R-04-02

Äspö Pillar Stability Experiment

Final 2D coupled thermo-mechanical modelling

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Golder Associates AB

Februrary 2004

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Keywords: Äspö Pillar Stability Experiment, Spalling, JobFem, Deformation stresses.

Abstract

A site scale Pillar Stability Experiment is planned in the Äspö Hard Rock Laboratory. One of the experiment's aims is to demonstrate the possibilities of predicting spalling in the fractured rock mass.

In order to investigate the probability and conditions for spalling in the pillar "prior to experiment" numerical simulations have been undertaken. This report presents the results obtained from 2D coupled thermo-mechanical numerical simulations that have been done with the Finite Element based programme JobFem.

The 2D numerical simulations were conducted at two different depth levels, 0.5 and 1.5 m below tunnel floor.

The in situ stresses have been confirmed with convergence measurements during the excavation of the tunnel. After updating the mechanical and thermal properties of the rock mass the final simulations have been undertaken.

According to the modelling results the temperature in the pillar will increase from the initial 15.2° up to 58° after 120 days of heating. Based on these numerical simulations and on the thermal induced stresses the total stresses are expected to exceed 210 MPa at the border of the pillar for the level at 0.5 m below tunnel floor and might reach 180–182 MPa for the level at 1.5 m below tunnel floor. The stresses are slightly higher at the border of the confined hole.

Upon these results and according to the rock mechanical properties the Crack Initiation Stress is exceeded at the border of the pillar already after the excavation phase. These results also illustrate that the Crack Damage Stress is exceeded only for the level at 0.5 m below tunnel floor and after at least 80 days of heating.

The interpretation of the results shows that the required level of stress for spalling can be reached in the pillar.

Sammanfattning

Ett fullskaleförsök angående pelarstabilitet planeras vid Äspö laboratoriet. En av målsättningarna med experiment är att demonstrera möjligheten att prediktera risken för smällberg i en uppsprucken bergmassa.

För att undersöka sannolikheten och förutsättningarna till smällberg i bergmassan har prediktioner med numeriska simuleringar genomförts. Denna rapport redovisar resultaten från 2D kopplade termomekaniska numeriska beräkningar som utfördes med det finita element baserade programmet JobFem.

De 2-dimensionella simuleringarna genomfördes på två olika djup, 0,5 och 1,5 meter under sulan.

Storleken på de initiala spänningarna i bergmassan har bekräftats genom konvergens-mätningar vid uttag av experimenttunneln. Bergmassans mekaniska och termiska egenskaper har uppdaterats efter kompletterade provning.

Enligt resultaten från simuleringarna kommer temperaturen i pelaren att öka från initiala 15,2° till 58 °C efter 120 dygns värmning av den. Baserat på dessa numeriska simuleringar och de termiska tillskottsspänningarna bedöms den totala spänningen i pelarväggens yta att bli 210 MPa på 0,5 m djup och kan nå upp till 180–182 MPa 1,5 m under sulan. Spänningarna är något större i det trycksatta hålets pelarväggs yta.

Erhållna resultat tillsammans med de kunskaper om bergets hållfasthet som finns indikerar att Crack Initiation Stress kommer att överskridas redan under borrningen av deponeringshålen. Resultaten illustrerar även att Crack Damage Stress endast överskrids på 0,5 metersnivån och det efter åtminstone 80 dagars uppvärmning.

Tolkningen av resultaten ger att den spänningsnivå som krävs för att initiera smällberg i pelaren kommer att uppnås.

Contents

1 Introduction

1.1 Background

SKB is planning a full-scale rock mechanics experiment. The experiment will study pillar stability. The main objectives with the pillar stability experiment are summarized in /Andersson, 2003/:

1. Demonstrate the capability to predict spalling in a fractured rock mass.
2. Demonstrate the effect of backfill (confining pressure) on the rock mass response.
3. Comparison of 2D and 3D mechanical and thermal predicting capabilities.

The experiment will be performed in the Äspö Hard Rock Laboratory (HRL) at level –450 m, see Figure 1-1. A new tunnel called TASQ has been excavated with start from the TBM-tunnel (or A-tunnel) and from the floor of the new tunnel two vertical holes will be drilled. The pillar between the holes will be heated and the additional thermal stresses shall force the rock in the holes walls to spall.

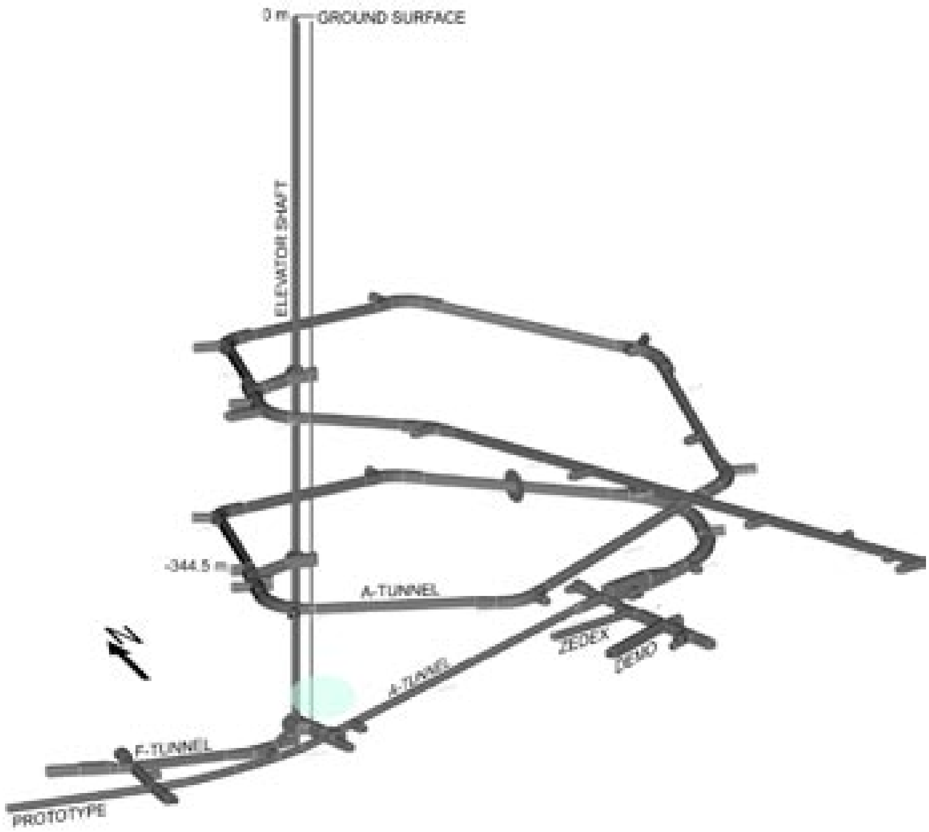

Figure 1-1. *3D view of the tunnel-system. Localization of the of the experiment volume.*

1.2 Objective

Coupled 2D thermo-mechanical simulations have been conducted prior to the excavation of the TASQ tunnel to determine the optimal layout for the experiment. Input data for this modelling was based on preliminary mechanical and thermal properties assigned to the rock mass that are estimated in /Staub et al. 2003/. The results of the preliminary 2D modelling are presented in /Fredriksson et al. 2003/. The preliminary predictions of the thermo-induced stresses made by simulations with Flac3D are presented by /Wanne and Johansson, 2003/.

After the excavation of the tunnel and the drilling of 15 pilot holes, complementary samples of rock have been collected and supplementary laboratory testing has been conducted. The updated thermal and mechanical rock mass properties are presented in /Staub et al. 2004/.

Complementary 2D coupled thermo-mechanical simulations have been run using the updated parameters as input data and the results are presented in this report. Complementary 3D modelling has also been conducted in 3D using FLAC3D and the PFC software. The results are presented in /Wanne et al, 2004/.

2 2D coupled thermo-mechanical modelling

This section presents the final results of the coupled 2D thermo-mechanical modelling with the numerical code JobFem. The modelling has been conducted in order to determine the temperatures and level of stresses reached in the pillar as a function of heating time.

2.1 Modelling strategy

The aim of the modelling is to predict the thermo-induced stresses and the resulting total stresses in the pillar. The predictions of thermo-induced stresses were made in 2D with the numerical code JobFem. Two horizontal sections at 0.5 m and 1.5 m depth below the tunnel floor were designed as a reference for comparisons between results obtained in 2D and 3D.

A short presentation of JobFem is presented in section 2.1.1. The assumptions made for this project and the input parameters are presented in section 2.1.2 and 2.2.

2.1.1 The numerical code: JobFem

The numerical code JobFem is based on the Finite Element Method. The programme has been available for 20 years and used for different applications in the construction sector. The module for coupled thermo-mechanical modelling has been developed and validated in the frame of the hot water cavern project in Avesta /Rehbinder and Stille, 1985/.

The quality and relevance of the results are related to the assumptions made on the rock mass behaviour and properties. The agreement of the theoretical thermo-induced stresses to the measured stresses increases in correlation with the knowledge of rock mass fracturing and properties.

2.1.2 Set-up of the model for the experiment

Heat flow and temperature induced stresses have been calculated under plain strain conditions. The effect of the heater is set to 200 W/m, with a maximal temperature of 200°C specified at the heaters.

The temperature increase and thermo-induced stresses are monitored at different stages of the modelling:

- before heating after excavation of the holes, and after applying the confining stress of 0.8 MPa,
- during heating after 30, 60, 90 and 120 days of heating.

The total stresses at each stage are achieved by adding for each node of the element mesh stress values after excavation to thermo-induced stresses.

Three types of input parameters are required to build the model:

- mechanical and thermal properties of the rock mass,
- stresses after excavation,
- geometry and layout of the experiment.

The used finite-element mesh is shown for the whole model in Figure 2-1 and a detail zoomed around the holes in Figure 2-2. The sizes of the elements around the holes are 1/20 of the diameter of the holes.

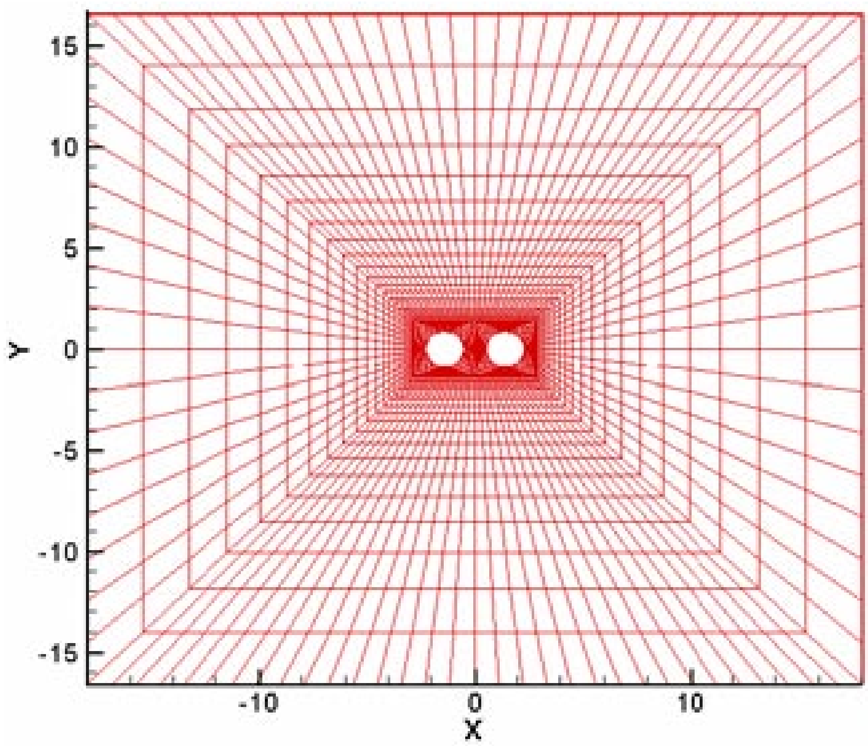

Figure 2-1. *The Finite-element mesh.*

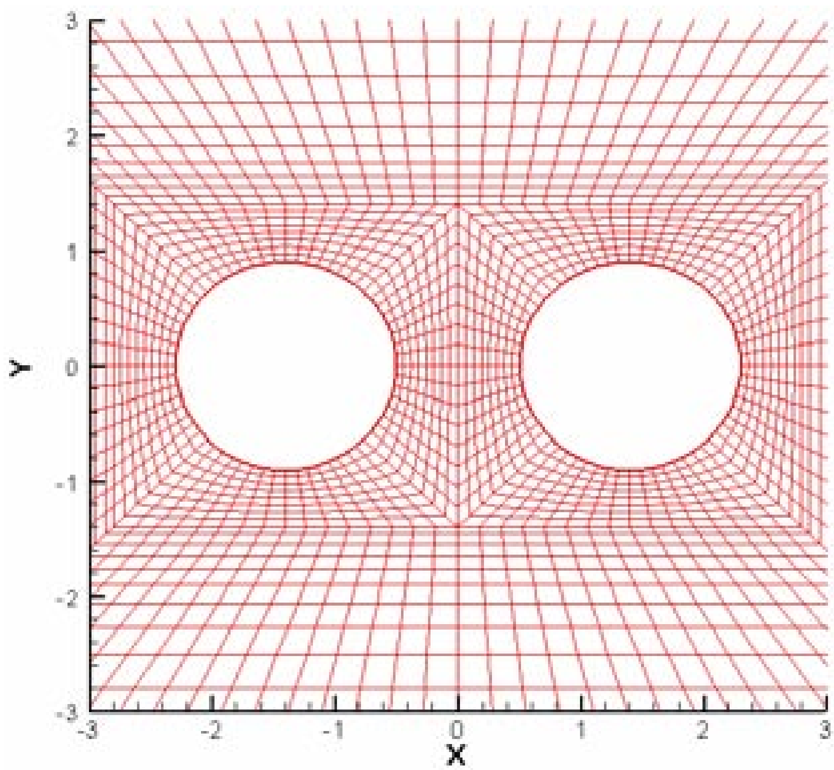

Figure 2-2. *Detail of the finite-element mesh around the deposition holes.*

2.2 Material data

After supplementary testing on cores collected in pilot boreholes drilled in the experiment area and back-analysis of convergence measurements when the tunnel was excavated the rock mass properties were updated. The parameters finally chosen for the experiment are listed in Table 2-1.

