corners */
```

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```
    y1 = yfw[node];
    y2 = yfw[node+2];
    y3 = yhw[node+2];
    y4 = yhw[node];
    dip = (fwDip[node+1] + hwDip[node+1])/2.0;

    tau = LimEquilShearStress(y1,y2,y3,y4,dip,unitWeight,k3Ratio);

/*
    Equivalent loading for footwall beams:
    dirFactor=1.0 to give up-dip loading
*/

    dip = fwDip[node+1];
    EquivalentBeamLoad(tau,1.0,dip,&fx,&fy);
    if (dip<89.999 || dip>90.001)
      fprintf(FfOut,"%d,PX,%.5f\n",fwElnum,fx);
    if (dip<179.999 || dip>180.001)
      fprintf(FfOut,"%d,PY,%.5f\n",fwElnum,fy);

/*
    Equivalent loading for hangingwall beams:
    dirFactor=-1.0 to give down-dip loading
*/

    dip = hwDip[node+1];
    EquivalentBeamLoad(tau,-1.0,dip,&fx,&fy);
    if (dip<89.999 || dip>90.001)
      fprintf(FhOut,"%d,PX,%.5f\n",hwElnum,fx);
    if (dip<179.999 || dip>180.001)
      fprintf(FhOut,"%d,PY,%.5f\n",hwElnum,fy);

    ++fwElnum;
    ++hwElnum;
    node += 2;
  }

  fclose(FfOut);
  fclose(FhOut);
}

float LimEquilShearStress(float y1,float y2,float y3,float y4,float dip,
  float unitWeight,float k3Ratio)
{

  float yGroundSurface,fricAngle,mu;
```

```
  float pi,alpha,ysig,xsig,nsig,depth;
  float tau,ca,sa;

  pi = 4.0*atan(1.0);
  yGroundSurface = 12000.0;
  fricAngle = 37.0;
  mu = tan(fricAngle * pi/180.0);

  depth = yGroundSurface - 0.25*(y1 + y2 + y3 + y4);
  ysig = unitWeight*depth;
  xsig = k3Ratio * ysig;
  alpha = 0.5*pi + (dip * pi/180.0);
  ca = cos(alpha);
  sa = sin(alpha);
  nsig = xsig*ca*ca + ysig*sa*sa;
  tau = mu*nsig;
  return(tau);
}

int EquivalentBeamLoad(float tau,float dirFactor,float dip,
  float* fx,float* fy)
{

  float pi,f,theta;

  pi = 4.0*atan(1.0);
  f = dirFactor*tau;
  theta = dip * pi/180.0;
  *fx = f*cos(theta);
  *fy = f*sin(theta);
  return(0);
}

DumpAndQuit(s)
char *s;
{
  printf("\n *** %s ***\n\n",s);
  exit(0);
}
```

8.5 Analysis Cases

Different cases of slip on fault F0 will be modeled by varying the location of applied shear stress (beam axial loading) on the fault. The cases are intended to represent (i) a shallow-focus earthquake, (ii) an earthquake with a moderate-depth focus, (iii) a deep-focus earthquake originating

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from the steep segment of F0, and (iv) another deep-focus earthquake originating from the detachment segment. The zone of application of fictitious-beam loading are described below.

8.5.1 Shallow-Focus Earthquake

Footwall beam elements	4003–4006
Hangingwall beam elements	4074–4077
Fault elements	37–40
Footwall-surface nodes	164–172
Hangingwall-surface nodes	111–119
Length of fault segment	2.04 km
Approximate depth	1.5 km

8.5.2 Earthquake with Focus at Moderate Depth

Footwall beam elements	4013–4016
Hangingwall beam elements	4084–4087
Fault elements	47–50
Footwall-surface nodes	184–192
Hangingwall-surface nodes	131–139
Length of fault segment	2.04 km
Approximate depth	6 km

8.5.3 Deep Focus Earthquake on Steep Segment of F0

Footwall beam elements	4026–4029
Hangingwall beam elements	4097–4100
Fault elements	146–149
Footwall-surface nodes	553–561
Hangingwall-surface nodes	503–511
Length of fault segment	1.91 km
Approximate depth	10 km

8.5.4 Deep Focus Earthquake on Detachment Segment of F0

Footwall beam elements	4037–4044
Hangingwall beam elements	4108–4115
Fault elements	154–158 and 201–203
Footwall-surface nodes	573–579 and 732–741
Hangingwall-surface nodes	523–529 and 715–724
Length of fault segment	1.93 km
Approximate depth	12 km

8.5.5 Other Cases

Other cases to be analyzed include those for which shear loading is applied (v) over the entire length, (vi) over the entire steep segment only, and (vii) over the entire detachment segment only, of fault F0.

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9.1 Determination of Down-dip Rupture Length for Finite Element Simulations of Earthquakes

Down-dip rupture length (DRL) is defined as the distance measured parallel to the fault surface over which fault slip occurs during a seismic event (i.e., an earthquake). For natural earthquakes, the down-dip rupture length is usually determined from the spatial pattern of early aftershocks. An estimate of the DRL provides a means to determining the rupture area for the finite element simulations. The rupture area is ultimately necessary for determining the size (i.e., moment magnitude) of the simulated seismic event.

The *C* codes *FaultSurfaceDisp.c* and *FaultDisp.c* written by G.I. Ofoegbu are used to calculate the displacement at each node along each fault in the models. After some discussion, we (i.e., Ferrill and Smart) have decided to make three separate determinations of down-dip rupture length. The DRL, measured from the surface downward, is estimated as the distance in kilometers to the first node that experiences: (1) zero displacement; (2) < 0.5 cm displacement; and (3) < 1.0 cm displacement. The latter two cutoffs, while somewhat arbitrary, are selected because they could be considered near the lower limit of what could be measured in the field and they can be consistently applied to all of the finite element models. Together, these three estimates of down-dip rupture length provide a reasonable range for calculating the magnitude of the simulated seismic event.

KJS

9.2 Determination of Rupture Area in Finite Element Models from Estimate of Downdip Rupture Length

A relationship between earthquake size (i.e., magnitude) and fault rupture parameters is provided by the seismic moment. Seismic moment (M_O) is given by:

$$M_o = \mu \overline{D} A \tag{1}$$

where μ is the rigidity (or shear) modulus, $\overline{D}$ is the average fault displacement, and A is the rupture area (Kanamori & Anderson 1975). The moment magnitude (**M**) scale developed by Hanks & Kanamori (1979) is related to the seismic moment by:

$$\mathbf{M} = \tfrac{2}{3} \log M_o - 10.7 \tag{2}$$

Consequently, an accurate determination of fault rupture area is necessary for an accurate assessment of the moment magnitude.

Wells & Coppersmith (1994) provide empirical relationships for both downdip rupture length (DRL) and rupture area in terms of moment magnitude. By combining these two relationships, it is possible to develop a relationship between DRL and RA so that RA can be determined for the finite element simulations. The relationship for DRL of normal faults is:

$$\mathbf{M} = 4.04 + 2.11 \log(\mathrm{DRL}) \tag{3}$$

and the relatioship for RA is:

$$\mathbf{M} = 3.93 + 1.02 \log(\mathrm{RA}) \tag{4}$$

Setting equations (3) and (4) equal and solving for RA yields:

$$\mathrm{RA} = \frac{(\mathrm{DRL}^{2.11})^{1/1.02}}{(10^{-0.11})} \tag{5}$$

Substitution of downdip rupture length estimates into equation (5) provides an estimate of the rupture area that can then be used to determine the moment magnitude of the finite element simulation.

Sources Cited

Kanamori, H. & Anderson, D.L. 1975. Theoretical basis of some empirical relations in seismology. *Bulletin of the Seismological Society of America* **65**, 1073-1095.

Hanks, T.C. & Kanamori, H. 1979. A moment-magnitude scale. *Journal of Geophysical Research* **84**, 2348-2350.

Wells, D.L. & Coppersmith, K.J. 1994. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bulletin of the Seismological Society of America* **84**, 974-1002.

