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Scientific Notebook # 306 - Thermal
Mechanical and Seismic Analyses of
Underground Openings

CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

CNWRA
CONTROLLED
COPY 306

Project Title: Thermal-Mechanical and seismic analyses of underground openings. (Theoretical / Computer Analyses)

Project Personnel: MIKKO AHOLA LITT Industries, Systems Div
Simon Hsiung, Amit Ghosh (SwRI/CNWRA)

Task #1: Objective of Task #1 is to conduct thermal-mechanical (TM) analyses of multiple waste emplacement drifts (i.e. 3 to 4) in which a distinct vertical transition zone between strong rock (i.e, DOE rock mass category 5) and weak rock (i.e, DOE rock mass category 1) exists both midway between two drifts, or directly along the vertical centerline of one drift. The numerical analysis is intended to investigate potential differential displacement, strain, and stress / rock failure regions around the tunnels due to TM loading and implications on drift stability as well as non-uniform loading of support systems (steel sets / concrete liner.)

Technical Approach: The technical approach for task #1 will be to utilize the two-dimensional computer code UDEC (Universal Distinct Element Code) Version 3.0, currently under configuration management control at the CNWRA.

MPA
2/9/99

Computer Platform: Personal Computer (333 MHz, 256 Mb RAM, Windows NT 4.0)

Task #2: The objective of Task #2 of this project is to run a numerical validation exercise between the 2D distinct element code UDEC and 3D explicit finite element code K-DYNA3D. The UDEC dynamic drift stability analyses were previously conducted at the CNWRA by Roi Chen and documented in her paper titled "Analyses of Drift Stability and Rockfall Due to Earthquake Ground Motion at Yucca Mountain, Nevada." [to be submitted to 1999 U.S. Rock Mechanics Symposium]. One specific case [i.e, Case C], incorporating 3 distinct joint sets, was chosen to conduct the validation with K-DYNA3D. as it appeared to cause the largest amount of rockfall with seismic loading.

Technical Approach: As briefly stated above, the approach will be to utilize the 3D explicit finite element code K-DYNA3D for the study. K-DYNA3D is an ITT Industries modified version of DYNA3D, the structural dynamics finite element code originally developed by Lawrence Livermore National Lab.

The capability of K-DYNA3D has been extended into domains involving extensive structural damage, allowing the solution of structural analysis problems that are not solvable by standard finite element tools. Extensive slideline logic implemented into K-DYNA3D and object tracking, allows the code to simulate correctly the interaction of objects and or failure of a structure due to impact loading or collapse.
K-DYNA3D is currently not under any CNWRA configuration control, and is only at this time being used ~~to~~ an additional validation of results generated by UDEC. If it is to be used beyond this validation exercise, then some sort of configuration management of the code will have to be discussed.

Computer Platform:

K-DYNA3D runs – Personal Computer (333 MHz, 256 MB RAM, Windows NT 4.0)

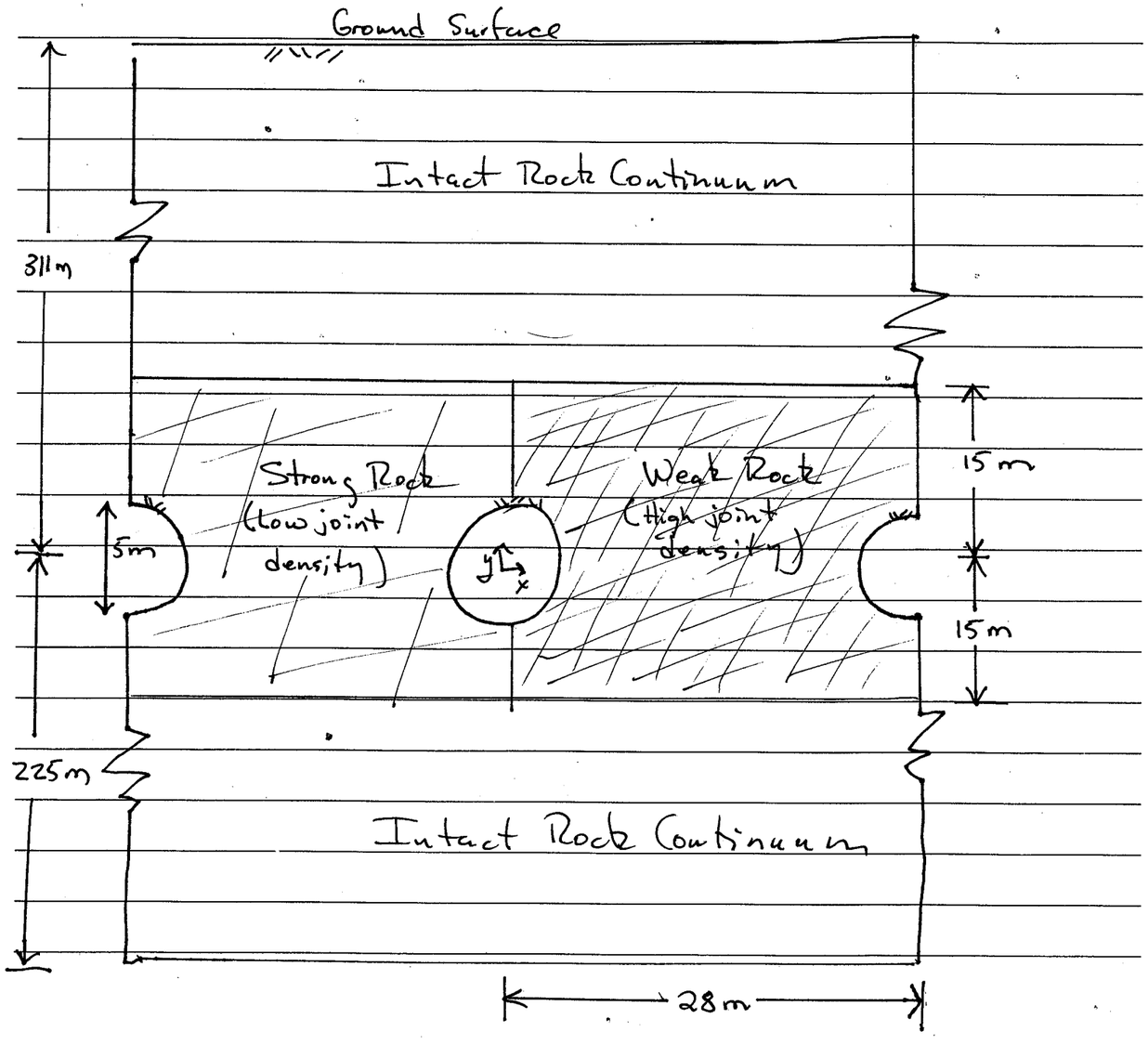
PATRAN Version 7.5 – PATRAN will be used to generate the 3D K-DYNA3D Model. PATRAN platform is a Silicon Graphics R10000 workstation.

Note: Task #2 in-process entries begin on Page 100 of this Scientific Notebook, to keep them separate from Task #1 entries. NPA 3/9/99

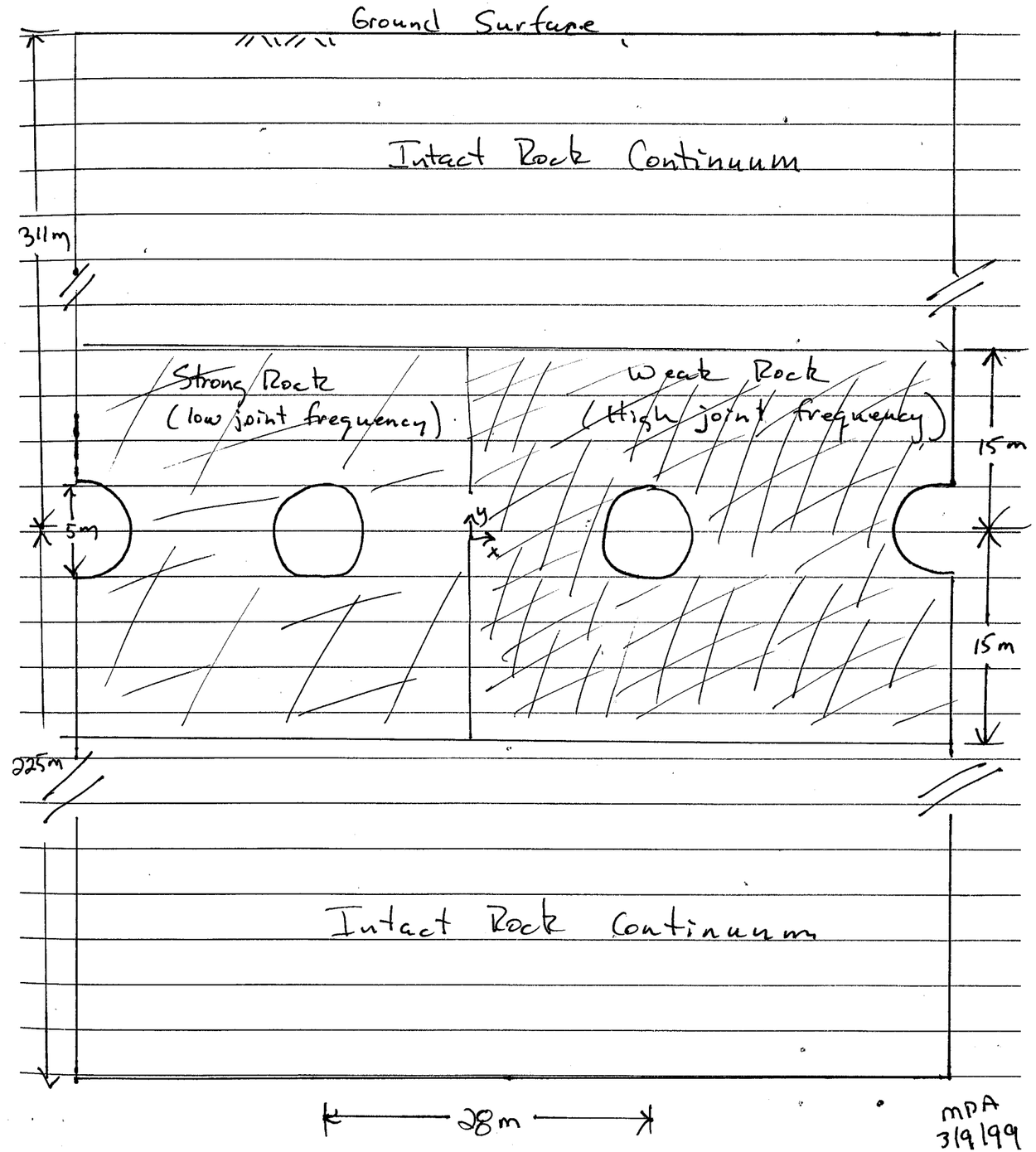
Task #1

Based on discussions held on Feb 3-5, 1999 with S. Hsiung and A. Ghosh at the CNWRA, the following 2 drift scale Thermal - Mechanical analyses using UDEC would be run.

Case 1: Three waste emplacement drift model with strong rock/weak rock transition zone along vertical centerline of central tunnel.



Case 2: Four waste emplacement drift model with strong rock/weak rock transition zone vertically located between two central drifts.