In the analysis presented in this report the modulus of the rock mass, 55 GPa, has been used.

The values of the in situ stresses used for the modelling are listed in Table 2-2. They are somewhat different to the ones presented in /Staub et al. 2004/ depending on the fact that the assessment of the in-situ stress field was revised at a late stage. The change in the stress tensor is though so small that it does not have any practical effect on the final results.

2.3 Stresses after excavation

The calculations of stresses along the new tunnel are achieved with the 3D numerical model built with Examine3D. Table 2-2 lists the stress tensors that have been used for the calculations of the stresses around the new tunnel. Stress values along the tunnel and in the rock mass around the pillar are monitored at two different stages of excavation: after tunnel excavation, and after drilling of the deposition holes.

Table 2-1. Input mechanical and thermal properties for the rock mass.

Parameter	Value	Unit
Young's modulus, intact rock	76	GPa
Young's modulus, rock mass	55	GPa
Poisson's ratio, intact rock	0.25	–
Poisson's ratio, rock mass	0.26	–
Thermal conductivity	2.60	W/m, K
Volume heat capacity	2.10	MJ/m^3, K
Linear expansion	7.0E–06	l/K
Density	2.731	g/cm^3
Initial temperature of the rock mass	15	°C
Crack initiation stress	121	MPa
Crack damage stress	204	MPa

Table 2-2. In-situ stresses.

σ1 [MPa]	σ2 [MPa]	σ3 [MPa]	Trend [Äspö 96]	Dip [°]
27			310	07
	15		090	83
		10	208	00

The coordinates of the nodes of the element mesh of the 2D sections modelled in JobFem have been imported to the Examine3D model in order to obtain the stress tensor at each node of the element mesh of both horizontal 2D sections. These stress values were then transformed to fit a 2D model and the recalculated values are the one used for the evaluation of total stresses after heating. The procedure is to add these stress values to the thermo-induced stresses monitored during the JobFem's modelling.

2.4 Layout of the experiment

The geometry of the pillar and the layout of heaters and Acoustic Emission (AE) sensors are illustrated in Figure 2-3. A confinement pressure of 0.8 MPa is achieved with water in one hole. The geometry of the holes has been optimized on the basis of stress calculations in Examine3D. The position of the AE sensors is optimal for the monitoring of microseismic events. The position of the heaters is based on preliminary modelling results obtained with the 2D numerical programme JobFem, see /Fredriksson et al. 2003/.

The heaters used for modelling present the following characteristics:
∅: 25 mm; effect: 200 W/m.

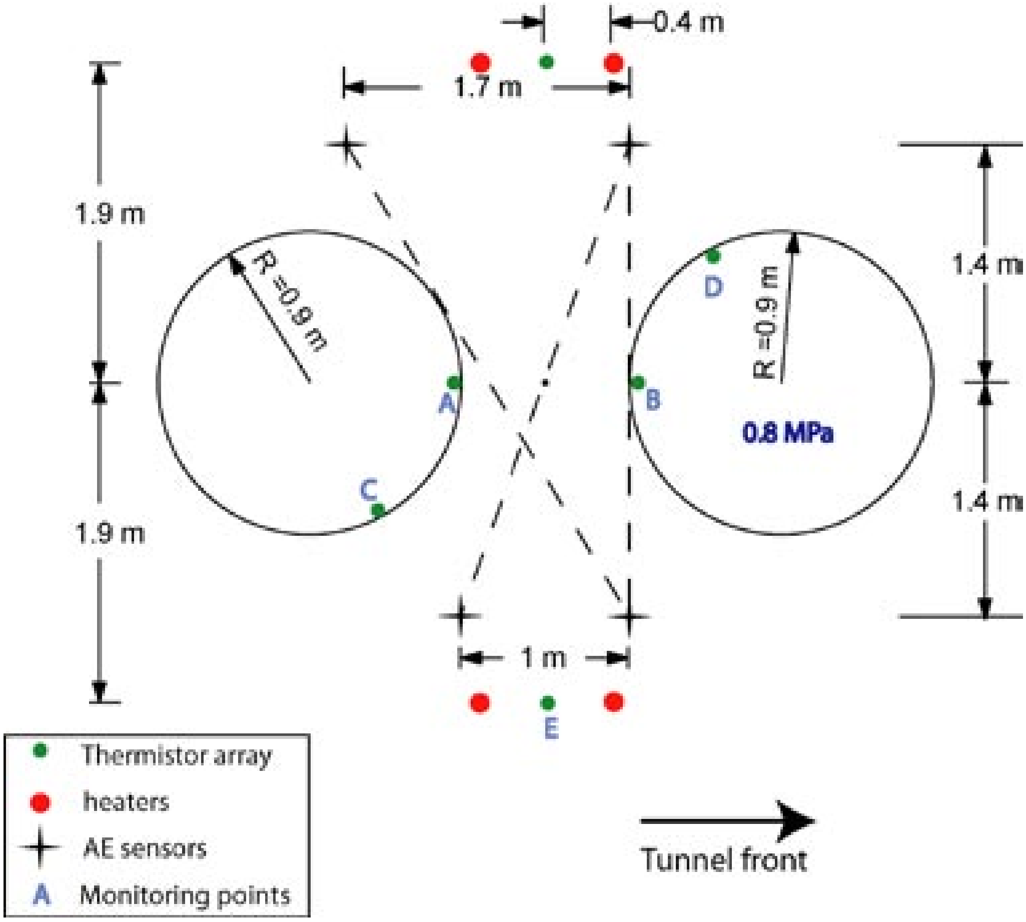

Figure 2-3. *Experiment layout.*

2.5 Modelling results

The results are presented at the two depth levels, named in the graphs level a (1.5 m below the tunnel floor) and level b (0.5 m below the tunnel floor).

2.5.1 Analysis of the temperature

The evolution of temperature is illustrated as contour figures at different stages of the experiment for both depth levels in Appendix A.

Figure 2-4 illustrates the development of temperature with time in monitoring points located according to Figure 2-3. The difference of temperature observed between both holes is caused by water used for confinement in the front hole (points B and D). Point E reflects the evolution of temperature at the heaters.

The evolution of temperature in the pillar during the experiment is also simulated. The results are presented as sections across the pillar, from x = –0.5 (hole with air) to x = 0.5 m (hole with confining pressure). 20 measurement points are extracted along this 1 m "fictive" line and the data at each point for the different stages of heating are plotted in Figure 2-5.

As illustrated in Figure 2-5 temperatures reached at different stages of modelling are identical for both depth levels. This is an implication of the plain strain assumptions made on the model: the tunnel will have no effect on the temperature flow in the rock mass. However the tunnel has a strong influence on the stress level, and the stresses reached in the section closed to the tunnel floor (level b) are very high, see the following section.

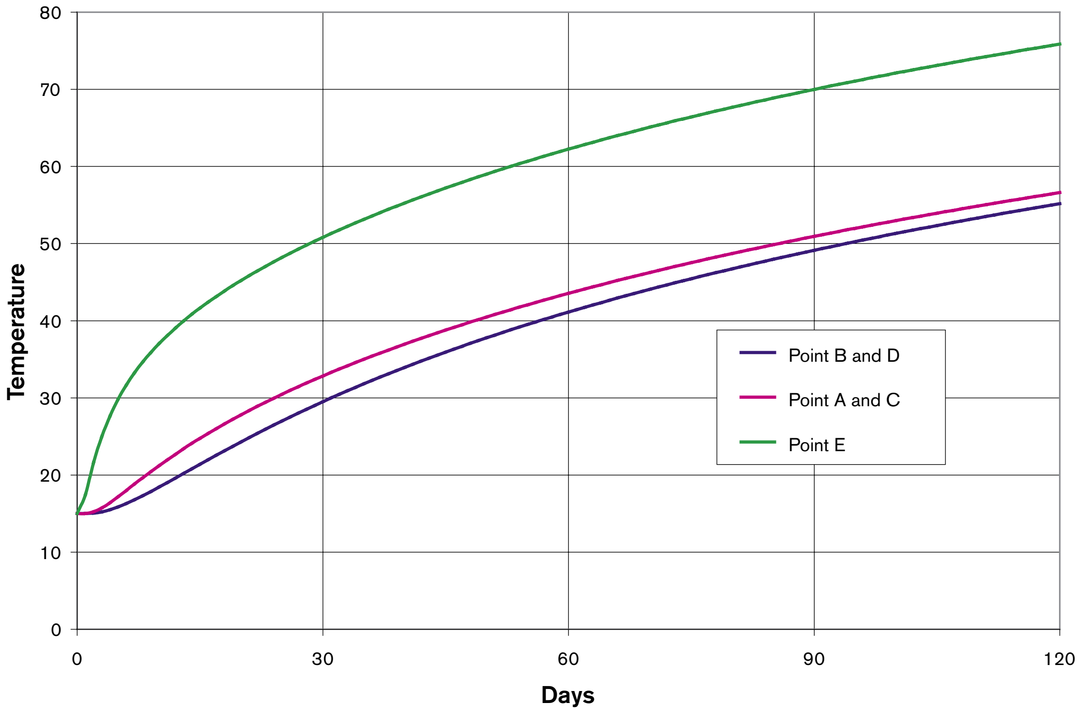

Figure 2-4. *Development of the temperature in monitoring points as a function of time.*

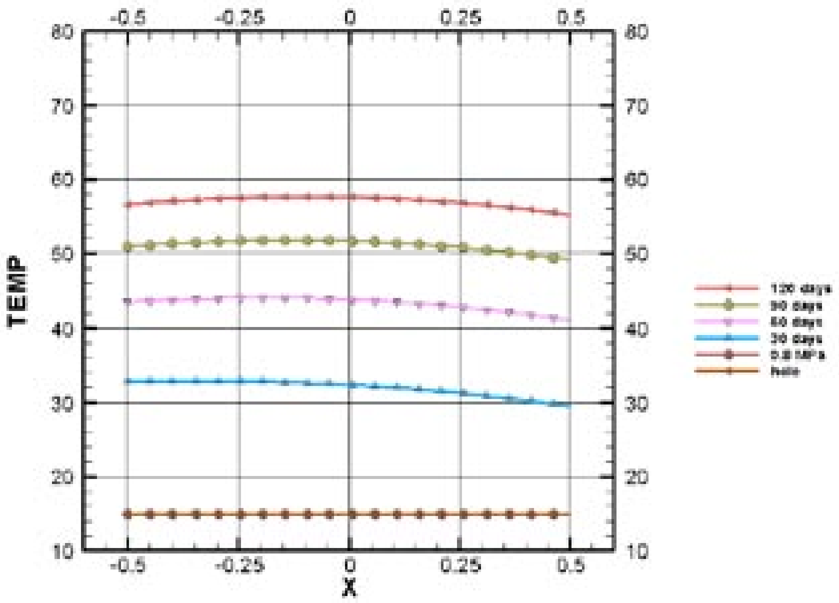

Figure 2-5. *Temperature monitored in the pillar at different stages of modelling, depth levels a and b.*

2.5.2 Analysis of the stresses

The evolution of total major stresses at different stages of the experiment is illustrated as contour figures for both depth levels in Appendix B. The evolution of the principal total stress in the pillar is illustrated as a function of time for level b (0.5 m depth) in Figure 2-6, and for level a (1.5 m depth) in Figure 2-7. X=0.5 m represents the border of the confined hole.

In order to determine if spalling might occur in the pillar the simulated total stresses have been compared to the Crack Initiation Stress (CIS) and the Crack Damage stress (CDS) which have been estimated to be respectively 121 MPa and 204 MPa.

A graphical presentation is illustrated in Appendix C as contour maps where the scale grading is based on the values of CIS and CDS. Total stresses in the border of the pillar exceed the CIS after excavation of the holes at the depth level b and after 30 days of heating for the depth level a. At the end of the simulated experiment (120 days of heating) the total stresses exceed the CIS all through the pillar for both depth levels.

These graphs show also that the CDS is exceeded in only one case, after 120 days of heating for the depth level b (0.5 m below the tunnel floor). The CDS is not exceeded at any stage of the simulated experiment at level b (1.5 m below the tunnel floor).

