OPG's DEEP GEOLOGIC

REPOSITORY

FOR LOW & INTERMEDIATE LEVEL WASTE

Supporting Technical Report

Geomechanical Modeling

May 2008

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HATCH™ Hatch Mott MacDonald CNA Consulting Engineers

OPG's Deep Geologic Repository for Low and Intermediate Level Waste Conceptual Design Study

Supporting Technical Report GEOMECHANICAL MODELING

May 2008

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Table of Contents

1. Introduction 1

2. Objectives of the Modeling 1

3. Input Information and Assumptions 1

4. Methodology 3

4.1 Software 3
4.2 Rock Mass Constitutive Behaviour 3
4.3 Intact Rock and Rock Mass Parameters 6

5. Model Development 8

5.1 Pillar Factor of Safety from Numerical Analysis 8
5.2 Pillar Damage Assessment 9

6. Modeling Results 10

6.1 Pre-Closure (100 year) Model Development 10
6.2 Model Zone Size Selection 10
6.3 Explicit Modeling of Bedding Planes 11
6.4 Room Excavation Sequence 11
6.5 Pre-Closure (100 year) Model - Pillar Response over Range of Geomechanical Conditions 13
6.6 Pre-Closure (100 year) Model - Impact of Rock Dowels on Results 20

7. Conclusions 23

8. References 24

APPENDICES

Appendix A – Basis for Assumed Rock Mass Classification

Appendix B1 – Multi-Pillar Analysis

Appendix B2 – Single Pillar Analysis - Wide Range of Parameters

Appendix C – Single Pillar Analysis - Selected Range of Parameters

1. Introduction

Ontario Power Generation (OPG) intends to construct a Deep Geologic Repository (DGR) at a depth of approximately 680 metres beneath the Bruce Site located near Kincardine, Ontario. The facility would safely dispose of Low and Intermediate Level Waste (LLW and ILW respectively) from OPG nuclear operations in emplacement rooms in a geologically stable environment.

This supporting technical report summarises the results of geomechanical numerical modeling performed to address the stability of the emplacement rooms and pillars under the full range of credible geomechanical conditions for the anticipated service life of 100 years (pre-closure case).

2. Objectives of the Modeling

The primary objective of this modeling exercise was to predict the geomechanical behaviour and response of the rock mass pillar due to emplacement room excavation. The results of these analyses support the establishment of minimum safe rock pillar widths between DGR emplacement rooms appropriate to the range of credible geomechanical conditions.

Since the site-specific geotechnical conditions are not yet fully established for the repository site, the modeling has been carried out for a number of sets of rock mass conditions that are considered representative of the range of credible rock properties at the site. Each set of analyses provides predictions of rock mass behaviour in response to excavation for different pillar widths.

The rock pillar safety factor from the numerical analysis and estimates of the extent of rock damage caused by creating an emplacement room opening that disturbs the initial stress state in the rock mass have been numerically predicted. A sensitivity analysis has thereby been performed to determine the key parameters that have the most significant effect on the pillar requirements.

3. Input Information and Assumptions

The modeling has required the following inputs and assumptions:

- The main emplacement rooms and ancillary access and support tunnels of the DGR will be constructed in the Cobourg limestone formation that is located at a depth that is approximately between 660 m and 687 m below grade surface (bgs).
- For the purposes of the numerical analyses, this formation has been characterised from a geomechanical perspective to be sub-horizontally bedded with medium to massive bedding thickness. Aspects of Rock Mass Rating (RMR) classification (Bieniawski, 1989) and Geologic Strength Index (GSI) classification (Hoek and Brown, 1997) assessments including bedding plane and joint discontinuity features that have been assumed for the analyses are described in Appendix A.

- The repository emplacement rooms will be constructed as rib and pillar rooms meaning that rooms will be constructed parallel to each other with a long, continuous and uniform width pillar between them. Emplacement rooms will be arrayed in panels with their length-to-span aspect ratio greater than 10.
- Room shape will be rectangular due to sub-horizontal bedding planes (see Figure 3-1). Limited size corner rounding or chamfers (necessary due to construction methods) will occur but will not affect geomechanical behaviour.
- Room sizes – analyses have been performed using room sizes from previous studies – 8.1 m wide and 7.5 m high for the low-level waste emplacement rooms, as the base case for design.
- Only minimal rock reinforcement will be provided within emplacement rooms (shotcrete and rock dowels) that is designed to prevent fallout of loosened and failed material from the roof and upper walls for the safety of workers and to avoid damage to waste packages in the pre-closure phase. Correspondingly, no structural reinforcement of pillars or the roof has been considered in the model.
- The modeling has been conducted for horizontal to vertical in-situ stresses ratios (K_0) ranging from 1.0 to 2.5. The minor horizontal in-situ stress has been kept at the same value as the vertical stress. The orientation of the highest horizontal stress has been assumed to be perpendicular to the room length.

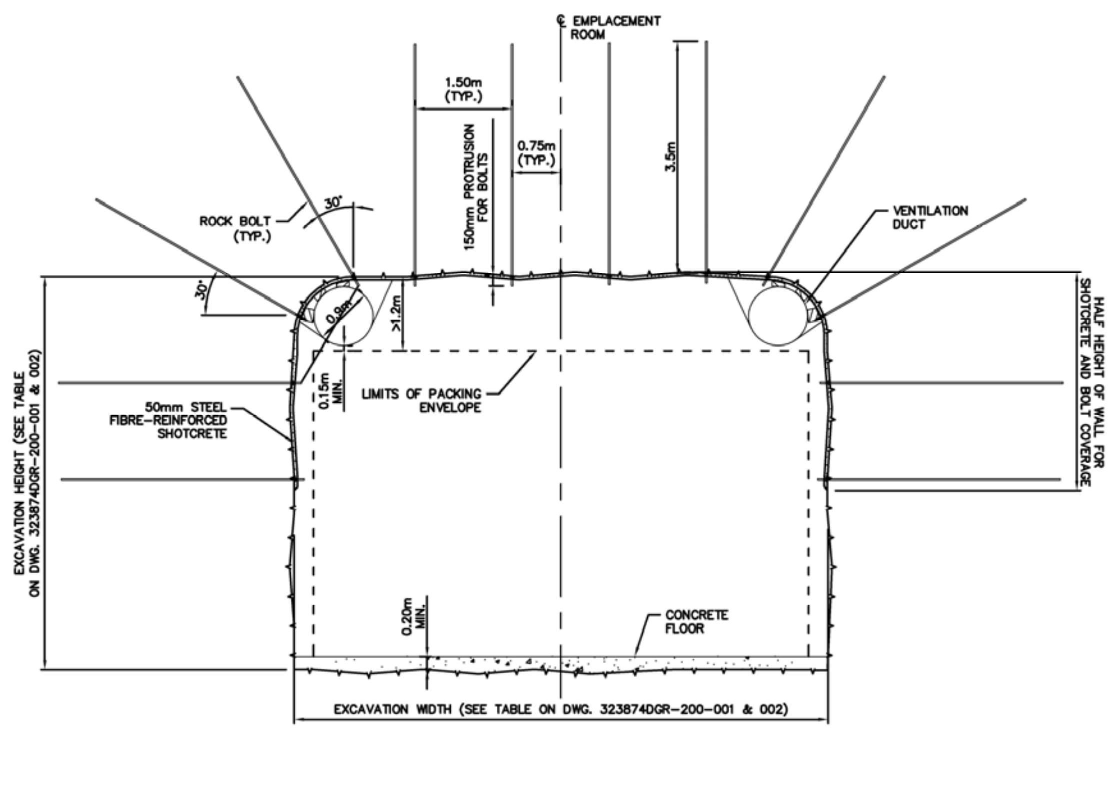


Figure 3-1 – Typical Emplacement Room Shape and Layout

4. Methodology

4.1 Software

The models were analyzed using finite difference software developed by Itasca Consulting Group (FLAC). FLAC Version 5.0 has been used for the two-dimensional numerical models described herein. The software is produced by Itasca Inc. of Minnesota and the programs are based on explicit finite difference method, specifically developed for modeling geotechnical problems. These programs can simulate the behaviour of media consisting of soil, rock or other materials that may undergo plastic flow when their yield limits are reached. Materials are represented by zones (elements) that are configured in a grid created by the user. Each zone behaves according to a user-prescribed linear or nonlinear constitutive behaviour (stress/strain law) in response to the applied forces or boundary restraints, with ground water/pore pressure effects included in the model. Explicit discontinuities, as well as distinct structural elements, can be modeled within the grid.

4.2 Rock Mass Constitutive Behaviour

The behaviour of a rock mass is controlled by the stress redistribution that occurs after excavation relative to the geomechanical (strength) properties of the discontinuities (joints) and the intact rock between them. According to Hoek-Brown (1997), a discontinuous rock mass can be numerically modeled as a continuum by modifying intact rock material properties to account for the presence and condition of joints and other discontinuities. Comparison of the magnitude and difference of major and minor principal stresses (denoted σ_1 and σ_3 respectively) after excavation induced stress redistribution relative to a failure criterion based on rock strength parameters is used to assess the behaviour of the rock mass (elastic or plastic failure). Reference is made to Hoek-Brown (1997) for more details. An example of the Hoek-Brown failure criterion is shown in Figure 4-1.

An elasto-plastic constitutive behaviour for the rock mass modeled as a continuum has been adopted for the study by using a modified or compound Hoek-Brown failure criterion. The compound failure criterion recognises the brittle behaviour recommended by Martin et al (1999) for low confinement stresses and reverts to the standard Hoek-Brown failure line at higher confining stresses. Figure 4-2 shows the resulting compound failure envelope and Figure 4-3 shows the stress ranges governed by each failure criterion. The resulting composite failure curve varies only slightly from the simple Hoek-Brown failure envelope. Therefore, this composite curve has been used for single pillar assessment. No post-peak strain softening has been modeled at this stage of investigation.

Rock Lab 1.0 version 1.031 developed by RocScience was used to obtain the Hoek Brown parameters, m_b, s and a, from the assumed intact rock unconfined compressive strength (UCS) and rock mass characterisation values (RMR and GSI). A sensitivity study comparing results for single pillar models using explicitly modeled bedding planes and implicitly modeled bedding was also performed.

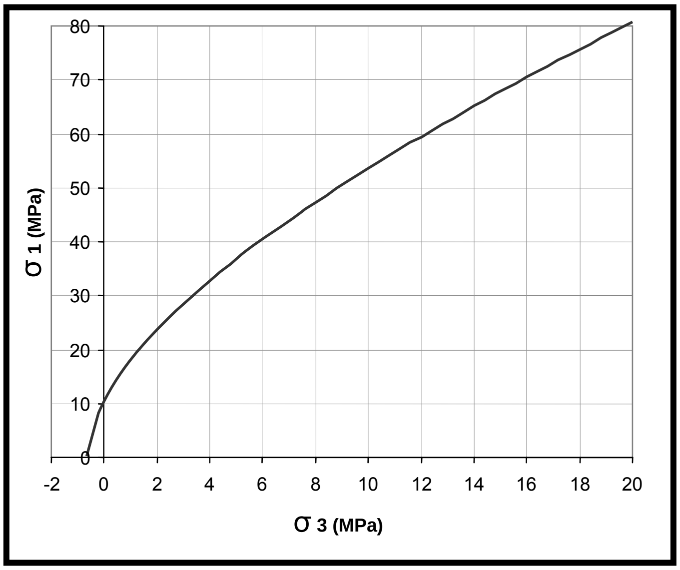


Figure 4-1 – Hoek-Brown Failure Criteria at Peak Resistance

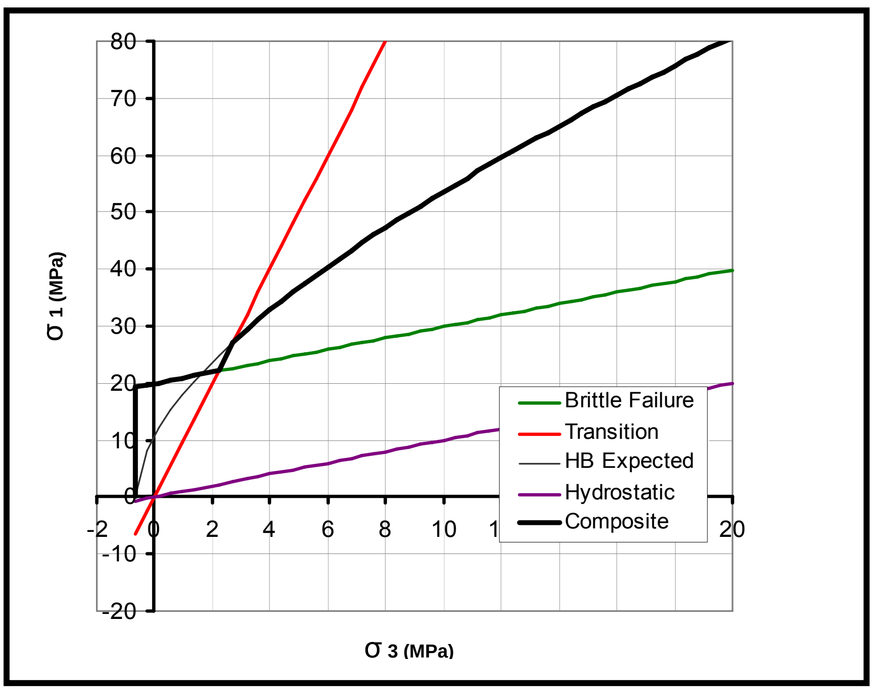


Figure 4-2 – Composite Failure Criteria

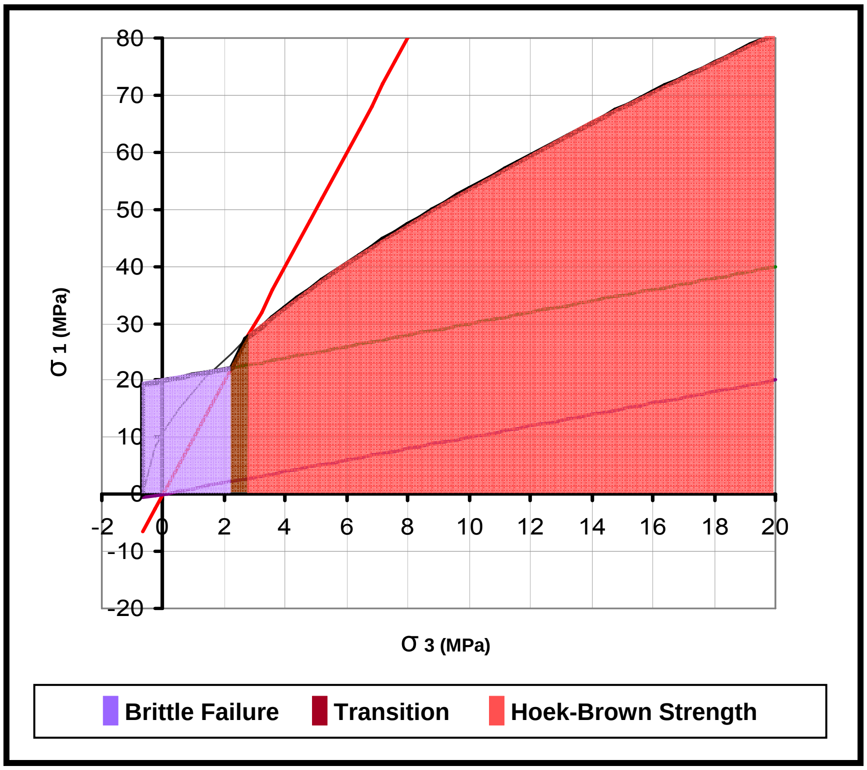


Figure 4-3 – Zones of Failure Envelope Criteria

4.3 Intact Rock and Rock Mass Parameters

The credible range of possible geomechanical properties has been summarised by Lam et al (2007) and the analysed range of geomechanical parameters is presented in Table 4-1, Table 4-2, and Table 4-3 are felt to reflect that range.

Parameter		***Least Favourable***	***Selected Range***	***Most Favourable***
Bedding Joint Parameters	Friction Angle	20	30	40
	Cohesion (MPa)	0	0.3	0.6
	Tensile Strength (MPa)	0	0.3	0.6
	Normal Stiffness K_n (GPa/m)	175	250	325
	Shear Stiffness K_s (GPa/m)	7	10	15
Horizontal Joint spacing (m)		0.3	1	2

Table 4-1: Bedding Plane Parameters

Parameter	***Lower Bound***	***Expected***	***Upper Bound***
In situ horizontal pressure coefficient, K_0	1.0	1.5	2.5
In situ vertical stress, σ_v (MPa) (at 660m below grade)	17.2	17.2	17.2
Unit Weight of Rock (MN/m^3)	0.026	0.026	0.026

Table 4-2: Rock Stress Conditions

Parameter	***Least Favourable***	***Low End of Selected Range***			***Middle of Selected Range "Expected" with GSI 69***			***High End of Selected Range***			***Most Favourable***
UCS Intact Rock (MPa)	25	48			60			72			140
Rock Quality (Geological Strength Index or GSI)[1]	66	55	69	80	55	69	80	55	69	80	80
Modulus of elasticity of intact rock (GPa)	16	37	37	37	47	47	47	56	56	56	66
Modulus of elasticity of rock mass[2] (GPa)	10	15	27	33	19	33	41	23	40	49	58
Poisson's ratio	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Hoek-Brown Parameter m_i	9	9	9	9	9	9	9	9	9	9	9
Hoek-Brown Parameter m_b	2.67	1.80	2.97	4.41	1.80	2.97	4.41	1.80	2.97	4.41	4.41
Hoek-Brown Parameter s	0.023	0.007	0.032	0.108	0.007	0.032	0.108	0.007	0.032	0.108	0.108
Hoek-Brown Parameter a	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Tested for Modeling issues						Yes					
K_o range considered	1.0, 1.5, 2.5	1.5	1.5	1.5	1.5	1.0, 1.5, 2.5	1.5	1.5	1.5	1.5	1.0, 1.5, 2.5

Table 4-3: Range of Considered Rock Parameters

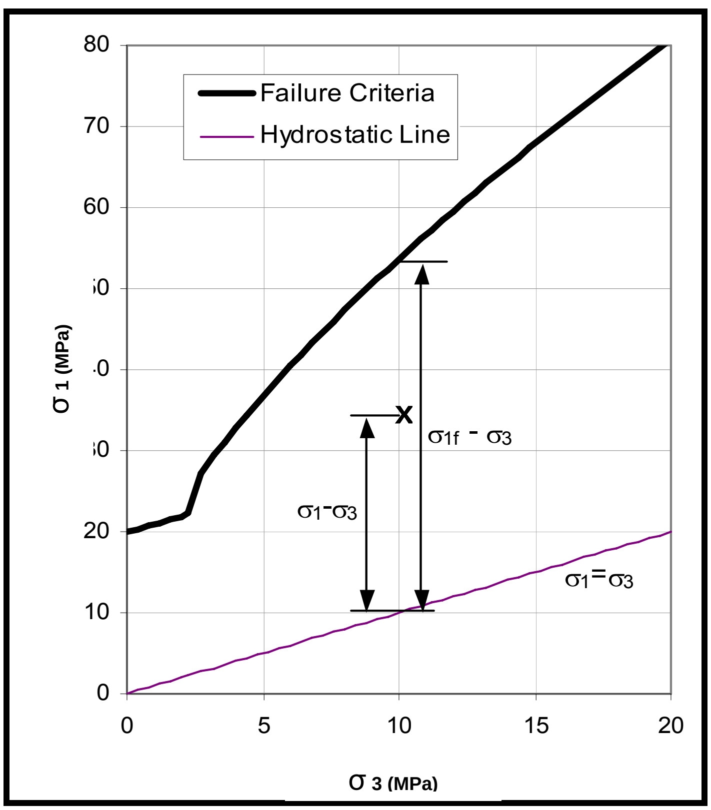
5. Model Development

5.1 Pillar Factor of Safety from Numerical Analysis

Typically, the level of safety (often denoted factor of safety) of pillars in mining applications is assessed by comparing pillar capacity determined using empirical relations relative to the average vertical stresses in a pillar calculated on the basis of overburden pressures and pillar tributary widths. While this has served the mining industry well, empirical assessments of pillar capacity are often based on unknown definitions of failure, in-situ stress conditions and rock mass characteristics. Further, average stress levels do not provide an indication of the localised damage that may occur at free surfaces and areas of stress concentration.

To consider these behavioural characteristics, numerical modeling is used as it is capable of calculating the state of stress throughout the entire rock mass (i.e. stress distribution across the pillar) and compares that stress state to constitutive failure criteria at each calculation location. Consequently, the level of stress relative to rock capacity will vary across the pillar.

For each of the geomechanical conditions and for various pillar widths, the stress state across a horizontal section through the pillar (typically at the pillar mid-height) was assessed and used to quantitatively express the level of pillar stability. From each element along the investigated section of the pillar, the stresses were extracted and the individual zone Factor of Safety was assessed as the ratio of the differences between the principal stresses at failure σ_{1f} for the measured σ_3 and the actual differences between the measured principal stresses, as shown in Figure 5-1.



$$FS = \frac{\sigma_{1f} - \sigma_3}{\sigma_1 - \sigma_3}$$

Figure 5-1 – Factor of Safety Calculation

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The Safety Factor calculated by this method will always be ≥ 1.0. If the measured σ_3 approaches the value of σ_1 the Safety Factor will be approaching infinity. In order to limit the possibility that a few zones across the pillar with σ_1 close to σ_3 would distort the results, an artificial limit of FS ≤ 20 for any zone has been set. To obtain the total pillar Safety Factor, the individual zone Safety Factors are then added and averaged. To make a distinction between the Safety Factor calculated from numerical analysis and empirical or otherwise obtained Safety Factors, the factor obtained from the numerical analysis is referred to as Numerical Analysis Factor of Safety (NAFS).

5.2 Pillar Damage Assessment

An additional pillar acceptance criterion has been established based on the extent of plasticised zone as a proportion of the original pillar width:

- Type A has the plastic zone equal to 0% to 10% of the pillar width
- Type B has the plastic zone equal to 10% to 28% of the pillar width
- Type C has the plastic zone equal to 28% to 50% of the pillar width
- Type D has the plastic zone equal to 50% to 78% of the pillar width
- Type E has the plastic zone equal to 78% to 100% of the pillar width

The numerical modeling results were used to assess the magnitude of pillar damage.

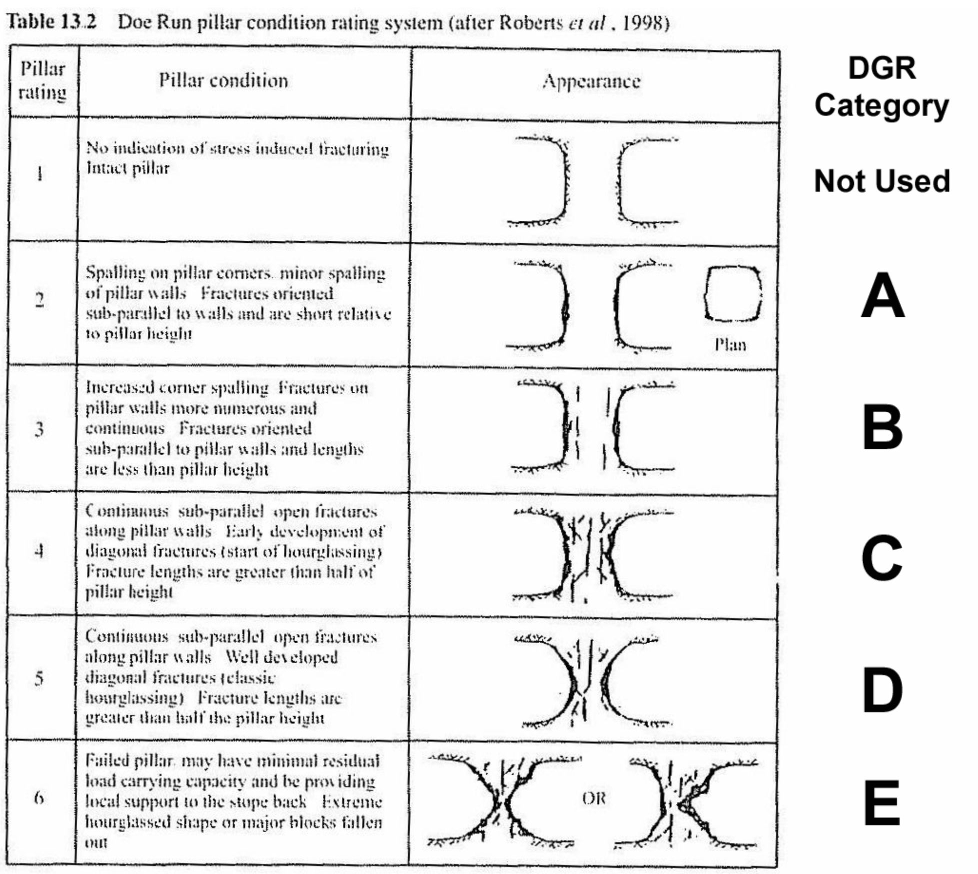


Table 13.2 Doe Run pillar condition rating system (after Roberts *et al*, 1998)

Pillar rating	Pillar condition	Appearance	DGR Category
1	No indication of stress induced fracturing Intact pillar		Not Used
2	Spalling on pillar corners, minor spalling of pillar walls. Fractures oriented sub-parallel to walls and are short relative to pillar height	Plan	A
3	Increased corner spalling. Fractures on pillar walls more numerous and continuous. Fractures oriented sub-parallel to pillar walls and lengths are less than pillar height		B
4	Continuous sub-parallel open fractures along pillar walls. Early development of diagonal fractures (start of hourglassing). Fracture lengths are greater than half of pillar height		C
5	Continuous sub-parallel open fractures along pillar walls. Well developed diagonal fractures (classic hourglassing). Fracture lengths are greater than half the pillar height		D
6	Failed pillar, may have minimal residual load carrying capacity and be providing local support to the stope back. Extreme hourglassed shape or major blocks fallen out	OR	E

Figure 5-2 – Pillar Condition Rating System for Sedimentary Rock (Brady et al, 1985)

6. Modeling Results

6.1 Pre-Closure (100 year) Model Development

During model development, modeling simplifications were sought with the objective of reducing computing time to allow more alternative parametric models to be analysed. Various aspects of the modeling tasks were investigated. These included:

- The effect of mesh size on result accuracy and on computing time
- The effect of explicitly modeling horizontal bedding planes compared with a implicit allowance for such bedding planes by appropriately degrading the geotechnical properties used in the model
- The effect of progressive incremental expansion of the facility compared with all adjacent rooms being excavated concurrently

The 2-D models were run for the range of geotechnical properties shown in Section 3 and a range of pillar widths from 8 to 28 m.

6.2 Model Zone Size Selection

Figure 6-1 shows the sensitivity of the Numerical Analysis Factor of Safety, calculated for a single pillar model, to the grid element size in the model. It can be reasonably assumed that a smaller size element model would provide more accurate results.

From Figure 6-1 it can be seen that while there is a trend to obtain somewhat higher values of the NAFS for larger elements, the difference is relatively small; from 1.20 for the grid size of 0.05 m through 1.25 for the element size of 0.25 m up to 1.29 for a 0.5 m grid. It should be noted that the model with the grid size of 0.05 m is 25 times larger compared to a 0.25 m grid model with a corresponding increase in computational time. Therefore, a grid element size of 0.25 m has been chosen as the best balance between accuracy and computational time.

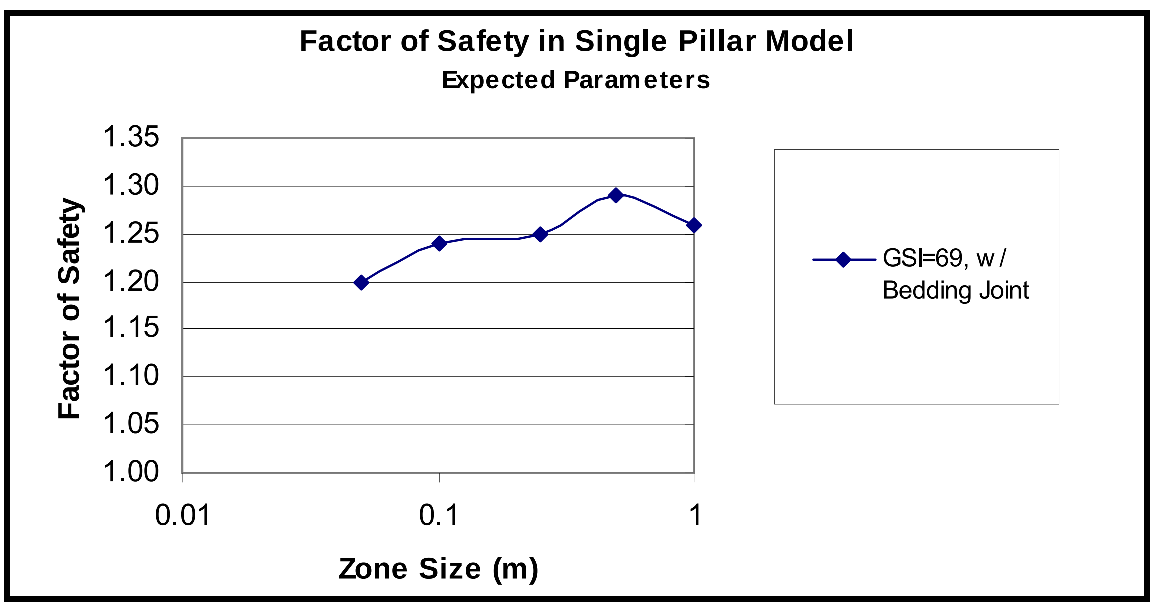


Figure 6-1 – Numerical Analysis Factor of Safety Variation with Element Size

6.3 Explicit Modeling of Bedding Planes

Figure 6-2 assesses the effect of modeling the bedding planes explicitly and selects a modifier for the rock quality to produce similar results and thereby implicitly allow for the presence of the bedding planes. Figure 6-2 shows the comparison between the pillar NAFS results for a model with the rock with GSI of 69 with explicitly modelled bedding planes, and the results for a model with GSI of 67 without explicit bedding planes, and shows that the results are similar. It can be concluded that, considering the accuracy of the material properties of the rock that will be measured and known, the differences between the explicit and implicit modeling of bedding planes will not have significant impact on the overall accuracy of the predictions obtained from the analytical models. Therefore, implicit bedding plane modeling was used with a GSI reduction of 2 to allow for the bedding planes.

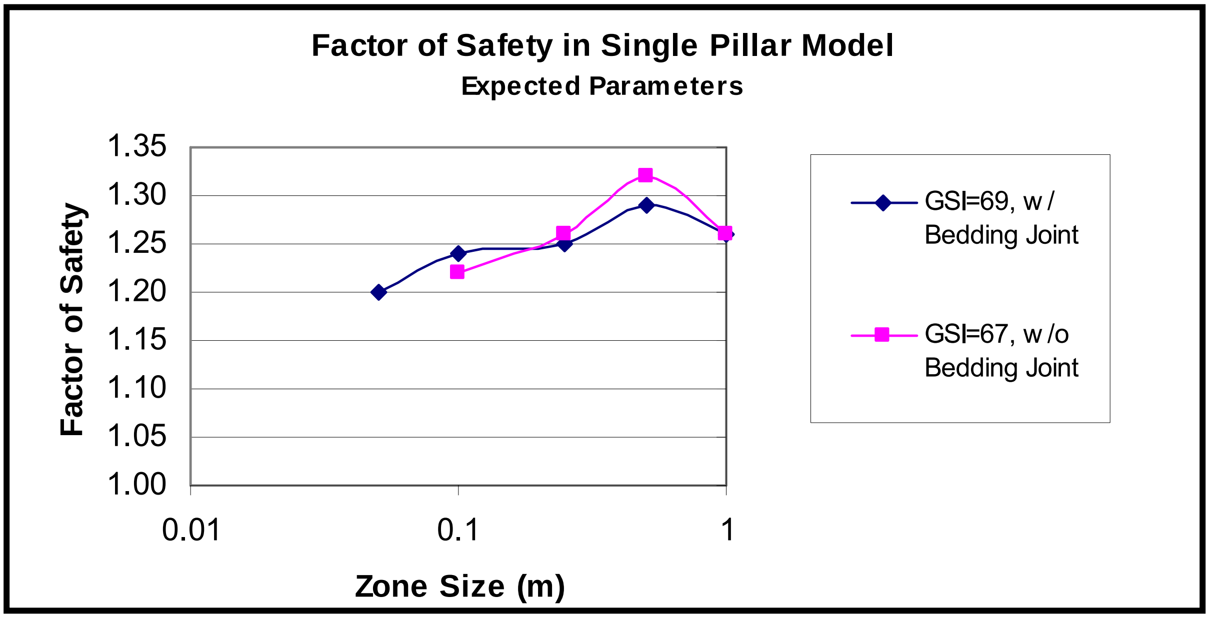


Figure 6-2 – Numerical Analysis Factor of Safety Variation with Element Size and Bedding Modeling

6.4 Room Excavation Sequence

An assessment of the impact of room excavation sequence was made to determine how the successive excavation of rooms would alter the stress state in the initial or exterior pillars in the emplacement room panels. This assessment was performed to determine if the modeling of a single symmetrical pillar (see Figure 6-3) that represents an infinite number of parallel rooms (and is significantly less computationally intensive) provides similar results to discrete modeling of the actual number of rooms in a panel (see Figure 6-4).

Figure 6-4 and Table 6-1 show how the pillar model-calculated Numerical Analysis Factor of Safety changes with the number of sequentially excavated rooms. If a single pillar is created (2 rooms are excavated), the NAFS of the pillar will be 1.83, based on the expected rock properties used in this calibration model. When subsequent rooms are excavated in the same model, the NAFS for the first pillar will start decreasing gradually to about 1.74. After about 6 – 7 rooms have been created there is no further decrease in the Numerical Analysis Factor of Safety value of the first pillar.

The single pillar 2-D model represents one of an infinite number of pillars and would therefore be expected to predict the lowest safety factor. The single pillar model that has been used in all the analysis is therefore conservative.

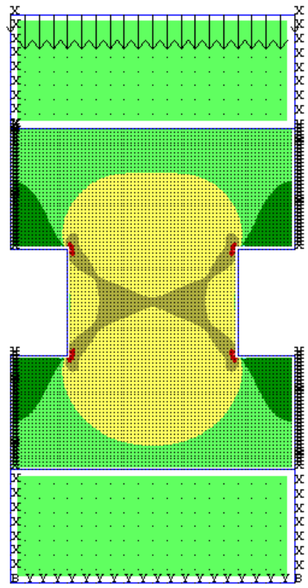


Figure 6-3 – Example of Single Rib Pillar Model Showing Vertical Stresses

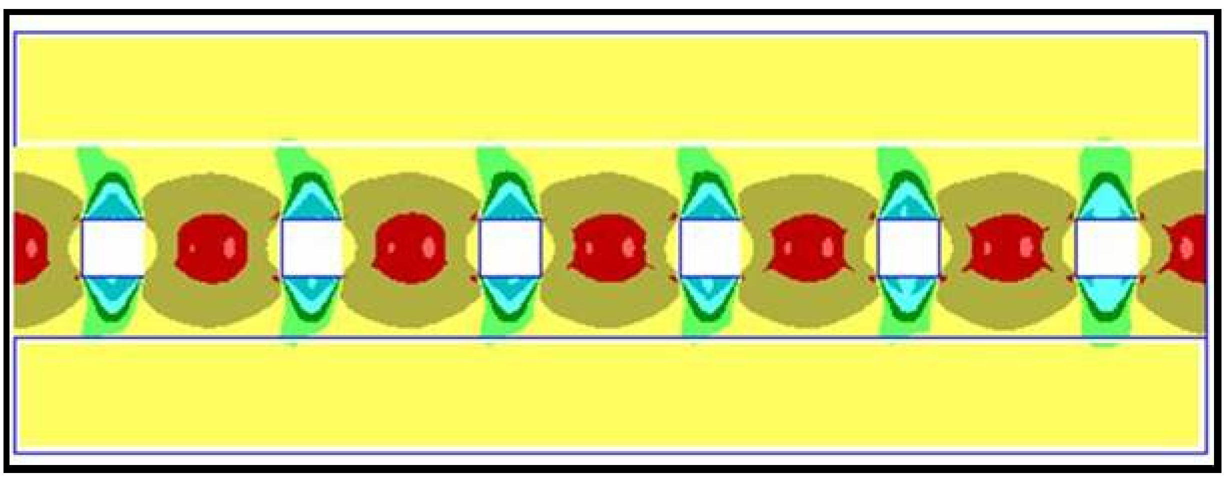


Figure 6-4 – Vertical Stresses in a Multiple Room Model

0.5m Zone size w/ Bedding Joint; Pillar Width = 15m, K_0 = 1.5 Expected						
No. of Excavated Vaults	***Pillar #***					
	1	**2**	**3**	**4**	**5**	**6**
1	2.00					
2	1.83					
3	1.81	1.79	1.84			
4	1.77		1.80	1.84		
5	1.76	1.75	1.77	1.80	1.83	
6	1.75	1.74	1.76	1.78	1.79	1.83

Table 6-1 – Decrease of NAFS With Increasing Number of Rooms

6.5 Pre-Closure (100 year) Model - Pillar Response over Range of Geomechanical Conditions

This group of results is with reference to the "Least Favourable", "Expected" and "Most Favourable" rock property assumptions as shown in Table 4-3.

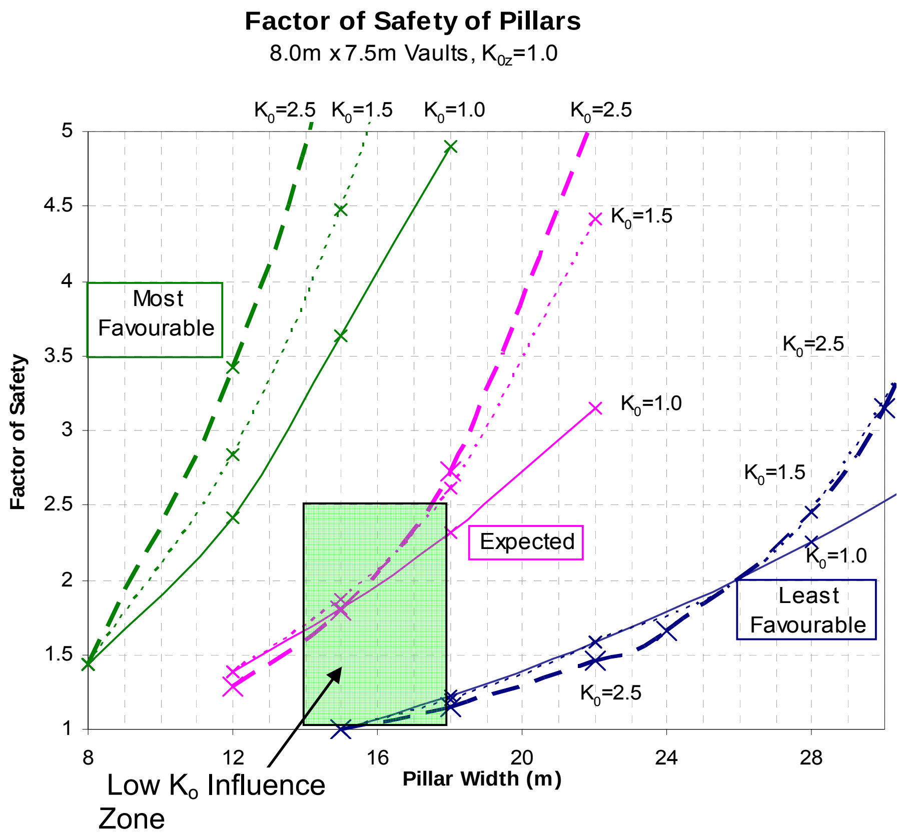


Figure 6-5 – Numerical Analysis Factor of Safety of Pillars for the Wide Range Rock Properties (7.5 m x 8.1 m Room Size, K0z = 1.0)

Figure 6-5 shows the results of the analyses for the least favourable, expected and most favourable parameters shown on presented graphically. As expected, the Numerical Analysis Factor of Safety of a pillar increases with rock strength and the pillar width. Conversely, for the same NAFS the pillar width can be decreased if the rock strength increases.

The effect of higher K_0 values is quite apparent for wider pillars. It is apparent that as the pillar gets wider a portion of the high pre-excavation initial horizontal stress stays locked in the pillar and provides lateral confinement for the pillar core. For very large pillars and for K_0 >> 1.0 this may lead to a reversal of the principal stresses in the pillar when the horizontal stress may become larger than the vertical stress, as shown in Figure 6-6 below where the distribution of factors of safety across a wide pillar is presented showing σ_3 to be orientated horizontally near the edge of the pillar and vertically near the centre of the pillar. For narrower pillars this effect is small, however.

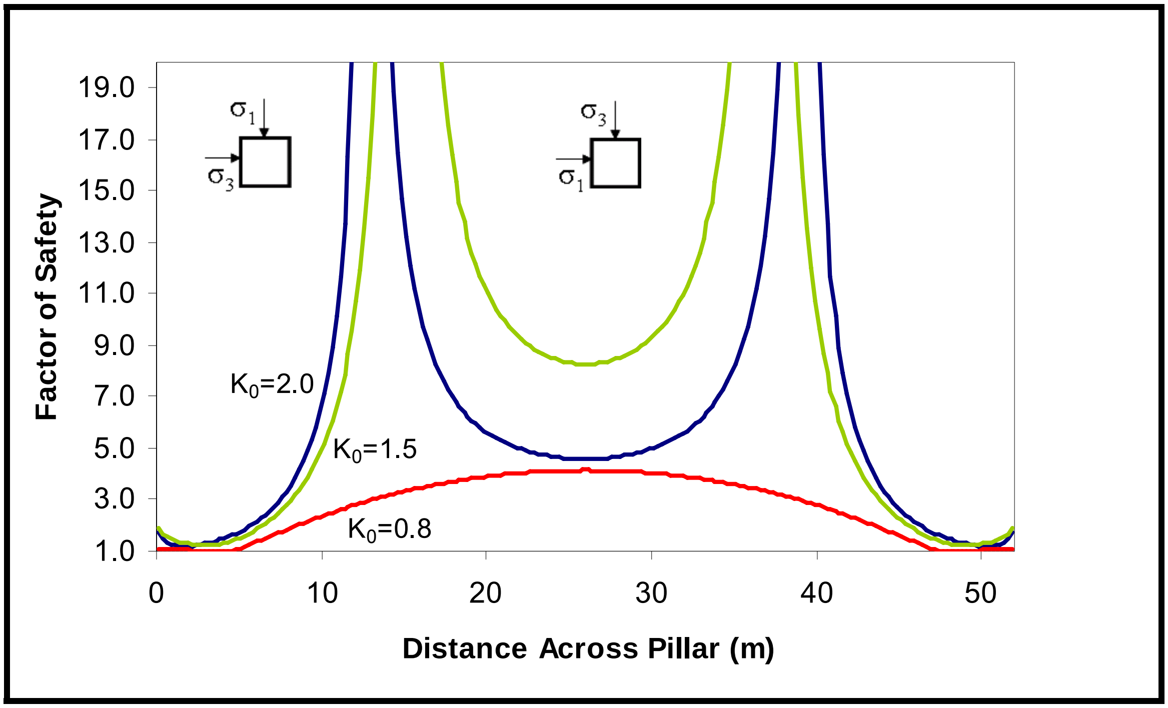


Figure 6-6 – Wide Pillar Local NAFS across a Wide Pillar With Varying K_0

Within the range of pillar widths that can be expected for this facility, with the range shown as the shaded area on Figure 6-5, the effect of K_0 on the results is relatively small as indicated by the adjacency of the curves for the various K_0 values within this zone.

For this reason, when the selected narrower range of rock properties was considered as probable on the site, and the large number of analysis cases for the parameters shown on Table 4-1, only K_0 equal to 1.5 was used in the analyses. The results of these analyses are shown below in Figure 6-7.

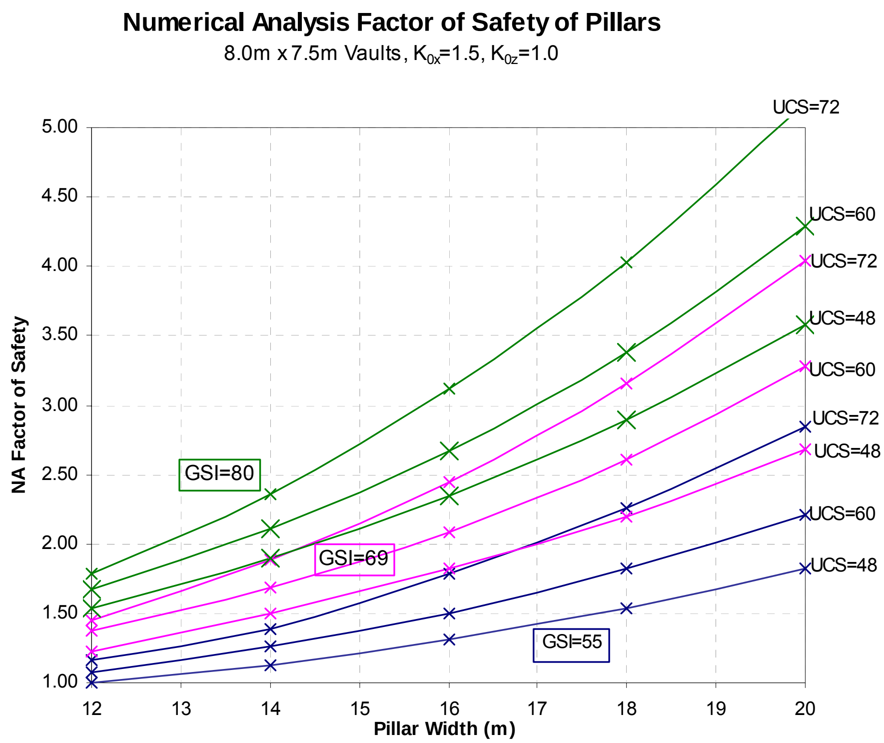


Figure 6-7 – NAFS Results for the Selected Range of Rock Properties

The typical results for the extent of pillar damage are shown in figures, Figure 6-8 to Figure 6-12 below. The purple colour shown on the stress plots identifies the zone of the pillar that is yielding, the green zone identifies the portion that has yielded in the past. The total pillar damaged zone as quantified as the percentage of the pillar width is the sum of both of these zones.

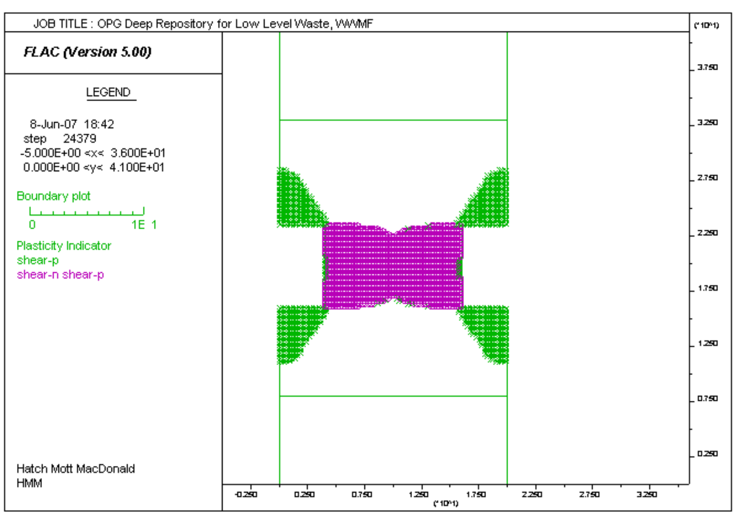


Figure 6-8 – Pillar Model UCS = 48, GSI = 55, Pillar Width = 12.0m, NAFS = 1.0 Damage Category E, Plasticity zone 100% of the pillar width

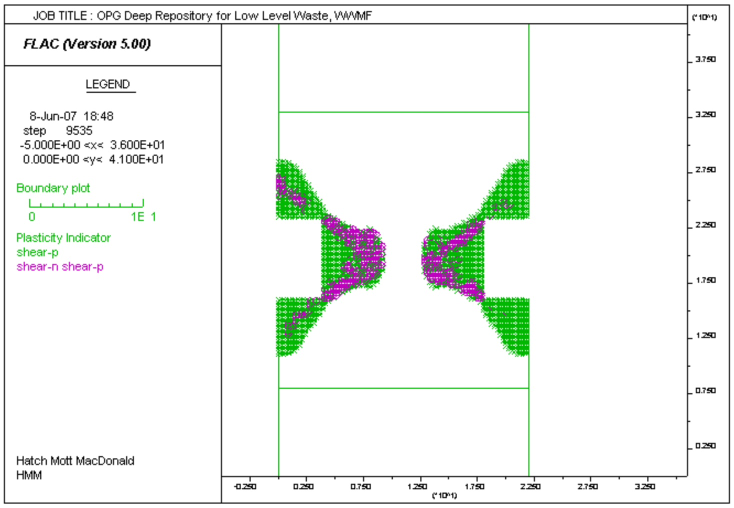


Figure 6-9 – Pillar Model UCS = 48, GSI = 55, Pillar Width = 14.0m, NAFS = 1.1 Damage Category E, Plasticity zone 78% of the pillar width

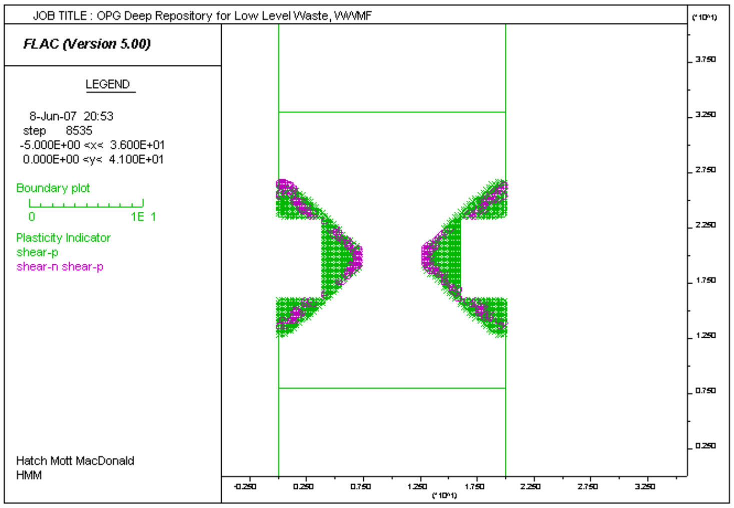


Figure 6-10 – Pillar Model UCS = 60, GSI = 69, Pillar Width = 12.0m, NAFS = 1.4 Damage Category D, Plasticity zone 57% of the pillar width

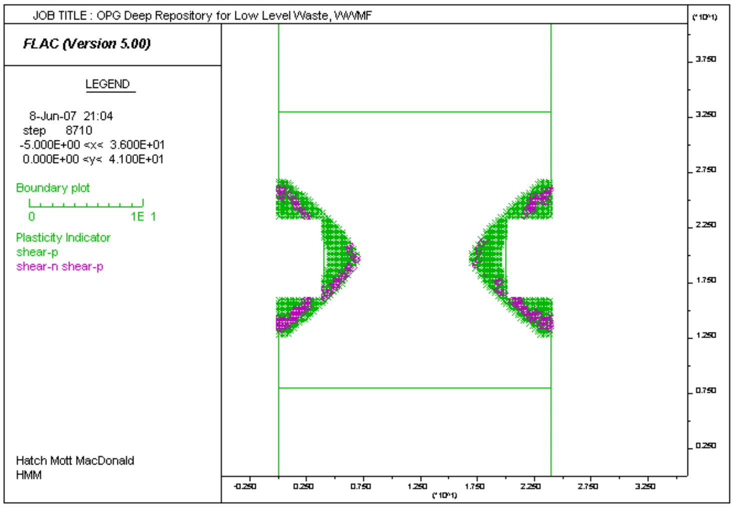


Figure 6-11 – Pillar Model UCS = 60, GSI = 69, Pillar Width = 16.0m, NAFS = 2.1 Damage Category C, Plasticity zone 39% of the pillar width

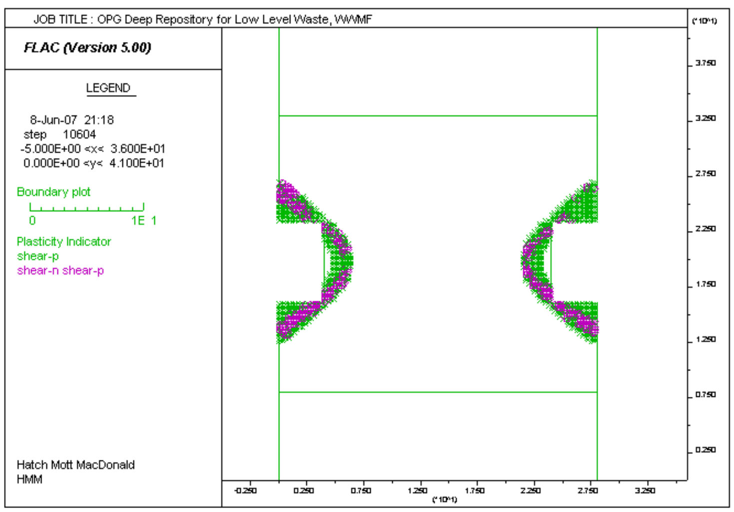


Figure 6-12 – Pillar Model UCS = 60, GSI = 69, Pillar Width = 20.0m, NAFS = 3.3 Damage Category B, Plasticity zone 26% of the pillar width

The conclusions that can be made from the single pillar models are as follows:

It appears that for a constant room size, that varying the width of the pillar has little influence on the size of the plasticised (damaged) zone. Figure 6-13 shows a comparison of the depth of the damaged zones for 12, 16 and 20 m wide pillars with identical rock properties. It can be seen that when the pillar widths increases by 66%, the depth of damaged zone decreases by less than 25%.

Figure 6-14 shows the depth of damage in relation to the strength of the rock, (i.e. its UCS). It can be seen that there is a near linear dependence between the UCS and the depth of the damaged zone. Therefore, it is apparent that the depth of the damaged zone is chiefly controlled by the rock strength and that the influence the pillar width is much less significant.

Table 6-2, Table 6-3 and Table 6-4 present the Numerical Analysis Factors of Safety and the pillar Damage Levels for all the analyses. The results of the individual pillar analyses are presented in Appendix B2 for the "wide range of rock properties" defined as the least favourable, expected and most favourable properties and in Appendix C for the "selected range of rock properties" defined as the more limited range of rock strength values selected for more detailed study with a distribution of GSI values.

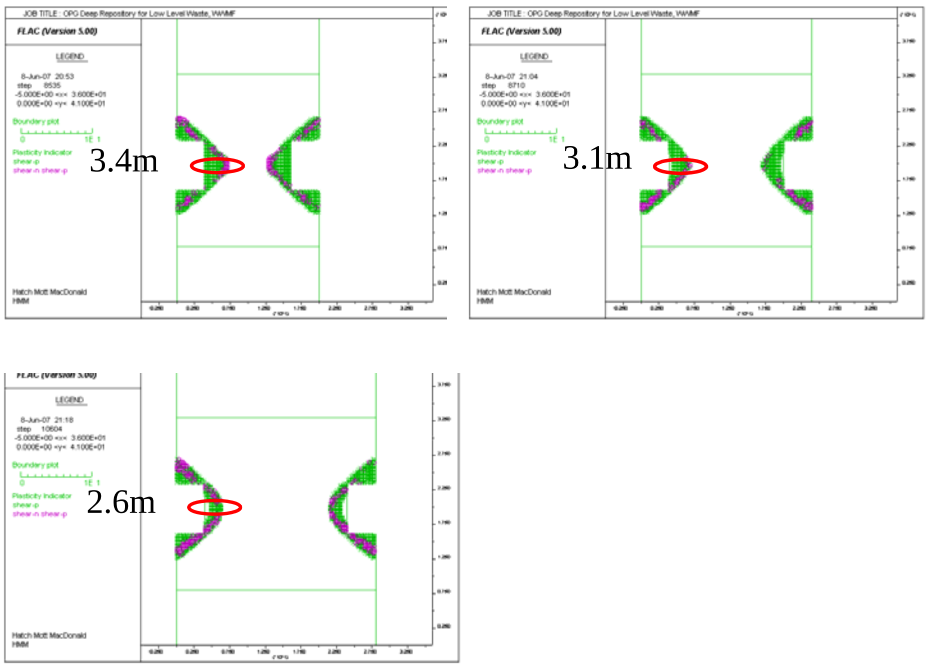


Figure 6-13 – Pillar Model UCS = 60, GSI = 69, Width = 12, 16, 20 m, Depth of Damage.

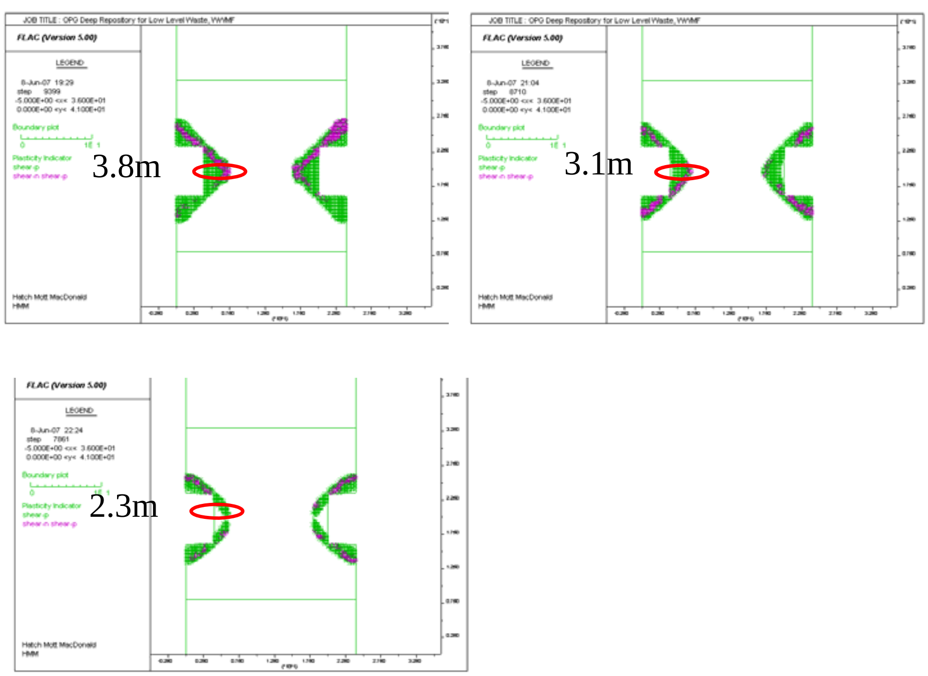


Figure 6-14 – Pillar Model UCS = 48, 60, 72 GSI = 69, Width = 16 m, Depth of Damage

Rock Properties K_0 = 1.5	***UCS intact rock (MPa)***	***Rock Mass Quality (GSI)***	***Values***	***Pillar 8.0m***	***Pillar 12.0m***	***Pillar 14.0m***	***Pillar 15.0m***	***Pillar 16.0m***	***Pillar 18.0m***	***Pillar 20.0m***	***Pillar 22.0m***	***Pillar 24.0m***	***Pillar 28.0m***	***Pillar 40.0m***
Least Favourable	25	66	NAFS				1.0		1.20		1.58		2.45	7.60
			Damage				E		D		D		N/A	N/A
Low End of Selected Range K	48	55	NAFS		1.00	1.12		1.31	1.54	1.82				
			Damage		E	E		D	D	C				
		69	NAFS		1.23	1.50		1.82	2.20	2.68				
			Damage		D	D		C	C	C				
		80	NAFS		1.54	1.90		2.35	2.90	3.58				
			Damage		D	C		C	C	C				
Middle of Selected Range / "Expected" with GSI 69	60	55	NAFS		1.08	1.26		1.50	1.82	2.21				
			Damage		E	D		D	C	C				
		69	NAFS		1.38	1.68	1.87	2.09	2.62	3.28	4.41			
			Damage		D	C	C	C	C	B	N/A			
		80	NAFS		1.67	2.11		2.67	3.38	4.29				
			Damage		D	C		C	C	B				
High End of Selected Range	72	55	NAFS		1.16	1.39		1.78	2.26	2.84				
			Damage		D	D		C	C	B				
		69	NAFS		1.45	1.88		2.45	3.16	4.04				
			Damage		D	C		C	B	B				
		80	NAFS		1.78	2.36		3.12	4.03	5.18				
			Damage		C	C		B	B	B				
Most Favourable	140	80	NAFS	1.43	2.84		4.48		6.70					
			Damage	A	A		A		N/A					

Note: N/A = not evaluated.

Table 6-2 – NAFS and the Level of Damage for Analyzed Cases K_o = 1.50

Hatch Mott MacDonald HATCH CNA Consulting Engineers

Rock Properties $K_0 = 1.0$	***UCS intact rock (MPa)***	***Rock Mass Quality (GSI)***	***Values***	***Pillar 8.0 m***	***Pillar 12.0m***	***Pillar 15 0m***	***Pillar 18.0m***	***Pillar 22.0m***	***Pillar 28.0m***
Least Favourable	25	66	NAFS			1.00	1.22	1.59	2.26
			Damage			E	D	D	N/A
Expected	60	69	NAFS		1.38	1.81	2.32	3.15	
			Damage		D	C	C	N/A	
Most Favourable	140	80	NAFS	1.43	2.42	3.63	4.90		
			Damage	A	A	A	N/A		

Table 6-3 – NAFS and the Level of Damage for Analyzed Cases K_o = 1.00

Rock Properties $K_0 = 2.5$	***UCS intact rock (MPa)***	***Rock Mass Quality (GSI)***	***Values***	***Pillar 8.0 m***	***Pillar 12.0m***	***Pillar 15 0m***	***Pillar 18.0m***	***Pillar 22.0m***	***Pillar 24.0m***
Least Favourable	25	66	NAFS			1.00	1.15	1.46	1.66
			Damage			E	D	C	N/A
Expected	60	69	NAFS		1.29	1.79	2.73	5.12	
			Damage		D	C	B	N/A	
Most Favourable	140	80	NAFS	1.44	3.42	6.11	12.90		
			Damage	A	A	A	N/A		

Table 6-4 – NAFS and the Level of Damage for Analyzed Cases K_o = 2.50

6.6 Pre-Closure (100 year) Model - Impact of Rock Dowels on Results

In order to assess the possible effect of rock dowel reinforcing of the repository room roof on the pillar behaviour, an additional single pillar model analysis was performed. For this analysis the parameters of UCS 60, GSI 69 and K_0 equal to 1.50 for were selected for the rock mass properties. The modelled pillar width was 16m. The assumed roof reinforcing consists of 25 mm diameter dowels with the yield strength of 400 MPa, prestressed to 50% of their yield strength and placed on a 1.5 x 1.5 m grid. The dowels are 5 m long to ensure that they are well anchored into the undamaged zone of the rock.

The analysis showed that the dowels have very little effect on the extent of the plastic zone in the roof and no effect on the pillar behaviour. The likely reason is that the stress changes in the rock from the in-situ pre-excavation stress to post-excavation stress state are very high. The dowels can provide only a rough equivalent of less then 0.1 MPa of a confining pressure to the rock with the assumed size and spacing. This compares to the in-situ stresses that are in the order of 20 MPa. Therefore, the dowels are useful for providing support for possible rock wedges/slabs fall outs as well as holding the damaged rock in place, where it provides confinement to the load carrying portion of the pillar. However, the dowels would have small effect on the extent of damaged rock zone itself.

This exercise was carried out solely for the purpose of assessing the influence of doweling on the extent of the plasticity zones. For the true assessment of doweling requirements a more refined methodology should be employed that models the timing of the rock dowel installation after the excavation and after some degree of stress relaxation following excavation, and not with the rock dowels installed prior to excavation as assumed here. The parameters modeled are:

- Rock-Dowels: 25 mm diameter x 5000 mm Full dowel length bond, 1.5 m x 1.5 m spacing
- UCS = 60, GSI = 69, Pillar Width = 16.0 m

Figures, Figure 6-15 to Figure 6-20, show the comparisons of results with and without roof rock dowels.

Left Picture: <u>Without</u> Rock Dowels **Right Picture: <u>With</u> Rock Dowels**

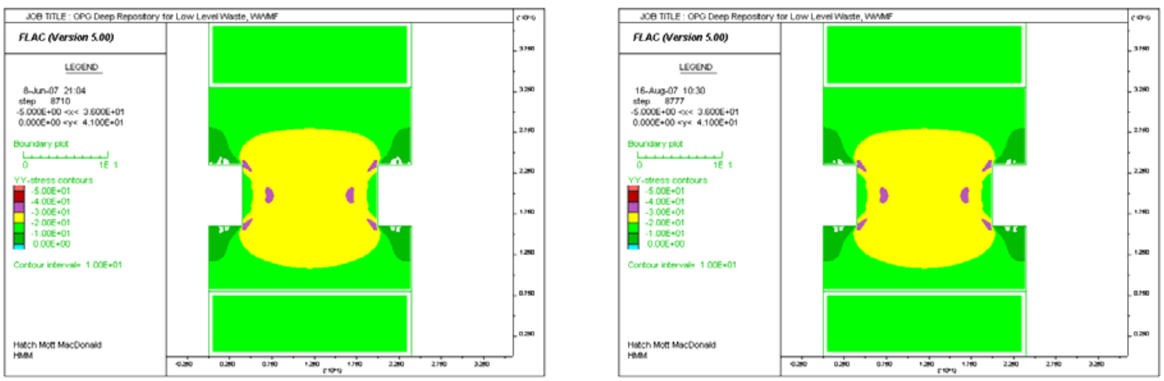


Figure 6-15 – Comparison of Vertical Stresses between Doweled and Undoweled Roofs

Left Picture: <u>Without</u> Rock Dowels **Right Picture: <u>With</u> Rock Dowels**

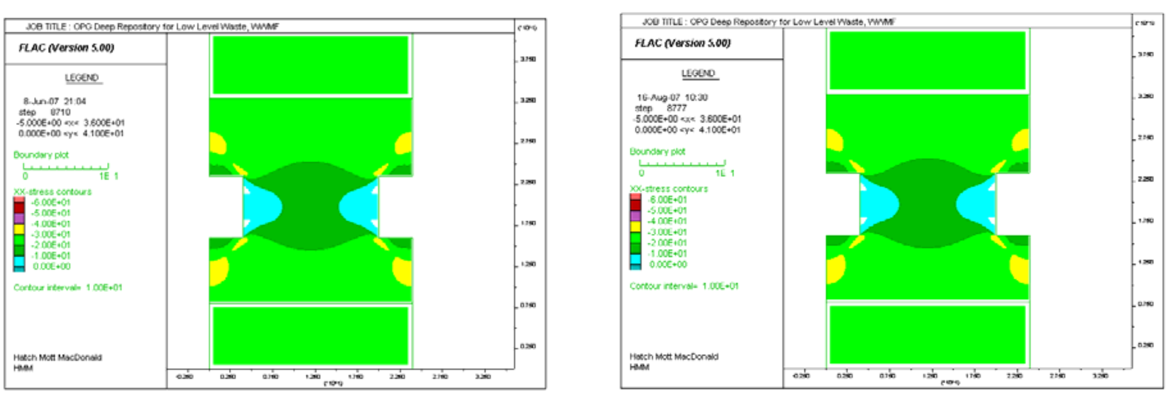


Figure 6-16 – Comparison of Horizontal Stresses between Doweled and Undoweled Roofs

Left Picture: Without Rock Dowels **Right Picture: With Rock Dowels**

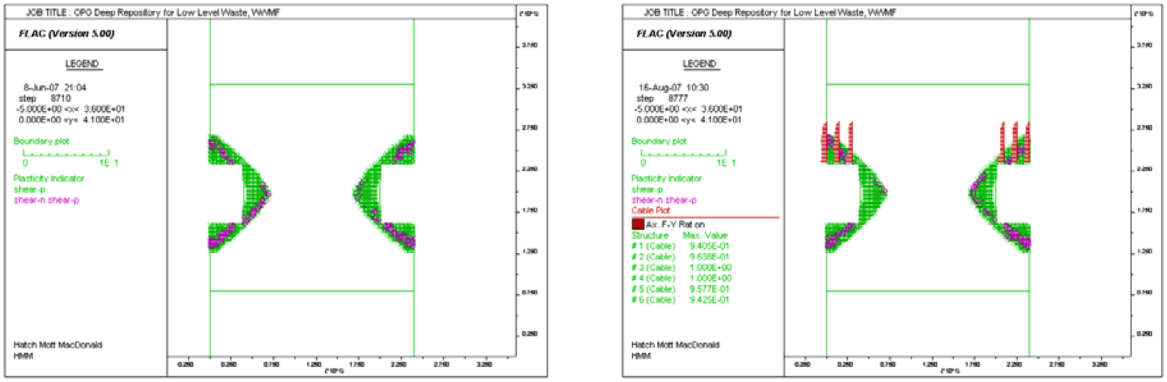


Figure 6-17 – Comparison of Plasticity Indicators, and Rock Dowels Utilisation Ratio

Left Picture: Without Rock Dowels **Right Picture: With Rock Dowels**

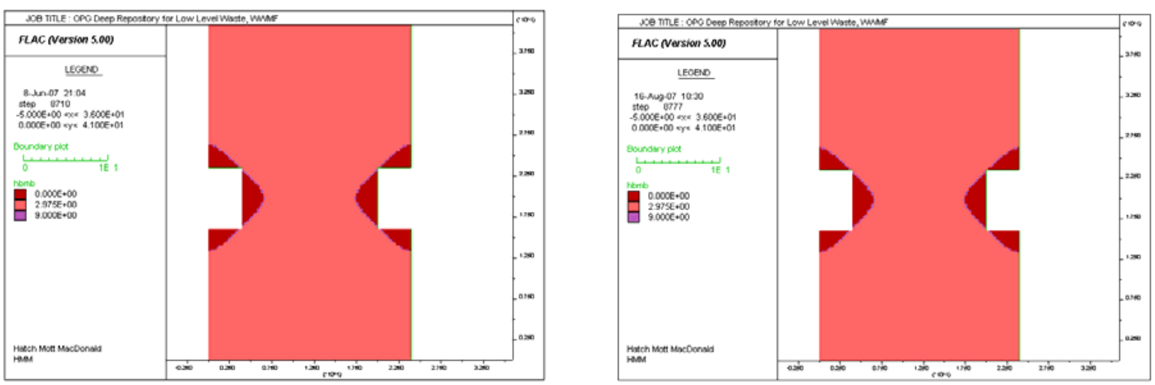


Figure 6-18 – Failure Criteria
(Brittle Failure, Transition, Hoek-Brown Peak Strength)

Left Picture: Without Rock Dowels **Right Picture: With Rock Dowels**

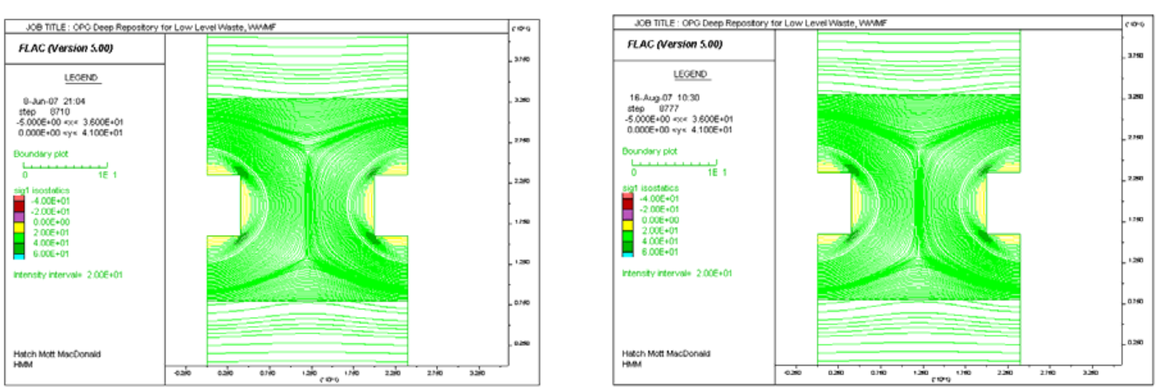


Figure 6-19 – Maximum Principal Stress Trajectories (MPa)

Left Picture: <u>Without</u> Rock Dowels **Right Picture: <u>With</u> Rock Dowels**

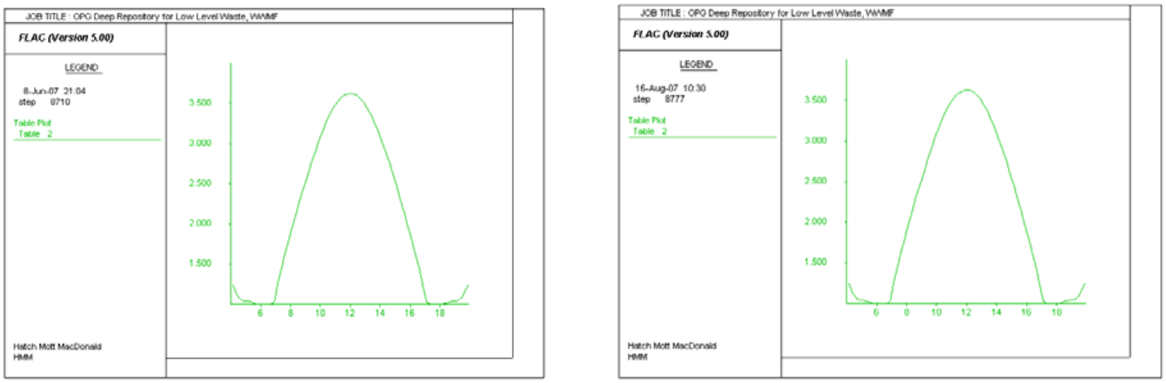


Figure 6-20 – Factor Of Safety Across The Pillar

7. Conclusions

The numerical analyses have provided important input into the pillar width recommendation by analysing a wide range of possible rock property scenarios with a range of possible pillar widths.

The analyses included modified failure envelopes that recognised the brittle behaviour of the rock at low levels of confinement. The zones of plasticity around the openings were clearly shown and for wide pillars were shown to vary only marginally with adjustment to the pillar width. The plastic zones were found to vary significantly with changes in rock strength.

At the pillar widths presently under study, it has been shown that changing K_0 within its potential range has an insignificant effect on the results and therefore the variation in the value of horizontal stresses between the major and minor axes is similarly not significant. This means that there is no impact to the room design from a particular orientation of the room axis and therefore the rooms can be orientated to suit the facility operation without detriment to the room design.

The introduction of roof doweling, that will obviously be required, was investigated and shown to have an insignificant influence on the prediction of zones of plasticity around the openings.

In future phases of the project, it will be appropriate to rerun the analyses with updated room geometry as well as rock properties obtained from the site geotechnical investigation. At that point it may be more appropriate to incorporate explicit modeling of the bedding planes.

8. References

Bieniawski, Z.T., Engineering Rock Mass Classifications, JohnWiley & Sons, New York, 1989.

Brady, B.H.G., and Brown, E.T. Rock Mechanics for Underground Mining, George Allen & Unwin, London, 1985.

Hoek, E. and Brown E.T., "Practical Estimates of Rock Mass Strength", *Int. J. Rock Mech.& Mining Sci. & Geomechanics Abstracts*, 34(8), pp. 1165 - 1186, 1997

Lam, T., Martin, D. and McCreath, D., "Characterising the Geomechanics Properties of Sedimentary Rocks for the DGR Excavations", Canadian Geotechnical Society 2007 Conference, Ottawa 2007.

Martin C.D., Kaiser P.K., McCreath D.R., Hoek Brown Parameters for Predicting the Depth of Brittle Failure around Tunnels, Canadian Geotechnical Journal 36 136-151, 1999.

Appendix A

Basis for Assumed Rock Mass Classification

Rock Mass Rating System (RMR) (After Bieniawski 1989) **OPG Geologic Repository - Least Favourable Values**

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

	Parameter		Range of values					
1	Strength of intact rock material	Point-load strength index	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range - uniaxial compressive test is preferred	
		Uniaxial comp.strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa / 1 - 5 MPa / <1 MPa	
		Rating	**15**	**12**	**7**	**4**	**2** / **1** / **0**	**4**
2	Drill core Quality *RQD*		90% - 100%	75% - 90%	50% - 75%	25% - 50%	<25%	
	Rating		**20**	**17**	**13**	**8**	**3**	**20**
3	Spacing of discontinuities		>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm	
	Rating		**20**	**15**	**10**	**8**	**5**	**15**
4	Condition of discontinuities (See E)		Very rough surfaces. Not continuous. No separation. Unweathered wall rock	Slightly rough surfaces. Separation < 1 mm. Slightly weathered walls	Slightly rough surfaces. Separation < 1 mm. Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge > 5 mm thick or Separation > 5 mm Continuous	
	Rating		**30**	**25**	**20**	**10**	**0**	
5	Ground water	Inflow per 10 m tunnel length (l/m)	None	< 10	10 - 25	25 -125	> 125	
		(Joint water press)/ (Major principal stress)	0	< 0.1	0.1 - 0.2	0.2 - 0.5	> 0.5	
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing	
	Rating		**15**	**10**	**7**	**4**	**0**	**15**

B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)

Strike and dip orientations		Very Favourable	Favourable	Fair	Unfavourable	Very unfavourable	
Ratings	**Tunnels & mines**	**0**	**-2**	**-5**	**-10**	**-12**	**0**
	Foundations	**0**	**-2**	**-7**	**-15**	**-25**	
	Slopes	**0**	**-5**	**-25**	**-50**		

C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS

Rating	100 - 81	80 - 61	60 - 41	40 - 21	< 21
Class number	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

D. MEANING OF ROCK CLASSES

Class number	I	II	III	IV	V
Average stand-up time	20 years for 15 m span	1year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 mins for 1 m span
Cohesion of rock mass (MPa)	>400	300 - 400	200 - 300	100 - 200	<100
Friction angle of rock mass (deg)	> 45	35 - 45	25 - 35	15 - 25	< 15

E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY CONDITIONS

Discontinuity length persistence	< 1 m	1 -3 m	3 -10 m	10 - 20 m	> 20 m	
Rating	**6**	**4**	**2**	**1**	**0**	**0**
Separation (aperture)	None	< 0.1 mm	0.1 -1.0 mm	1 - 5 mm	> 5 mm	
Rating	**6**	**5**	**4**	**1**	**0**	**4**
Roughness	Very rough	Rough	Slightly rough	Smooth	Slickensided	
Rating	**6**	**4**	**3**	**1**	**0**	**3**
Infilling (gouge)	None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5mm	
Rating	**5**	**4**	**2**	**2**	**0**	**4**
Weathering	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed	
Rating	**6**	**5**	**3**	**1**	**0**	**6**

F. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATION IN TUNNELLING**

Strike perpendicular to tunnel axis		Strike parallel to tunnel axis	
Drive with dip - Dip 45 to 90	Drive with dip - Dip 20 - 45	Dip 45 - 90	Dip 20 - 45
Very favourable	**Favourable**	**Very favourable**	**Fair**
Drive against dip - Dip 45 to 90	Drive against dip - Dip 20 - 45	Dip 0 to 20 - Irrespective of strike*	
Fair	**Unfavourable**	**Fair**	

* Some conditions are mutually exclusive. For example, if infilling is present, the roughness of the surface will be overshadowed by the influence of the gouge. In such cases use A.4 directly

** Modified after Wickham et al (1972)

RMR **71**
GSI **66**

Rock Mass Rating System (RMR) (After Bieniawski 1989) **OPG Geologic Repository - Low End Low Quality Values**

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

	Parameter		Range of values							Selected
1	Strength of intact rock material	Point-load strength index	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range - uniaxial compressive test is preferred			
		Uniaxial comp.strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa	1 - 5 MPa	<1 MPa	
		Rating	**15**	**12**	**7**	**4**	**2**	**1**	**0**	**4**
2	Drill core Quality *RQD*		90% - 100%	75% - 90%	50% - 75%	25% - 50%	<25%			
		Rating	**20**	**17**	**13**	**8**	**3**			**17**
3	Spacing of discontinuities		>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm			
		Rating	**20**	**15**	**10**	**8**	**5**			**8**
4	Condition of discontinuities (See E)		Very rough surfaces. Not continuous. No separation. Unweathered wall rock	Slightly rough surfaces. Separation < 1 mm. Slightly weathered walls	Slightly rough surfaces. Separation < 1 mm. Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge > 5 mm thick or Separation > 5 mm Continuous			
		Rating	**30**	**25**	**20**	**10**	**0**			
5	Ground water	Inflow per 10 m tunnel length (l/m)	None	< 10	10 - 25	25 -125	> 125			
		(Joint water press)/ (Major principal stress)	0	< 0.1	0.1 - 0.2	0.2 - 0.5	> 0.5			
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing			
		Rating	**15**	**10**	**7**	**4**	**0**			**15**

B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)

Strike and dip orientations		Very Favourable	Favourable	Fair	Unfavourable	Very unfavourable	Selected
Ratings	**Tunnels & mines**	**0**	**-2**	**-5**	**-10**	**-12**	**0**
	Foundations	**0**	**-2**	**-7**	**-15**	**-25**	
	Slopes	**0**	**-5**	**-25**	**-50**		

C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS

Rating	100 - 81	80 - 61	60 - 41	40 - 21	< 21
Class number	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

D. MEANING OF ROCK CLASSES

Class number	I	II	III	IV	V
Average stand-up time	20 years for 15 m span	1year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 mins for 1 m span
Cohesion of rock mass (MPa)	>400	300 - 400	200 - 300	100 - 200	<100
Friction angle of rock mass (deg)	> 45	35 - 45	25 - 35	15 - 25	< 15

E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY CONDITIONS

						Selected
Discontinuity length persistence	< 1 m	1 -3 m	3 -10 m	10 - 20 m	> 20 m	
Rating	**6**	**4**	**2**	**1**	**0**	**1**
Separation (aperture)	None	< 0.1 mm	0.1 -1.0 mm	1 - 5 mm	> 5 mm	
Rating	**6**	**5**	**4**	**1**	**0**	**4**
Roughness	Very rough	Rough	Slightly rough	Smooth	Slickensided	
Rating	**6**	**4**	**3**	**1**	**0**	**3**
Infilling (gouge)	None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5mm	
Rating	**5**	**4**	**2**	**2**	**0**	**2**
Weathering	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed	
Rating	**6**	**5**	**3**	**1**	**0**	**6**

F. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATION IN TUNNELLING**

Strike perpendicular to tunnel axis		Strike parallel to tunnel axis	
Drive with dip - Dip 45 to 90	Drive with dip - Dip 20 - 45	Dip 45 - 90	Dip 20 - 45
Very favourable	**Favourable**	**Very favourable**	**Fair**
Drive against dip - Dip 45 to 90	Drive against dip - Dip 20 - 45	Dip 0 to 20 - Irrespective of strike*	
Fair	**Unfavourable**	**Fair**	

* Some conditions are mutually exclusive. For example, if infilling is present, the roughness of the surface will be overshadowed by the influence of the gouge. In such cases use A.4 directly

** Modified after Wickham et al (1972)

RMR 60
GSI 55

Rock Mass Rating System (RMR) (After Bieniawski 1989) **OPG Geologic Repository - Low End Med Quality Values**

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

	Parameter		Range of values							
1	Strength of intact rock material	Point-load strength index	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range - uniaxial compressive test is preferred			
		Uniaxial comp.strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa	1 - 5 MPa	<1 MPa	
		Rating	**15**	**12**	**7**	**4**	**2**	**1**	**0**	**4**
2	Drill core Quality *RQD*		90% - 100%	75% - 90%	50% - 75%	25% - 50%	<25%			
		Rating	**20**	**17**	**13**	**8**	**3**			**20**
3	Spacing of discontinuities		>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm			
		Rating	**20**	**15**	**10**	**8**	**5**			**15**
4	Condition of discontinuities (See E)		Very rough surfaces. Not continuous. No separation. Unweathered wall rock	Slightly rough surfaces. Separation < 1 mm. Slightly weathered walls	Slightly rough surfaces. Separation < 1 mm. Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge > 5 mm thick or Separation > 5 mm Continuous			
		Rating	**30**	**25**	**20**	**10**	**0**			
5	Ground water	Inflow per 10 m tunnel length (l/m)	None	< 10	10 - 25	25 -125	> 125			
		(Joint water press)/ (Major principal stress)	0	< 0.1	0.1 - 0.2	0.2 - 0.5	> 0.5			
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing			
		Rating	**15**	**10**	**7**	**4**	**0**			**15**

B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)

Strike and dip orientations		Very Favourable	Favourable	Fair	Unfavourable	Very unfavourable	
Ratings	**Tunnels & mines**	**0**	**-2**	**-5**	**-10**	**-12**	**0**
	Foundations	**0**	**-2**	**-7**	**-15**	**-25**	
	Slopes	**0**	**-5**	**-25**	**-50**		

C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS

Rating	100 - 81	80 - 61	60 - 41	40 - 21	< 21
Class number	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

D. MEANING OF ROCK CLASSES

Class number	I	II	III	IV	V
Average stand-up time	20 years for 15 m span	1year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 mins for 1 m span
Cohesion of rock mass (MPa)	>400	300 - 400	200 - 300	100 - 200	<100
Friction angle of rock mass (deg)	> 45	35 - 45	25 - 35	15 - 25	< 15

E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY CONDITIONS

Discontinuity length persistence	< 1 m	1 -3 m	3 -10 m	10 - 20 m	> 20 m	
Rating	**6**	**4**	**2**	**1**	**0**	**1**
Separation (aperture)	None	< 0.1 mm	0.1 -1.0 mm	1 - 5 mm	> 5 mm	
Rating	**6**	**5**	**4**	**1**	**0**	**5**
Roughness	Very rough	Rough	Slightly rough	Smooth	Slickensided	
Rating	**6**	**4**	**3**	**1**	**0**	**4**
Infilling (gouge)	None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5mm	
Rating	**5**	**4**	**2**	**2**	**0**	**4**
Weathering	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed	
Rating	**6**	**5**	**3**	**1**	**0**	**6**

F. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATION IN TUNNELLING**

Strike perpendicular to tunnel axis		Strike parallel to tunnel axis	
Drive with dip - Dip 45 to 90	Drive with dip - Dip 20 - 45	Dip 45 - 90	Dip 20 - 45
Very favourable	**Favourable**	**Very favourable**	**Fair**
Drive against dip - Dip 45 to 90	Drive against dip - Dip 20 - 45	Dip 0 to 20 - Irrespective of strike*	
Fair	**Unfavourable**	**Fair**	

* Some conditions are mutually exclusive. For example, if infilling is present, the roughness of the surface will be overshadowed by the influence of the gouge. In such cases use A.4 directly

** Modified after Wickham et al (1972)

RMR **74**
GSI **69**

Rock Mass Rating System (RMR) (After Bieniawski 1989) **OPG Geologic Repository - Low End High Quality Values**

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS									
	Parameter			Range of values					
1	Strength of intact rock material	Point-load strength index		>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range - uniaxial compressive test is preferred	
		Uniaxial comp.strength		>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa / 1 - 5 MPa / <1 MPa	
		Rating		**15**	**12**	**7**	**4**	**2** / **1** / **0**	**4**
2	Drill core Quality *RQD*			90% - 100%	75% - 90%	50% - 75%	25% - 50%	<25%	
	Rating			**20**	**17**	**13**	**8**	**3**	**20**
3	Spacing of discontinuities			>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm	
	Rating			**20**	**15**	**10**	**8**	**5**	**20**
4	Condition of discontinuities (See E)			Very rough surfaces. Not continuous. No separation. Unweathered wall rock	Slightly rough surfaces. Separation < 1 mm. Slightly weathered walls	Slightly rough surfaces. Separation < 1 mm. Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge > 5 mm thick or Separation > 5 mm Continuous	
	Rating			**30**	**25**	**20**	**10**	**0**	
5	Ground water	Inflow per 10 m tunnel length (l/m)		None	< 10	10 - 25	25 -125	> 125	
		(Joint water press)/ (Major principal stress)		0	< 0.1	0.1 - 0.2	0.2 - 0.5	> 0.5	
		General conditions		Completely dry	Damp	Wet	Dripping	Flowing	
	Rating			**15**	**10**	**7**	**4**	**0**	**15**
B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)									
Strike and dip orientations				Very Favourable	Favourable	Fair	Unfavourable	Very unfavourable	
Ratings	**Tunnels & mines**			**0**	**-2**	**-5**	**-10**	**-12**	**0**
	Foundations			**0**	**-2**	**-7**	**-15**	**-25**	
	Slopes			**0**	**-5**	**-25**	**-50**		
C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS									
Rating				100 - 81	80 - 61	60 - 41	40 - 21	< 21	
Class number				I	II	III	IV	V	
Description				Very good rock	Good rock	Fair rock	Poor rock	Very poor rock	
D. MEANING OF ROCK CLASSES									
Class number				I	II	III	IV	V	
Average stand-up time				20 years for 15 m span	1year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 mins for 1 m span	
Cohesion of rock mass (MPa)				>400	300 - 400	200 - 300	100 - 200	<100	
Friction angle of rock mass (deg)				> 45	35 - 45	25 - 35	15 - 25	< 15	
E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY CONDITIONS									
Discontinuity length persistence				< 1 m	1 -3 m	3 -10 m	10 - 20 m	> 20 m	
Rating				**6**	**4**	**2**	**1**	**0**	**6**
Separation (aperture)				None	< 0.1 mm	0.1 -1.0 mm	1 - 5 mm	> 5 mm	
Rating				**6**	**5**	**4**	**1**	**0**	**6**
Roughness				Very rough	Rough	Slightly rough	Smooth	Slickensided	
Rating				**6**	**4**	**3**	**1**	**0**	**4**
Infilling (gouge)				None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5mm	
Rating				**5**	**4**	**2**	**2**	**0**	**4**
Weathering				Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed	
Rating				**6**	**5**	**3**	**1**	**0**	**6**

F. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATION IN TUNNELLING**			
Strike perpendicular to tunnel axis		Strike parallel to tunnel axis	
Drive with dip - Dip 45 to 90	Drive with dip - Dip 20 - 45	Dip 45 - 90	Dip 20 - 45
Very favourable	**Favourable**	**Very favourable**	**Fair**
Drive against dip - Dip 45 to 90	Drive against dip - Dip 20 - 45	Dip 0 to 20 - Irrespective of strike*	
Fair	**Unfavourable**	**Fair**	

* Some conditions are mutually exclusive. For example, if infilling is present, the roughness of the surface will be overshadowed by the influence of the gouge. In such cases use A.4 directly

** Modified after Wickham et al (1972)

RMR 85
GSI 80

Rock Mass Rating System (RMR) (After Bieniawski 1989) **OPG Geologic Repository - Expected Low Qual Values**

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

	Parameter		Range of values							
1	Strength of intact rock material	Point-load strength index	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range - uniaxial compressive test is preferred			
		Uniaxial comp.strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa	1 - 5 MPa	<1 MPa	
		Rating	**15**	**12**	**7**	**4**	**2**	**1**	**0**	**7**
2	Drill core Quality *RQD*		90% - 100%	75% - 90%	50% - 75%	25% - 50%	<25%			
	Rating		**20**	**17**	**13**	**8**	**3**			**13**
3	Spacing of discontinuities		>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm			
	Rating		**20**	**15**	**10**	**8**	**5**			**10**
4	Condition of discontinuities (See E)		Very rough surfaces. Not continuous. No separation. Unweathered wall rock	Slightly rough surfaces. Separation < 1 mm. Slightly weathered walls	Slightly rough surfaces. Separation < 1 mm. Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge > 5 mm thick or Separation > 5 mm Continuous			
	Rating		**30**	**25**	**20**	**10**	**0**			
5	Ground water	Inflow per 10 m tunnel length (l/m)	None	< 10	10 - 25	25 -125	> 125			
		(Joint water press)/ (Major principal stress)	0	< 0.1	0.1 - 0.2	0.2 - 0.5	> 0.5			
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing			
	Rating		**15**	**10**	**7**	**4**	**0**			**15**

B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)

Strike and dip orientations		Very Favourable	Favourable	Fair	Unfavourable	Very unfavourable	
Ratings	**Tunnels & mines**	**0**	**-2**	**-5**	**-10**	**-12**	**0**
	Foundations	**0**	**-2**	**-7**	**-15**	**-25**	
	Slopes	**0**	**-5**	**-25**	**-50**		

C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS

Rating	100 - 81	80 - 61	60 - 41	40 - 21	< 21
Class number	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

D. MEANING OF ROCK CLASSES

Class number	I	II	III	IV	V
Average stand-up time	20 years for 15 m span	1year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 mins for 1 m span
Cohesion of rock mass (MPa)	>400	300 - 400	200 - 300	100 - 200	<100
Friction angle of rock mass (deg)	> 45	35 - 45	25 - 35	15 - 25	< 15

E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY CONDITIONS

Discontinuity length persistence	< 1 m	1 -3 m	3 -10 m	10 - 20 m	> 20 m	
Rating	**6**	**4**	**2**	**1**	**0**	**0**
Separation (aperture)	None	< 0.1 mm	0.1 -1.0 mm	1 - 5 mm	> 5 mm	
Rating	**6**	**5**	**4**	**1**	**0**	**4**
Roughness	Very rough	Rough	Slightly rough	Smooth	Slickensided	
Rating	**6**	**4**	**3**	**1**	**0**	**3**
Infilling (gouge)	None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5mm	
Rating	**5**	**4**	**2**	**2**	**0**	**2**
Weathering	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed	
Rating	**6**	**5**	**3**	**1**	**0**	**6**

F. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATION IN TUNNELLING**

Strike perpendicular to tunnel axis		Strike parallel to tunnel axis	
Drive with dip - Dip 45 to 90	Drive with dip - Dip 20 - 45	Dip 45 - 90	Dip 20 - 45
Very favourable	**Favourable**	**Very favourable**	**Fair**
Drive against dip - Dip 45 to 90	Drive against dip - Dip 20 - 45	Dip 0 to 20 - Irrespective of strike*	
Fair	**Unfavourable**	**Fair**	

* Some conditions are mutually exclusive. For example, if infilling is present, the roughness of the surface will be overshadowed by the influence of the gouge. In such cases use A.4 directly

** Modified after Wickham et al (1972)

RMR **60**
GSI **55**

Rock Mass Rating System (RMR) (After Bieniawski 1989) **OPG Geologic Repository - Expected Med Quality Values**

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

	Parameter		Range of values					
1	Strength of intact rock material	Point-load strength index	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range - uniaxial compressive test is preferred	
		Uniaxial comp.strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa / 1 - 5 MPa / <1 MPa	
		Rating	**15**	**12**	**7**	**4**	**2** / **1** / **0**	**7**
2	Drill core Quality *RQD*		90% - 100%	75% - 90%	50% - 75%	25% - 50%	<25%	
		Rating	**20**	**17**	**13**	**8**	**3**	**20**
3	Spacing of discontinuities		>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm	
		Rating	**20**	**15**	**10**	**8**	**5**	**15**
4	Condition of discontinuities (See E)		Very rough surfaces. Not continuous. No separation. Unweathered wall rock	Slightly rough surfaces. Separation < 1 mm. Slightly weathered walls	Slightly rough surfaces. Separation < 1 mm. Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge > 5 mm thick or Separation > 5 mm Continuous	
		Rating	**30**	**25**	**20**	**10**	**0**	
5	Ground water	Inflow per 10 m tunnel length (l/m)	None	< 10	10 - 25	25 -125	> 125	
		(Joint water press)/ (Major principal stress)	0	< 0.1	0.1 - 0.2	0.2 - 0.5	> 0.5	
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing	
		Rating	**15**	**10**	**7**	**4**	**0**	**15**

B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)

Strike and dip orientations		Very Favourable	Favourable	Fair	Unfavourable	Very unfavourable	
Ratings	**Tunnels & mines**	**0**	**-2**	**-5**	**-10**	**-12**	**0**
	Foundations	**0**	**-2**	**-7**	**-15**	**-25**	
	Slopes	**0**	**-5**	**-25**	**-50**		

C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS

Rating	100 - 81	80 - 61	60 - 41	40 - 21	< 21
Class number	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

D. MEANING OF ROCK CLASSES

Class number	I	II	III	IV	V
Average stand-up time	20 years for 15 m span	1year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 mins for 1 m span
Cohesion of rock mass (MPa)	>400	300 - 400	200 - 300	100 - 200	<100
Friction angle of rock mass (deg)	> 45	35 - 45	25 - 35	15 - 25	< 15

E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY CONDITIONS

Discontinuity length persistence	< 1 m	1 -3 m	3 -10 m	10 - 20 m	> 20 m	
Rating	**6**	**4**	**2**	**1**	**0**	**0**
Separation (aperture)	None	< 0.1 mm	0.1 -1.0 mm	1 - 5 mm	> 5 mm	
Rating	**6**	**5**	**4**	**1**	**0**	**4**
Roughness	Very rough	Rough	Slightly rough	Smooth	Slickensided	
Rating	**6**	**4**	**3**	**1**	**0**	**3**
Infilling (gouge)	None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5mm	
Rating	**5**	**4**	**2**	**2**	**0**	**4**
Weathering	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed	
Rating	**6**	**5**	**3**	**1**	**0**	**6**

F. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATION IN TUNNELLING**

Strike perpendicular to tunnel axis		Strike parallel to tunnel axis	
Drive with dip - Dip 45 to 90	Drive with dip - Dip 20 - 45	Dip 45 - 90	Dip 20 - 45
Very favourable	**Favourable**	**Very favourable**	**Fair**
Drive against dip - Dip 45 to 90	Drive against dip - Dip 20 - 45	Dip 0 to 20 - Irrespective of strike*	
Fair	**Unfavourable**	**Fair**	

* Some conditions are mutually exclusive. For example, if infilling is present, the roughness of the surface will be overshadowed by the influence of the gouge. In such cases use A.4 directly

** Modified after Wickham et al (1972)

RMR **74**
GSI **69**

Rock Mass Rating System (RMR) (After Bieniawski 1989) **OPG Geologic Repository - Expected High Qual Values**

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

	Parameter		Range of values					
1	Strength of intact rock material	Point-load strength index	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range - uniaxial compressive test is preferred	
		Uniaxial comp.strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa / 1 - 5 MPa / <1 MPa	
	Rating		**15**	**12**	**7**	**4**	**2** / **1** / **0**	**7**
2	Drill core Quality *RQD*		90% - 100%	75% - 90%	50% - 75%	25% - 50%	<25%	
	Rating		**20**	**17**	**13**	**8**	**3**	**20**
3	Spacing of discontinuities		>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm	
	Rating		**20**	**15**	**10**	**8**	**5**	**20**
4	Condition of discontinuities (See E)		Very rough surfaces. Not continuous. No separation. Unweathered wall rock	Slightly rough surfaces. Separation < 1 mm. Slightly weathered walls	Slightly rough surfaces. Separation < 1 mm. Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge > 5 mm thick or Separation > 5 mm Continuous	
	Rating		**30**	**25**	**20**	**10**	**0**	
5	Ground water	Inflow per 10 m tunnel length (l/m)	None	< 10	10 - 25	25 -125	> 125	
		(Joint water press)/ (Major principal stress)	0	< 0.1	0.1 - 0.2	0.2 - 0.5	> 0.5	
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing	
	Rating		**15**	**10**	**7**	**4**	**0**	**15**

B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)

Strike and dip orientations		Very Favourable	Favourable	Fair	Unfavourable	Very unfavourable	
Ratings	**Tunnels & mines**	**0**	**-2**	**-5**	**-10**	**-12**	**0**
	Foundations	**0**	**-2**	**-7**	**-15**	**-25**	
	Slopes	**0**	**-5**	**-25**	**-50**		

C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS

Rating	100 - 81	80 - 61	60 - 41	40 - 21	< 21
Class number	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

D. MEANING OF ROCK CLASSES

Class number	I	II	III	IV	V
Average stand-up time	20 years for 15 m span	1year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 mins for 1 m span
Cohesion of rock mass (MPa)	>400	300 - 400	200 - 300	100 - 200	<100
Friction angle of rock mass (deg)	> 45	35 - 45	25 - 35	15 - 25	< 15

