Appendix A. Extraction ratio ... II
Appendix B. Qualitative risk assessment ... IX
Appendix C. Northparkes Mines E26 lift #2 ... XI
Appendix D. Rock Mass Rating ... XVII
Appendix E. Rock Tunneling Quality Index Q ... XVIII
Appendix F. Poisson's ratio ... XXII
Appendix G. Empirical pillar formulae ... XXIII
Appendix H. Disturbance factor ... XXX
Appendix I. Hoek-Brown m_i parameter ... XXXI
Appendix J. Flow Chart of Method ... XXXII
Appendix K. Factual report of the real-time monitoring system ... XXXIII
Appendix L. Undercut development MPBX data ... XXXV
Appendix M. Lithological plan E48 lift #1 ... XXXVI
Appendix N. MPBX Data processing ... XXXVII
Appendix O. Horizontal and vertical convergence ... XL
Appendix P. User-Defined S-shape *FISH* function ... XLII
Appendix Q. Design of NPM E48 lift #1 ... XLIV
Appendix R. FLAC^{3D} script ... XLVI
Appendix S. Joint surface condition factor ... LXX
Appendix T. Numerical modelling results ... LXXI
Appendix U. Virtual MPBX results ... CXI

Appendix A. Extraction ratio

According to Laubscher & Esterhuizen (1992), the stability of pillars and the packing of draw cones are not influenced to a great extent by the design of the extraction level. They emphasize that the orientation of pillars in the stress field is of more importance. For example, rock failures in mines with the El Teniente layout are more common when the major horizontal stress is aligned with the minor apices. The weakest parts of the pillar are the brows, bullnoses and camelbacks. Figure A-1 shows that brow stability is also linked to the orientation of discontinuities.

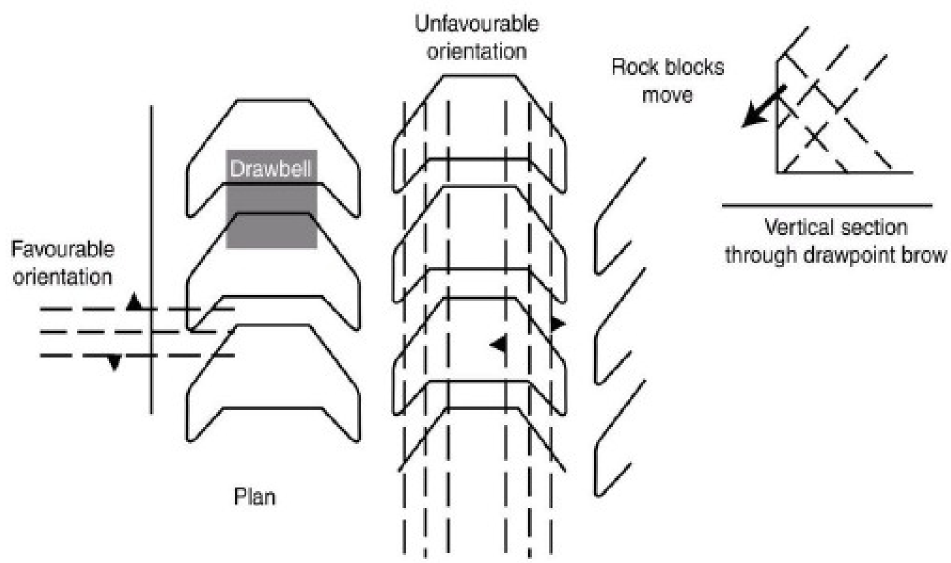


Figure A-1: The influence of discontinuity orientation on brow stability. (Laubscher, 2000)

Butcher (1999) came up with five design rules to minimise damage to the extraction levels.

1. Apply an advanced undercutting strategy if possible.
2. Irregularities in the undercut front should be kept to a minimum.
3. The rate of undercutting must be sufficient to prevent increasing amounts of damage.
4. The undercut level should be as high as possible above the extraction level.
5. The undercut must advance from the weakest to the strongest rock mass to ensure a quick start of cave propagation.

A large increase in damage on pillars occurs once the break-away drifts are (partly) developed prior to undercut advance. Furthermore, an increase in draw point spacing has not shown significant improvements. Research at the Henderson Mine concluded that a low extraction ratio reduces peak stress in tunnel walls, decreases sidewall movement up to 50%, decreases shear strain in the tunnel skin and results in less pillar failure. The remainder of this appendix shows the extraction ratio throughout development stages and compares extraction ratios for an advanced undercut and a post undercut strategy. Also, indications of the volumetric decrease of a pillar, once a damaged skin has emerged, are given. (Leach, *et al.*, 2000)

A.1 Two-dimensional

The application of post-undercutting strategies has shown severe damage to excavations at the extraction level. The amount of development at the extraction level prior to undercut advance is more important than the layout style with respect to stability. There are four stages of development that can be implemented in an advanced undercutting strategy if a horizontal cross-section of the extraction level is considered at half the tunnel height of the extraction drift. The drawbell is always developed after the undercut has advanced in this strategy. All four stages have different two-dimensional extraction ratios as described in Table 1. The dimensions of the infrastructure of block E26 lift #2 at Northparkes Mines, listed in Table 5, are used to calculate the extraction ratios. According to Butcher (1999), stress-induced damages become unmanageable after an extraction ratio of 60% and 40% extraction should not be exceeded to prevent moderate extraction level damage.

Table 1: Two-dimensional extraction ratios

Development	Extraction Ratio
None	0 %
Production drifts	14.1 %
Production drifts + 2 meter stubs	16.9 %
Production and break-away drifts	29.4 %
Production, break-away and trough drifts	36.7 %

A.2 Three-dimensional

The error between the design and the model of E26 lift #2 is negligible. No simplifications have been applied. The dimensions of the excavations and their corresponding error are shown in Table 2.

Table 2: Modelling accuracy

Offset herringbone layout with skull-shaped drawbells		Error
Production drift spacing	30 m	< 0.0015 m
Trough length	8.7m	< 0.0005 m
Draw point spacing (across minor apex)	18 m	< 0.0005 m
Break-away angle	45 °	< 0.05 ° (no ~)
Production drift dimension (w x h)	4.2 x 4.2 m	< 0.0005 m
Draw point drift dimension (w x h)	3.8 x 3.8	< 0.0005 m
Undercut inclination	54 °	< 0.05 ° (no ~)
Difference undercut and production level	14 m	< 0.0005 m

An 'initial volume' allocates a volume of rock that belongs to a repeatable section of the extraction level and has per definition an extraction ratio of 0%. This geometrical definition is required when defining a three-dimensional extraction ratio. The perimeter of the 'initial volume' is defined by applying the tributary area method on the pillars at the extraction level. The upper boundary is defined by the bottom surface of the crinkle cut profile. The lower boundary is not at the floor of the extraction level, because the damage skin of drifts at the extraction level extents all around the excavation, so also below the floor of the drifts. The position of the lower boundary is 5 meters below the floor of the production tunnel, this distance is chosen arbitrarily. Figure A-2a shows the obtained geometrical shape of the volume dedicated to the repeatable section. The rock mass immediately surrounding a single pillar contributes to a great extent to the pillar strength. The 'initial volume' and all its derived calculations should therefore not be related directly with stability issues.

A.2.1 Advanced undercut application

Mining operations applying the advanced undercut strategy expose a part or all of their tunnels at the extraction and undercut level to high abutment stresses. The unconfined rock surrounding these excavations has to remain stable long after the stress shadow of the undercut has passed over. These initial high stresses and lower long-term stresses may cause brittle failure. A full development of extraction and undercut level tunnels (production, break-away and trough drifts) is assumed in all scenarios described below. Confinement created by fragmented ore prevents the initiation of a damage zone inside the drawbell. After blasting the drawbell this condition also accounts for the trough drift, but the same damage skin is allocated to the trough drift as to the others in the following calculations. The volume and extraction ratios that accompany damage skins of 1.0, 1.5 and 2.0 meters are listed in Table 3.

Table 3: Damage skin simulation of tunnels

	Method	Damage skin (m)	Volume (m^3)	3D Extraction Ratio
a	'Initial volume'	0	11,887	-
b	Initial design	0	9,743	18%
c	Damage skin	1	8,673	27%
d	Damage skin	1.5	7,999	33%
e	Damage skin	2.0	7,245	39%

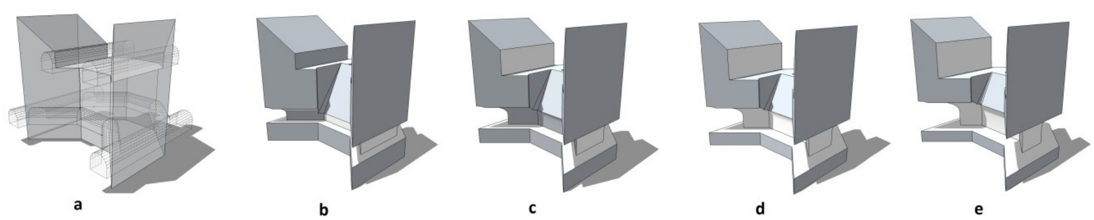


Figure A-2: Pillar dedicated volume (a) and damage zones of 0m (b), 1m (c), 1.5m (d) and 2.0m (e)

A.2.2 Post-undercut application

A damage skin can be applied to the drawbell as extension to the scenarios described in the previous section. Mining operations using the post-undercut strategy blast drawbells before the undercut advances. Therefore, the drawbells are subjected to high stresses for a brief period of time. Section A.3 and A.4 describe two different methods to calculate the volume of a damaged pillar. The 'Joint Push Pull'-tool and the manual method both have their advantages and disadvantages, but the volumetric differences between the two approaches is negligible on mining scale. The geometrical result of the manual method is much more realistic, but the ease of operation and the repeatability of actions plead for the use of the 'Joint Push Pull'-tool. The lower boundary of the 'pillar dedicated volume' in the following scenarios is set to floor of the extraction level and all tunnels are initially assumed to be square. The comparability of calculated volumes with real cases is compromised by these assumptions. The results of the scenarios applied on all drifts at the extraction level, undercut level and the drawbell are listed in Table 4.

Table 4: Damage skin simulation including drawbell

	Method	Damage skin (m)	Volume (m^3)	3D Extraction Ratio
	'Initial volume'	0	9187	-
a	Initial design	0	7137	22%
b	Manual modelling	1	5477	40%
c	'Joint Push Pull'	1	5503	40%
d	'Joint Push Pull'	1.5	4693	49%
e	'Joint Push Pull'	2.0	3913	57%

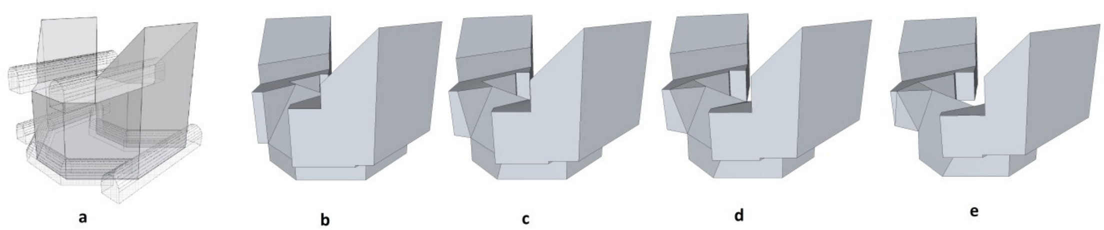


Figure A-3: Pillar dedicated volume (a) and damage zones of 0 (b), 1.0m (c), 1.5m (d) and 2.0m (e)

A.3 'Joint Push Pull'-tool

The standard 'Push Pull' function in SketchUp Pro 8 can add volume to or subtract volume from the model. It will perform this operation normal to the selected face and is not able to handle more than one face in a single operation. The 'Joint Push Pull'-tool is able to handle multiple faces in a single operation. The tool is a mix between an offset of faces along their normal and a vector to generate a uniform thickness and contiguous shape, see Figure A-4. It works well with both curved and straight angled faces.

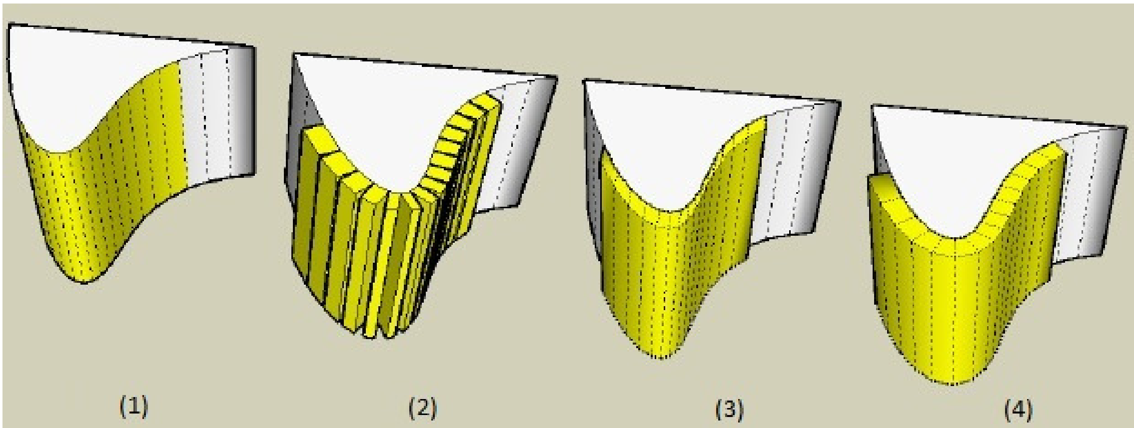


Figure A-4: The 'Joint Push Pull'-tool (4) is a combination of vectorial (3) and normal (2) extension of the original faces (1).

An exact mathematical solution for this application is not available. This tool calculates the arithmetic mean of normal vectors by group to come up with new edges and faces. The tool is able to privilege a plane while reshaping. This function is irrelevant for this model since it needs multiple planar constraints for different sections of the model.

The operation is performed on all unconfined surfaces, which should be selected on forehand. The original faces should be erased and only borders on outer faces should be allowed. One of the settings, the 'Angle of Influence', is vital for a good geometrical result. All surfaces with a difference between their normal vectors smaller than the 'Angle of Influence' are weighted as one when calculating new coordinates for edges and their intersections. The smallest difference in the orientation of faces that matters to the geometry of the pillar is the slope of the minor apex (34.8°). Therefore, the 'Angle of Influence' is set to 30° make sure that it accounts for the border between these faces. The 'Joint Push Pull'-tool is now able to create a damage skin of preferred thickness. This skin has to be connected manually to the confined faces, not included in the operation. The outer borders of the confined faces can be erased. After some minor changes on extra faces created by the tool, the damage skin is created.

The result of the 'Joint Push Pull'-tool is geometrically not optimal. Multiple edges that intersect at one point in the original design cannot be disconnected by the tool to create new edges. This leads to new orientations for, for example, previously horizontal or vertical edges and subsequently to a deviated geometry as depicted in Figure A-5. Figure A-6 shows increasing loss of geometry with an increasing damage skin.

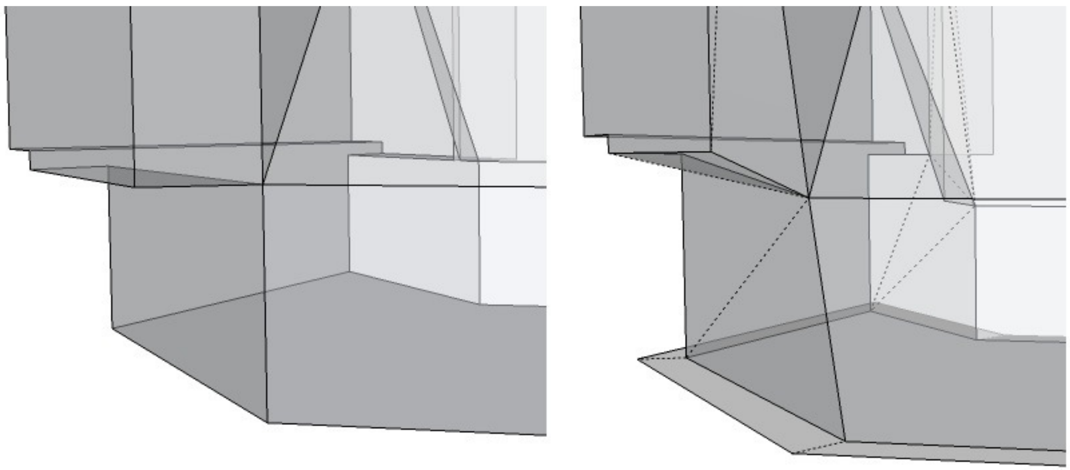


Figure A-5: Geometrical error in Joint Push Pull tool

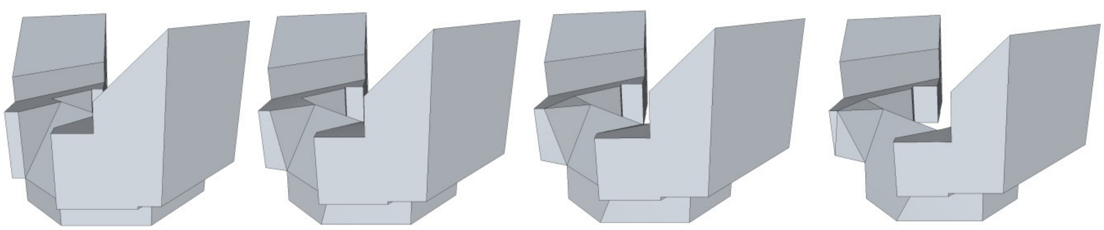


Figure A-6: Loss of geometry due to the "Joint Push Pull'-tool. The initial design is depicted on the left and the damage skin increases towards the right.

A.4 Manual modelling

Manual modelling of small details, especially at intersections of a great amount of edges, has to be done in order to meet the requirement of a damage skin of at least one meter, normal to all free faces. Although the geometry stays intact, the volume reduction is overestimated in sharp corners. The differences between manual modelling and the use of the 'Joint Push Pull'-tool are shown in Figure A-7.

The interpretation of a volume reduction along the normal of surfaces of a solid creates difficulties at corners when arcs are not used. When a corner is bigger than 180°, measured at the exterior, the true skin is simulated. In other words, the shortest distance from the new face to the old face is exactly the requested amount. When a corner is smaller than 180°, measured at the exterior, the volume reduction is overestimated. The shortest distance towards the old face is for some points along the new face more than the requested amount. These places are relatively confined compared to other places in the skin and thus will not easily fail. The sharper the corner is, the bigger the total deviation in volume. This issue is illustrated in two dimensions in Figure A-8. Thus, the three-dimensional extraction ratio retrieved by manual modelling is a worst case scenario.

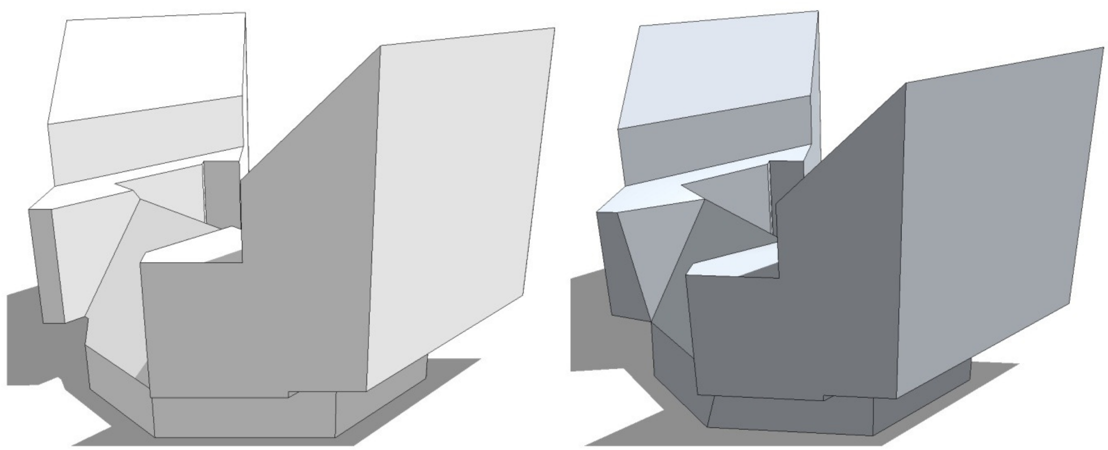


Figure A-7: Manual modelling on the left versus the result from "Joint Push Pull"

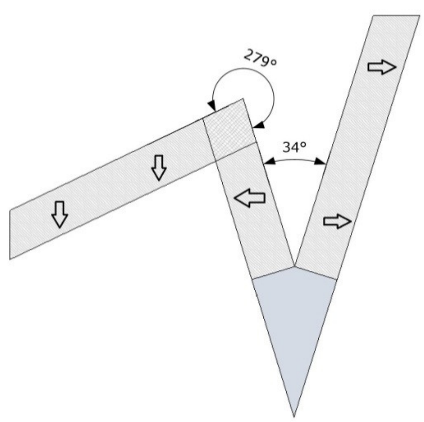


Figure A-8: Hypothetical two-dimensional overestimate in volume reduction

Appendix B. Qualitative risk assessment

Consequence		Minor (1)	Medium (2)	Serious (3)	Major (4)	Catastrophic (5)
Health		Reversible health effects of little concern, requiring first aid treatment at most. Can include minor irritations of eyes, throat, nose and or skin, or minor unaccustomed muscular discomfort.	Reversible health effects of concern that would typically result in medical treatment. Can include temperature effects; travel effects; stress; and sunburn.	Severe, reversible health effects of concern that would typically result in a lost time illness. Can include acute / short-term effects associated with extreme temperature effects; or musculo-skeletal effects; vibration effects; nervous system effects; some infectious diseases.	Single fatality or irreversible health effects or disabling illness. Can include progressive chronic conditions and/or acute / short-term high-risk effects.	Multiple fatalities or serious disabling illness to multiple people. Can include effects of carcinogens, mutagens, teratogens and reproductive toxicants (known and suspected), and life-threatening respiratory sensitization and malaria
Safety		Low level short term subjective inconvenience or symptoms. Typically a first aid and no medical treatment.	Reversible injuries requiring treatment, but does not lead to restricted duties. Typically a medical treatment.	Reversible injury or moderate irreversible damage or impairment to one or more persons. Typically a lost time injury.	Single fatality and/or severe irreversible damage or severe impairment to one or more persons.	Multiple fatalities or permanent damage to multiple people.
Environment		Near-source confined and promptly reversible impact (Typically a shift)	Near-source confined and short-term reversible impact (Typically a week)	Near-source confined and medium-term recovery impact (Typically a month)	Impact that is unconfined and requiring long-term recovery, leaving residual damage (Typically years)	Impact that is widespread-unconfined and requiring long-term recovery, leaving major residual damage (Typically years)
Community / Reputation		Damage to reputation of reputation of work area within an operation	Damage to reputation of several work areas within an operation. One off public exposure in local media, word of mouth or local mythologies	Damage to reputation of Business. Significant public exposure in local media	Damage to reputation of Product Group. Criticism from national NGO which impacts credibility with neighbours/regional government. Public exposure in national media	Damage to reputation of Rio Tinto Group. Criticism from international NGO. Public exposure in international media
Compliance		Non-conformance with internal operational procedure with low potential for impact.	Non-compliance with external standard, contract or operating procedure with low potential for impact	Non-compliance with moderate potential for impact eg. one-off non compliance with work permit or licence; fine for breach of permit or licence	Breach of licences, legislation, regulation or repeated non-compliance with high potential for prosecution. Breach of contract with penalty clauses imposed. Non-conformance with Corporate or Product Group work cycles or standards	Suspended or severely reduced operations imposed by regulators

B-1: Qualification of the consequence of events per category.

Likelihood		Likelihood description	Frequency	Substance Exposure (Health)
A	ALMOST CERTAIN	Recurring event during the life-time of an operation / project	Occurs more than twice per year	Frequent (daily) exposure at > 10 x OEL
B	LIKELY	Event that may occur frequently during the life-time of an operation / project	Typically occurs once or twice per year	Frequent (daily) exposure at > OEL
C	POSSIBLE	Event that may occur during the life-time of an operation / project	Typically occurs in 1-10 years	Frequent (daily) exposure at > 50% of OEL Infrequent exposure at > OEL
D	UNLIKELY	Event that is unlikely to occur during the life-time of an operation / project	Typically occurs in 10-100 years	Frequent (daily) exposure at > 10% of OEL Infrequent exposure at > 50% of OEL
E	RARE	Event that is very unlikely to occur very during the life-time of an operation / project	Greater than 100 year event	Frequent (daily) exposure at < 10% of OEL Infrequent exposure at > 10% of OEL

B-2: Qualification of the likelihood of occurrence of an event.

Likelihood	Consequence				
	1 - Minor	2 - Medium	3 - Serious	4 - Major	5 - Catastrophic
A - Almost Certain	Moderate	High	Critical	Critical	Critical
B - Likely	Moderate	High	High	Critical	Critical
C - Possible	Low	Moderate	High	Critical	Critical
D - Unlikely	Low	Low	Moderate	High*	Critical
E - Rare	Low	Low	Moderate	High*	High*

B-4: Risk matrix

RISK CLASS (AS PER RIO TINTO GUIDE)

Critical	Class IV (URGENT ACTION)
High	Class III (PROACTIVE MANAGEMENT)
Moderate	Class II (ACTIVE MONITORING)
Low	Class I (DO NOT REQUIRE ACTIVE MANAGEMENT)

B-3: Risk classes

Appendix C. Northparkes Mines E26 lift #2

Full production at the E26 ore body commenced in 1997 at the extraction level of Lift #1, 480 meters below surface, after three years and nine months of development. Much has been learned from experiences during construction and production of lift #1. The Endeavour 26 lift #1 was the first block cave in Australia. The second production zone, called lift #2, was developed 350 meters below lift #1, depicted in Figure C-1. (Duffield, 2000)

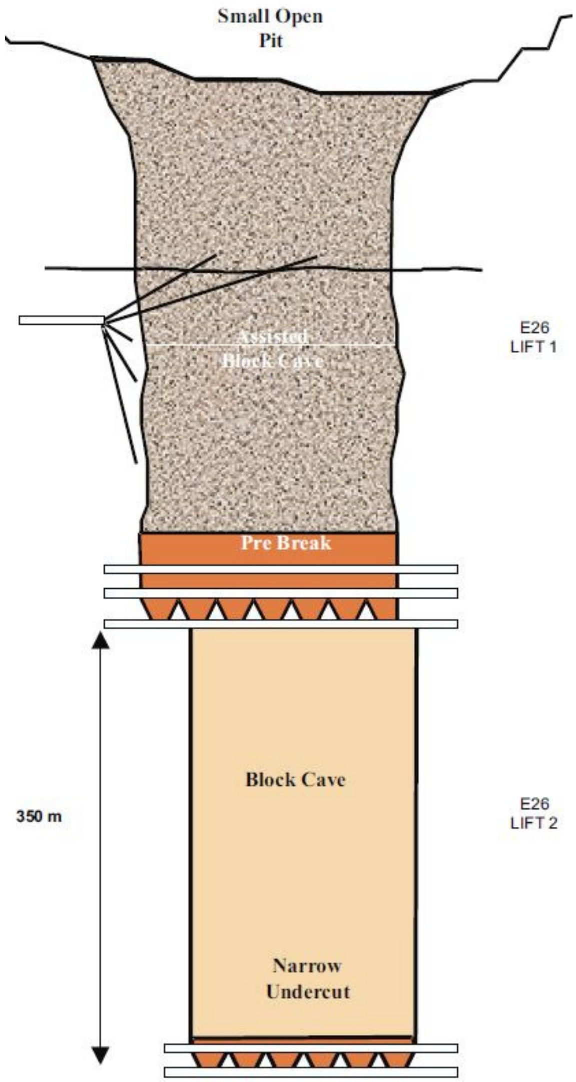


Figure C-1: Cross-section ore body E26 (Duffield, 2000)

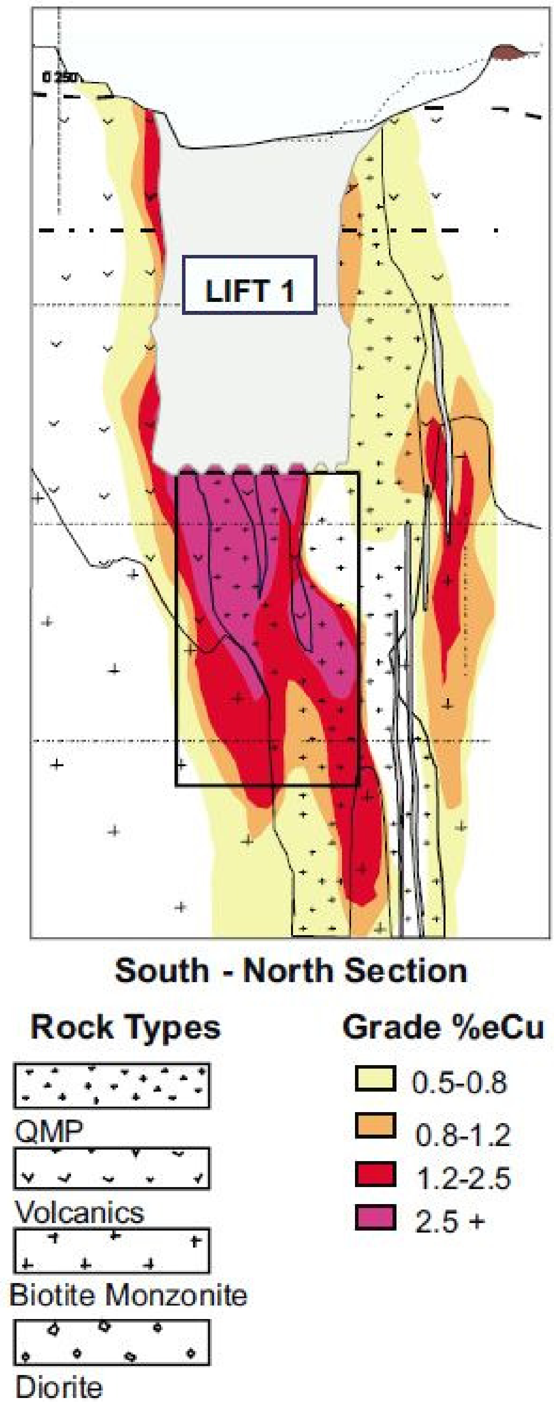


Figure C-2: Local geology E26 ore body (Duffield, 2000)

Reserves of 24.5 Mt @ 1.21 per cent copper and 0.47 g/t gold were reported in 2000. The copper sulphides are contained in a Quartz Monzonite Porphyry (QMP) which intrudes volcanic rock and Biotite Quartz Monzonite (BQM). The central core of the deposit has high copper grades, since the copper is contained within fractures and quartz veins. The grade decreases radially outwards into the surrounding rock (Figure C-2). The intact rock strength is on average 80 – 91 MPa, but outside the porphyry it can reach a maximum of 136 MPa in the BQM and 227 MPa in the volcanics. The rock mass is well jointed and some faults and shear zones are present with a northwest trend. Most fractures are pervaded with gypsum. (Duffield, 2000) These findings conclude in MRMR values of 50 for the volcanics, 51 for the QMP and 57 for the BQM. At the undercut level, the major principal stress is sub-horizontal and orientated east-west. The minimum principal stress is vertical and equals approximately the overburden pressure.

$\boldsymbol{\sigma_1}$	east-west	52 MPa
$\boldsymbol{\sigma_2}$	north-south	33 MPa
$\boldsymbol{\sigma_3}$	vertical	23 MPa

The emphasis during the feasibility study was on a minimisation of capital expenditure and the detainment of extremely low operating costs. The caveability of lift #2 was better compared to lift #1, due to higher *in situ* stresses, favourable joint orientation and a crinkle-cut. Lift #2 used an advanced undercut strategy. The shape of a section of the undercut is narrow and inclined, also called ‘crinkle cut’, and exists of 14 parallel drives running from east to west. The undercut is inclined above the major apices and flat above the draw bells. Detailed dimensions are discussed in subsection C.1. The plan view dimensions are 210 x 182 meters. The face advanced from west to east, retreating towards the access and protecting the crusher chamber in the west from high abutment stresses. The bearing of the cave line of 065 degrees was optimal to minimise abutment stresses and maximise lag distances. The position of the cave line in November 2003 is shown in Figure C-3. (Silveira, 2004).

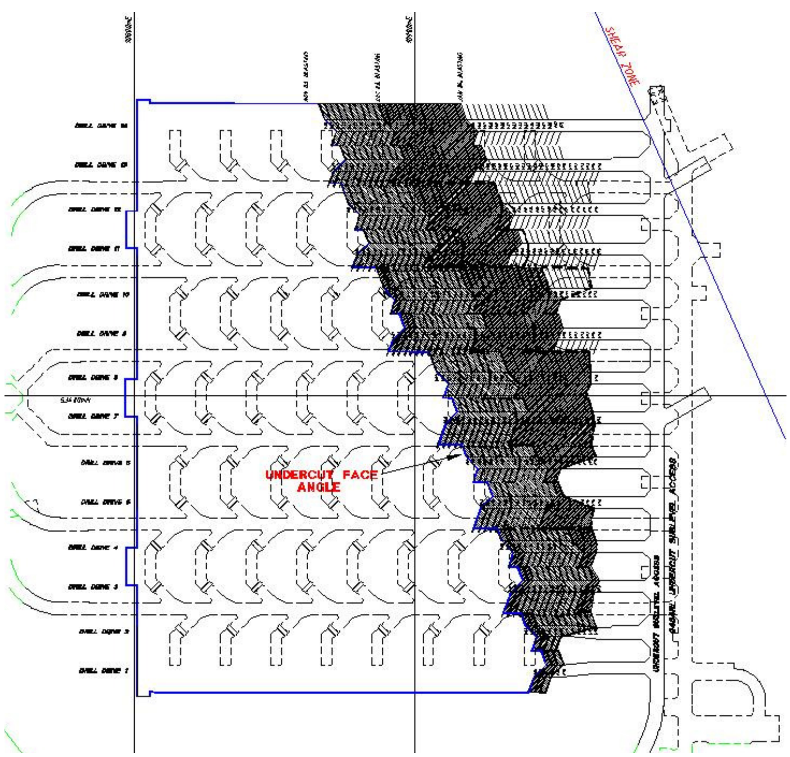


Figure C-3: Advancing cave line over the extraction level (Silveira, 2004)

Only the production drifts were developed ahead of the cave line. The undercut creates a stress shadow for the development of draw bell drifts and draw bells on the extraction level. These developments are carried out under an angle of 45 degrees, lacking at least 14 meters, from the cave front. The abutment stresses at the cave front make the extraction level vulnerable at high extraction ratios. The advanced undercut strategy minimizes the extraction ratio in areas subjected to abutment stresses.

Production drilling of the undercut has started on the 5th of February 2003 and was successfully completed within budget 11 months later. During this period, 70 per cent of the fired tonnes of ore have been mucked. Undercutting rates were increased in the second half of 2003 so the average standing period of a heading was 1 week. This way, the abutment zone was continuously moving and stress did not have time to build up significantly. The amount and length of cracking in the shotcrete of the undercut drives was recorded monthly as well as minor spalling between the floor and the bottom of shotcrete. These observations were limited to 15-20 m in front of the undercut. Horizontal extensometers between the undercut drives showed less than one millimetre dilation in the pillars. The draw bell drilling commenced at the end of 2003 and was finished 8 months later. In total the project included 59 draw bells, which were developed throughout the life of the project. They should count for a total planned production of five million tonnes per annum. The estimated life of mine was around six years. (Silveira, 2004)

The extraction level is developed according to the offset herringbone layout. Since it is very hard for LHDs to take a right angled turn, let alone a sharper one, all draw points in this layout are accessed from the same direction. This favours the use of electric LHDs, since the electric cable behind the vehicle cannot be run over in this setup as it is tethered at one point. Six Toro 450E units have been taken over from lift #1 to start the operation. Their capacity is six cubic meters and they have 260 meters of trailing cable. The offset herringbone layout enables a setting where an LHD can drive always in the same direction and arrive bucket first at the crusher. The crusher station is located at the junction of all six production drifts on the west side in Figure C-3. There is just a single jaw-gyratory type crusher which handles all material from the six production drifts. The crusher reduces the ore down to less than 150 mm lump size. The ore is then transported via inclined conveyor belts and a 26 meter vertical transfer conveyor to the ore bins at the old loading station of lift #1. The continuous ore handling system (also called the ‘Rock Factory concept’) applied at lift #1 has been a great success. As the last, the ore is taken to surface by skips of 18 tonne capacity. (deWolfe, 2009) (Duffield, 2000)

The drawbells were shot at once, which was quite rare in the industry at the time. They were ‘skull-shaped’ according to Duffield (2000) and Lovitt (2006), a similar geometry as the drawbells of lift #1. The two designs have a lot in common as can be seen from their plan view at the undercut level in Figure C-4.

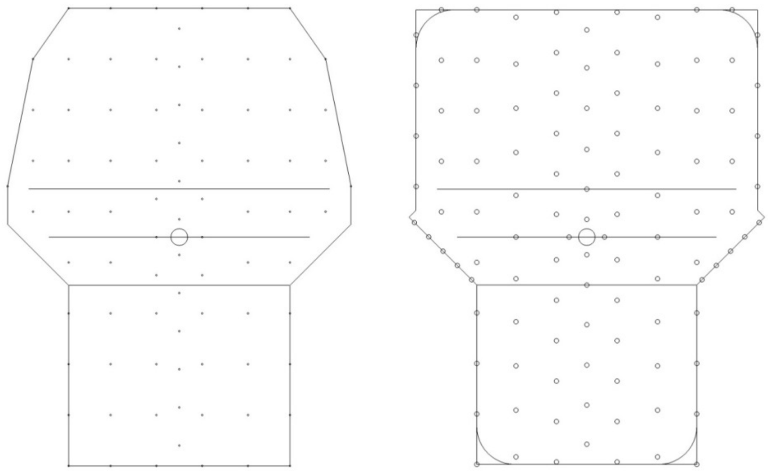


Figure C-4: Cork- (left) and skull-shape (right) including blasting patterns

One of the main geotechnical issues was clay inrushes that jeopardized production. Figure C-5 shows a reddish clayey substance that found its way through the cave and entered the extraction level at draw point 5-South in extraction drift 6.

Figure C-5: Clay inrush at draw point 6S5.

C.1 Infrastructure dimensions

The extraction level of Northparkes Mines E26 Lift #2 has a 18x30 offset herringbone layout. The undercut level is located 14 meters above the extraction level and consists of parallel drifts of 4.2 meters in width and 4.5 meters in height. The distances between the undercut drifts are alternating. The drifts adjacent to the flat undercut are 14.2 meters apart and the drifts at both sides of the inclined undercut are 15.8 meters apart. The inclined undercut starts from a height of 3.8 meters in the undercut drift and makes an angle of 50 ° with the horizontal. The realized angle was reported to be 54 °. This forms the crinkle cut as shown in Figure C-6.

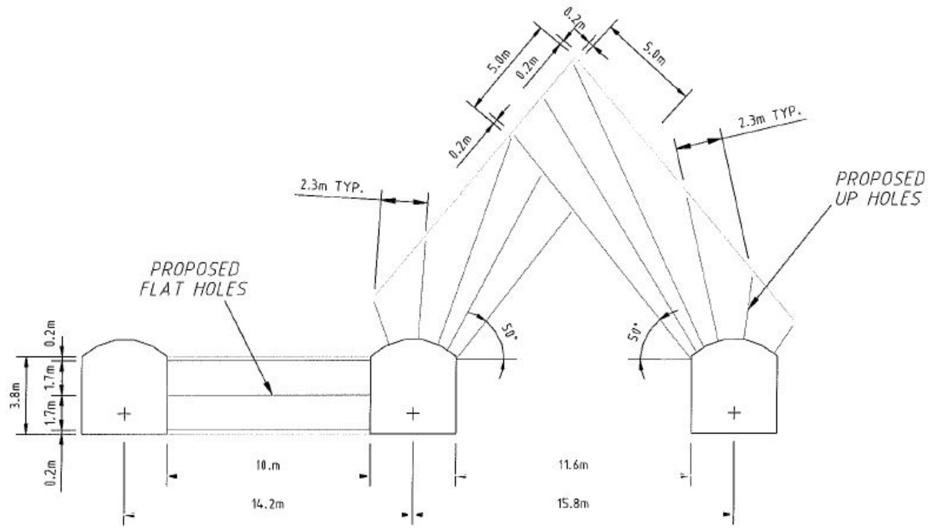


Figure C-6: Crinkle cut design at Northparkes Mine E26 Lift #2 (Lovitt, 2006)

The production drifts are 4.2 x 4.2 meters. They are on both sides connected with the break-away and trough drifts, leading to the brow and draw points. These drifts are developed under an angle of 45 degrees from the production tunnel axis and are 3.8 x 3.8 meters. The trough drift connects the two break-away drifts at the bottom of the draw bell and has the same dimensions as the break-away drifts. The drawbell has a 'skull-shape' according to Lovitt (2006). This means that the two opposing sides of the minor apex are not evenly wide. The width of the draw bell at the camelback is 8.7 meters, on the other side of the minor apex the width is 13.5 meters.

Figure C-7 shows the dimensions of all excavations in three vertical sections of the extraction level. Table 5 gives an overview of the dimensions discussed in this section. Appendix A has used these dimensions to calculate two- and three-dimensional extraction ratios.

Table 5: Dimensions of block E26 Lift #2

Offset herringbone layout		Source:
Production drift spacing	30 m	(deWolfe, 2009)
Trough length	8.7m	(Lovitt, 2006)
Draw point spacing (across minor apex)	18 m	(deWolfe, 2009)
Break-away angle	45 °	(deWolfe, 2009)
Production drift dimension (w x h)	4.2 x 4.2 m	(deWolfe, 2009)
Draw point drift dimension (w x h)	3.8 x 3.8 m	(Silveira, 2004)
Undercut drift dimension (w x h)	4.2 x 4.5 m	(Silveira, 2004)
Undercut inclination	54 °	(Silveira, 2004)
Difference undercut and production level	14 m	(Silveira, 2004)

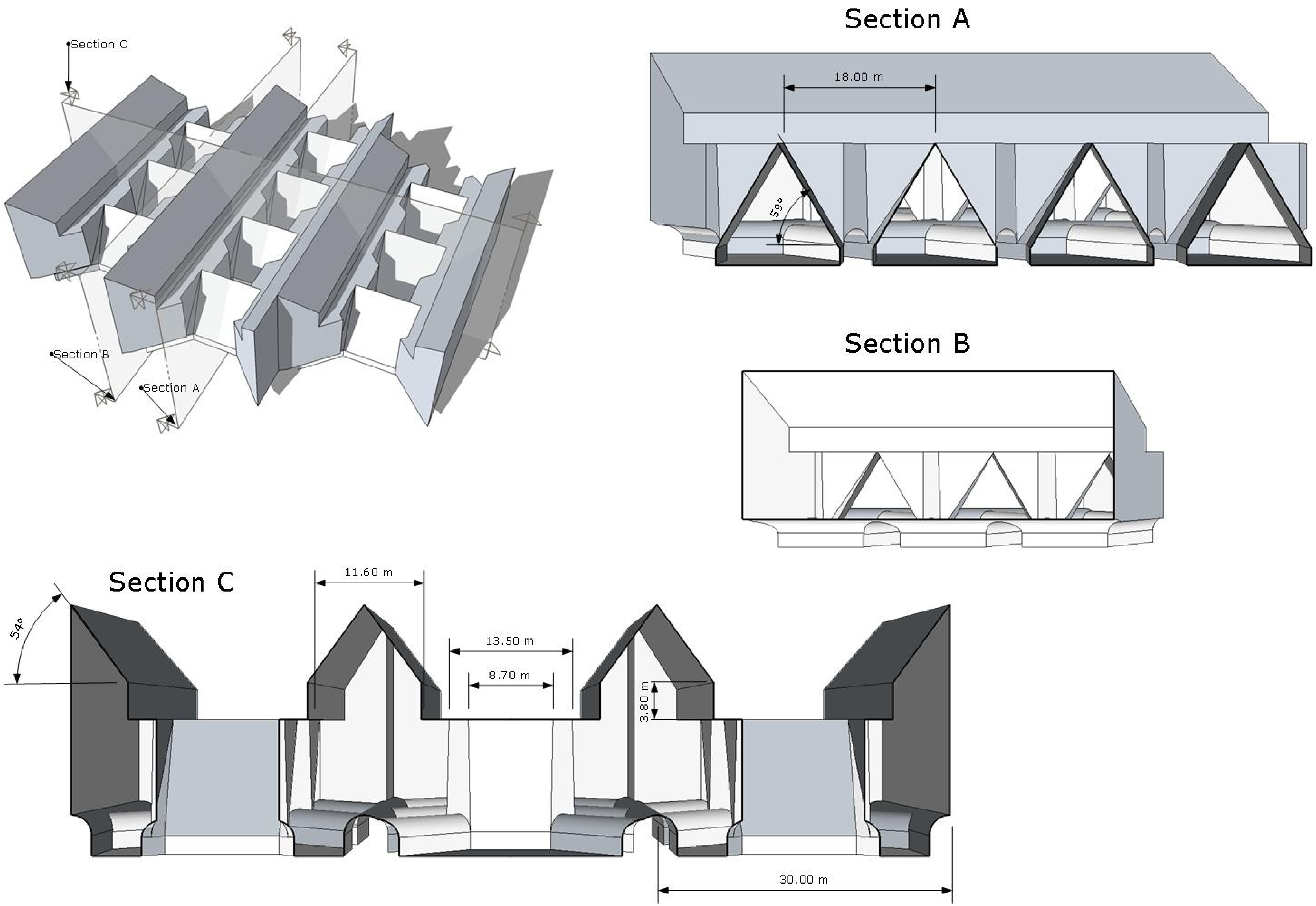


Figure C-7: Three vertical cross-sections of the extraction level infrastructure of block E26 lift #2, constructed with SketchUp Pro 8 and LayOut 3

Appendix D. Rock Mass Rating

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
2	Drill core Quality *RQD*		90% - 100%	75% - 90%	50% - 75%	25% - 50%	< 25%		
	Rating		20	17	13	8	3		
3	Spacing of discontinuities		> 2 m	0.6 - 2 . m	200 - 600 mm	60 - 200 mm	< 60 mm		
	Rating		20	15	10	8	5		
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 σ)	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		

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
	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 yrs for 15 m span	1 year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 min for 1 m span
Cohesion of rock mass (kPa)	> 400	300 - 400	200 - 300	100 - 200	< 100
Friction angle of rock mass (deg)	> 45	35 - 45	25 - 35	15 - 25	< 15

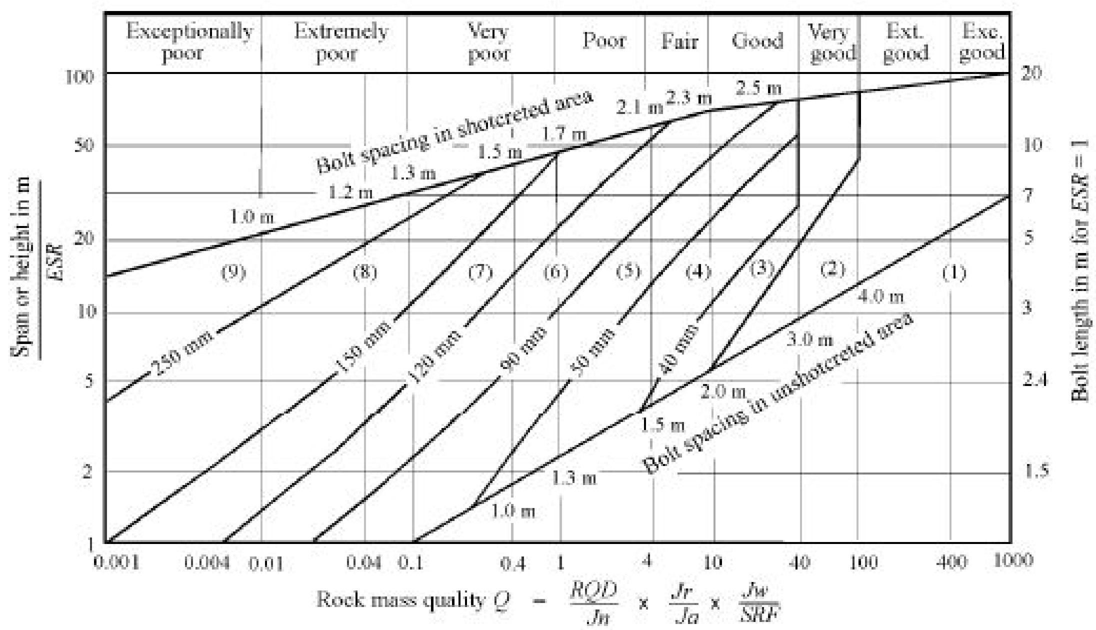
E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY conditions					
Discontinuity length (persistence) Rating	< 1 m 6	1 - 3 m 4	3 - 10 m 2	10 - 20 m 1	> 20 m 0
Separation (aperture) Rating	None 6	< 0.1 mm 5	0.1 - 1.0 mm 4	1 - 5 mm 1	> 5 mm 0
Roughness Rating	Very rough 6	Rough 5	Slightly rough 3	Smooth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

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 - 90°	Drive with dip - Dip 20 - 45°	Dip 45 - 90°	Dip 20 - 45°
Very favourable	Favourable	Very unfavourable	Fair
Drive against dip - Dip 45-90°	Drive against dip - Dip 20-45°	Dip 0-20 - 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).

