Ground Control Studies for Mining Through a Fault Using Retreat Longwall Mining: Field and Analytical Observations

Y. P. Chugh, Harrold Gurley, Behrooz Abbasi
Mining and Minerals Resources Engineering
Southern Illinois University Carbondale
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American Coal Company
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Acknowledgements

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- Dr. Joseph Hirschi for his technical guidance and oversight.
- Sincere thanks to Mark Mormino, Gary Vancil and their staff members of American Coal Company for their technical support and cooperation.
- Additional thanks are due to Itasca Consultants, Inc. for allowing the use of Version 5 FLAC3D software.

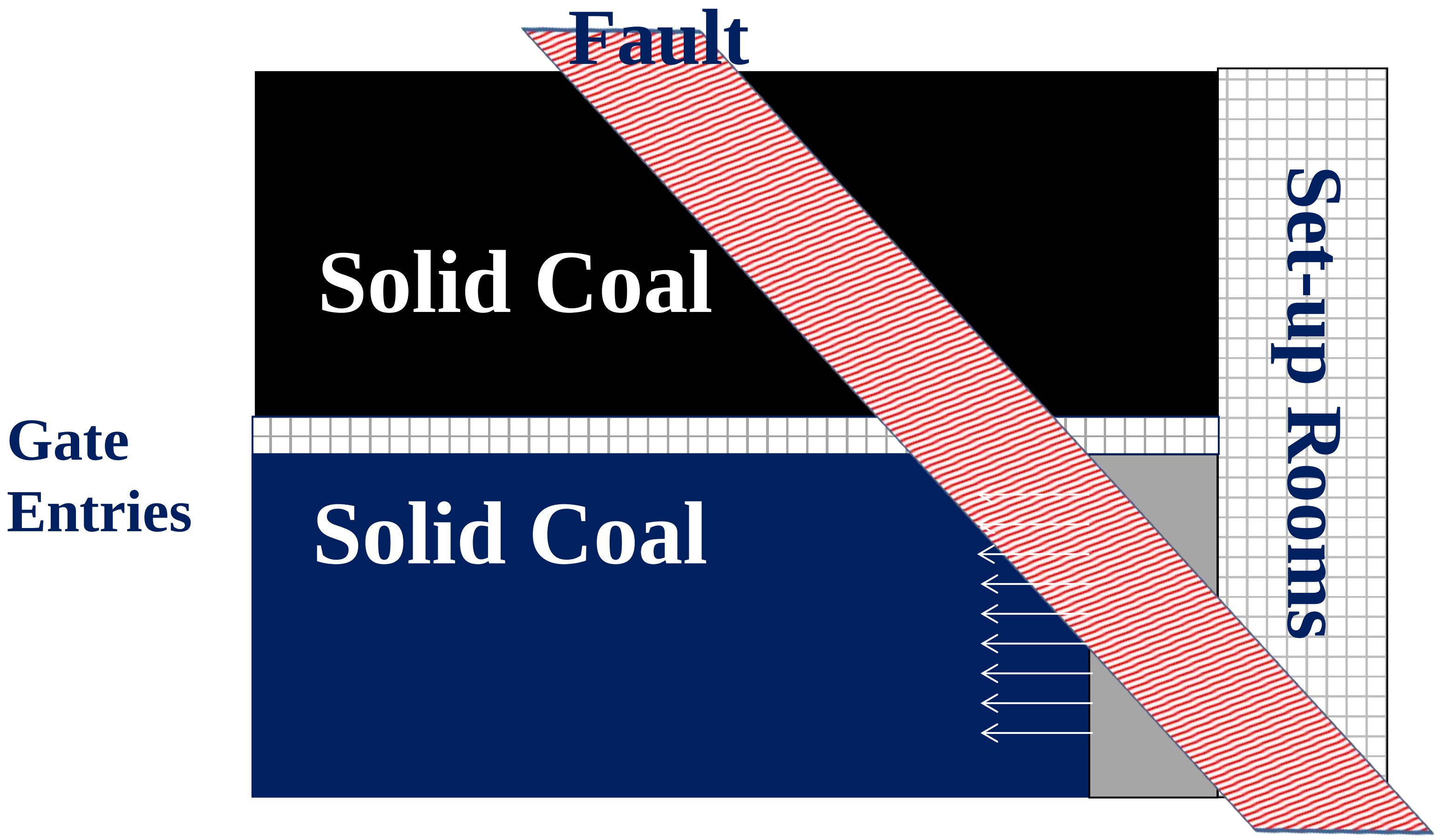
Goals of the Cooperative Study

- Develop better understanding of longwall mining operations around geologic anomalies.
- Quantify the movements that can occur in development areas while mining around faults.
- Assess if these movements can be projected with some confidence using numerical models even with large number of uncertainties.
- Develop a better understanding of the mechanisms of movements as the face advances.
- Have made progress in all these areas and will be working more over the next 1-2 years.

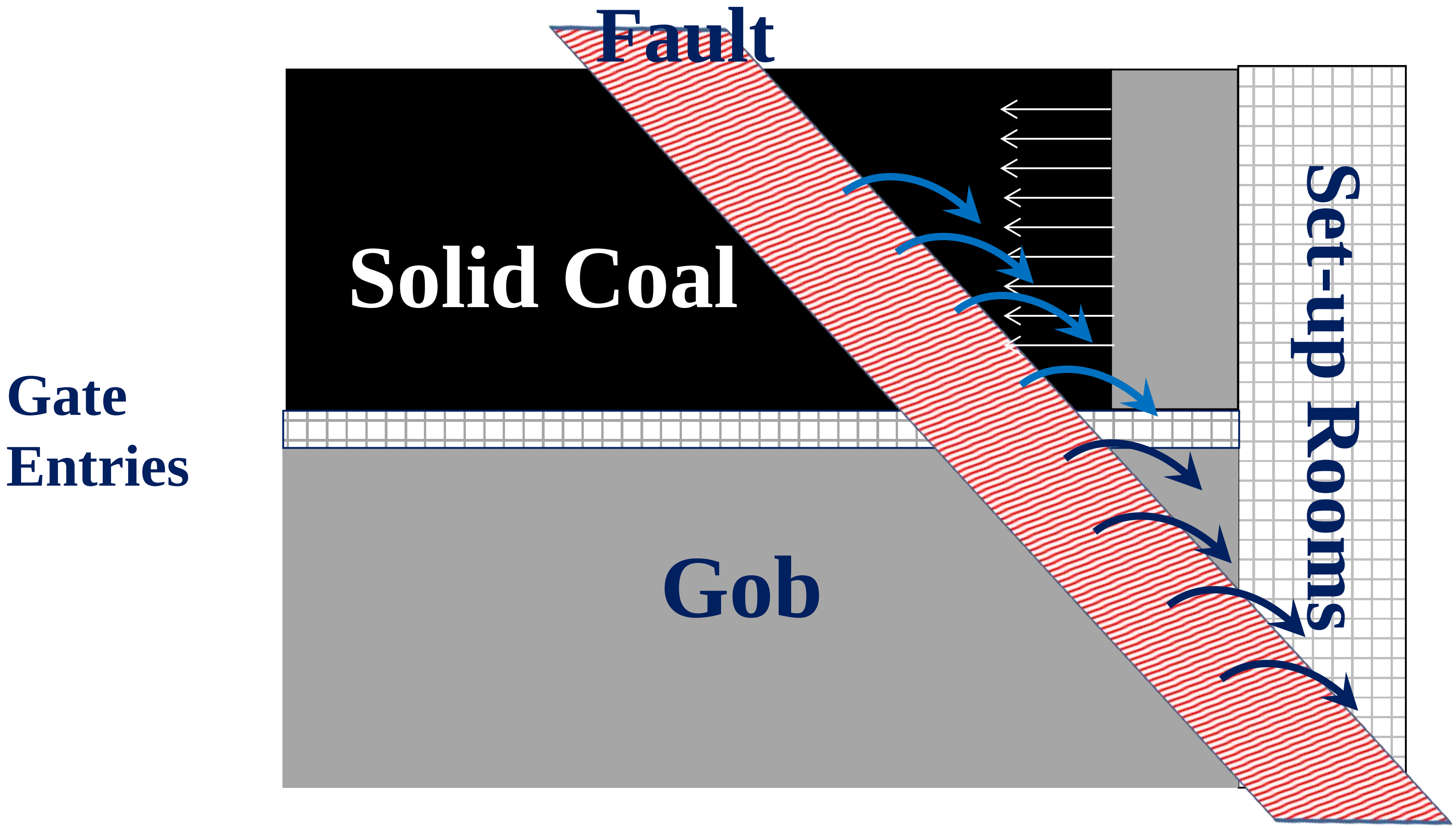
Effects of fault on ground movements and ground control in longwall mining?

- Ground movements can be significantly affected around a fault in longwall mining areas due to varying support provided to the fault plane and adjoining rock mass by gob, pillars in development entries, and longwall face itself.
- Ground movements depend upon face location in relation to fault, spatial geometry of the fault, engineering properties of fault interfaces, gob, and coal measure rocks and interaction between them.
- Ground movements impacts can significantly affect production, productivity, and safety in the face area.
- Therefore, it is critical to understand these movements assess impacts of fault in advance of mining- even if there are large number of unknowns.

Impacts of fault on ground control in headgate entries and face area

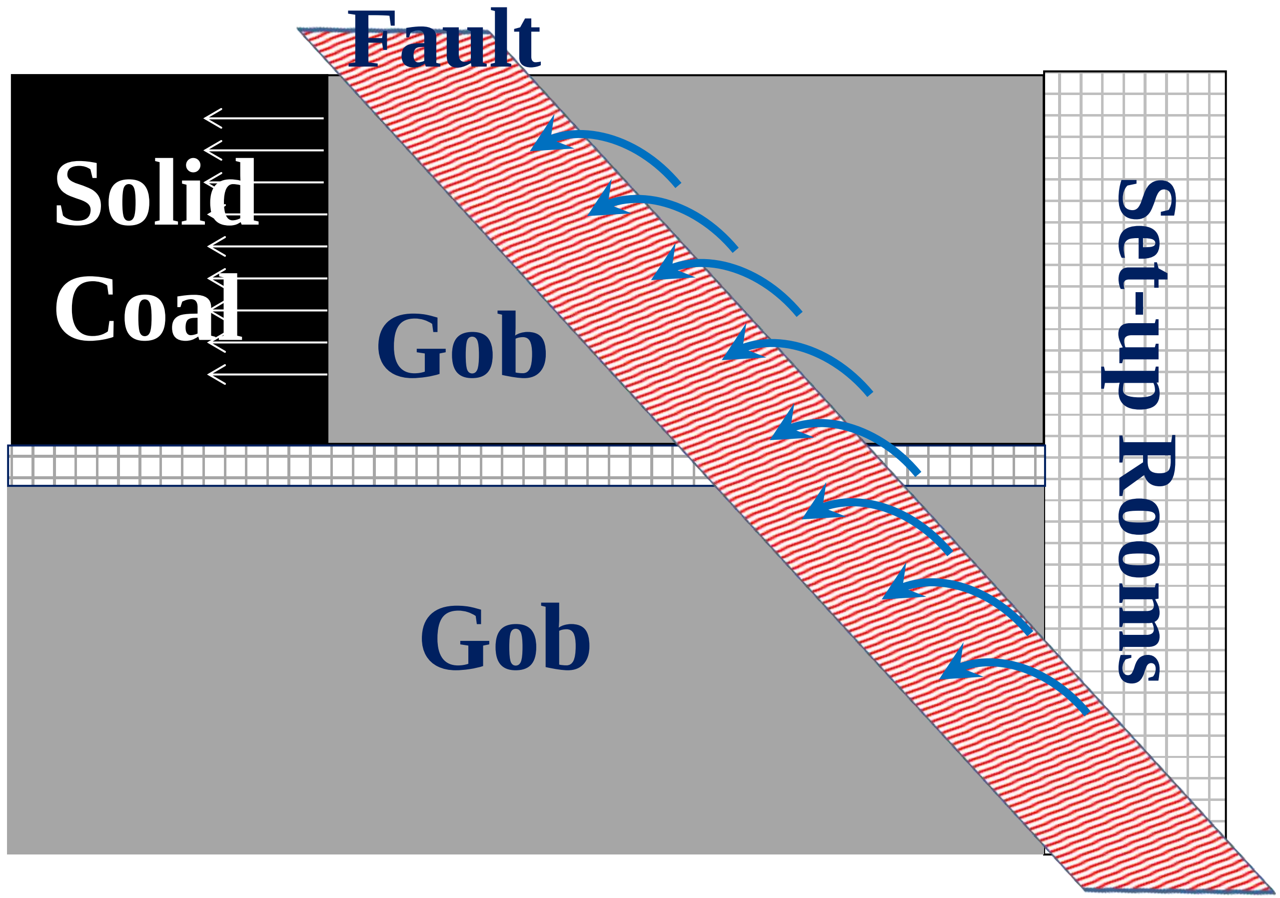


Impacts of fault on ground control around tail gate entries and face



Impact of fault on head gate, tail gate entries, and face areas

Gate Entries

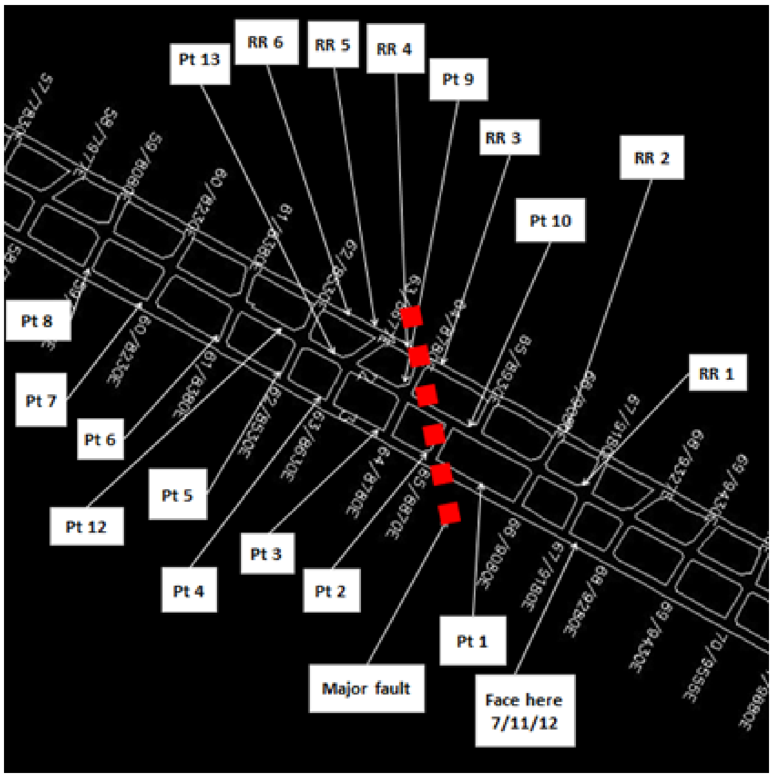


Research Summary

- Research performed in two adjacent panels with very complex faulting.
- Studies involved field measurements in development entries as the face advanced toward the fault.
- Developed a 3-D structural behavior model for the mine using FLAC3D, and estimated ground movements.
- The results show that development of a macro-level structural model is the key to success.
- Agreement between projected ground movements and field observations is reasonable for mine planning purposes.

Field Geotechnical Studies

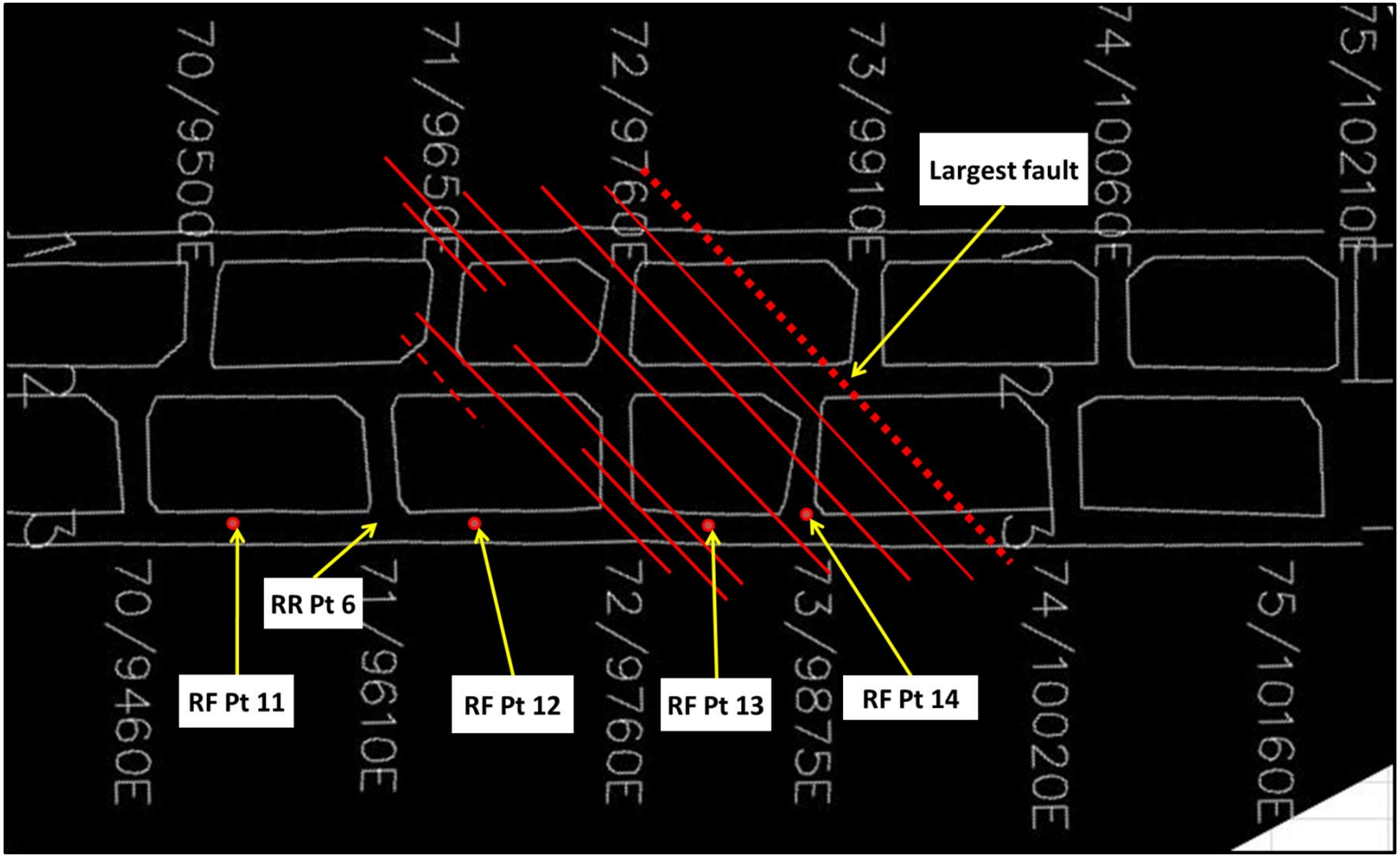
Location of Major Faults and Monitoring Locations in Headgate Entries (Areas 1, 2)