E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY CONDITIONS

Discontinuity length persistence	< 1 m	1 -3 m	3 -10 m	10 - 20 m	> 20 m	
Rating	**6**	**4**	**2**	**1**	**0**	**4**
Separation (aperture)	None	< 0.1 mm	0.1 -1.0 mm	1 - 5 mm	> 5 mm	
Rating	**6**	**5**	**4**	**1**	**0**	**5**
Roughness	Very rough	Rough	Slightly rough	Smooth	Slickensided	
Rating	**6**	**4**	**3**	**1**	**0**	**4**
Infilling (gouge)	None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5mm	
Rating	**5**	**4**	**2**	**2**	**0**	**4**
Weathering	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed	
Rating	**6**	**5**	**3**	**1**	**0**	**6**

F. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATION IN TUNNELLING**

Strike perpendicular to tunnel axis		Strike parallel to tunnel axis	
Drive with dip - Dip 45 to 90	Drive with dip - Dip 20 - 45	Dip 45 - 90	Dip 20 - 45
Very favourable	**Favourable**	**Very favourable**	**Fair**
Drive against dip - Dip 45 to 90	Drive against dip - Dip 20 - 45	Dip 0 to 20 - Irrespective of strike*	
Fair	**Unfavourable**	**Fair**	

* Some conditions are mutually exclusive. For example, if infilling is present, the roughness of the surface will be overshadowed by the influence of the gouge. In such cases use A.4 directly

** Modified after Wickham et al (1972)

RMR **85**
GSI **80**

Rock Mass Rating System (RMR) (After Bieniawski 1989) **OPG Geologic Repository - High End Low Values**

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

	Parameter		Range of values							
1	Strength of intact rock material	Point-load strength index	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range - uniaxial compressive test is preferred			
		Uniaxial comp.strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa	1 - 5 MPa	<1 MPa	
		Rating	**15**	**12**	**7**	**4**	**2**	**1**	**0**	**7**
2	Drill core Quality *RQD*		90% - 100%	75% - 90%	50% - 75%	25% - 50%	<25%			
	Rating		**20**	**17**	**13**	**8**	**3**			**13**
3	Spacing of discontinuities		>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm			
	Rating		**20**	**15**	**10**	**8**	**5**			**10**
4	Condition of discontinuities (See E)		Very rough surfaces. Not continuous. No separation. Unweathered wall rock	Slightly rough surfaces. Separation < 1 mm. Slightly weathered walls	Slightly rough surfaces. Separation < 1 mm. Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge > 5 mm thick or Separation > 5 mm Continuous			
	Rating		**30**	**25**	**20**	**10**	**0**			
5	Ground water	Inflow per 10 m tunnel length (l/m)	None	< 10	10 - 25	25 -125	> 125			
		(Joint water press)/ (Major principal stress)	0	< 0.1	0.1 - 0.2	0.2 - 0.5	> 0.5			
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing			
	Rating		**15**	**10**	**7**	**4**	**0**			**15**

B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)

Strike and dip orientations		Very Favourable	Favourable	Fair	Unfavourable	Very unfavourable	
Ratings	**Tunnels & mines**	**0**	**-2**	**-5**	**-10**	**-12**	**0**
	Foundations	**0**	**-2**	**-7**	**-15**	**-25**	
	Slopes	**0**	**-5**	**-25**	**-50**		

C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS

Rating	100 - 81	80 - 61	60 - 41	40 - 21	< 21
Class number	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

D. MEANING OF ROCK CLASSES

Class number	I	II	III	IV	V
Average stand-up time	20 years for 15 m span	1year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 mins for 1 m span
Cohesion of rock mass (MPa)	>400	300 - 400	200 - 300	100 - 200	<100
Friction angle of rock mass (deg)	> 45	35 - 45	25 - 35	15 - 25	< 15

E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY CONDITIONS

Discontinuity length persistence	< 1 m	1 -3 m	3 -10 m	10 - 20 m	> 20 m	
Rating	**6**	**4**	**2**	**1**	**0**	**0**
Separation (aperture)	None	< 0.1 mm	0.1 -1.0 mm	1 - 5 mm	> 5 mm	
Rating	**6**	**5**	**4**	**1**	**0**	**4**
Roughness	Very rough	Rough	Slightly rough	Smooth	Slickensided	
Rating	**6**	**4**	**3**	**1**	**0**	**3**
Infilling (gouge)	None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5mm	
Rating	**5**	**4**	**2**	**2**	**0**	**2**
Weathering	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed	
Rating	**6**	**5**	**3**	**1**	**0**	**6**

F. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATION IN TUNNELLING**

Strike perpendicular to tunnel axis		Strike parallel to tunnel axis	
Drive with dip - Dip 45 to 90	Drive with dip - Dip 20 - 45	Dip 45 - 90	Dip 20 - 45
Very favourable	**Favourable**	**Very favourable**	**Fair**
Drive against dip - Dip 45 to 90	Drive against dip - Dip 20 - 45	Dip 0 to 20 - Irrespective of strike*	
Fair	**Unfavourable**	**Fair**	

* Some conditions are mutually exclusive. For example, if infilling is present, the roughness of the surface will be overshadowed by the influence of the gouge. In such cases use A.4 directly

** Modified after Wickham et al (1972)

RMR **60**
GSI **55**

Hatch Mott MacDonald HATCH™ CNA Consulting Engineers

Rock Mass Rating System (RMR) (After Bieniawski 1989) **OPG Geologic Repository - High End Med Values**

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS								
Parameter			Range of values					
1	Strength of intact rock material	Point-load strength index	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range - uniaxial compressive test is preferred	
		Uniaxial comp.strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa / 1 - 5 MPa / <1 MPa	
		Rating	**15**	**12**	**7**	**4**	**2** / **1** / **0**	**7**
2	Drill core Quality *RQD*		90% - 100%	75% - 90%	50% - 75%	25% - 50%	<25%	
	Rating		**20**	**17**	**13**	**8**	**3**	**17**
3	Spacing of discontinuities		>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm	
	Rating		**20**	**15**	**10**	**8**	**5**	**15**
4	Condition of discontinuities (See E)		Very rough surfaces. Not continuous. No separation. Unweathered wall rock	Slightly rough surfaces. Separation < 1 mm. Slightly weathered walls	Slightly rough surfaces. Separation < 1 mm. Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge > 5 mm thick or Separation > 5 mm Continuous	
	Rating		**30**	**25**	**20**	**10**	**0**	
5	Ground water	Inflow per 10 m tunnel length (l/m)	None	< 10	10 - 25	25 -125	> 125	
		(Joint water press)/ (Major principal stress)	0	< 0.1	0.1 - 0.2	0.2 - 0.5	> 0.5	
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing	
	Rating		**15**	**10**	**7**	**4**	**0**	**15**
B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)								
Strike and dip orientations			Very Favourable	Favourable	Fair	Unfavourable	Very unfavourable	
Ratings	**Tunnels & mines**		**0**	**-2**	**-5**	**-10**	**-12**	**0**
	Foundations		**0**	**-2**	**-7**	**-15**	**-25**	
	Slopes		**0**	**-5**	**-25**	**-50**		
C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS								
Rating			100 - 81	80 - 61	60 - 41	40 - 21	< 21	
Class number			I	II	III	IV	V	
Description			Very good rock	Good rock	Fair rock	Poor rock	Very poor rock	
D. MEANING OF ROCK CLASSES								
Class number			I	II	III	IV	V	
Average stand-up time			20 years for 15 m span	1year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 mins for 1 m span	
Cohesion of rock mass (MPa)			>400	300 - 400	200 - 300	100 - 200	<100	
Friction angle of rock mass (deg)			> 45	35 - 45	25 - 35	15 - 25	< 15	
E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY CONDITIONS								
Discontinuity length persistence			< 1 m	1 -3 m	3 -10 m	10 - 20 m	> 20 m	
Rating			**6**	**4**	**2**	**1**	**0**	**1**
Separation (aperture)			None	< 0.1 mm	0.1 -1.0 mm	1 - 5 mm	> 5 mm	
Rating			**6**	**5**	**4**	**1**	**0**	**5**
Roughness			Very rough	Rough	Slightly rough	Smooth	Slickensided	
Rating			**6**	**4**	**3**	**1**	**0**	**4**
Infilling (gouge)			None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5mm	
Rating			**5**	**4**	**2**	**2**	**0**	**4**
Weathering			Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed	
Rating			**6**	**5**	**3**	**1**	**0**	**6**

F. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATION IN TUNNELLING**			
Strike perpendicular to tunnel axis		Strike parallel to tunnel axis	
Drive with dip - Dip 45 to 90	Drive with dip - Dip 20 - 45	Dip 45 - 90	Dip 20 - 45
Very favourable	**Favourable**	**Very favourable**	**Fair**
Drive against dip - Dip 45 to 90	Drive against dip - Dip 20 - 45	Dip 0 to 20 - Irrespective of strike*	
Fair	**Unfavourable**	**Fair**	

* Some conditions are mutually exclusive. For example, if infilling is present, the roughness of the surface will be overshadowed by the influence of the gouge. In such cases use A.4 directly

** Modified after Wickham et al (1972)

RMR **74**
GSI **69**

Rock Mass Rating System (RMR) (After Bieniawski 1989) **OPG Geologic Repository - High End High Values**

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

	Parameter		Range of values					
1	Strength of intact rock material	Point-load strength index	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range - uniaxial compressive test is preferred	
		Uniaxial comp.strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa / 1 - 5 MPa / <1 MPa	
		Rating	**15**	**12**	**7**	**4**	**2** / **1** / **0**	**7**
2	Drill core Quality *RQD*		90% - 100%	75% - 90%	50% - 75%	25% - 50%	<25%	
	Rating		**20**	**17**	**13**	**8**	**3**	**20**
3	Spacing of discontinuities		>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm	
	Rating		**20**	**15**	**10**	**8**	**5**	**20**
4	Condition of discontinuities (See E)		Very rough surfaces. Not continuous. No separation. Unweathered wall rock	Slightly rough surfaces. Separation < 1 mm. Slightly weathered walls	Slightly rough surfaces. Separation < 1 mm. Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge > 5 mm thick or Separation > 5 mm Continuous	
	Rating		**30**	**25**	**20**	**10**	**0**	
5	Ground water	Inflow per 10 m tunnel length (l/m)	None	< 10	10 - 25	25 -125	> 125	
		(Joint water press)/ (Major principal stress)	0	< 0.1	0.1 - 0.2	0.2 - 0.5	> 0.5	
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing	
		Rating	**15**	**10**	**7**	**4**	**0**	**15**

B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)

Strike and dip orientations		Very Favourable	Favourable	Fair	Unfavourable	Very unfavourable	
Ratings	**Tunnels & mines**	**0**	**-2**	**-5**	**-10**	**-12**	**0**
	Foundations	**0**	**-2**	**-7**	**-15**	**-25**	
	Slopes	**0**	**-5**	**-25**	**-50**		

C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS

Rating	100 - 81	80 - 61	60 - 41	40 - 21	< 21
Class number	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

D. MEANING OF ROCK CLASSES

Class number	I	II	III	IV	V
Average stand-up time	20 years for 15 m span	1year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 mins for 1 m span
Cohesion of rock mass (MPa)	>400	300 - 400	200 - 300	100 - 200	<100
Friction angle of rock mass (deg)	> 45	35 - 45	25 - 35	15 - 25	< 15

E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY CONDITIONS

Discontinuity length persistence	< 1 m	1 -3 m	3 -10 m	10 - 20 m	> 20 m	
Rating	**6**	**4**	**2**	**1**	**0**	**4**
Separation (aperture)	None	< 0.1 mm	0.1 -1.0 mm	1 - 5 mm	> 5 mm	
Rating	**6**	**5**	**4**	**1**	**0**	**5**
Roughness	Very rough	Rough	Slightly rough	Smooth	Slickensided	
Rating	**6**	**4**	**3**	**1**	**0**	**4**
Infilling (gouge)	None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5mm	
Rating	**5**	**4**	**2**	**2**	**0**	**4**
Weathering	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed	
Rating	**6**	**5**	**3**	**1**	**0**	**6**

F. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATION IN TUNNELLING**

Strike perpendicular to tunnel axis		Strike parallel to tunnel axis	
Drive with dip - Dip 45 to 90	Drive with dip - Dip 20 - 45	Dip 45 - 90	Dip 20 - 45
Very favourable	**Favourable**	**Very favourable**	**Fair**
Drive against dip - Dip 45 to 90	Drive against dip - Dip 20 - 45	Dip 0 to 20 - Irrespective of strike*	
Fair	**Unfavourable**	**Fair**	

* Some conditions are mutually exclusive. For example, if infilling is present, the roughness of the surface will be overshadowed by the influence of the gouge. In such cases use A.4 directly

** Modified after Wickham et al (1972)

RMR **85**
GSI **80**

Rock Mass Rating System (RMR) (After Bieniawski 1989) **OPG Geologic Repository - Most Favourable Values**

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

	Parameter		Range of values							
1	Strength of intact rock material	Point-load strength index	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range - uniaxial compressive test is preferred			
		Uniaxial comp.strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa	1 - 5 MPa	<1 MPa	
		Rating	**15**	**12**	**7**	**4**	**2**	**1**	**0**	**12**
2	Drill core Quality *RQD*		90% - 100%	75% - 90%	50% - 75%	25% - 50%	<25%			
	Rating		**20**	**17**	**13**	**8**	**3**			**20**
3	Spacing of discontinuities		>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	< 60 mm			
	Rating		**20**	**15**	**10**	**8**	**5**			**20**
4	Condition of discontinuities (See E)		Very rough surfaces. Not continuous. No separation. Unweathered wall rock	Slightly rough surfaces. Separation < 1 mm. Slightly weathered walls	Slightly rough surfaces. Separation < 1 mm. Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge > 5 mm thick or Separation > 5 mm Continuous			
	Rating		**30**	**25**	**20**	**10**	**0**			
5	Ground water	Inflow per 10 m tunnel length (l/m)	None	< 10	10 - 25	25 -125	> 125			
		(Joint water press)/ (Major principal stress)	0	< 0.1	0.1 - 0.2	0.2 - 0.5	> 0.5			
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing			
	Rating		**15**	**10**	**7**	**4**	**0**			**15**

B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)

Strike and dip orientations		Very Favourable	Favourable	Fair	Unfavourable	Very unfavourable	
Ratings	**Tunnels & mines**	**0**	**-2**	**-5**	**-10**	**-12**	**0**
	Foundations	**0**	**-2**	**-7**	**-15**	**-25**	
	Slopes	**0**	**-5**	**-25**	**-50**		

C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS

Rating	100 - 81	80 - 61	60 - 41	40 - 21	< 21
Class number	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

D. MEANING OF ROCK CLASSES

Class number	I	II	III	IV	V
Average stand-up time	20 years for 15 m span	1year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 mins for 1 m span
Cohesion of rock mass (MPa)	>400	300 - 400	200 - 300	100 - 200	<100
Friction angle of rock mass (deg)	> 45	35 - 45	25 - 35	15 - 25	< 15

E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY CONDITIONS

Discontinuity length persistence	< 1 m	1 -3 m	3 -10 m	10 - 20 m	> 20 m	
Rating	**6**	**4**	**2**	**1**	**0**	**0**
Separation (aperture)	None	< 0.1 mm	0.1 -1.0 mm	1 - 5 mm	> 5 mm	
Rating	**6**	**5**	**4**	**1**	**0**	**5**
Roughness	Very rough	Rough	Slightly rough	Smooth	Slickensided	
Rating	**6**	**4**	**3**	**1**	**0**	**3**
Infilling (gouge)	None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5mm	
Rating	**5**	**4**	**2**	**2**	**0**	**4**
Weathering	Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed	
Rating	**6**	**5**	**3**	**1**	**0**	**6**

F. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATION IN TUNNELLING**

Strike perpendicular to tunnel axis		Strike parallel to tunnel axis	
Drive with dip - Dip 45 to 90	Drive with dip - Dip 20 - 45	Dip 45 - 90	Dip 20 - 45
Very favourable	**Favourable**	**Very favourable**	**Fair**
Drive against dip - Dip 45 to 90	Drive against dip - Dip 20 - 45	Dip 0 to 20 - Irrespective of strike*	
Fair	**Unfavourable**	**Fair**	

* Some conditions are mutually exclusive. For example, if infilling is present, the roughness of the surface will be overshadowed by the influence of the gouge. In such cases use A.4 directly

** Modified after Wickham et al (1972)

RMR **85**
GSI **80**

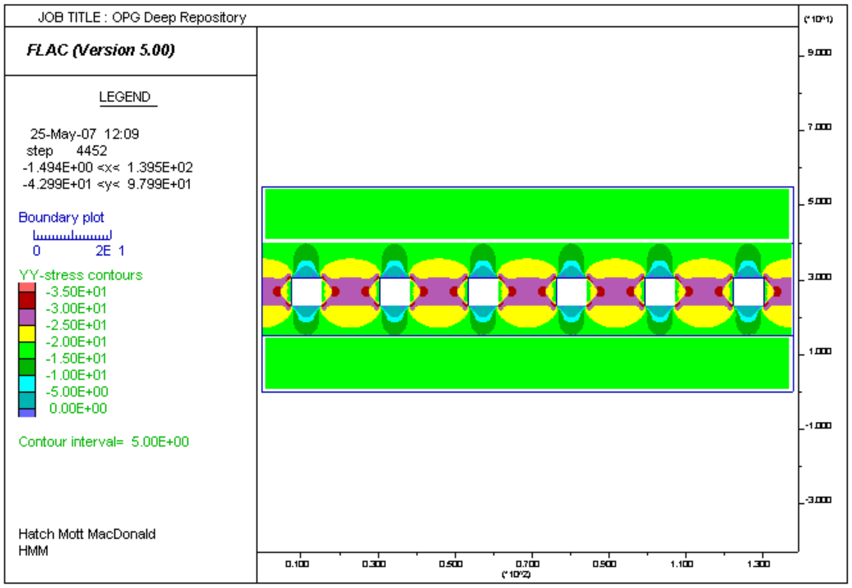
Appendix B1

Multi-Pillar Analysis
(2D FLAC Analysis Results)

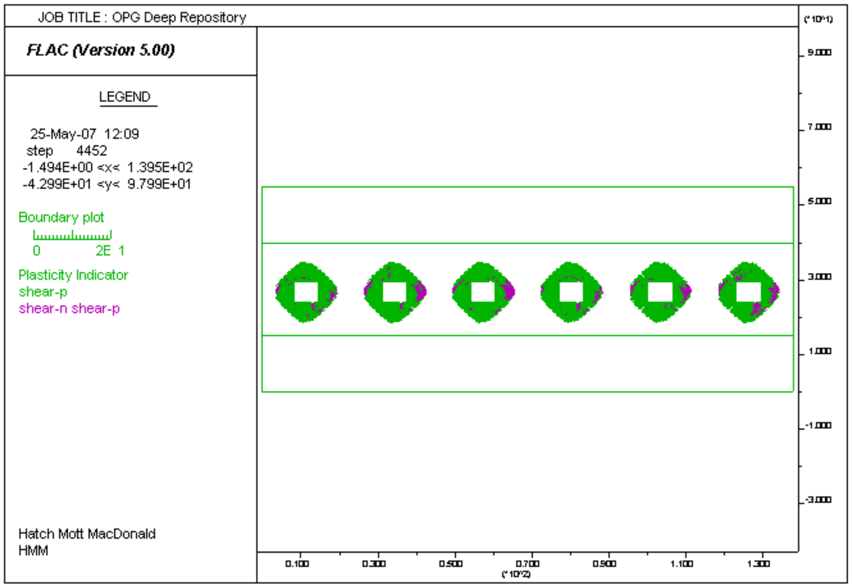
Expected Parameters, K_0 = 1.5, Pillar Width = 15.0m

Simultaneous Excavation

Vertical Stresses (MPa)

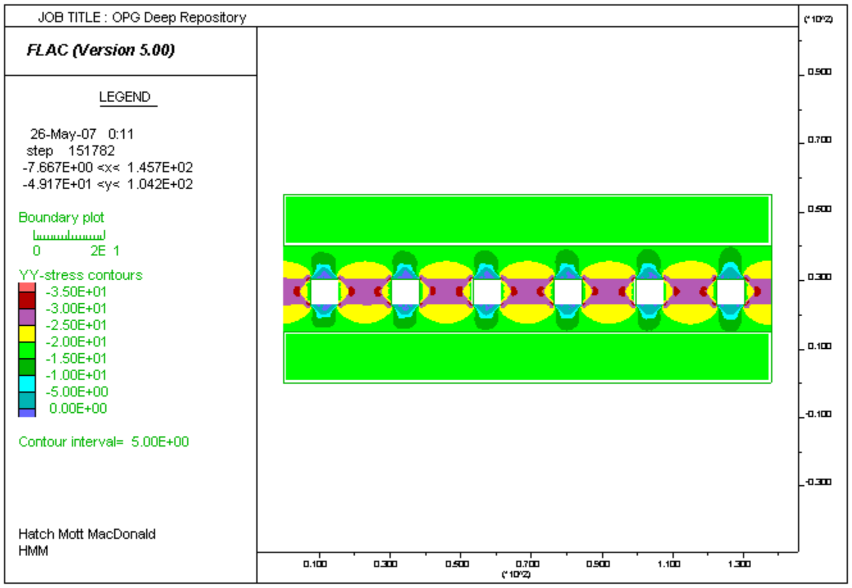


Plasticity Indicators



Step-by-step Excavation

Vertical Stresses (MPa)



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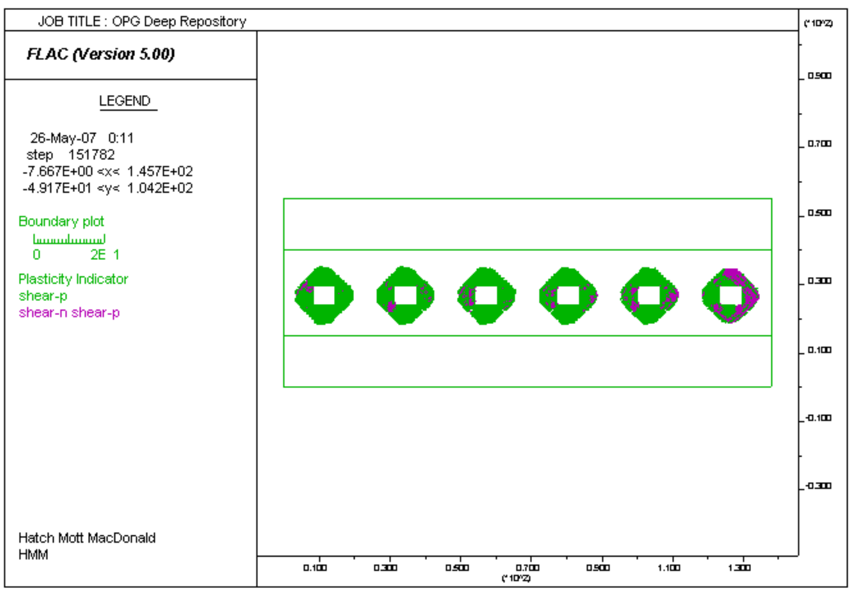
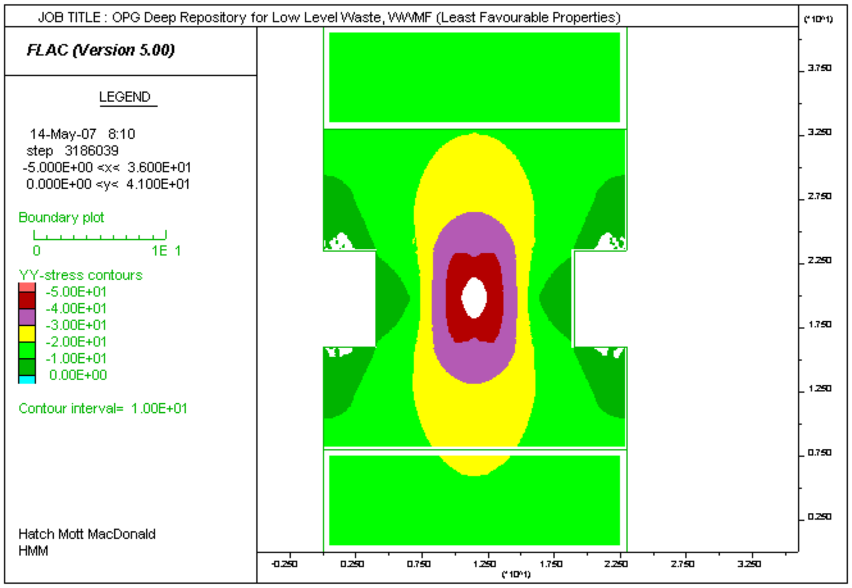


Appendix B2

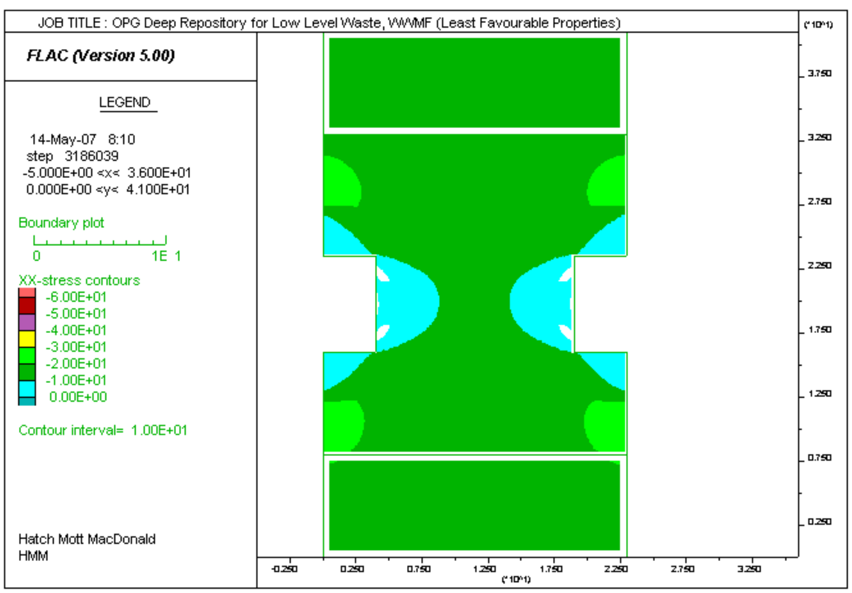
Single-Pillar Analysis
Wide Range of Parameters
(2D FLAC Analysis Results)

Least Favourable Parameters, K_0 = 1.0, Pillar Width = 15.0m

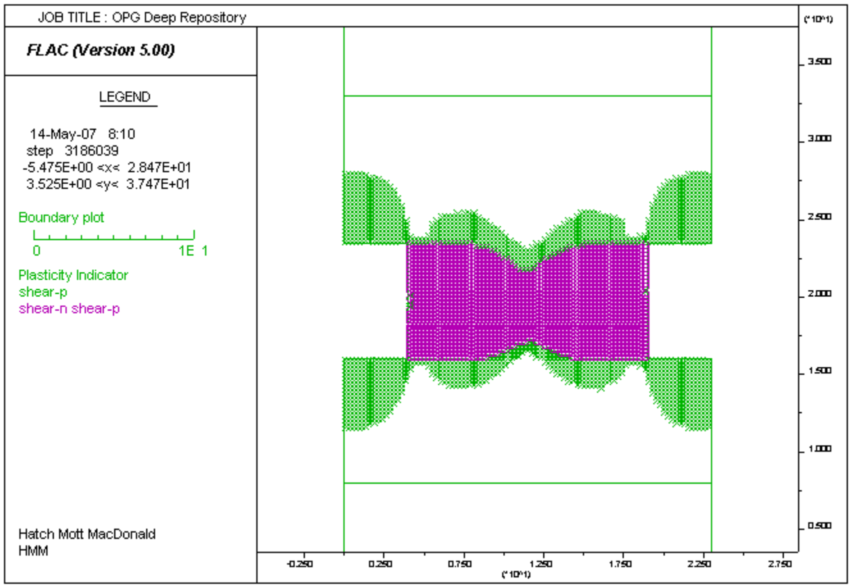
Vertical Stresses (MPa)



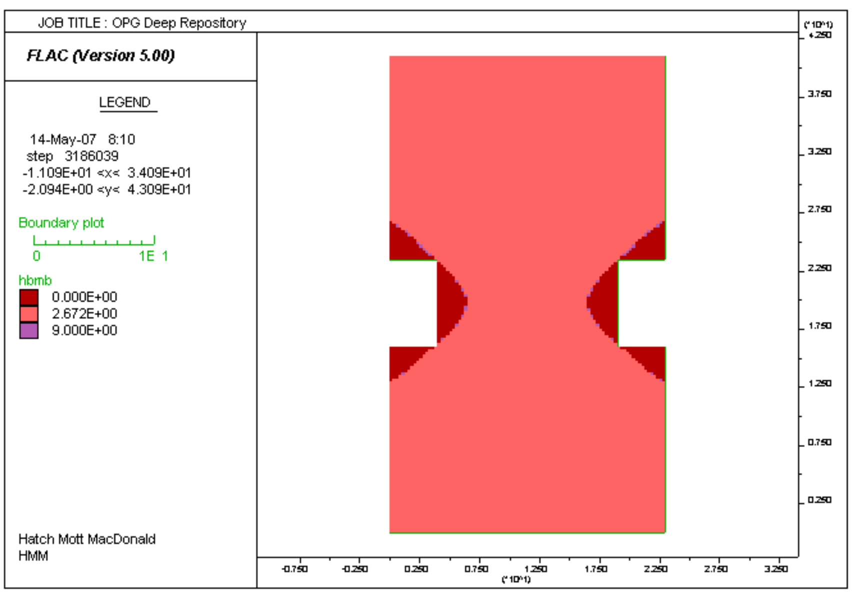
Horizontal Stresses (MPa)



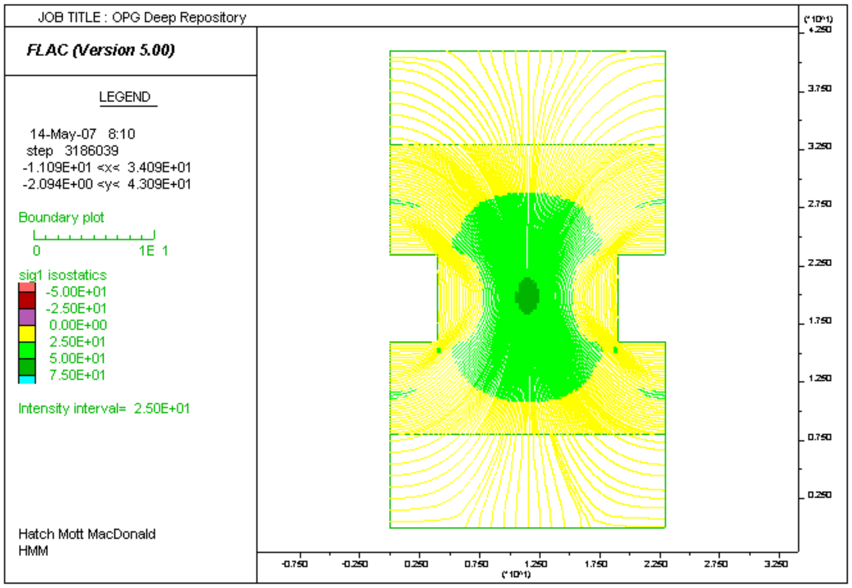
Plasticity Indicators



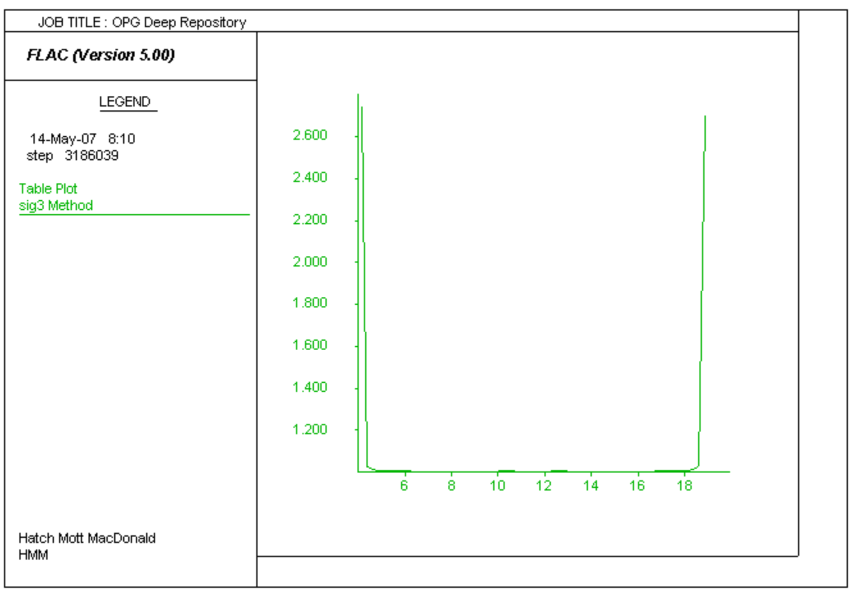
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

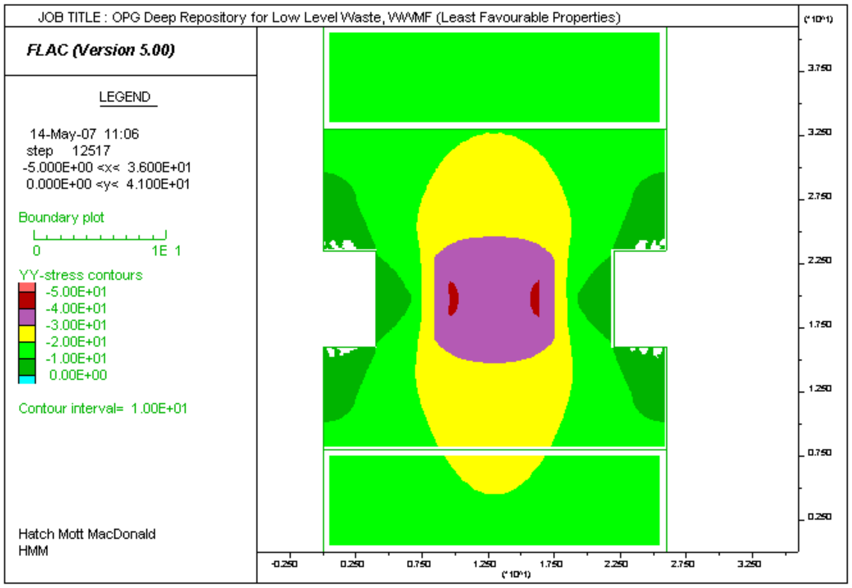


Factor Of Safety Across The Pillar

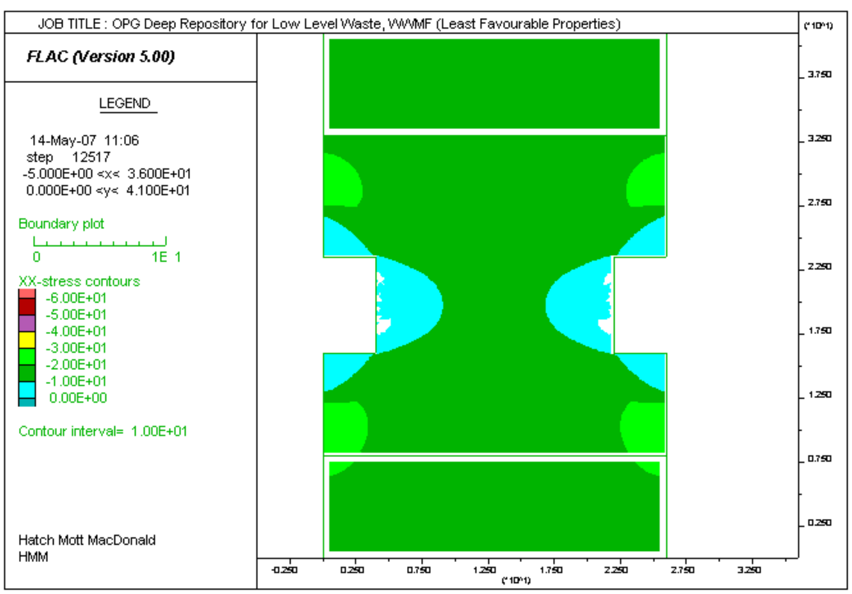


Least Favourable Parameters, K_0 = 1.0, Pillar Width = 18.0m

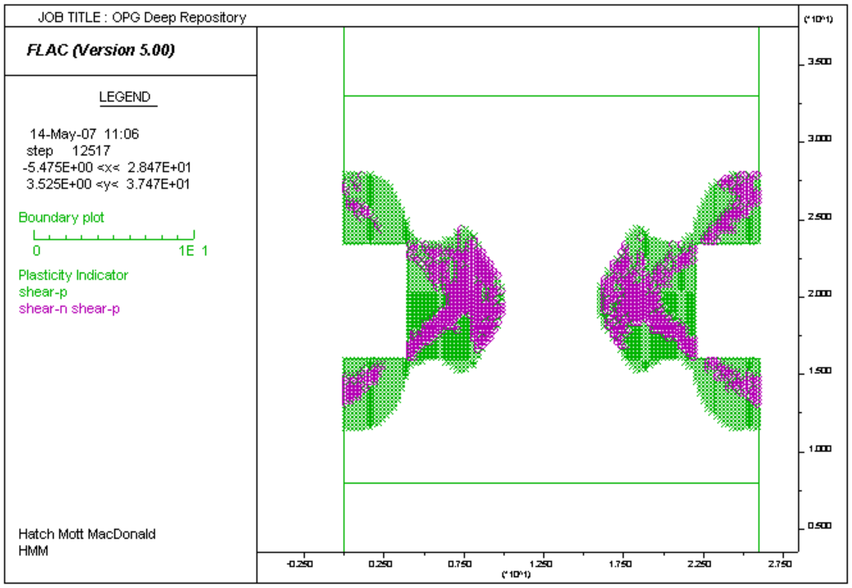
Vertical Stresses (MPa)



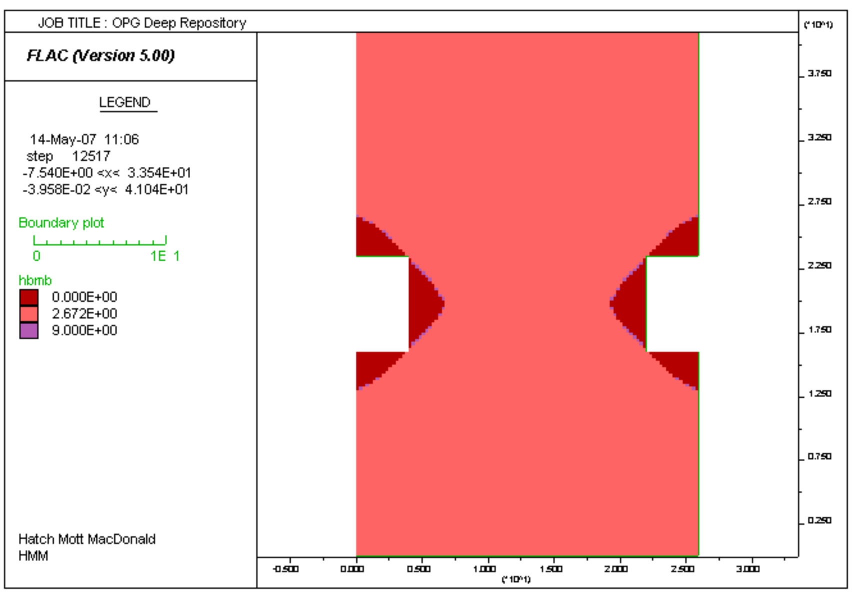
Horizontal Stresses (MPa)



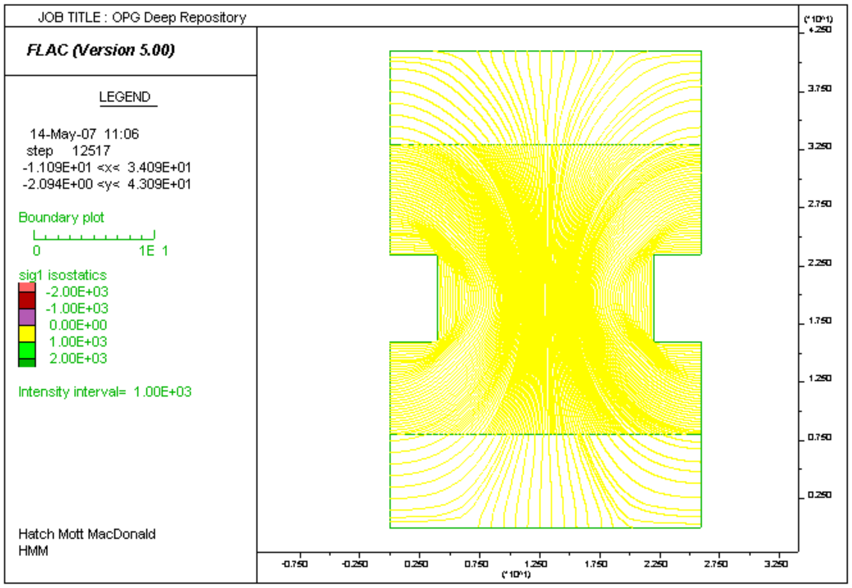
Plasticity Indicators



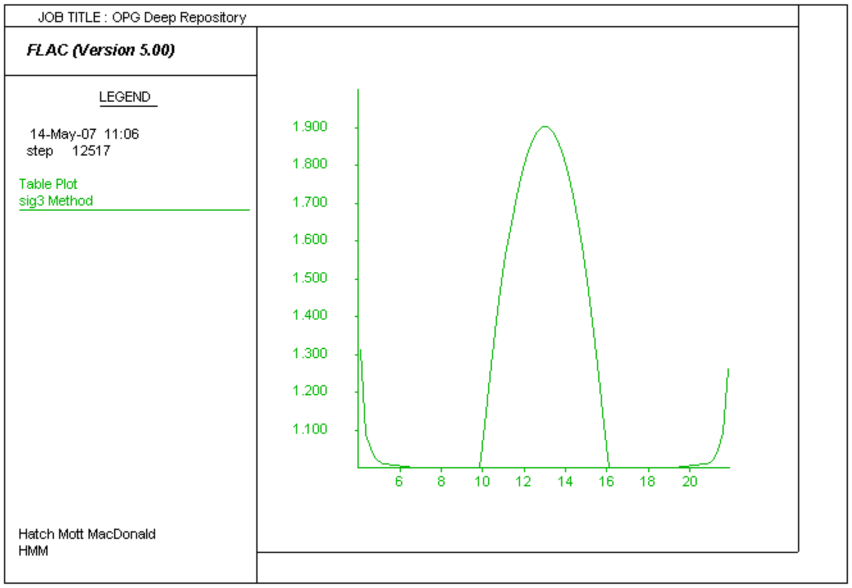
Failure Criteria (■ Brittle Failure, ■ Hoek-Brown Peak Strength, ■ Transition)



Maximum Principal Stress Trajectories (MPa)

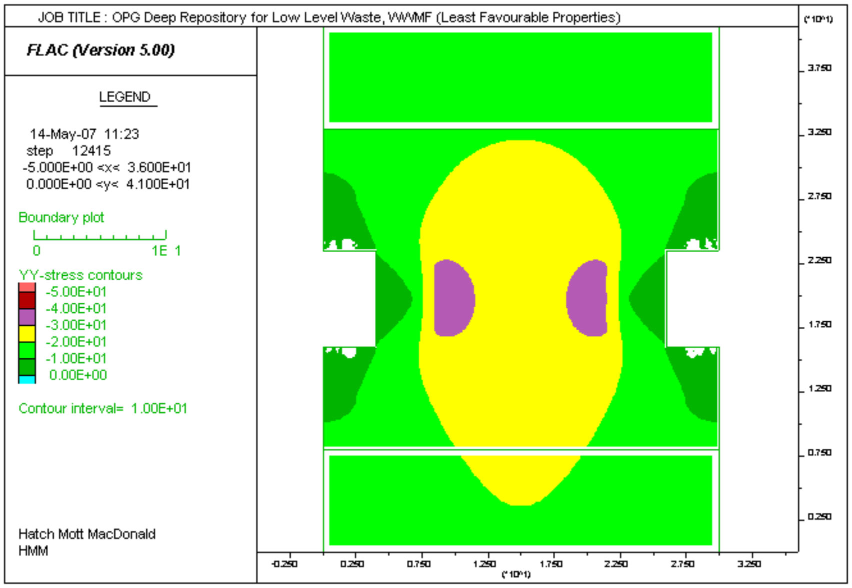


Factor Of Safety Across The Pillar

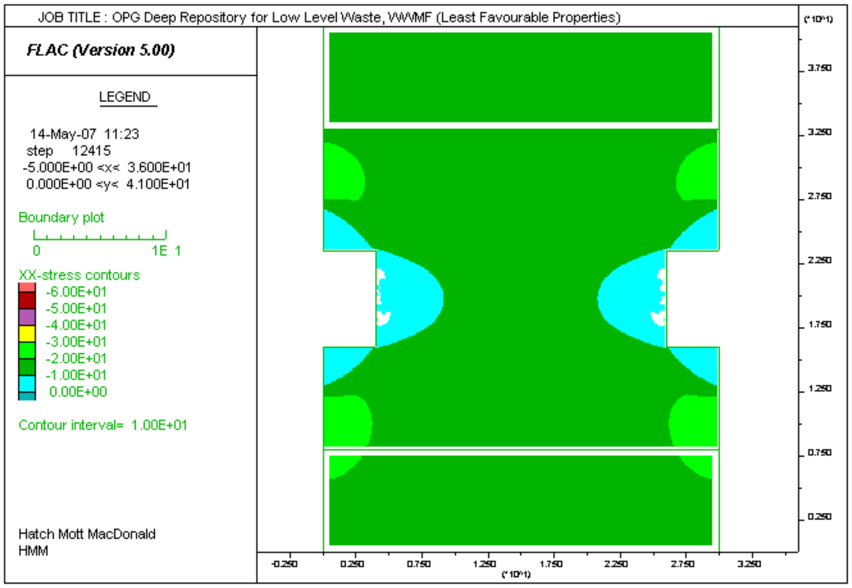


Least Favourable Parameters, K_0 = 1.0, Pillar Width = 22.0m

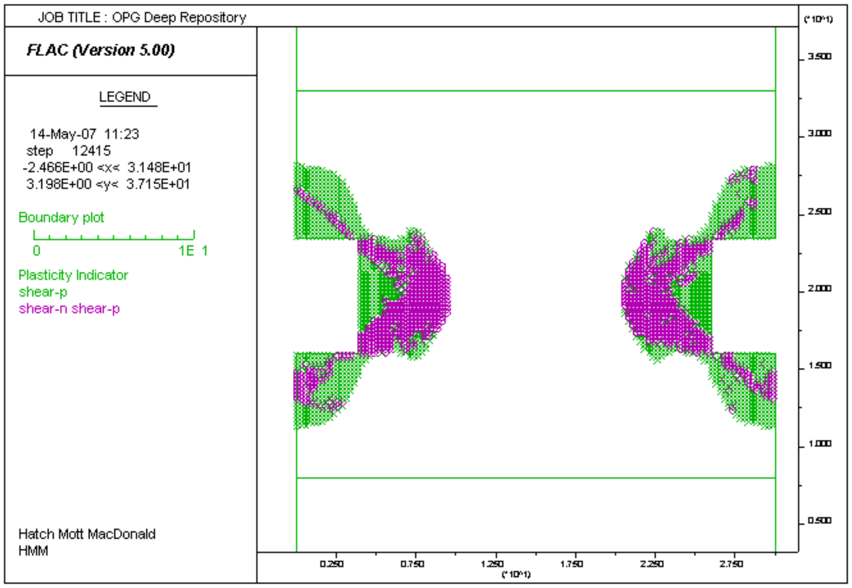
Vertical Stresses (MPa)



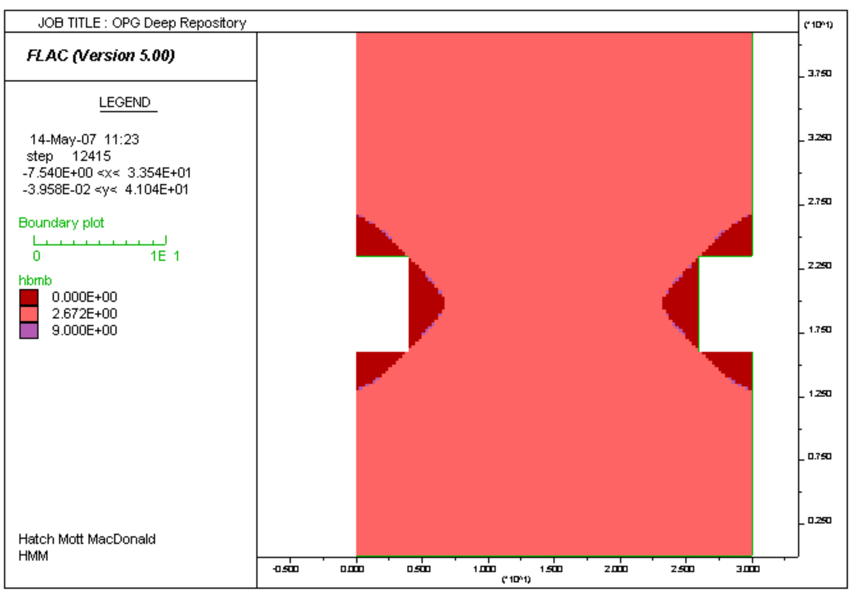
Horizontal Stresses (MPa)



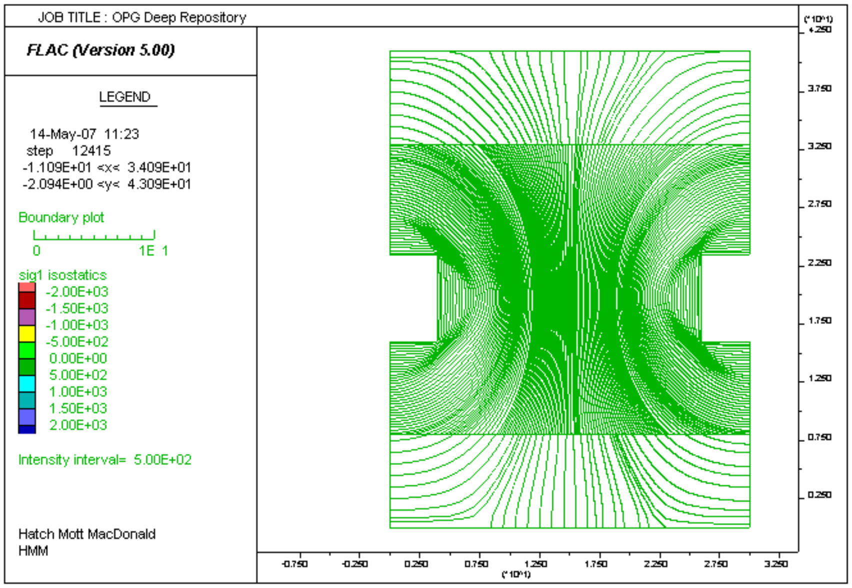
Plasticity Indicators



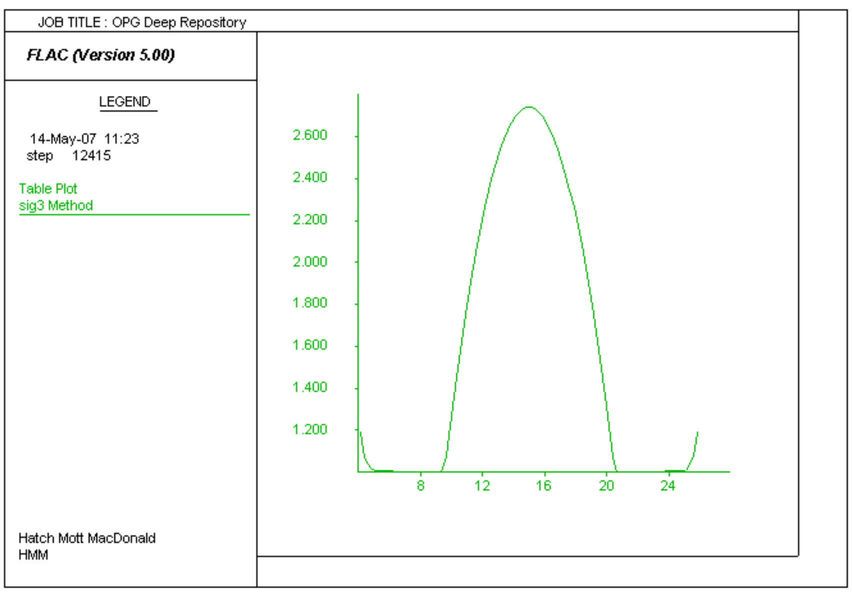
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

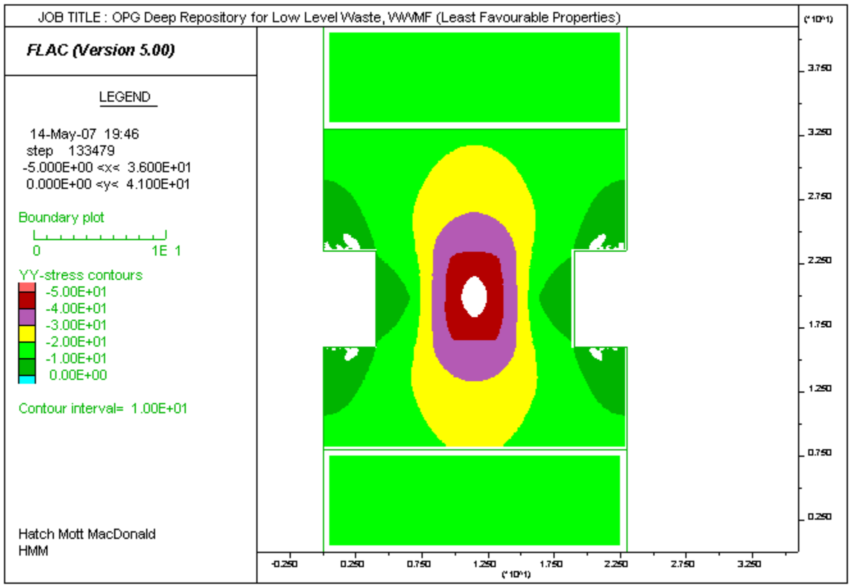


Factor Of Safety Across The Pillar

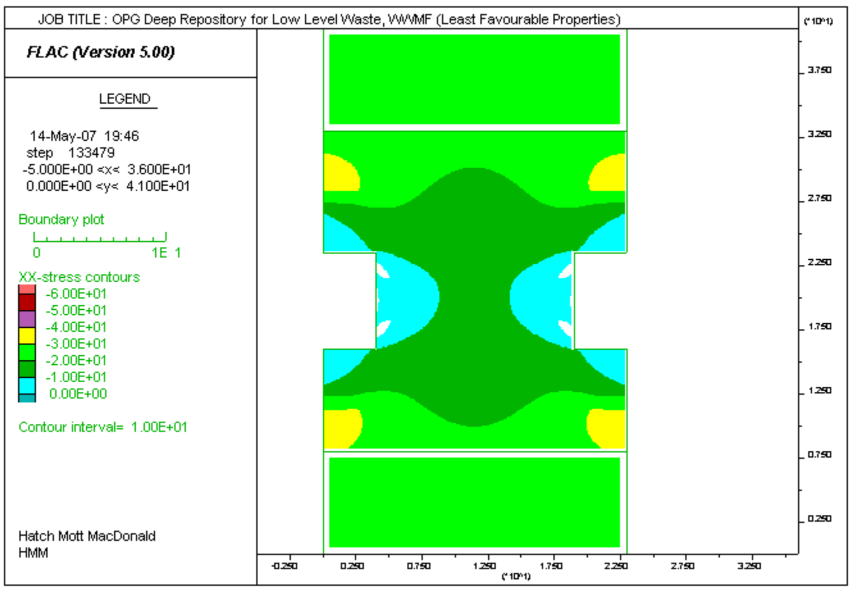


Least Favourable Parameters, K_0 = 1.5, Pillar Width = 15.0m

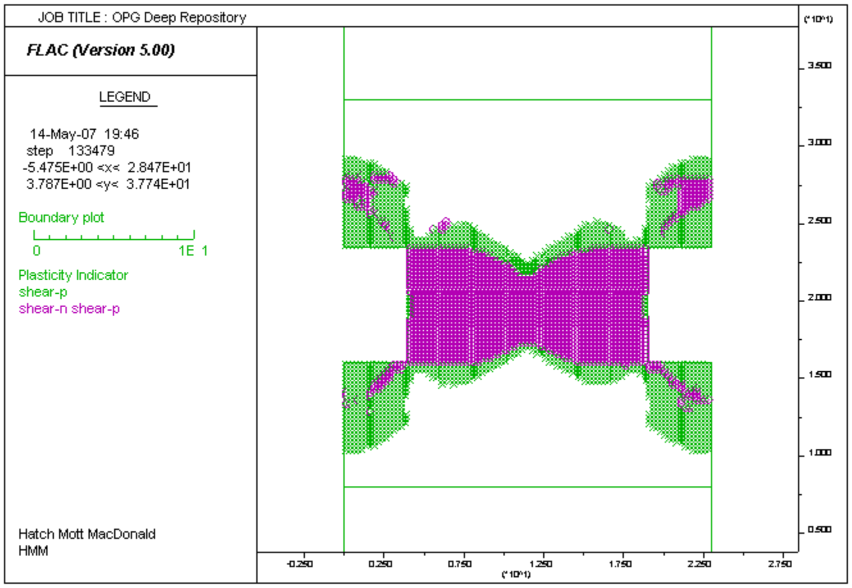
Vertical Stresses (MPa)



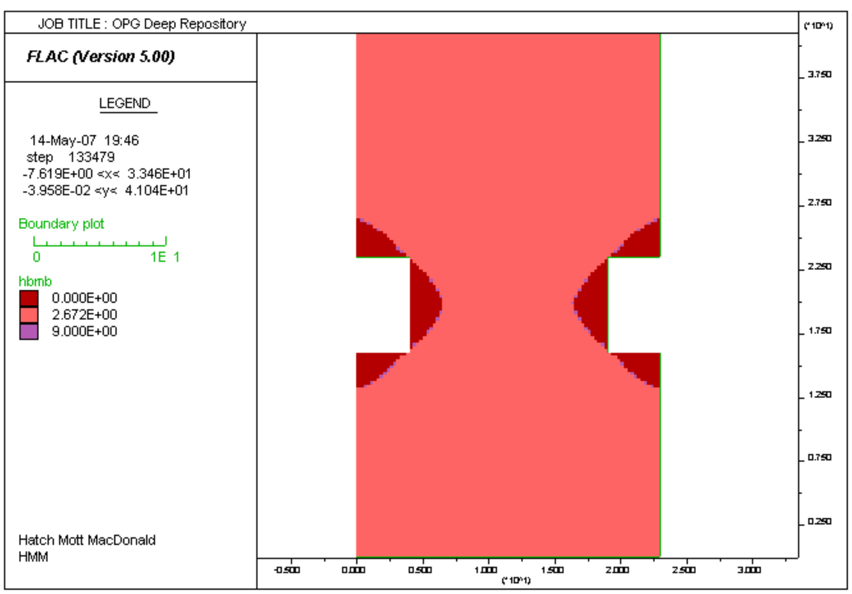
Horizontal Stresses (MPa)



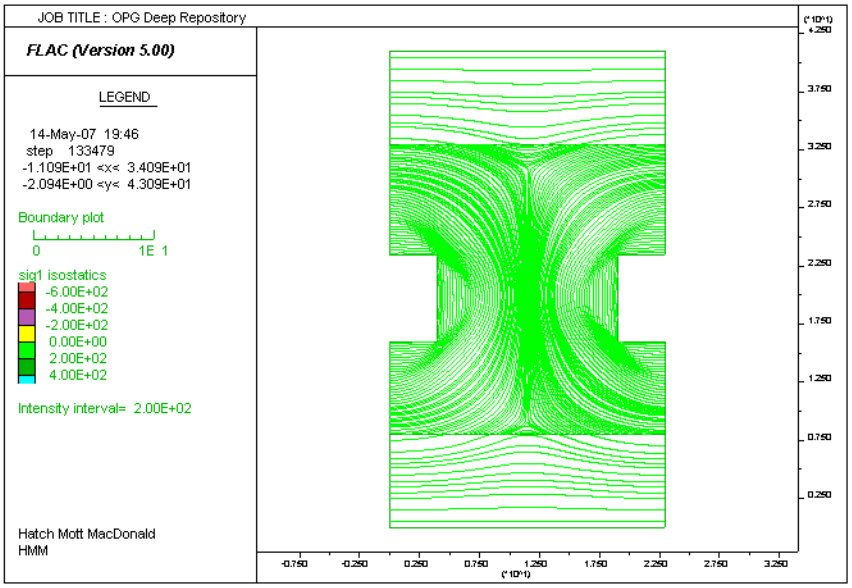
Plasticity Indicators



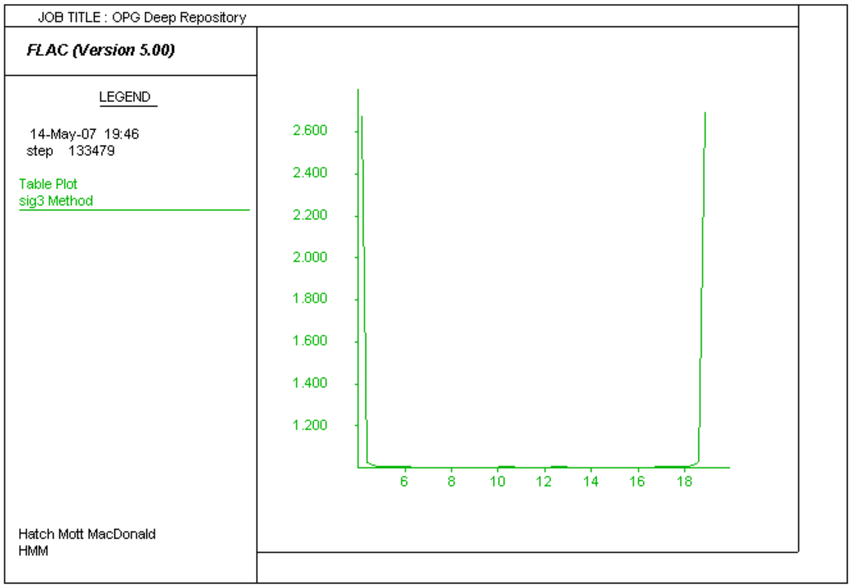
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

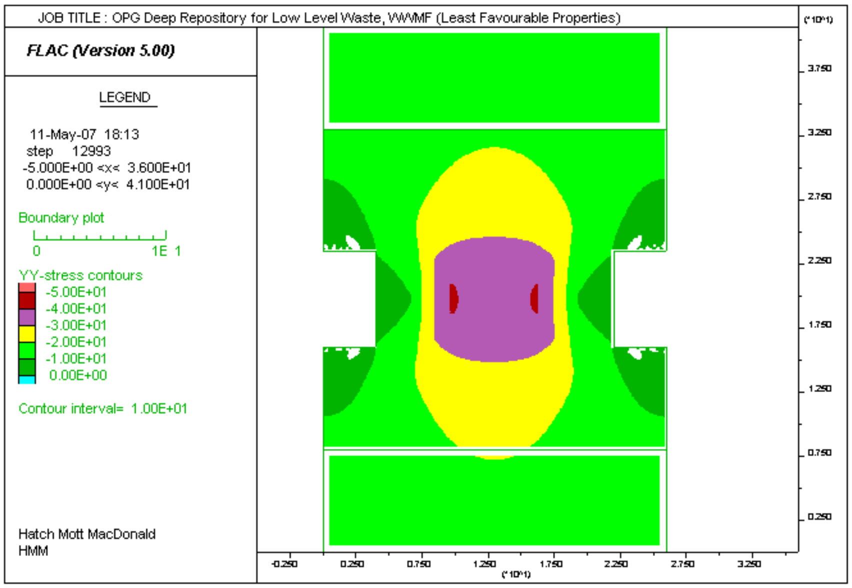


Factor Of Safety Across The Pillar

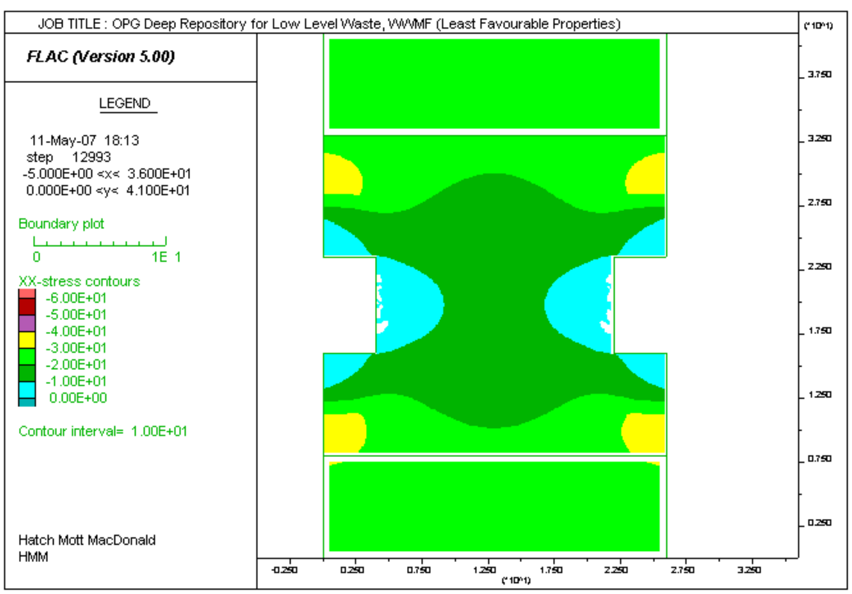


Least Favourable Parameters, K_0 = 1.5 Pillar Width = 18.0m

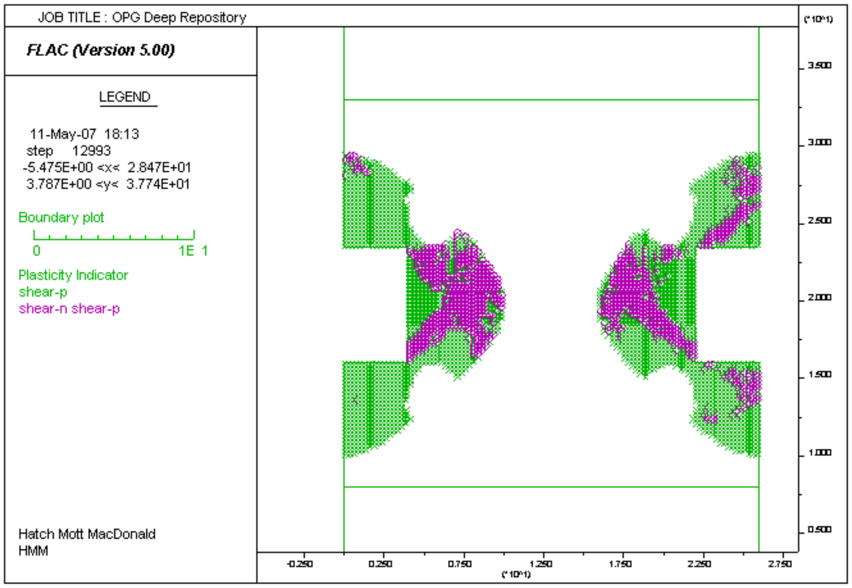
Vertical Stresses (MPa)



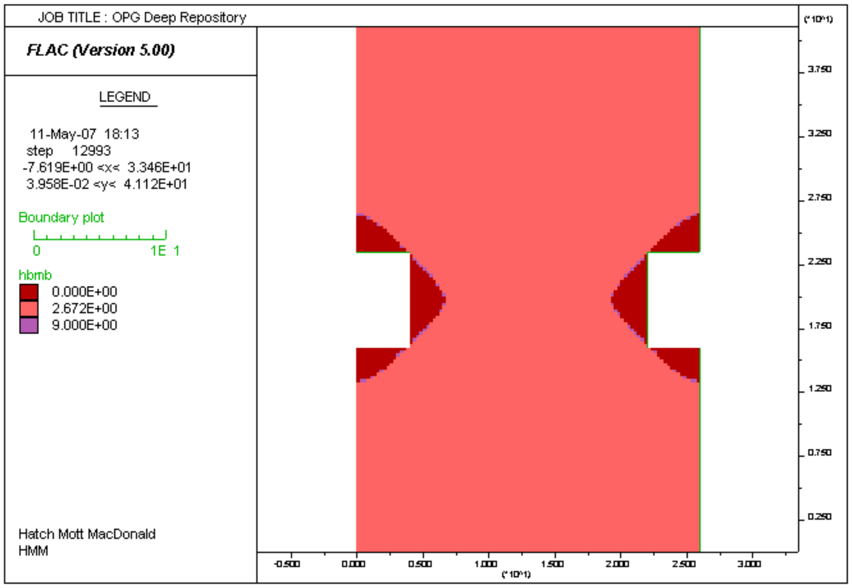
Horizontal Stresses (MPa)



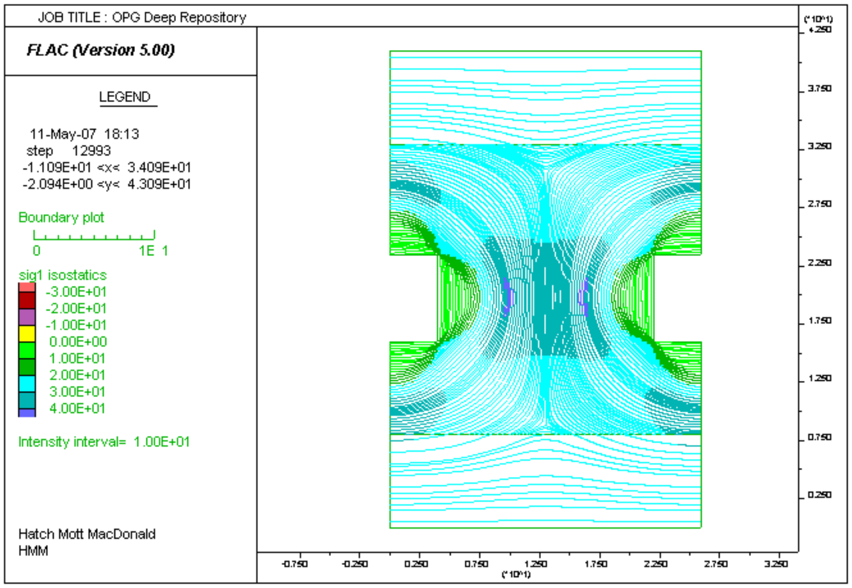
Plasticity Indicators



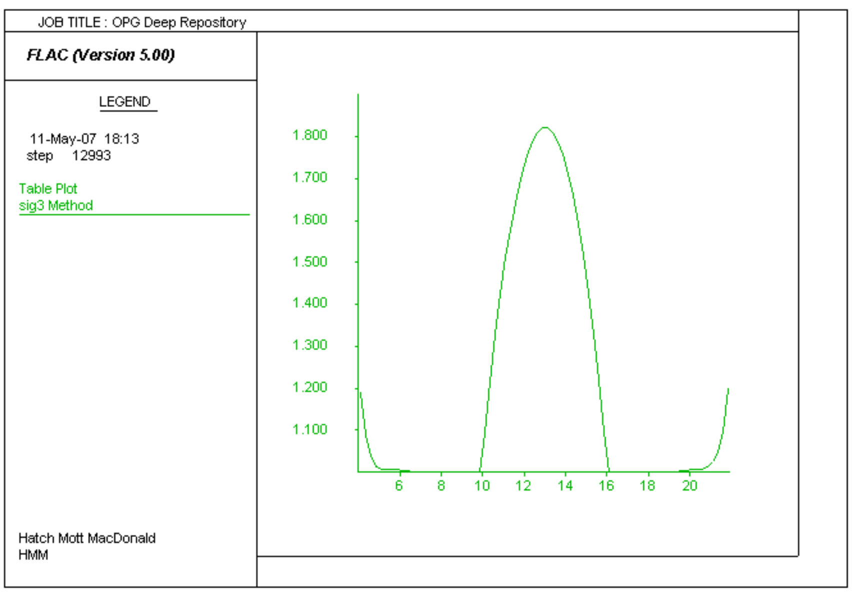
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)



Factor Of Safety Across The Pillar



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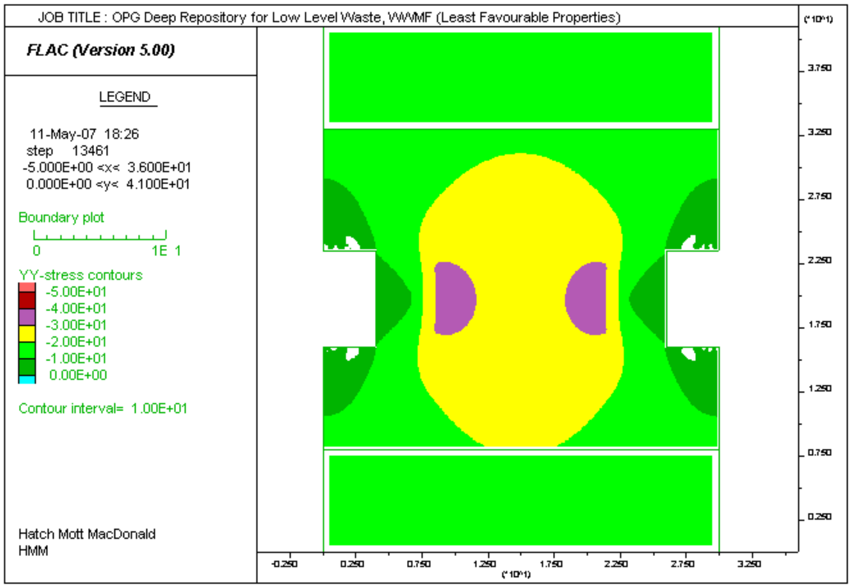
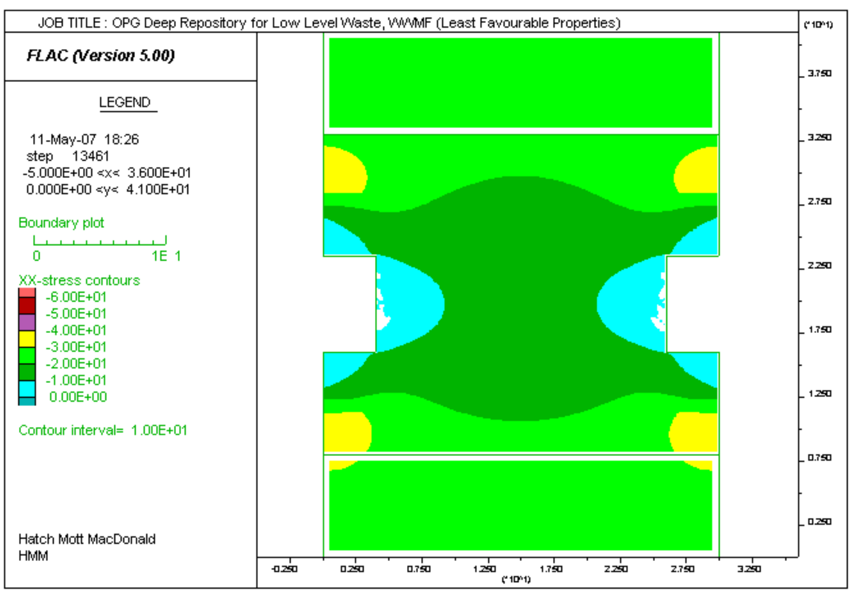
Least Favourable Parameters, $K_0 = 1.5$, Pillar Width = 22.0m

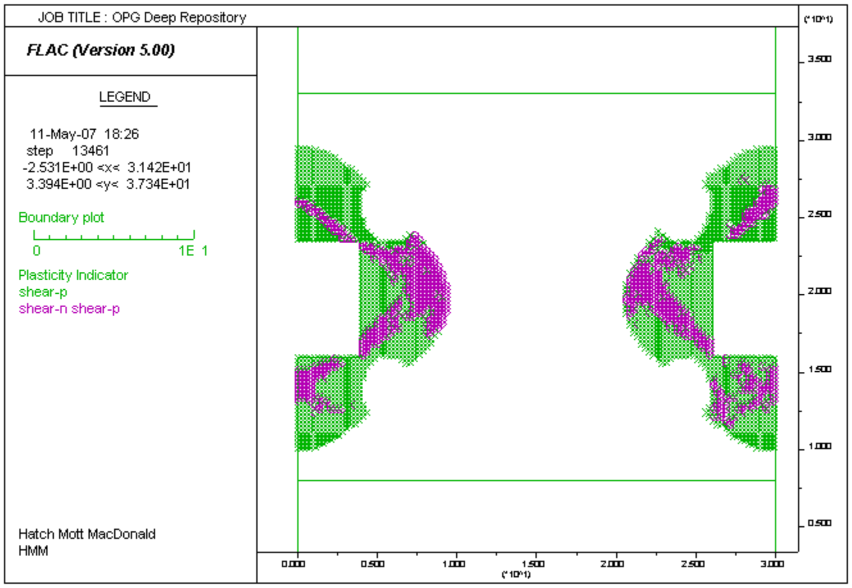
Vertical Stresses (MPa)



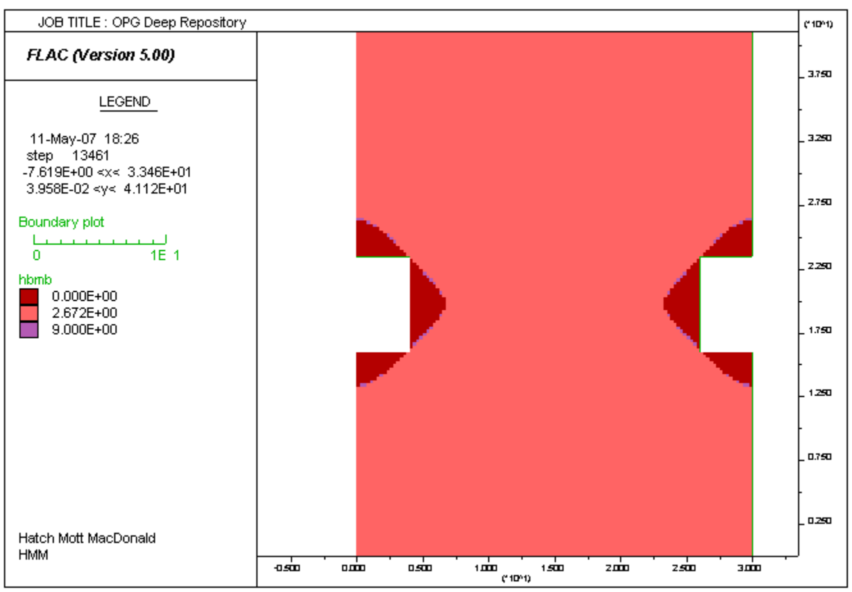
Horizontal Stresses (MPa)



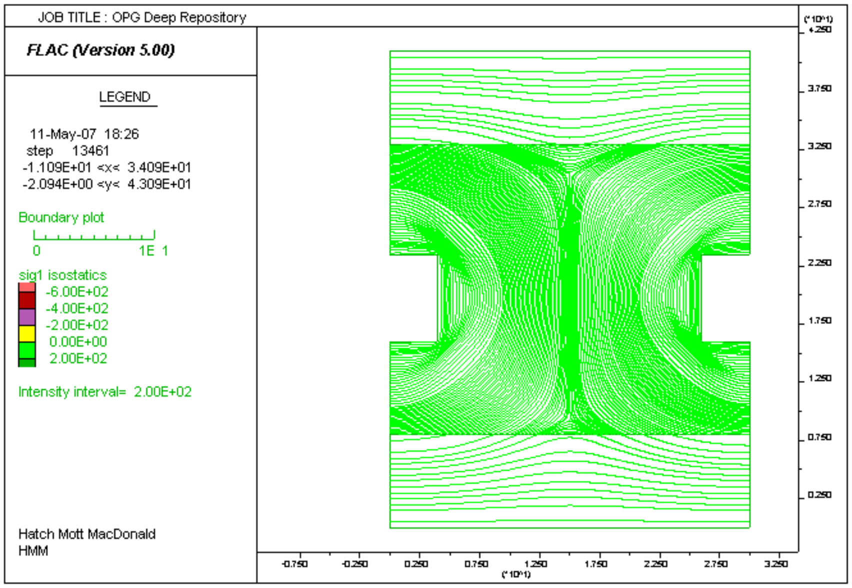
Plasticity Indicators



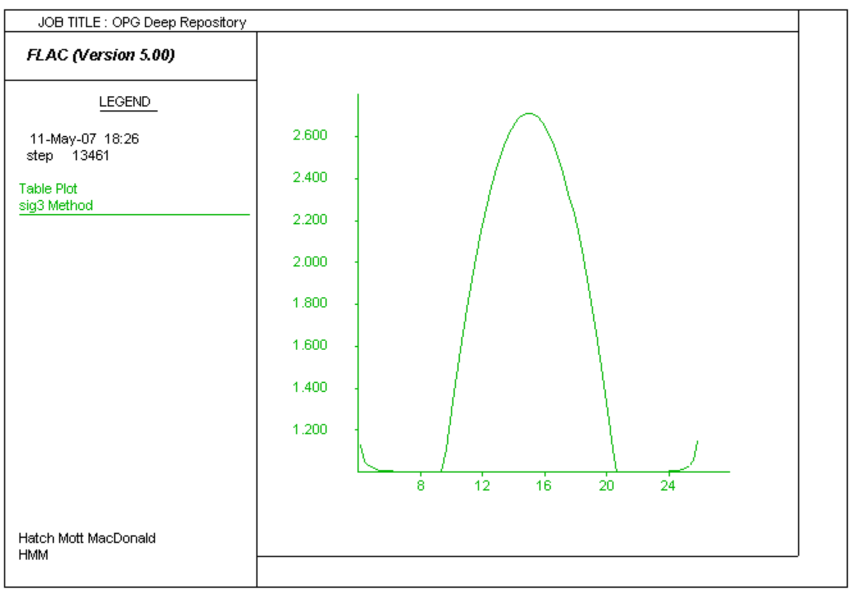
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

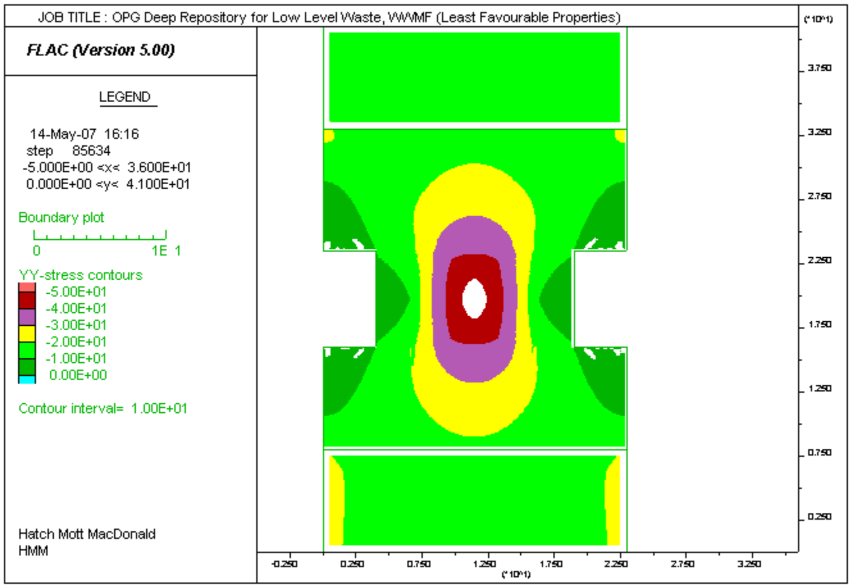


Factor Of Safety Across The Pillar

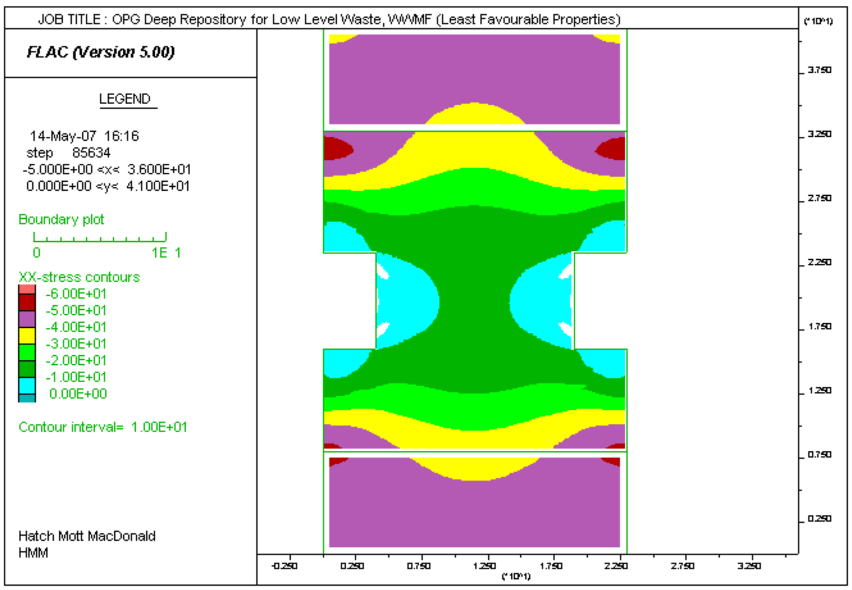


Least Favourable Parameters, $K_0 = 2.5$, Pillar Width = 15.0m

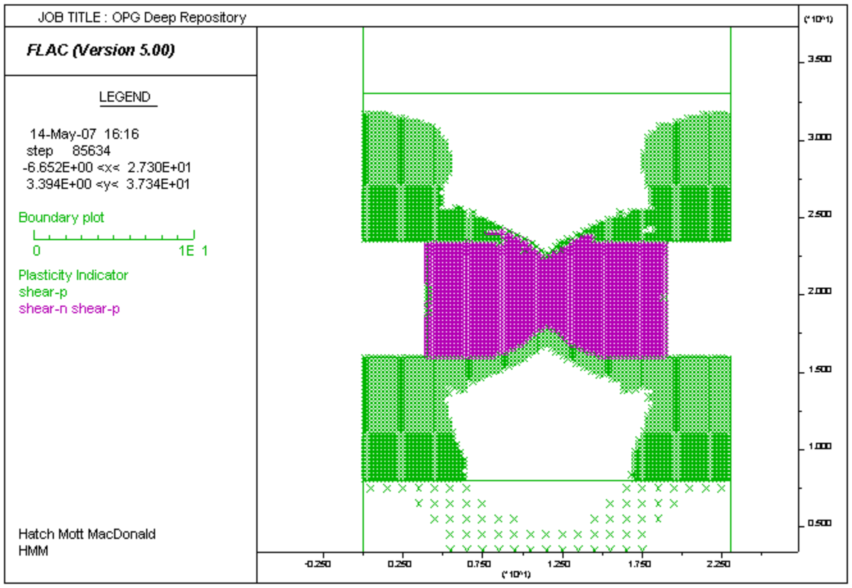
Vertical Stresses (MPa)



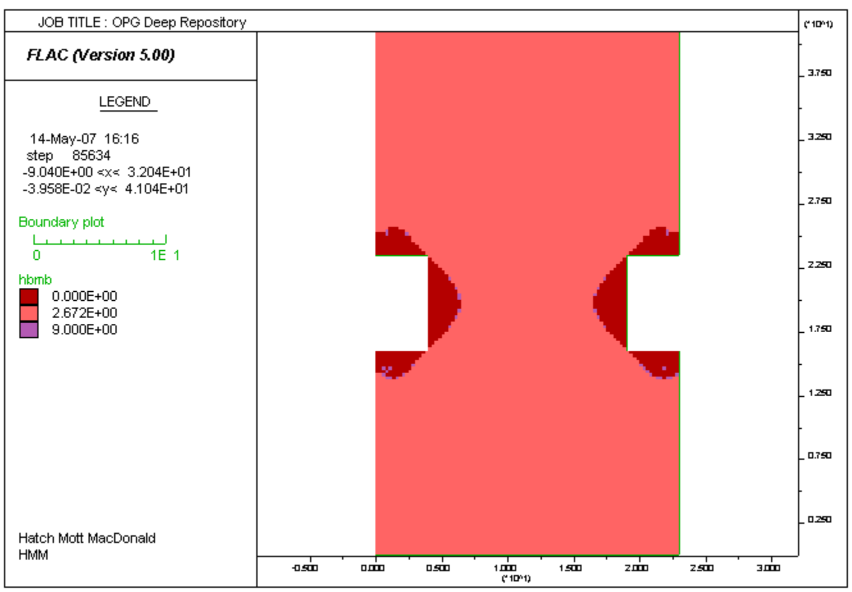
Horizontal Stresses (MPa)



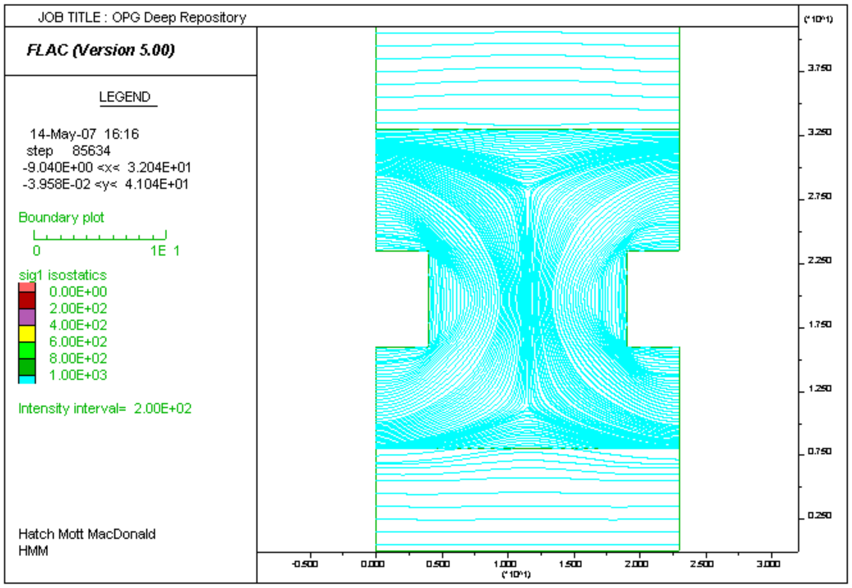
Plasticity Indicators



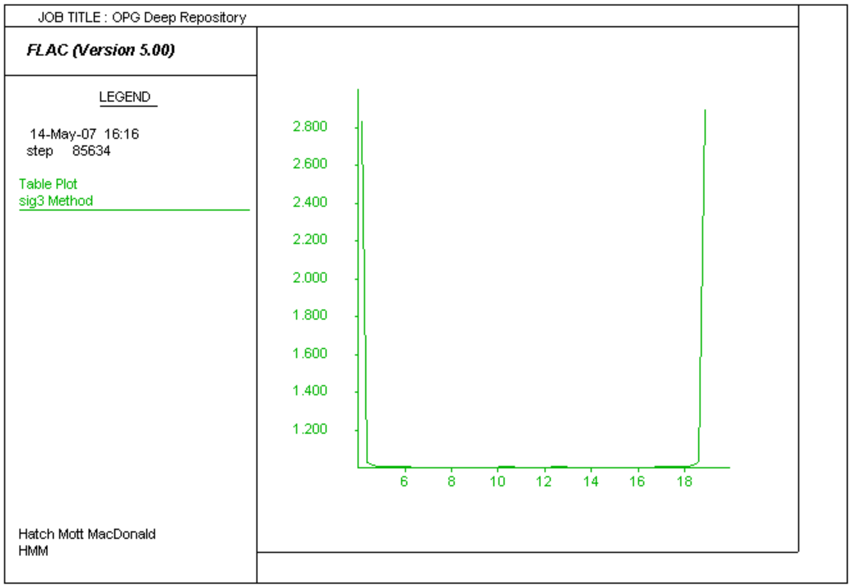
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

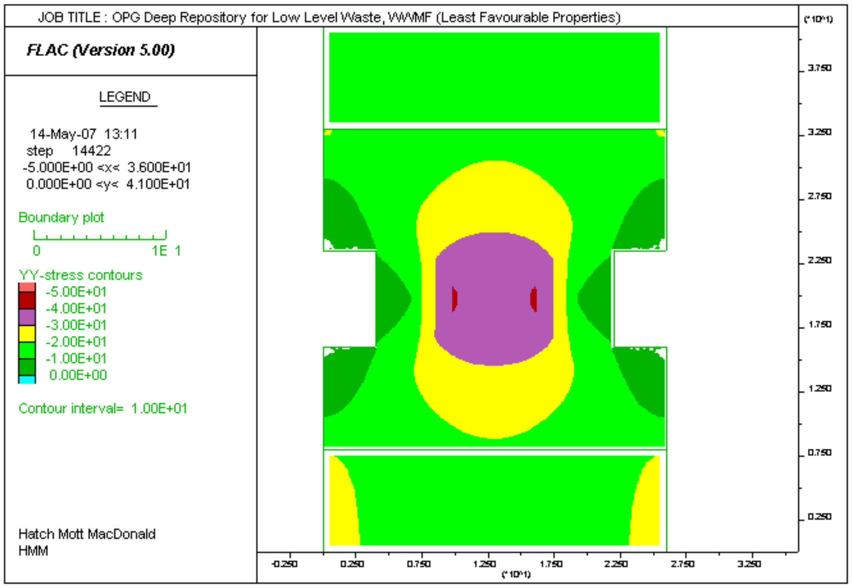


Factor Of Safety Across The Pillar

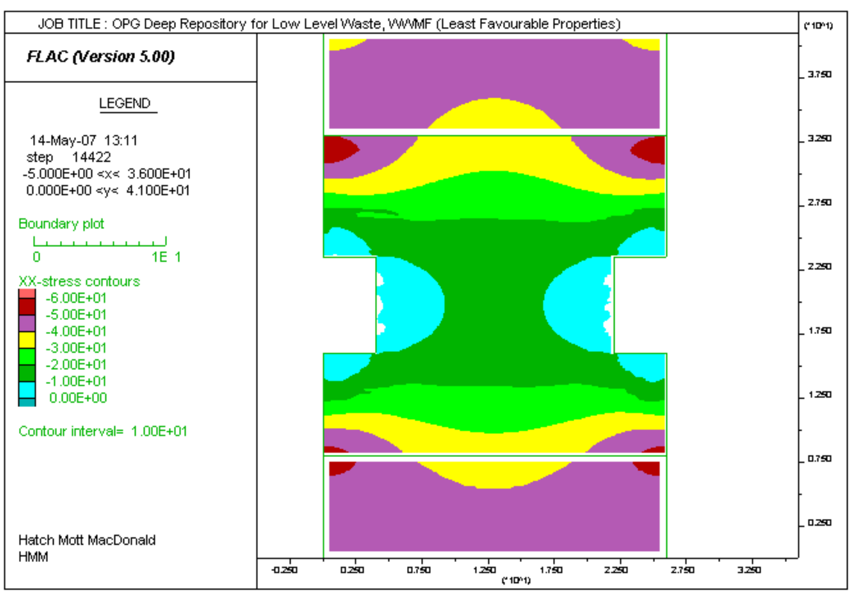


Least Favourable Parameters, K_0 =2.5, Pillar Width = 18.0m

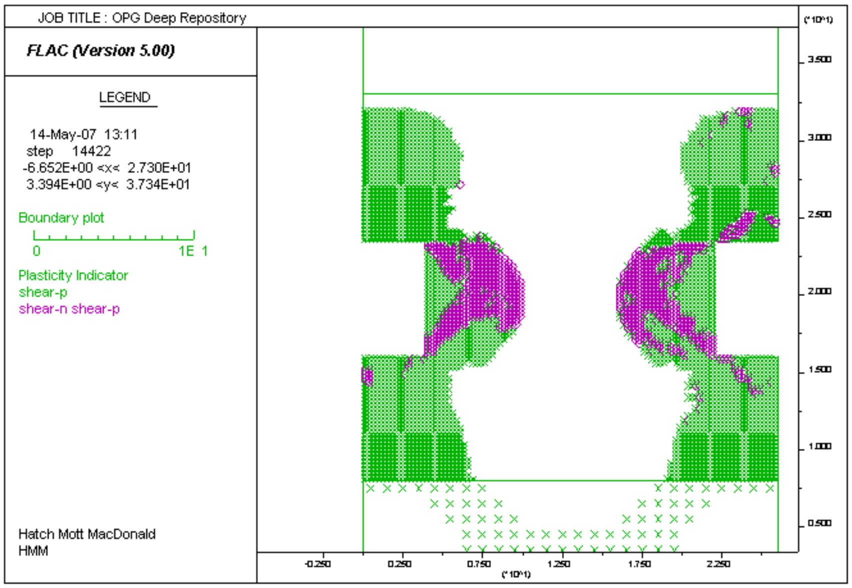
Vertical Stresses (MPa)



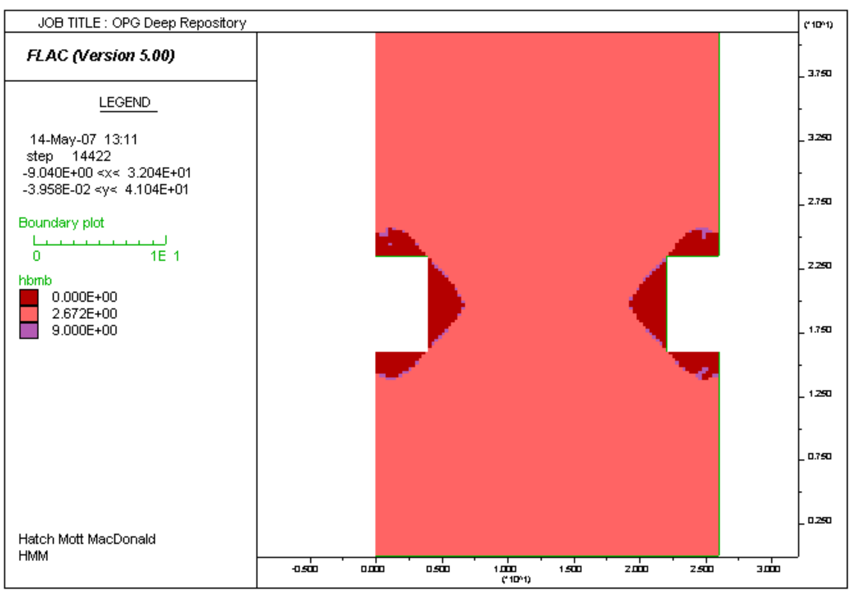
Horizontal Stresses (MPa)



