Appendix: D4
2D FEM analysis: Arncliffe Caverns

AURECON JACOBS NEW M5 JOINT VENTURE

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1 2D FEM Analysis

1.1 Introduction

This document presents the tunnel stability analysis using 2D Finite Element Method (FEM) for the tunnel support types proposed in Arncliffe Caverns: YJ-HS-TYPE A/B/C/D-W6, YJ-HS-TYPE A/B/C/D-W7, YJ-HS-TYPE A/B/C/D-W8, YJ-HS-TYPE A/B/C/D-W9, YJ-HS-TYPE A/B/C/D-W10. In addition to the 2D FEM analysis, 2D Discrete Element Method (DEM) analysis for the proposed supports types including M2-HS-TYPE A/B/C/D-M2 was also carried out (Appendix D5).

The numerical analysis has been performed using the RS2/Phase2 (Version 9) software program developed by Rocscience. Further details of the adopted method, assumptions, inputs and analysis cases are provided below.

1.2 Assumptions and Limitations

- Typical surcharge of 20kPa was considered in the analysis
- Since the direction of major horizontal in-situ stress is toward North East direction and Arncliffe tunnel alignment is toward North East direction, hence it was assumed that orientation of major horizontal in-situ stress is parallel to Arncliffe caverns alignment. Hence, minor horizontal in-situ stress and major horizontal in-situ stress are considered in the plane and out of plane of FEM model, respectively. For sensitivity analysis, major horizontal in-situ stress has also been considered in the plane of analysis in Appendix D5 (2D DEM Analysis).
- Support types developed for each anticipated ground types based on GIR (M5N-GOL-TER-100-200-GT-1505) and tunnel wide support class (M5N-AJV-DRT-150-520-TU-1690).
- Defect orientations, frequencies and its properties in the Arncliffe area were adopted as provided in the GIR.
- Generalised Hoek-Brown elastic-plastic with brittle softening model was considered in the analysis. Residual/post peak parameters were used as suggested by Cai et al. (2007) for block scale and Lorig and Varona (2013) for tunnel scale.
- In order to capture the stress induced failures, the conceptual model proposed by Diederichs et al. (2010) to capture the brittle behaviour of rock mass has been used. The details of method and strength parameters have been adopted as provided in Oliveira and Diederichs (2016).
- The analyses were carried out under drained conditions using long-term parameters.
- Other assumptions and limitation inherent in the numerical modelling are discussed in the standard calculations of the Tunnel DCR (M5N-AJV-DRT-150-500-TR-1500).

1.3 Design Inputs

1.3.1 Proposed Ground Types

The ground types provided in Table 1.1 are defined in accordance with Tunnel wide support class (M5N-AJV-DRT-150-520-TU-1690) and the anticipated ground conditions given in the GIR (M5N-GOL-TER-100-200-GT-1505):

Table 1.1 Proposed ground types for Arncliffe caverns

*Ground type	Proposed support type
GT-H-1	YJ-HS-TYPE A
GT-H-2	YJ-HS-TYPE B
GT-H-3	YJHS-TYPE C
GT-H-4	YJ-HS-TYPE D

Ground type GT-H-4 is consisted of minor fault with the width of 1m to 2m of SS-IV and SS-III layer at tunnel crown.

1.3.2 Tunnel Geometry and Input

The geometry and tunnel support of Arncliffe Caverns are defined in the following design drawings:

- M5N-AJV-DWG-400-520-TU-4061 to M5N-AJV-DWG-400-520-TU-4084

1.3.3 Proposed Support Types

The proposed primary support types for Arncliffe caverns are given in the following table:

Table 1.2 The proposed ground support types for Arncliffe caverns

Ground support type	Roof support			Side wall		Abutment support	Temporary Pillar support		Face support	
	Rock bolt	Spot bolt	shotcrete	Rock bolt	shotcrete	Rock bolt	Rock bolt	shotcrete	dowels	shotcrete
YJ-HS-TYPE A-W6	E-6000-75 at 1.75m Tran. ×1.75m Long, Plate type PL5	Provisional, B-3900-50, Plate type PL1	P1 100mm	Provisional, B-3900-50, Plate type PL3	Provisional, P1 50mm	Provisional, B-2100-50, Plate type PL3	Provisional, J-2100-50, Plate type PL3	Provisional, P1 50mm	Provisional, A-6000-0	Provisional, S2 50mm
YJ-HS-TYPE B-W6	E-6000-75 at 1.5m Tran. ×1.5m Long, Plate type PL5	Provisional, B-3900-50, Plate type PL1	P1 150mm	Provisional, B-3900-50, Plate type PL3	Provisional, P1 50mm	Provisional, B-2100-50, Plate type PL3	Provisional, J-2100-50, Plate type PL3	Provisional, P1 50mm	Provisional, A-6000-0	Provisional, S2 50mm
YJ-HS-TYPE C-W6	E-6000-75 at 1.25m Tran. ×1.25m Long, Plate type PL5	Provisional, B-3900-50, Plate type PL1	P1 200mm	Provisional, B-3900-50, Plate type PL3	Provisional, P1 50mm	Provisional, B-2100-50, Plate type PL3	Provisional, J-2100-50, Plate type PL3	Provisional, P1 50mm	Provisional, A-6000-0	Provisional, S2 50mm
YJ-HS-TYPE D-W6	E-6000-75 at 1.0m Tran. ×1.0m Long, Plate type PL5	Provisional, B-3900-50, Plate type PL1	P1 250mm	Provisional, B-3900-50, Plate type PL3	Provisional, P1 50mm	Provisional, B-2100-50, Plate type PL3	Provisional, J-2100-50, Plate type PL3	Provisional, P1 50mm	Provisional, A-6000-0	Provisional, S2 50mm
YJ-HS-TYPE A-W7	E-7000-75 at 1.75m Tran. ×1.75m Long, Plate type PL5	Provisional, B-3900-50, Plate type PL1	P1 100mm	Provisional, B-3900-50, Plate type PL3	Provisional, P1 50mm	Provisional, B-2100-50, Plate type PL3	Provisional, J-2100-50, Plate type PL3	Provisional, P1 50mm	Provisional, A-6000-0	Provisional, S2 50mm
YJ-HS-TYPE B-W7	E-7000-75 at 1.5m Tran. ×1.5m Long,	Provisional, B-3900-50, Plate type	P1 150mm	Provisional, B-3900-50,	Provisional, P1 50mm	Provisional, B-2100-50,	Provisional, J-2100-50, Plate type PL3	Provisional, P1 50mm	Provisional, A-6000-0	Provisional, S2 50mm

Ground support type	Roof support			Side wall		Abutment support	Temporary Pillar support		Face support	
	Rock bolt	Spot bolt	shotcrete	Rock bolt	shotcrete	Rock bolt	Rock bolt	shotcrete	dowels	shotcrete
	Plate type PL5	PL1		Plate type PL3		Plate type PL3				
YJ-HS-TYPE C-W7	E-7000-75 at 1.25m Tran. ×1.25m Long, Plate type PL5	Provisional, B-3900-50, Plate type PL1	P1 200mm	Provisional, B-3900-50, Plate type PL3	Provisional, P1 50mm	Provisional, B-2100-50, Plate type PL3	Provisional, J-2100-50, Plate type PL3	Provisional, P1 50mm	Provisional, A-6000-0	Provisional, S2 50mm
YJ-HS-TYPE D-W7	E-7000-75 at 1.0m Tran. ×1.0m Long, Plate type PL5	Provisional, B-3900-50, Plate type PL1	P1 250mm	Provisional, B-3900-50, Plate type PL3	Provisional, P1 50mm	Provisional, B-2100-50, Plate type PL3	Provisional, J-2100-50, Plate type PL3	Provisional, P1 50mm	Provisional, A-6000-0	Provisional, S2 50mm
YJ-HS-TYPE A-W8	E-8000-75 at 1.75m Tran. ×1.75m Long, Plate type PL5	Provisional, B-3900-50, Plate type PL1	P1 100mm	Provisional, B-3900-50, Plate type PL3	Provisional, P1 50mm	Provisional, B-2100-50, Plate type PL3	Provisional, J-2100-50, Plate type PL3	Provisional, P1 50mm	Provisional, A-6000-0	Provisional, S2 50mm
YJ-HS-TYPE B-W8	E-8000-75 at 1.5m Tran. ×1.5m Long, Plate type PL5	Provisional, B-3900-50, Plate type PL1	P1 150mm	Provisional, B-3900-50, Plate type PL3	Provisional, P1 50mm	Provisional, B-2100-50, Plate type PL3	Provisional, J-2100-50, Plate type PL3	Provisional, P1 50mm	Provisional, A-6000-0	Provisional, S2 50mm
YJ-HS-TYPE C-W8	E-8000-75 at 1.25m Tran. ×1.25m Long, Plate type PL5	Provisional, B-3900-50, Plate type PL1	P1 200mm	Provisional, B-3900-50, Plate type PL3	Provisional, P1 50mm	Provisional, B-2100-50, Plate type PL3	Provisional, J-2100-50, Plate type PL3	Provisional, P1 50mm	Provisional, A-6000-0	Provisional, S2 50mm
YJ-HS-TYPE D-W8	E-8000-75 at 1.0m Tran. ×1.0m Long, Plate type PL5	Provisional, B-3900-50, Plate type PL1	P1 250mm	Provisional, B-3900-50, Plate type PL3	Provisional, P1 50mm	Provisional, B-2100-50, Plate type PL3	Provisional, J-2100-50, Plate type PL3	Provisional, P1 50mm	Provisional, A-6000-0	Provisional, S2 50mm
YJ-HS-TYPE A-W9	E-8500-75 at 1.75m Tran. ×1.75m Long, Plate type PL5	Provisional, B-3900-50, Plate type PL1	P1 100mm	Provisional, B-3900-50, Plate type PL3	Provisional, P1 50mm	Provisional, B-2100-50, Plate type PL3	Provisional, J-2100-50, Plate type PL3	Provisional, P1 50mm	Provisional, A-6000-0	Provisional, S2 50mm

Ground support type	Roof support			Side wall		Abutment support	Temporary Pillar support		Face support	
	Rock bolt	**Spot bolt**	**shotcrete**	**Rock bolt**	**shotcrete**	**Rock bolt**	**Rock bolt**	**shotcrete**	**dowels**	**shotcrete**
YJ-HS-TYPE B-W9	E-8500-75 at 1.5m Tran. ×1.5m Long, Plate type PL5	Provisional, B-3900-50, Plate type PL1	P1 150mm	Provisional, B-3900-50, Plate type PL3	Provisional, P1 50mm	Provisional, B-2100-50, Plate type PL3	Provisional, J-2100-50, Plate type PL3	Provisional, P1 50mm	Provisional, A-6000-0	Provisional, S2 50mm
YJ-HS-TYPE C-W9	E-8500-75 at 1.25m Tran. ×1.25m Long, Plate type PL5	Provisional, B-3900-50, Plate type PL1	P1 200mm	Provisional, B-3900-50, Plate type PL3	Provisional, P1 50mm	Provisional, B-2100-50, Plate type PL3	Provisional, J-2100-50, Plate type PL3	Provisional, P1 50mm	Provisional, A-6000-0	Provisional, S2 50mm
YJ-HS-TYPE D-W9	E-8500-75 at 1.0m Tran. ×1.0m Long, Plate type PL5	Provisional, B-3900-50, Plate type PL1	P1 250mm	Provisional, B-3900-50, Plate type PL3	Provisional, P1 50mm	Provisional, B-2100-50, Plate type PL3	Provisional, J-2100-50, Plate type PL3	Provisional, P1 50mm	Provisional, A-6000-0	Provisional, S2 50mm
YJ-HS-TYPE A-W10	E-9000-75 at 1.75m Tran. ×1.75m Long, Plate type PL5	Provisional, B-3900-50, Plate type PL1	P1 100mm	Provisional, B-3900-50, Plate type PL3	Provisional, P1 50mm	Provisional, B-2100-50, Plate type PL3	Provisional, J-2100-50, Plate type PL3	Provisional, P1 50mm	Provisional, A-6000-0	Provisional, S2 50mm
YJ-HS-TYPE B-W10	E-9000-75 at 1.5m Tran. ×1.5m Long, Plate type PL5	Provisional, B-3900-50, Plate type PL1	P1 150mm	Provisional, B-3900-50, Plate type PL3	Provisional, P1 50mm	Provisional, B-2100-50, Plate type PL3	Provisional, J-2100-50, Plate type PL3	Provisional, P1 50mm	Provisional, A-6000-0	Provisional, S2 50mm
YJ-HS-TYPE C-W10	E-9000-75 at 1.25m Tran. ×1.25m Long, Plate type PL5	Provisional, B-3900-50, Plate type PL1	P1 200mm	Provisional, B-3900-50, Plate type PL3	Provisional, P1 50mm	Provisional, B-2100-50, Plate type PL3	Provisional, J-2100-50, Plate type PL3	Provisional, P1 50mm	Provisional, A-6000-0	Provisional, S2 50mm
YJ-HS-TYPE D-W10	E-9000-75 at 1.0m Tran. ×1.0m Long, Plate type PL5	Provisional, B-3900-50, Plate type PL1	P1 250mm	Provisional, B-3900-50, Plate type PL3	Provisional, P1 50mm	Provisional, B-2100-50, Plate type PL3	Provisional, J-2100-50, Plate type PL3	Provisional, P1 50mm	Provisional, A-6000-0	Provisional, S2 50mm

Note: Square bolt pattern is preferable for construction suitability because it simplifies the bolt layout in a varying cross section. The analysis shows that the square patterns works effectively.