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Material Properties: Data extracted from DOE report titled "Repository Ground Support Analysis for Viability Assessment" (Doc # BCAA00000-01717-0200-00004 REV00)

Thermal Properties. (TSW2 Unit)
Ave. Ground Surface Rock Temp. = 18.7 °C (fixed)
Ave. Thermal Gradient = 0.02 °C/m

Thermal Conductivity (K) = 2.10 W/m·K
Specific Heat (C_p) = 932 J/kg·K
Thermal Expansion Coeff (α) = 6.0×10^{-6} /°C

Note: K, C_p, and α are all functions with temperature, however UDEC is not presently capable of incorporating temperature dependent properties.

Mechanical Properties (Intact Rock, TSW2)

Young's Modulus (E) = 33.03 GPa
Poisson's Ratio (ν) = 0.21
Cohesion (c) = 36.9 MPa
Friction Angle (ϕ) = 46°
Rock Tensile strength (T) = 8.91 MPa.

G = 13.65 GPa (Shear Modulus)
B = 18.98 GPa (Bulk Modulus)

Joint Properties

Joint Friction Angle = 41°
Joint Cohesion = 0.03 MPa
Joint Tensile Strength = 0.0
Joint Normal Stiffness = 5.0×10^4 MPa/m
Joint Shear Stiffness = 5.0×10^4 MPa/m.

Two joint sets were included in the UDEC model for both the strong rock and weak rock regions. Orientations, trace lengths, etc were taken from paper by Rui Chen "Analyses of Drift Stability and Rockfall Due to Earthquake Ground Motion at Yucca Mountain, Nevada".

Joint Set #1

Mean Inclination = 85°, Deviation = 10°
measured ccw from horizontal
Mean Trace Length = 7.5 m, Deviation = 1 m
Mean Gap Length = 0.2 m, Deviation = 0

Joint Set #2

Mean Inclination = 20°, Deviation = 5°
Mean Trace Length = 5 m, Deviation = 1 m
Mean Gap Length = 0.2 m, Deviation = 0.

A higher joint spacing was used to simulate the strong rock region, while a small joint spacing was used to simulate weaker rock.

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3/9/99

The intent was to try and represent as closely as possible the DOE rock mass modulus (E_m) for Category 5 rock (strong) and Category 1 rock (weak).

Based on DOE data:

Rock Mass Category 1 (weak Rock)

Elastic Mod (E_m) = 6.37 GPa

Poisson's Ratio (ν) = 0.21

Cohesion = 1.3 MPa

Friction Angle = 49°

Rock Mass Category 5 (Strong Rock)

Elastic Modulus (E_m) = 23.51 GPa

Poisson's Ratio (ν) = 0.21

Cohesion = 3.8 MPa

Friction Angle = 50°

As a first analyses, it was decided to use the following mean joint spacings for the 2 joint sets and rock regions.

Strong Rock

Joint Inclination 85° → Joint Spacing = 1.0 m

Joint Inclination 20° → Joint Spacing = 2.0 m

Weak Rock

Joint Inclination 85° → Joint Spacing = 0.5 m

Joint Inclination 20° → Joint Spacing = 1.0 m

Note: Mean joint spacings given in Rui Chen's paper based on DOE measurements were 0.4 m for the 85° joint set and 0.75 m for the 20° joint set. It is not clear which rock mass category this would represent.

One can estimate the rock mass modulus in a particular direction, knowing the intact rock Young's modulus, joint normal stiffness and joint spacing ⊥ to the direction of interest. The equation can be developed to relate the two as.

$$\frac{1}{E_m} = \frac{1}{E_r} + \frac{1}{K_n S}$$

where E_m = rock mass modulus

E_r = intact rock Young's Modulus = 33.03 GPa

K_n = joint normal stiffness = 5.0×10^5 MPa/m

S = ⊥ joint spacing.

For the horizontal direction (i.e. direction of highest thermal load) we can estimate the rock mass modulus using the subvertical joint set spacings.

Strong Rock

$S \approx 1.0$ m

$$\frac{1}{E_m} = \frac{1}{E_r} + \frac{1}{K_n S}$$

or $$E_m = \frac{E_r K_n S}{K_n S + E_r}$$

$$\therefore E_m = \frac{(3.303\times10^4\ MPa)(5.0\times10^4\ \frac{MPa}{m})(1.0\ m)}{(5.0\times10^4\ \frac{MPa}{m})(1.0\ m) + 3.303\times10^4\ MPa}$$

$E_m = 19.89$ GPa Strong Rock Zone, Horizontal Direction

Weak Rock

$S \approx 0.5$ m

$$E_m = \frac{(3.303\times10^4\ MPa)(5.0\times10^4\ \frac{MPa}{m})(0.5\ m)}{(5.0\times10^4\ \frac{MPa}{m})(0.5\ m) + 3.303\times10^4\ MPa}$$

$E_m = 14.23$ GPa Weak Rock Zone, Horizontal Direction

Recall from Page 8, DOE rock mass moduli

$E_m = 23.51$ GPa Category 5 Strong Rock
$E_m = 6.37$ GPa Category 1 Weak Rock

Thus, the rock mass moduli used in this first analyses are still somewhat different from those 2 DOE rock mass categories, assuming the intact rock Young's Modulus is used used for distinct rock blocks in both regions.

MPa 3/9/99

The thermal input applied to the tunnel boundaries was based on an 85 MTU/acre head load as discussed in Rui Chen's paper and based on DOE recommended thermal load. DOE analysis shows that to maintain 85 MTU/acre AML, a uniform drift spacing of 28 m is needed.
For a 28 m drift spacing, the waste package spacing (WP) is calculated to be 13.26 m (Rui, Chen, 1999)
Assuming a waste package of type 44-BWR HLW 44-BWR, and initial heat output (Q_o) was specified at 8993.88 W.
Assuming that heat is uniformly distributed on the drift wall, the decay heat flux ($q(t)$) is calculated as

$$q(t) = \frac{Q(t)}{\pi D L_{wp}}$$

where
$D = 5.0$ m (drift diameter)
L_{wp} : 13.26 m (WP center to center spacing)

$\therefore$ Initial heat flux

$$q_o = \frac{Q_o}{\pi D L_{wp}} = \frac{8993.88\ W}{\pi (5.0\ m)(13.26\ m)} = 43.18\ \frac{W}{m^2}$$

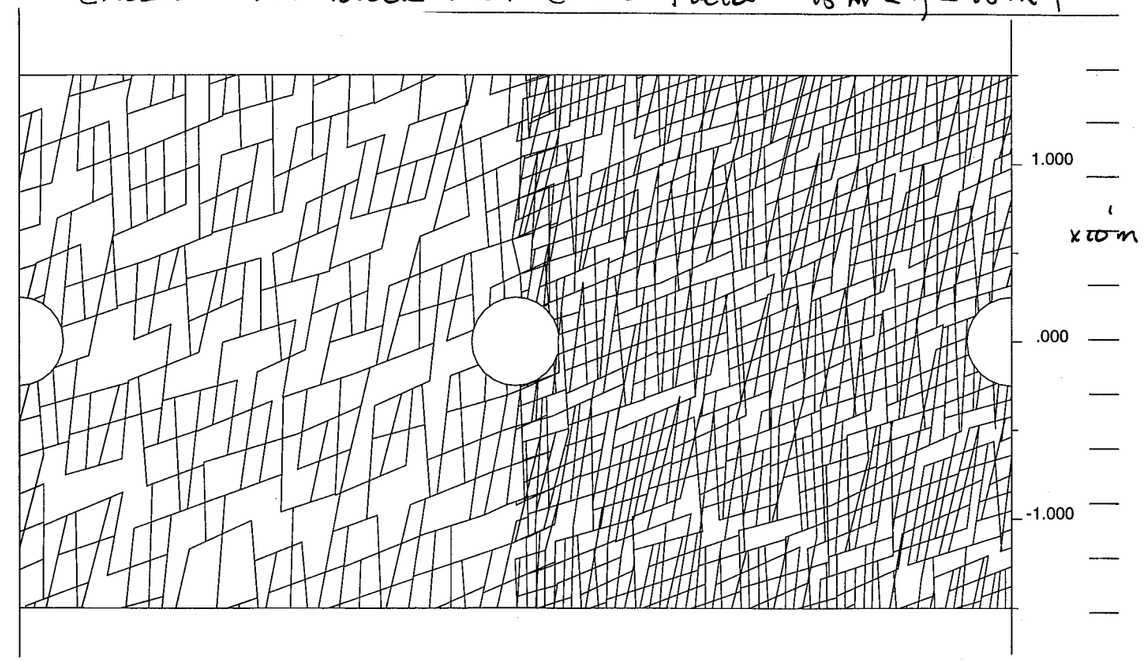
4/12/99

All TM runs for Cases 1 and 2 were made with the udec.exe (Version 3.0) dated 2/24/99 as downloaded from the Itasca web site (www.itascacg.com). The executable version of udec mailed to me by Itasca and dated 9/17/98 had a serious bug in the thermal logic (i.e., any triangular block containing only a single triangular finite difference zone) was treated for some reason as a heat sink, causing gross errors in temperature fields.

For Case 1, a plot of the near-field fracture zone region around the 3-tunnels is shown on the next page (pg 13). As stated in Task # 1 Objectives, the transition zone between stronger and weaker rock occurs at the vertical centerline of the middle tunnel. For comparison purposes, a base case analyses assuming only large joint spacing (strong rock throughout region) was also analyzed. A plot of the near-field fracture zone is also shown in the bottom figure on next page. The fracture spacings for this entire model are representative of the left side of model shown at top of page 13.