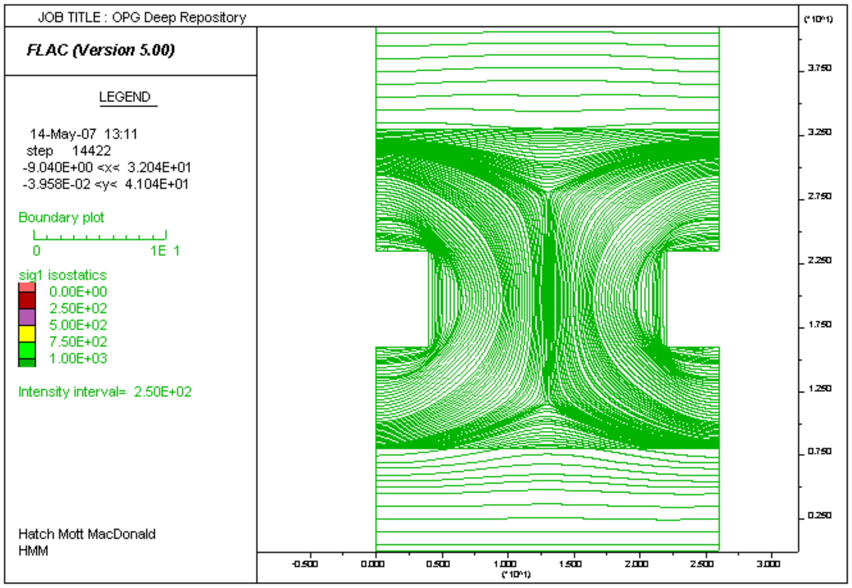
Plasticity Indicators



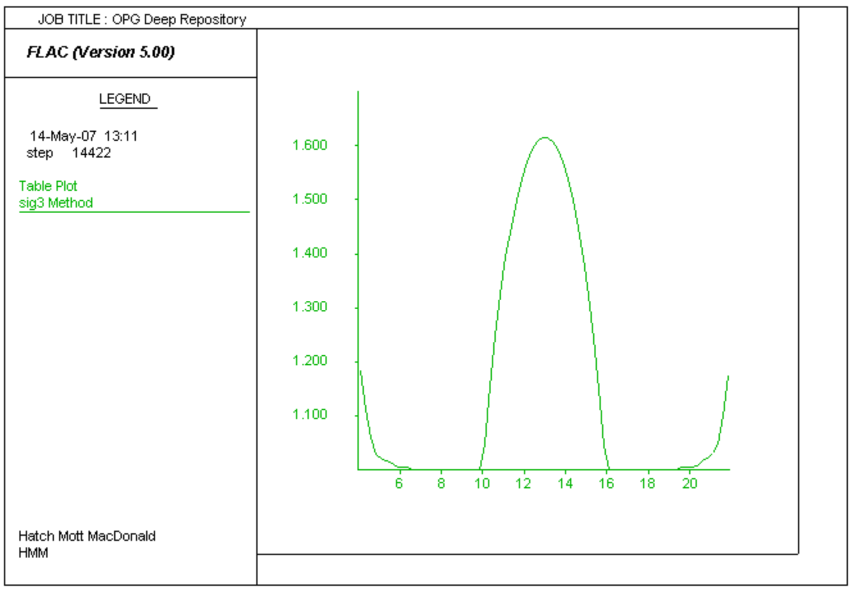
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

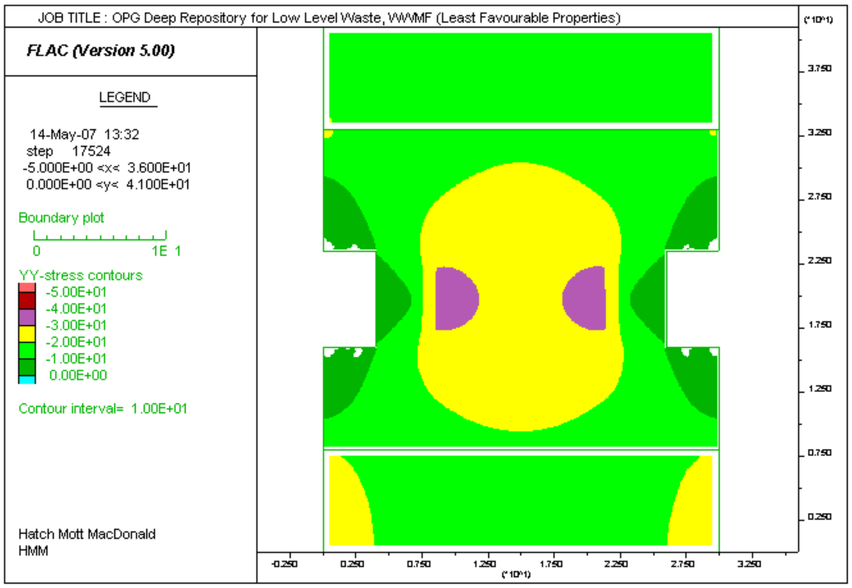


Factor Of Safety Across The Pillar

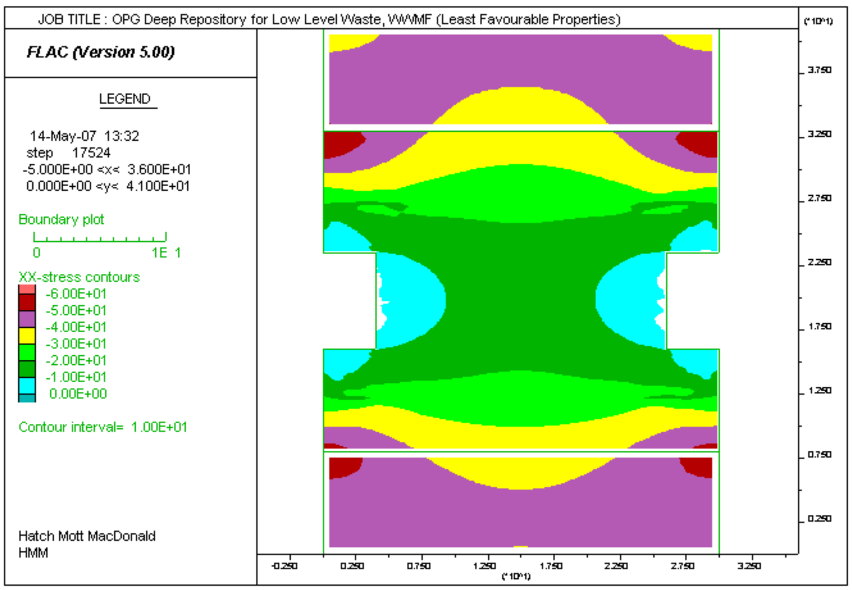


Least Favourable Parameters, K_0 = 2.5, Pillar Width = 22.0m

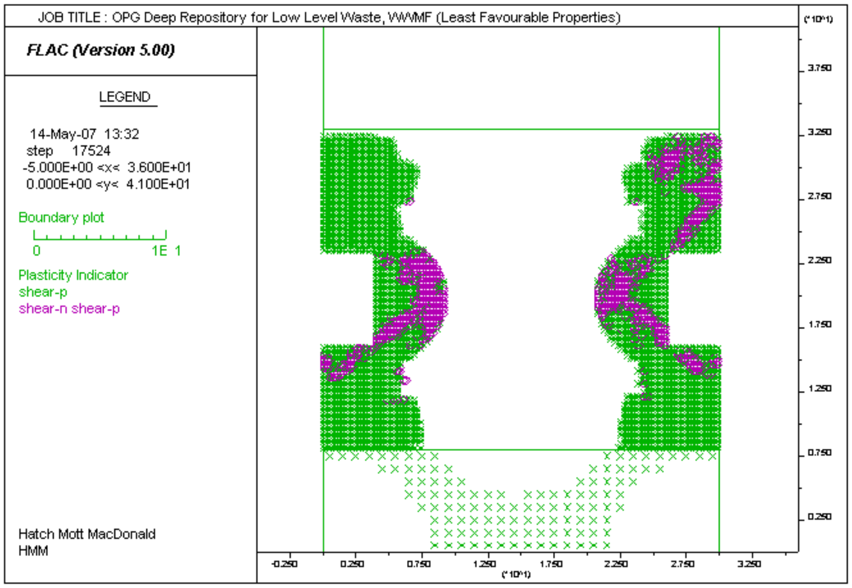
Vertical Stresses (MPa)



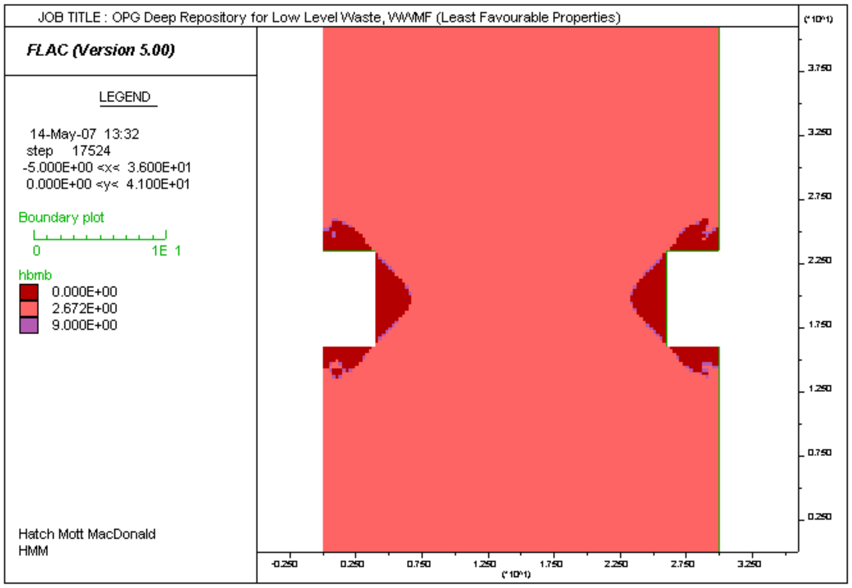
Horizontal Stresses (MPa)



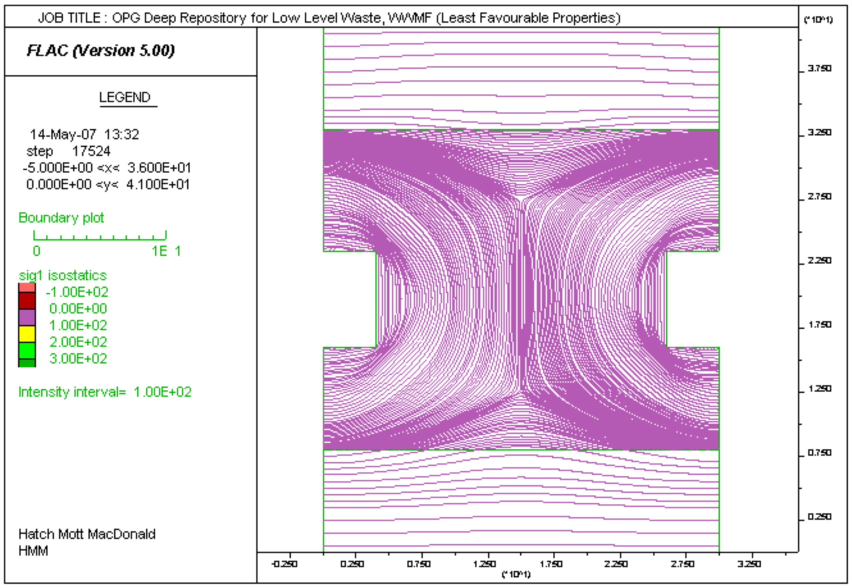
Plasticity Indicators



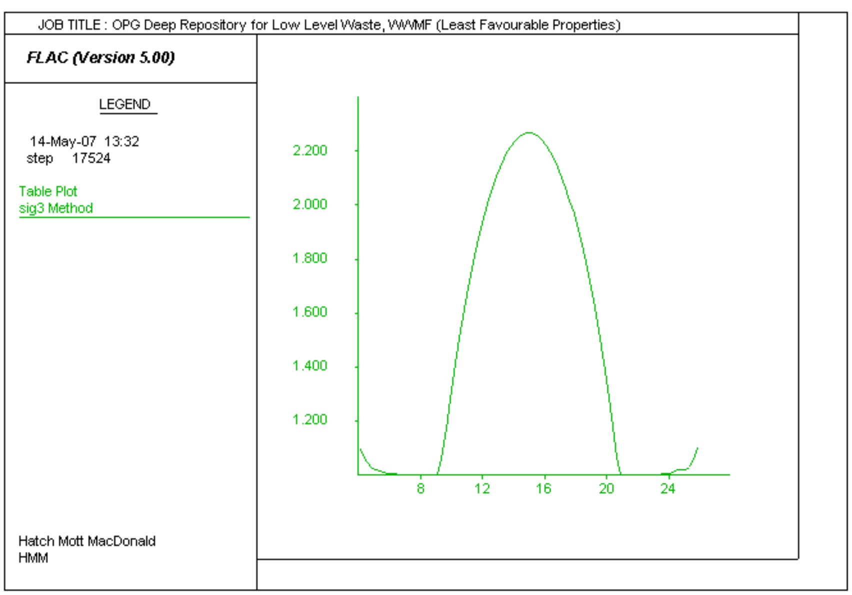
Failure Criteria (■ Brittle Failure, ■ Hoek-Brown Peak Strength, ■ Transition)



Maximum Principal Stress Trajectories (MPa)

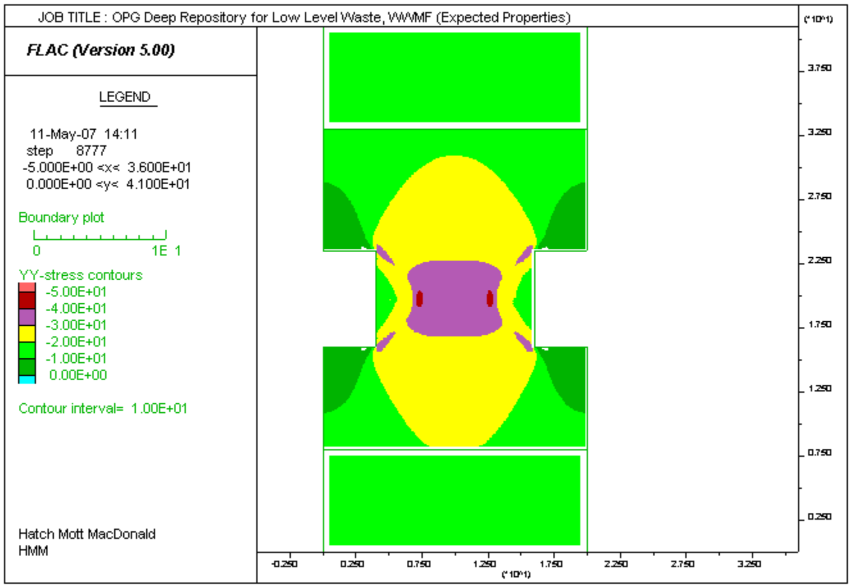


Factor Of Safety Across The Pillar

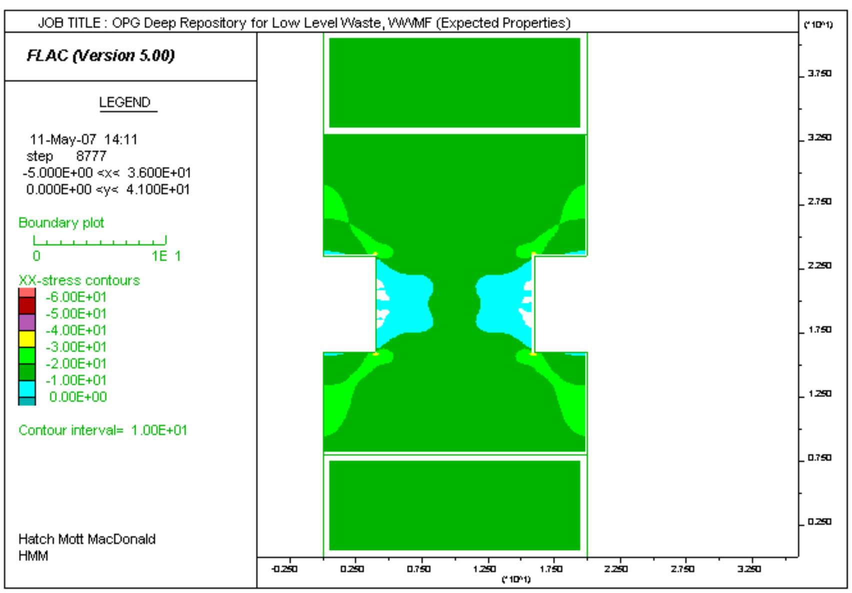


Expected Parameters, $K_0 = 1.0$, Pillar Width = 12.0m

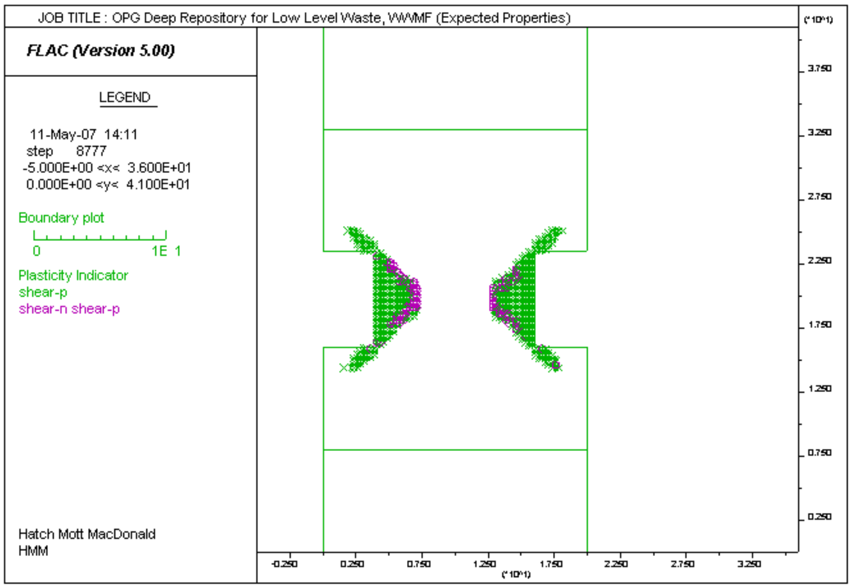
Vertical Stresses (MPa)



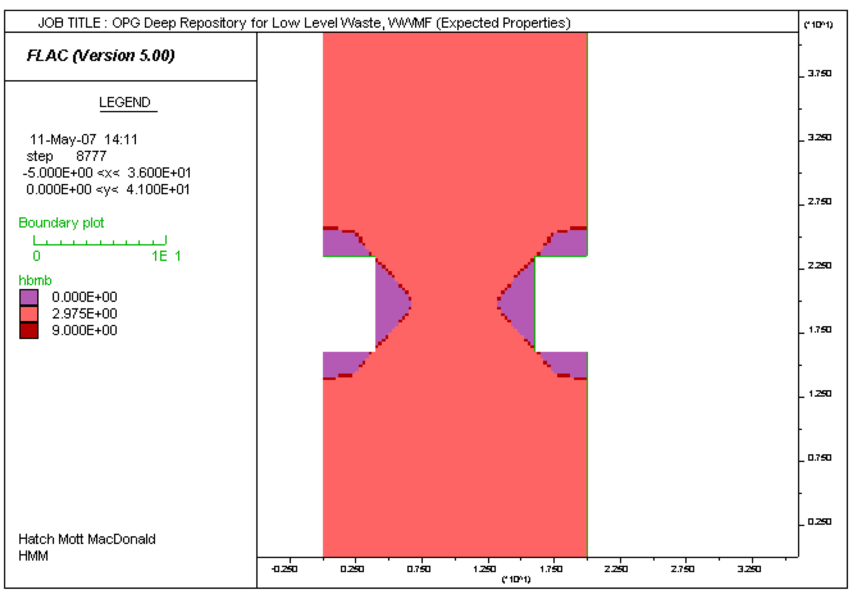
Horizontal Stresses (MPa)



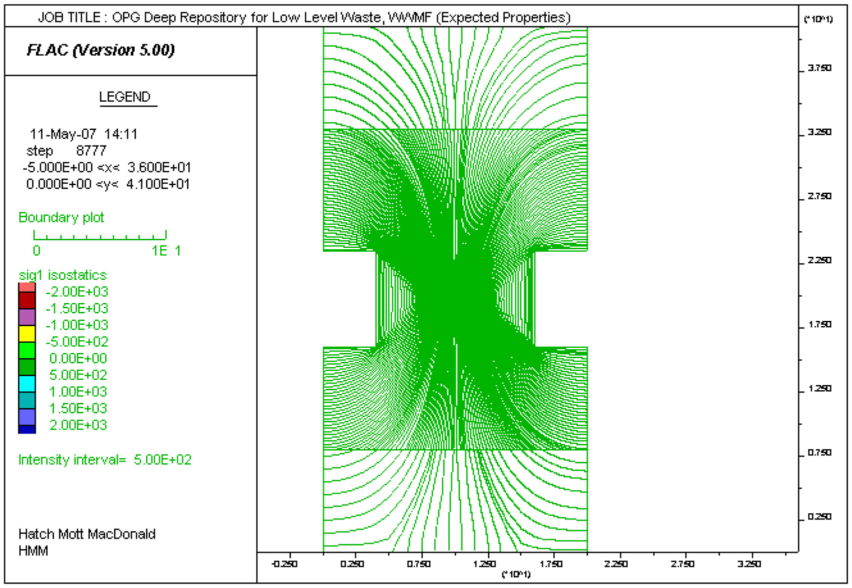
Plasticity Indicators



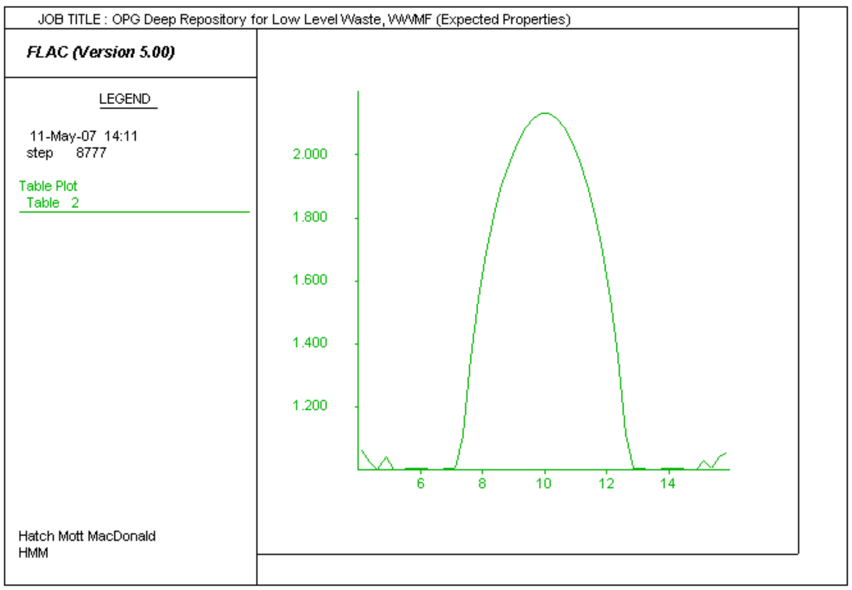
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

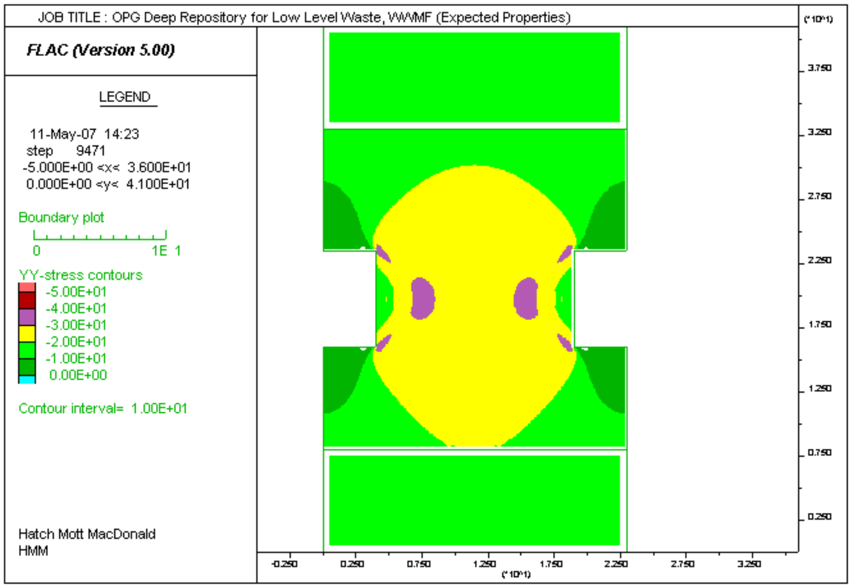


Factor Of Safety Across The Pillar

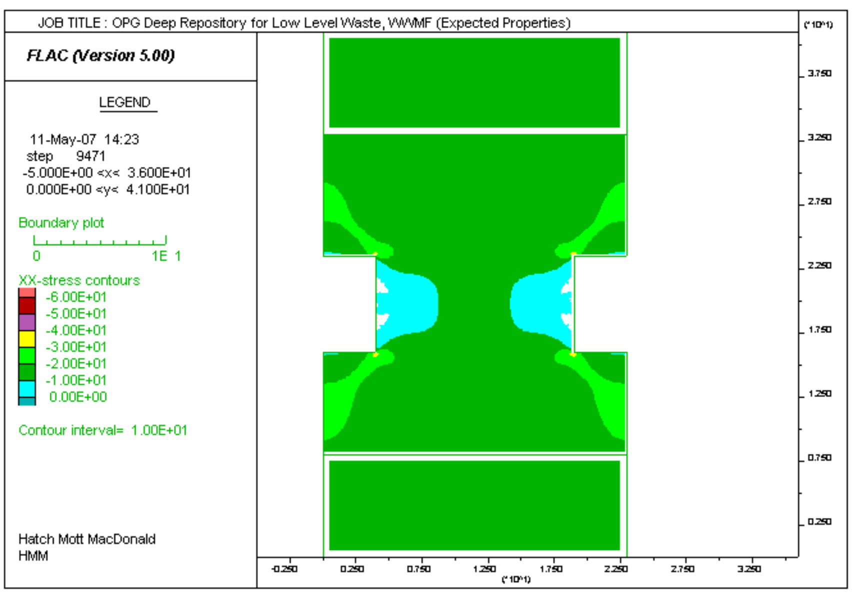


Expected Parameters, $K_0 = 1.0$, Pillar Width = 15.0m

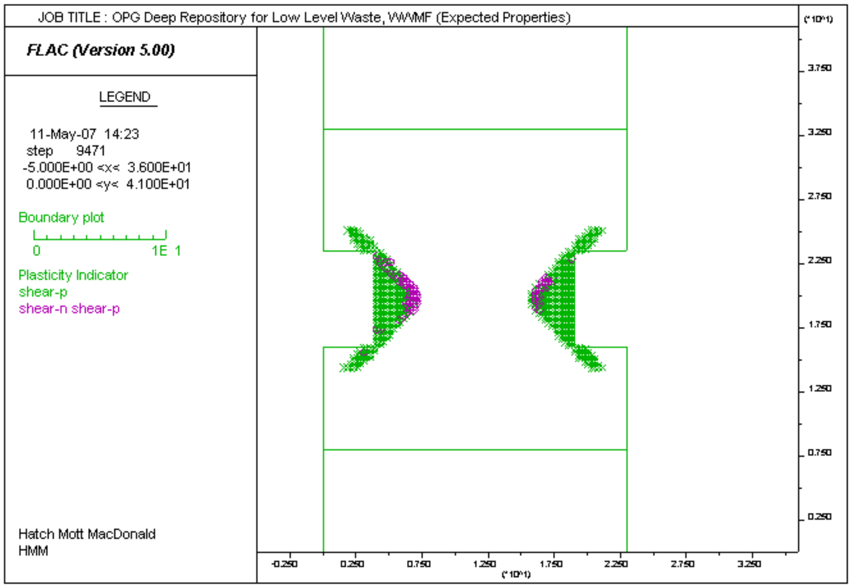
Vertical Stresses (MPa)



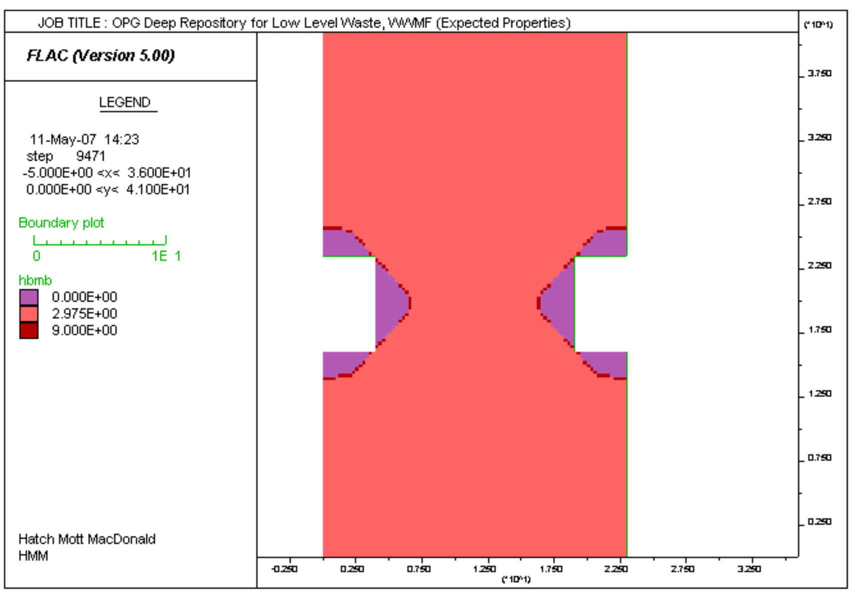
Horizontal Stresses (MPa)



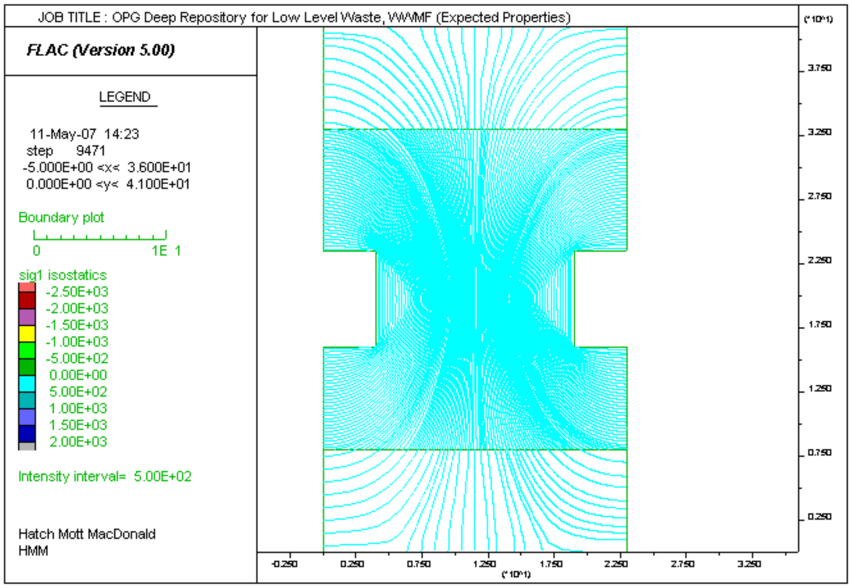
Plasticity Indicators



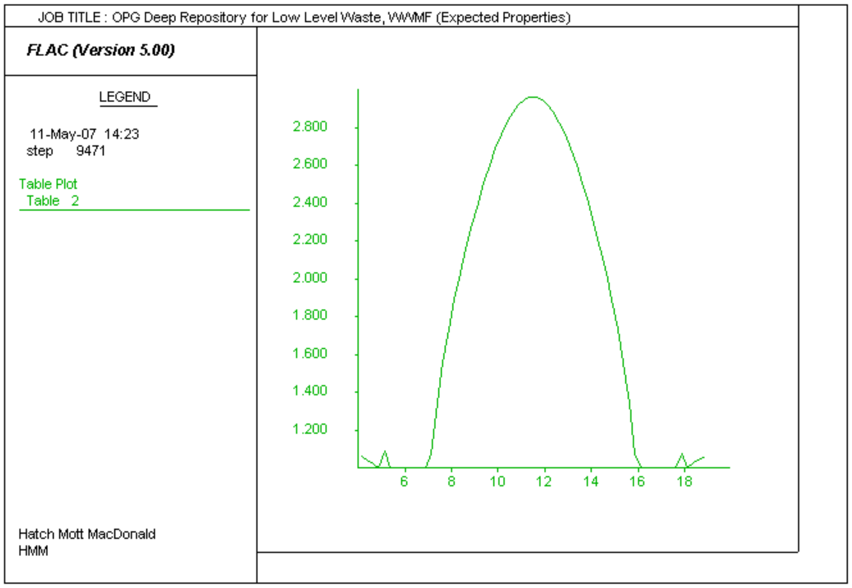
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

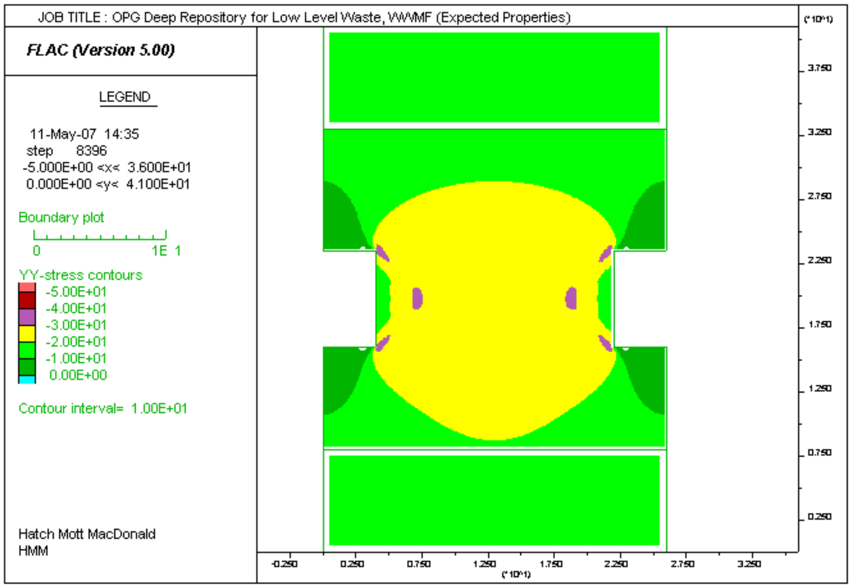


Factor Of Safety Across The Pillar

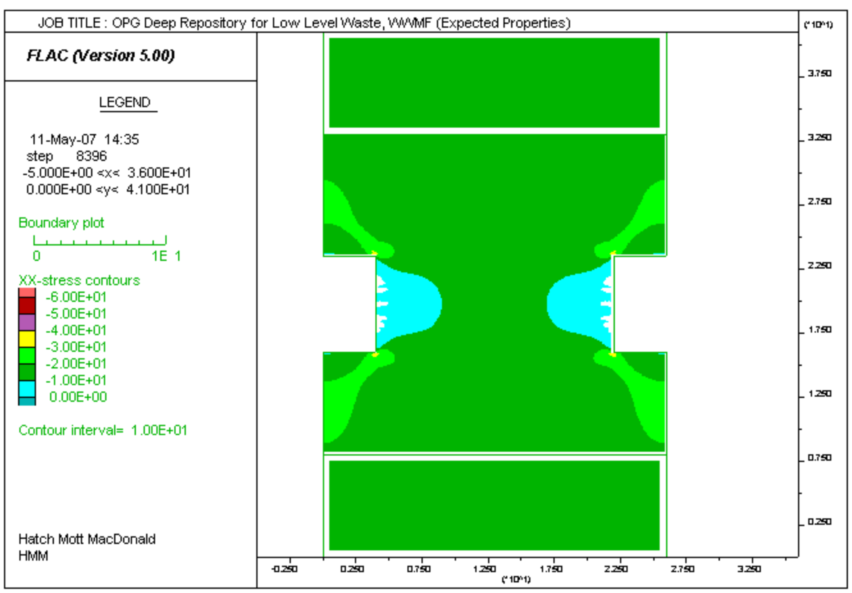


Expected Parameters, $K_0 = 1.0$, Pillar Width = 18.0m

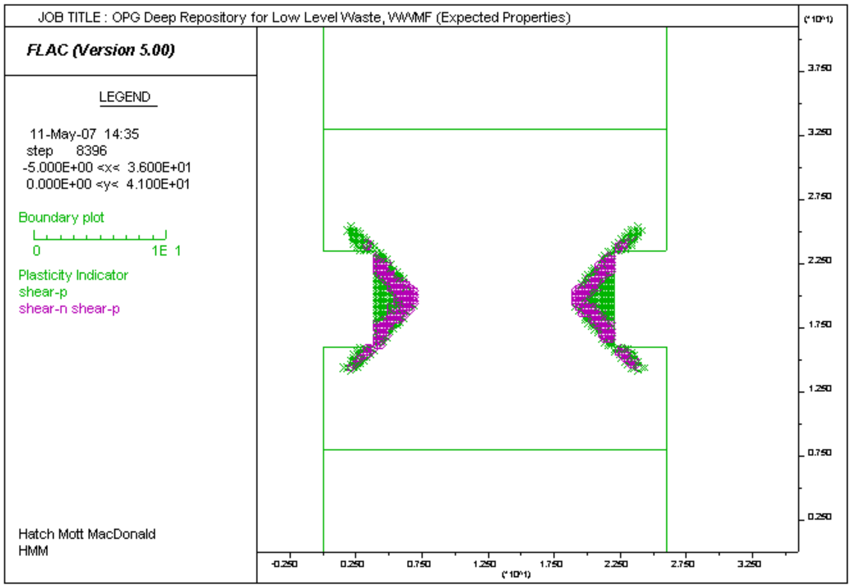
Vertical Stresses (MPa)



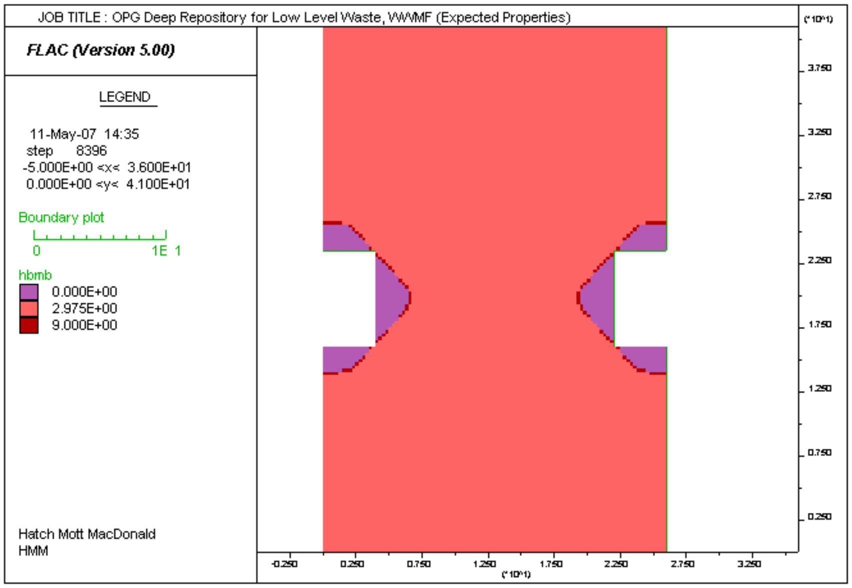
Horizontal Stresses (MPa)



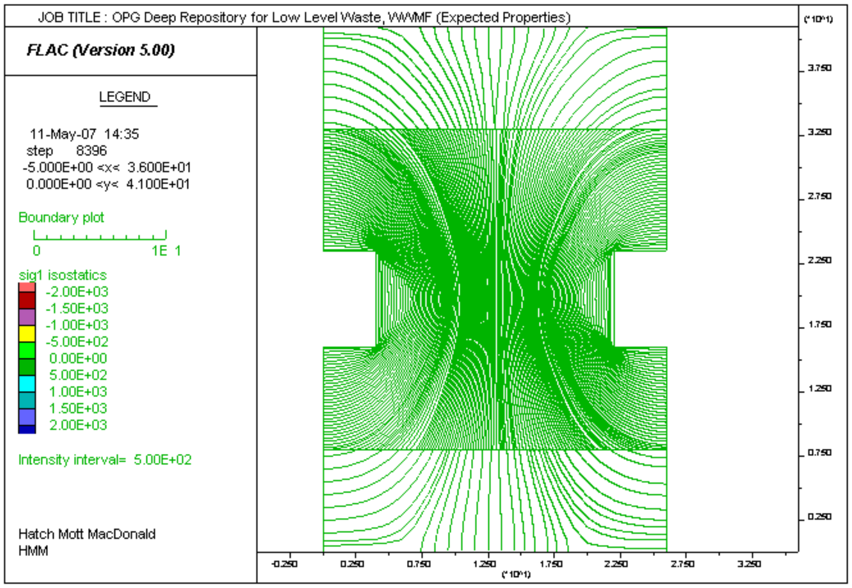
Plasticity Indicators



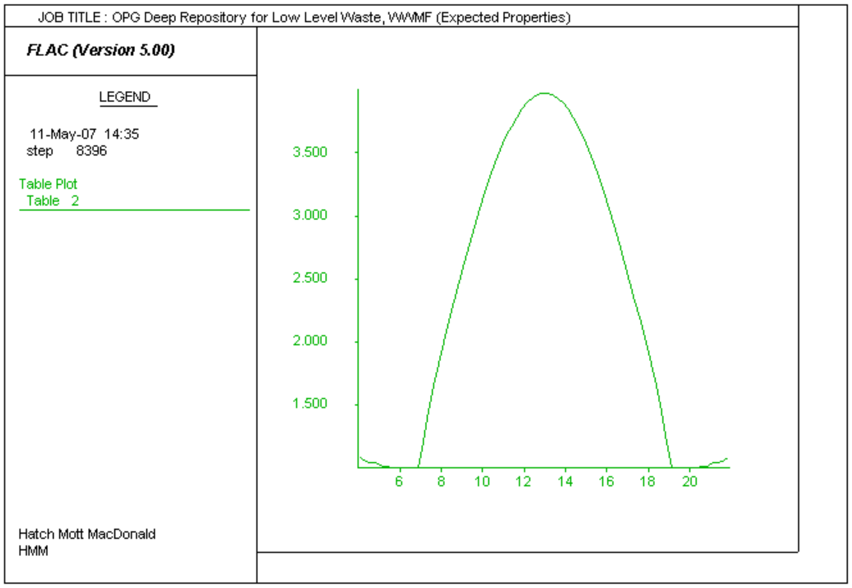
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)



Factor Of Safety Across The Pillar



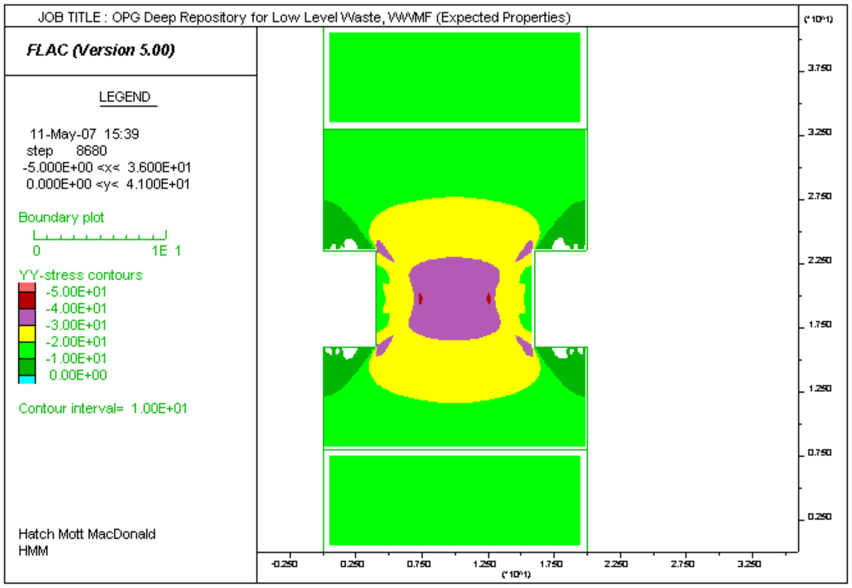
For Expected Parameters, $K_0 = 1.5$,

Pillar Width of 12.0m, 14.0m, 16.0m, 18.0m and 20.0m

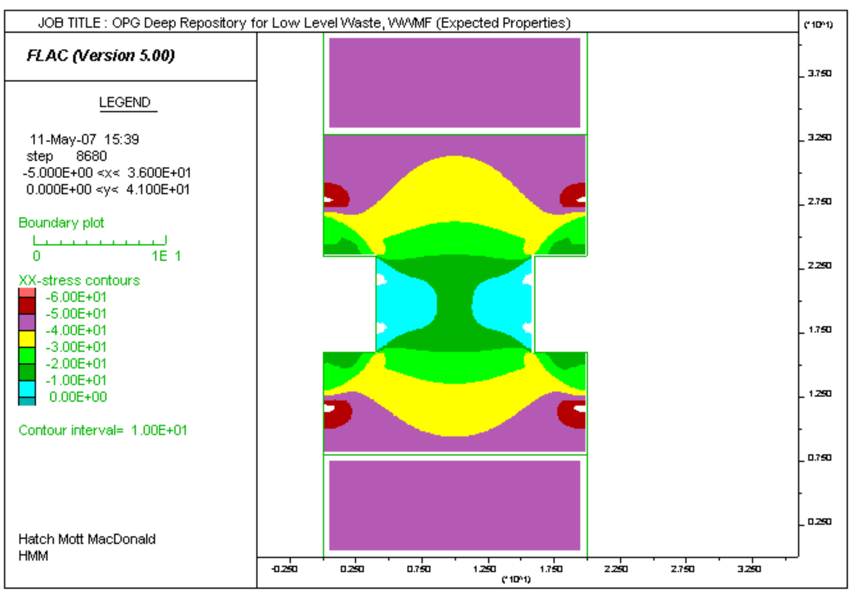
See Appendix C

Expected Parameters, K_0 = 2.5, Pillar Width = 12.0m

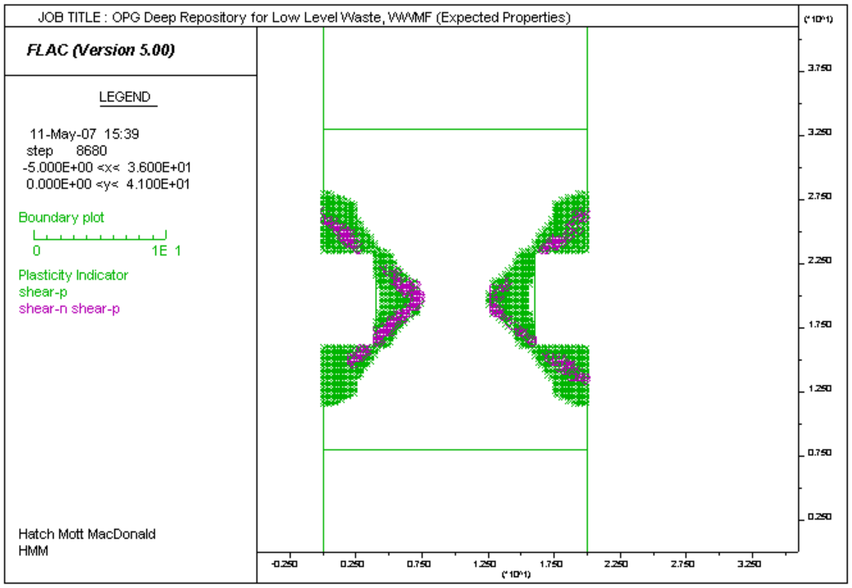
Vertical Stresses (MPa)



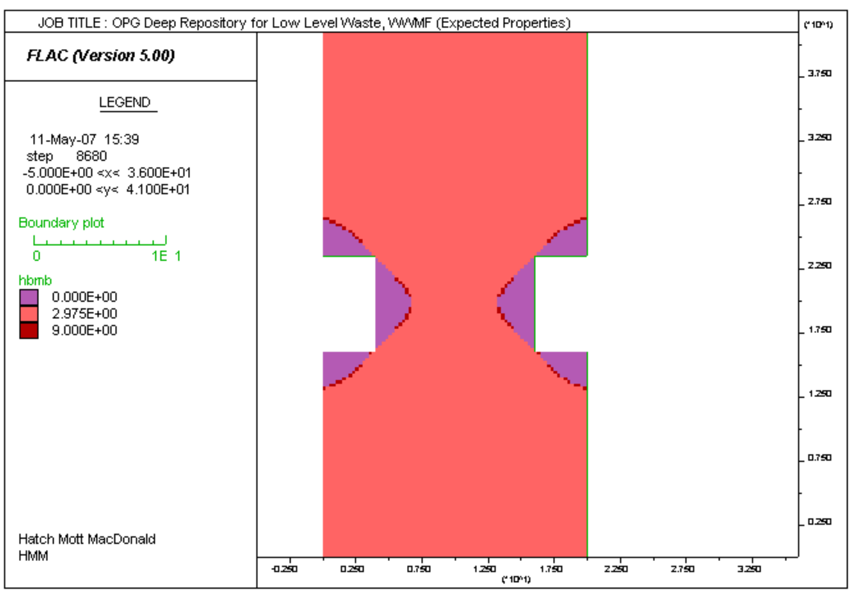
Horizontal Stresses (MPa)



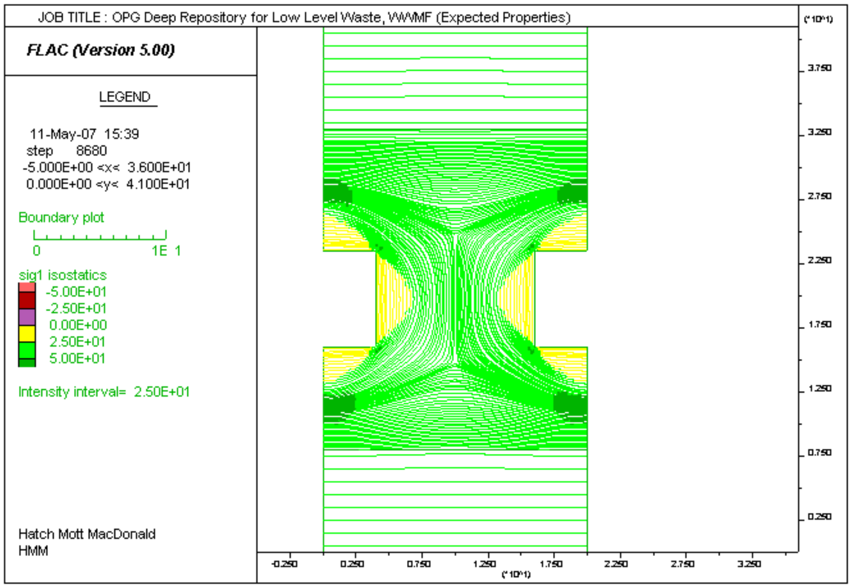
Plasticity Indicators



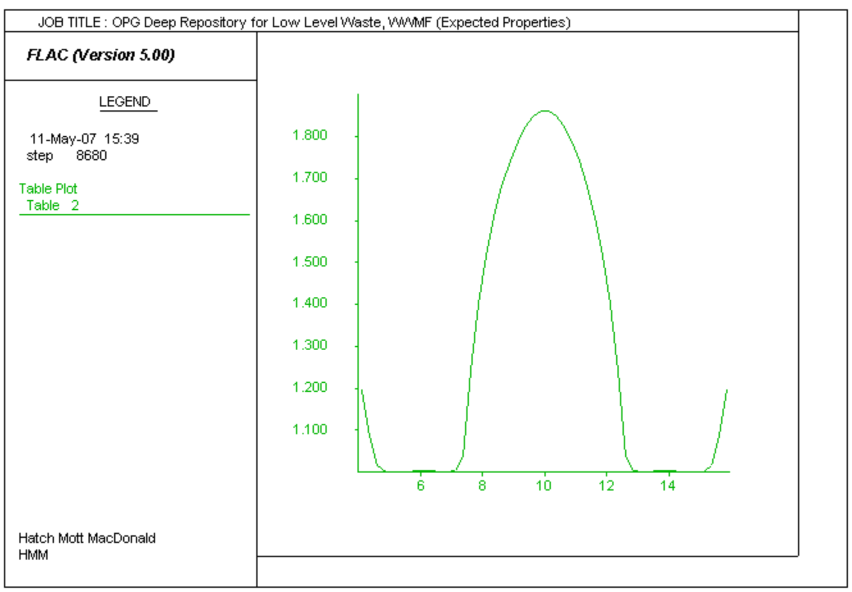
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

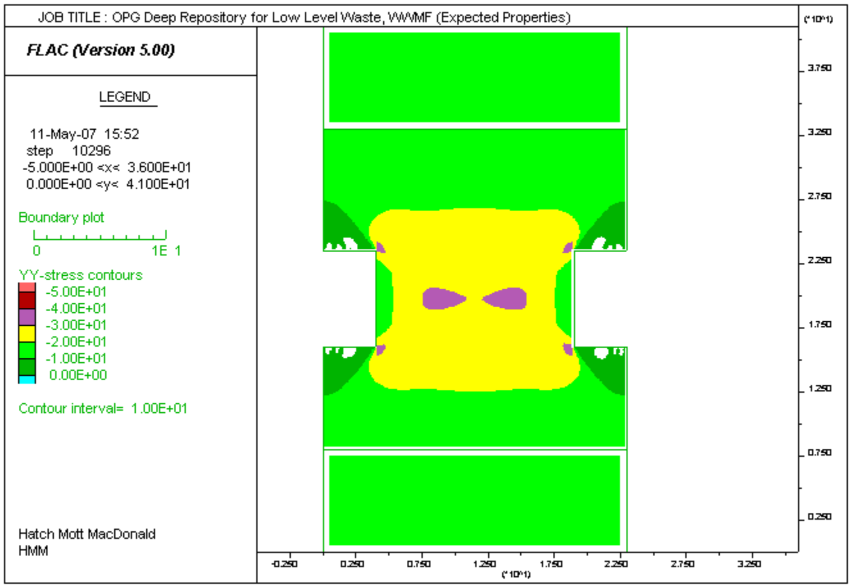


Factor Of Safety Across The Pillar

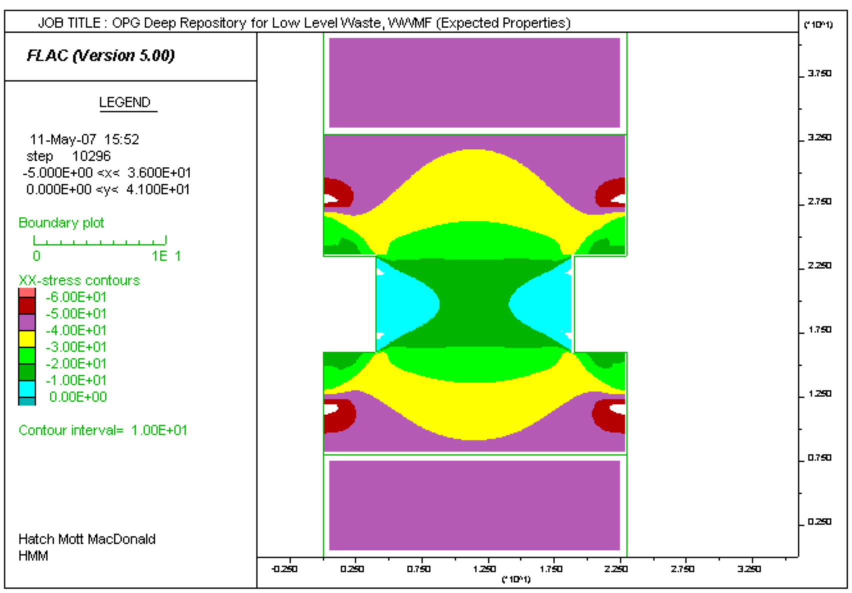


Expected Parameters, K_0 = 2.5, Pillar Width = 15.0m

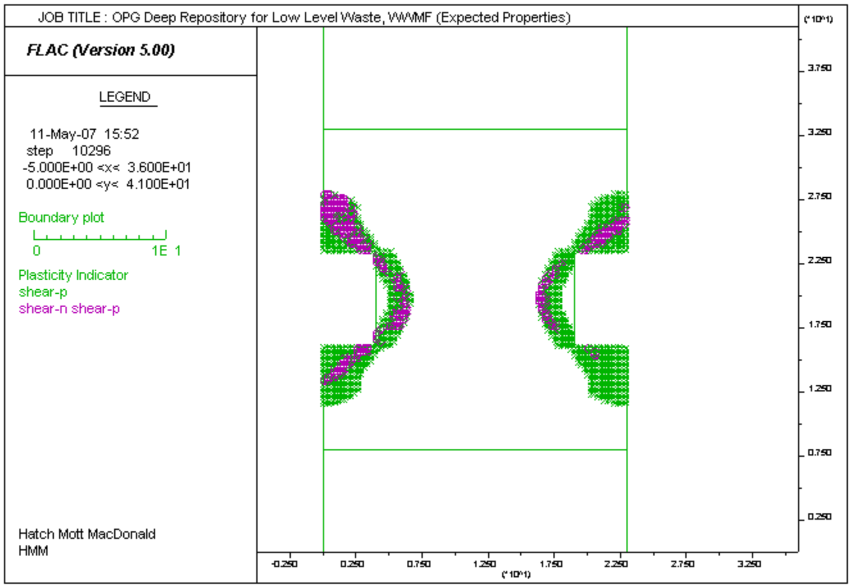
Vertical Stresses (MPa)



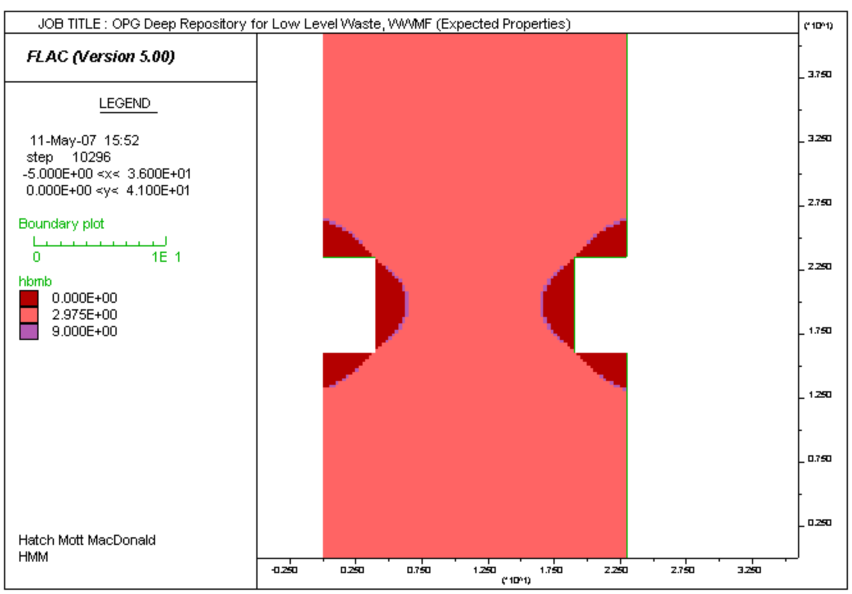
Horizontal Stresses (MPa)



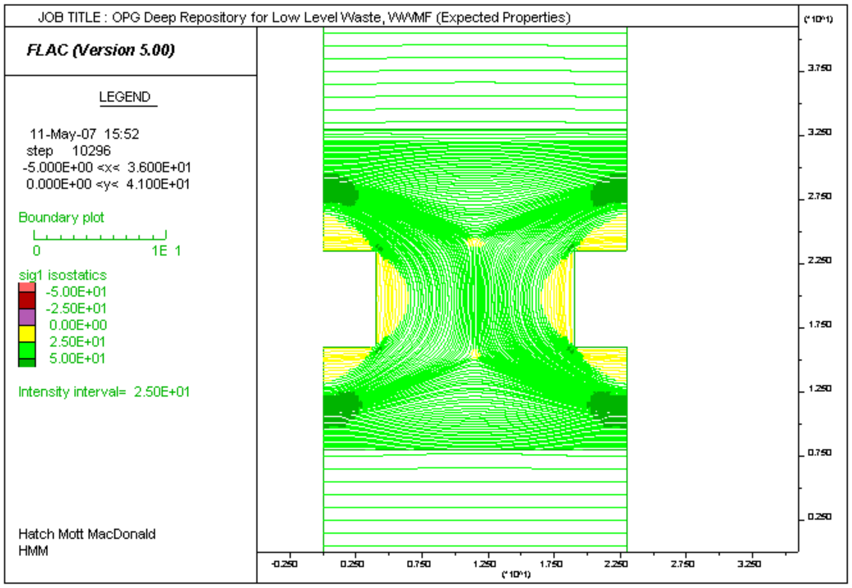
Plasticity Indicators



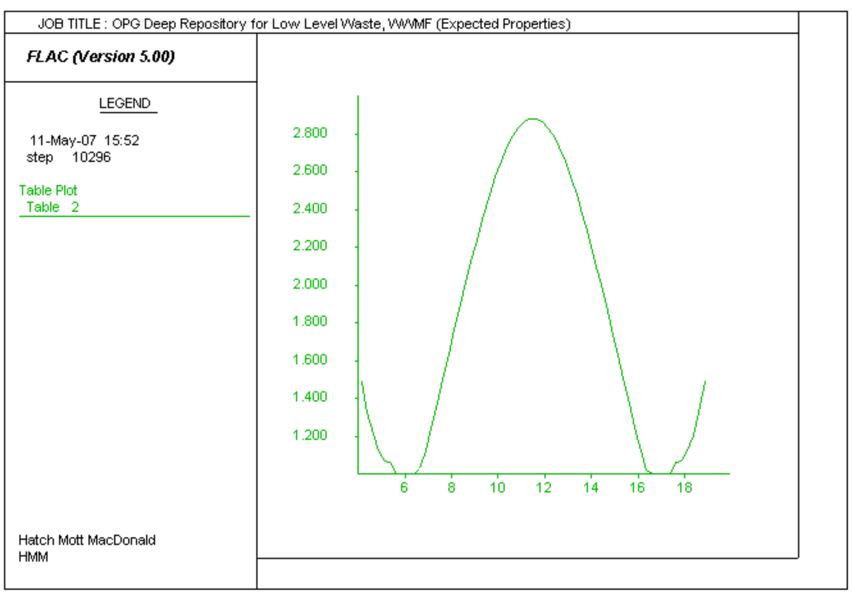
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

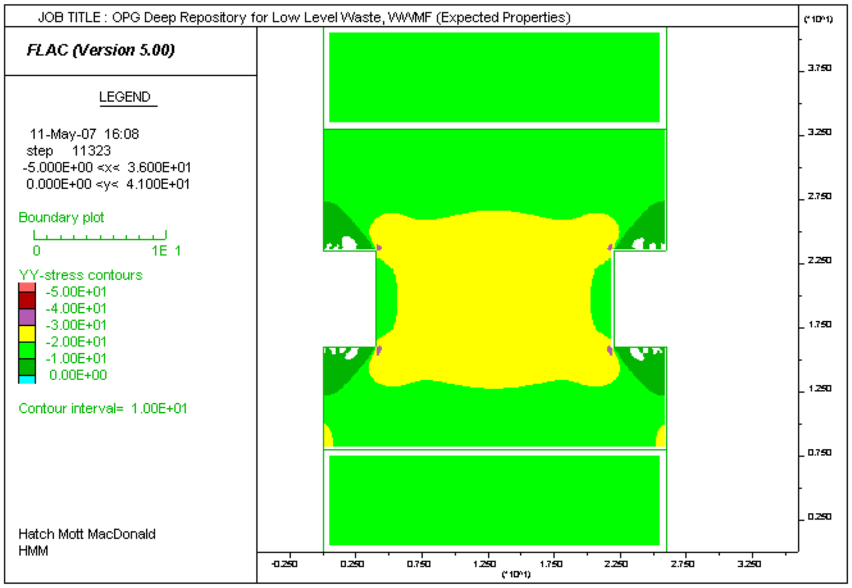


Factor Of Safety Across The Pillar

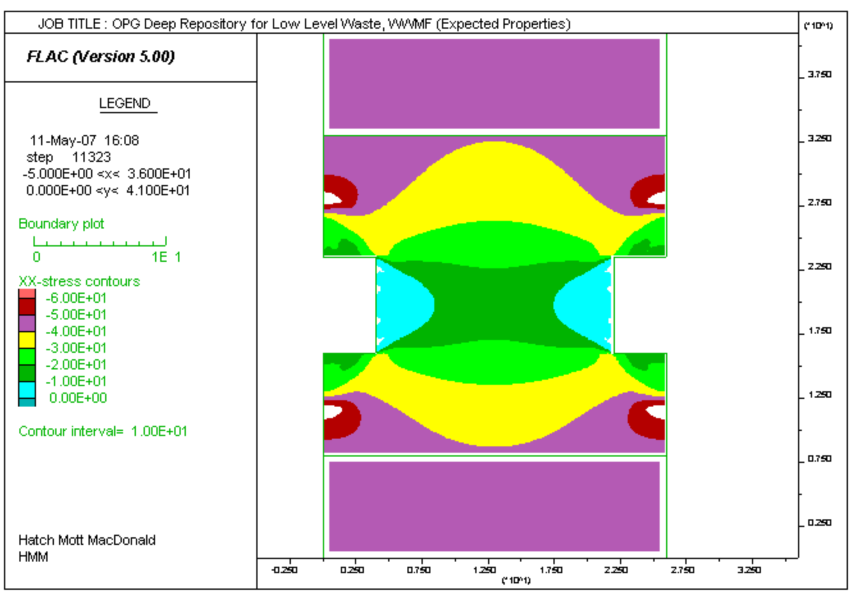


Expected Parameters, K_0 = 2.5, Pillar Width = 18.0m

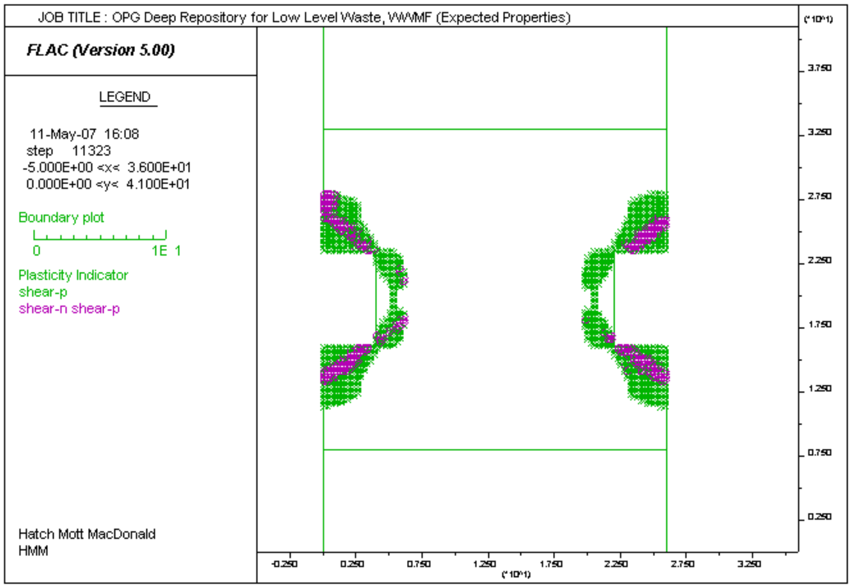
Vertical Stresses (MPa)



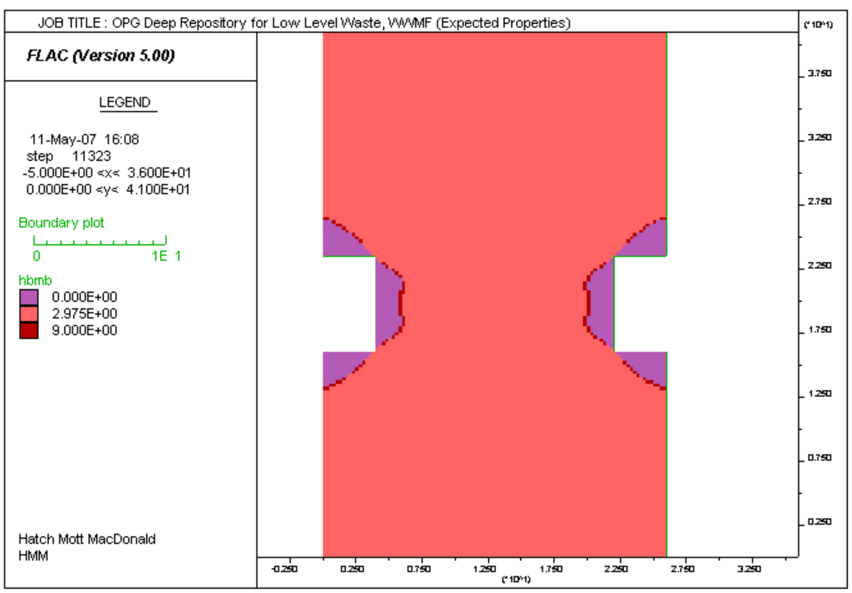
Horizontal Stresses (MPa)



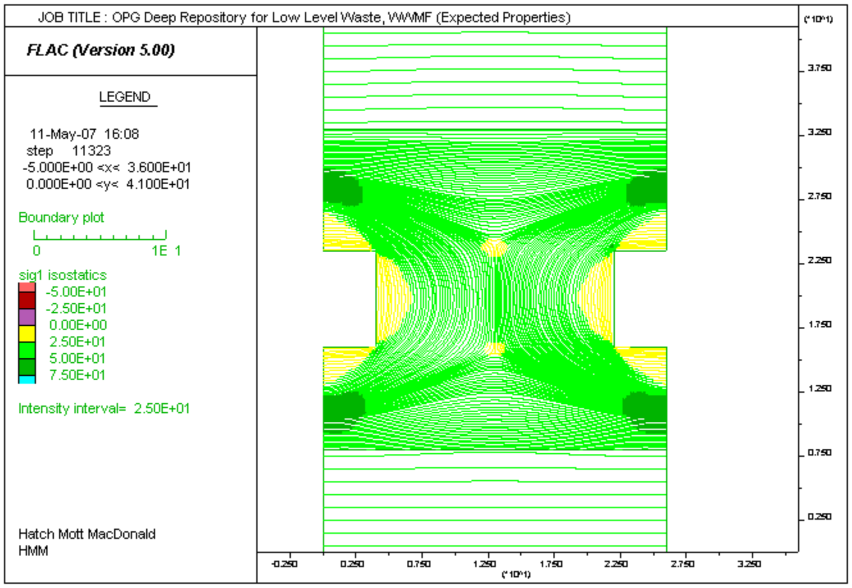
Plasticity Indicators



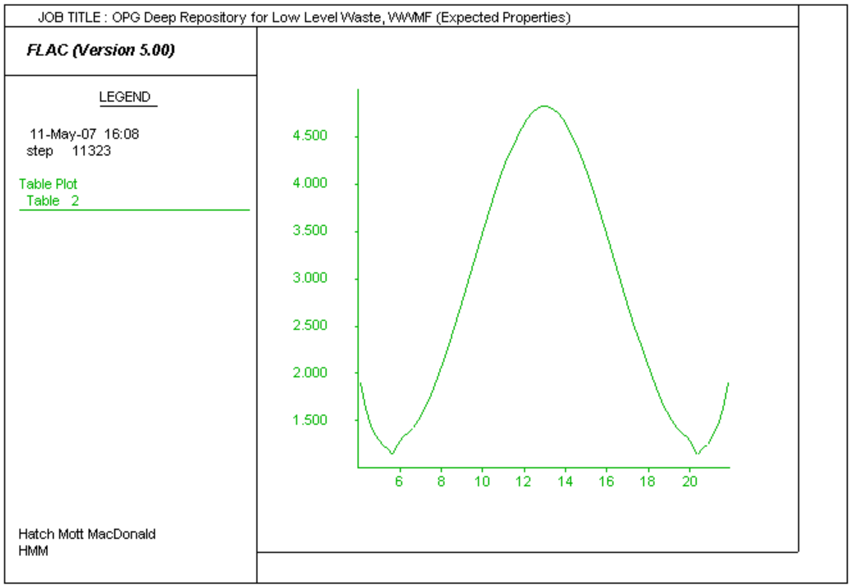
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

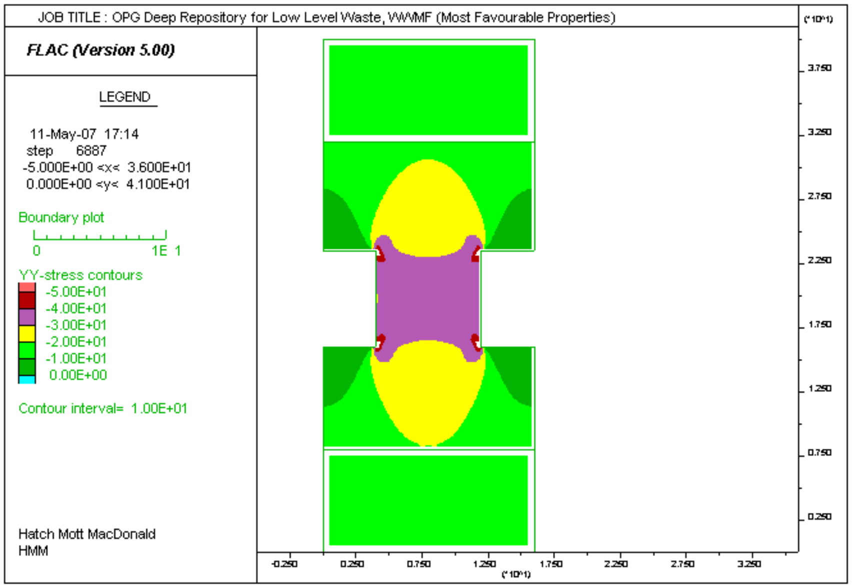


Factor Of Safety Across The Pillar

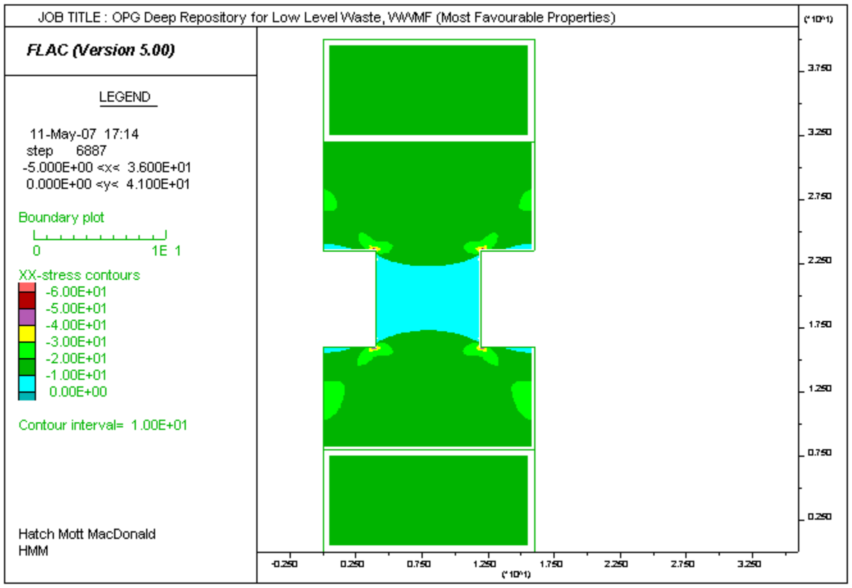


Most Favourable Parameters, K_0 = 1.0, Pillar Width = 8.0m

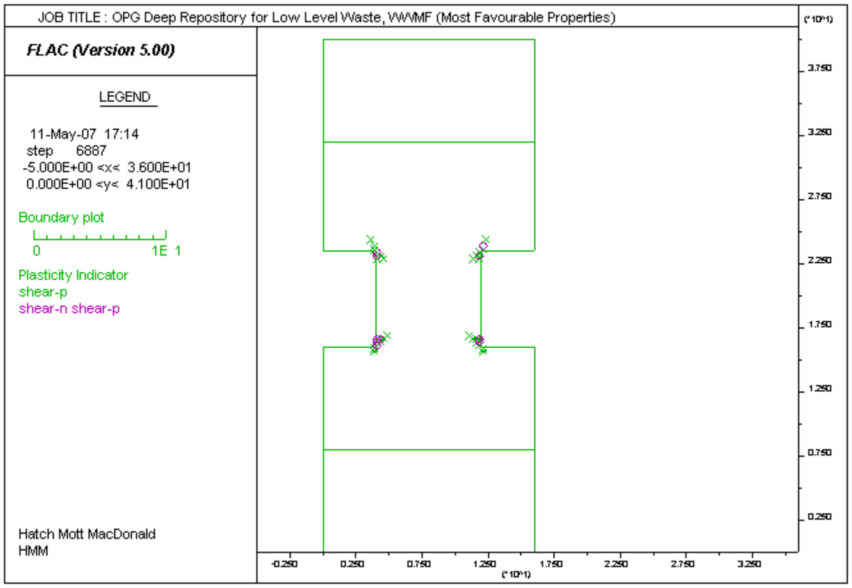
Vertical Stresses (MPa)



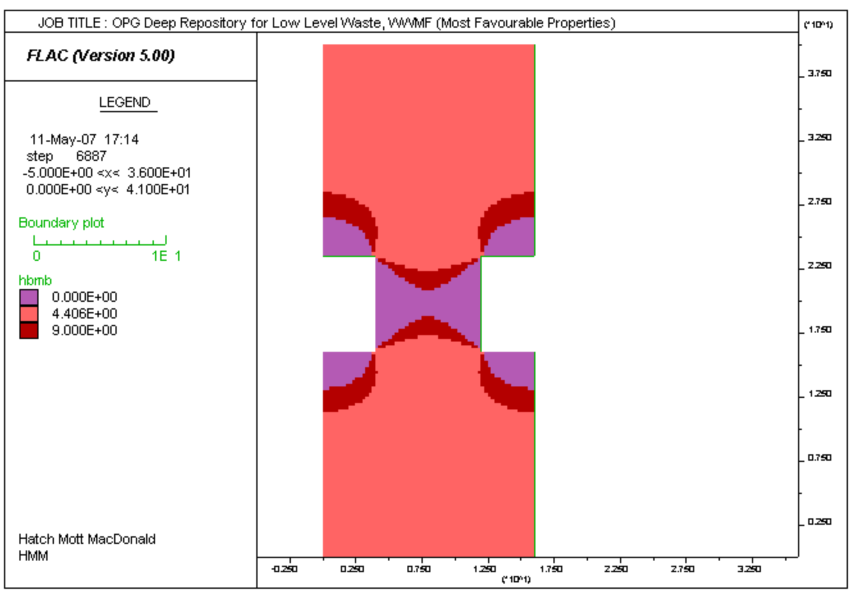
Horizontal Stresses (MPa)



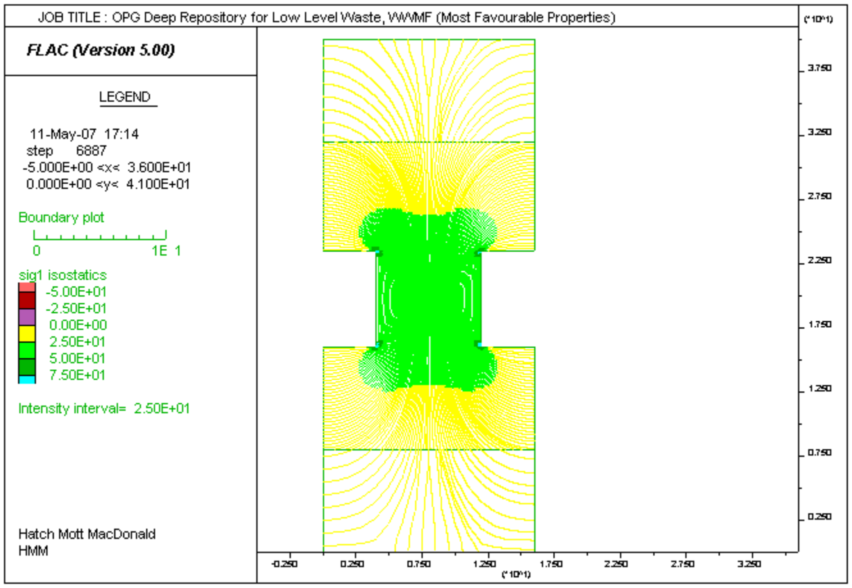
Plasticity Indicators



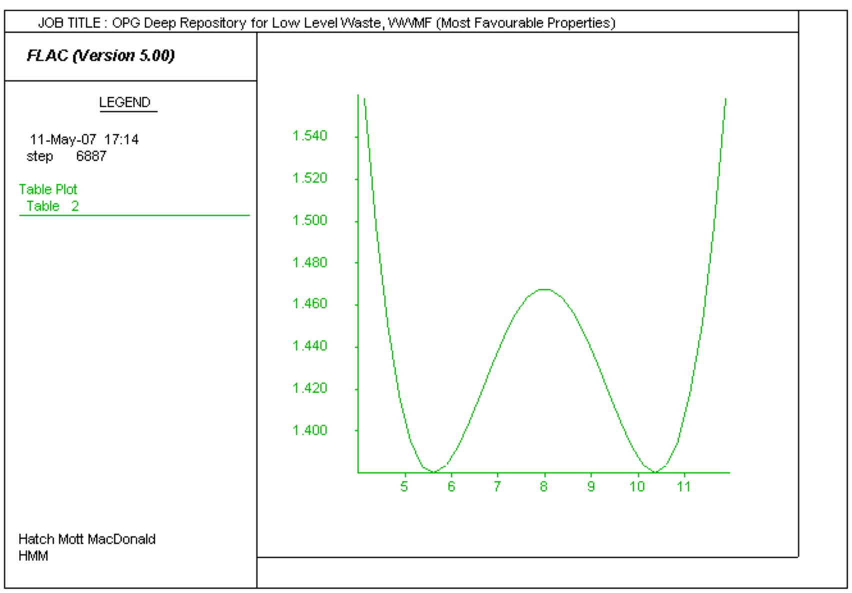
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

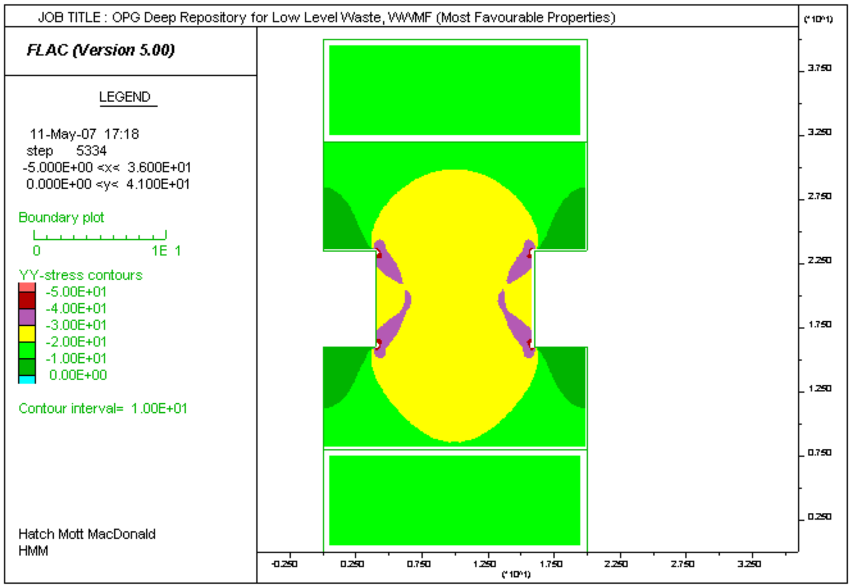


Factor Of Safety Across The Pillar

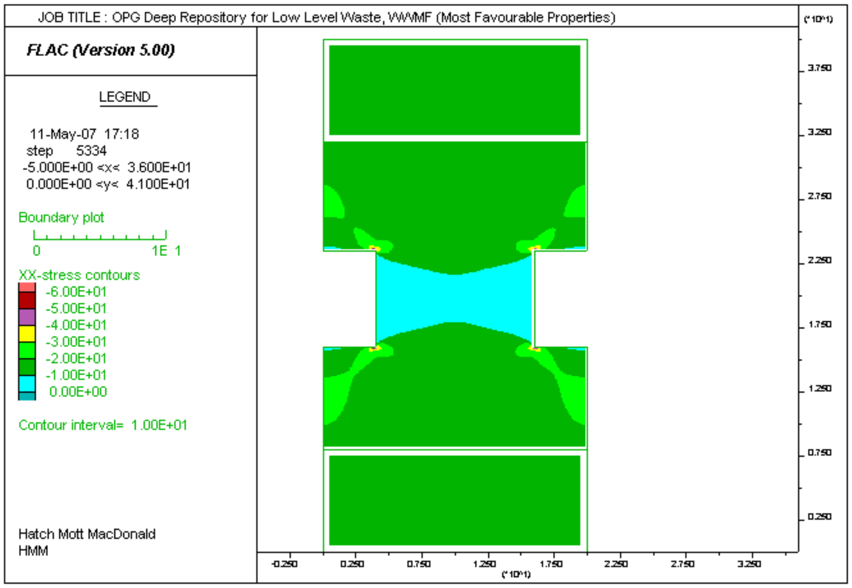


Most Favourable Parameters, K_0 = 1.0, Pillar Width = 12.0m

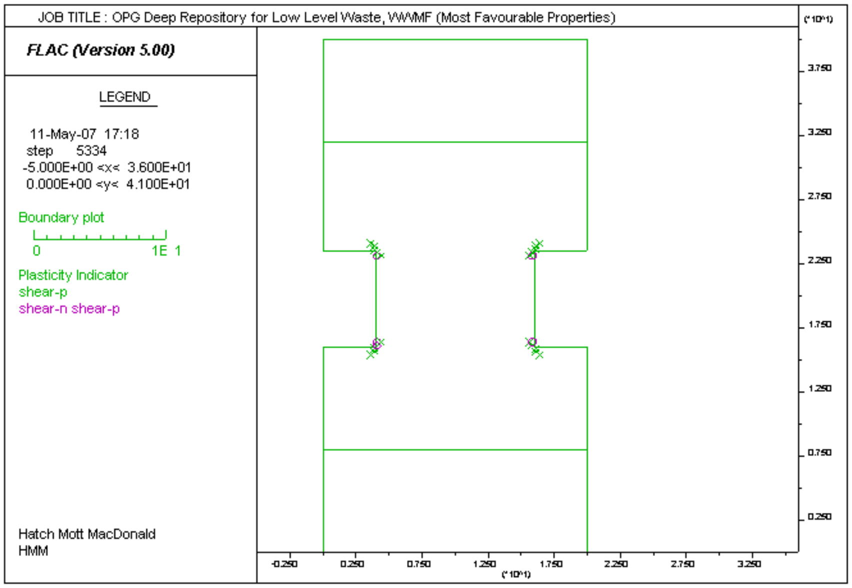
Vertical Stresses (MPa)



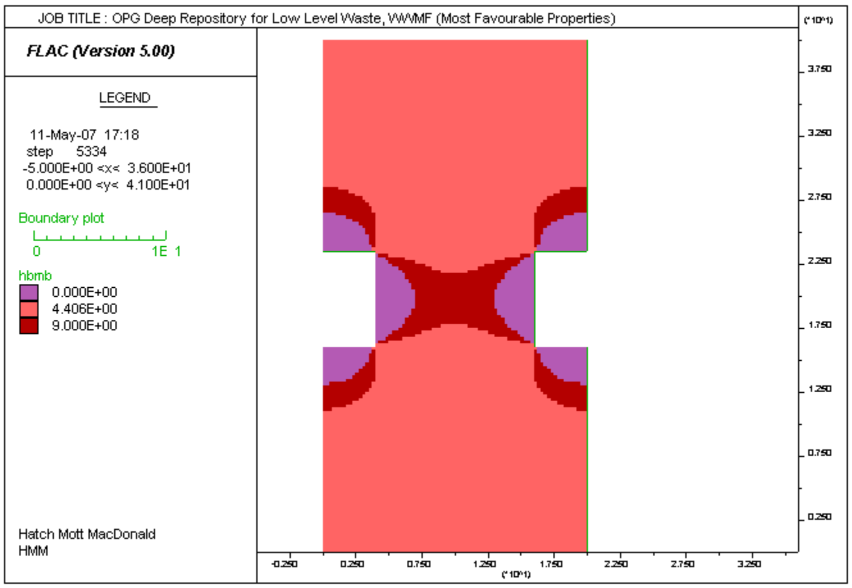
Horizontal Stresses (MPa)



Plasticity Indicators



Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



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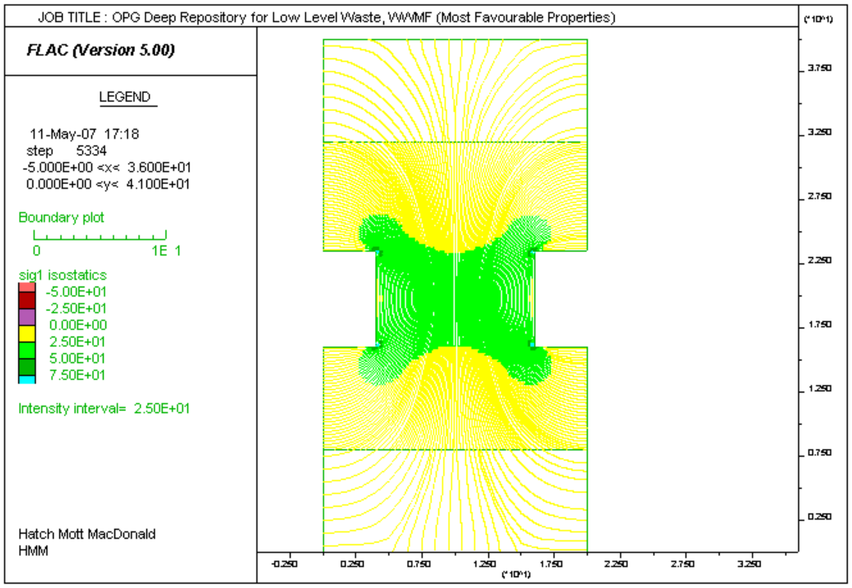
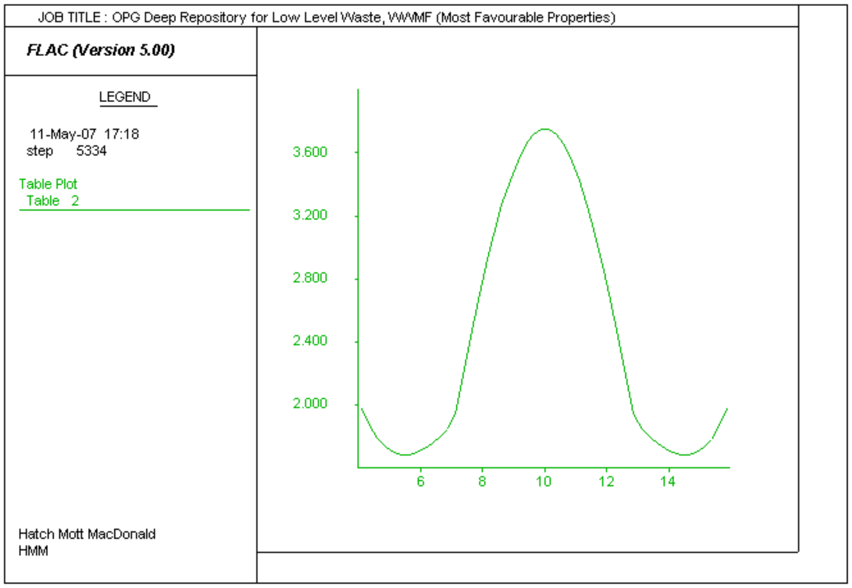
Maximum Principal Stress Trajectories (MPa)

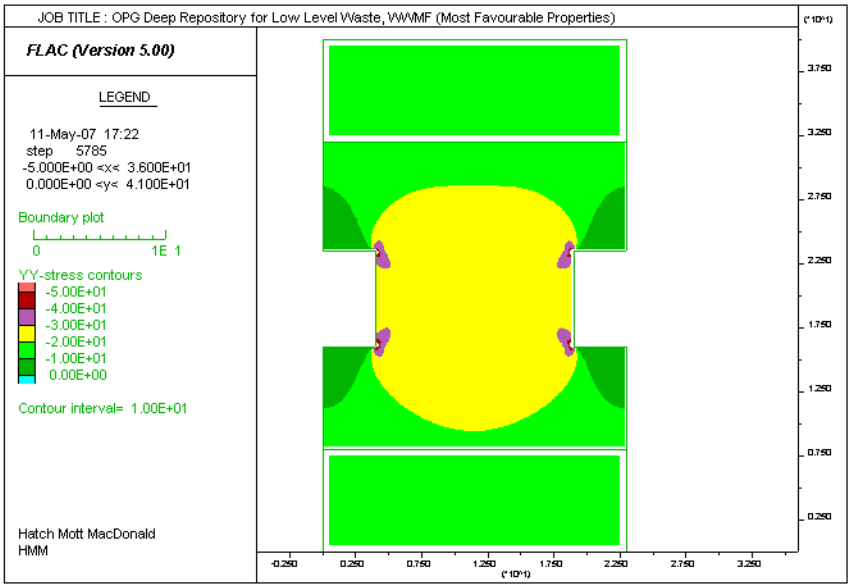


Factor Of Safety Across The Pillar

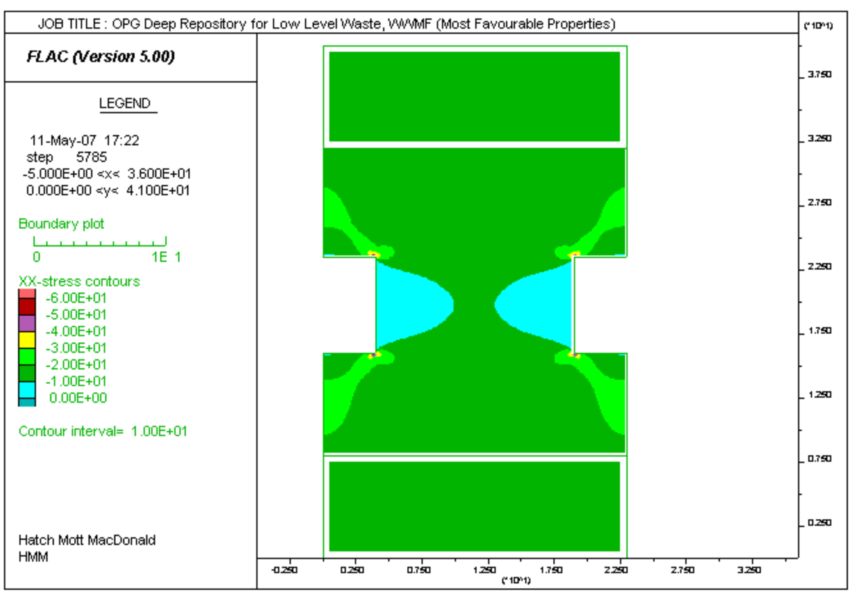


Most Favourable Parameters, K_0 = 1.0, Pillar Width = 15.0m

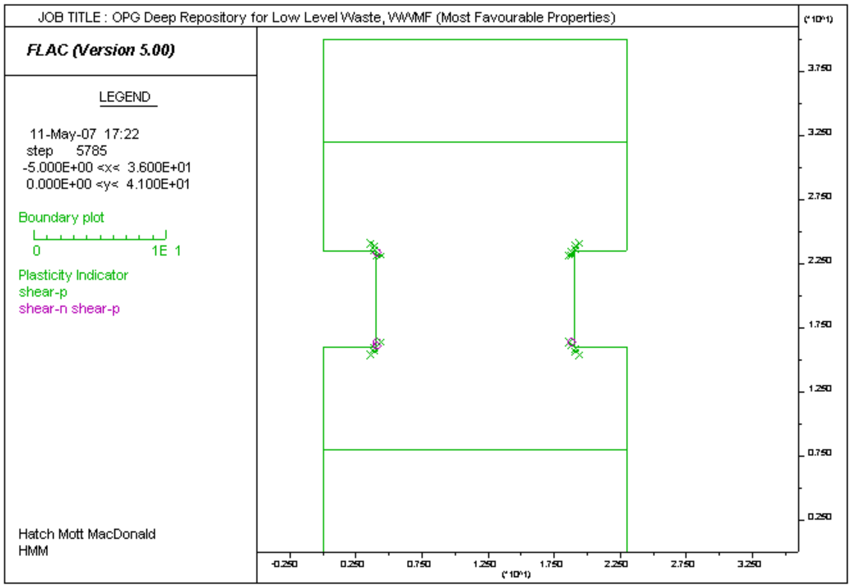
Vertical Stresses (MPa)



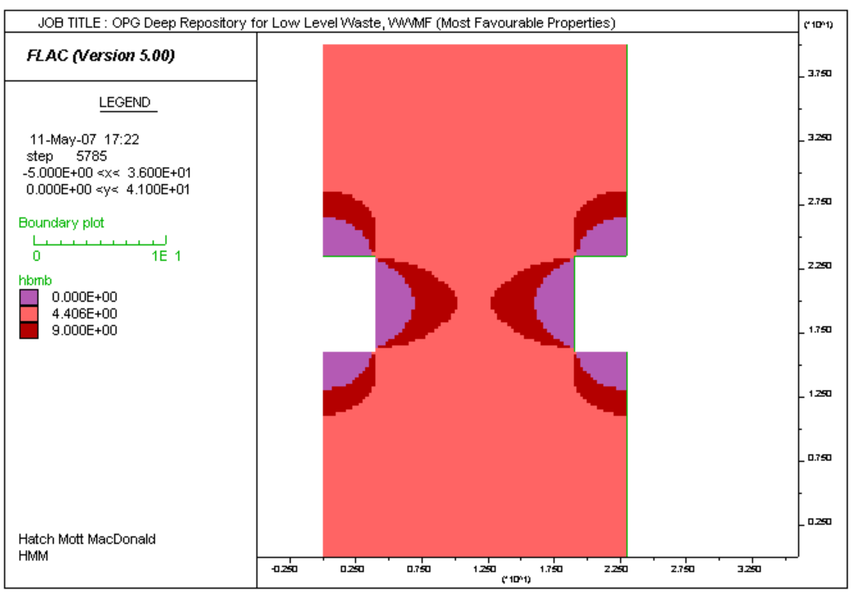
Horizontal Stresses (MPa)



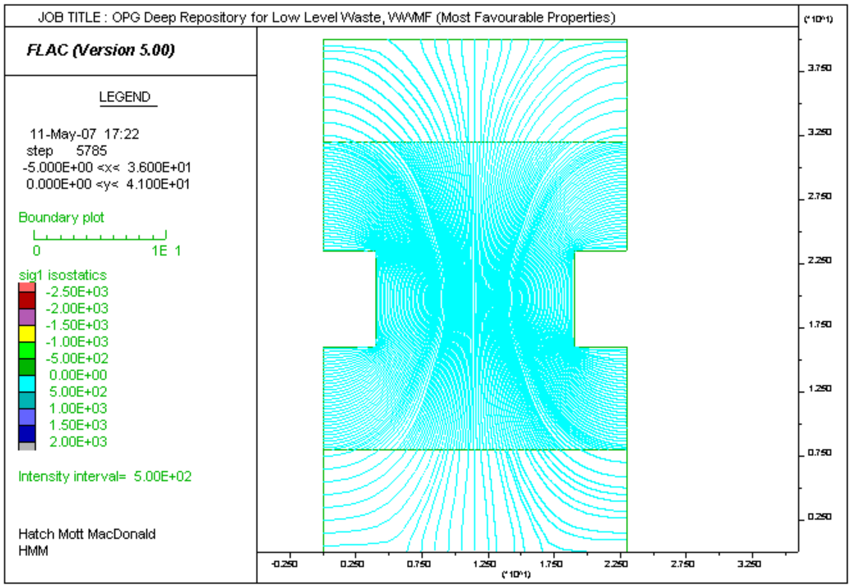
Plasticity Indicators



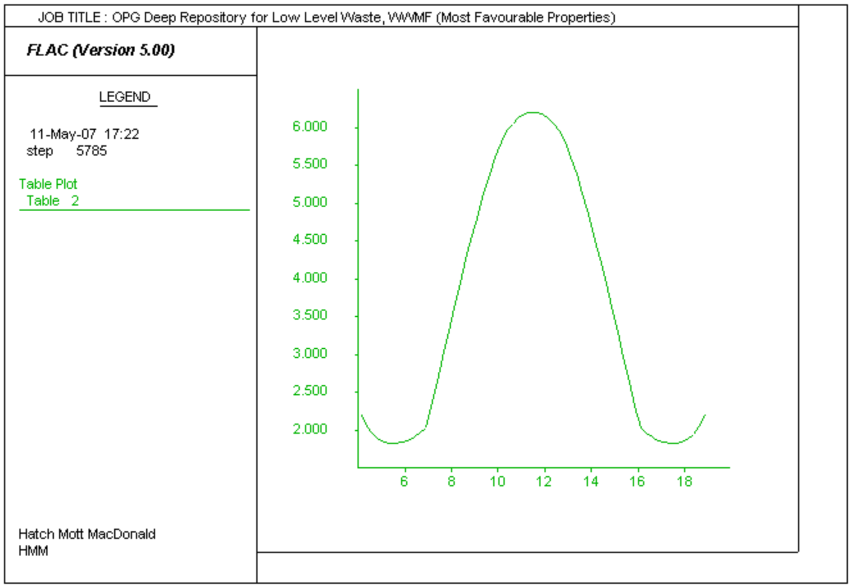
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