1.3.4 Geotechnical Input

The geotechnical input has been adopted from the Geotechnical Interpretive Report (M5N-GOL-TER-100-200-GT-1505).

Table 1.3 Geotechnical Properties for Rock Mass – Tunnel Scale

Ground Type	Unit Weight	E	Poisson's Ratio	Intact UCS	m_i	GSI_{peak}	[1]D_{res}
	[kN/m^3]	[MPa]	[-]	[MPa]	[-]	[-]	[-]
SS-I	24	3000	0.2	30	13	75	1.0
SS-II	24	2000	0.2	25	13	65	1.0
SS-III	24	1000	0.2	20	13	55	0.9
SS-IV	23	500	0.25	10	13	45	0.6
SH-II	24	1000	0.2	15	8	50	0.7

[1]Value of damage factor D_{res} estimated for residual strength according to Lorig and Varona (2013).

Table 1.4 Geotechnical Properties for Rock Mass– Block Scale

Ground Type	Unit Weight	E	Poisson's Ratio	Intact UCS	mi	GSI_{peak}	[1]GSI_{res}
	[[kN/m^3]]	[MPa]	[-]	[MPa]	[-]	[-]	[-]
SS-I	24	6000	0.2	30	13	90	27
SS-II	24	4000	0.2	25	13	85	27
SS-III	24	2500	0.2	20	13	65	27
SS-IV	23	1500	0.25	10	13	55	26
SH-II	24	1500	0.2	15	8	60	27

[1]Value of GSI_{res} estimated for residual strength according to Cai et al. (2007)

Table 1.5 Geotechnical Properties for soil

Ground Type		Unit Weight	*E	Poisson's Ratio	Cohesion	Friction Angle
		[kN/m3]	[MPa]	[-]	[MPa]	[deg]
Fill (UF2/UF3)		18	30	0.3	0.002	28
Alluvium (Q3B)		20	45	0.3	0.005	28
Residual soil	RS-1B	20	45	0.3	0.005	28
	RS-1A	21	105	0.3	0.006	28

Note: * - unload elastic modulus, and soil parameters given in table are in drained parameters

Table 1.6 Block Scale Parameters for Brittle Failure Criterion

Ground Type	Unit weight	E	Poisson's ratio	Intact UCS	m_{peak}	m_{res}	s_{peak}	s_{res}	a_{peak}	a_{res}
	[kN/m3]	[MPa]	[-]	[MPa]	[-]	[-]	[-]	[-]	[-]	[-]
SS-I	24	6000	0.2	30	1.189585	12	0.091506	0.001	0.25	0.75
SS-II		4000		25						
SS-III		2500		20						

Table 1.7 Discontinuity Parameters

Rock Mass Class	Type	kn	ks	JCS	JRC	ϕ_r
	[-]	GPa/m	GPa/m	[MPa]	[-]	[deg]
SS–I	[a]B1	6	0.6	10	8	32
SS I	J1 & J2	10	1	15	10	32
SS-II	[a]B2	4	0.4	8	6	32
SS-II	J3 & J4	8	0.8	10	8	32
SS-III/SS-IV	[a]B3	2	0.2	6	4	32
SS-III/SS-IV	J5 & J6	4	0.4	8	6	32

Note: a –bedding plane is filled with 5% of clay fill material

Table 1.8 Discontinuity Orientations

Rock Mass Class	Type	Dip	Spacing	
			Range	Mean
	[-]	[deg]	[m]	[m]
SS-I	B1	1	1.5< x<5	2.5
SS-I	J1	80	3<x<8	5
SS-I	J2	20	1.5<x<10	5
SS-II	B2	1	1< x <3	1.5
SS-II	J3	80	2< x <6	3
SS-II	J4	20	1< x <6	3
SS-III/IV	B3	1	0.3< x <1.5	0.5
SS-III/IV	J5	85	0.5< x <2	1
SS-III/IV	J6	20	0.3< x <3	1

Note: J2, J4 and J6 are cross beddings and normal statistical distribution was used to create joint network in FEM model.

1.3.5 In Situ Field Stress

Table 1.9 shows the in-situ stress relations given in GIR. Since the direction of major in-situ stress (σ_H) is toward North East direction and Arncliffe alignment is also toward North East direction, hence it was assumed that orientation of major in-situ stress is parallel to Arncliffe caverns alignment.

Table 1.9 Major and Minor In-Situ Stress Relations

Material	Class	σ_H	σ_h
Fill	UF2/UF3	0.5×σ_v	0.5×σ_v
Alliuvum	Q-3B	0.5×σ_v	0.5×σ_v
Residual	RS	1×σ_v	1×σ_v
	I (Massive)	1.7 MPa+5.3 ×σ_v	1.0 MPa+3.18 ×σ_v
Sandstone	I	1.2 MPa+3.8 ×σ_v	0.72 MPa+2.28 ×σ_v
	II	1.0 MPa +3.0 ×σ_v	0.6 MPa +1.8×σ_v
	III	0.7 MPa +2.2×σ_v	0.42 MPa +1.32×σ_v
	IV	0.4 MPa +1.4×σ_v	0.24 MPa +0.84×σ_v
Shale	II	0.7 MPa +2.2×σ_v	0.42 MPa +1.32×σ_v

Note: (1) σ_H – major in-situ stress, σ_h – minor in-situ stress, σ_v – vertical in-situ stress (2) the above relationship between σ_H and σ_v for sandstone and shale can be found in Oliveira and Parker (2014)

1.3.6 Rock Bolt Design Parameters

Rock bolt properties used for the assessment are summarised in Table 1.10.

Table 1.10 Rock bolt Design Parameters

Rock reinforcement Properties	Rock reinforcement	
	Rock bolt (type B)[a]	Cable bolt (type E)[b]
Design Tensile Capacity [MN]	0.216	0.48
Tributary Area [mm^2]	370	N/A
Bolt Modulus, E [MPa]	200000	210000
Bond Stiffness [MN/m/m]	130	130

a - As suggested by M5N-AJV-WPR-150-500-TU-0001-A, Swellex / Split Set elements in Phase2/RS2 have been considered to capture the mechanical behaviour of fully grouted tension rockbolt with a pre-tension force of 50 kN was used in the analysis
b – End-anchored elements have been considered to capture the mechanical behaviour of cable bolt

Table 1.11 Bond Strength

Rock Type	Bond Strength [kN/m]
SS-I	300
SS-II	300
SS-III	150
SS-IV	60
SH-II	150

1.3.7 Shotcrete Design parameters

Table 1.12 Shotcrete Design Parameters.

Description	Type	Unit Weight [kN/m^3]	Compressive Strength (28 days) [MPa]	Modulus of Elasticity [MPa]	Poisson's Ratio [-]
Steel Fibre Reinforced Shotcrete	SFRS	24	40	10000	0.2

Note: For this analysis, the intermediate modulus case has been assessed.

1.4 Analysis Cases

1.4.1 GRC and LDP

In order to consider the 3D effect of tunnel excavation face in a 2D FEM analysis, the convergence confinement method was used to estimate the tunnel relaxation in the analysis as per tunnel DCR. Since multiple headings construction sequence is proposed in design, the equivalent radius of 4m (which is equivalent to area of a heading) has been chosen to estimate a ground reaction curve (GRC) and longitudinal deformation profile (LDP). GRC and LDP curves for the proposed support types are shown in Figure 1.1 to Figure 1.4. The estimated tunnel relaxation for the proposed support types are given in Table 1.13.

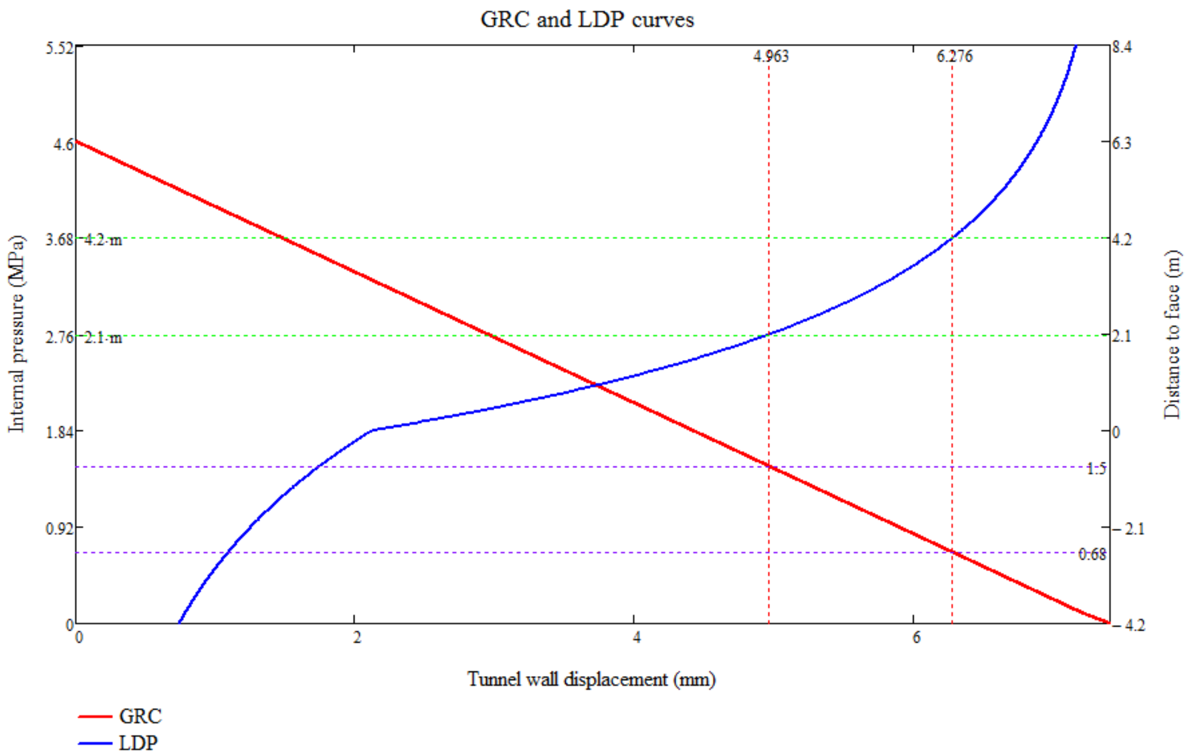

Figure 1.1 Estimated GRC and LDP curves for the proposed support type YJ-HS-TYPE A (Sandstone class –I).