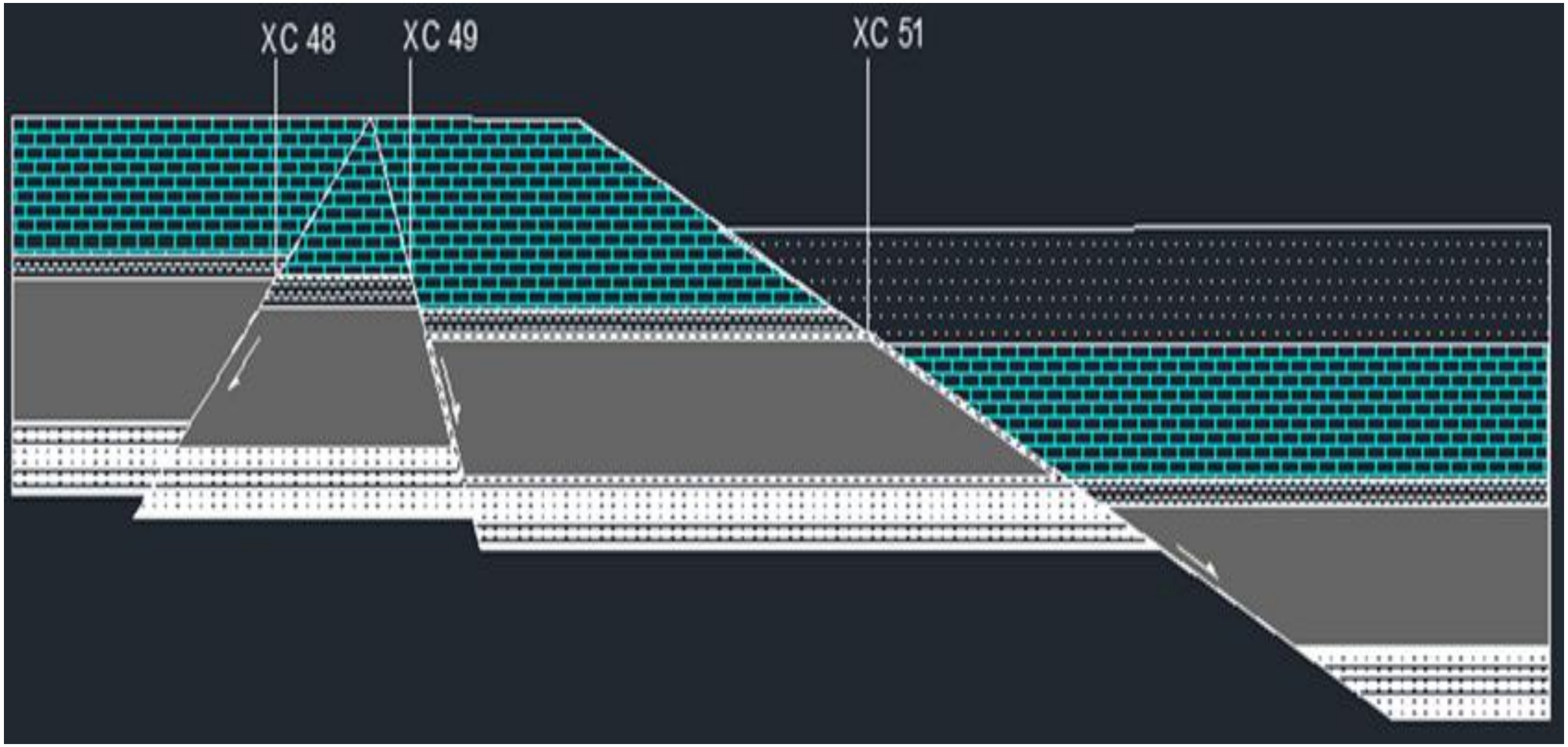
Area 1

Area 2

Smaller Faults in Area 2 Near Set-up Rooms



Faulted Area Geology



Area 1 Studies

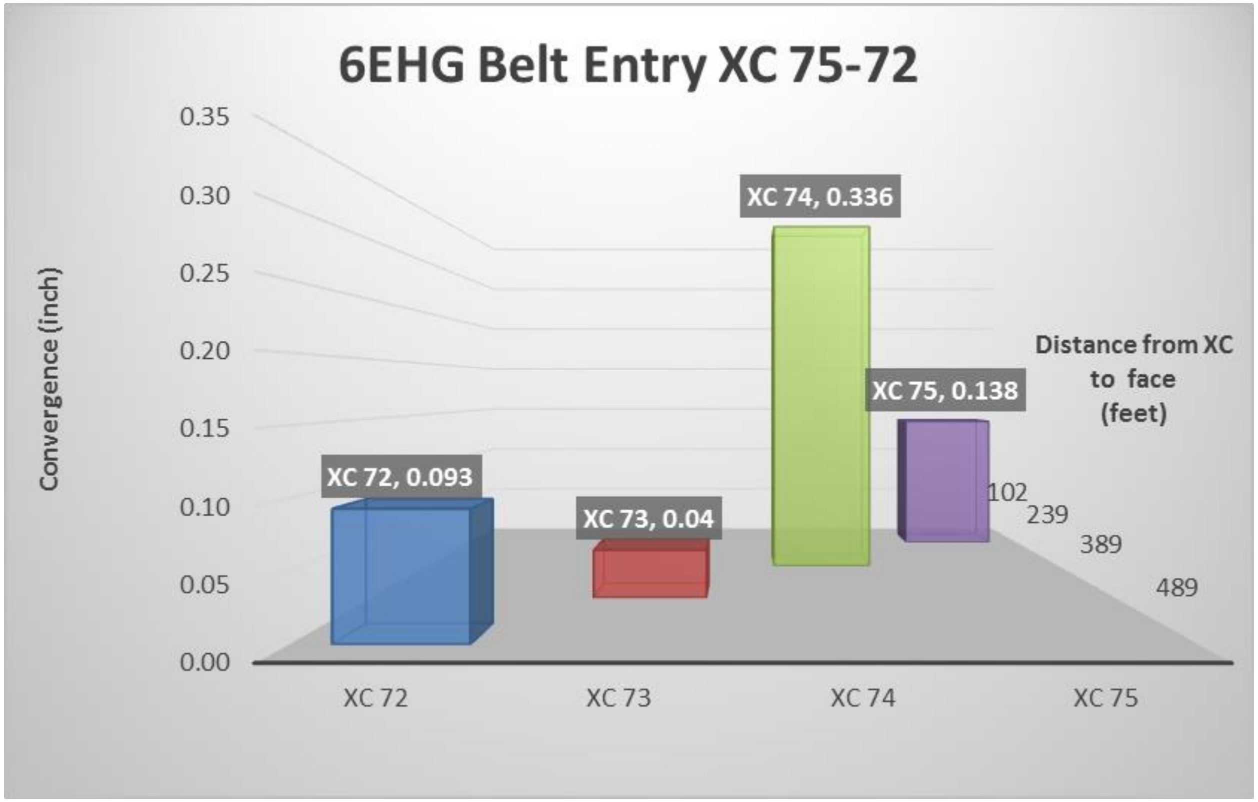
Area 1 Fault Profile

- The Major fault had down-throw displacement of 7 ft.
- Fault down-thrown east with strike of N30°W and dip of 60-63°.
- A smaller fault was located 300 ft. inby (east) and was down-thrown to the west.

Ground Movement Monitoring

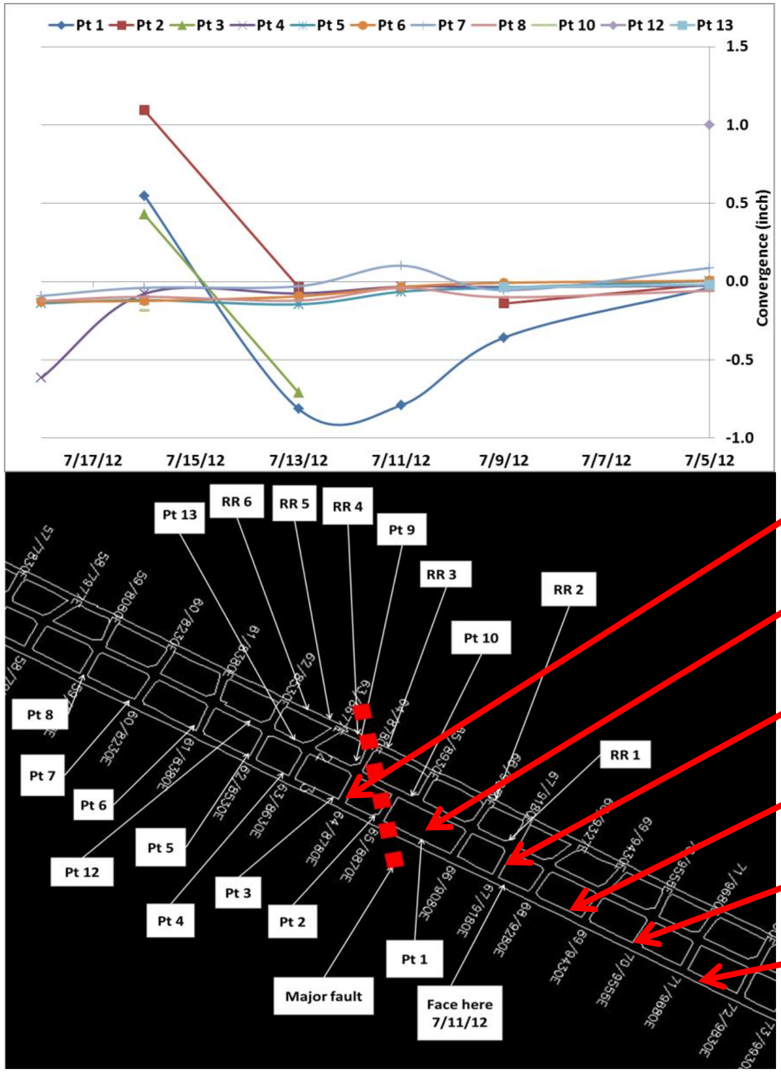
- Roof-to-floor convergence using rod extensometer
- Roof and rib rosettes.
- Each data point was measured 3-4 times and the average was used for inference development.

Area 1 – Outby of Set-up Rooms in the headgate entries



Four crosscuts were monitored for roof-to-floor convergence as longwall began production.

Convergence as Longwall Face Approached Fault Area



Face 7/18

Face 7/16

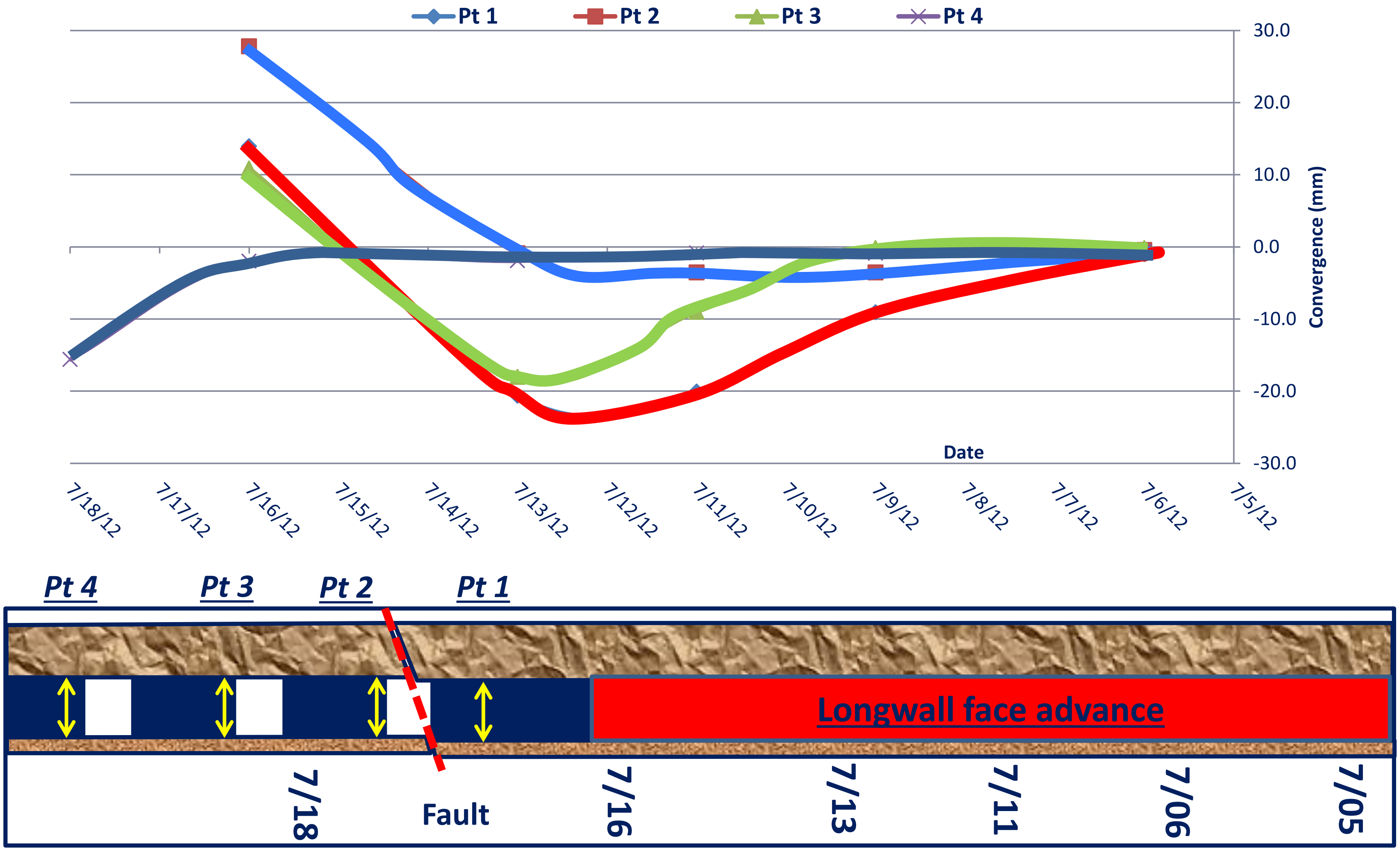
Face 7/13

Face 7/09

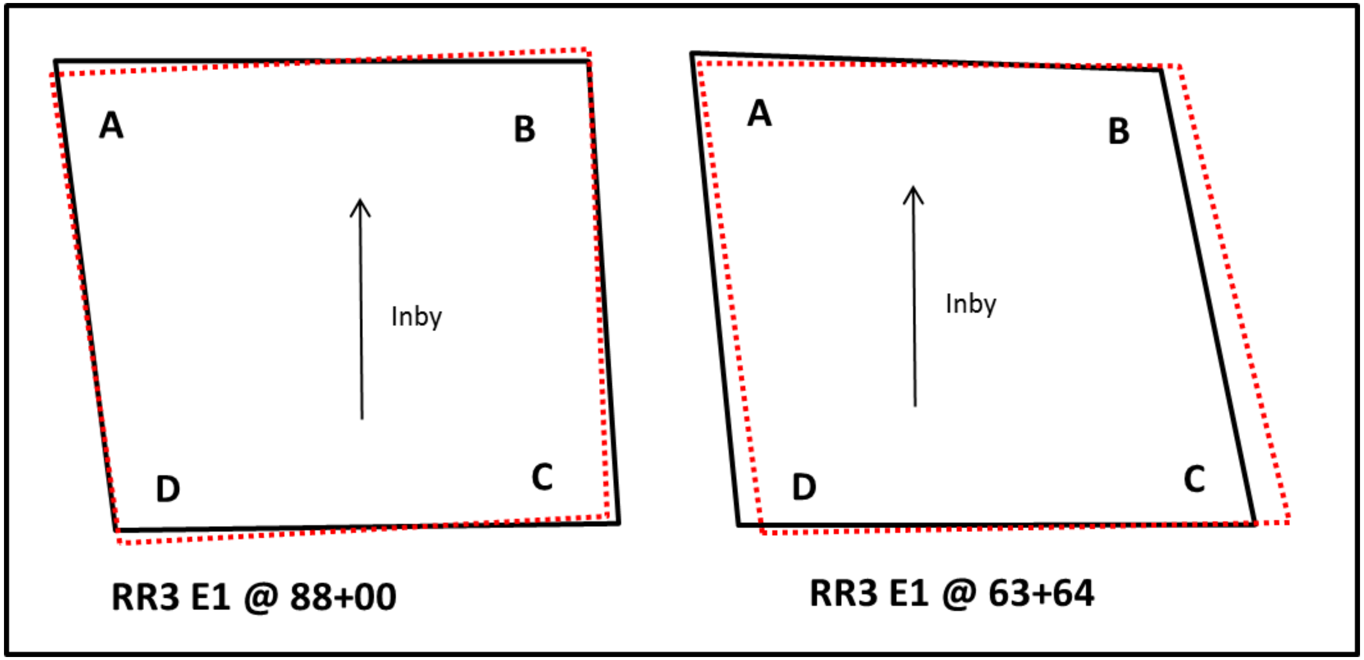
Face 7/06

Face 7/05

Area 1 Convergence in Belt Entry as Longwall Face Approaches



Area 1- Roof Rosette Indicated Movements

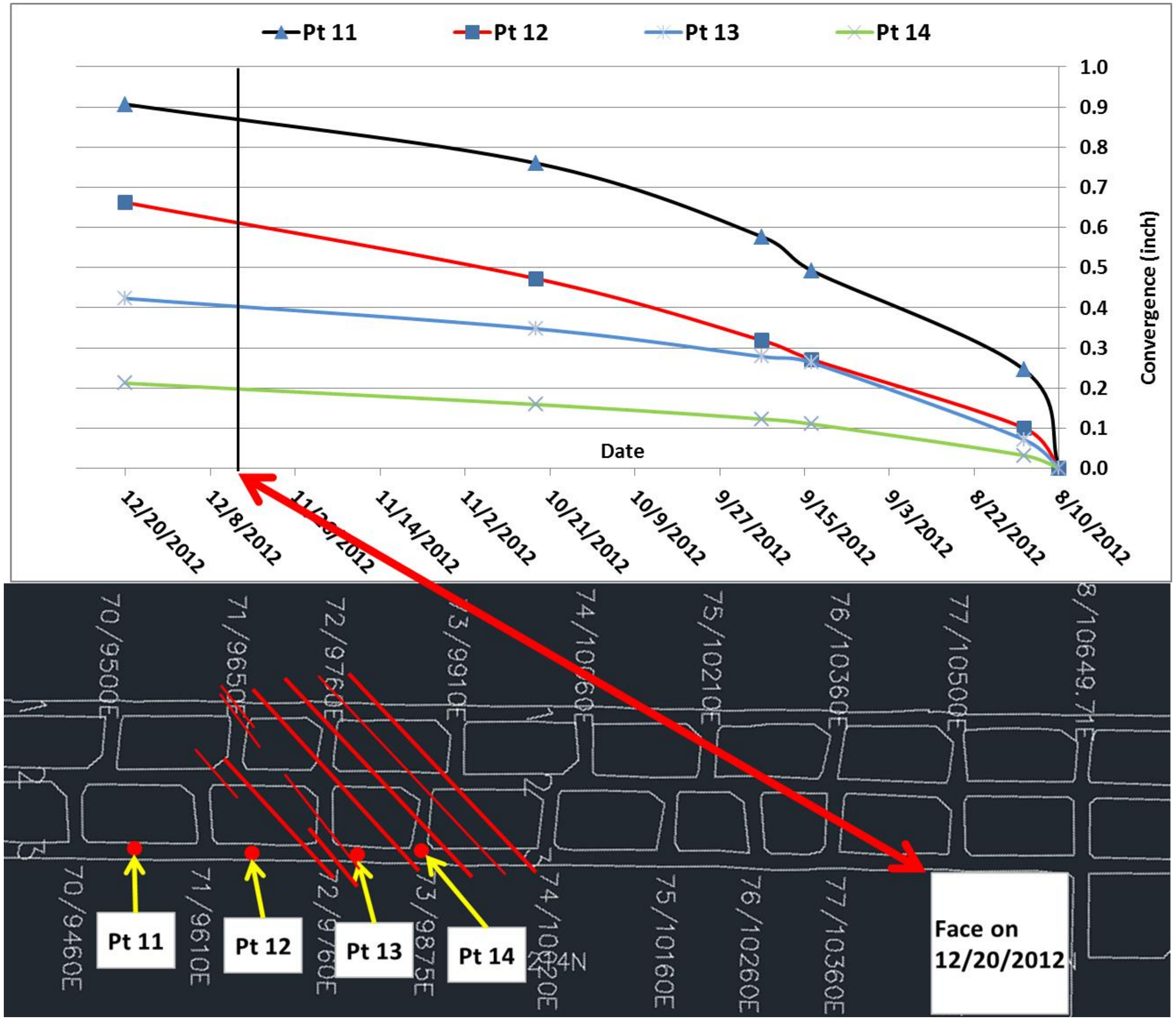


Summary In-Mine Studies: Area 1

- Around the fault area 25-30 mm of roof-floor convergence observed.
- Significant distortions of the roof in entries when the longwall face is within 100 ft of the fault.
- Away from the fault roof to floor convergence is only on the order of 4-5 mm.
- Even divergence was observed in some areas.
- Divergence was attributed to beam action with fault as the rotation point (by authors).