Appendix E. Rock Tunneling Quality Index Q

Excavation category		*ESR*
A	Temporary mine openings.	3-5
B	Permanent mine openings, water tunnels for hydro power (excluding high pressure penstocks), pilot tunnels, drifts and headings for large excavations.	1.6
C	Storage rooms, water treatment plants, minor road and railway tunnels, surge chambers, access tunnels.	1.3
D	Power stations, major road and railway tunnels, civil defence chambers, portal intersections.	1.0
E	Underground nuclear power stations, railway stations, sports and public facilities, factories.	0.8



REINFORCEMENT CATEGORIES

1) Unsupported
2) Spot bolting
3) Systematic bolting
4) Systematic bolting with 40-100 mm unreinforced shotcrete
5) Fibre reinforced shotcrete, 50 - 90 mm, and bolting
6) Fibre reinforced shotcrete, 90 - 120 mm, and bolting
7) Fibre reinforced shotcrete, 120 - 150 mm, and bolting
8) Fibre reinforced shotcrete, > 150 mm, with reinforced ribs of shotcrete and bolting
9) Cast concrete lining

DESCRIPTION	VALUE	NOTES
1. ROCK QUALITY DESIGNATION	*RQD*	
A. Very poor	0 - 25	1. Where *RQD* is reported or measured as ≤ 10 (including 0), a nominal value of 10 is used to evaluate *Q*.
B. Poor	25 - 50	
C. Fair	50 - 75	
D. Good	75 - 90	2. *RQD* intervals of 5, i.e. 100, 95, 90 etc. are sufficiently accurate.
E. Excellent	90 - 100	
2. JOINT SET NUMBER	J_n	
A. Massive, no or few joints	0.5 - 1.0	
B. One joint set	2	
C. One joint set plus random	3	
D. Two joint sets	4	
E. Two joint sets plus random	6	
F. Three joint sets	9	1. For intersections use $(3.0 \times J_n)$
G. Three joint sets plus random	12	
H. Four or more joint sets, random, heavily jointed, 'sugar cube', etc.	15	2. For portals use $(2.0 \times J_n)$
J. Crushed rock, earthlike	20	
3. JOINT ROUGHNESS NUMBER	J_r	
a. Rock wall contact		
b. Rock wall contact before 10 cm shear		
A. Discontinuous joints	4	
B. Rough and irregular, undulating	3	
C. Smooth undulating	2	
D. Slickensided undulating	1.5	1. Add 1.0 if the mean spacing of the relevant joint set is greater than 3 m.
E. Rough or irregular, planar	1.5	
F. Smooth, planar	1.0	
G. Slickensided, planar	0.5	2. $J_r = 0.5$ can be used for planar, slickensided joints having lineations, provided that the lineations are oriented for minimum strength.
c. No rock wall contact when sheared		
H. Zones containing clay minerals thick enough to prevent rock wall contact	1.0 (nominal)	
J. Sandy, gravely or crushed zone thick enough to prevent rock wall contact	1.0 (nominal)	

DESCRIPTION	VALUE	ϕr degrees (approx.)	NOTES
4. JOINT ALTERATION NUMBER	J_a	ϕr degrees (approx.)	
a. Rock wall contact			
A. Tightly healed, hard, non-softening, impermeable filling	0.75		1. Values of ϕr, the residual friction angle, are intended as an approximate guide to the mineralogical properties of the alteration products, if present.
B. Unaltered joint walls, surface staining only	1.0	25 - 35	
C. Slightly altered joint walls, non-softening mineral coatings, sandy particles, clay-free disintegrated rock, etc.	2.0	25 - 30	
D. Silty-, or sandy-clay coatings, small clay-fraction (non-softening)	3.0	20 - 25	
E. Softening or low-friction clay mineral coatings, i.e. kaolinite, mica. Also chlorite, talc, gypsum and graphite etc., and small quantities of swelling clays. (Discontinuous coatings, 1 - 2 mm or less)	4.0	8 - 16	

DESCRIPTION	VALUE	NOTES
4, JOINT ALTERATION NUMBER	J_a	ϕr degrees (approx.)
b. Rock wall contact before 10 cm shear		
F. Sandy particles, clay-free, disintegrating rock etc.	4.0	25 - 30
G. Strongly over-consolidated, non-softening clay mineral fillings (continuous < 5 mm thick)	6.0	16 - 24
H. Medium or low over-consolidation, softening clay mineral fillings (continuous < 5 mm thick)	8.0	12 - 16
J. Swelling clay fillings, i.e. montmorillonite, (continuous < 5 mm thick). Values of J_a depend on percent of swelling clay-size particles, and access to water.	8.0 - 12.0	6 - 12
c. No rock wall contact when sheared		
K. Zones or bands of disintegrated or crushed	6.0	
L. rock and clay (see G, H and J for clay	8.0	
M. conditions)	8.0 - 12.0	6 - 24
N. Zones or bands of silty- or sandy-clay, small clay fraction, non-softening	5.0	
O. Thick continuous zones or bands of clay	10.0 - 13.0	
P. & R. (see G.H and J for clay conditions)	6.0 - 24.0	
5. JOINT WATER REDUCTION	J_w	approx. water pressure (kgf/cm^2)
A. Dry excavation or minor inflow i.e. < 5 l/m locally	1.0	< 1.0
B. Medium inflow or pressure, occasional outwash of joint fillings	0.66	1.0 - 2.5
C. Large inflow or high pressure in competent rock with unfilled joints	0.5	2.5 - 10.0 — 1. Factors C to F are crude estimates; increase J_w if drainage installed.
D. Large inflow or high pressure	0.33	2.5 - 10.0
E. Exceptionally high inflow or pressure at blasting, decaying with time	0.2 - 0.1	> 10 — 2. Special problems caused by ice formation are not considered.
F. Exceptionally high inflow or pressure	0.1 - 0.05	> 10
6. STRESS REDUCTION FACTOR		*SRF*
a. Weakness zones intersecting excavation, which may cause loosening of rock mass when tunnel is excavated		
A. Multiple occurrences of weakness zones containing clay or chemically disintegrated rock, very loose surrounding rock any depth)		10.0 — 1. Reduce these values of *SRF* by 25 - 50% but only if the relevant shear zones influence do not intersect the excavation
B. Single weakness zones containing clay, or chemically dis-tegrated rock (excavation depth < 50 m)		5.0
C. Single weakness zones containing clay, or chemically dis-tegrated rock (excavation depth > 50 m)		2.5
D. Multiple shear zones in competent rock (clay free), loose surrounding rock (any depth)		7.5
E. Single shear zone in competent rock (clay free). (depth of excavation < 50 m)		5.0
F. Single shear zone in competent rock (clay free). (depth of excavation > 50 m)		2.5
G. Loose open joints, heavily jointed or 'sugar cube', (any depth)		5.0

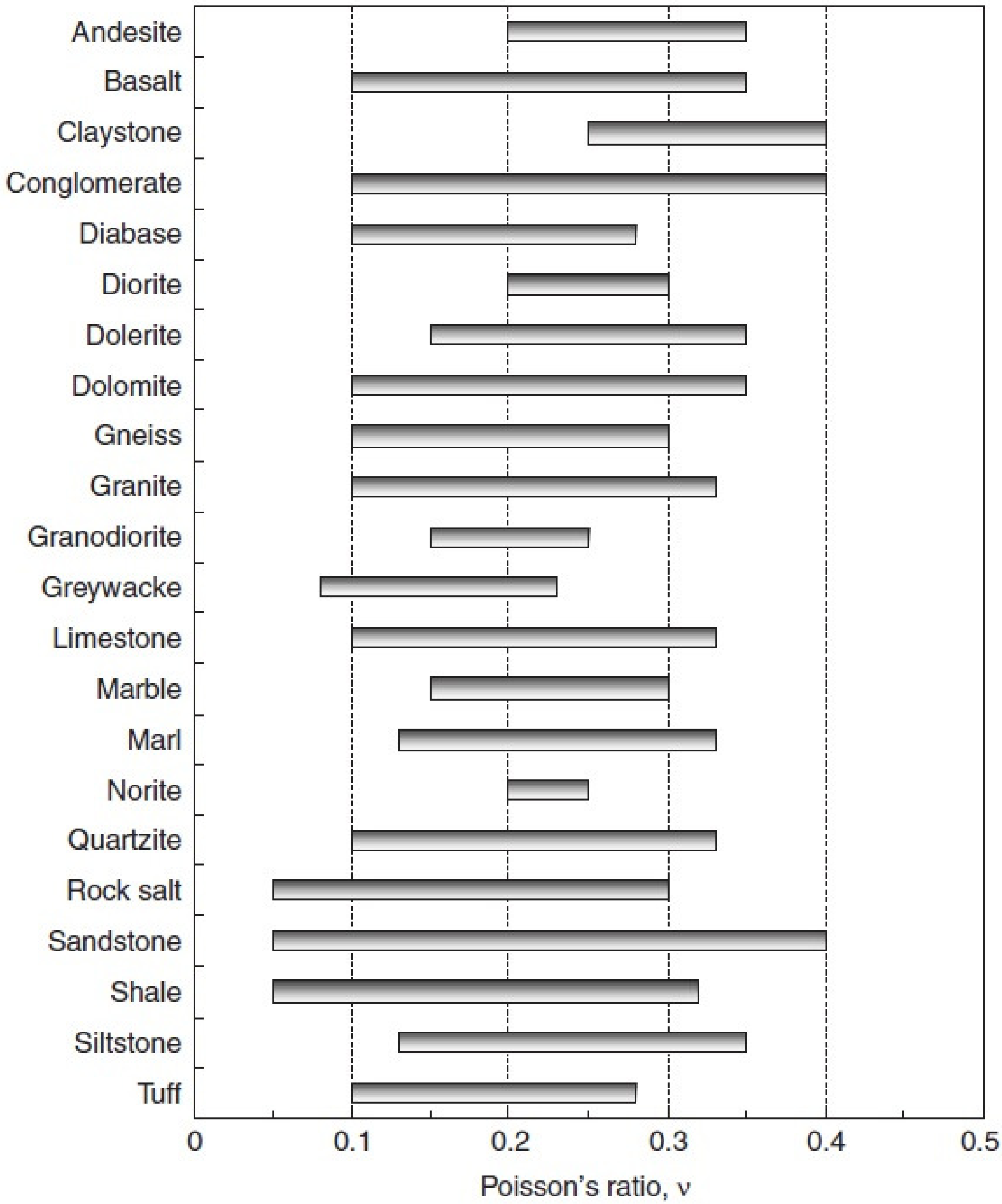
DESCRIPTION			VALUE	NOTES
6. STRESS REDUCTION FACTOR			*SRF*	
b. Competent rock, rock stress problems				
	σ_c/σ_1	$\sigma_t\sigma_1$		2. For strongly anisotropic virgin stress field (if measured): when $5 \leq \sigma_1/\sigma_3 \leq 10$, reduce σ_c to $0.8\sigma_c$ and σ_t to $0.8\sigma_t$. When $\sigma_1/\sigma_3 > 10$, reduce σ_c and σ_t to $0.6\sigma_c$ and $0.6\sigma_t$, where σ_c = unconfined compressive strength, and σ_t = tensile strength (point load) and σ_1 and σ_3 are the major and minor principal stresses.
H. Low stress, near surface	> 200	> 13	2.5	
J. Medium stress	200 - 10	13 - 0.66	1.0	
K. High stress, very tight structure (usually favourable to stability, may be unfavourable to wall stability)	10 - 5	0.66 - 0.33	0.5 - 2	
L. Mild rockburst (massive rock)	5 - 2.5	0.33 - 0.16	5 - 10	
M. Heavy rockburst (massive rock)	< 2.5	< 0.16	10 - 20	3. Few case records available where depth of crown below surface is less than span width. Suggest *SRF* increase from 2.5 to 5 for such cases (see H).
c. Squeezing rock, plastic flow of incompetent rock under influence of high rock pressure				
N. Mild squeezing rock pressure			5 - 10	
O. Heavy squeezing rock pressure			10 - 20	
d. Swelling rock, chemical swelling activity depending on presence of water				
P. Mild swelling rock pressure			5 - 10	
R. Heavy swelling rock pressure			10 - 15	

ADDITIONAL NOTES ON THE USE OF THESE TABLES

When making estimates of the rock mass Quality (Q), the following guidelines should be followed in addition to the notes listed in the tables:

1. When borehole core is unavailable, *RQD* can be estimated from the number of joints per unit volume, in which the number of joints per metre for each joint set are added. A simple relationship can be used to convert this number to *RQD* for the case of clay free rock masses: $RQD = 115 - 3.3\, J_v$ (approx.), where J_v = total number of joints per m^3 ($0 < RQD < 100$ for $35 > J_v > 4.5$).
2. The parameter J_n representing the number of joint sets will often be affected by foliation, schistosity, slaty cleavage or bedding etc. If strongly developed, these parallel 'joints' should obviously be counted as a complete joint set. However, if there are few 'joints' visible, or if only occasional breaks in the core are due to these features, then it will be more appropriate to count them as 'random' joints when evaluating J_n.
3. The parameters J_r and J_a (representing shear strength) should be relevant to the weakest significant joint set or clay filled discontinuity in the given zone. However, if the joint set or discontinuity with the minimum value of J_r/J_a is favourably oriented for stability, then a second, less favourably oriented joint set or discontinuity may sometimes be more significant, and its higher value of J_r/J_a should be used when evaluating Q. The value of J_r/J_a should in fact relate to the surface most likely to allow failure to initiate.
4. When a rock mass contains clay, the factor *SRF* appropriate to loosening loads should be evaluated. In such cases the strength of the intact rock is of little interest. However, when jointing is minimal and clay is completely absent, the strength of the intact rock may become the weakest link, and the stability will then depend on the ratio rock-stress/rock-strength. A strongly anisotropic stress field is unfavourable for stability and is roughly accounted for as in note 2 in the table for stress reduction factor evaluation.
5. The compressive and tensile strengths (σ_c and σ_t) of the intact rock should be evaluated in the saturated condition if this is appropriate to the present and future in situ conditions. A very conservative estimate of the strength should be made for those rocks that deteriorate when exposed to moist or saturated conditions.

Appendix F. Poisson's ratio



F-1: Poisson ratio of intact rock for several rock types. (Gercek, 2007)

Appendix G. Empirical pillar formulae

Early pillar strength formulae were based on the back-analysis of numerous pillars in coal mining operations. The pillar strength is derived from the width / height ratio of the pillar. Pillars in soft rock coal operations belong to completely different rock mass classes and have much higher width / height ratios than hard rock pillars. Hard rock pillar strength followed investigations in coal mines and the resulting formulae can be categorised in two groups; the size effect group and the shape effect group. Equation G.1 is the size effect formula and it describes the increase of pillar strength as pillars of the same shape increase in size. They have been developed for room and pillar mining of horizontal coal seams according to Martin & Maybee (2000). The shape effect formula is linked to the slenderness of the pillar, thus assumes a linear link between pillar strength and the width / height ratio, independent of pillar volume, as described by equation G.2. The pillar width is measured normal to the major principal stress. (González-Nicieza, *et al.*, 2006)

$$S_p = K \cdot \sigma_c \cdot \frac{{W_p}^{\alpha}}{{H_p}^{\beta}} \tag{G.1}$$

$$S_p = K \cdot \sigma_c \cdot \left(a + b \cdot \frac{W_p}{H_p}\right) \tag{G.2}$$

Parameter	Unit	Description
S_p	MPa	Compressive pillar strength
K	-	Strength size factor
σ_{UCS}	MPa	Uniaxial Compressive Strength of the intact rock
W_p	m	Width of the pillar
H_p	m	Height of the pillar
α, β, a and b	-	Empirical parameters

G.1 Historic formulae and their origin

Table 6 lists five different empirical strength formulae that satisfy either equation G.1 or G.2. The formula satisfies equation G.1 if parameters α and β are stated and it satisfies equation G.2 if parameters a and b are stated. The scale factor reduces the compressive strength of intact rock of a sample to retrieve the compressive strength of the pillar. Because each formula is derived from the analysis of different rock masses, the last column states the uniaxial compressive strength of the rock mass used in the design. The validity of empirical relations is limited by the extension of their dataset. The origin of all these formulae will be discussed briefly in the following sections based on Lunder (1994).

Table 6: Pillar design parameters based on González-Nicieza *et al.* (2006) and Martin & Maybee (2000)

Author	Anno	α	β	a	b	K	σ_{UCS}	# pillars
Hedley-Grant	1972	0.5	0.75			0.578	230	28
Von Kimmelman *et al.*	1984	0.46	0.66			0.691	94	57
Potvin *et al.*	1989	1	1			0.420	-	23
Krauland & Soder	1987			0.778	0.222	0.354	100	14
Sjöberg	1992			0.778	0.222	0.308	240	9

Hedley-Grant (1972)

Twenty eight pillar case histories from uranium mines in Ontaria, Canada, formed this formula, which shows average values compared to all others. They calculated pillar stress according to their own modification of the tributary area theory.

Von Kimmelman *et al.* (1984)

They evaluated fifty seven square pillars from the strata bound massive sulphide deposit of the Selbi-Phikwe Mines in South Africa. The pillars were located between 80 and 400 meters depth. Pillar stresses were calculated with a two dimensional Boundary Element Model.

Potvin *et al.* (1989)

They collected 177 case studies from hard-rock mines in the Canadian Shield. Among them was a Phase2 modelling study of Elliot Lake. They found Q' values ranging from 0.1 to 120 and GSI values from 31 to 87. The value for the UCS of the intact rock in Table 6 is not stated, because the GSI does not use the UCS in its calculation. Although, a UCS value of approximately 230 is generally accepted for Canadian underground hard-rock mines. (Martin & Maybee, 2000)

Krauland & Soder (1987)

They evaluated 14 approximately square pillars from the Black Angel Mine in Greenland. Pillar stresses were calculated with the same discontinuity model as Von Kimmelman *et al.* (1984). They invented a six-class classification system of relative pillar stability.

Sjöberg (1992)

Sjöberg's formula is based on data of nine pillars from the Zinkgruvan Mine in Sweden. The massive, homogeneous rock mass has a low joint frequency. Again, the same two dimensional displacement discontinuity stress model as Von Kimmelman *et al.* (1984) and Krauland & Soder (1987) was used.

G.2 Confinement based formulae

All previously mentioned empirical pillar strength formulae ignore the effect of confinement. This section presents three different approaches which implement confinement. Confinement started to play a big role since Starfield & Fairhurst (1968) proved on laboratory specimens that peak strength and post-peak bearing capacity increase as confinement increases.

The oldest approach is the 'Confined core method' by Wilson (1972). After which Lunder & Pakalnis (1997) defined the term 'average pillar confinement'. It is a function of the width and height of a pillar and is defined as the average σ_3/σ_1 across the mid-height centreline, see equation G.3. The log-power shape effect and the confinement formula both make use of the average pillar confinement. Thus, pillar strength depends on the unconfined compressive strength of intact rock, the average pillar confinement and the stress field.

$$\mathrm{Cp_{av}} = \frac{\sigma_3}{\sigma_1} = 0.46 \cdot \left(\log\left(\frac{W}{H} + 0.75\right)\right)^{\frac{1.4}{W/H}} \qquad \text{G.3}$$

G.2.1 Wilson's Confined Core Method

Wilson (1972) mathematically defined a method to define the strength of longwall chain pillars. These pillars commonly have a width / height ratio above 4.5. His method is based on a theory of two clearly defined zones within a pillar; a yielding zone at the pillar boundary and an undisturbed elastic zone at the pillar core. Esterhuizen (2006) argues about the acceptance of Wilson's method as a design tool. It is generally acknowledged that his theory has helped understanding pillar failure mechanics.

Pillars are considered slender if equation G.4 is met. If so, the pillar load for square slender pillars is calculated by equation G.5 which is a form of the shape effect formula. All parameters can be found in Table 7.

$$W < 0.003 \cdot D \cdot H \qquad \text{G.4}$$

$$L = 444 \cdot \rho \cdot \frac{W^3}{H} \qquad \text{G.5}$$

If the pillar is wide enough, the pillar load is defined by equation G.6. The location of the boundary between the two zones is defined by equation G.7. Equation G.8 shows how the triaxial stress coefficient is calculated.

$$L = 4 \cdot \rho \cdot H \cdot (W^2 - 0.003 \cdot W \cdot D \cdot H + 0.000003 \cdot D^2 \cdot H^2) \qquad \text{G.6}$$

$$\frac{Y}{D} = \frac{1}{\sqrt{\tan\beta \cdot \tan(\beta - 1)}} \cdot \ln\frac{\sigma_v}{UCS} \qquad \text{G.7}$$

$$\tan\beta = \frac{1 + \sin\varphi}{1 - \sin\varphi} \qquad \text{G.8}$$

Table 7: Parameters Wilson's confined core method

Parameter	Unit	Description
W	ft	Width of pillar
H	ft	Height of pillar
D	ft	Depth of cover
ρ	tons/ft^3	Average density
L	tons	Pillar load
Y	ft	Depth of yield zone from rib side
β	°	Triaxial stress coefficient (Mohr's circle)
σ_v	psi	Maximum stress at boundary
UCS	psi	Unconfined Compressive Strength
φ	°	Angle of internal friction

G.2.2 Log-power Shape Effect

This method is derived from a trial and error process to fit data on pillar stability by using the value of Cp_{av} to create the best fitting power coefficient, equation G.9. The results are shown by equation G.10 and fit the data very well. (Lunder, 1994)

$$\alpha = 1.31 - Cp_{av}{}^{0.1} \tag{G.9}$$

$$S_p = 0.44 \cdot \sigma_c \cdot \left(\frac{W_p}{H_p}\right)^{\alpha} \tag{G.10}$$

Parameter	Unit	Description
S_p	MPa	Pillar strength
σ_c	MPa	Unconfined Compressive Strength of 50mm sample
W_p	m	Width of pillar
H_p	m	Height of pillar
Cp_{av}	-	Average pillar confinement

G.2.3 The confinement formula

Lunder & Pakalnis (1997) compiled a database of 178 case histories, significantly more data compared to formulae from Table 6. It is mainly comprised of massive sulphides with rock mass ratings between 60 and 85. A major difference with all formulae described in this chapter is that Lunder & Pakalnis (1997) invented the formula in theory and then proved a relation between pillar strength and average pillar confinement by empirical research. Statistically it is the most reliable method compared to Hedley & Grant (1972) and many others. Confinement is obtained from the width / height ratio of the pillars or from numerical modelling. The confinement formula can be used to design new pillars in an operating mine if sufficient data on existing pillars is available. If calibrated, the confinement formula can be used in pillar design for a new mine as well.

Pillar strength can be expressed as a function of the friction term as in equation G.11. This friction term can be derived from Mohr's circle and is expressed in terms of average pillar confinement in equation G.12. In the original theory of Coulomb (1773), shear strength is an addition of cohesive shear strength and this friction term. At low width / height ratios the strength is controlled by the unconfined term and at high width / height ratios the strength is controlled by the confined and unconfined strength. The result is Figure G-1, on the next page, a plot of safety factors which represents the historic cases accurately. (Lunder, 1994)

$$P_s = K \cdot UCS \cdot (C_1 + C_2 \cdot \kappa) = 0.44 \cdot UCS \cdot (0.68 + 0.52 \cdot \kappa) \tag{G.11}$$

$$\kappa = \tan\left(\cos^{-1}\left(\frac{1 - Cp_{av}}{1 + Cp_{av}}\right)\right) = \tan\beta \tag{G.12}$$

Parameter	Unit	Description
P_s	MPa	Pillar strength
K	-	Pillar strength size factor
UCS	MPa	Unconfined compressive strength (50mm sample)
C_1	-	Empirical rock mass constant
C_2	-	Empirical rock mass constant
Cp_{av}	-	Average pillar confinement
β	°	Angle in Mohr's circle

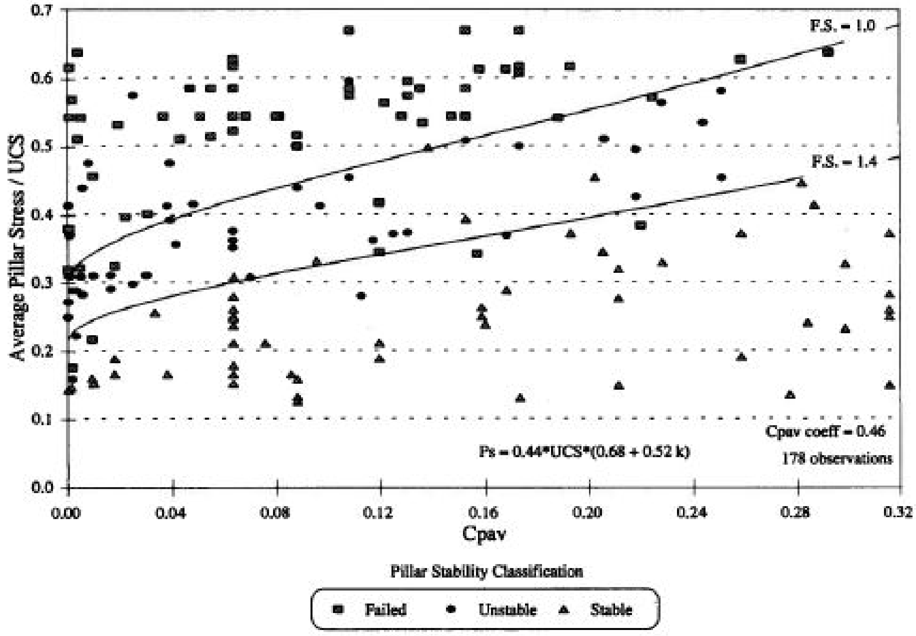


Figure G-1: Confinement formula graph and historic cases **(Lunder, 1994)**

G.3 Effective pillar width

It is a rough assumption that all pillars behave like they are square in plan. Other shapes could result in increased confinement and thus increased pillar strength. Pillar width in previous equations can be replaced by a pillar width as described by Sheorey & Singh (1974), Wagner (1980) and Stacey & Page (1986) in equation G.13.

$$W_e = 4 \cdot \frac{A_p}{R} \qquad \textbf{G.13}$$

The pillar width now becomes a function of the cross-sectional area and the circumference of the pillar. The formula is identical to the well-known hydraulic radius, which recognizes variation in geometry. Lunder (1994) recommends a minimum pillar width through the centre of the pillar instead of the effective pillar width.

G.4 RMR related size factor

A testing sample of intact rock has a higher strength, due to a lack of discontinuities, than a pillar. The scale effect reduces the uniaxial compressive strength of the sample regardless of the amount of discontinuities. Sheorey *et al.* (1987) created a formula which links the compressive strength of the rock mass to the RMR, to account for the quality of the rock mass. S_o can be replaced by σ_c in all previous equations.

$$\sigma_c = \sigma_{UCS} \cdot e^{\frac{RMR-100}{20}} \qquad \textbf{G.14}$$

G.5 Safety factor

A pillar might eventually fail because of insufficient compressive strength or shear failure along discontinuities. More parameters than only the pillar strength are needed to assess pillar stability. Lunder (1994) points out that the elastic modulus of the pillar, depending on the intact rock elastic modulus and the degree of fracturing, plays a significant role. Pillar stability is expressed by a safety factor. The first failing mode, insufficient compressive strength, is the ratio of pillar strength to the load acting on a pillar. The other failing mode concerns shear failure along a weakness plain. The safety factor for shear failure is the ratio of shear strength to shear stress. Shear strength is formulated by Mohr-Coulomb's criterion in equation G.15. (González-Nicieza, *et al.*, 2006)

$$s_j = c_j + \sigma_n \cdot \tan \varphi_j \qquad \text{G.15}$$

The normal and shear stress can be calculated from the major and minor principal stresses together with the inclination of the joint. This means that the safety factor can be written as a function of the inclination, cohesion and friction angle of the joint and the major and minor principal stresses. Thus, the safety factor is a function of the joint inclination (β) and confinement (σ_3). The assumed major principal stress in Figure G-2 is 10 MPa. (González-Nicieza, *et al.*, 2006)

The overall safety factor for the pillar is the minimum safety factor obtained from a compression failure analysis and a shear failure analysis.

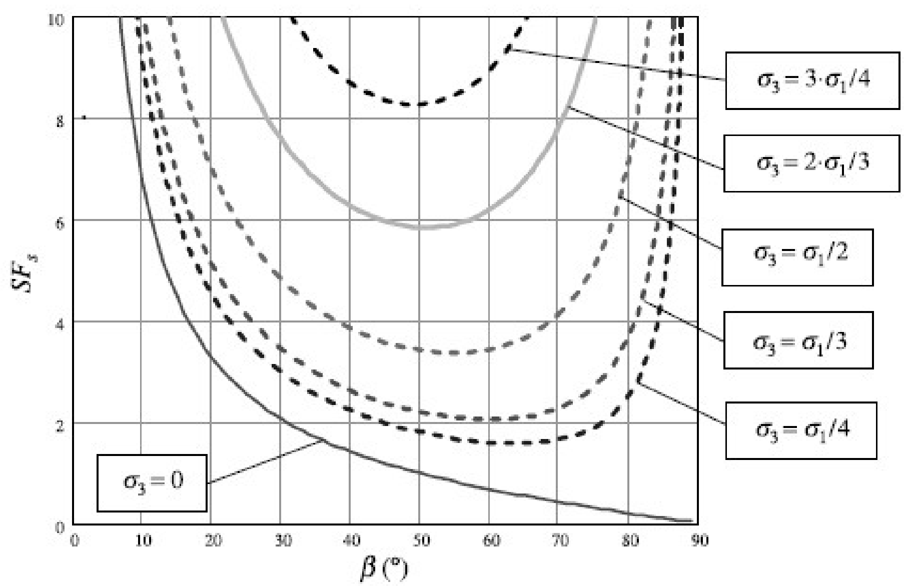


Figure G-2: Safety factor influenced by the dip angle of the joint and confinement. **(González-Nicieza, *et al.*, 2006)**

G.6 Discussion

Most empirical strength formulae discussed in this chapter are drawn in Figure G-3 on the next page to show their relative behaviour. A 10 m^2 pillar of a uniaxial compressive strength of 100 MPa is used as base case. The pillar strength is plotted against pillar height. The confinement formula from Lunder & Pakalnis (1997) shows the highest pillar strengths over the whole range of pillar heights and is clearly the least conservative one.

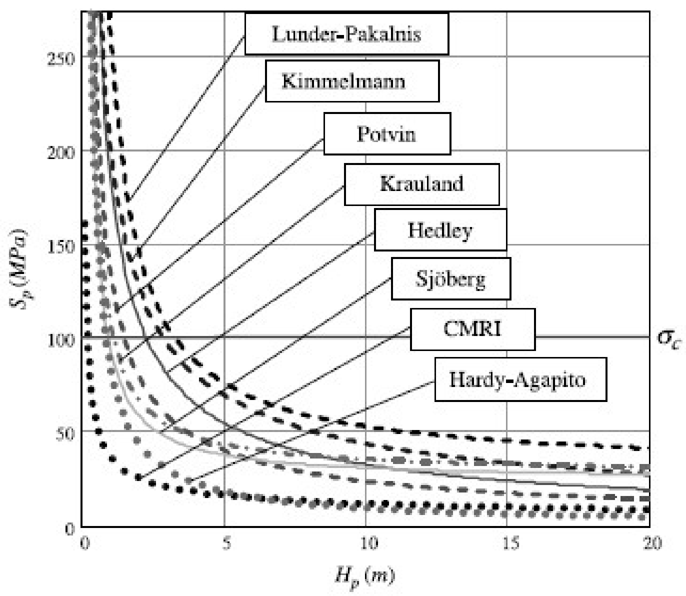


Figure G-3: Pillar strength variation per pillar strength formula as a function of pillar height (González-Nicieza, *et al.*, 2006).

Kaiser, *et al.* (2010) states that current empirical methods are limited to pillars with width / height ratios below 2 at shallow depth. Therefore, they are not applicable on pillars at depths greater than 1,000 meters. According to Martin & Maybee (2000), nearly all failures occur when the width / height ratio is less than 2.5 with progressive slabbing and spalling as the dominant mode of failure, eventually leading to an hour-glass shape. Recent numerical stress modelling shows a potential increase in pillar strength between width / height ratios of 1.5 and 5. (Kaiser, *et al.*, 2010)

A conceptual incorrectness in all empirical formulae is an asymptotic strength value as pillar width / height ratios increase, as can be seen in Figure G-4. Very wide pillars should show convex upwards graphs. The asymptotic shape does match pillar skin behaviour though. (Kaiser, *et al.*, 2000)

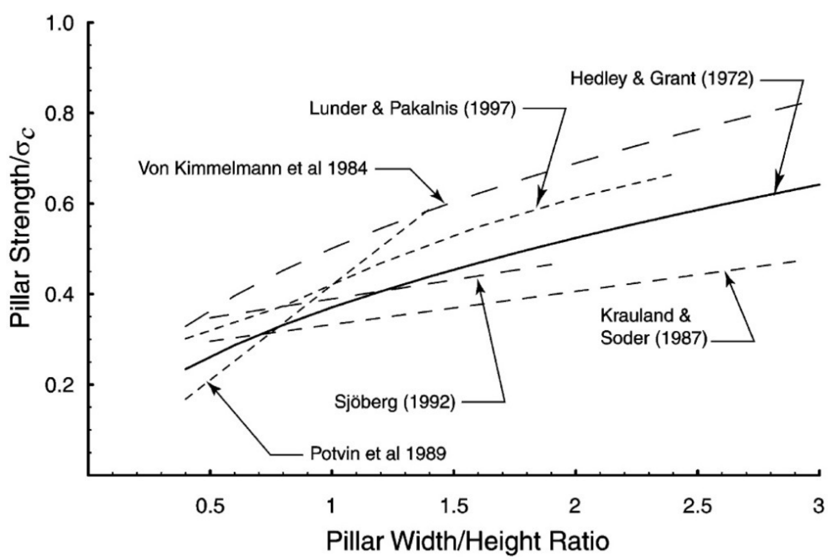
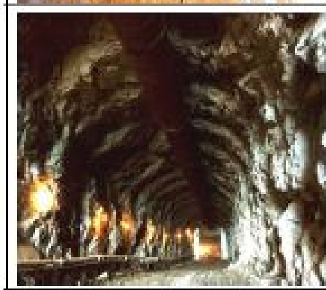
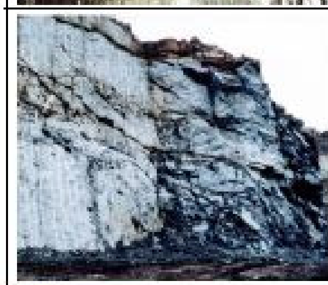


Figure G-4: Empirical failure criteria **(Martin & Maybee, 2000)**

Appendix H. Disturbance factor

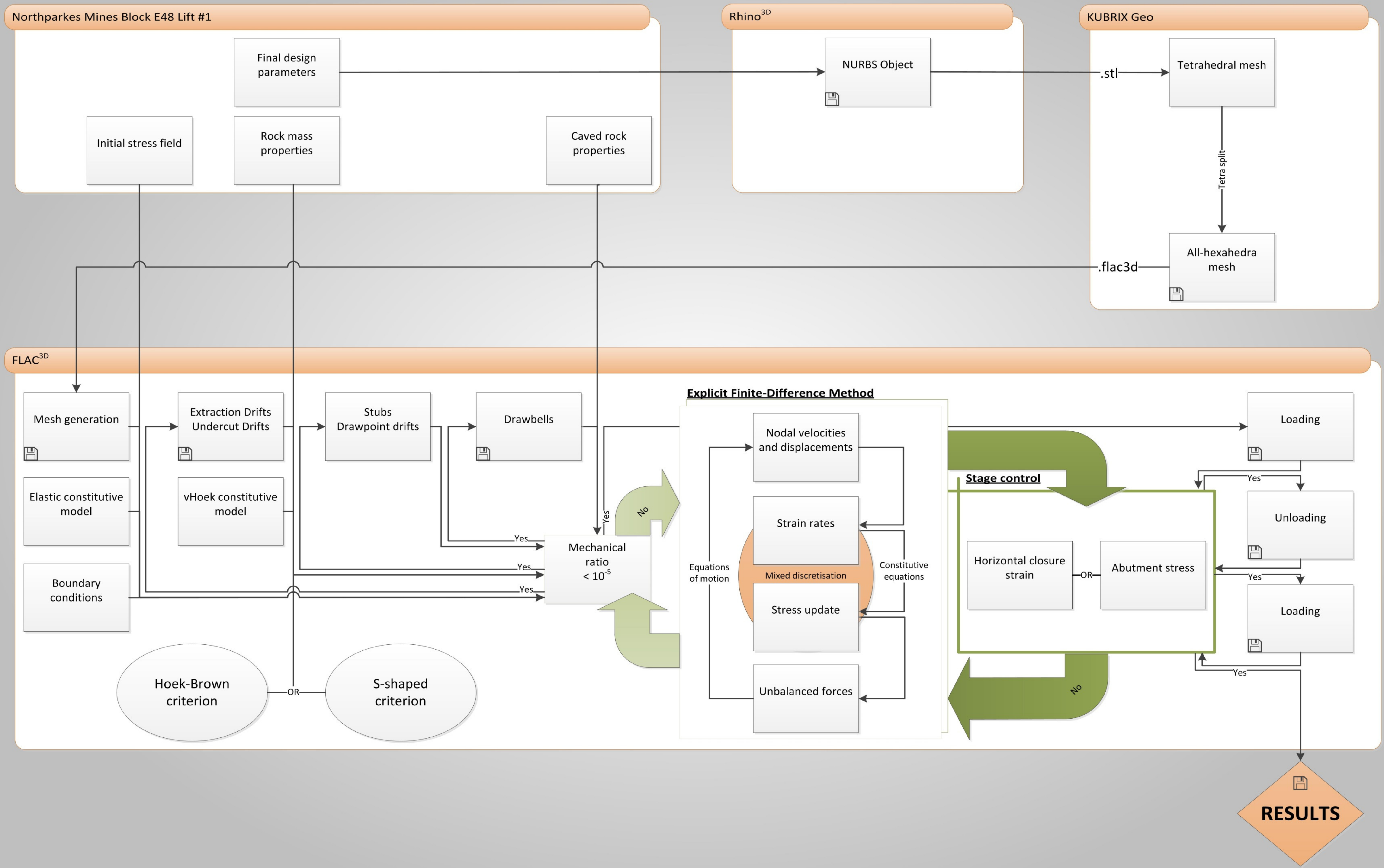
Appearance of rock mass	Description of rock mass	Suggested value of D
	Excellent quality controlled blasting or excavation by Tunnel Boring Machine results in minimal disturbance to the confined rock mass surrounding a tunnel.	$D = 0$
	Mechanical or hand excavation in poor quality rock masses (no blasting) results in minimal disturbance to the surrounding rock mass. Where squeezing problems result in significant floor heave, disturbance can be severe unless a temporary invert, as shown in the photograph, is placed.	$D = 0$ $D = 0.5$ No invert
	Very poor quality blasting in a hard rock tunnel results in severe local damage, extending 2 or 3 m, in the surrounding rock mass.	$D = 0.8$
	Small scale blasting in civil engineering slopes results in modest rock mass damage, particularly if controlled blasting is used as shown on the left hand side of the photograph. However, stress relief results in some disturbance.	$D = 0.7$ Good blasting $D = 1.0$ Poor blasting
	Very large open pit mine slopes suffer significant disturbance due to heavy production blasting and also due to stress relief from overburden removal. In some softer rocks excavation can be carried out by ripping and dozing and the degree of damage to the slopes is less.	$D = 1.0$ Production blasting $D = 0.7$ Mechanical excavation

Appendix I. Hoek-Brown m_i parameter

Rock type	Class	Group	Texture: Coarse	Texture: Medium	Texture: Fine	Texture: Very fine
SEDIMENTARY	Clastic		Conglomerate (22)	Sandstone 19	Siltstone 9	Claystone 4
				— Greywacke (18) —		
	Non-Clastic	Organic		— Chalk 7 —		
				— Coal (8-21) —		
		Carbonate	Breccia (20)	Sparitic Limestone (10)	Micritic Limestone 8	
		Chemical		Gypstone 16	Anhydrite 13	
METAMORPHIC	Non Foliated		Marble 9	Hornfels (19)	Quartzite 24	
	Slightly foliated		Migmatite (30)	Amphibolite 25 - 31	Mylonites (6)	
	Foliated*		Gneiss 33	Schists 4 - 8	Phyllites (10)	Slate 9
IGNEOUS	Light		Granite 33		Rhyolite (16)	Obsidian (19)
			Granodiorite (30)		Dacite (17)	
			Diorite (28)		Andesite 19	
	Dark		Gabbro 27	Dolerite (19)	Basalt (17)	
			Norite 22			
	Extrusive pyroclastic type		Agglomerate (20)	Breccia (18)	Tuff (15)	

* These values are for intact rock specimens tested normal to bedding or foliation. The value of m_i will be significantly different if failure occurs along a weakness plane.

Appendix J. Flow Chart of Method



May 21, 2013

Appendix K. Factual report of the real-time monitoring system

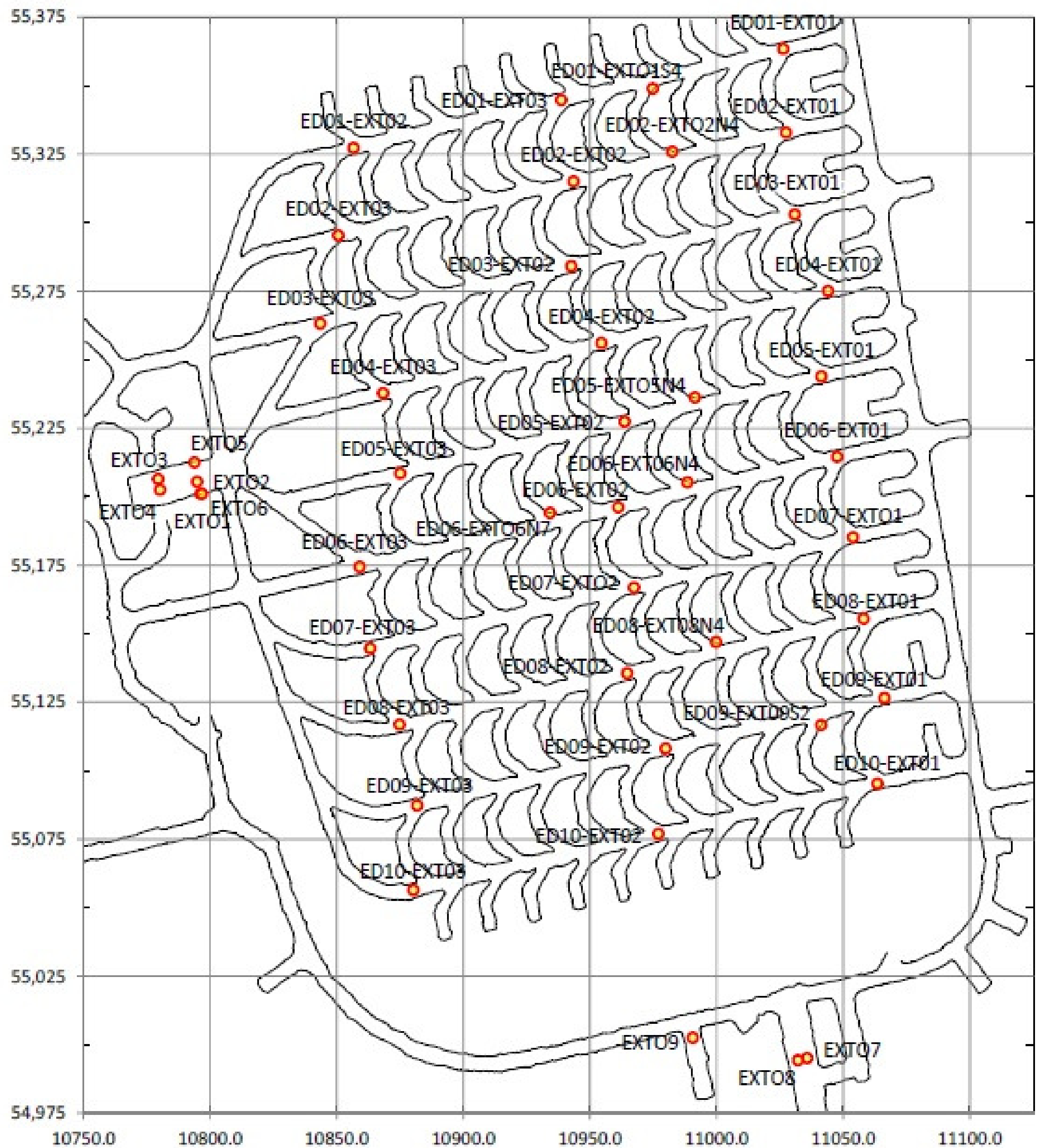
A factual report, dated to the 1st of February 2013, which shows correlation between production rates and relative displacements, is attached digitally.