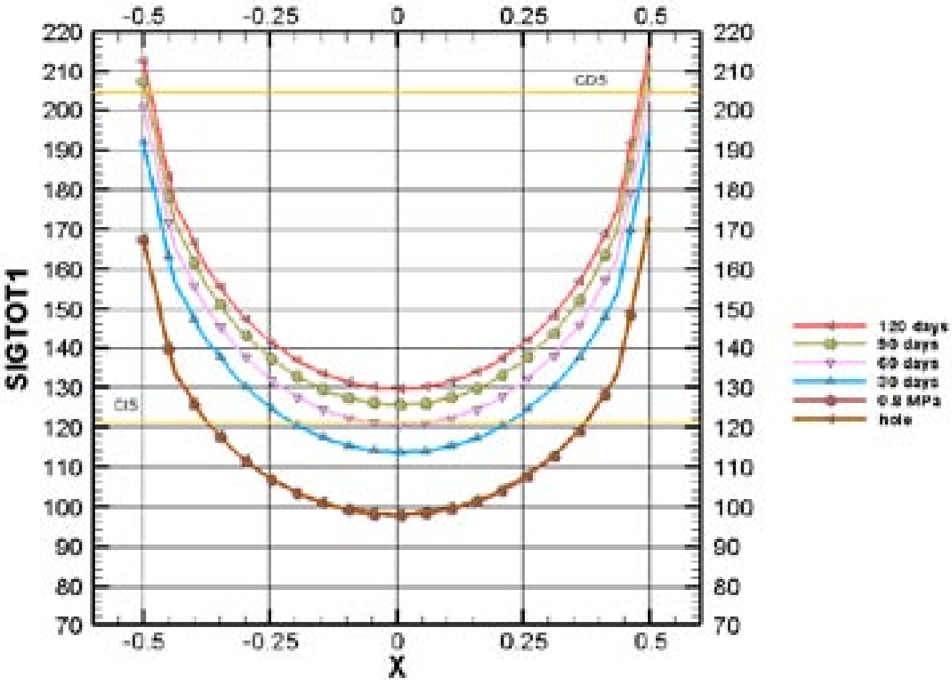

Figure 2-6. *Total major stress at different stages of the modelling, level b, 0.5 m below the floor.*

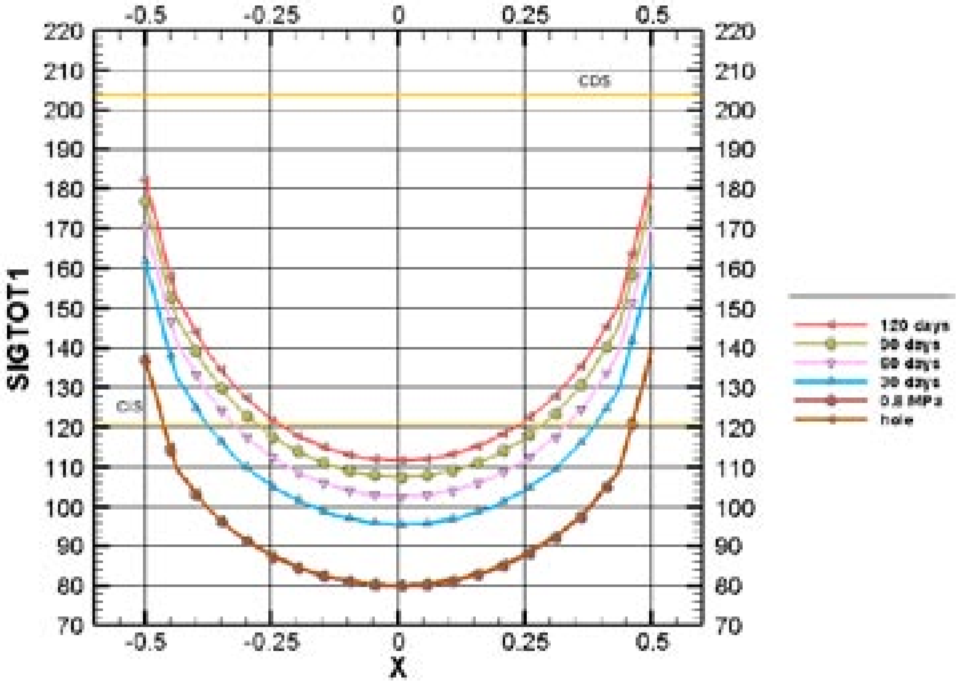

Figure 2-7. *Total major stress at different stages of the modelling, level a, 1.5 m below the floor.*

2.5.3 Analysis of the deformation in the pillar

The deformation vector related only to the 2D numerical simulations has also been studied. In order to investigate the evolution of deformation with time the vector value has been extracted at 24 points, located every 15° at the border of the boreholes (Figure 2-8).

The contour plots illustrating the absolute value of the displacement vector and its direction are presented before heating and during the different stages of heating in Appendix D.

The values of the vector deformation have been extracted at the different stages of the experiment for both depth levels. The vector deformation calculated and represented in these figures is only accounting for the deformation related to thermal stresses. As the temperature evolution and temperature stresses are equivalent at both depth levels in the 2D model, the value of the vector deformation is the same at both depth levels at each stage of the experiment. The results are illustrated in Figure 2-9 in the unconfined (a) and confined holes (b).

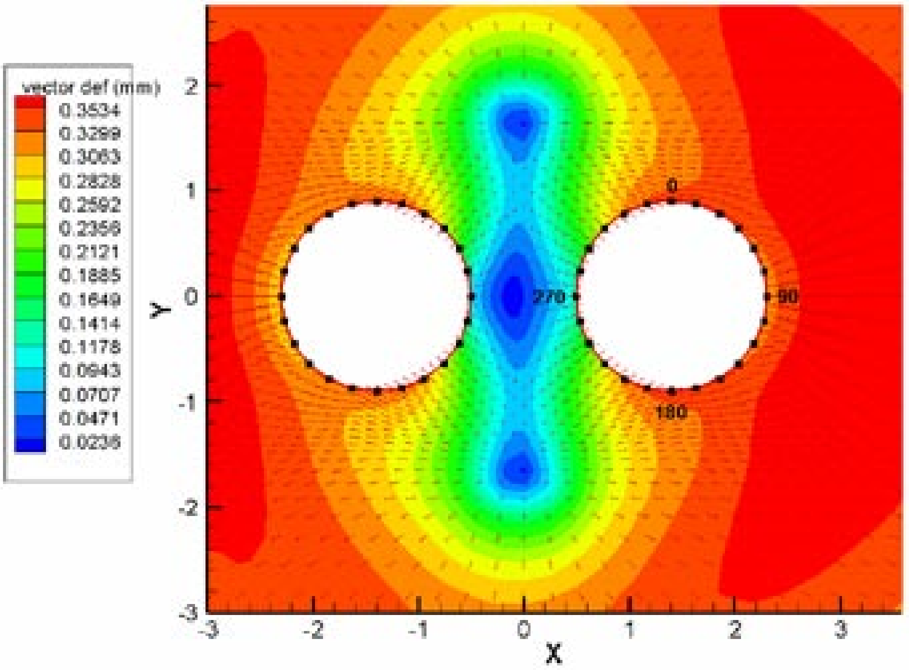

Figure 2-8. Vector deformation. Localisation of the extraction points around the holes.

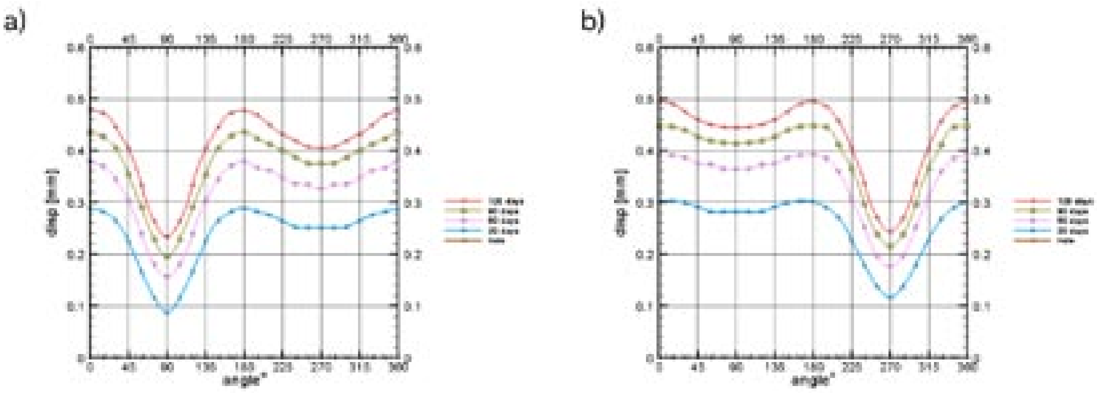

Figure 2-9. Vector deformation at different stages of heating for both depth levels. a) unconfined hole; b) confined hole.

The most important displacements occur at the outer border of the deposition holes and after 120 days of heating the maximal deformation value due to thermal stresses is 0.5 mm. In the inner walls of the holes the displacement value are minimum and reach 0.25 mm after 120 days of heating.

2.5.4 Extension of the spalling zone

The spalling can be expected to take place where the difference between the major stress and the minor stress is greater than the Crack Initiation Stress (CIS).

A graphical presentation of the spalling zone is illustrated in Appendix E. The depths of penetration in the rock of the spalling zones are also shown in table 2-3. After 120 days of heating the spalling zone will have a depth of 0.20 m at 0.5 m below the tunnel floor and 0.12 m at 1.5 m below the tunnel floor.

Table 2-3. Depth of penetration of the spalling zone.

	Depth of penetration of the spalling zone 0.5 m below the tunnel floor	Depth of penetration of the spalling zone 1.5 m below the tunnel floor
After axcavation	0.07 m	0.03 m
After 30 days of heating	0.13 m	0.06 m
After 60 days of heating	0.16 m	0.09 m
After 90 days of heating	0.19 m	0.10 m
After 120 days of heating	0.20 m	0.12 m

3 Conclusions

A final 2D modelling based on updated input mechanical and thermal parameters for the rock mass has been conducted and the range of temperature, total major and minor stresses as well as deformation reached in the pillar during heating have been analyzed.

The final results of the 2D-modelling point out that the level of stress required in the pillar to initiate spalling should be reached.