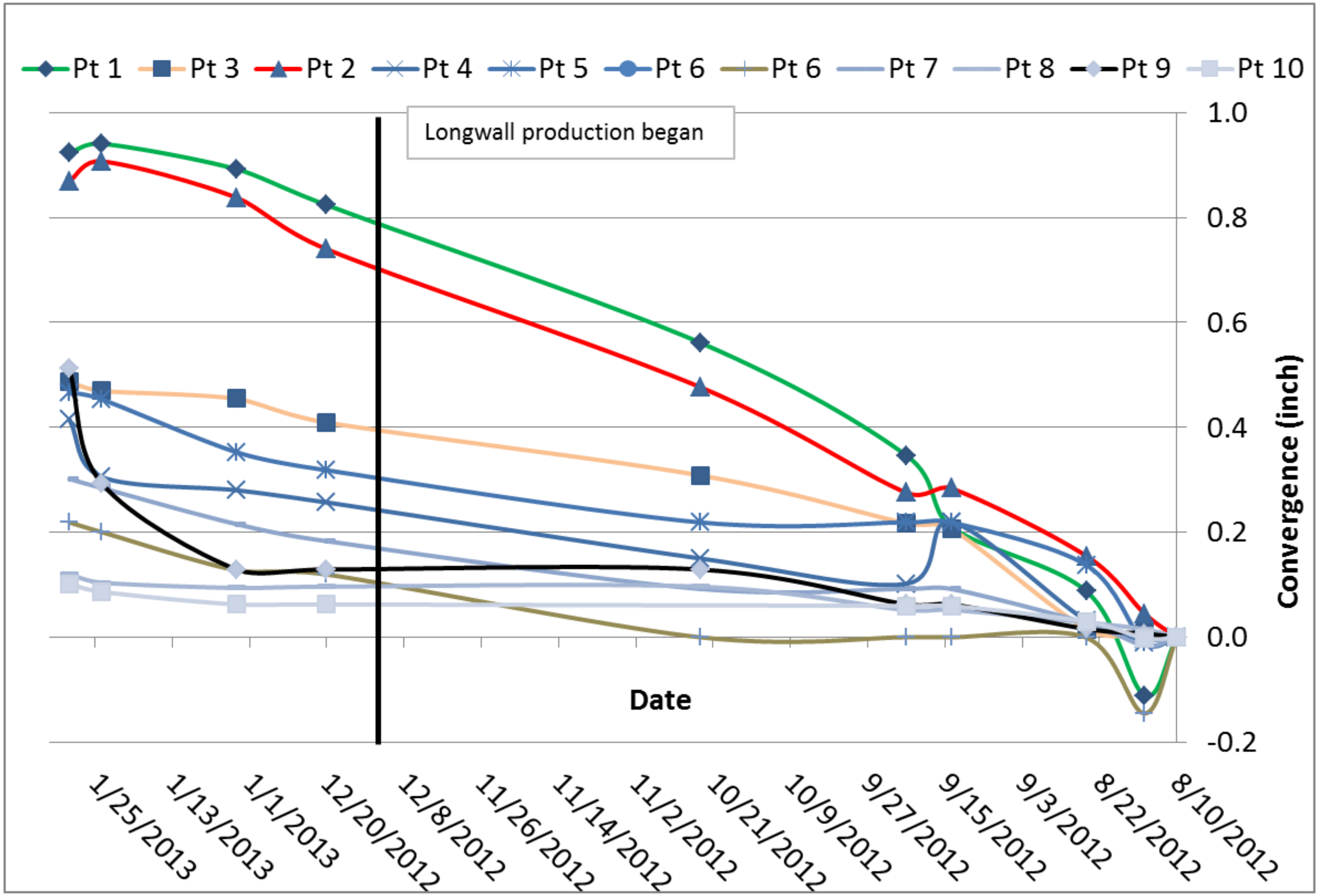
Area 2 Studies

Area 2 Studies – Small Fault Area Near Set-up Rooms

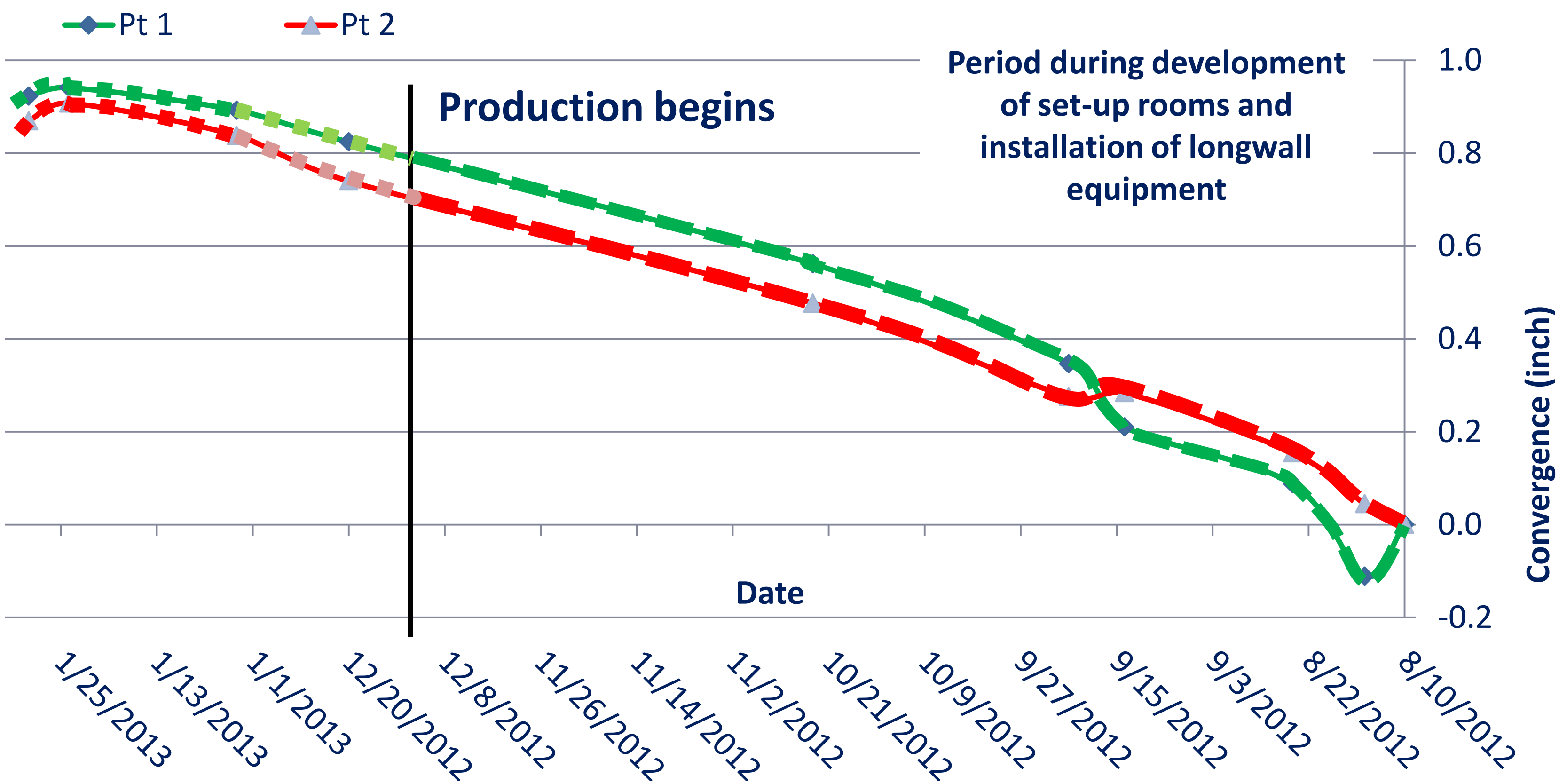


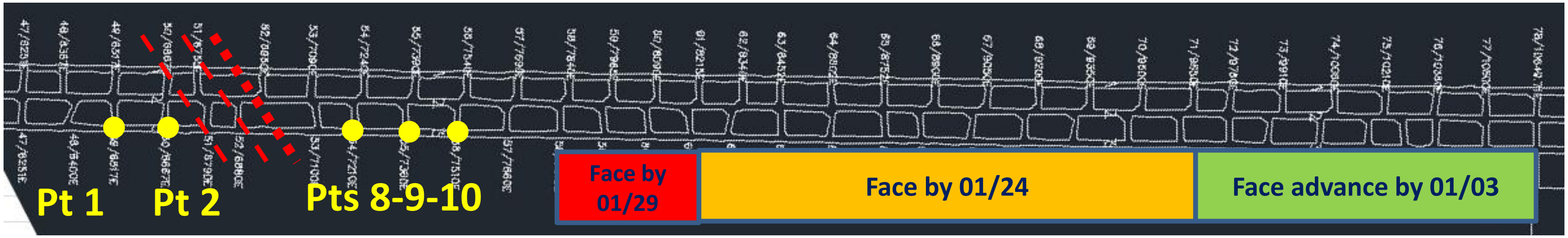
Face had advanced about 150 feet on December 20 to within 625 feet from first point – Pt 14. Points 11 and 12 show most convergence.

Area 2- Convergence Major Fault Area

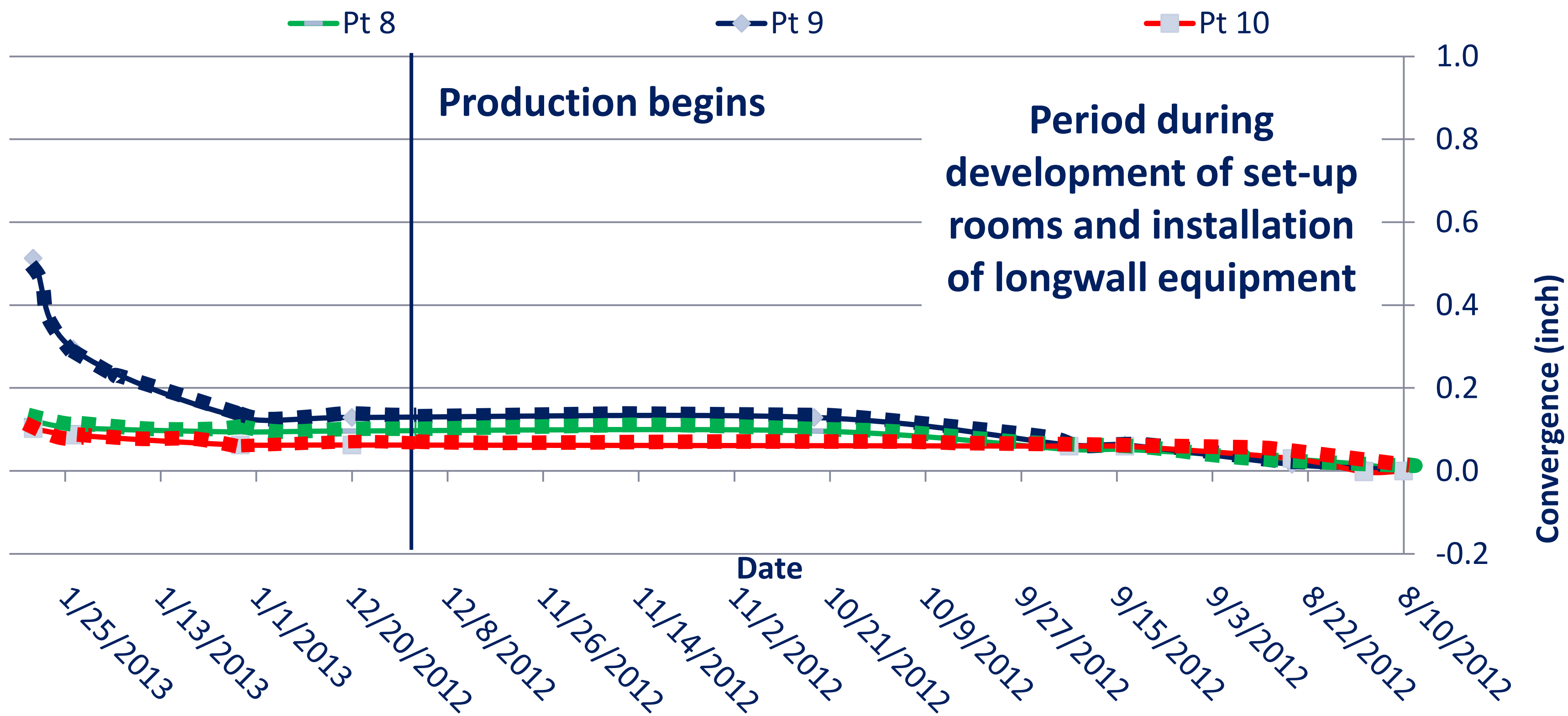


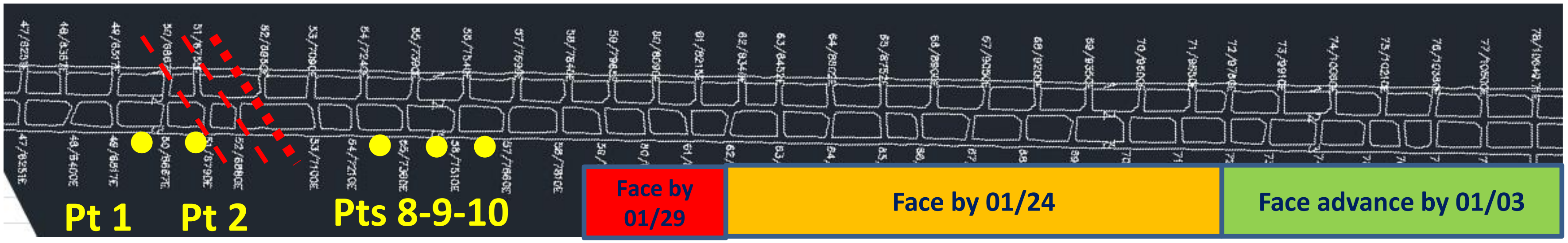
Area 2 Convergence/divergence as Longwall Face Approaches Points on Up-thrown Side of Fault





Area 2 Convergence/divergence as Longwall Face Approaches Points on Down-thrown Side of Fault



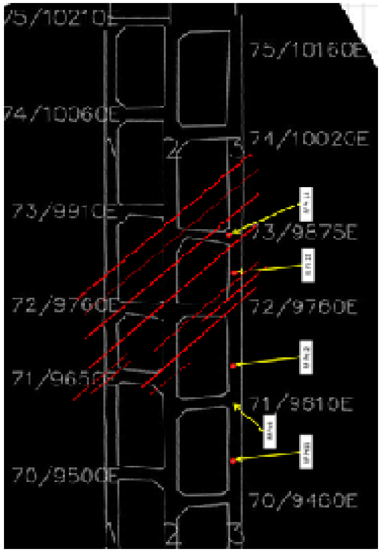


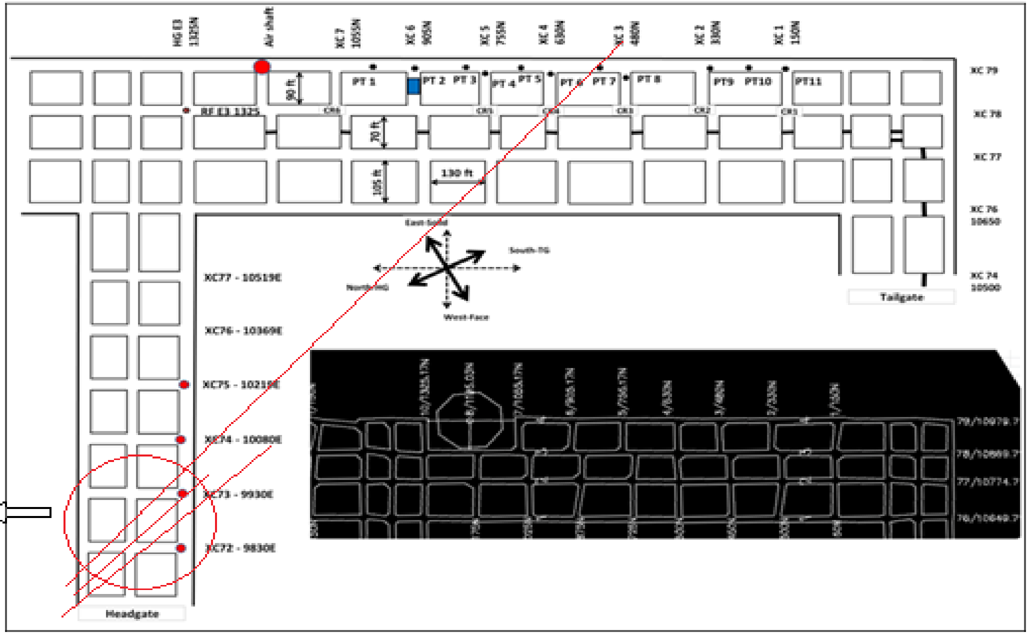
Bent Supplemental Supports While Crossing the Fault

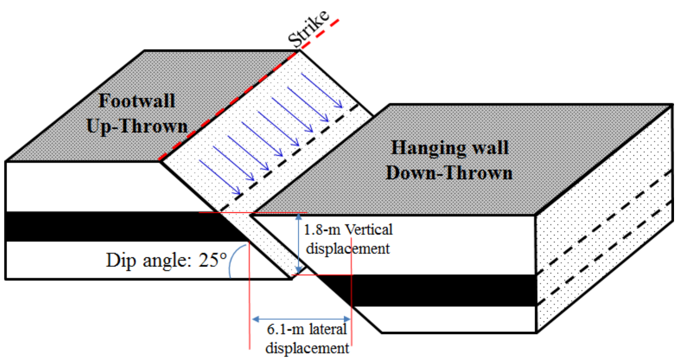
Summary In-Mine Studies: Area 2

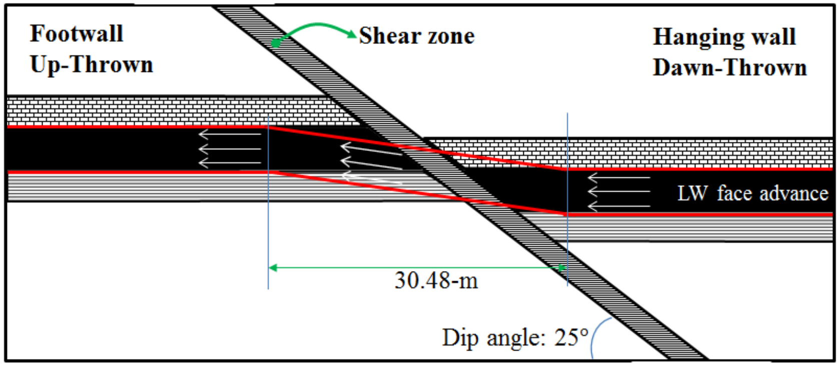
- Fault dip in this area was only 20-30 degrees as compared to 55-60 degrees in Area 1.
- Around the fault area 20-25 mm of roof-floor convergence observed.
- Distortions of the roof in entries toward mined out areas but it was not very severe.
- Away from the fault roof to floor convergence is only on the order of 5-7 mm.
- As in Area 1, divergence was observed in some areas.