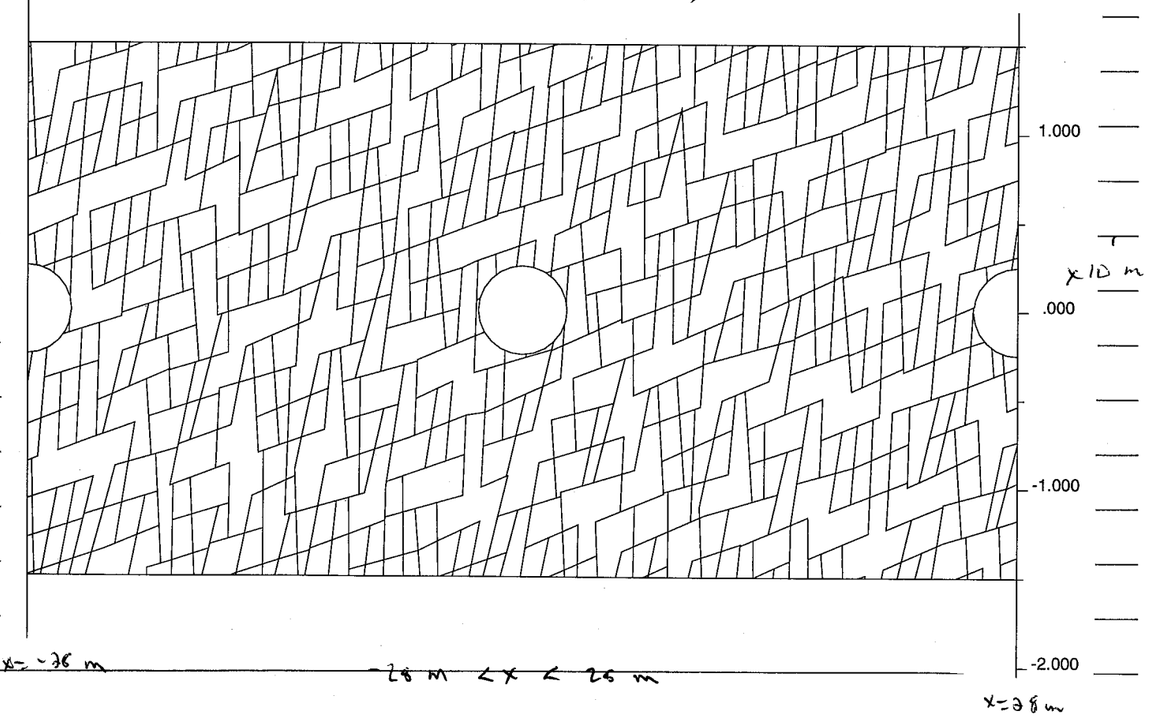
MDA 4/12/99

CASE 1 - TM Block Plot (Near field -15 m < y < 15 m)



-28 m < x < 28 m

Case 1 - Base Case Model (Strong Rock) - Block Plot



x = -28 m -28 m < x < 28 m x = 28 m

MDA 4/12/99

For Case 2, which contains 4 tunnels and a transition between stronger rock and weaker rock midway between the two central tunnels, a plot of the fracture geometry around all 4 tunnels is shown at top of adjacent page. A close up of the fracture pattern for the two central tunnels of the same model is shown at bottom of adjacent page. Again, the full vertical extent of the model is the ground surface (311 m above emplacement drift horizon) and 225 m below emplacement drift horizon. For modeling simplicity though, the fractured region extends only 15 m above and below the tunnels. As for Case 1, a base case model with 4 tunnels all in strong rock was also modeled for comparison purposes. Similar plots of fracture geometry for this model are shown on page 16.

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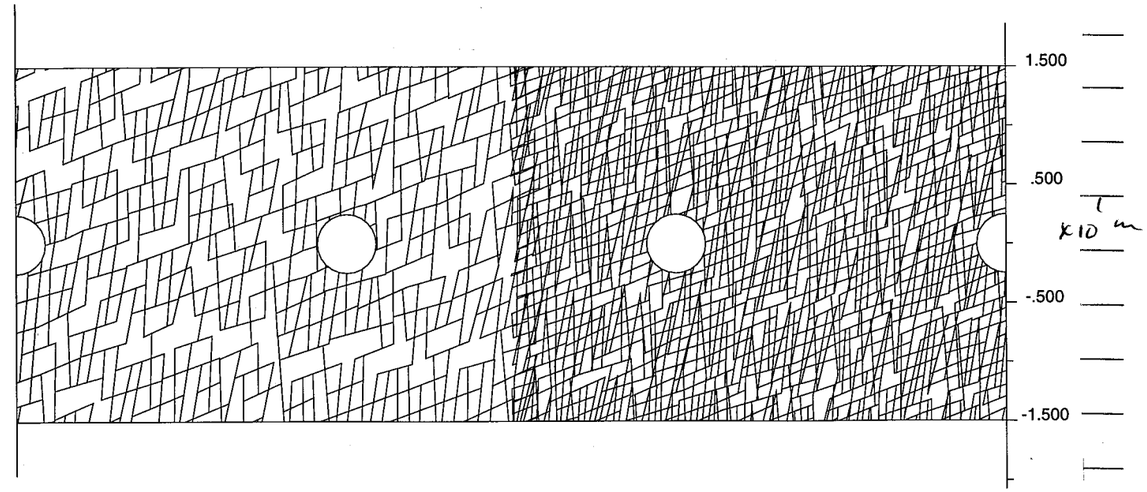
Case 2 - TM Block Plot (Near field) -42 m < x < 42 m



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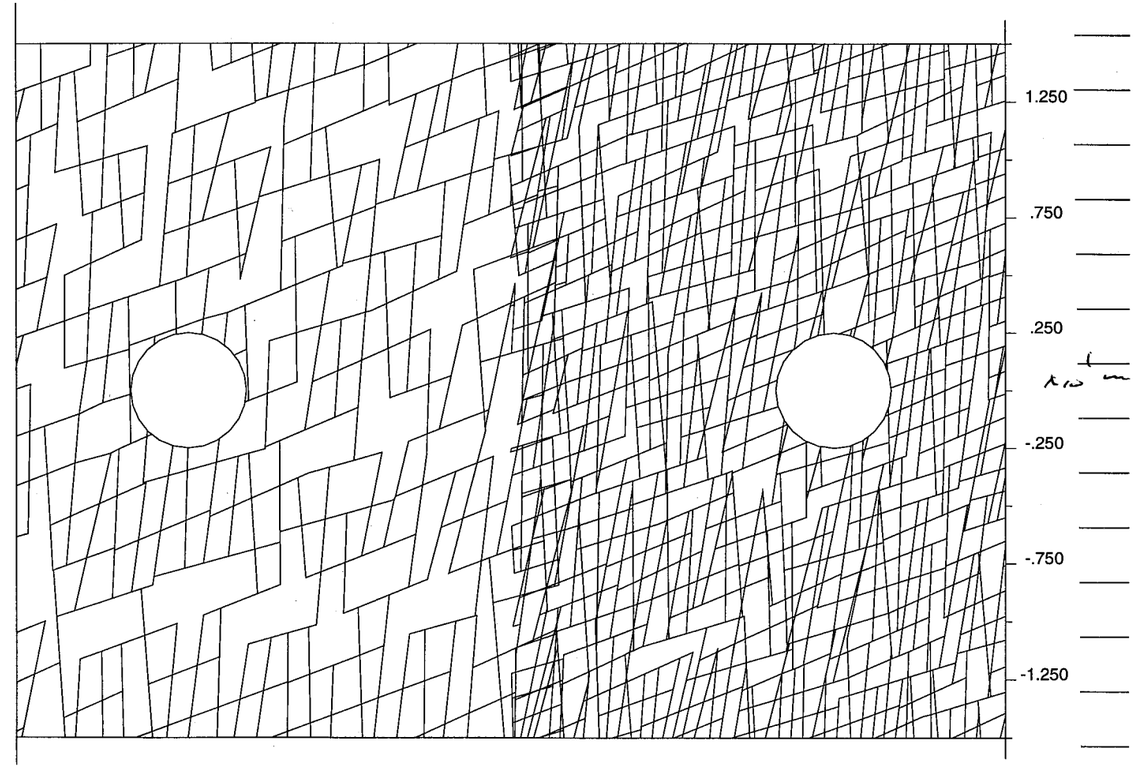
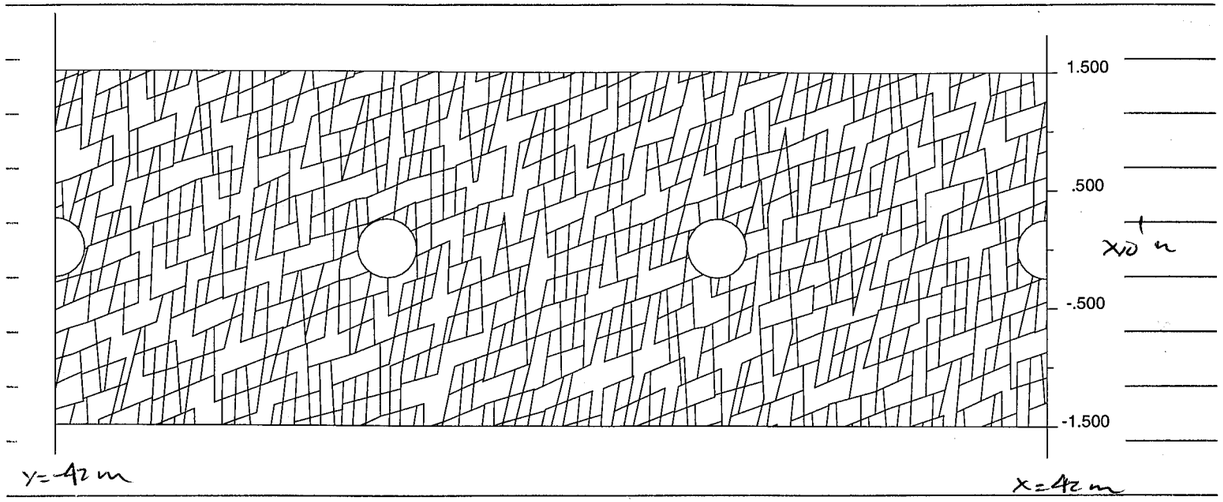
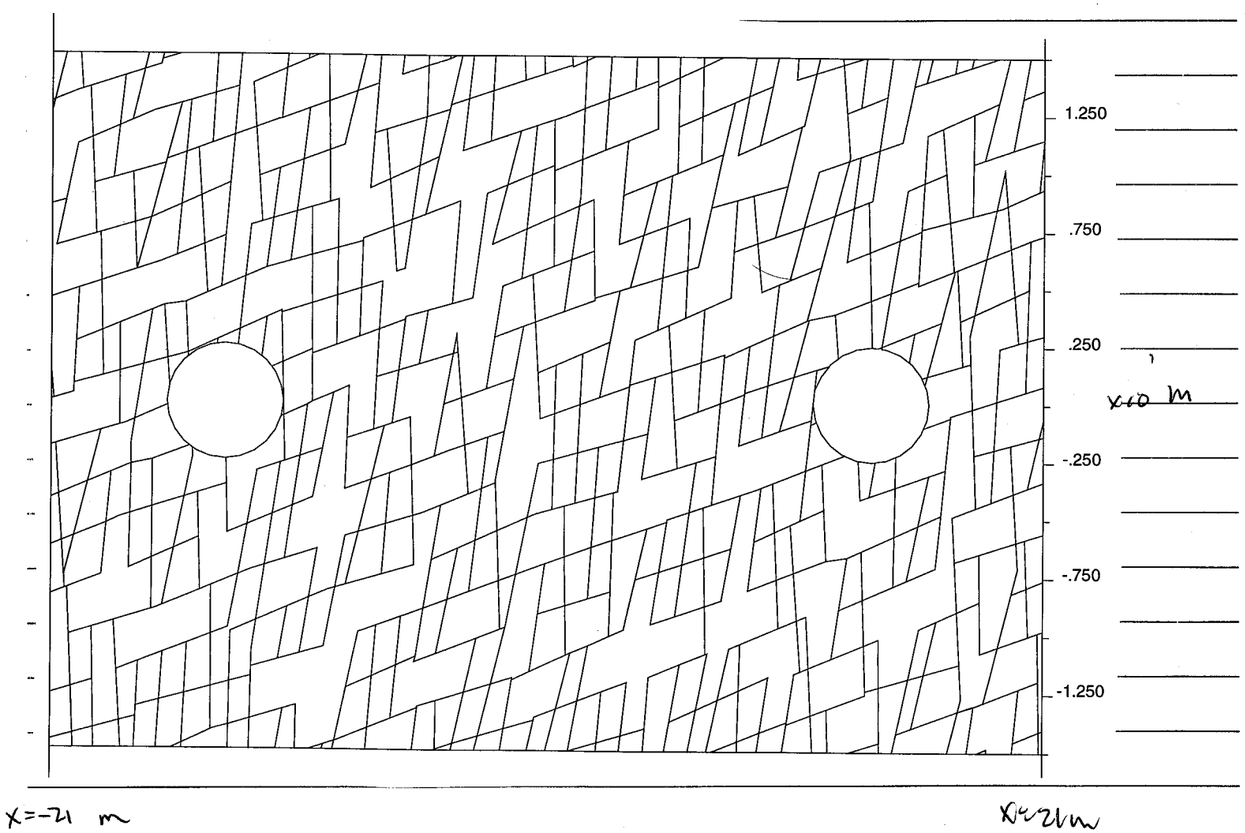
Case 1 - TM Block Plot (-21 m < x < 21 m)