KJS

10 Results for Analysis Cases sc01, sc02, and sc03

Results for cases sc01 (shallow focus), sc02 (moderate-depth focus) and sc03 (deep focus - steep segment) are presented below. All cases use the file *m05Base.res* as the starting condition and are analyzed for a total of 5 seconds after the seismic event is triggered.

10.1 Case sc01 (shallow focus earthquake on F0)

Maximum near-ground accelerations, occurring approximately 1.25 seconds after the simulated seismic event, are measured at group 3 monitoring nodes midway between faults F0 and F1. The maximum horizontal acceleration of 2.104 m/s^2 (0.21 g) occurs at node 2110 while the maximum vertical acceleration of 4.305 m/s^2 (0.44 g) occurs at node 2072. The average horizontal and vertical accelerations for group 3 are 1.51 ± 0.80 and 3.39 ± 1.02 m/s^2 (0.15 and 0.35 g), respectively. Maximum accelerations measured at group 4 nodes nodes midway between faults F1 and F2 (i.e., those closest to the proposed repository) are 0.87 and 0.35 m/s^2, horizontal and vertical respectively. Average horizontal and vertical accelerations for group 4 nodes are 0.71 ± 0.14 and 0.32 ± 0.02 m/s^2, respectively. KJS

Only fault F0 experiences measurable slip. The maximum displacement is 2.99 m occurring at a vertical depth of 1.98 km and a down-dip fault distance of 2.29 km. The surface displacement for fault F0 is 1.91 m. Estimates of down-dip rupture length for F0 vary from 13.93 to 19.00 km length (refer to section 9.1 on "Determination of Down-dip Rupture Length for Finite Element Simulations of Earthquakes" by K.J. Smart dated 7/17/96).

10.2 Case sc02 (moderate-depth focus earthquake on F0)

Maximum near-ground accelerations, occurring approximately 4 seconds after the simulated seismic event, are measured at group 4 monitoring. The maximum horizontal acceleration of 4.65 m/s^2 (0.47 g) occurs at node 10974 while the maximum vertical acceleration of 5.33 m/s^2 (0.54 g) occurs at node 10957. The average horizontal and vertical accelerations for the group 4 nodes are 3.75 ± 1.27 and 3.94 ± 0.99 m/s^2, respectively.

The maximum displacement on fault F0 is 9.94 m occurring at a vertical depth of 6.37 km and a down-dip fault distance of 7.36 km. Surface displacement for fault F0 is 1.24 m. The maximum displacement for fault F1 is 0.107 m occurring at a depth of 3.39 km and a down-dip fault length of 3.51 km. Surface displacement on F1 is 0.106 m. Fault F2 experiences negligible displacement. Estimates of down-dip rupture length for F0 range from 21.23 to 28.92 km and for F1 is approximately 7.78 km.

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10.3 Case sc03 (deep focus earthquake on steep segment of F0)

Maximum near-ground accelerations, occurring approximately 5 seconds after the simulated seismic event, are measured at group 4 nodes. The maximum horizontal acceleration of 3.34 m/s^2 (0.34 g) and the maximum vertical acceleration of 1.91 m/s^2 (0.19 g) both occur at node 10957. The average horizontal and vertical accelerations for the group 4 nodes are 2.55. ± 0.56 and 1.51 ± 0.37 m/s^2, respectively.

The maximum displacement on fault F0 is 12.5 m occurring at a depth of 10.03 km and a down-dip fault length of 11.58 km. Surface displacement for F0 is 0.729 m. The maximum displacement for F1 is 0.041 m occurring at a depth of 3.15 km and down-dip fault length of 3.26 km. Surface displacement for F1 is 0.016 m. The maximum displacement for F2 is 0.158 m and occurs at the surface. Estimates of down-dip rupture length are 19.50 to 27.68 km for F0, 5.52 to 6.02 km for F1, and 7.86 to 8.87 km for F2.

10.4 Estimation of Simulated Earthquake Magnitudes

Moment magnitudes are calculated for each simulated earthquake so that models can be more easily compared to actual seismic events. The moment magnitude (**M**), given by:

$$\mathbf{M} = \tfrac{2}{3} \log \mathrm{M_o} - 10.7 \qquad (10.4.1)$$

is defined in terms of the seismic moment (M_o). The seismic moment is defined by:

$$\mathrm{M_o} = \mu \overline{\mathrm{D}} \mathrm{A} \qquad (10.4.2)$$

where μ is the rigidity modulus (dynes/cm^2), $\overline{D}$ is the average fault displacement (cm), and A is the rupture area (cm^2). The rigidity modulus is determined from the elastic constants by:

$$\mu = \frac{E}{2(1+\nu)} \qquad (10.4.3)$$

where for these models Young's modus (E) $= 3.25\times10^4$ MPa $= 3.25\times10^{11}$ dynes/cm^2 and Poisson's ratio (ν) = 0.25. The rigidity modulus is therefore 1.3×10^{11} dynes/cm^2. The rupture area is calculated from each estimate of the down-dip rupture length using the procedure outlined in section 9.2. At present, a measure of the average fault displacement is unavailable (a solution to this problem is in progress) so two magnitude determinations are made using the maximum fault displacement and the surface fault displacement values for each case. Table 1 summarizes the results of the magnitude determinations. The average magnitudes based on the maximum fault displacement are 6.75, 7.33, and 7.38 for sc01, sc02, and sc03, respectively. The average magnitudes based on surface fault displacement are 6.62, 6.76, and 6.55 for sc01, sc02, and sc03, respectively. Magnitudes based on maximum displacement are consistent with observations of accelerations that suggest that

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the deeper sourced earthquakes generate the greater energy. In contrast, the surface displacement magnitudes suggest that sc01 is the largest event and sc03 the smallest. Clearly, magnitude estimates based solely on surface fault displacement is unreliable.

An alternative method for determining magnitude, also based only on surface displacement, was empirically derived by Wells & Coppersmith (1994). Their relationship is:

$$\mathbf{M} = 6.61 + 0.71\,log\,\mathrm{MD} \qquad (10.4.4)$$

where MD is the maximum surface displacement (m). Magnitudes calculated equation 10.4.4 are 6.81 for sc01, 6.68 for sc02, and 6.51 for sc03. The Wells & Coppersmith (1994) magnitudes do not accurately portray the earthquake intensity in these models since the largest magnitude is once again associated wtih the model with the smallest accelerations.

10.5 Summary and Conclusions

All models clearly demonstrate that maximum ground accelerations do not usually occur at the point where a fault intersects the ground surface. The contour plots of horizontal and vertical acceleration demonstrate that the seismic wave path is roughly circular and centered at the rupture zone, but maximum accelerations follow a path that is roughly perpendicular to the fault surface. As a result, model sc02 produces the largest ground accelerations at the group 4 monitoring nodes because the perpendicular to F0 drawn from the moderate-depth focus most nearly intersects the repository site.

Surface fault displacement is shown to be a very poor indicator of the size of a seismic event. Surface displacement is dependent more on the focus depth than on the size of the earthquake. Consequently, using surface fault displacement of a historical fault to predict earthquake magnitude subsequently ground accelerations is inherently flawed. As Table 10.5.1 shows, model sc01 produces the largest surface fault displacement, but the smallest maximum accelerations at the location of the proposed repository.

Analysis of model sc03, in particular, reveals a boundary effect problem that requires modification of the existing model. Interference patterns are observed after 4-5 seconds because acceleration waves are reaching the side and bottom boundaries of the model and reflecting back into the area of interest. This interference due to side and bottom reflections is not representative of a real geologic system. It indicates that the model boundaries need to be further from the area of interest so that longer analysis times can be obtained. To combat this problem, a new geometry incorporating infinite elements along the side and bottom boundaries will be used. Infinite elements should prevent the reflection problem without significantly increasing the computation times. Alternatively, the model could simply be expanded and so that more material is present on the sides and bottom. The disadvantage, however, would be considerable more nodes and elements, and consequently longer computation times.

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Table 10.4.1. Comparison of simulated earthquake magnitudes as a function of down-dip rupture length and fault displacement estimates for models sc01, sc02, and sc03.