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Temperature distribution

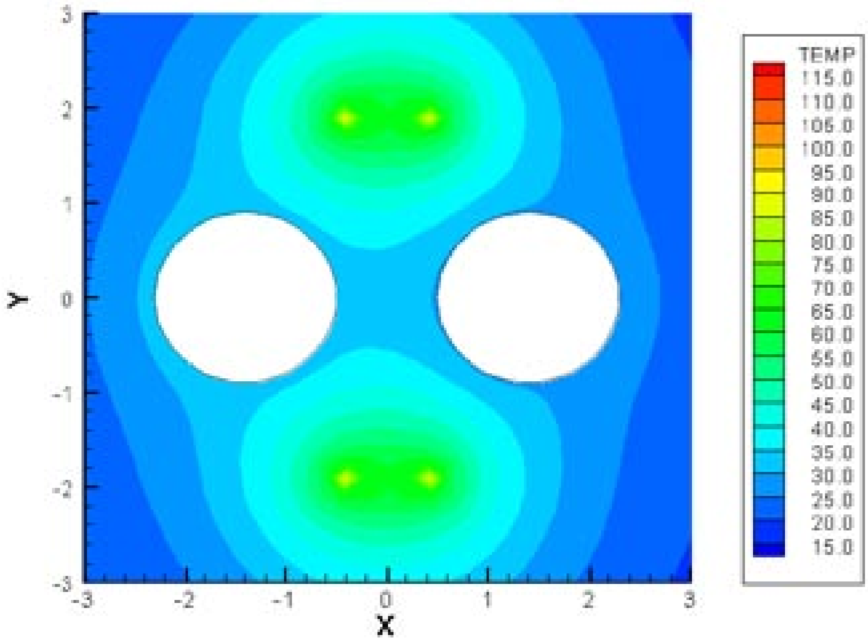

Figure A-1. *Temperature distribution after 30 days, °C.*

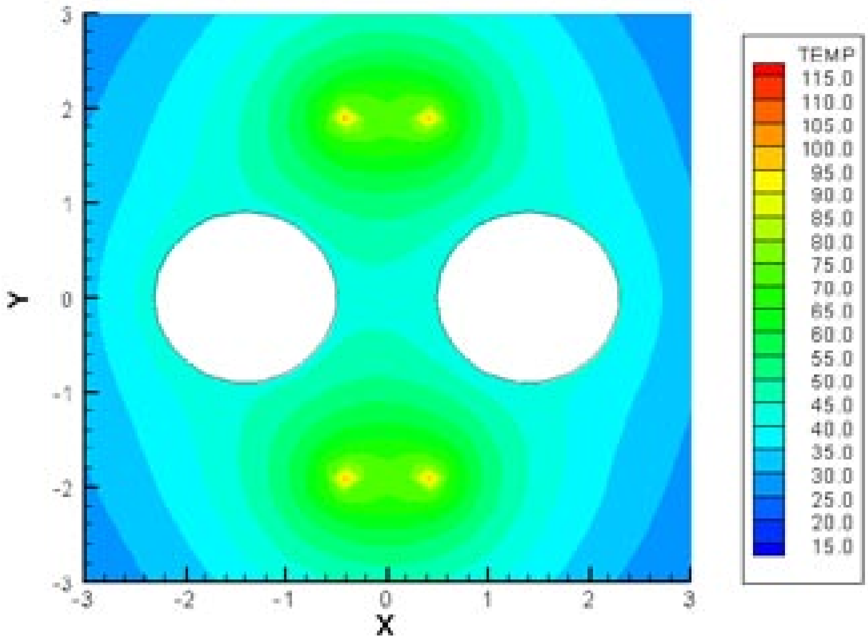

Figure A-2. *Temperature distribution after 60 days, °C.*

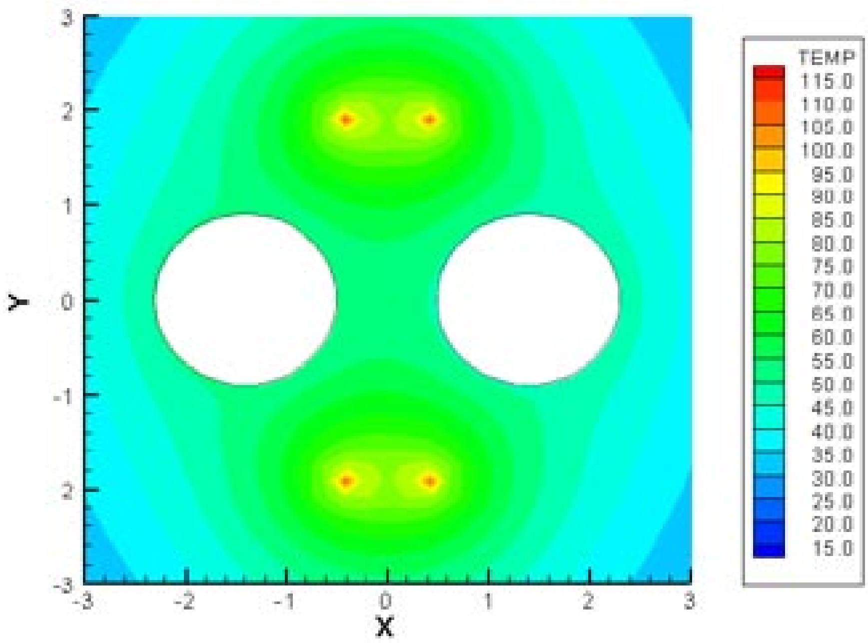

Figure A-3. *Temperature distribution after 90 days, °C.*

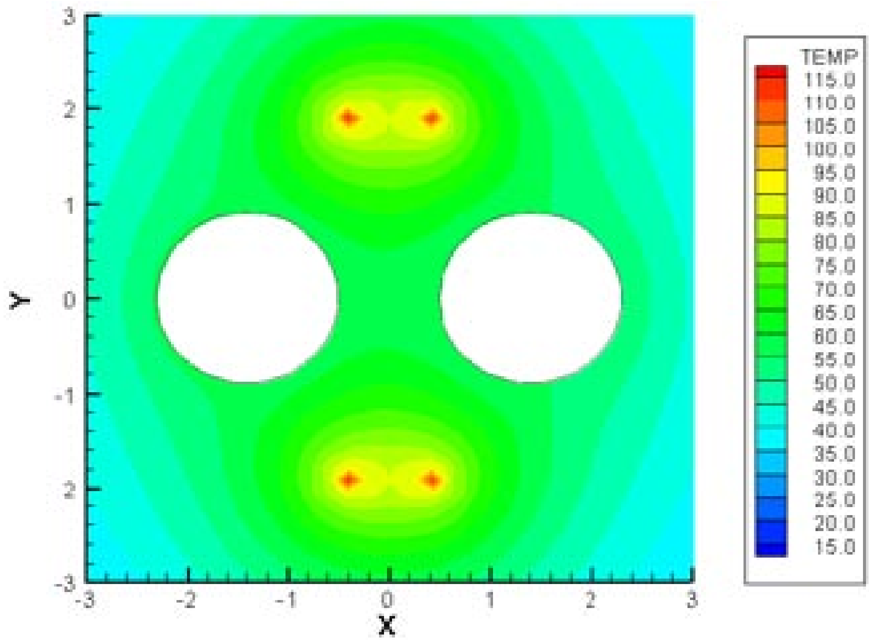

Figure A-4. *Temperature distribution after 120 days, °C.*

Major stresses

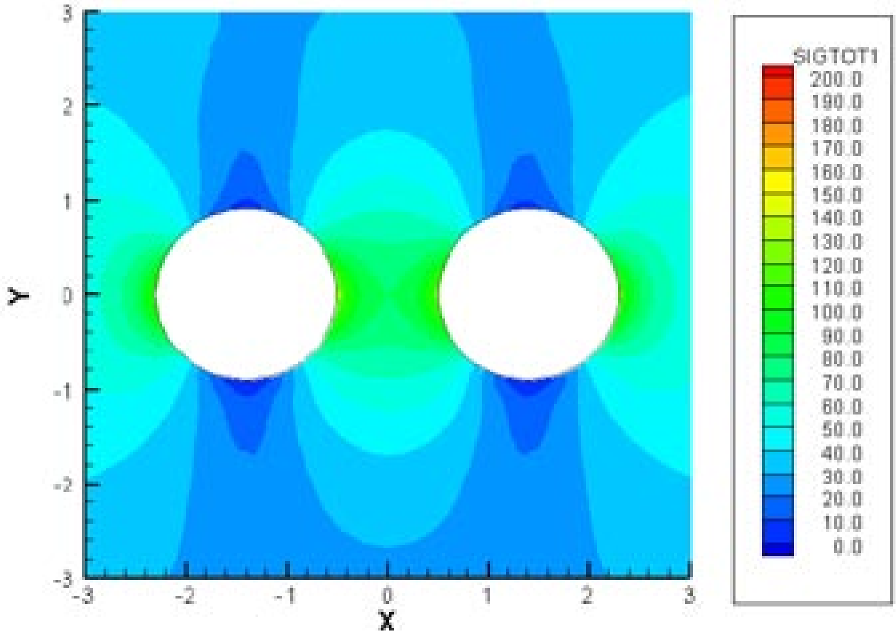

Figure B-1. *Major stresses 1.5 m below the tunnel floor before start heating.*

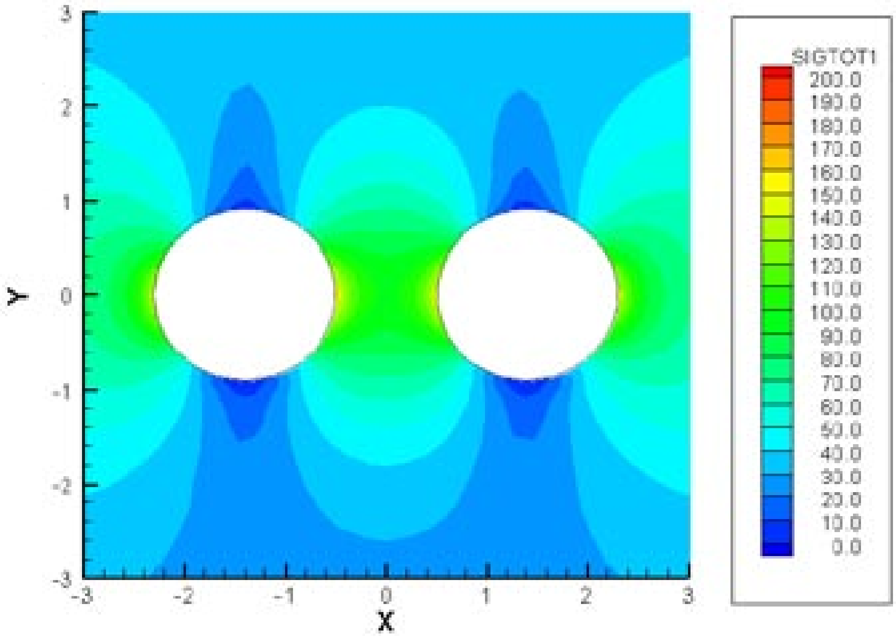

Figure B-2. *Major stresses 0.5 m below the tunnel floor before start heating.*

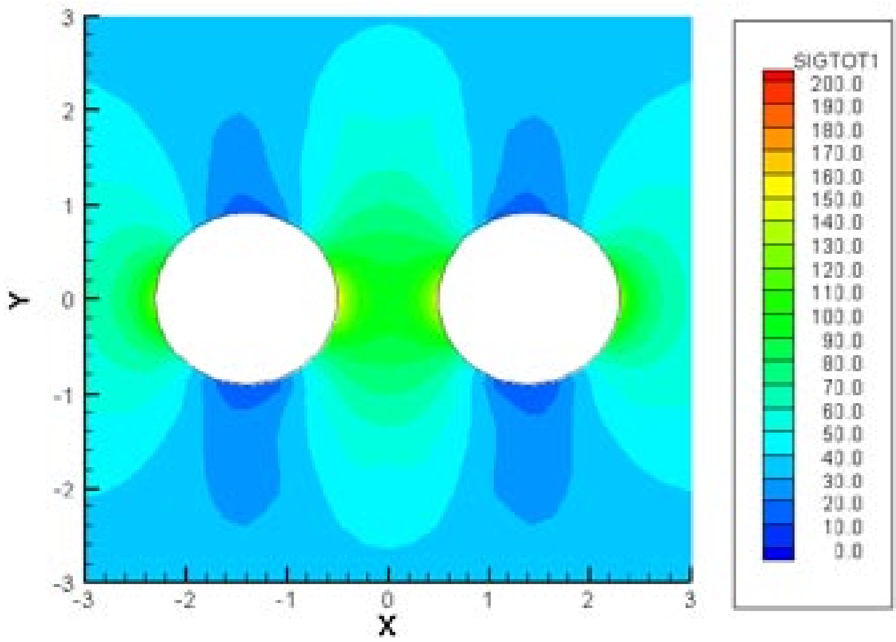

Figure B-3. *Major stresses 1.5 m below the tunnel floor after 30 days.*

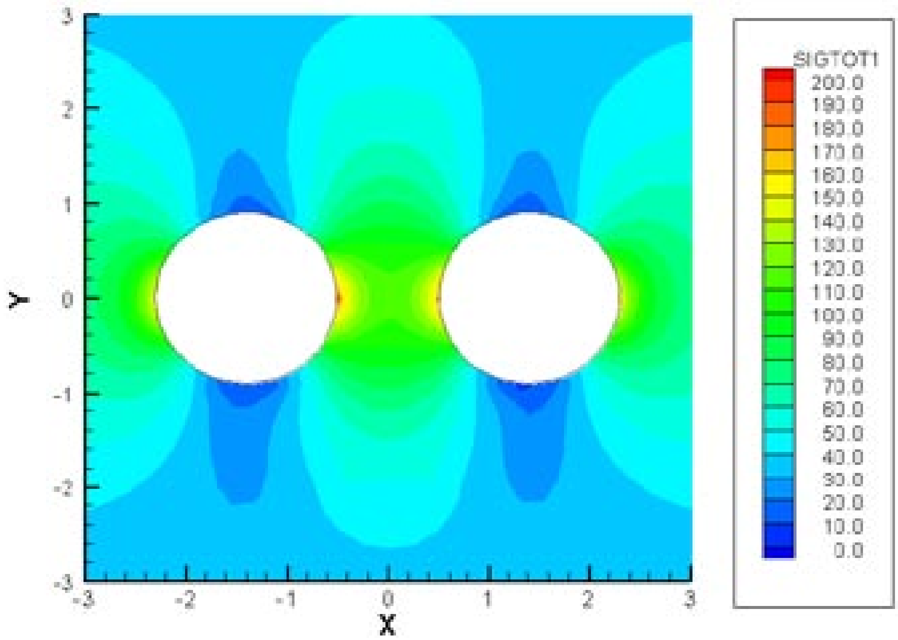

Figure B-4. *Major stresses 0.5 m below the tunnel floor after 30 days.*