Case 2 - Base Case Model (Strong Rock throughout Model





A few select results from the TM analyses (namely joint shear displacement plots, joint closure plots and plasticity failure index plots (i.e., Mohr-Coulomb plasticity model). Plots are shown for bothe the base case analysis (strong rock throughout) as well as the transition model containing strong and weak rock. In addition, plots are shown at two different periods of time, one after excavation of the emplacement tunnels (no heating) and the second ~~in~~ 4/14/99 after 50 years of thermal load (near ~~max~~ thermal loading time). Page 18 shows shear displacements along joints for the 4 tunnel Case 2 analyses (both base case strong rock and transition case) after excavation (top two figures) and after thermal loading (bottom two figures). From the plots shown on page 18, the shear displacements are primarily confined to the vertical joints after excavation, and then occur along the sub-horizontal joints after thermal loading is applied due to high lateral ~~com~~ 4/14/99 stresses that develop. The extent of joint shear displacement appears to be slightly greater for the base case strong rock model. Joint closure plots for both base case strong rock and transition model after 50 years of thermal load are shown on page 19. Closure was negligible after excavation phase. Base case model shows a much greater extent of joint closure than transition model.

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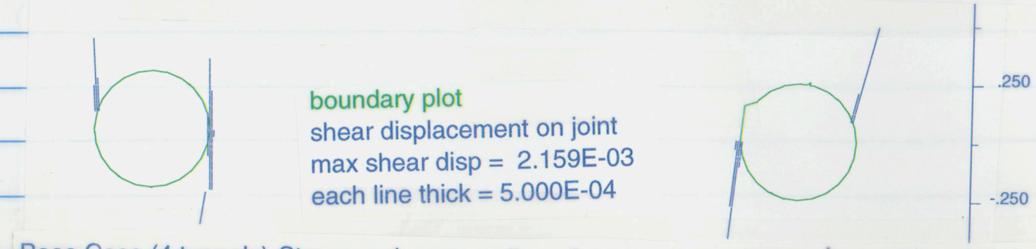
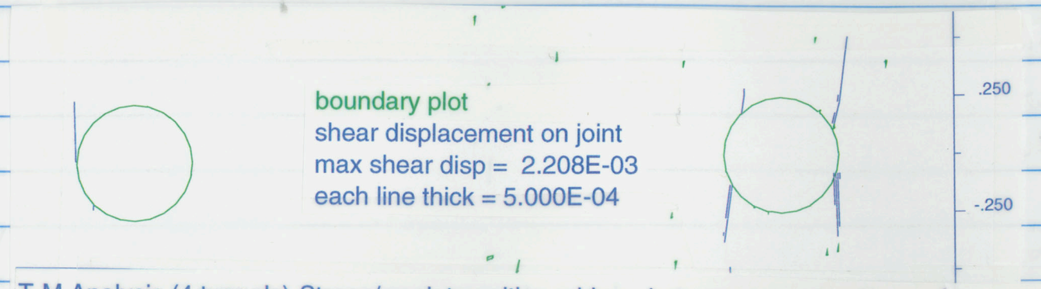
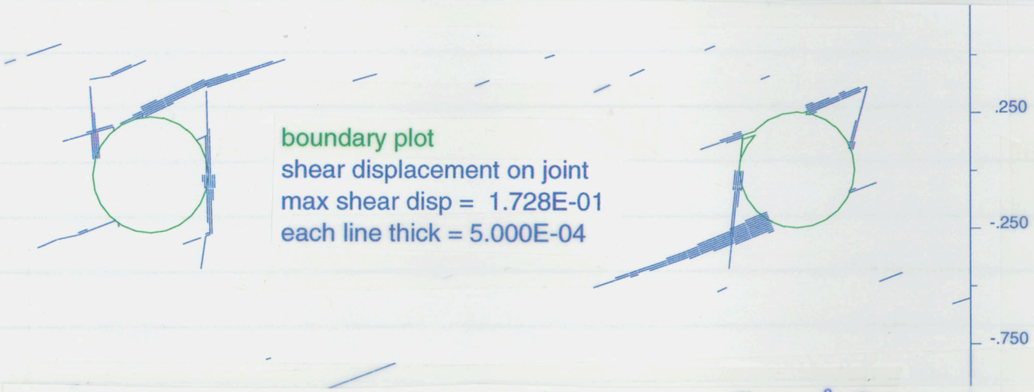
Joint Shear Displacement Plots



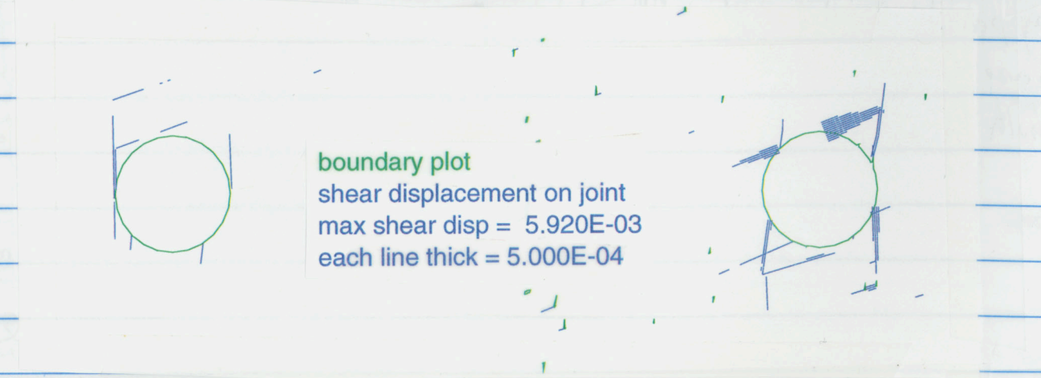
Base Case (4 tunnels)-Strong rock surrounding all 4 tunnels – Excavation Phase



T-M Analysis (4 tunnels)-Strong/weak transition midway between tunnels – Excavation Phase

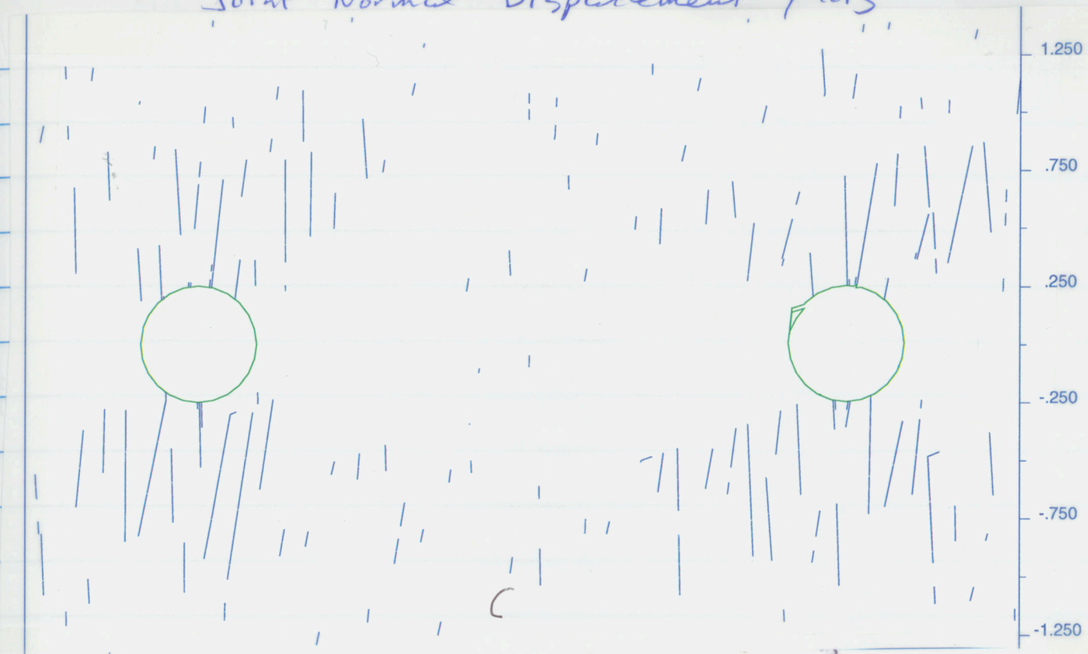


Base Case (4 tunnels)-Strong rock surrounding all 4 tunnels – Thermal Time = 50 years



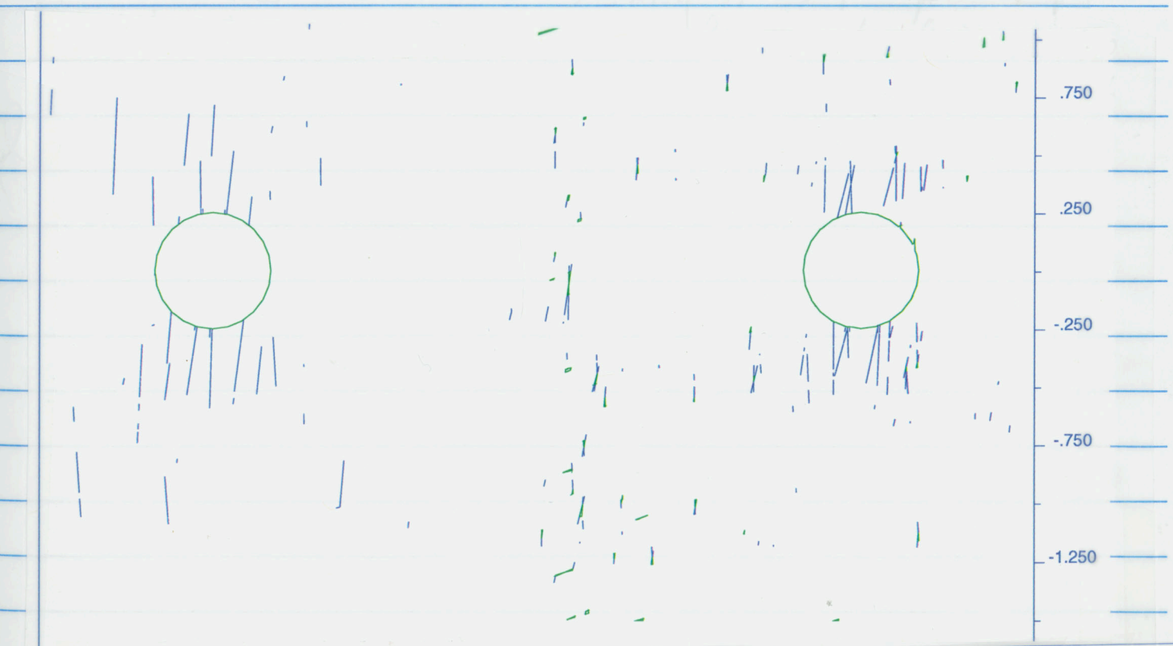
T-M Analysis (4 tunnels)-Strong/weak transition midway between tunnels – Thermal Time = 50 years

Joint Normal Displacement Plots



Base Case (4 tunnels)-Strong rock surrounding all 4 tunnels – Thermal Time = 50 years

joint closure
max jnt closure = 1.687E-03
each line thick = 5.000E-04



T-M Analysis (4 tunnels)-Strong/weak transition midway between tunnels – Thermal Time = 50 years

joint closure
max jnt closure = 2.223E-03
each line thick = 5.000E-04

Mohr-Coulomb plasticity failure plots for both ~~page 20~~ mpq 4 tunnel base case strong rock and 4 tunnel transition case are shown on page 21. Plots show tensile failure in a few locations in the roof and sidewall of central tunnels for the base case model after 50 yrs of heating and little plastic yielding. For the transition 4 tunnel model, no tensile failure of zones is indicated, however an increase in number of plastic yield zones is predicted especially in the right sidewall of left centermost tunnel (located in the strong rock region of model.