Model	Down-dip Rupture Length (km)	Magnitude using Maximum Fault Displacement	Magnitude using Surface Fault Displacement
	13.93	6.68	6.55
sc01	14.40	6.70	6.57
	19.00	6.86	6.73
	21.23	7.25	6.67
sc02	23.71	7.31	6.74
	28.92	7.43	6.86
	19.50	7.29	6.47
sc03	20.98	7.34	6.51
	27.68	7.50	6.68

Table 10.5.1. Comparison of maximum and surface fault displacement with maximum accelerations measured at proposed repository location for models sc01, sc02, and sc03.

Model	Maximum Fault Displacement (m)	Surface Displacement (m)	Maximum Horizontal Acceleration (m/s^2)	Maximum Vertical Acceleration (m/s^2)
sc01	2.99	1.91	0.870	0.350
sc02	9.94	1.24	4.648	5.326
sc03	12.50	0.73	3.338	1.909

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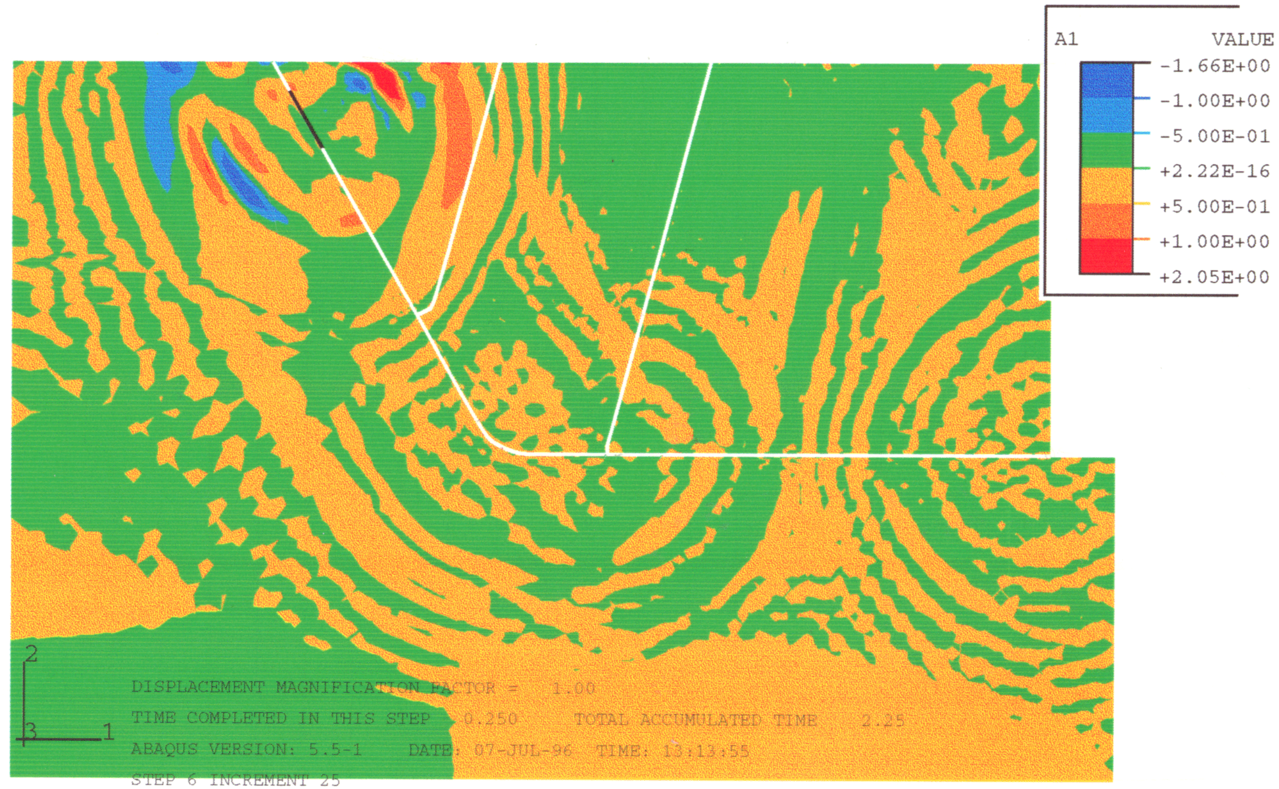
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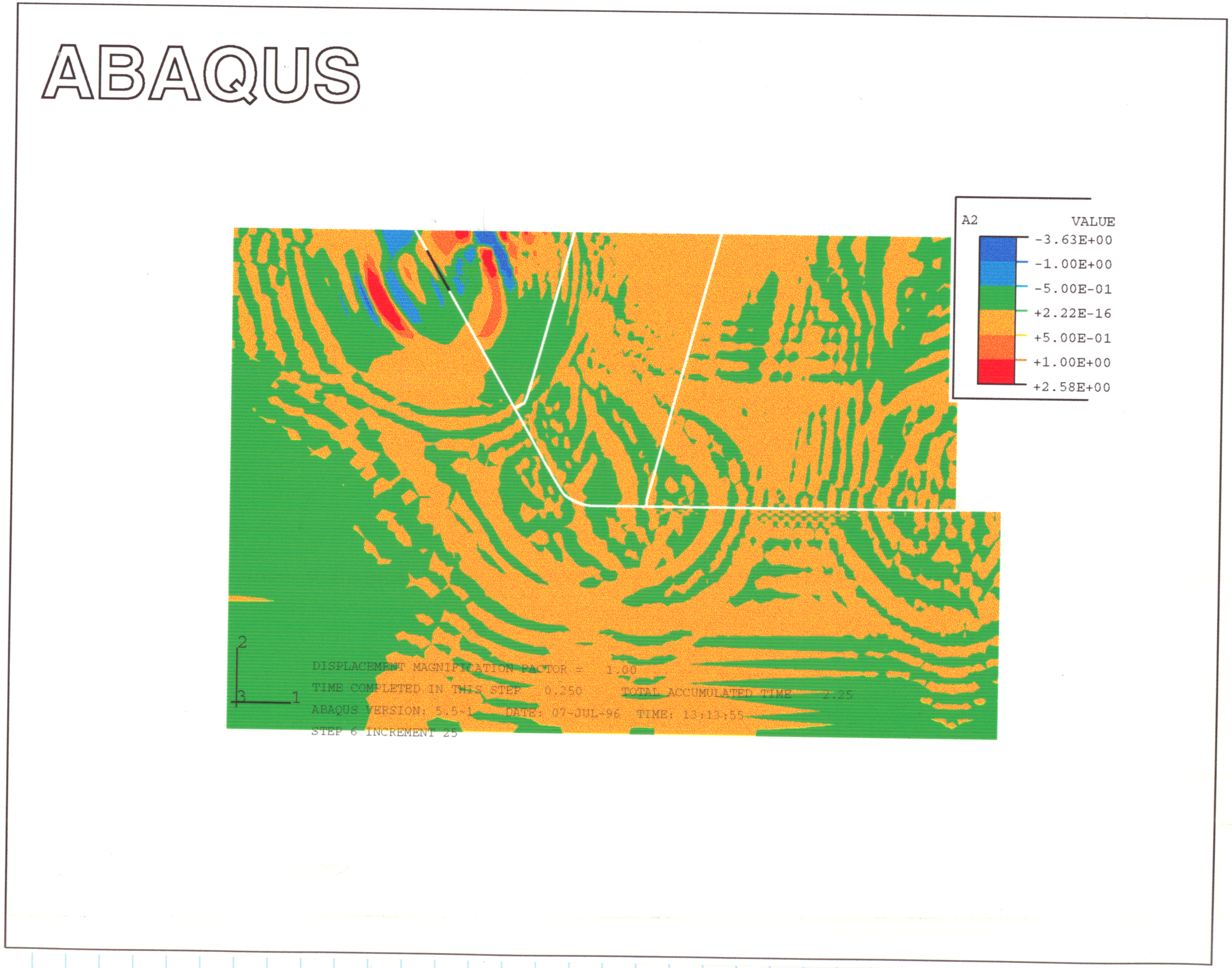
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2
3
1
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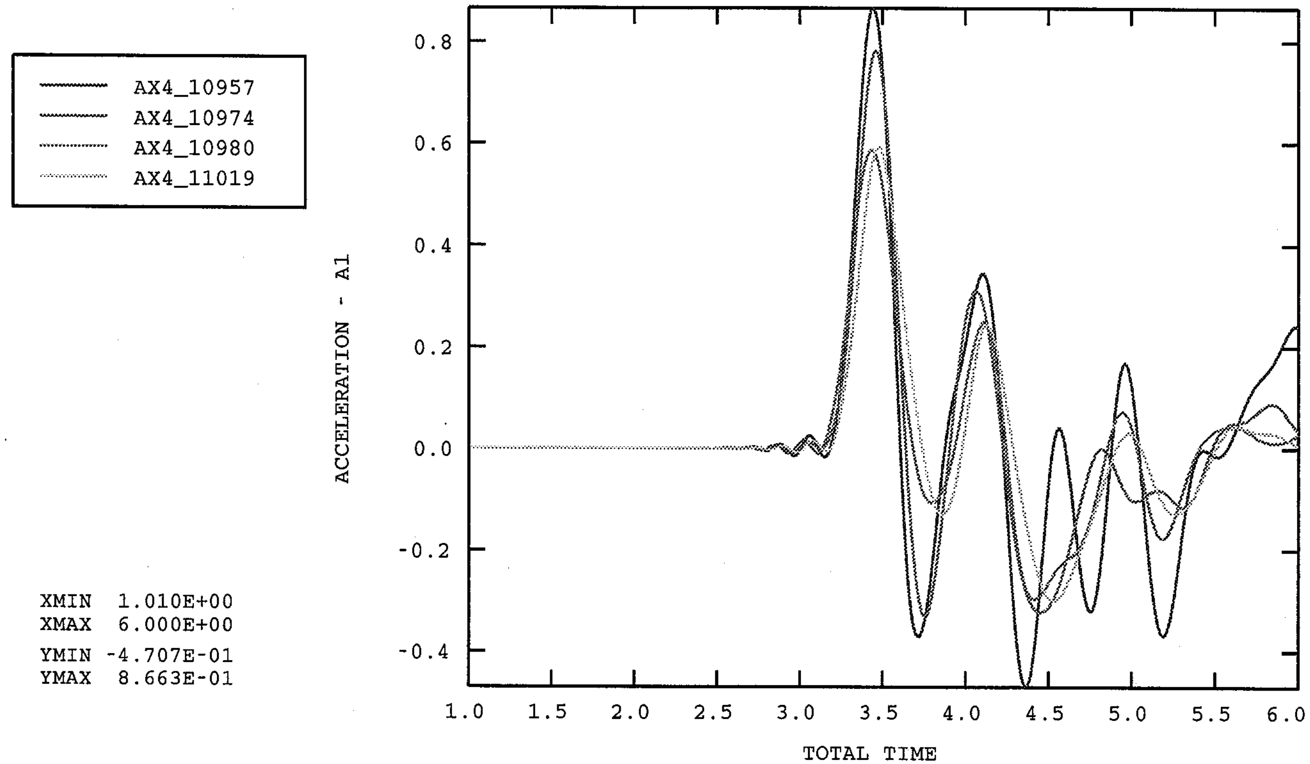
ABAQUS VERSION: 5.5-1 DATE: 07-JUL-96 TIME: 13:13:55
STEP 6 INCREMENT 25