										Distance From Head					
Line Ref	Cluster Ref	Logger	Exto Location	Revision	New Workbook File Extensometer ID	Orientation	Type	Reverse/Standard	Date Established Connection	Target 1	Target 2	Target 3	Target 4	Target 5	Target 6
1	1	4199	04N02		EXT-04N02-VM	Vertical	MPBX	S	23/06/2011	10	8.33	6.67	5	3.33	1.67
2		4199	01D02		EXT-01D02-TM	T	MPBX	S							
3		4199	01D03		EXT-01D03-TM	T	MPBX	S							
4	2	4149	05N06		EXT-05N06-HS	Horizontal	SMART	S	28/06/2011	15	12.5	10	7.5	5	2.5
5		4149	05N06		EXT-05N06-VM	Vertical	MPBX	S	28/06/2011	10	8.33	6.67	5	3.33	1.67
6		4149	05S05		EXT-05S05-HM	Horizontal	MPBX	S	28/06/2011	15	12.5	10	7.5	5	2.5
7	3	4154	05N04		EXT-05N04-HM	Horizontal	MPBX	S	28/06/2011	15	12.5	10	7.5	5	2.5
8		4154	05N01		EXT-05N01-VM	Vertical	MPBX	S	23/08/2011	10	8.33	6.67	5	3.33	1.67
9		4154	01D09		EXT-01D09-TM	T	MPBX	S							
10	4	4150	04N09	R1	EXT-04N09R1-HM	Horizontal	MPBX	S	27/06/2011	15	12.5	10	7.5	5	2.5
11		4150	04N11		EXT-04N11-VM	Vertical	MPBX	S	27/06/2011	10	8.33	6.67	5	3.33	1.67
12		4150	03N11		EXT-03N11-VM	Vertical	MPBX	S	07/10/2011	10	8.33	6.67	5	3.33	1.67
13	5	4203	03N02		EXT-03N02-VM	Vertical	MPBX	S	03/08/2011	10	8.33	6.67	5	3.33	1.67
14		4203	03S06		EXT-03S06-HS	Horizontal	SMART	R	09/12/2011	6	5	4	3	2	1
15		4203	03S05		EXT-03S05-HS	Horizontal	SMART	R	09/12/2011	6	5	4	3	2	1
16	6	4153	06N01		EXT-06N01-VM	Vertical	MPBX	S	30/06/2011	10	8.33	6.67	5	3.33	1.67
17		4153	06N04		EXT-06N04-HM	Horizontal	MPBX	S	30/06/2011	15	12.5	10	7.5	5	2.5
18		4153	06N02		EXT-06N02-HM	Horizontal	MPBX	S	19/07/2011	15	12.5	10	7.5	5	2.5
19	7	4152	05S09		EXT-05S09-HM	Horizontal	MPBX	S	19/07/2011	8	6.67	5.33	4	2.67	1.33
20		4152	05N10		EXT-05N10-HM	Horizontal	MPBX	S	19/07/2011	6	5	4	3	2	1
21		4152	05N09		EXT-05N09-HM	Horizontal	MPBX	S	19/07/2011	8	6.67	5.33	4	2.67	1.33
22	8	4156	06N08		EXT-06N08-HM	Horizontal	MPBX	S	19/07/2011	8	6.67	5.33	4	2.67	1.33
23		4156	06N07		EXT-06N07-HS	Horizontal	SMART	S	19/07/2011	6.001	5.001	4.001	3.001	2.001	1.001
24		4156	06N10		EXT-06N10-VM	Vertical	MPBX	S	03/08/2011	10	8.33	6.67	5	3.33	1.67
25	9	4158	02N01		EXT-02N01-VM	Vertical	MPBX	S	04/08/2011	10	8.33	6.67	5	3.33	1.67
26		4158	02S03		EXT-02S03-HM	Horizontal	MPBX	S	04/08/2011	15	12.5	10	7.5	5	2.5
27		4158	02N04		EXT-02N04-HM	Horizontal	MPBX	S	04/08/2011	15	12.5	10	7.5	5	2.5
28	10	4161	03S10		EXT-03S10-HM	Horizontal	MPBX	S	03/08/2011	8	6.67	5.33	4	2.67	1.33
29		4161	03S08		EXT-03S08-HM	Horizontal	MPBX	S	03/08/2011	8	6.67	5.33	4	2.67	1.33
30		4161	03N07		EXT-03N07-VM	Vertical	MPBX	S	03/08/2011	8	6.67	5.33	4	2.67	1.33
31	11	4160	02N06		EXT-02N06-VM	Vertical	MPBX	S	15/08/2011	10	8.33	6.67	5	3.33	1.67
32		4160	02S05		EXT-02S05-HM	Horizontal	MPBX	S		10	8.33	6.67	5	3.33	1.67
33		4160	02N06		EXT-02N06-HM	Horizontal	MPBX	S		10	8.33	6.67	5	3.33	1.67
34	12	4159	02S08		EXT-02S08-HM	Horizontal	MPBX	S	15/08/2011	10	8.33	6.67	5	3.33	1.67
35		4159	02N11		EXT-02N11-VM	Vertical	MPBX	S		10	8.33	6.67	5	3.33	1.67
36		4159	01N10		EXT-01N10-VM	Vertical	MPBX	S	17/01/2012	10	8.33	6.67	5	3.33	1.67
37	13	4155	06S05		EXT-06S05-HM	Horizontal	MPBX	S	12/08/2011	15	12.5	10	7.5	5	2.5
38		4155	06N05		EXT-06N05-VM	Vertical	MPBX	S	12/08/2011	10	8.33	6.67	5	3.33	1.67
39		4155	06N07		EXT-06N07-HM	Horizontal	MPBX	S	24/07/2012	6.001	5	4	3	2	1

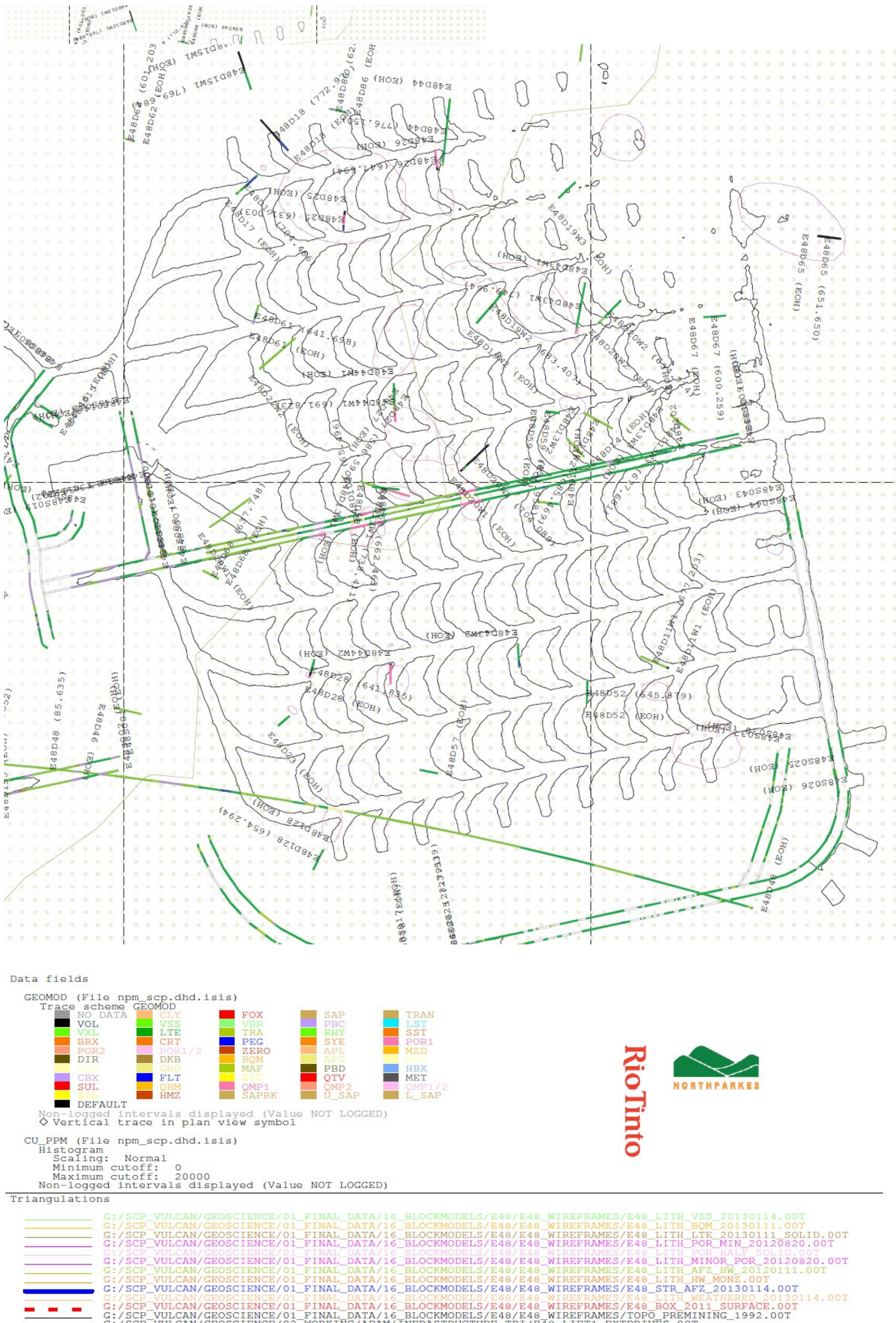
40	14	4106	08N04		EXT-08N04-HM	Horizontal	MPBX	S	24/08/2011	8.001	6.67	5.33	4	2.67	1.33
41		4106	08N01		EXT-08N01-VM	Vertical	MPBX	S	24/08/2011	10	8.33	6.67	5	3.33	1.67
42		4106	08N06		EXT-08N06-VM	Vertical	MPBX	S	01/09/2011	10	8.33	6.67	5	3.33	1.67
43	15	4104	08S09		EXT-08S09-HM	Horizontal	MPBX	S	24/08/2011	8	6.67	5.33	4	2.67	1.33
44		4104	08N11		EXT-08N11-VM	Vertical	MPBX	S	24/08/2011	10	8.33	6.67	5	3.33	1.67
45		4104	08N08		EXT-08N08-HM	Horizontal	MPBX	S	17/07/2012	10	7.5	5	3	2	1
46	16	4157	07N01		EXT-07N01-VM	Vertical	MPBX	S	24/08/2011	10	8.33	6.67	5	3.33	1.67
47		4157	07N06		EXT-07N06-VM	Vertical	MPBX	S	24/08/2011	10	8.33	6.67	5	3.33	1.67
48		4157	07N11		EXT-07N11-VM	Vertical	MPBX	S	24/08/2011	10	8.33	6.67	5	3.33	1.67
49	17	4103	09N01		EXT-09N01-VM	Vertical	MPBX	S	14/09/2011	10	8.33	6.67	5	3.33	1.67
50		4103	09S02		EXT-09S02-HM	Horizontal	MPBX	S	14/09/2011	15	12.5	10	7.5	5	2.5
51		4103	09N11		EXT-09N11-VM	Vertical	MPBX	S	14/09/2011	10	8.33	6.67	5	3.33	1.67
52	18	4105	09N06		EXT-09N06-VM	Vertical	MPBX	S	14/09/2011	10	8.33	6.67	5	3.33	1.67
53		4105	09N06		EXT-09N06-HM	Horizontal	MPBX	S	12/12/2011	8.001	6.67	5.33	4	2.67	1.33
54		4105	09S05		EXT-09S05-HM	Horizontal	MPBX	S	12/12/2011	8.001	6.67	5.33	4	2.67	1.33
55	19	4194	03S06		EXT-03S06-HM	Horizontal	MPBX	S	16/01/2012	10	7.5	5	3	2	1
56		4194	03N05		EXT-03N05-VM	Vertical	MPBX	S	16/01/2012	8	6.67	5.33	4	2.67	1.33
57		4194	03N05		EXT-03N05-HM	Horizontal	MPBX	S	16/01/2012	8	6.67	5.33	4	2.67	1.33
58	20	4182	01N01		EXT-01N01-VM	Vertical	MPBX	S	17/01/2012	10	8.33	6.67	5	3.33	1.67
59		4182	01S04		EXT-01S04-HM	Horizontal	MPBX	S	17/01/2012	15	12.5	10	7.5	5	2.5
60		4182	01N05		EXT-01N05-VM	Vertical	MPBX	S	17/01/2012	10	8.33	6.67	5	3.33	1.67
61	21	4193	10N01		EXT-10N01-VM	Vertical	MPBX	S	17/01/2012	10	8.33	6.67	5	3.33	1.67
62		4193	10N06		EXT-10N06-VM	Vertical	MPBX	S	17/01/2012	15	12.5	10	7.5	5	2.5
63		4193	10N11		EXT-10N11-VM	Vertical	MPBX	S	17/01/2012	10	8.33	6.67	5	3.33	1.67
64	22	4196	03S05		EXT-03S05-VM	Vertical	MPBX	S	15/02/2012	8	6.67	5.33	4	2.67	1.33
65		4196	03N05		EXT-03N05-HS	Horizontal	SMART	S	15/02/2012	6	5	4	3	2	1
66		4196	01D66		EXT-01D66-TM	T	MPBX	S							
67	23	4195	05N06	R1	EXT-05N06R1-VM	Vertical	MPBX	S	05/03/2012	8	6.67	5.33	4	2.67	1.33
68		4195	05S06	R1	EXT-05S06R1-VM	Vertical	MPBX	S	18/04/2012	8	6.67	5.33	4	2.67	1.33
69		4195	05S06		EXT-05S06-HS	Horizontal	SMART	S	03/05/2012	6	5	4	3	2	1
70	24	4204	08N06		EXT-08N06-HS	Horizontal	SMART	R	17/07/2012	6	5	4	3	2	1
71		4204	08S07		EXT-08S07-HS	Horizontal	SMART	R	17/07/2012	6	5	4	3	2	1
72		4204	01D72		EXT-01D72-TM	T	MPBX	S							
73	25	4177	05S08		EXT-05S08-VM	Vertical	MPBX	S	17/07/2012	8	6.67	5.33	4	2.67	1.33
74		4177	05S09		EXT-05S09-VM	Vertical	MPBX	S	17/07/2012	10	8.33	6.67	5	3.33	1.67
75		4177	05N08		EXT-05N08-VM	Vertical	MPBX	S	08/08/2012	8	6.67	5.33	4	2.67	1.33
76	26	4200	05N08		EXT-05N08-HM	Horizontal	MPBX	S	17/09/2012	6	5	4	3	2	1
77		4200	01D77		EXT-01D77-TM	T	MPBX	S							
78		4200	01D78		EXT-01D78-TM	T	MPBX	S							
79	27	4201	03S07		EXT-03S07-VM	Vertical	MPBX	S	28/09/2012	8	6.67	5.33	4	2.67	1.33
80		4201	03N06		EXT-03N06-HM	Horizontal	MPBX	S	24/10/2012	6	5	4	3	2	1
81		4201	03S07		EXT-03S07-HM	Horizontal	MPBX	S	21/10/2012	6	5	4	3	2	1
82	28	4222	03N06		EXT-03N06-VS	Vertical	SMART	R	09/11/2012	6	5	4	3	2	1
83		4222	03N07	R1	EXT-03N07R1-HM	Horizontal	MPBX	s	20/12/2012	6	5	4	3	2	1
84		4222	01D84		EXT-01D84-TM	T	MPBX	s							
85	29	4223	04S08		EXT-04S08-HM	Horizontal	MPBX	S	23/11/2012	6	5	4	3	2	1
86		4223	01D86		EXT-01D86-T	T									
87		4223	01D87		EXT-01D87-T	T									
88	30	4148	03N05	R1	EXT-03N05R1-VM	Vertical	MPBX	S	20/12/2012	8	6.67	5.33	4	2.67	1.33
89		4148	03S06	R1	EXT-03S06R1-HM	Horizontal	MPBX	S	20/12/2012	6	5	4	3	2	1
90		4148	01D90		EXT-01D90-T	T									

Appendix L. Undercut development MPBX data

Measurements taken at the MPBX stations indicated below are attached digitally.



Appendix M. Lithological plan E48 lift #1



Appendix N. MPBX Data processing

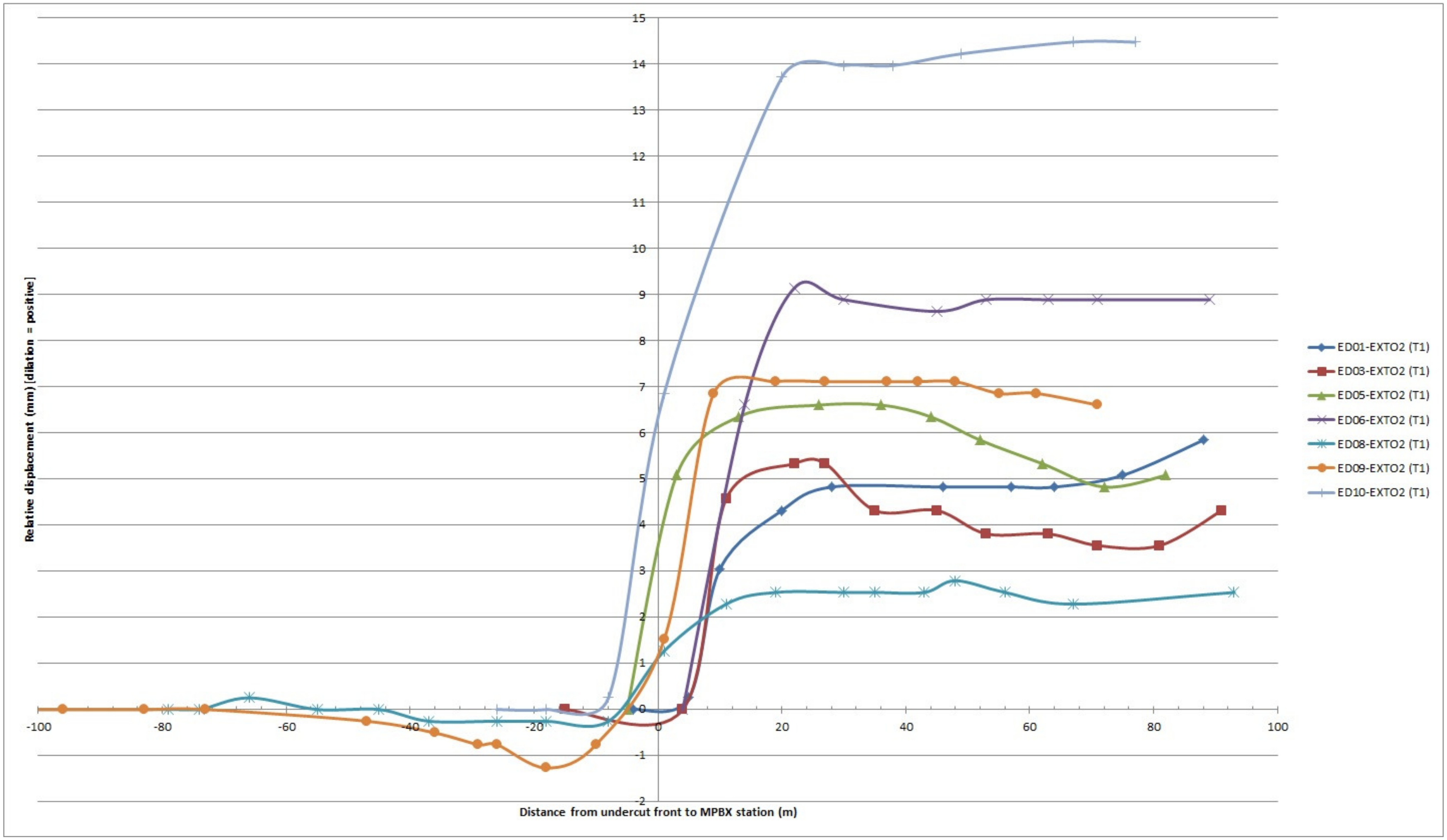


Figure N-1: Monitored rock mass response at target 1 to undercut development in the back of the extraction drifts [NPM E48 Lift 1]

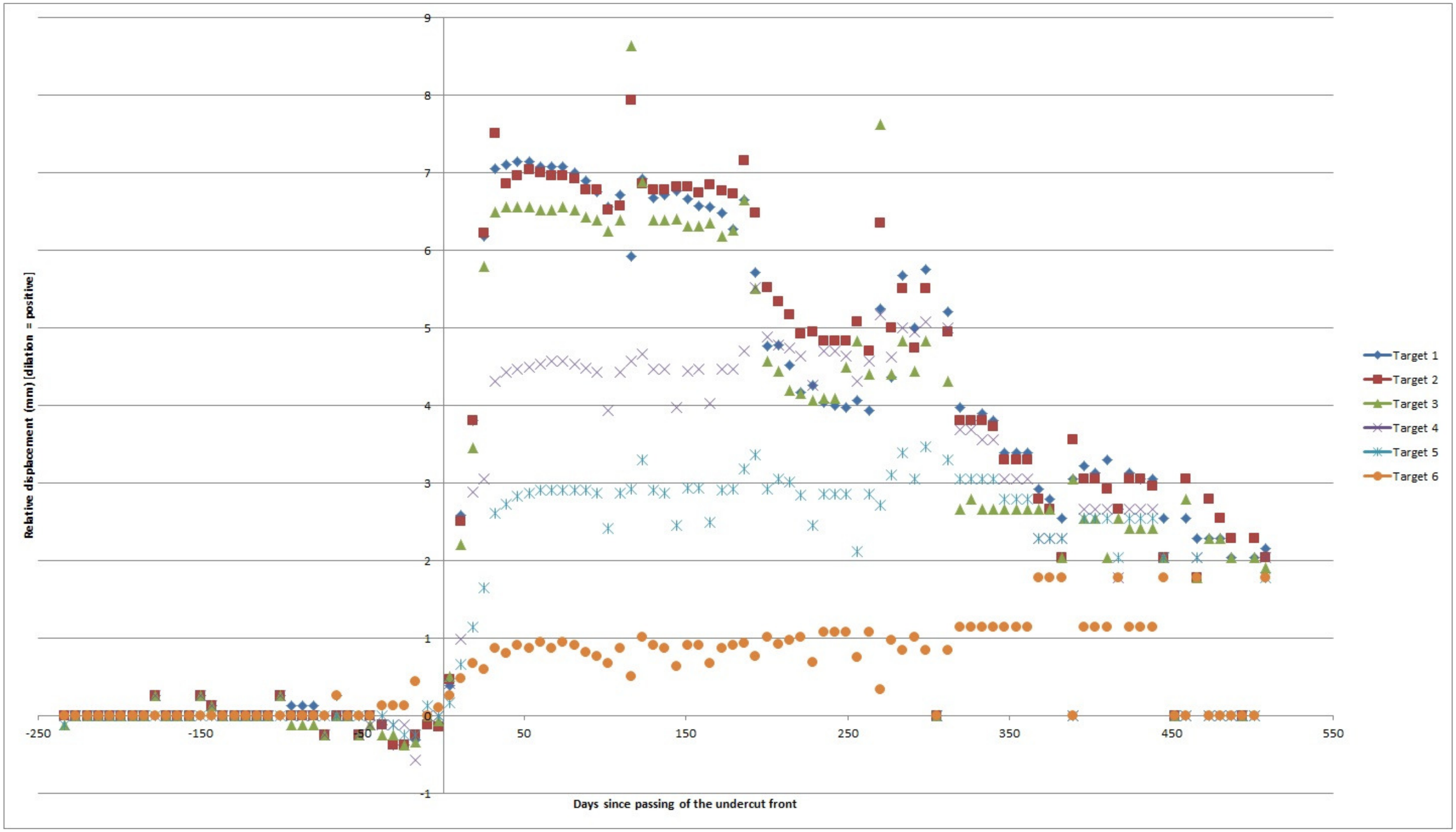


Figure N-2: Average rock mass response of all selected MPBX stations regardless the amount of available data [NPM E48 lift1]

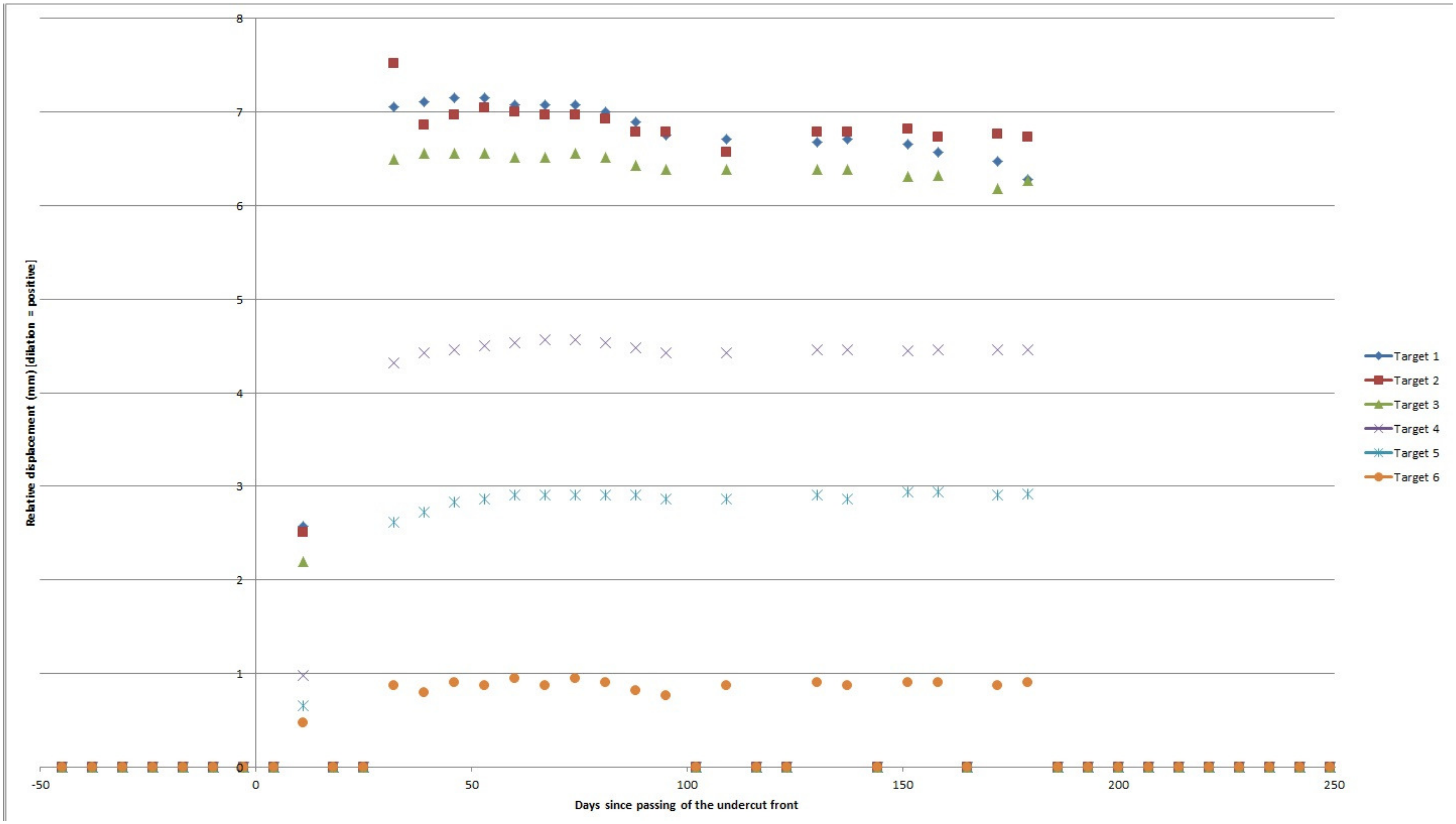
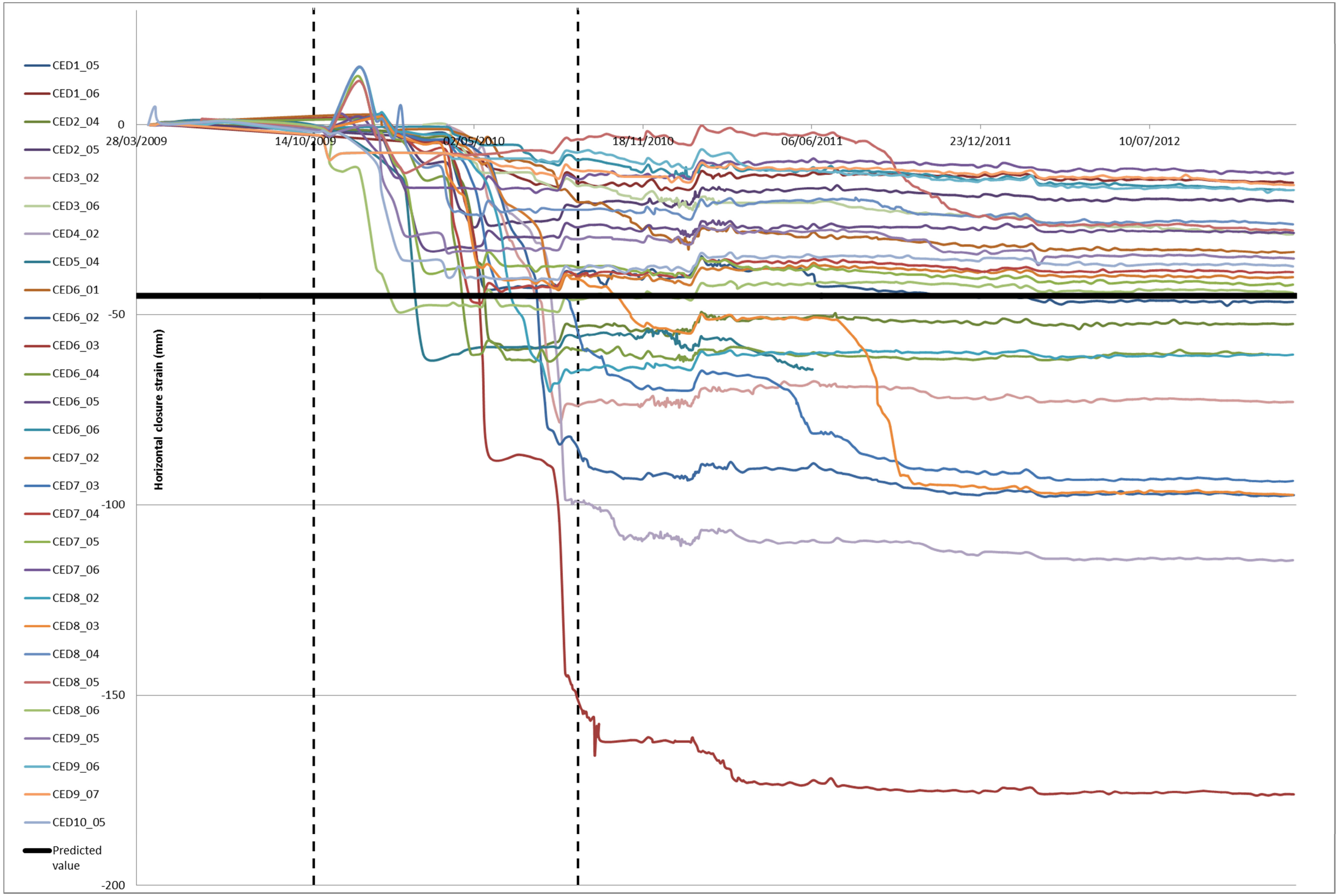
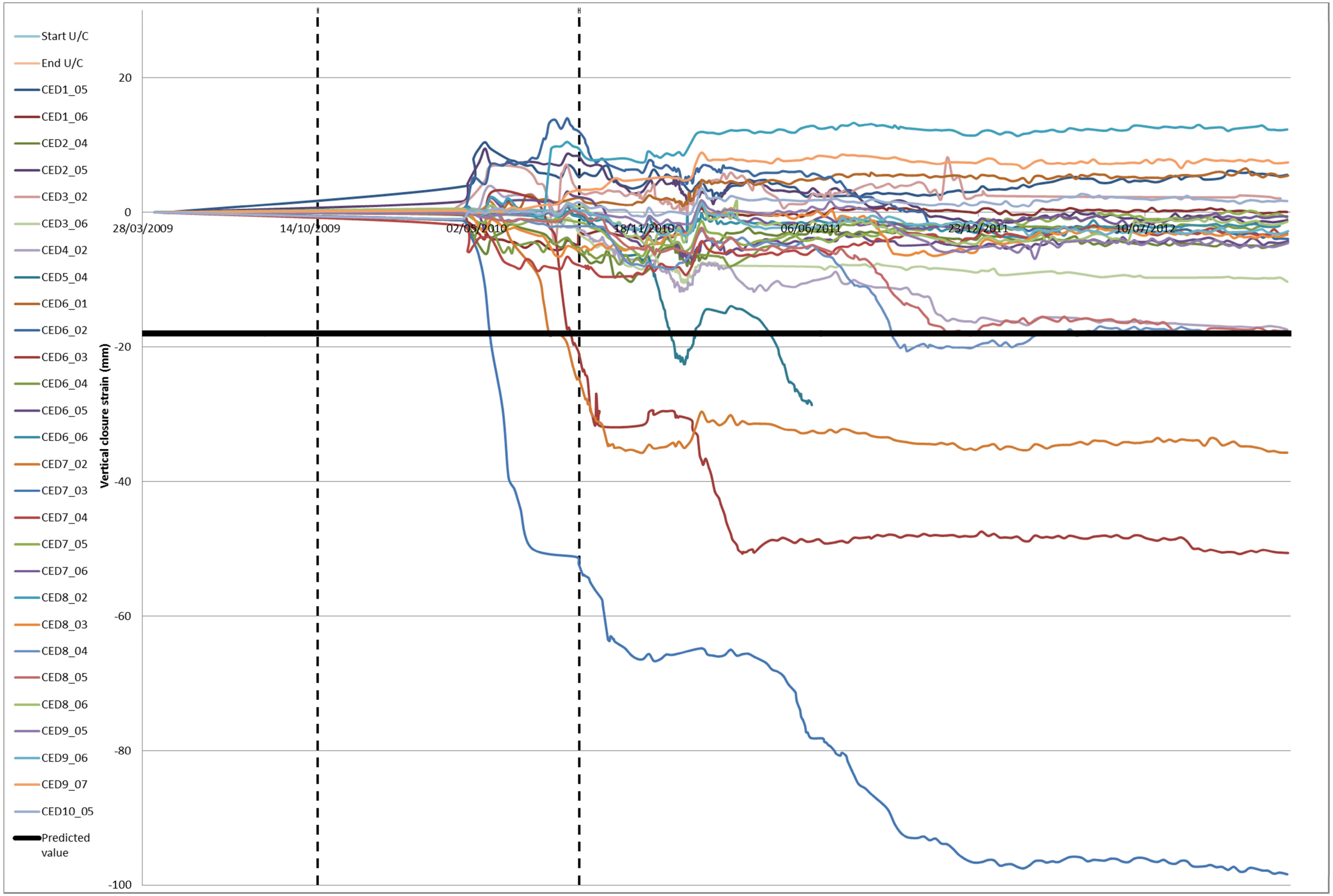


Figure N-3: Average rock mass response of all selected MPBX stations when data of all stations has to be available [NPM E48 lift1]

Appendix O. Horizontal and vertical convergence



O-1: Horizontal closure strain of all convergence stations installed prior to undercut development (marked by vertical dashed lines). A negative value means convergence of the tunnel walls.



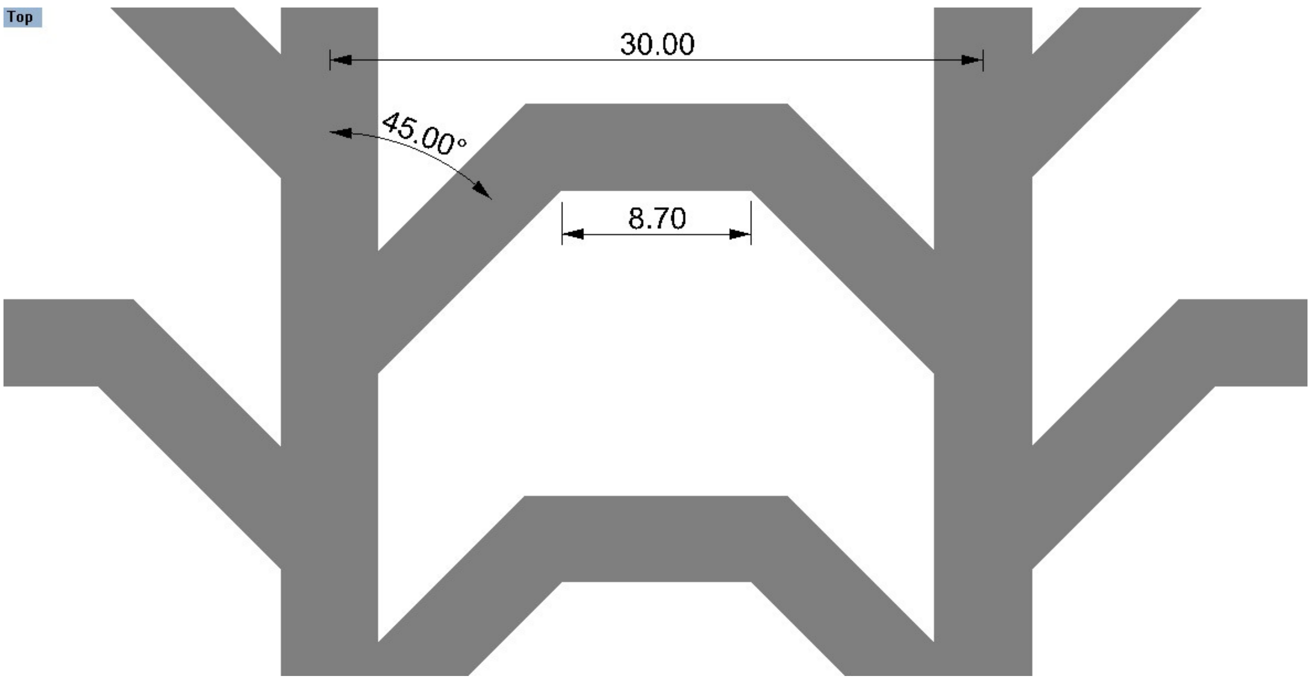
O-2: Vertical closure strain of all convergence stations installed prior to undercut development (marked by vertical dashed lines). A negative value means downwards displacement of the tunnel back.

Appendix P. User-Defined S-shape *FISH* function

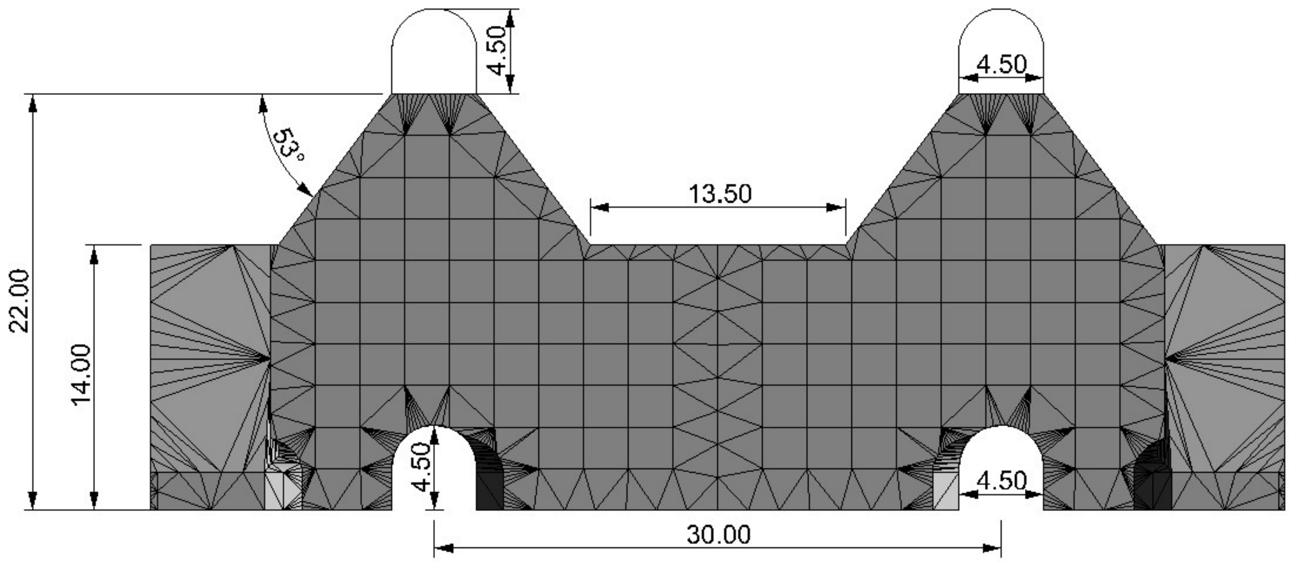
```
; Part A counts the number of zones in group rock_mass.
; Part B allocates the zones from A to an array.
; Part C alters the GSI as a function of confinement for all zones defined by B.

def setup_sshape
 ;part A
 local s_inzz = 0
 local s_pz   = zone_head
 loop while s_pz # null
   if z_model(s_pz) # 'null' then
     if z_model(s_pz) # 'mohr' then
       s_inzz = s_inzz + 1
     endif
   endif
   s_pz = z_next(s_pz)
 endloop

;part B
 local s_pzz = get_array(s_inzz)
 s_inzz = 0
 s_pz = zone_head
 loop while s_pz # null
   if z_model(s_pz) # 'null' then
     if z_model(s_pz) # 'mohr' then
       s_inzz = s_inzz + 1
       s_pzz(s_inzz) = s_pz
     endif
   endif
   s_pz = z_next(s_pz)
 endloop
 setup_sshape = s_pzz
end
```

```
; Part C  <Be sure to use values in MPa to calculate _GSI_local>
; The minor principle stress in each zone, z_sig3, is the highest stress value since all compressive stresses are negative.
; Therefore, counter-intuitive, z_sig3 equals smaximum. [VERIFIED]
def sshape(s_ratio)
  command
    step 1
  endcommand
  global s_zone_array = setup_sshape
  global s_inzz       = array_size(s_zone_array,1)
  loop while mech_ratio > s_ratio
    command
      cycle @_substep
    endcommand
    local uu
    loop  uu(1,s_inzz)
      local s_pz       = s_zone_array(uu)
      local _sig3      = z_sig3(s_pz) * 1e-6
      local _GSI_local = (_M - (_M / 100) * _GSI) / (1 + exp(_sig3 + ((_UCSi * 1e-6) / 10))) + _GSI
      z_prop(s_pz,'gsi') = _GSI_local
    end_loop
  endloop
  uu = lose_array(s_zone_array)
end
```

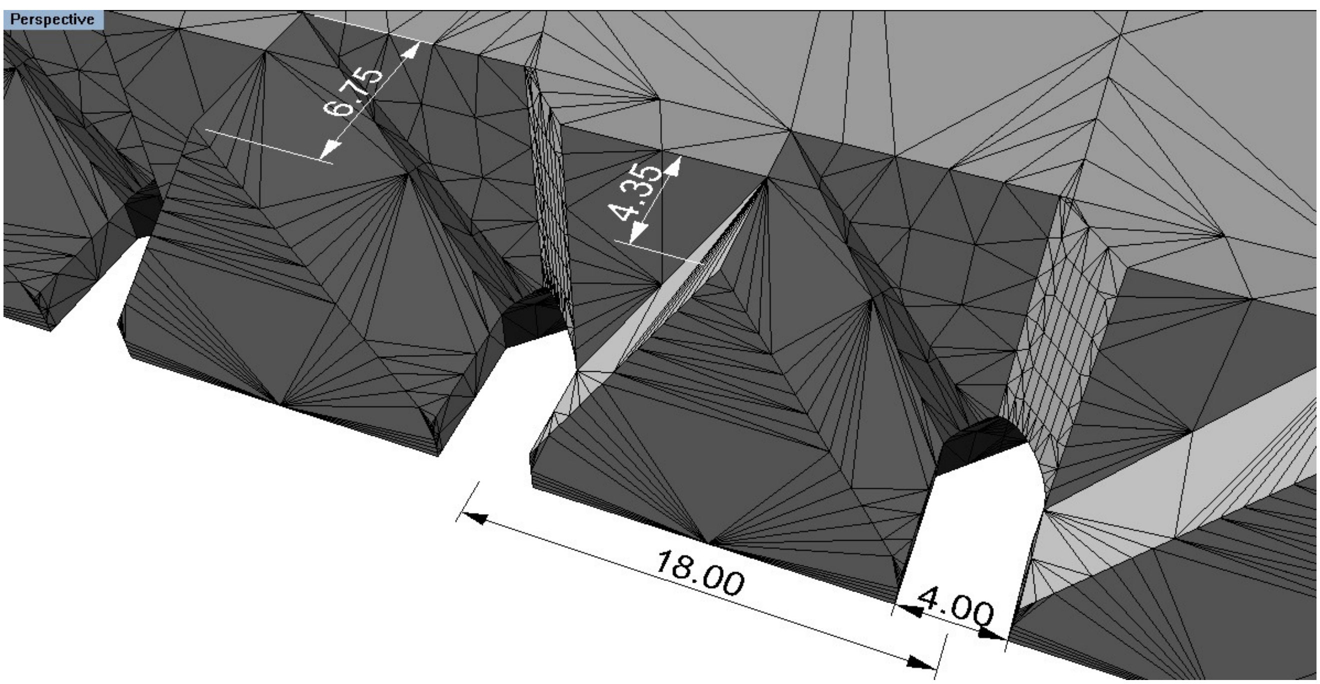
Appendix Q. Design of NPM E48 lift #1



Q-1: Horizontal cross-section of the triangulated NURBS object showing the extraction level layout of the E48 infrastructure



Q-2: Vertical cross-section of the triangulated NURBS object including final design dimensions of the E48 infrastructure.



Q-3: Perspective view of the triangulated NURBS object including final design dimensions of the E48 infrastructure.