A plot of the temperature distribution at a thermal time of 50 years for the 4 tunnel transition model is shown on page 21. Tunnel wall temperatures at this time are approximately 225°C (near peak thermal load).

mpq
4/12/99

Mohr Coulomb Plasticity / Tensile Failure Plots

Base Case (4 tunnels)-Strong rock surrounding all 4 tunnels - Thermal time = 50 years

boundary plot	
no. zones : total	8766
at yield surface (*)	0
yielded in past (X)	1
tensile failure (o)	4

T-M Analysis (4 tunnels)-Strong/weak transition midway between tunnels - Thermal time = 50 years.

boundary plot	
no. zones : total	26228
at yield surface (*)	0
yielded in past (X)	11
tensile failure (o)	0

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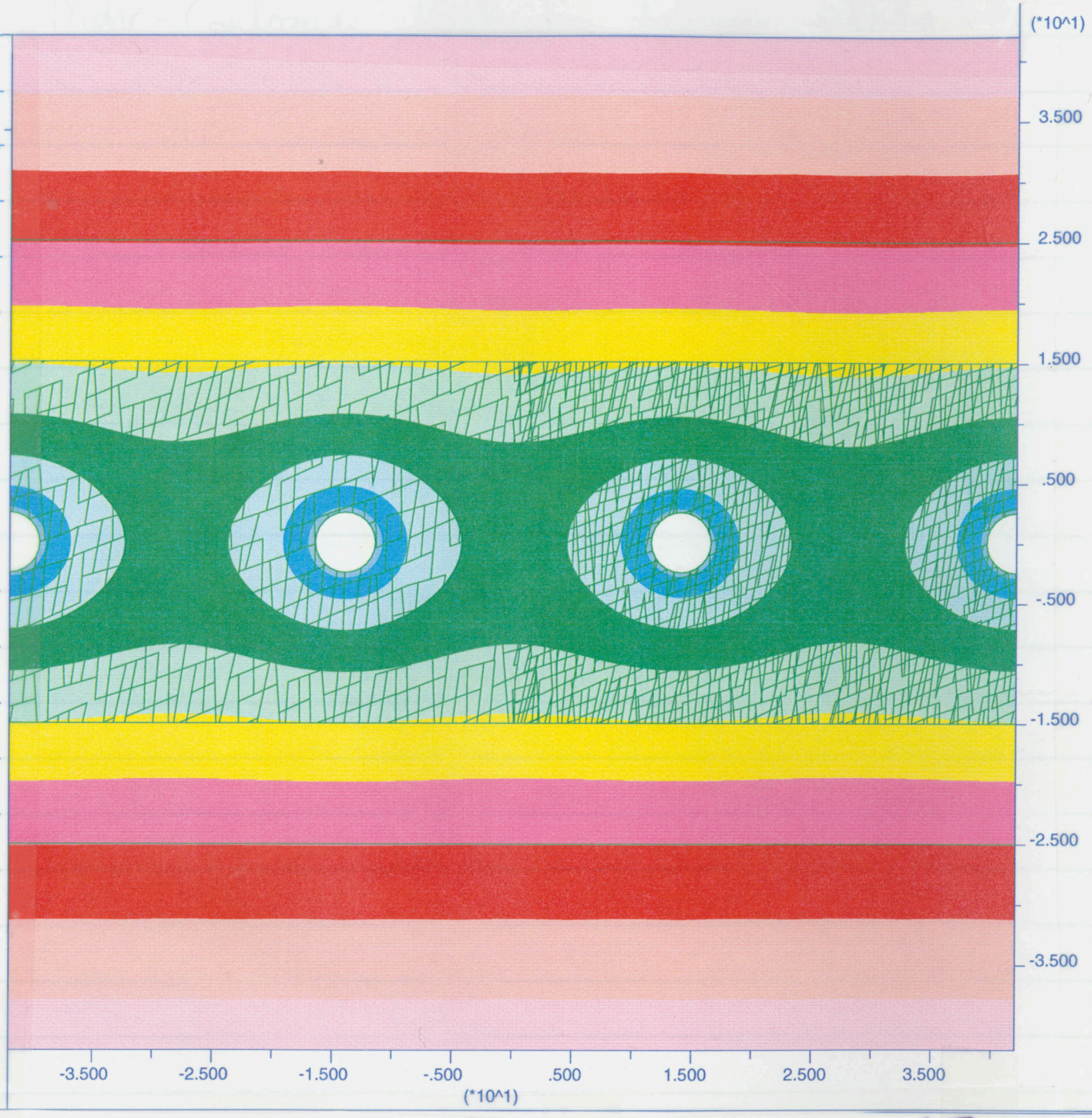
4/12/99



T-M Analysis (4 tunnels)-Strong/weak transition midway between tunnels - Thermal Time = 50 years

grid point temperature cont
contour interval= 1.500E+01
1.050E+02 to 2.250E+02

1.050E+02
1.200E+02
1.350E+02
1.500E+02
1.650E+02
1.800E+02
1.950E+02
2.100E+02
2.250E+02

For Case 1, an additional base case model was run assuming the smaller joint spacing throughout (weaker rock) as representative of the right hand portion of the model shown in the top figure on page 13. Based on discussions/e-mails with Simon Hsiung, all TM analyses were extended out to a time period of 150 years after waste emplacement.

A second set of runs was initiated for the Case 1 study (i.e, 3 tunnel base ~~case strong rock~~ MA 6/10/99 case models and transition model assuming reduced strength properties for both the intact rock and rock joints (see e-mail message below.).

Mikko;

I am unable to locate the document I need for modeling rockbolts. I will try Alamo Down. This may take a while. In the mean while, could you run several cases with reduced strength properties. The following is what I have in mind:

(1) reduce the uniaxial compressive strength and friction angle of intact rock, 6/10/99 strength properties for joints to half. The required cohesion could be backed out using conversion equation. Rerun the cases for transitional zone related investigations. Rock Tensile Strength = 1/2

(2) Using (1) and varying joint normal and shear stiffnesses in a systematic way to study how joint stiffnesses will effect rock mass responses.

Simon

MA. 6/10/99

Recall from page 6, the original intact rock property and joint property parameters used were the following:

Mechanical Strength Properties (Intact Rock - Original)

Uniaxial Compressive Strength = 166 MPa
Cohesion = 36.9 MPa
Friction Angle (ϕ) = 46°
Tensile Strength = 8.91 MPa

Per attached e-mail, request was made to rerun cases using reduced strength properties, namely, 1/2 uniaxial compressive strength, 1/2 friction angle, 1/2 tensile strength. New value for rock cohesion can be backed out from the following relation:

$$q_u = 2S_i \left[\tan\left(45 + \frac{\phi}{2}\right)\right]$$

where q_u = uniaxial compressive strength
S_i = cohesion
ϕ = friction angle.

alternative relation is also:

$$q_u = 2S_i \frac{\cos\phi}{1-\sin\phi}$$

The new set of reduced strength rock properties for this additional set of analyses is as follows:

Reduced Mechanical Strength Properties (Intact Rock)

Uniaxial Compressive Strength = 83 MPa
Rock Friction Angle = 23°
Rock Cohesion = 27.5 MPa
Rock Tensile Strength = 4.46 MPa.

For consistancy, the joint friction angle was also reduced by one-half from $\phi = 41°$ to $\phi = 20.5°$. The original joint tensile strength and joint cohesion were negligible.

MA
6/15/99

The 3-tunnel transition zone model was rerun varying the joint normal and shear stiffnesses. (See e-mail from Simon Hsiung on previous page). For the intact rock properties, the original values given on Page 6 were used. The joint properties given on Page 7 were also used except that the joint normal and shear stiffnesses were varied. The original joint stiffnesses were as follows.

K_n = Joint Normal Stiffness = 5.0×10^4 MPa/m

K_s = Joint Shear Stiffness = 5.0×10^4 MPa/m

Two additional runs were performed ~~with~~ 7/28/99 to study the impact of varying the joint stiffnesses on the results. The first run involved increasing both the joint normal and shear stiffnesses by a factor of 10 to $K_n = K_s = 5.0 \times 10^5$ MPa/m. The second run involved decreasing joint stiffnesses by a factor of 10 to values $K_n = K_s = 5.0 \times 10^3$ MPa/m. With these values set, UDEC™ runs were performed out to a thermal time of 150 years, as done for original case.

7/28/99

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As per e-mail below, a set of analyses were set up to run with rock bolts installed above the springline of each tunnel. Assuming a 5.5 m diameter (D) tunnel, the half-circumference of the tunnel is approximately $\frac{1}{2}(\pi D) = 8.6$ m. Thus, approximately 8 bolts evenly spaced above springline would roughly simulate a 1 m square bolting pattern assuming they were spaced 1 m apart along axis of drift also. Since UDEC is 2D, the

Mikko;

I have received you draft. The content looks good. However, the graphics look lousy. Could you send me the originals (UDEC postscripts). I know you sent me some already. But this way will save me some time. Some additional items I need you to do for me.