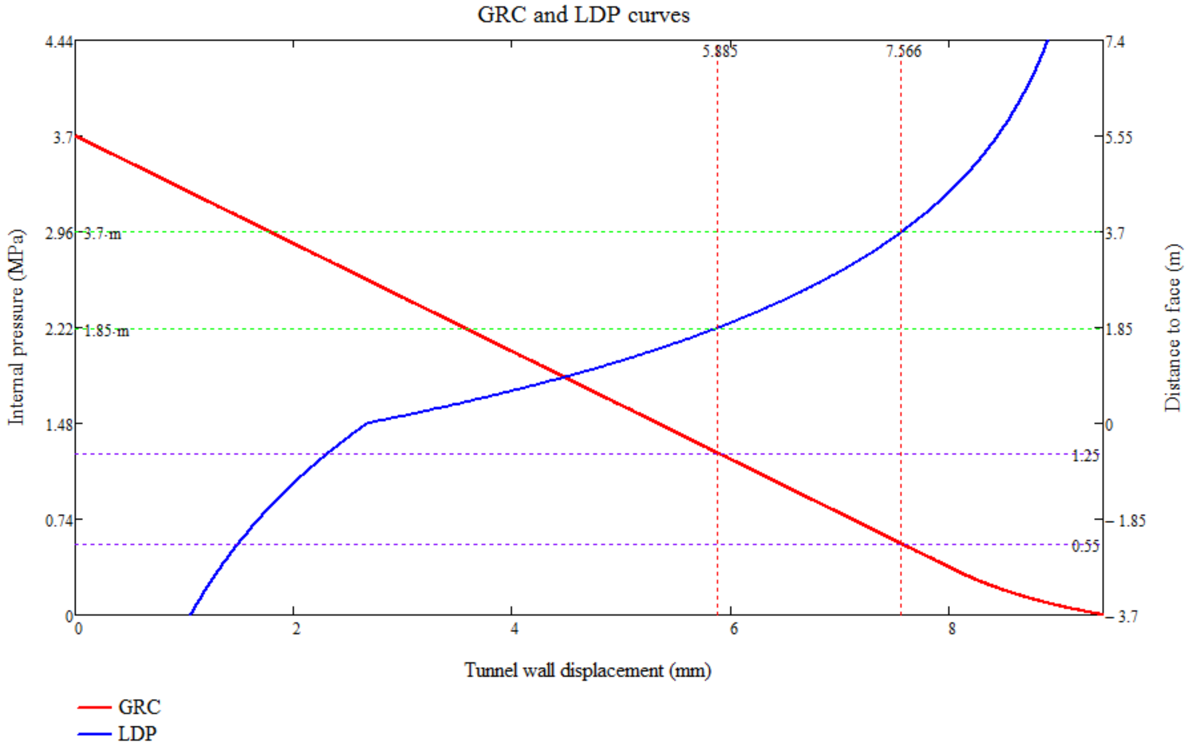

Figure 1.2 Estimated GRC and LDP curves for the proposed support type YJ-HS-TYPE B (Sandstone class –II).

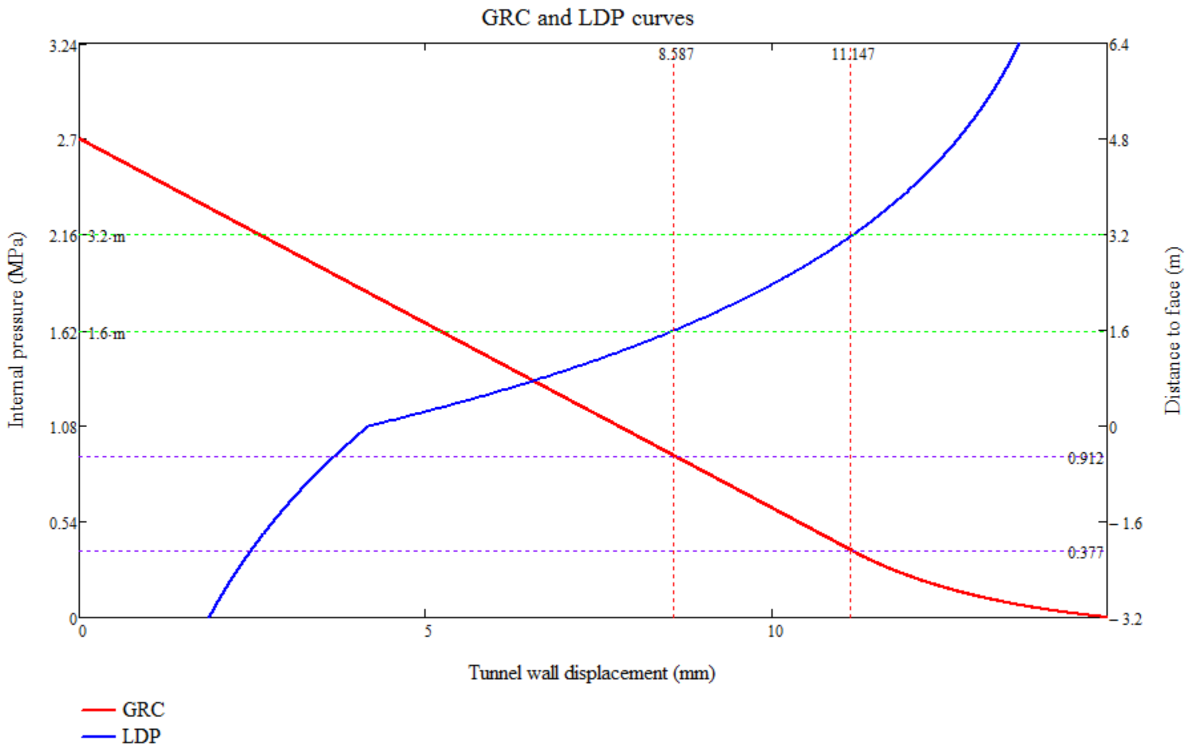

Figure 1.3 Estimated GRC and LDP curves for the proposed support type YJ-HS-TYPE C (Sandstone class –III).

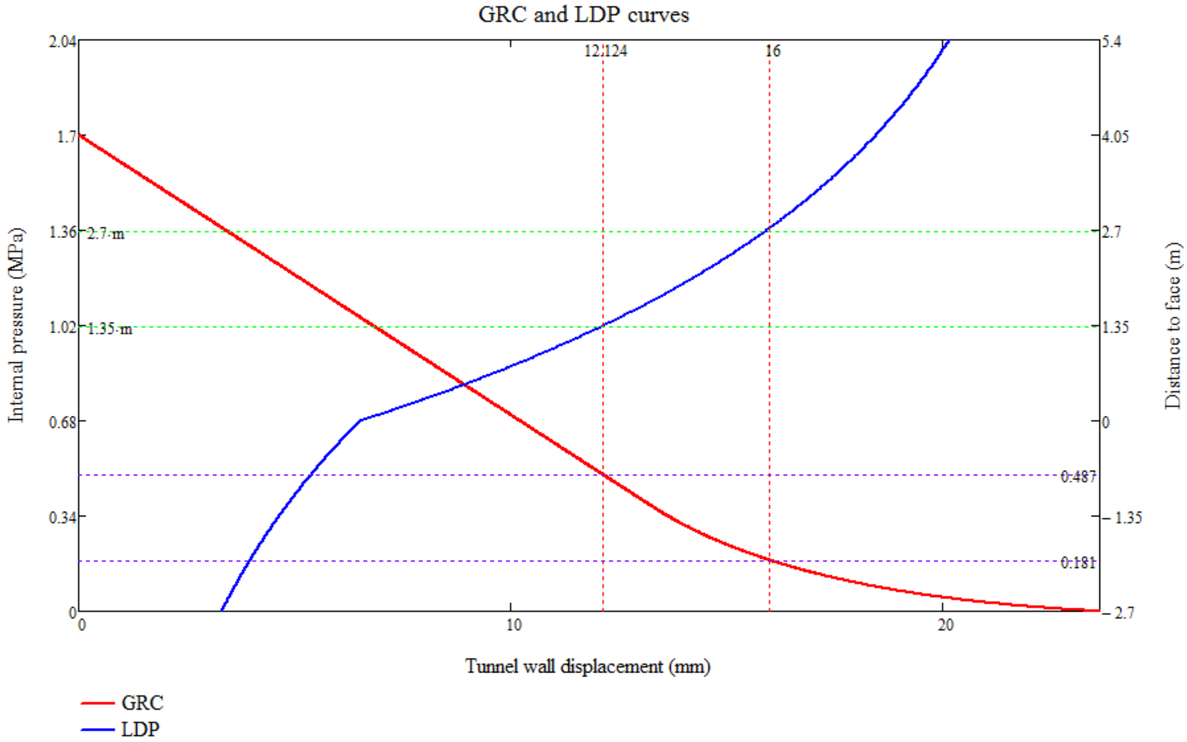

Figure 1.4 Estimated GRC and LDP curves for the proposed support type YJ-HS-TYPE D (Sandstone class –III and IV).

Table 1.13 Estimated tunnel relaxation for the proposed support types

Support type	Rock class	Average support installation distance to face (X/2+0.35)	Second layer of SFRS apply (Y)	Average initial in-situ stress	Internal stress at X/2+0.35	Internal stress at Y	Relaxation at (X/2+0.35)	Relaxation at Y
		m	m	MPa	MPa	MPa	%	%
YJ-HS-TYPE A	SS-I	2.1	4.2	4.6	1.5	0.68	65	85
YJ-HS-TYPE B	SS-II	1.85	3.7	3.7	1.25	0.55	65	85
YJ-HS-TYPE C	SS-III	1.6	3.2	2.7	0.91	0.38	65	85
YJ-HS-TYPE D	SS-III and SS-IV	1.35	2.7	1.7	0.49	0.18	70	90

Note:

1. X is the tunnel advance distance and Y is the distance between tunnel face and last round of rock bolts
2. GRC and LDP curves were estimated based on the method suggested by Carranza-Torres and Fairhurst C (2000) and Vlachopoulos and Diederichs (2009), respectively.

1.4.2 Model Staging

1.4.2.1 Four headings excavation

For support types YJ-HS-TYPE A/B/C/D -W10, YJ-HS-TYPE A/B/C/D -W9, YJ-HS-TYPE A/B/C/D -W8

Stage 1 – Initial stage

Stage 2 – Apply surcharge load to model (reset the initial model displacement)

Stage 3 – Excavate headings (in sequence from heading 1, 2, 4 and 5)

- Excavate heading and relax 65% for type A/B/C supports, and relax 70% for type D support
- Install primary support (type E rock cable bolts and first layer of 100 mm thick shotcrete to roof)
- Relax 85 % of heading for type A/B/C supports, relax 90 % of heading for type D support
- Install second layer of shotcrete to roof if primary shotcrete is more than 100mm
- Relax 100% of heading

Stage 4 – Excavate benches (in sequence from bench 1, 2, 4 and 5)

- Excavate bench and relax 90 % if applicable, install support to bench
- Relax bench 100%

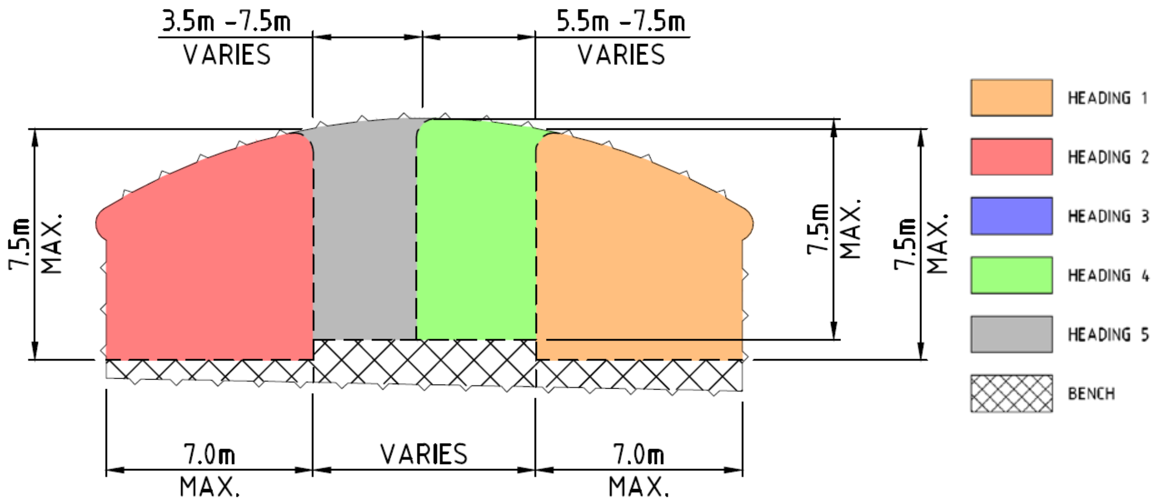

Figure 1.5 Sequence of four headings excavation

1.4.2.2 Three headings excavation

For support types YJ-HS-TYPE A/B/C/D–W7, YJ-HS-TYPE A/B/C/D -W7

Stage 1 – Initial stage

Stage 2 – Apply surcharge load to model (reset the initial model displacement)