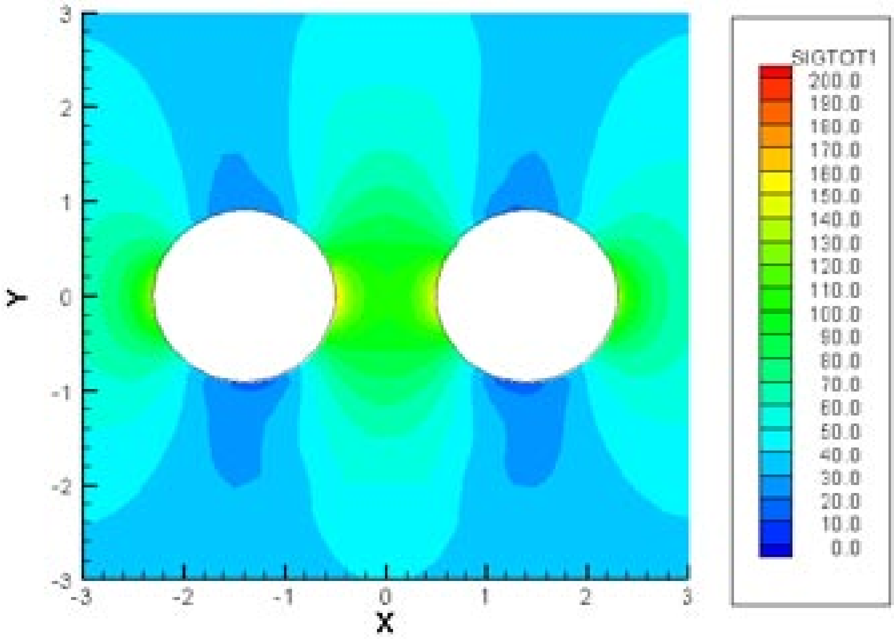

Figure B-5. *Major stresses 1.5 m below the tunnel floor after 60 days.*

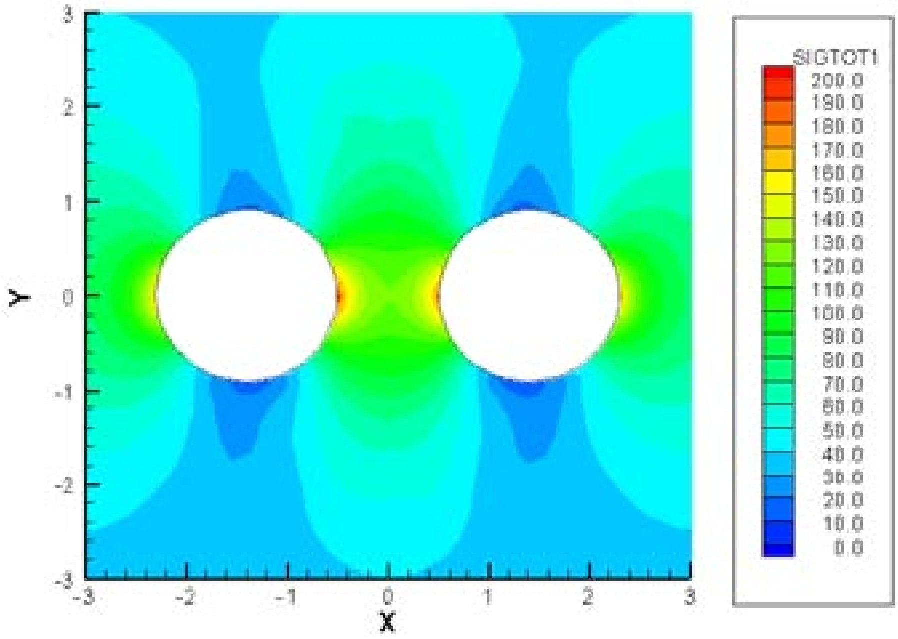

Figure B-6. *Major stresses 0.5 m below the tunnel floor after 60 days.*

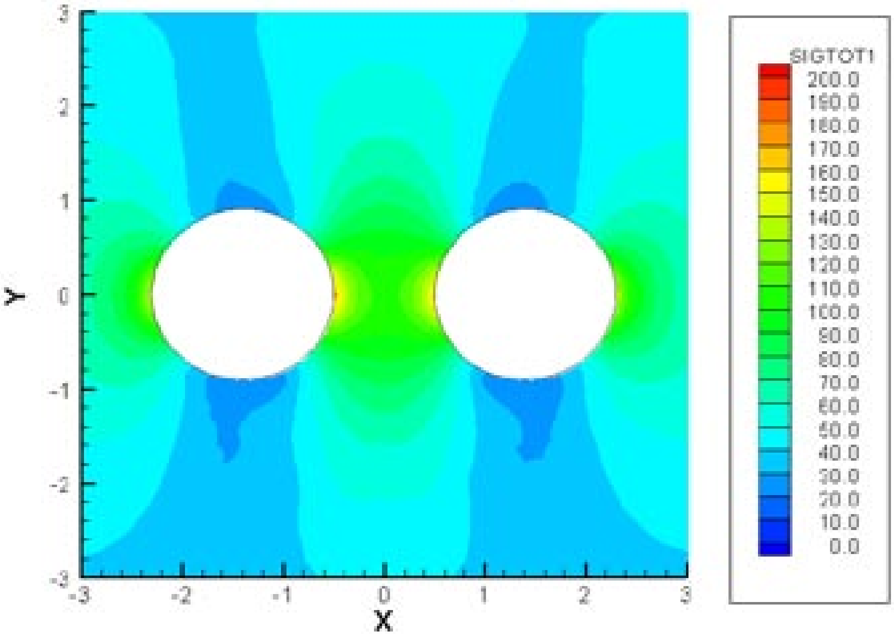

Figure B-7. *Major stresses 1.5 m below the tunnel floor after 90 days.*

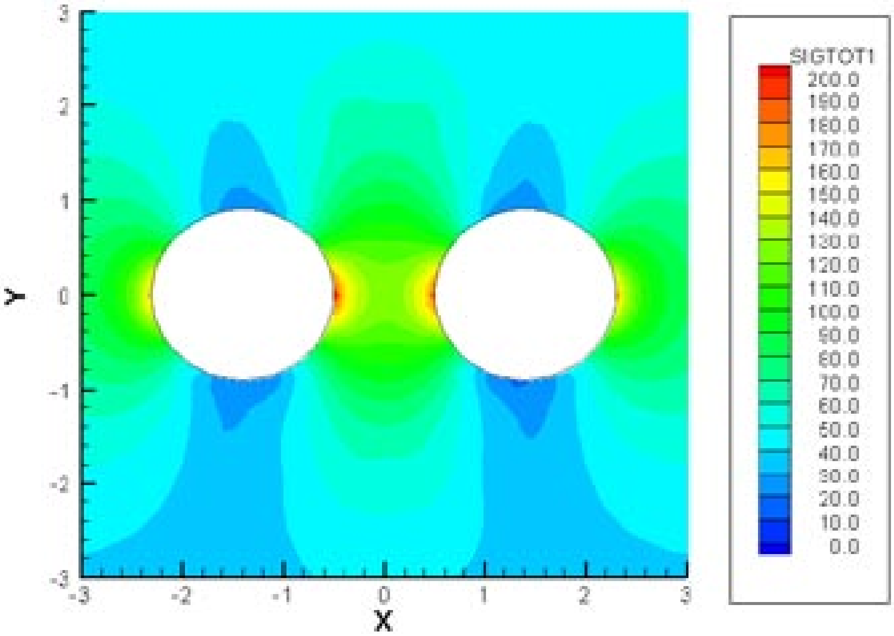

Figure B-8. *Major stresses 0.5 m below the tunnel floor after 90 days.*

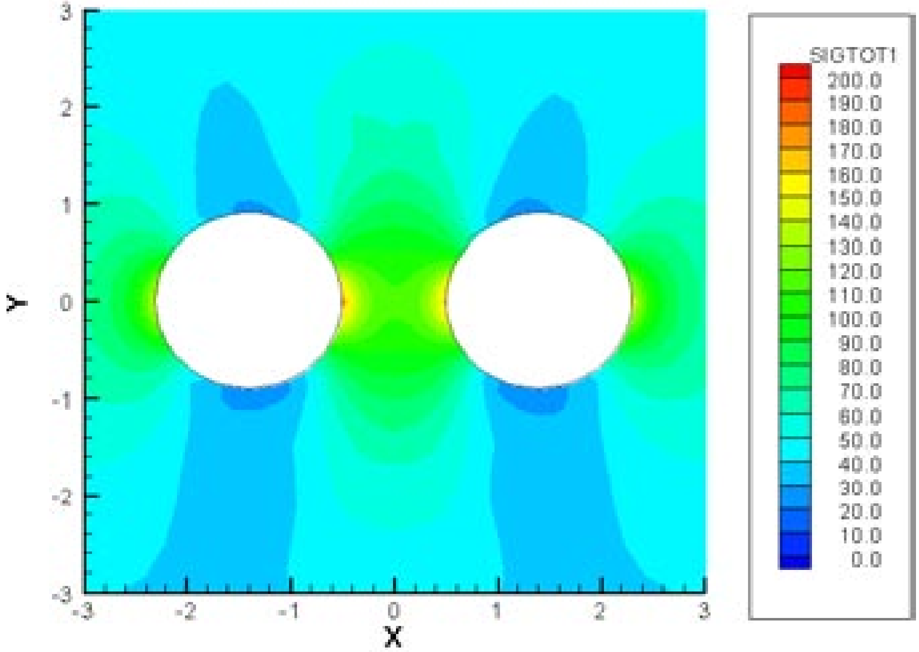

Figure B-9. *Major stresses 1.5 m below the tunnel floor after 120 days.*

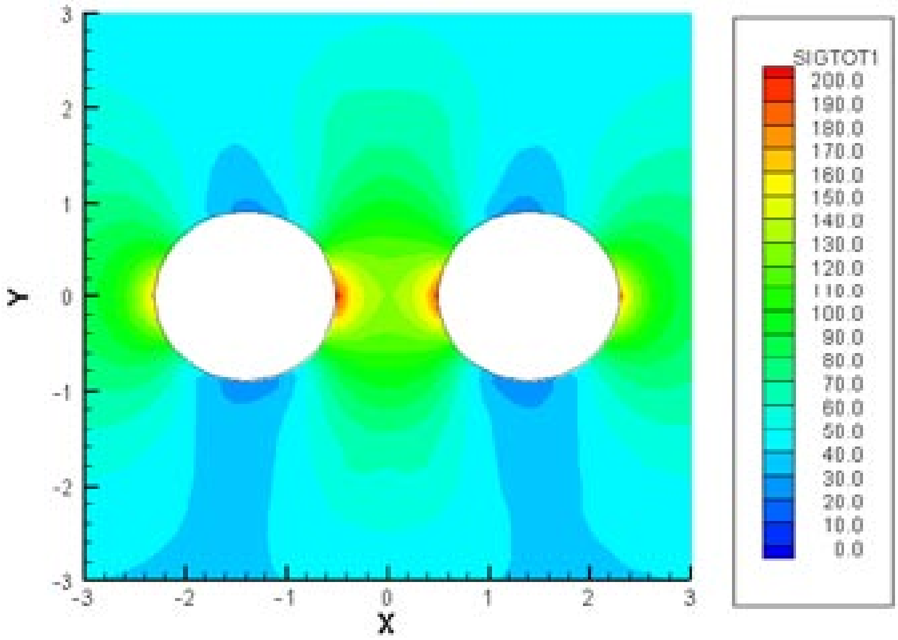

Figure B-10. *Major stresses 0.5 m below the tunnel floor after 120 days.*

Appendix C

Major stresses compared with crack initiation stress and crack damage stress

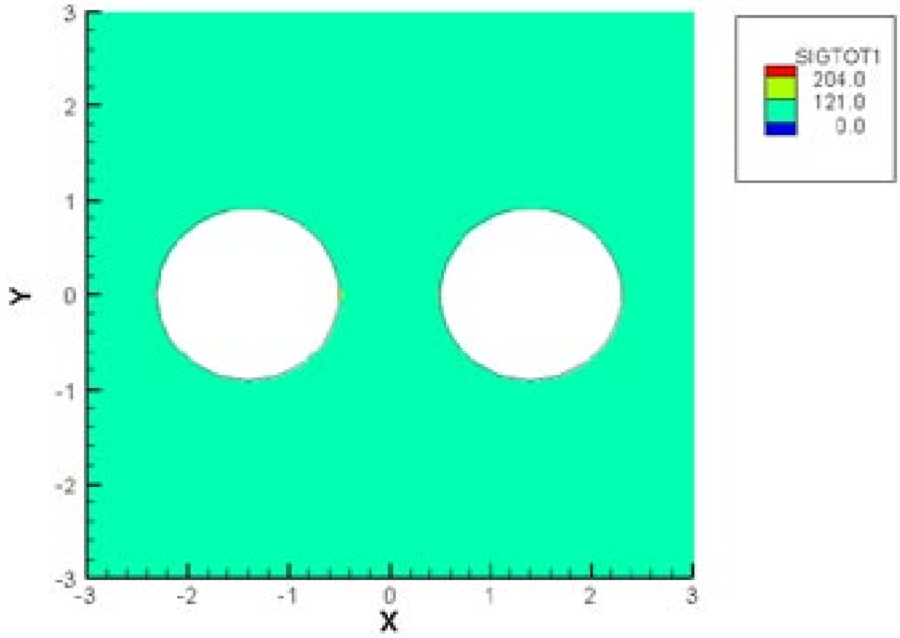

Figure C-1. *Major stresses 1.5 m below the tunnel floor before start heating.*