Model: sc01

		Horizontal Acceleration (m/s^2)		Vertical Acceleration (m/s^2)	
Group	Node	Positive Maximum	Negative Maximum	Positive Maximum	Negative Maximum
	6859	**1.0980**	-0.8439	0.4687	**-0.7294**
1	6860	**1.0260**	-0.7945	0.5150	**-0.7640**
	6861	**0.7088**	-0.6812	0.4159	**-0.5873**
	5485	0.7480	**-1.2240**	0.8975	**-0.9021**
	5486	0.7431	**-1.2260**	0.7750	**-0.8906**
2	5493	0.6215	**-1.0720**	**0.8693**	-0.8319
	5503	0.5297	**-0.8500**	**0.9422**	-0.9202
	5504	0.5193	**-0.8717**	**0.7392**	-0.7392
	2072	0.5961	**-0.7128**	1.7420	**-4.3050**
3	2091	**1.8250**	-1.5140	1.5190	**-3.5840**
	2110	**2.1040**	-1.7670	0.9394	**-2.2950**
	10957	**0.8663**	-0.4707	**0.2979**	-0.2837
4	10974	**0.7815**	-0.3032	0.2605	**-0.3184**
	10980	**0.5869**	-0.2969	0.2281	**-0.3526**
	11019	**0.5922**	-0.2995	0.2241	**-0.3265**
	3669	**0.5951**	-0.2465	**0.1973**	-0.1292
5	3687	**0.5581**	-0.2200	**0.1685**	-0.1128
	3714	**0.4620**	-0.1722	**0.1225**	-0.0934
	3657	**0.5056**	-0.1920	**0.1609**	-0.0933
6	3681	**0.4760**	-0.1796	**0.1410**	-0.0923
	3702	**0.4004**	-0.1013	**0.1032**	-0.0749
	3645	**0.1328**	-0.0007	**0.0449**	-0.0010
	3646	**0.3157**	-0.0008	**0.1028**	-0.0008
7	3694	**0.1453**	-0.0005	**0.0246**	-0.0004
	3731	**0.1902**	-0.0007	**0.0232**	-0.0008
	3732	**0.0741**	-0.0007	**0.0110**	-0.0007