Stage 3 – Excavate headings (in sequence from heading 1, 2 and 3)

- Excavate heading and relax 65% for type A/B/C supports, and relax 70% for type D support

- Install primary support (type E rock cable bolts and first layer of 100 mm thick shotcrete to roof)
- Relax 85 % of heading for type A/B/C supports, relax 90 % of heading for type D support
- Install second layer of shotcrete to roof if primary shotcrete is more than 100mm
- Relax 100% of heading

Stage 4 – Excavate benches (in sequence from bench 1, 2 and 3)

- Excavate bench and relax 90 % if applicable, install support to bench
- Relax bench 100%

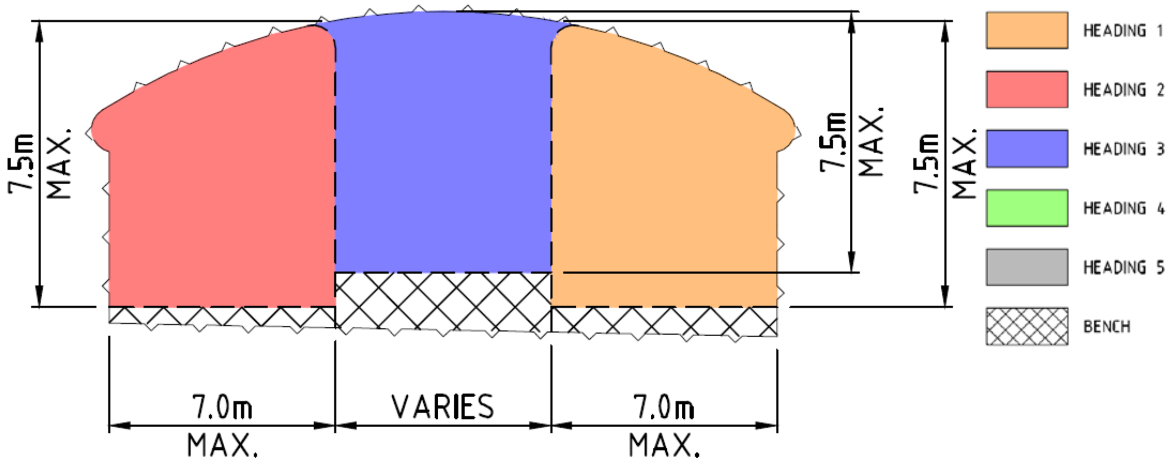

Figure 1.6 **Sequence of three headings excavation**

1.4.3 FEM Models

The brief description of FEM models are given in Table 1.14 and FEM models used in the analysis are shown from Figure 1.7 to Figure 1.26.

Table 1.14 **Model cases for 2D FEM analysis.**

Model ID	Chainage	Description	Figures ID
YJ-HS-TYPE A-W6	CH 8060-CH 8140 (M110) CH 8065-CH 8130 (M120)	▪ discontinuum approach used near tunnel opening area and continuum approach used other area with elastic-plastic Hoek-Brown and Mohr-Coulomb material parameters; ▪ brittle model parameters have been used for SS-I, SS-II and SS-III in order to capture the stress induced failure mechanism around tunnel opening; ▪ joint network has been created with bedding and near vertical cross joints; ▪ tunnel relaxation considered; with rockbolt and shotcrete support; ▪ minor horizontal in-situ stress in plane has been considered.	1.7
YJ-HS-TYPE B-W6			1.8
YJ-HS-TYPE C-W6			1.9
YJ-HS-TYPE D-W6			1.10
YJ-HS-TYPE A-W7	CH 8044-CH 8060 (M110) CH 8050-CH 8065 (M120)		1.11
YJ-HS-TYPE B-W7			1.12
YJ-HS-TYPE C-W7			1.13
YJ-HS-TYPE D-W7			1.14
YJ-HS-TYPE A-W8	CH 8002-CH 8044 (M110) CH 8013-CH 8050 (M120)		1.15
YJ-HS-TYPE B-W8			1.16
YJ-HS-TYPE C-W8			1.17
YJ-HS-TYPE D-W8			1.18

Model ID	Chainage	Description	Figures ID
YJ-HS-TYPE A-W9	CH 7975-CH 8002 (M110) CH 7992-CH 8013 (M120)		1.19
YJ-HS-TYPE B-W9			1.20
YJ-HS-TYPE C-W9			1.21
YJ-HS-TYPE D-W9			1.22
YJ-HS-TYPE A-W10	CH 7953-CH 7975 (M110) CH 7973-CH 7992 (M120)		1.23
YJ-HS-TYPE B-W10			1.24
YJ-HS-TYPE C-W10			1.25
YJ-HS-TYPE D-W10			1.26