Appendix R. FLAC^{3D} script

R.1 NPM_Param.dat

```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;PROJECT SETTINGS
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

new
set fish safe off ; The special charachter @ prefixed before all FISH variables is ignored
set nstep 100 ; Sampling interval for the history mechanism
;Make sure that modelvhoek005_64.dll is placed in ...\plugins\models\ to load automatically on FLAC3D startup

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;IMPORT KUBRIX MESH
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
set nmd on ;Any tetrahedral zones will use the nmd algorithm during the stress calculations
impgrid kubrix_out.flac3d ;Name of the file to import
ca NPM_Plot.f3dat ;Creates graphs to observe progress of simulation
ca NPM_Func_S.dat ;Calls the fish function file
@get_limits ;finds the limits of the model

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;KUBRIX GROUPS
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
set @conlaw_ = 2 ;1=Hoek-Brown          2=S-curve

set @stub_(1)= 2 ;stubs group numbers first half closer to the extraction drift
set @stub_(2)= 6
set @stub_(3)= 8
set @stub_(4)= 13
set @stub_(5)= 15
set @stub_(6)= 21
set @stub_(7)= 25
set @stub_(8)= 28
set @stub_(9)= 29
set @stub_(10)= 35
set @stub_(11)= 36
set @stub_(12)= 42
set @stub_(13)= 44
set @stub_(14)= 45
set @stub_(15)= 47
set @stub_(16)= 50
set @stub_(17)= 55
set @stub_(18)= 58
set @stub_(19)= 59
set @stub_(20)= 64
set @stub_(21)= 67
set @stub_(22)= 68
set @stub_(23)= 69
set @stub_(24)= 70


set @dbell_(1)= 4 ;draw bells group numbers
set @dbell_(2)= 5
set @dbell_(3)= 9
set @dbell_(4)= 11
set @dbell_(5)= 17
set @dbell_(6)= 19
set @dbell_(7)= 22
set @dbell_(8)= 24
```

```
set @dbell_(9)= 26
set @dbell_(10)= 30
set @dbell_(11)= 33
set @dbell_(12)= 34
set @dbell_(13)= 40
set @dbell_(14)= 43
set @dbell_(15)= 46
set @dbell_(16)= 49
set @dbell_(17)= 51
set @dbell_(18)= 53
set @dbell_(19)= 56
set @dbell_(20)= 60
set @dbell_(21)= 62
set @dbell_(22)= 66


set @drawd_(1)= 3 ;draw drifts group numbers
set @drawd_(2)= 10
set @drawd_(3)= 12
set @drawd_(4)= 16
set @drawd_(5)= 20
set @drawd_(6)= 23
set @drawd_(7)= 27
set @drawd_(8)= 31
set @drawd_(9)= 32
set @drawd_(10)= 41
set @drawd_(11)= 48
set @drawd_(12)= 52
set @drawd_(13)= 54
set @drawd_(14)= 57
set @drawd_(15)= 61
set @drawd_(16)= 63
set @drawd_(17)= 65


set @extdrift_(1)= 7 ;extraction drifts group numbers
set @extdrift_(2)= 14


set @underdrift_(1)= 37 ;undercut drifts group numbers
set @underdrift_(2)= 38


set @topgp_(1)= 18 ;material above undercut group number

set @botgp_(1)= 1 ;material below undercut group number
set @botgp_(2)= 39


set @nstub_ = 24 ;number of stub groups
set @ndbell_ = 22 ;number of draw bell groups
set @ndrawd_ = 17 ;number of draw drifts groups
set @nextdrift_ = 2 ;number of extraction drift groups
set @nunderdrift_ = 2 ;number of undercut drift groups
set @ntopgp_ = 1 ;number of material above undercut groups
set @nbotgp_ = 2 ;number of material below undercut groups

set @dp_space = 18. ;drawpoint spacing
set @tr_length = 8.7 ;trough length
set @tn_space = 30. ;extraction drift spacing
set @tn_width = 4.5 ;extraction drift width
set @tn_height = 4.5 ;extraction drift height
```

```
set @nb_unit = 5 ;number of drawbells along the drift (middle)
set @kub_height = 40. ;height of the kubrix model from the top to the floor of the extraction drift
set @drawd_angle = 45. ;draw drifts angle (smallest angle between extraction drift and draw drift, negative for negative slope)
set @uc_level = 22. ;difference in height between floor of extraction drift and undercut drift

@_crIMZ ;creates a table with the drawpoint coordinates

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;MODEL CONTROL
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

;stage 1 loading
set @crit_= 1 ;criterion used to stop stage1 0=strain 1=abutment stress 2=strain or stress which ever comes first
;use if crit_= 0 or 2
set @max_strain=0.01 ;when this strain is reached by 1/2 or more of the history points in the walls and roof stage1 stops and stage2 begins
;use if crit_=1 or 2
set @max_stress_st1= 37.7e6 ;when this abutment stress (absolute value) is reached stage1 stops and stage2 begins

;stage 2 unloading
set @min_stress=3.0e6 ;when this abutment stress (absolute value) is reached stage2 stops and stage3 begins


;stage 3 loading
set @max_stress_st3=5.0e6 ;when this abutment stress (absolute value) is reached stage3 stops

set @_appliedvelocity_= 1.e-5  ;loading rate stage 1, 2 and 3 (absolute value)
set @step_chk= 100 ;number of steps between each strain and stress calculations
set @str_incr_ = 5.e6 ;Stress increment for save files

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;MESH GENERATION
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

set @top_thick =  120. ;Thickness of the zone above the kubrix mesh
set @bot_thick =   50. ;Thickness of the zone below the kubrix mesh
set @zone_size =  4. ;zone size of the mesh above and below the kubrix mesh
set @iface_zonesize = 1.5   ;set this to about 90% of the edge length in the zones at the top of the Kubrix mesh

@add_topandbot ;generates top and bottom mesh
@_rangename ;defines ranges
@get_limits ;finds the limits of the model

save vHoekMesh.sav  ;name of save file after mesh generation

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;MATERIAL PROPERTIES
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

;INTERFACE PROPERTIES
interface 1 prop kn 2.e10 ;Interface Top/Kubrix
interface 1 prop ks 2.e10
interface 1 prop fric 40.
interface 1 prop coh 1.e20
interface 1 prop ten 1.e20

interface 2 prop kn 2.e10 ;Interface Bottom/Kubrix
interface 2 prop ks 2.e10
interface 2 prop fric 40.
interface 2 prop coh 1.e20
interface 2 prop ten 1.e20

;ROCK MASS PROPERTIES
```

```
set @Density_=2710.
set @Dilation_=10.
set @_Poissons=0.14
set @_Mbr=1.283
set @_sr_=0.0001
set @_ar_=0.55
set @_GSI=59.
set @_M=80.
set @_Mi=24.
set @_UCSi=81.6e6
set @_Modulus=27.35e9

;CAVED ROCK PROPERTIES
set @_DilationCR= 10.
set @CRDensity_ = 1491.
set @_PoissonsCR=0.25
set @_vsiCR = 0.67

@_PropCalc ;calculates additional properties
@_ElasProp ;apply Elastic properties to every zones of the model

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;INITIAL STRESS CONDITIONS
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

set @x_kfac = 1.7054
set @y_kfac = 2.9612
set @gravity_ = -9.81
set @zcoord_of_gs = 580.
@ini_stresses

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;BOUNDARY CONDITIONS
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

;SET VELOCITY BOUNDARY CONDITION
set @bc_direction = 'x'    ;location: 'x' or 'y' or 'z'
set @bc_vel       = 0.0          ;positive velocity means compression
@set_bc_vel

;SET VELOCITY BOUNDARY CONDITION
set @bc_direction = 'y'    ;location: 'x' or 'y' or 'z'
set @bc_vel       = 0.0          ;positive velocity means compression
@set_bc_vel

;SET BOTTOM BOUNDARY CONDITION
@bot_boun_

;SET TOP BOUNDARY CONDITION
set @bc_direction = 'z'    ;location: 'x' or 'y' or 'z'
set @bc_vel       = 0.0          ;positive velocity means compression
@set_bc_vel

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;INITIAL EQUILIBRIUM
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
hist add id 1 ratio
hist add id 2 unbalance

solve
save vHoekInit.sav  ;name of initial save file
ini disp 0,0,0 ;resets displacements to zero
```

```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;EXCAVATION AND STAGES
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

@loc_MPBX         ;Look up gridpoints for all targets on 2 artificial MPBX

@_RecHist         ;Records histories

@_vHoekProp       ;Assign vHoek properties to every zone of the model

model null range group "extdrift" slot 2 ;excavates extraction drifts

model null range group "udrift" slot 2   ;excavates undercut drifts

@_loading_alt   ;Applies GSI' when the S-curve is enabled and 'solve' when the H-B criterion is enabled

model null range group "stub" slot 2     ;excavates stubs

model null range group "ddrift" slot 2   ;excavates draw drifts

@_loading_alt   ;Applies GSI' when the S-curve is enabled and 'solve' when the H-B criterion is enabled

save vHoekInitTunnels.sav

@_DbellProp       ;Assign Caved Rock properties to draw bells and drawdrifts

@_loading_alt     ;Applies GSI' when the S-curve is enabled and 'solve' when the H-B criterion is enabled

save vHoekInitMining.sav

@inst_MPBX        ;Calculate displacements that took place before installation of the MPBX
@rel_disp         ;Calculate relative dispalcements between the targets and the instrument head
@_MPBXHist        ;Assign histories to all nodes on all MPBX

@_stage1          ;Starts stage1 and stops when the previously defined criteria is met (loading)

@_stage2          ;Starts stage2 and stops when the previously defined criteria is met (unloading)

@_TopProp         ;Assign Caved Rock properties to the top of the model and undercut drifts

@setup_sshape     ;Updates the array with all zones in the unbroken rock mass (excludes "top" this time)

@_stage3          ;Starts stage3 and stops when the previously defined criteria is met (loading)

ca NPM_Plot_write.f3dat ;Creates history data files and figures of cross-sections
```

R.2 NPM_Func.dat

```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;INITIALIZE PARAMETERS
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

def ini_param
 Density_ = Density_
 Dilation_ = Dilation_
 _DilationCR = _DilationCR
 CRDensity_ = CRDensity_
 _MbrCR=_MbrCR
 _srCR_=_srCR
 _arCR_= _arCR_
 _GSICR=  _GSICR
 _MiCR= _MiCR
 _UCSiCR= _UCSiCR
 _vsiCR =  _vsiCR
 _vsi =  _vsi
 _Poissons = _Poissons
 _Mbr=_Mbr
 _sr_=_sr_
 _ar_=_ar_
 _GSI= _GSI
 _M=_M
 _UCSi=_UCSi
 _Mi=_Mi
 _Modulus=_Modulus
 _Bulk = _Bulk
 _Shear = _Shear
 _Mb=_Mb
 _s_=_s_
 _a_=_a_
 gravity_=gravity_
 _third = 1.0/3.0
 st_numb=0.
 beg_unl=0
 num=0.
 _end_st2=0
 _end_st3=0
 step_chk = step_chk
 ntopgp_ = ntopgp_
 nbotgp_ = nbotgp_
 array botgp_(10)
 array topgp_(10)
 array stub_(100)
 array dbell_(100)
 array drawd_(100)
 array extdrift_(30)
 array underdrift_(30)
end
ini_param

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;DETERMINES LIMITS OF MODEL
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

def get_limits
 min_x=1e20
 max_x=-1e20
 min_y=1e20
 max_y=-1e20
 min_z=1e20
```

```
 max_z=-1e20
 p_gp=gp_head
 loop while p_gp # null
  min_x=min(min_x,gp_xpos(p_gp))
  max_x=max(max_x,gp_xpos(p_gp))
  min_y=min(min_y,gp_ypos(p_gp))
  max_y=max(max_y,gp_ypos(p_gp))
  min_z=min(min_z,gp_zpos(p_gp))
  max_z=max(max_z,gp_zpos(p_gp))
  p_gp=gp_next(p_gp)
 end_loop
 x_pladis=0.1
 y_pladis=0.1
 z_pladis=0.1
 mid_x=((max_x - min_x)/ 2.)+ min_x
 mid_y=((max_y - min_y)/ 2.)+ min_y
 ela_z=0.
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;RANGE NAME
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

def _rangename
 command
  set echo off
 end_command

 loop i (1, nstub_)
  gpname = 'group' + string(stub_(i))
  command
   group zone "stub" slot 2 range group gpname
  end_command
 end_loop

 loop i (1, ndbell_)
  gpname = 'group' + string(dbell_(i))
  command
   group zone "dbell" slot 2 range group gpname
  end_command
 end_loop

 loop i (1, ndrawd_)
  gpname = 'group' + string(drawd_(i))
  command
   group zone "ddrift" slot 2 range group gpname
  end_command
 end_loop

 loop i (1, nextdrift_)
  gpname = 'group' + string(extdrift_(i))
  command
   group zone "extdrift" slot 2 range group gpname
  end_command
 end_loop


 loop i (1, nunderdrift_)
  gpname = 'group' + string(underdrift_(i))
  command
   group zone "udrift" slot 2 range group gpname
  end_command
```

```
 end_loop

 loop i (1, nbotgp_)
  gpname = 'group' + string(botgp_(i))
  command
   group zone "bottom" slot 2 range group gpname
  end_command
 end_loop

  loop i (1, ntopgp_)
  gpname = 'group' + string(topgp_(i))
  command
   group zone "top" slot 2 range group gpname
  end_command
 end_loop

 command
  group zone "top" slot 2 range group "top"
  group zone "bottom" slot 2 range group "bottom"
 end_command

 command
  set echo on
 end_command

end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;MESH GENERATION
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

def add_topandbot
 iface_zonesize=iface_zonesize
 top_z=max_z+top_thick
 top_xzones=int((max_x-min_x)/zone_size)+1
 top_yzones=int((max_y-min_y)/zone_size)+1
 top_zzones=int(top_thick/zone_size)+1
 bot_z=min_z-bot_thick
 bot_xzones=int((max_x-min_x)/zone_size)+1
 bot_yzones=int((max_y-min_y)/zone_size)+1
 bot_zzones=int(bot_thick/zone_size)+1
 command
  gen zone bri p0 min_x min_y max_z p1 max_x min_y max_z p2 min_x max_y max_z p3 min_x min_y top_z &
  size top_xzones top_yzones top_zzones group 'top' nomerge
  gen zone bri p0 min_x min_y bot_z p1 max_x min_y bot_z p2 min_x max_y bot_z p3 min_x min_y min_z &
  size bot_xzones bot_yzones bot_zzones group 'bottom' nomerge
  interface 1 face  &
        range pla dip 0 dd 0 ori 0 0 max_z dis z_pladis &
     group top
  interface 1 maxedge iface_zonesize
  interface 2 face  &
        range pla dip 0 dd 0 ori 0 0 min_z dis z_pladis &
     group bottom
  interface 2 maxedge iface_zonesize
 end_command
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;INITIAL STRESS CONDITIONS
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

def ini_stresses
```

```
 rep_density = Density_
 szz_orig=gravity_*rep_density*zcoord_of_gs
 sxx_orig=x_kfac*szz_orig
 syy_orig=y_kfac*szz_orig
 szz_grad=-1*gravity_*rep_density
 sxx_grad=x_kfac*szz_grad
 syy_grad=y_kfac*szz_grad
 command
  set gravity 0 0 @gravity_
  initial szz @szz_orig grad 0 0 @szz_grad
  initial sxx @sxx_orig grad 0 0 @sxx_grad
  initial syy @syy_orig grad 0 0 @syy_grad
 end_command
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;BOUNDARY CONDITIONS
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

def set_bc_vel
 command
  ini xvel 0 yvel 0 zvel 0
 end_command
 if bc_direction='x'
  command
   fix x range plane dip 90 dd 90 ori @min_x 0 0 dis @x_pladis
   ini xvel @bc_vel range plane dip 90 dd 90 ori @min_x 0 0 dis @x_pladis
  end_command
  bc_vel=-bc_vel
  command
   fix x range plane dip 90 dd 90 ori @max_x 0 0 dis @x_pladis
   ini xvel @bc_vel range plane dip 90 dd 90 ori @max_x 0 0 dis @x_pladis
  end_command
 end_if
 if bc_direction='y'
  command
   fix y range plane dip 90 dd 0 ori 0 @min_y 0 dis @y_pladis
   ini yvel @bc_vel range plane dip 90 dd 0 ori 0 @min_y 0 dis @y_pladis
  end_command
  bc_vel=-bc_vel
  command
   fix y range plane dip 90 dd 0 ori 0 @max_y 0 dis @y_pladis
   ini yvel @bc_vel range plane dip 90 dd 0 ori 0 @max_y 0 dis @y_pladis
  end_command
 end_if
if bc_direction='z'
  command
   fix z range plane dip 0 dd 0 ori 0 0 @min_z dis @z_pladis
   ini zvel @bc_vel range plane dip 0 dd 0 ori 0 0 @min_z dis @z_pladis
  end_command
  bc_vel=-bc_vel
  command
   fix z range plane dip 0 dd 0 ori 0 0 @max_z dis @z_pladis
   ini zvel @bc_vel range plane dip 0 dd 0 ori 0 0 @max_z dis @z_pladis
  end_command
 end_if
end

def bot_boun_
 command
  fix x range plane dip 0 dd 0 ori 0 0 @min_z dis @z_pladis
  ini xvel 0 range plane dip 0 dd 0 ori 0 0 @min_z dis @z_pladis
```

```
  fix y range plane dip 0 dd 0 ori 0 0 @min_z dis @z_pladis
  ini yvel 0 range plane dip 0 dd 0 ori 0 0 @min_z dis @z_pladis
  fix z range plane dip 0 dd 0 ori 0 0 @min_z dis @z_pladis
  ini zvel 0 range plane dip 0 dd 0 ori 0 0 @min_z dis @z_pladis
 end_command
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;MATERIAL PROPERTIES
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

def _PropCalc
 _Bulk      =_Modulus/(3.0*(1.0-2.0*_Poissons))
 _Shear     =_Modulus/(2.0*(1.0+_Poissons))
 _Mb        =_Mi*exp((_GSI-100.)/28.)
 _s_        =exp((_GSI-100.)/9.)
 _a_        =0.5+1./6.*(exp(-_GSI/15.)-(exp(-20./3.)))
 _x1        =102.e6
 _x2        =0.5
 _x1c       =0.1316*_vsiCR^(-2.145)
 _x2c       =1110.5*_vsiCR^(-2.574)
 _constc    =981.14*_vsiCR^(-2.318)
 _ModulusCR =(_x1c*_x1/6894.+_x2c*_x2-_constc)*6894.
 _BulkCR    =_ModulusCR/(3.0*(1.0-2.0*_PoissonsCR))
 _ShearCR   =_ModulusCR/(2.0*(1.0+_PoissonsCR))
 _MiCR      =_Mi
 _MbCR      =_Mbr
 _MbrCR     =_Mbr
 _sCR_      =_sr_
 _srCR_     =_sr_
 _aCR_      =_ar_
 _arCR_     =_ar_
 _GSICR     =_GSI
 _UCSiCR    =_UCSi
end

def _vHoekProp
command
 set echo off
 config cppudm
end_command
 pz=zone_head
 loop while pz # null
   if z_model(pz) # "null" then
     z_model(pz)  = "Vhoek"
     z_prop(pz, "zsize")  = z_volume(pz)^_third
   endif
  pz=z_next(pz)
 end_loop
 command
  ini density Density_ range model "Vhoek"
  prop bulk _Bulk shear _Shear hb_sci _UCSi range model "Vhoek"
  prop hb_aai _a_ hb_mmi _Mb hb_ssi _s_ range model "Vhoek"          ; Peak strength H-B parameters
  prop hb_ssr _sr_ hb_aar _ar_ hb_mmr _Mbr range model "Vhoek"   ; Residual H-B parameters
  prop gsi  _GSI range model "Vhoek"
  prop hb_do 0 hb_psi Dilation_ hb_po 1 range model "Vhoek"          ;Setting dilation and Plastic shear strain
  set echo on
 end_command
end

def _ElasProp
 command
```

```
  model elastic
  prop bulk _Bulk shear _Shear
  ini density Density_
 end_command
end

def _DbellProp
 command
  model vhoek range group "ddrift" slot 2
  ini density CRDensity_ range group "dbell" slot 2 or "ddrift" slot 2
  prop bulk _BulkCR shear _ShearCR hb_sci _UCSiCR range group "dbell" slot 2 or "ddrift" slot 2
  prop hb_aai _aCR_ hb_mmi _MbCR hb_ssi _sCR_ range group "dbell" slot 2 or "ddrift" slot 2          ; Peak H-B parameters for caved rock equal residual
  prop hb_ssr _srCR_ hb_aar _arCR_ hb_mmr _MbrCR range group "dbell" slot 2 or "ddrift" slot 2 ; Residual H-B parameters for caved rock
  prop gsi _GSICR range group "dbell" slot 2 or "ddrift" slot 2
  prop hb_do 0 hb_psi _DilationCR hb_po 1 range group "dbell" slot 2 or "ddrift" slot 2          ;Setting dilation and Plastic shear strain
  ini stress 0 range group "dbell" slot 2 or "ddrift" slot 2
  set echo off
 end_command
 pz=zone_head
 loop while pz # null
   if z_group(pz,2) = "ddrift" then
     z_prop(pz, "zsize")  = z_volume(pz)^_third
   endif
   if z_group(pz,2) = "dbell" then
     z_prop(pz, "zsize")  = z_volume(pz)^_third
   endif
  pz=z_next(pz)
 end_loop
 command
  set echo on
 end_command
end

def _TopProp
 command
  ini density CRDensity_ range group "top" slot 2
  property bulk _BulkCR shear _ShearCR range group "top" slot 2
  prop hb_psi _DilationCR  hb_aai _aCR_  hb_mmi _MbCR  hb_ssi _sCR_  hb_sci _UCSiCR range group "top" slot 2
  prop hb_ssr  _srCR_   hb_aar _arCR_  hb_mmr _MbrCR range group "top" slot 2  ; Residual properties
  prop gsi  _GSICR range group "top" slot 2
  prop hb_do 0 hb_po 1 range group "top" slot 2  ;Setting dilation and Plastic shear strain
  model vhoek range group "udrift" slot 2
  ini density CRDensity_ range group  "udrift" slot 2
  property bulk _BulkCR shear _ShearCR range group "udrift" slot 2
  prop hb_psi _DilationCR  hb_aai _aCR_  hb_mmi _MbCR  hb_ssi _sCR_  hb_sci _UCSiCR range group "udrift" slot 2
  prop hb_ssr  _srCR_   hb_aar _arCR_  hb_mmr _MbrCR range group "udrift" slot 2  ; Residual properties
  prop gsi  _GSICR range group "udrift" slot 2
  prop hb_do 0 hb_po 1 range group "udrift" slot 2  ;Setting dilation and Plastic shear strain
  set echo off
 end_command
 pz=zone_head
 loop while pz # null
   if z_group(pz,2) = "udrift" then
     z_prop(pz, "zsize")  = z_volume(pz)^_third
   endif
  pz=z_next(pz)
 end_loop
 command
  set echo on
 end_command
```

```
 if conlaw_ = 2
  rr = lose_array(s_pzz)
 end_if
end

def setup_sshape
 ; Count the number of zones in the rock mass (exclude caved rock)
 s_inzz = 0
 s_pz   = zone_head
 loop while s_pz # null
  if z_model(s_pz) # 'null' then
   if z_prop(s_pz,"density") = Density_ then
    s_inzz = s_inzz + 1
   endif
  endif
  s_pz = z_next(s_pz)
 end_loop
 ; Allocates these zones to an array
 s_pzz = get_array(s_inzz)
 s_inzz = 0
 s_pz = zone_head
 loop while s_pz # null
  if z_model(s_pz) # 'null' then
   if z_prop(s_pz,"density") = Density_ then
    s_inzz = s_inzz + 1
    s_pzz(s_inzz) = s_pz
   endif
  endif
  s_pz = z_next(s_pz)
 end_loop
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;LOADING RATE
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
def _loadingrate
 _negappliedvelocity_ = -1. * _appliedvelocity_
 command
 apply remove range plane dip 0 dd 0 ori 0 0 @max_z dis @z_pladis
 free z range plane dip 0 dd 0 ori 0 0 @max_z dis @z_pladis
 apply zvel _negappliedvelocity_ range plane dip 0 dd 0 ori 0 0 @max_z dis @z_pladis
 end_command
end

def _loading_alt
 if conlaw_ = 1
  command
   solve
  end_command
 end_if

 if conlaw_ = 2
  command
   setup_sshape
   step step_chk
  end_command
  local uu
  s_inzz = array_size(s_pzz,1)
  loop while mech_ratio > 1.e-5
   loop uu(1,s_inzz)
    s_pz = s_pzz(uu)
    _sig3 = z_sig3(s_pz) * 1.e-6
```

```
    _GSI_local     = (_M-(_M/100.)*_GSI) / (1.+exp(_sig3+((_UCSi*1.e-6)/10.))) + _GSI
    _Mblocal       = _Mi*exp((_GSI_local-100.)/28.)
    _s_local       = exp((_GSI_local-100.)/9.)
    _a_local       = 0.5+1./6.*(exp(-_GSI_local/15.)-(exp(-20./3.)))
    _Modulus_local = 55.e9*(0.02+(1./(1+exp((60.-_GSI_local)/11.))))
    _Bulk_local    = _Modulus_local/(3.0*(1.0-2.0*_Poissons))
    _Shear_local   = _Modulus_local/(2.0*(1.0+_Poissons))
    z_prop(s_pz,"gsi")    = _GSI_local
    z_prop(s_pz,"hb_mmi") = _Mblocal
    z_prop(s_pz,"hb_ssi") = _s_local
    z_prop(s_pz,"hb_aai") = _a_local
    z_prop(s_pz,"bulk")   = _Bulk_local
    z_prop(s_pz,"shear")  = _Shear_local
   end_loop
   command
    step step_chk
   end_command
  end_loop
 endif
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;EXTENSOMETERS
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

def loc_MPBX
 ;The instrument head should be installed at the face of the excavation
 drawd_angle = drawd_angle * (pi / 180.)
 _ygonio = ((tn_space-tn_width-tr_length)/2.)+(0.5*tn_width)-(2.*tan(0.5*drawd_angle))
 nb_mpbx = 2          ; Amount of MPBX stations
 nb_target = 7        ; Six targets + instrument head
 _MPBX = get_array(nb_mpbx,nb_target,3)
 _pnt  = get_array(nb_mpbx,nb_target)
 _id   = get_array(nb_mpbx,nb_target)
  loop aa (1,nb_mpbx)
  mulx = aa-0.5
  muly = (aa-1.)*0.25
   loop bb (1,nb_target)
   mulz = nb_target-bb
   _MPBX(aa,bb,1) = min_x+(mulx*tn_space) ; xcoor of all targets centre of tunnel
   _MPBX(aa,bb,2) = min_y+(3.*dp_space)-_ygonio-(muly*dp_space) ; ycoor different in respect to exit stub
   _MPBX(aa,bb,3) = tn_height+(mulz*10./6.) ; zcoor of each target (1=deepest - nb_target=instrument head)
   _pnt(aa,bb) = gp_near(_MPBX(aa,bb,1),_MPBX(aa,bb,2),_MPBX(aa,bb,3))
   _id(aa,bb) = gp_id(_pnt(aa,bb))
  end_loop
 end_loop
end

def inst_MPBX
 idisp = get_array(nb_mpbx,nb_target,6)
 nb_target = nb_target-1
 loop cc (1,nb_mpbx)
  loop dd (1,nb_target)
   idisp(cc,dd,1) = gp_xdisp(_pnt(cc,7)) - gp_xdisp(_pnt(cc,dd))
   idisp(cc,dd,2) = gp_ydisp(_pnt(cc,7)) - gp_ydisp(_pnt(cc,dd))
   idisp(cc,dd,3) = gp_zdisp(_pnt(cc,7)) - gp_zdisp(_pnt(cc,dd))
   idisp(cc,dd,4) = (idisp(cc,dd,1)^2+idisp(cc,dd,2)^2+idisp(cc,dd,3)^2)^0.5
   idisp(cc,dd,5) = gp_zdisp(_pnt(cc,7))
   idisp(cc,dd,6) = gp_zdisp(_pnt(cc,dd))
  end_loop
 end_loop
end
```

```
def rel_disp
  rdisp11_x = gp_xdisp(_pnt(1,7)) - gp_xdisp(_pnt(1,1))
  rdisp11_y = gp_ydisp(_pnt(1,7)) - gp_ydisp(_pnt(1,1))
  rdisp11_z = gp_zdisp(_pnt(1,7)) - gp_zdisp(_pnt(1,1))
  rdisp11 = (rdisp11_x^2 + rdisp11_y^2 + rdisp11_z^2)^0.5 - idisp(1,1,4)
  rdisp12_x = gp_xdisp(_pnt(1,7)) - gp_xdisp(_pnt(1,2))
  rdisp12_y = gp_ydisp(_pnt(1,7)) - gp_ydisp(_pnt(1,2))
  rdisp12_z = gp_zdisp(_pnt(1,7)) - gp_zdisp(_pnt(1,2))
  rdisp12 = (rdisp12_x^2 + rdisp12_y^2 + rdisp12_z^2)^0.5 - idisp(1,2,4)
  rdisp13_x = gp_xdisp(_pnt(1,7)) - gp_xdisp(_pnt(1,3))
  rdisp13_y = gp_ydisp(_pnt(1,7)) - gp_ydisp(_pnt(1,3))
  rdisp13_z = gp_zdisp(_pnt(1,7)) - gp_zdisp(_pnt(1,3))
  rdisp13 = (rdisp13_x^2 + rdisp13_y^2 + rdisp13_z^2)^0.5 - idisp(1,3,4)
  rdisp14_x = gp_xdisp(_pnt(1,7)) - gp_xdisp(_pnt(1,4))
  rdisp14_y = gp_ydisp(_pnt(1,7)) - gp_ydisp(_pnt(1,4))
  rdisp14_z = gp_zdisp(_pnt(1,7)) - gp_zdisp(_pnt(1,4))
  rdisp14 = (rdisp14_x^2 + rdisp14_y^2 + rdisp14_z^2)^0.5 - idisp(1,4,4)
  rdisp15_x = gp_xdisp(_pnt(1,7)) - gp_xdisp(_pnt(1,5))
  rdisp15_y = gp_ydisp(_pnt(1,7)) - gp_ydisp(_pnt(1,5))
  rdisp15_z = gp_zdisp(_pnt(1,7)) - gp_zdisp(_pnt(1,5))
  rdisp15 = (rdisp15_x^2 + rdisp15_y^2 + rdisp15_z^2)^0.5 - idisp(1,5,4)
  rdisp16_x = gp_xdisp(_pnt(1,7)) - gp_xdisp(_pnt(1,6))
  rdisp16_y = gp_ydisp(_pnt(1,7)) - gp_ydisp(_pnt(1,6))
  rdisp16_z = gp_zdisp(_pnt(1,7)) - gp_zdisp(_pnt(1,6))
  rdisp16 = (rdisp16_x^2 + rdisp16_y^2 + rdisp16_z^2)^0.5 - idisp(1,6,4)

  rdisp21_x = gp_xdisp(_pnt(2,7)) - gp_xdisp(_pnt(2,1))
  rdisp21_y = gp_ydisp(_pnt(2,7)) - gp_ydisp(_pnt(2,1))
  rdisp21_z = gp_zdisp(_pnt(2,7)) - gp_zdisp(_pnt(2,1))
  rdisp21 = (rdisp21_x^2 + rdisp21_y^2 + rdisp21_z^2)^0.5 - idisp(2,1,4)
  rdisp22_x = gp_xdisp(_pnt(2,7)) - gp_xdisp(_pnt(2,2))
  rdisp22_y = gp_ydisp(_pnt(2,7)) - gp_ydisp(_pnt(2,2))
  rdisp22_z = gp_zdisp(_pnt(2,7)) - gp_zdisp(_pnt(2,2))
  rdisp22 = (rdisp22_x^2 + rdisp22_y^2 + rdisp22_z^2)^0.5 - idisp(2,2,4)
  rdisp23_x = gp_xdisp(_pnt(2,7)) - gp_xdisp(_pnt(2,3))
  rdisp23_y = gp_ydisp(_pnt(2,7)) - gp_ydisp(_pnt(2,3))
  rdisp23_z = gp_zdisp(_pnt(2,7)) - gp_zdisp(_pnt(2,3))
  rdisp23 = (rdisp23_x^2 + rdisp23_y^2 + rdisp23_z^2)^0.5 - idisp(2,3,4)
  rdisp24_x = gp_xdisp(_pnt(2,7)) - gp_xdisp(_pnt(2,4))
  rdisp24_y = gp_ydisp(_pnt(2,7)) - gp_ydisp(_pnt(2,4))
  rdisp24_z = gp_zdisp(_pnt(2,7)) - gp_zdisp(_pnt(2,4))
  rdisp24 = (rdisp24_x^2 + rdisp24_y^2 + rdisp24_z^2)^0.5 - idisp(2,4,4)
  rdisp25_x = gp_xdisp(_pnt(2,7)) - gp_xdisp(_pnt(2,5))
  rdisp25_y = gp_ydisp(_pnt(2,7)) - gp_ydisp(_pnt(2,5))
  rdisp25_z = gp_zdisp(_pnt(2,7)) - gp_zdisp(_pnt(2,5))
  rdisp25 = (rdisp25_x^2 + rdisp25_y^2 + rdisp25_z^2)^0.5 - idisp(2,5,4)
  rdisp26_x = gp_xdisp(_pnt(2,7)) - gp_xdisp(_pnt(2,6))
  rdisp26_y = gp_ydisp(_pnt(2,7)) - gp_ydisp(_pnt(2,6))
  rdisp26_z = gp_zdisp(_pnt(2,7)) - gp_zdisp(_pnt(2,6))
  rdisp26 = (rdisp26_x^2 + rdisp26_y^2 + rdisp26_z^2)^0.5 - idisp(2,6,4)
end

def _MPBXHist
 command
  hist add id _id(1,1) fish rdisp11
  hist add gp zdisp id 881101
  hist add id _id(1,2) fish rdisp12
  hist add gp zdisp id 101943
  hist add id _id(1,3) fish rdisp13
  hist add gp zdisp id 279714
  hist add id _id(1,4) fish rdisp14
```

```
 hist add gp zdisp id 73062
 hist add id _id(1,5) fish rdisp15
 hist add gp zdisp id 739382
 hist add id _id(1,6) fish rdisp16
 hist add gp zdisp id 808488
 hist add gp zdisp id 662524
 hist add id _id(2,1) fish rdisp21
 hist add gp zdisp id 190997
 hist add id _id(2,2) fish rdisp22
 hist add gp zdisp id 119875
 hist add id _id(2,3) fish rdisp23
 hist add gp zdisp id 737708
 hist add id _id(2,4) fish rdisp24
 hist add gp zdisp id 25864
 hist add id _id(2,5) fish rdisp25
 hist add gp zdisp id 1312112
 hist add id _id(2,6) fish rdisp26
 hist add gp zdisp id 1115131
 hist add gp zdisp id 496453
end_command
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;HISTORIES
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
def _RecHist
 nb_unit=nb_unit-1
 command
  hist add id 3 zone szz mid_x, mid_y, max_z
  hist add id 4 fish hstrain_
 end_command

 ;History points in the major apex
 loop aa (1,nb_mpbx)
  maj_zloc = ((uc_level-tn_height) / 2.) + tn_height       ;Halfway the roof of the extraction drift and the floor of the undercut drift
  maj_znear = z_near(_MPBX(aa,1,1),_MPBX(aa,1,2),maj_zloc)
  maj_zid = z_id(maj_znear)
  gpidmpbx = _id(aa,1)
  command
   hist add gp disp id gpidmpbx                  ;Check if deepest targets of MPBX are in stable rock
   hist add zone smax id maj_zid        ;Minor principal stress @centre of major apex
   hist add zone smid id maj_zid        ;Intermediate principal stress @centre of major apex
   hist add zone smin id maj_zid        ;Major principal stress @centre of major apex
   hist add zone szz id maj_zid                  ;Vertical stress @centre of major apex
  end_command
 end_loop

 ;History points in the minor apex
 loop tt (1,2)
  minor_xloc = -0.5*tn_space            ;Centre of minor apex
  minor_yloc = min_y + ((1+tt)*dp_space);Select two different minor appices next to middle of the y-axis
  minor_zloc = 2.25                     ;Half the height of the extraction drift
  minor_znear = z_near(minor_xloc,minor_yloc,minor_zloc)
  minor_zid = z_id(minor_znear)
  command
   hist add zone smax id minor_zid      ;Minor principal stress @centre of minor apex
   hist add zone smid id minor_zid      ;Intermediate principal stress @centre of minor apex
   hist add zone smin id minor_zid      ;Major principal stress @centre of minor apex
   hist add zone szz id minor_zid       ;Vertical stress @centre of minor apex
  end_command
 end_loop
```

```
 ;History points at the extraction drift wall / roof
 wa_hist_z = max_z - top_thick - kub_height + (tn_height / 2.)
 fl_hist_z = max_z - top_thick - kub_height - z_pladis
 rf_hist_z = max_z - top_thick - kub_height + tn_height + z_pladis
 nb_hist = nb_ext_tnl * nb_unit * 4
 ext_tn_hist = get_array(nb_ext_tnl,nb_unit,4,3)
 hist_disp = get_array(nb_hist)

 loop i (1,nb_ext_tnl)
  loop x (1,nb_unit)
   mul=1+((i-1)*2)

   ext_tn_hist(i,x,1,1) = max_x - (mul * (tn_space/2)) + (tn_width/2) + x_pladis;hist xcoor x+ wall
   ext_tn_hist(i,x,1,2) = max_y - (x * dp_space);hist ycoor x+ wall
   ext_tn_hist(i,x,1,3) = wa_hist_z;hist zcoor x+ wall

   ext_tn_hist(i,x,2,1) = max_x - (mul * (tn_space/2)) - (tn_width/2) - x_pladis;hist xcoor x- wall
   ext_tn_hist(i,x,2,2) = max_y - (x * dp_space);hist ycoor x- wall
   ext_tn_hist(i,x,2,3) = wa_hist_z ;hist zcoor x- wall

   ext_tn_hist(i,x,3,1) = max_x - (mul * (tn_space/2));hist xcoor roof
   ext_tn_hist(i,x,3,2) = max_y - (x * dp_space) ;hist ycoor roof
   ext_tn_hist(i,x,3,3) = rf_hist_z ;hist zcoor roof

   ext_tn_hist(i,x,4,1) = max_x - (mul * (tn_space)/2) ;hist xcoor floor
   ext_tn_hist(i,x,4,2) = max_y - (x * dp_space)  ;hist ycoor floor
   ext_tn_hist(i,x,4,3) = fl_hist_z ;hist zcoor floor

  end_loop
 end_loop

 loop k (1,nb_ext_tnl)
  loop q (1,nb_unit)
   loop g (1,4)
    num=num+1
    gpnear = gp_near(ext_tn_hist(k,q,g,1), ext_tn_hist(k,q,g,2), ext_tn_hist(k,q,g,3))
    gpid=gp_id(gpnear)
    command
     hist add gp disp id gpid
     hist add gp xdisp id gpid
     hist add gp ydisp id gpid
     hist add gp zdisp id gpid
    end_command
   end_loop
  end_loop
 end_loop
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;STAGE1 LOADING UNTILL THE CRITERION HAS BEEN MET
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
def _stage1
 x_count_ = step_chk
 znear = z_near(mid_x, mid_y, max_z)
 beg_stress_ = abs(z_szz(znear))
  loop while beg_unl # 1
   if conlaw_ = 2
    local uu
    s_inzz = array_size(s_pzz,1)
    loop uu(1,s_inzz)
     s_pz = s_pzz(uu)
     _sig3 = z_sig3(s_pz) * 1.e-6
```

```
  _GSI_local     = (_M-(_M/100.)*_GSI) / (1.+exp(_sig3+((_UCSi*1.e-6)/10.))) + _GSI
  _Mblocal       = _Mi*exp((_GSI_local-100.)/28.)
  _s_local       = exp((_GSI_local-100.)/9.)
  _a_local       = 0.5+1./6.*(exp(-_GSI_local/15.)-(exp(-20./3.)))
  _Modulus_local = 55.e9*(0.02+(1./(1+exp((60.-_GSI_local)/11.))))
  _Bulk_local    = _Modulus_local/(3.0*(1.0-2.0*_Poissons))
  _Shear_local   = _Modulus_local/(2.0*(1.0+_Poissons))
  z_prop(s_pz,"gsi")    = _GSI_local
  z_prop(s_pz,"hb_mmi") = _Mblocal
  z_prop(s_pz,"hb_ssi") = _s_local
  z_prop(s_pz,"hb_aai") = _a_local
  z_prop(s_pz,"bulk")   = _Bulk_local
  z_prop(s_pz,"shear")  = _Shear_local
 end_loop
end_if
if x_count_ < 4001
_negappliedvelocity_ = -1. * _appliedvelocity_/( 4000/ ( x_count_))
 command
  apply remove range plane dip 0 dd 0 ori 0 0 @max_z dis @z_pladis
  free z range plane dip 0 dd 0 ori 0 0 @max_z dis @z_pladis
  apply zvel _negappliedvelocity_ range plane dip 0 dd 0 ori 0 0 @max_z dis @z_pladis
 end_command
end_if
if x_count_ > 4001
_negappliedvelocity_ = -1. * _appliedvelocity_
 command
  apply remove range plane dip 0 dd 0 ori 0 0 @max_z dis @z_pladis
  free z range plane dip 0 dd 0 ori 0 0 @max_z dis @z_pladis
  apply zvel _negappliedvelocity_ range plane dip 0 dd 0 ori 0 0 @max_z dis @z_pladis
 end_command
end_if
x_count_ = x_count_ + step_chk
hstrain_ = 0.
v=0
loop k (1,nb_ext_tnl)
 loop q (1,nb_unit)
   v = v+1
   g = 1
   gpnear = gp_near(ext_tn_hist(k,q,g,1), ext_tn_hist(k,q,g,2), ext_tn_hist(k,q,g,3))
   disp_x1 = gp_xdisp(gpnear)
   g = g + 1
   gpnear = gp_near(ext_tn_hist(k,q,g,1), ext_tn_hist(k,q,g,2), ext_tn_hist(k,q,g,3))
   disp_x2 = gp_xdisp(gpnear)
   hist_disp(v)= abs((disp_x1 - disp_x2)/ (tn_width))
   hstrain_ = hstrain_ + hist_disp(v)
   if hist_disp(v) > max_strain
    st_numb = st_numb + 1.
   end_if
 end_loop
end_loop
hstrain_ = hstrain_ / (nb_ext_tnl * nb_unit)
znear = z_near(mid_x, mid_y, max_z)
abt_stress_ = abs(z_szz(znear))
st_numb = st_numb / (num/4.)
rel_disp

if crit_=0
 if st_numb >= 0.5
  beg_unl=1
   command
    print st_numb
    print abt_stress_
```

```
    print hstrain_
   end_command
 end_if
 if st_numb < 0.5
  command
   print st_numb
   print abt_stress_
   print hstrain_
   apply remove range plane dip 0 dd 0 ori 0 0 @max_z dis @z_pladis
   free z range plane dip 0 dd 0 ori 0 0 @max_z dis @z_pladis
   apply zvel _negappliedvelocity_ range plane dip 0 dd 0 ori 0 0 @max_z dis @z_pladis
   step step_chk
  end_command
  st_numb=0
 end_if
 _stress1_ = beg_stress_ - (str_incr_)
 if abt_stress_ <= _stress1_
  st_name = "Stage1_" + string(_stress1_) + ".sav"
  beg_stress_ = abt_stress_
  command
   sav st_name
  end_command
 end_if
 _stress2_ = beg_stress_ + (str_incr_)
 if abt_stress_ >= _stress2_
  st_name = "Stage1_" + string(_stress2_) + ".sav"
  beg_stress_ = abt_stress_
  command
   sav st_name
  end_command
 end_if
end_if

if crit_=2
 if st_numb >= 0.5
  beg_unl=1
   command
    print st_numb
    print abt_stress_
    print hstrain_
   end_command
 end_if
 if abt_stress_ >= max_stress_st1
  beg_unl=1
   command
    print st_numb
    print abt_stress_
    print hstrain_
   end_command
 end_if
 if abt_stress_ < max_stress_st1
  if st_numb < 0.5
   command
    print st_numb
    print abt_stress_
    print hstrain_
    step step_chk
   end_command
   st_numb=0
  end_if
 end_if
 _stress1_ = beg_stress_ - (str_incr_)
```

```
    if abt_stress_ <= _stress1_
     st_name = "Stage1_" + string(_stress1_) + ".sav"
     beg_stress_ = abt_stress_
     command
      sav st_name
     end_command
    end_if
    _stress2_ = beg_stress_ + (str_incr_)
    if abt_stress_ >= _stress2_
     st_name = "Stage1_" + string(_stress2_) + ".sav"
     beg_stress_ = abt_stress_
     command
      sav st_name
     end_command
    end_if
   end_if

   if crit_=1
    if abt_stress_ >= max_stress_st1
     beg_unl=1
     command
      print st_numb
      print abt_stress_
      print hstrain_
     end_command
    end_if
    if abt_stress_ < max_stress_st1
     command
      print st_numb
      print abt_stress_
      print hstrain_
      step step_chk
     end_command
    end_if
    _stress1_ = beg_stress_ - (str_incr_)
    if abt_stress_ <= _stress1_
     st_name = "Stage1_" + string(_stress1_) + ".sav"
     beg_stress_ = abt_stress_
     command
      sav st_name
     end_command
    end_if
    _stress2_ = beg_stress_ + (str_incr_)
    if abt_stress_ >= _stress2_
     st_name = "Stage1_" + string(_stress2_) + ".sav"
     beg_stress_ = abt_stress_
     command
      sav st_name
     end_command
    end_if
   end_if
  end_loop
  command
  sav Stage1_END.sav ;name of save file after stage 1
  end_command
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;STAGE2 UNLOADING UNTILL THE CRITERION HAS BEEN MET
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
def _stage2
 _appliedvelocity_ = -_appliedvelocity_
```

```
znear = z_near(mid_x, mid_y, max_z)
beg_stress_ = abs(z_szz(znear))
command
 @_loadingrate
end_command
loop while _end_st2 # 1
 if conlaw_ = 2
  local uu
  s_inzz = array_size(s_pzz,1)
  loop uu(1,s_inzz)
   s_pz = s_pzz(uu)
   _sig3 = z_sig3(s_pz) * 1.e-6
   _GSI_local     = (_M-(_M/100.)*_GSI) / (1.+exp(_sig3+((_UCSi*1.e-6)/10.))) + _GSI
   _Mblocal       = _Mi*exp((_GSI_local-100.)/28.)
   _s_local       = exp((_GSI_local-100.)/9.)
   _a_local       = 0.5+1./6.*(exp(-_GSI_local/15.)-(exp(-20./3.)))
   _Modulus_local = 55.e9*(0.02+(1./(1+exp((60.-_GSI_local)/11.))))
   _Bulk_local    = _Modulus_local/(3.0*(1.0-2.0*_Poissons))
   _Shear_local   = _Modulus_local/(2.0*(1.0+_Poissons))
   z_prop(s_pz,"gsi")    = _GSI_local
   z_prop(s_pz,"hb_mmi") = _Mblocal
   z_prop(s_pz,"hb_ssi") = _s_local
   z_prop(s_pz,"hb_aai") = _a_local
   z_prop(s_pz,"bulk")   = _Bulk_local
   z_prop(s_pz,"shear")  = _Shear_local
  end_loop
 end_if
 hstrain_ = 0.
 v=0
 loop k (1,nb_ext_tnl)
  loop q (1,nb_unit)
   v = v+1
   g = 1
   gpnear = gp_near(ext_tn_hist(k,q,g,1), ext_tn_hist(k,q,g,2), ext_tn_hist(k,q,g,3))
   disp_x1=gp_xdisp(gpnear)
   g = g + 1
   gpnear = gp_near(ext_tn_hist(k,q,g,1), ext_tn_hist(k,q,g,2), ext_tn_hist(k,q,g,3))
   disp_x2=gp_xdisp(gpnear)
   hist_disp(v)= abs((disp_x1 - disp_x2)/ (tn_width))
   hstrain_ = hstrain_ + hist_disp(v)
   if hist_disp(v) > max_strain
    st_numb = st_numb+1.
   end_if
  end_loop
 end_loop
 hstrain_ = hstrain_ / (nb_ext_tnl * nb_unit)
 abt_stress_ = abs(z_szz(znear))
 st_numb = st_numb / (num/4.)
 rel_disp

 if abt_stress_ <= min_stress
  _end_st2=1
 end_if
 if abt_stress_ > min_stress
  command
   print st_numb
   print abt_stress_
   print hstrain_
   step step_chk
  end_command
 end_if
 _stress1_ = beg_stress_ - (str_incr_)
```

```
  if abt_stress_ <= _stress1_
   st_name = "Stage2_" + string(_stress1_) + ".sav"
   beg_stress_ = abt_stress_
   command
    sav st_name
   end_command
  end_if
  _stress2_ = beg_stress_ + (str_incr_)
  if abt_stress_ >= _stress2_
   st_name = "Stage2_" + string(_stress2_) + ".sav"
   beg_stress_ = abt_stress_
   command
    sav st_name
   end_command
  end_if
 end_loop
 znear = z_near(mid_x, mid_y, max_z)
 abt_stress_ = z_szz(znear)
 command
  print st_numb
  print abt_stress_
  print hstrain_
  sav Stage2_END.sav ;name of save file after stage 2
 end_command
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;STAGE3 LOADING UNTILL THE CRITERION HAS BEEN MET
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
def _stage3
 _appliedvelocity_ = -_appliedvelocity_
 znear = z_near(mid_x, mid_y, max_z)
 beg_stress_ = abs(z_szz(znear))
 command
  @_loadingrate
 end_command
 loop while _end_st3 # 1
  if conlaw_ = 2
   local uu
   s_inzz = array_size(s_pzz,1)
   loop uu(1,s_inzz)
    s_pz = s_pzz(uu)
    _sig3 = z_sig3(s_pz) * 1.e-6
    _GSI_local     = (_M-(_M/100.)*_GSI) / (1.+exp(_sig3+((_UCSi*1.e-6)/10.))) + _GSI
    _Mblocal       = _Mi*exp((_GSI_local-100.)/28.)
    _s_local       = exp((_GSI_local-100.)/9.)
    _a_local       = 0.5+1./6.*(exp(-_GSI_local/15.)-(exp(-20./3.)))
    _Modulus_local = 55.e9*(0.02+(1./(1+exp((60.-_GSI_local)/11.))))
    _Bulk_local    = _Modulus_local/(3.0*(1.0-2.0*_Poissons))
    _Shear_local   = _Modulus_local/(2.0*(1.0+_Poissons))
    z_prop(s_pz,"gsi")    = _GSI_local
    z_prop(s_pz,"hb_mmi") = _Mblocal
    z_prop(s_pz,"hb_ssi") = _s_local
    z_prop(s_pz,"hb_aai") = _a_local
    z_prop(s_pz,"bulk")   = _Bulk_local
    z_prop(s_pz,"shear")  = _Shear_local
   end_loop
  end_if
  hstrain_ = 0.
  v=0
  loop k (1,nb_ext_tnl)
   loop q (1,nb_unit)
```

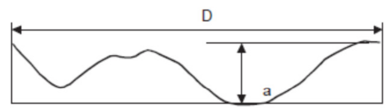
```
    v= v+1
    g = 1
    gpnear = gp_near(ext_tn_hist(k,q,g,1), ext_tn_hist(k,q,g,2), ext_tn_hist(k,q,g,3))
    disp_x1=gp_xdisp(gpnear)
    g = g + 1
    gpnear = gp_near(ext_tn_hist(k,q,g,1), ext_tn_hist(k,q,g,2), ext_tn_hist(k,q,g,3))
    disp_x2=gp_xdisp(gpnear)
    hist_disp(v)= abs((disp_x1 - disp_x2)/ (tn_width))
    hstrain_ = hstrain_ + hist_disp(v)
    if hist_disp(v) > max_strain
     st_numb = st_numb+1.
    end_if
   end_loop
  end_loop
  hstrain_ = hstrain_ / (nb_ext_tnl * nb_unit)
  abt_stress_ = abs(z_szz(znear))
  st_numb = st_numb / (num/4.)
  rel_disp

  if abt_stress_ >= max_stress_st3
   _end_st3=1
  end_if
  if abt_stress_ < max_stress_st3
   command
    print st_numb
    print abt_stress_
    print hstrain_
    step step_chk
   end_command
  end_if
  _stress1_ = beg_stress_ - (str_incr_)
  if abt_stress_ <= _stress1_
   st_name = "Stage3_" + string(_stress1_) + ".sav"
   beg_stress_ = abt_stress_
   command
    sav st_name
   end_command
  end_if
  _stress2_ = beg_stress_ + (str_incr_)
  if abt_stress_ >= _stress2_
   st_name = "Stage3_" + string(_stress2_) + ".sav"
   beg_stress_ = abt_stress_
   command
    sav st_name
   end_command
  end_if
 end_loop
 znear = z_near(mid_x, mid_y, max_z)
 abt_stress_ = z_szz(znear)
 command
  print st_numb
  print abt_stress_
  print hstrain_
  sav Stage3_END.sav ;name of save file after stage 3
 end_command
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;DRAWPOINT POSITIONS
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
def _crIMZ
 dy_dp = 0
```

```
x_dp = max_x + (tr_length / 2.) - (tn_width / 2.)
y_dp = max_y - 0.1
nb_ext_tnl = nextdrift_
dx_dp = -(tr_length - tn_width)
z_dp = tn_height
_ci_ =  0
nIMZ_ = 0
dpx_ = x_dp
offset_ = 0
y_min = min_y - 0.3
loop while dpx_ > min_x
 y_dp_next = y_dp + (abs(dy_dp / dx_dp) * tn_space * _ci_)
 if offset_ = 1
  offset_= 0
  y_dp_next = y_dp_next  + 0.5 * dp_space
 else
  offset_ = 1
 end_if
 loop while y_dp_next > max_y
  y_dp_next = y_dp_next - dp_space
 end_loop
 dpy_ = y_dp_next
 loop while dpy_ > y_min
  if dpx_ < max_x
   nIMZ_ = nIMZ_ + 1
  end_if
  cond = dpx_ + dx_dp
  if cond > min_x
   cond2 = dpy_ + dy_dp
   if cond2 > y_min
    if cond2 < max_y
     nIMZ_ = nIMZ_ +1
    end_if
   end_if
  end_if
  dpy_ =  dpy_ - dp_space
 end_loop
 cond = dpx_ + dx_dp
 if cond > min_x
  cond2 = dpy_ + dy_dp
  if cond2 > y_min
   if cond2 < max_y
    nIMZ_ = nIMZ_ +1
   end_if
  end_if
 end_if
dpx_ = dpx_ - tn_space
_ci_ = _ci_ + 1
end_loop

IMZ = get_array(nIMZ_,4)

_ci_ = 0
_ct_ = 1
offset_ = 0
dpx_ = x_dp
loop while dpx_ > min_x
 y_dp_next = y_dp + (abs(dy_dp / dx_dp) * tn_space * _ci_)
 if offset_ = 1
  offset_= 0
  y_dp_next = y_dp_next  + 0.5 * dp_space
 else
```

```
   offset_ = 1
  end_if
  loop while y_dp_next > max_y
   y_dp_next = y_dp_next - dp_space
  end_loop
  dpy_ = y_dp_next
  loop while dpy_ > y_min
   if dpx_ < max_x
    IMZ(_ct_,1) = dpx_
    IMZ(_ct_,2) = dpy_
    IMZ(_ct_,3) = z_dp
    _ct_ = _ct_ + 1
   end_if
   cond = dpx_ + dx_dp
   if cond > min_x
    cond2 = dpy_ + dy_dp
    if cond2 > y_min
     if cond2 < max_y
      dpx2_ = dpx_ + dx_dp
      dpy2_ = dpy_ + dy_dp
      IMZ(_ct_,1) = dpx2_
      IMZ(_ct_,2) = dpy2_
      IMZ(_ct_,3) = z_dp
      _ct_ = _ct_ + 1
     end_if
    end_if
   end_if
   dpy_ =  dpy_ - dp_space
  end_loop
  cond = dpx_ + dx_dp
   if cond > min_x
    cond2 = dpy_ + dy_dp
    if cond2 > y_min
     if cond2 < max_y
      dpx2_ = dpx_ + dx_dp
      dpy2_ = dpy_ + dy_dp
      IMZ(_ct_,1) = dpx2_
      IMZ(_ct_,2) = dpy2_
      IMZ(_ct_,3) = z_dp
      _ct_ = _ct_ + 1
     end_if
    end_if
   end_if
  dpx_ = dpx_ - tn_space
  _ci_ = _ci_ + 1
 end_loop
end
```