ABAQUS



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AX4_10974
AX4_10980
AX4_11019
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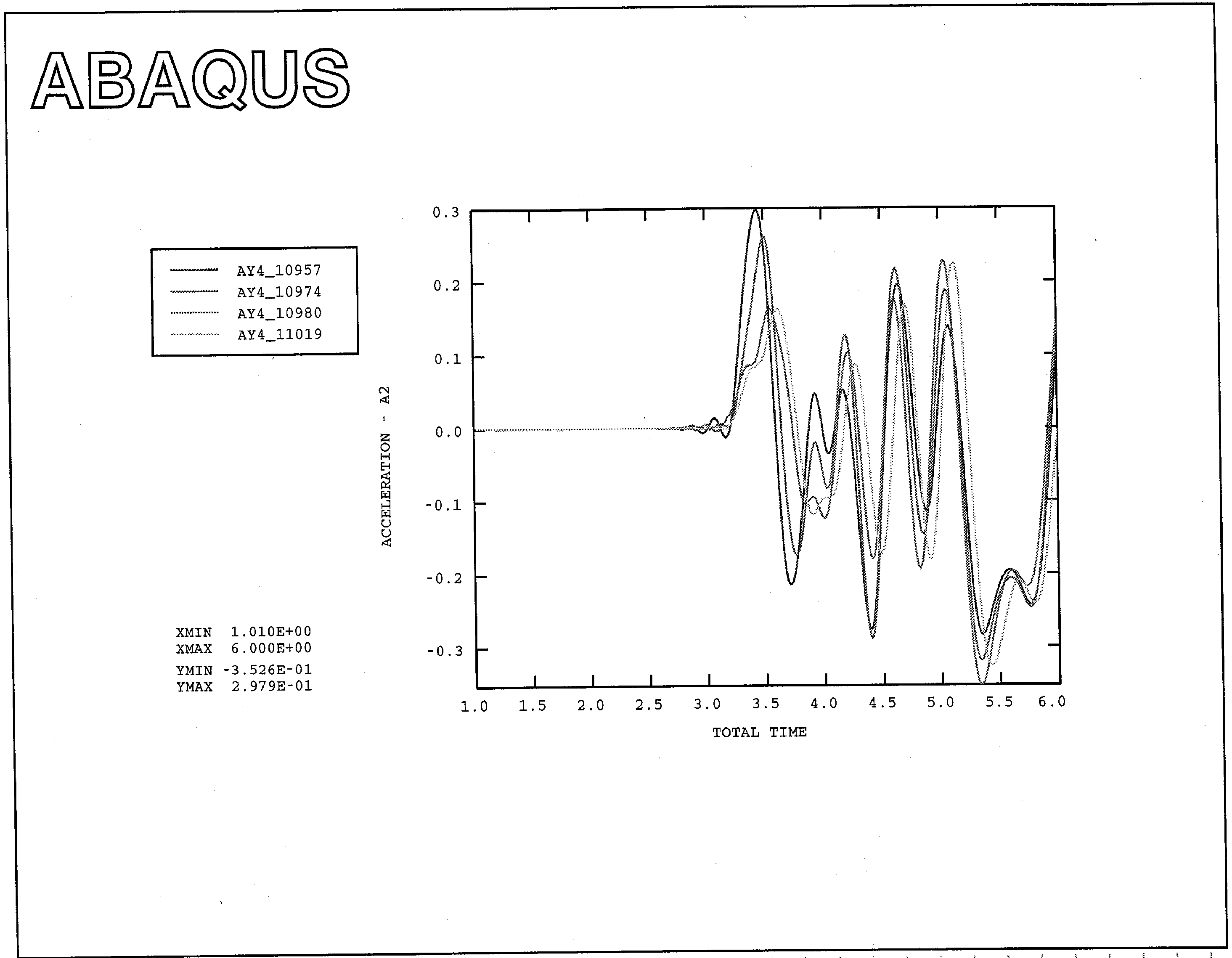
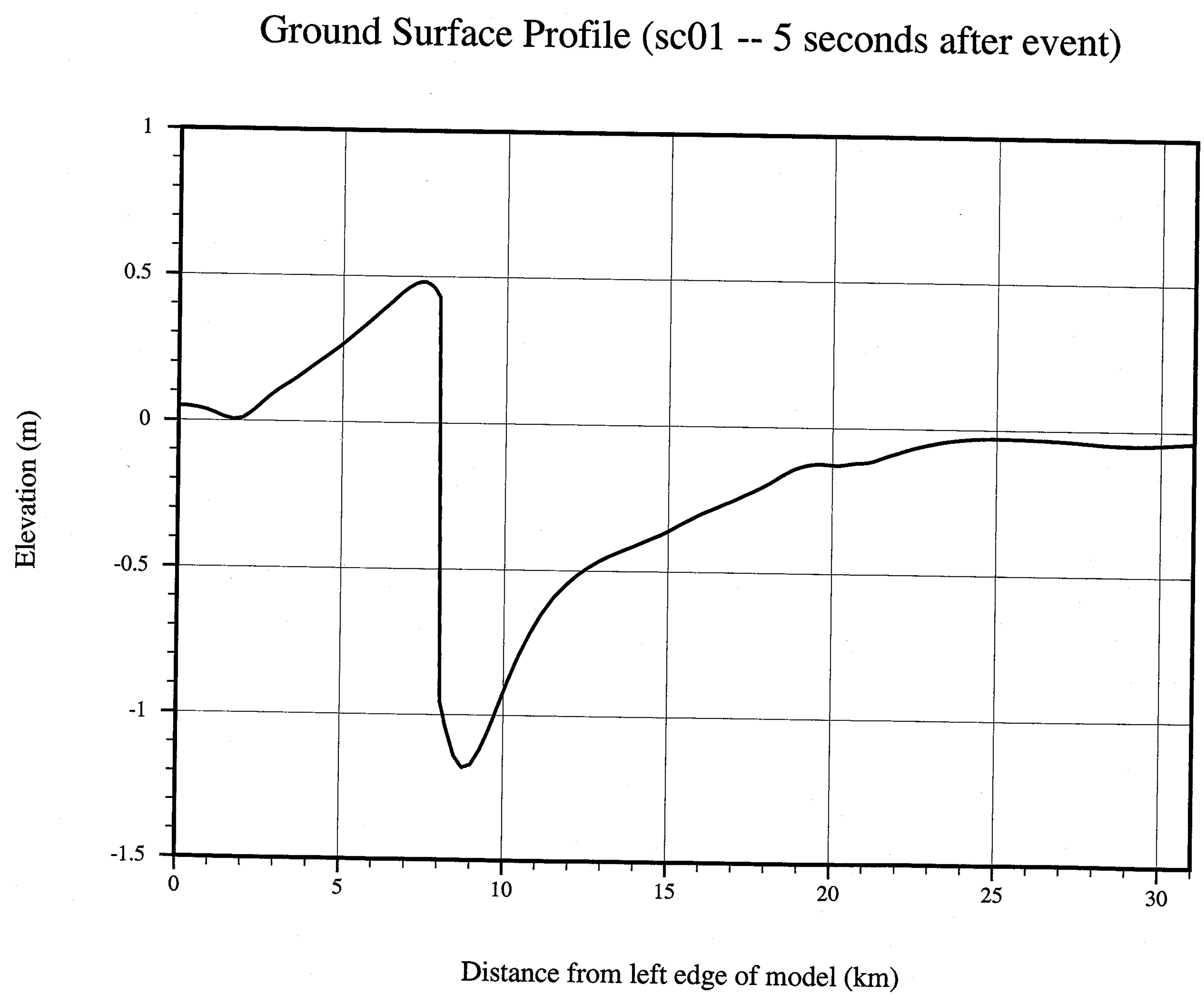
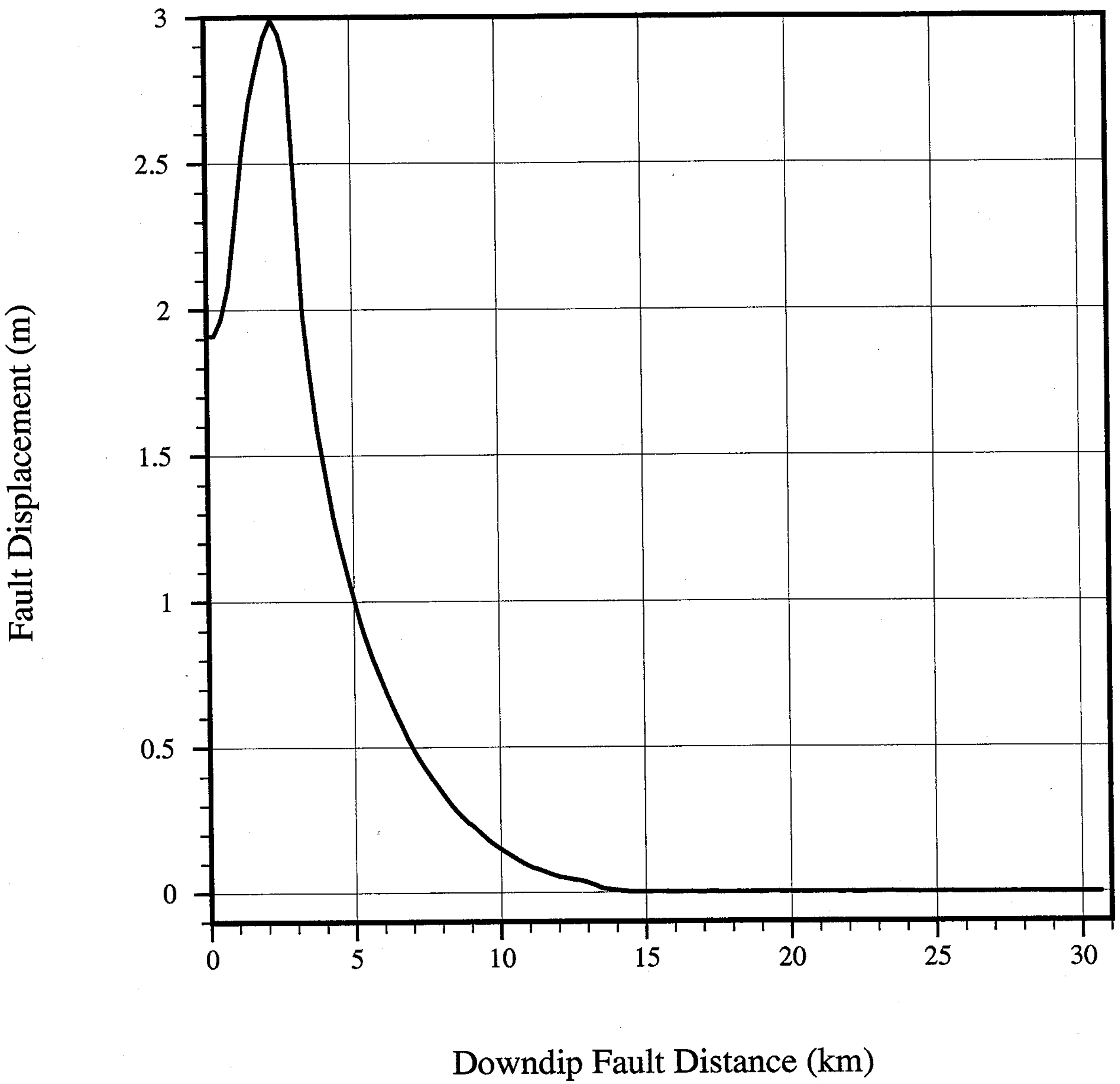
XMAX 6.000E+00
YMIN -4.707E-01
YMAX 8.663E-01
ACCELERATION - A1
TOTAL TIME
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0