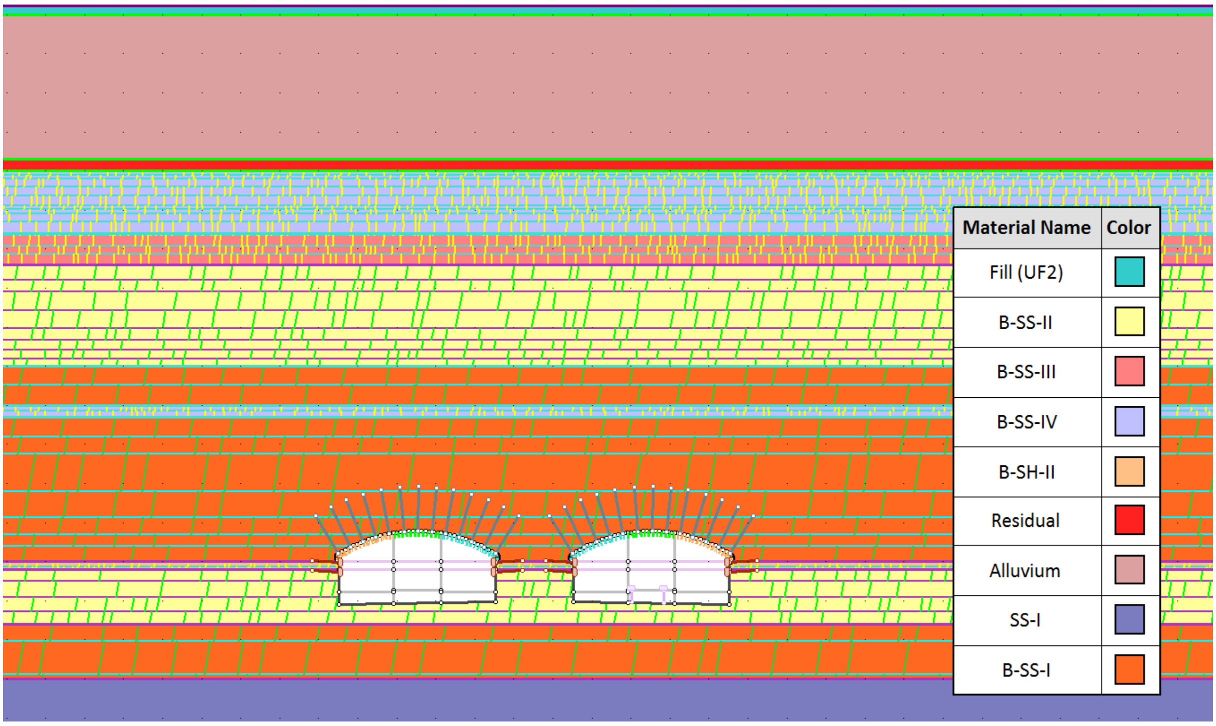

Figure 1.7 FEM model of YJ-HS-TYPE A-W6

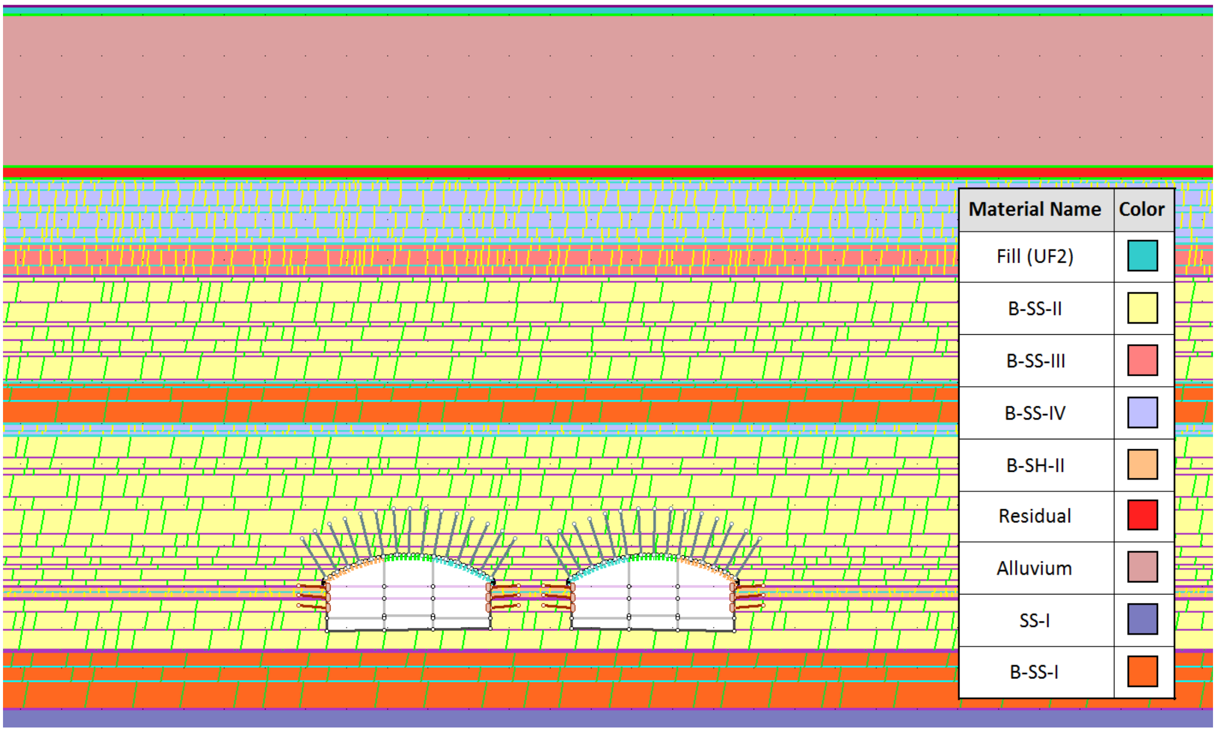

Figure 1.8 FEM model of YJ-HS-TYPE B-W6

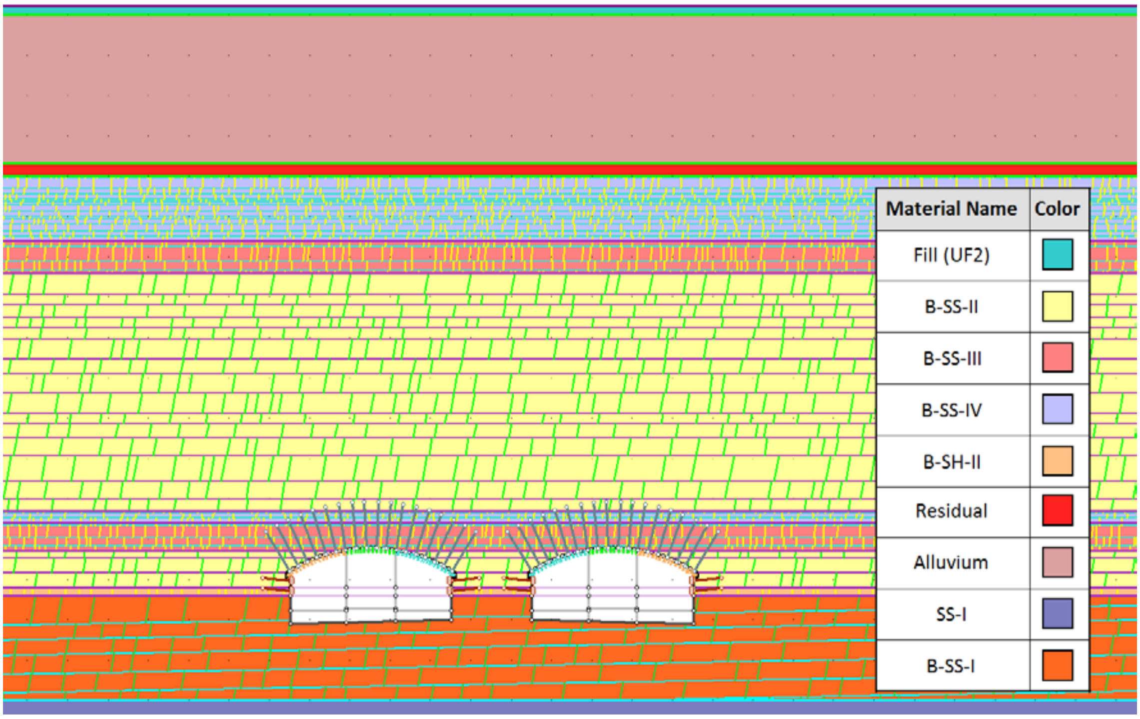

Figure 1.9 FEM model of YJ-HS-TYPE C-W6

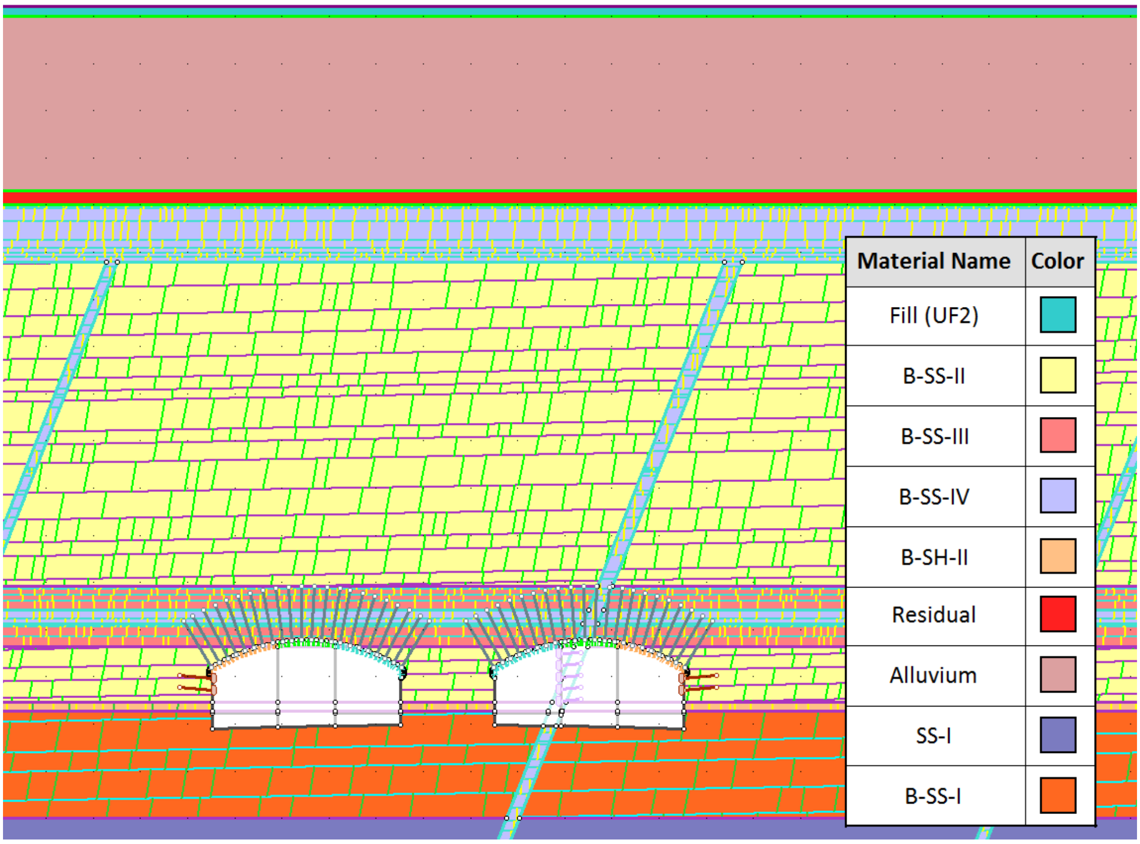

Figure 1.10 FEM model of YJ-HS-TYPE D-W6

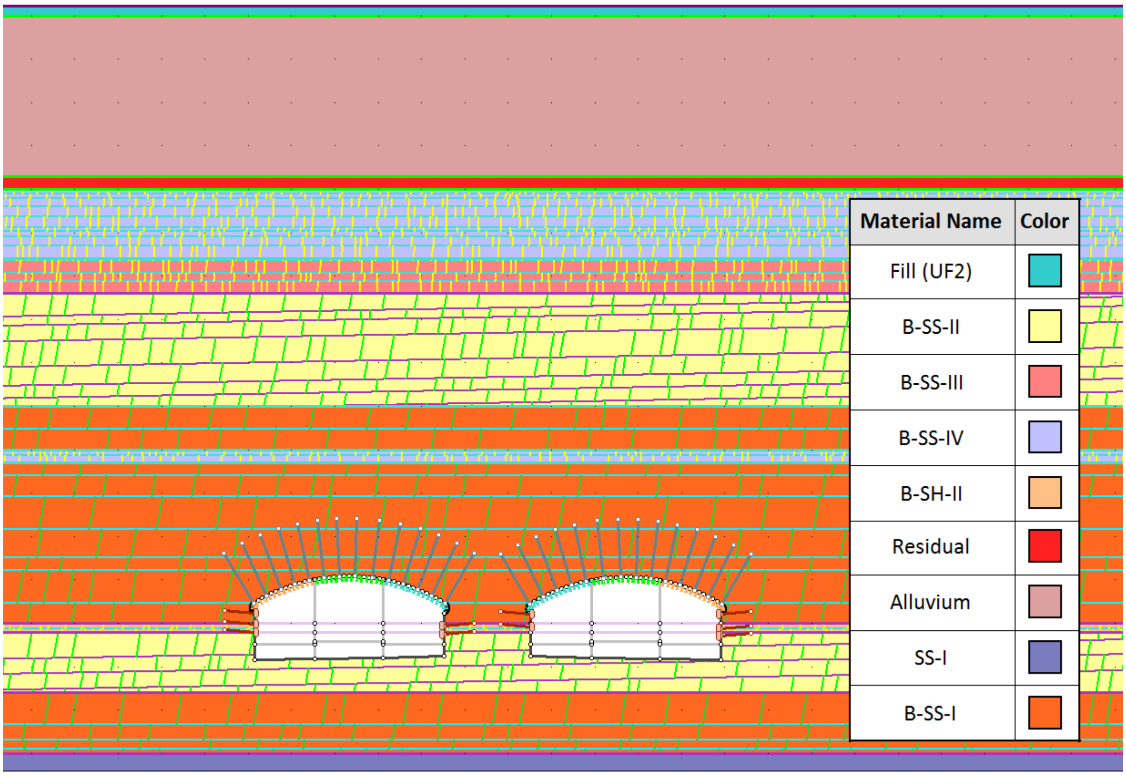

Figure 1.11 FEM model of YJ-HS-TYPE A-W7