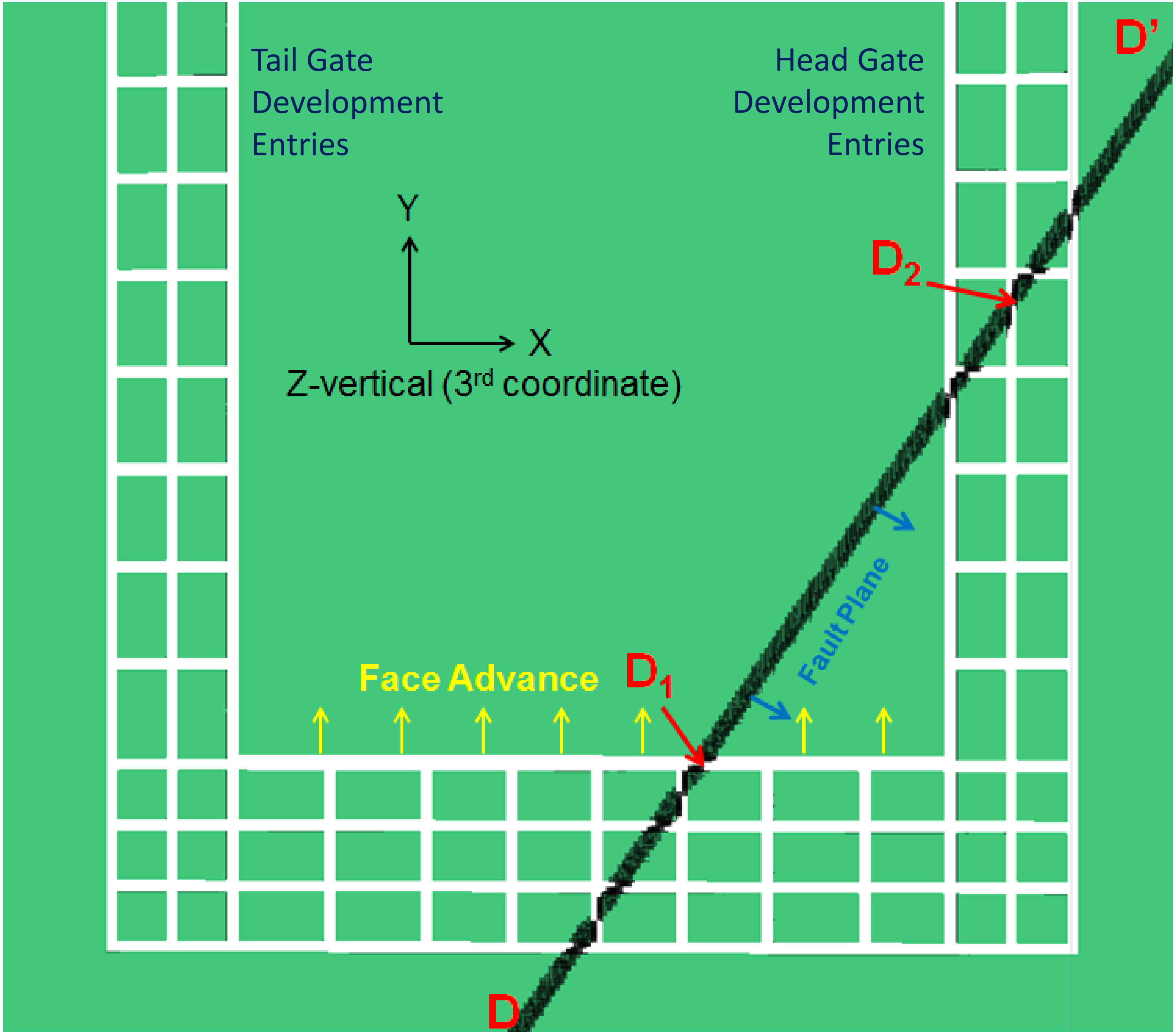
Model Development and Analysis Techniques (Area 2)









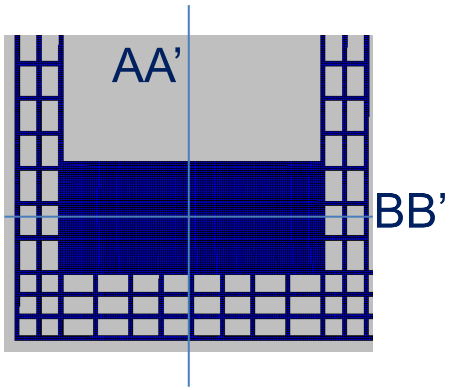

D'
Tail Gate
Development
Entries
Head Gate
Development
Entries
Y
X
Z-vertical (3rd coordinate)
D_2
Fault Plane
Face Advance
D_1
D

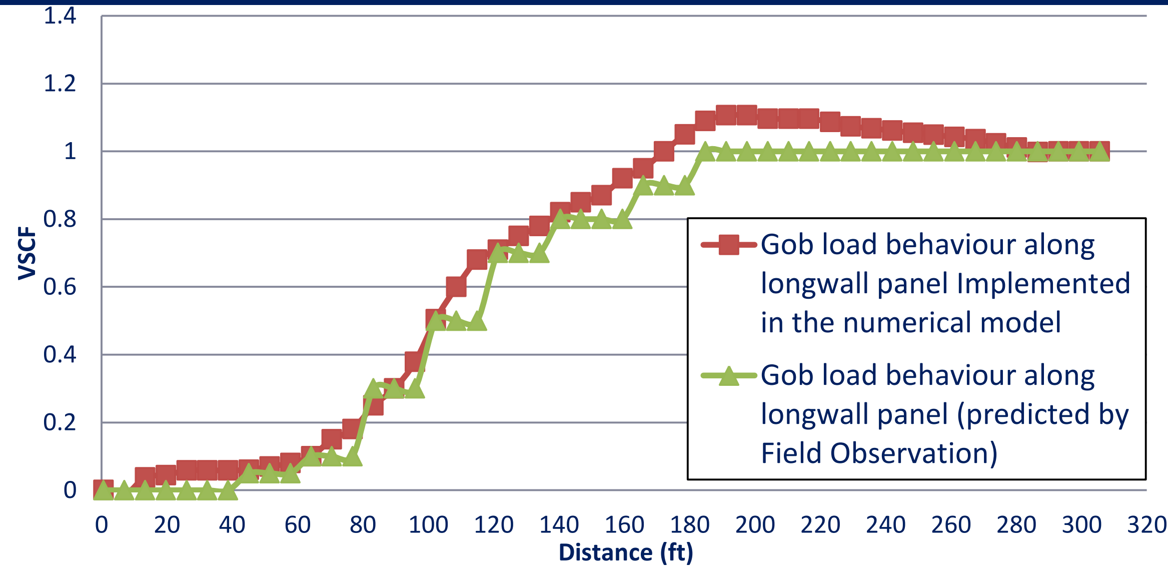
Numerical modeling: Some major points

- Fault geometry in Area 2 was modeled as a single fault. Fault was modeled as a joint (UJRM) with Mohr-Coulomb properties.
- Engineering properties on cores from the mine were transformed to rock mass properties using Hoek-Brown models.
- GSI was used for estimating rock mass properties.
- Gob load carrying behavior was estimated as non-linear based on field observations.
- Both linear and non-linear analyses were performed.

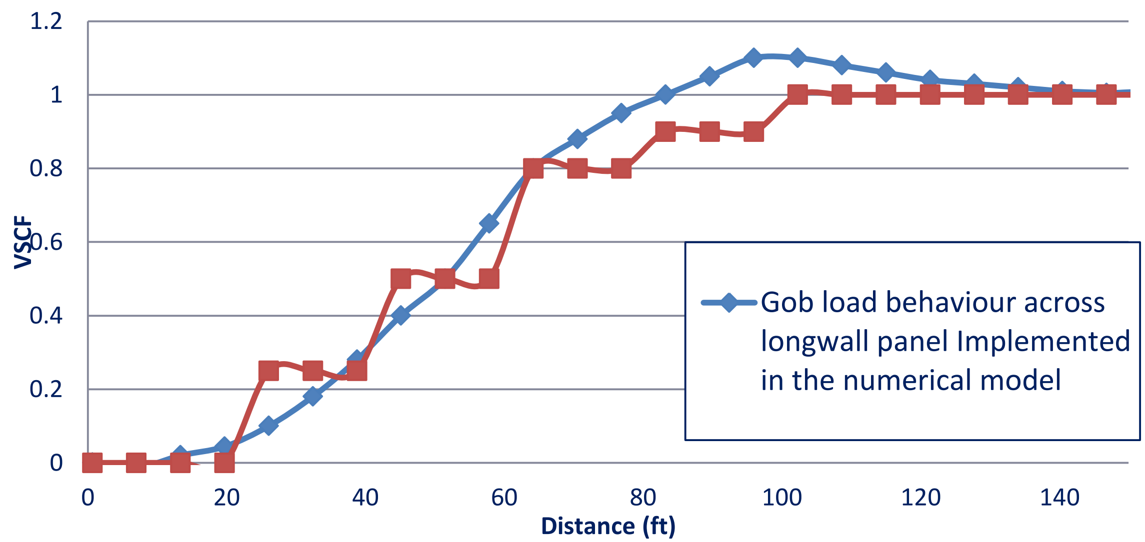
Model Development and Analysis Techniques: Gob Behavior

VSCF vs. cross section AA' after 500 ft. face advance

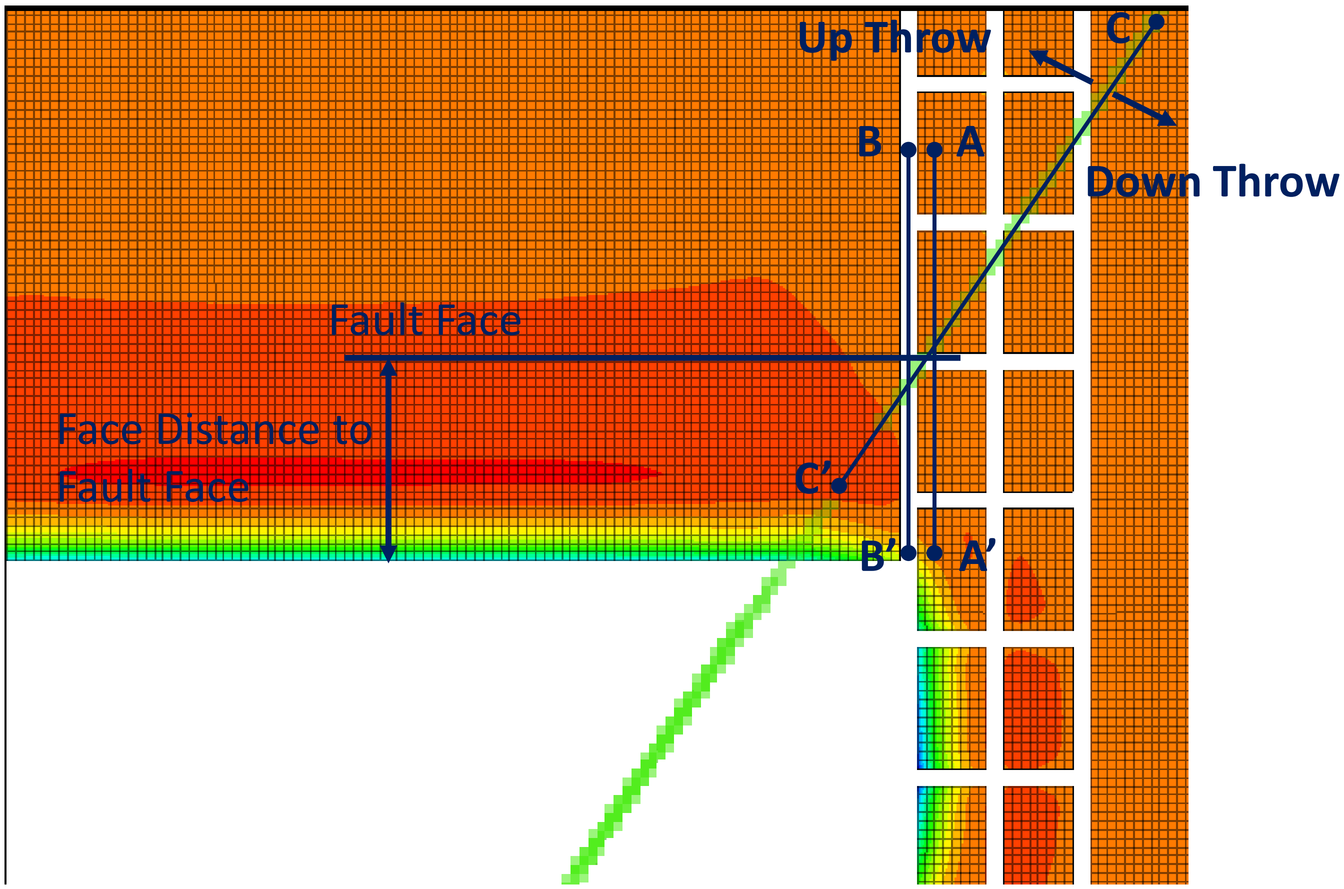


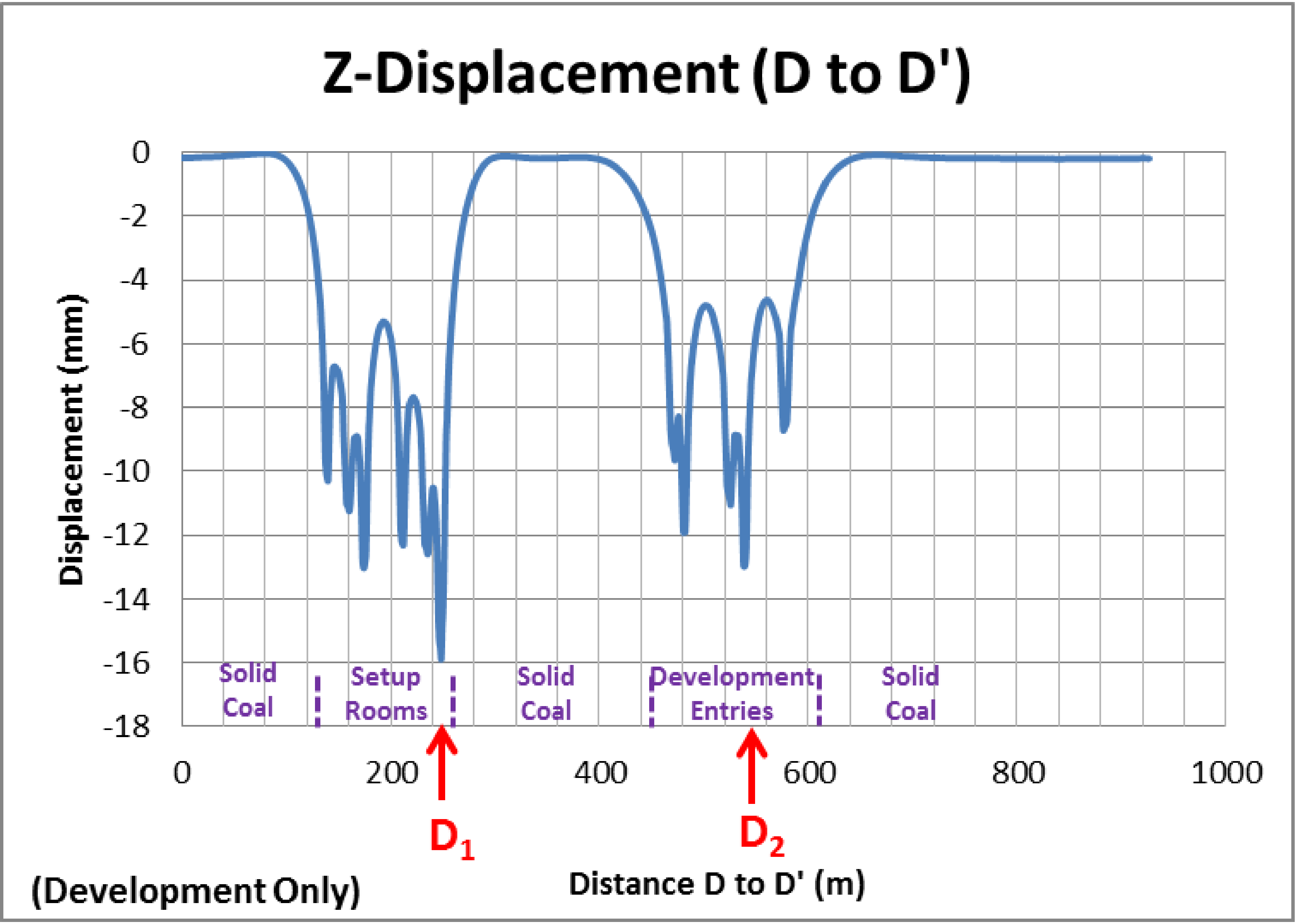


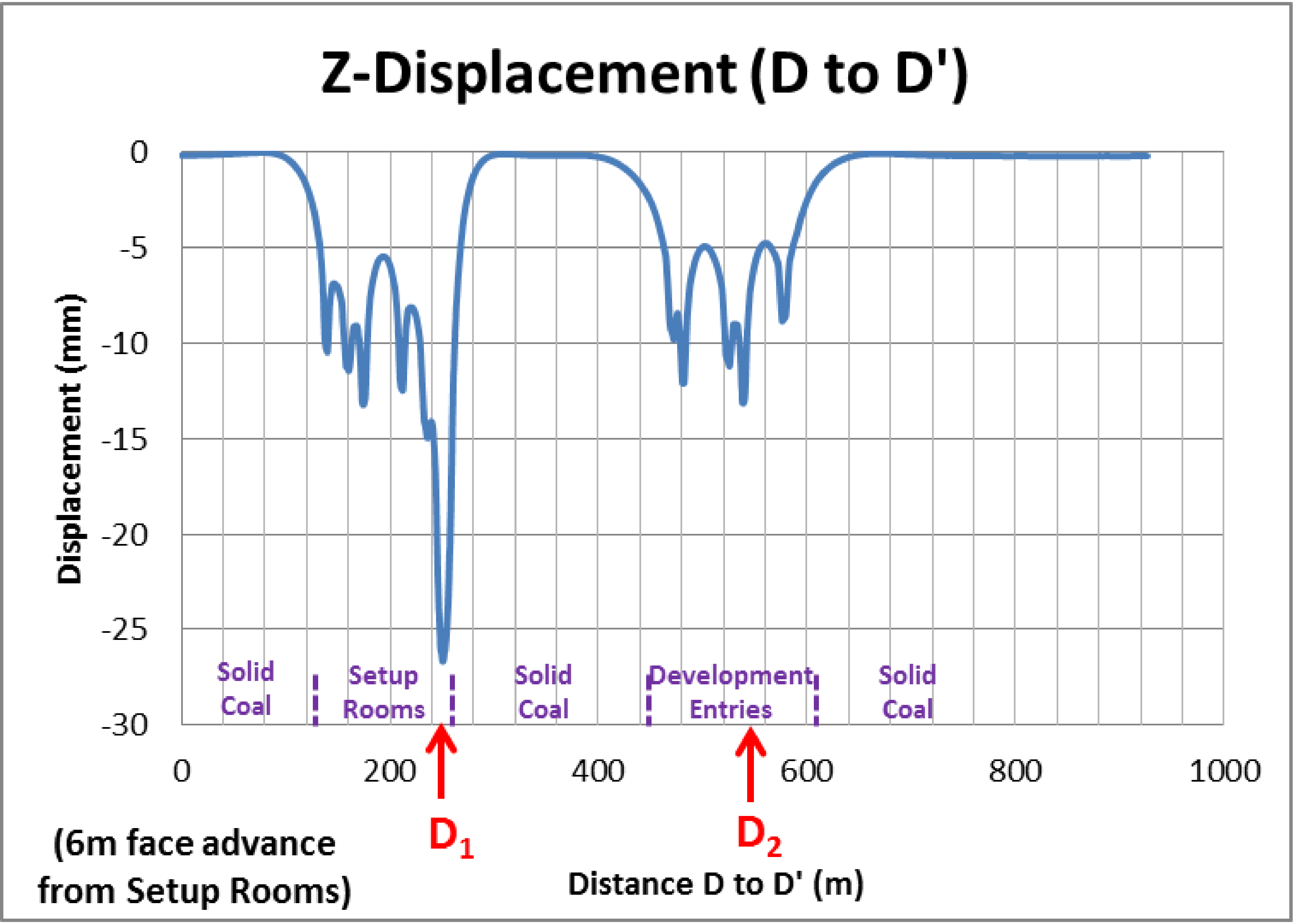
VSCF vs. cross section BB' after 500 ft. face advance