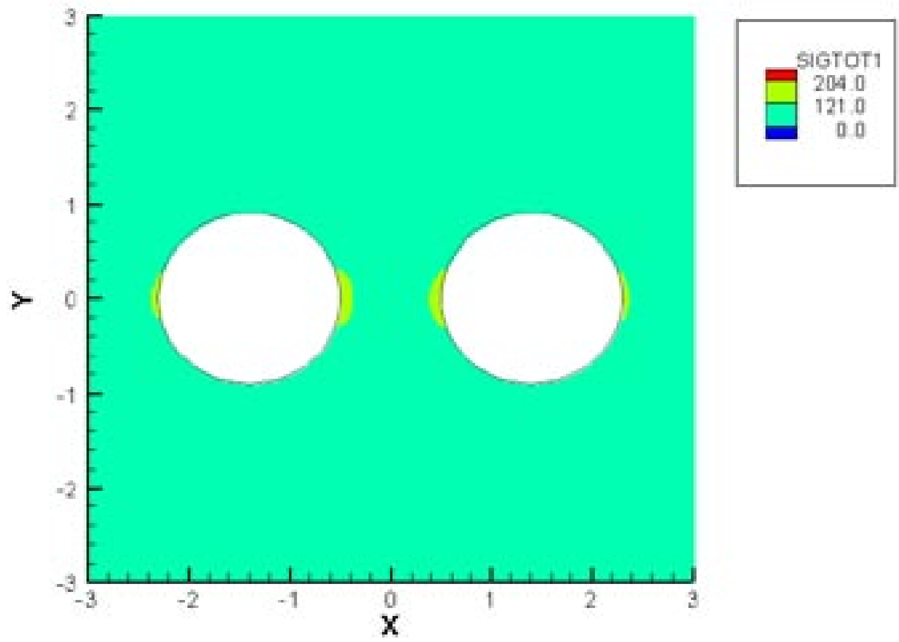

Figure C-2. *Major stresses 0.5 m below the tunnel floor before start heating.*

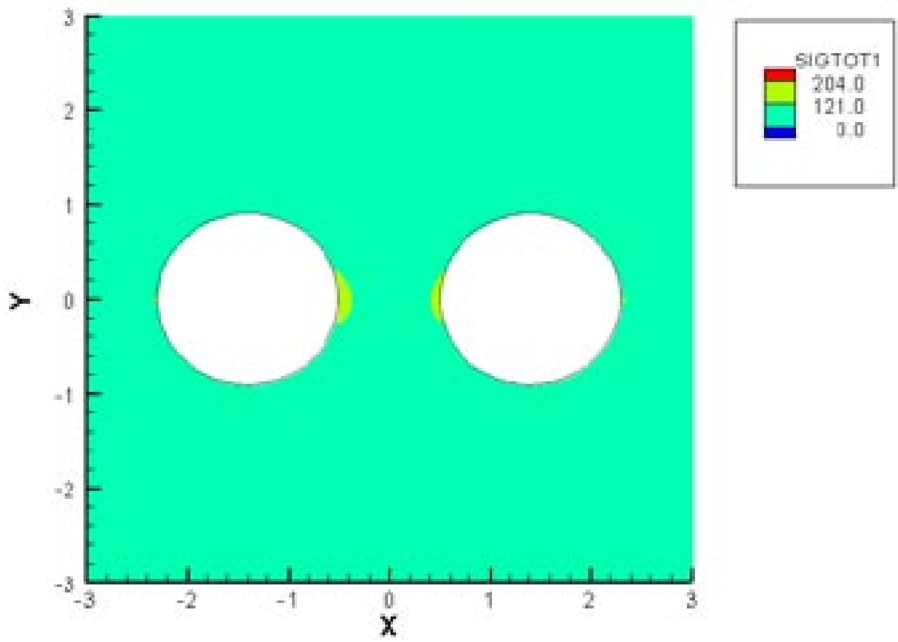

Figure C-3. *Major stresses 1.5 m below the tunnel floor after 30 days.*

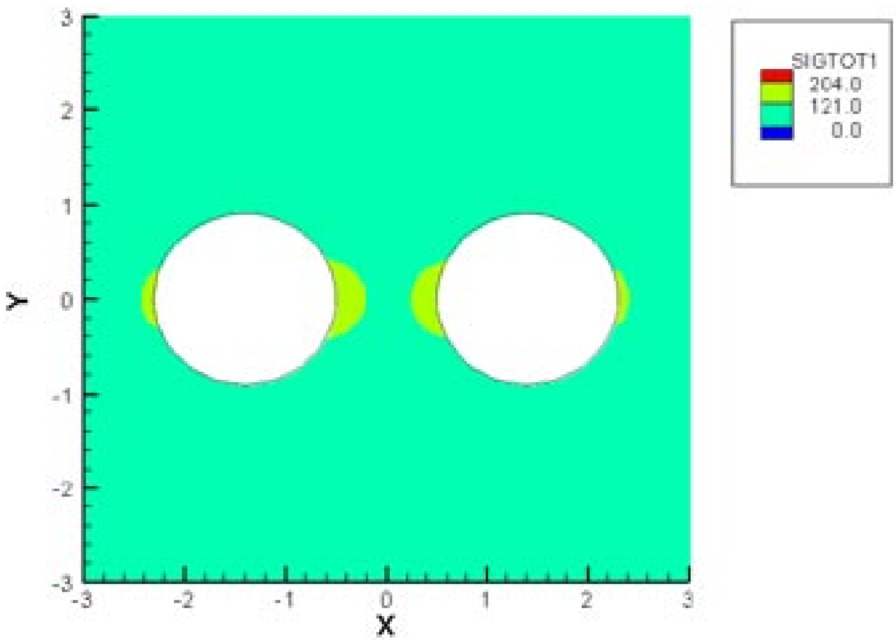

Figure C-4. *Major stresses 0.5 m below the tunnel floor after 30 days.*

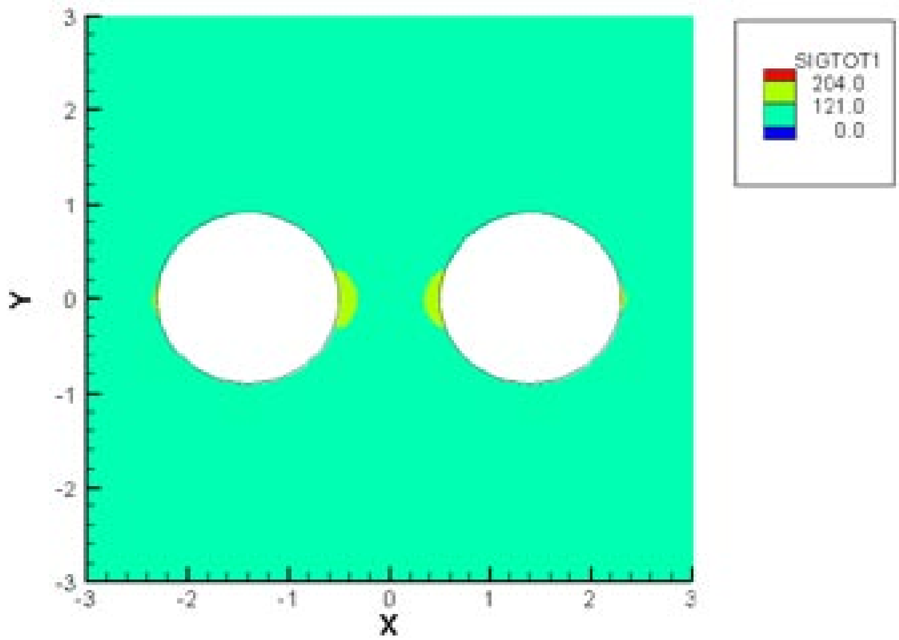

Figure C-5. *Major stresses 1.5 m below the tunnel floor after 60 days.*

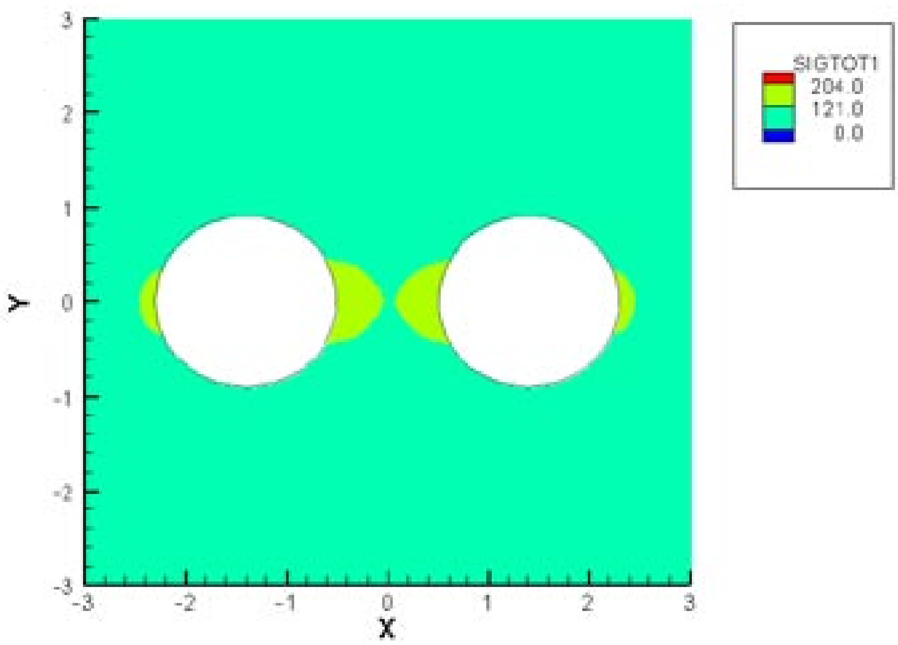

Figure C-6. *Major stresses 0.5 m below the tunnel floor after 60 days.*

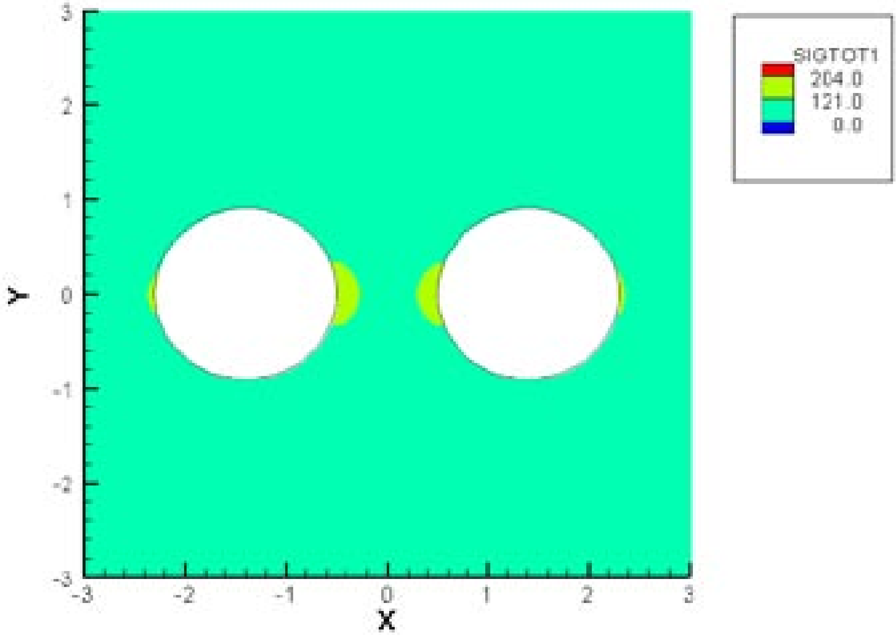

Figure C-7. *Major stresses 1.5 m below the tunnel floor after 90 days.*

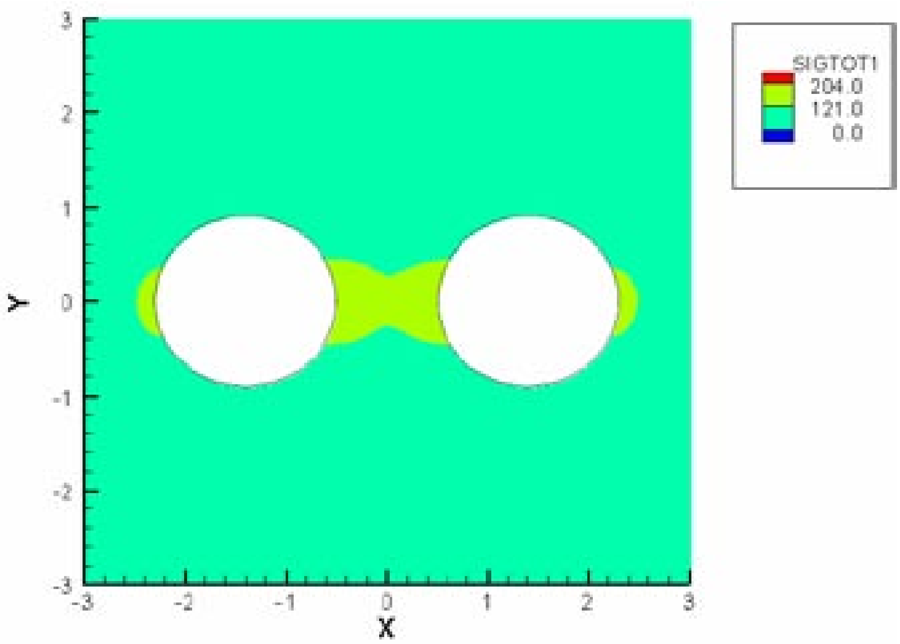

Figure C-8. *Major stresses 0.5 m below the tunnel floor after 90 days.*

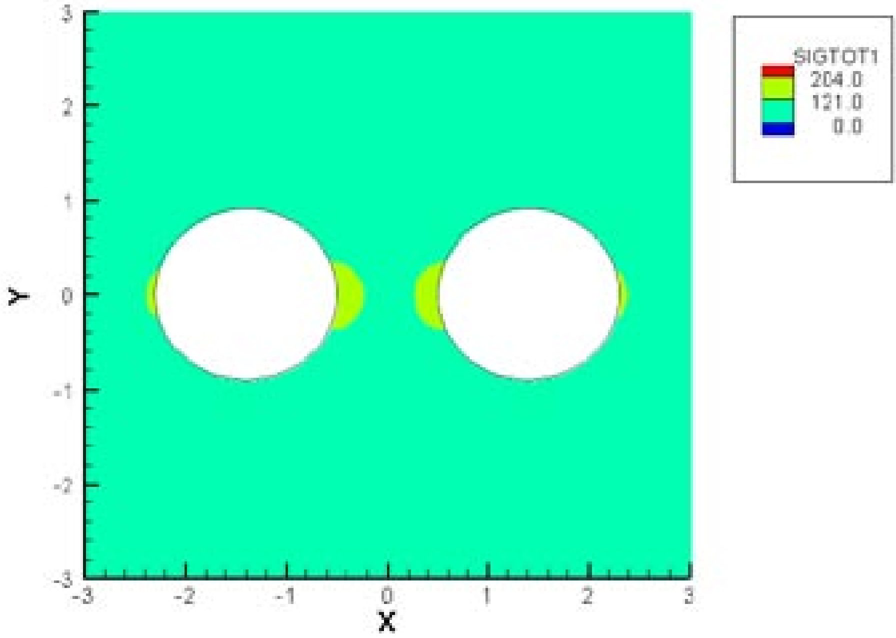

Figure C-9. *Major stresses 1.5 m below the tunnel floor after 120 days.*

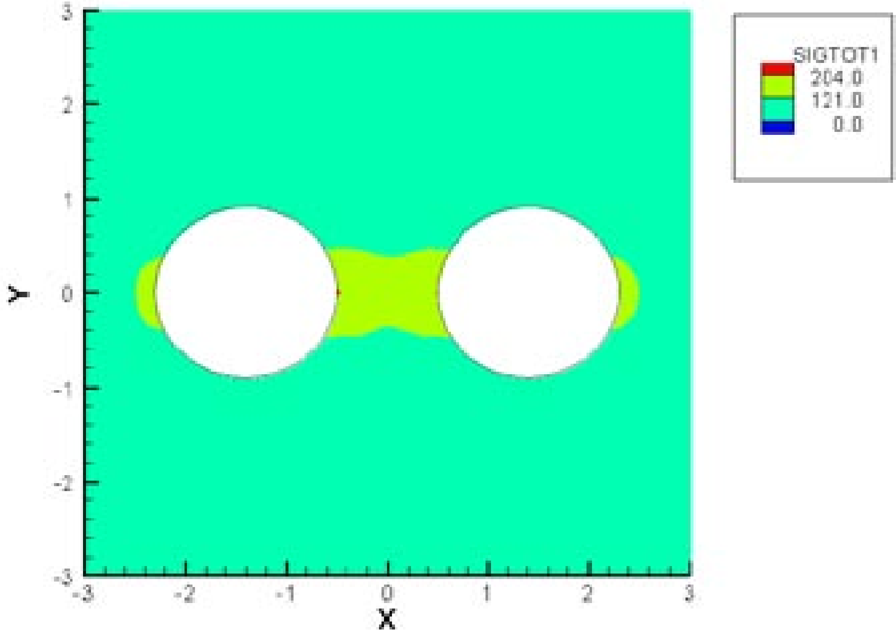