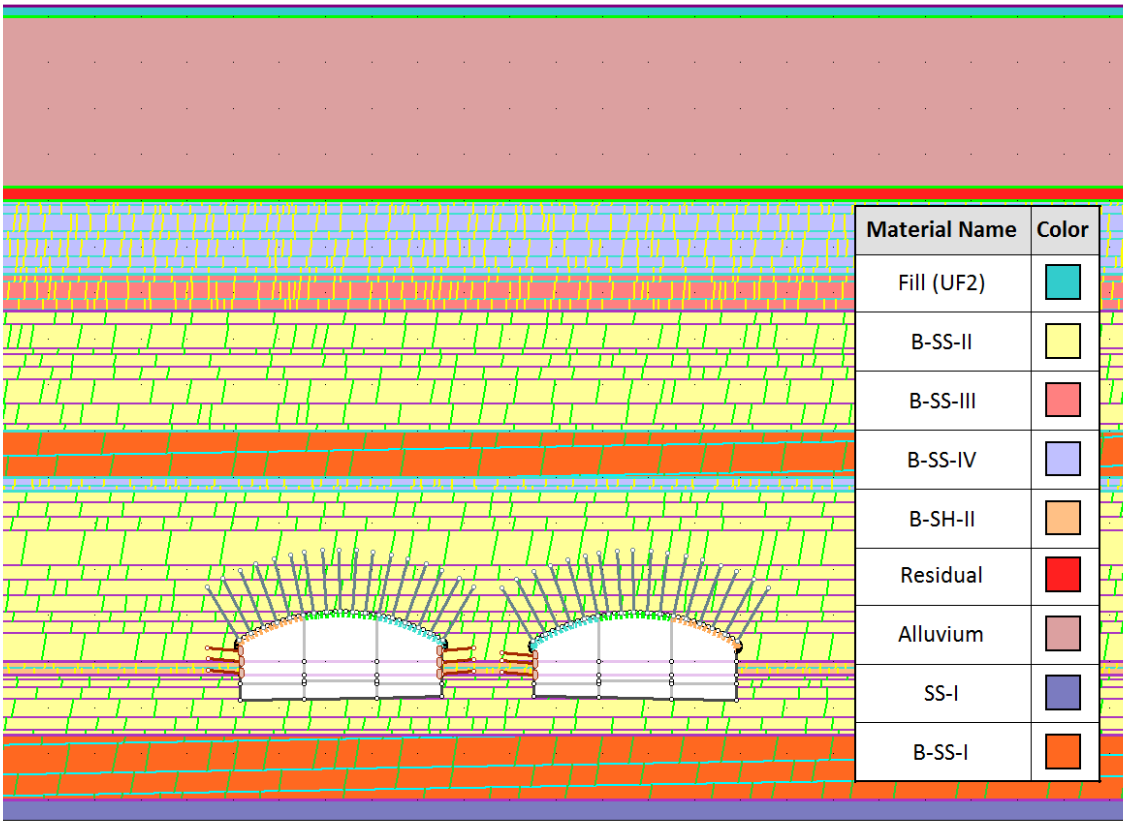

Figure 1.12 FEM model of YJ-HS-TYPE B-W7

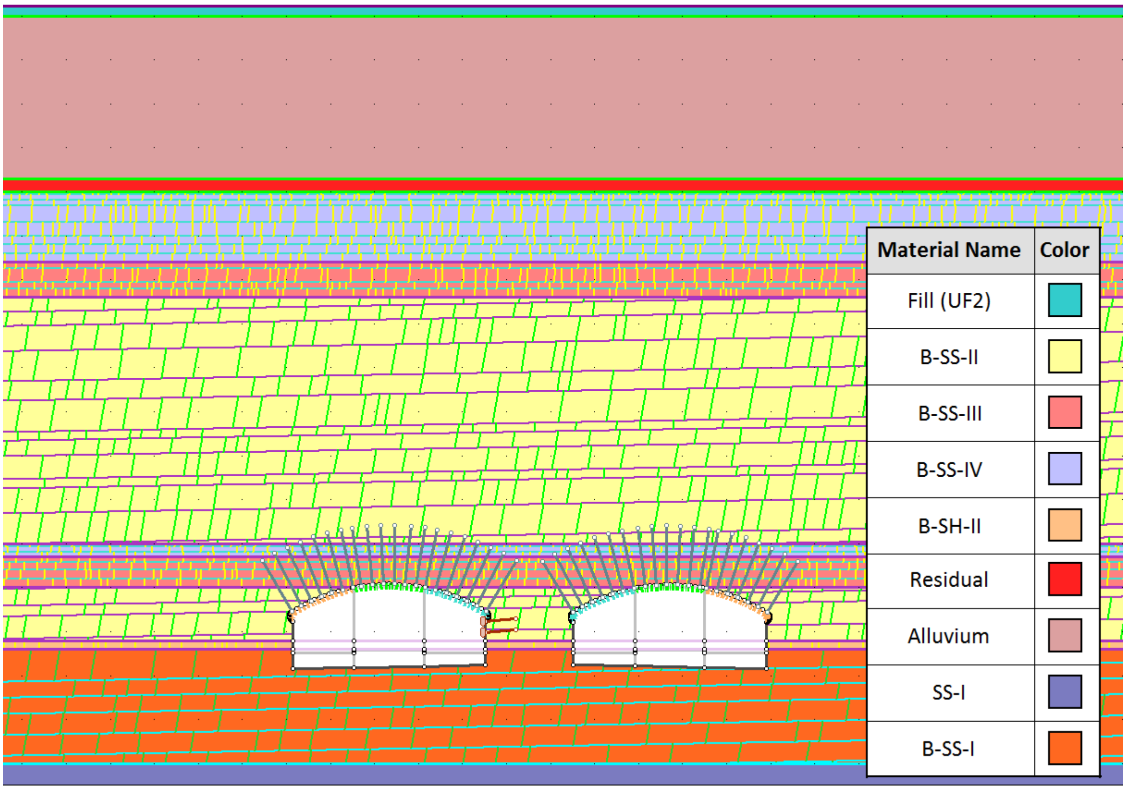

Figure 1.13 FEM model of YJ-HS-TYPE C-W7

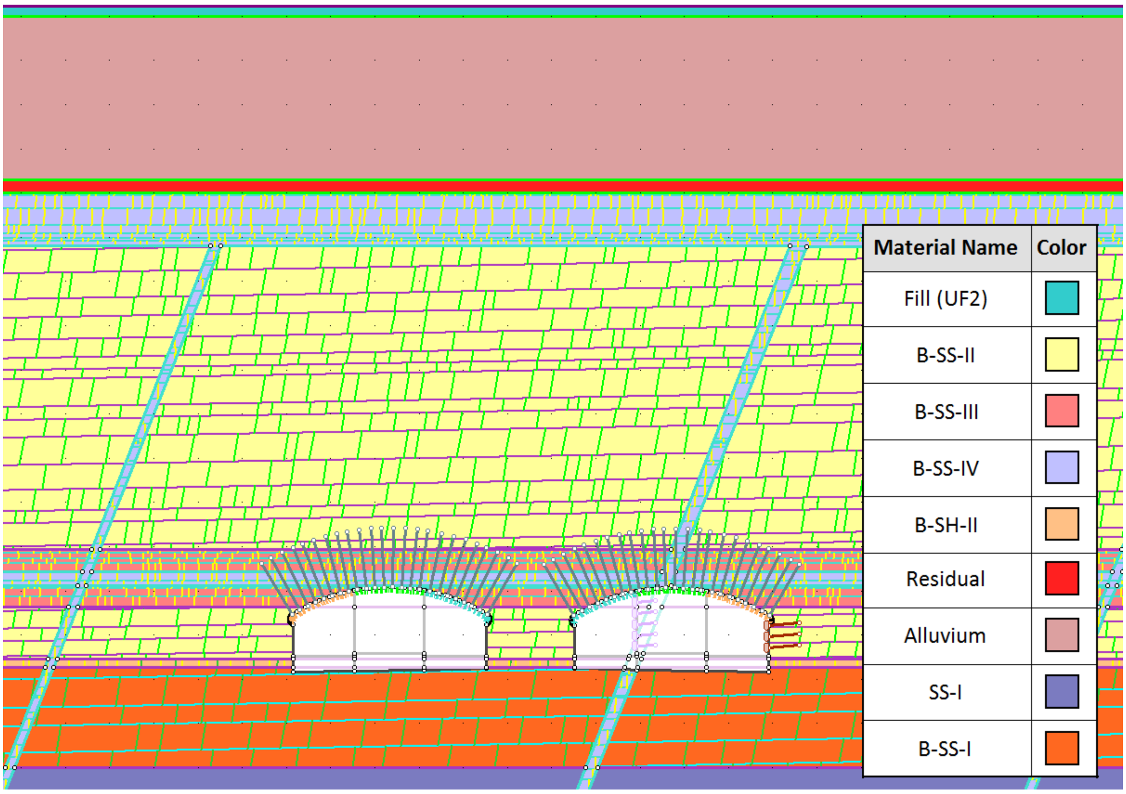

Figure 1.14 FEM model of YJ-HS-TYPE D-W7

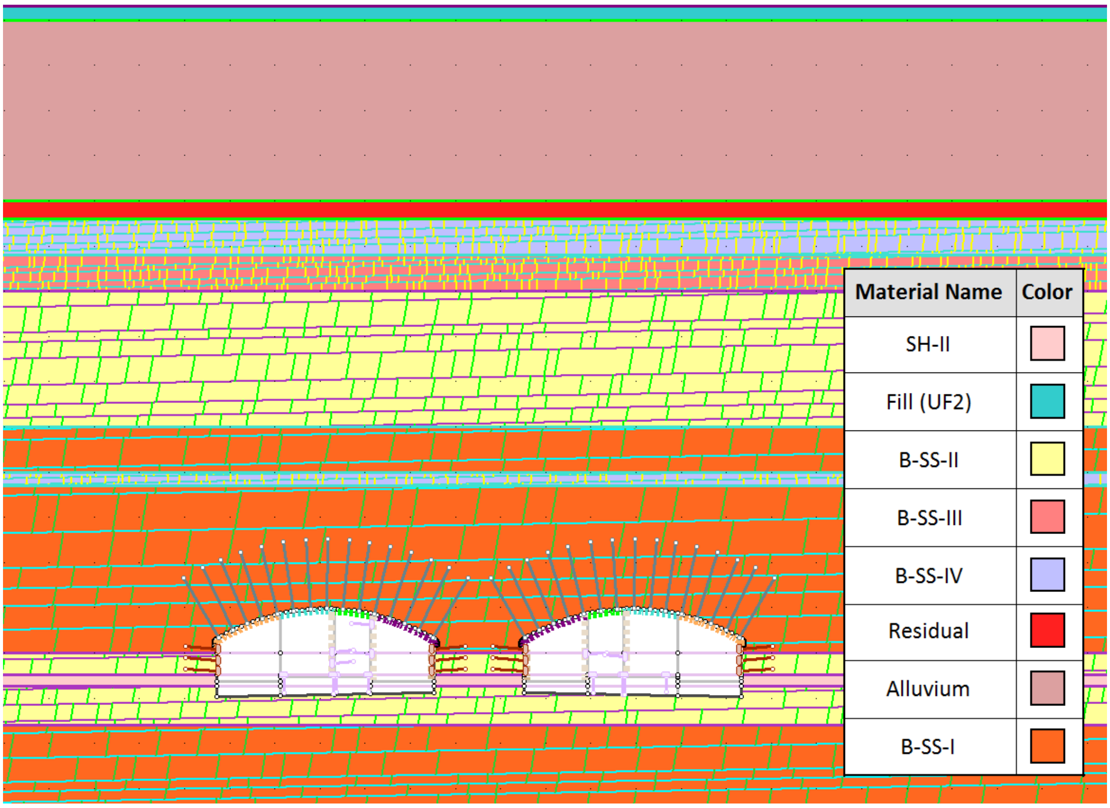

Figure 1.15 FEM model of YJ-HS-TYPE A-W8

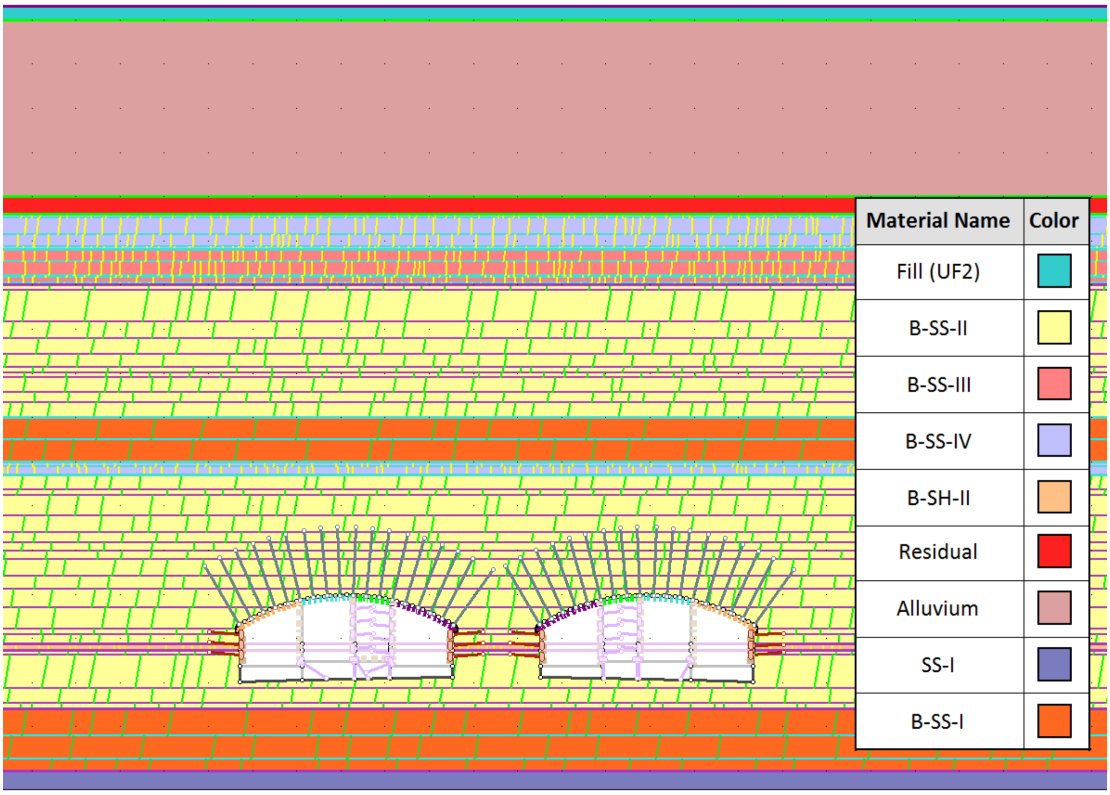