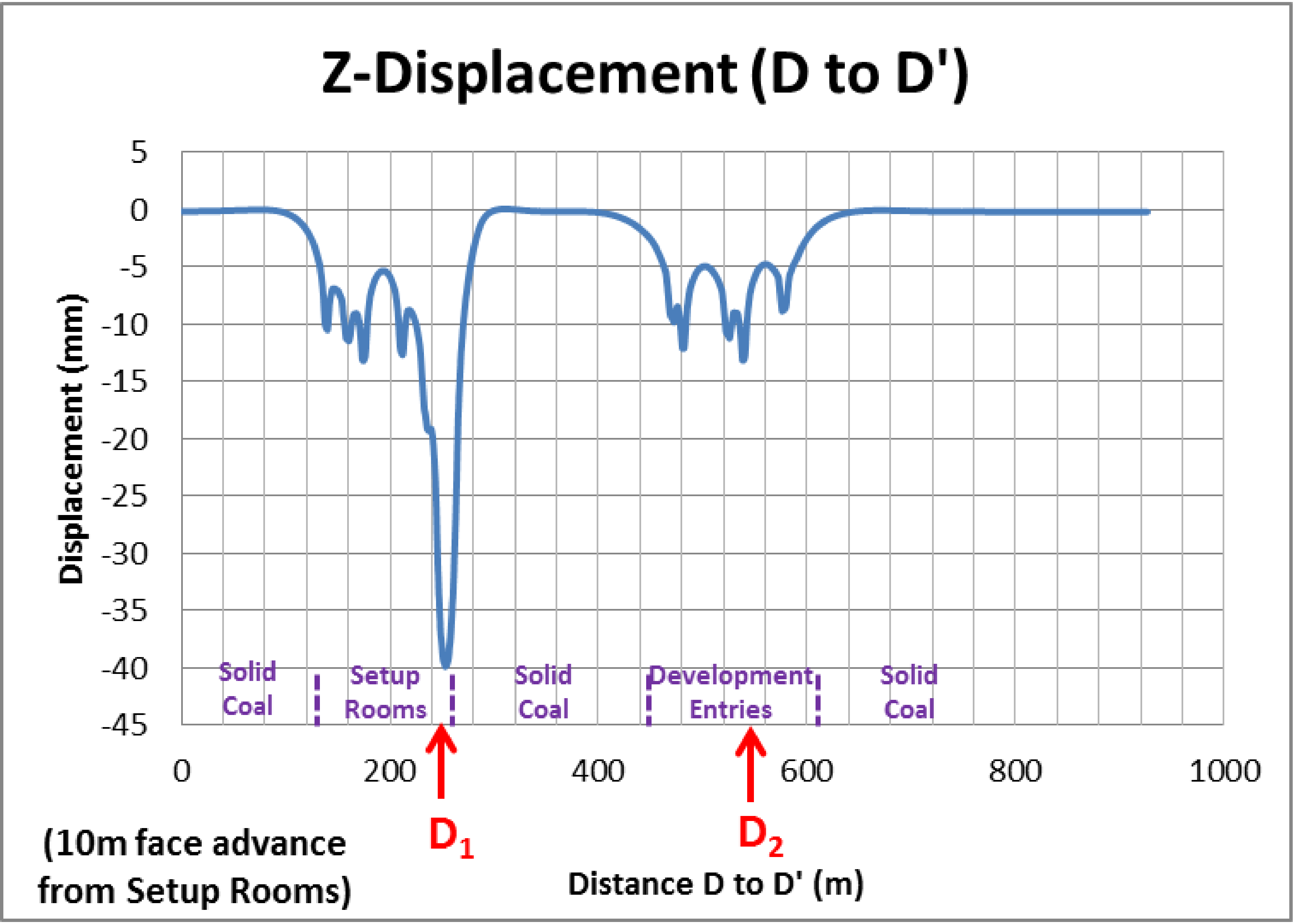


Location of Cross-sections AA’, BB’, and CC’ Used for Displacement Analysis




Z-Displacement (D to D')
Displacement (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
0
200
400
600
800
1000
Solid Coal
Setup Rooms
Solid Coal
Development Entries
Solid Coal
D_1
D_2
Distance D to D' (m)
(Development Only)

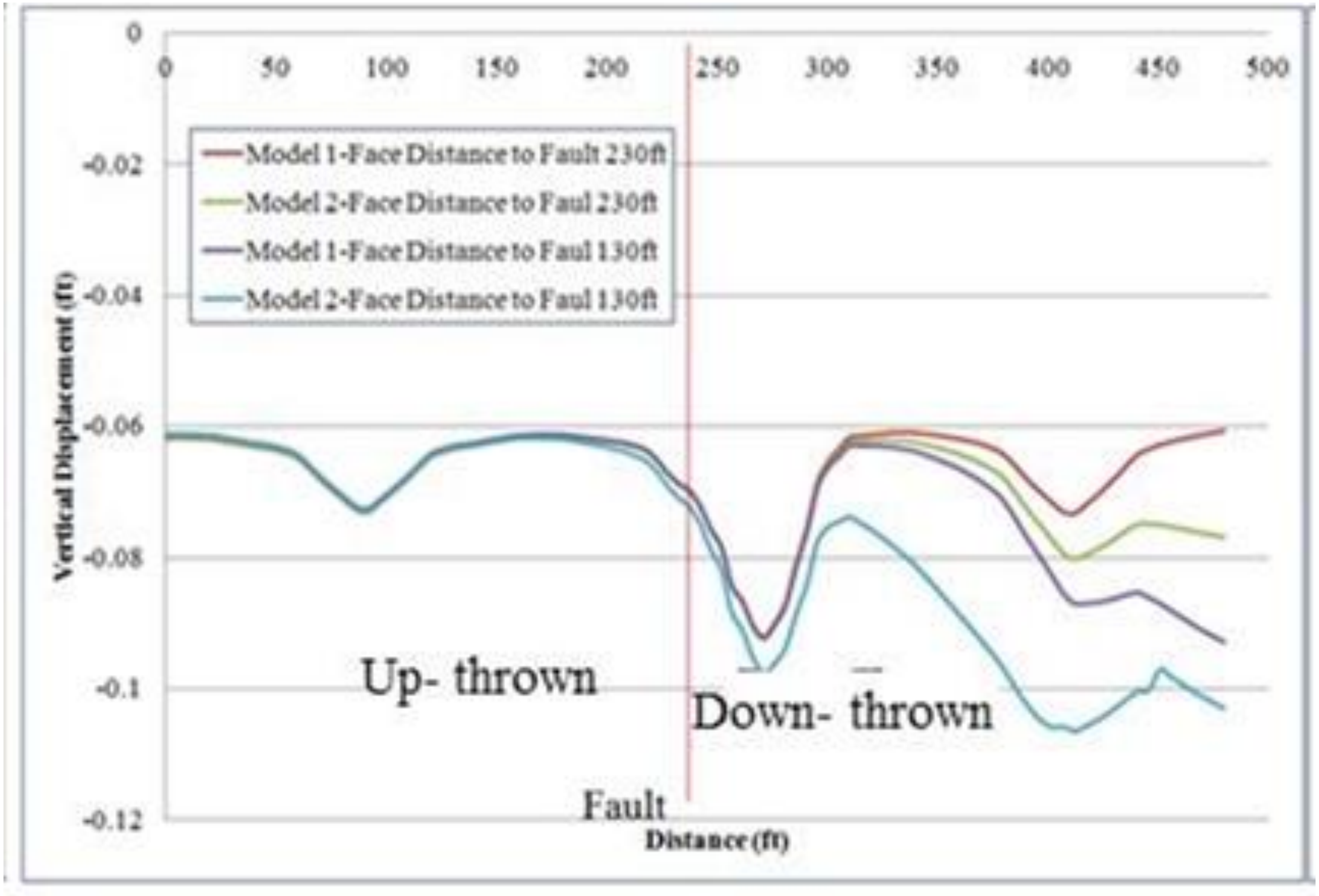

Z-Displacement (D to D')
Displacement (mm)
0
-5
-10
-15
-20
-25
-30
Solid Coal
Setup Rooms
Solid Coal
Development Entries
Solid Coal
0
200
400
600
800
1000
D1
D2
(6m face advance from Setup Rooms)
Distance D to D' (m)



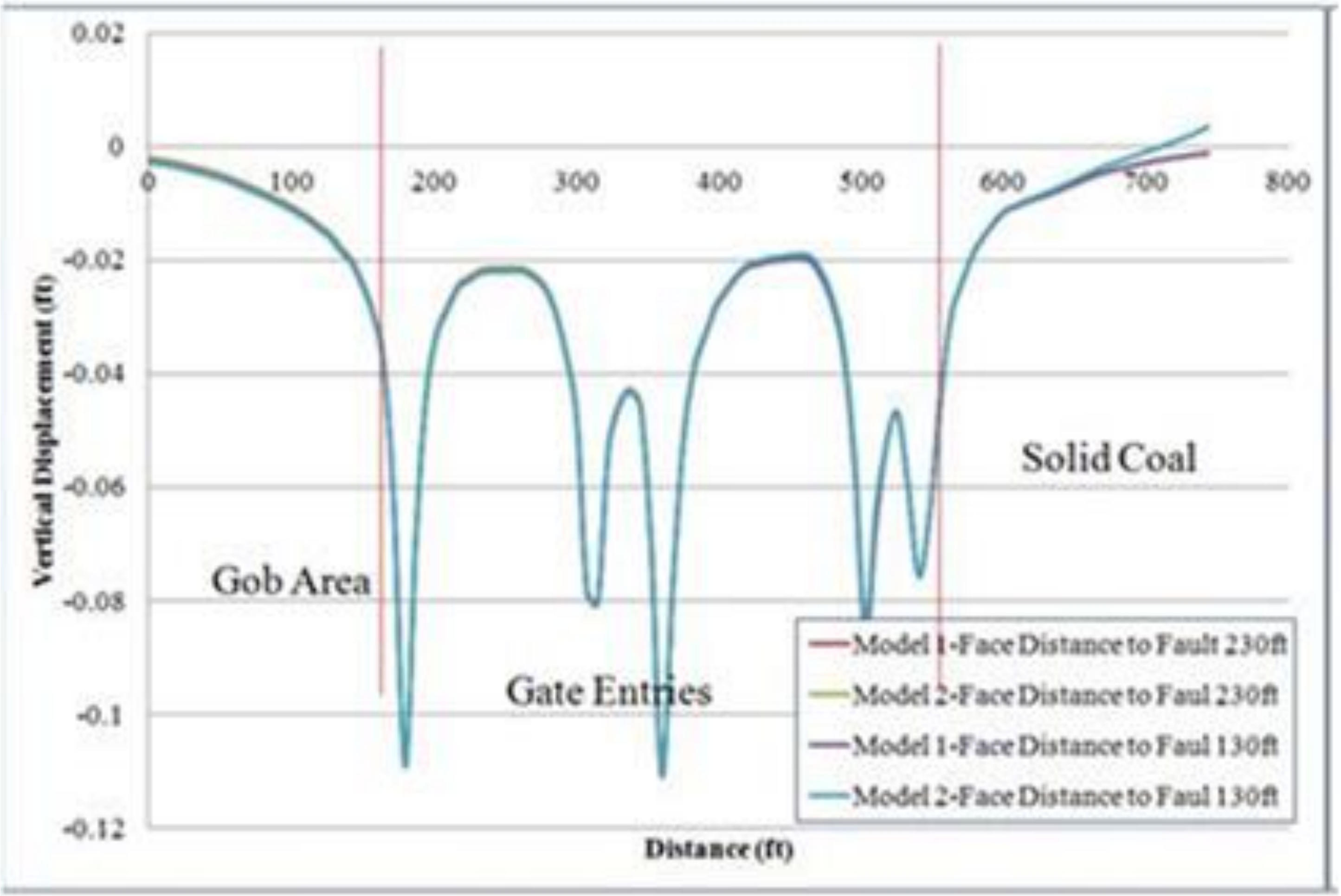
Z-Displacement (D to D')
Displacement (mm)
5
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
Solid Coal
Setup Rooms
Solid Coal
Development Entries
Solid Coal
0
200
400
600
800
1000
D_1
D_2
(10m face advance from Setup Rooms)
Distance D to D' (m)

Vertical Displacement Along Cross-section AA’ for Models 1 and 2

Vertical Displacement Along Cross-section BB' for Models 1 and 2



Vertical Displacement Along Cross-section CC’ for Models 1 and 2



Results: Field Measurements in Gate Entries Related to Fault Zone

Additional vertical displacement due to fault (cm)				
	Side	Field data	Numerical analysis	Percent (%) difference
LW face 70-m away from fault	Up-Thrown	1.47	1.70	+13.43
	Down-Thrown	0.30	0.44	+13.64
LW face 39.6-m away from fault	Up-Thrown	2.06	2.39	+16.36
	Down-Thrown	0.53	0.66	+10.23

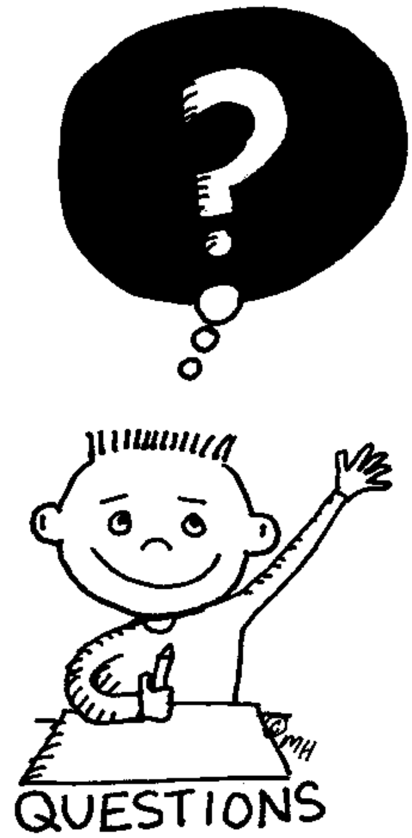
Numerical Modeling Predicted Values of Peak Displacements for Models 1 and 2

	Cross-section	LF 70-m away from fault		LF 39.6-m away from fault	
		Model 1	Model 2	Model 1	Model 2
Vertical Displacement	AA'	1.74	2.01	2.25	2.83
	BB'	2.23	2.44	2.68	3.35
	CC'	3.66	3.66	3.66	3.66
X-Horizontal Displacement	AA'	0.06	0.27	0.67	0.98
	BB'	0.3	0.46	0.67	0.82
	CC'	0.64	0.85	0.94	1.04
Y-Horizontal Displacement	AA'	0.52	0.76	1.04	1.13
	BB'	0.16	0.67	0.94	1.13
	CC'	0.46	0.64	0.76	0.88

Concluding Remarks

- There were large number of unknowns in this study.
- In spite of all the simplifications, field convergence while crossing faults in reasonable agreement with models.
- It can be used to plan ahead of mining to improve safety and productivity in mining.
- Guided the coal company through faults without unsafe incident and significant loss in production or productivity.
- Key to success: development of the structural model.
- Model used to redesign more efficient and stable setup rooms geometries (size of pillars and entries), and behavior of the fault.
- Over the years, Chugh has advocated a combination of analytical modeling- field studies to improve productivity and safety in coal mines. This study represents a success story in that regard.
- Authors urge companies to develop simplified structural models of their mine to assess effects of mining through geologic anomalies.

Questions??