Figure C-10. *Major stresses 0.5 m below the tunnel floor after 120 days.*

Vector deformation, vector and contour lines

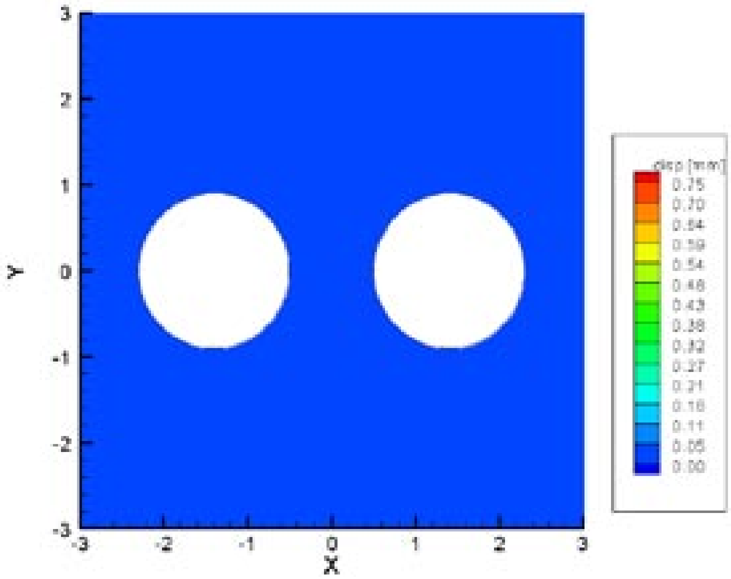

Figure D-1. *Vector deformation (mm) before start heating.*

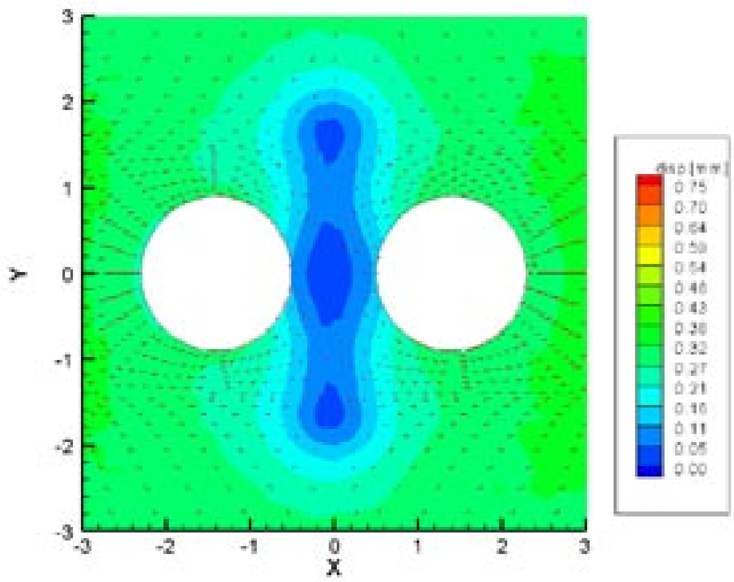

Figure D-2. *Vector deformation (mm) after 30 days of heating.*

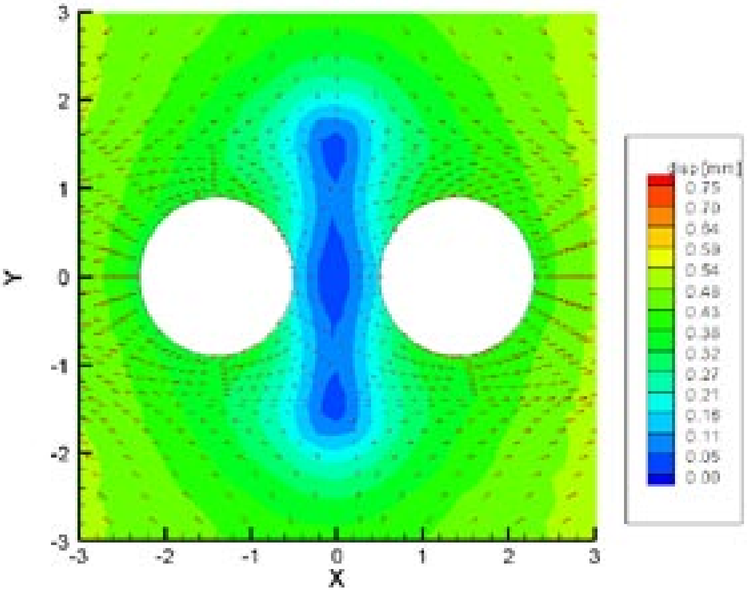

Figure D-3. *Vector deformation (mm) after 60 days of heating.*

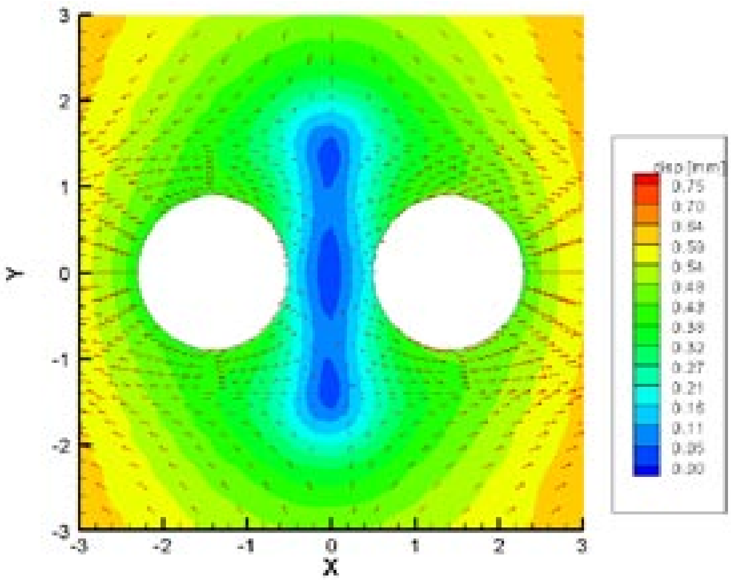

Figure D-4. *Vector deformation (mm) after 90 days of heating.*

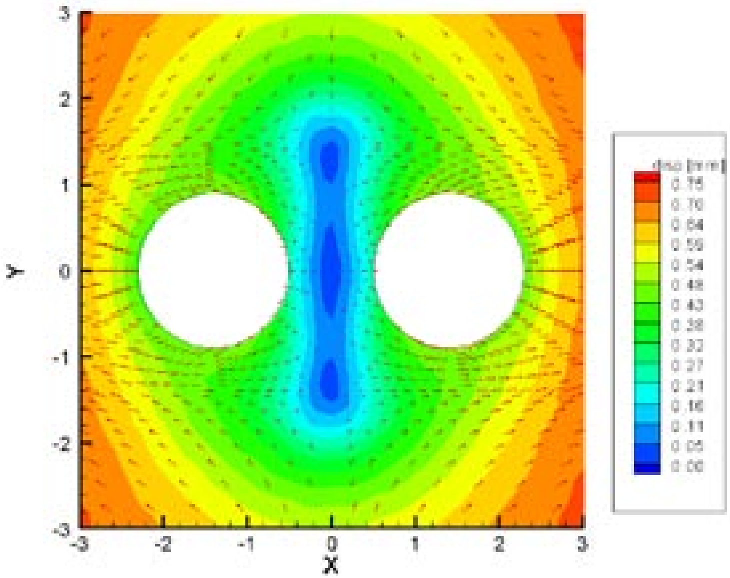

Figure D-5. *Vector deformation (mm) after 120 days of heating.*

Appendix E

Zone of spalling

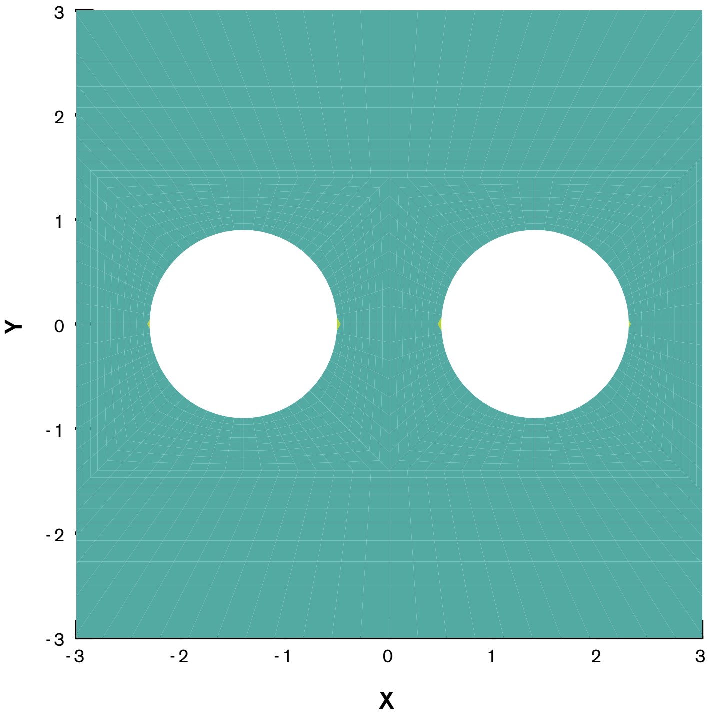

Figure E-1. *Zone of spalling 1.5 m below the tunnel floor before start of heating.*

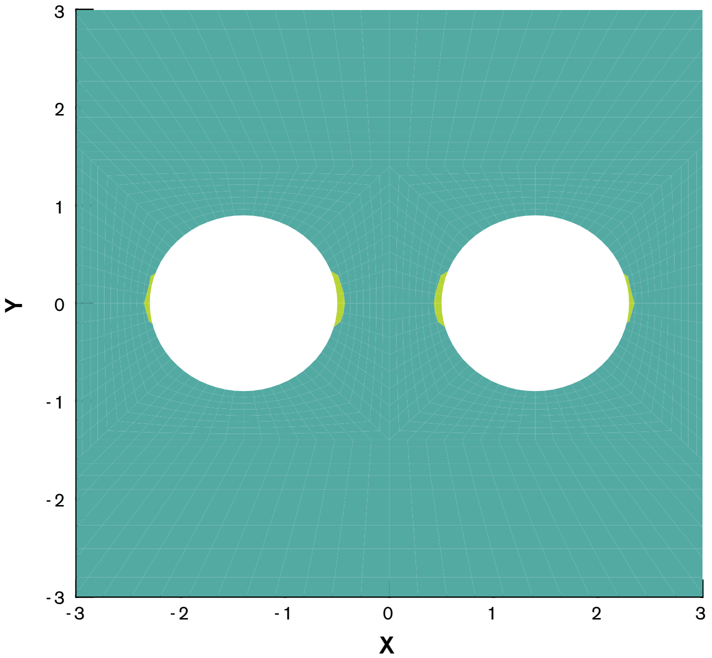

Figure E-2. *Zone of spalling 0.5 m below the tunnel floor before start of heating.*