Figure 1.16 FEM model of YJ-HS-TYPE B-W8

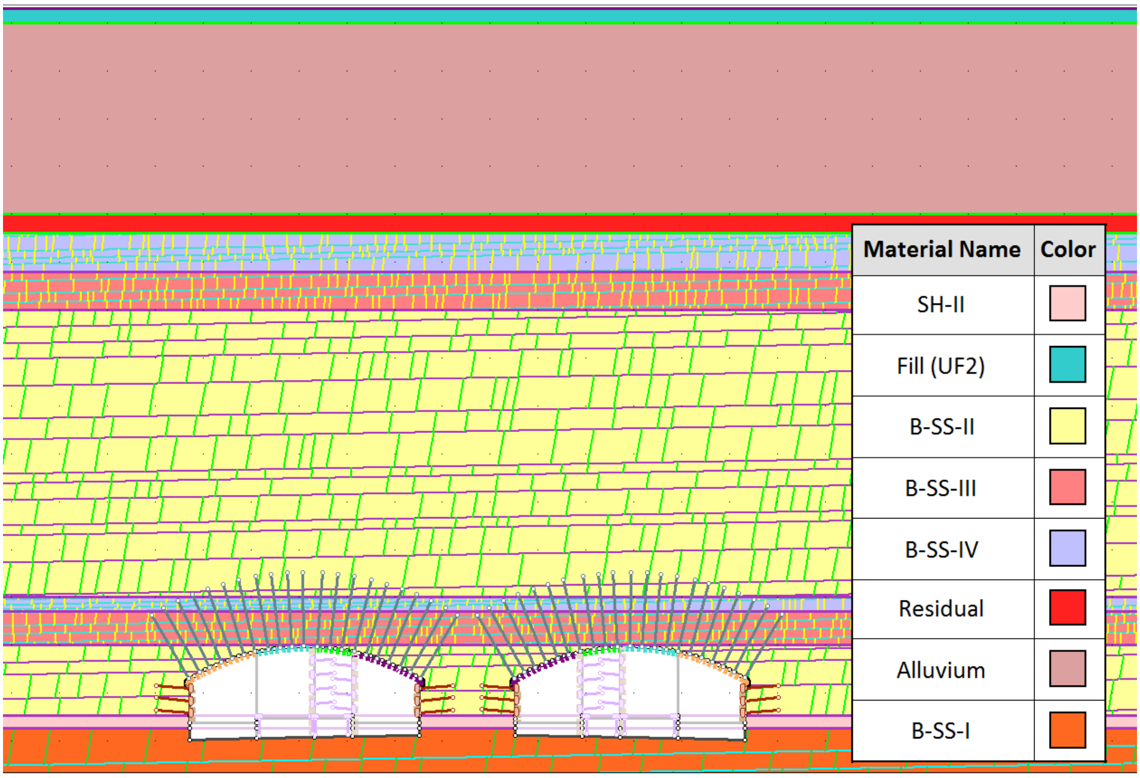

Figure 1.17 FEM model of YJ-HS-TYPE C-W8

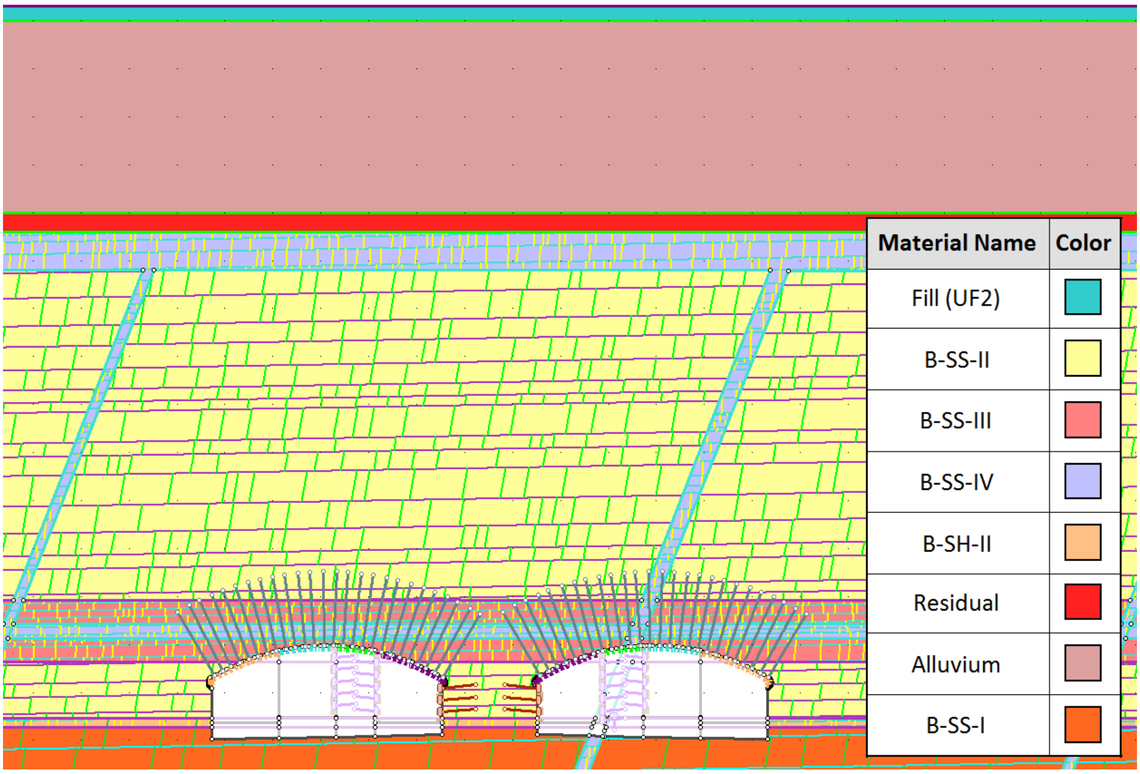

Figure 1.18 FEM model of YJ-HS-TYPE D-W8

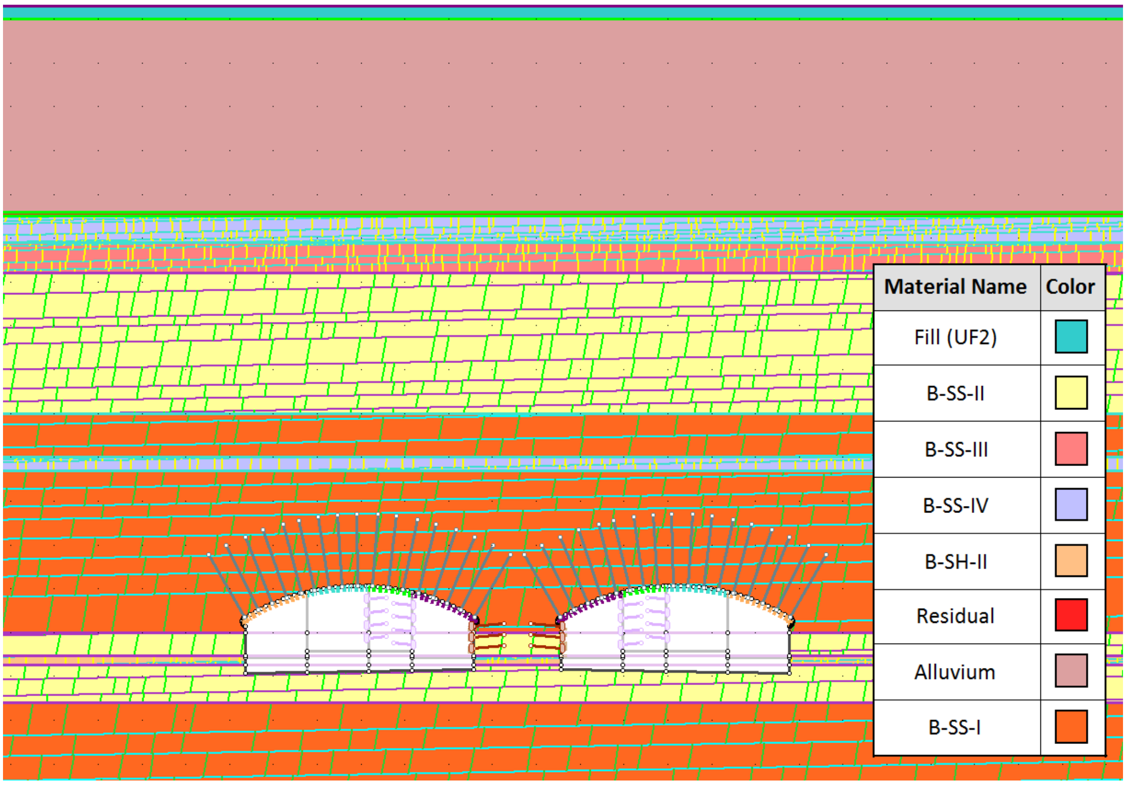

Figure 1.19 FEM model of YJ-HS-TYPE A-W9

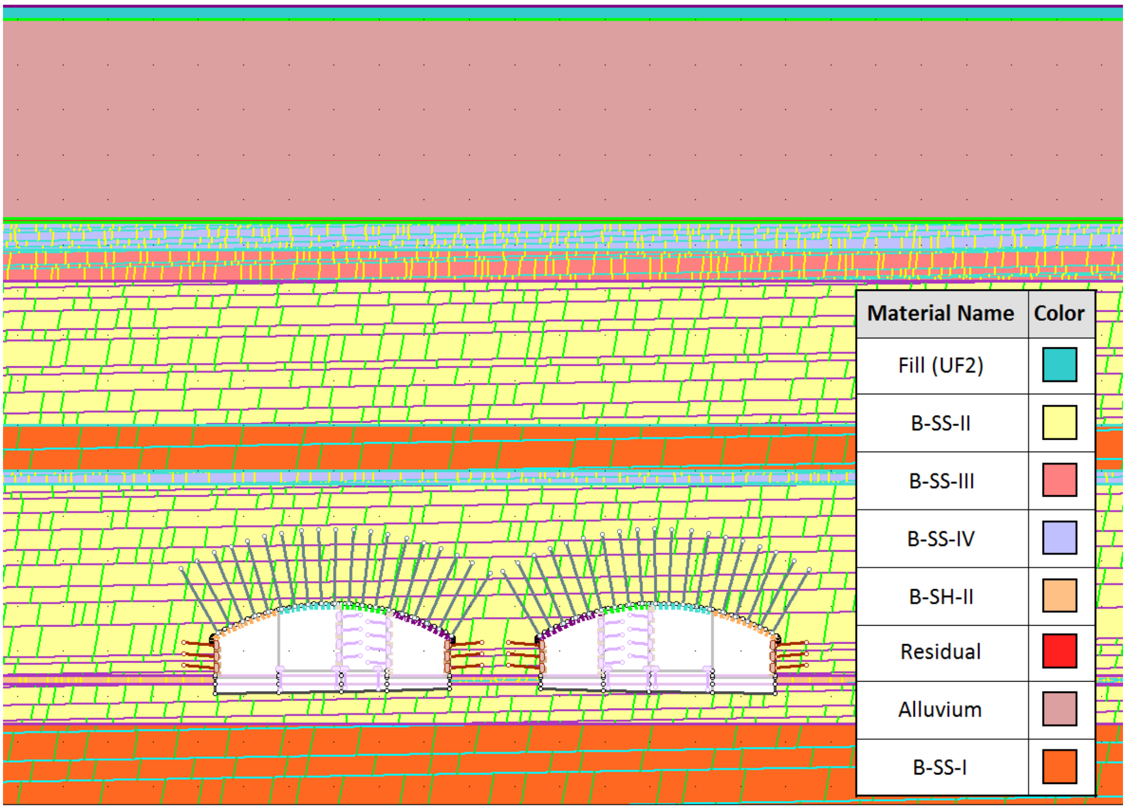

Figure 1.20 FEM model of YJ-HS-TYPE B-W9

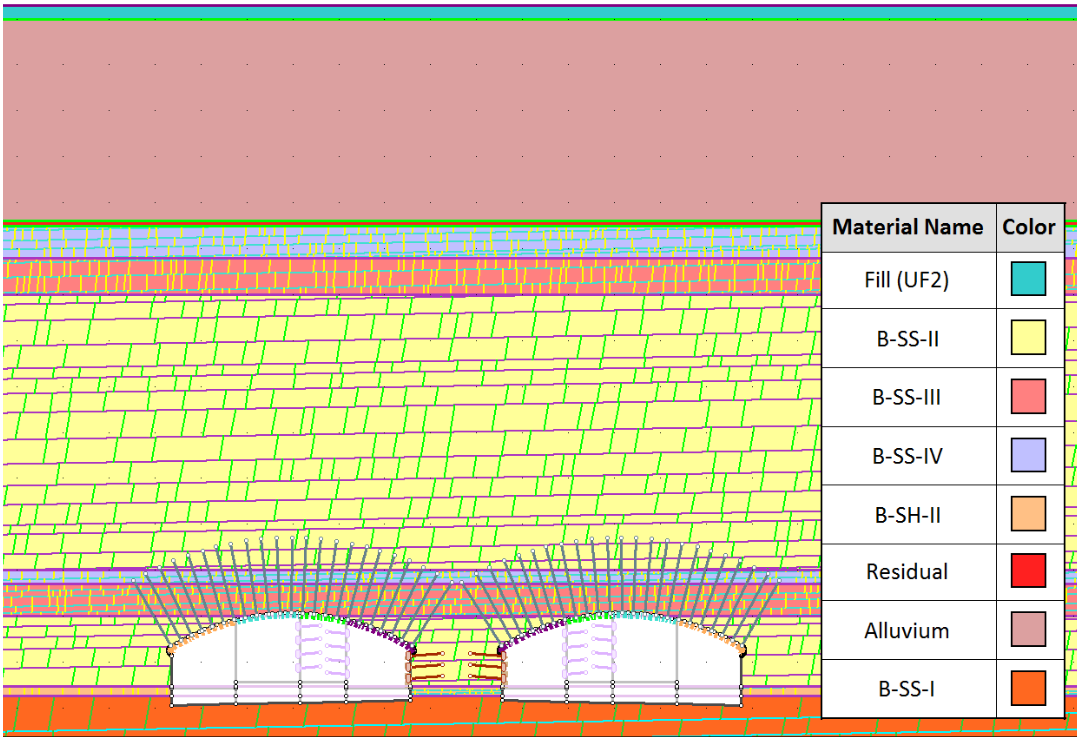