ABAQUS
AY4_10957
AY4_10974
AY4_10980
AY4_11019
ACCELERATION - A2
TOTAL TIME
XMIN 1.010E+00
XMAX 6.000E+00
YMIN -3.526E-01
YMAX 2.979E-01


Ground Surface Profile (sc01 -- 5 seconds after event)
Elevation (m)
1
0.5
0
-0.5
-1
-1.5
0
5
10
15
20
25
30
Distance from left edge of model (km)

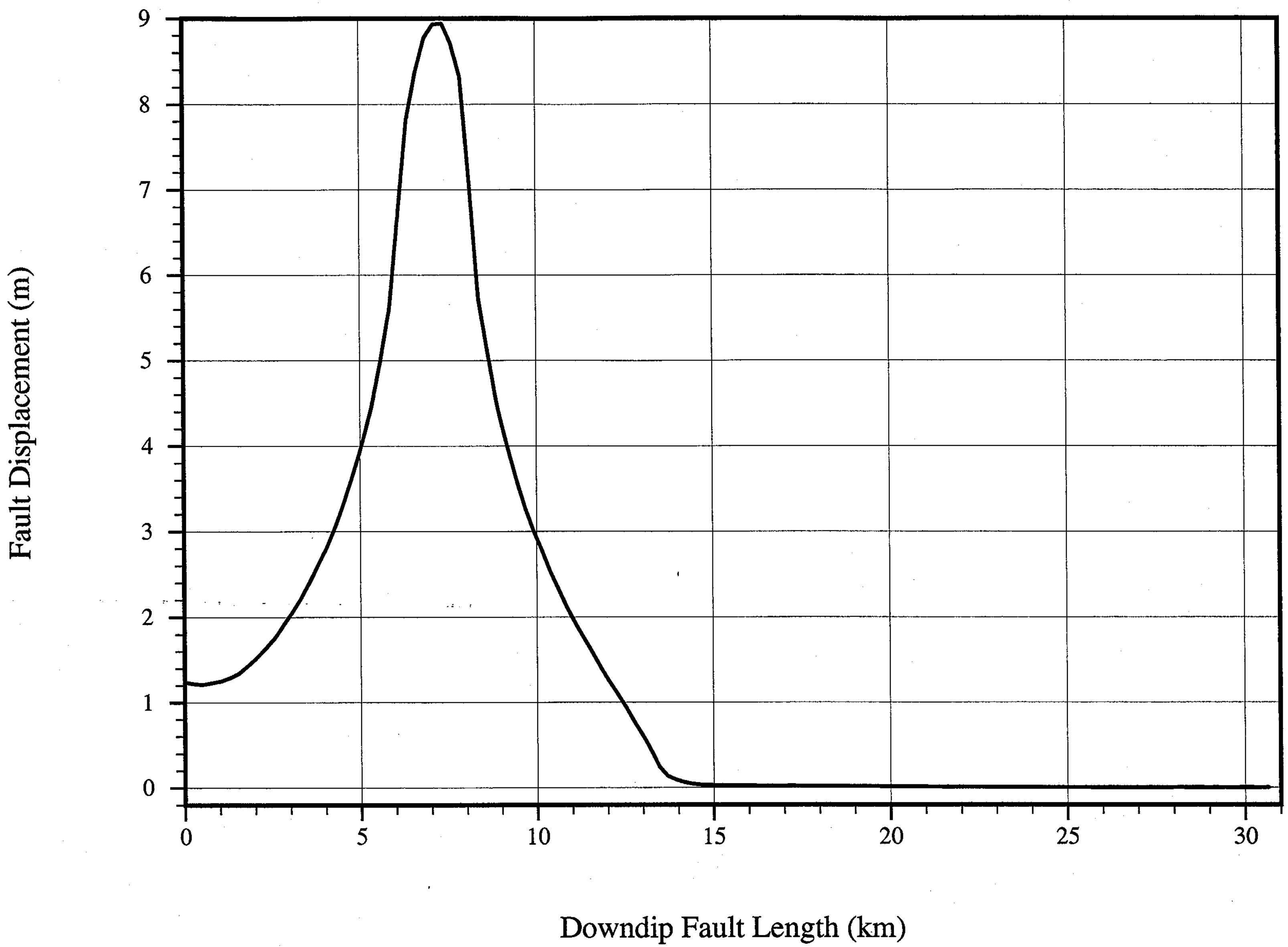
Model = sc01 (Shallow Source, Fault F0)