For the report

1. Generate plots for max and min principal stresses contours for all cases.
2. Generate plots for safety factor contours for all cases using Coulomb or Hoek and Brown criterion whichever is appropriate or both
3. Extend the analyses to 150 years
4. Run all the cases with rock bolts installed. (Bolting pattern: 1 m square, 2.5 m long, fully grouted, above spring line)

Other analysis

1. Construct a model similar to that of strong rock mass base case (four-tunnel model). The diameter of the drift is 5.5 m. Drift spacing is 81 m (center to center). Thermal load is 60 MTU. Young's modulus is 15 GPa, Poison's ratio is 0.16 Cohesion is 11 MPa Friction angle 14 degree Tensile strength 1 MPa

2. Run the model without rockbolts and with rockbolts

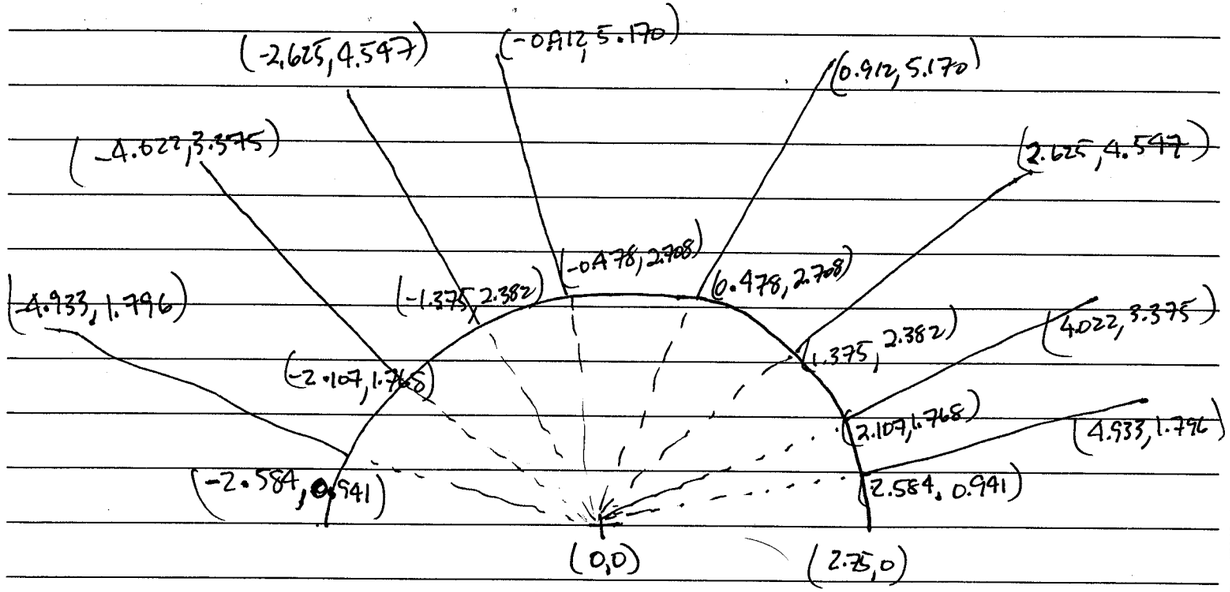
If it is possible, establishing and running the model for "Other analysis" quickly. I really need want to have the result ASAP.

Do not worry about the hours. It should be easy to transfer fund from other tasks that we have not give you any assignment (Is it true?). I will give you some activities on review plan development shortly. By the way, please e-mail me the save files for the case studies you have completed.

Regards

Simon

effect of bolt is smeared along length of tunnel. The bolt length modeled was 2.5 m. Assuming a tunnel centered at the origin, the following bolt beginning and end points are calculated.



radius = 2.75 m.

For the UDEC analyses, the following bolt parameters need to be specified in the UDEC PROPERTY command when using the REINFORCEMENT command to simulate the rock bolts

r_aexp	(bolt axial stiffness exponent)
r_astiff	(bolt axial stiffness MN/m)
r_length	(1/2 active bolt length)
r_rfac	(reversal factor)
r_sexp	(bolt shear stiffness exponent)
r_sstif	(bolt shear stiffness)
r_str	(axial failure strain)
r_uaxial	(ultimate bolt axial capacity MN)
r_ushear	(ultimate bolt shear capacity MN)

The following bolt parameters were used for the UDEC TM analyses. Note, some values were assumed as little to no data was available on bolt pull-tests or other test which are needed to accurately specify bolt parameters.

r_aexp = 1
r_astiff = 1.0×10^2 MN/m
r_length = 1 m
r_rfac = 1
r_sexp = 1
r_sstiff = 1.0×10^2 MN/m
r_str = 10^{10} (default UDEC value)
r_uaxial = 1.0 MN
r_ushear = 1.0 MN

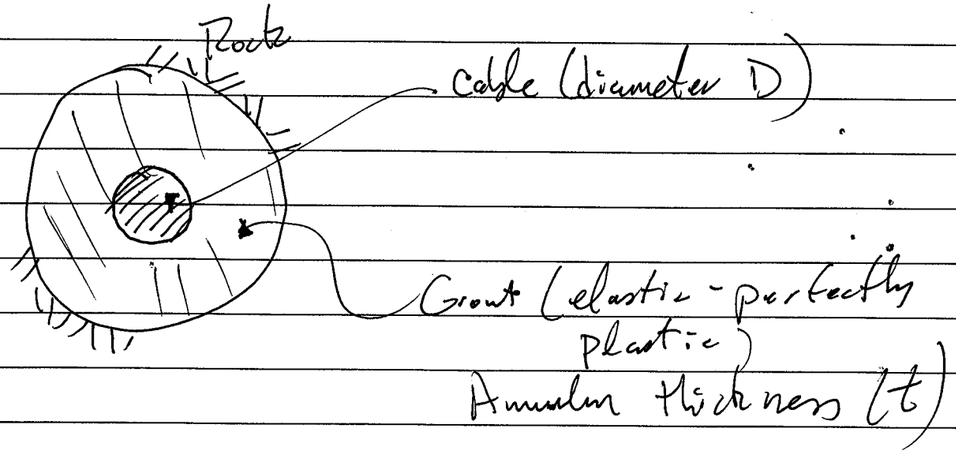
M.A.
8/1/99

Upon consultation with Itasca Consulting Group, it was best decided not to use local reinforcement (REINFORCE) command and instead use the global reinforcement (CABLE) command. Local reinforcement acts only across the joint interfaces and not along the full grouted length of the bolt which would appear more correct.

Cable Element Properties include:

(1) Cross-Sectional area of cable (A)
(2) Mass density for cable
(3) Elastic Modulus (Young's) for cable (E)
(4) Tensile yield strength [force] of the cable
(5) Compressive yield strength [force] of cable
(6) Extensional failure strain for the cable
(7) Stiffness of the grout (K_{bond}) [force/cable length/displacement]
(8) Cohesive capacity of the grout (S_{bond}) [force/cable length]

K_{bond}
S_{bond}



Per UDEC Manual (Page G-23)

$$K_{bond} \simeq \frac{2\pi G}{10 \ln[1 + 2t/D]}$$

where G = grout shear modulus.

Since results from pull-out tests on bolts at different confining pressures is not available. Maximum force per length may be estimated from the peak shear strength. (UDEC Manual, Page G-23).

$$\tau_{peak} = \tau_I Q_B$$

where $\tau_I \cong$ 1/2 uniaxial compressive strength of weaker of the rock and grout

Q_B = quality of bond between grout and rock ($Q_B = 1$ for perfect bonding).

Neglecting frictional Effects

$$S_{bond} = \pi (D + 2t) \tau_{peak}$$

assuming failure at the grout/rock interface.

Assume following properties:

Grout Compressive Strength = 20 MPa.

✓ Grout Shear Modulus (G) = 9 GPa. = 9×10^3 MPa

Bolt/Cable diameter (D) = 0.75 in = 19 mm

Hole Diameter (D+2t) = 1.5 in = 38 mm

Steel Bolt Modulus (Young's) (E) = 200 GPa = 2.0×10^5 MPa

Bolt Ultimate tensile capacity (F_y) = 0.1375 MN

Annulus Thickness (t) = $\frac{(D+2t)}{2} - D$ = 9.5 mm = 9.5×10^{-3} m

For Bolt, assume Grade 40 Billet Steel, #6 Bare (having 0.75 in diameter)

Axial Tensile Strength = 70,000 psi = 482.5 MPa

D = 0.75 in

$A = \pi D^2/4 = 2.85 \times 10^{-4}\ m^2$

∴ Axial yield strength = $\left(482.5\ \frac{MN}{m^2}\right)\left(2.85 \times 10^{-4}\ m^2\right)$

F_y = 0.1375 MN

Assuming failure occurs at the cable/grout interface, the maximum bond force/length is (Equation on bottom of Page 31 with D+2t replaced by D):

$$S_{bond} = \pi D \tau_{peak}$$

where $\tau_{peak} \cong$ ½ grout compressive strength = 10 MPa assuming perfect bonding

$$\therefore \boxed{S_{bond} = \pi (0.019\ m)(10\ MPa) \cong 600\ kN/m}$$

$$K_{bond} \cong \frac{2\pi (9.0 \times 10^3\ MPa)}{10 \ln\left[1 + \frac{2(9.5 \times 10^{-3}\ m)}{1.9 \times 10^{-2}\ m}\right]} = 8.158 \times 10^9\ \frac{N/m}{m}$$

$$\boxed{K_{bond} = 8.158 \times 10^9\ \frac{N/m}{m}}$$

Estimate of Maximum Length of Cable Element Segments.

(UDEC Manual Page C-24)

$$l_d = \frac{F_y}{S_{bond}}$$

where S_{bond} = grout bond strength

F_y = cable yield force capacity

$F_y = 0.1375\ MN = 1.375 \times 10^5\ N$

$S_{bond} = 6.0 \times 10^5\ N/m$.

$$l_d = \frac{F_y}{S_{bond}} = \frac{1.375 \times 10^5\ N}{6.0 \times 10^5\ N/m}$$

$l_d \cong 0.223$ m. (Estimate of cable segment length, i.e., distance between nodes.

Bolt Length = 2.5 m.

$$\#\ elements = \frac{2.5\ m}{0.223\ m} \cong 11$$

$$\therefore \boxed{npoint = \#elements + 1 = 12}$$

Cable bolt density

#6 Bar

Unit weight/foot = 1.502 lbs

Diameter = 0.75 in

Area = 0.44 in^2

Length = 12 in

$$\text{Density } (\rho) = \frac{1.502 \text{ lbs}}{(0.44 \text{ in}^2)(12 \text{ in})} = 0.2845 \frac{\text{lb}}{\text{in}^3}\left(\frac{12 \text{ in}}{\text{ft}}\right)^3$$

$$= 491.62 \frac{\text{lb}}{\text{ft}^3}$$

Metric Units

Note: 1 lb mass/ft^3 = 1.601846×10^1 Ks/m^3

$$\text{Bolt Density } (\rho) = \left(491.62 \frac{\text{lbm}}{\text{ft}^3}\right) * \left(\frac{16.01846 \text{ Ks/m}^3}{1 \text{ lbm/ft}^3}\right)$$

m.a.

$$\boxed{\text{Bolt Density } (\rho) = 7875 \text{ Ks/m}^3}$$

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UDEC Model - Bolt material property #'s

mat5 = 9

mat9 = 10

Note: Since cable/bolt spacing perpendicular to model cross-section is 1 m, values for K_{bond}, S_{bond}, E, and tensile yield force do not need to be adjusted, and full values are used.

m.a.
8/30/99

All ~~and~~ m.a. UDE TM analyses were written up and documented in a September 1999 CNWRA report titled "Rock Mass Behavior in the Transitional Zone Between Strong and Weak Rock Conditions" authored by Mikko P. Ahola, Simon Hsiung, and Amitava Ghosh. Conclusions as well as recommendations for future work are given in this report. All UDEC input files, restart (.sav files) and postscript plots for the various TM analyses conducted are provided on PC zip disks to be kept in the QA files with this scientific notebook.