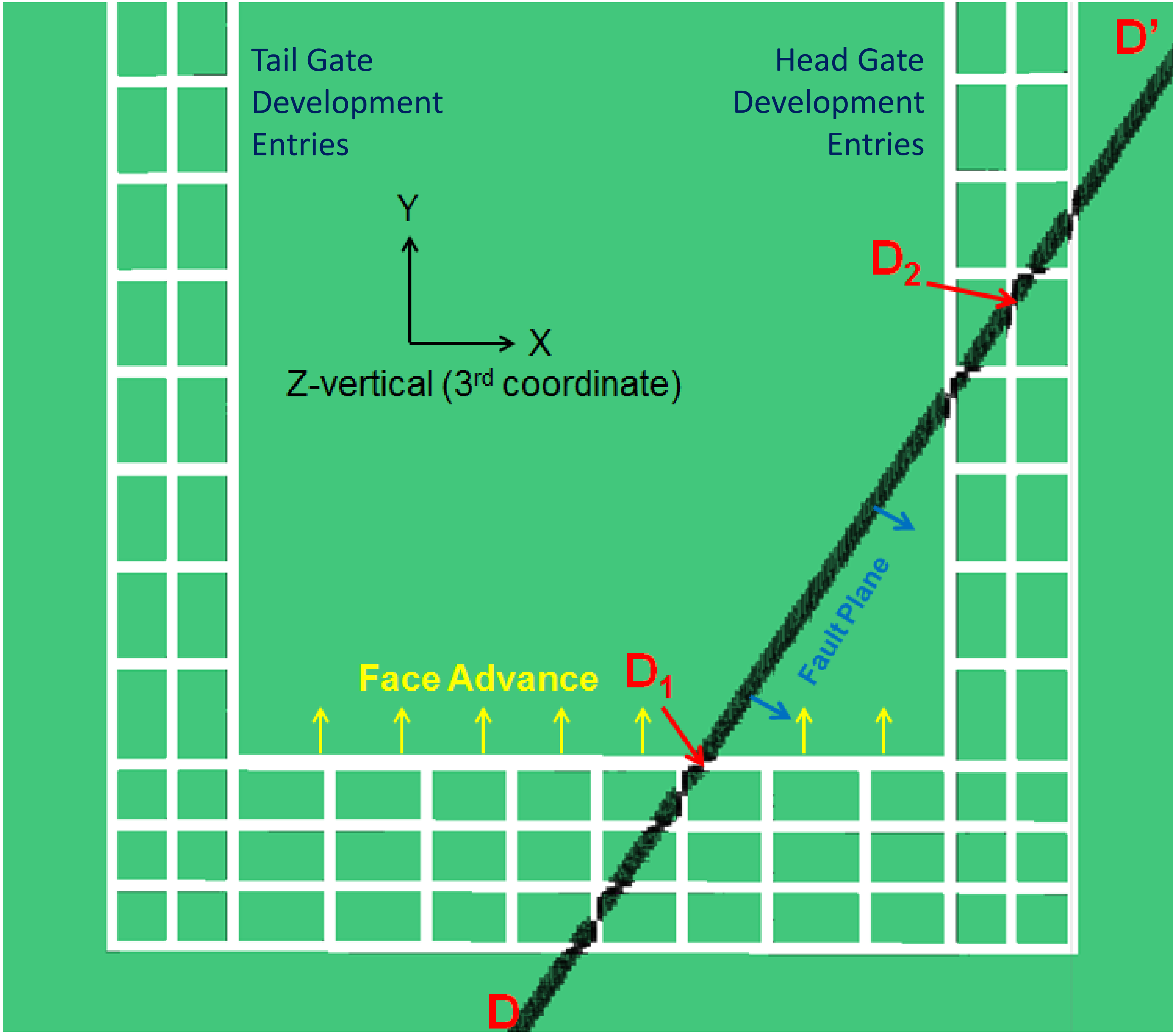


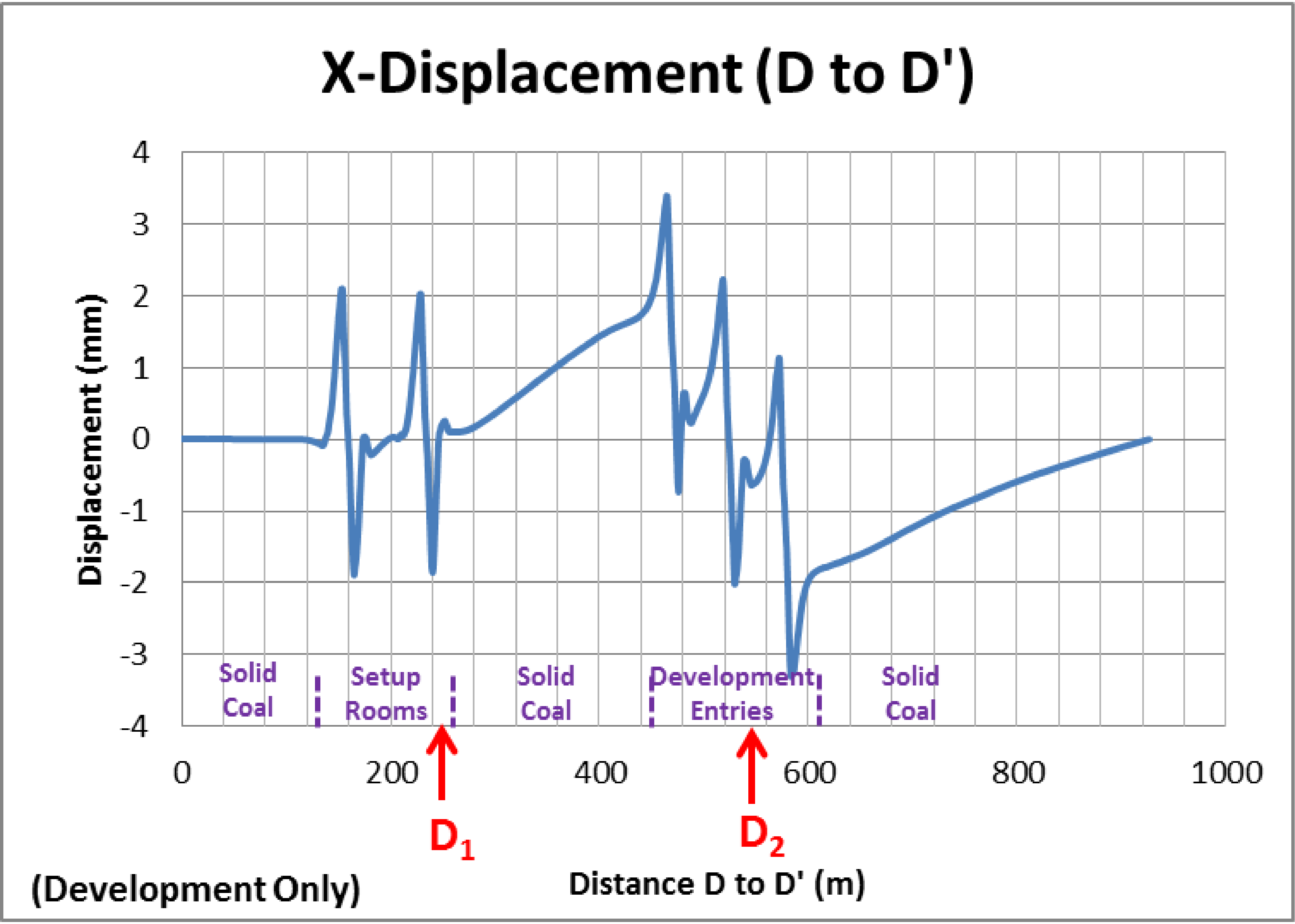
Hoek-Brown Rock Mass Properties Used for Analytical Modeling

Parameters	GSI	mi	σ_c MPa	m_r	s_r	a_r
Strong Limestone	95	20	100	0.42	0.6	1
Black Shale	45	10	37	0.8118	0.001188	1
Weak Limestone	75	17	60	2.46	0.1134	1
Lawson Shale	45	10	35	0.8118	0.001188	1
Grey Shale	55	12	41	1.719	0.0123	1
Coal	50	10	27.5	0.8118	0.001188	1
Weak Claystone	35	8	11	0.3834	0.000114	1

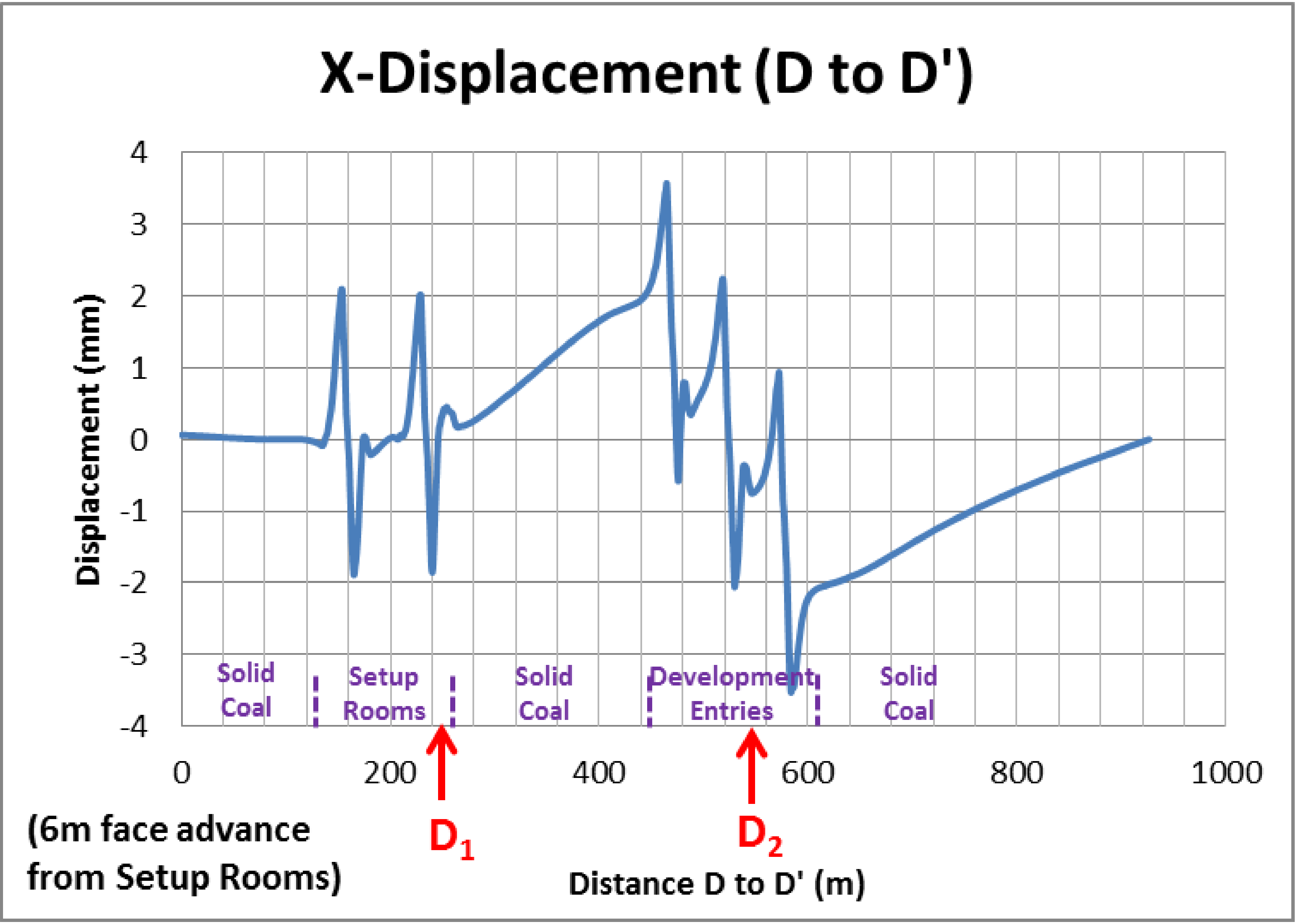
UJRM Zone Engineering Properties Used for Analytical Modeling

Parameters	Cohesion MPa	Friction Angle (deg.)	Joint Cohesion MPa	Joint Friction Angle (deg.)
Strong Limestone	12	30	6	20
Black Shale	4.5	22	2.7	15
Weak Limestone	8	30	4	17
Lawson Shale	3	22	1.3	15
Grey Shale	6.5	27	3.2	15
Coal	4.5	26	2.2	15
Weak Claystone	0.9	20	0.4	15


D'
Tail Gate
Development
Entries
Head Gate
Development
Entries
Y
X
Z-vertical (3rd coordinate)
D2
Fault Plane
Face Advance
D1
D



X-Displacement (D to D')
Displacement (mm)
4
3
2
1
0
-1
-2
-3
-4
0
200
400
600
800
1000
Solid Coal
Setup Rooms
Solid Coal
Development Entries
Solid Coal
D1
D2
Distance D to D' (m)
(Development Only)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Displacement (mm)
4
3
2
1
0
-1
-2
-3
-4
0
200
400
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800
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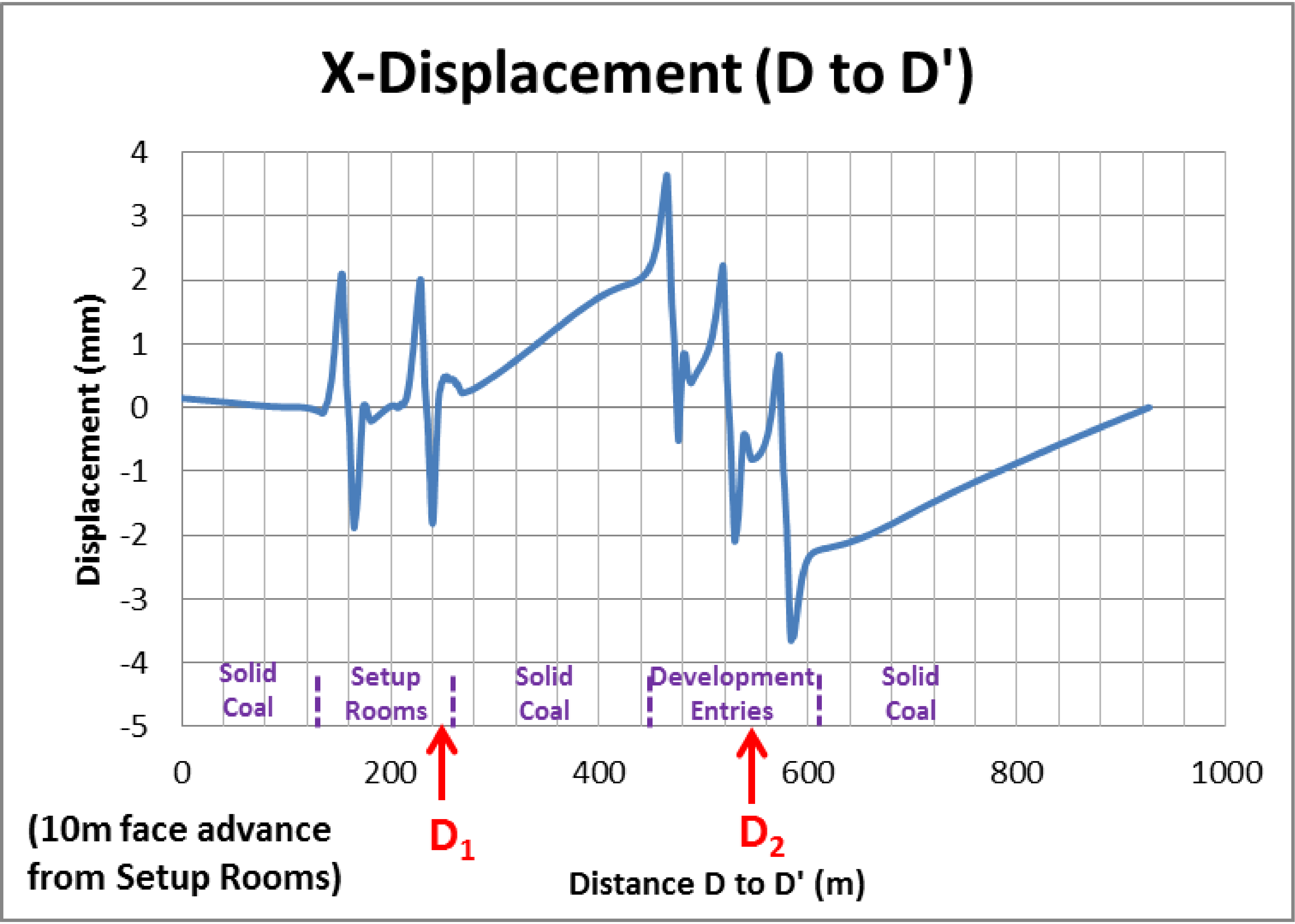
Solid Coal
Setup Rooms
Solid Coal
Development Entries
Solid Coal
D1
D2
(6m face advance from Setup Rooms)
Distance D to D' (m)



X-Displacement (D to D')
Displacement (mm)
4
3
2
1
0
-1
-2
-3
-4
-5
Solid Coal
Setup Rooms
Solid Coal
Development Entries
Solid Coal
0
200
400
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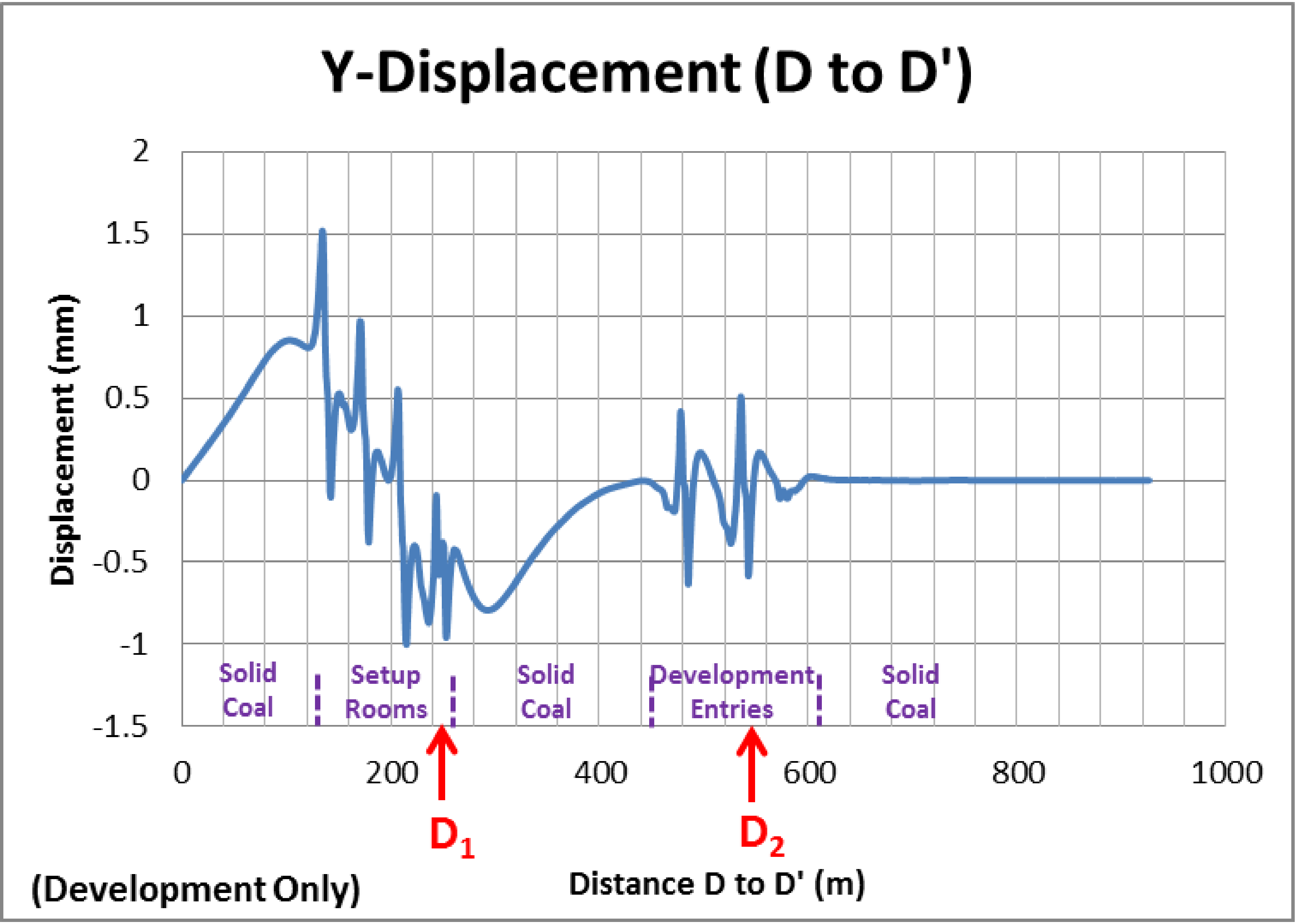
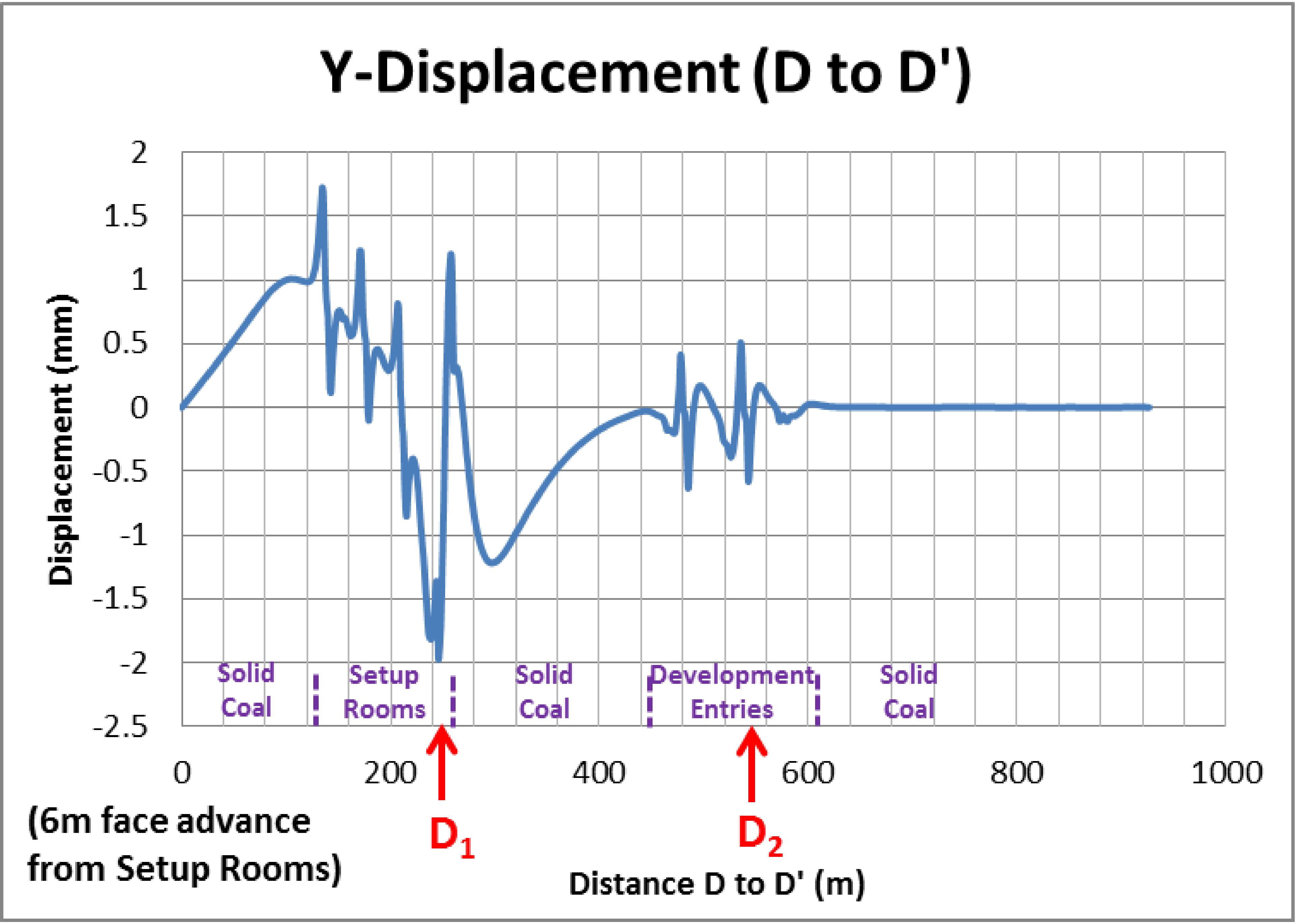
800
1000
D1
D2
(10m face advance from Setup Rooms)
Distance D to D' (m)