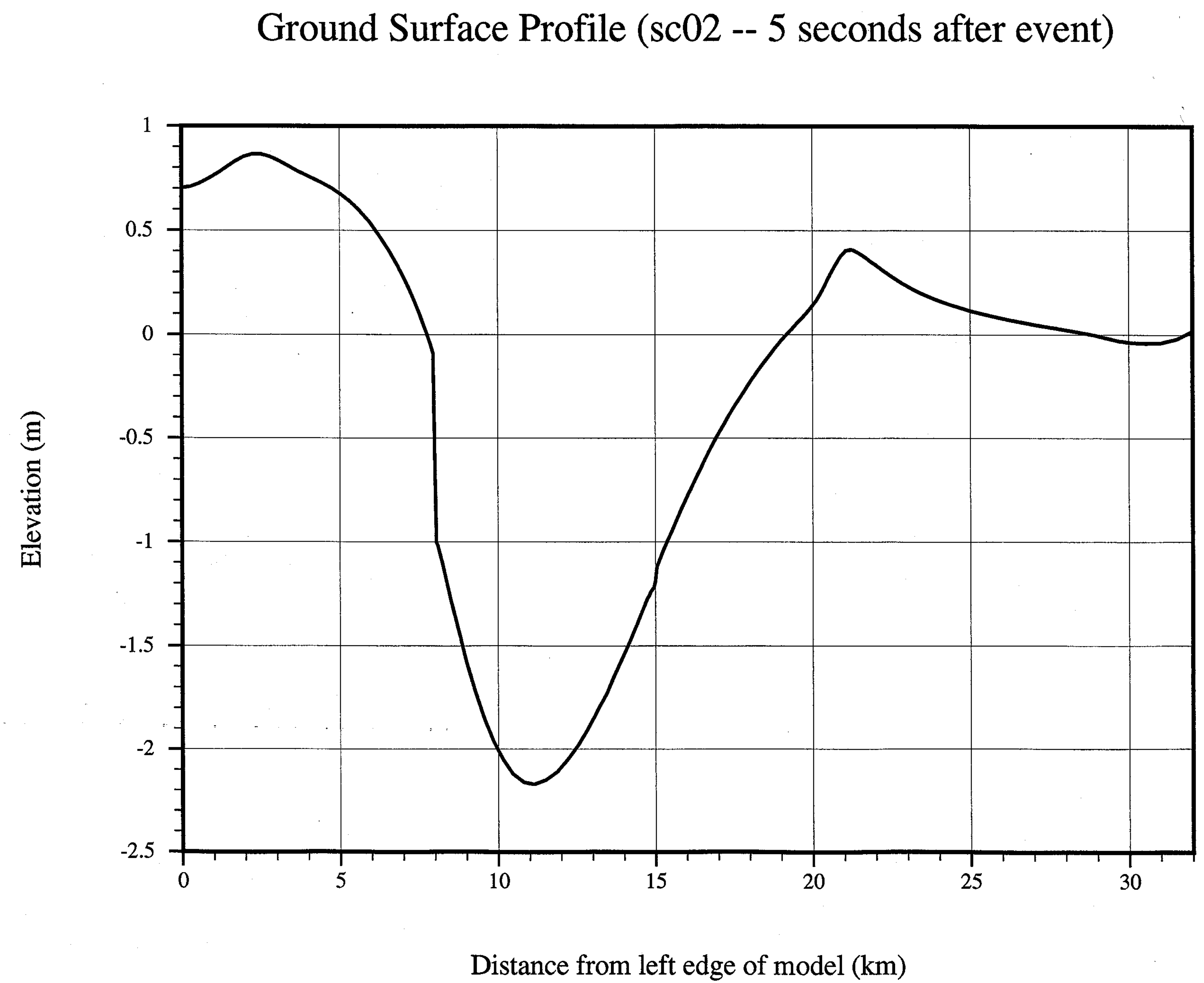


Model: sc02

Group	Node	Horizontal Acceleration (m/s^2) Positive Maximum	Horizontal Acceleration (m/s^2) Negative Maximum	Vertical Acceleration (m/s^2) Positive Maximum	Vertical Acceleration (m/s^2) Negative Maximum	in (m/s^2) Horizontal Acceleration	in (m/s^2) Vertical Acceleration	in g Horizontal Acceleration	in g Vertical Acceleration
1	6859	**1.8230**	-1.3120	**1.1870**	-0.4204	1.8230	1.1870	0.1858	0.1210
	6860	**1.6090**	-1.1480	**1.0930**	-0.4731	1.6090	1.0930	0.1640	0.1114
	6861	**1.0930**	-0.7991	**0.8964**	-0.4104	1.0930	0.8964	0.1114	0.0914
2	5485	0.5845	**-0.9164**	1.0330	**-1.1990**	0.9164	1.1990	0.0934	0.1222
	5486	0.5684	**-0.8679**	1.0160	**-1.1810**	0.8679	1.1810	0.0885	0.1204
	5493	0.4101	**-0.8841**	1.0210	**-1.1630**	0.8841	1.1630	0.0901	0.1186
	5503	0.3123	**-0.7952**	0.9783	**-1.0350**	0.7952	1.0350	0.0811	0.1055
	5504	0.2963	**-0.8288**	0.9522	**-1.0180**	0.8288	1.0180	0.0845	0.1038
3	2072	**1.3860**	-0.8261	0.8074	**-1.2730**	1.3860	1.2730	0.1413	0.1298
	2091	**1.0780**	-0.6528	0.7329	**-1.2500**	1.0780	1.2500	0.1099	0.1274
	2110	0.4000	**-0.5867**	0.6353	**-1.1130**	0.5867	1.1130	0.0598	0.1135
4	10957	**1.8760**	-0.4962	0.8114	**-5.3260**	1.8760	5.3260	0.1912	0.5429
	10974	**4.6480**	-1.1640	0.7188	**-3.9650**	4.6480	3.9650	0.4738	0.4042
	10980	**4.1290**	-0.3937	0.6086	**-3.0840**	4.1290	3.0840	0.4209	0.3144
	11019	**4.3480**	-0.4759	0.8735	**-3.3790**	4.3480	3.3790	0.4432	0.3444
5	3669	**1.3890**	-0.7461	**0.8564**	-0.3532	1.3890	0.8564	0.1416	0.0873
	3687	**1.1530**	-0.6119	**0.7736**	-0.2917	1.1530	0.7736	0.1175	0.0789
	3714	**0.7659**	-0.3963	**0.5278**	-0.1702	0.7659	0.5278	0.0781	0.0538
6	3657	**1.4900**	-0.0043	**0.7529**	-0.0022	1.4900	0.7529	0.1519	0.0767
	3681	**1.2760**	-0.0015	**0.6634**	-0.0004	1.2760	0.6634	0.1301	0.0676
	3702	**0.9071**	-0.0024	**0.4524**	-0.0003	0.9071	0.4524	0.0925	0.0461
7	3645	**0.0015**	-0.0007	**0.0011**	-0.0010	0.0015	0.0011	0.0002	0.0001
	3646	**0.0017**	-0.0014	**0.0014**	-0.0008	0.0017	0.0014	0.0002	0.0001
	3694	**0.0008**	-0.0005	**0.0009**	-0.0004	0.0008	0.0009	0.0001	0.0001
	3731	0.0011	**-0.0012**	0.0008	**-0.0008**	0.0012	0.0008	0.0001	0.0001
	3732	**0.0007**	-0.0005	**0.0009**	-0.0007	0.0007	0.0009	0.0001	0.0001

Model sc02, Fault F0 Displacement (5 seconds after event)




Ground Surface Profile (sc02 -- 5 seconds after event)
Elevation (m)
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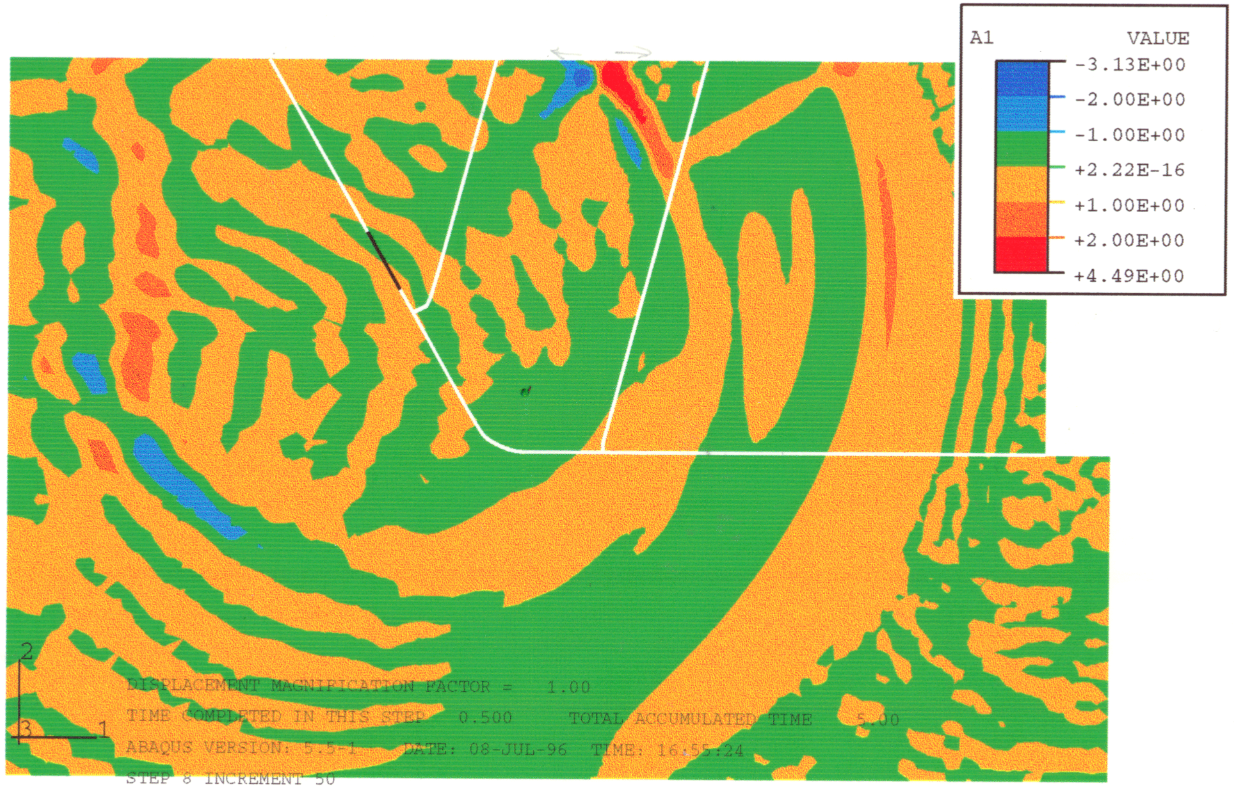
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
5
10
15
20
25
30
Distance from left edge of model (km)