Appendix S. Joint surface condition factor

Waviness terms	Undulation	Rating for waviness J_W
Interlocking (large-scale)		3
Stepped		2.5
Large undulation	>3%	2
Small to moderate undulation	0.3–3%	1.5
Planar	<0.3%	1



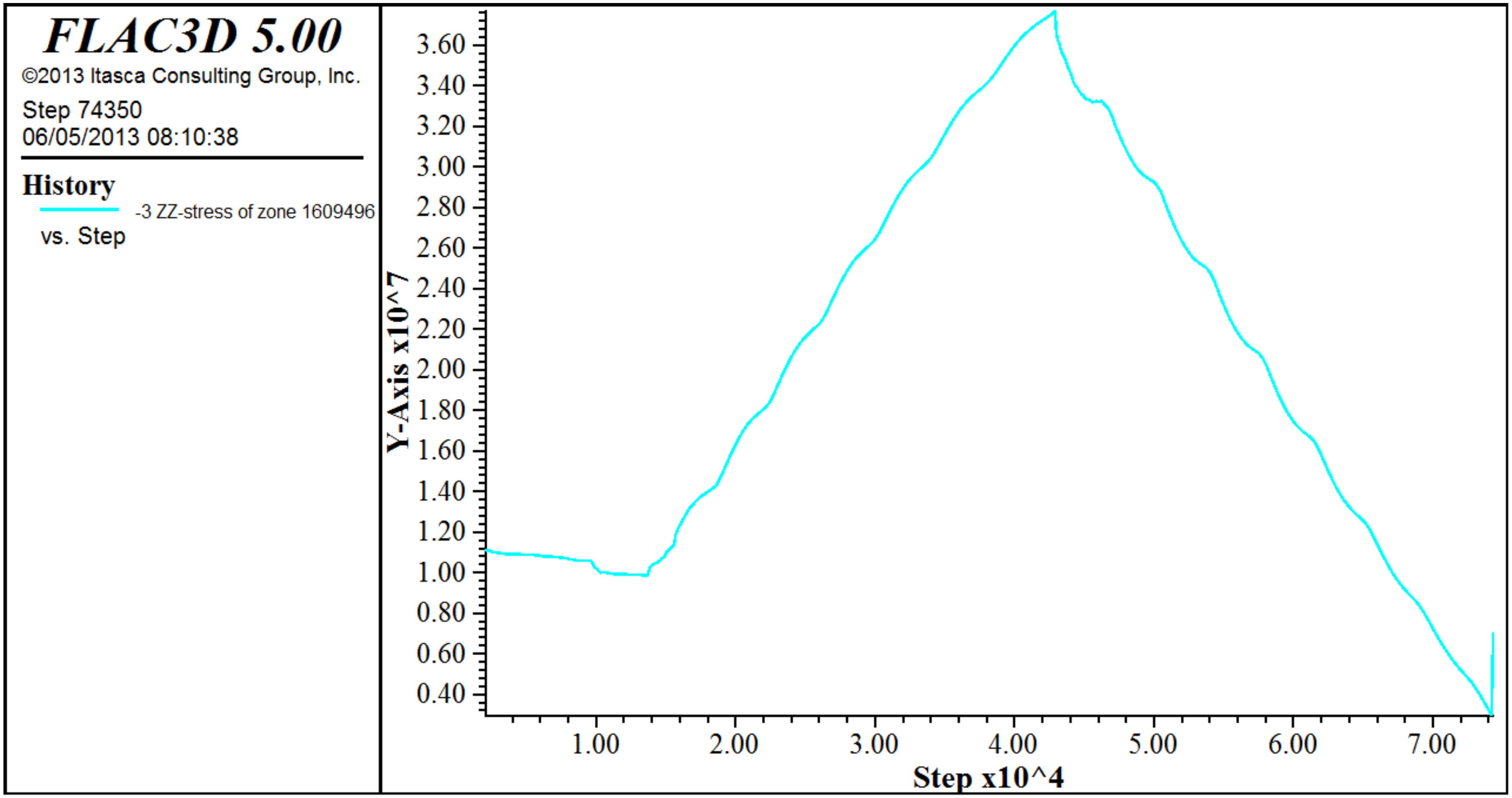
Undulation = a/D
D - length between maximum amplitudes

Smoothness terms	Description	Rating for smoothness J_S
Very rough	Near vertical steps and ridges occur with interlocking effect on the joint surface	3
Rough	Some ridge and side-angle are evident; asperities are clearly visible; discontinuity surface feels very abrasive (rougher than sandpaper grade 30)	2
Slightly rough	Asperities on the discontinuity surfaces are distinguishable and can be felt (like sandpaper grade 30–300)	1.5
Smooth	Surface appear smooth and feels so to touch (smoother than sandpaper grade 300)	1
Polished	Visual evidence of polishing exists. This is often seen in coating of chlorite and specially talc	0.75
Slickensided	Polished and striated surface that results from sliding along a fault surface or other movement surface	0.6–1.5

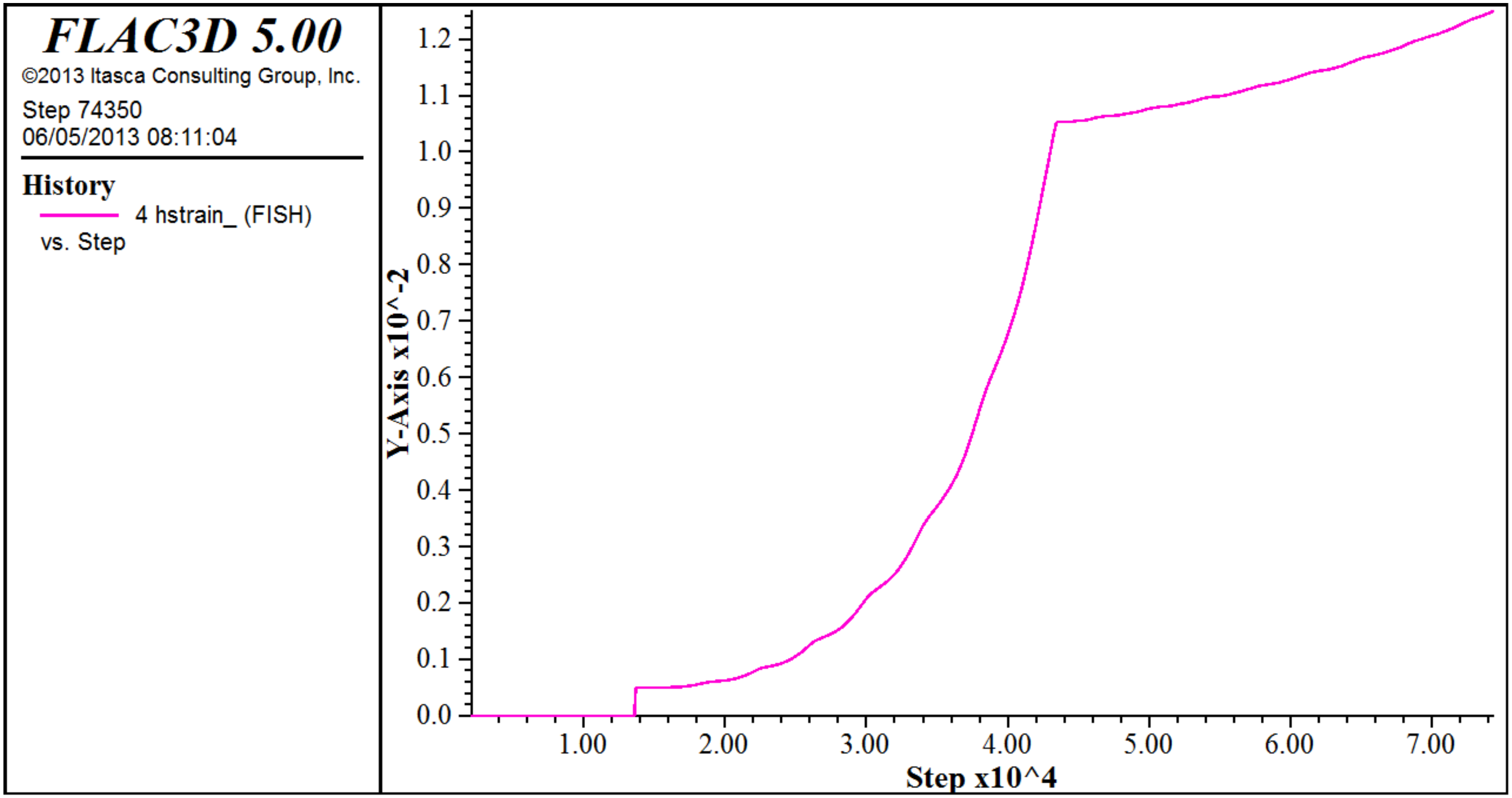
	Term	Description	J_A
Rock wall contact	*Clear joints*		
	Healed or "welded" joints (unweathered)	Softening, impermeable filling (quartz, epidote, etc.)	0.75
	Fresh rock walls (unweathered)	No coating or filling on joint surface, except for staining	1
	Alteration of joint wall: slightly to moderately weathered	The joint surface exhibits one class higher alteration than the rock	2
	Alteration of joint wall: highly weathered	The joint surface exhibits two classes higher alteration than the rock	4
	Coating or thin filling		
	Sand, silt, calcite, etc.	Coating of frictional material without clay	3
	Clay, chlorite, talc, etc.	Coating of softening and cohesive minerals	4
Filled joints with partial or no contact between the rock wall surfaces	Sand, silt, calcite, etc.	Filling of frictional material without clay	4
	Compacted clay materials	"Hard" filling of softening and cohesive materials	6
	Soft clay materials	Medium to low over-consolidation of filling	8
	Swelling clay materials	Filling material exhibits swelling properties	8–12

Appendix T. Numerical modelling results

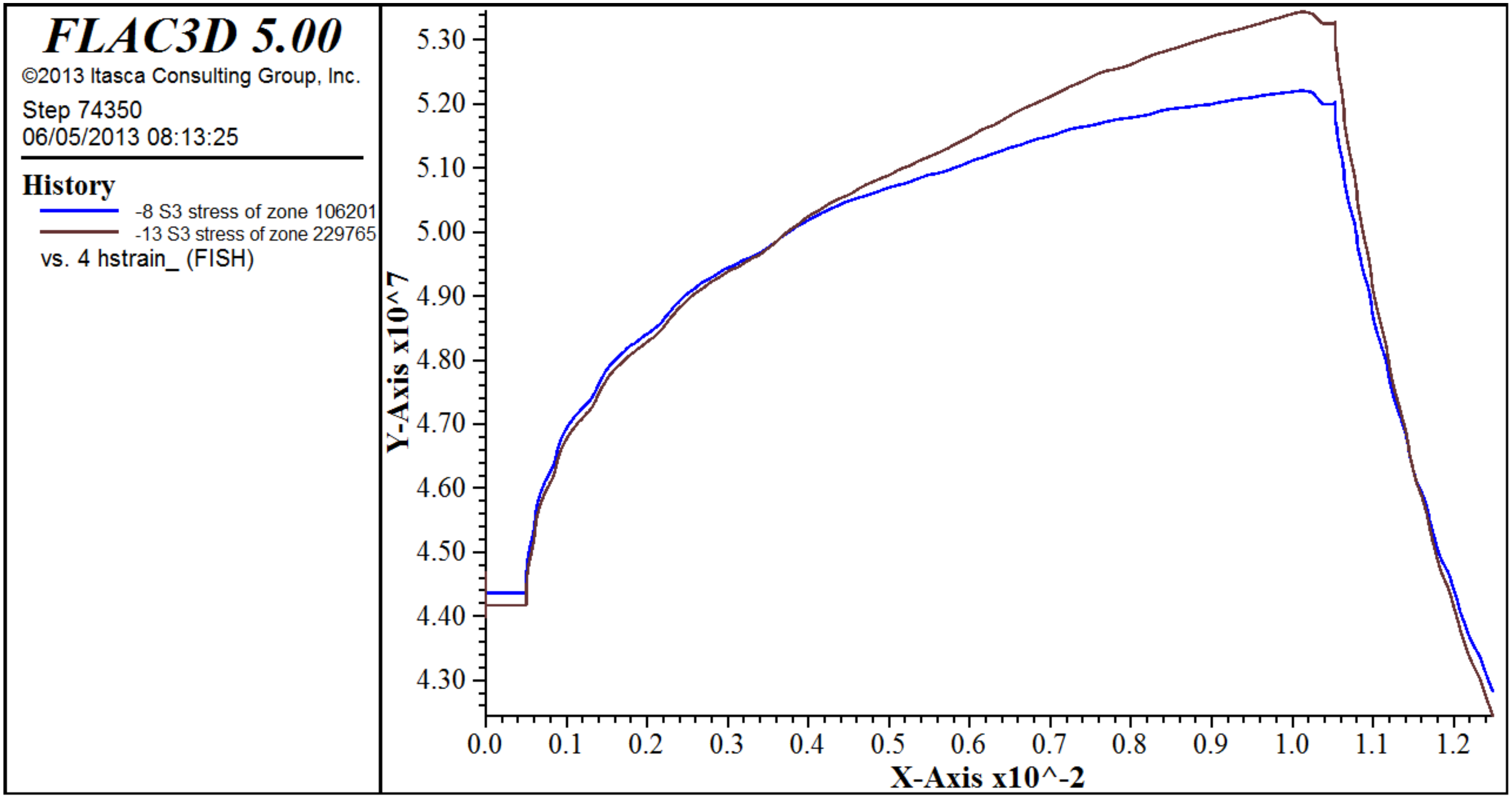
T.1 Scenario HB base case



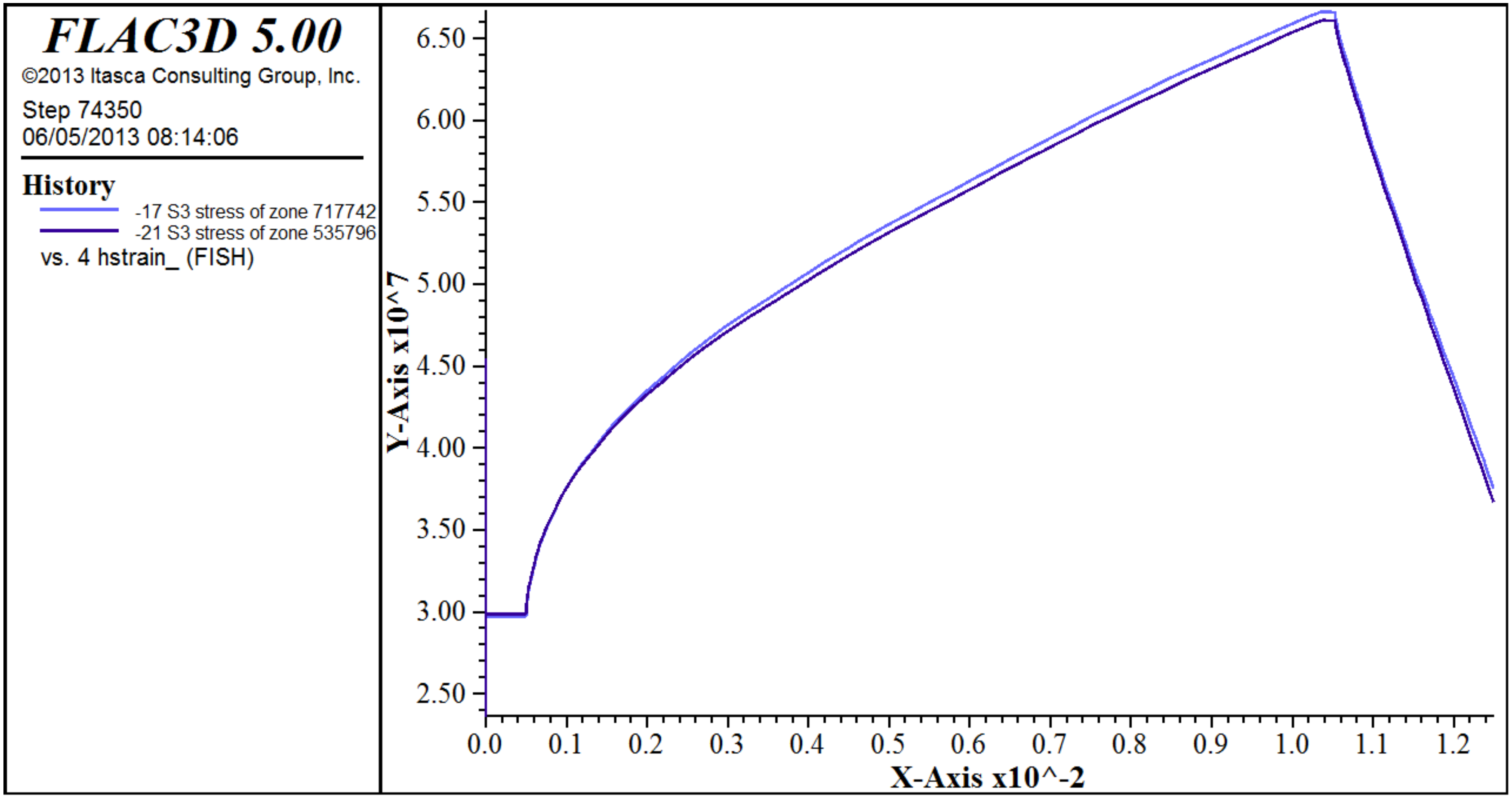
T-1: Abutment stress (MPa) at the top of the model versus calculation steps



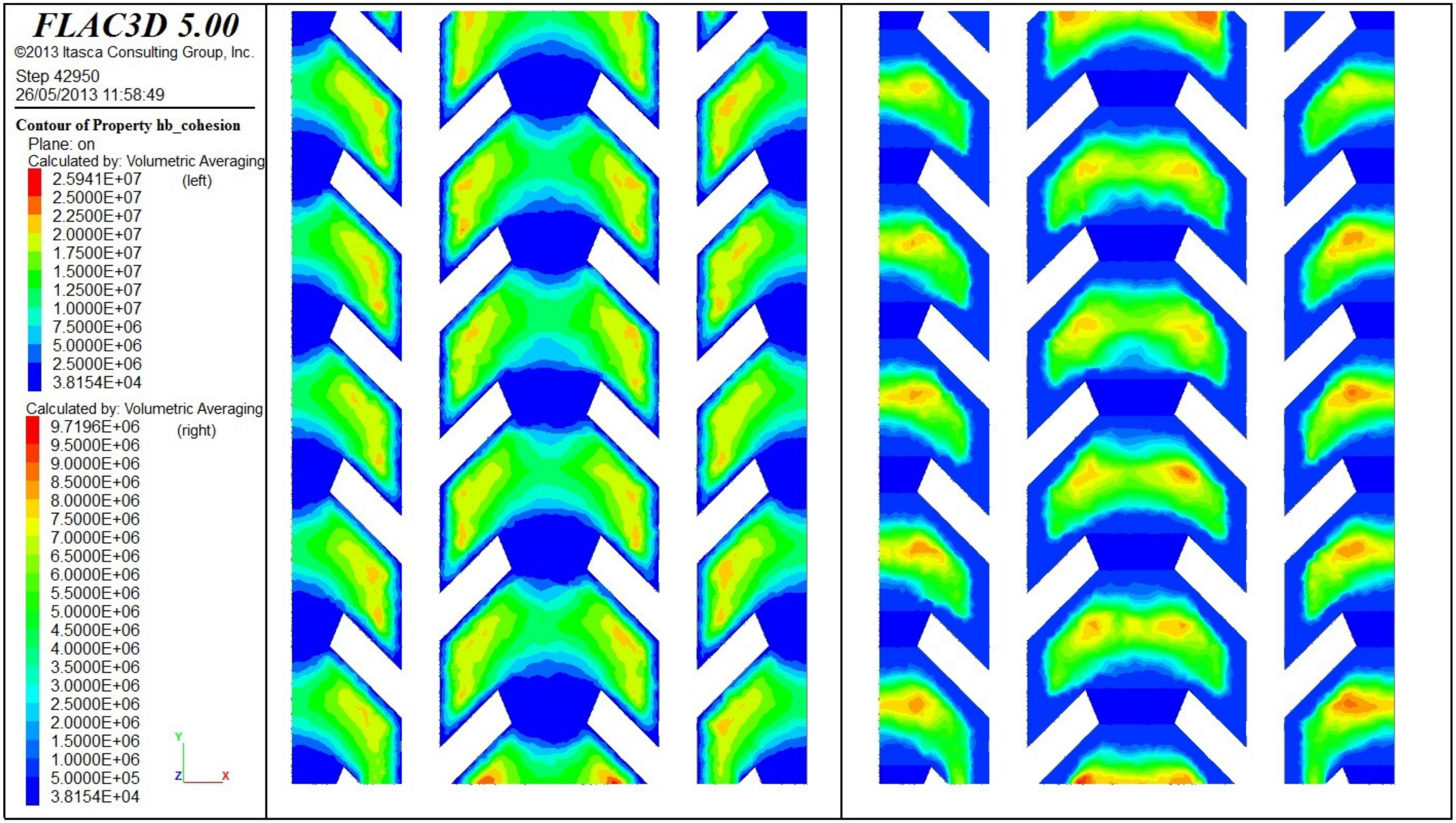
T-2: The average horizontal closure strain (-) of 8 monitoring stations versus calculations steps



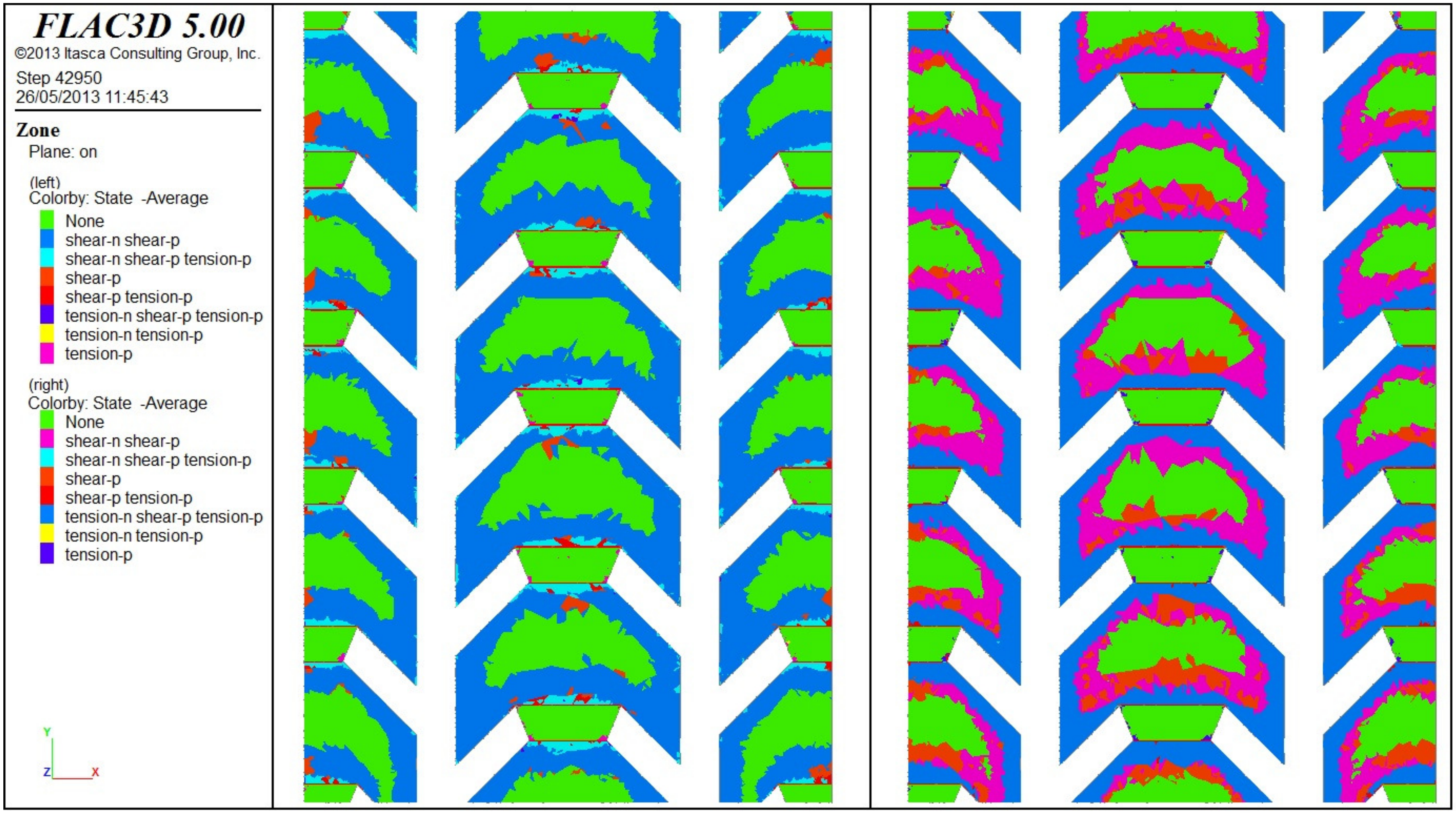
T-3: Major principal stress (Pa) versus closure strain (-) at the centre of the major apex at the location of 'MPBX1' (blue) and 'MPBX2' (brown)



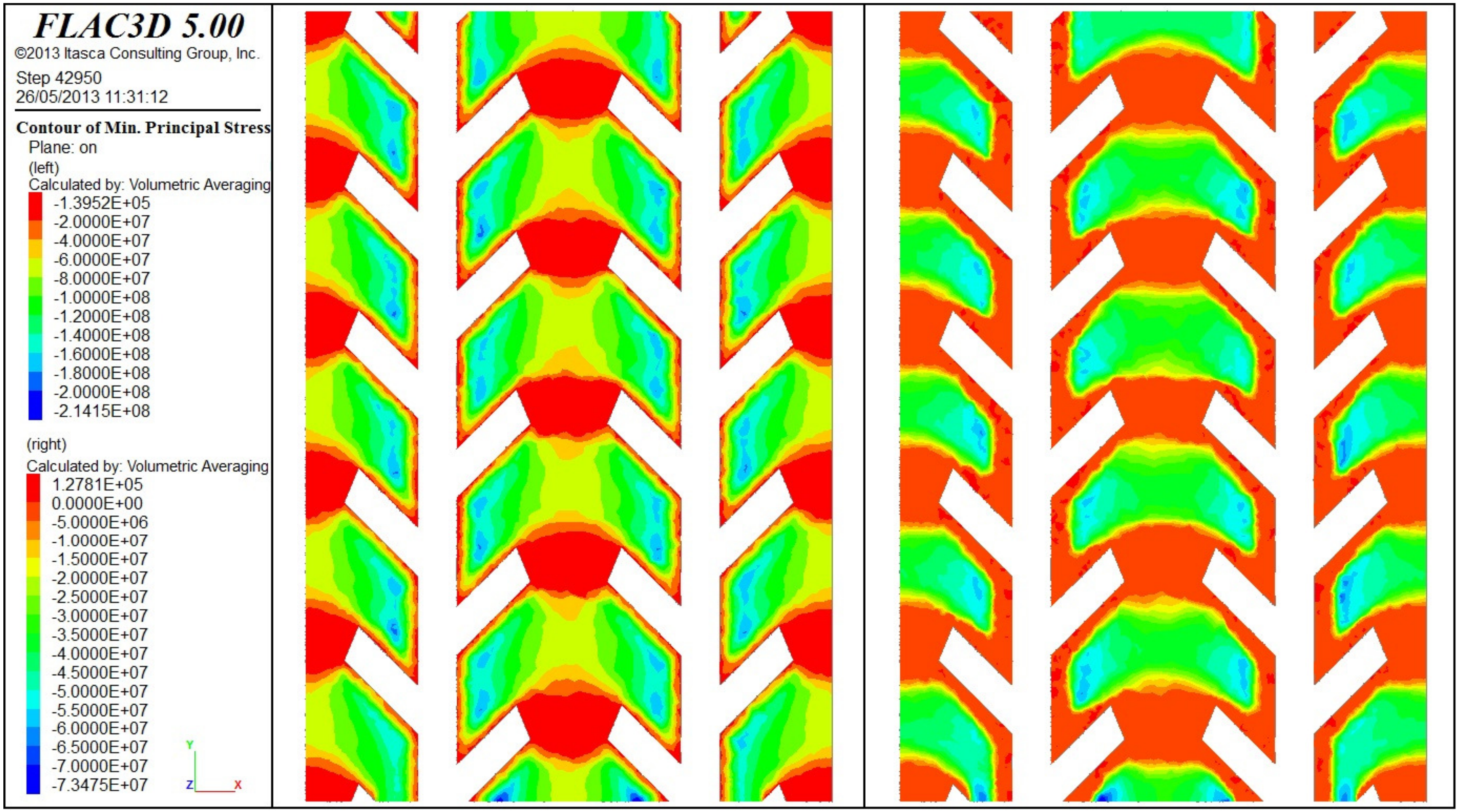
T-4: Major principal stress (Pa) versus closure strain (-) at the centre of the minor apex at locations 'minor1' (light blue) and 'minor2' (dark blue)



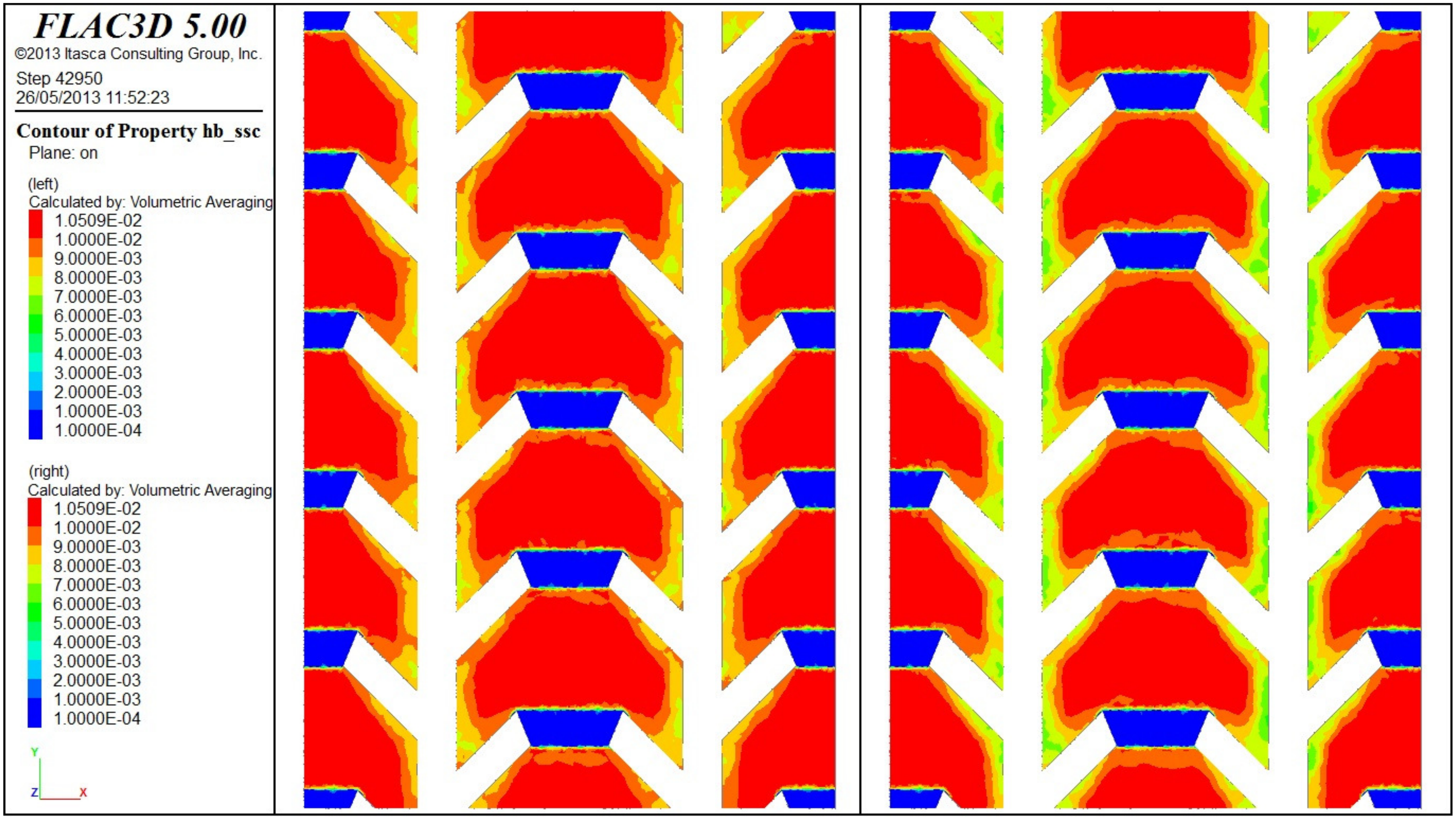
T-5: Plot of apparent cohesion (Pa) after the loading stage (left) and after unloading stage (right)



T-6: Plot of the plasticity state after the loading stage (left) and after unloading stage (right)

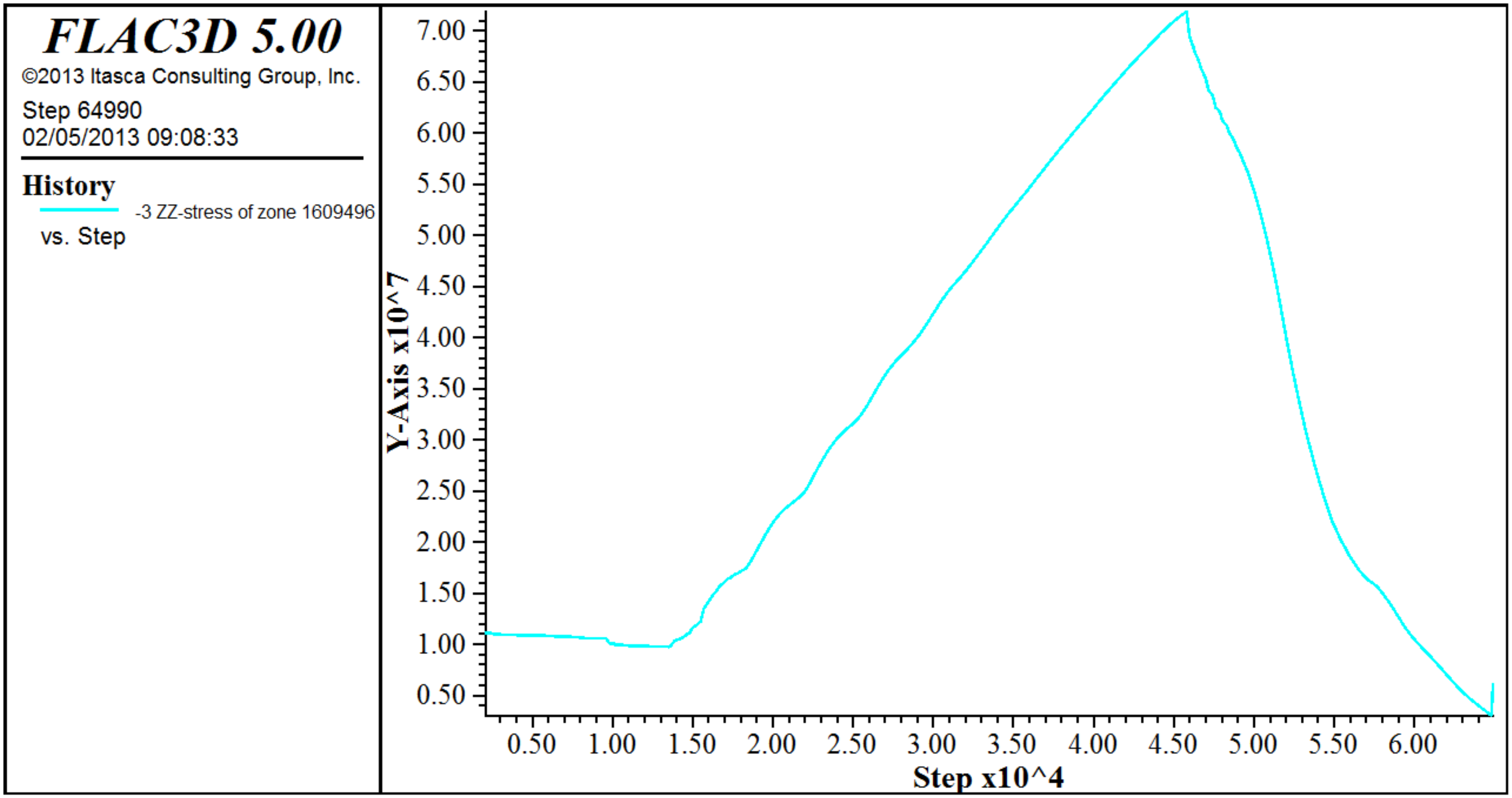


T-7: Plot of the major principal stress (Pa) after the loading stage (left) and after unloading stage (right)

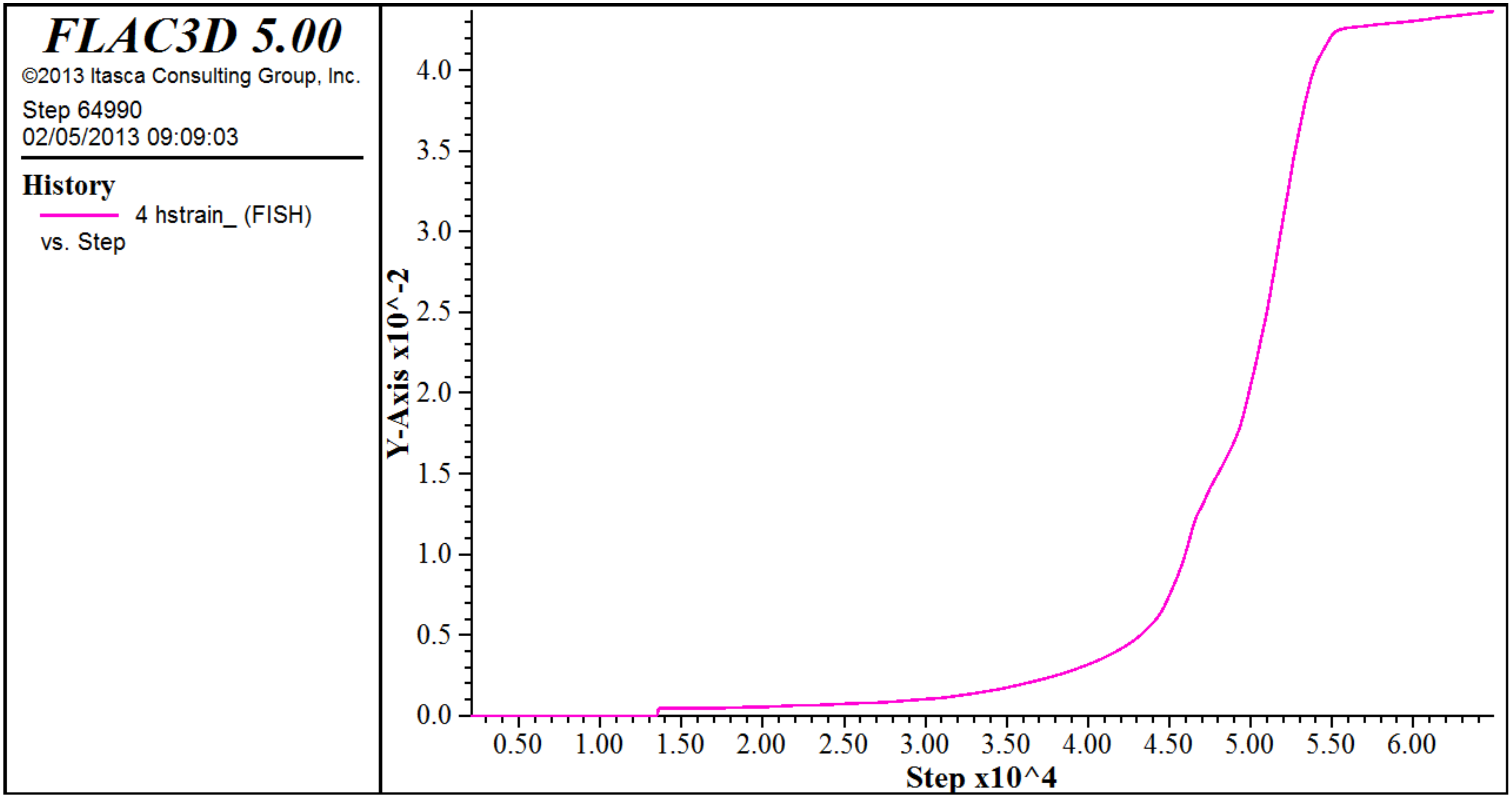


T-8: Plot of the Hoek-Brown *s* parameter after the loading stage (left) and after unloading stage (right)

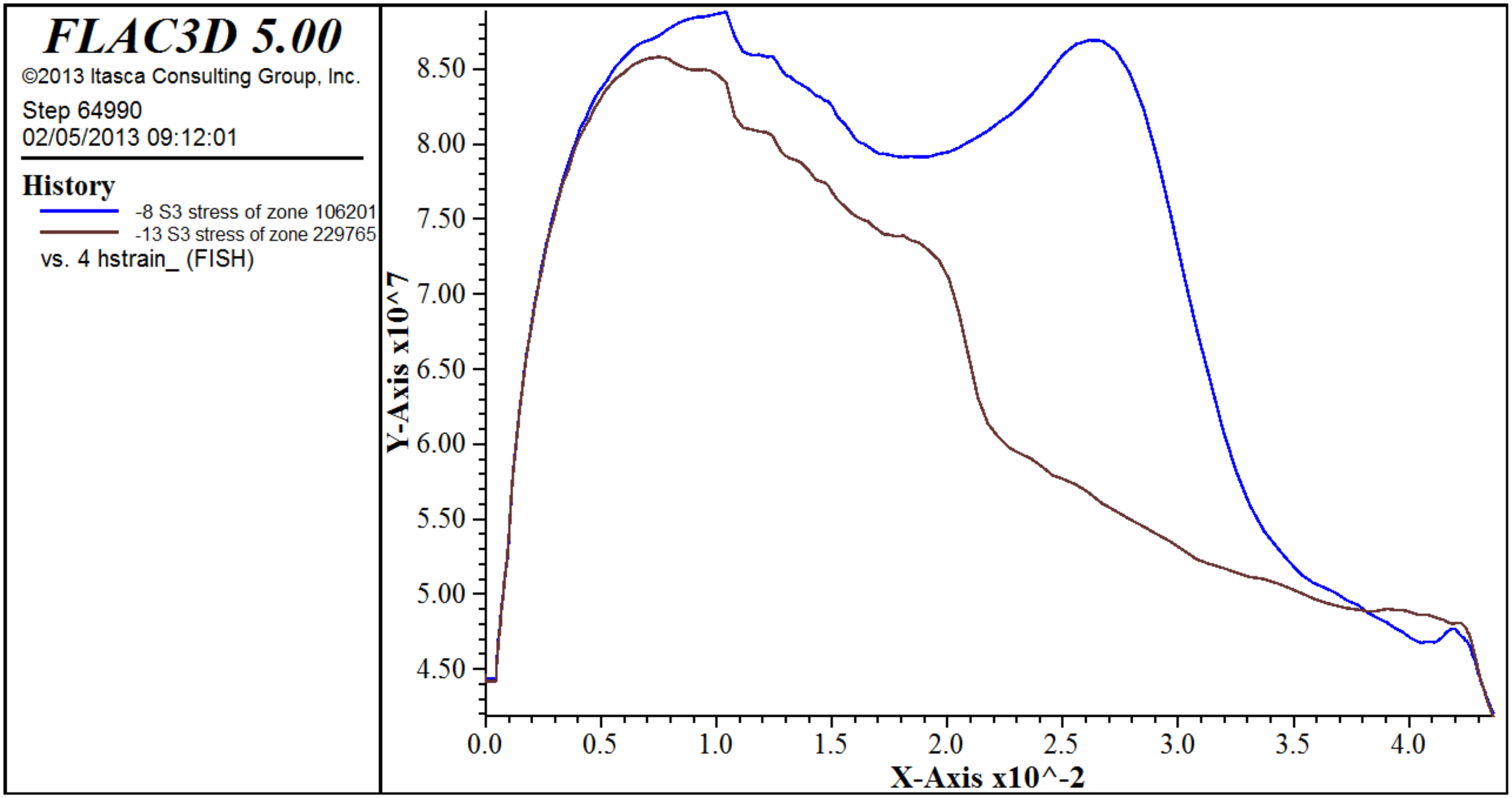
T.2 Scenario S base case



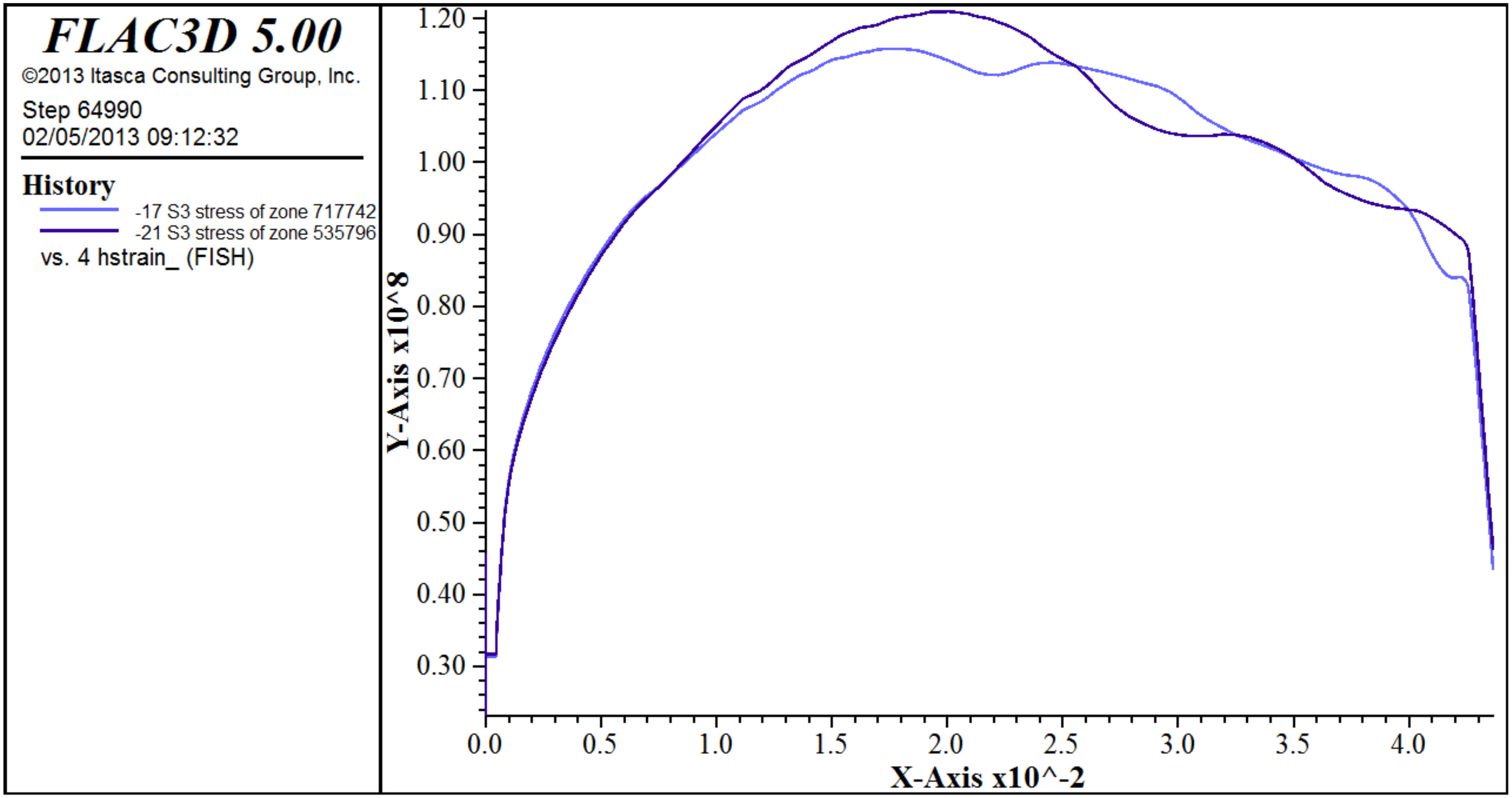
T-9: Abutment stress (MPa) at the top of the model versus calculation steps