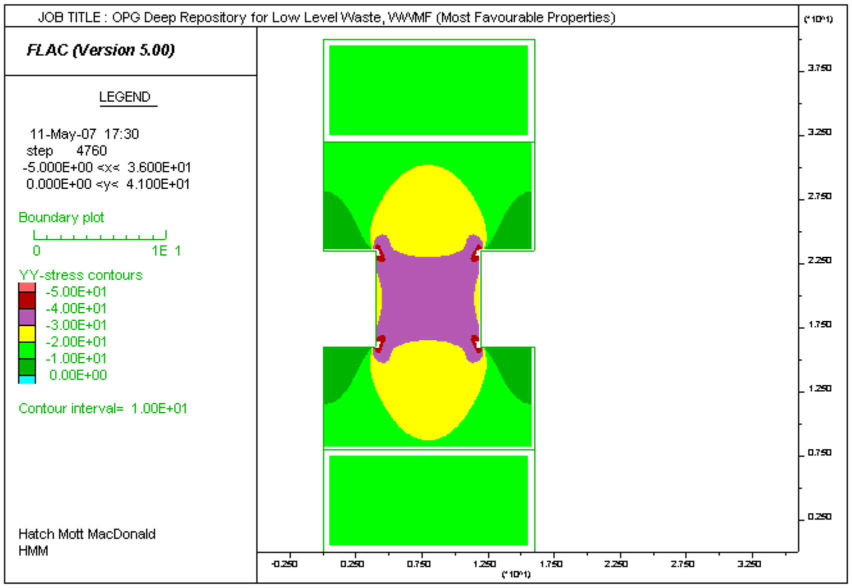


Factor Of Safety Across The Pillar

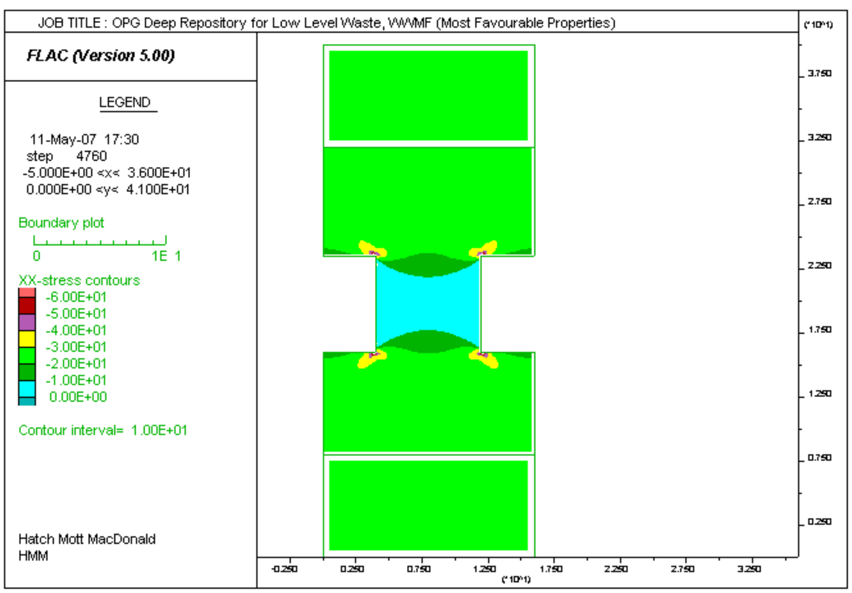


Most Favourable Parameters, $K_0 = 1.5$, Pillar Width = 8.0m

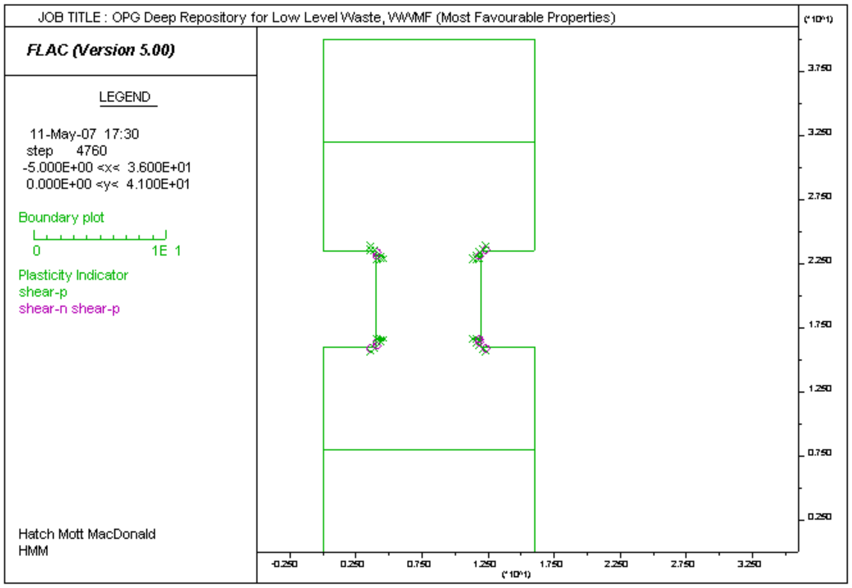
Vertical Stresses (MPa)



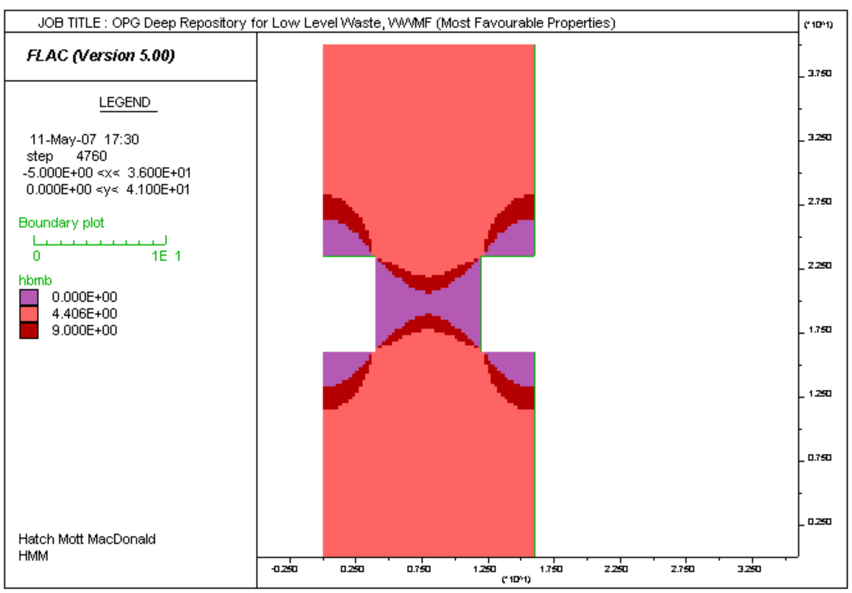
Horizontal Stresses (MPa)



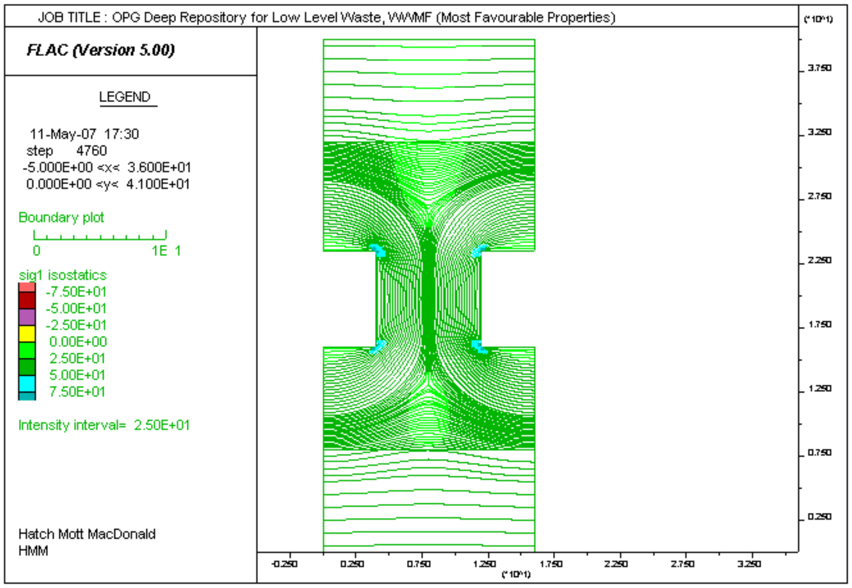
Plasticity Indicators



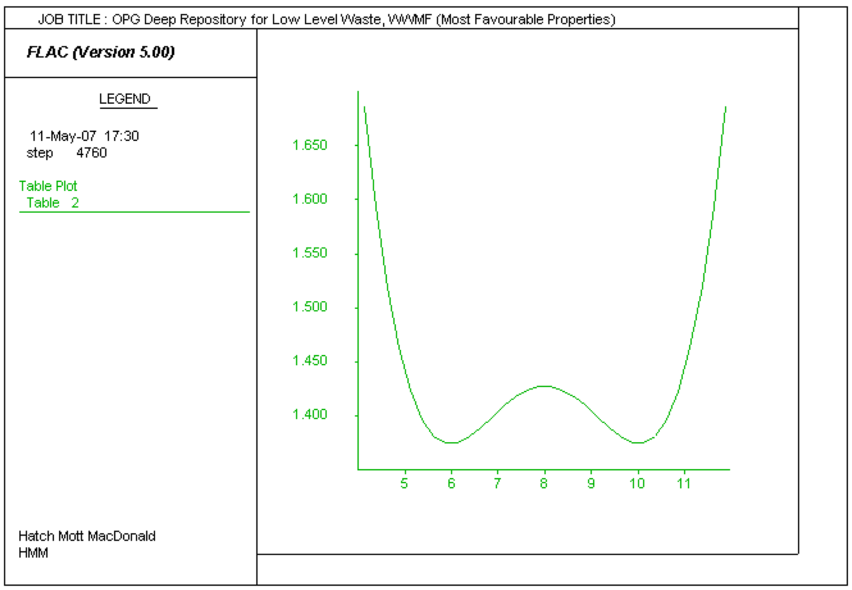
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)



Factor Of Safety Across The Pillar



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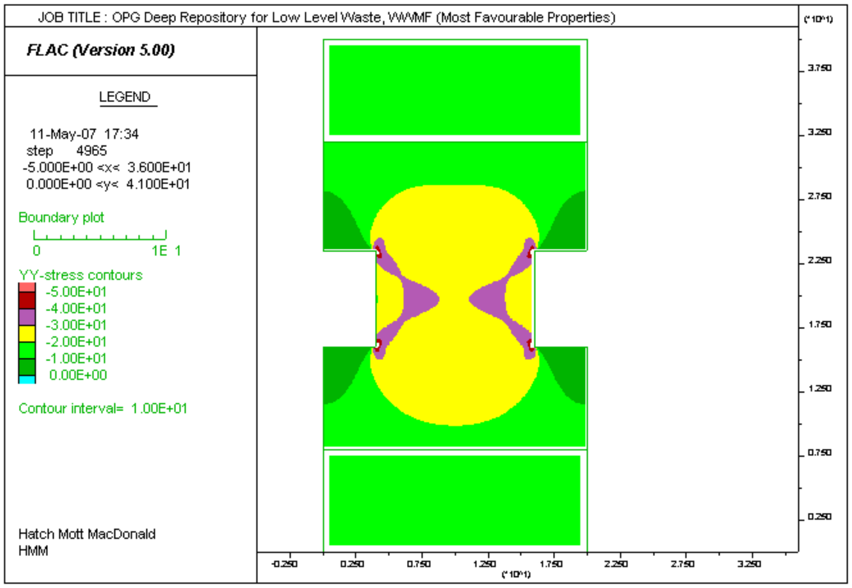
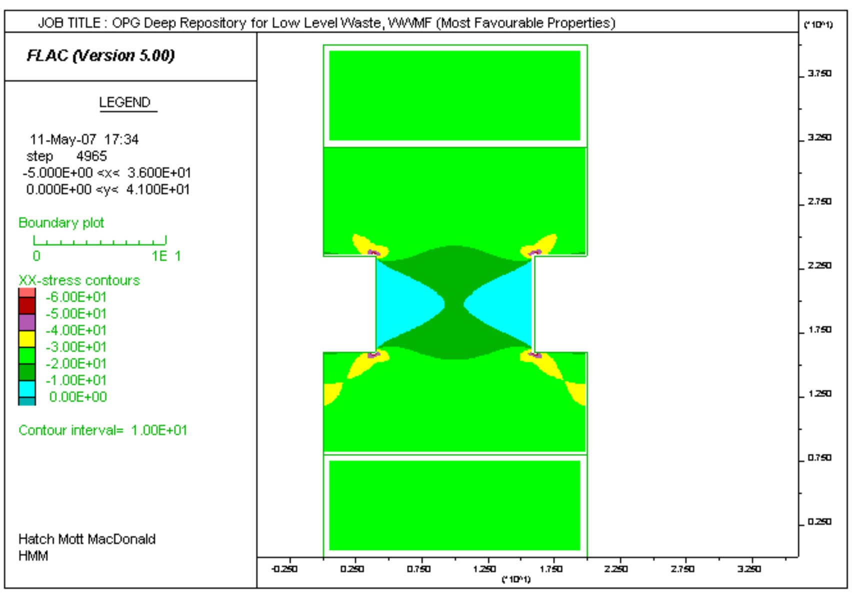
Most Favourable Parameters, K_0 = 1.5, Pillar Width = 12.0m

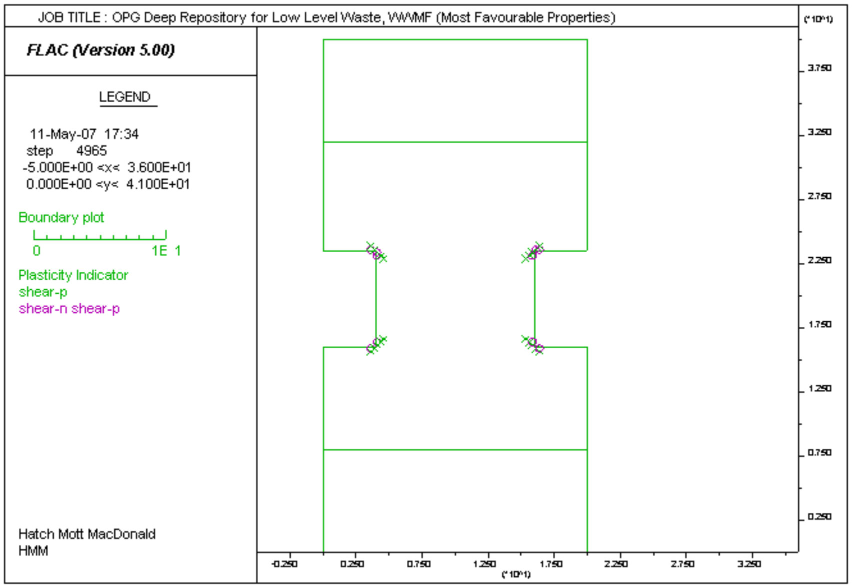
Vertical Stresses (MPa)



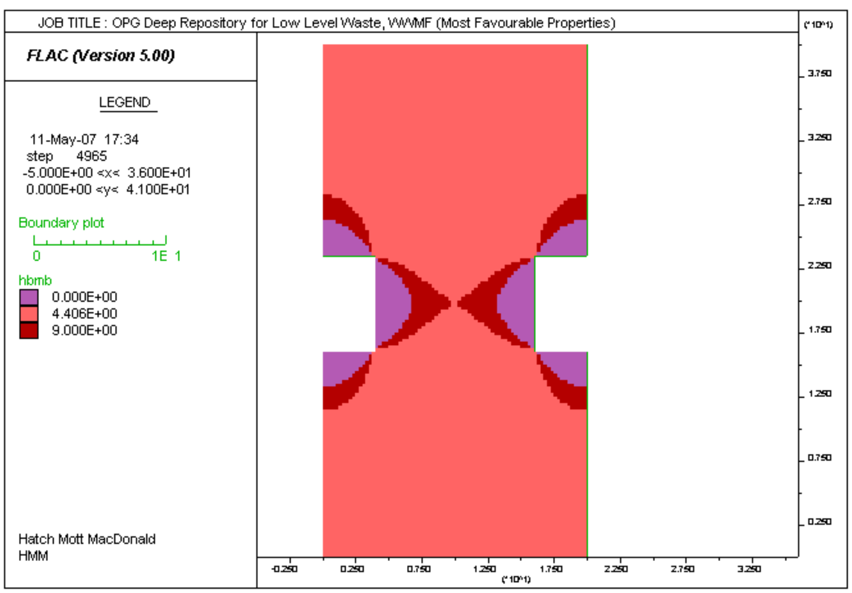
Horizontal Stresses (MPa)



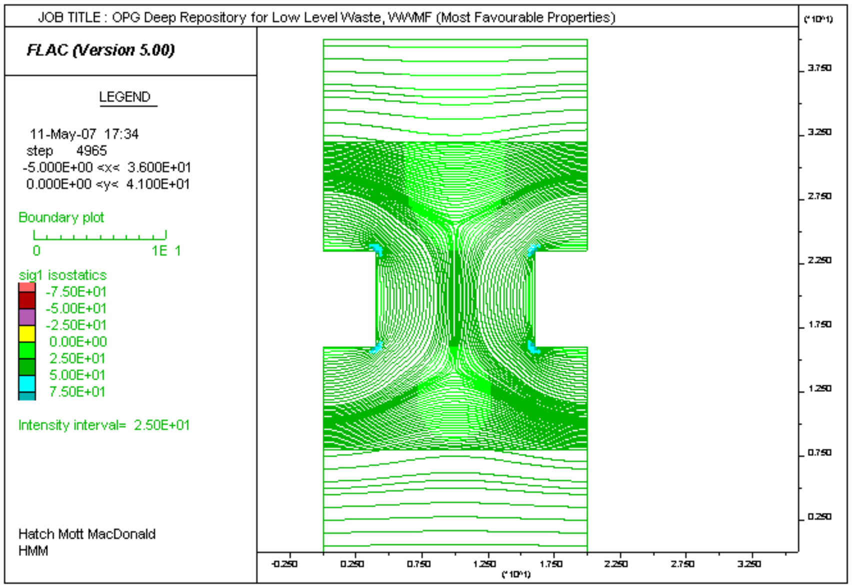
Plasticity Indicators



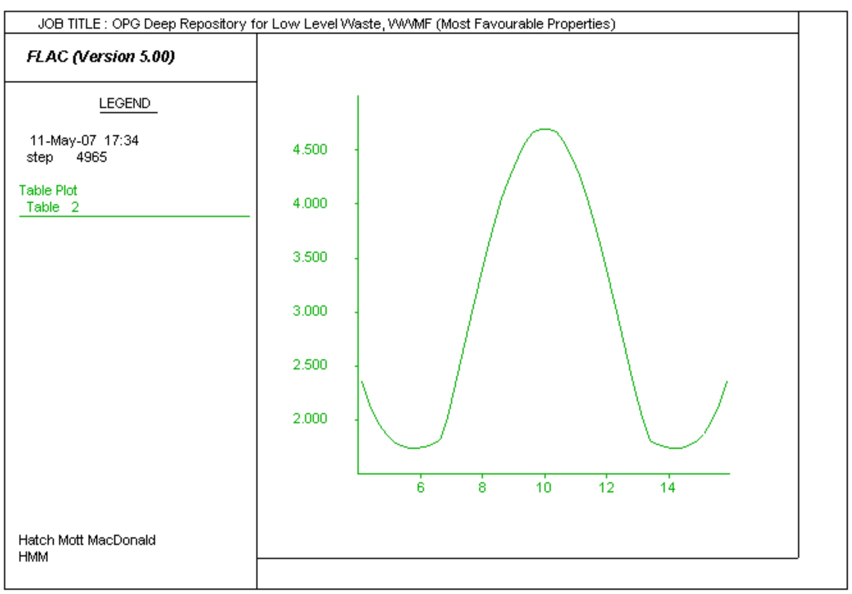
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

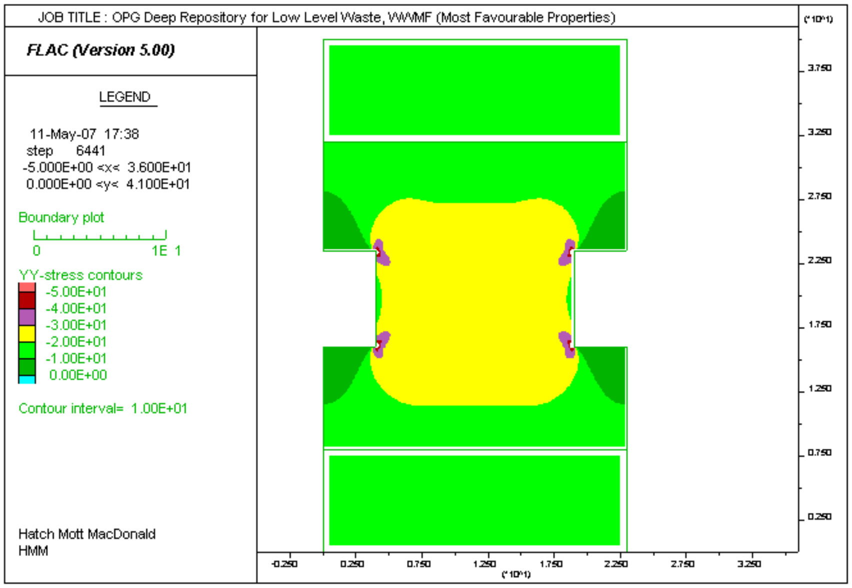


Factor Of Safety Across The Pillar

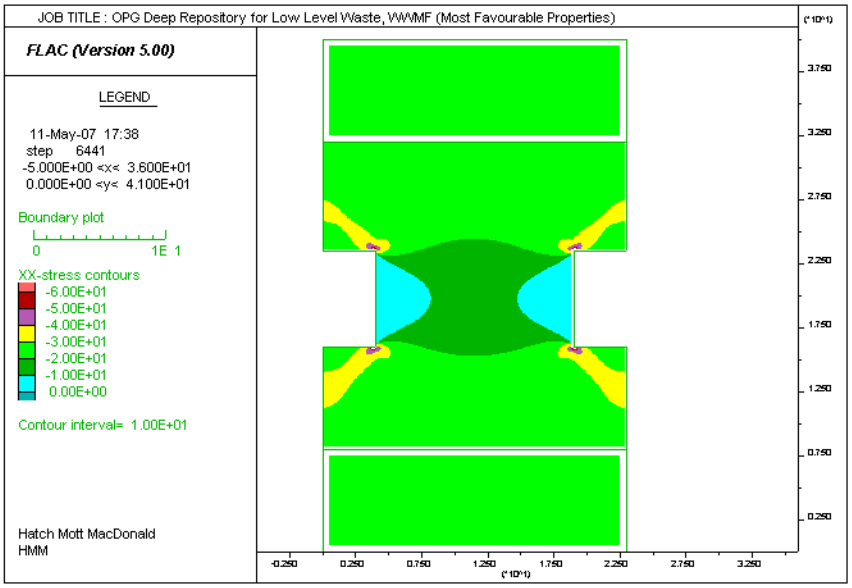


Most Favourable Parameters, K_0 = 1.5, Pillar Width = 15.0m

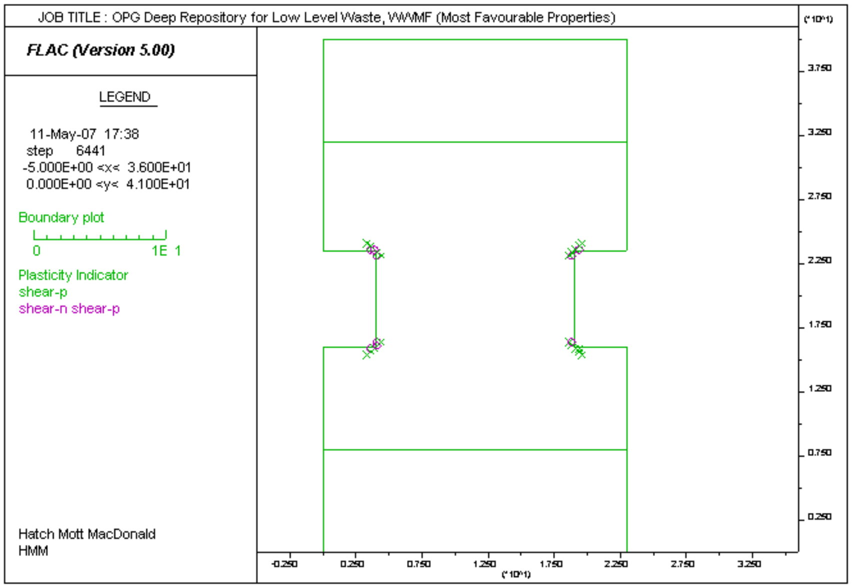
Vertical Stresses (MPa)



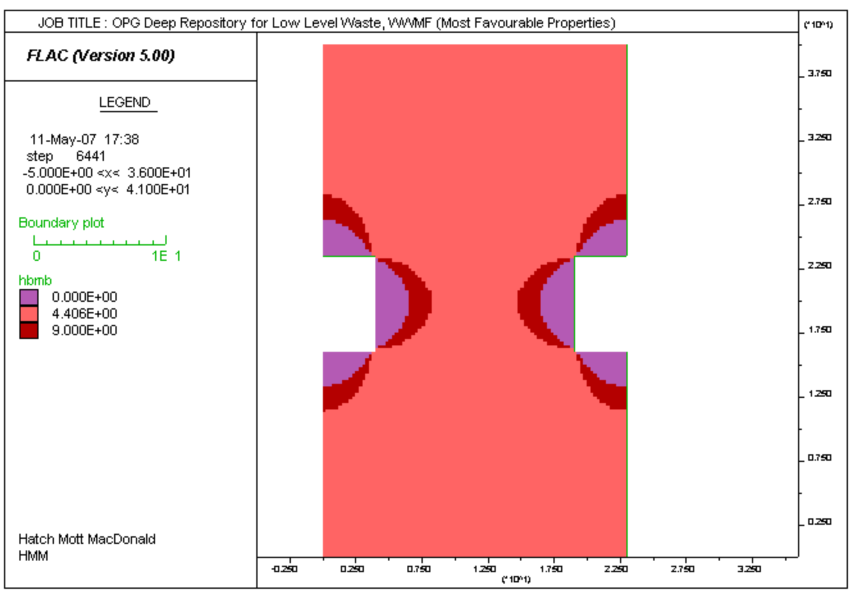
Horizontal Stresses (MPa)



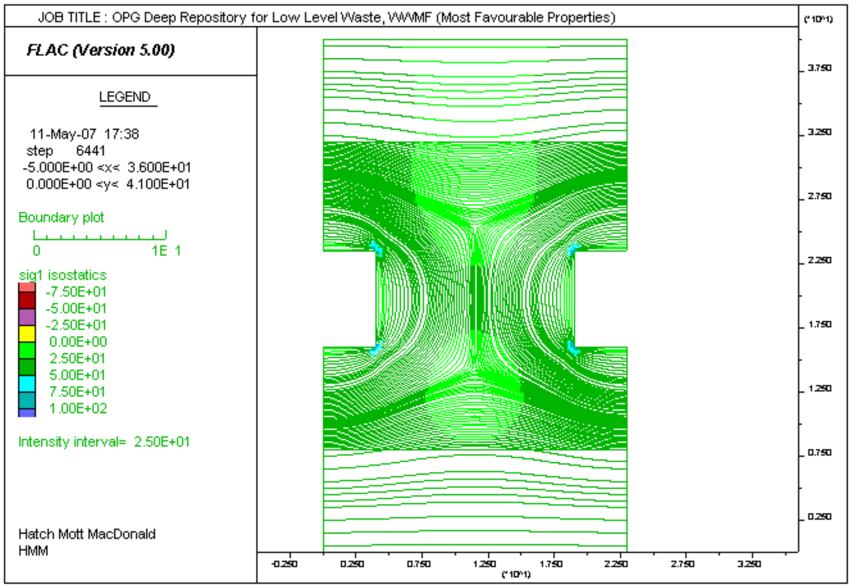
Plasticity Indicators



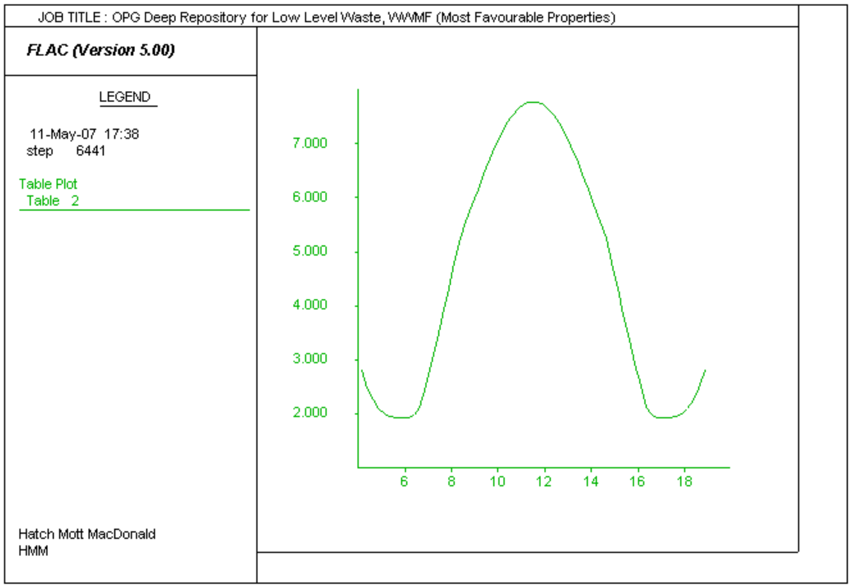
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

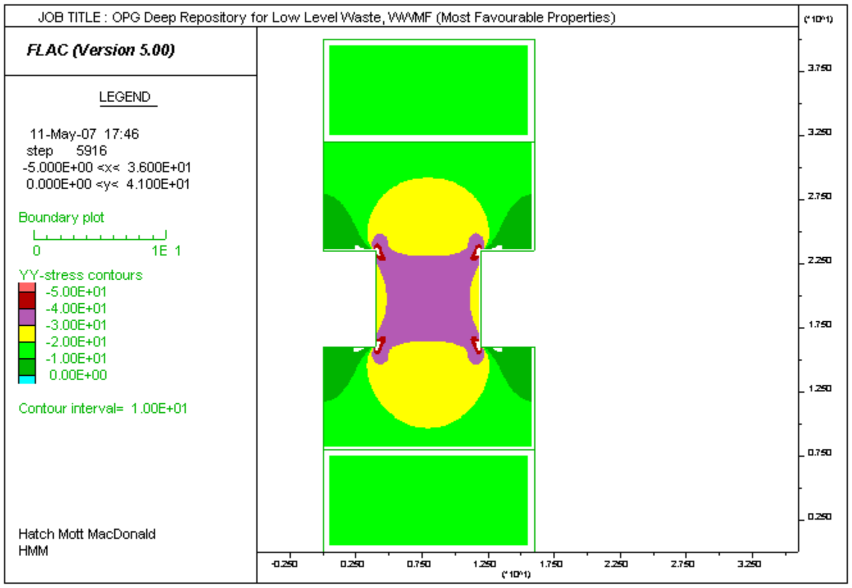


Factor Of Safety Across The Pillar

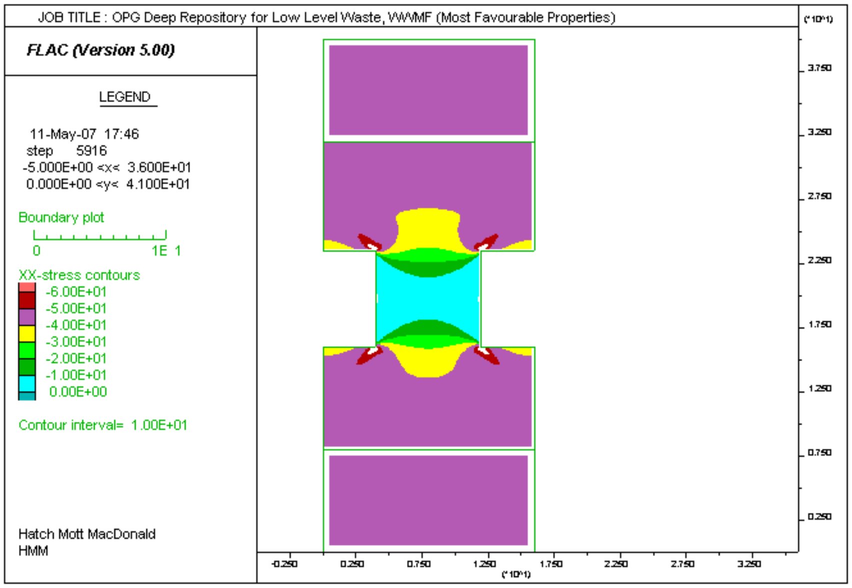


Most Favourable Parameters, K_0 = 2.5, Pillar Width = 8.0m

Vertical Stresses (MPa)



Horizontal Stresses (MPa)



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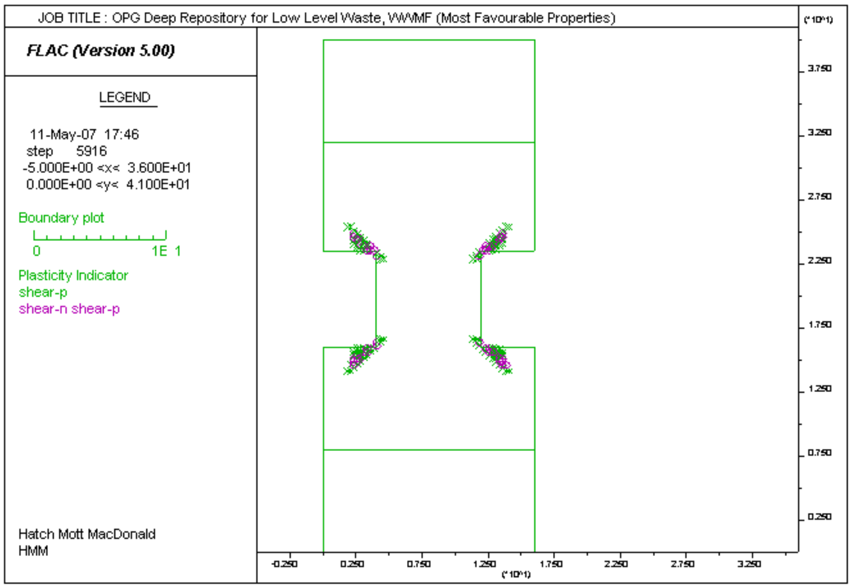
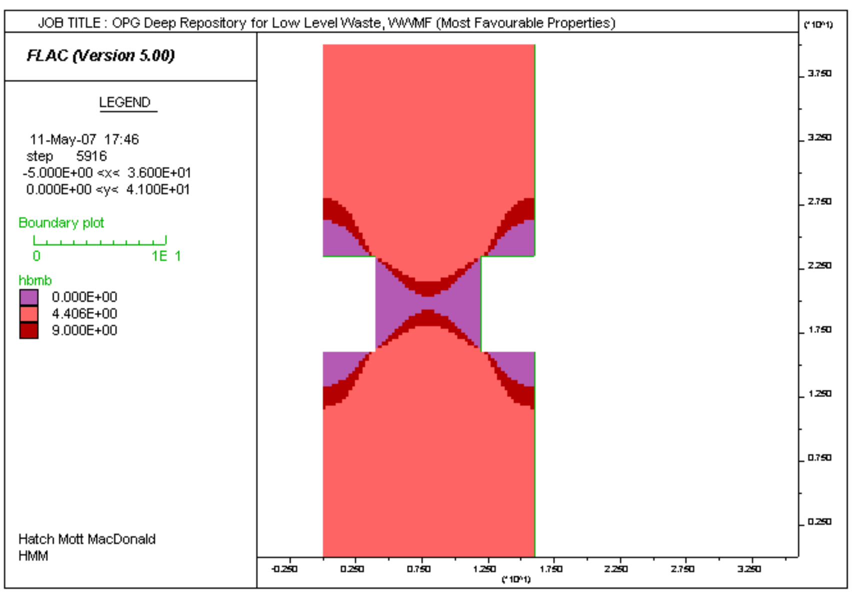
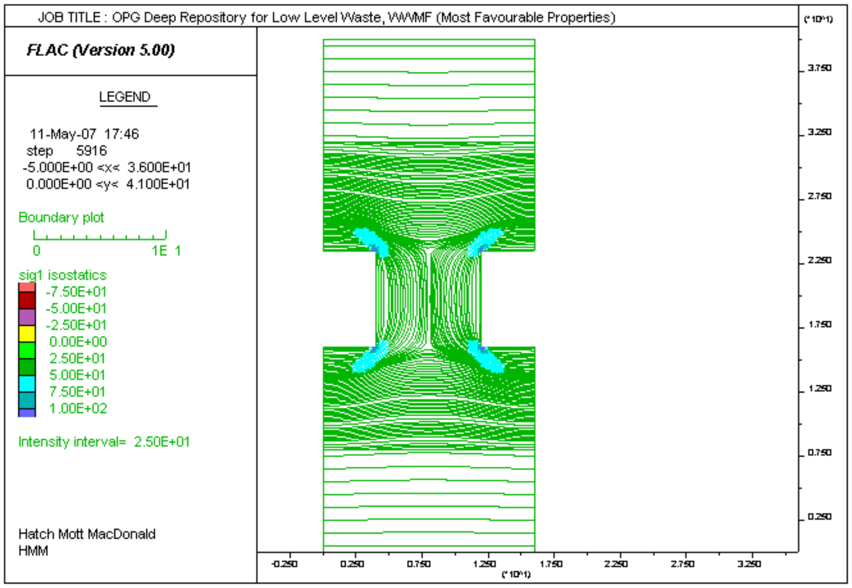
Plasticity Indicators



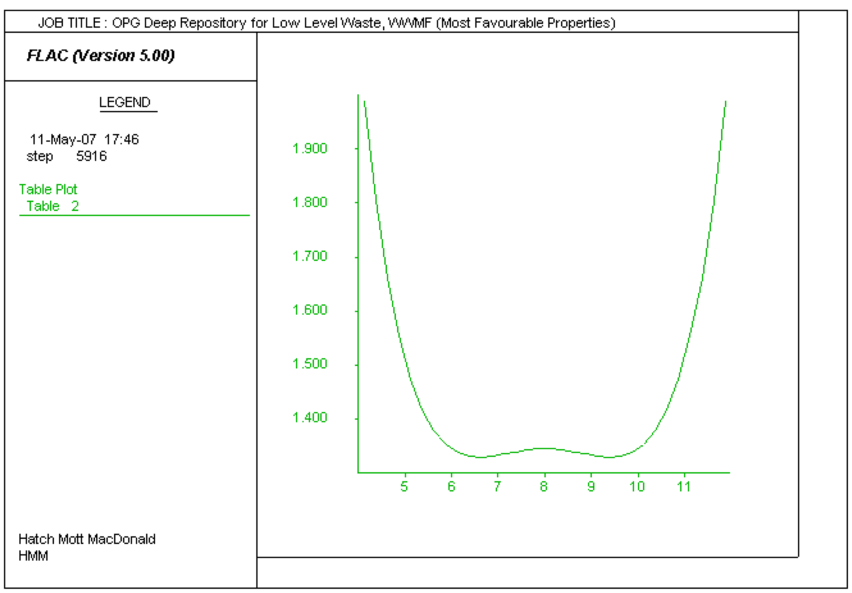
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)



Factor Of Safety Across The Pillar



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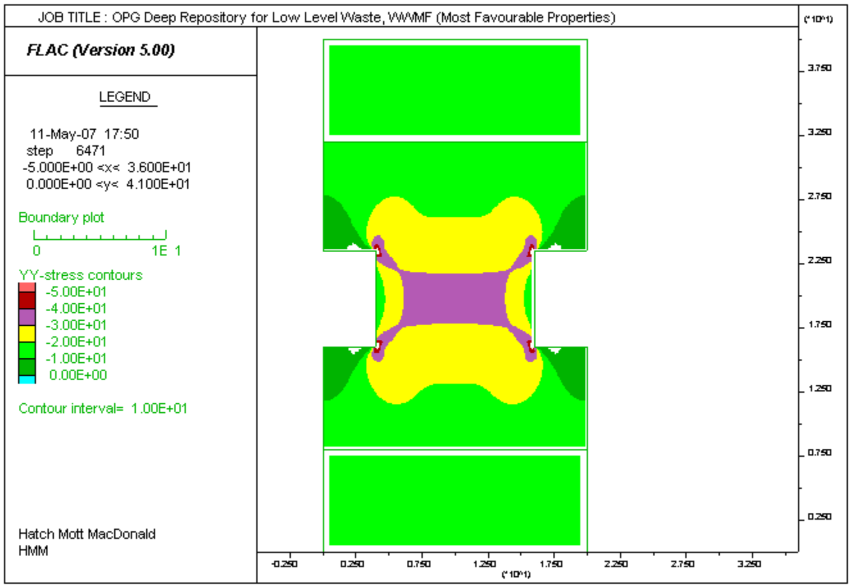
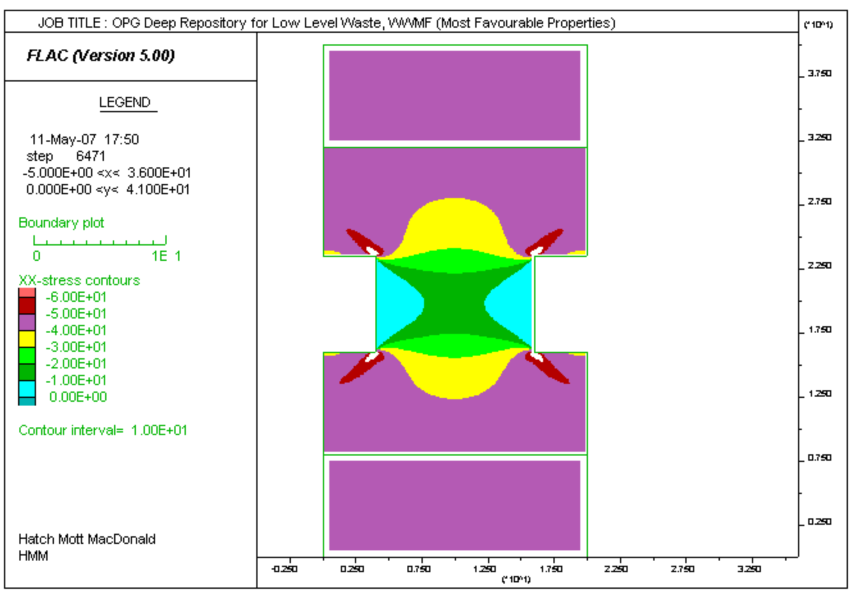
Most Favourable Parameters, K_0 = 2.5, Pillar Width = 12.0m

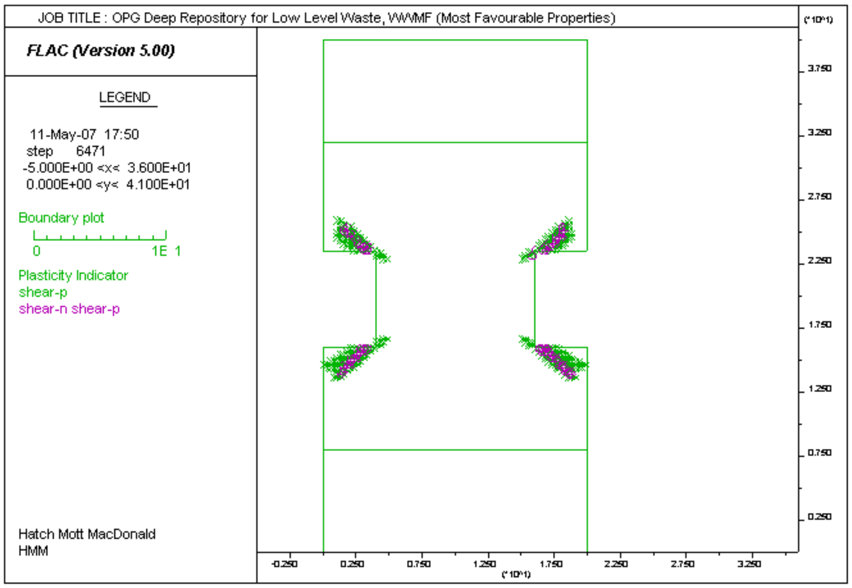
Vertical Stresses (MPa)



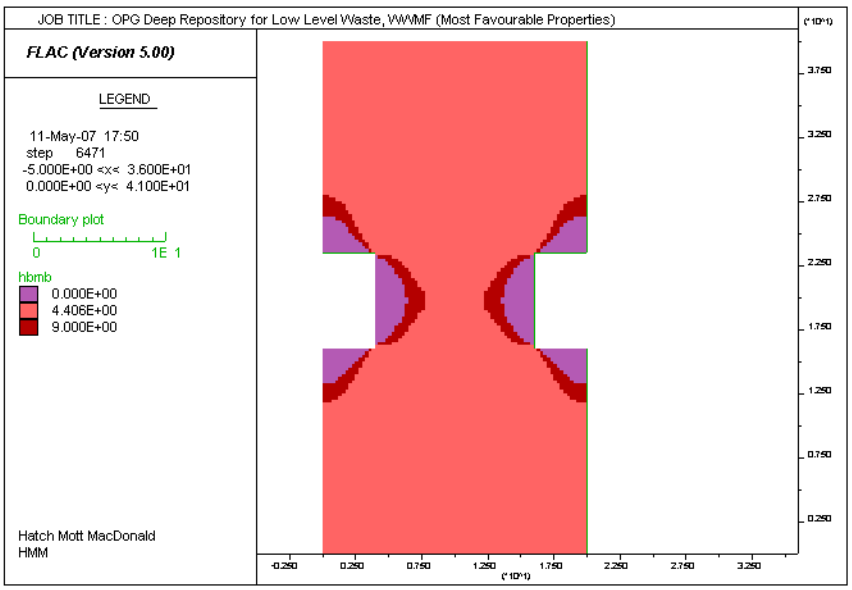
Horizontal Stresses (MPa)



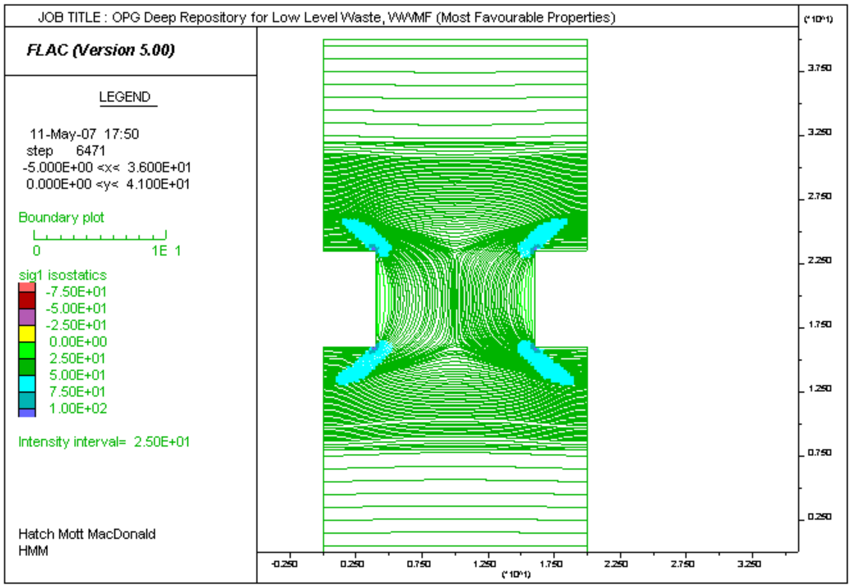
Plasticity Indicators



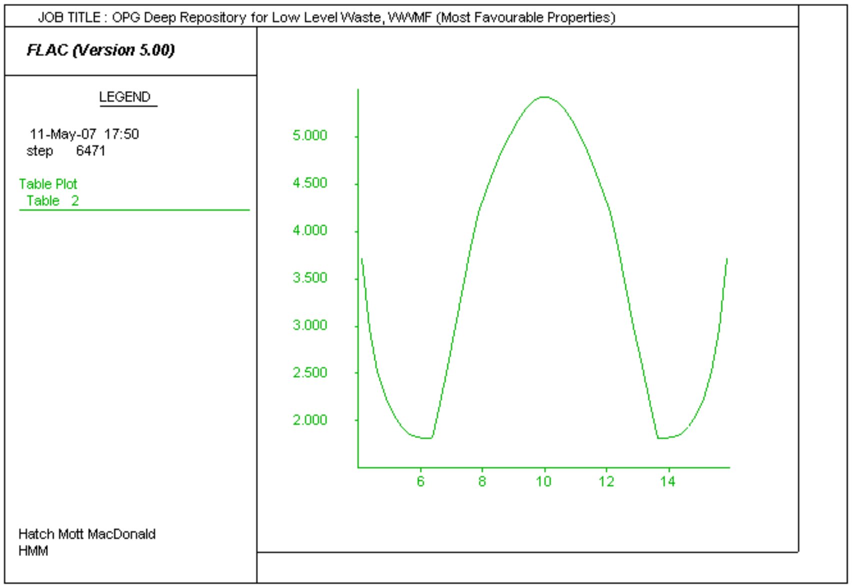
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

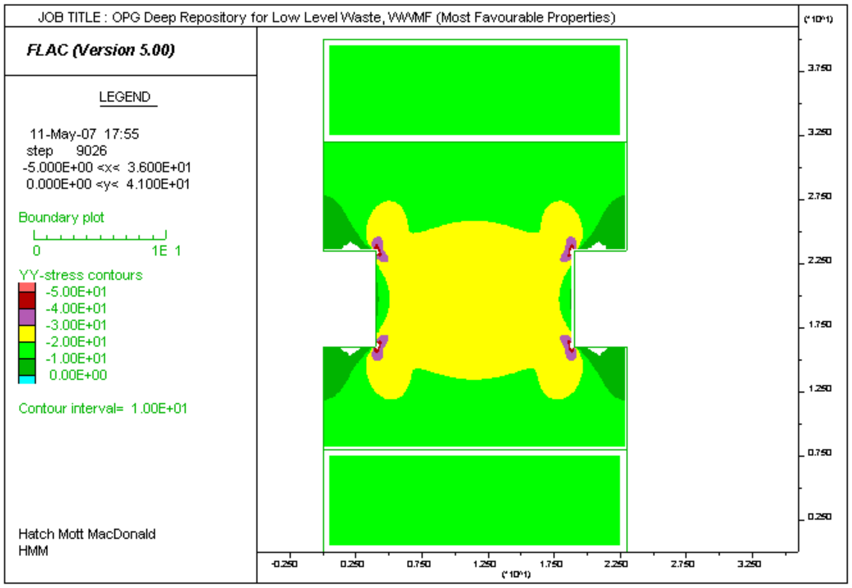


Factor Of Safety Across The Pillar

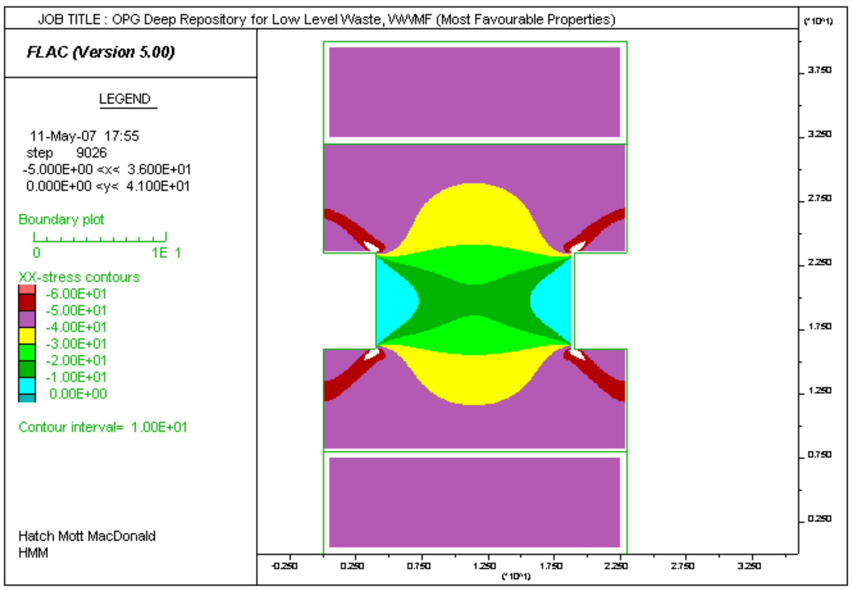


Most Favourable Parameters, K_0 = 2.5, Pillar Width = 15.0m

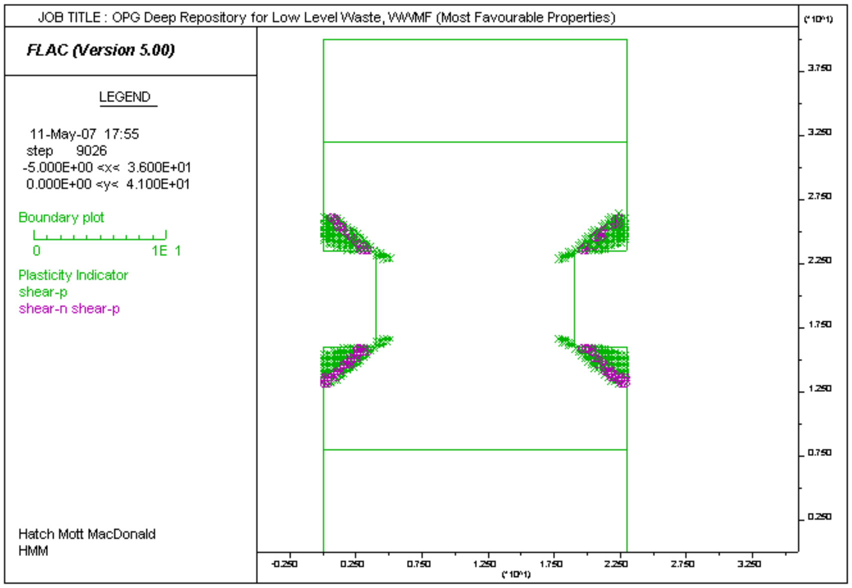
Vertical Stresses (MPa)



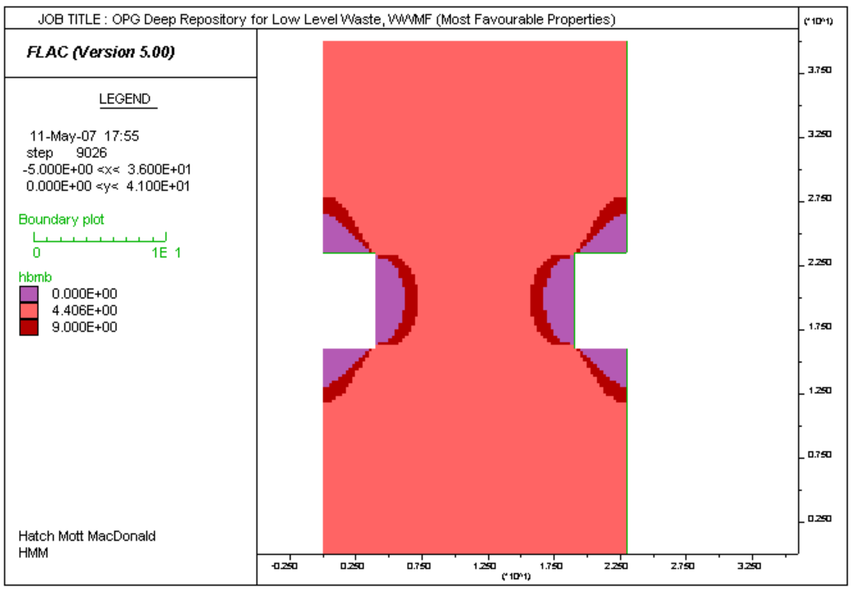
Horizontal Stresses (MPa)



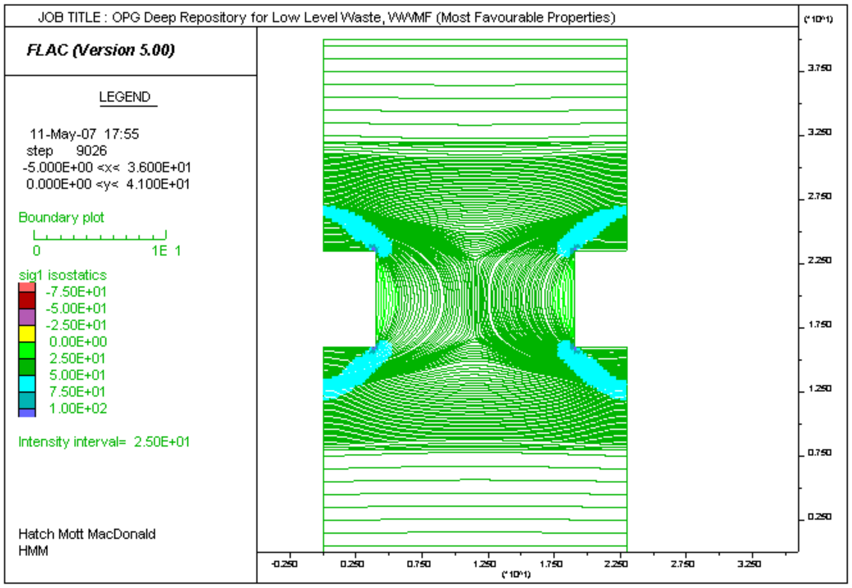
Plasticity Indicators



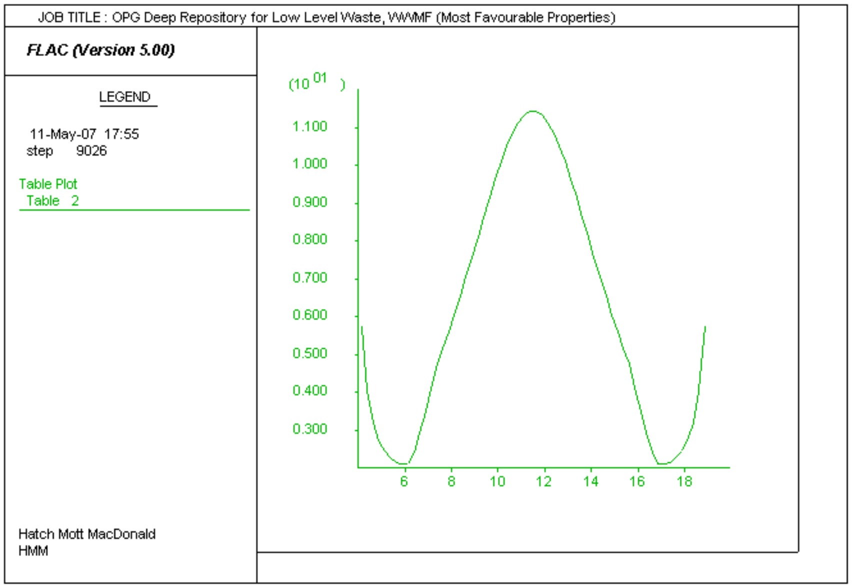
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)



Factor Of Safety Across The Pillar



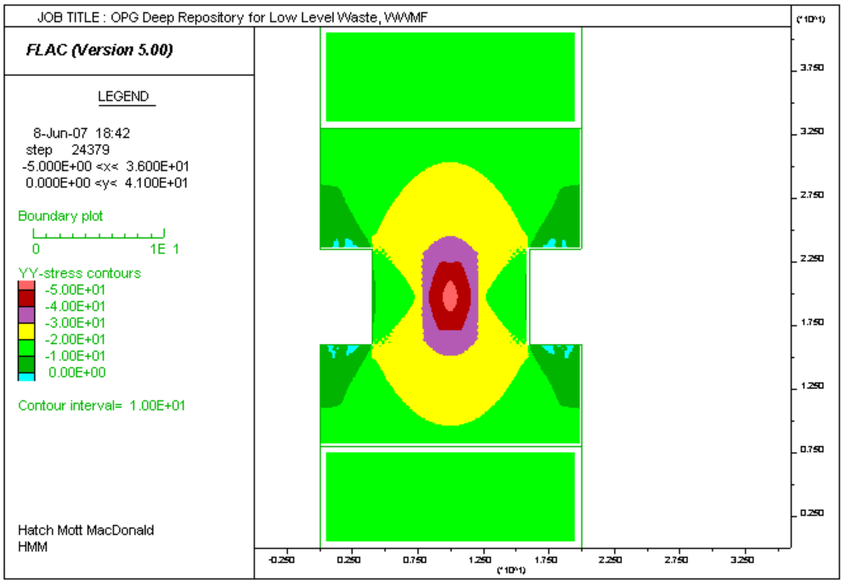
Appendix C

Single Pillar Analysis
Selected Range of Parameters
(2D FLAC Analysis Results)

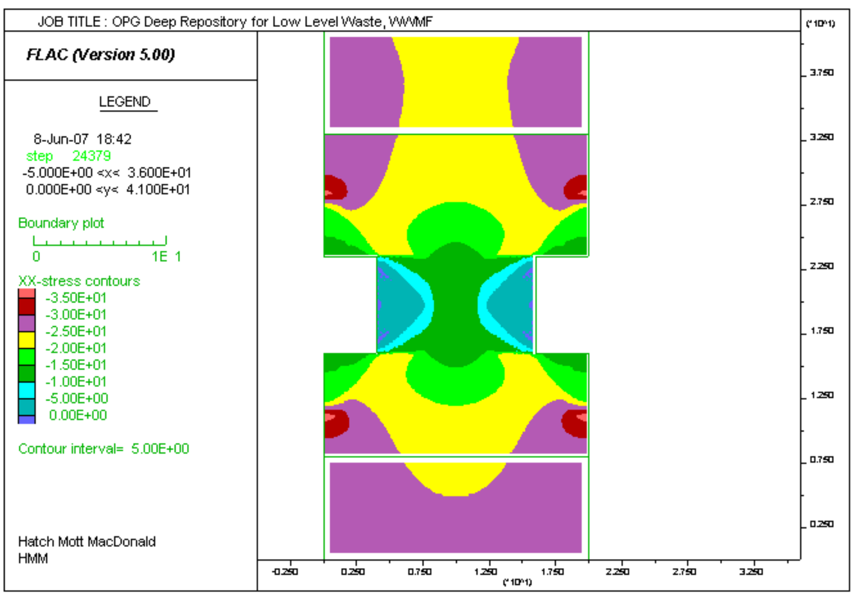
(K_{0x}=1.5, K_{0z} = 1.0 in all analyses)

UCS = 48, GSI = 55, Pillar Width = 12.0m

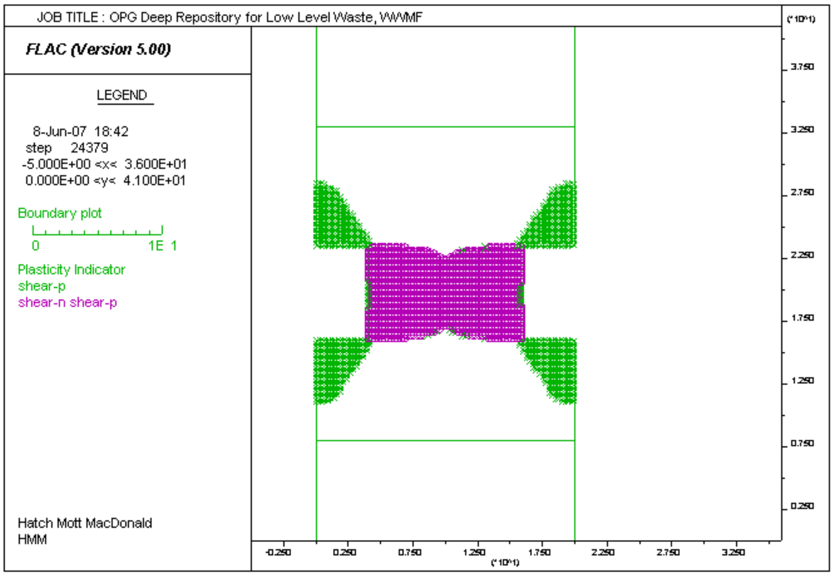
Vertical Stresses (MPa)



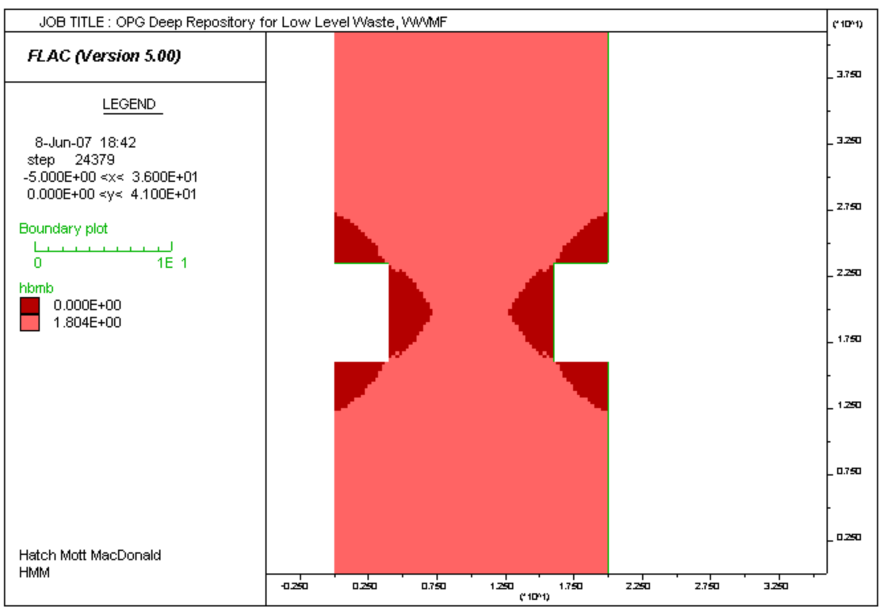
Horizontal Stresses (MPa)



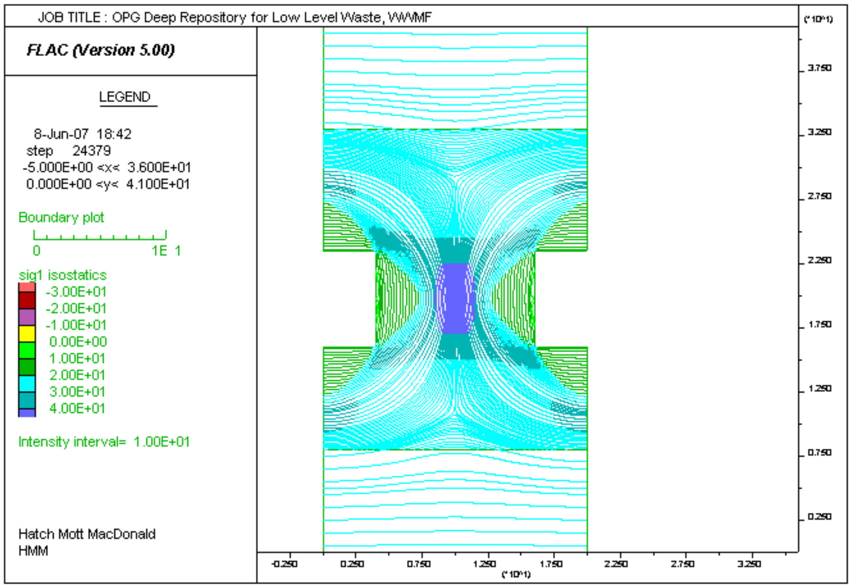
Plasticity Indicators



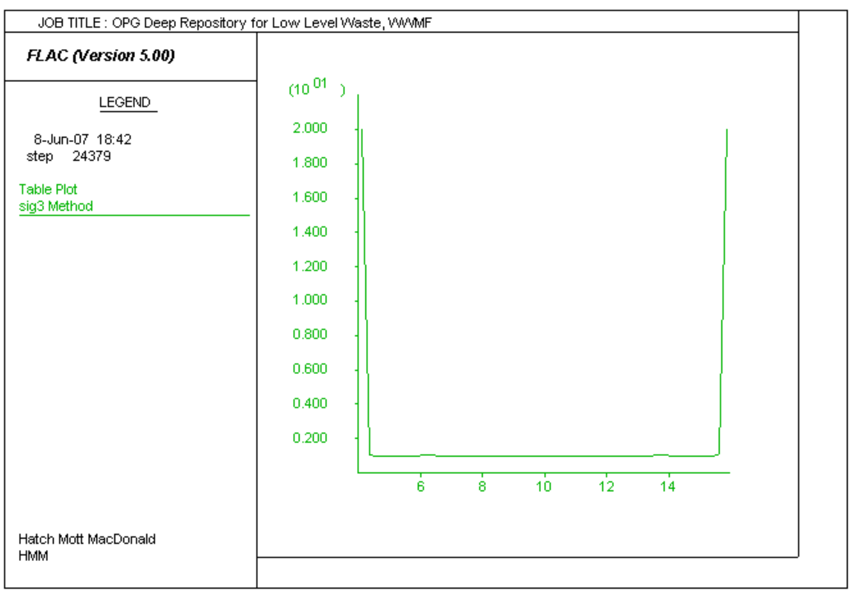
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

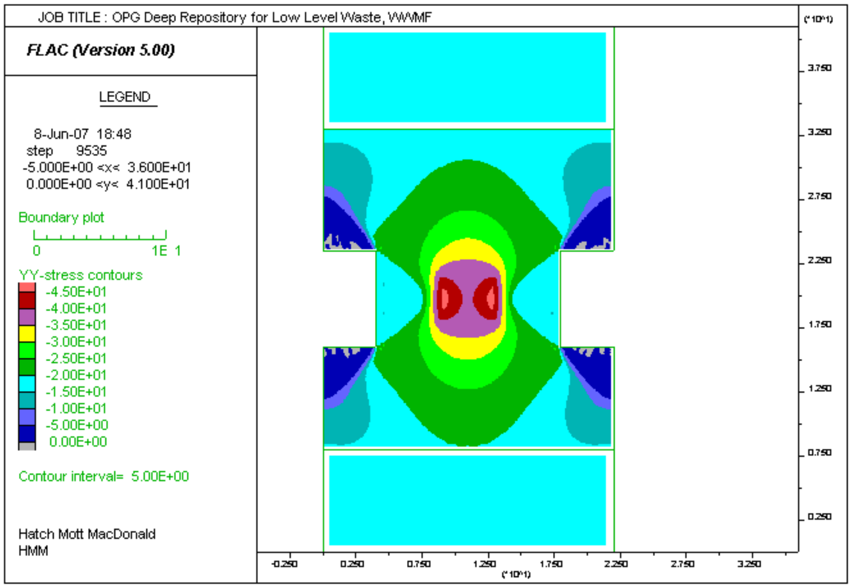


Factor Of Safety Across The Pillar

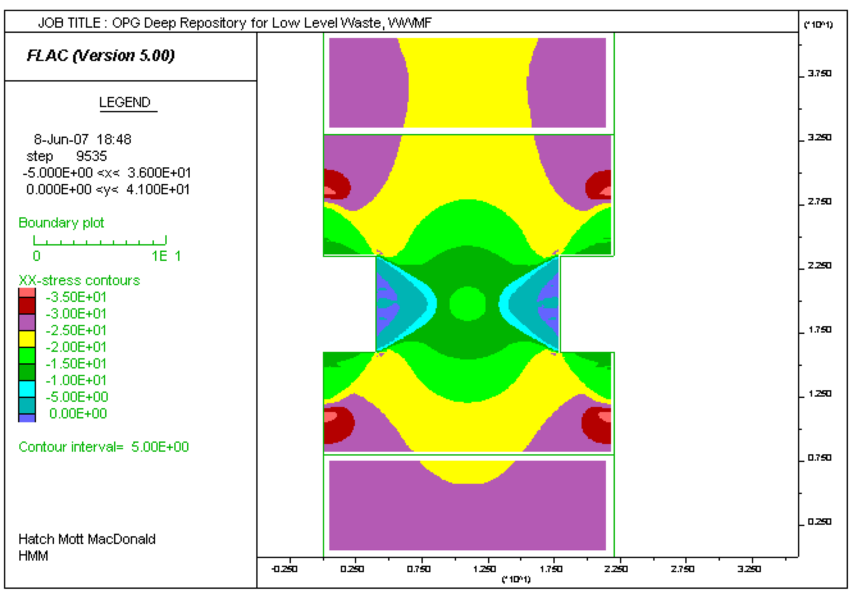


UCS = 48, GSI = 55, Pillar Width = 14.0m

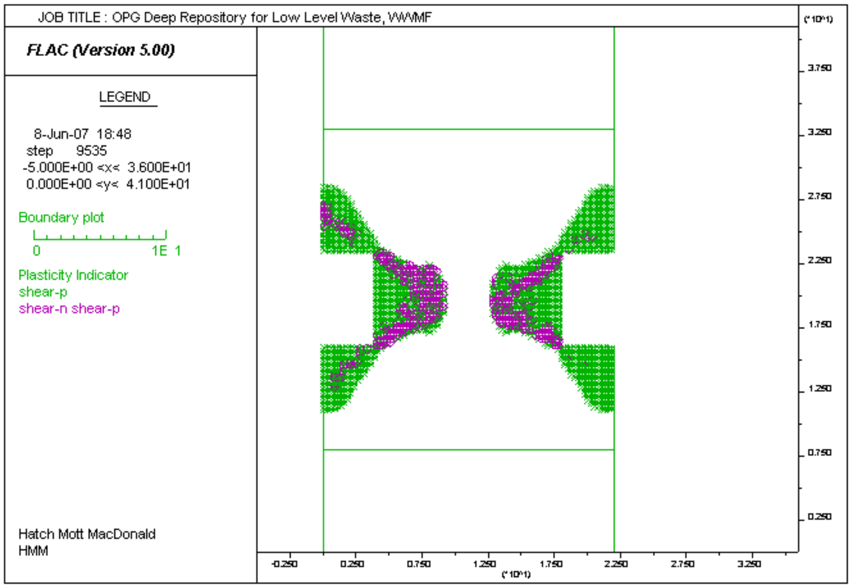
Vertical Stresses (MPa)



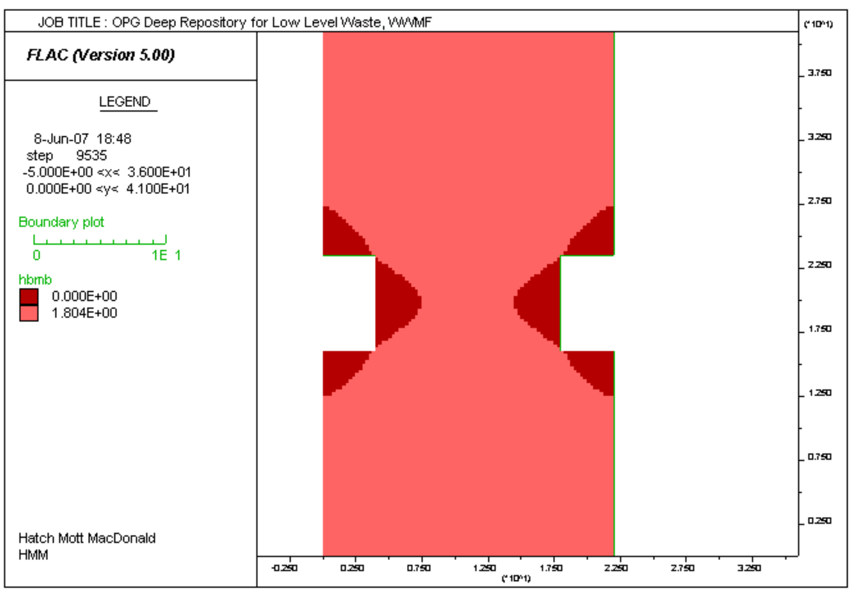
Horizontal Stresses (MPa)



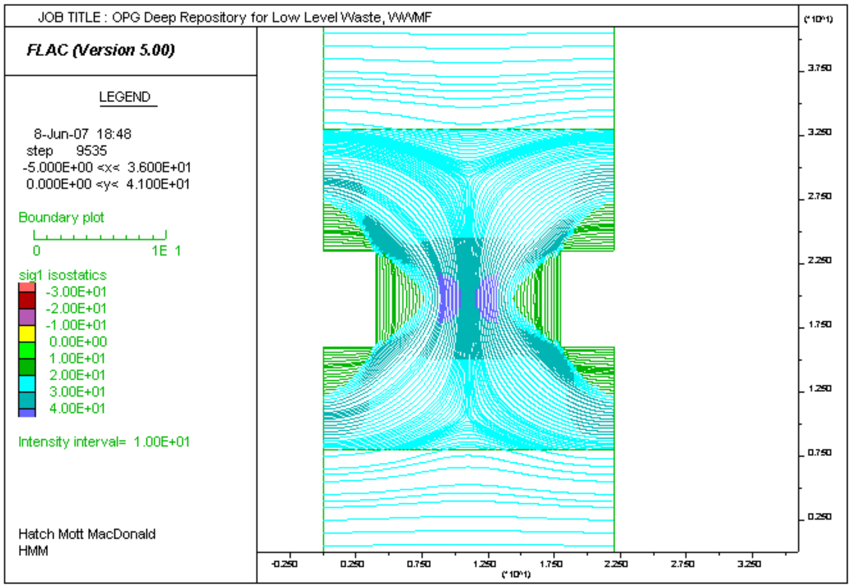
Plasticity Indicators



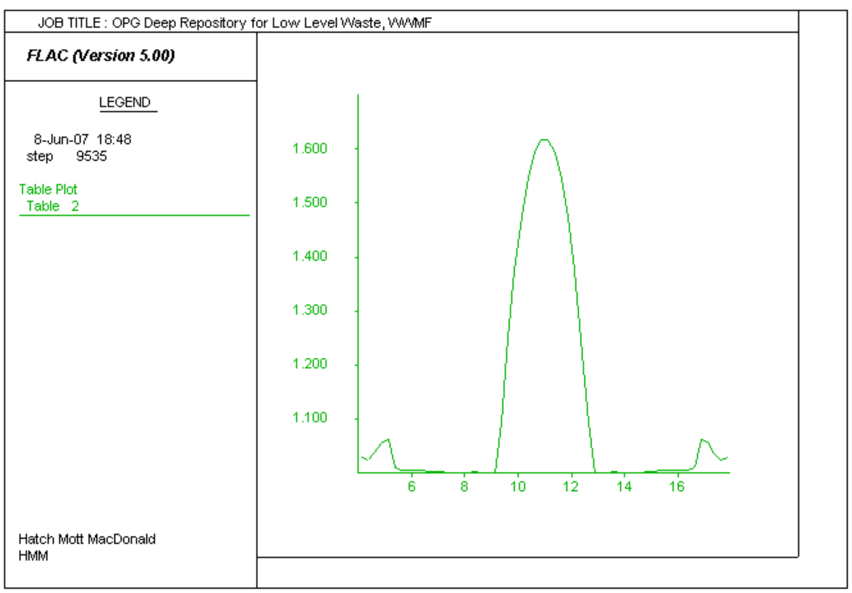
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

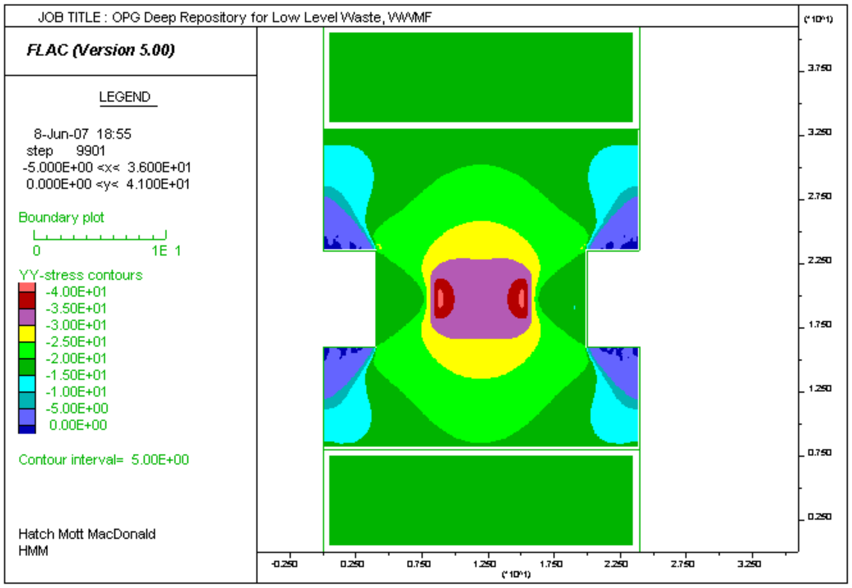


Factor Of Safety Across The Pillar

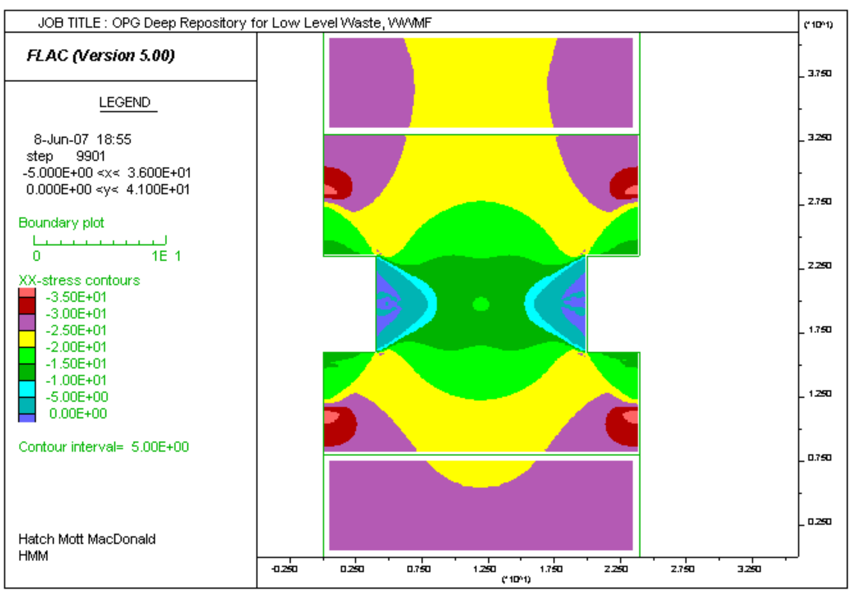


UCS = 48, GSI = 55, Pillar Width = 16.0m

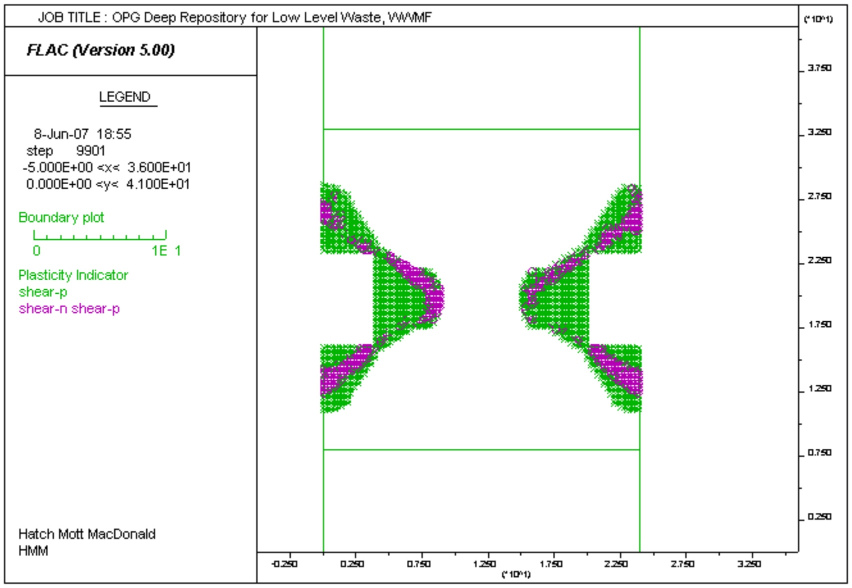
Vertical Stresses (MPa)



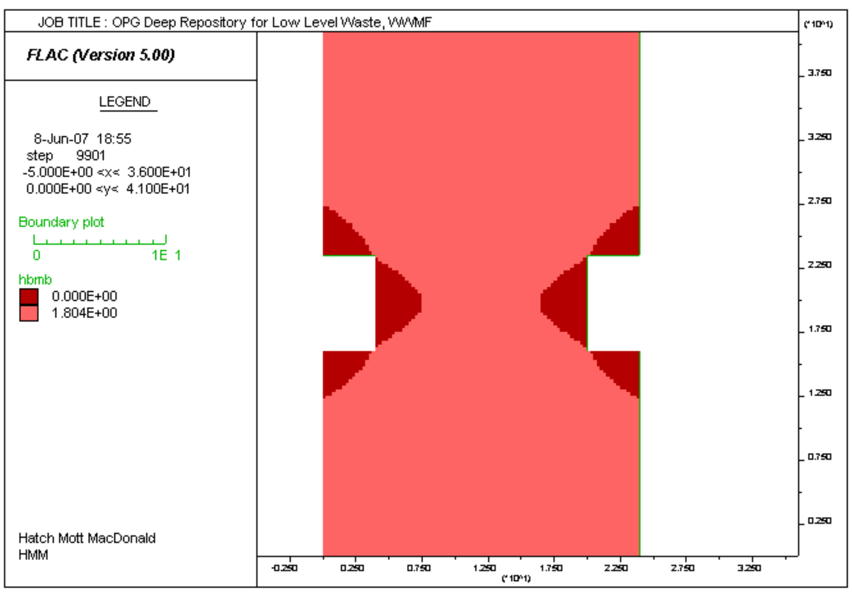
Horizontal Stresses (MPa)



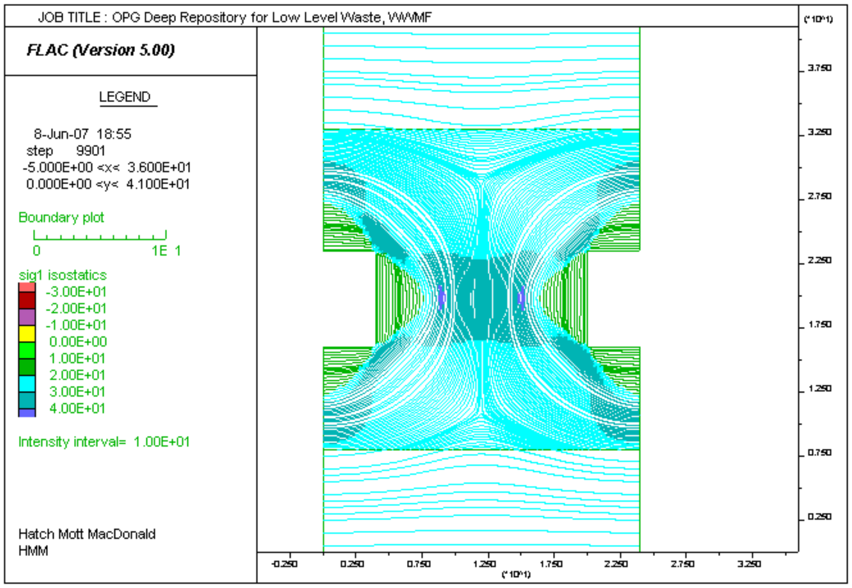
Plasticity Indicators



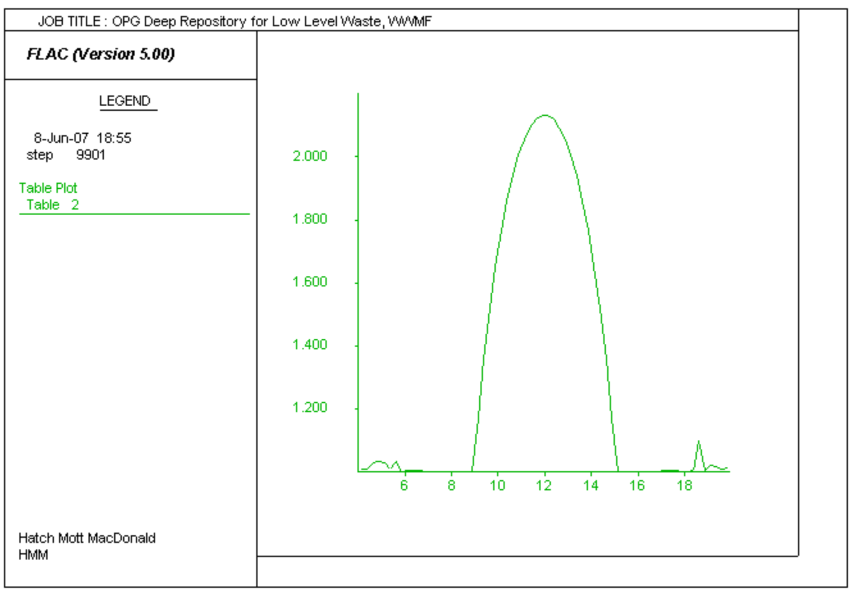
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

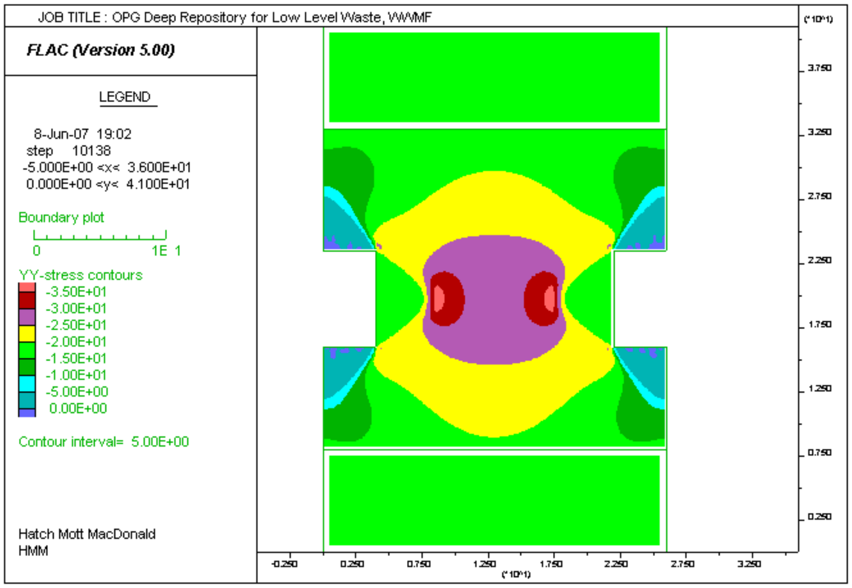


Factor Of Safety Across The Pillar

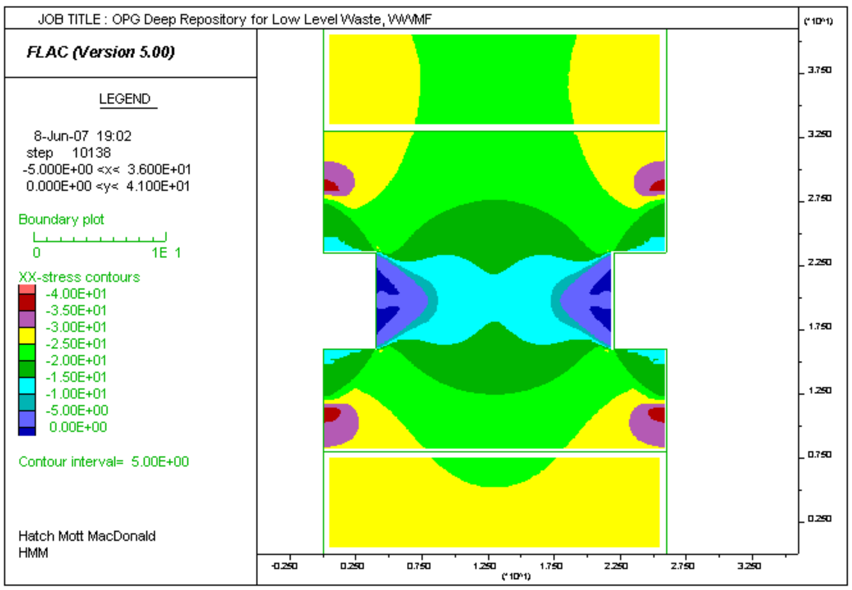


UCS = 48, GSI = 55, Pillar Width = 18.0m

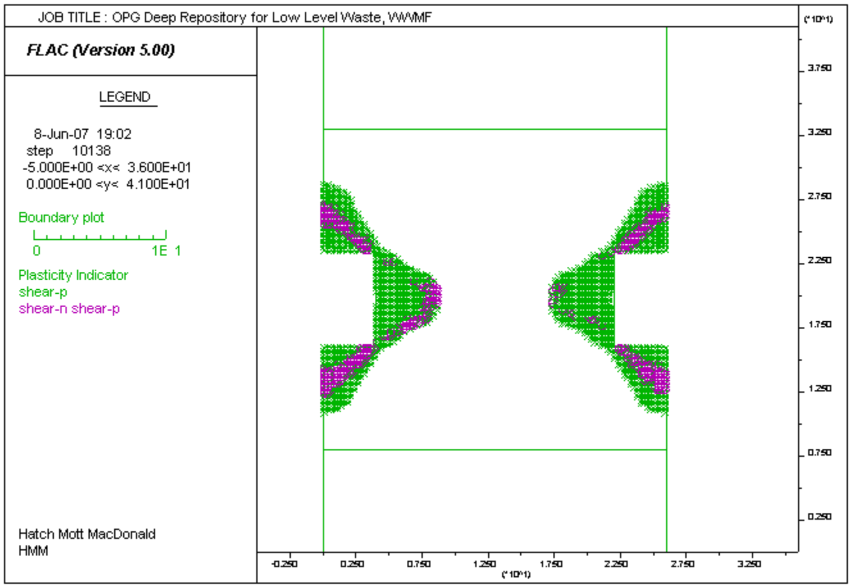
Vertical Stresses (MPa)



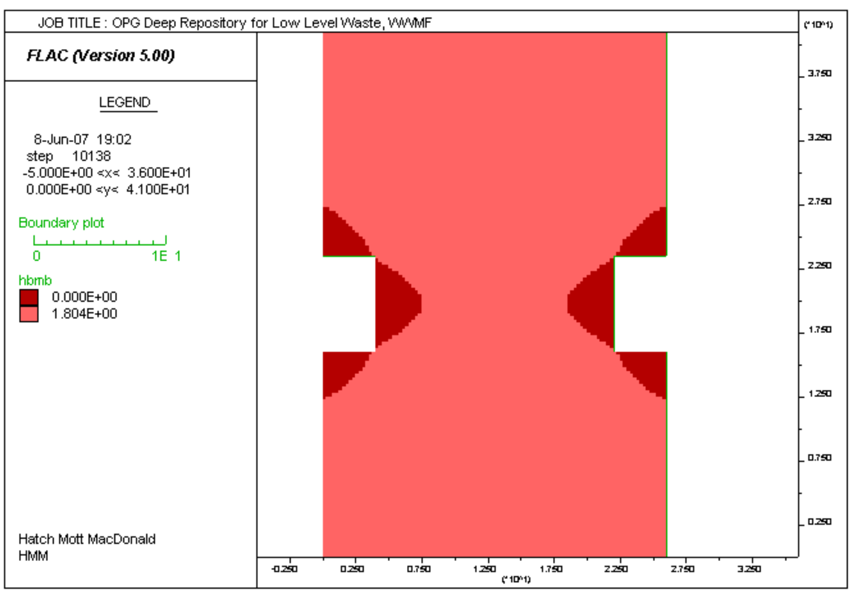
Horizontal Stresses (MPa)



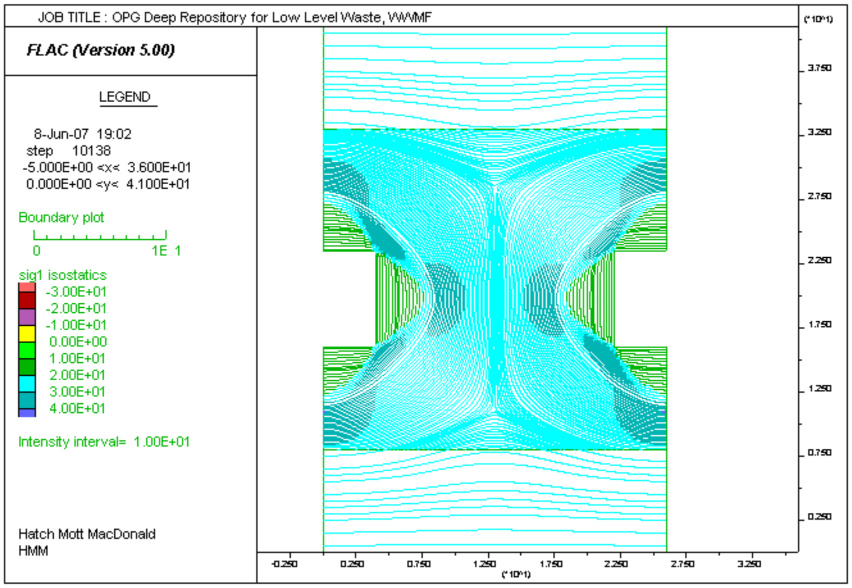
Plasticity Indicators



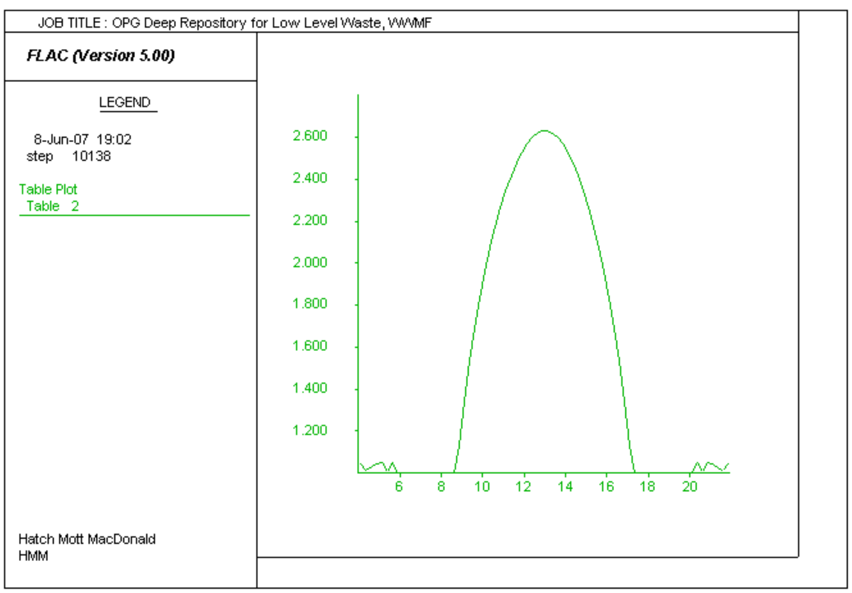
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