ABAQUS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-2.00E+00
-1.00E+00
+2.22E-16
+1.00E+00
+2.00E+00
+4.49E+00
2
3
1
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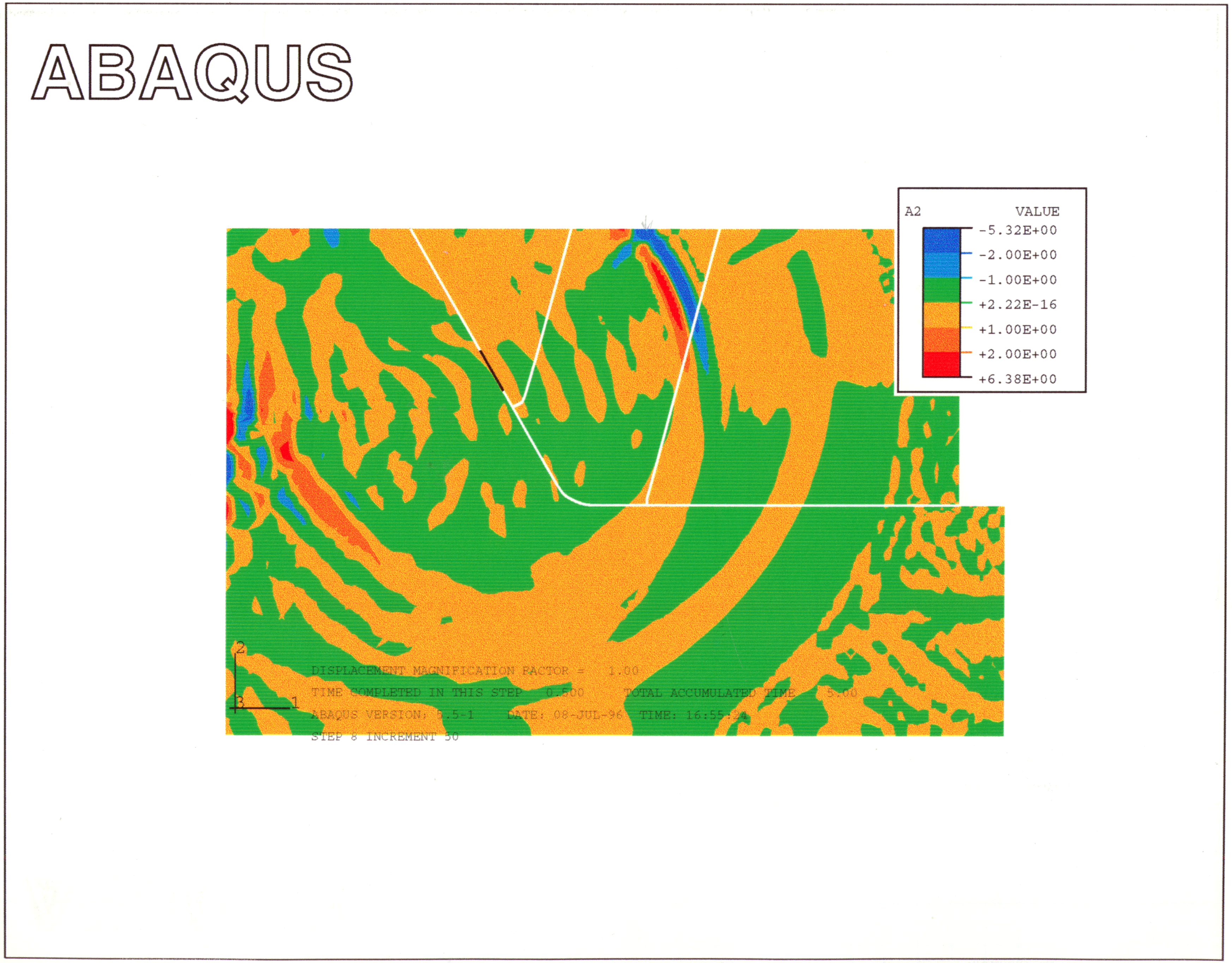

ABAQUS
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+2.22E-16
+1.00E+00
+2.00E+00
+6.38E+00
2
3
1
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TIME COMPLETED IN THIS STEP 0.500 TOTAL ACCUMULATED TIME 5.00
ABAQUS VERSION: 5.5-1 DATE: 08-JUL-96 TIME: 16:55:24
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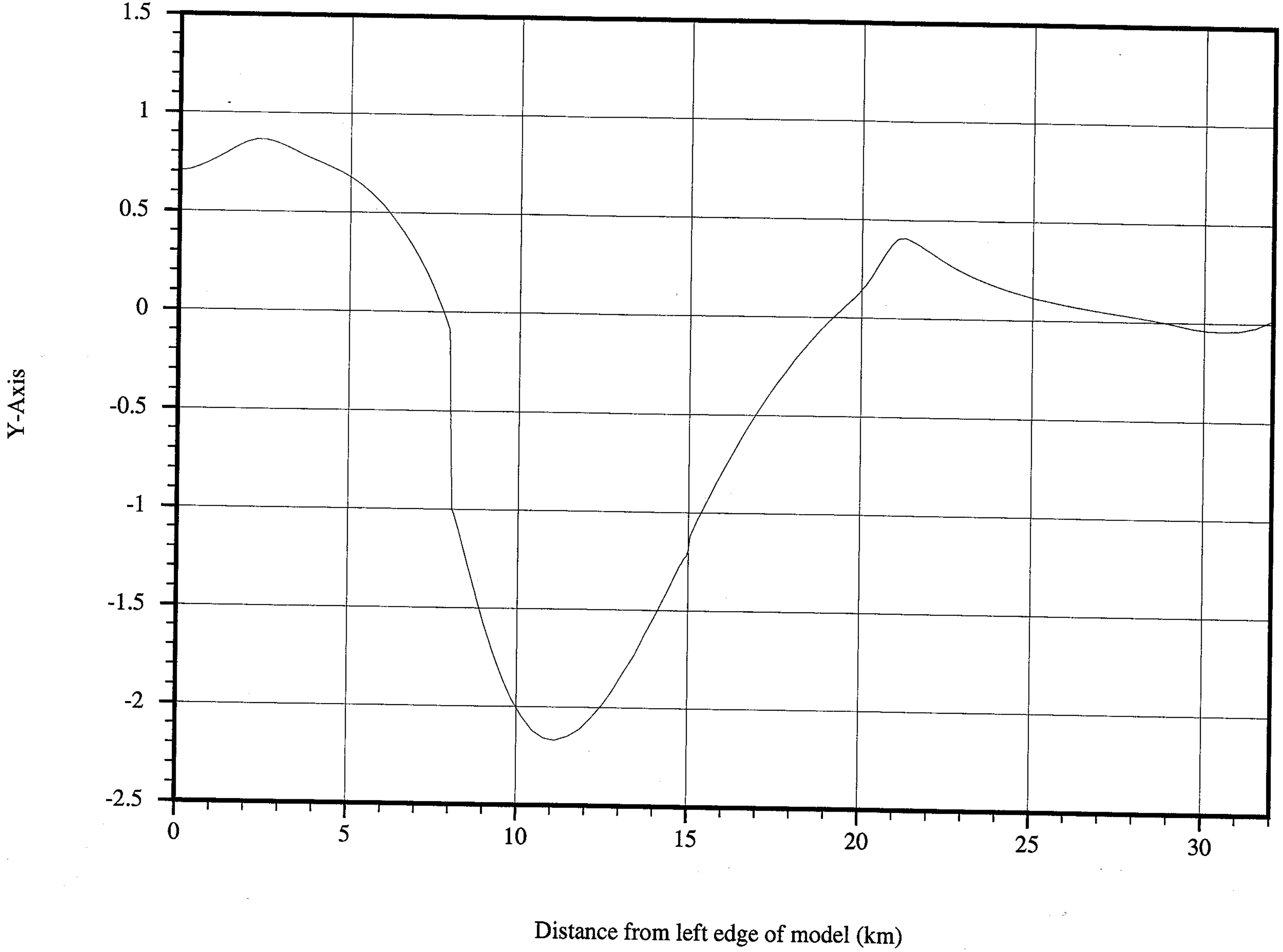
Ground Surface Profile (sc03 5 seconds after event)



Entries continued on Notebook #188, GWD

AHC