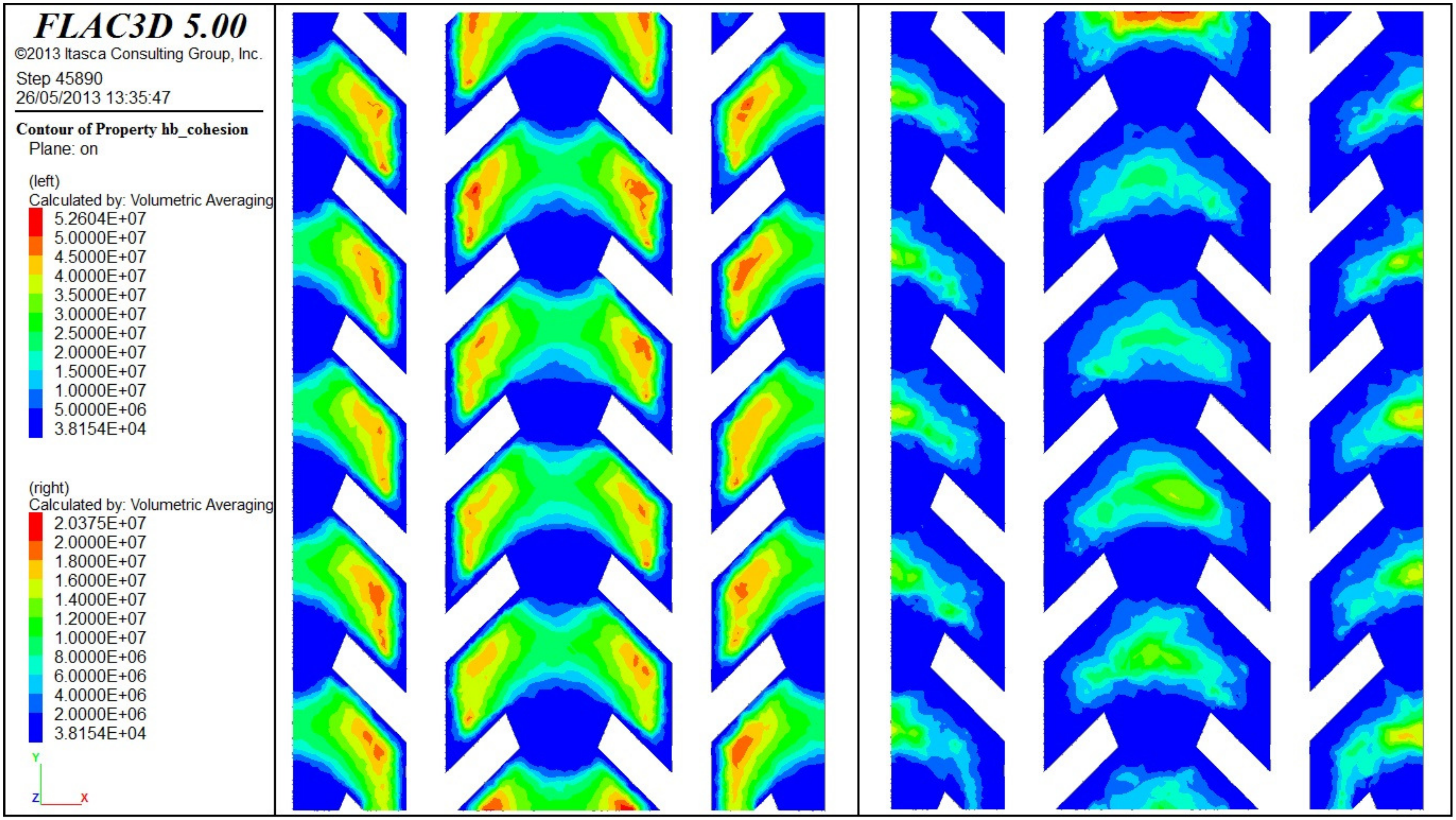
T-10: The average horizontal closure strain (-) of 8 monitoring stations versus calculations steps



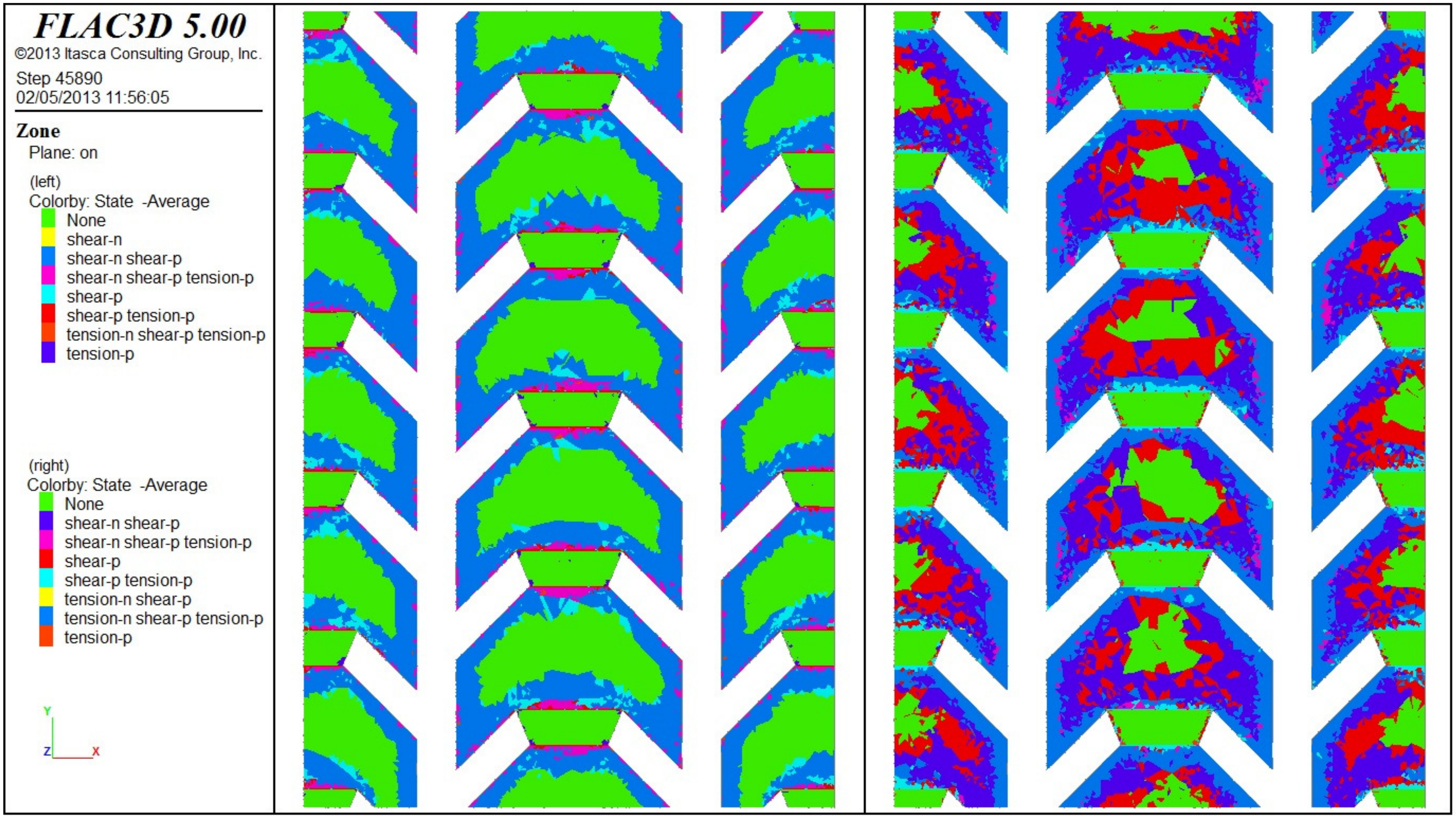
T-11: Major principal stress (Pa) versus closure strain (-) at the centre of the major apex at the location of 'MPBX1' (blue) and 'MPBX2' (brown)



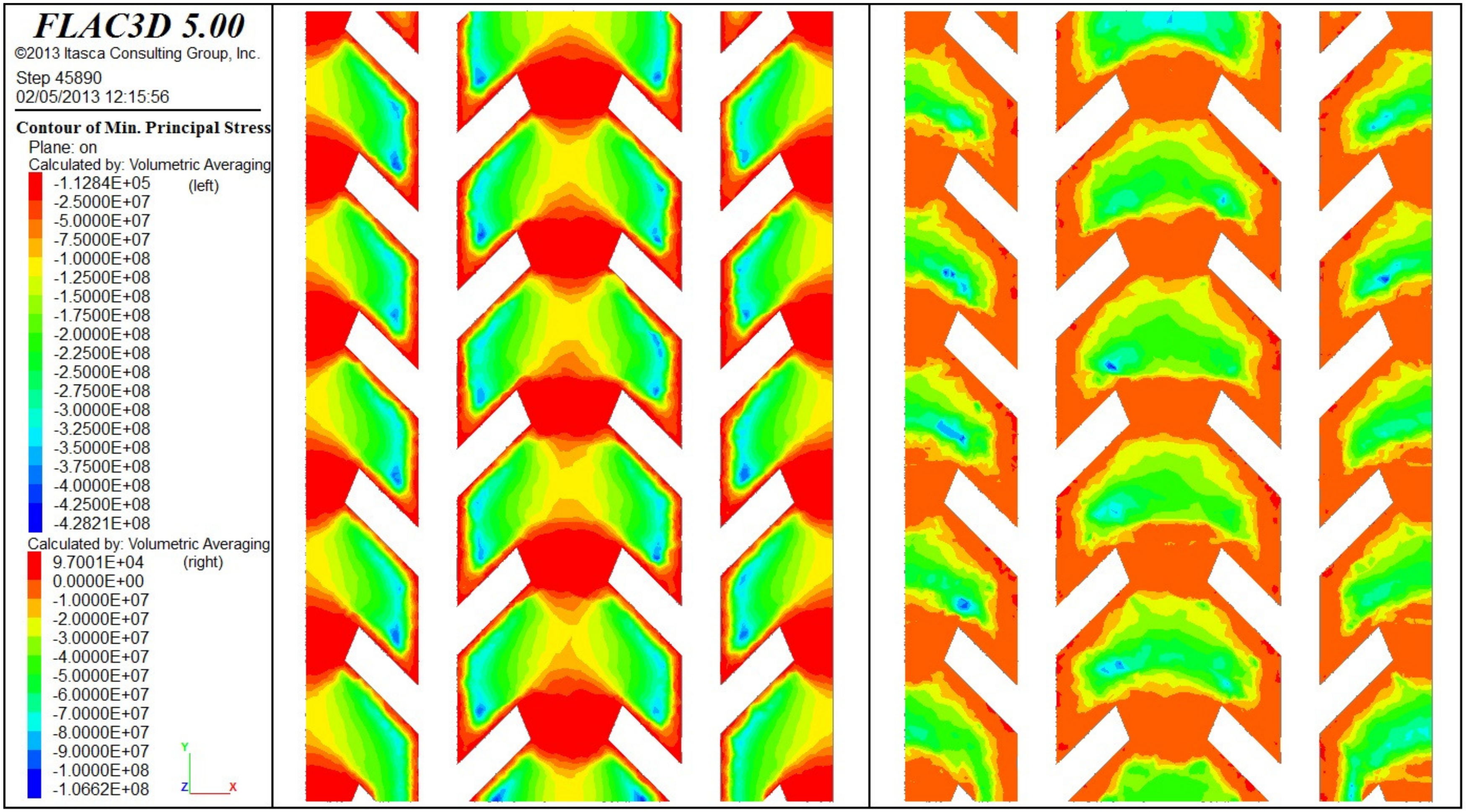
T-12: Major principal stress (Pa) versus closure strain (-) at the centre of the minor apex at locations 'minor1' (light blue) and 'minor2' (dark blue)



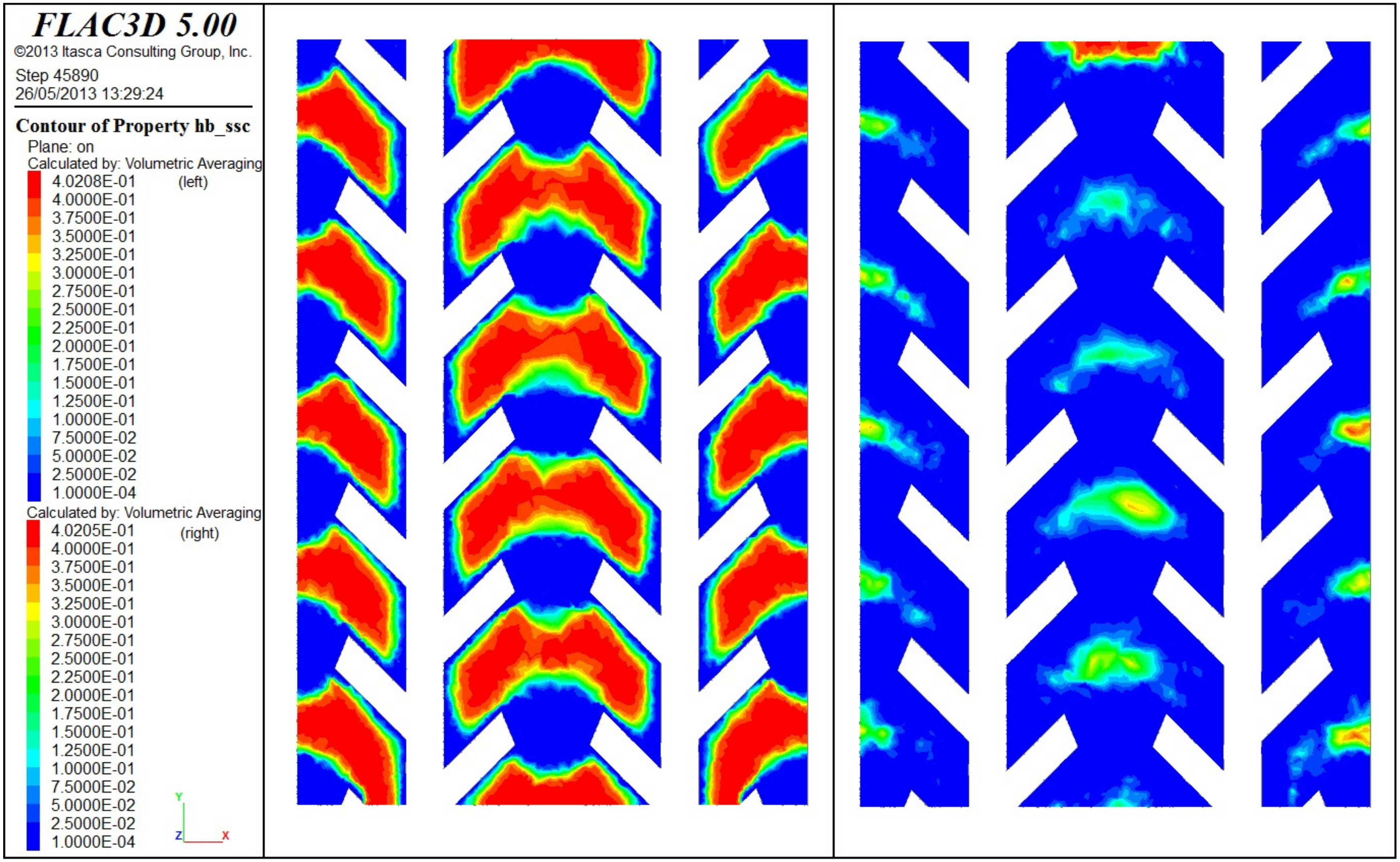
T-13: Plot of apparent cohesion (Pa) after the loading stage (left) and after unloading stage (right)



T-14: Plot of the plasticity state after the loading stage (left) and after unloading stage (right)

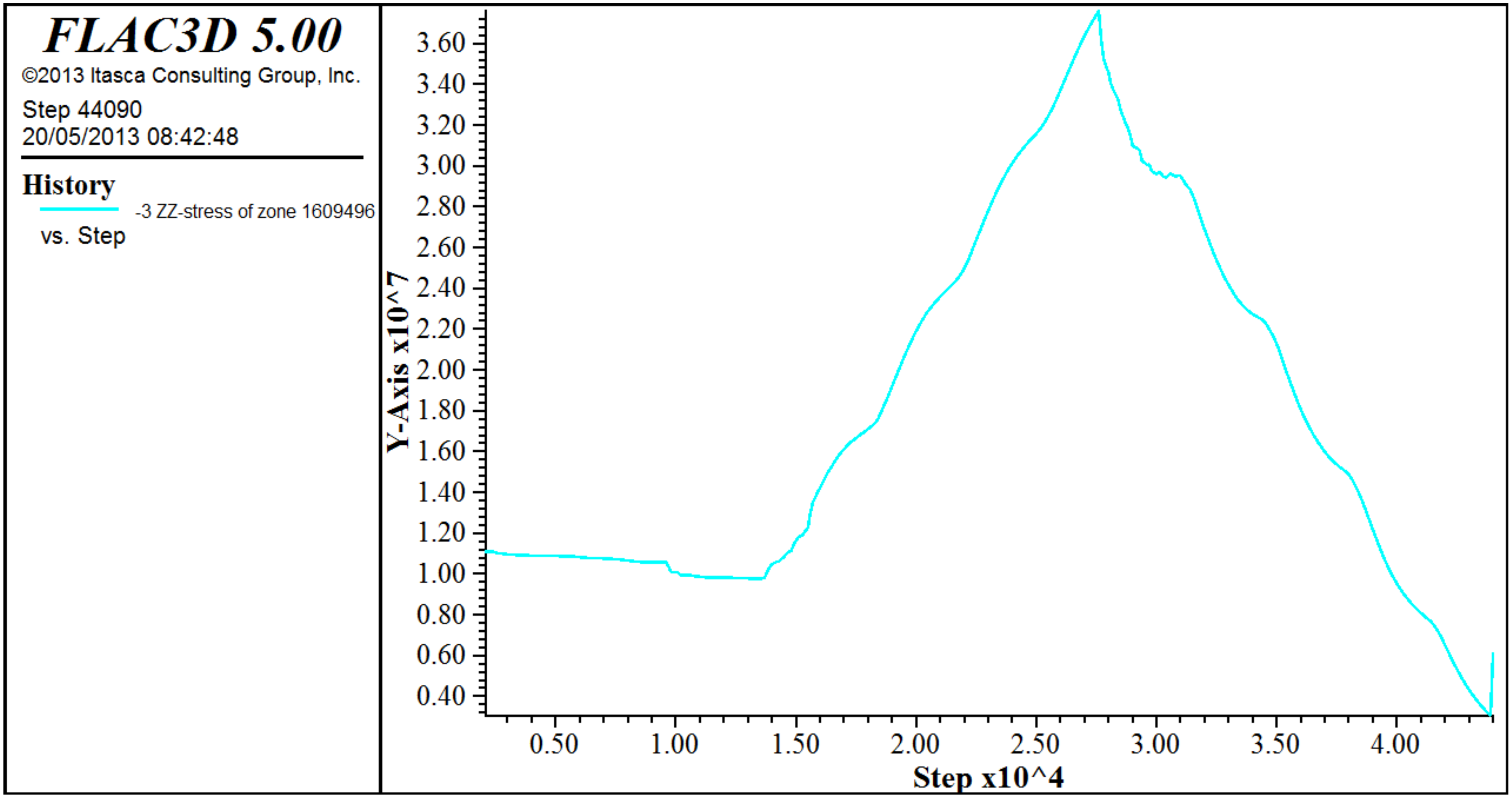


T-15: Plot of the major principal stress (Pa) after the loading stage (left) and after unloading stage (right)

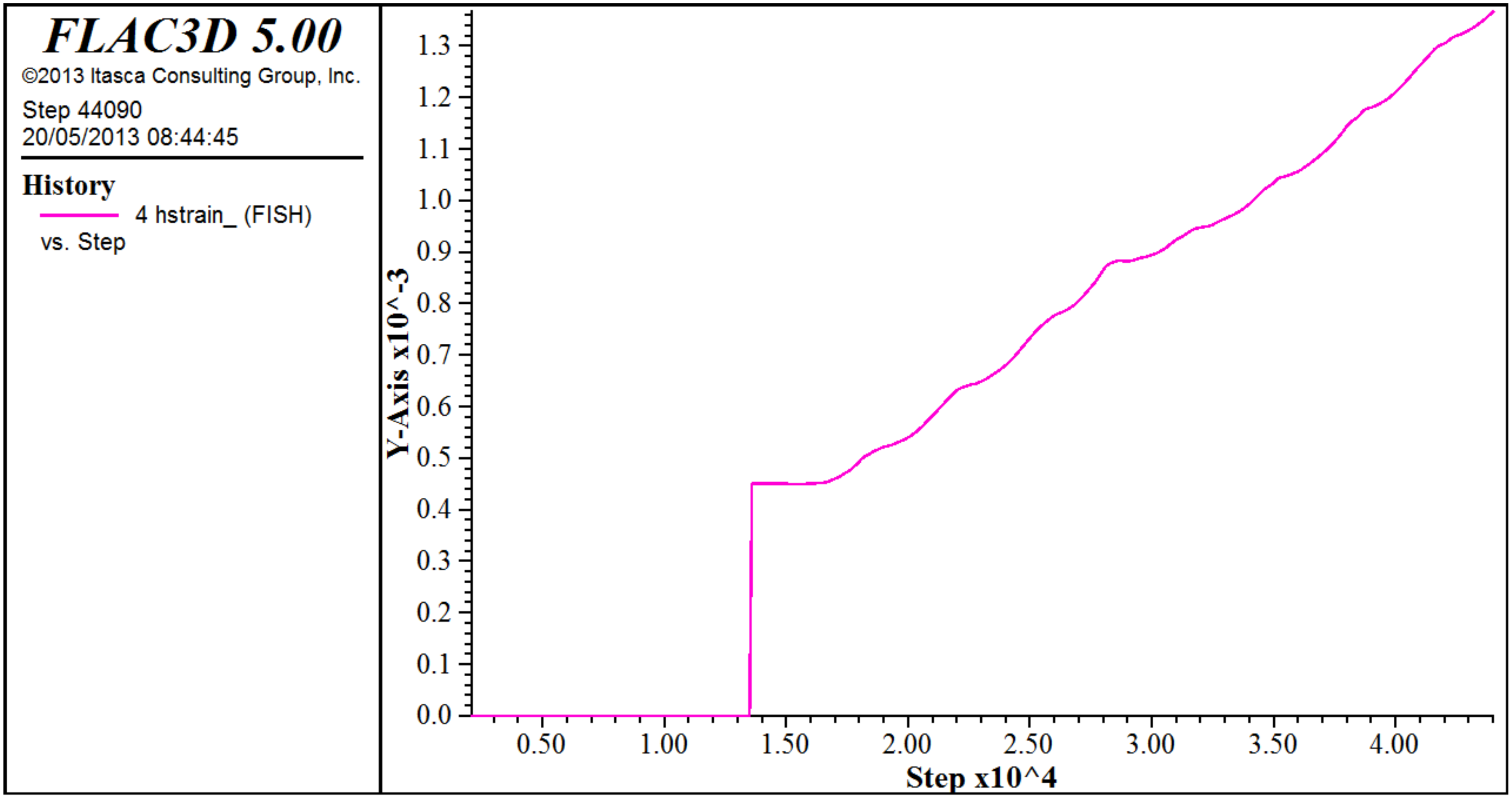


T-16: Plot of the Hoek-Brown s parameter after the loading stage (left) and after unloading stage (right)

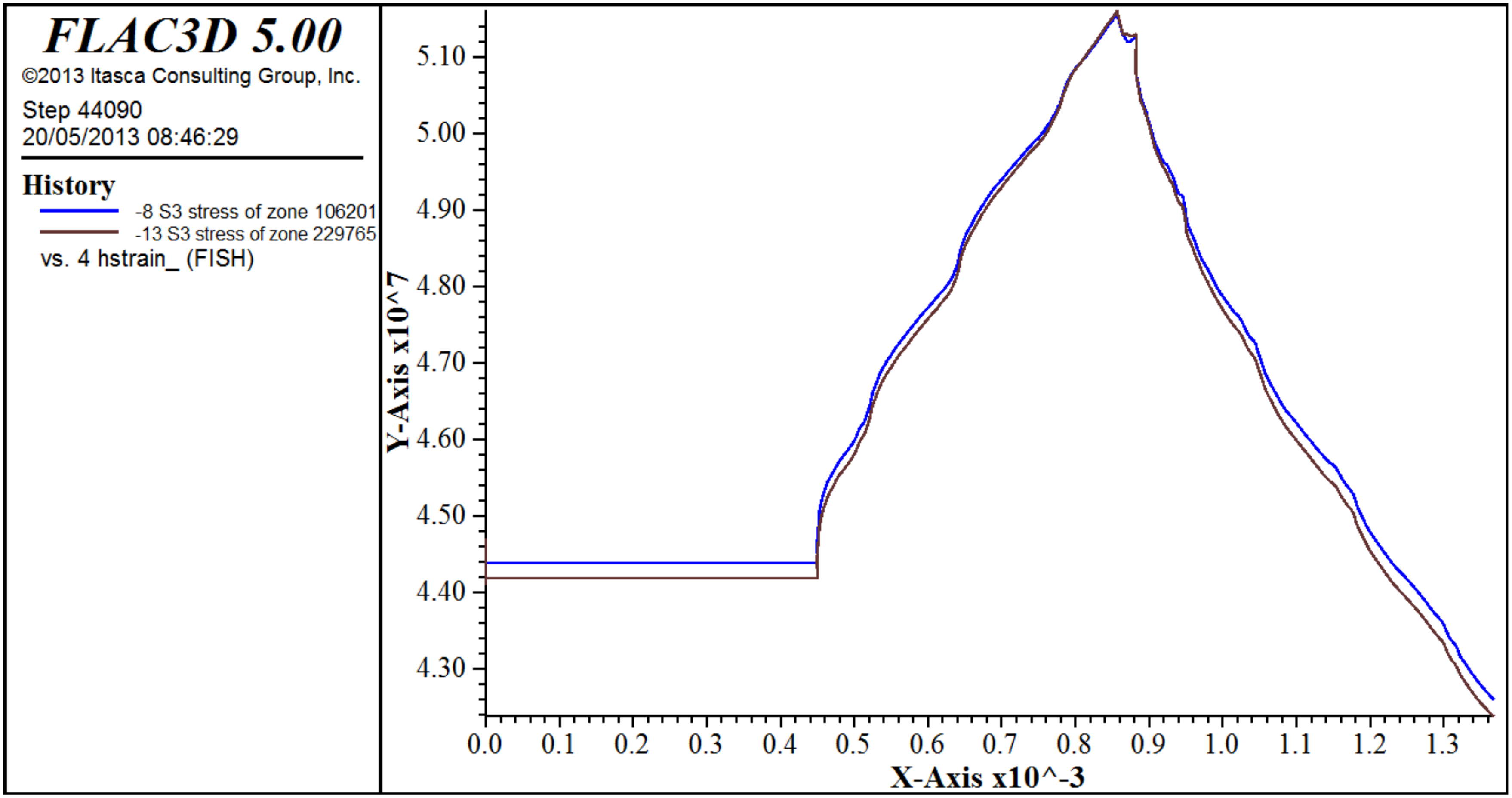
T.3 Scenario S_{abut}



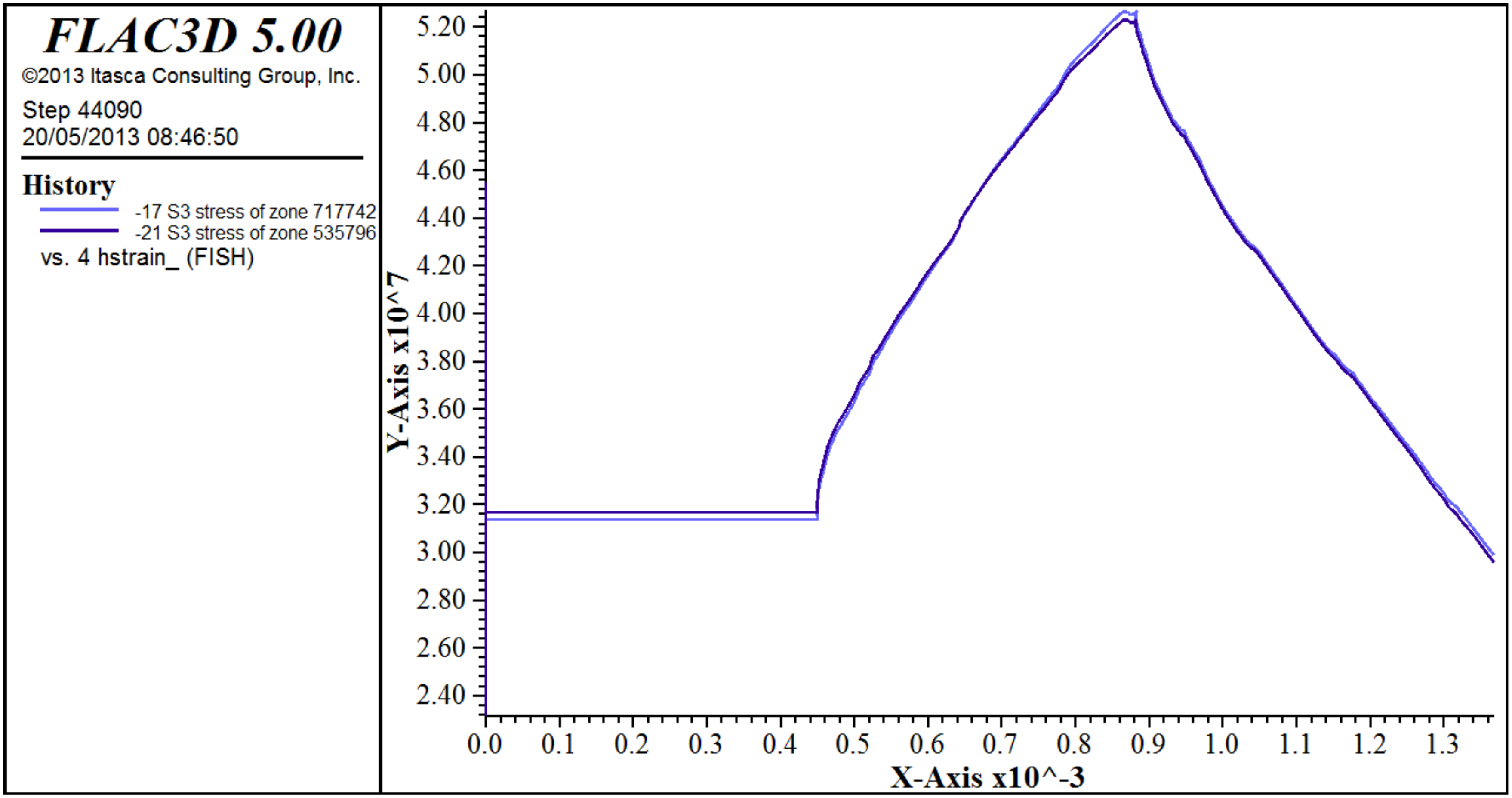
T-17: Abutment stress (MPa) at the top of the model versus calculation steps



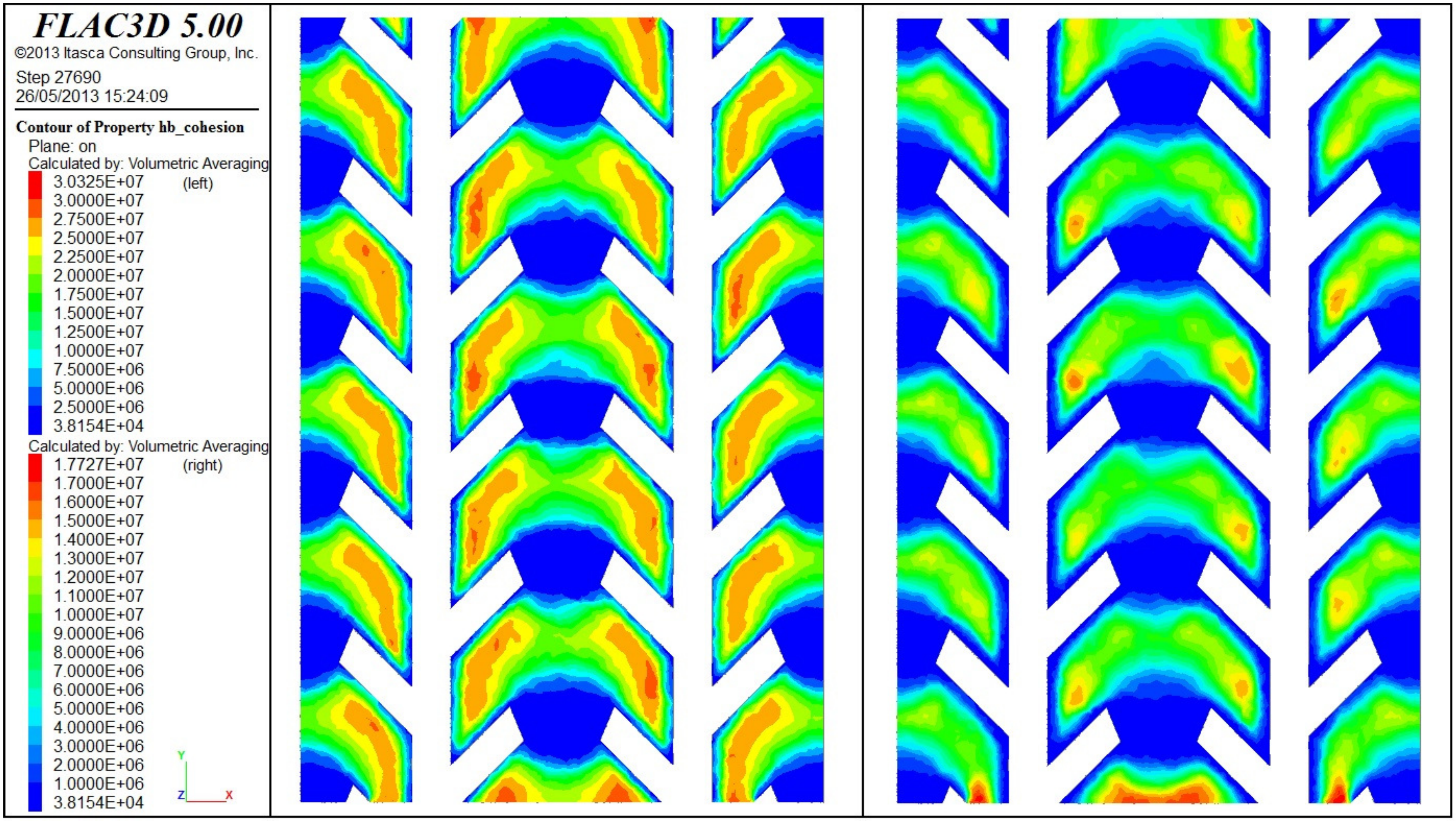
T-18: The average horizontal closure strain (-) of 8 monitoring stations versus calculations steps



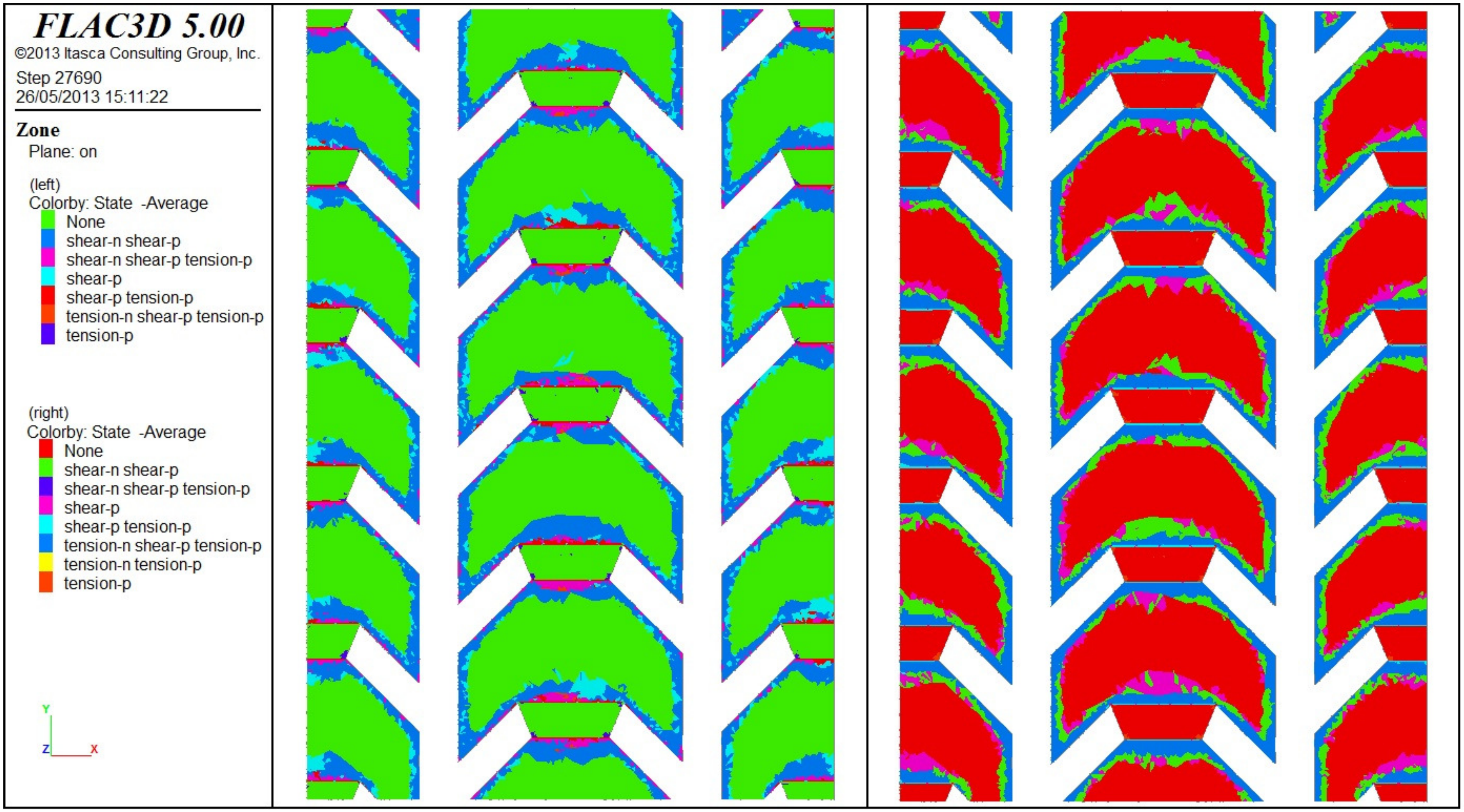
T-19: Major principal stress (Pa) versus closure strain (-) at the centre of the major apex at the location of 'MPBX1' (blue) and 'MPBX2' (brown)



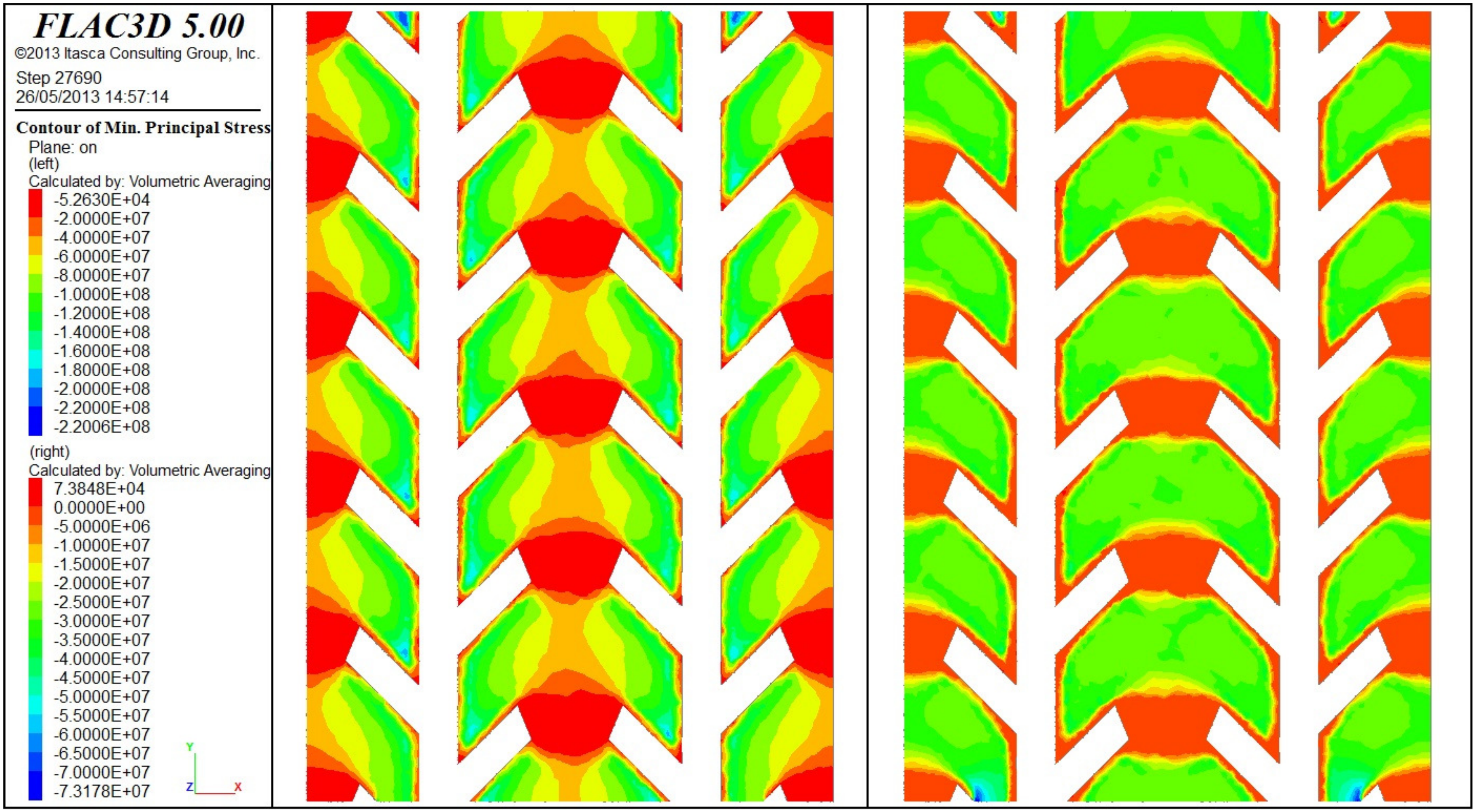
T-20: Major principal stress (Pa) versus closure strain (-) at the centre of the minor apex at locations 'minor1' (light blue) and 'minor2' (dark blue)



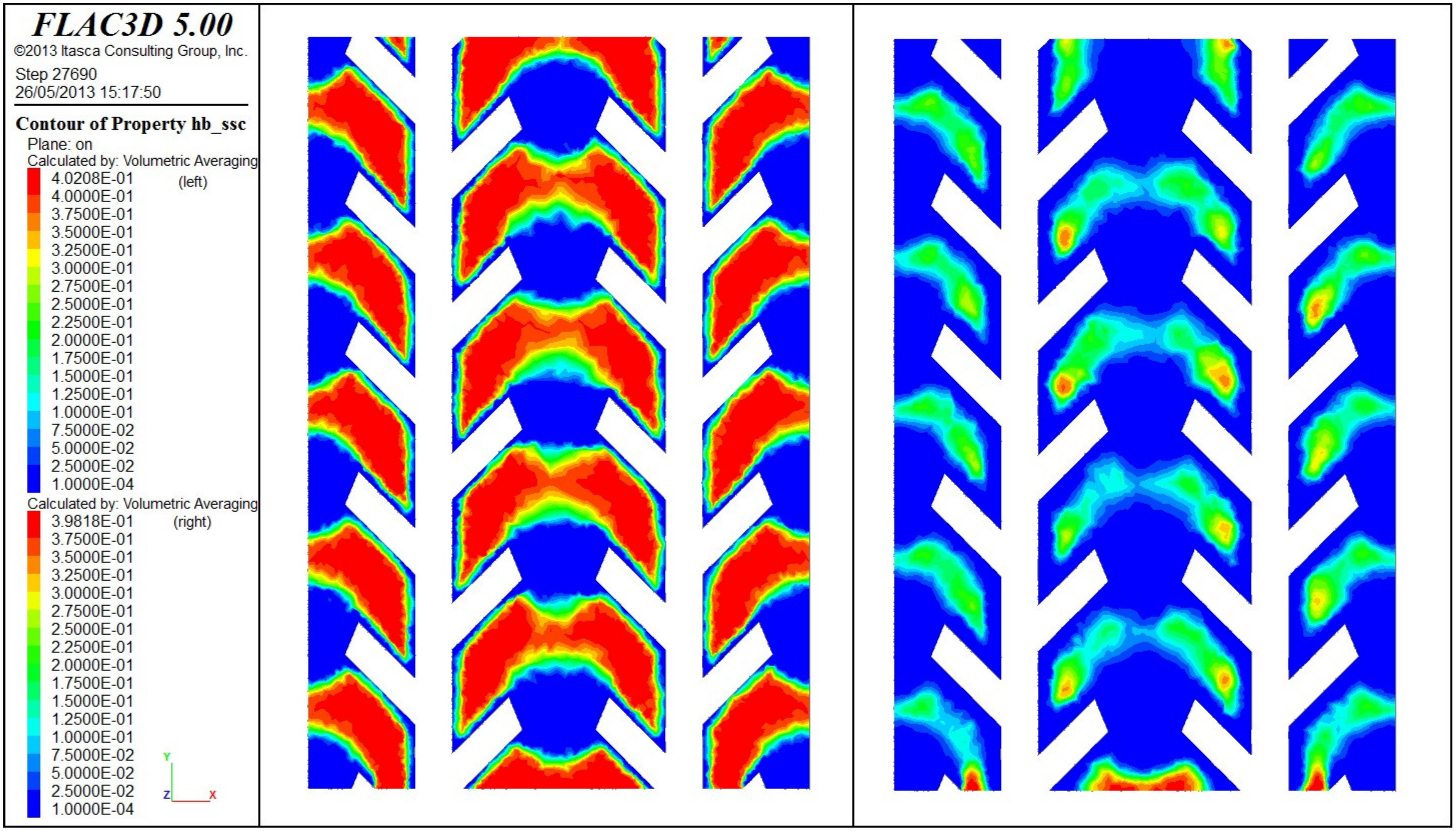
T-21: Plot of apparent cohesion (Pa) after the loading stage (left) and after unloading stage (right)



T-22: Plot of the plasticity state after the loading stage (left) and after unloading stage (right)

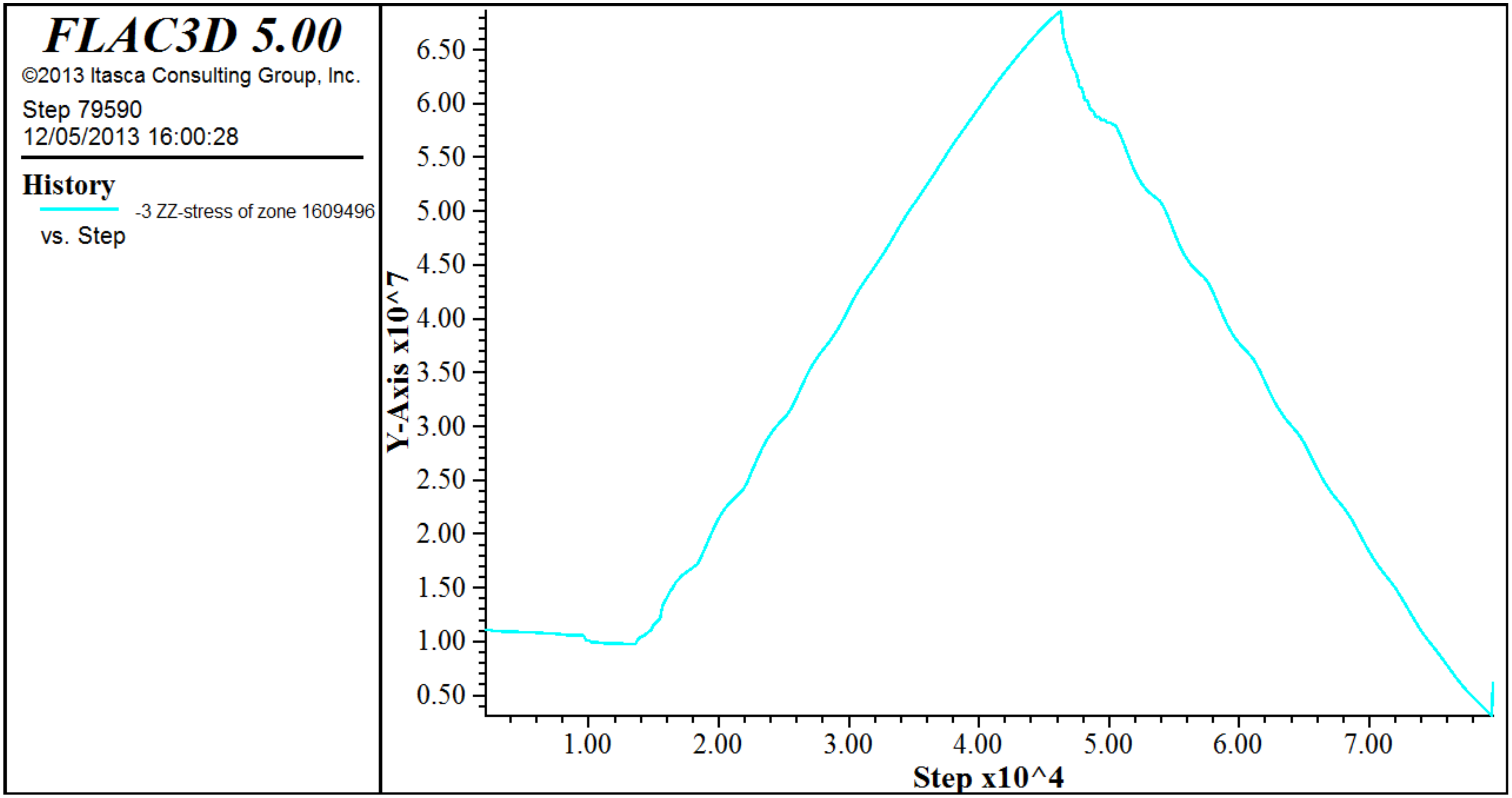


T-23: Plot of the major principal stress (Pa) after the loading stage (left) and after unloading stage (right)