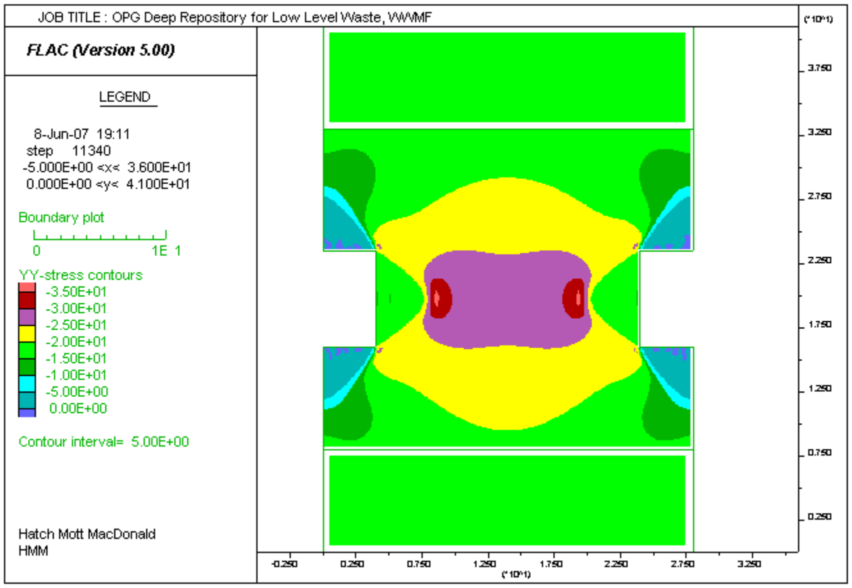


Factor Of Safety Across The Pillar

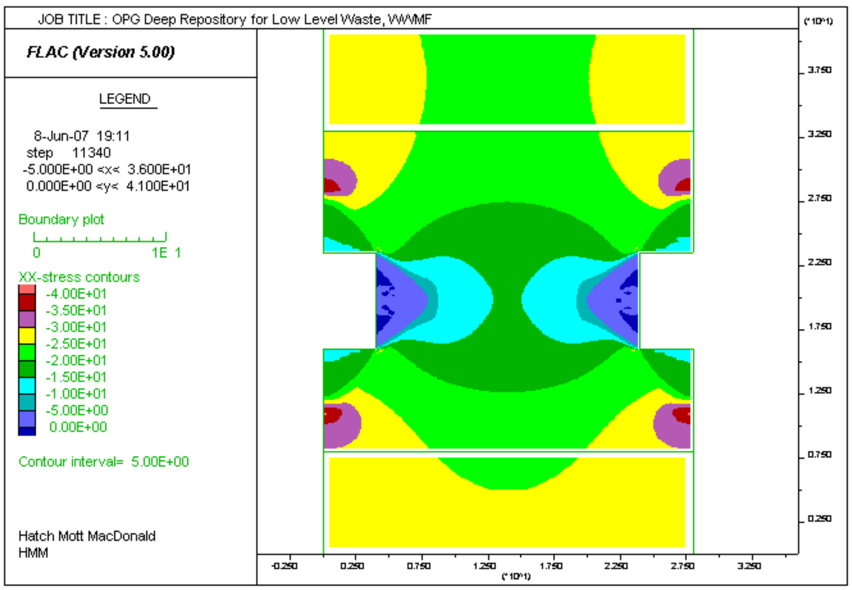


UCS = 48, GSI = 55, Pillar Width = 20.0m

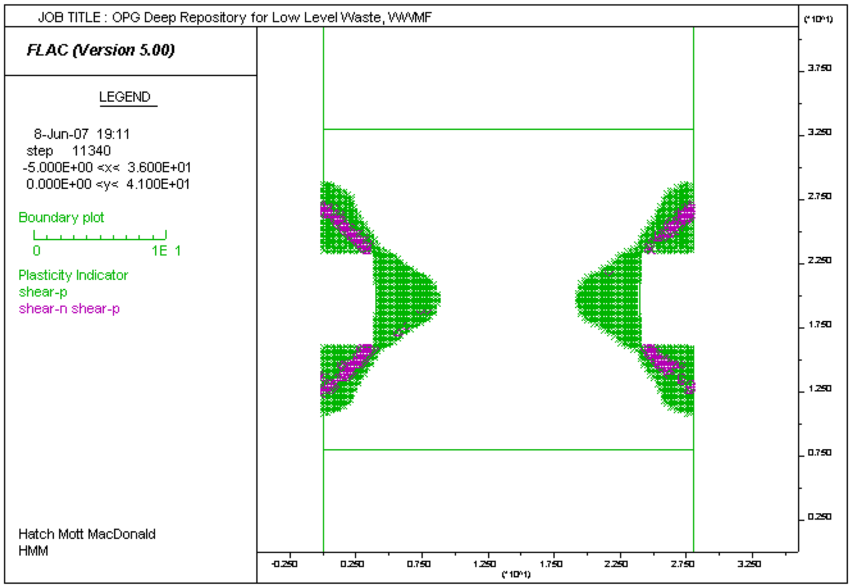
Vertical Stresses (MPa)



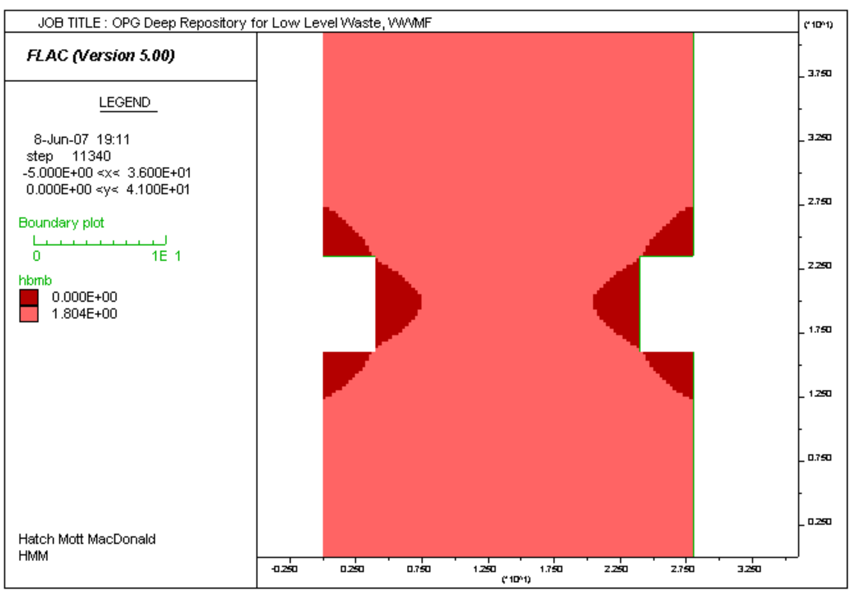
Horizontal Stresses (MPa)



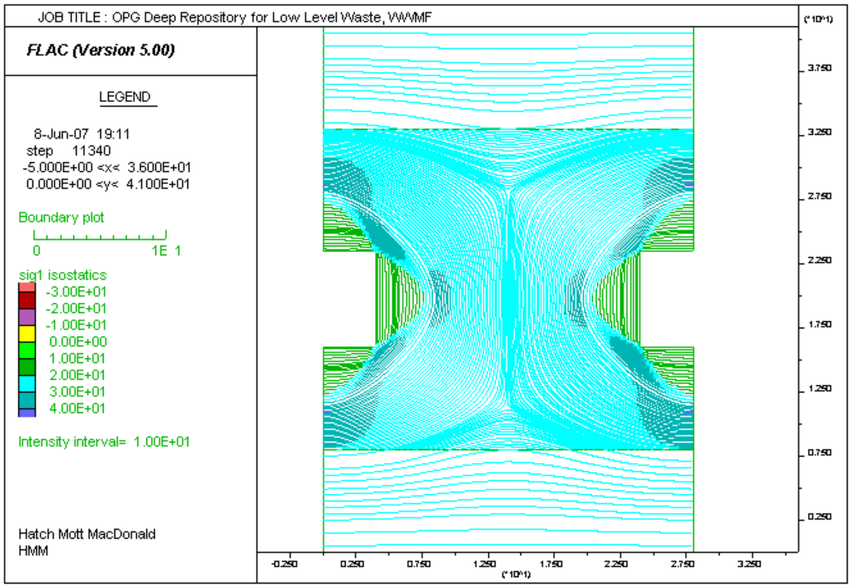
Plasticity Indicators



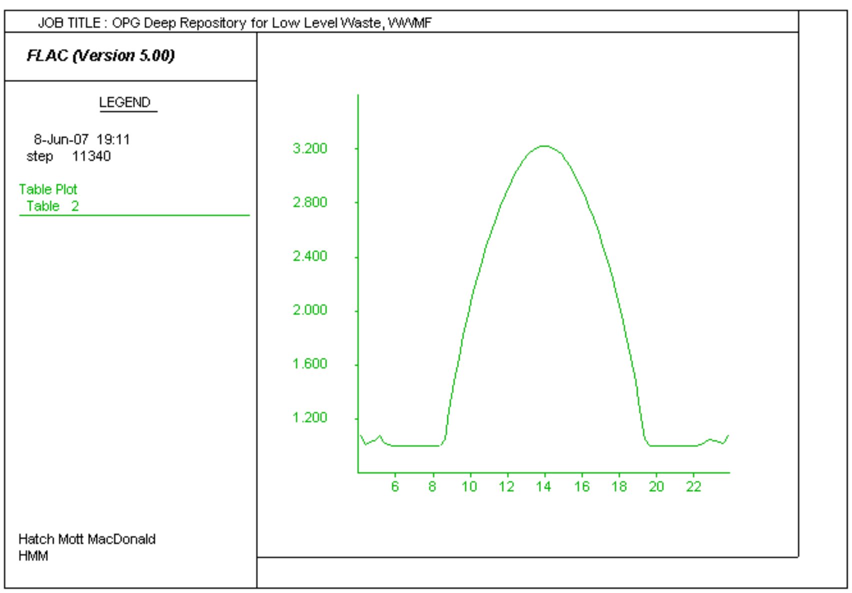
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

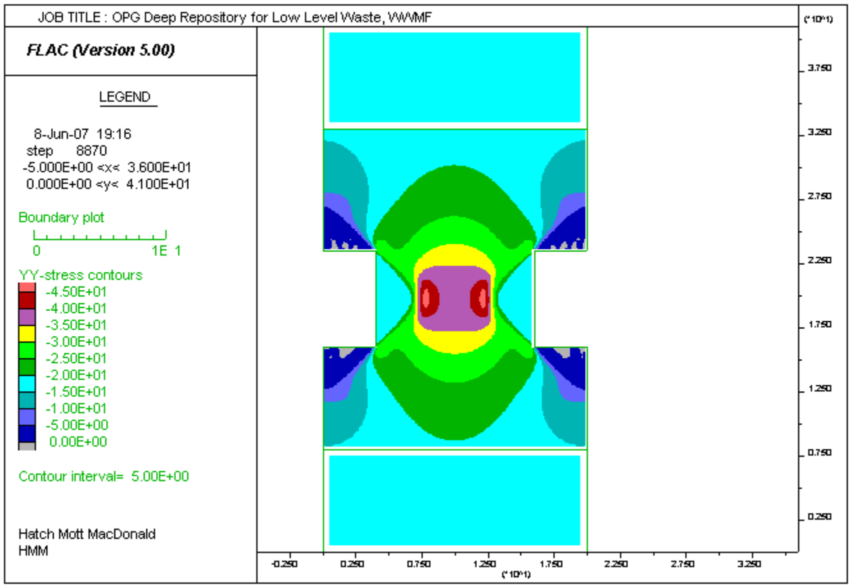


Factor Of Safety Across The Pillar

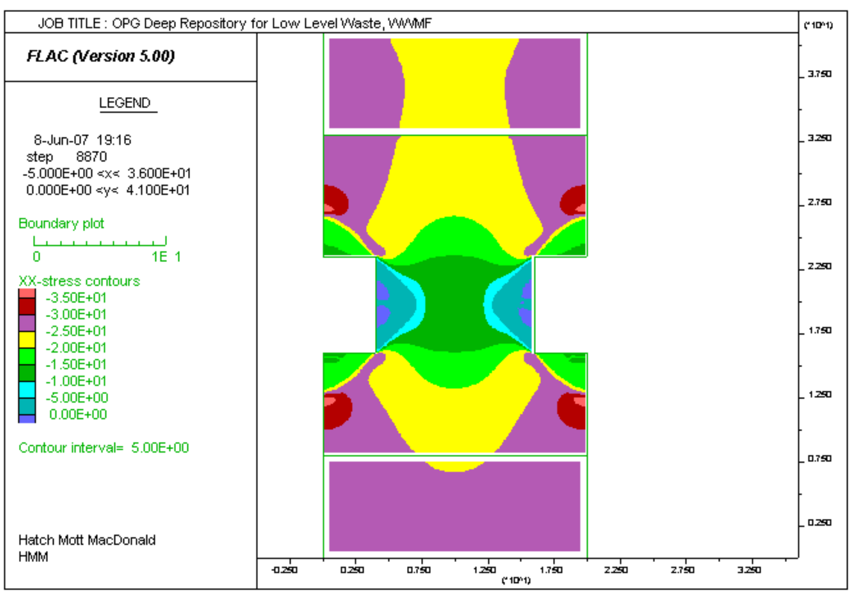


UCS = 48, GSI = 69, Pillar Width = 12.0m

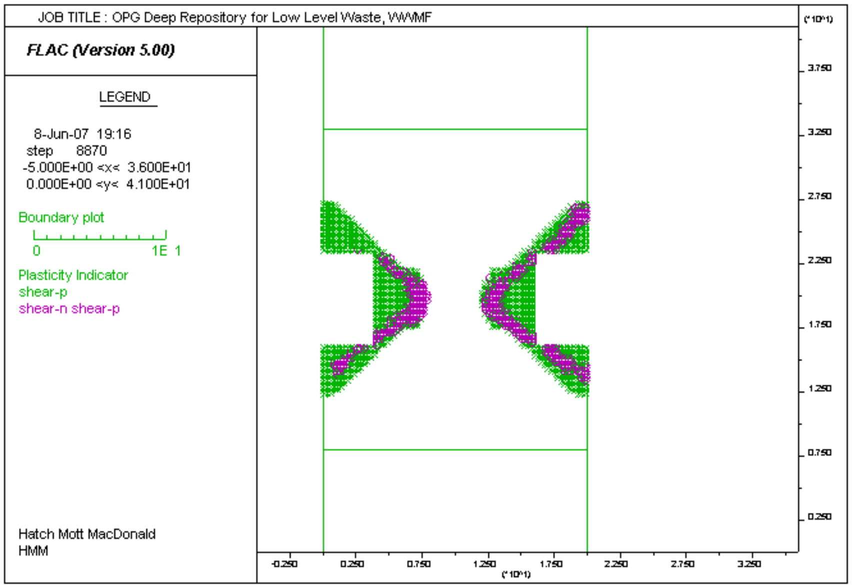
Vertical Stresses (MPa)



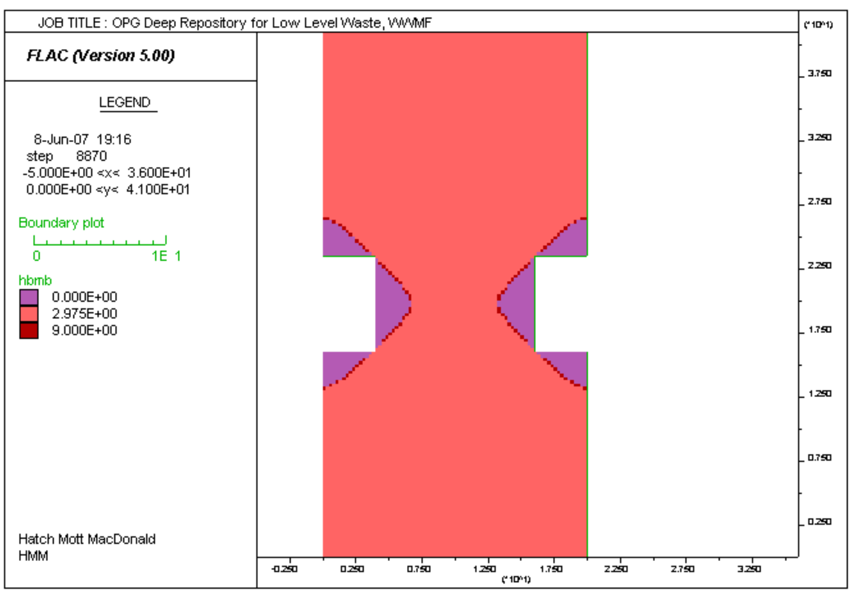
Horizontal Stresses (MPa)



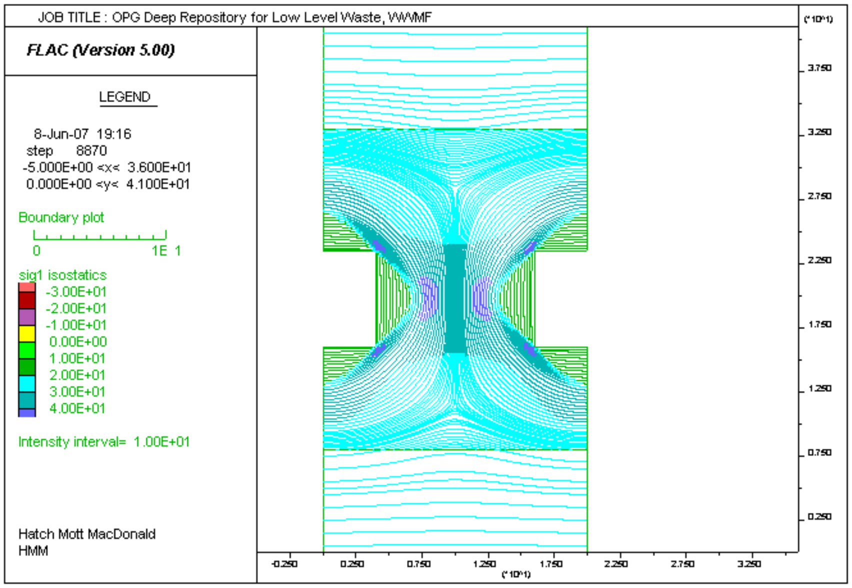
Plasticity Indicators



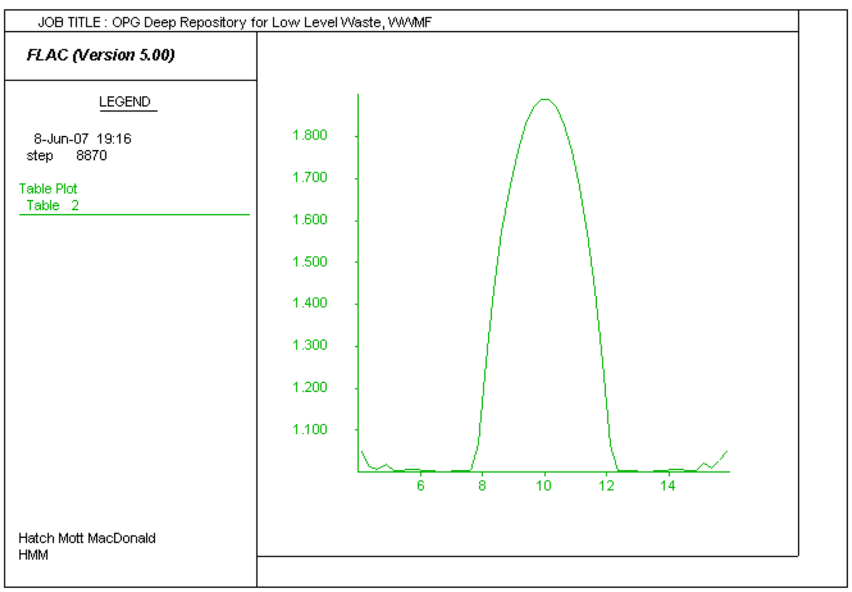
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

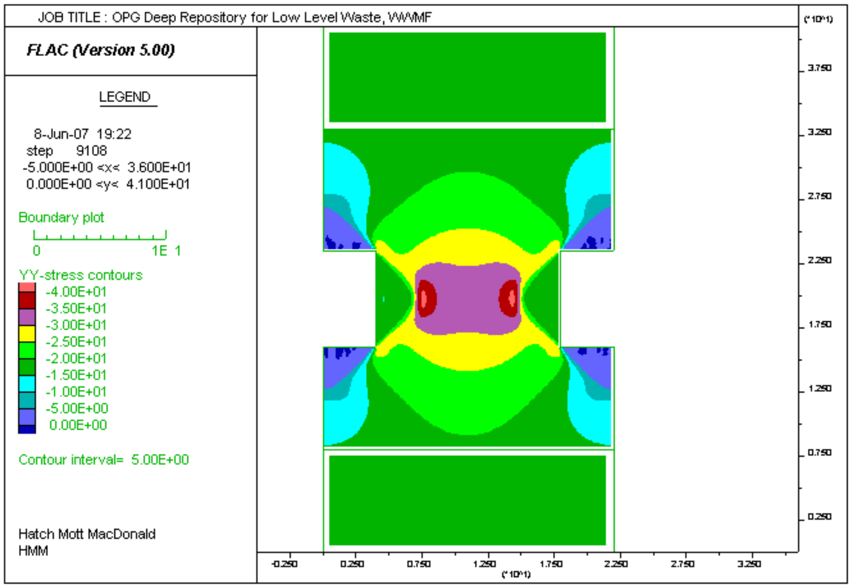


Factor Of Safety Across The Pillar

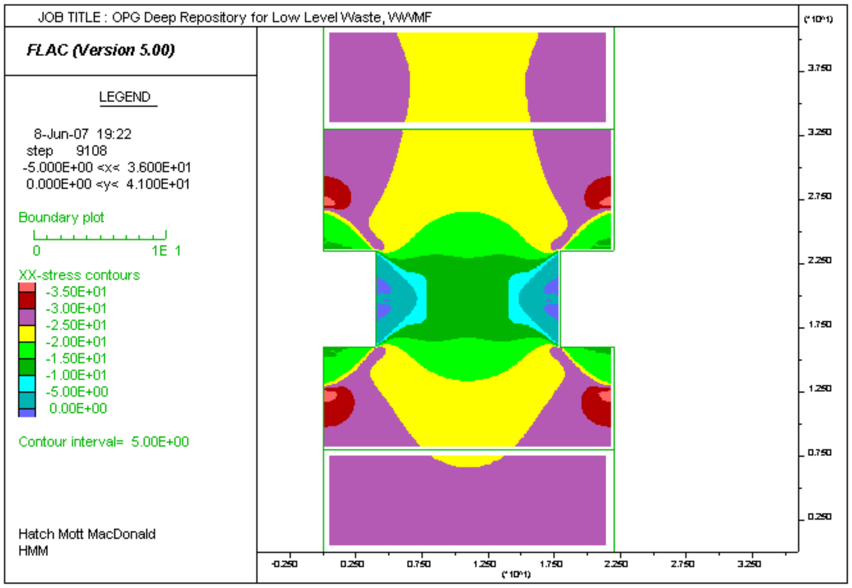


UCS = 48, GSI = 69, Pillar Width = 14.0m

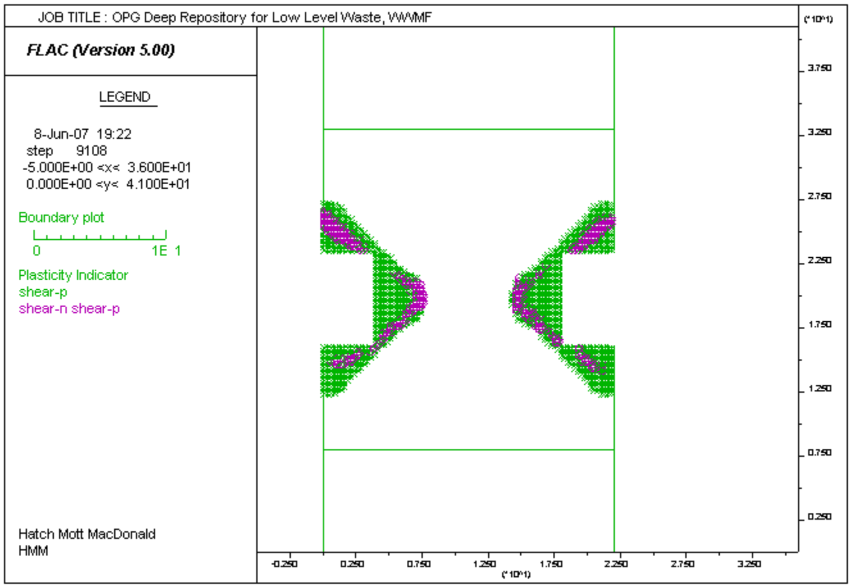
Vertical Stresses (MPa)



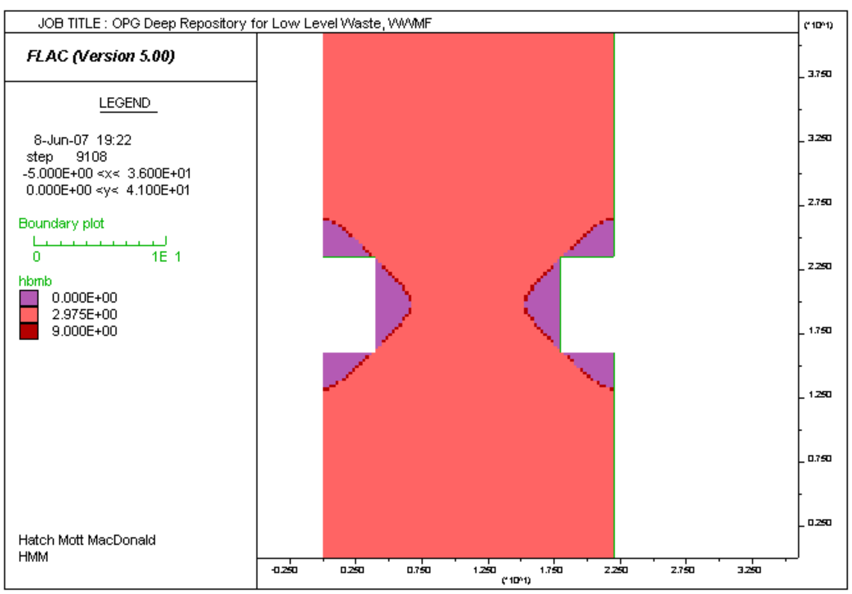
Horizontal Stresses (MPa)



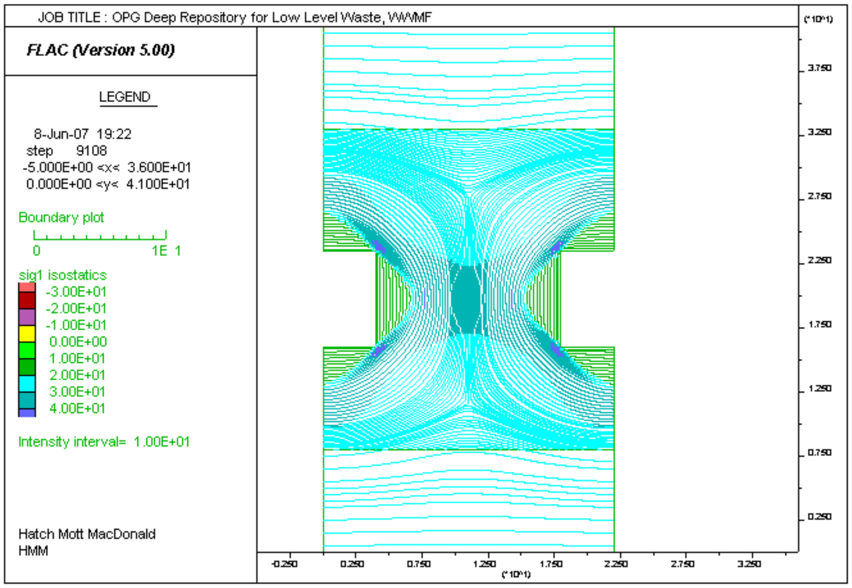
Plasticity Indicators



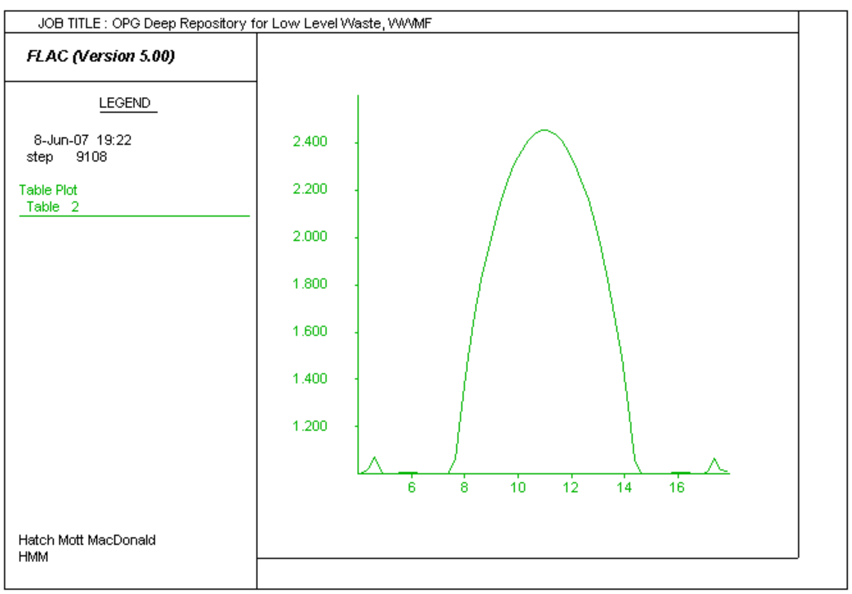
Failure Criteria (■ Brittle Failure, ■ Hoek-Brown Peak Strength, ■ Transition)



Maximum Principal Stress Trajectories (MPa)



Factor Of Safety Across The Pillar



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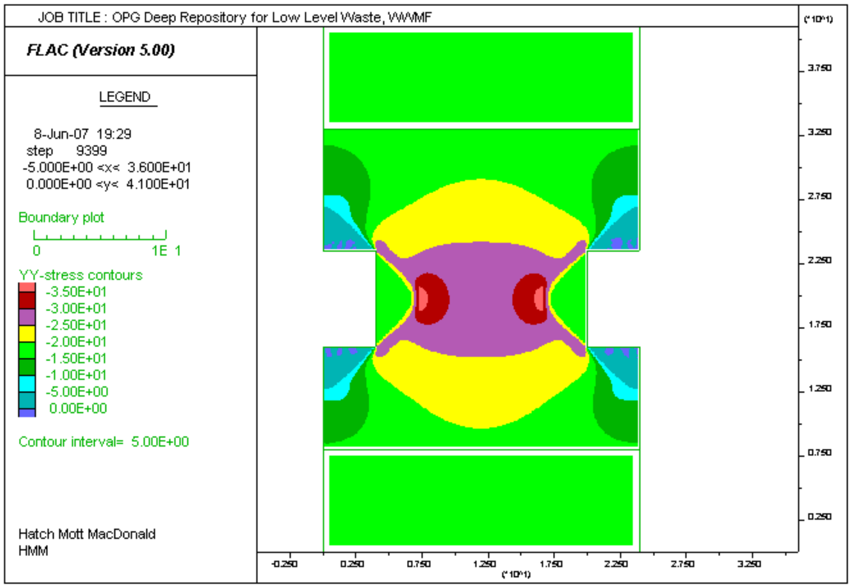
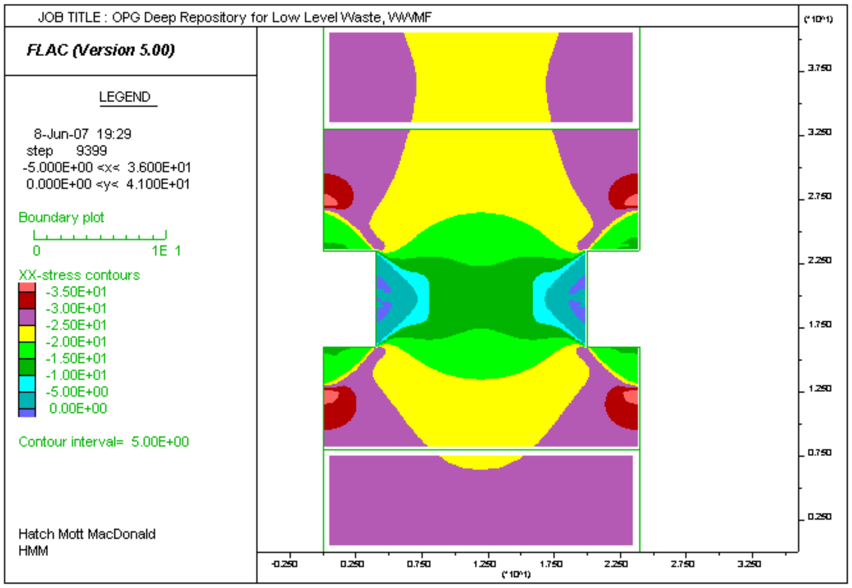
UCS = 48, GSI = 69, Pillar Width = 16.0m

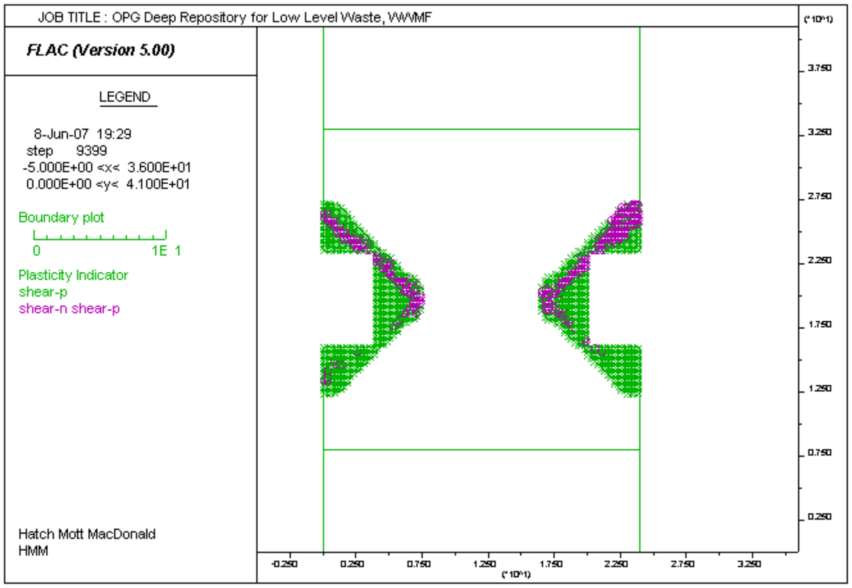
Vertical Stresses (MPa)



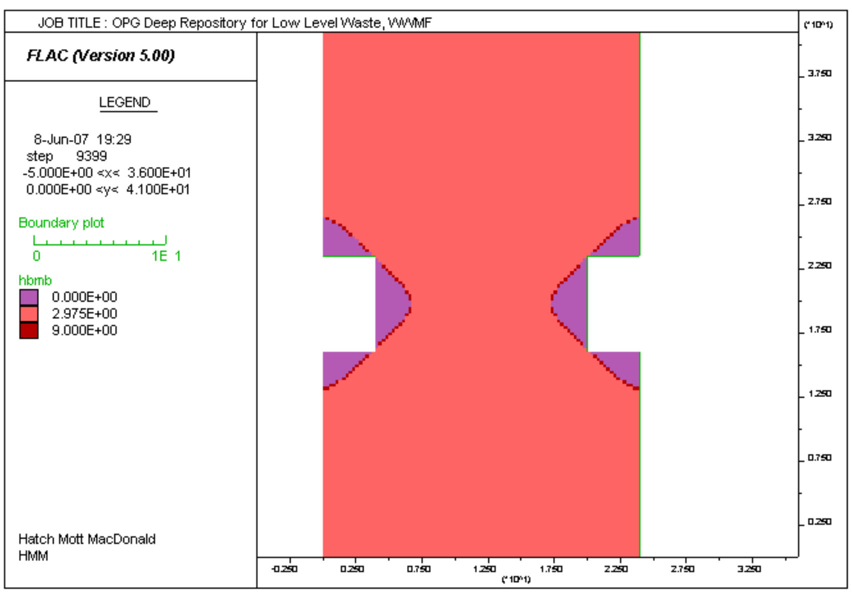
Horizontal Stresses (MPa)



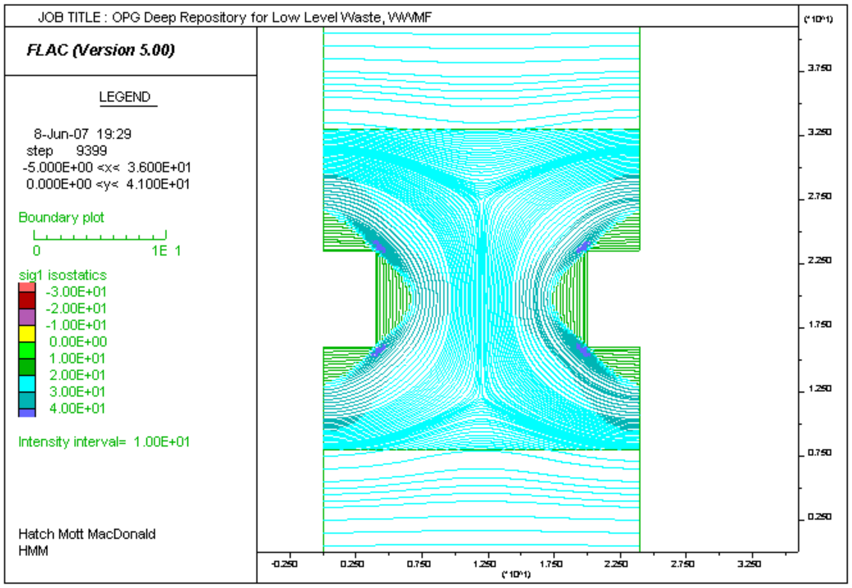
Plasticity Indicators



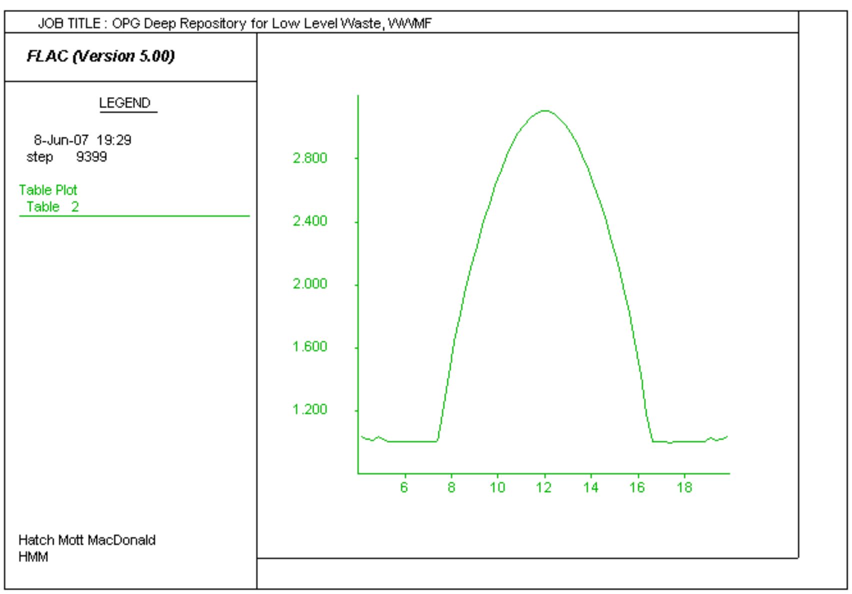
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

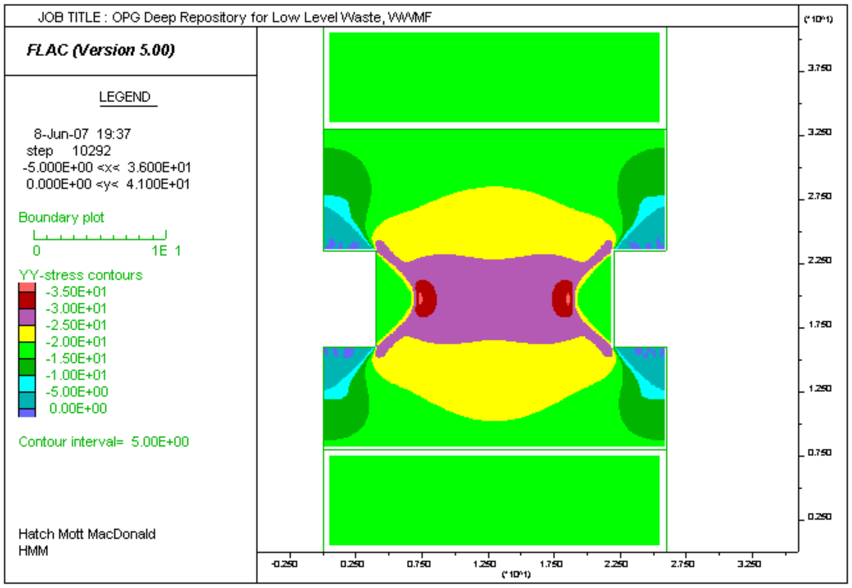


Factor Of Safety Across The Pillar

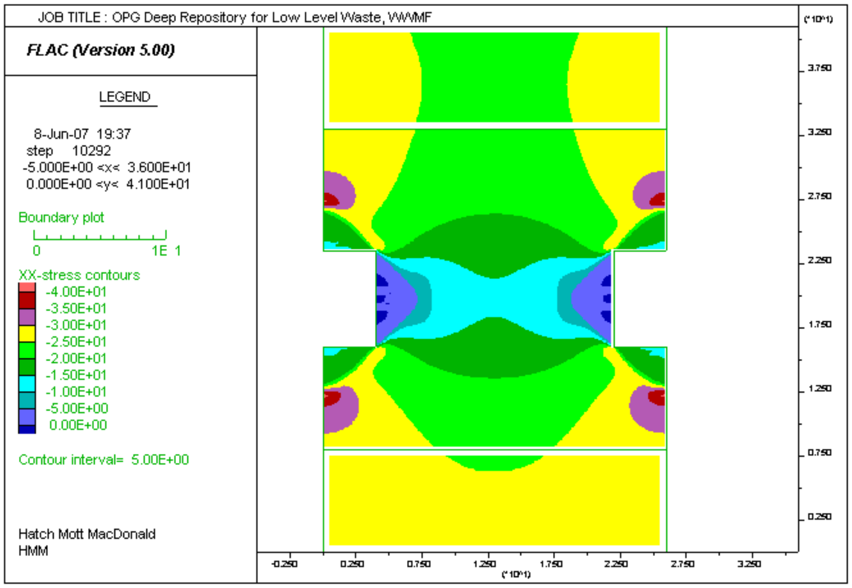


UCS = 48, GSI = 69, Pillar Width = 18.0m

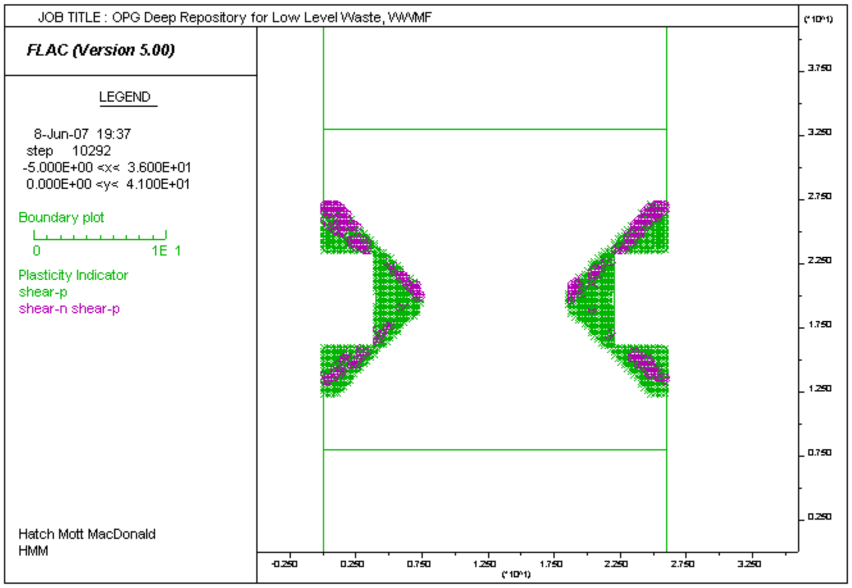
Vertical Stresses (MPa)



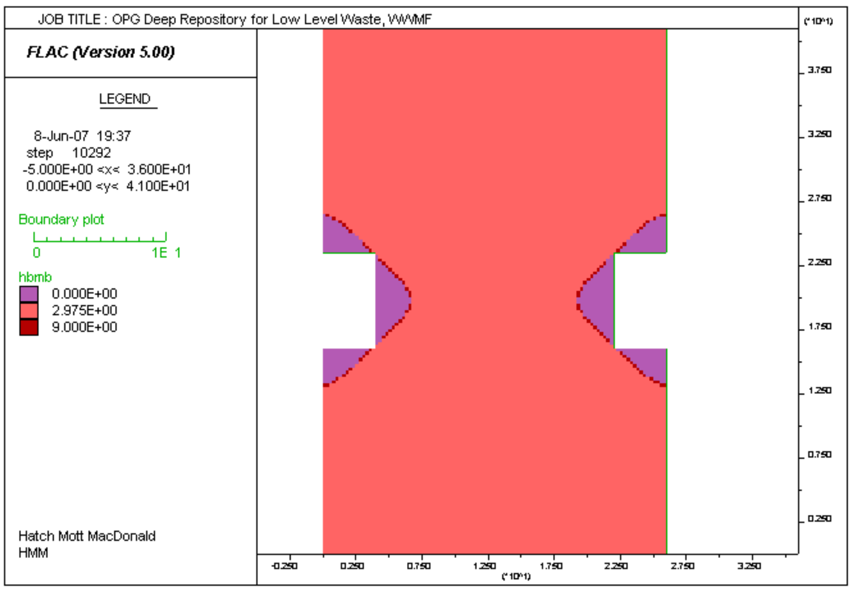
Horizontal Stresses (MPa)



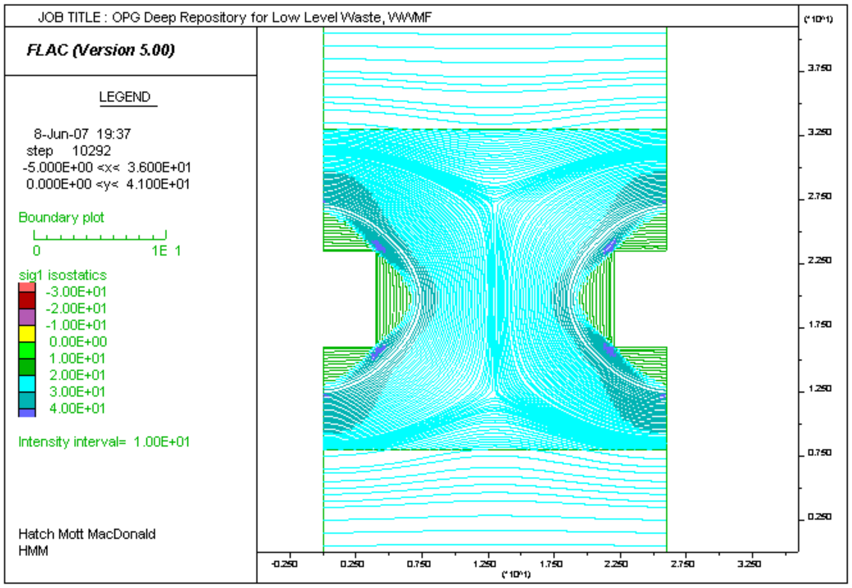
Plasticity Indicators



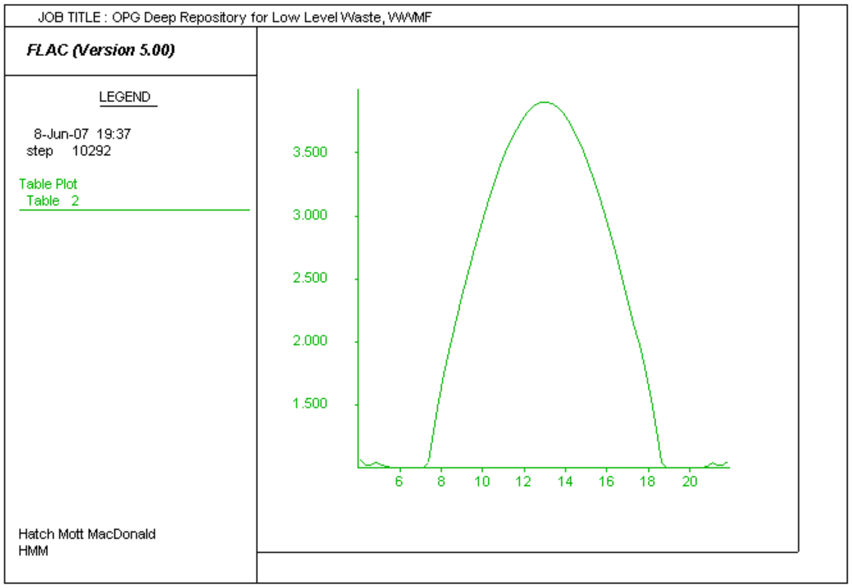
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

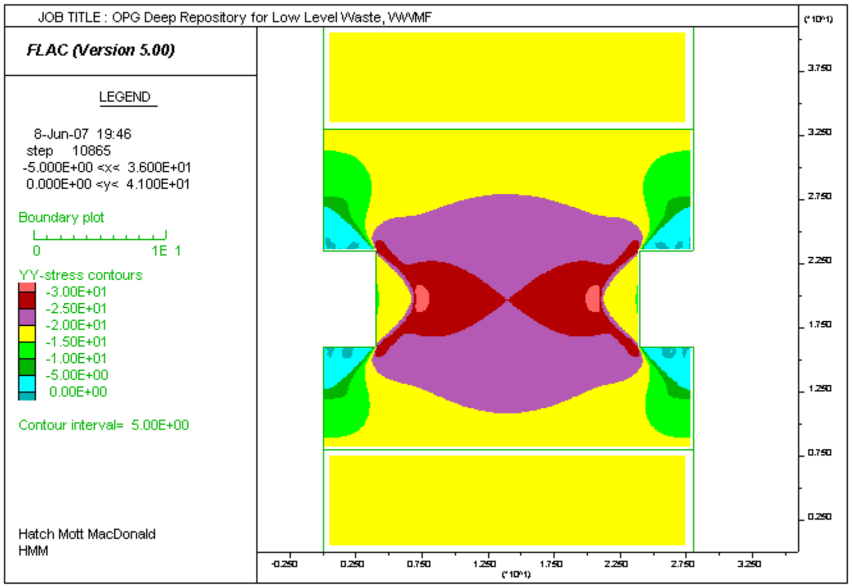


Factor Of Safety Across The Pillar

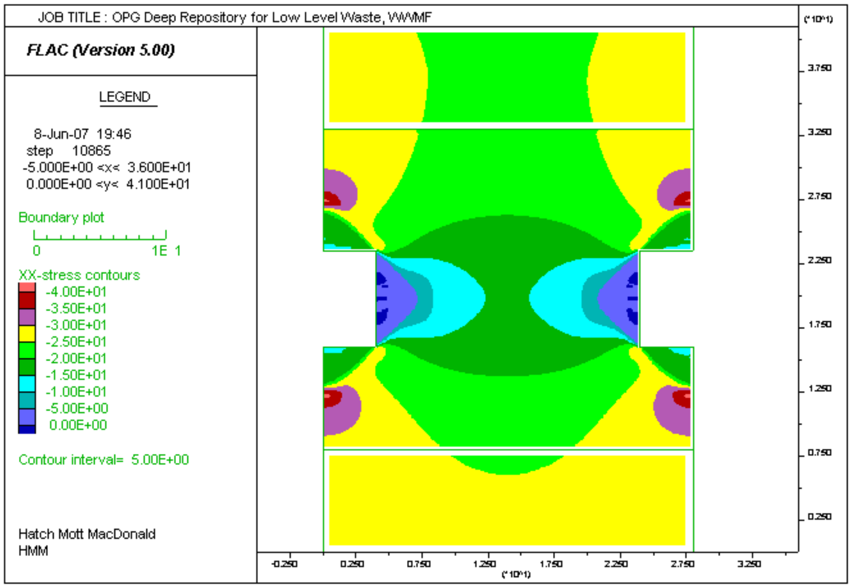


UCS = 48, GSI = 69, Pillar Width = 20.0m

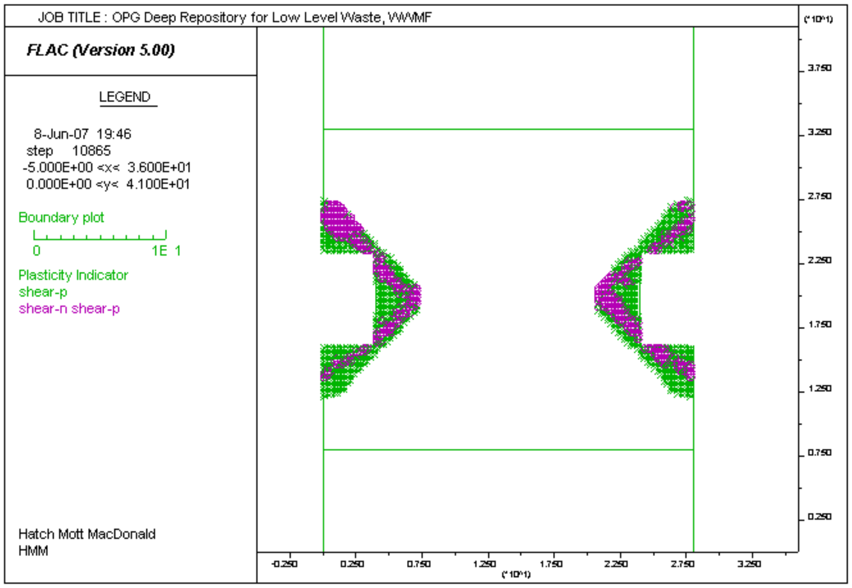
Vertical Stresses (MPa)



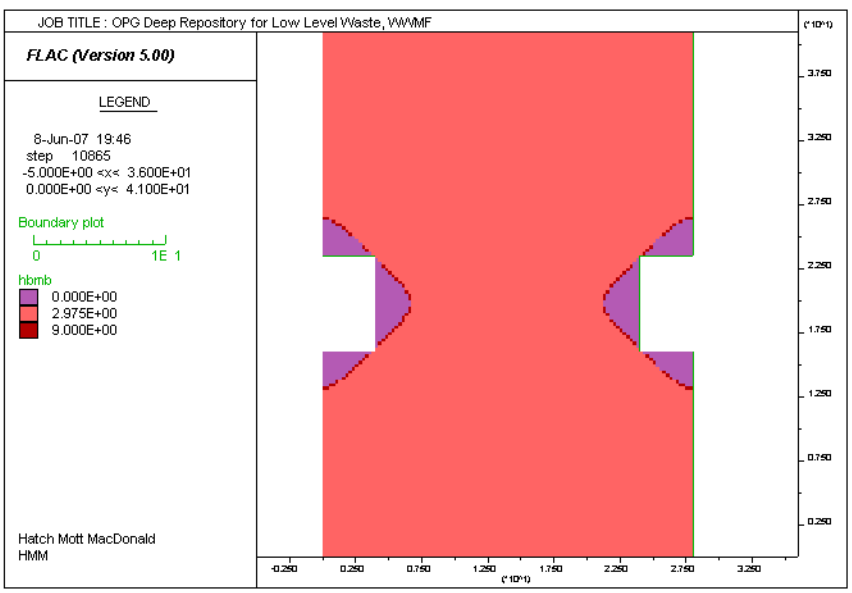
Horizontal Stresses (MPa)



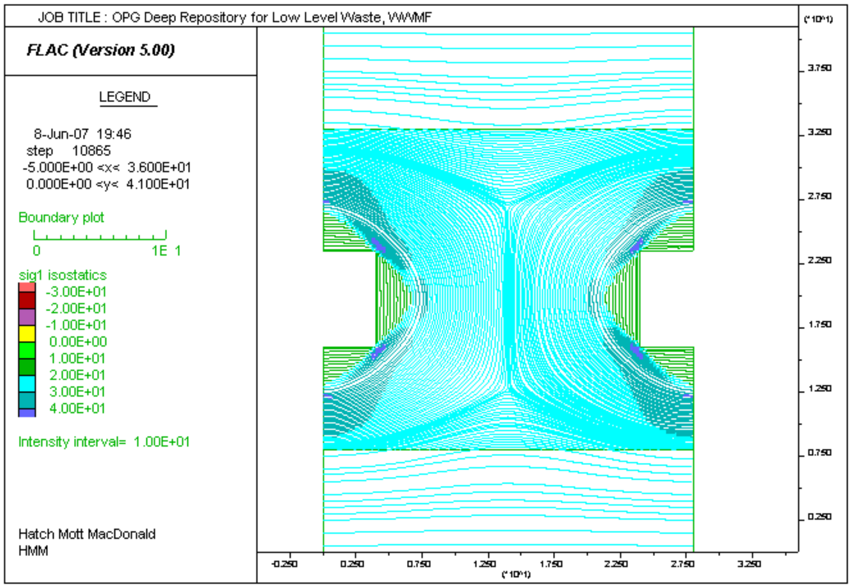
Plasticity Indicators



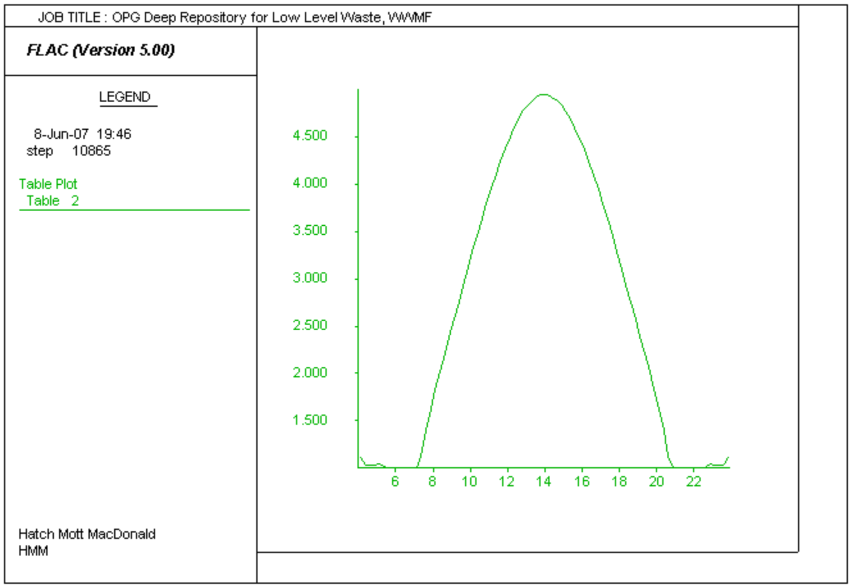
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

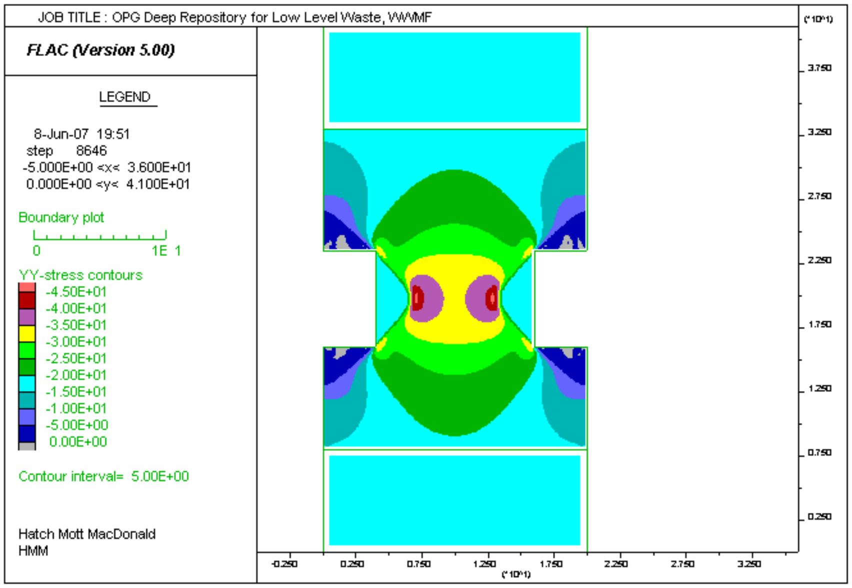


Factor Of Safety Across The Pillar

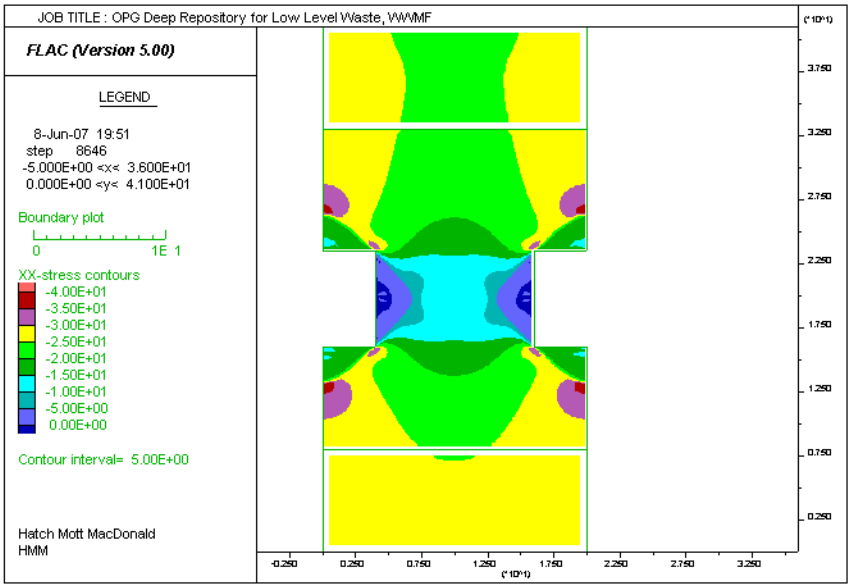


UCS = 48, GSI = 80, Pillar Width = 12.0m

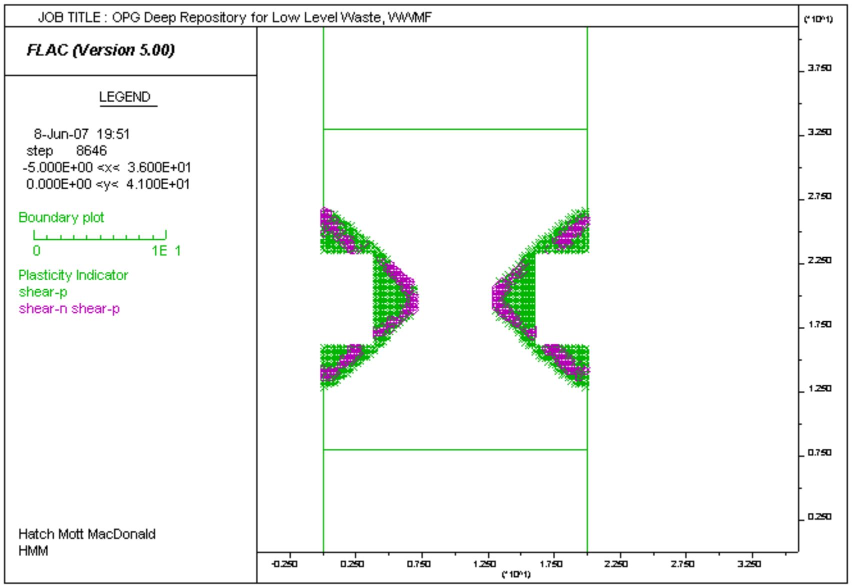
Vertical Stresses (MPa)



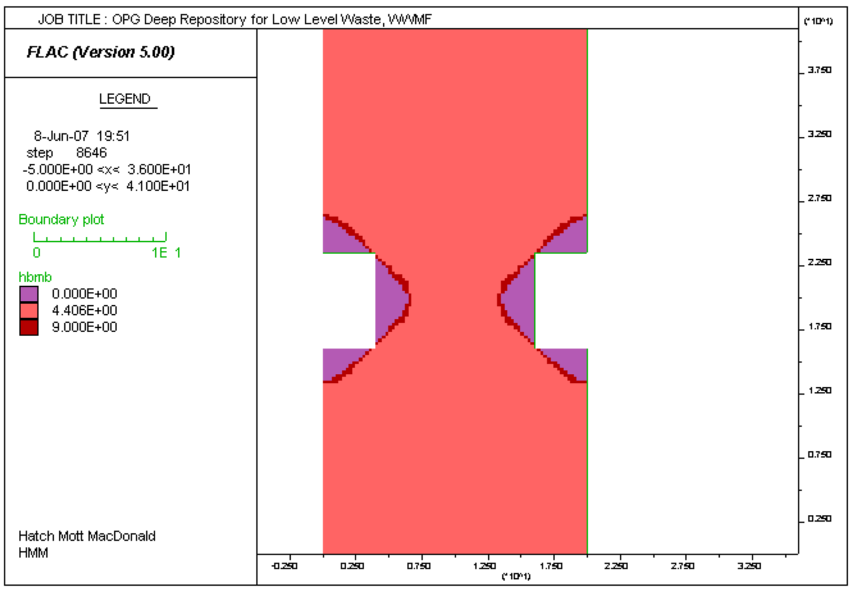
Horizontal Stresses (MPa)



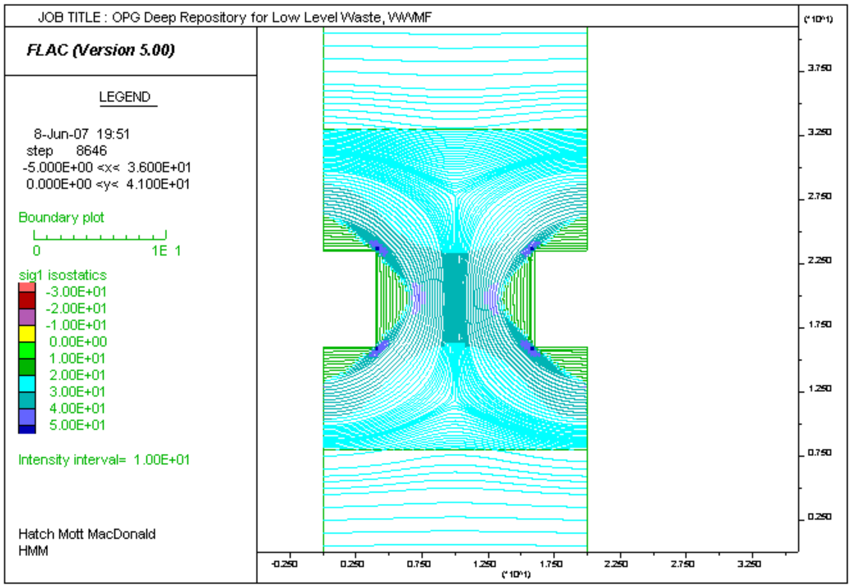
Plasticity Indicators



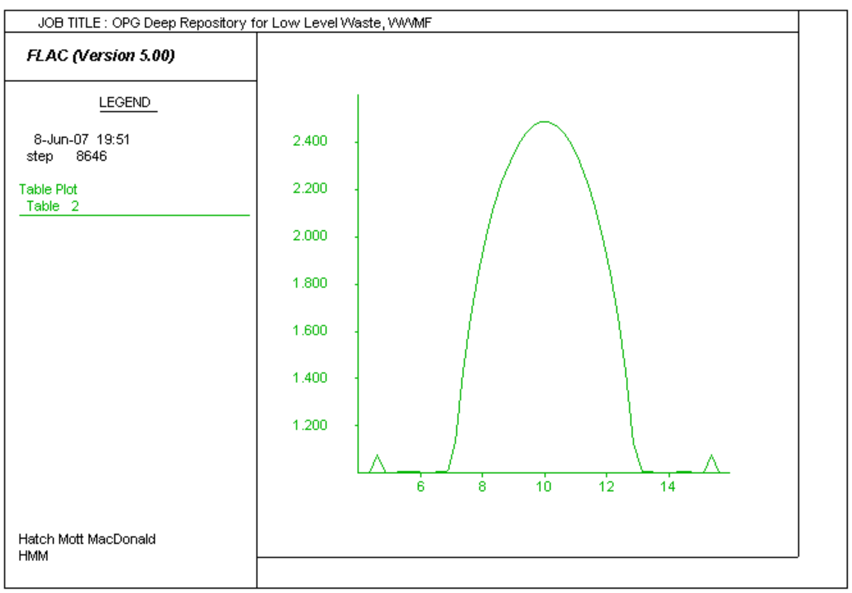
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

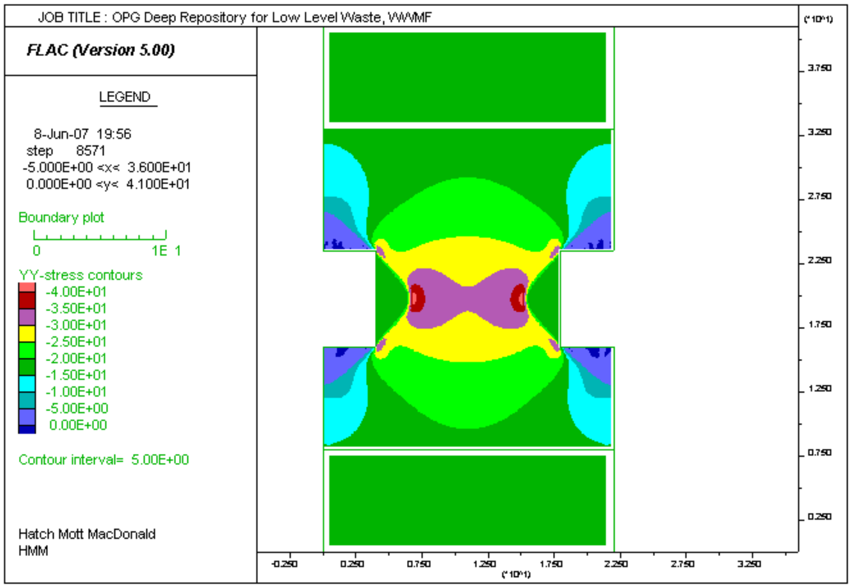


Factor Of Safety Across The Pillar

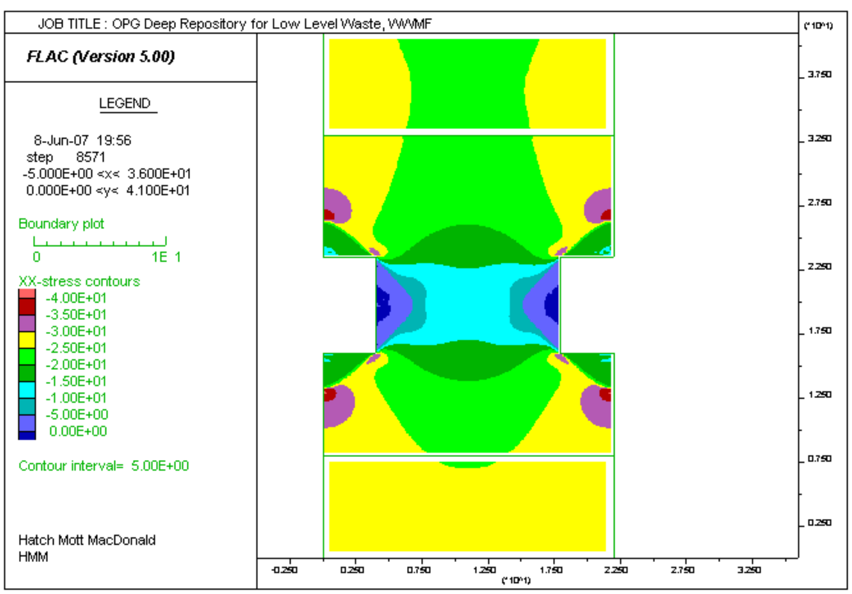


UCS = 48, GSI = 80, Pillar Width = 14.0m

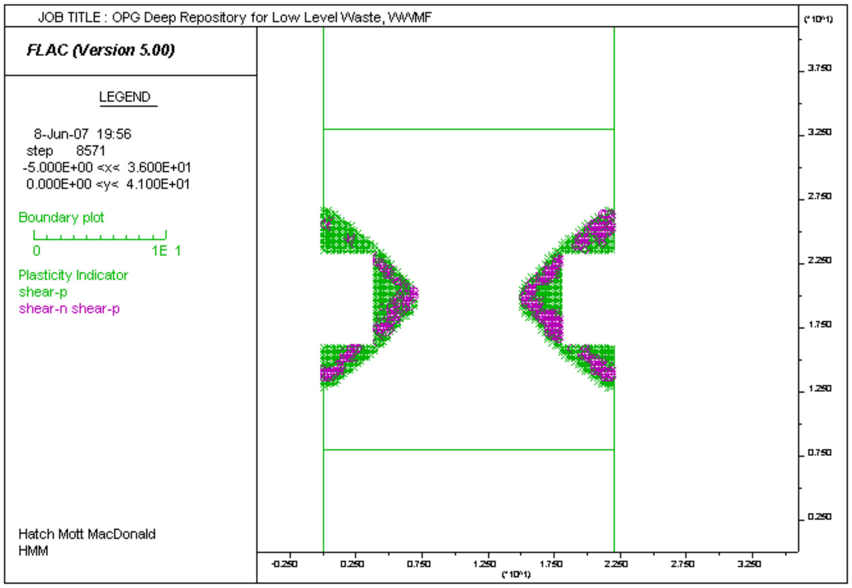
Vertical Stresses (MPa)



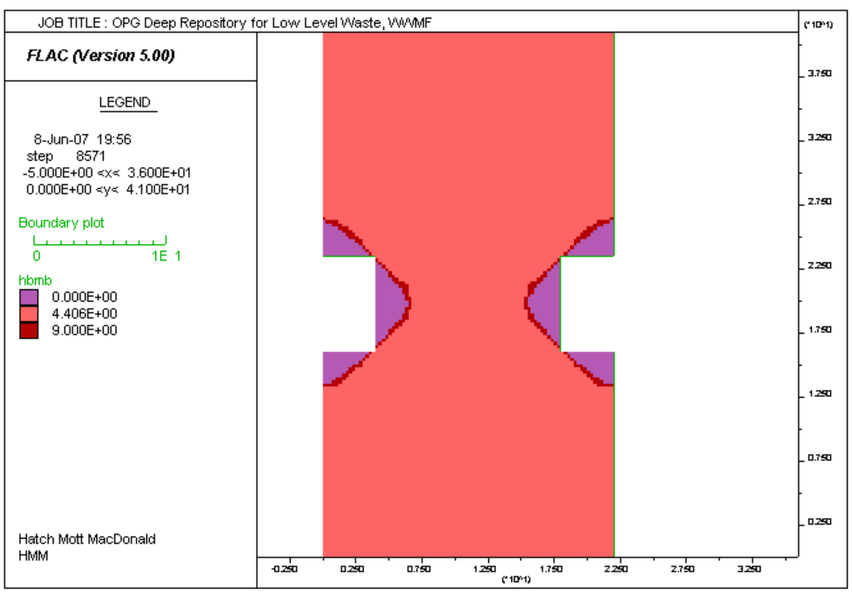
Horizontal Stresses (MPa)



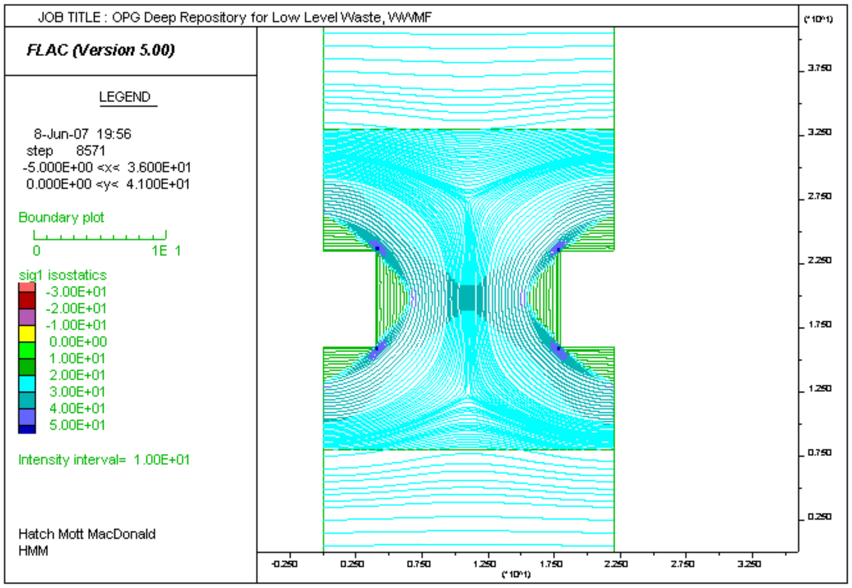
Plasticity Indicators



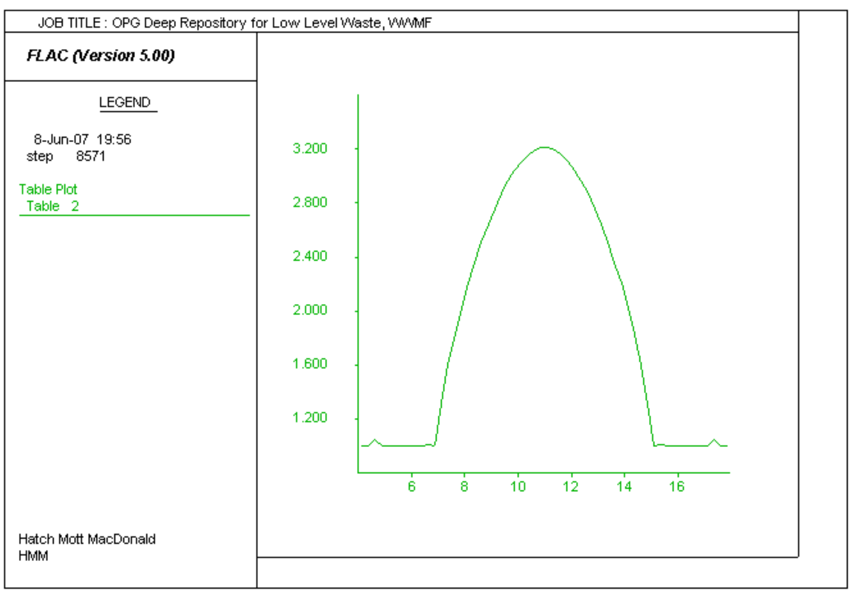
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

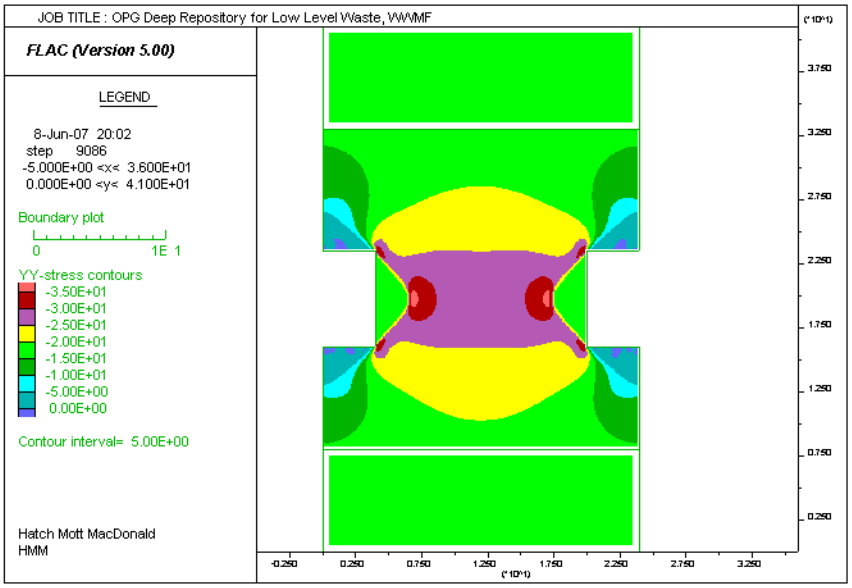


Factor Of Safety Across The Pillar

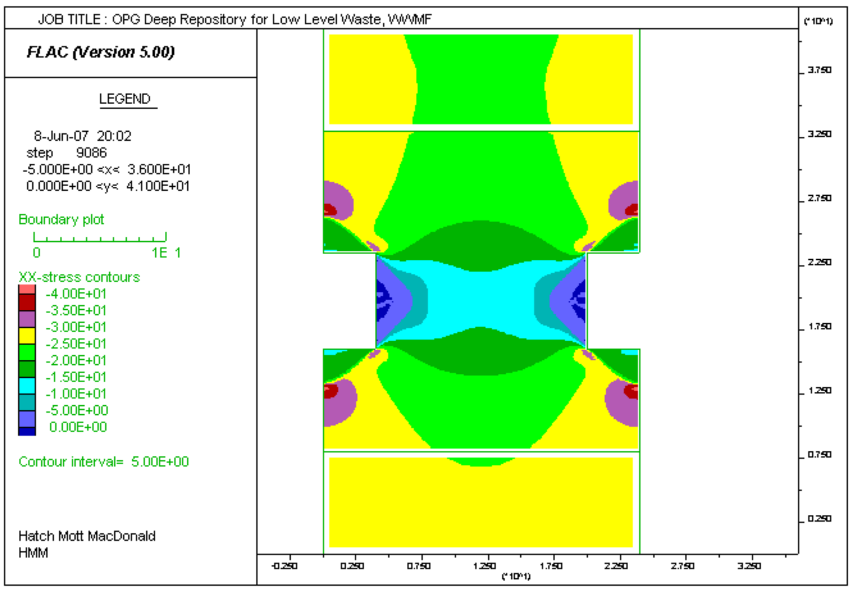


UCS = 48, GSI = 80, Pillar Width = 16.0m

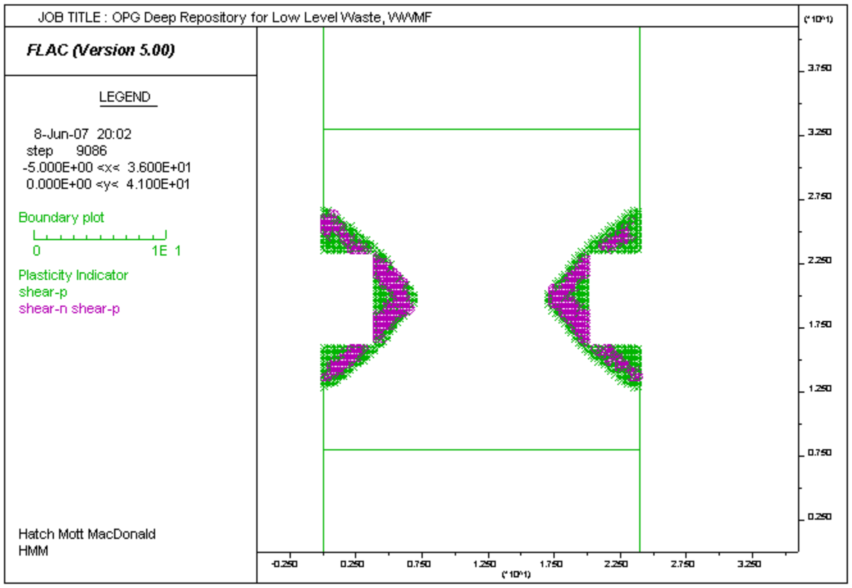
Vertical Stresses (MPa)



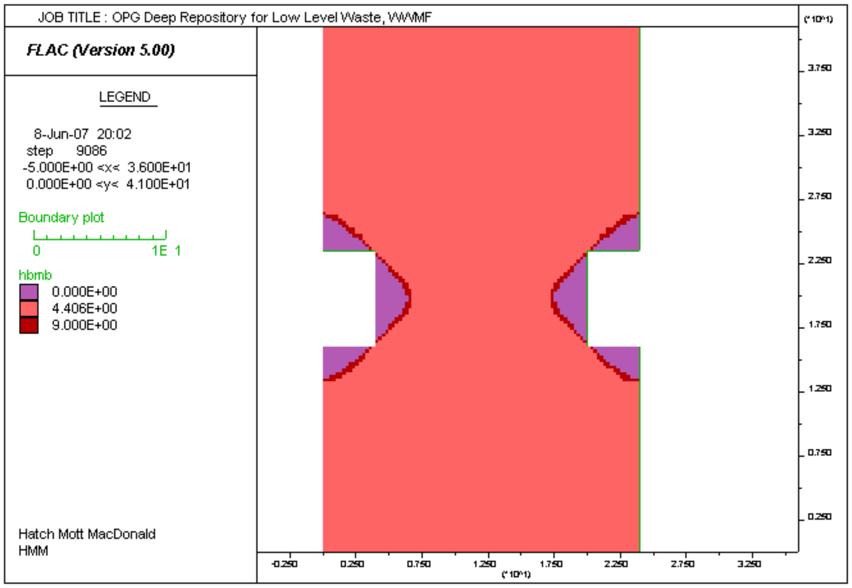
Horizontal Stresses (MPa)



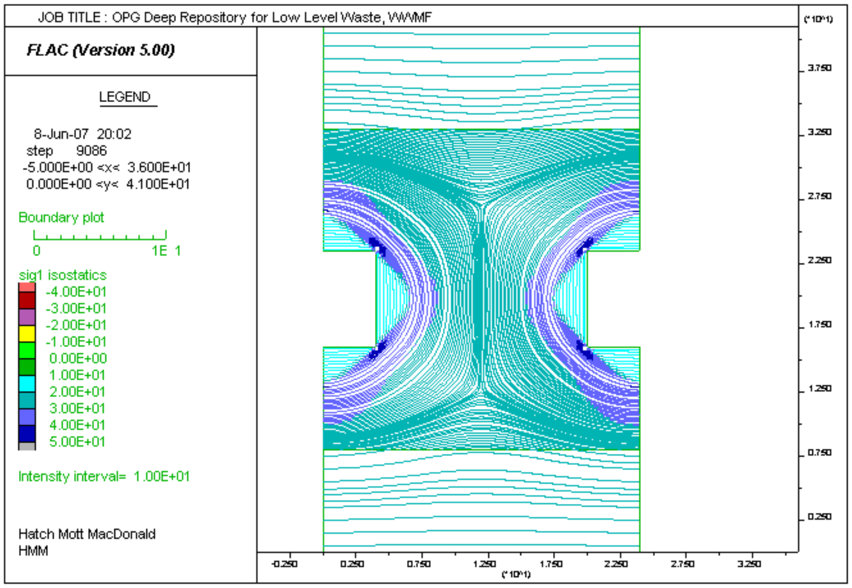
Plasticity Indicators



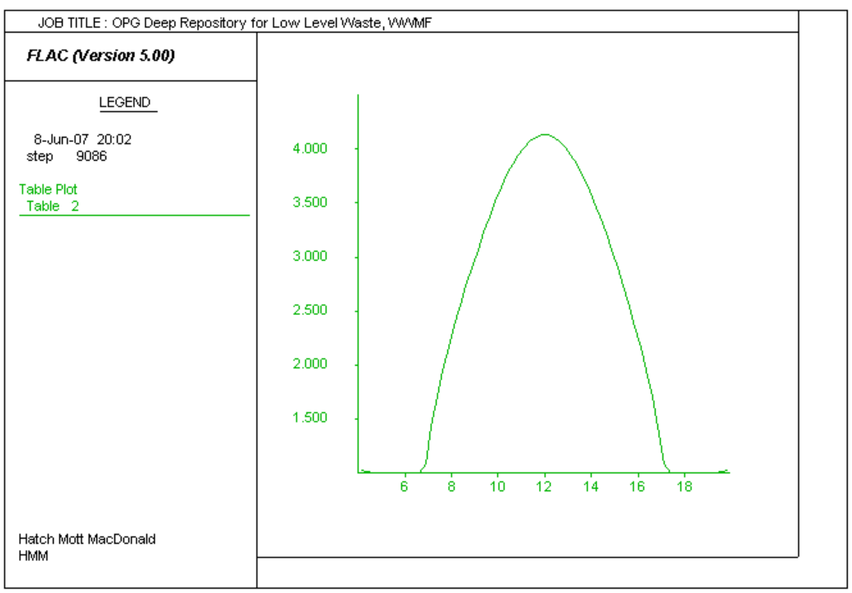
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)



Factor Of Safety Across The Pillar



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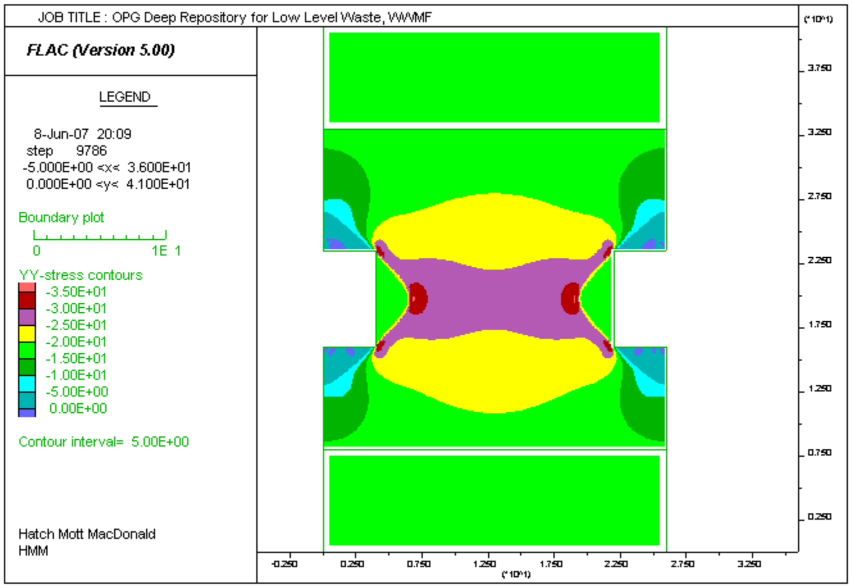
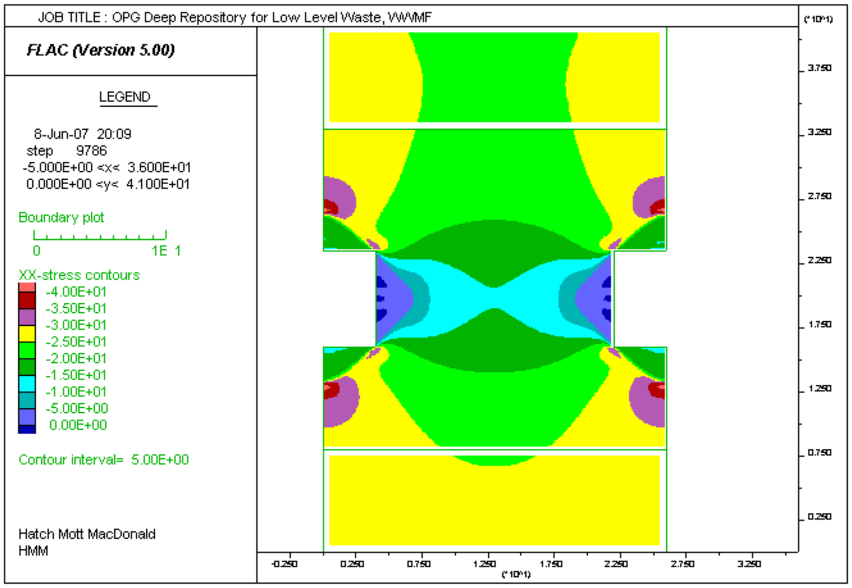
UCS = 48, GSI = 80, Pillar Width = 18.0m

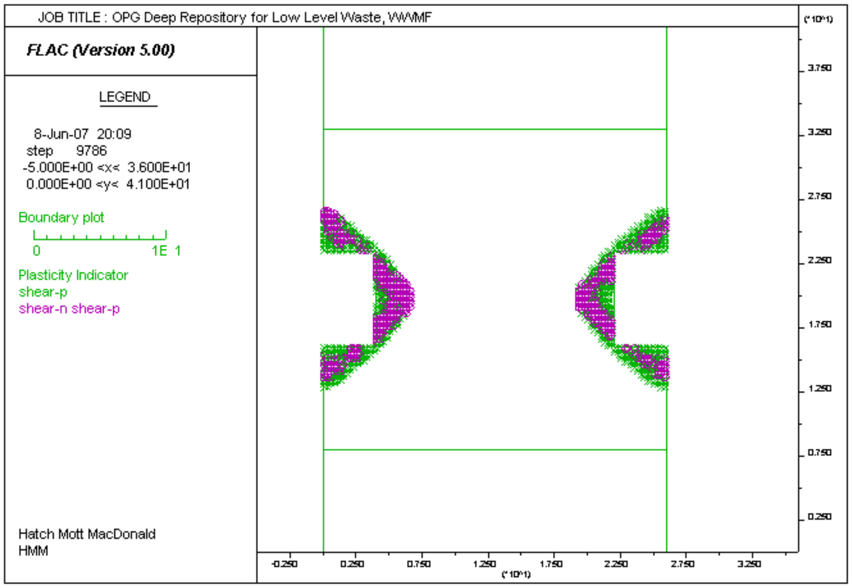
Vertical Stresses (MPa)



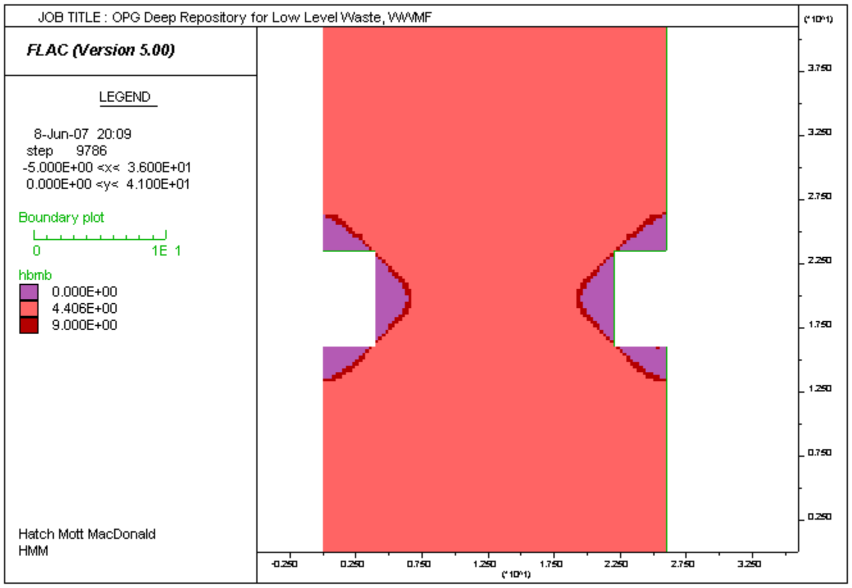
Horizontal Stresses (MPa)



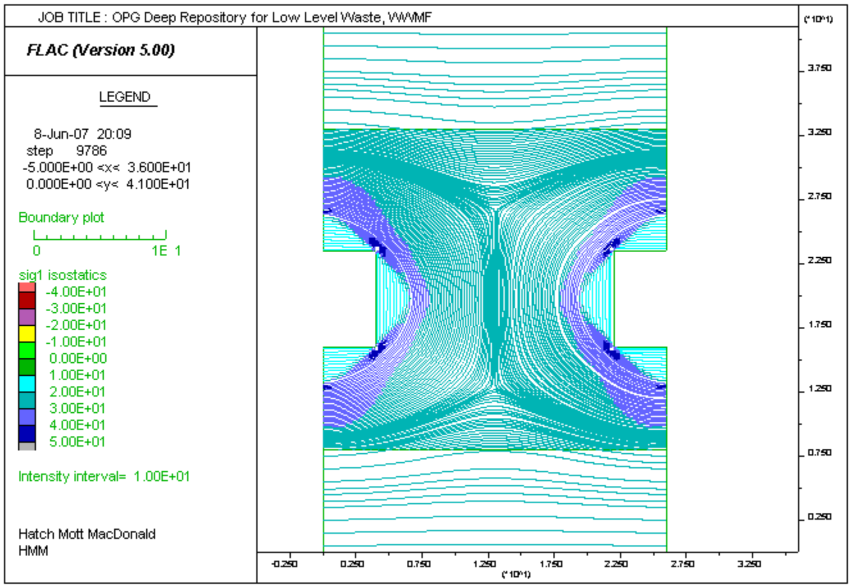
Plasticity Indicators



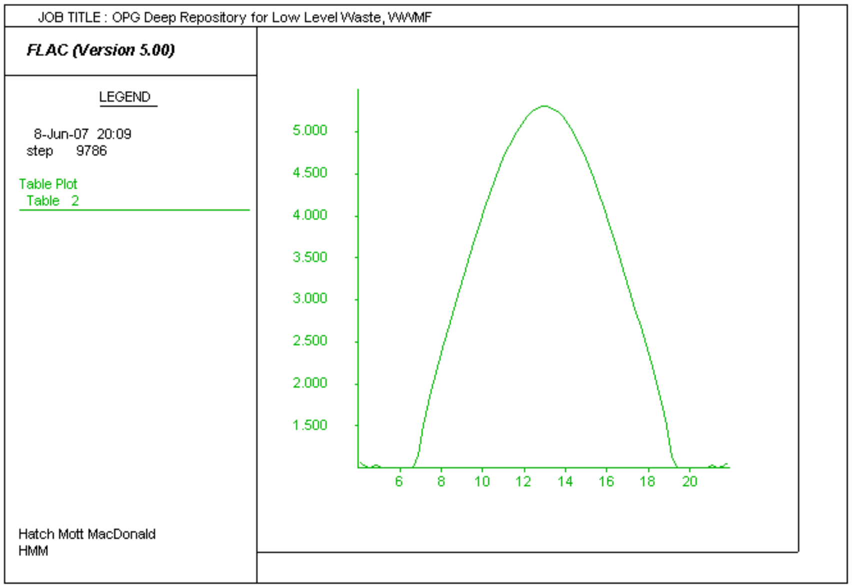
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

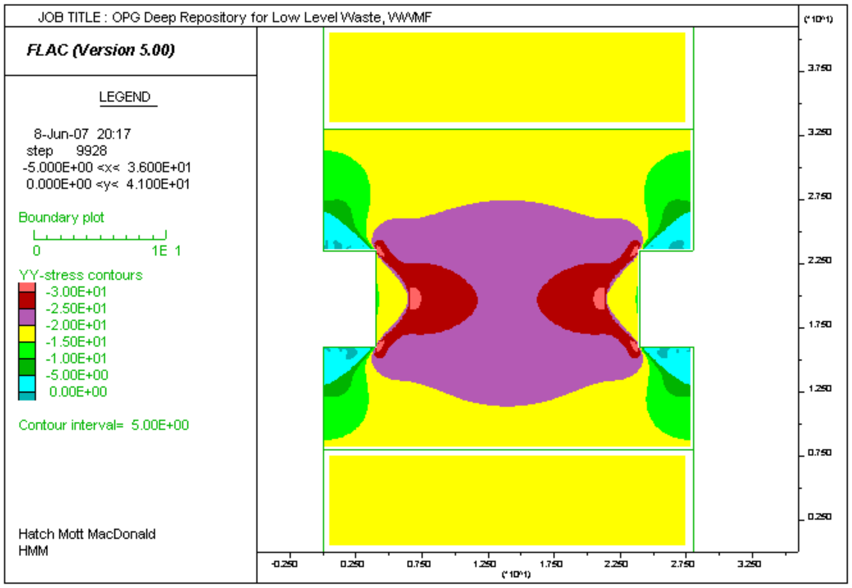


Factor Of Safety Across The Pillar

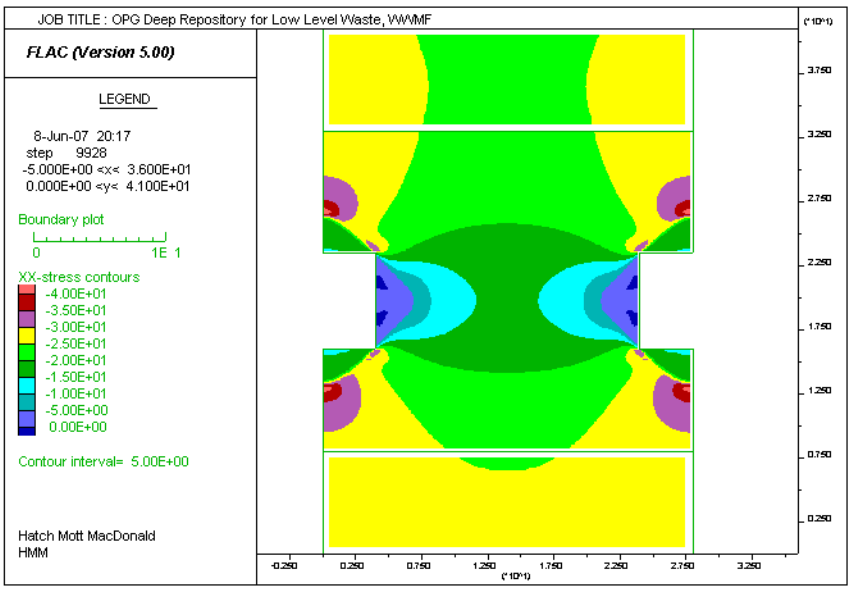


UCS = 48, GSI = 80, Pillar Width = 20.0m

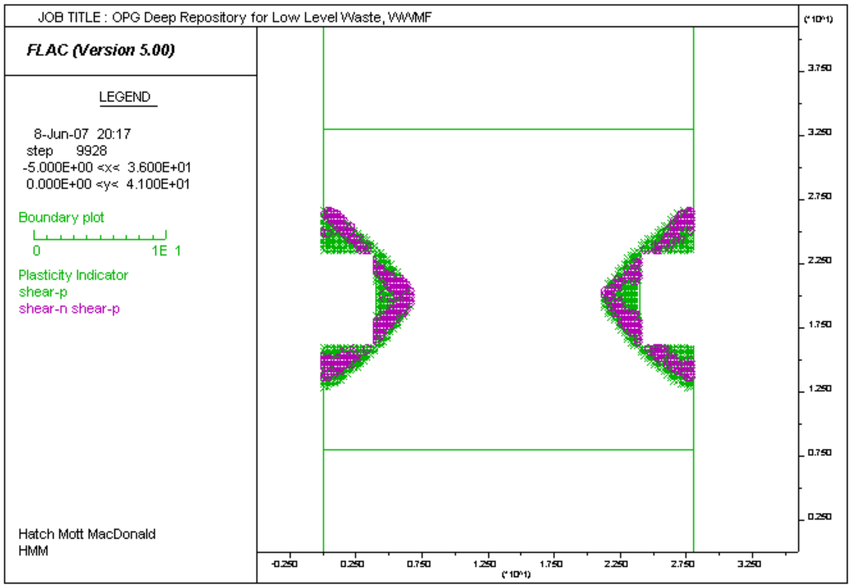
Vertical Stresses (MPa)