Y-Displacement (D to D')
Displacement (mm)
2
1.5
1
0.5
0
-0.5
-1
-1.5
0
200
400
600
800
1000
Solid Coal
Setup Rooms
Solid Coal
Development Entries
Solid Coal
D1
D2
Distance D to D' (m)
(Development Only)


Y-Displacement (D to D')
Displacement (mm)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
Solid Coal
Setup Rooms
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Development Entries
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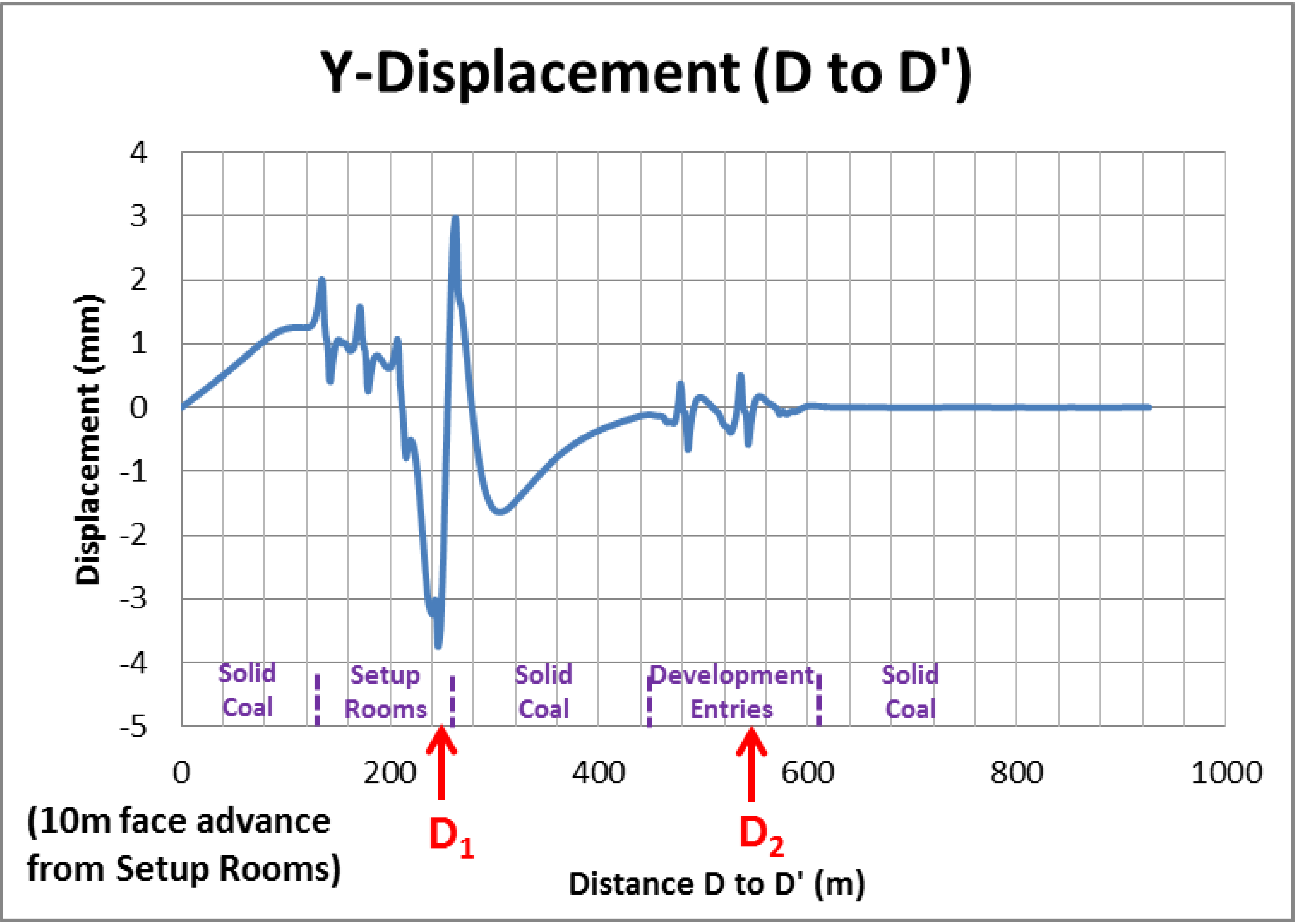
1000
(6m face advance from Setup Rooms)
D_1
D_2
Distance D to D' (m)



Y-Displacement (D to D')
Displacement (mm)
4
3
2
1
0
-1
-2
-3
-4
-5
Solid Coal
Setup Rooms
Solid Coal
Development Entries
Solid Coal
0
200
400
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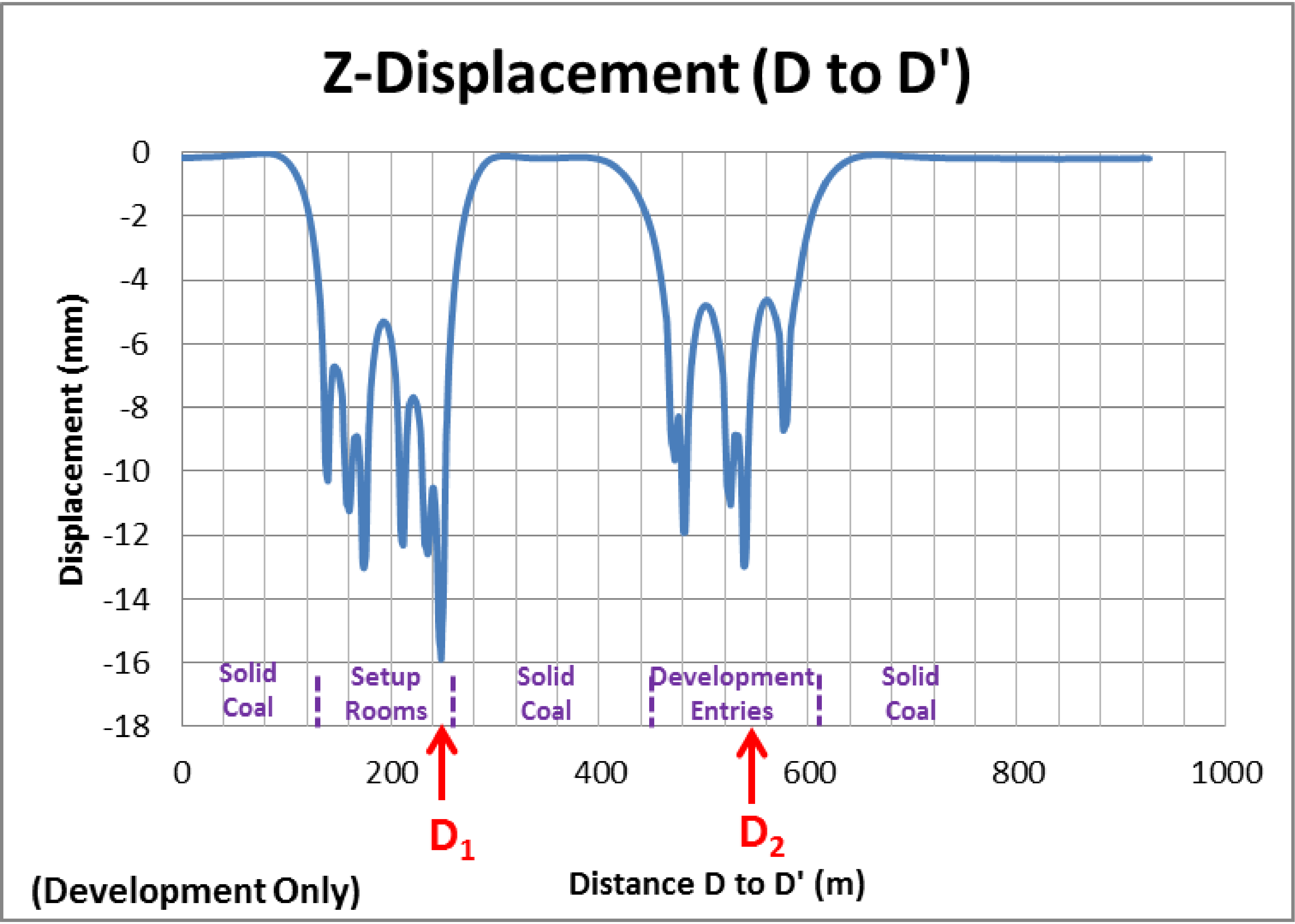
D1
D2
(10m face advance from Setup Rooms)
Distance D to D' (m)


Z-Displacement (D to D')
Displacement (mm)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
Solid Coal
Setup Rooms
Solid Coal
Development Entries
Solid Coal
0
200
400
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800
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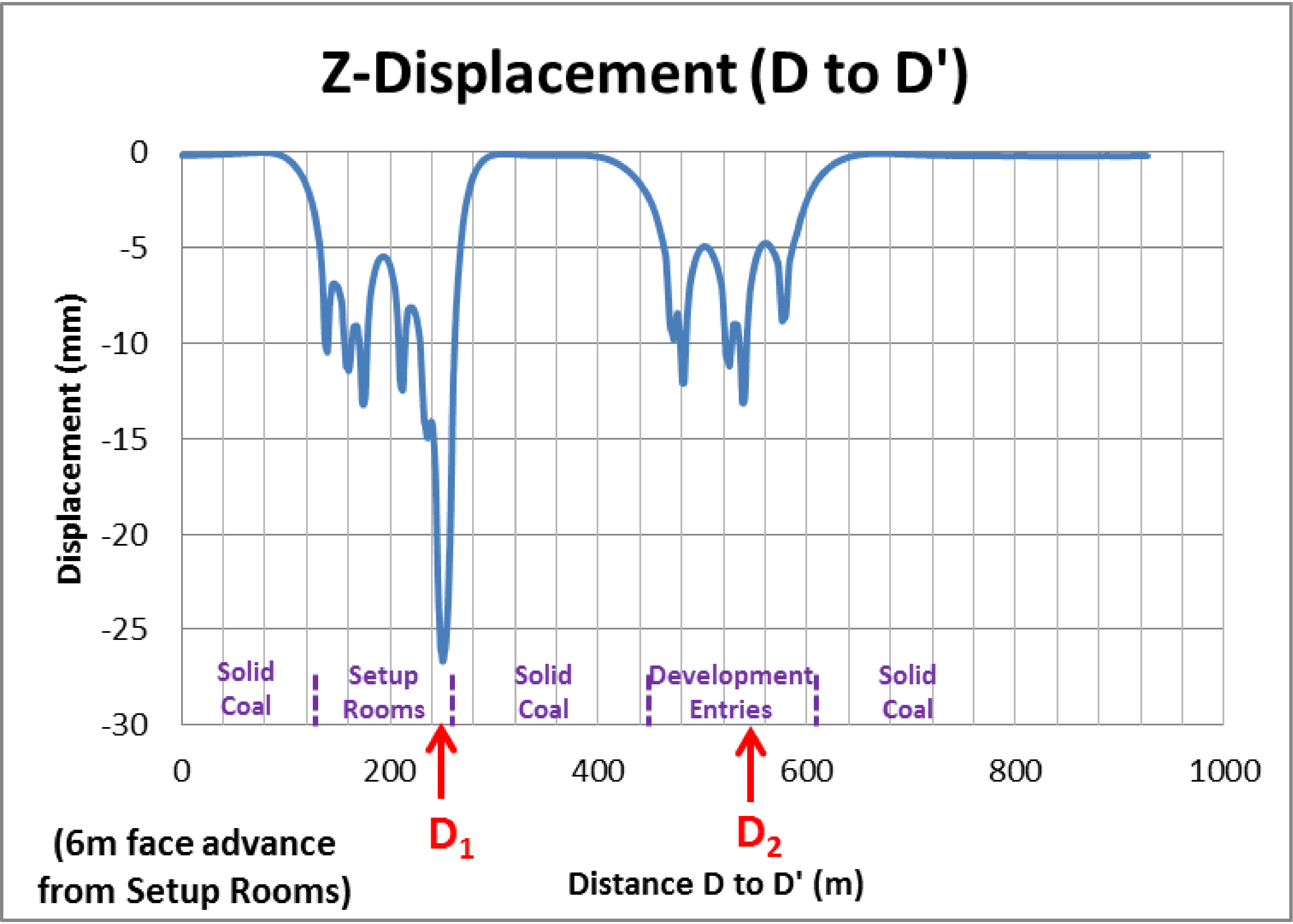
D_1
D_2
Distance D to D' (m)
(Development Only)


Z-Displacement (D to D')
Displacement (mm)
0
-5
-10
-15
-20
-25
-30
0
200
400
600
800
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Solid Coal
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Development Entries
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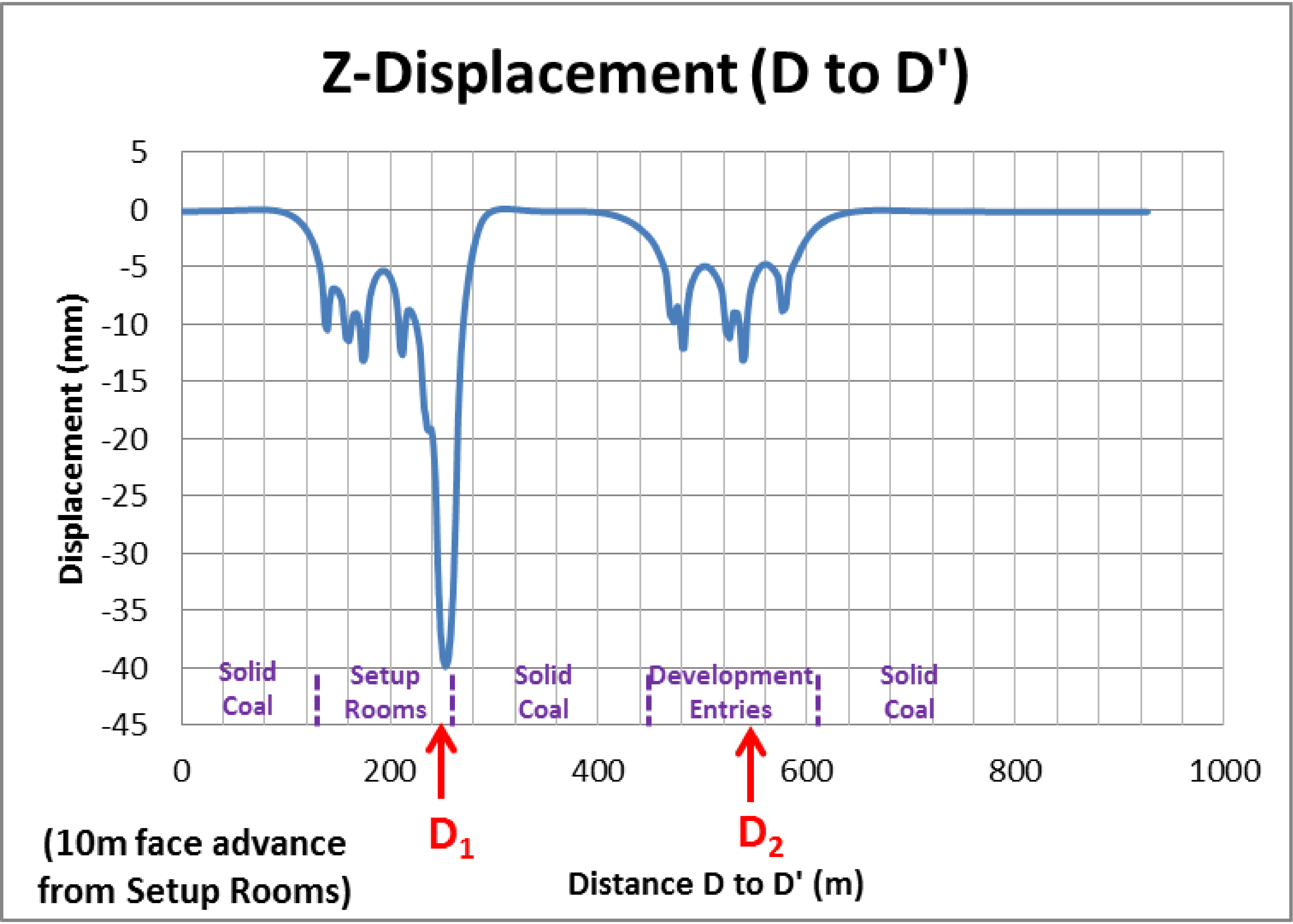
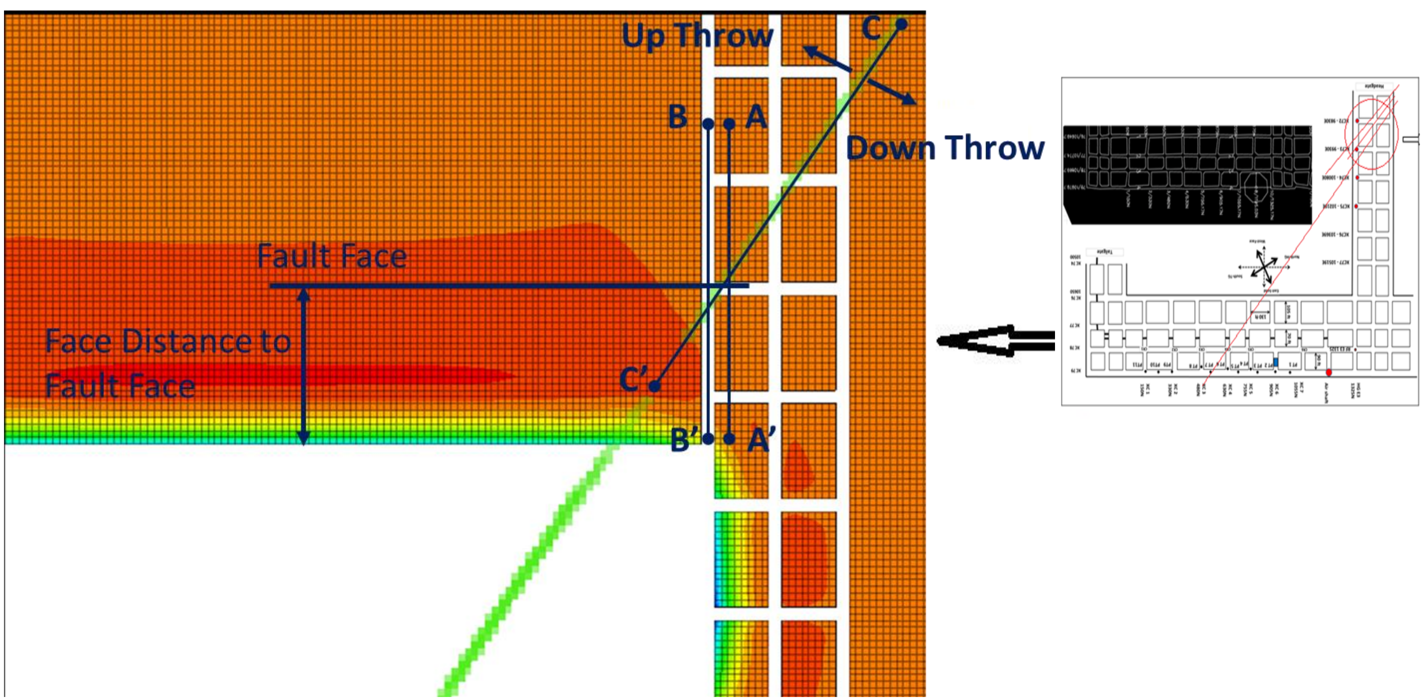
D1
D2
(6m face advance from Setup Rooms)
Distance D to D' (m)