m.a.
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T. Mayer 8/8/00

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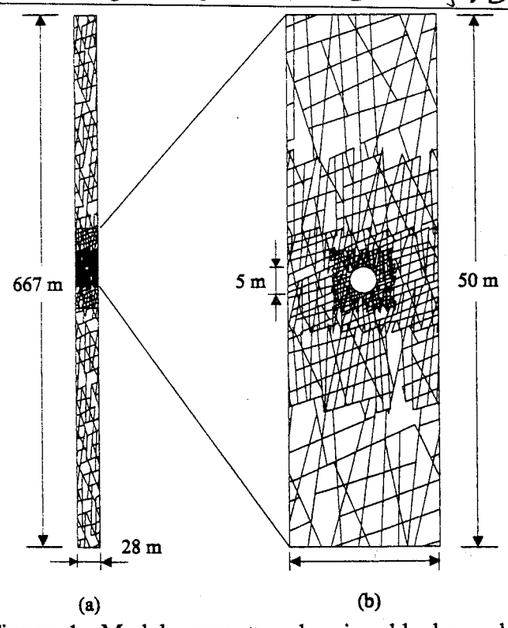
Task #2

The objective of task #2 of project consists of a dynamic analysis using K-DYNA3D to validate results run for a dynamic earthquake analysis using UDEC. The test case chosen for the validation was the UDEC model identified as Case C (Chen, 1999). The Case C model consists of a single 5 m diameter emplacement drift and surrounding rock mass containing 3 ~~meas~~ 3/18/99 point sets as obtained from DOE data. Earthquake loading (vertical compressive wave) was applied to base of model as a sinusoidal input with frequency of 2 Hertz for a duration of 1 sec, after excavation of tunnel. (i.e., no thermal loading considered. Figure 1 below shows the Case C model as extracted from Chen 1999.



(Chen, 1999)

Figure 1. Model geometry showing blocks and a particular fracture pattern (case C). (a) full model for TM analyses. (b) Submodel for dynamic analyses.

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Figure 2 shows the tunnel response obtained from UDEC after earthquake loading as extracted from Chen, 1999.

Information potentially subject to copyright protection was redacted from this location. The redacted material is from the following reference:

Chen, R. "Analyses of drift stability and Rockfall Due to Earthquake Ground Motion at Yucca Mountain, Nevada. Proceedings of the 37th U.S. Rock Mechanics Symposium, Rock Mechanics for Industry, Vail, Colorado, June 5-9, 1999. B. Amadei, R.L. Kranz, G.A. Scott, and P.H. Smeallie, eds. pp. 759-766. 1999.

Task #1

In order to run a validation of this dynamic analysis using K-DYNA3D, the geometry (i.e. # of joints as well as extent of jointing) within the model needed to be simplified. The goal was to try and represent as closely as possible the joint patterns in the very near-field region around the tunnel and represent the outer far-field region as an elastic continuum. A more simplified UDEC model containing the near-field joint pattern and elastic continuum for the outer domain was also generated in the process so as

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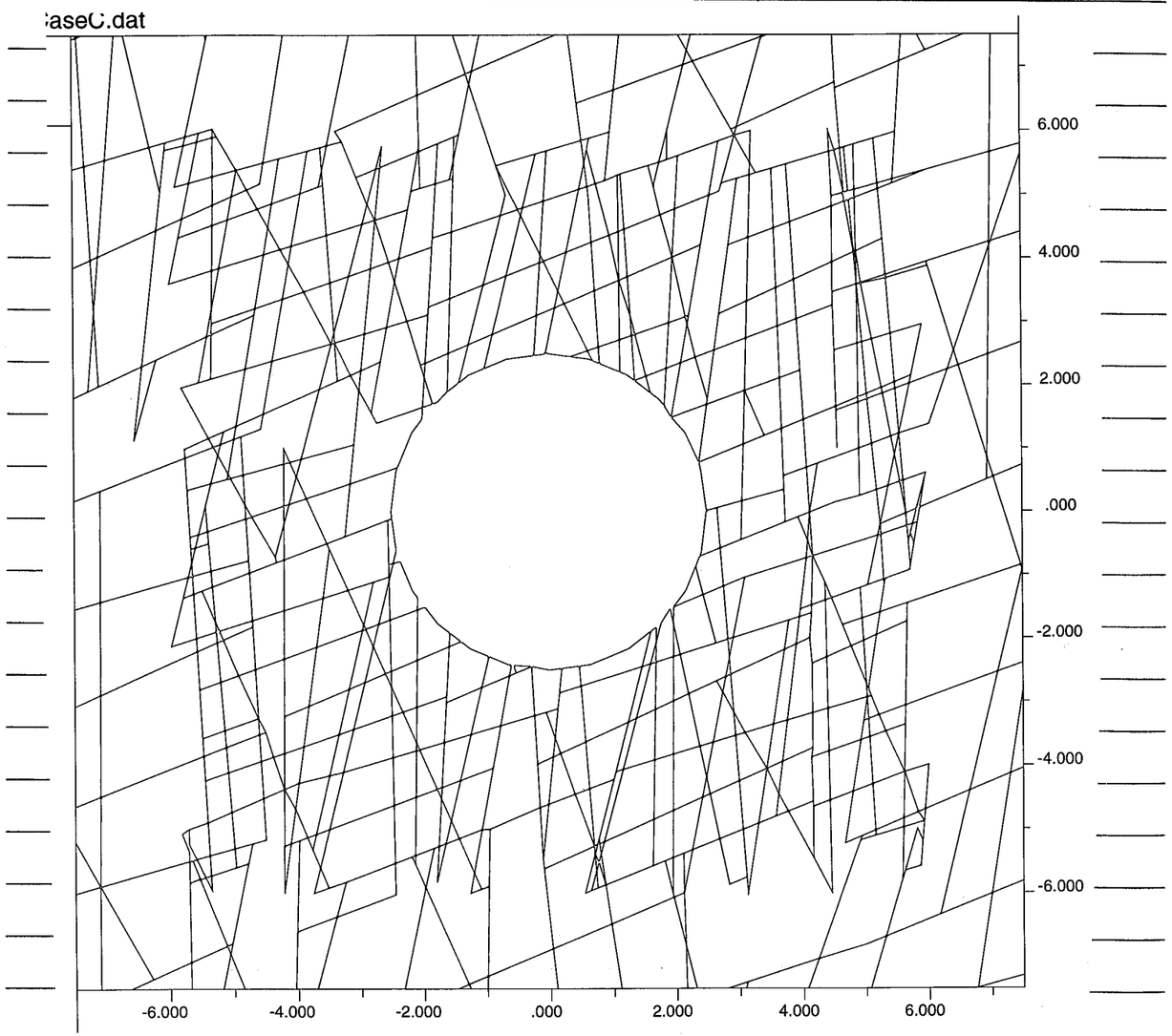
not only to run faster, but provide a direct comparison the the. K-DYNA3D model.

The plot below shows the near-field region from Rui Chen's model as shown on previous page (100). that was chosen for the dynamic analyses comparison w/ K-Dyna 3D. The fractured region extends ± 7.5 m in the x and y directions as measured from the origin. The remainder of the model is assumed as a continuum.



In order to get the UDEC crack geometry data into a PATRAN database for the K-DYNA3D analyses, some data processing steps were necessary. The UDEC joint geometry was generated using a generator that used mean and standard deviations for joint angles, etc. As such, to get the crack coordinates a UDEC ASCII file printout file of block corner data was generated. The following C# file reads the UDEC block corner output file and creates a new file with just beginning and ending points for each joint segment. The C# file name is udec_cor.cpp (located on zip disk #6 under the fracture directory). A second C# computer program was written to write this UDEC crack data into a Patran Neutral file format containing gridpoint and line data. Patran was then used to read this neutral file containing gridpoint and line data and to then create a new Patran data base for the K-Dyna 3d model. ~~Both C#~~ m.a. 8/30/99 This C# program is titled pat_neut.cpp. Both C# files are listed on the following pages.

M.a.