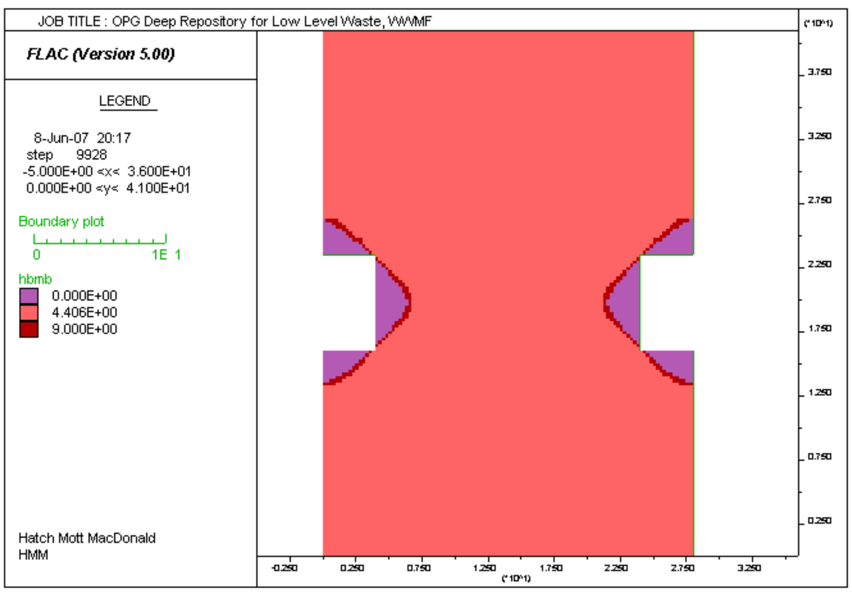
Horizontal Stresses (MPa)



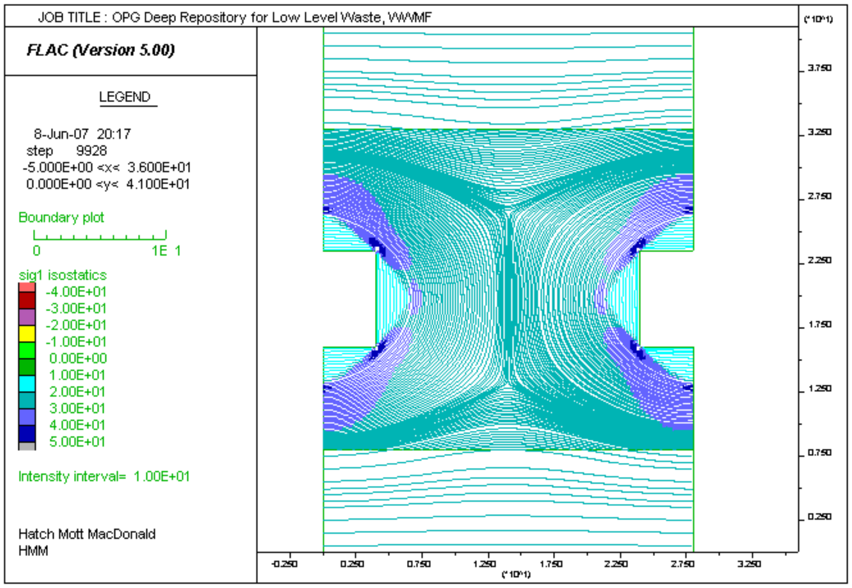
Plasticity Indicators



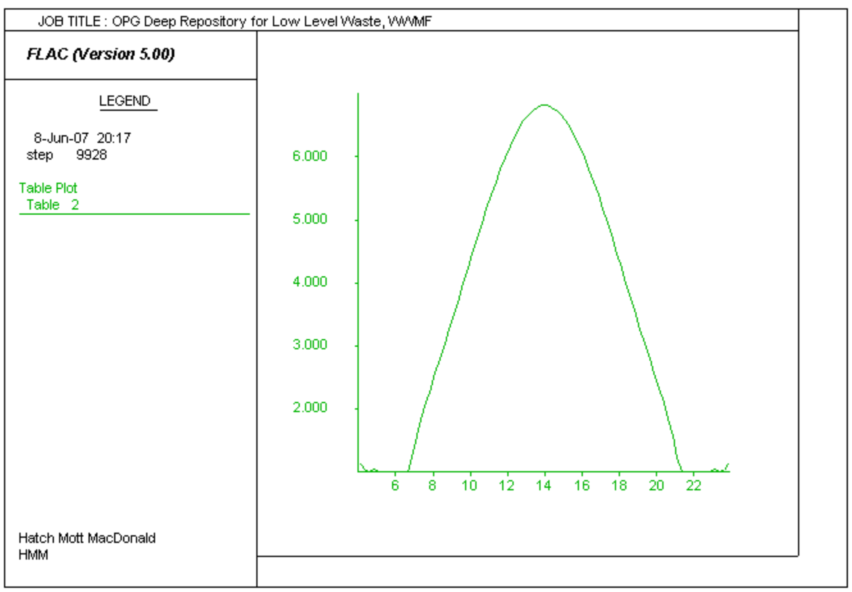
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

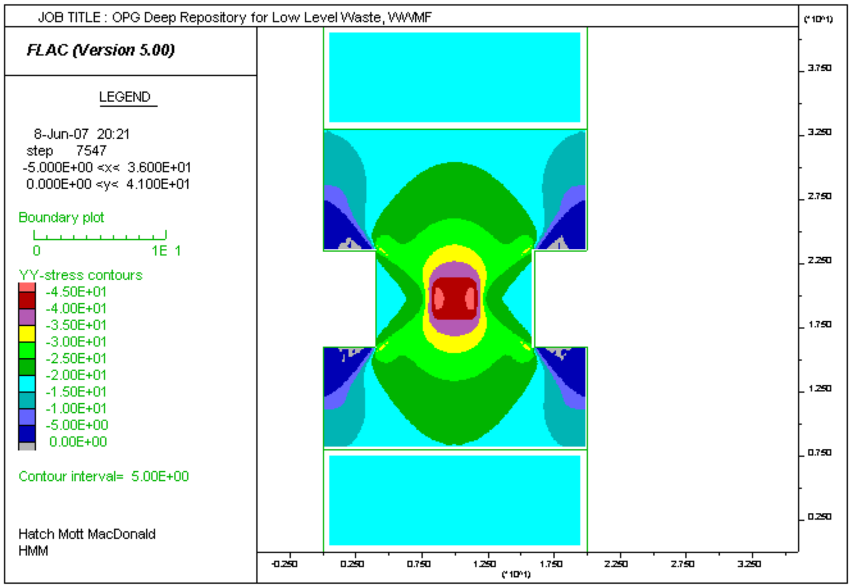


Factor Of Safety Across The Pillar

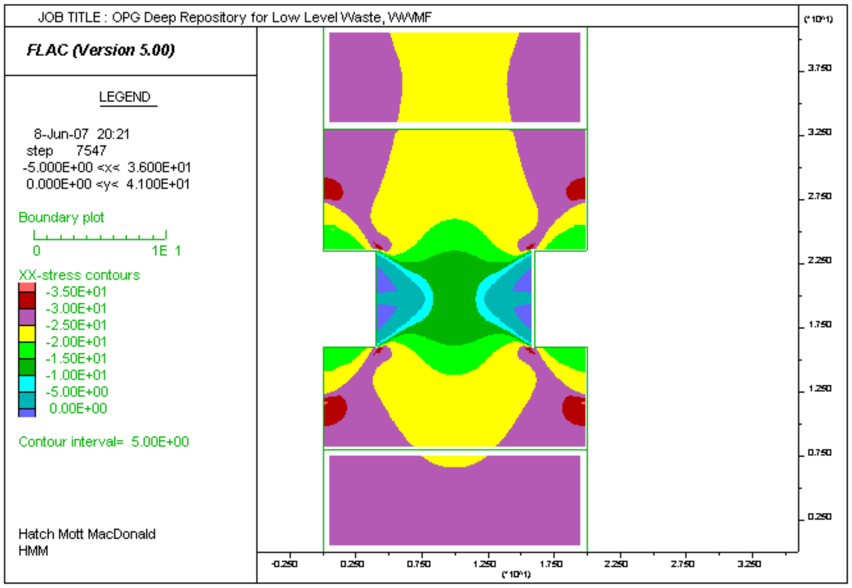


UCS = 60, GSI = 55, Pillar Width = 12.0m

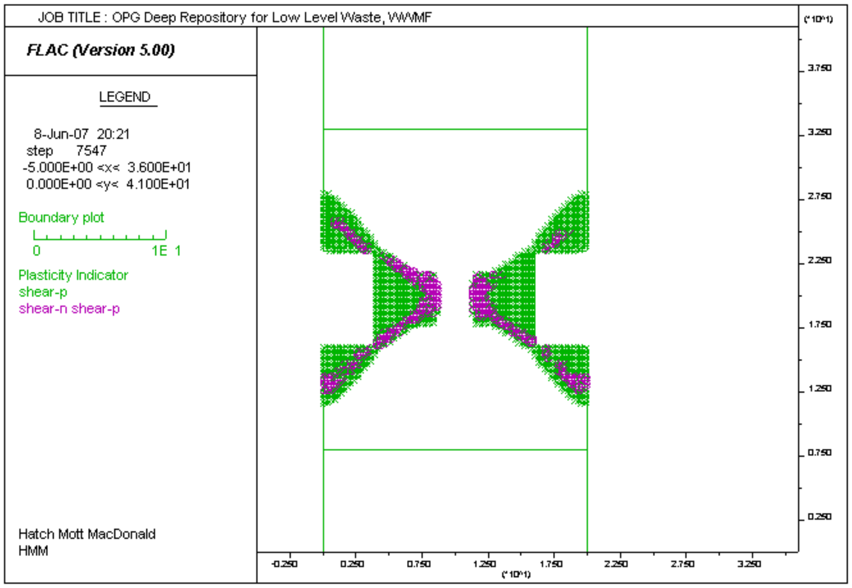
Vertical Stresses (MPa)



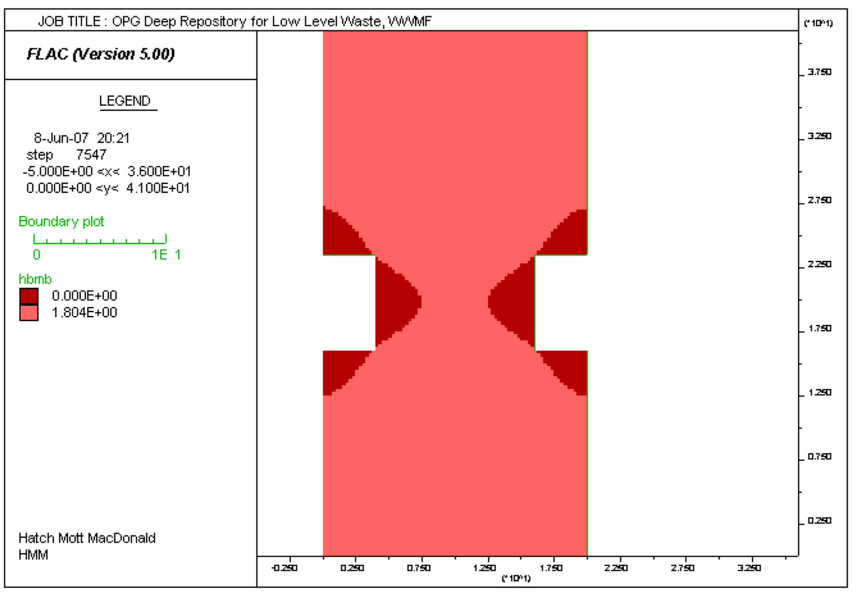
Horizontal Stresses (MPa)



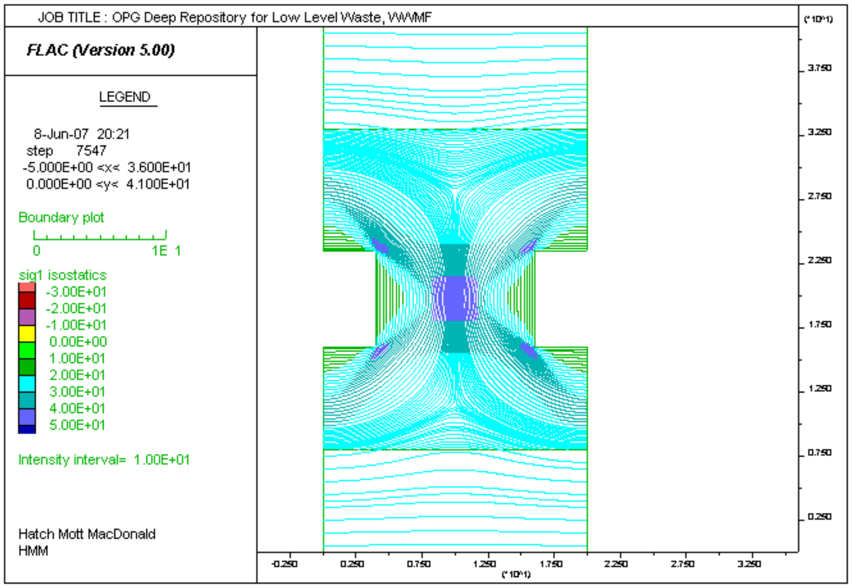
Plasticity Indicators



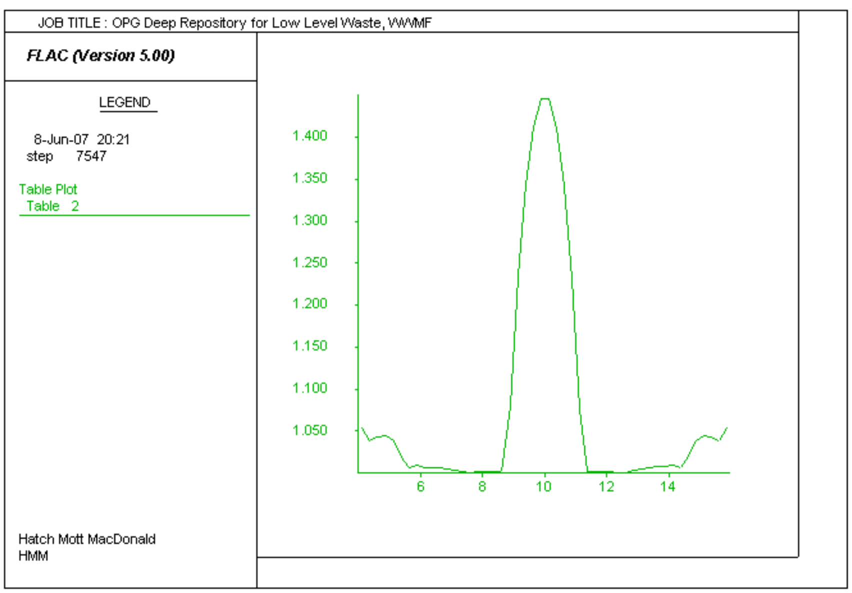
Failure Criteria (■ Brittle Failure, ■ Hoek-Brown Peak Strength, ■ Transition)



Maximum Principal Stress Trajectories (MPa)

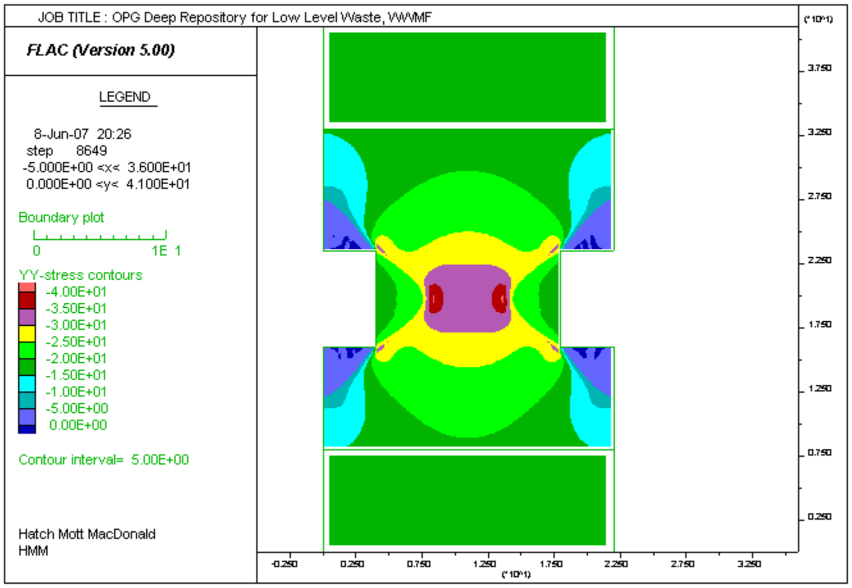


Factor Of Safety Across The Pillar

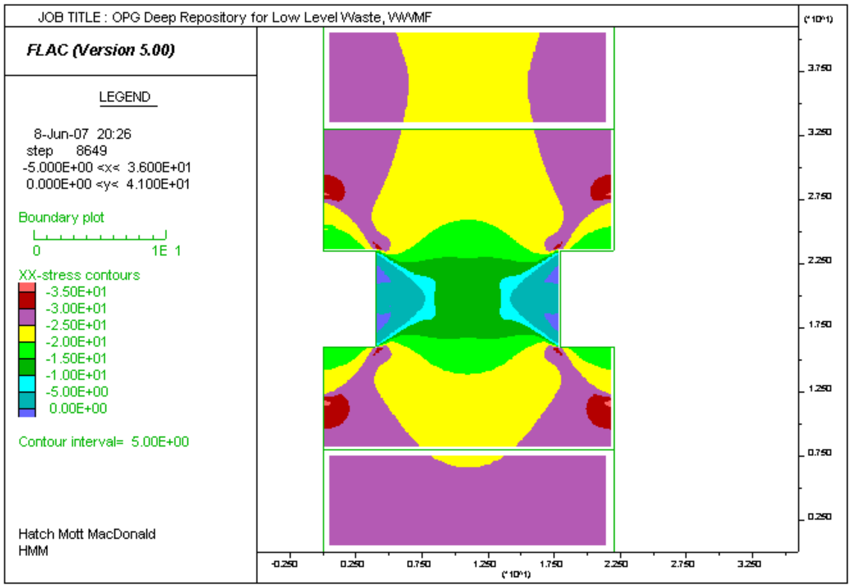


UCS = 60, GSI = 55, Pillar Width = 14.0m

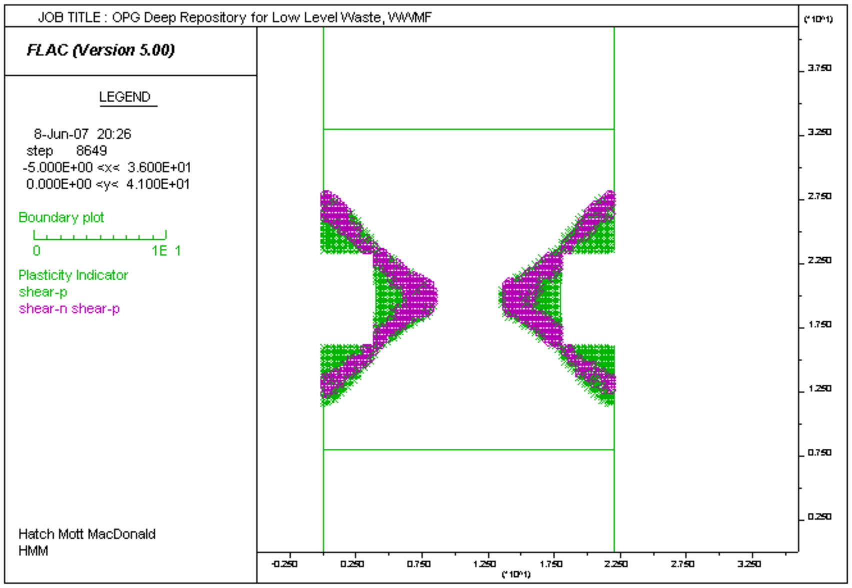
Vertical Stresses (MPa)



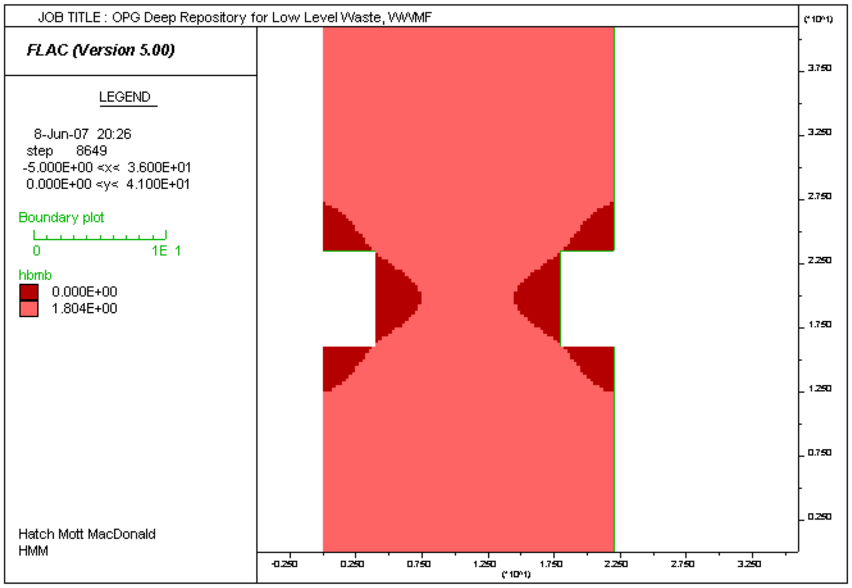
Horizontal Stresses (MPa)



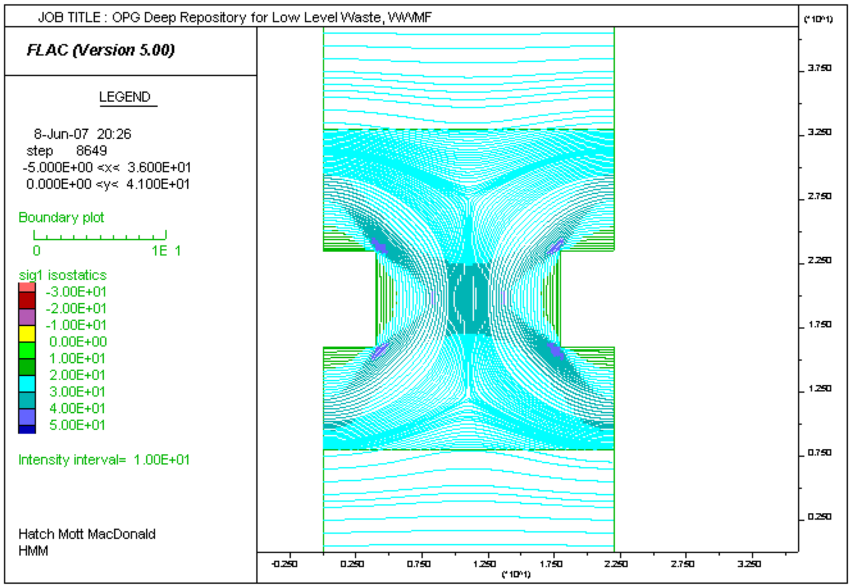
Plasticity Indicators



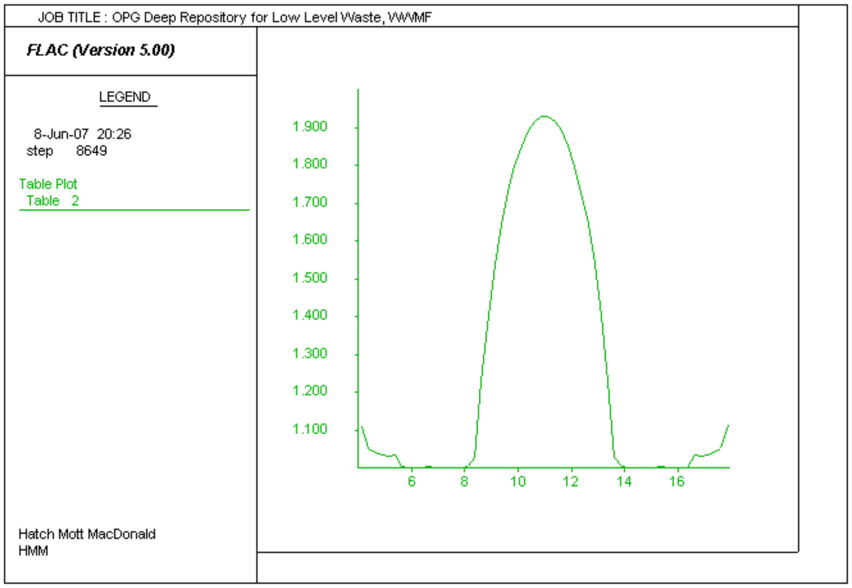
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)



Factor Of Safety Across The Pillar



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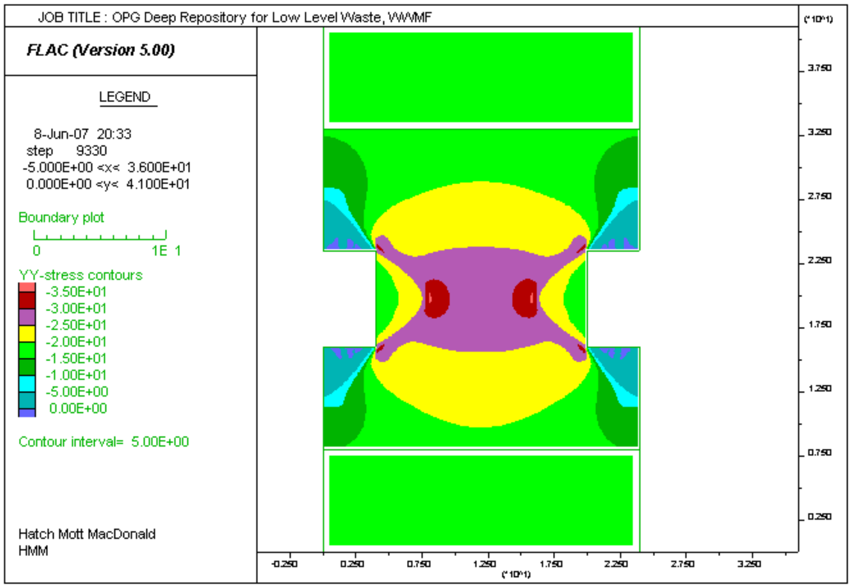
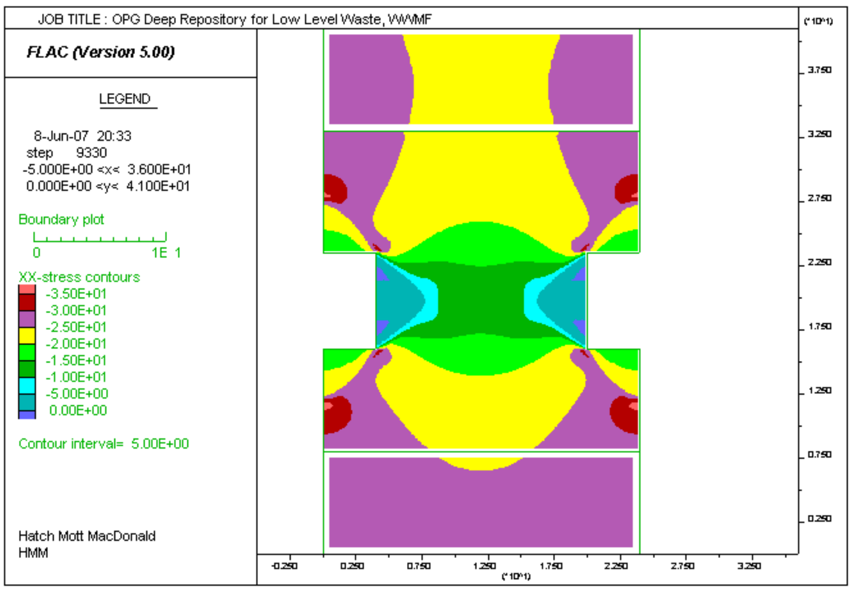
UCS = 60, GSI = 55, Pillar Width = 16.0m

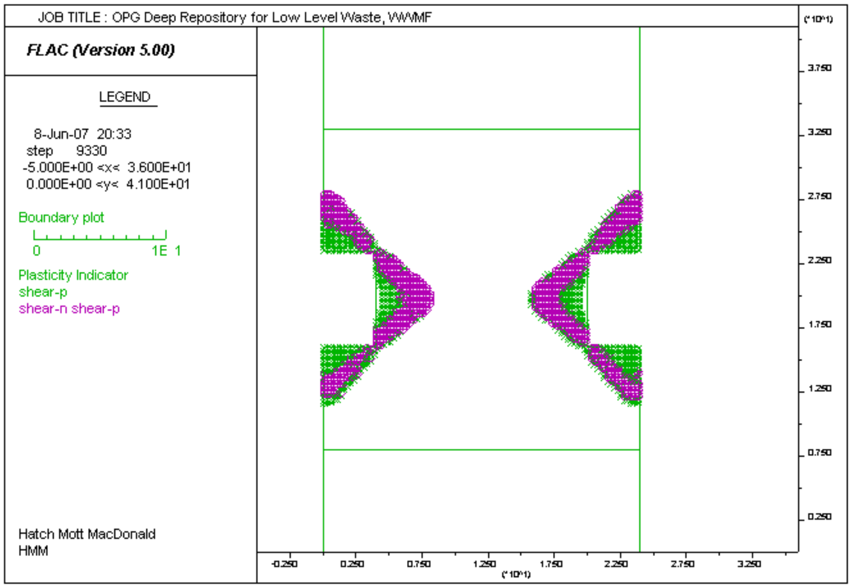
Vertical Stresses (MPa)



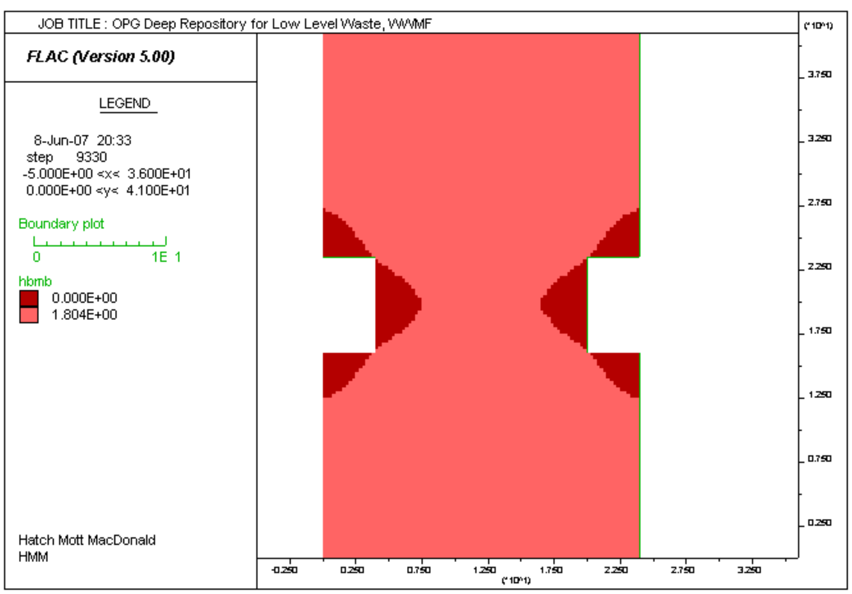
Horizontal Stresses (MPa)



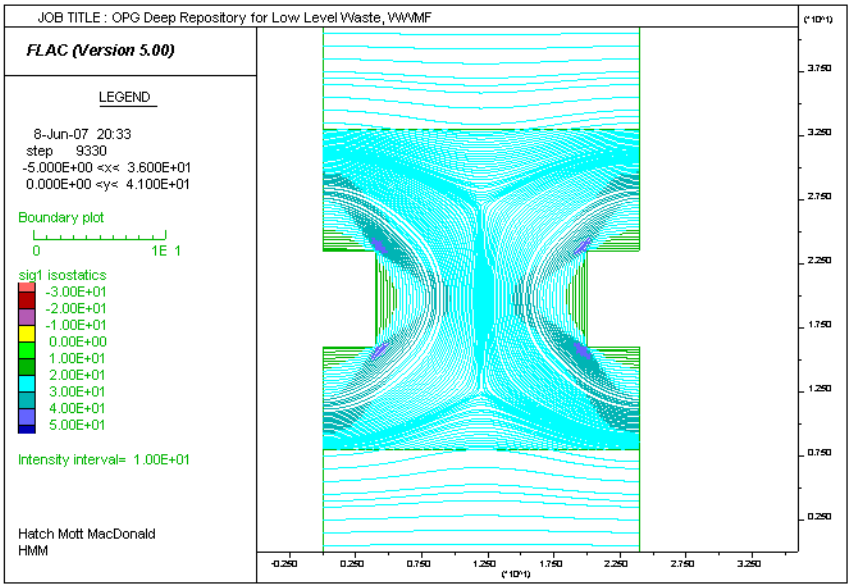
Plasticity Indicators



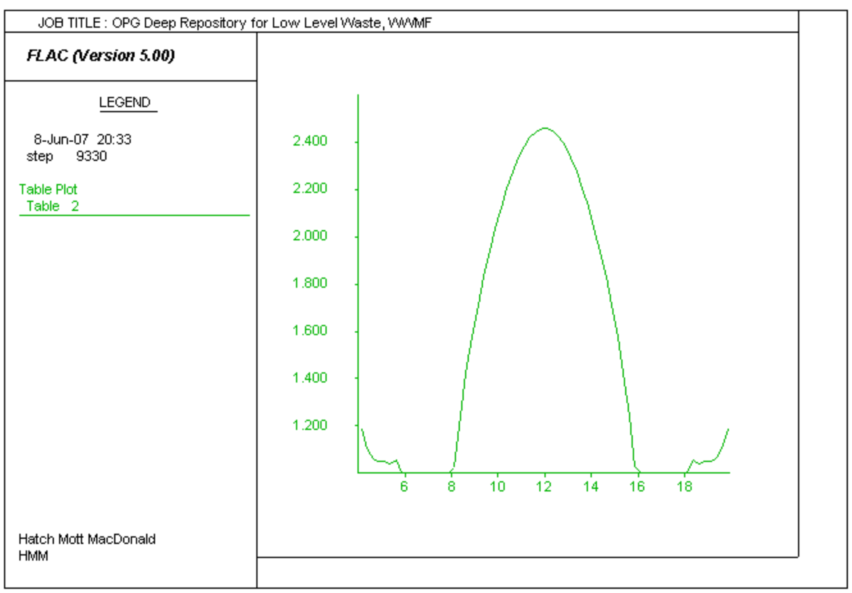
Failure Criteria (■ Brittle Failure, ■ Hoek-Brown Peak Strength, ■ Transition)



Maximum Principal Stress Trajectories (MPa)

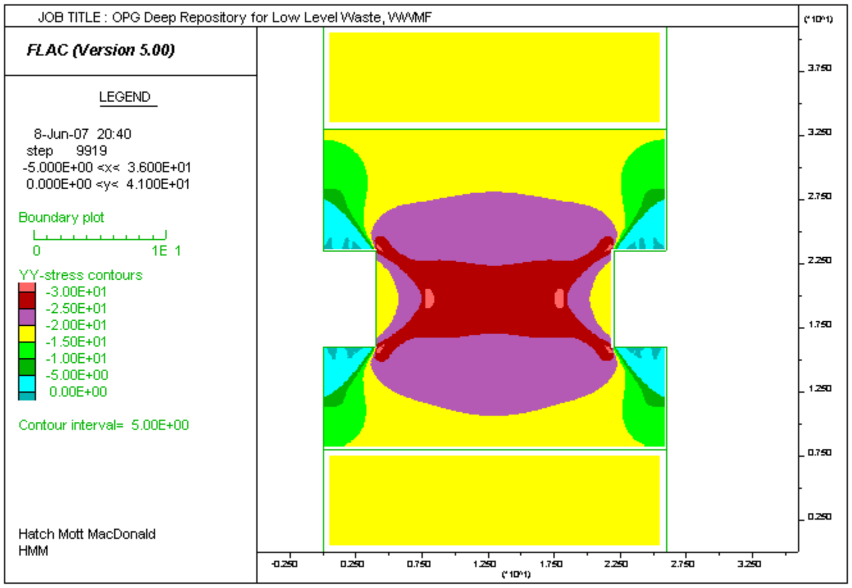


Factor Of Safety Across The Pillar

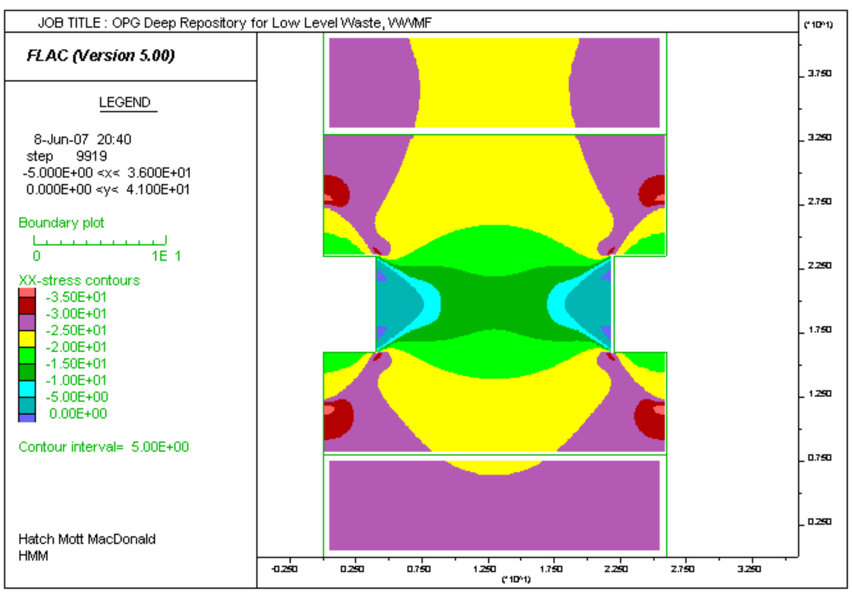


UCS = 60, GSI = 55, Pillar Width = 18.0m

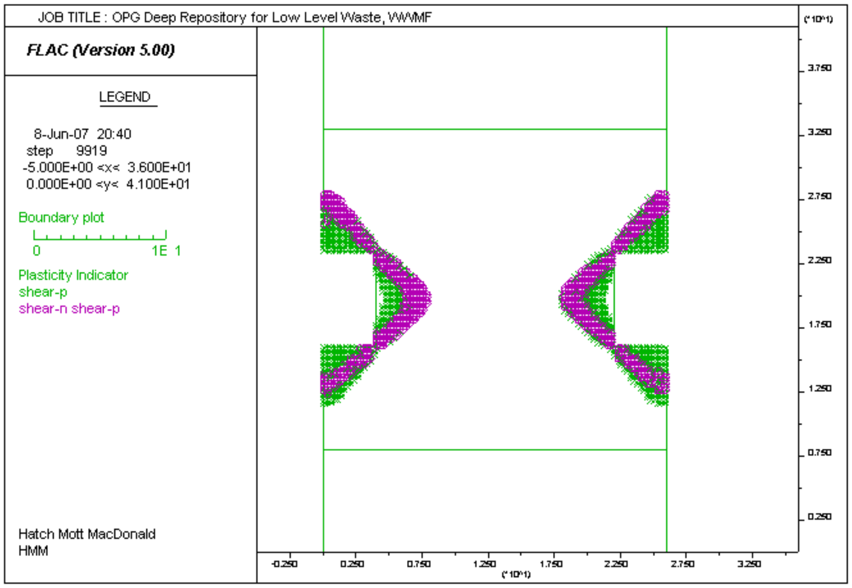
Vertical Stresses (MPa)



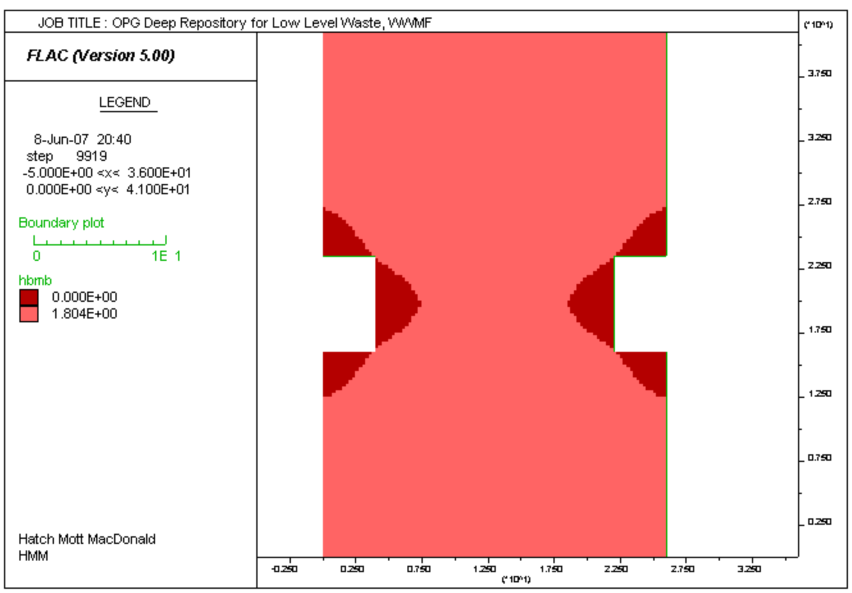
Horizontal Stresses (MPa)



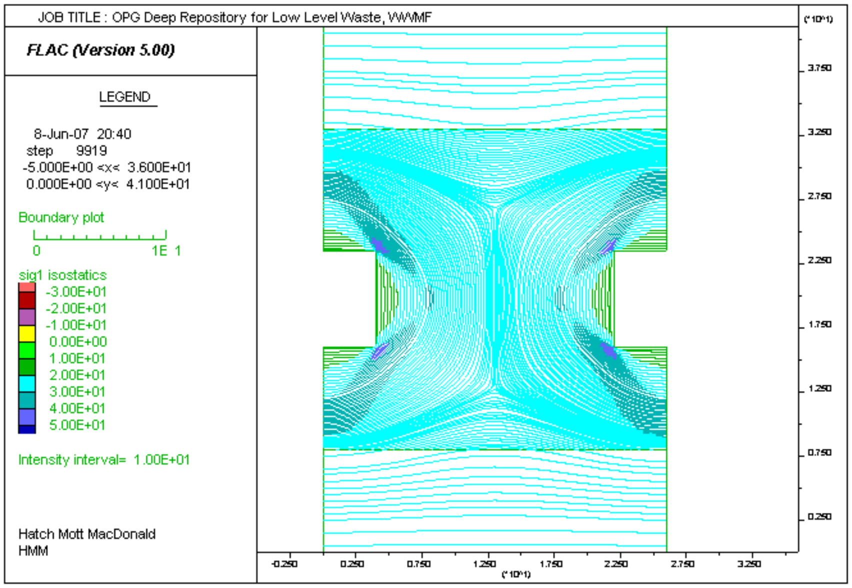
Plasticity Indicators



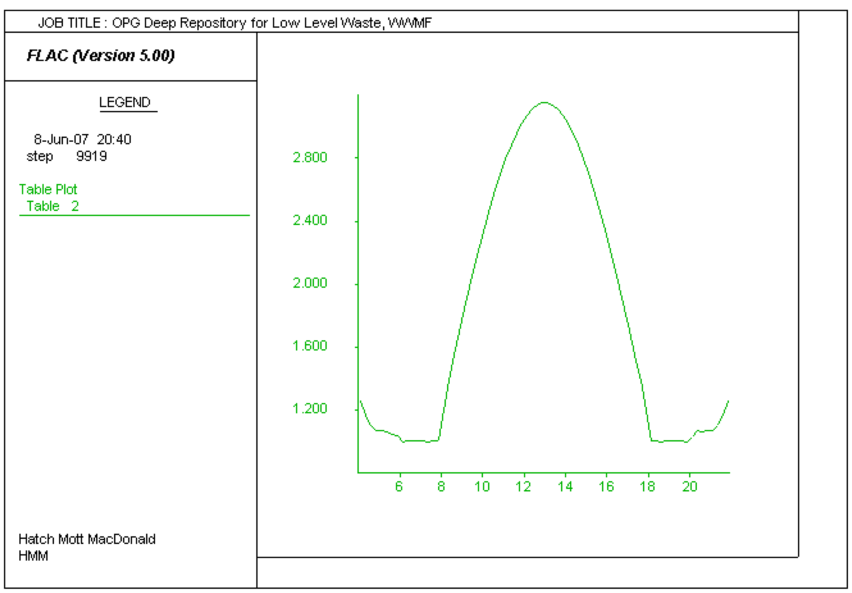
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

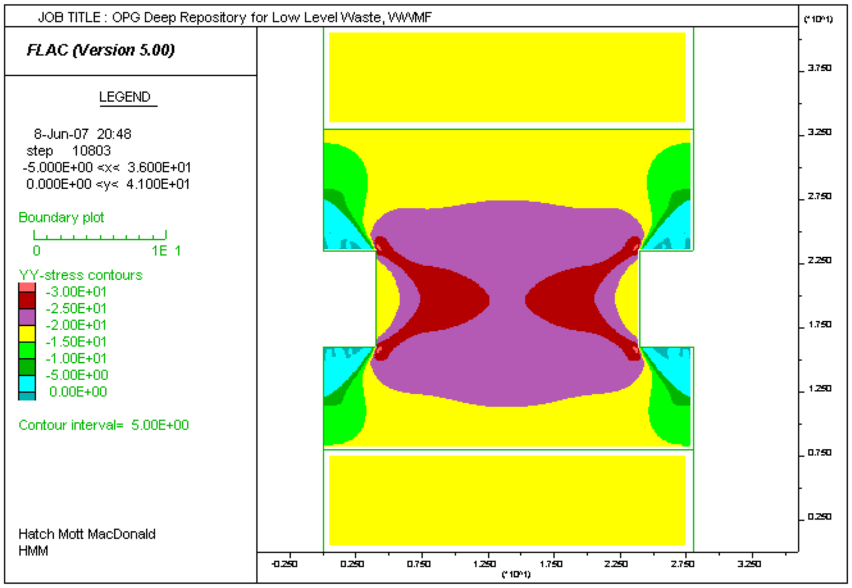


Factor Of Safety Across The Pillar

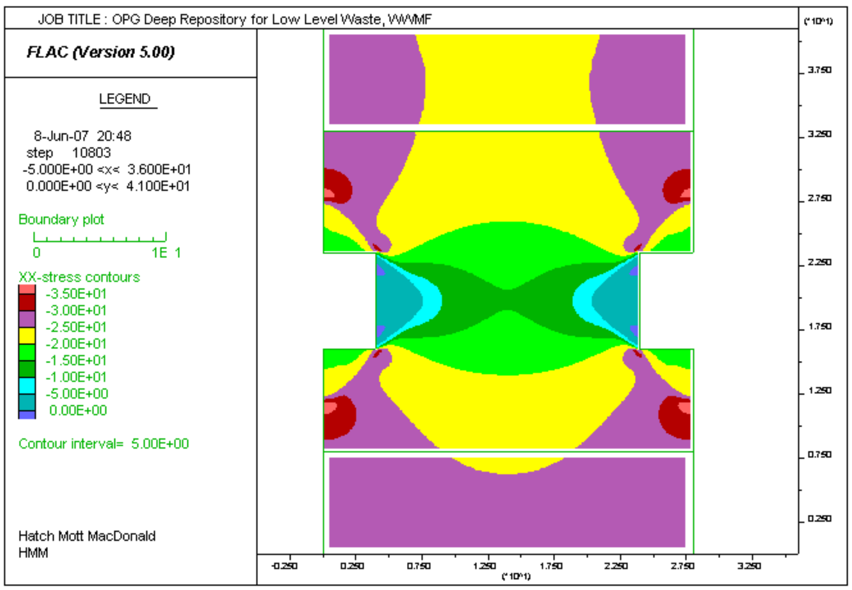


UCS = 60, GSI = 55, Pillar Width = 20.0m

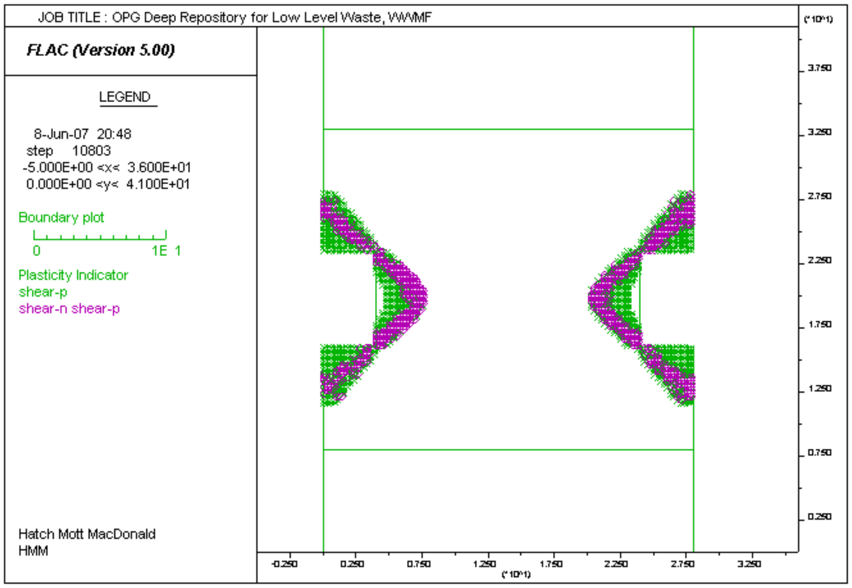
Vertical Stresses (MPa)



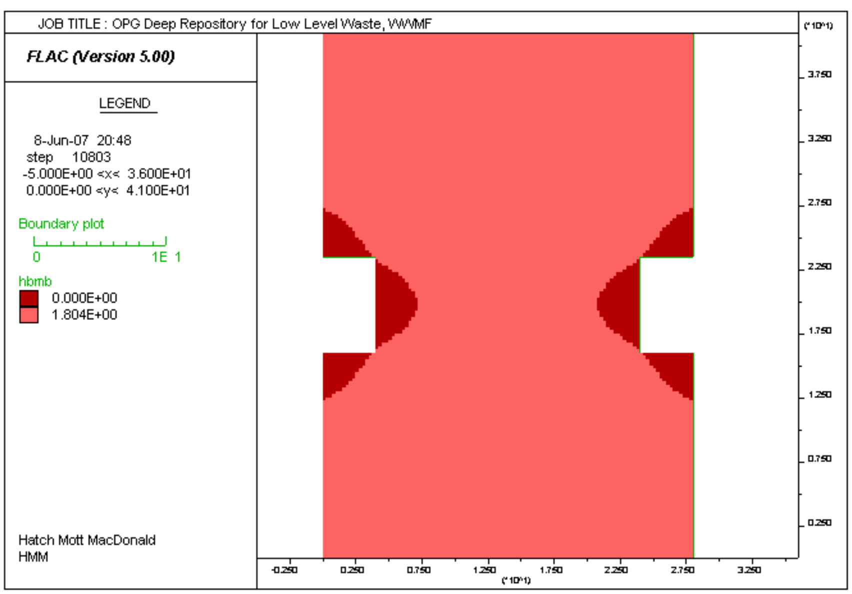
Horizontal Stresses (MPa)



Plasticity Indicators



Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



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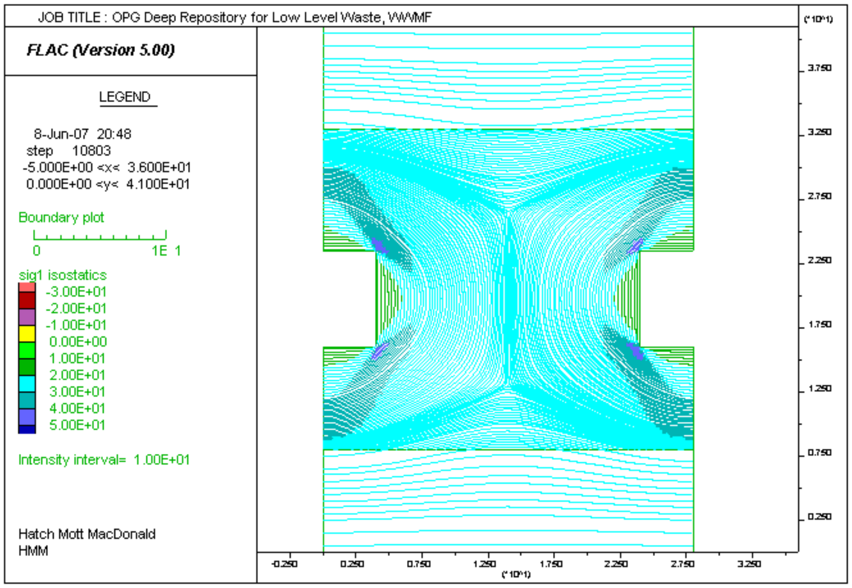
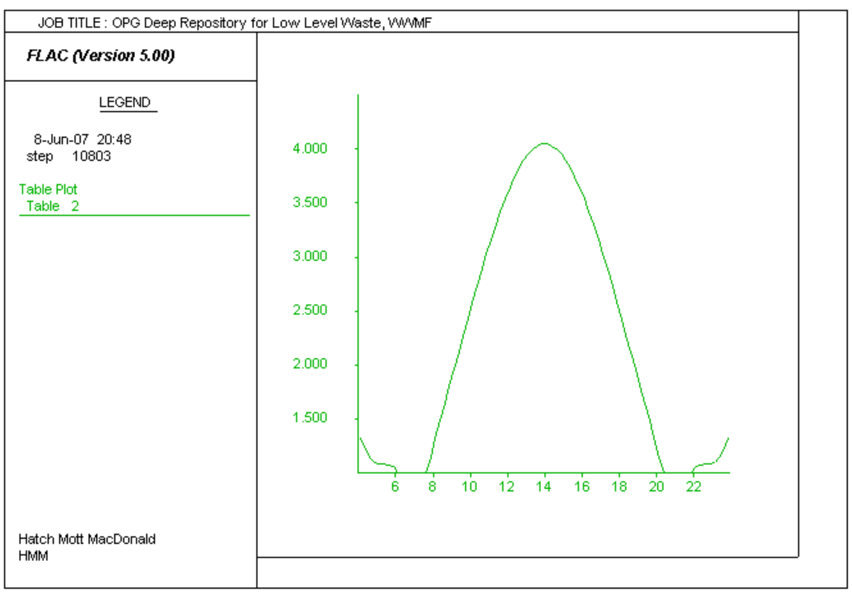
Maximum Principal Stress Trajectories (MPa)

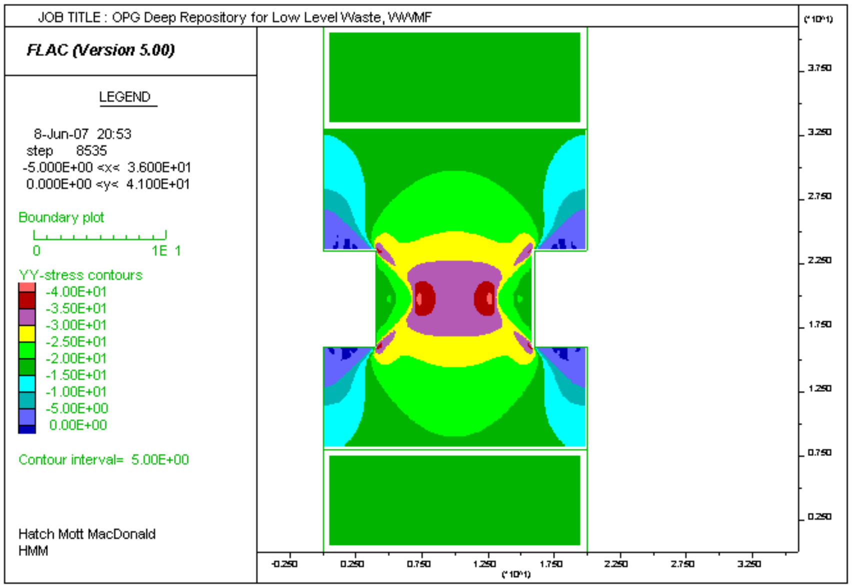


Factor Of Safety Across The Pillar

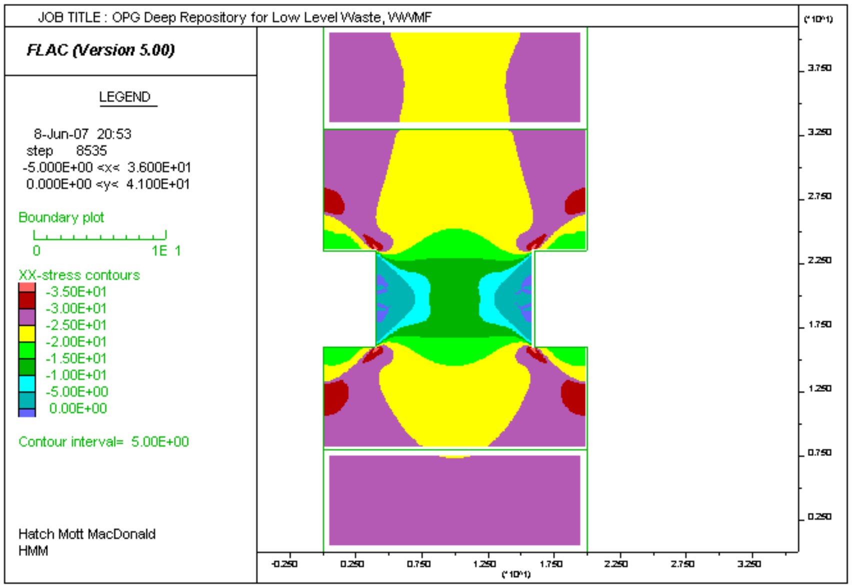


UCS = 60, GSI = 69, Pillar Width = 12.0m

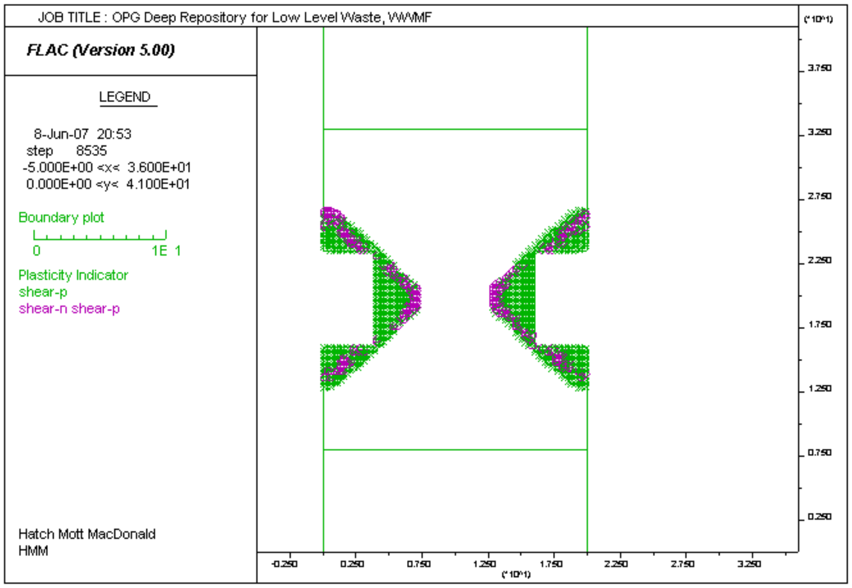
Vertical Stresses (MPa)



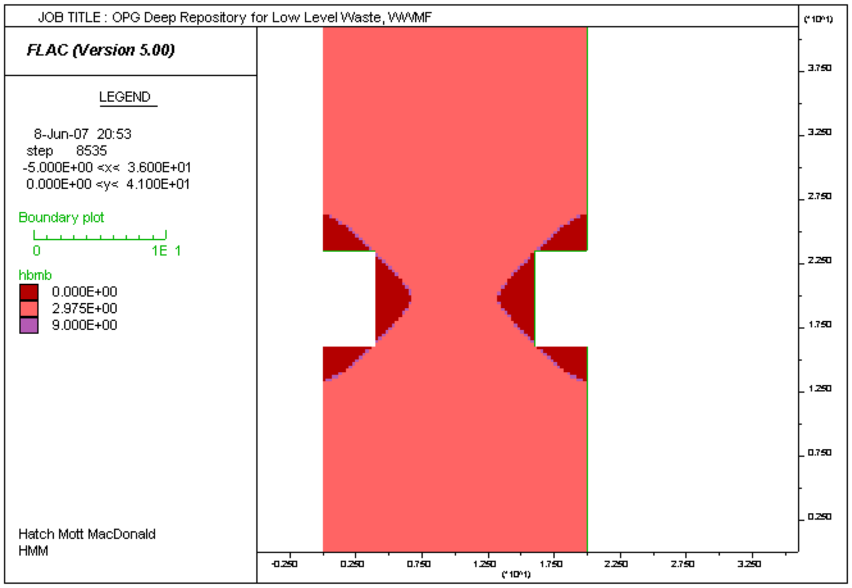
Horizontal Stresses (MPa)



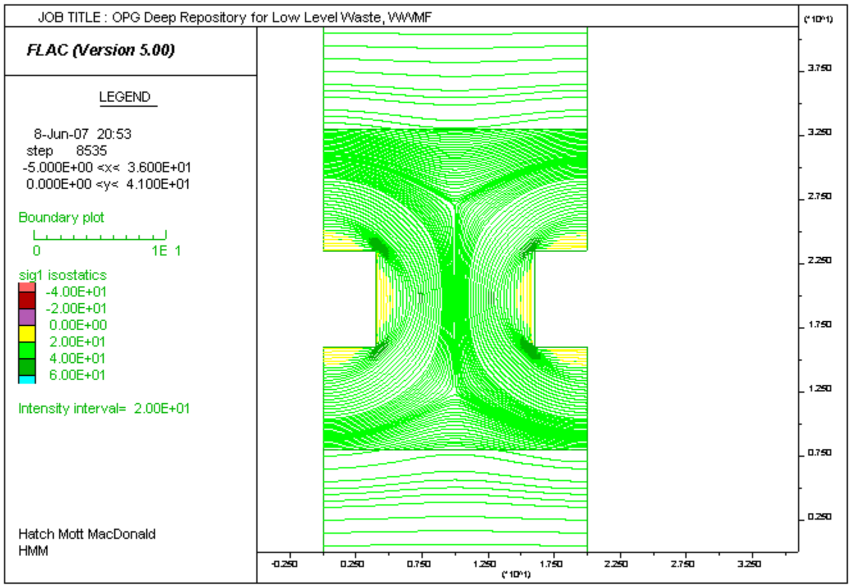
Plasticity Indicators



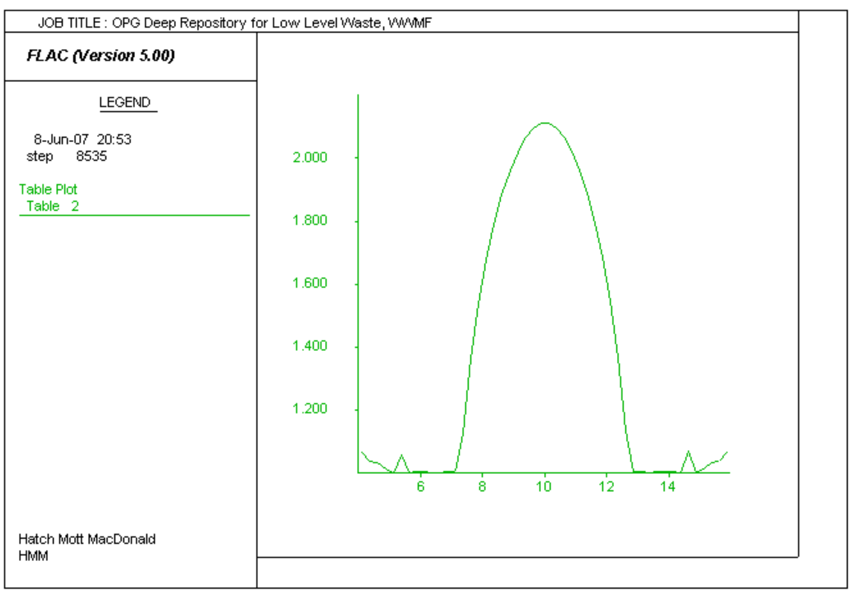
Failure Criteria (■ Brittle Failure, ■ Hoek-Brown Peak Strength, ■ Transition)



Maximum Principal Stress Trajectories (MPa)

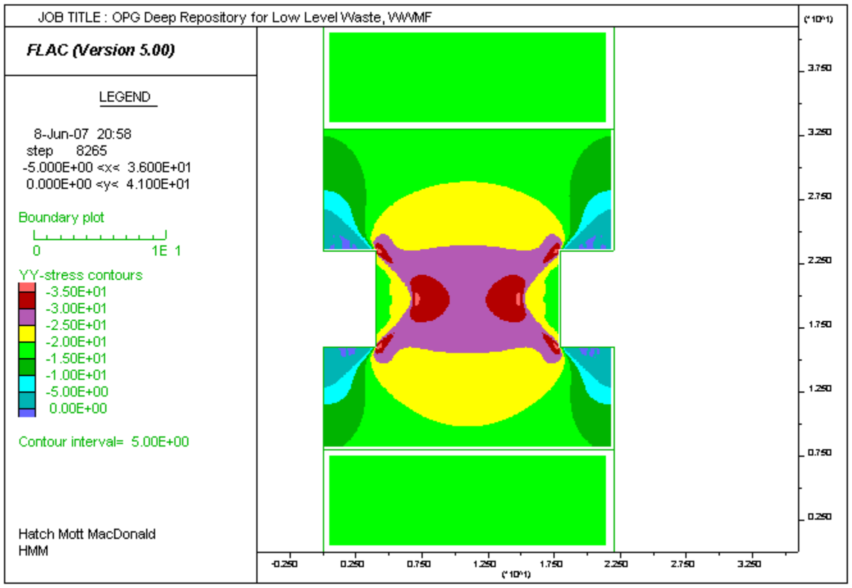


Factor Of Safety Across The Pillar

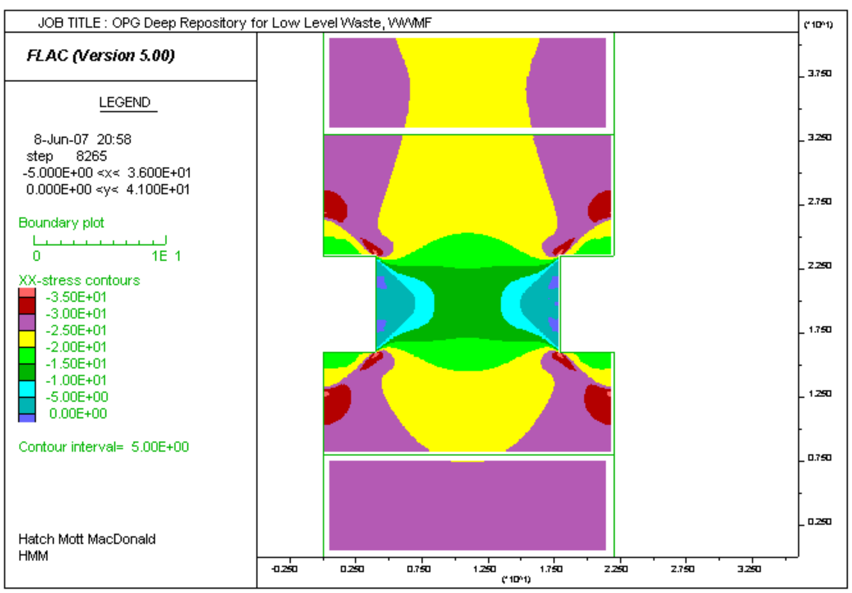


UCS = 60, GSI = 69, Pillar Width = 14.0m

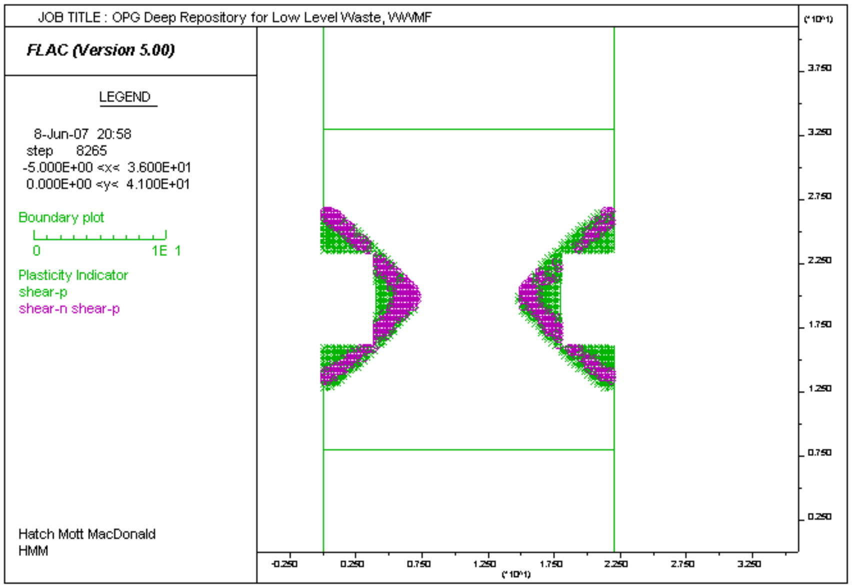
Vertical Stresses (MPa)



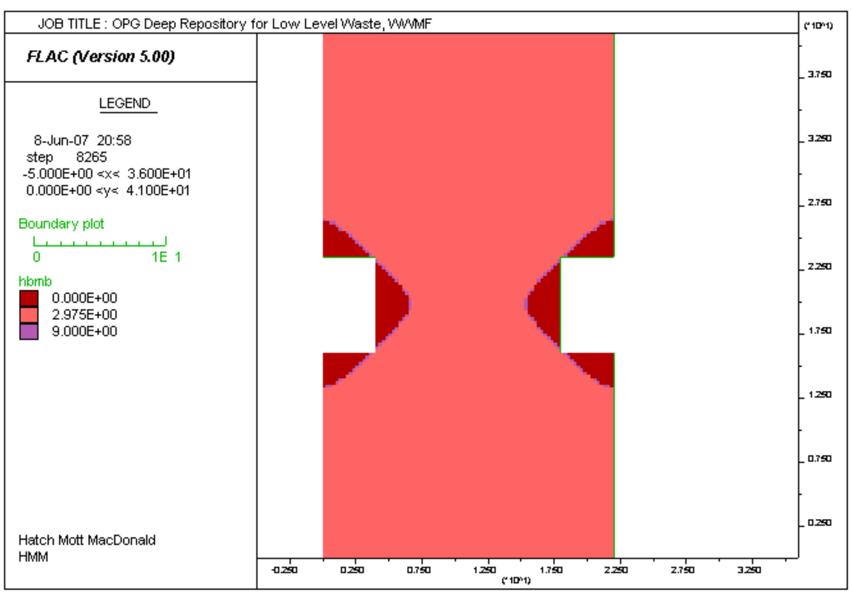
Horizontal Stresses (MPa)



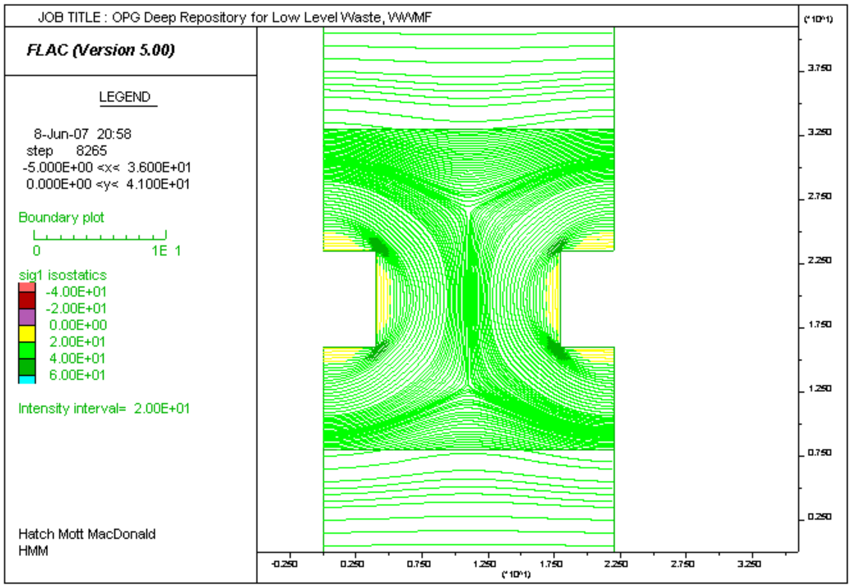
Plasticity Indicators



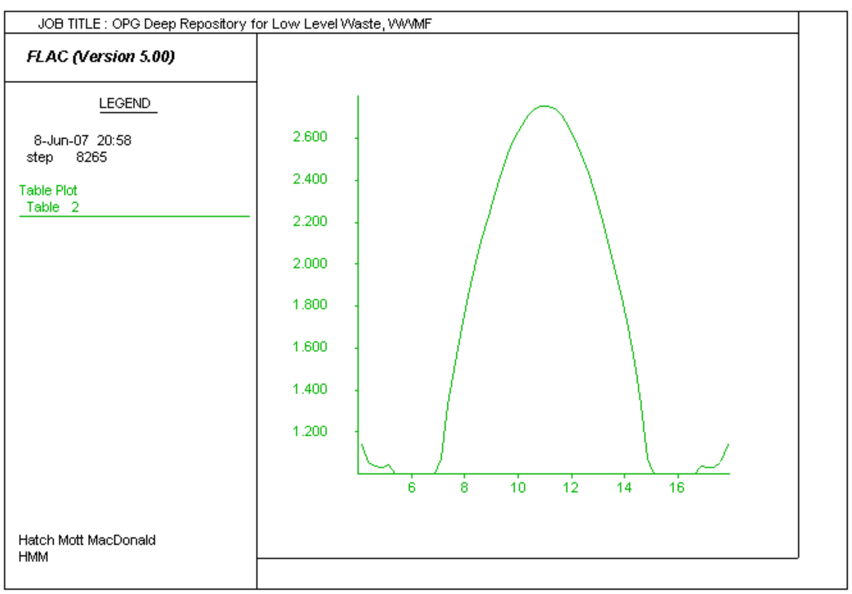
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

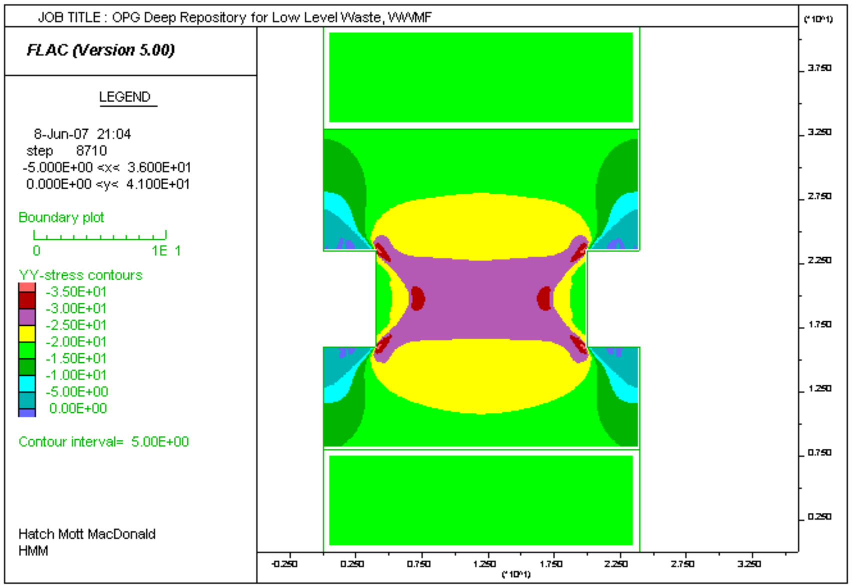


Factor Of Safety Across The Pillar

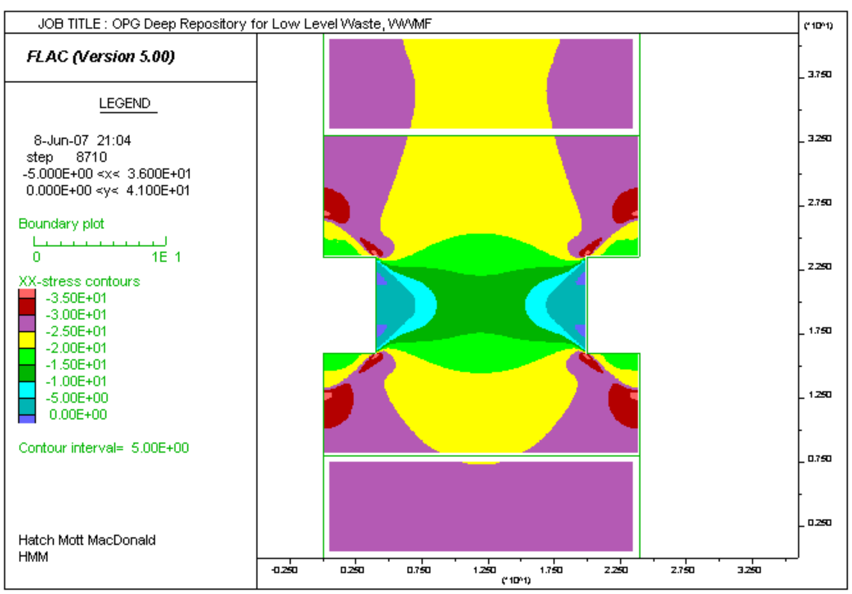


UCS = 60, GSI = 69, Pillar Width = 16.0m

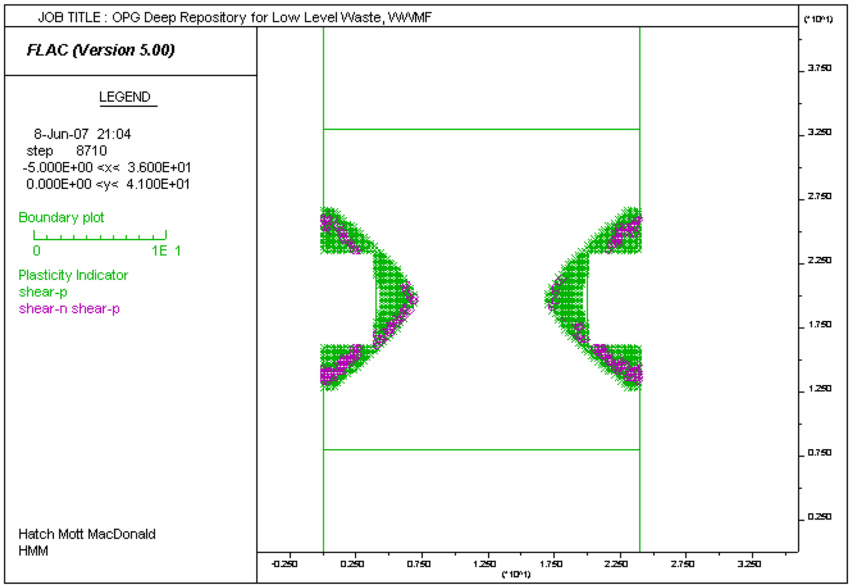
Vertical Stresses (MPa)



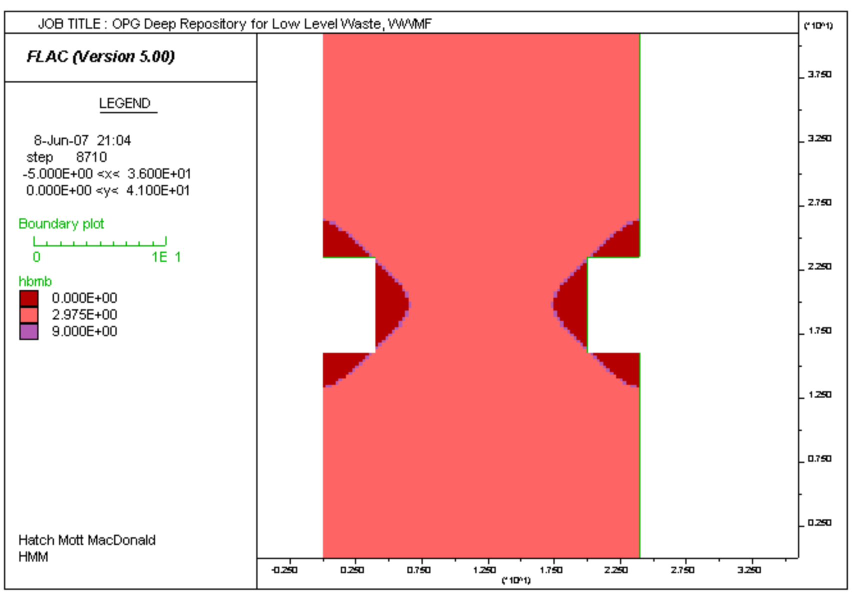
Horizontal Stresses (MPa)



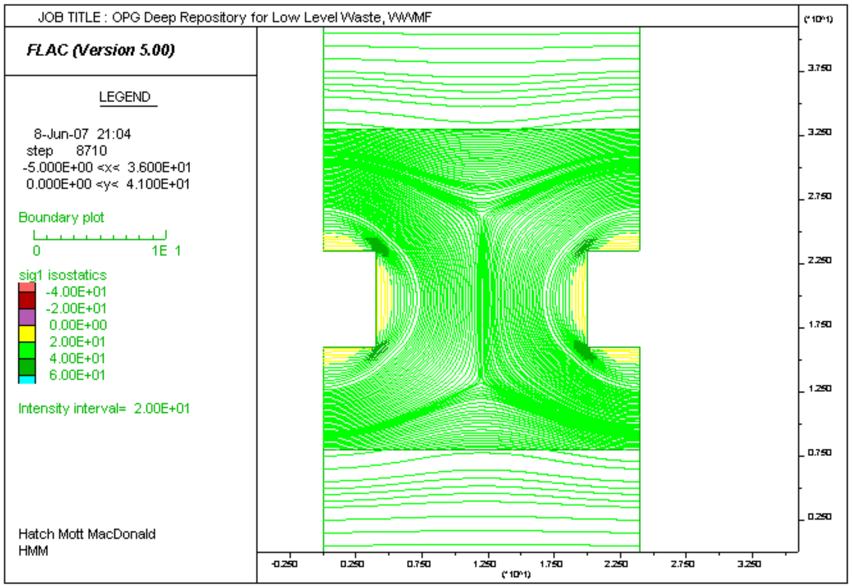
Plasticity Indicators



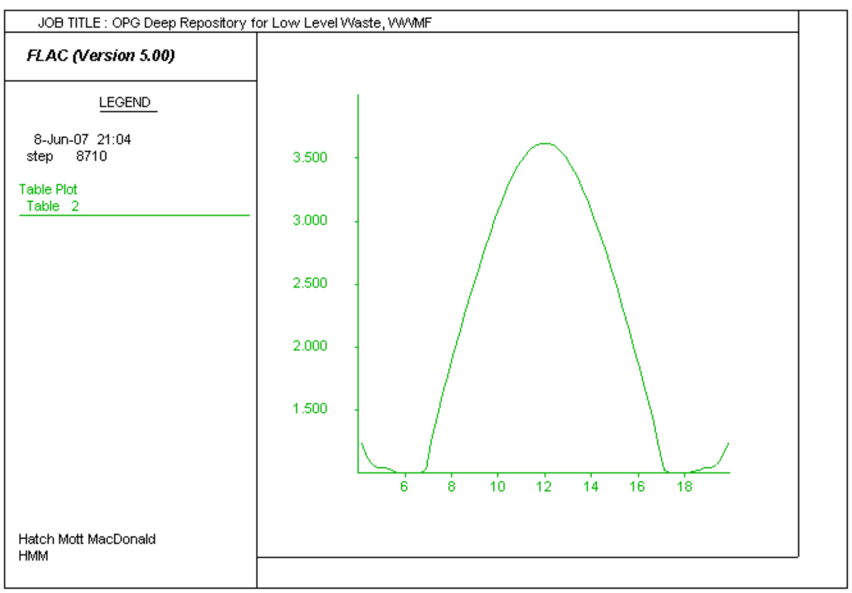
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

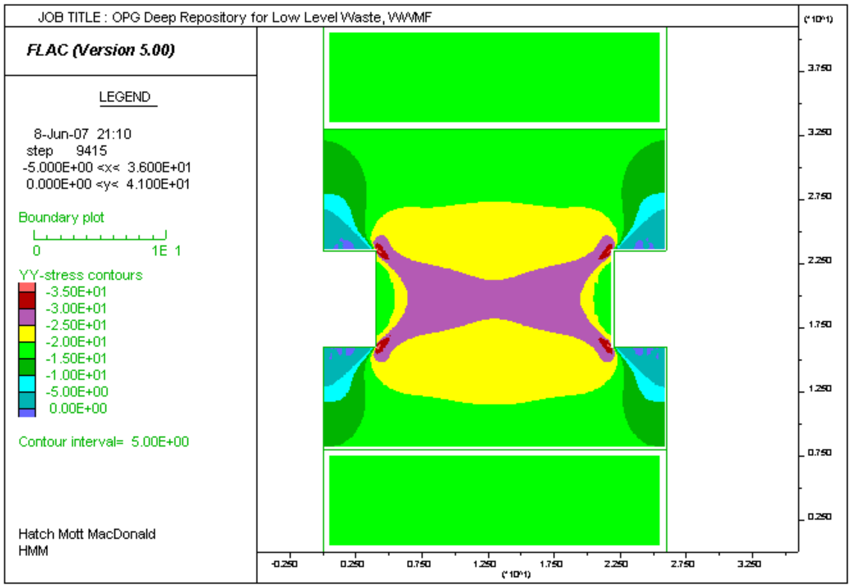


Factor Of Safety Across The Pillar

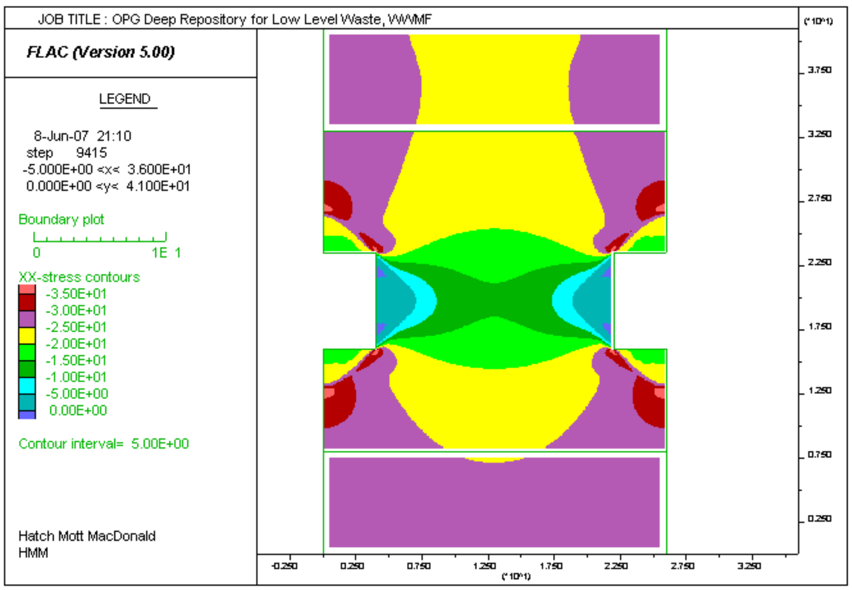


UCS = 60, GSI = 69, Pillar Width = 18.0m

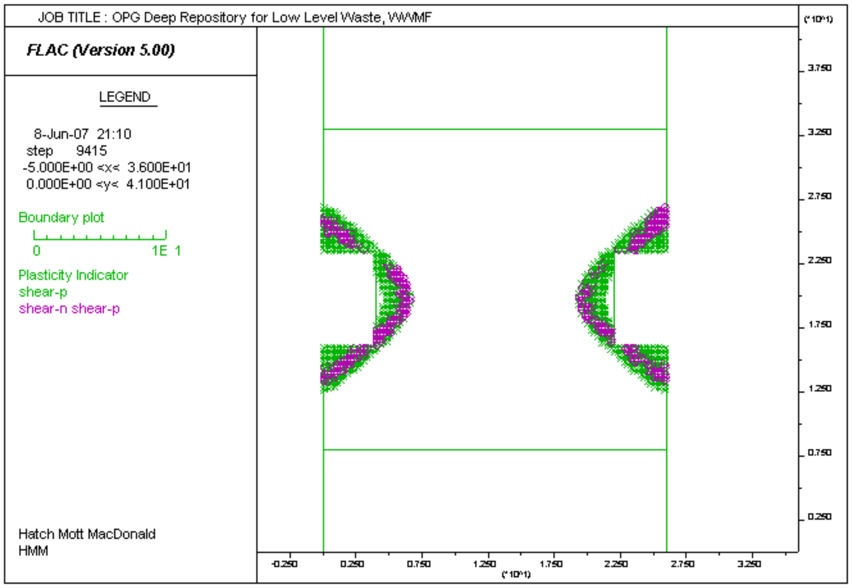
Vertical Stresses (MPa)



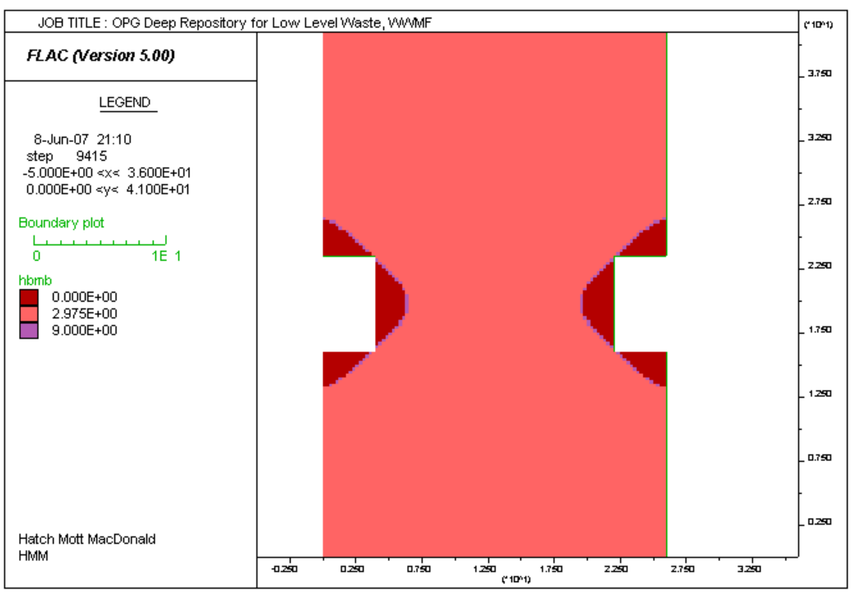
Horizontal Stresses (MPa)



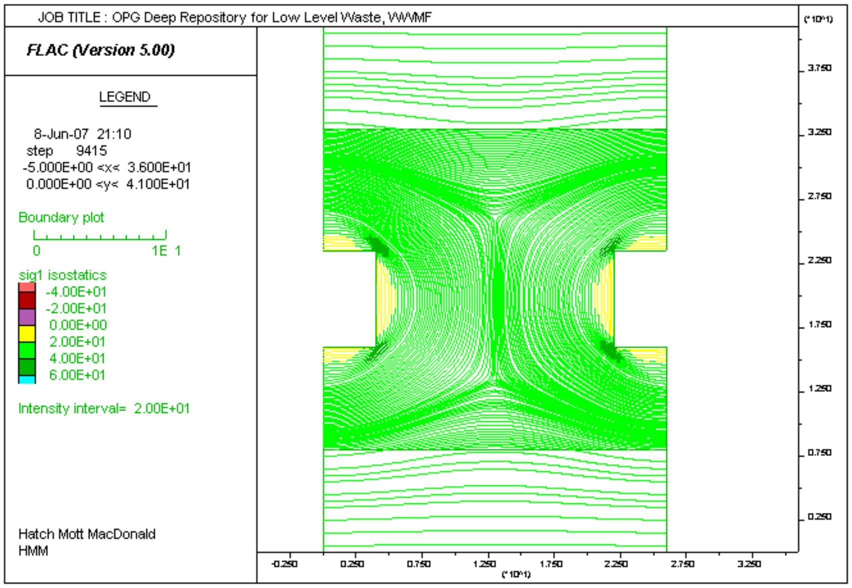
Plasticity Indicators



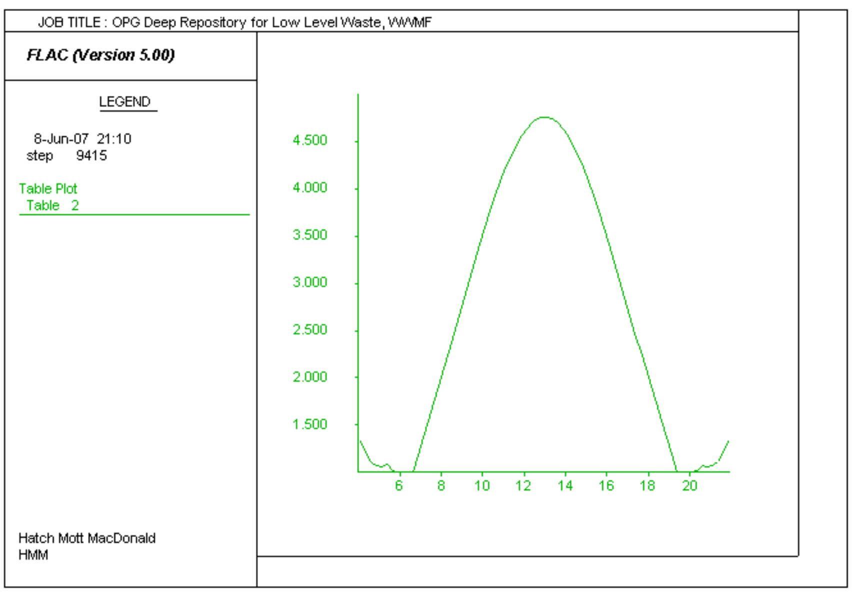
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

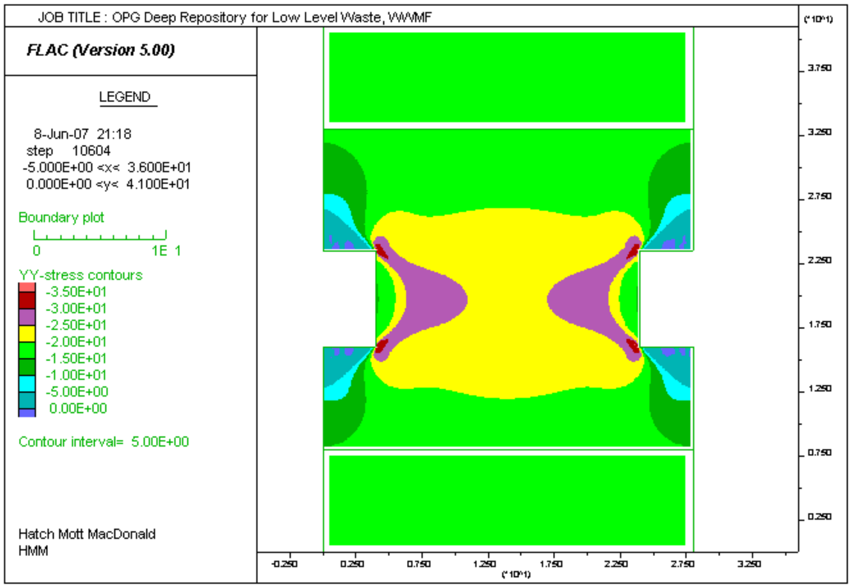


Factor Of Safety Across The Pillar

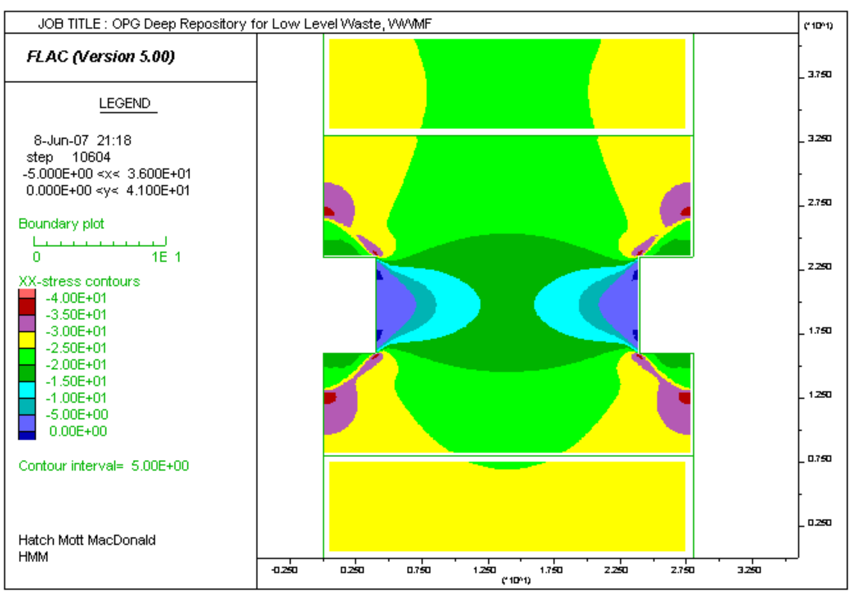


UCS = 60, GSI = 69, Pillar Width = 20.0m

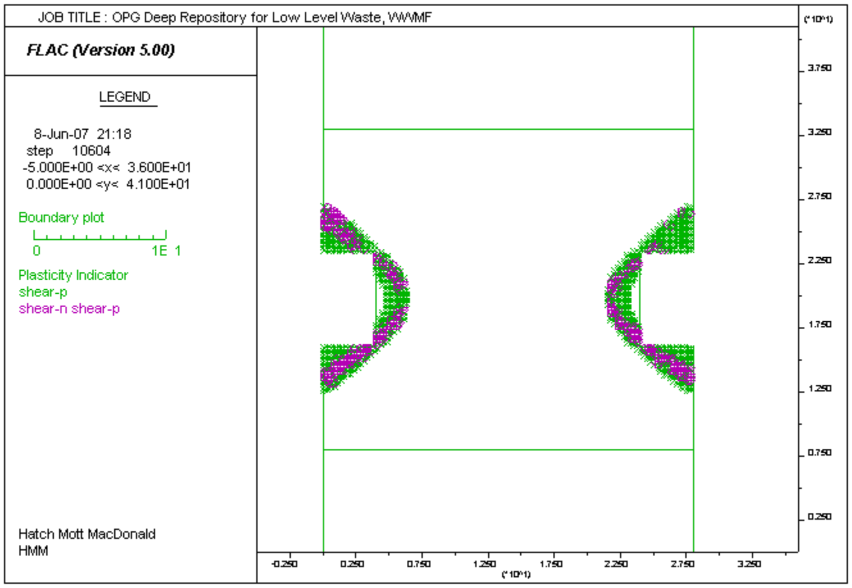
Vertical Stresses (MPa)