Z-Displacement (D to D')
Displacement (mm)
5
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
Solid Coal
Setup Rooms
Solid Coal
Development Entries
Solid Coal
0
200
400
600
800
1000
D1
D2
(10m face advance from Setup Rooms)
Distance D to D' (m)

Analytical Studies: Model Development and Analysis Techniques

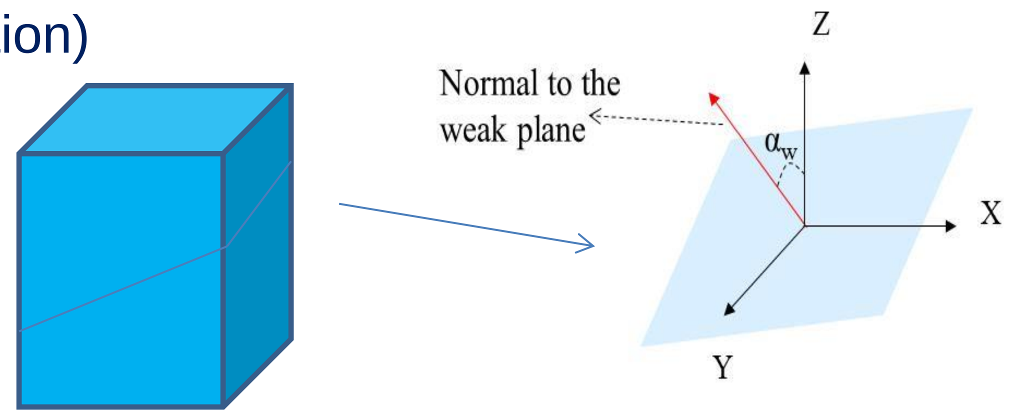
Model	Type of Analysis	Description
1	Longwall panel without fault zone	Longwall face 230-ft away from intersection of fault and gate entries. Longwall face 130-ft away from intersection of fault and gate entries.
2	Longwall panel with fault zone	Longwall face 230-ft away from intersection of fault and gate entries. Longwall face 130-ft away from intersection of fault and gate entries.



Model Development and Analysis Techniques

Fault Modeling

- Ubiquitous Joint Rock Mass (UJRM) is a technique for introducing rock mass anisotropy (weak planes such as discontinuity and lamination) in a continuum numerical modeling
- UJRM is a weak plane with a user defined cohesion, friction angle, dip direction and dip orientation
- UJRM does not consider
  - Joint spacing, stiffness and length
  - UJRM can't consider more than one weak plane (anisotropic direction)

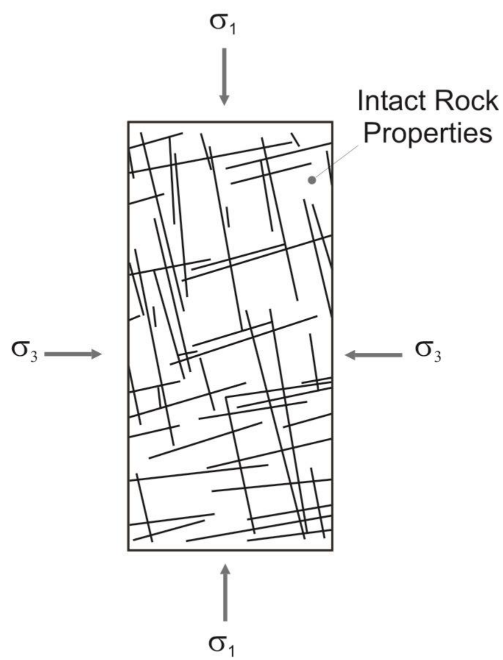


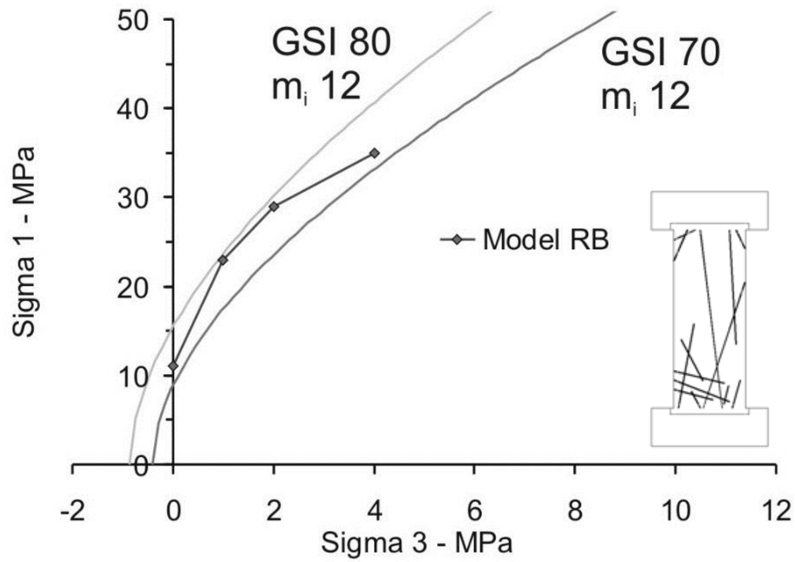
Mohr-Coulomb failure criteria

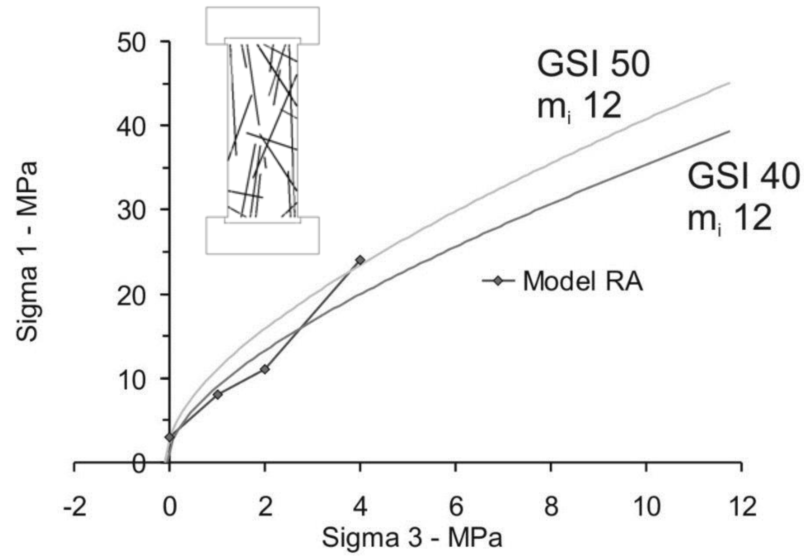
$$\tau = c + \sigma_n \tan \emptyset$$

Rock Mass Properties

A combined Discrete/DFN modelling approach can be used to derive equivalent continuum properties.





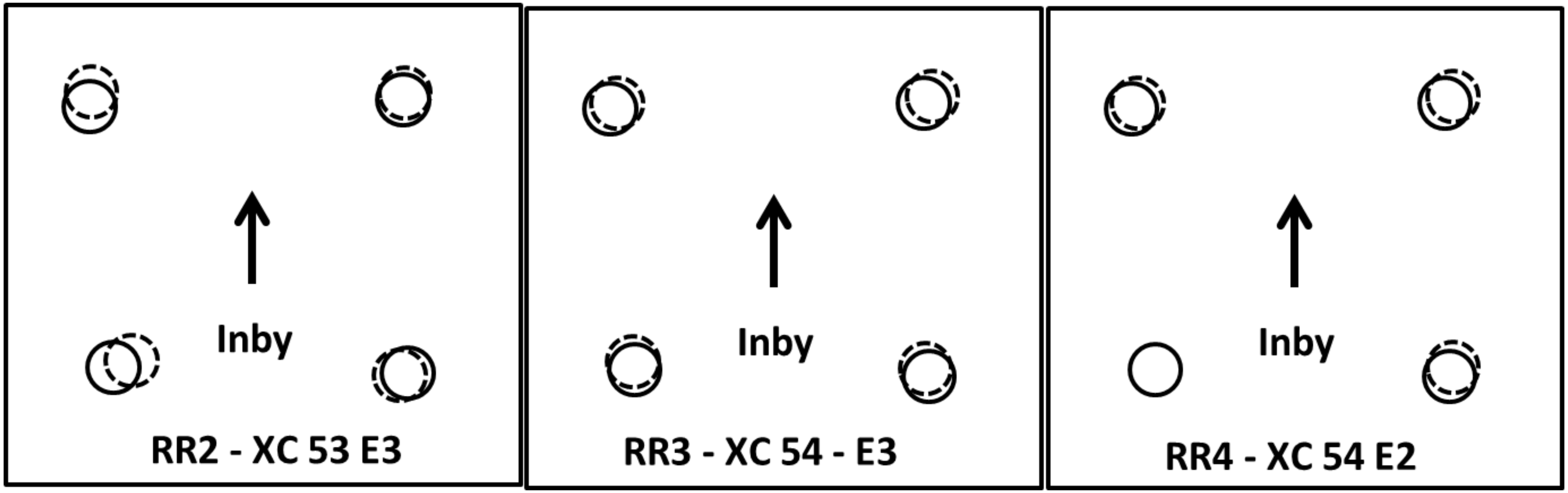


Limitations of 2D approach. Ideally the analysis should be carried out in 3D.

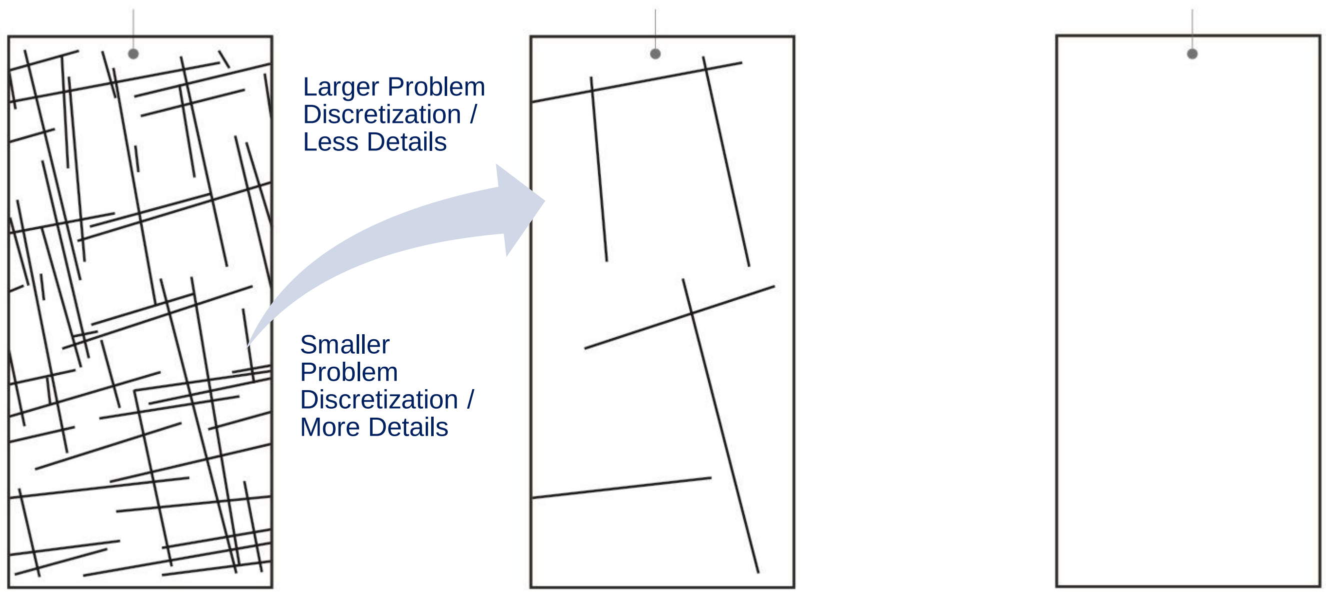
! Structurally Controlled Response !

Elmo, PhD Thesis (2006)

Area 2- Roof Rosette Indicated Movements



Rock Mass Properties



Idealized Discrete Model

Simplified Discrete Model

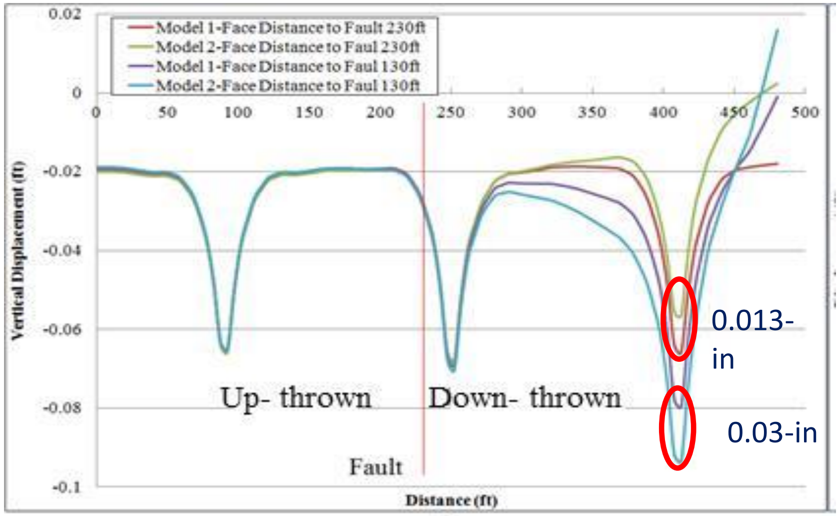
Continuum Model

Simulation of step-path and intact rock bridge failure

Randomly oriented ubiquitous joint planes could be distributed in the model to account for the effects of jointing

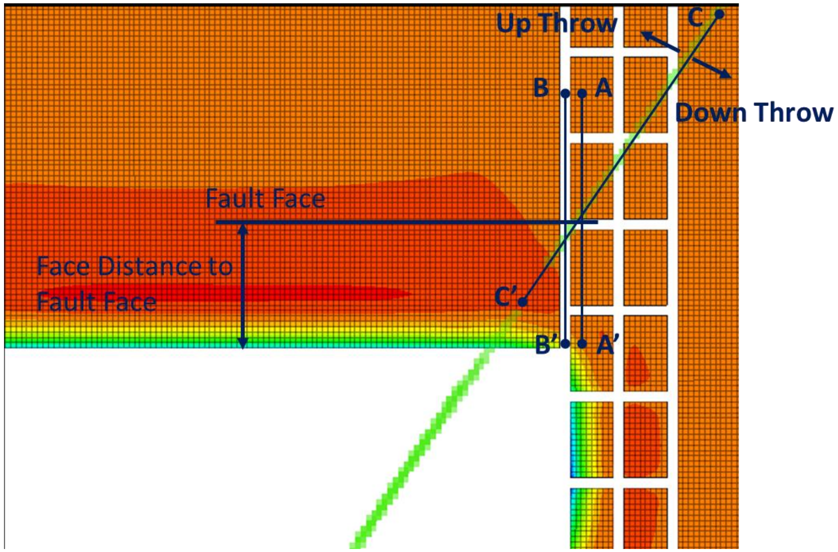
Problem Scale

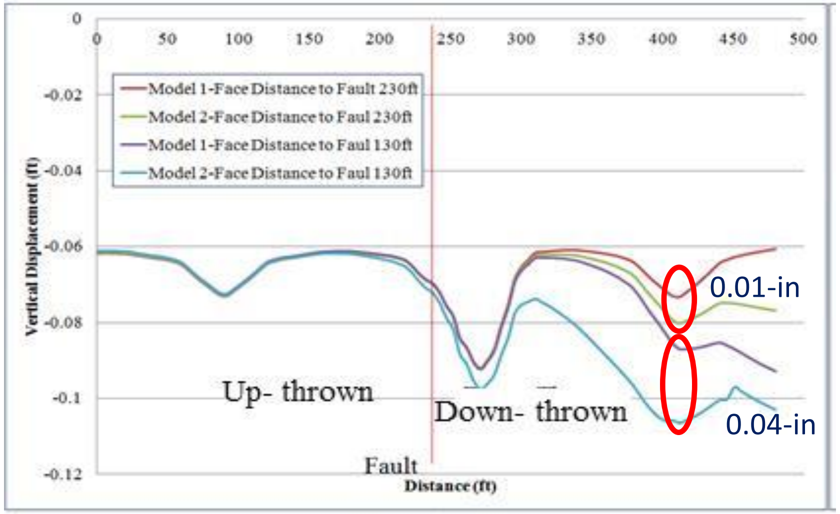
Vertical Displacement Along Cross-section AA' and BB'



a)

cross-section AA'





c)

cross-section BB'

Results: Field Measurements in Gate Entries Related to Fault Zone

Additional vertical displacement due to fault (cm)				
	Side	Field data	Numerical analysis	Percent (%) difference
LW face 70-m away from fault	Up-Thrown	1.47	1.70	+13.43
	Down-Thrown	0.30	0.44	+13.64
LW face 39.6-m away from fault	Up-Thrown	2.06	2.39	+16.36
	Down-Thrown	0.53	0.66	+10.23

Comparison of Model Data to Field Data

Distance to face to fault – Model - Field	Model Predicted Convergence	Field Measured Convergence
70 m (230 ft.) – 84 m (275 ft.)	24.4 mm	13 mm
39 m (130 ft.) – 43 m (140 ft.)	33.5 mm	2.6 mm

Differences: Field points were installed after openings were created. Model predicted values include movements of excavations. Model data did not account for additional supports. Entries had supplemental crib supports in each intersection, T-channels and cable bolts, and intermittent installation of “Super Props”.