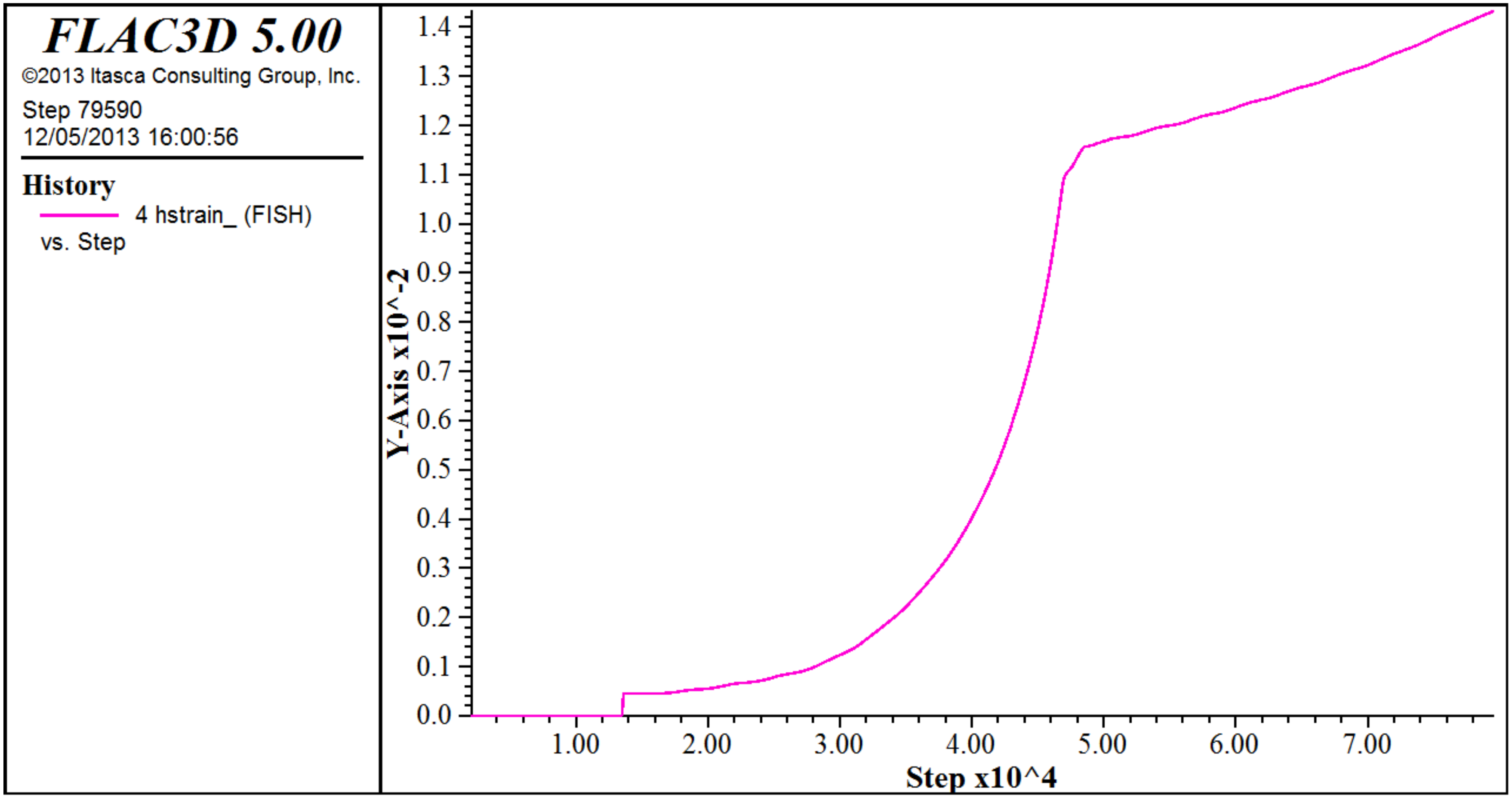


T-24: Plot of the Hoek-Brown s parameter after the loading stage (left) and after unloading stage (right)

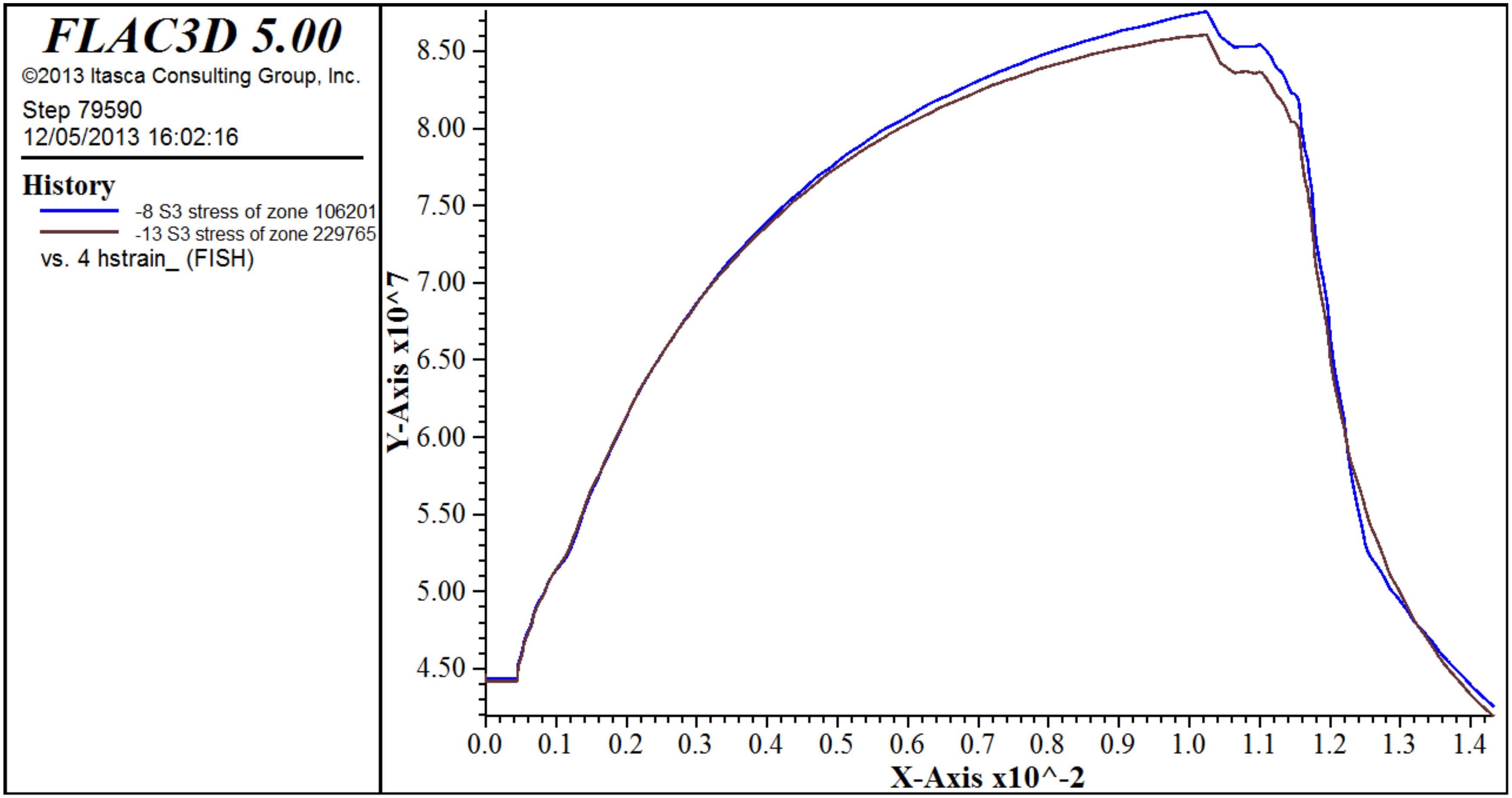
T.4 Scenario S_{64}



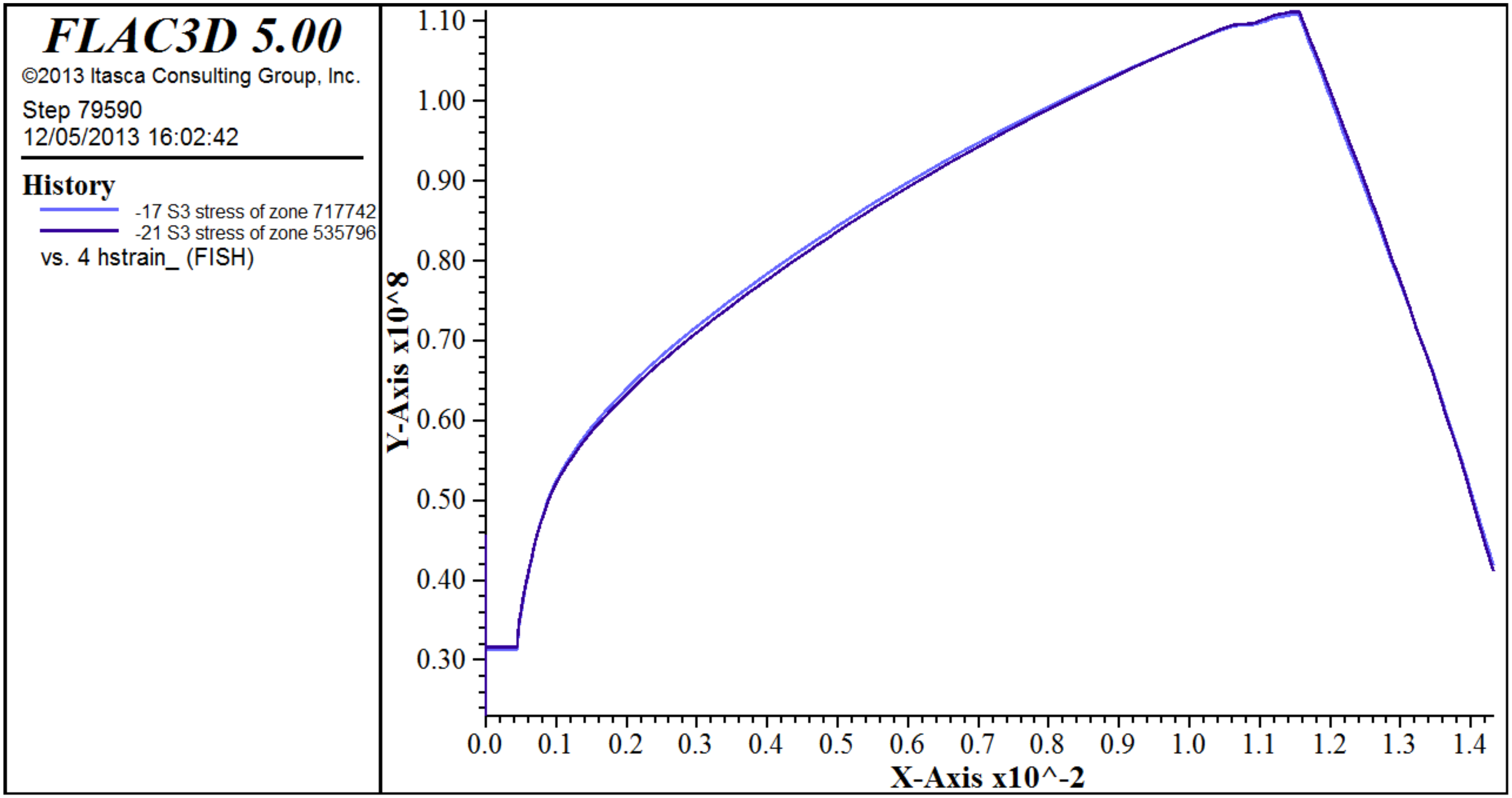
T-25: Abutment stress (MPa) at the top of the model versus calculation steps



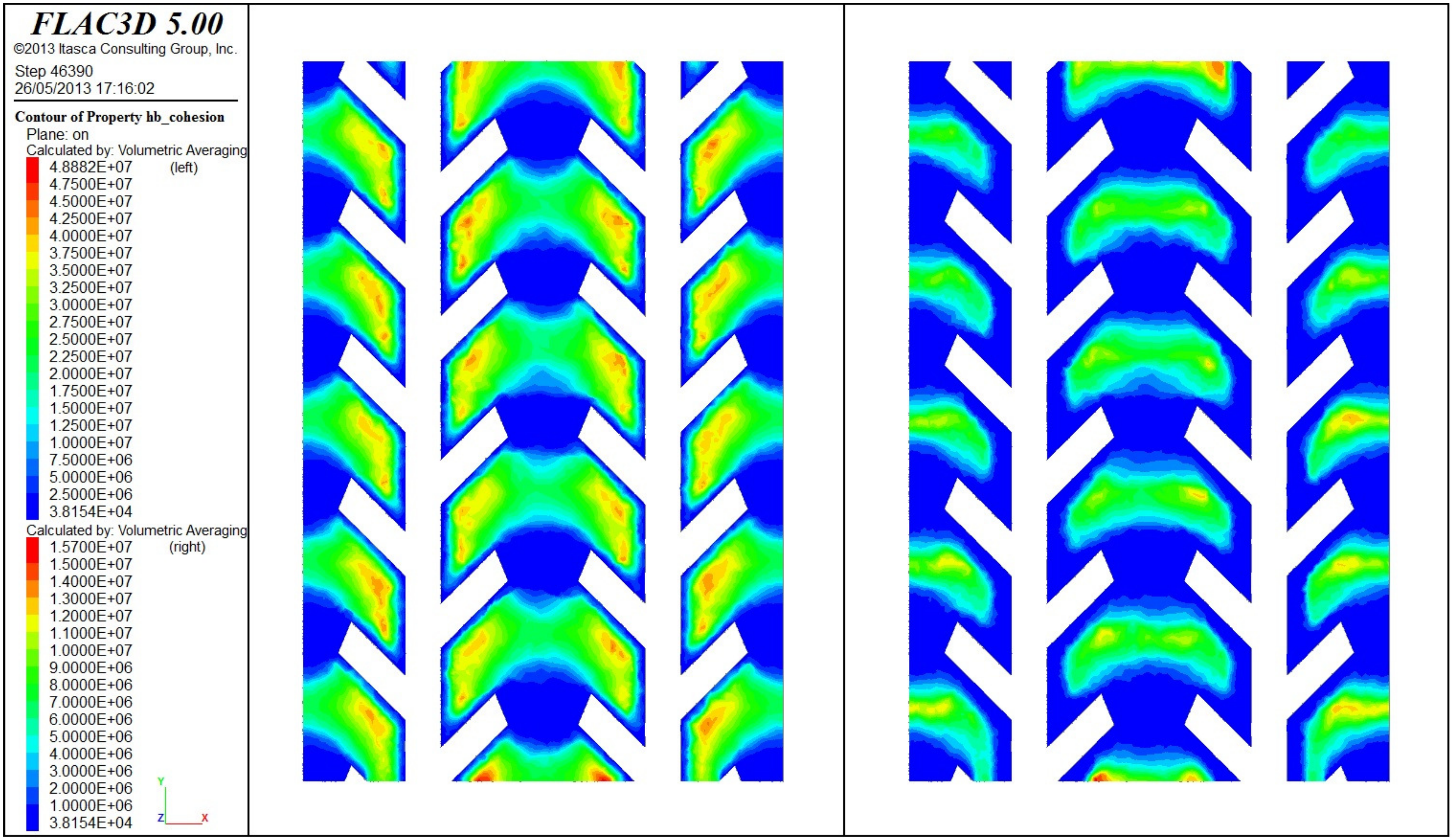
T-26: The average horizontal closure strain (-) of 8 monitoring stations versus calculations steps



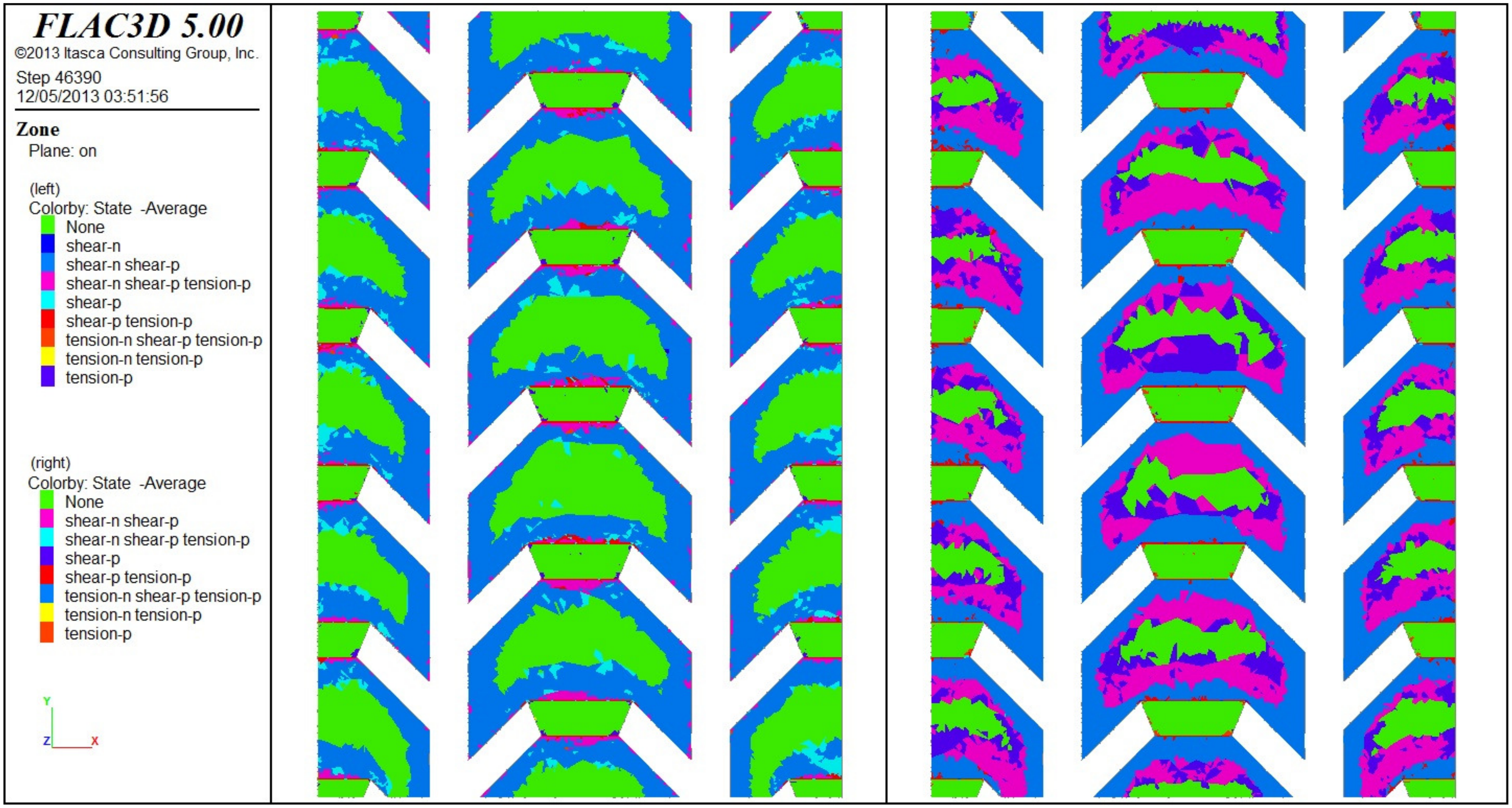
T-27: Major principal stress (Pa) versus closure strain (-) at the centre of the major apex at the location of 'MPBX1' (blue) and 'MPBX2' (brown)



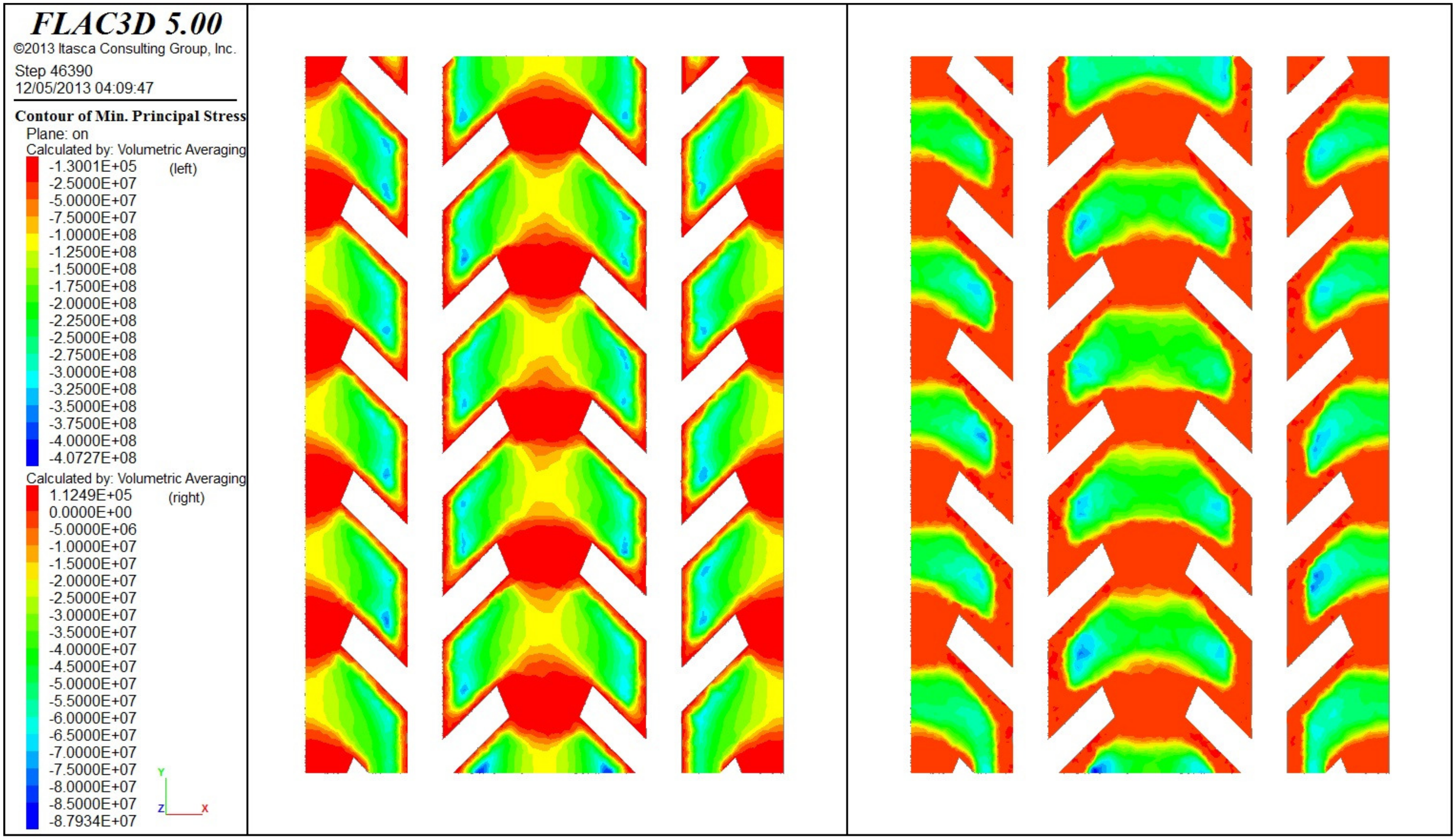
T-28: Major principal stress (Pa) versus closure strain (-) at the centre of the minor apex at locations 'minor1' (light blue) and 'minor2' (dark blue)



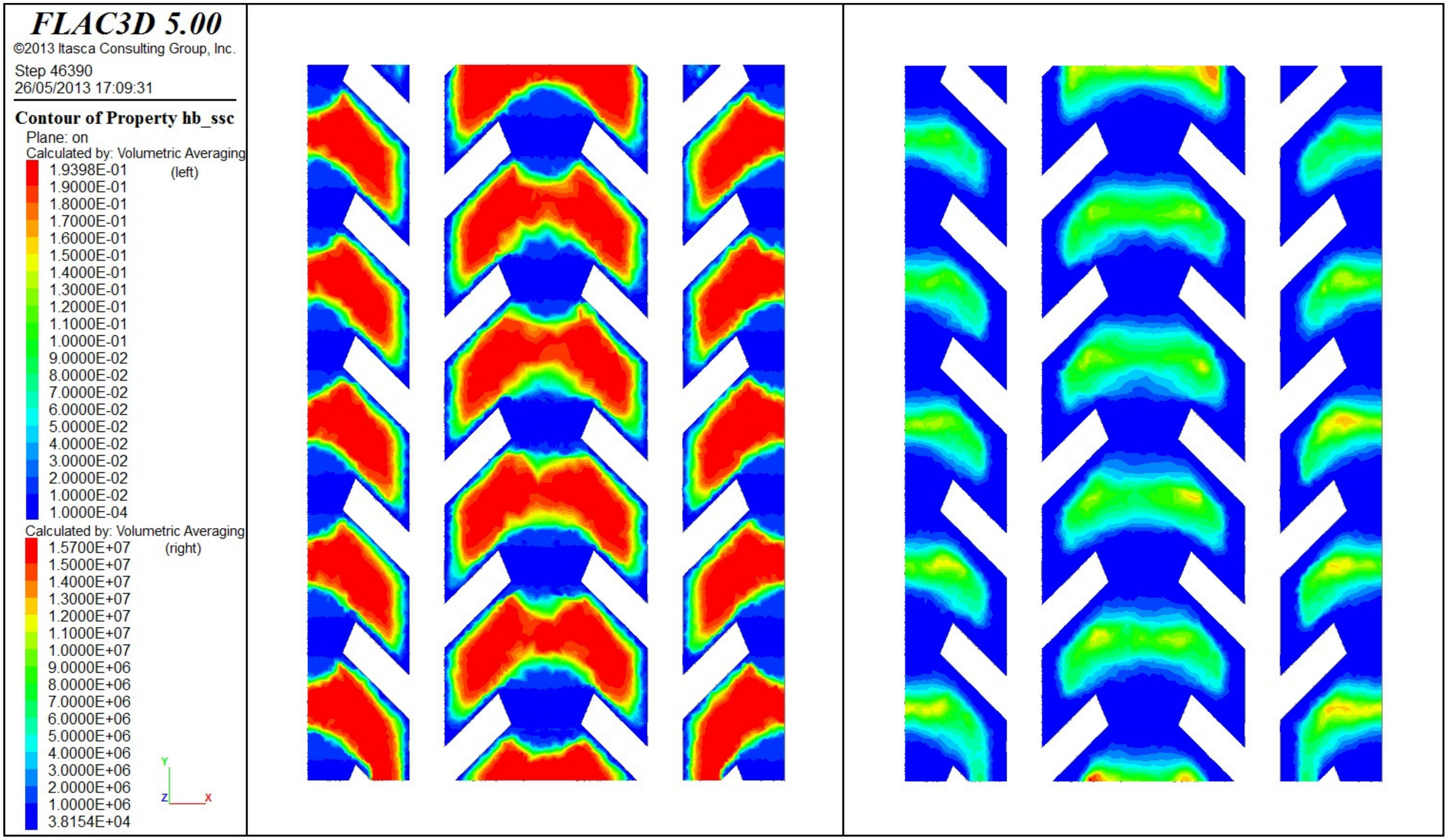
T-29: Plot of apparent cohesion (Pa) after the loading stage (left) and after unloading stage (right)



T-30: Plot of the plasticity state after the loading stage (left) and after unloading stage (right)

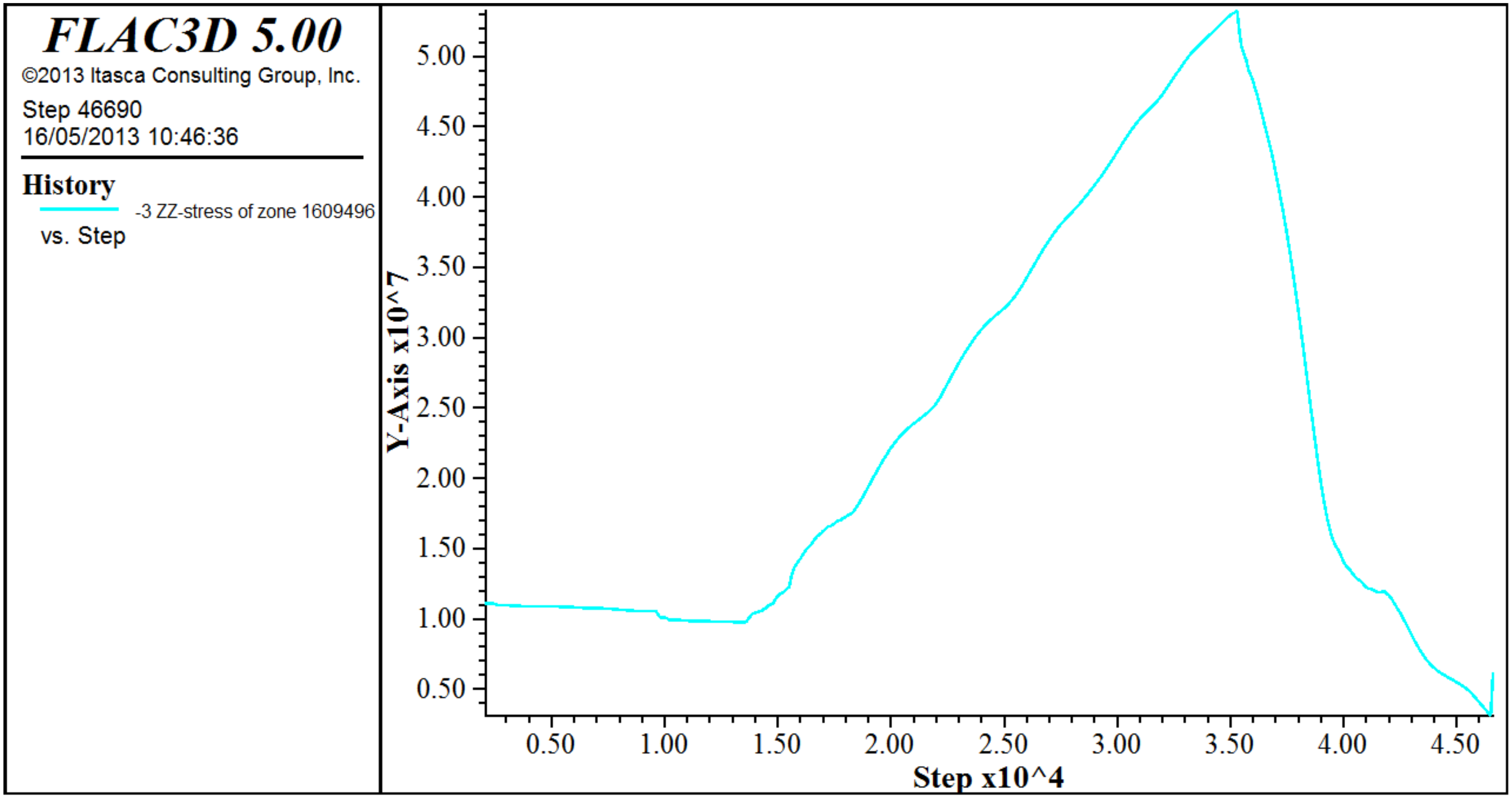


T-31: Plot of the major principal stress (Pa) after the loading stage (left) and after unloading stage (right)

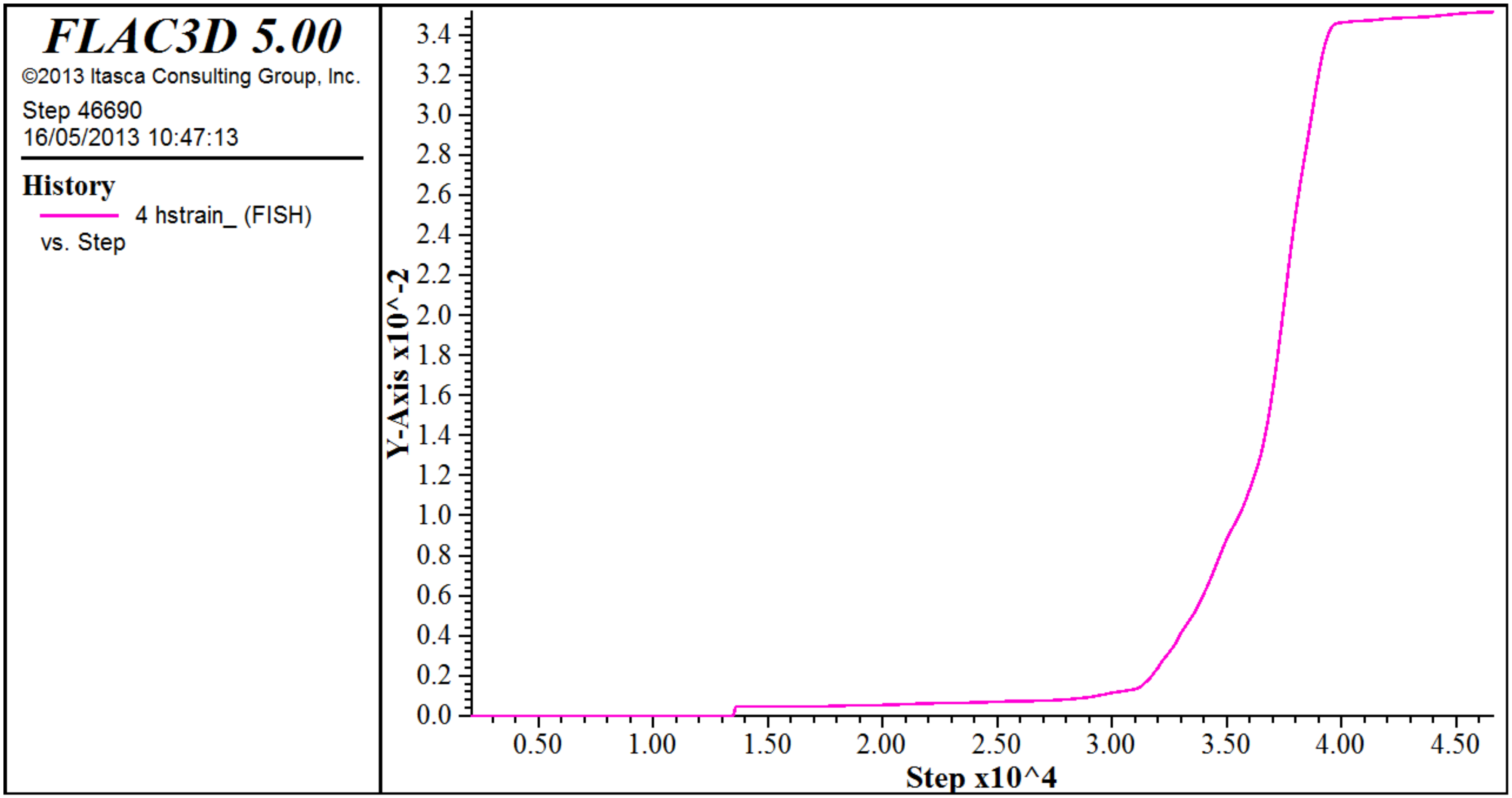


T-32: Plot of the Hoek-Brown s parameter after the loading stage (left) and after unloading stage (right)

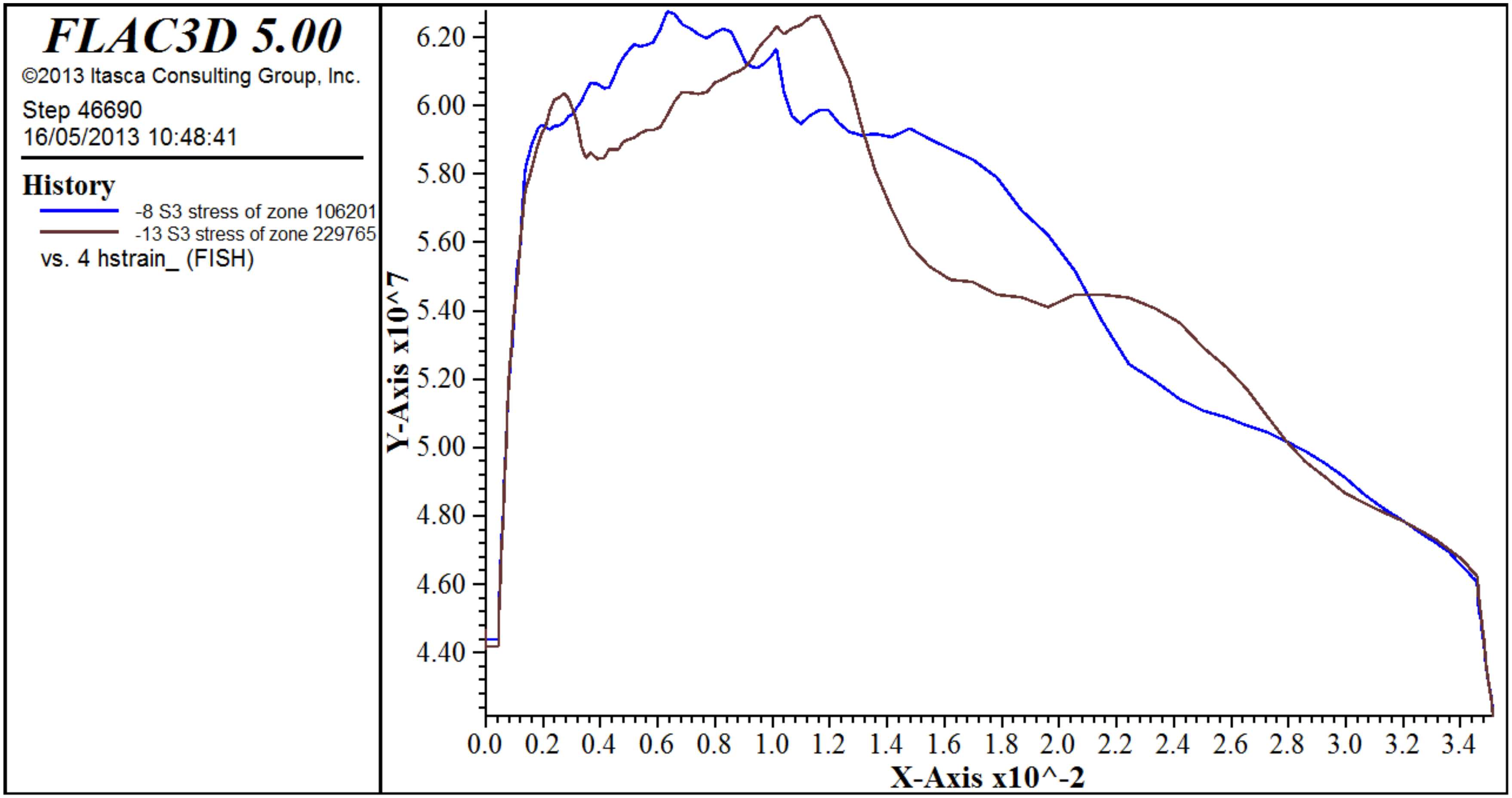
T.5 Scenario S_{96}



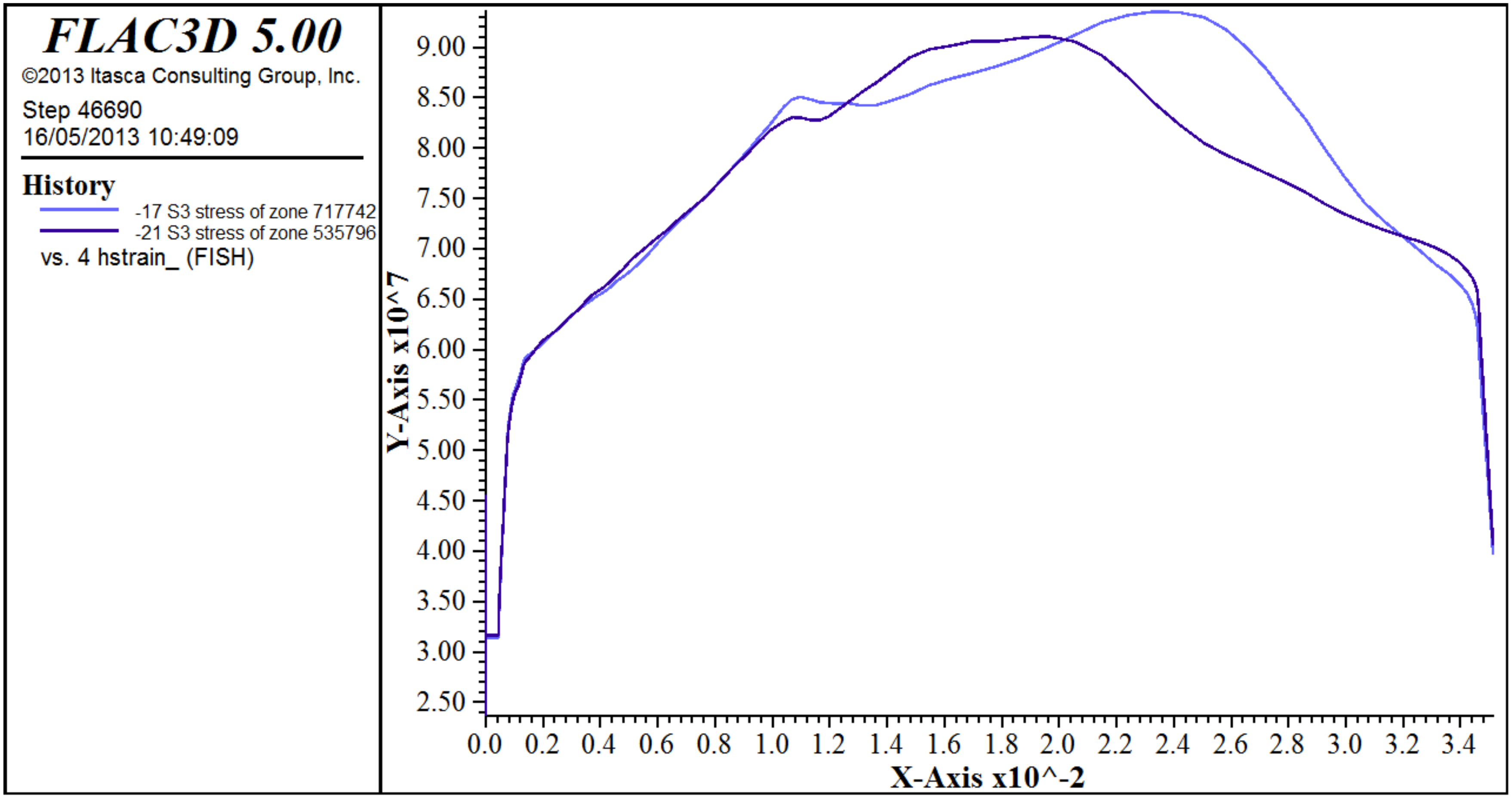
T-33: Abutment stress (MPa) at the top of the model versus calculation steps



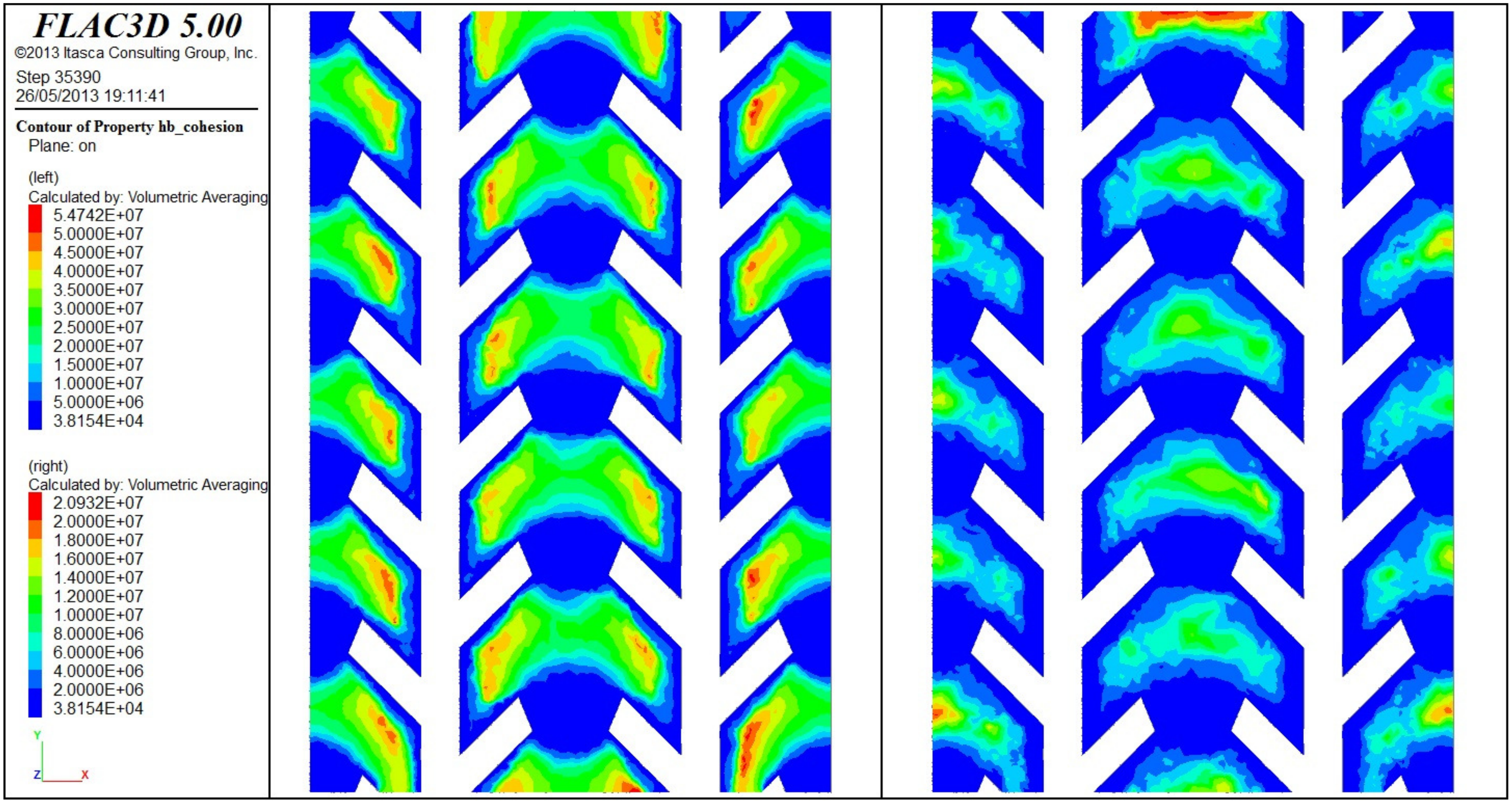
T-34: The average horizontal closure strain (-) of 8 monitoring stations versus calculations steps