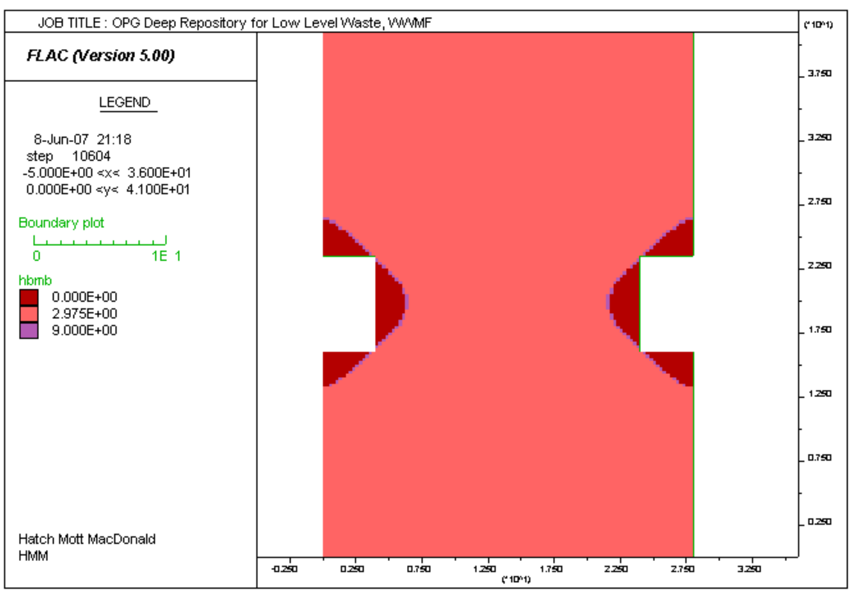
Horizontal Stresses (MPa)



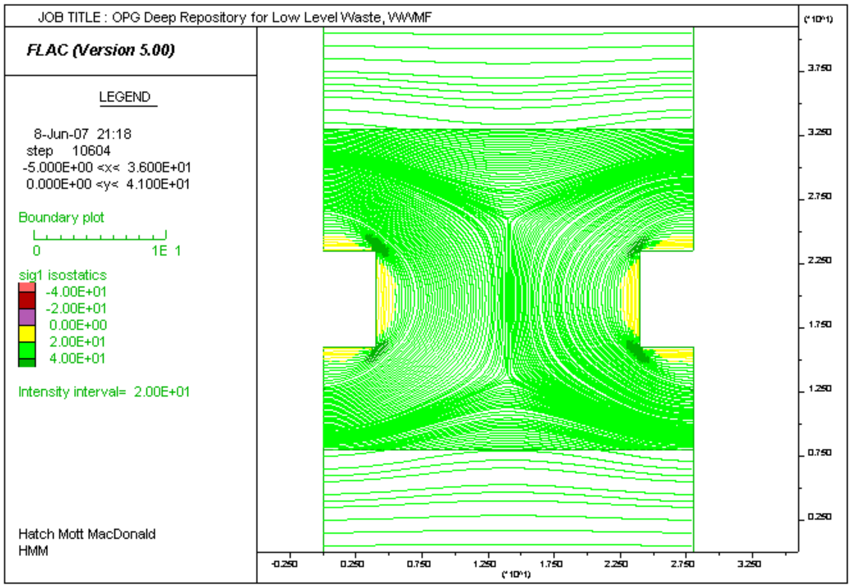
Plasticity Indicators



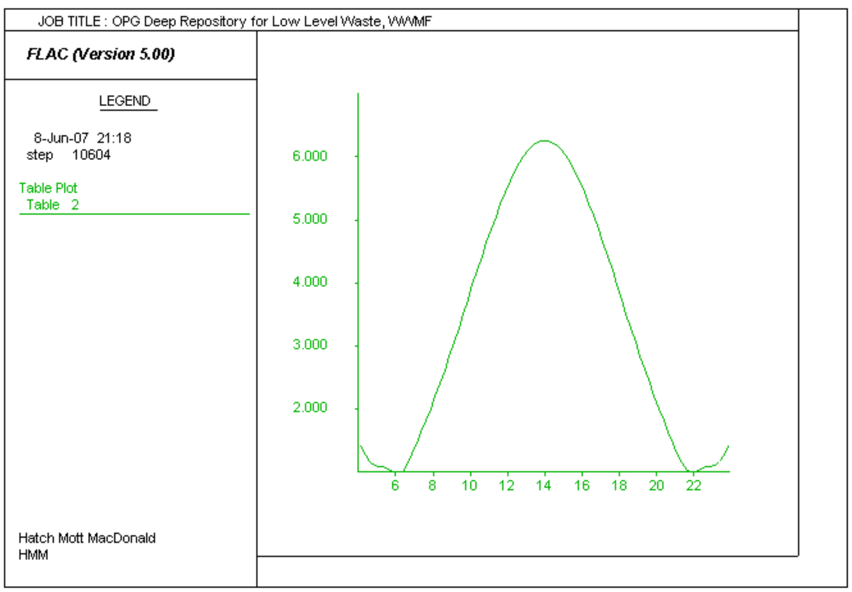
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)



Factor Of Safety Across The Pillar



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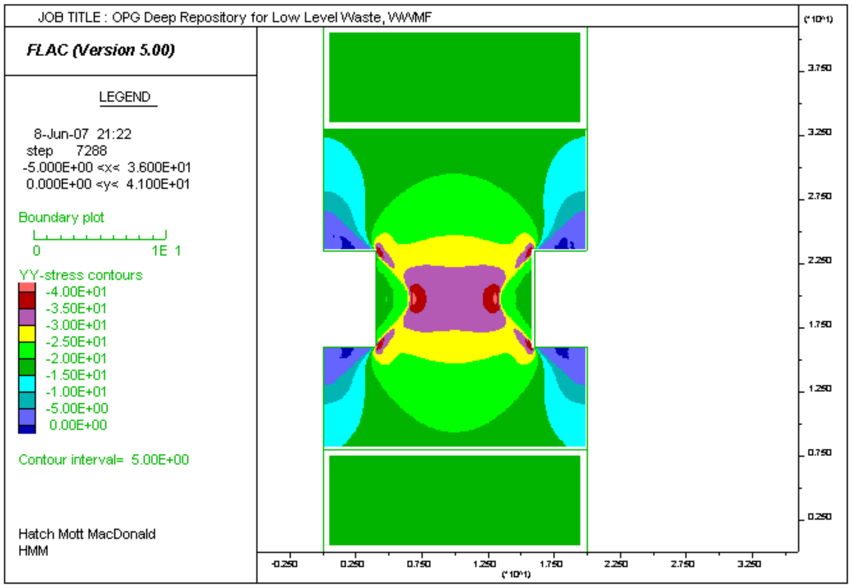
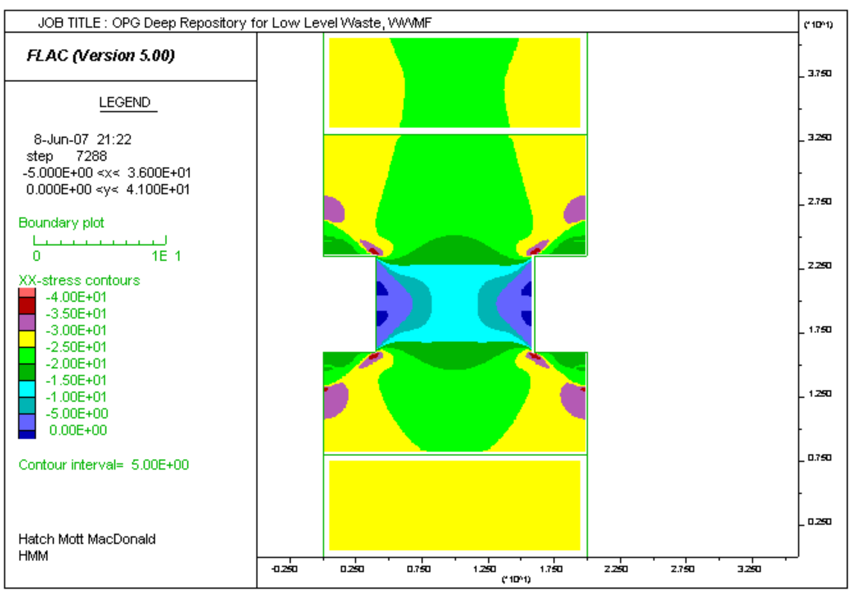
UCS = 60, GSI = 80, Pillar Width = 12.0m

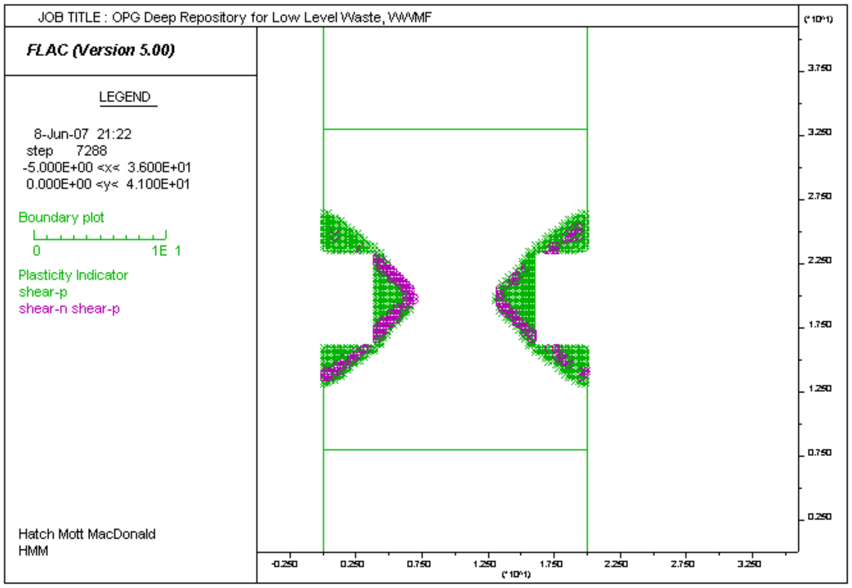
Vertical Stresses (MPa)



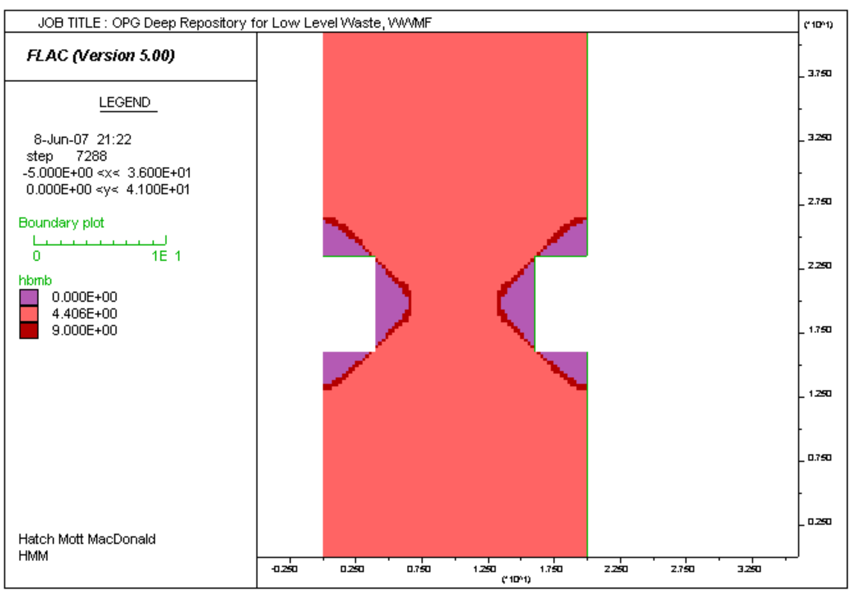
Horizontal Stresses (MPa)



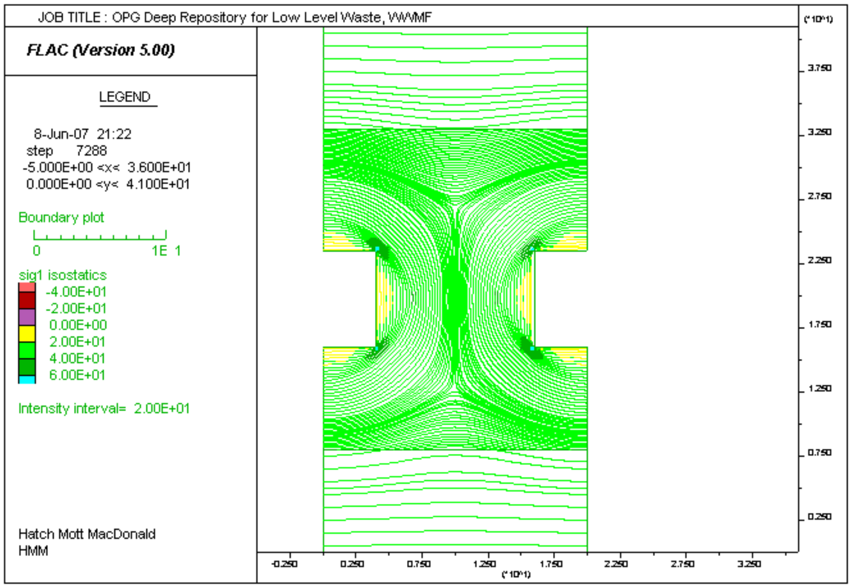
Plasticity Indicators



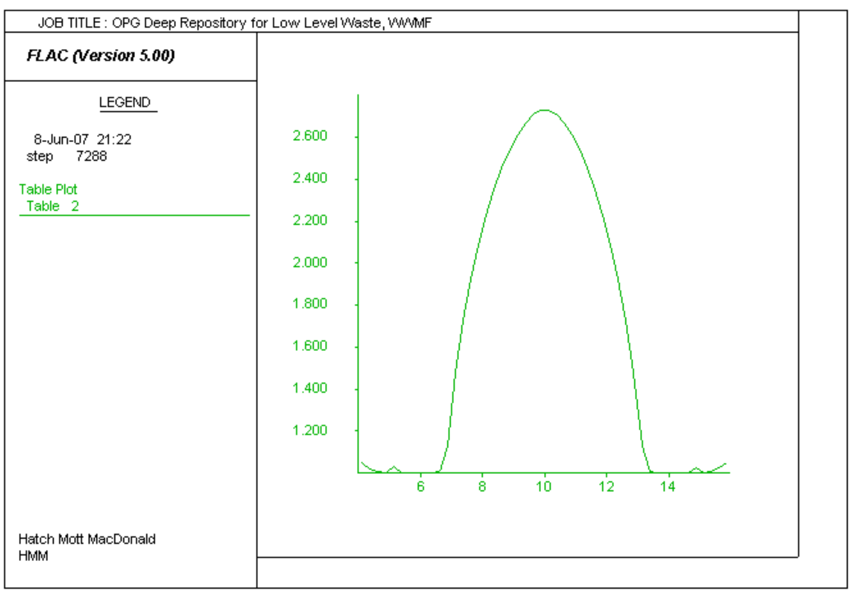
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

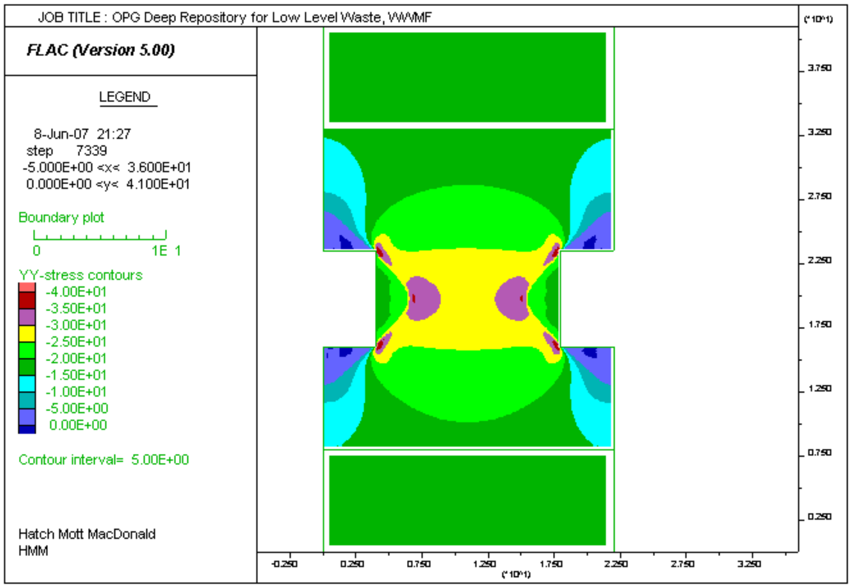


Factor Of Safety Across The Pillar

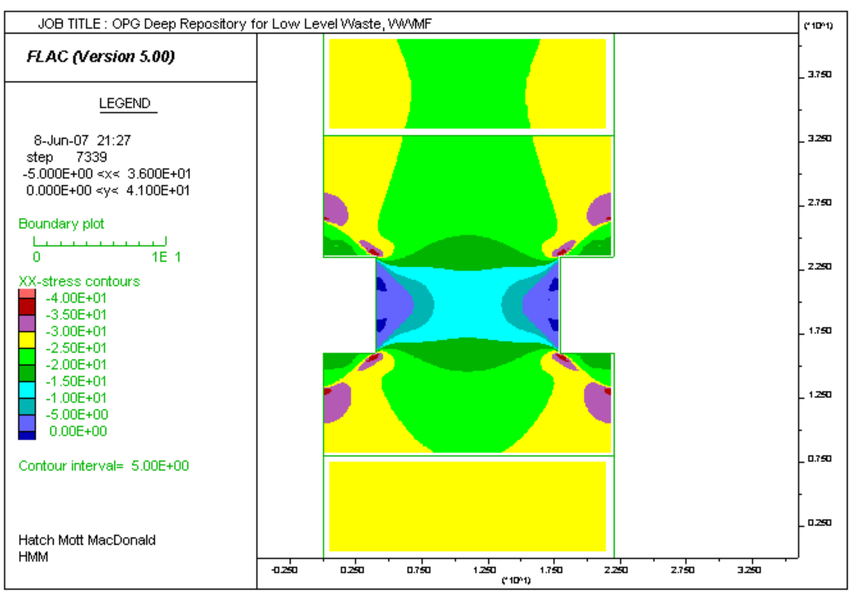


UCS = 60, GSI = 80, Pillar Width = 14.0m

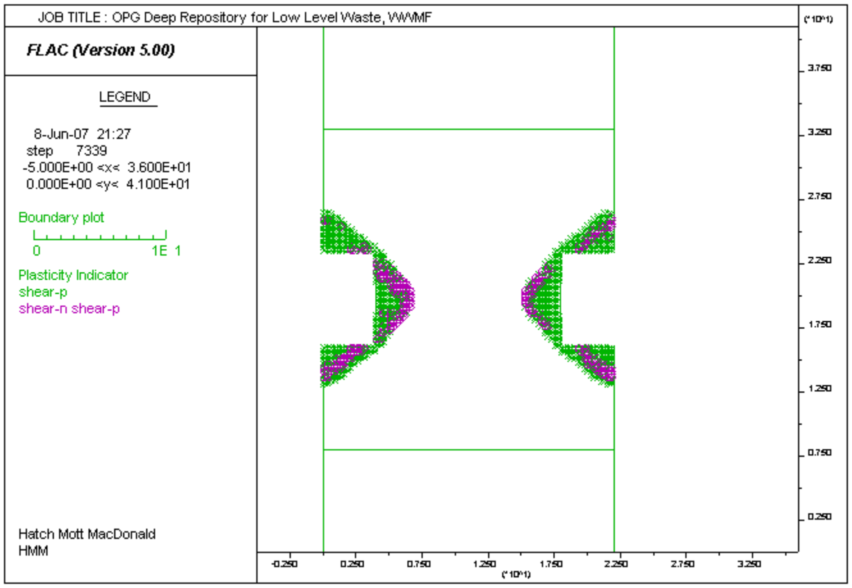
Vertical Stresses (MPa)



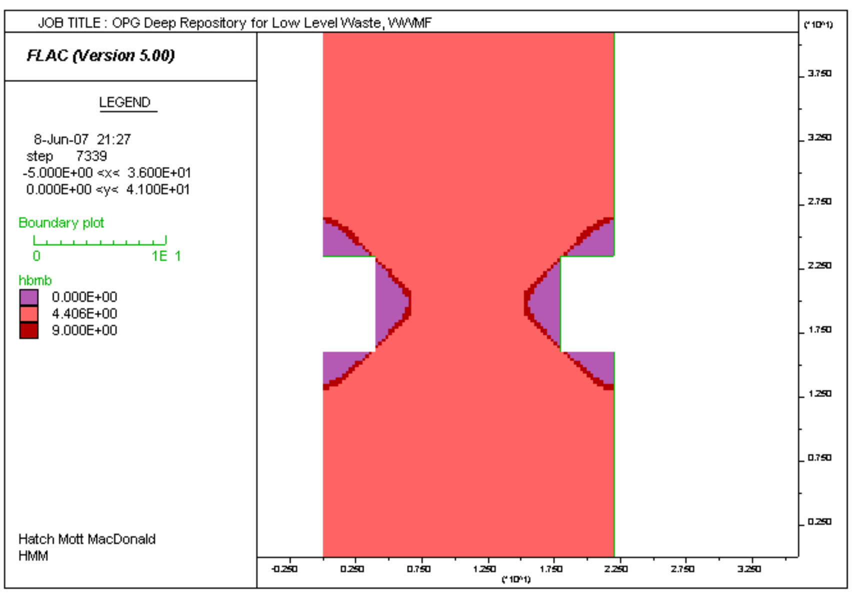
Horizontal Stresses (MPa)



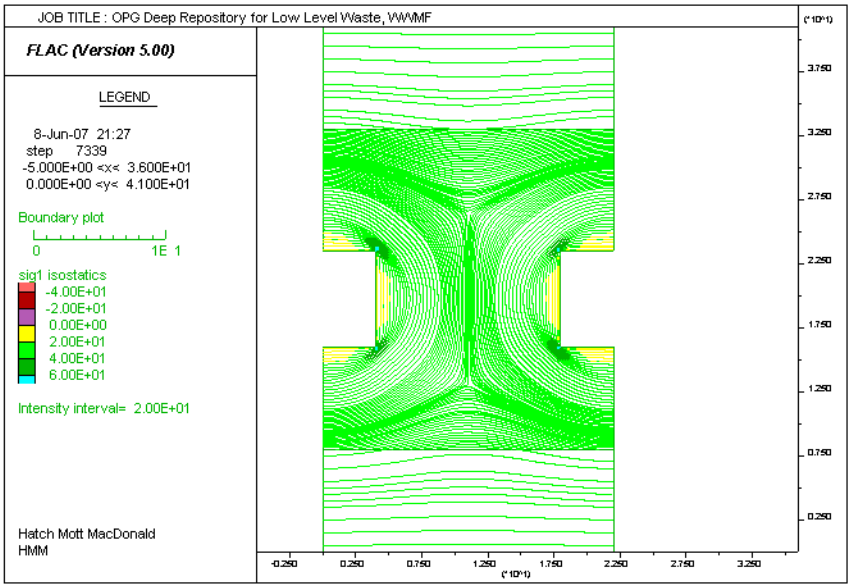
Plasticity Indicators



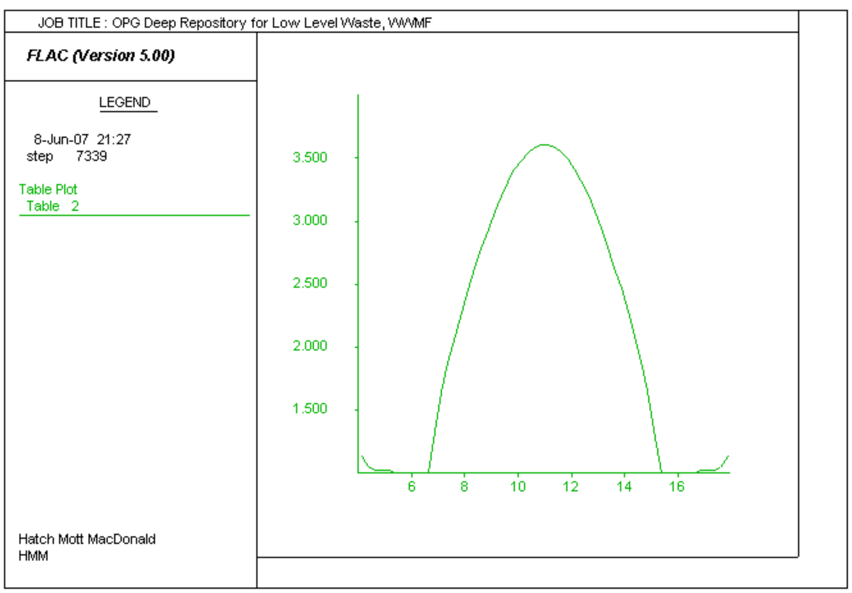
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

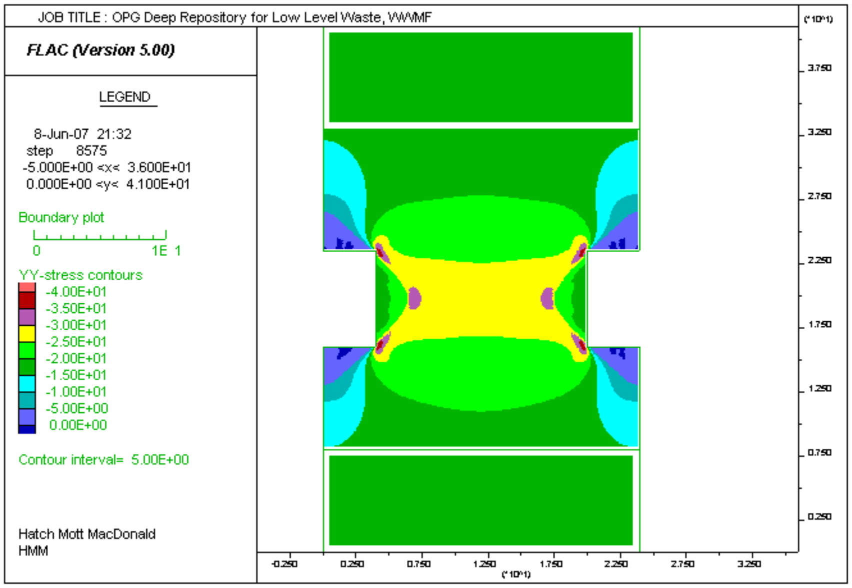


Factor Of Safety Across The Pillar

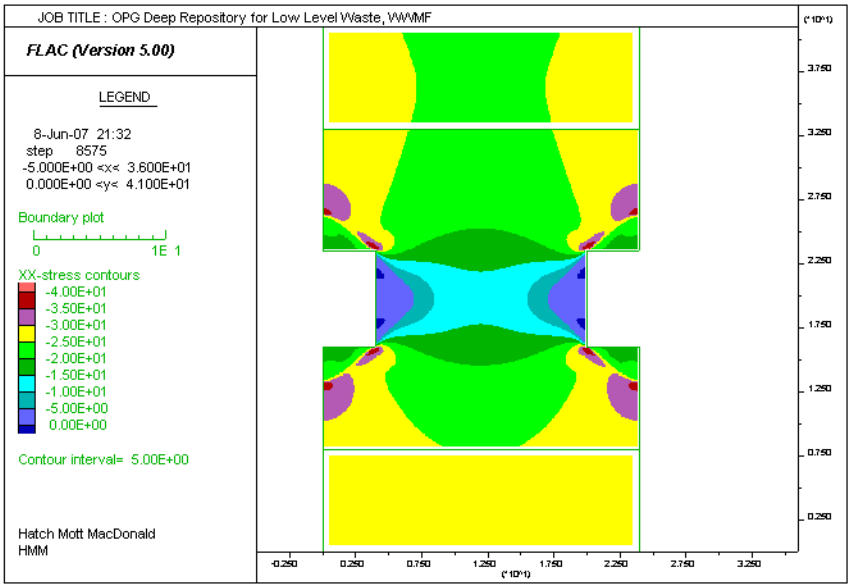


UCS = 60, GSI = 80, Pillar Width = 16.0m

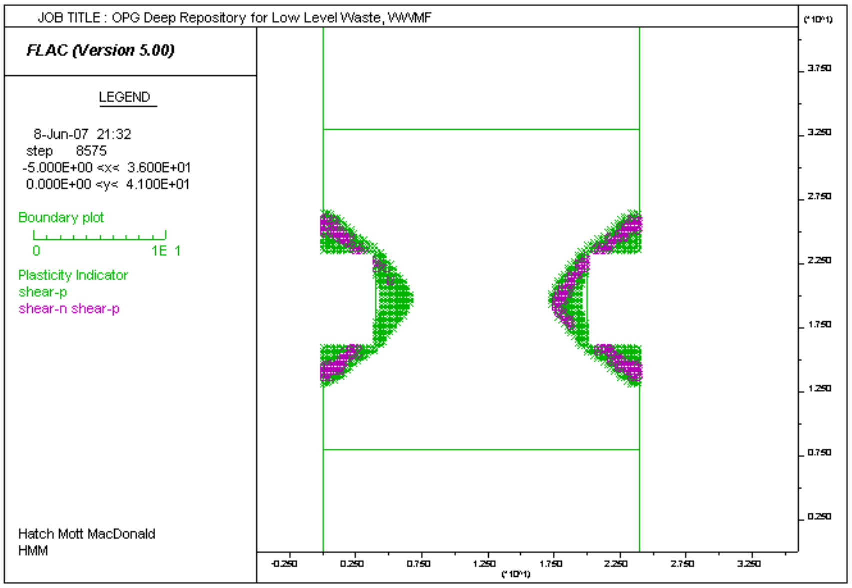
Vertical Stresses (MPa)



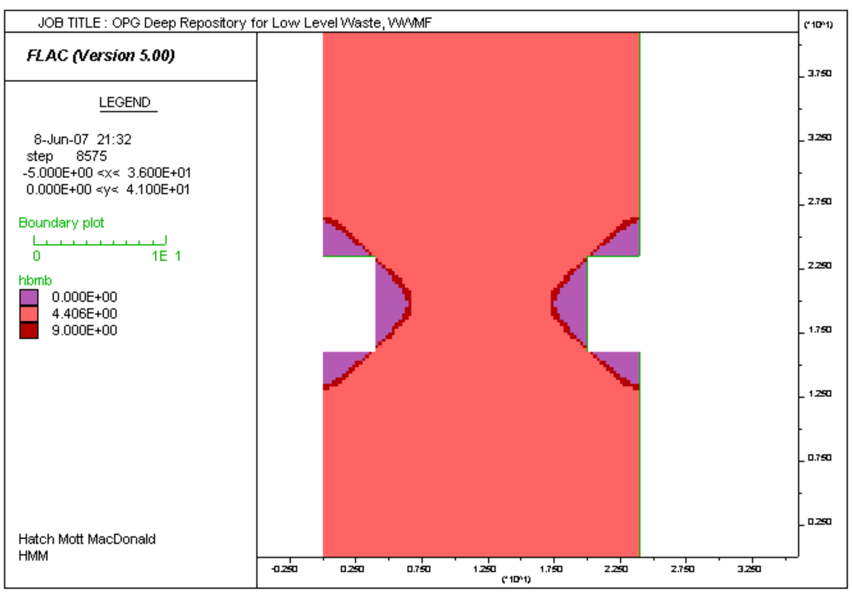
Horizontal Stresses (MPa)



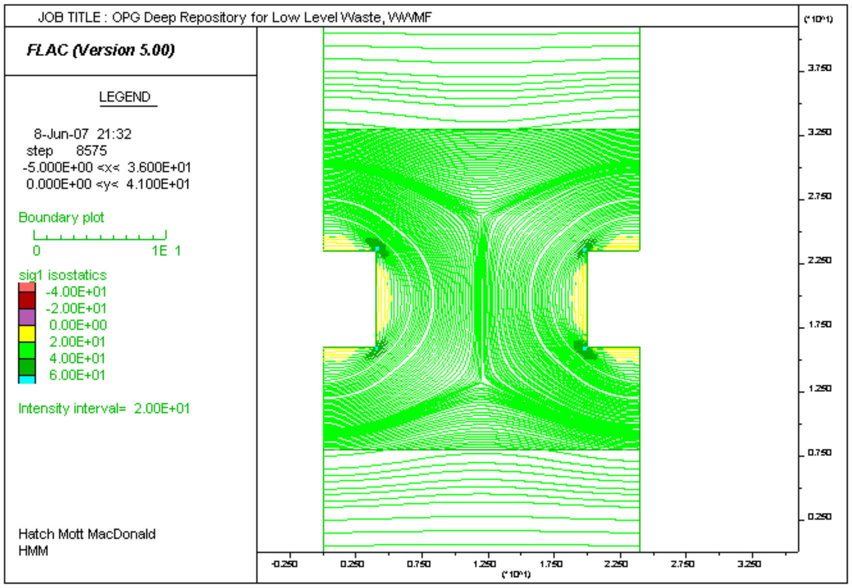
Plasticity Indicators



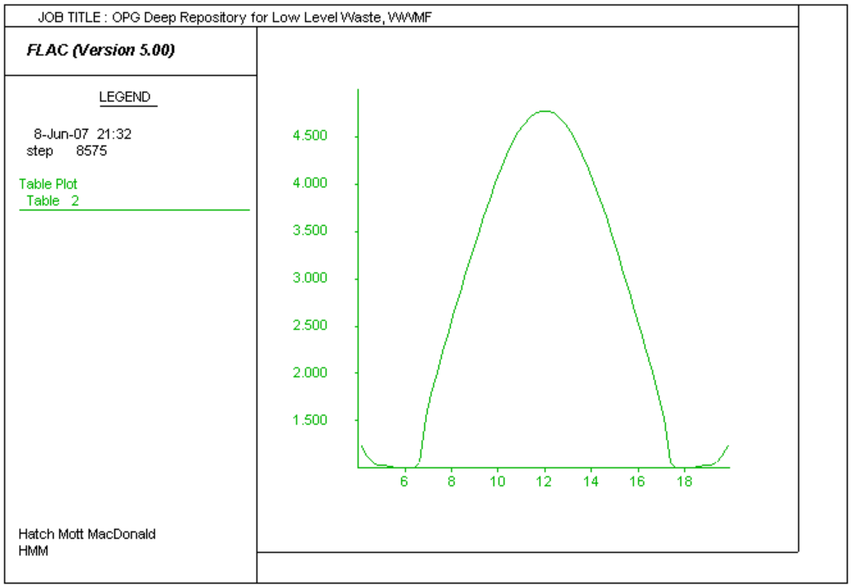
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

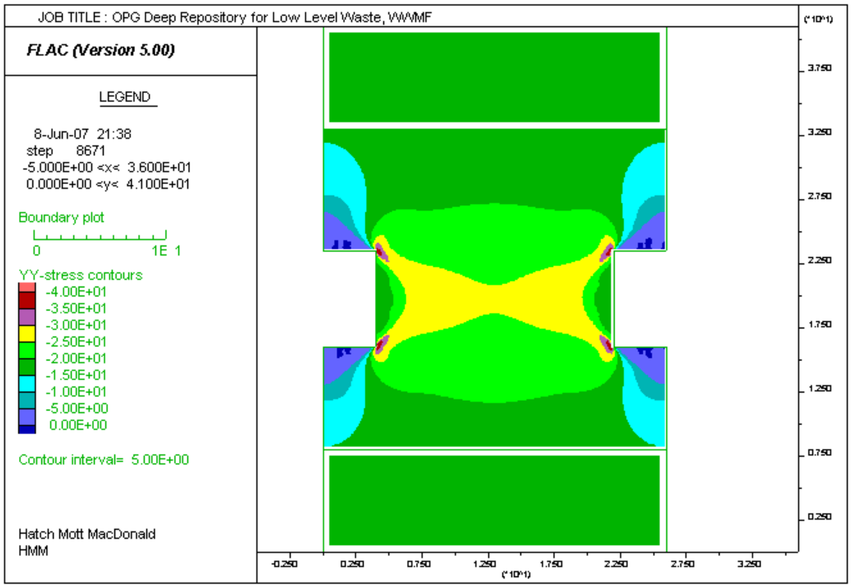


Factor Of Safety Across The Pillar

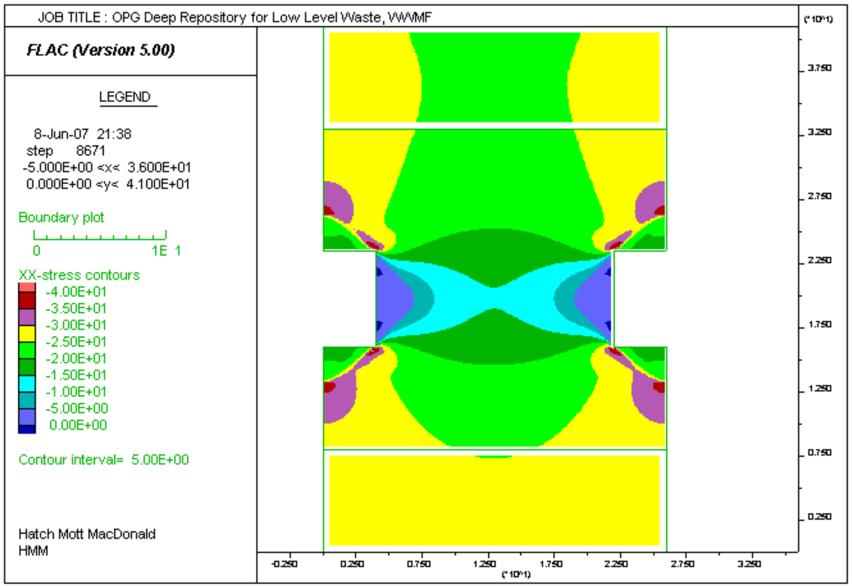


UCS = 60, GSI = 80, Pillar Width = 18.0m

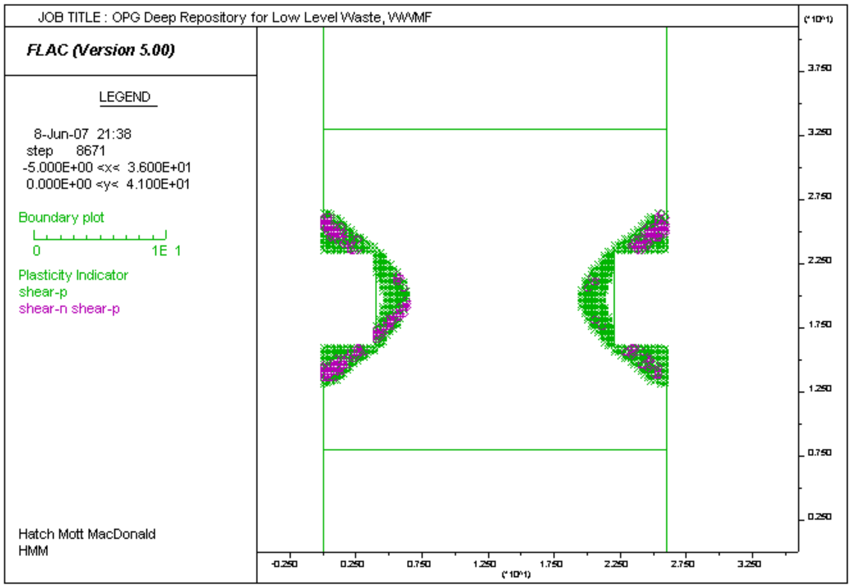
Vertical Stresses (MPa)



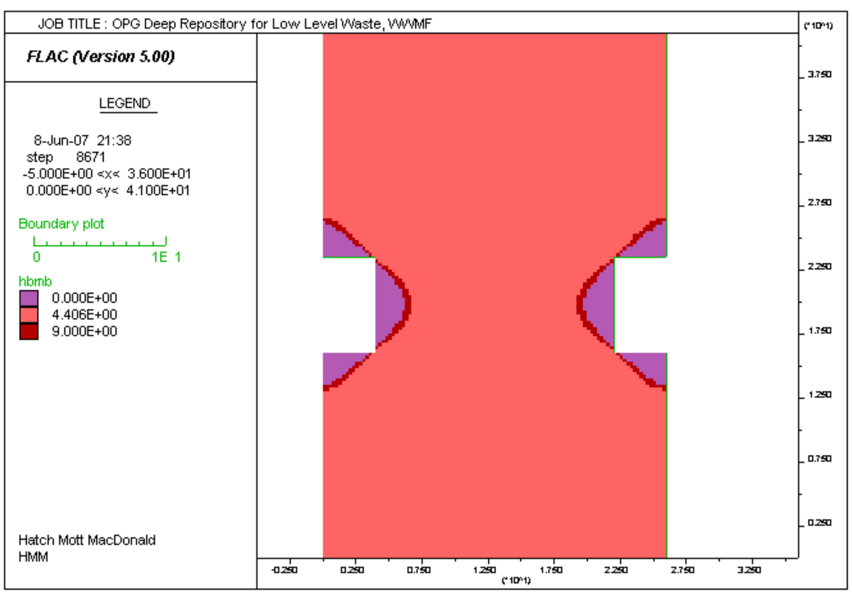
Horizontal Stresses (MPa)



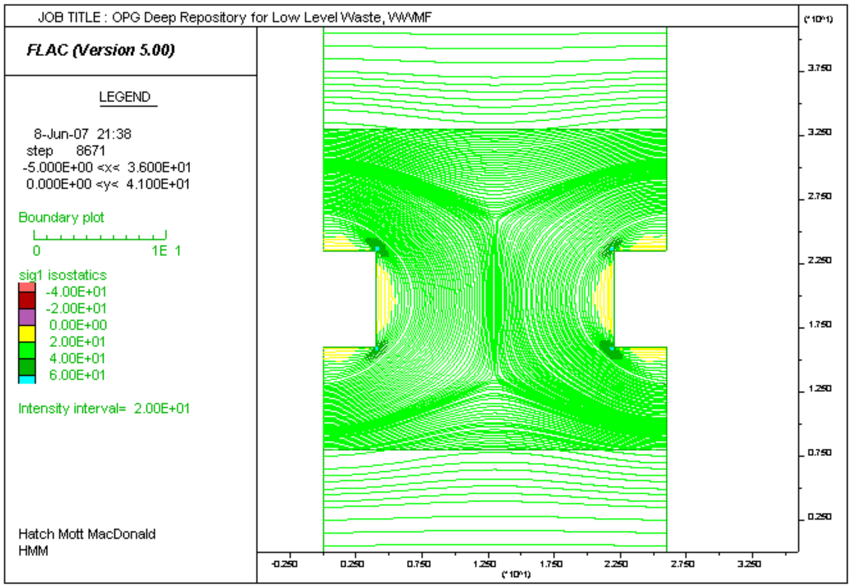
Plasticity Indicators



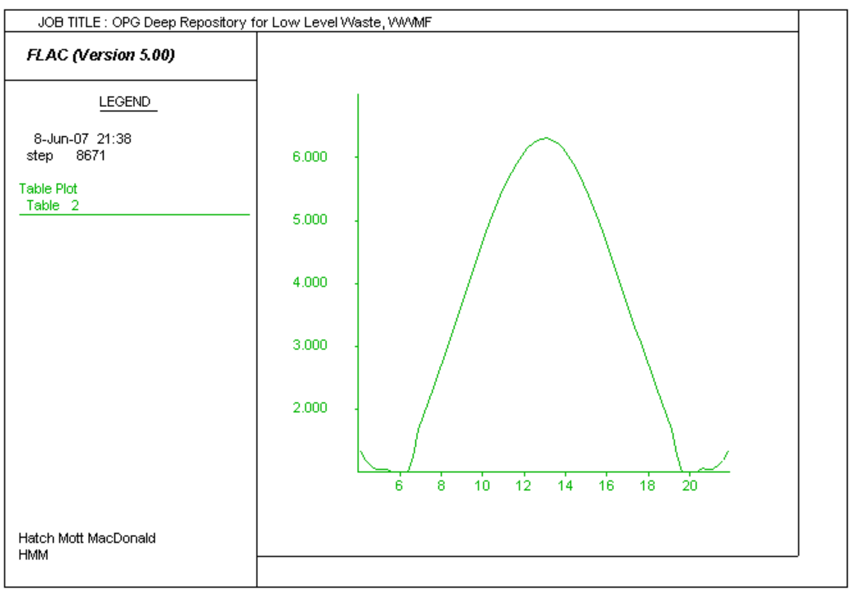
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)



Factor Of Safety Across The Pillar



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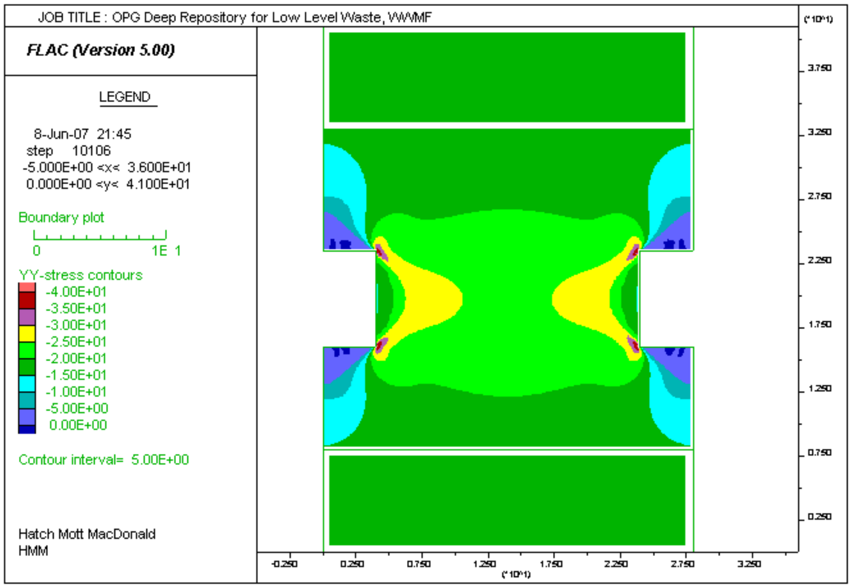
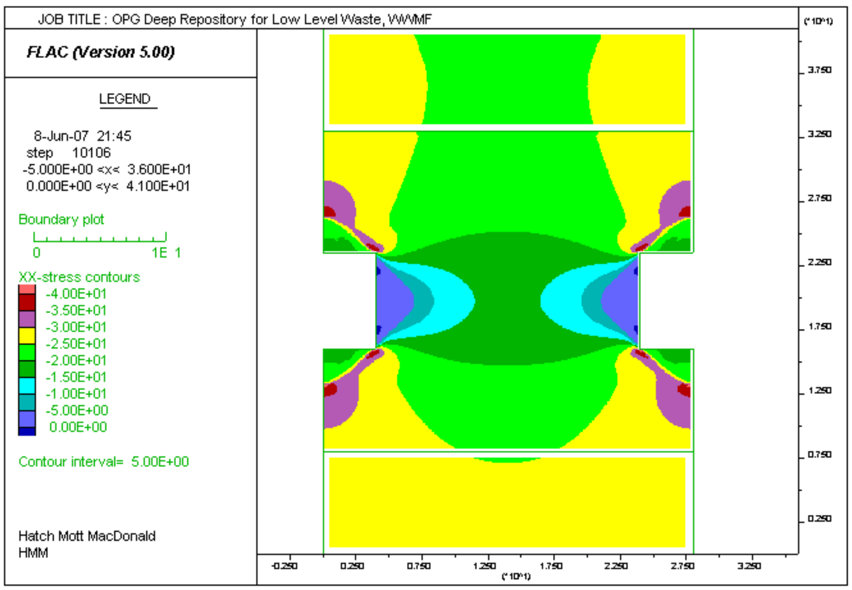
UCS = 60, GSI = 80, Pillar Width = 20.0m

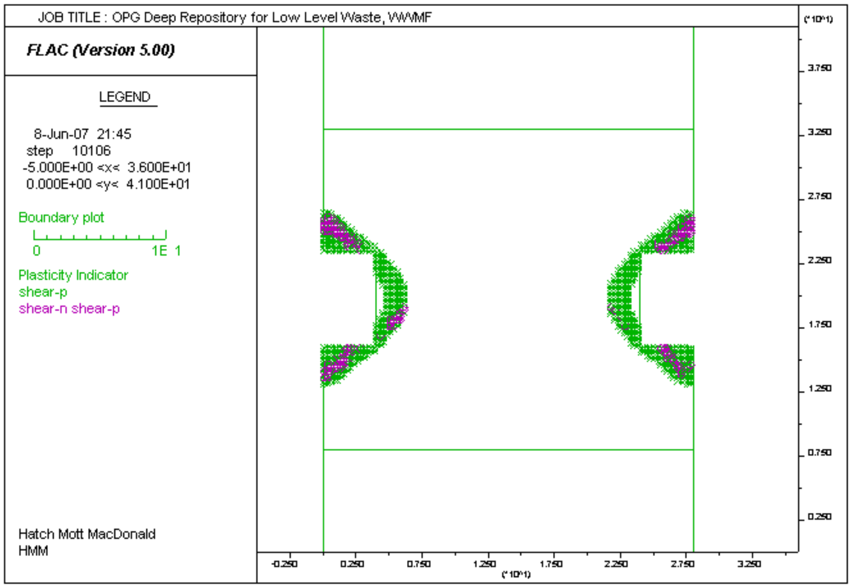
Vertical Stresses (MPa)



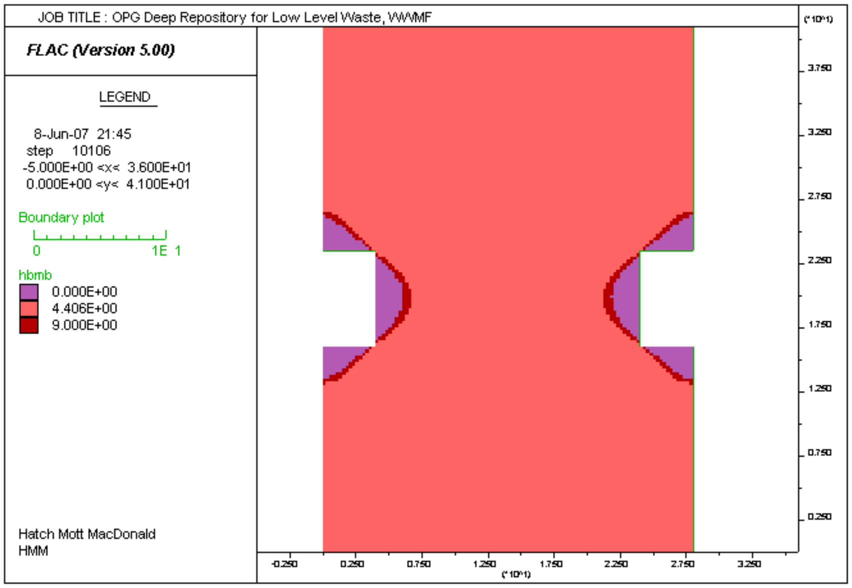
Horizontal Stresses (MPa)



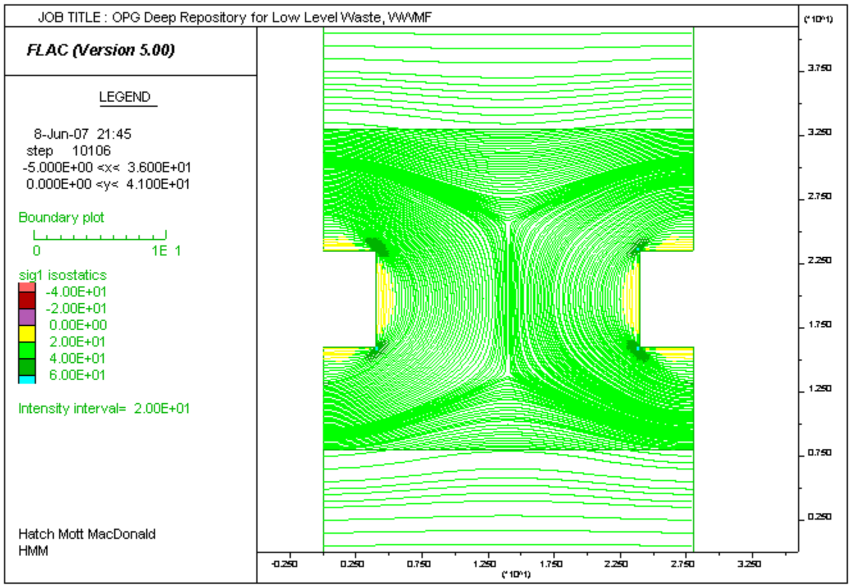
Plasticity Indicators



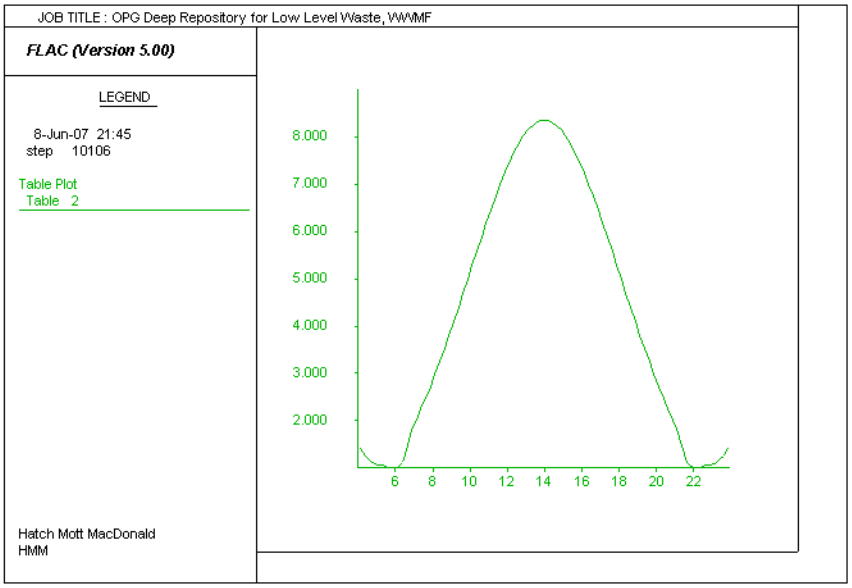
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

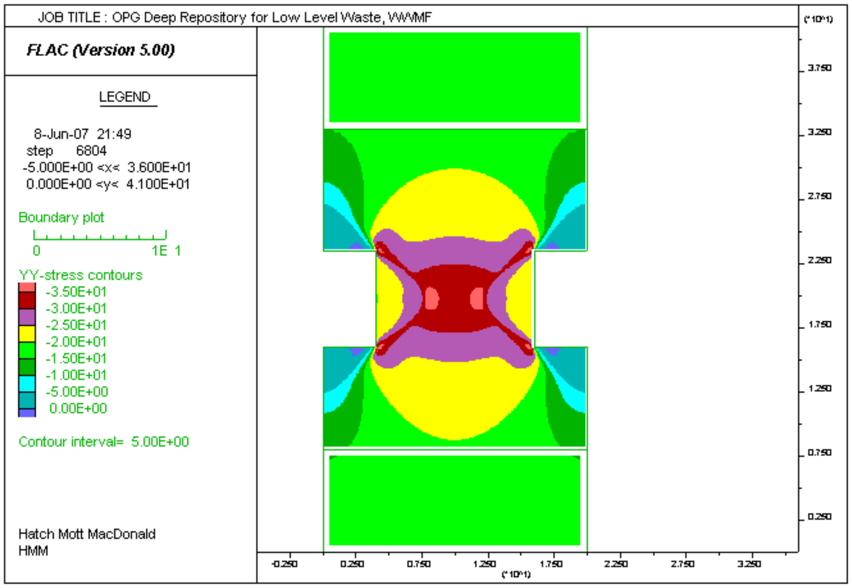


Factor Of Safety Across The Pillar

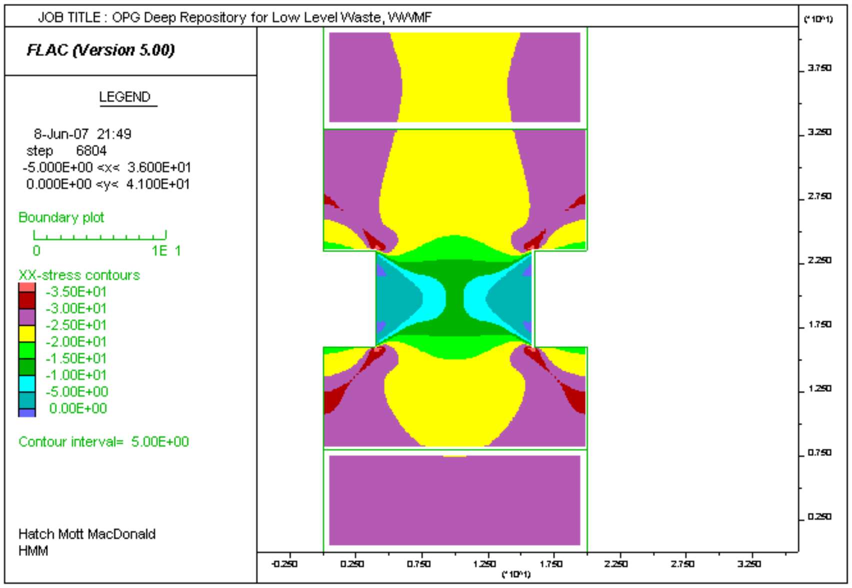


UCS = 72, GSI = 55, Pillar Width = 12.0m

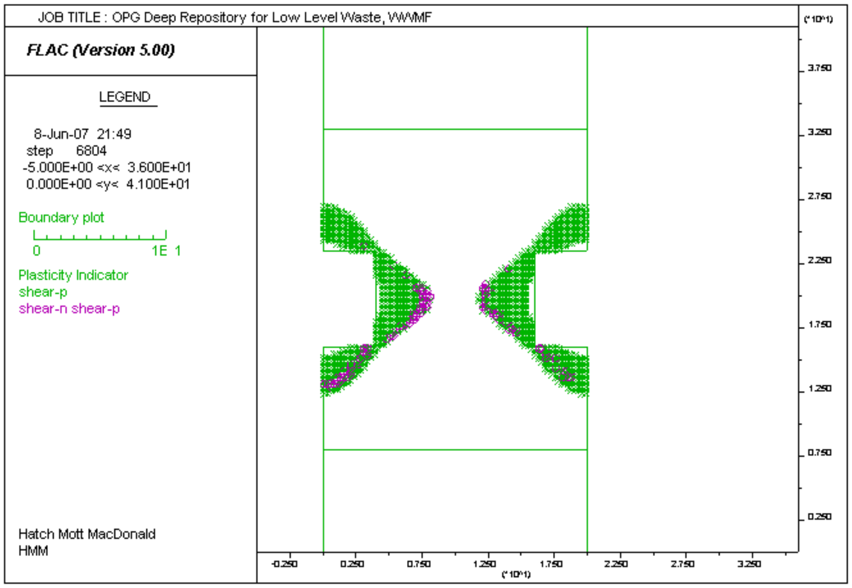
Vertical Stresses (MPa)



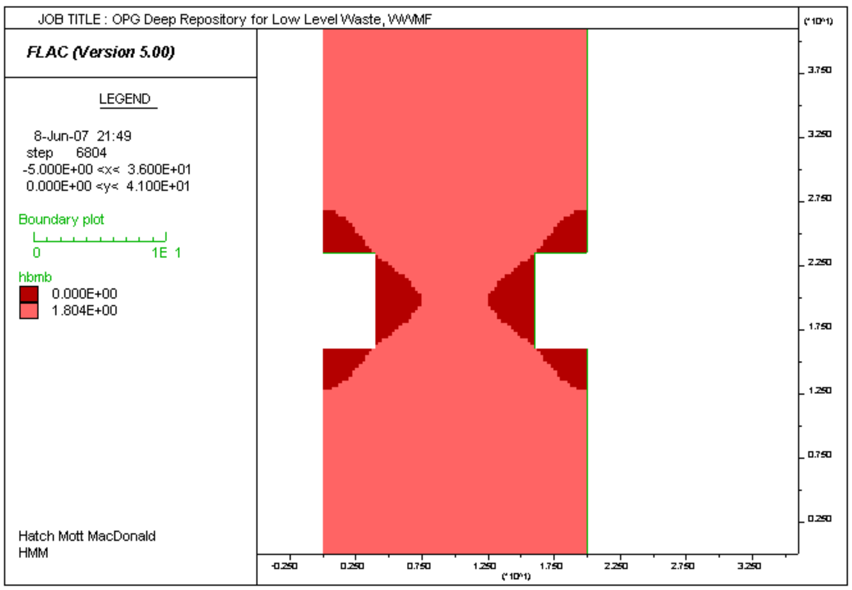
Horizontal Stresses (MPa)



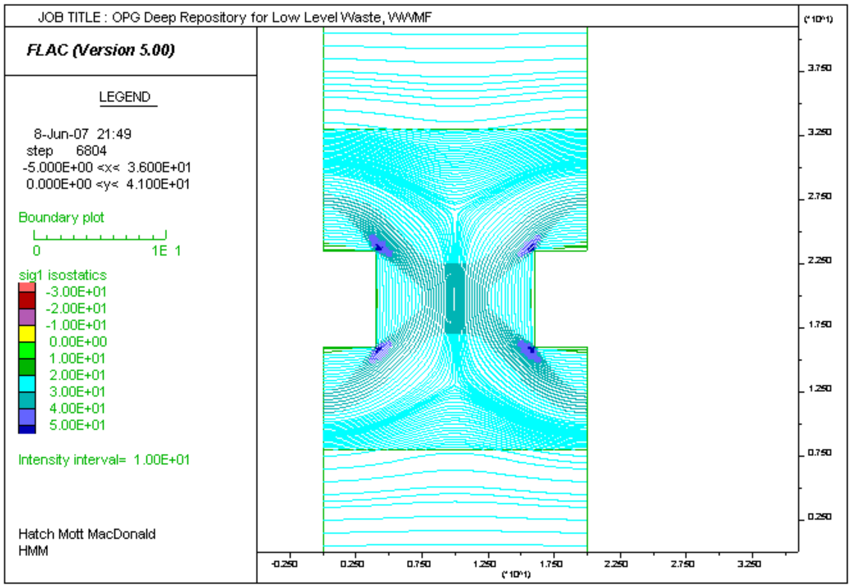
Plasticity Indicators



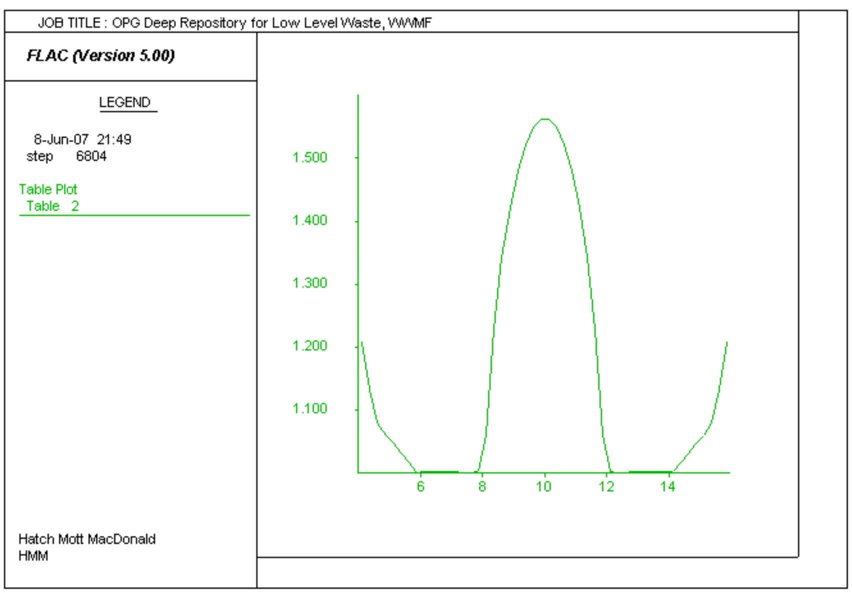
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

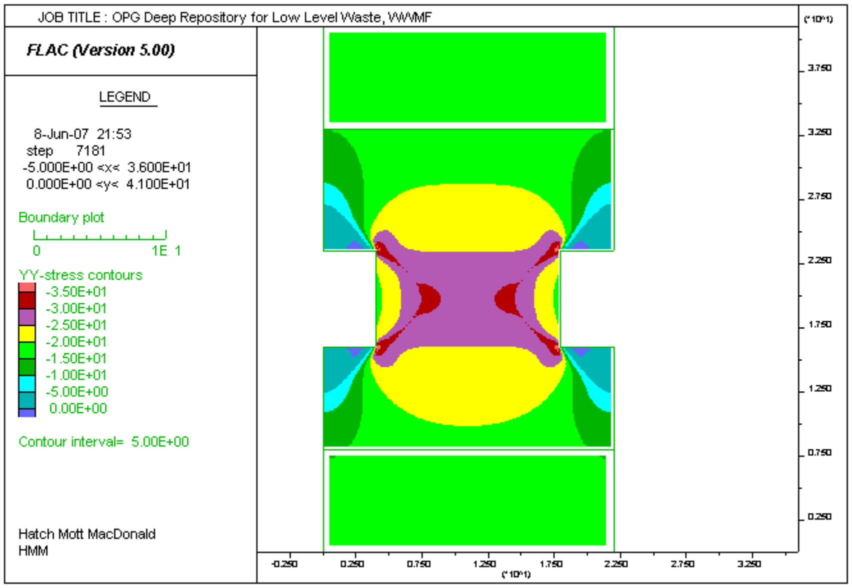


Factor Of Safety Across The Pillar

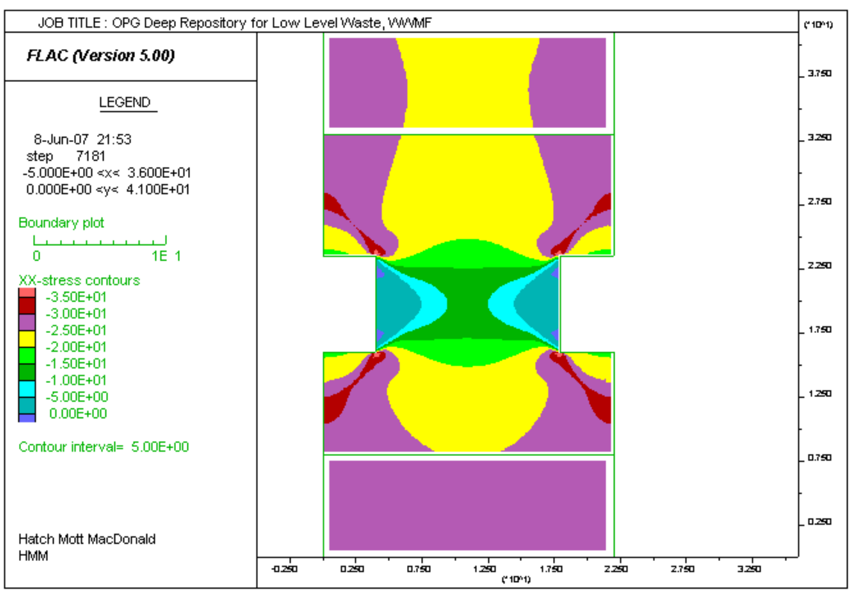


UCS = 72, GSI = 55, Pillar Width = 14.0m

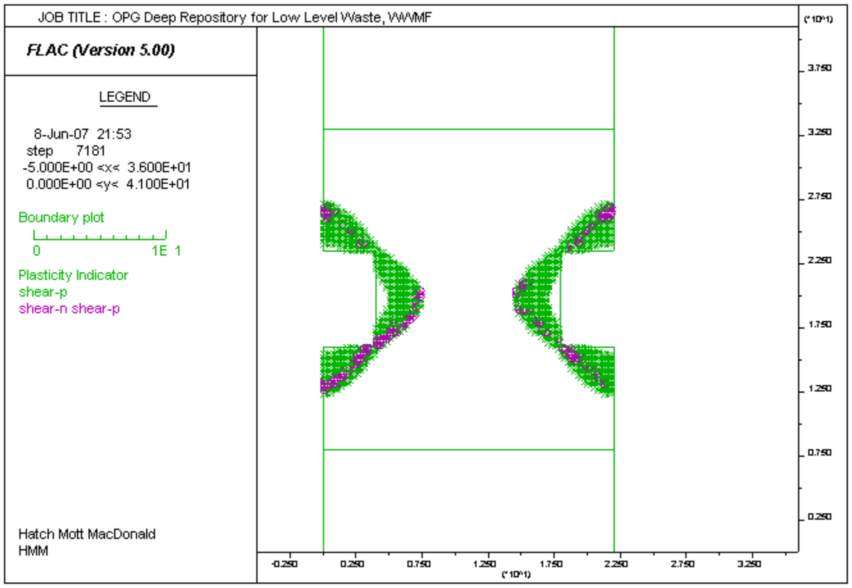
Vertical Stresses (MPa)



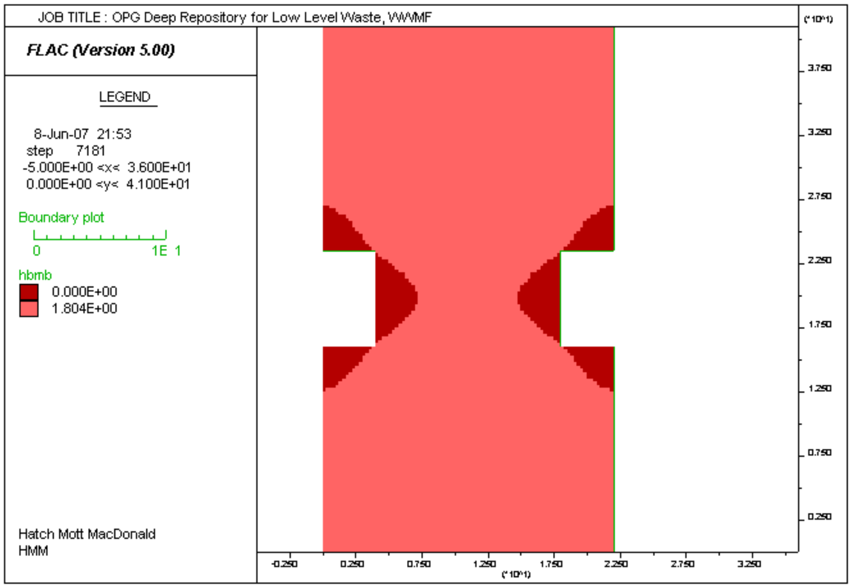
Horizontal Stresses (MPa)



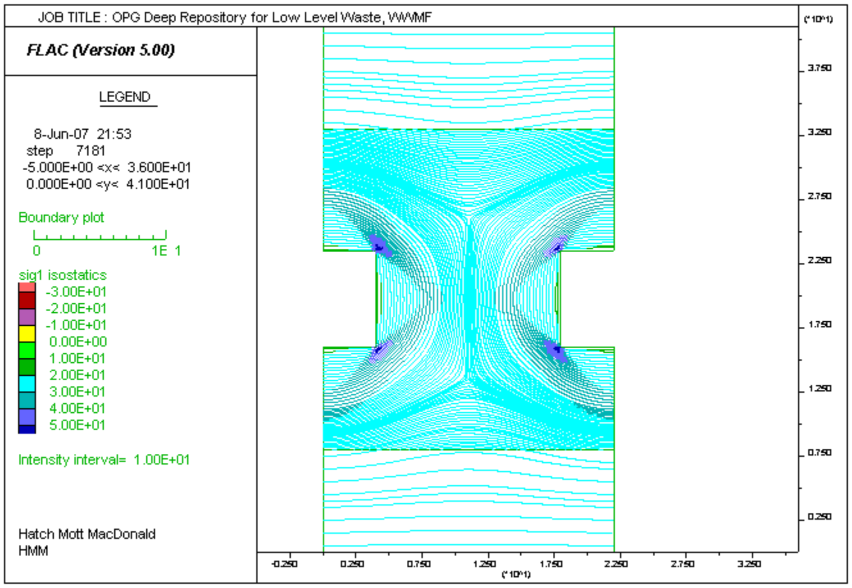
Plasticity Indicators



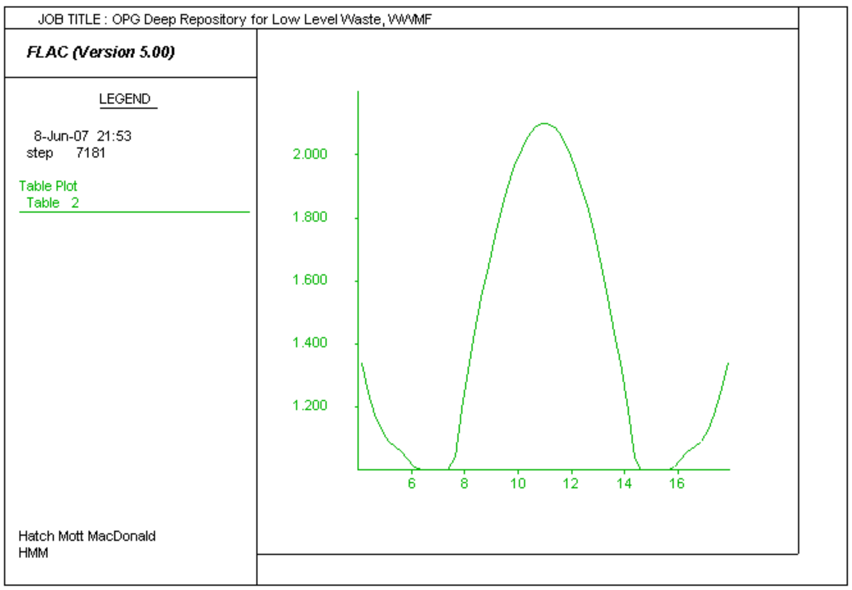
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

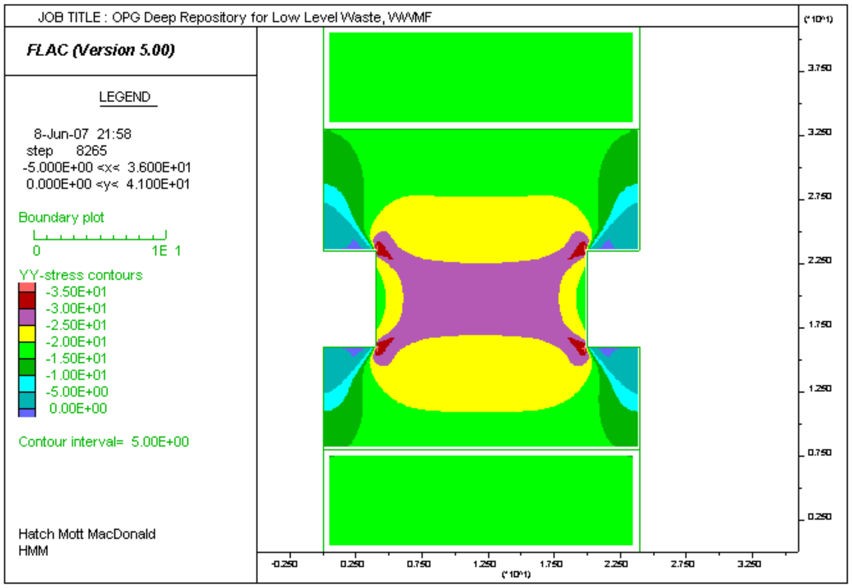


Factor Of Safety Across The Pillar

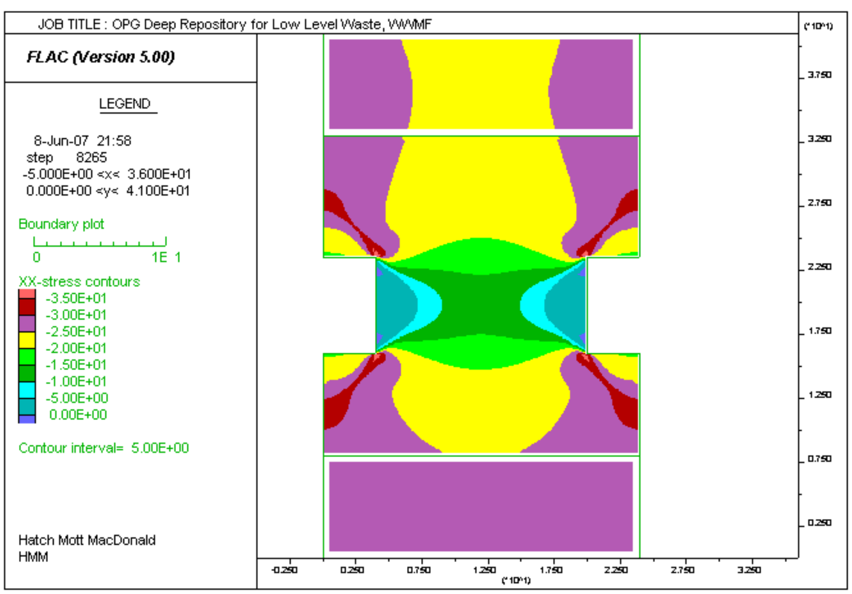


UCS = 72, GSI = 55, Pillar Width = 16.0m

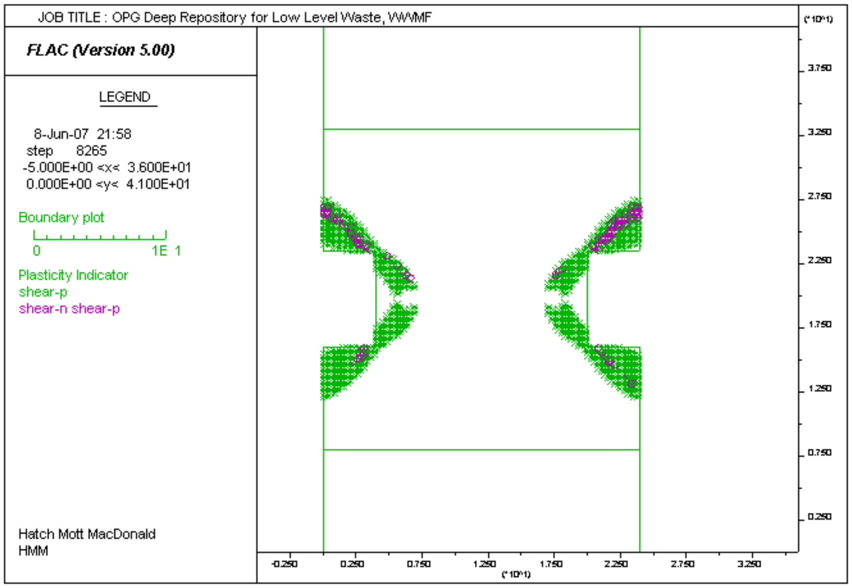
Vertical Stresses (MPa)



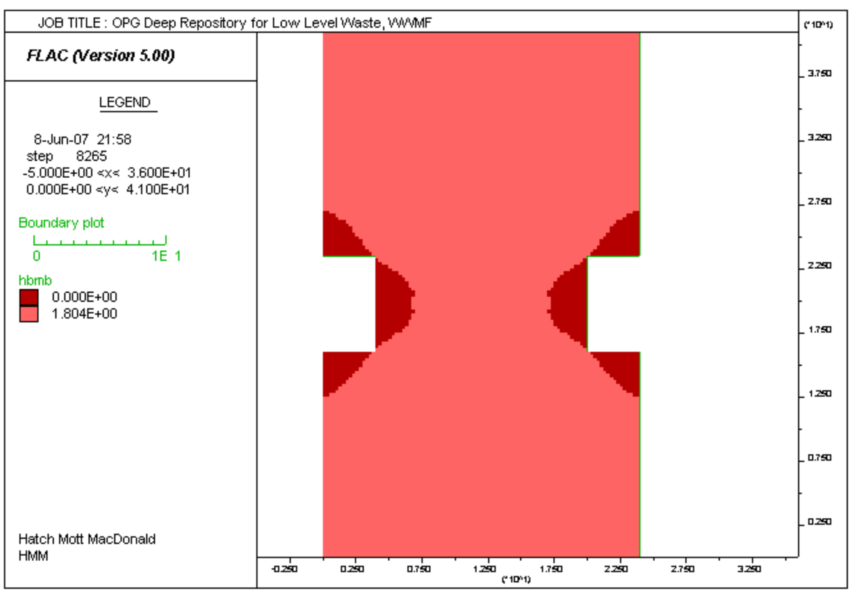
Horizontal Stresses (MPa)



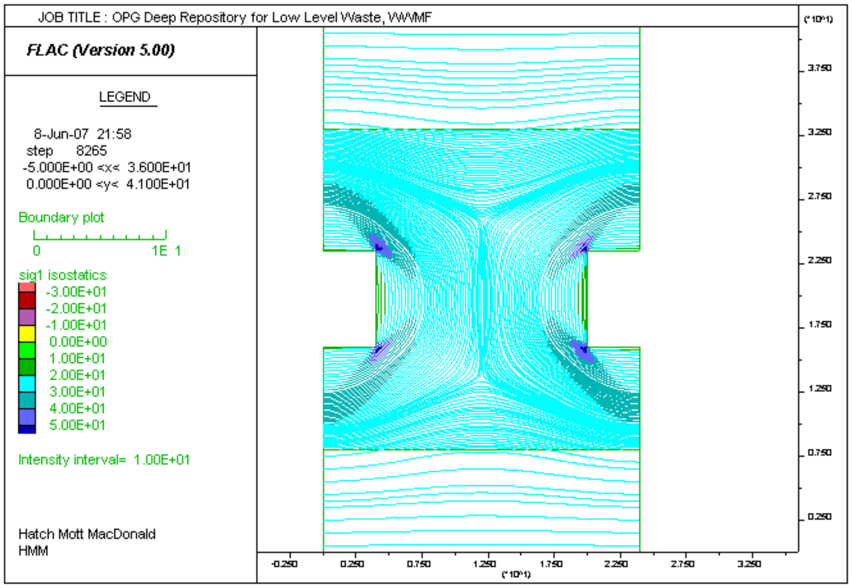
Plasticity Indicators



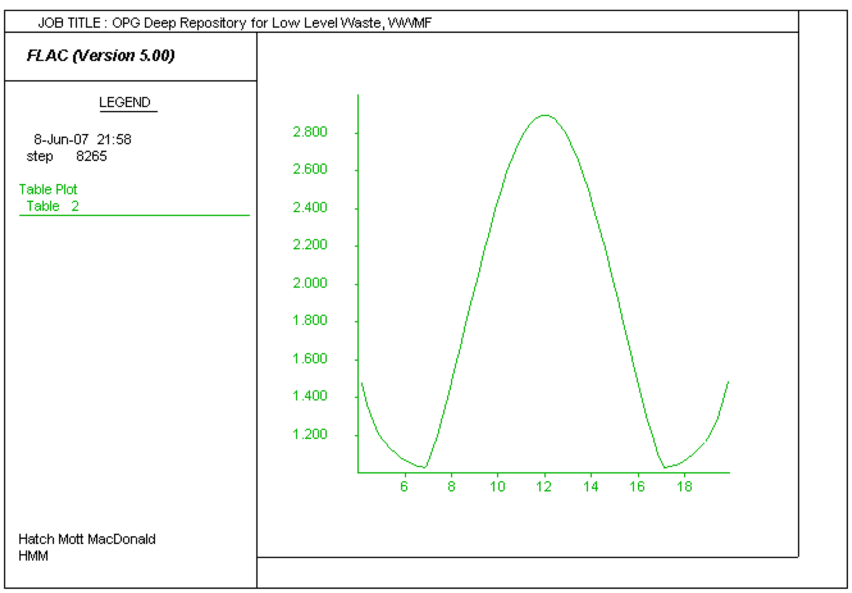
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

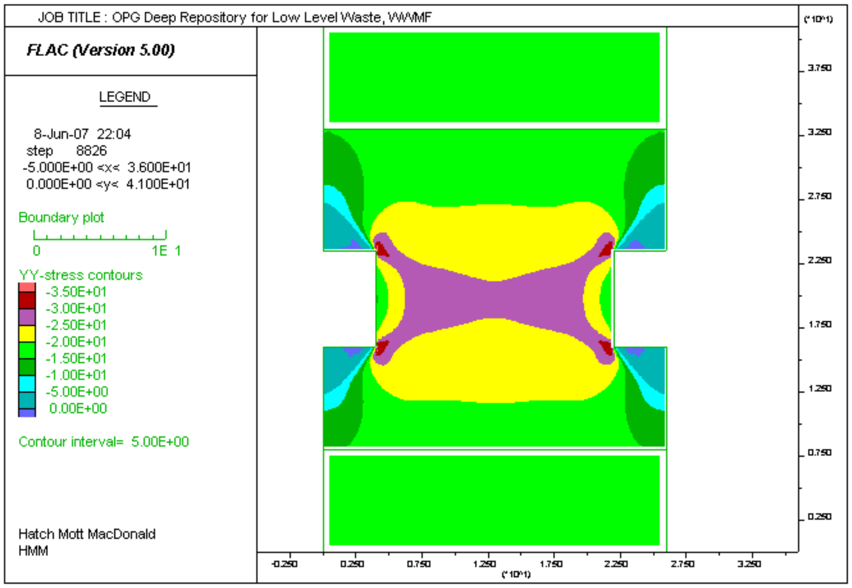


Factor Of Safety Across The Pillar

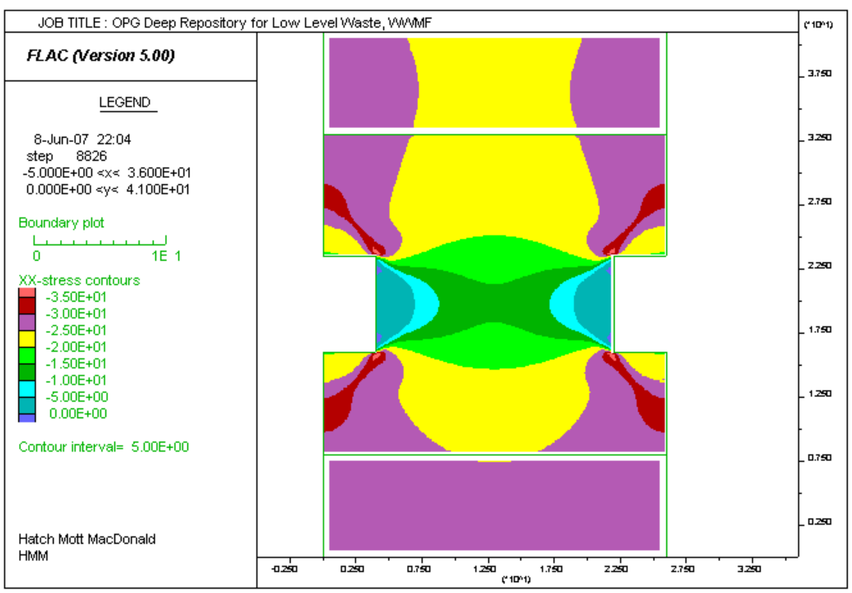


UCS = 72, GSI = 55, Pillar Width = 18.0m

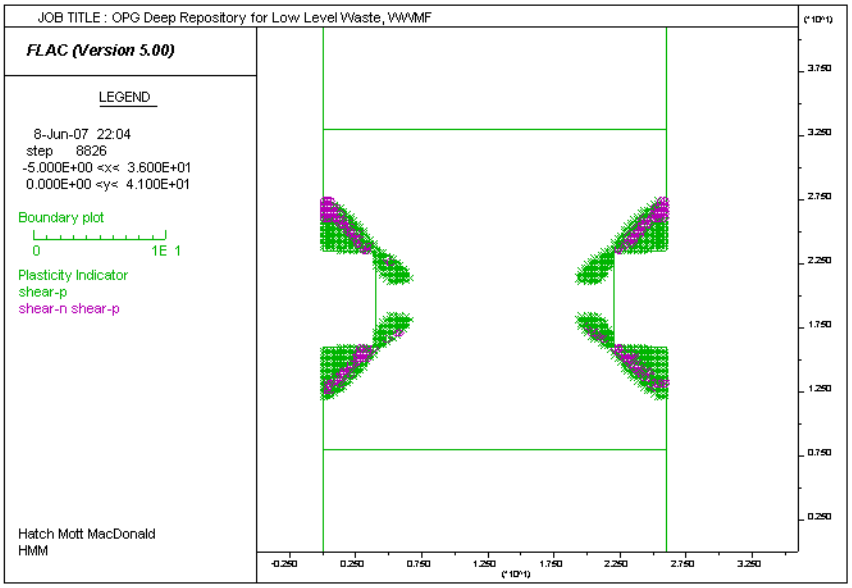
Vertical Stresses (MPa)



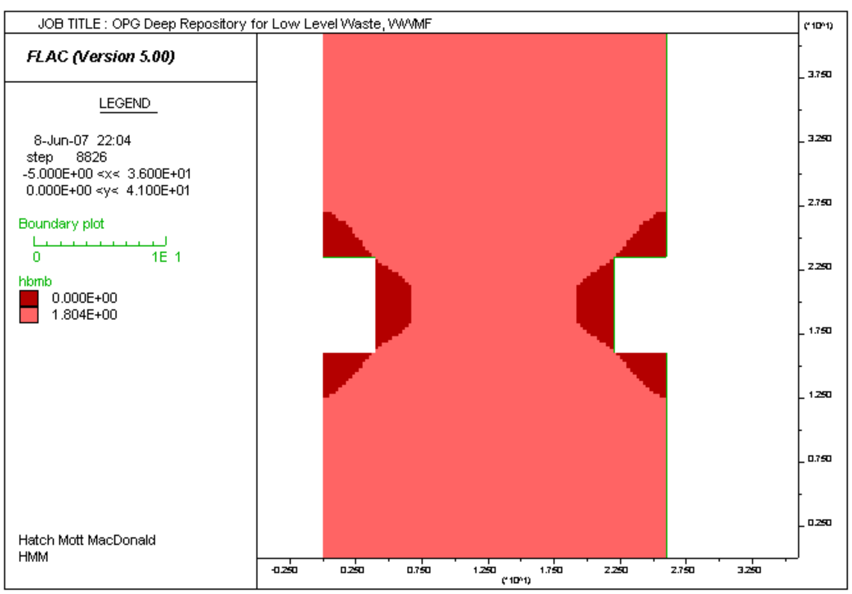
Horizontal Stresses (MPa)



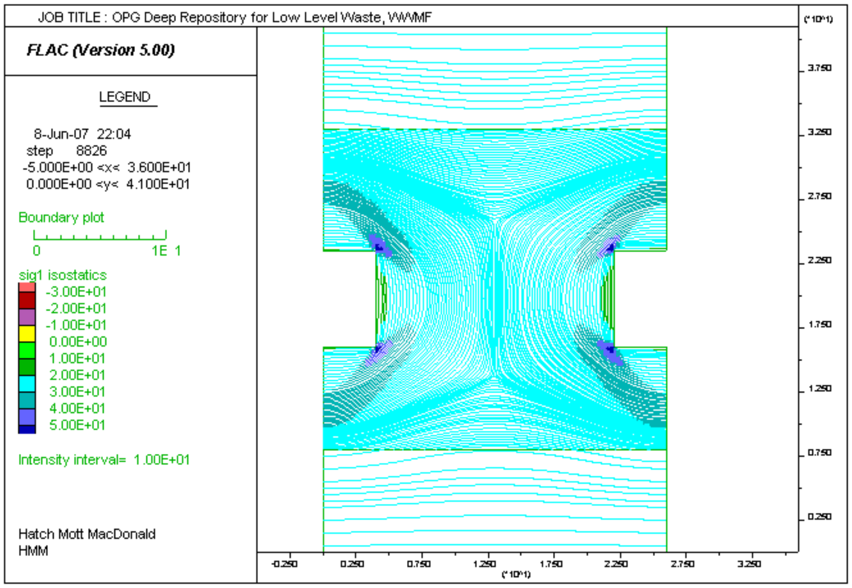
Plasticity Indicators



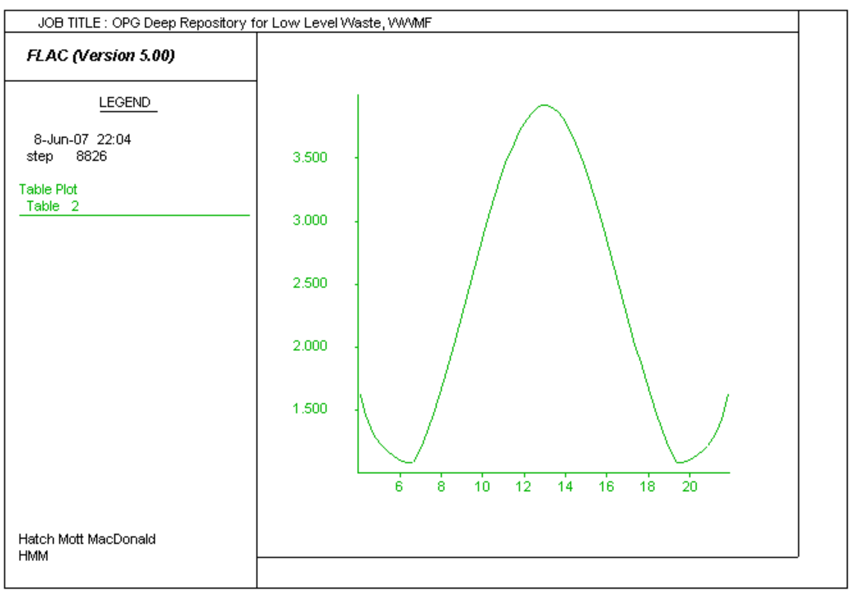
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

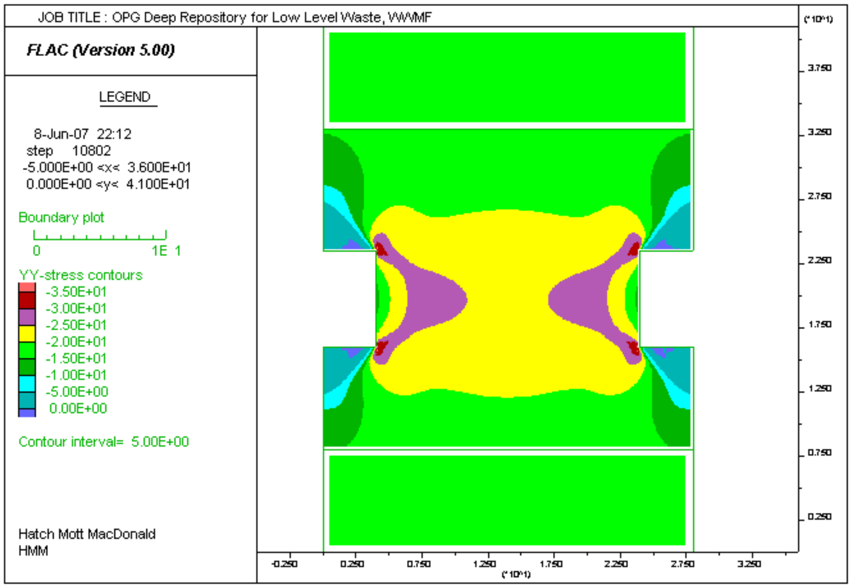


Factor Of Safety Across The Pillar

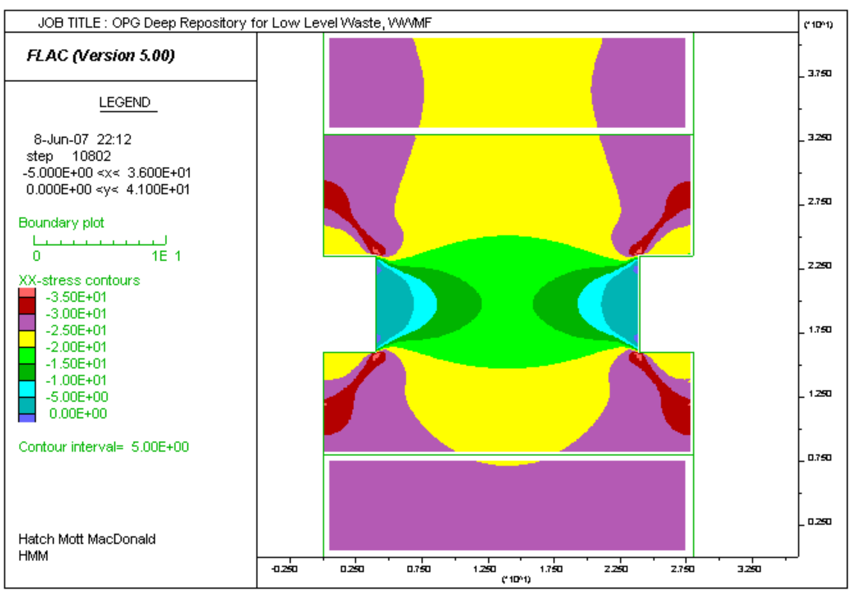


UCS = 72, GSI = 55, Pillar Width = 20.0m

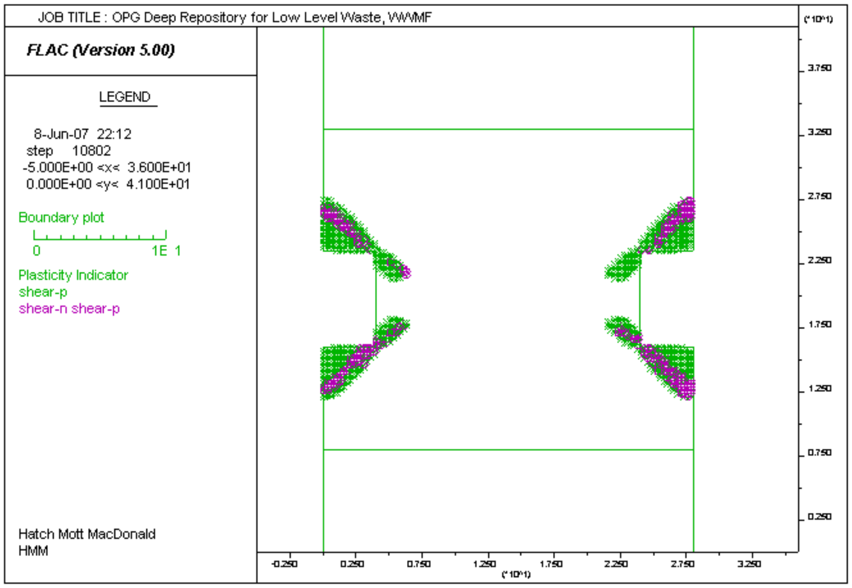
Vertical Stresses (MPa)



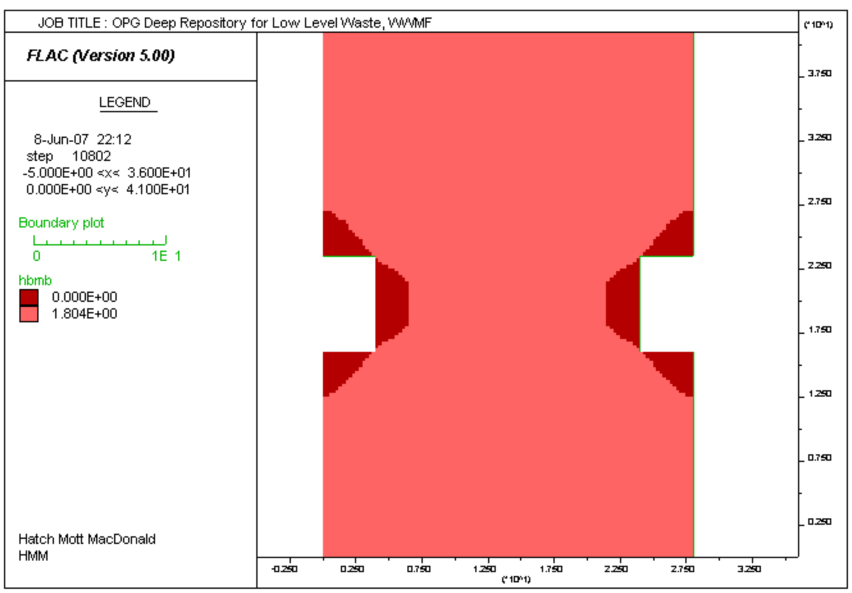
Horizontal Stresses (MPa)