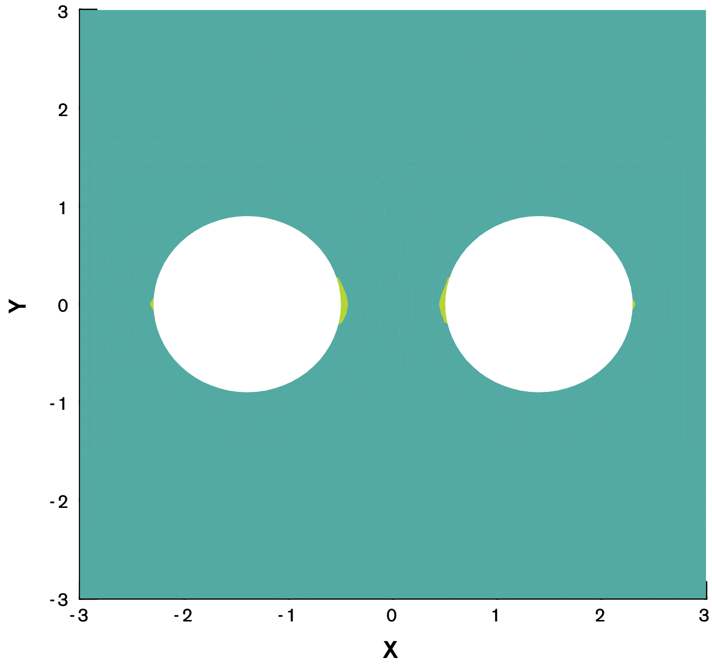

Figure E-3. *Zone of spalling 1.5 m below the tunnel floor after 30 days.*

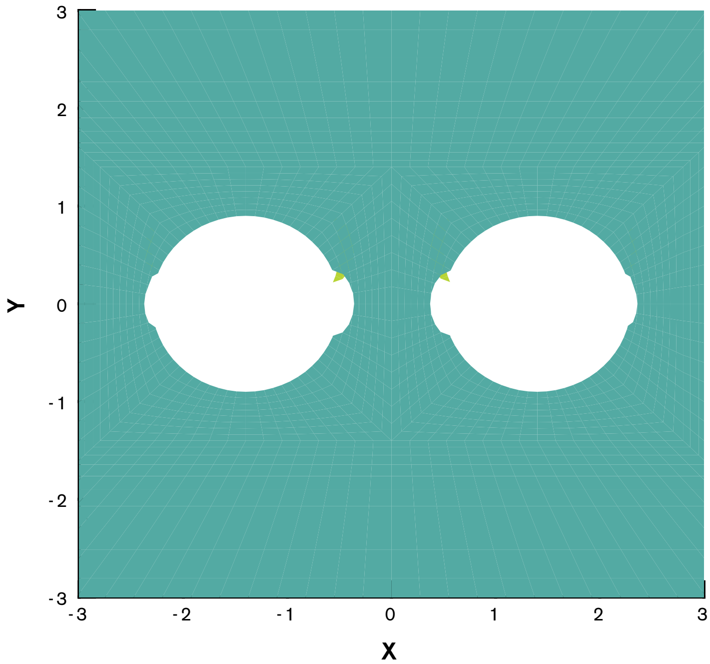

Figure E-4. *Zone of spalling 0.5 m below the tunnel floor after 30 days.*

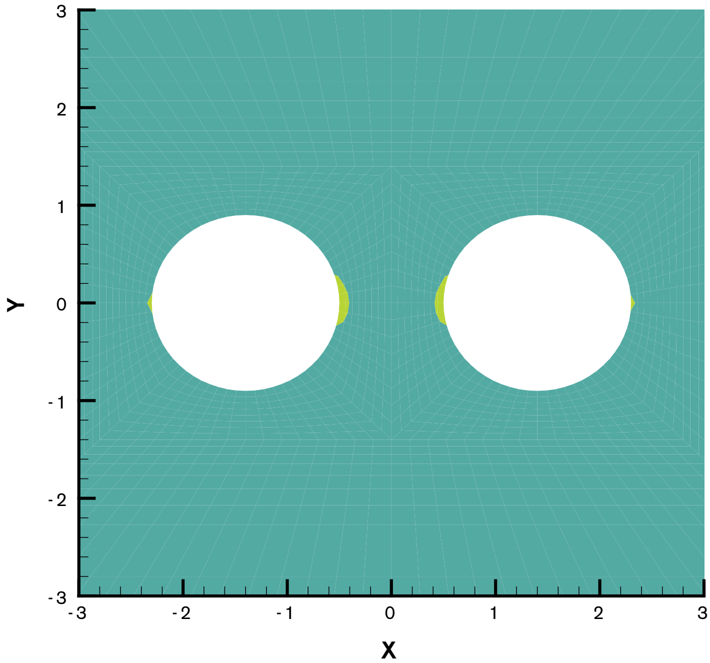

Figure E-5. *Zone of spalling 1.5 m below the tunnel floor after 60 days.*

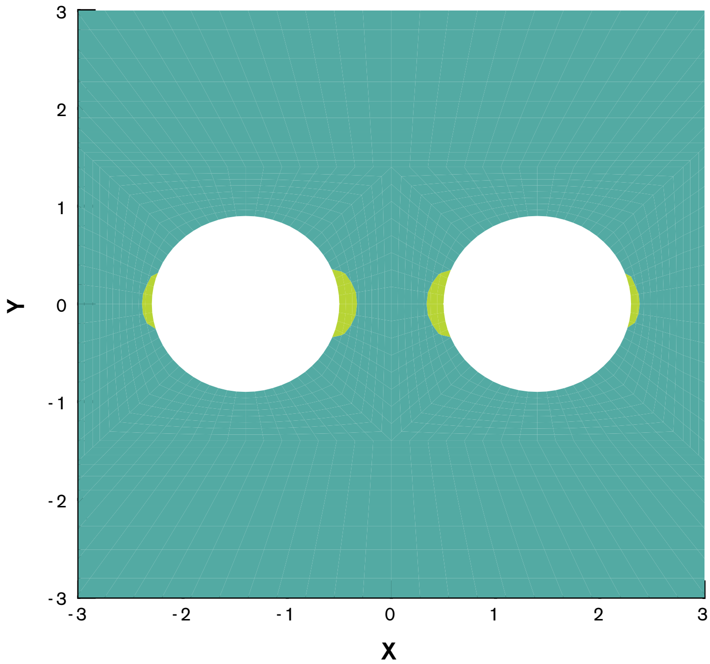

Figure E-6. *Zone of spalling 0.5 m below the tunnel floor after 60 days.*

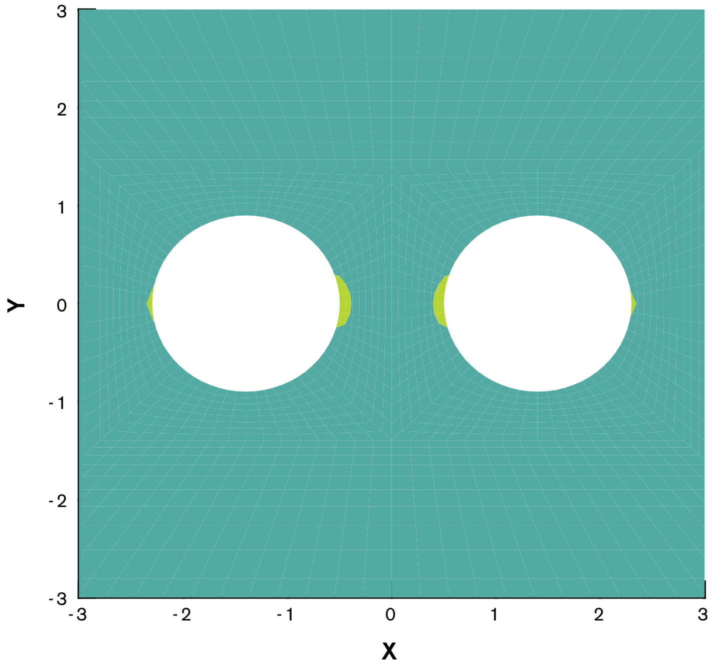

Figure E-7. *Zone of spalling 1.5 m below the tunnel floor after 90 days.*

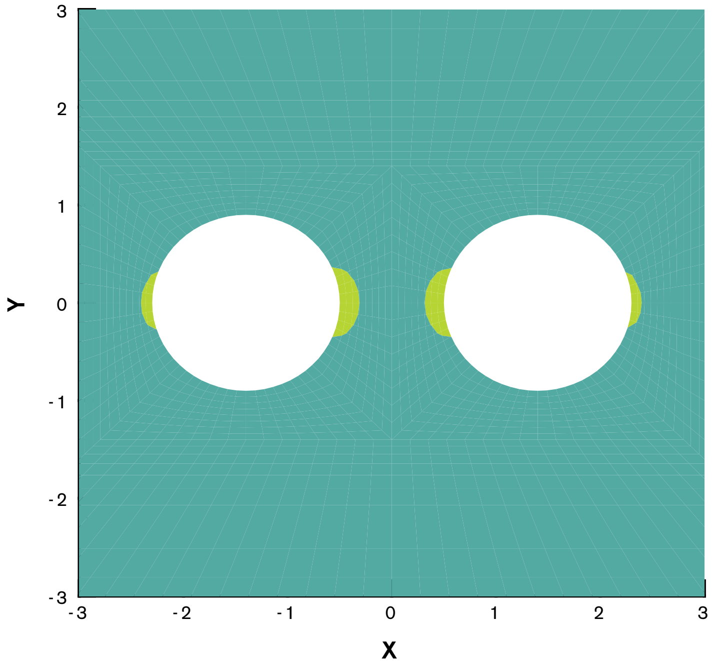

Figure E-8. *Zone of spalling 0.5 m below the tunnel floor after 90 days.*

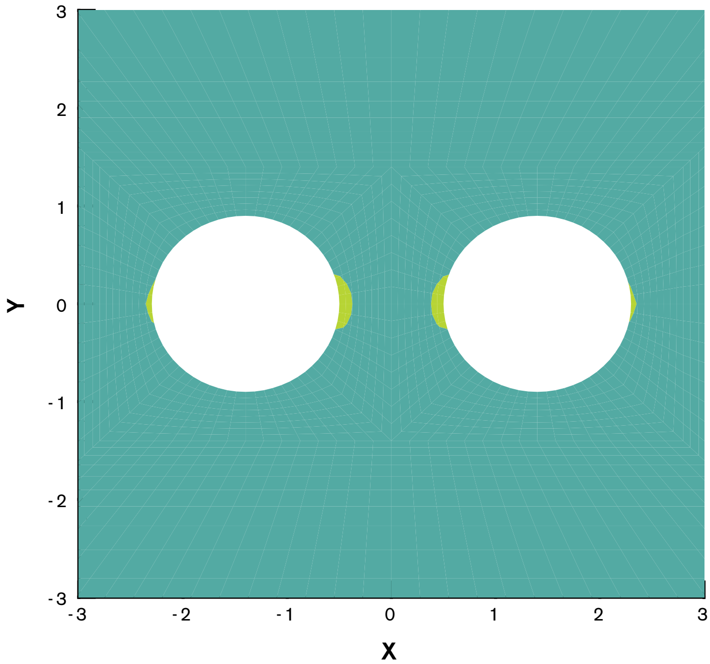

Figure E-9. *Zone of spalling 1.5 m below the tunnel floor after 120 days.*

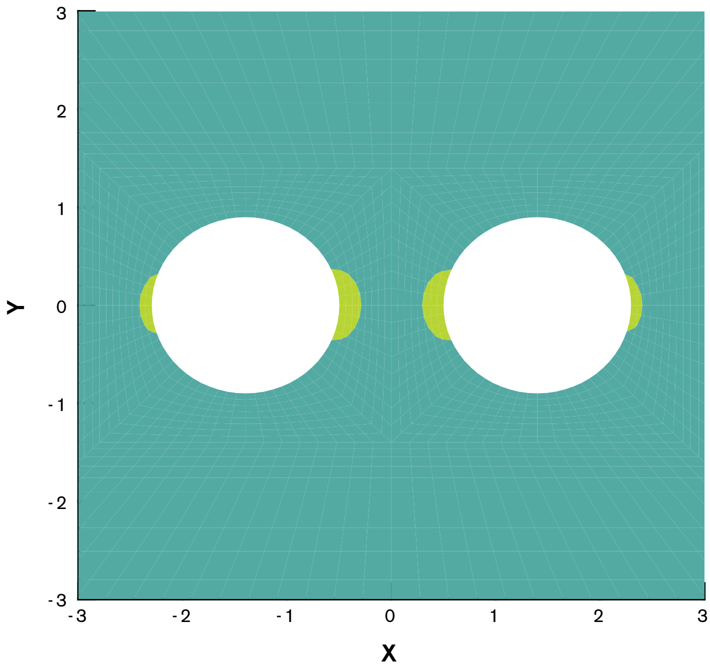

Figure E-10. *Zone of spalling 0.5 m below the tunnel floor after 120 days.*