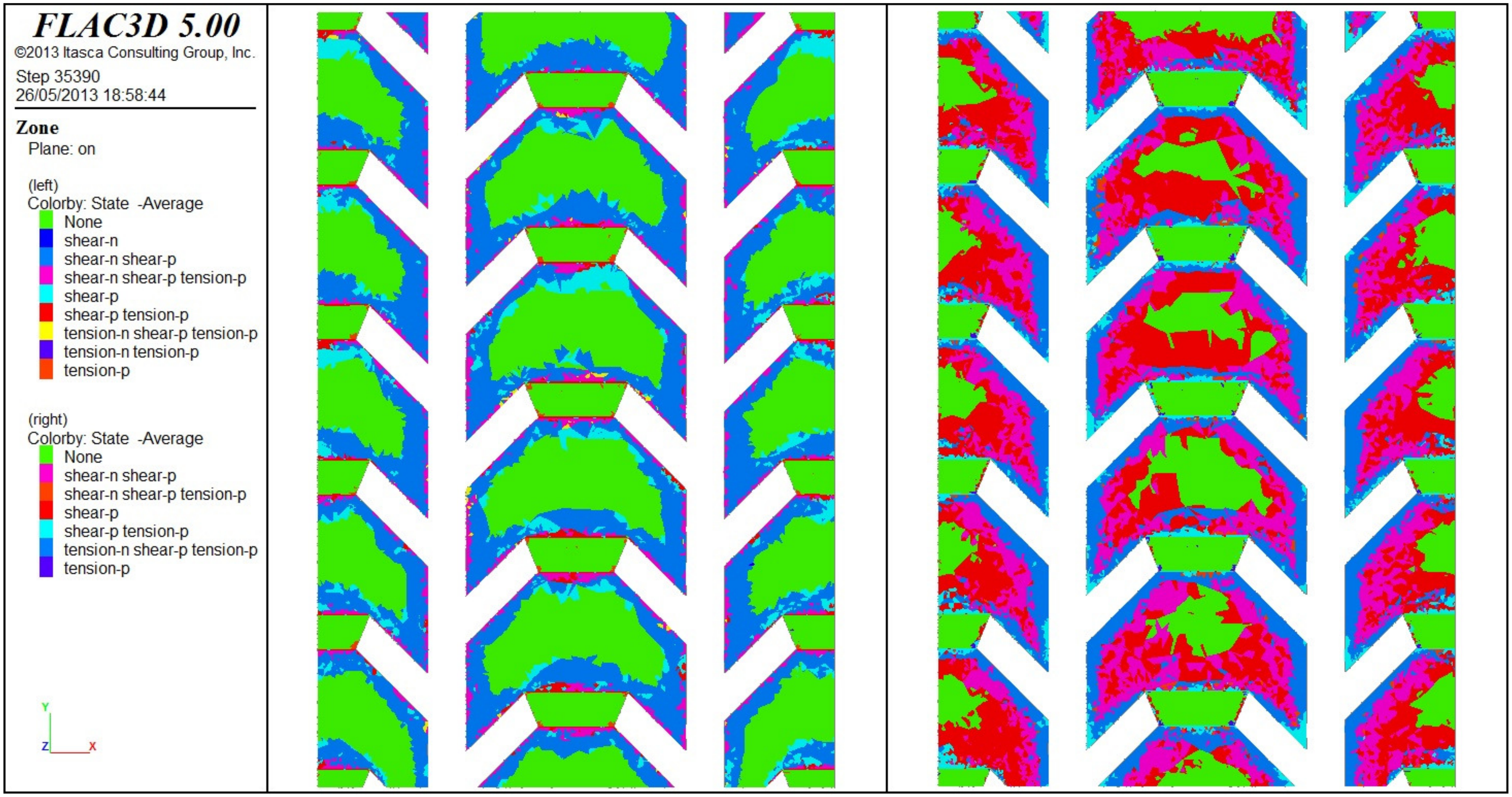
T-35: Major principal stress (Pa) versus closure strain (-) at the centre of the major apex at the location of 'MPBX1' (blue) and 'MPBX2' (brown)



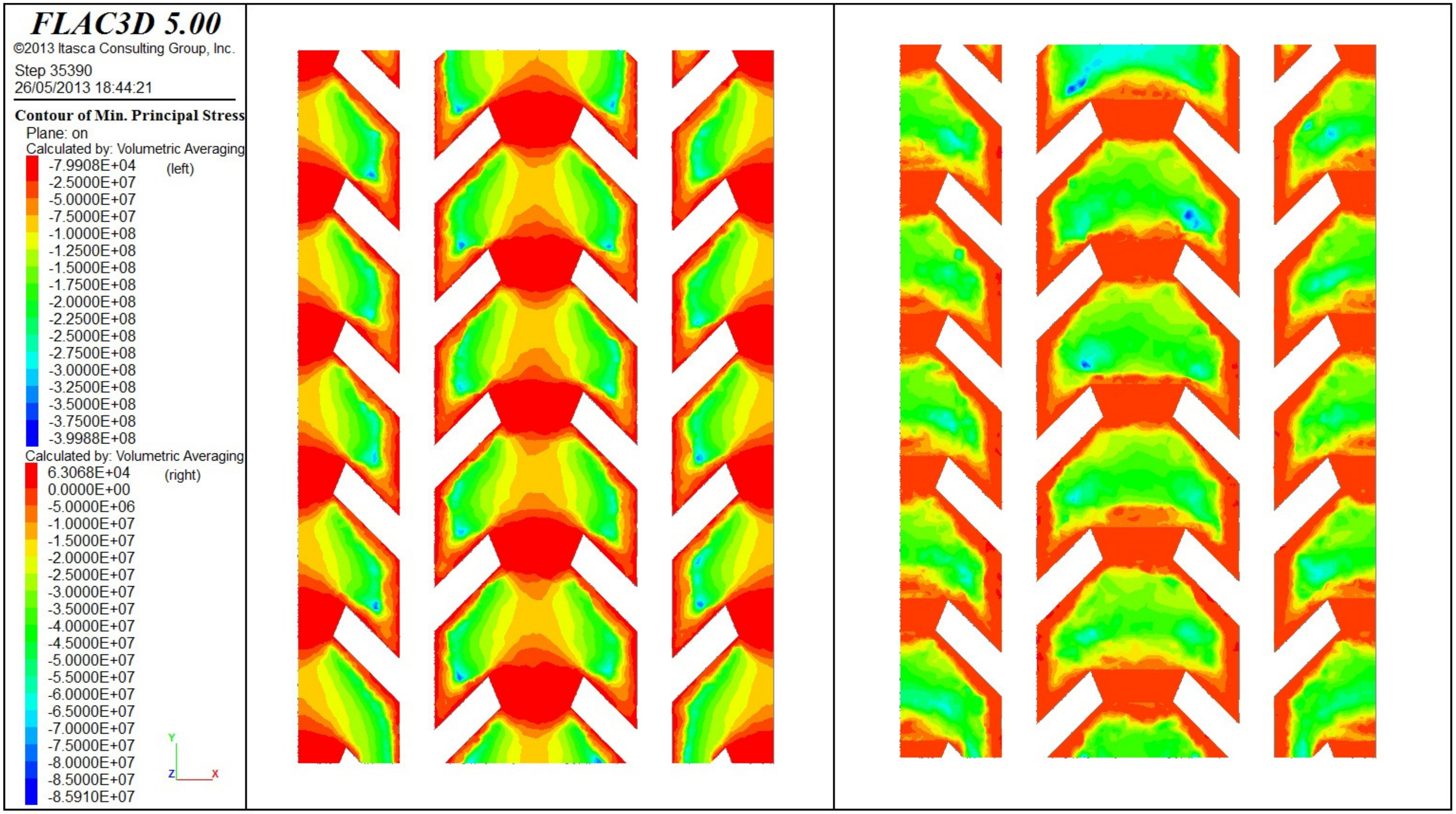
T-36: Major principal stress (Pa) versus closure strain (-) at the centre of the minor apex at locations 'minor1' (light blue) and 'minor2' (dark blue)



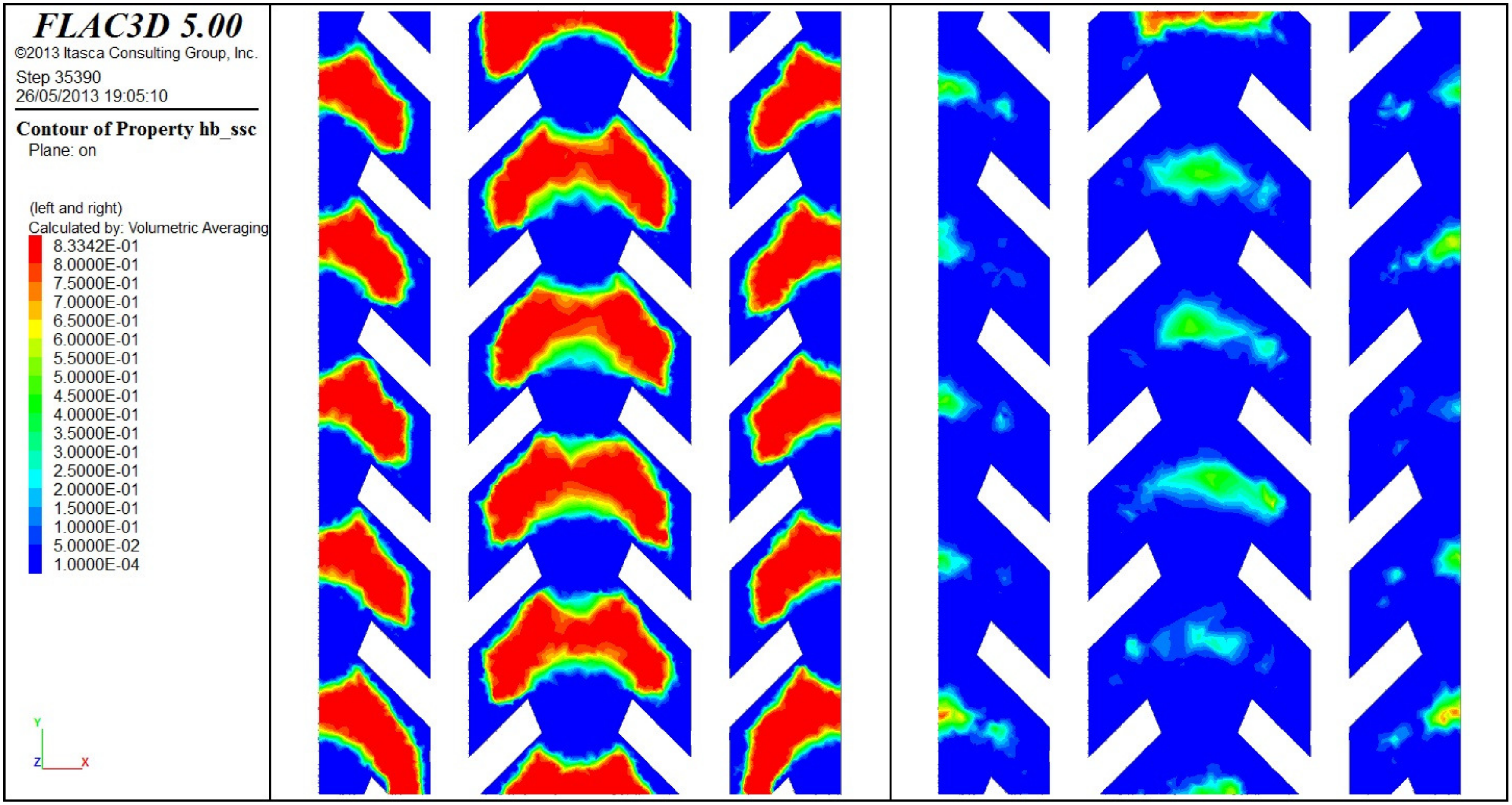
T-37: Plot of apparent cohesion (Pa) after the loading stage (left) and after unloading stage (right)



T-38: Plot of the plasticity state after the loading stage (left) and after unloading stage (right)



T-39: Plot of the major principal stress (Pa) after the loading stage (left) and after unloading stage (right)



T-40: Plot of the Hoek-Brown s parameter after the loading stage (left) and after unloading stage (right)

Appendix U. Virtual MPBX results

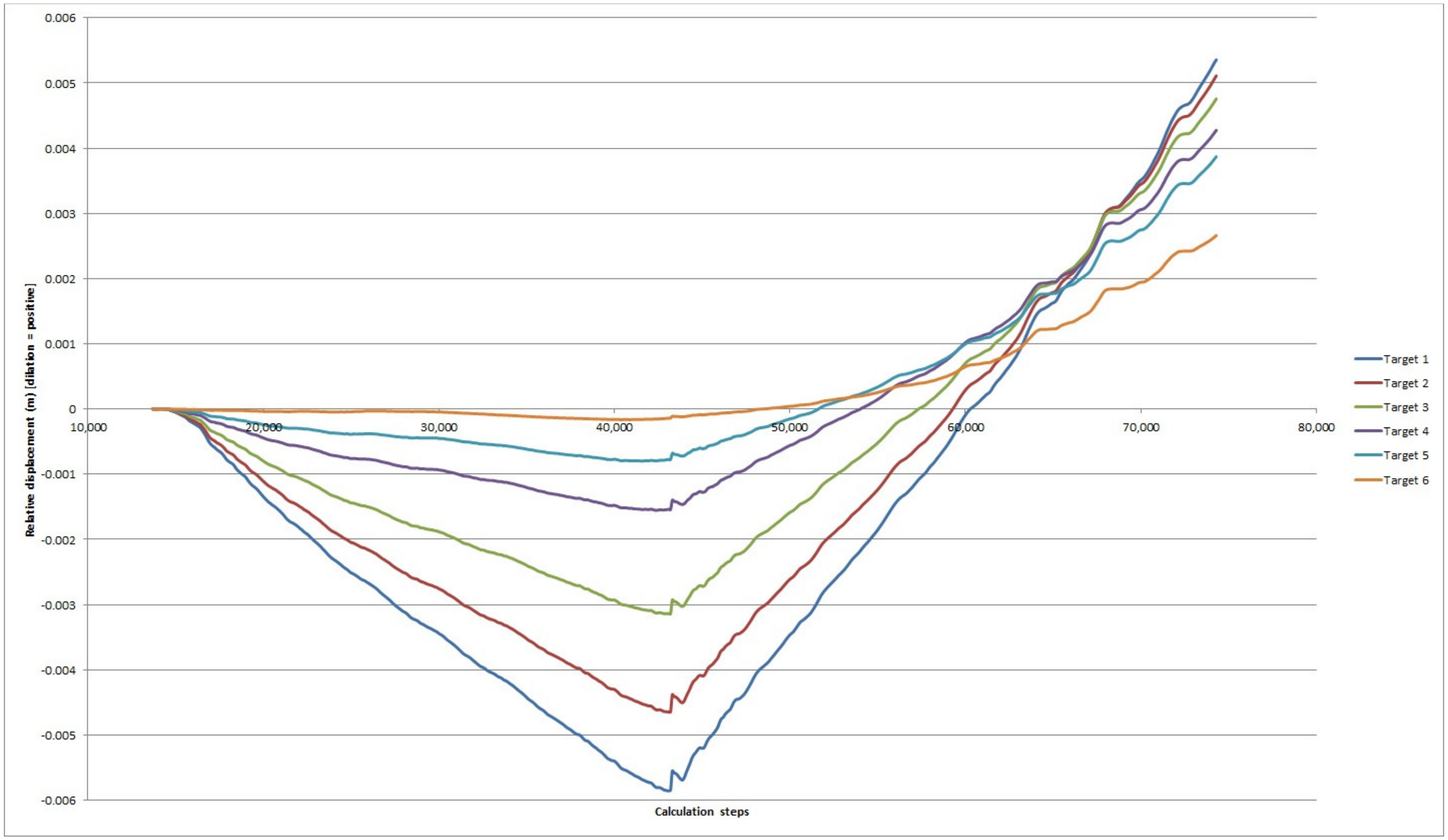


Figure U-1: Relative displacements of MPBX1 in scenario HB base case.

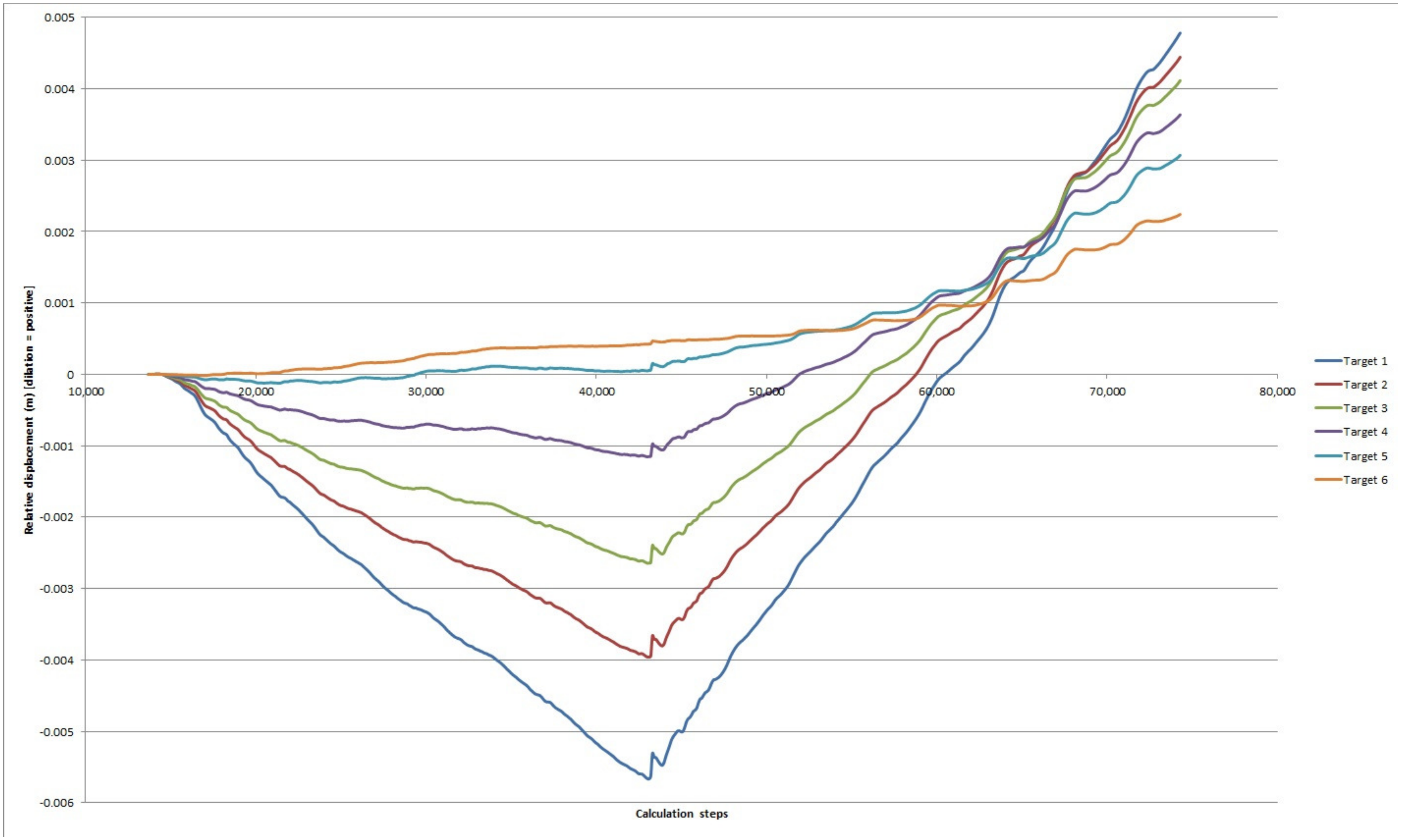


Figure U-2: Relative displacements of MPBX2 in scenario HB base case.

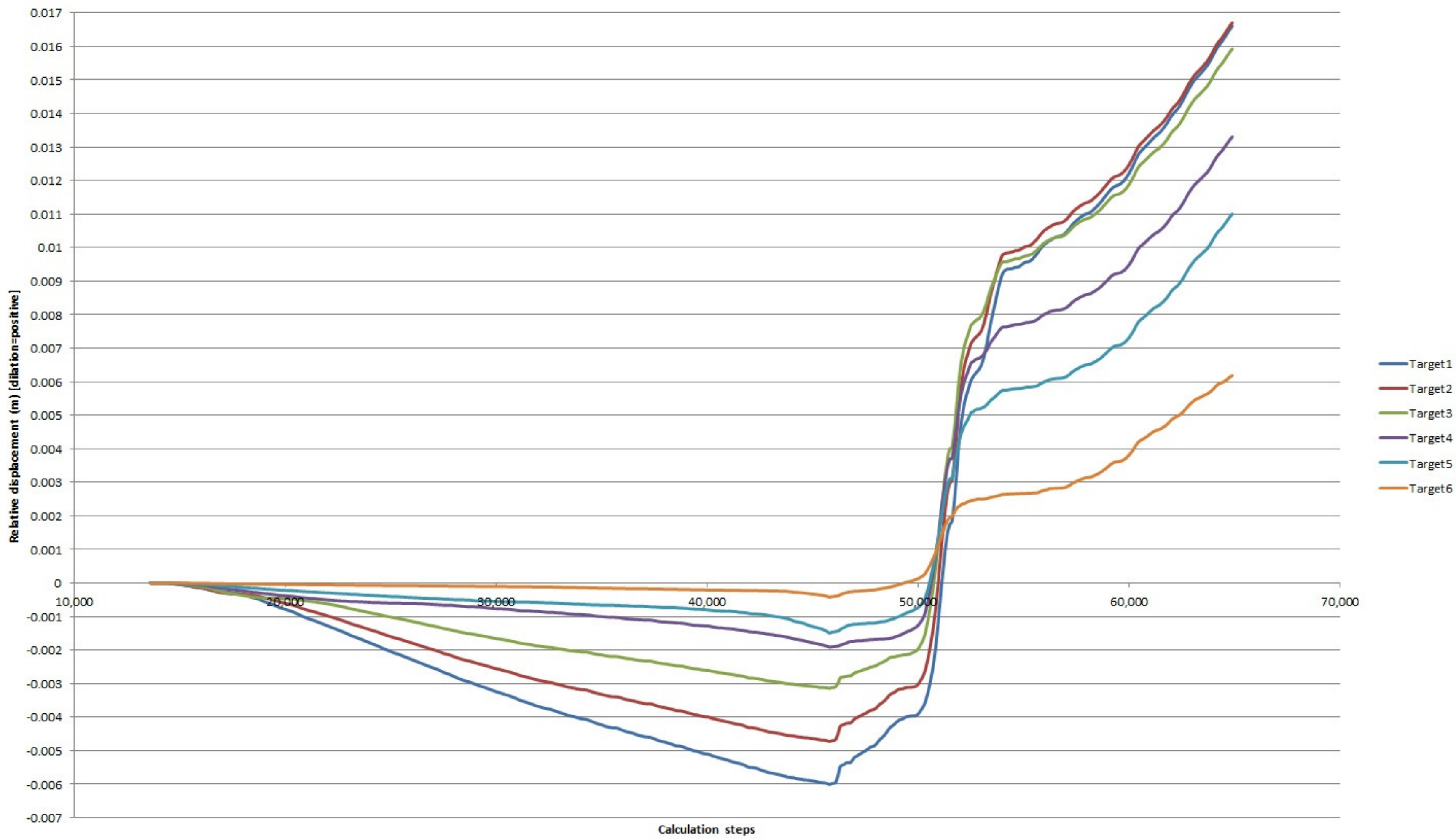


Figure U-3: Relative displacements of MPBX1 in scenario S base case. (alternative correction)

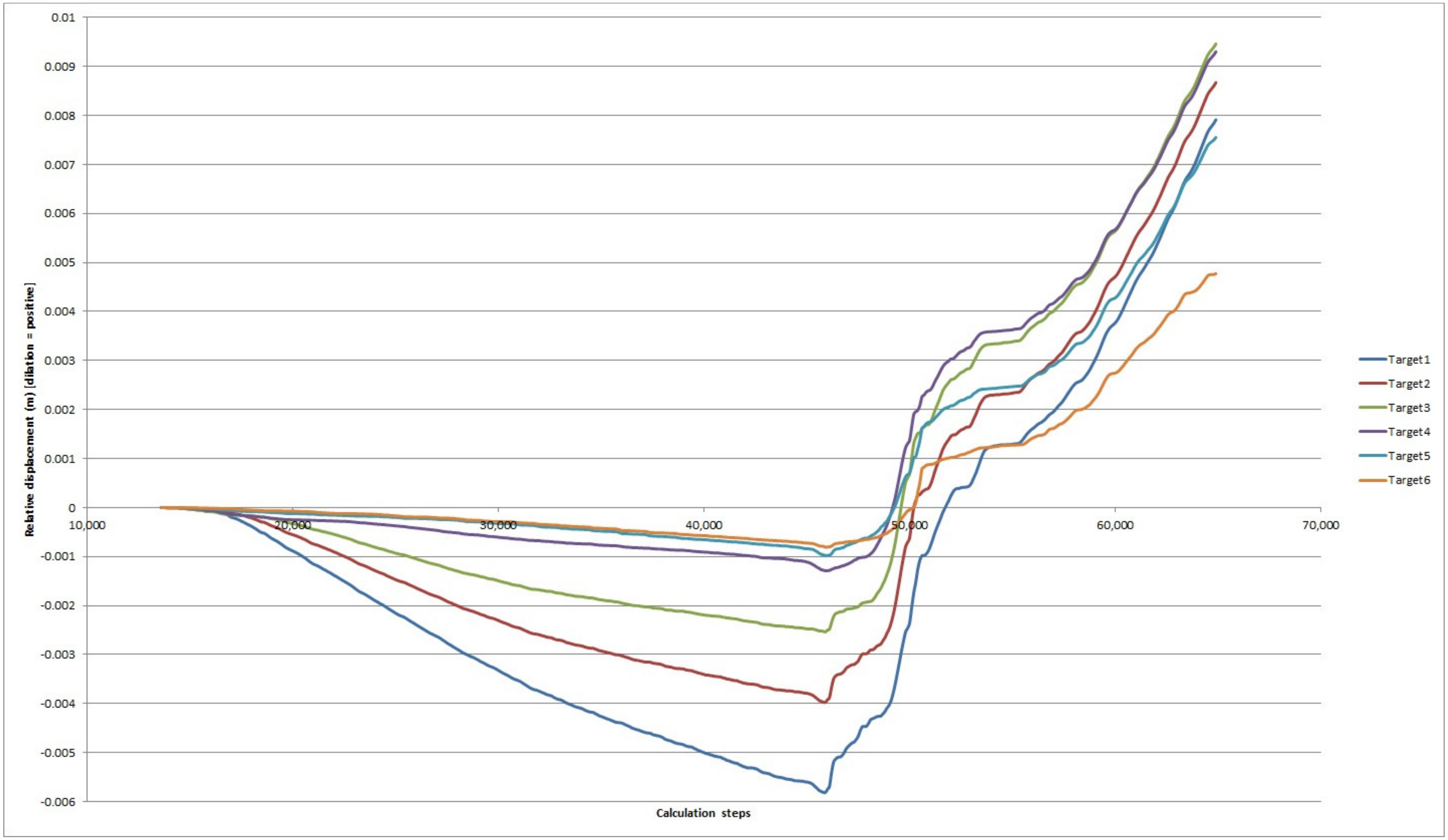


Figure U-4: Relative displacements of MPBX2 in scenario S base case. (alternative correction)

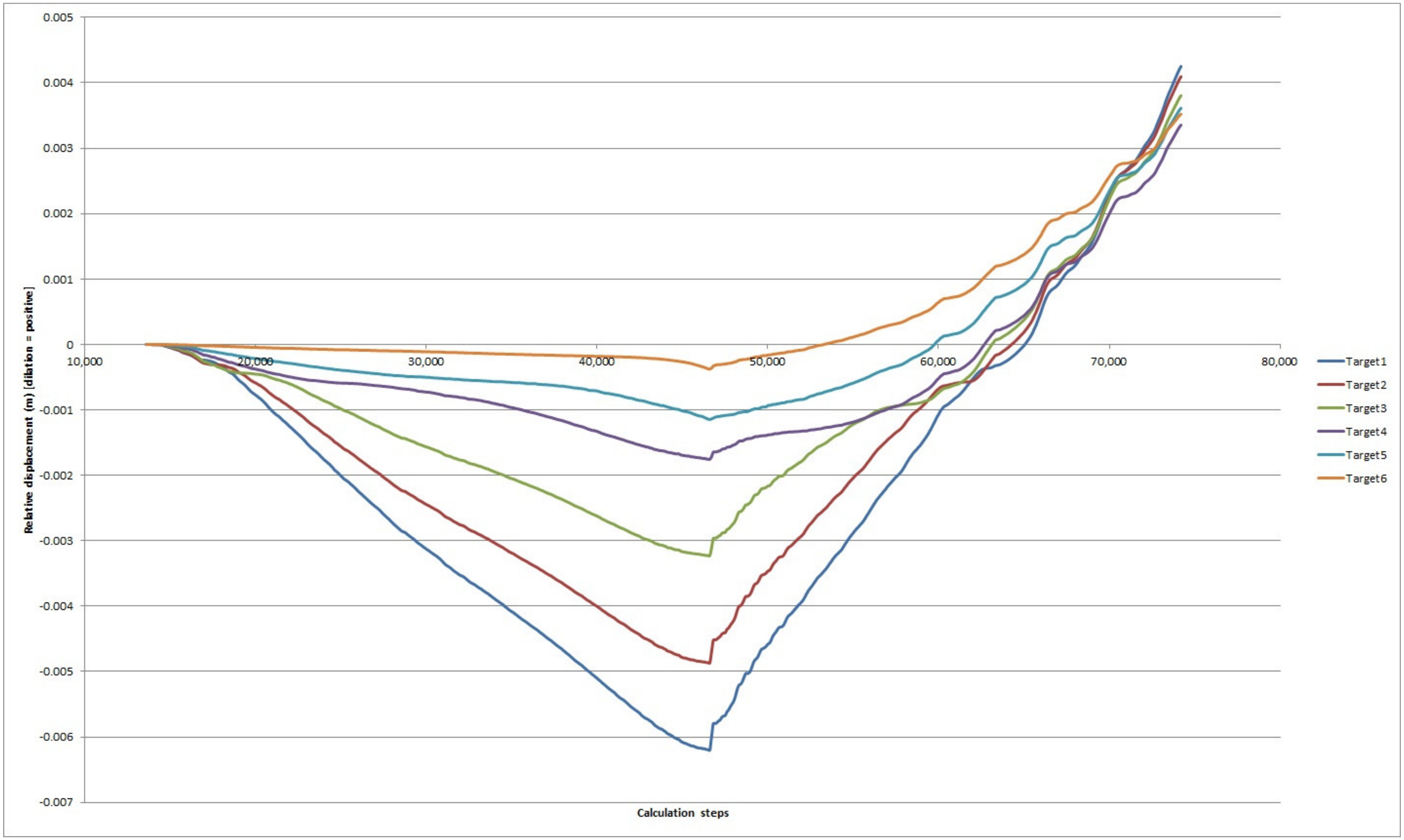


Figure U-5: Relative displacements of MPBX1 in scenario S_{64}. (alternative correction)

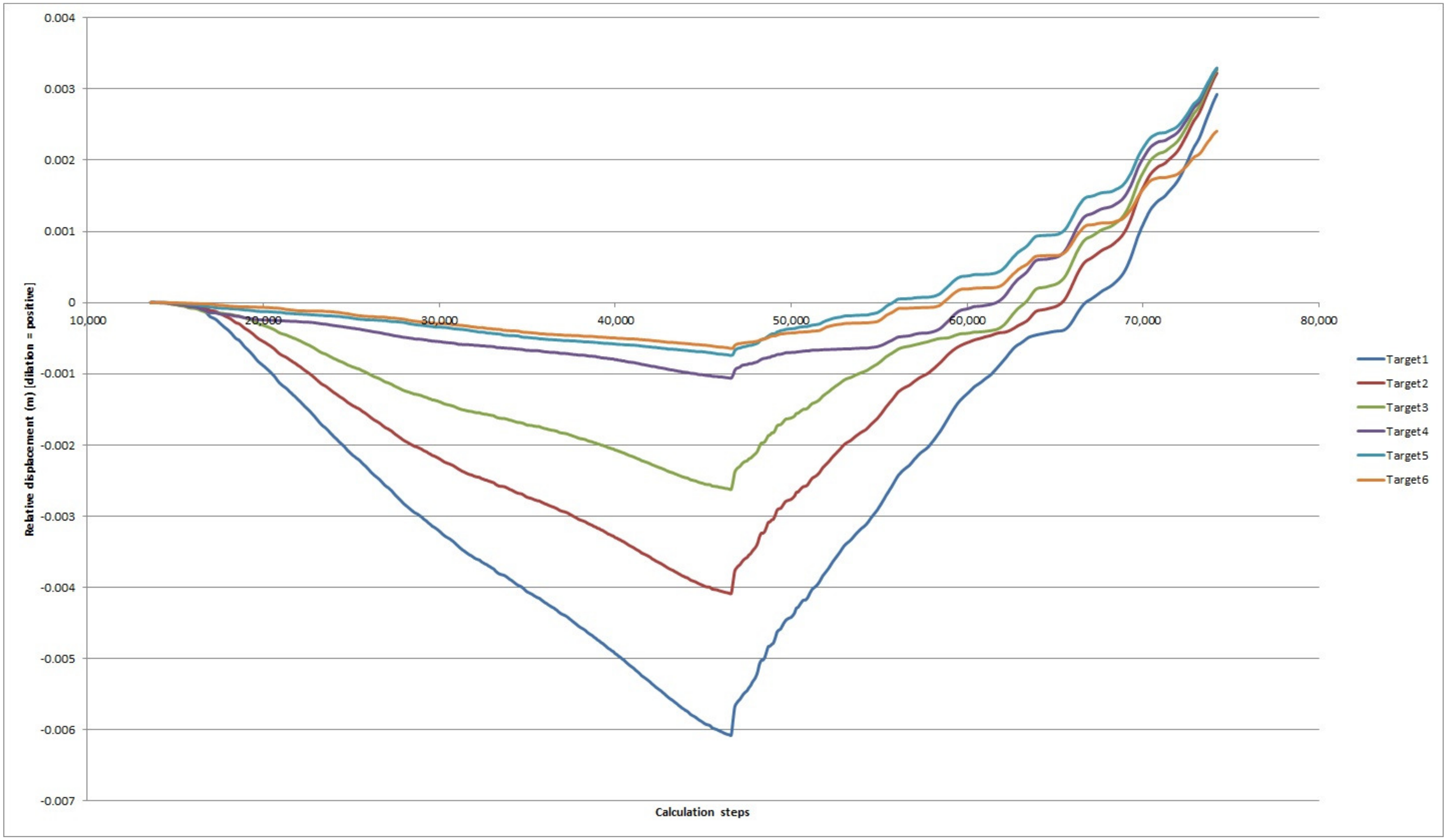


Figure U-6: Relative displacements of MPBX2 in scenario S_{64}. (alternative correction)

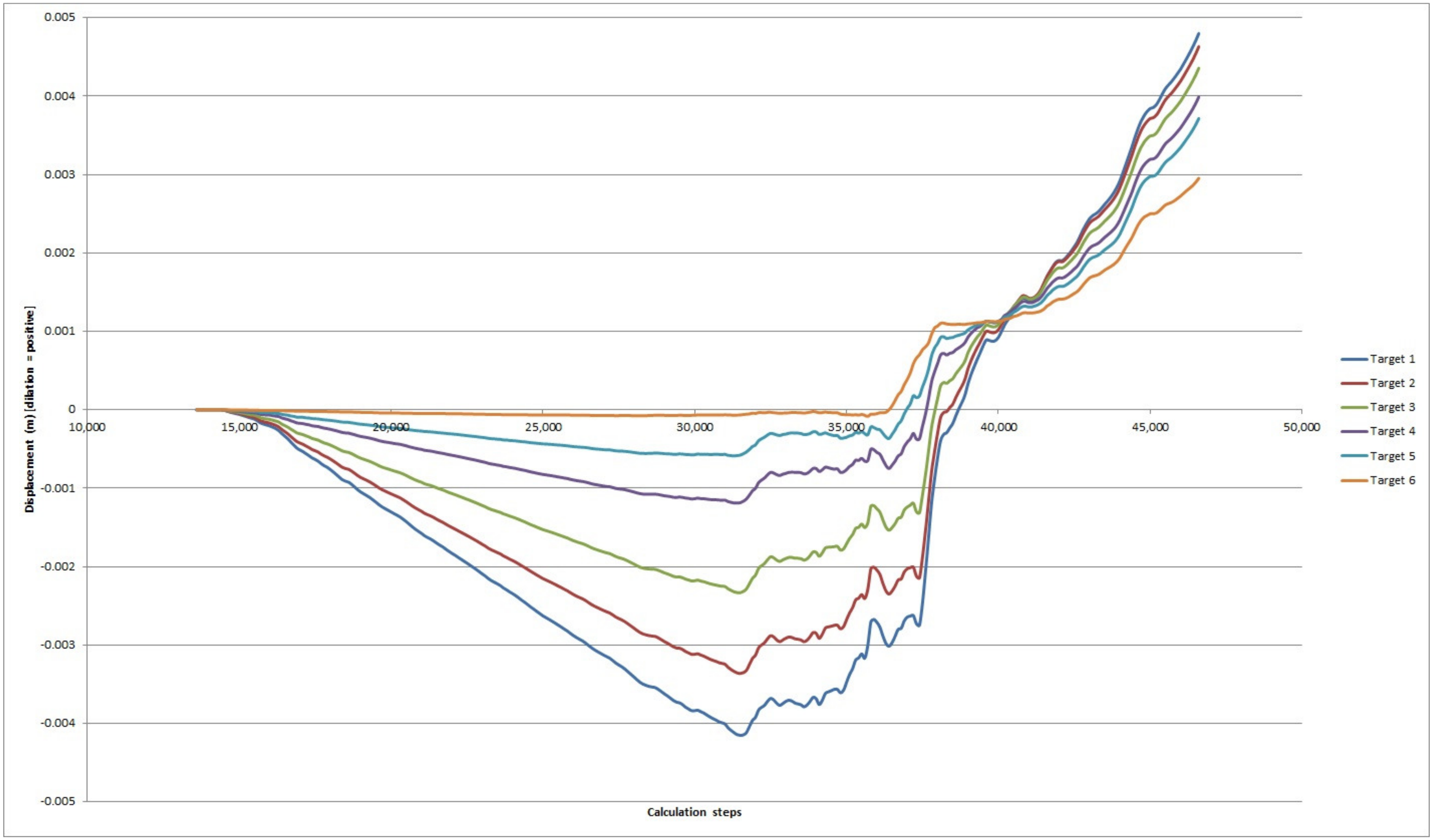


Figure U-7: Relative displacements of MPBX1 in scenario S_{96}.

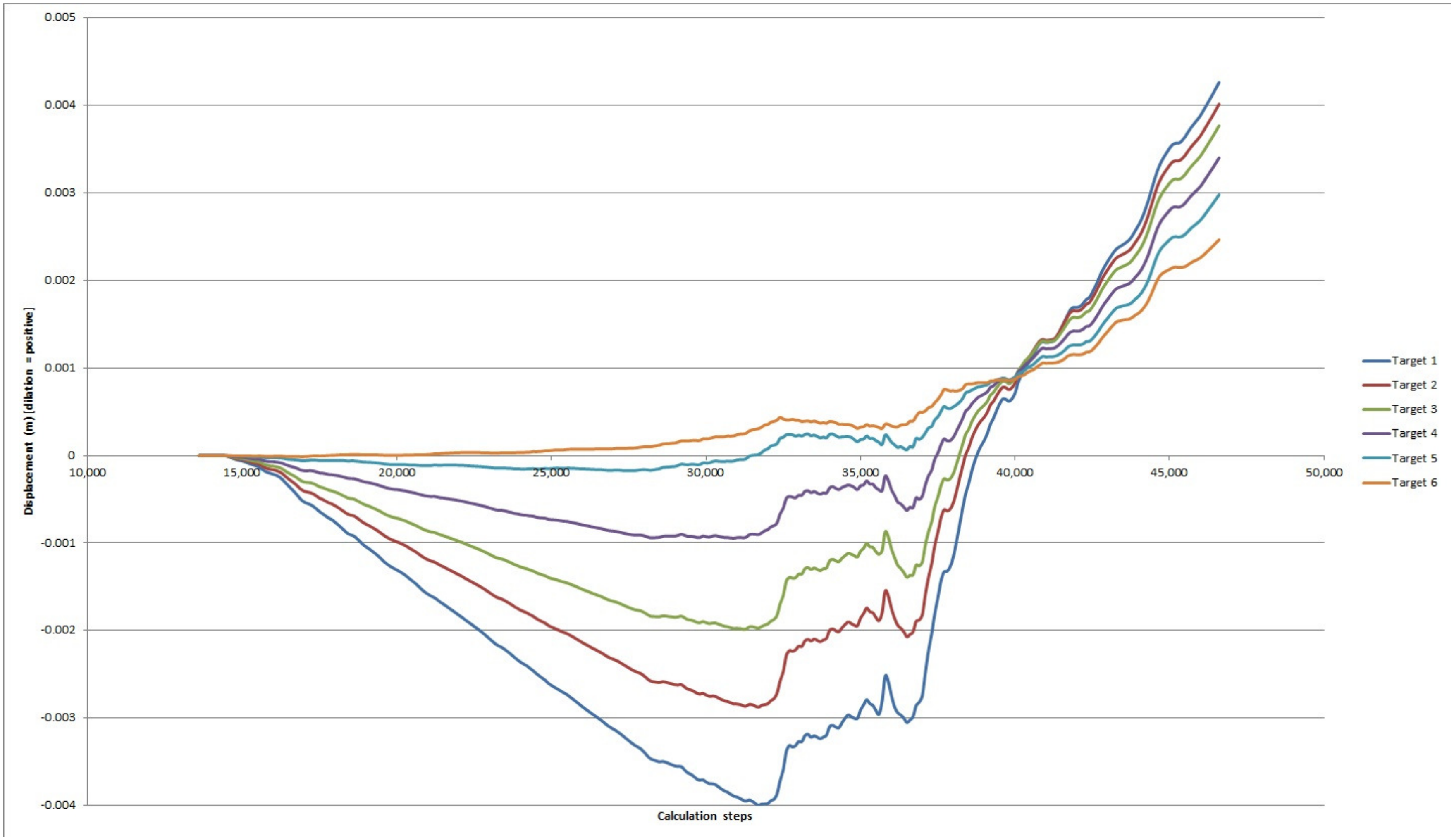


Figure U-8: Relative displacements of MPBX2 in scenario S_{96}.

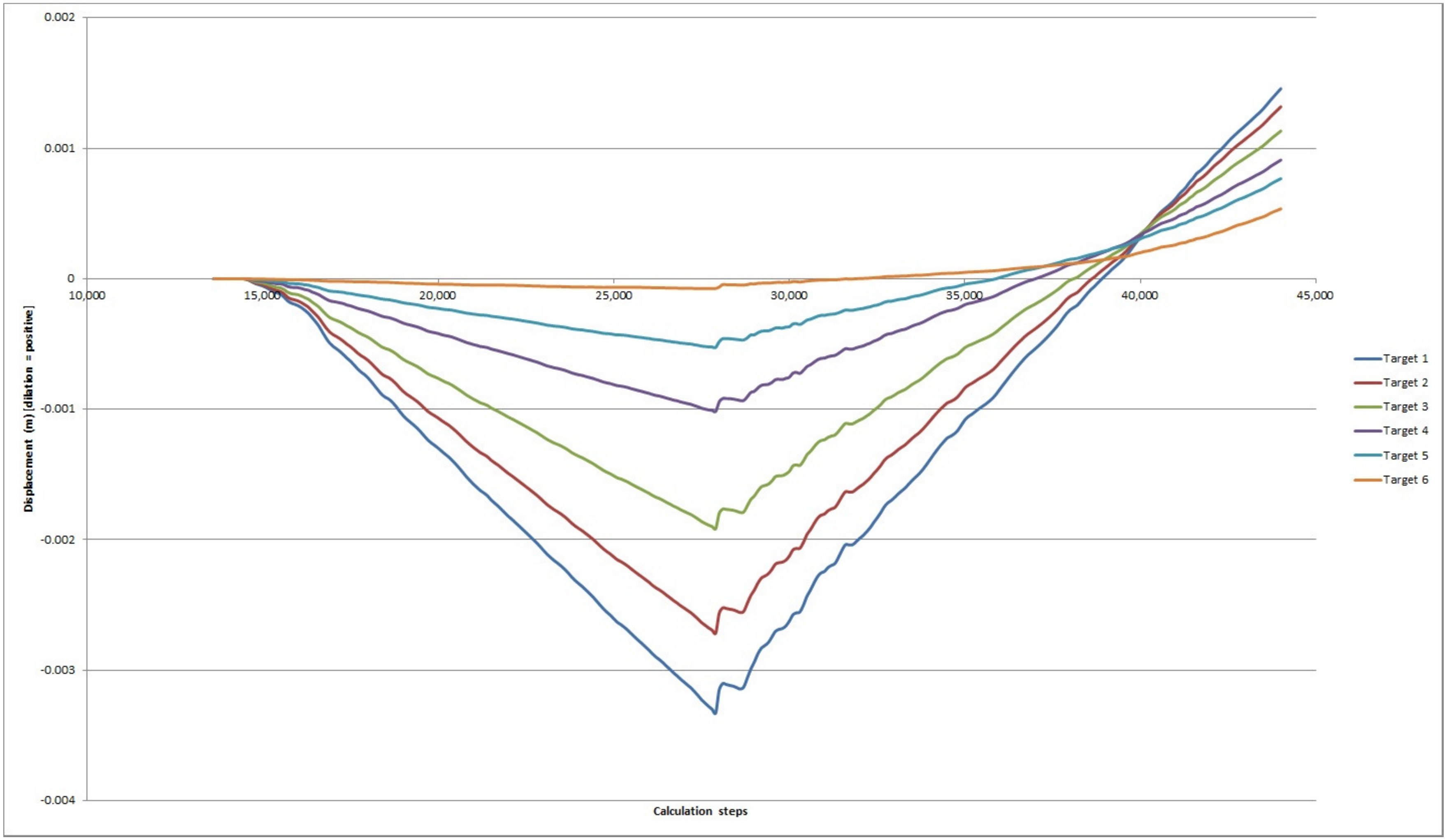


Figure U-9: Relative displacements of MPBX1 in scenario S_{abut}.

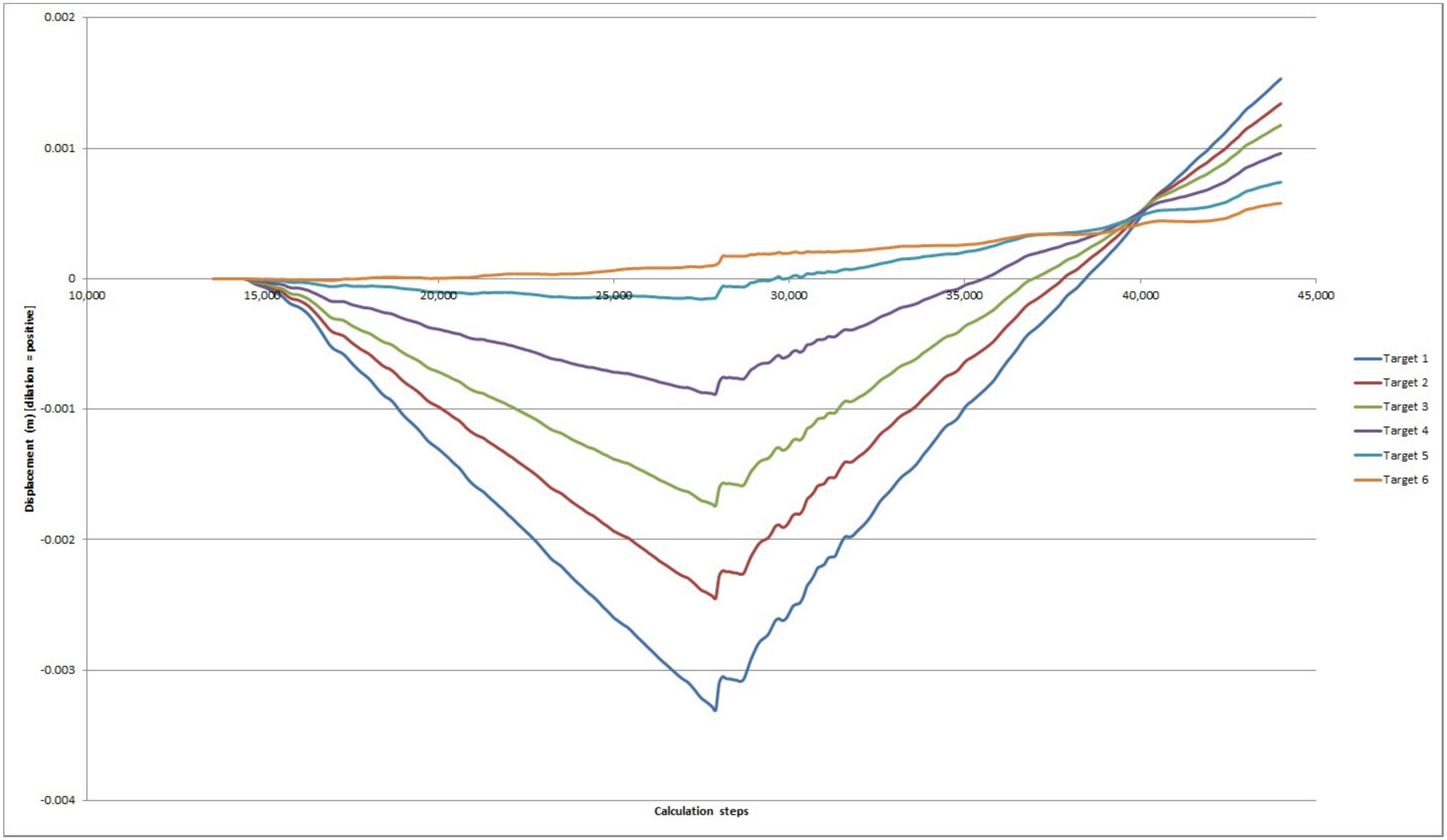


Figure U-10: Relative displacements of MPBX2 in scenario S_a