8/30/99

```
// FILE NAME:            udec_cor.cpp
// TARGET PLATFORM:      Windows NT
// DEVELOPMENT DATE:     2/19/99
// DEVELOPER:            Mikko Ahola
// COMPILER USED:        Microsoft Visual C++ (Version 5.0)
//=================================================================
// PROJECT FILES:
//     udec_cor.cpp
//=================================================================
// PROGRAM DESCRIPTION:
// This program reads a UDEC ASCII printout file of block corner
// data and generates UDEC crack line segment commands to be included
// back into a UDEC data file to regenerate block geometry.  Program
// was needed as UDEC uses random seed numbers to generate joint
// patterns using the UDEC JSET command. Trying to simplify a joint
// pattern in the far field region around a tunnel while keeping the
// same JSET joint commands in the near-field tunnel region would still
// result in a somewhat different joint in the near-field tunnel region
// due to a different random seed number selected.  Thus in order to
// simplify Rui Chen's Case C dynamic tunnel model and keep the same
// near-field geometry, this code was needed.
// ================================================================
//   INCLUDE FILES
// ================================================================
#include <iostream.h>
#include <iomanip.h>
#include <stddef.h>
#include <fstream.h>
#include <stdlib.h>
#include <ctype.h>
//=================================================================
//*****************************************************************
// BEGINNING OF PROGRAM CODE
//*****************************************************************
void main()
{
    char Infile[15], Outfile[15], Scratchfile[15];
    char Text[80];
    int c, icor, nblocks=10000, ncrack, iflag, nmatch;
    float Corner_address, Xcoord[20], Ycoord[20], xc_beg, xc_end, yc_beg, yc_end;
    float xc_beg1, xc_end1, yc_beg1, yc_end1;

    cout << "Enter input file:\n";
    cin >> Infile;

    cout << "Enter temporary scratch file\n";
    cin >> Scratchfile;

    cout << "Enter output file:\n";
    cin.ignore(1);
    cin >> Outfile;

    ifstream InputStream  (Infile, ios::in);
    ofstream OutputStream (Scratchfile, ios::out);

    if (!InputStream)
    {
        cout << "Unable to open file" << endl;
        exit(1);
    }

    OutputStream.setf(ios::scientific);
    OutputStream.precision(3);


    for (int i=1; i<=nblocks; i++)    //loop over blocks in file (set nblocks to large #)
    {
        InputStream.ignore(2);            // ignore 1st two blank characters
        icor = 0;                         // initialize # block corners to zero

        while ((c=InputStream.get()) != 'b' && c != 'z')
        {
            icor +=1;
            InputStream >> Corner_address >> Xcoord[icor] >> Ycoord[icor];
            InputStream.ignore();         // ignore new line character
            InputStream.ignore(2);        // ignore 1st two blank characters
        }

        for (int j=1; j<=icor; j++)
        {
```



```
            if (j == icor)
                OutputStream<<"crack "<<setw(12)<<Xcoord[j]<<setw(12)<<Ycoord[j]
                            <<setw(12)<<Xcoord[1]<<setw(12)<<Ycoord[1] << endl;
            else
                OutputStream<<"crack "<<setw(12)<<Xcoord[j]<<setw(12)<<Ycoord[j]
                            <<setw(12)<<Xcoord[j+1]<<setw(12)<<Ycoord[j+1] << endl;
        }

        if (c == 'z')
            break;        // inserted 'z' to signal end of file (3rd char position on last line)

//      OutputStream << endl;
        InputStream.getline(Text, 79);
    }

    InputStream.close();
    OutputStream << "z";   // write out end of file character "z" to the temporary scratch file
    OutputStream.close();

    ifstream InputStream1 (Scratchfile, ios::in); // re-open the scratch file for further processing

// following coding reads the temporary scratch file, filters out duplicate crack statements and
// writes out the final file for the UDEC crack segments for the near field tunnel region to match
// those generated in Rui Chen's model
//
    nmatch = 0;
    ncrack = 0;
    while ((c=InputStream1.get()) != 'z')
    {
        InputStream1.ignore(6);
        InputStream1 >> xc_beg >> yc_beg >> xc_end >> yc_end;
        InputStream1.ignore();                        // flush the new line character

        iflag = 0;
        if (ncrack != 0)
        {
            ifstream InputStream2 (Outfile, ios::in);
            for (int k=1; k<=ncrack; k++)
            {
                InputStream2.ignore(6);
                InputStream2 >> xc_beg1 >> yc_beg1 >> xc_end1 >> yc_end1;
                InputStream2.ignore();                // flush the new line character

                // check for duplicate crack segment and if match found,
                //  exit loop and do not write crack segment to final output file.
                // crack segments need to be checked in both directions for possible match

                if (xc_beg == xc_beg1&&yc_beg == yc_beg1&&xc_end == xc_end1&&yc_end == yc_end1)
                {
                    iflag = 1;
                    nmatch += 1;
                    break;
                }
                if (xc_beg == xc_end1&&yc_beg == yc_end1&&xc_end == xc_beg1&&yc_end == yc_beg1)
                {
                    iflag = 1;
                    nmatch += 1;
                    break;
                }
            }

            InputStream2.close();
        }

        if (iflag != 1)
        {
            ofstream OutputStream1 (Outfile, ios::app);  // append crack data to output file

            OutputStream1.setf(ios::scientific);      // set output write format
            OutputStream1.precision(3);

            OutputStream1 << "crack " << setw(12) << xc_beg << setw(12) << yc_beg
                          << setw(12) << xc_end << setw(12) << yc_end << endl;
            ncrack += 1;
            OutputStream1.close();
        }
    }

    InputStream1.close();
```

```
    cout << "Number of crack segment matches = " << nmatch << endl;

    return;
}
//*****************************************************************
// END OF MAIN PROGRAM
//*****************************************************************
```



```
// FILE NAME:            pat_neut.cpp
// TARGET PLATFORM:      Windows NT
// DEVELOPMENT DATE:     2/24/99
// DEVELOPER:            Mikko Ahola
// COMPILER USED:        Microsoft Visual C++ (Version 5.0)
//=================================================================
// PROJECT FILES:
//     pat_neut.cpp
//=================================================================
// PROGRAM DESCRIPTION:
// This program reads a file containing UDEC crack segment commands
// and writes out a PATRAN 2.5 neutral file containing gridpoints and
// line segments to establish the corresponding fracture geometry
// in PATRAN.  Note: multiple grid points will exist at the
// same physical location, unless code is further enhanced to filter
// out duplicate gridpoints (i.e., crack endpoints).
// =================================================================
//   INCLUDE FILES
// =================================================================
#include <iostream.h>
#include <iomanip.h>
#include <stddef.h>
#include <fstream.h>
#include <stdlib.h>
#include <ctype.h>
//=================================================================
//*****************************************************************
// BEGINNING OF PROGRAM CODE
//*****************************************************************
void main()
{
    char Infile[15], Outfile[15];
    char Title[81] = "K-DYNA3D NEUTRAL FILE - UDEC GRID POINT/LINE DATA
  ";
    char Date[11] = "01-Mar-99 ", Time[11] = "  00:00:00", Version[11] = "     2.5-5";
    int c, grid_id, p_type, iv, kc, ig1, ig2, line_id, id;
    float xc_beg, xc_end, yc_beg, yc_end, zc_beg = 0.0, zc_end = 0.0,
          b11, b12, b13, b21, b22, b23, b31, b32, b33, b41, b42, b43;

    cout << "Enter input UDEC crack segment file name:\n";
    cin >> Infile;

    cout << "Enter output PATRAN neutral file name:\n";
    cin.ignore(1);
    cin >> Outfile;

    ifstream InputStream  (Infile, ios::in);
    ofstream OutputStream (Outfile, ios::out);

    if (!InputStream)
    {
        cout << "Unable to open input file" << endl;
        exit(1);
    }


    // write out title card and summary information to Patran neutral file
    p_type = 25;
    id = 0;
    iv = 0;
    kc = 1;
    OutputStream << setw(2) << p_type << setw(8) << id << setw(8) << iv
                 << setw(8) << kc << endl;
    OutputStream << Title << endl;

    p_type = 26;
    OutputStream << setw(2) << p_type << setw(8) << id << setw(8) << iv
                 << setw(8) << kc << endl;
    OutputStream << Date << Time << Version << endl;


    OutputStream.setf(ios::scientific);
//  OutputStream.precision(9);

    // write out grid data (packet type 31 Patran neutral file format) for
    // each crack endpoint

    grid_id = 0;
    p_type = 31;
    iv = 0;
```

```
kc = 1;
while ((c=InputStream.get()) != 'z')
{
    grid_id += 1;
    InputStream.ignore(6);
    InputStream >> xc_beg >> yc_beg >> xc_end >> yc_end;
    InputStream.ignore();                    // flush the new line character

    OutputStream << setw(2) << p_type << setw(8) << grid_id << setw(8)
                 << iv << setw(8) << kc << endl;
    OutputStream << setw(16) << xc_beg << setw(16) << yc_beg
                 << setw(16) << zc_beg << endl;

    grid_id += 1;
    OutputStream << setw(2) << p_type << setw(8) << grid_id << setw(8)
                 << iv << setw(8) << kc << endl;
    OutputStream << setw(16) << xc_end << setw(16) << yc_end
                 << setw(16) << zc_end << endl;
}

InputStream.close();

// re-open input crack segment file, read crack segment data and write out line data
// (packet type 32 Patran neutral file format) for each crack segment

ifstream InputStream1 (Infile, ios::in);
grid_id = 0;
p_type = 32;
line_id = 0;
kc = 3;

OutputStream.setf(ios::scientific);
OutputStream.precision(9);

while ((c=InputStream1.get()) != 'z')
{
    line_id += 1;
    grid_id += 1;
    InputStream1.ignore(6);
    InputStream1 >> xc_beg >> yc_beg >> xc_end >> yc_end;
    InputStream1.ignore();                   // flush the new line character

    ig1 = grid_id;
    ig2 = ig1 + 1;
    grid_id += 1;

    // establish 4 X 3 matrix of geometric format line coefficients
    b11 = xc_beg;
    b12 = yc_beg;
    b13 = zc_beg;

    b21 = xc_end;
    b22 = yc_end;
    b23 = zc_end;

    b31 = xc_end - xc_beg;
    b32 = yc_end - yc_beg;
    b33 = zc_end - zc_beg;

    b41 = b31;
    b42 = b32;
    b43 = b33;

    OutputStream << setw(2) << p_type << setw(8) << line_id << setw(8)
                 << iv << setw(8) << kc << endl;
    OutputStream << setw(16) << b11 << setw(16) << b21 << setw(16) << b31
                 << setw(16) << b41 << setw(16) << b12 << endl;
    OutputStream << setw(16) << b22 << setw(16) << b32 << setw(16) <<b42
                 << setw(16) << b13 << setw(16) << b23 << endl;
    OutputStream << setw(16) << b33 << setw(16) << b43 << setw(8) << ig1
                 << setw(8) << ig2 << endl;

}

// write out end of Patran neutral file (packet type 99)
p_type = 99;
id = 0;
iv = 0;
kc = 1;
```



```
    OutputStream << setw(2) << p_type << setw(8) << id << setw(8) << iv
                 << setw(8) << kc << endl;

    InputStream1.close();
    OutputStream.close();

    return;
}
//*****************************************************************
// END OF MAIN PROGRAM
//*****************************************************************
```

Once the Patran Neutral file was read in to Patran containing grid point and line data representing near field joint geometry, the line data was used to create surfaces. Some of the line data was further filtered before creating surfaces to eliminate those segments that were very close or parallel to each other which would have made meshing difficult. Once the surfaces (i.e. individual 2D blocks) were created, the continuum region extending outward to the vertical twaned symmetry planes as well as approximately 50 m above and below the drift horizon was created. All surfaces were then extruded into the 3rd dimension by a unit depth (in this case 1m) to create the 3d blocks. These front and back surfaces had rigid wall b.c. to simulate the 2D plain strain analyses. The lateral vertical boundaries were designated symmetry planes. The bottom boundary cond. was a rigid base, while the top boundary had an applied pressure based on the cut-off depth of the model. Slidelines were created between the individual K-DINA3D blocks.

Each block was also meshed into 8-noded brick elements.

The difficulties in the K-DINA3D analyses arose in trying to equilibrate the finite element model containing many slide surfaces to a static gravity loading (i.e., in situ stress field). This in situ stress at the repository horizon is ≈ 7.0 MPa in the vertical direction. K-DINA3D like its predessessor DINA3D are dynamic codes. Although the code documentation states that if applied slowly, static loads have been successfully applied as initial conditions to a subsequent dynamic analyses, this was not the case. Even dynamic relaxation techniques applied as well as ramping up the nodal forces representing gravity failed to stabilize the model. The version of K-DINA3D used also did not have mass damping which appeared to add to the instability. If slidesurfaces were tied together, gravity loads could successfully be applied across a slideline and equilibrium reached.

The K-DINA3D analyses was subsequently halted until such additional testing and modifications to code could be implemented.

MA. 8/30/99

I have reviewed this Scientific Notebook and find it in compliance with QAP-001. There is sufficient information regarding procedures used for conducting tests, acquiring and analyzing data so that another qualifie individual could repeat the activity

2/18/2000

Mgr-MGFE

ADDITIONAL INFORMATION FOR SCIENTIFIC NOTEBOOK #: 306

Document Date:	03/09/1999
Availability:	Southwest Research Institute® Center for Nuclear Waste Regulatory Analyses 6220 Culebra Road San Antonio, Texas 78228
Contact:	Southwest Research Institute® Center for Nuclear Waste Regulatory Analyses 6220 Culebra Road San Antonio, TX 78228-5166 Attn.: Director of Administration 210.522.5054
Data Sensitivity:	■"Non-Sensitive" □ Sensitive □"Non-Sensitive - Copyright" □ Sensitive - Copyright
Date Generated:	02/04/2000
Operating System: (including version number)	Windows NT
Application Used: (including version number)	UDEC, Version 3.0
Media Type: (CDs, 3 1/2, 5 1/4 disks, etc.)	7 CDs
File Types: (.exe, .bat, .zip, etc.)	Various
Remarks: (computer runs, etc.)	Media contains input/output files: Tunnel Thermal Mechanical Analyses