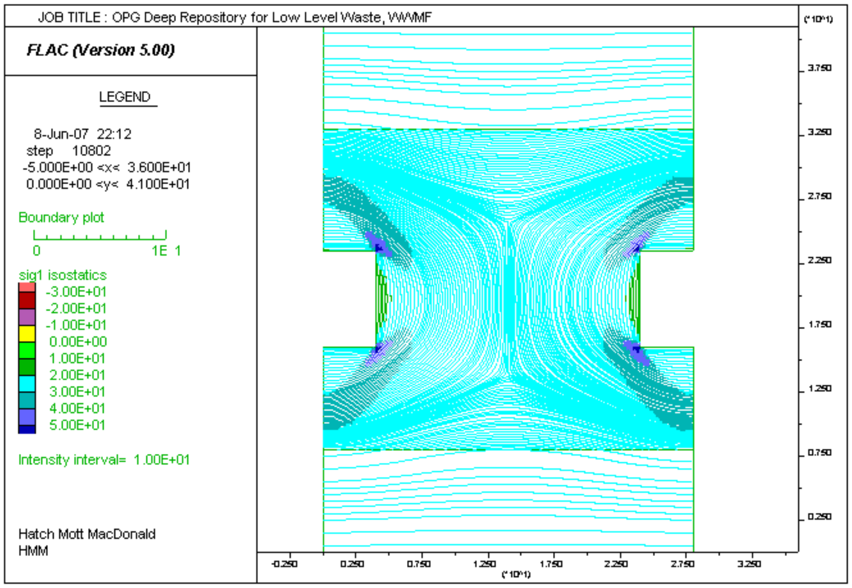
Plasticity Indicators



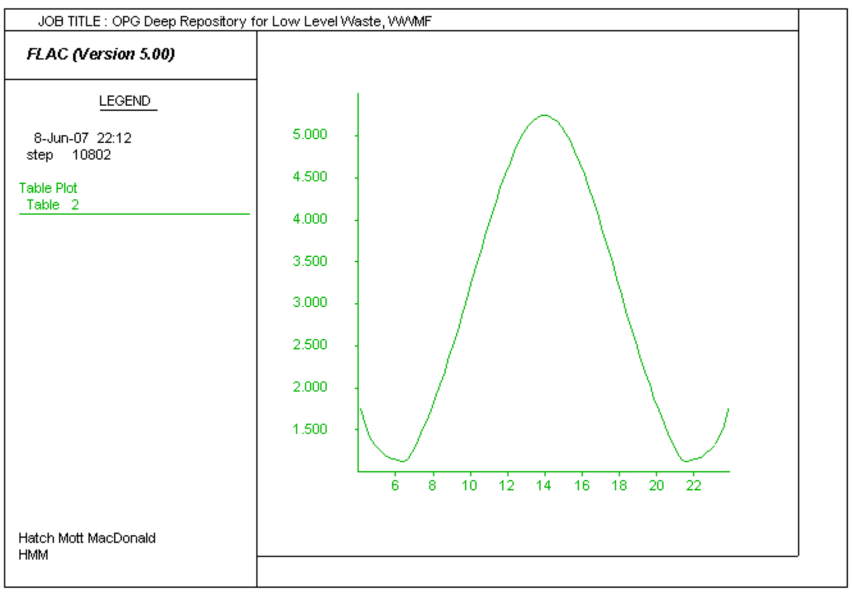
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

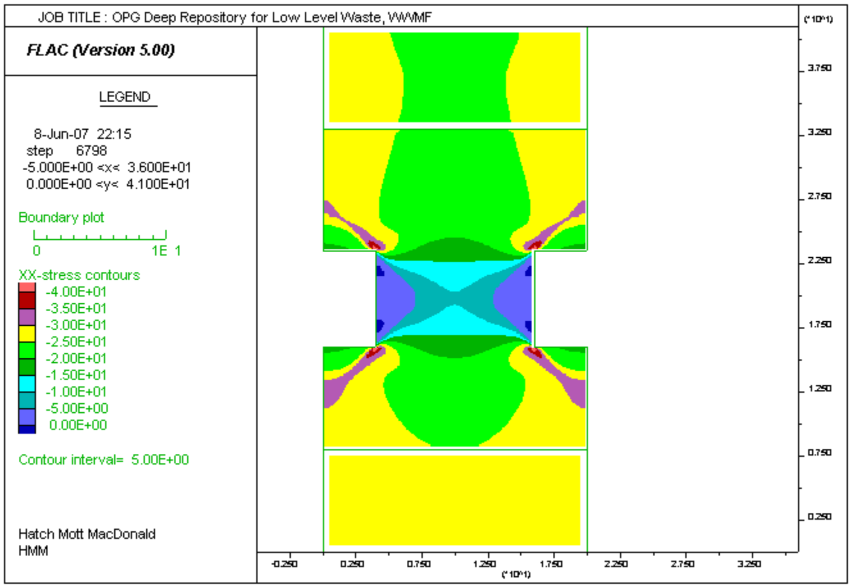


Factor Of Safety Across The Pillar

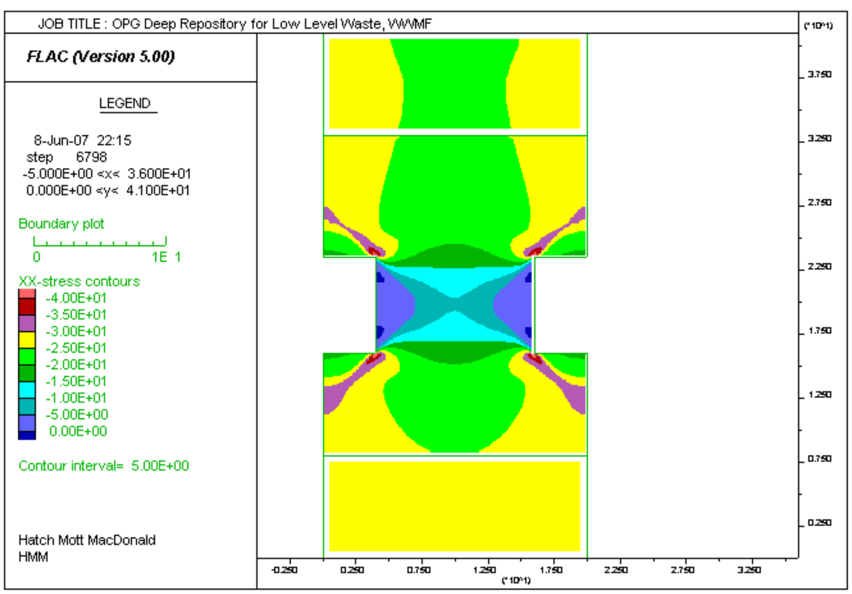


UCS = 72, GSI = 69, Pillar Width = 12.0m

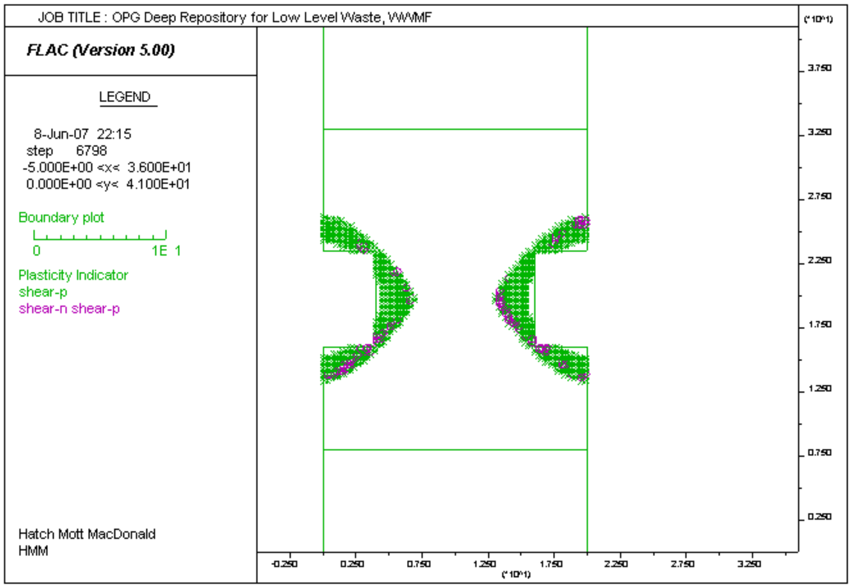
Vertical Stresses (MPa)



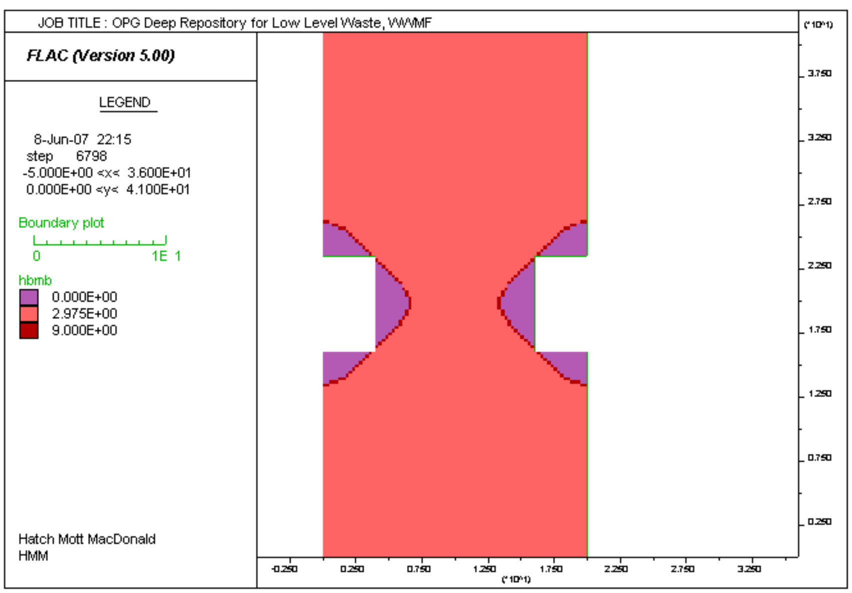
Horizontal Stresses (MPa)



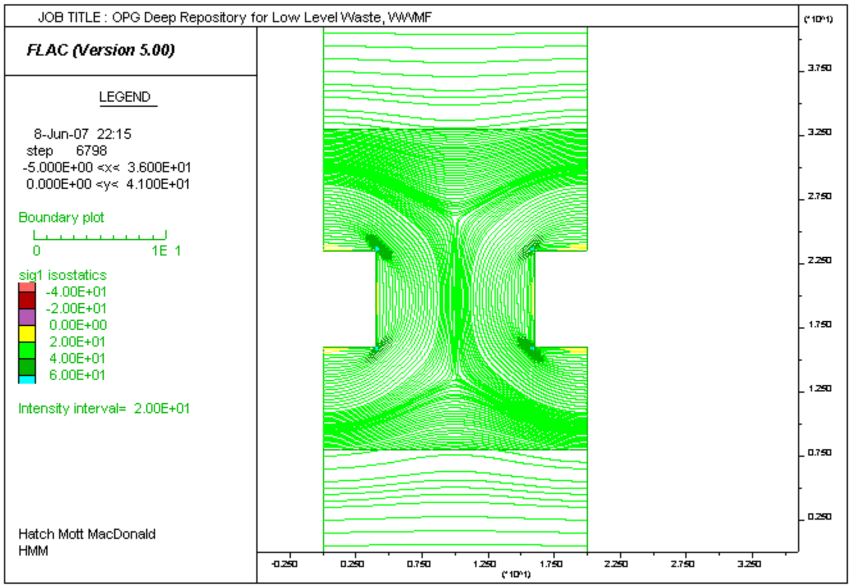
Plasticity Indicators



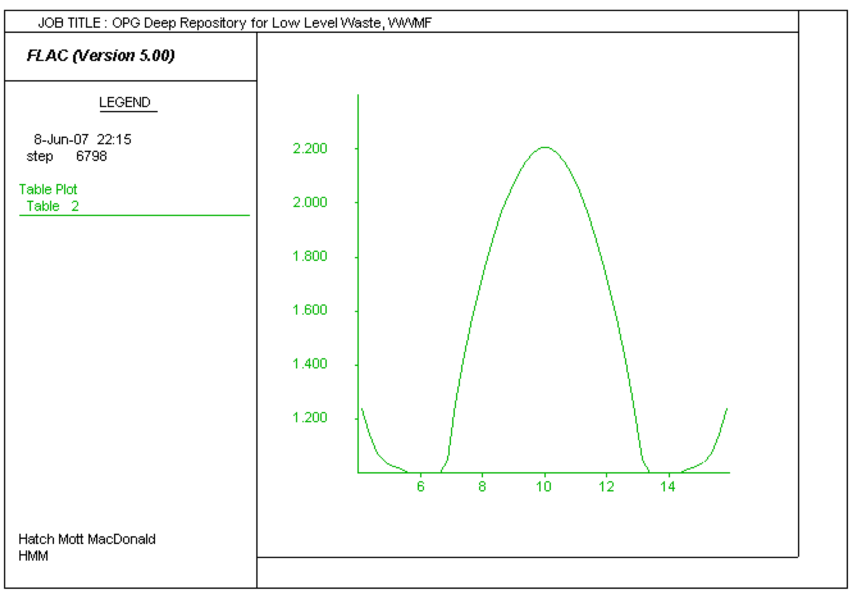
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

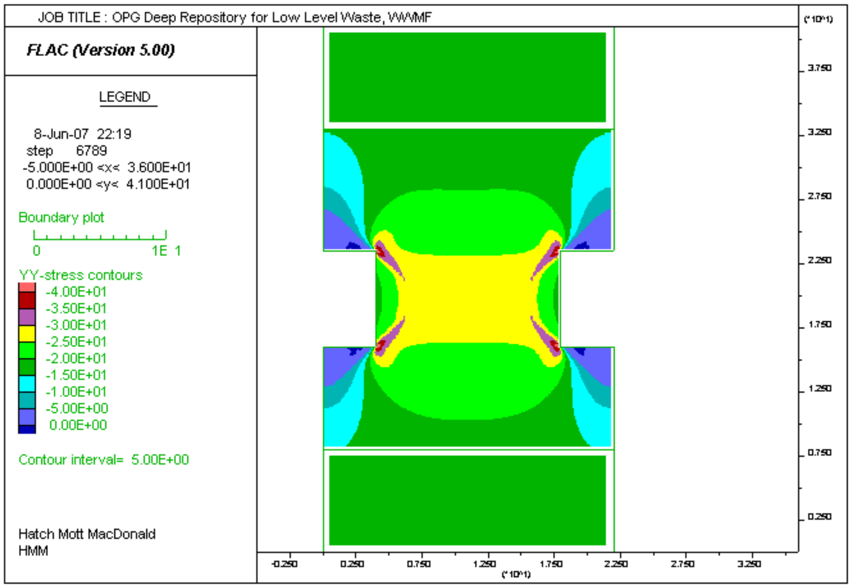


Factor Of Safety Across The Pillar

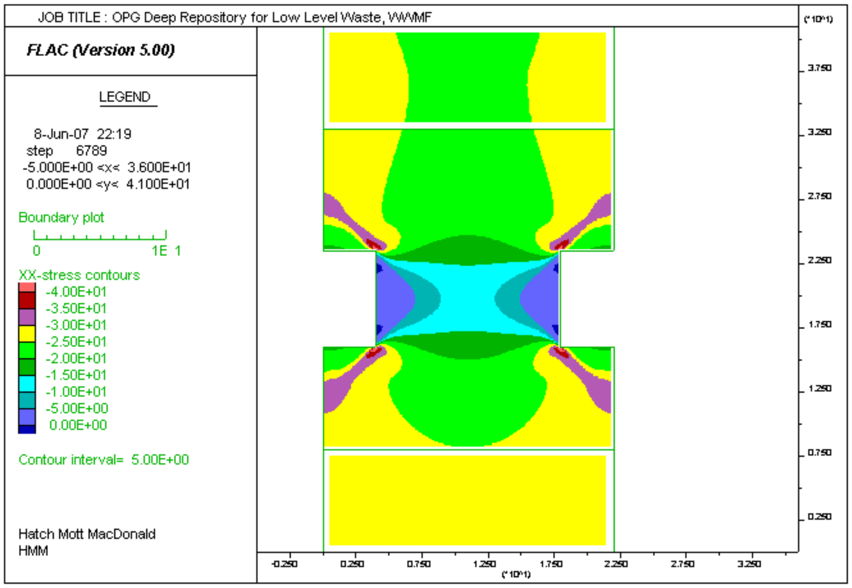


UCS = 72, GSI = 69, Pillar Width = 14.0m

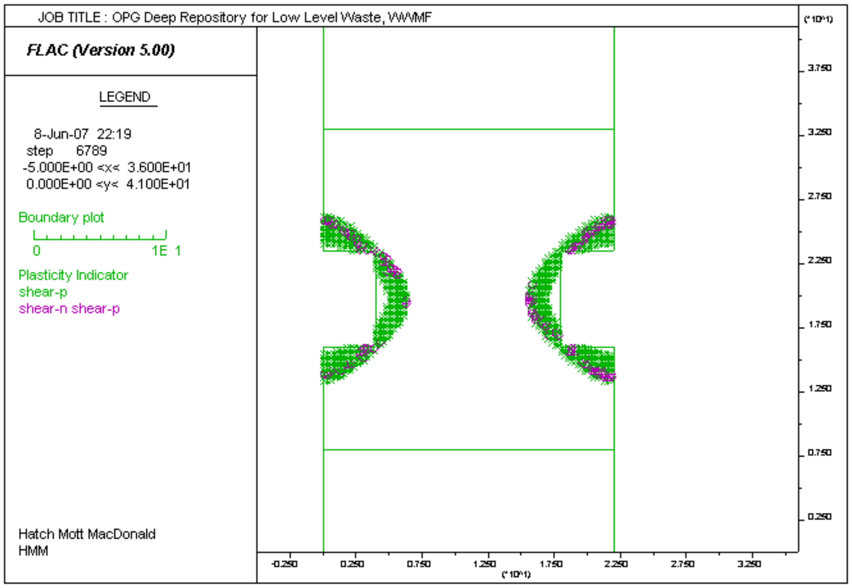
Vertical Stresses (MPa)



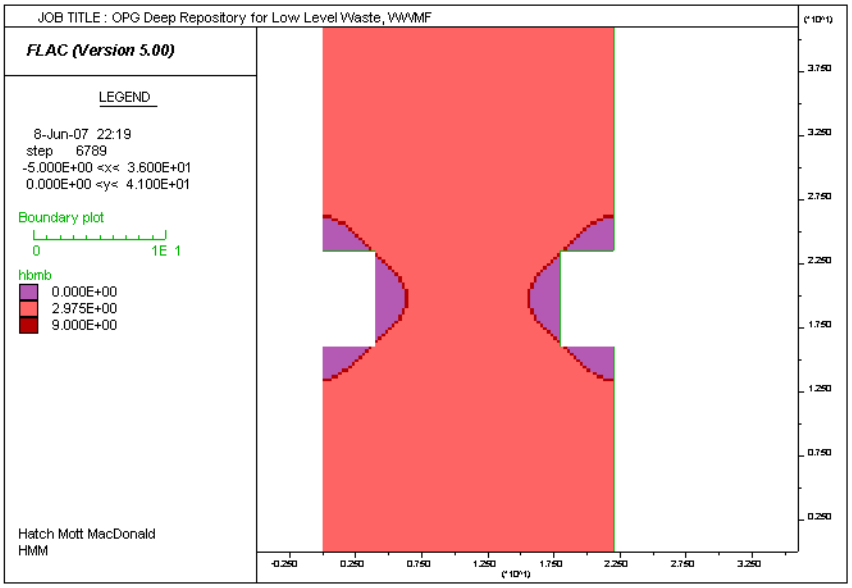
Horizontal Stresses (MPa)



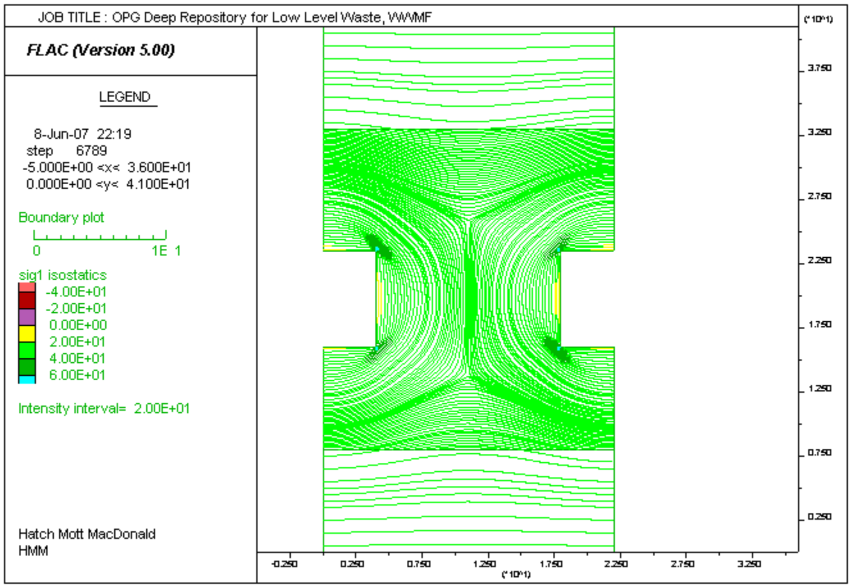
Plasticity Indicators



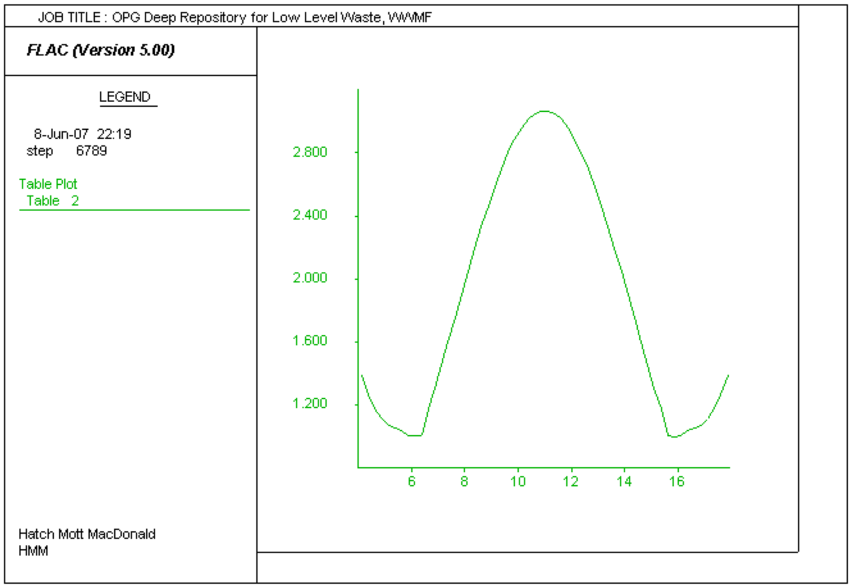
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

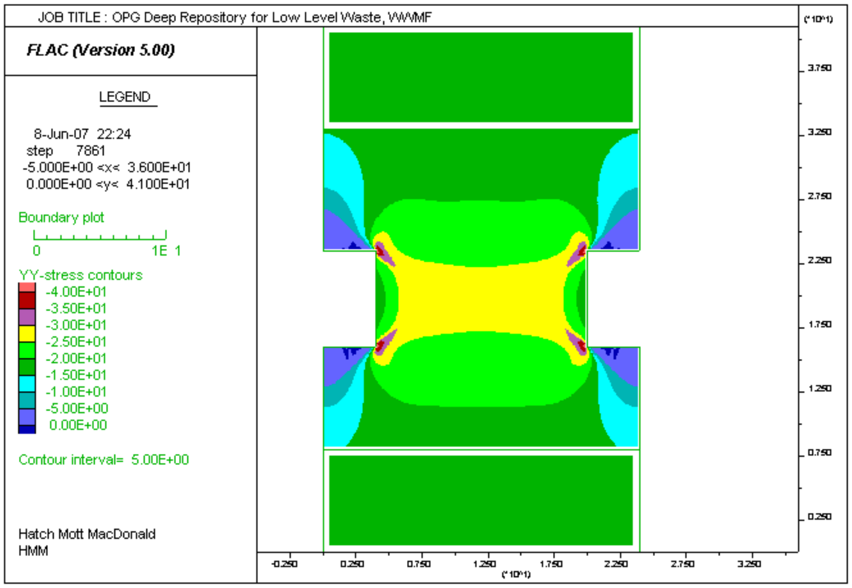


Factor Of Safety Across The Pillar

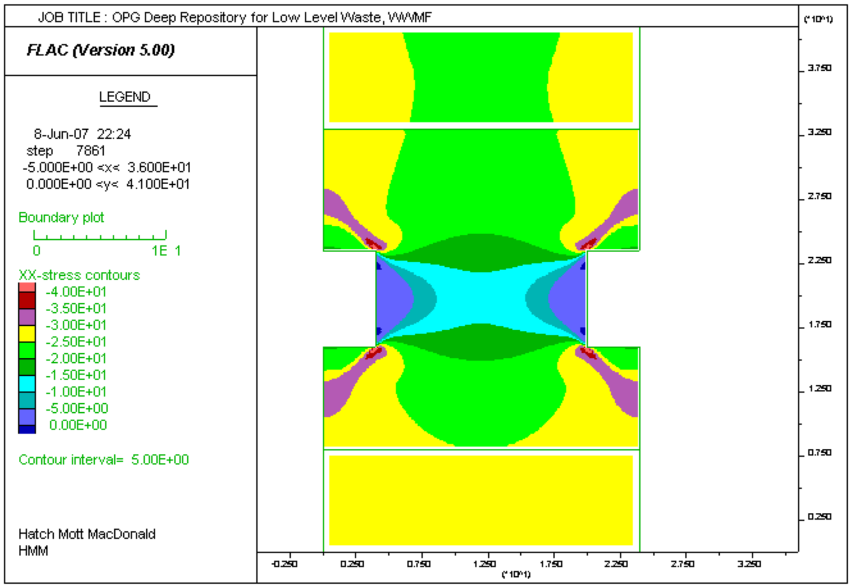


UCS = 72, GSI = 69, Pillar Width = 16.0m

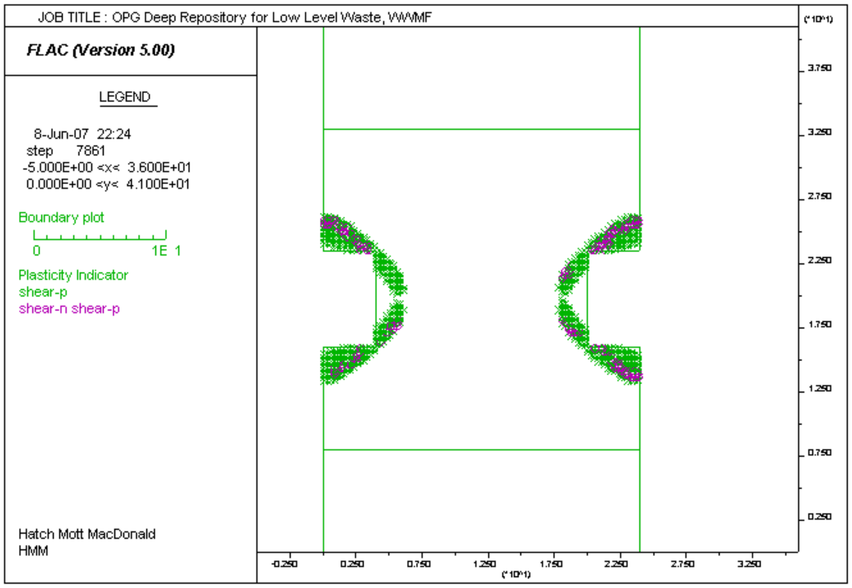
Vertical Stresses (MPa)



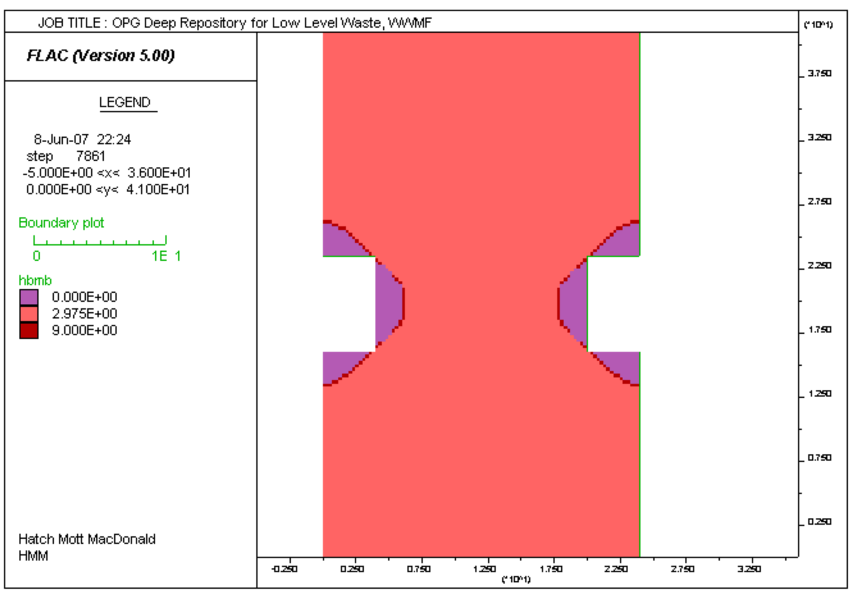
Horizontal Stresses (MPa)



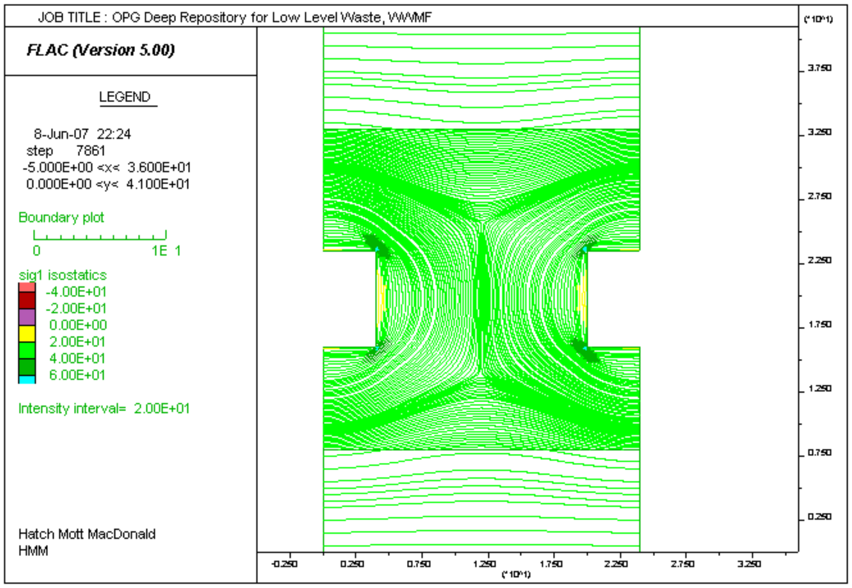
Plasticity Indicators



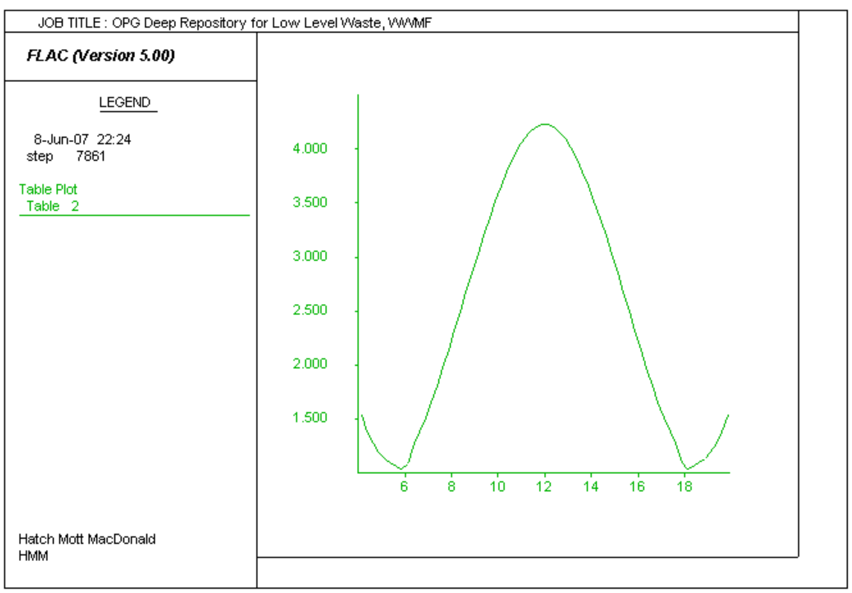
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)



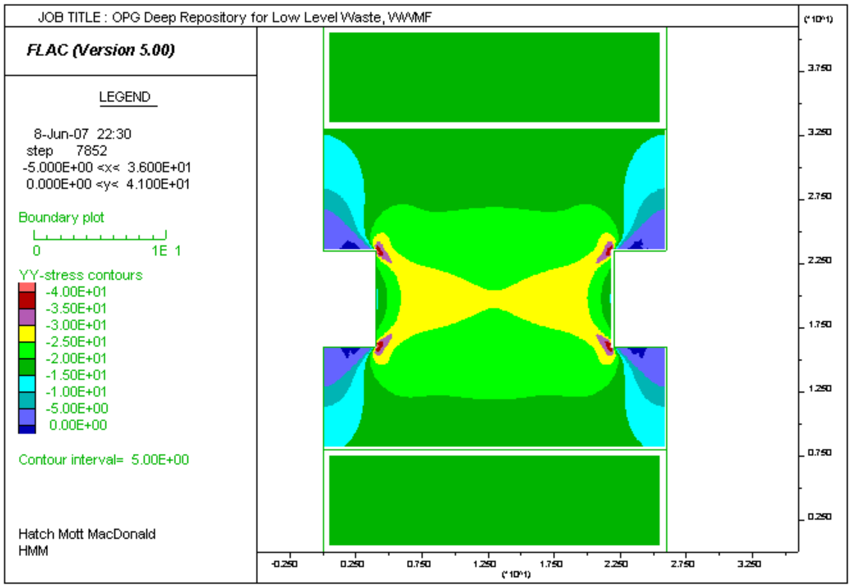
Factor Of Safety Across The Pillar



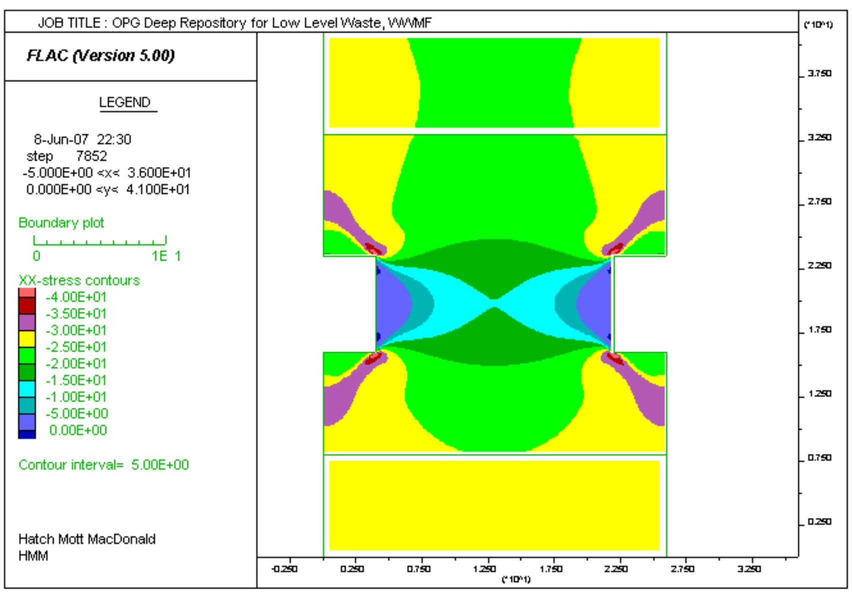
Hatch Mott MacDonald HATCH CNA Consulting Engineers

UCS = 72, GSI = 69, Pillar Width = 18.0m

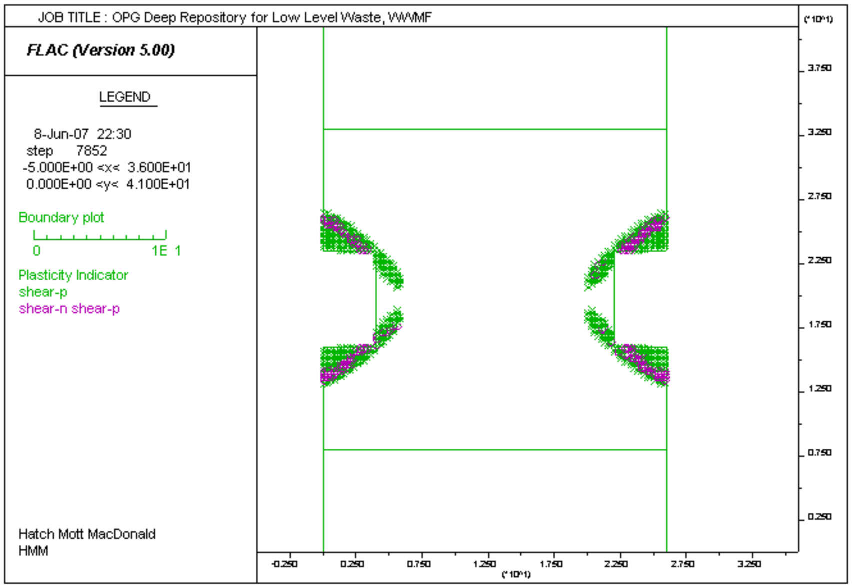
Vertical Stresses (MPa)



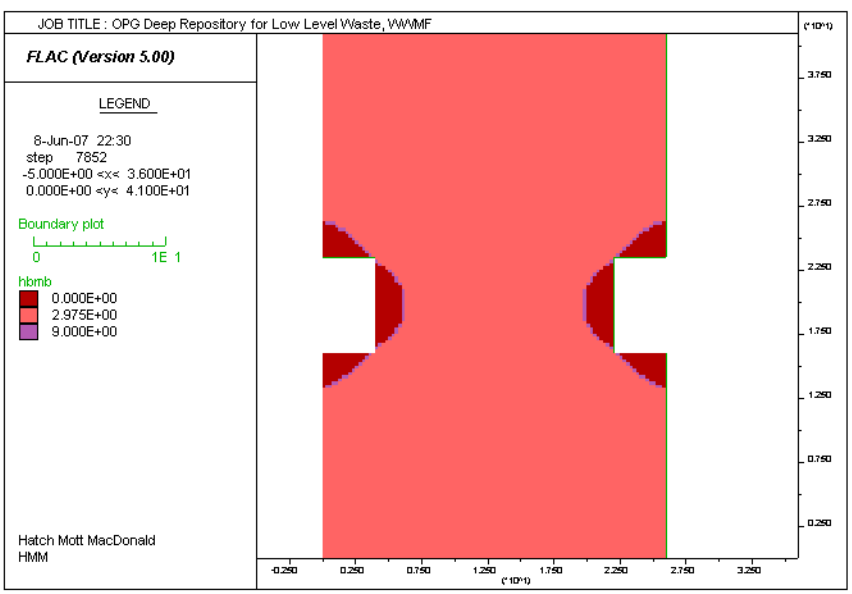
Horizontal Stresses (MPa)



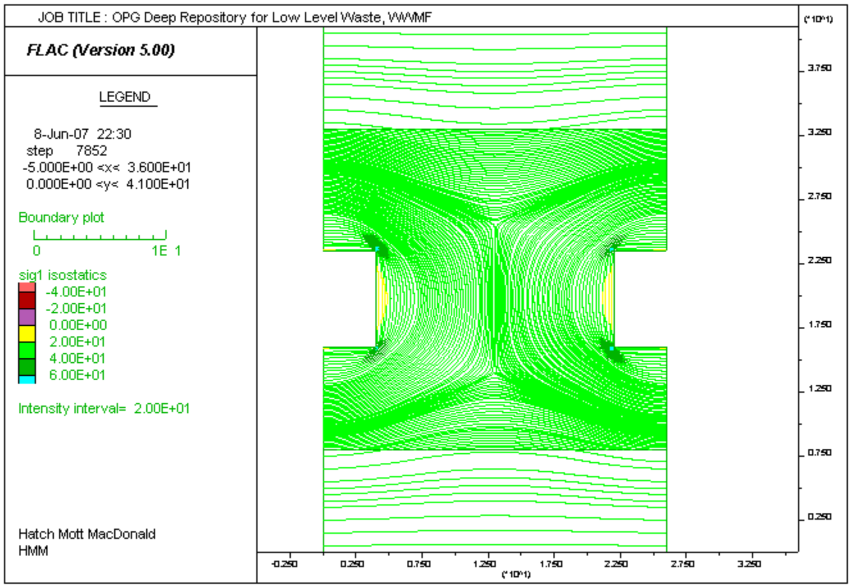
Plasticity Indicators



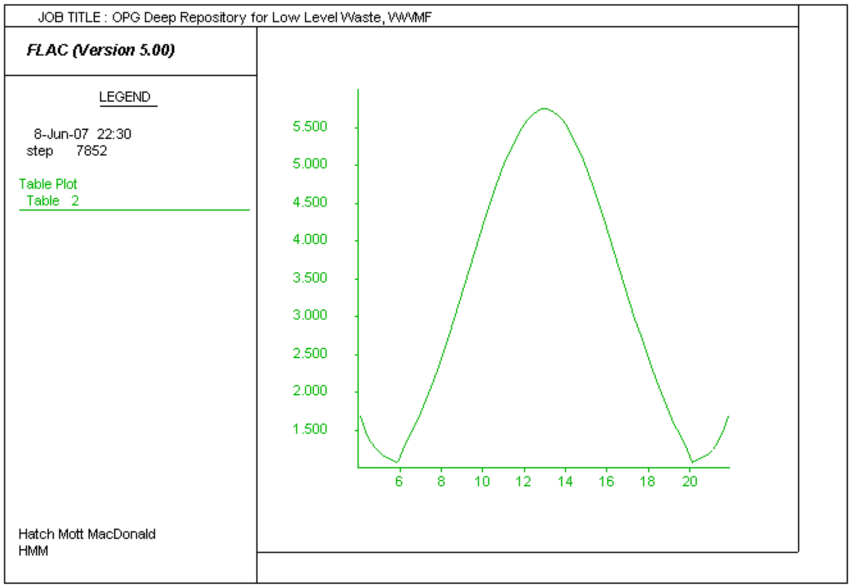
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

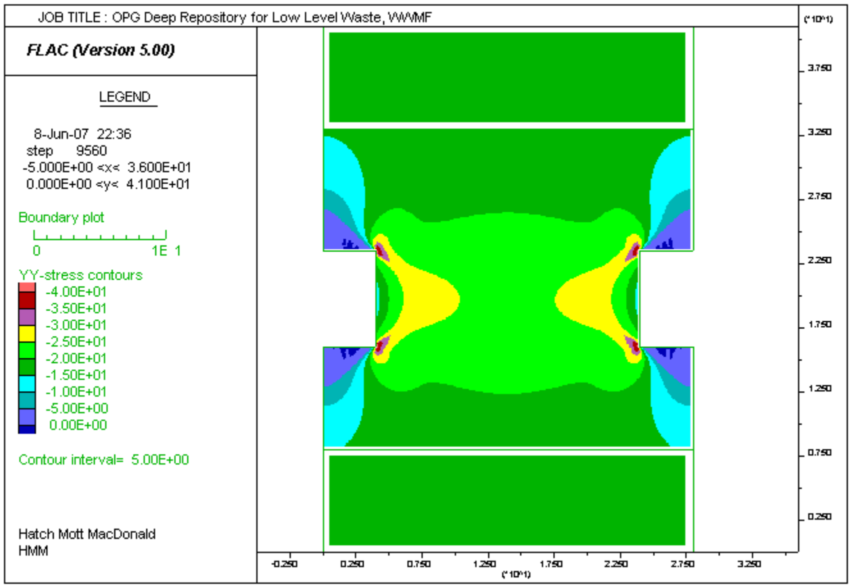


Factor Of Safety Across The Pillar

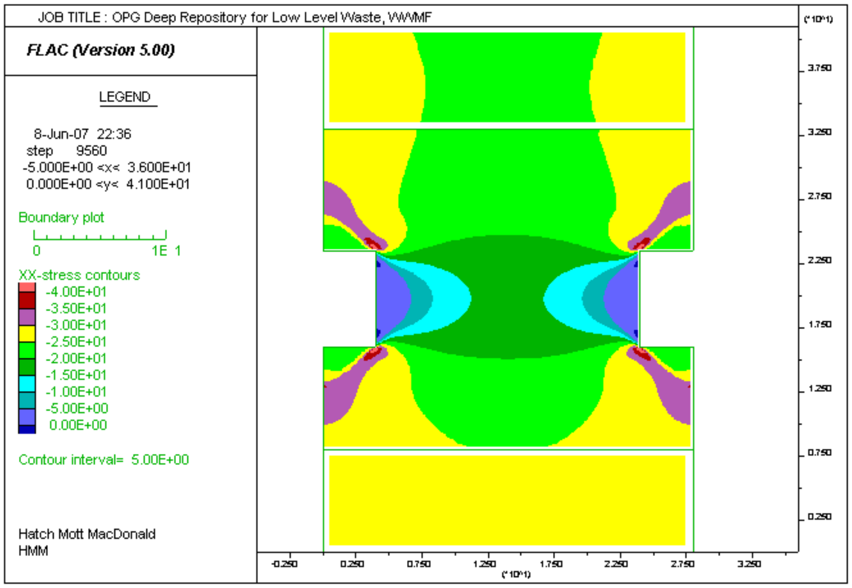


UCS = 72, GSI = 69, Pillar Width = 20.0m

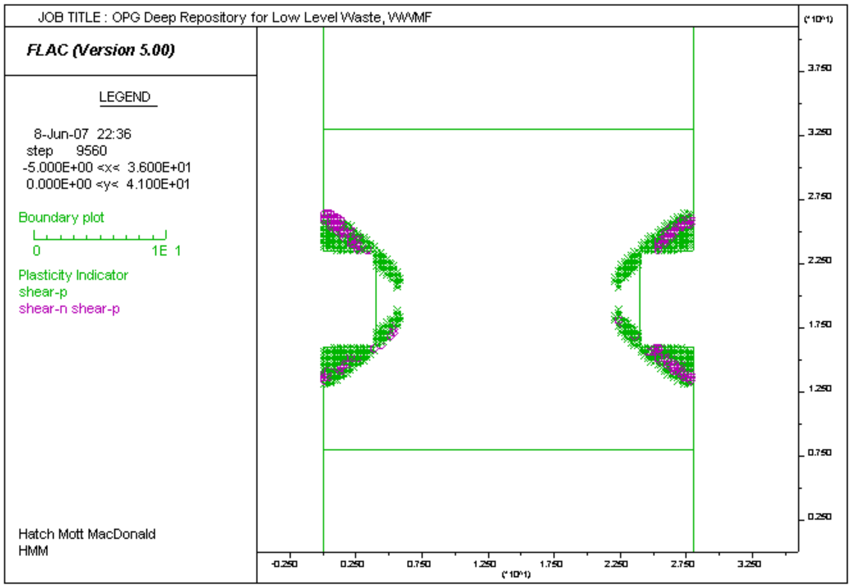
Vertical Stresses (MPa)



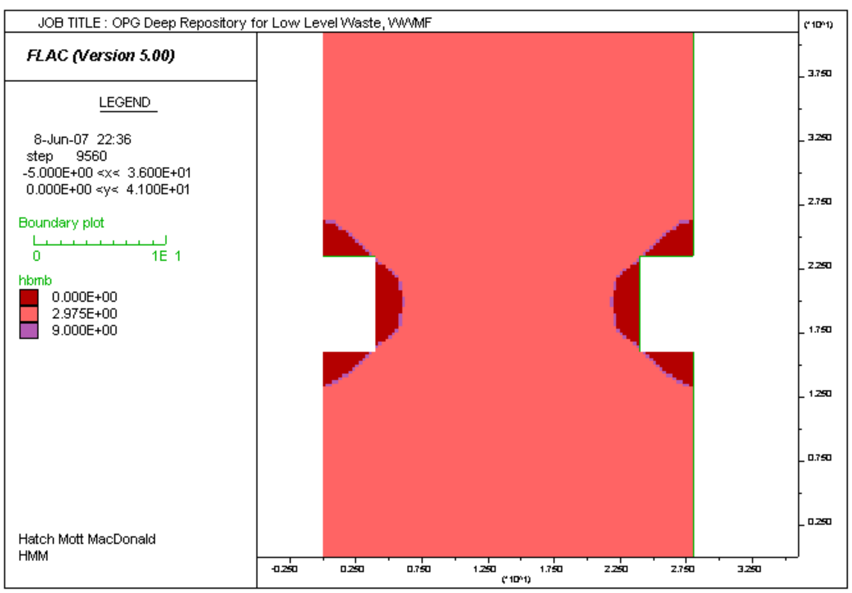
Horizontal Stresses (MPa)



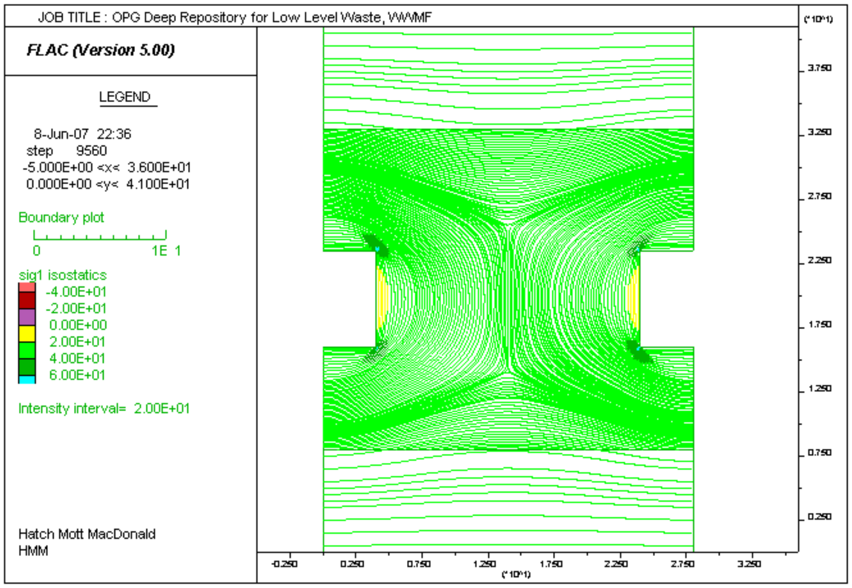
Plasticity Indicators



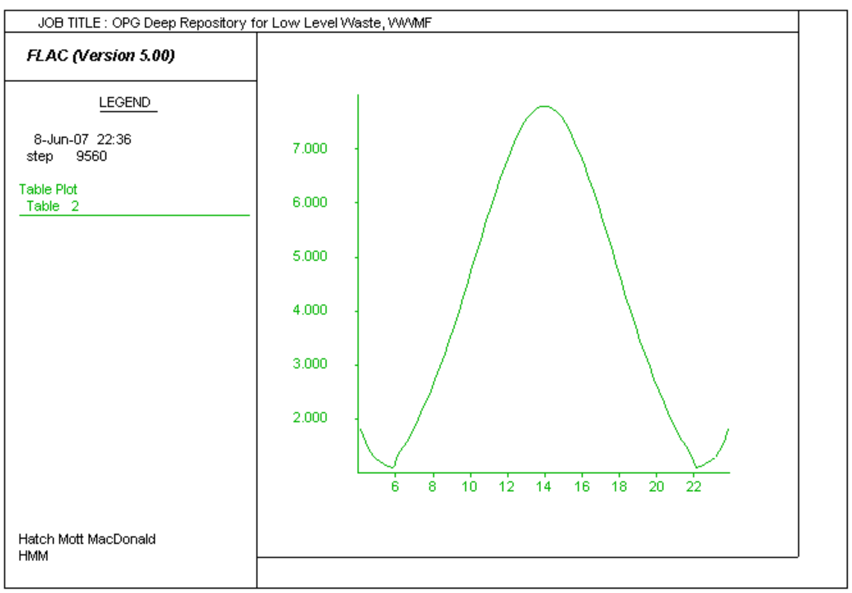
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

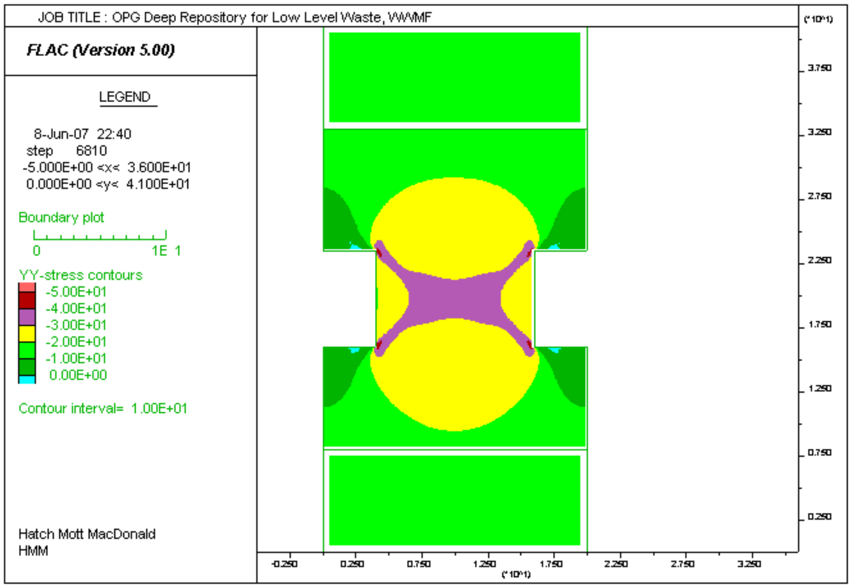


Factor Of Safety Across The Pillar

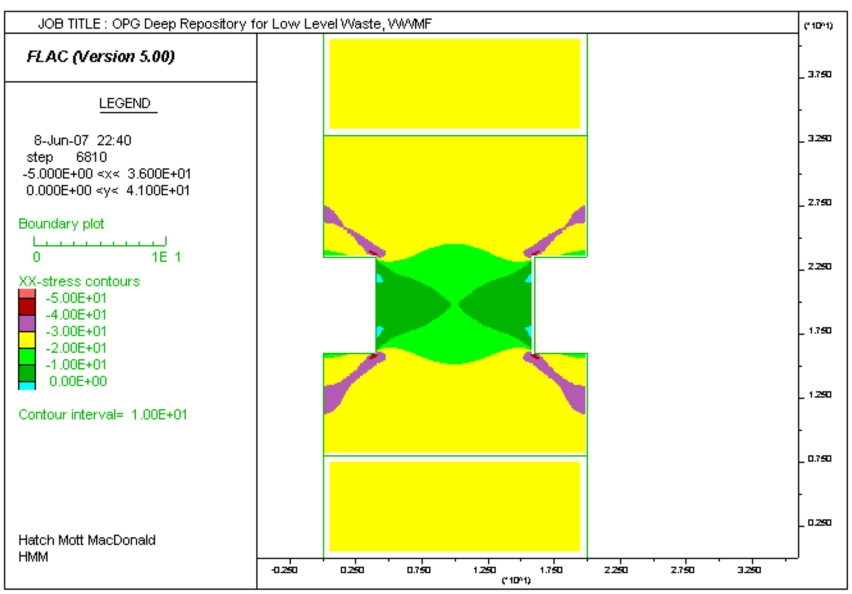


UCS = 72, GSI = 80, Pillar Width = 12.0m

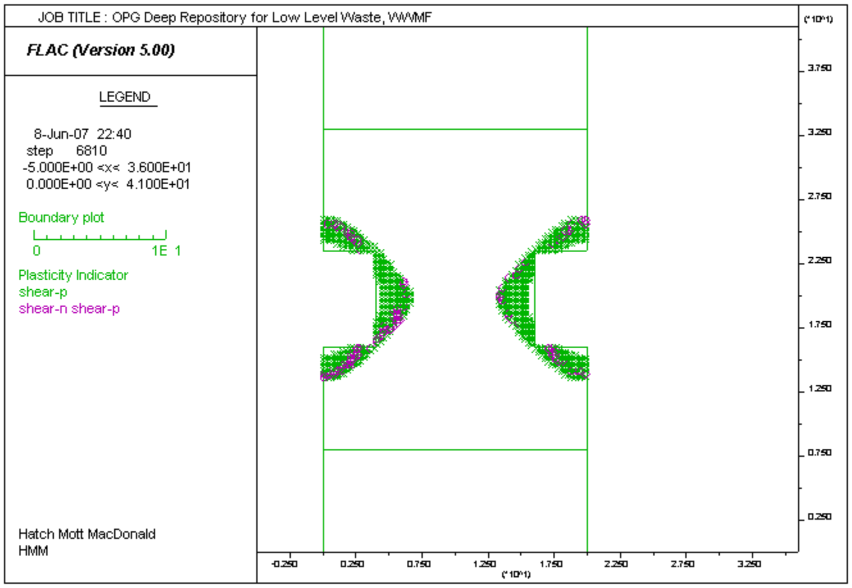
Vertical Stresses (MPa)



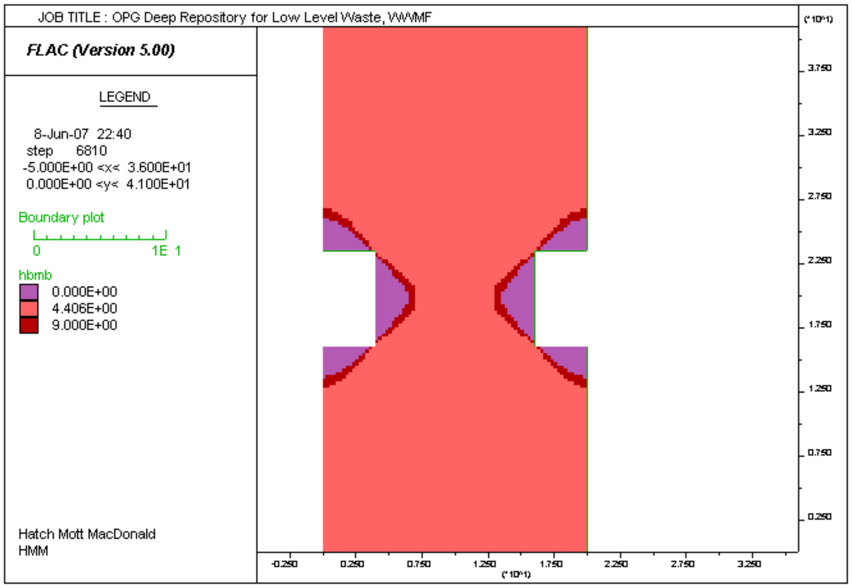
Horizontal Stresses (MPa)



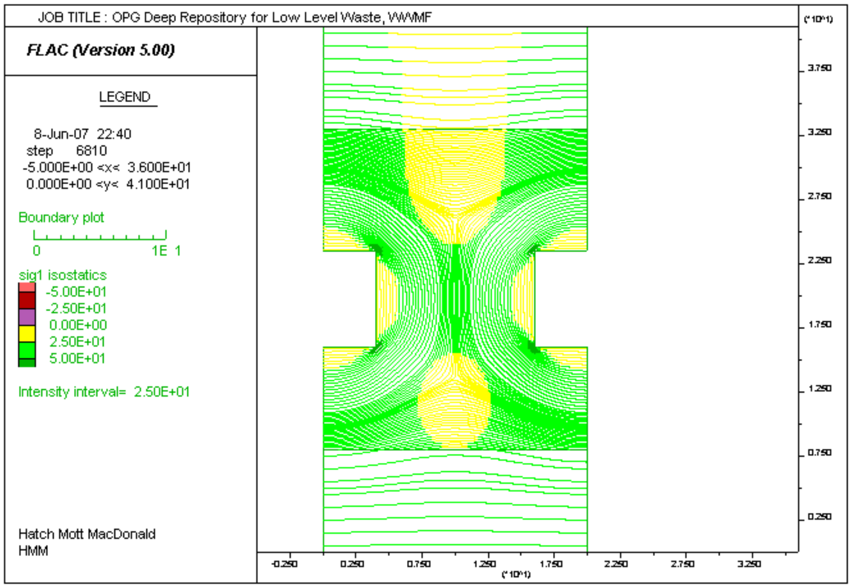
Plasticity Indicators



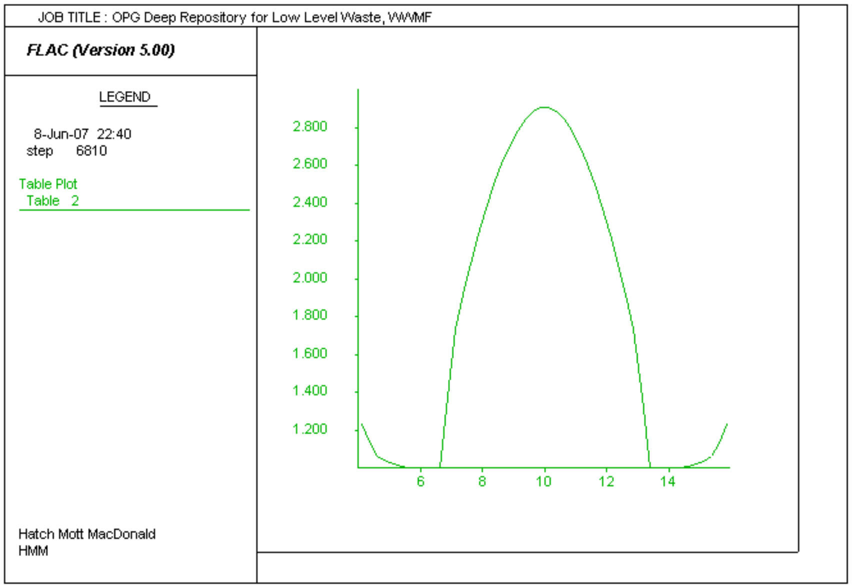
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

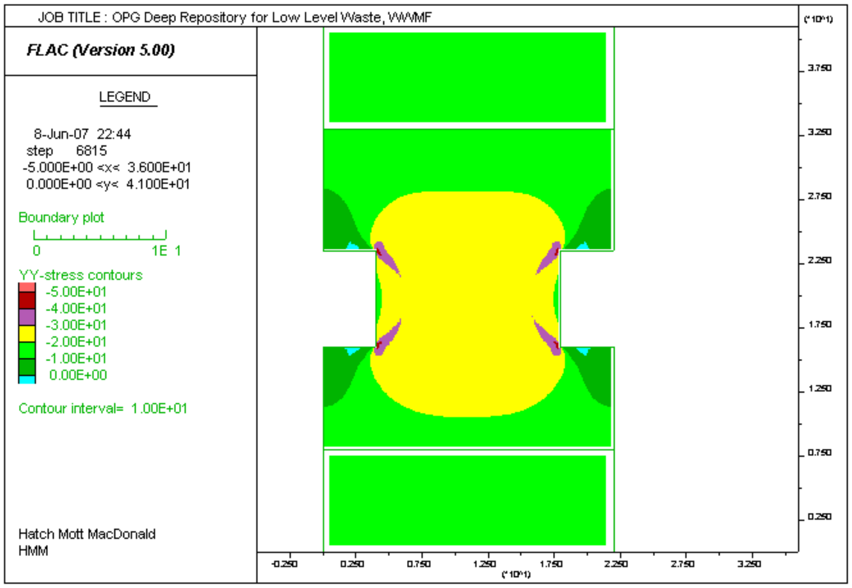


Factor Of Safety Across The Pillar

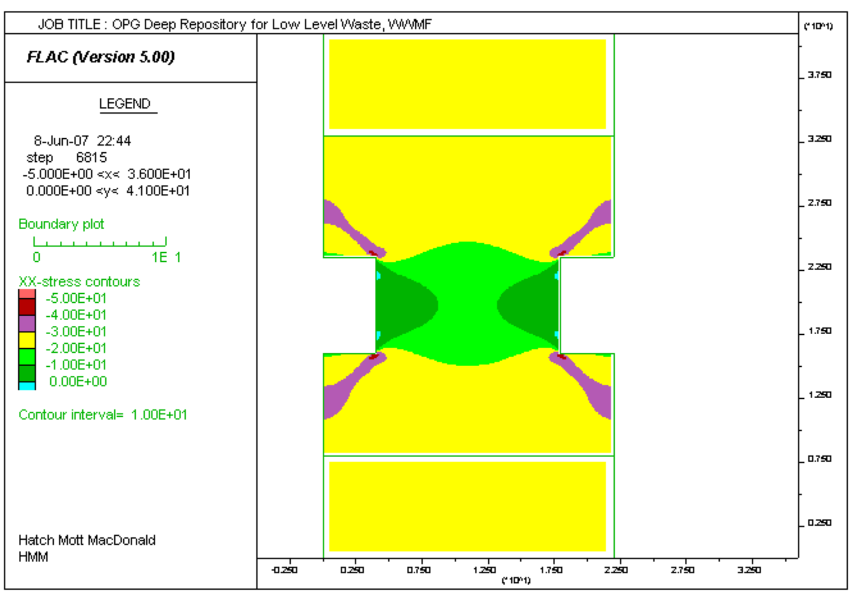


UCS = 72, GSI = 80, Pillar Width = 14.0m

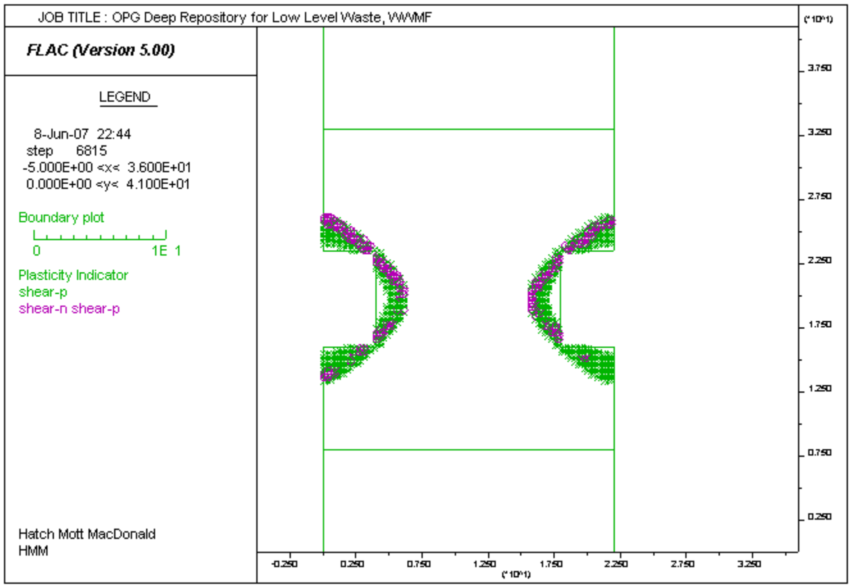
Vertical Stresses (MPa)



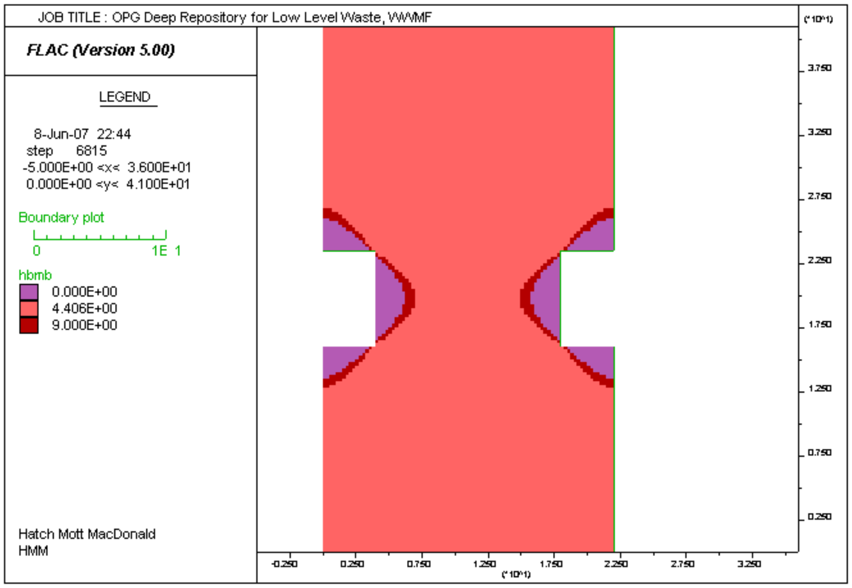
Horizontal Stresses (MPa)



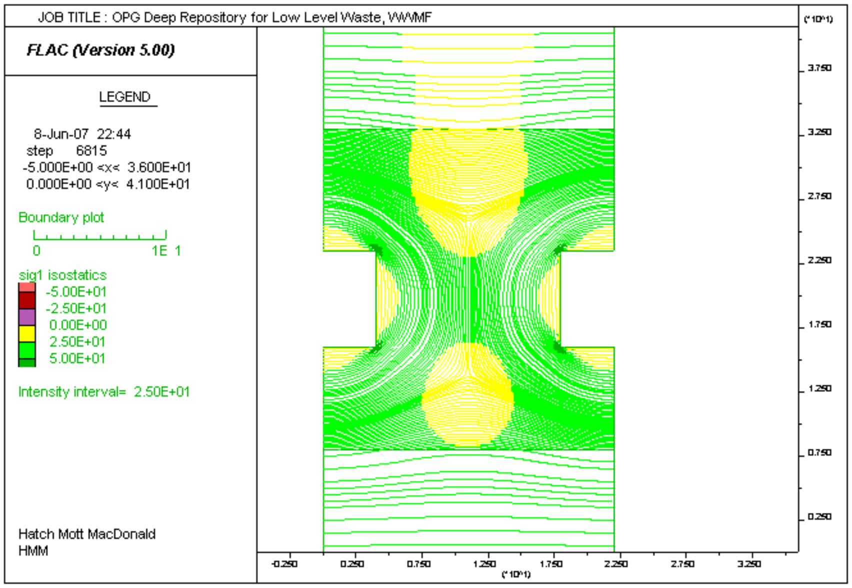
Plasticity Indicators



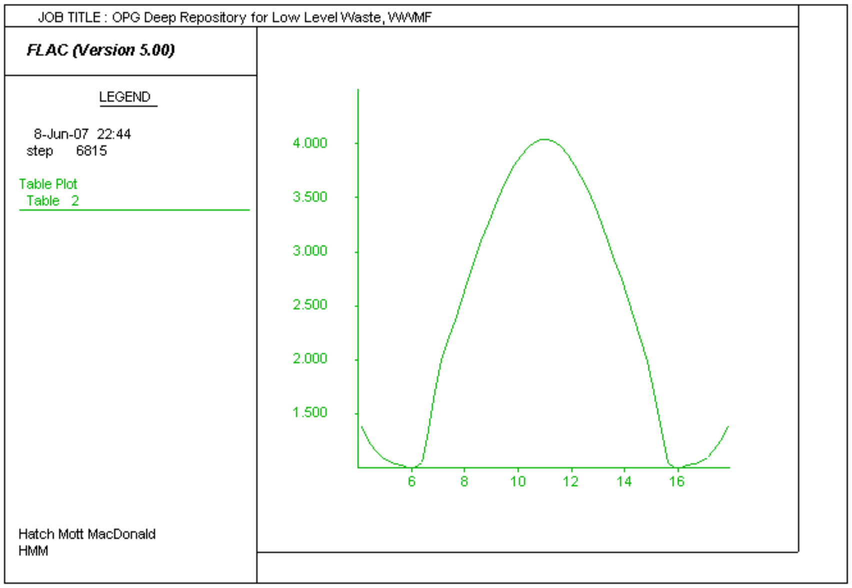
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

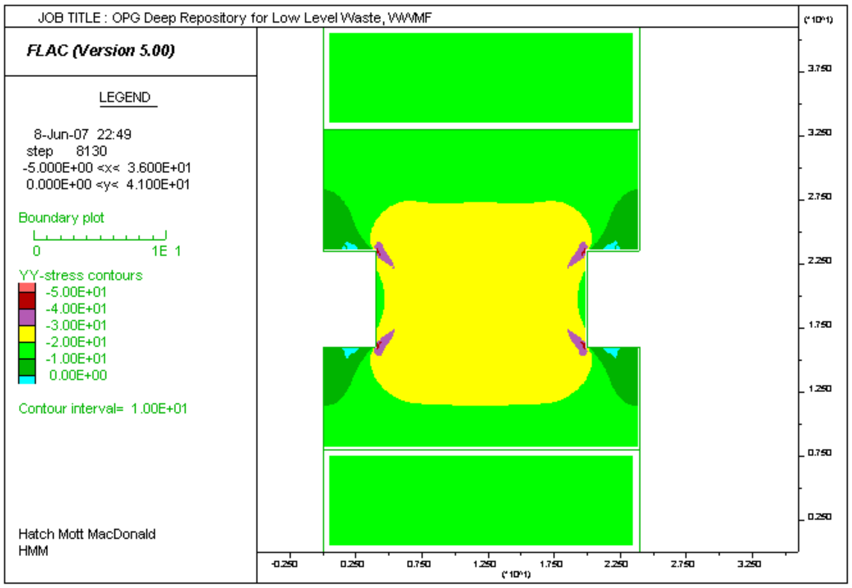


Factor Of Safety Across The Pillar

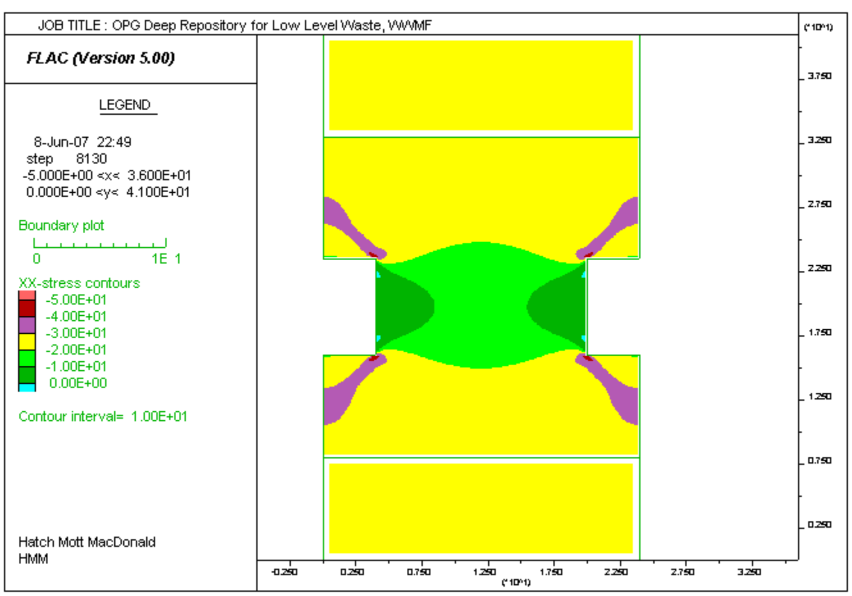


UCS = 72, GSI = 80, Pillar Width = 16.0m

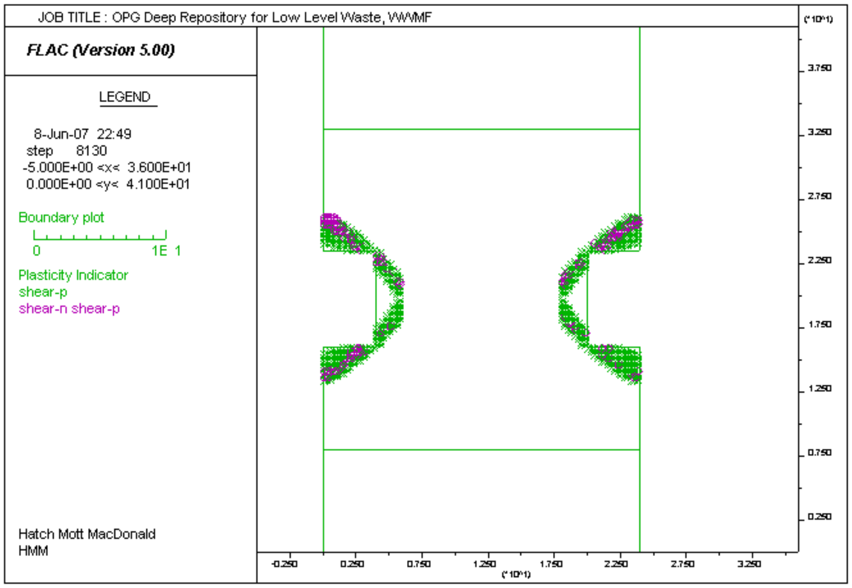
Vertical Stresses (MPa)



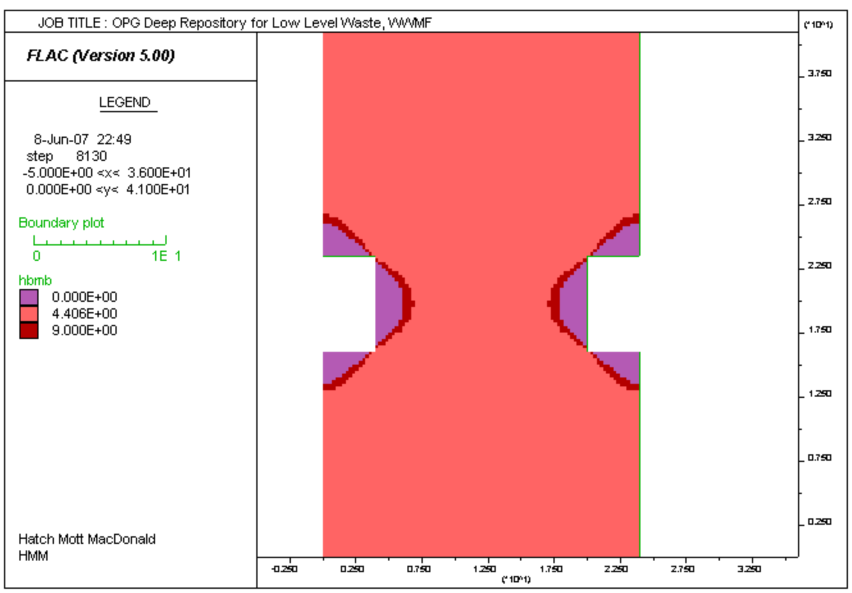
Horizontal Stresses (MPa)



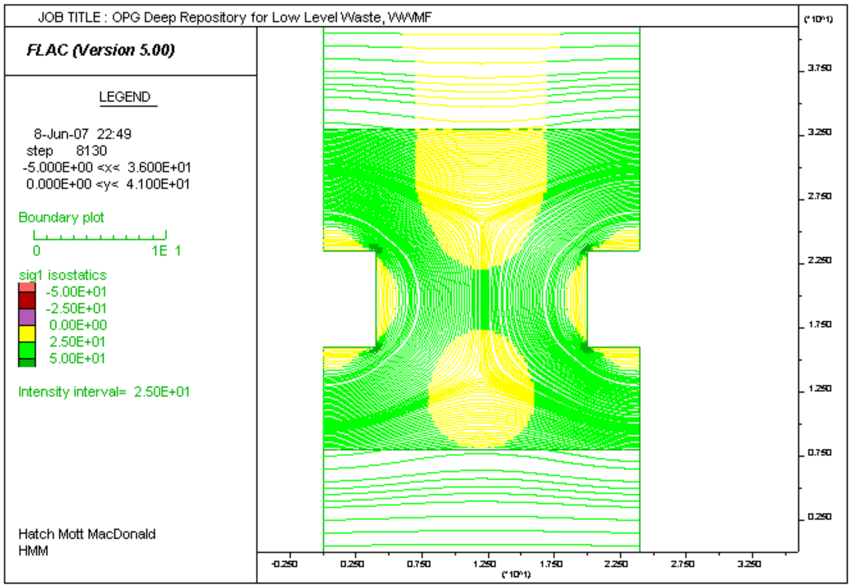
Plasticity Indicators



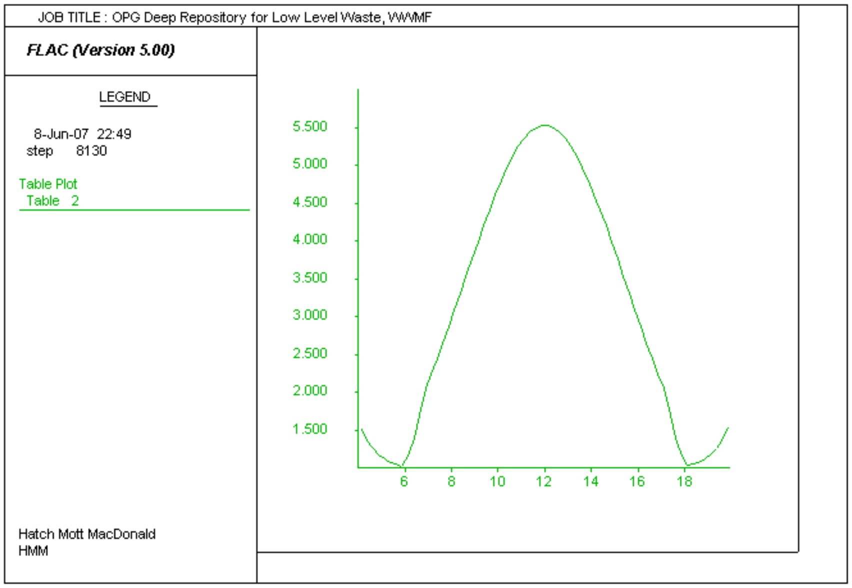
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

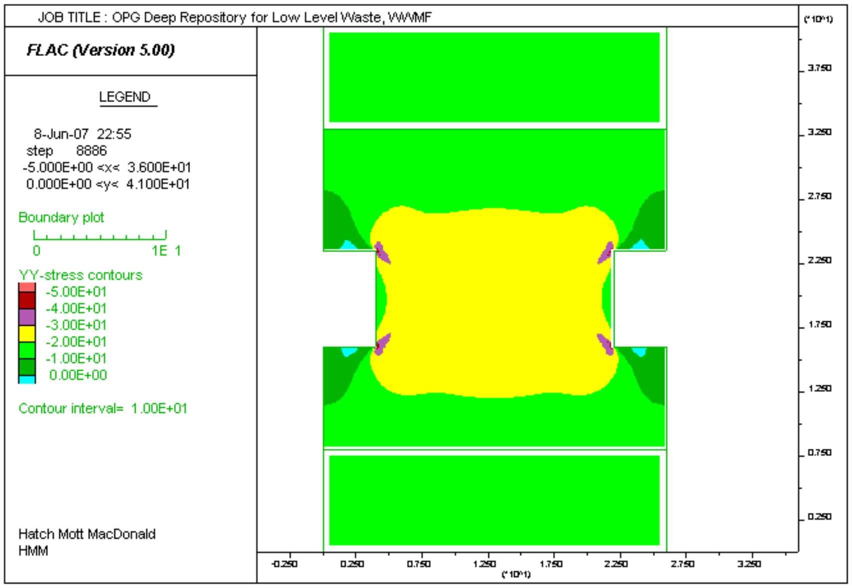


Factor Of Safety Across The Pillar

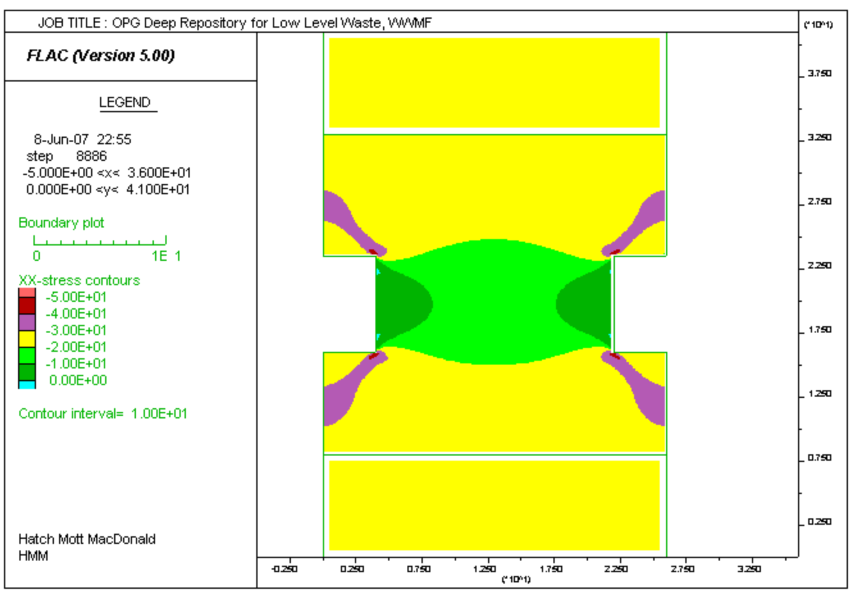


UCS = 72, GSI = 80, Pillar Width = 18.0m

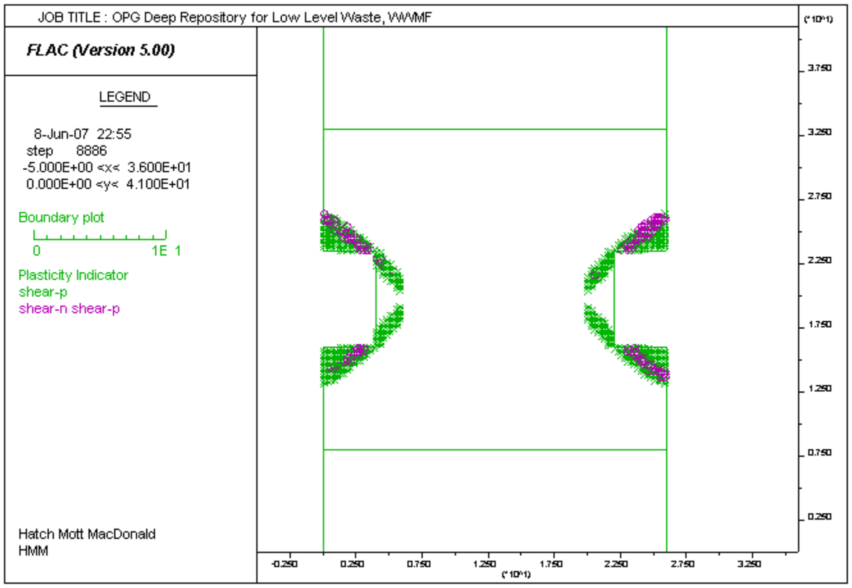
Vertical Stresses (MPa)



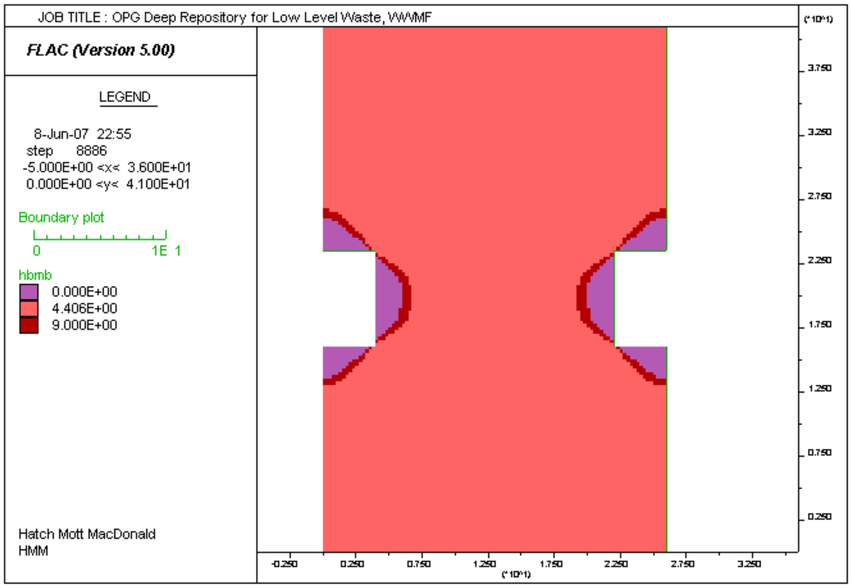
Horizontal Stresses (MPa)



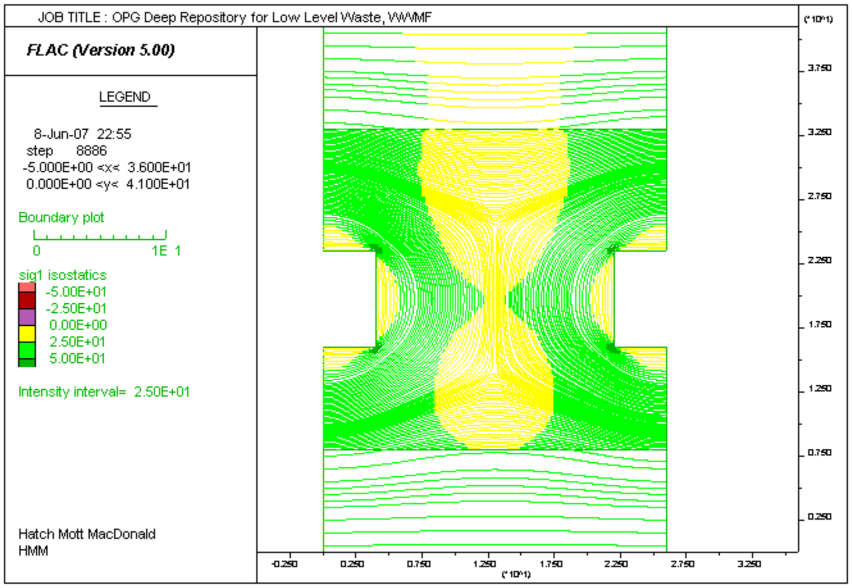
Plasticity Indicators



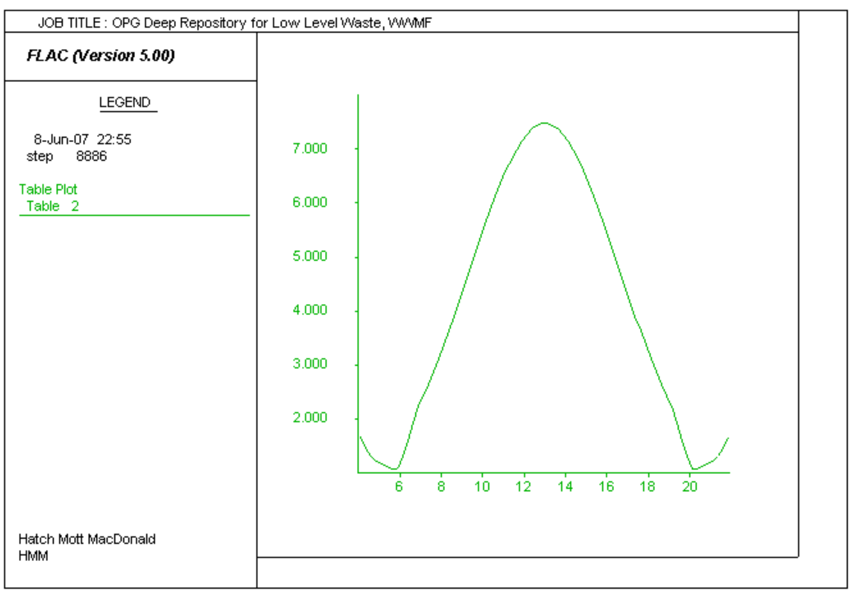
Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)

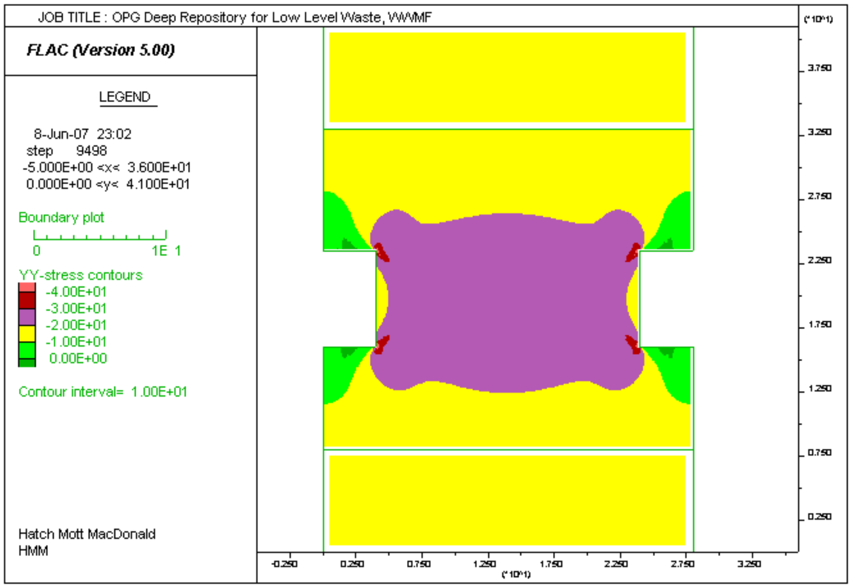


Factor Of Safety Across The Pillar

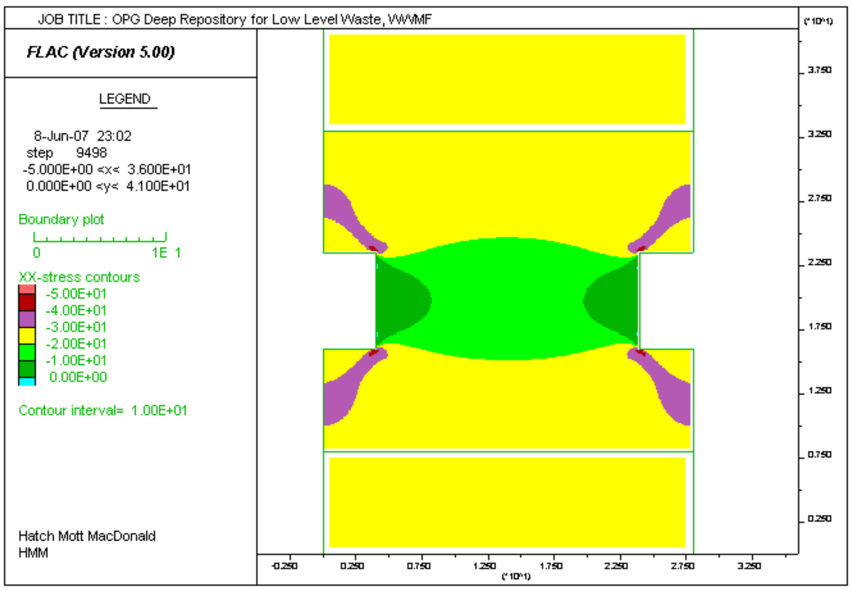


UCS = 72, GSI = 80, Pillar Width = 20.0m

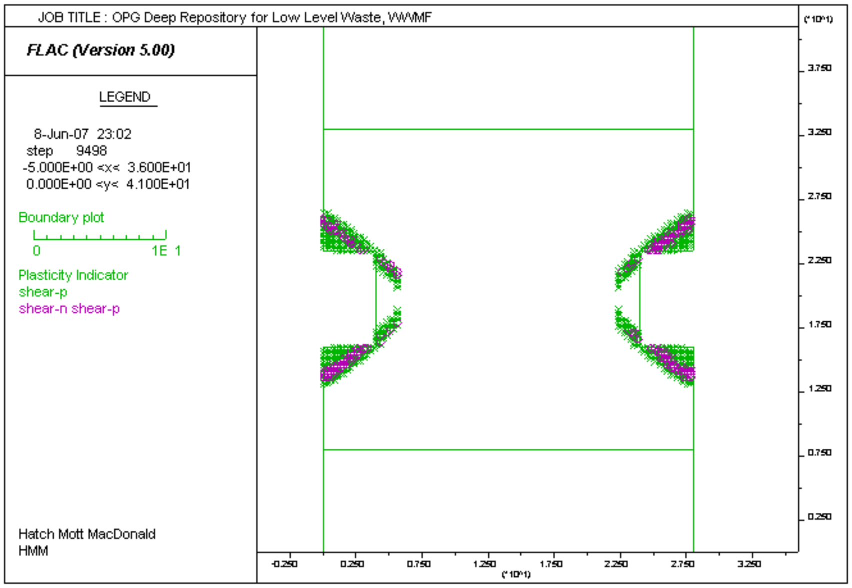
Vertical Stresses (MPa)



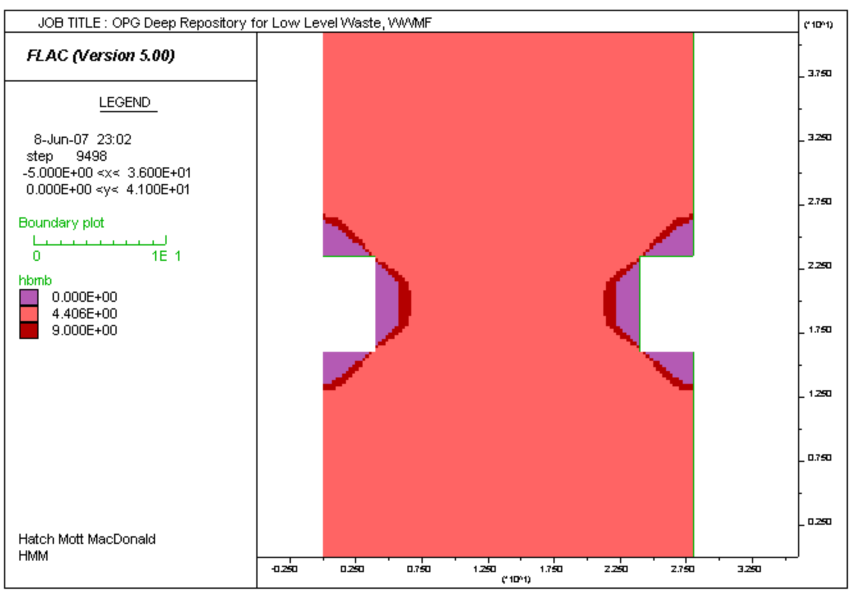
Horizontal Stresses (MPa)



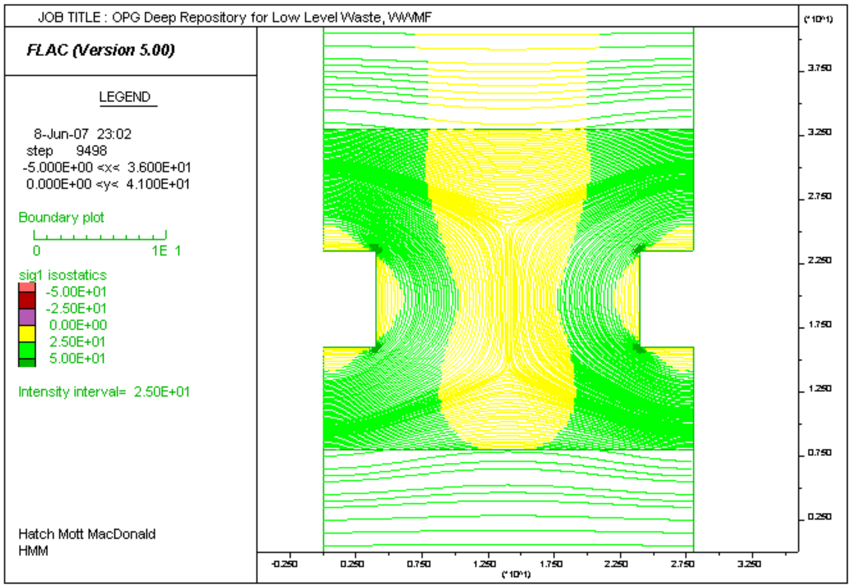
Plasticity Indicators



Failure Criteria (Brittle Failure, Hoek-Brown Peak Strength, Transition)



Maximum Principal Stress Trajectories (MPa)



Factor Of Safety Across The Pillar