Figure 1.21 FEM model of YJ-HS-TYPE C-W9

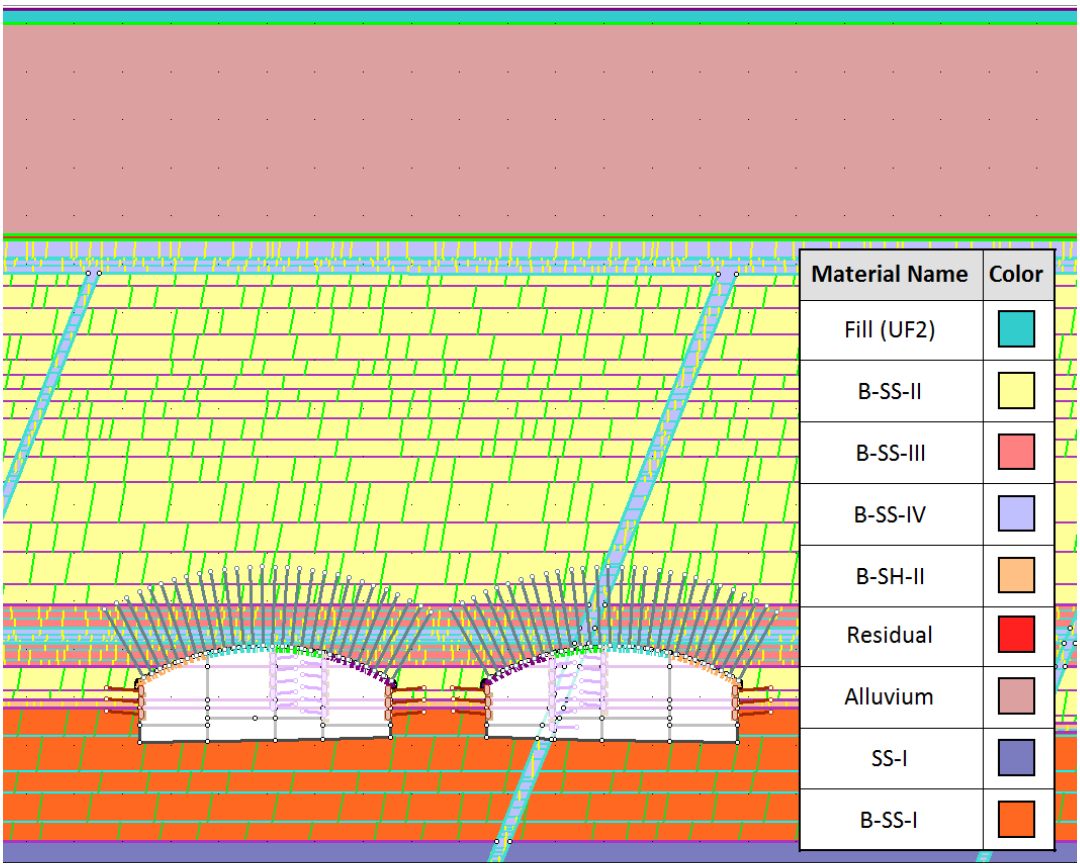

Figure 1.22 FEM model of YJ-HS-TYPE D-W9

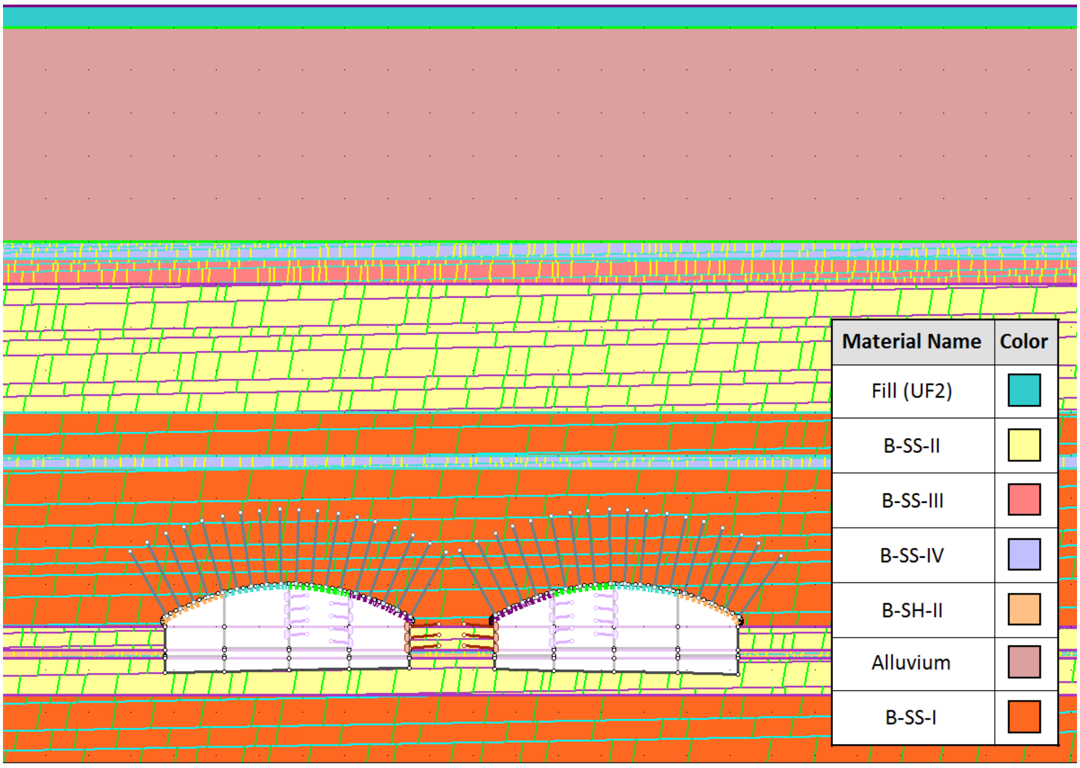

Figure 1.23 FEM model of YJ-HS-TYPE A-W10

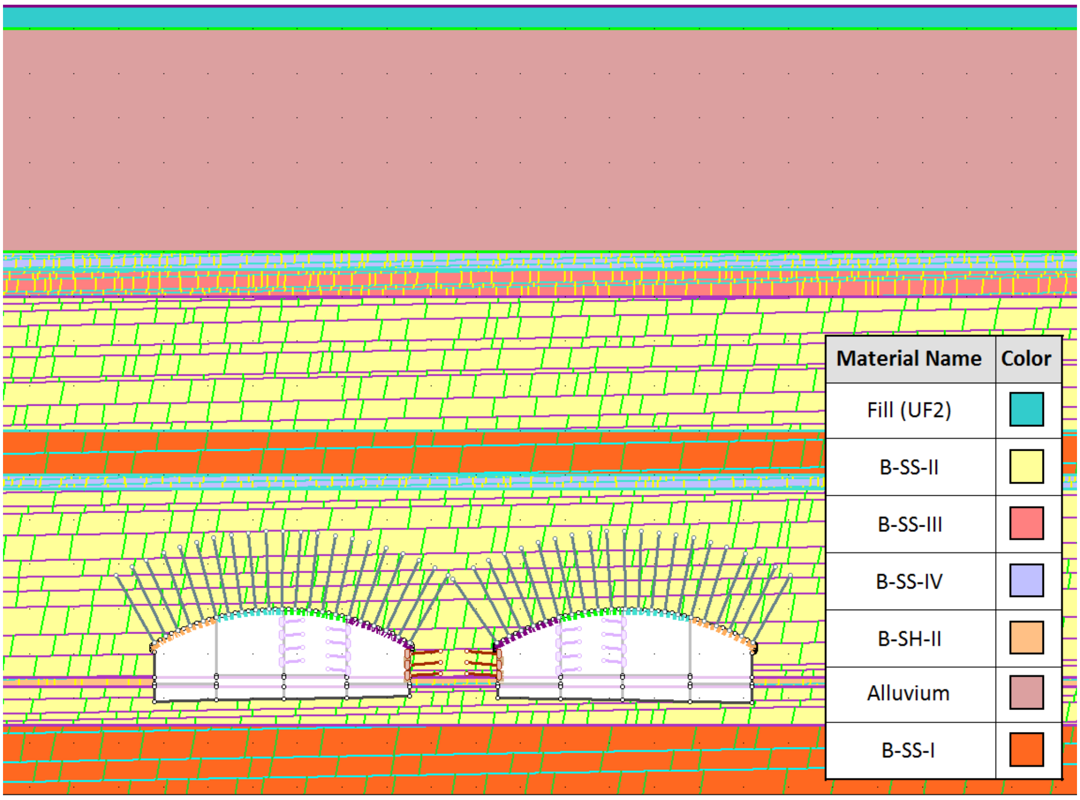

Figure 1.24 FEM model of YJ-HS-TYPE B-W10

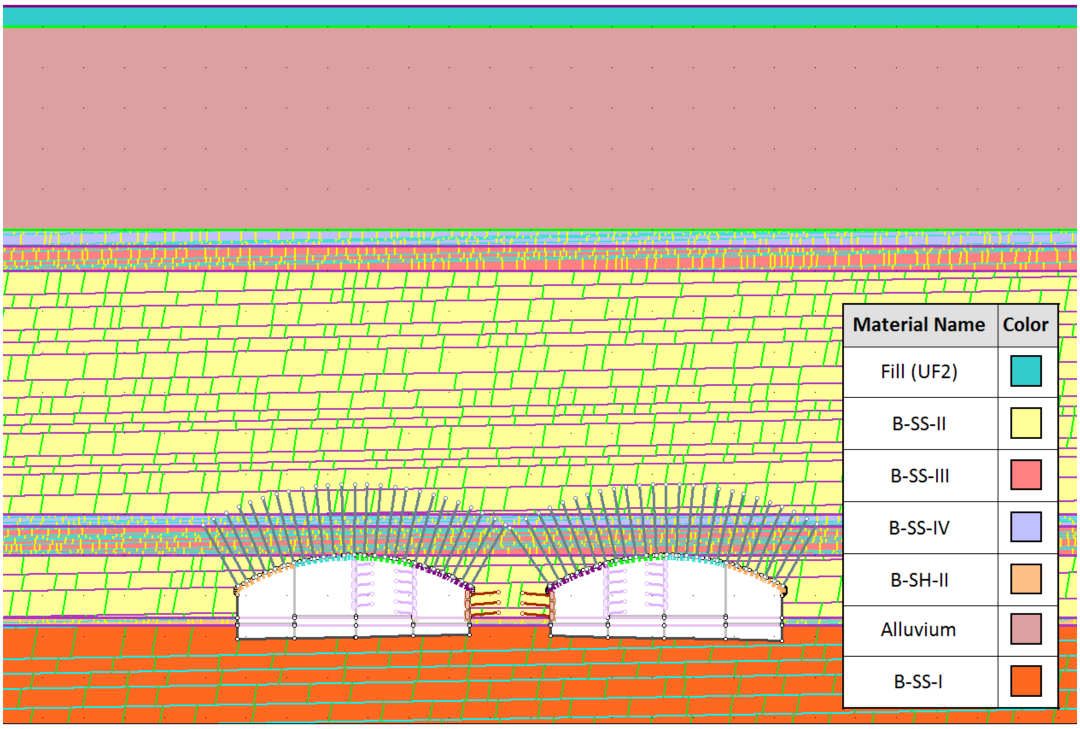

Figure 1.25 FEM model of YJ-HS-TYPE C-W10

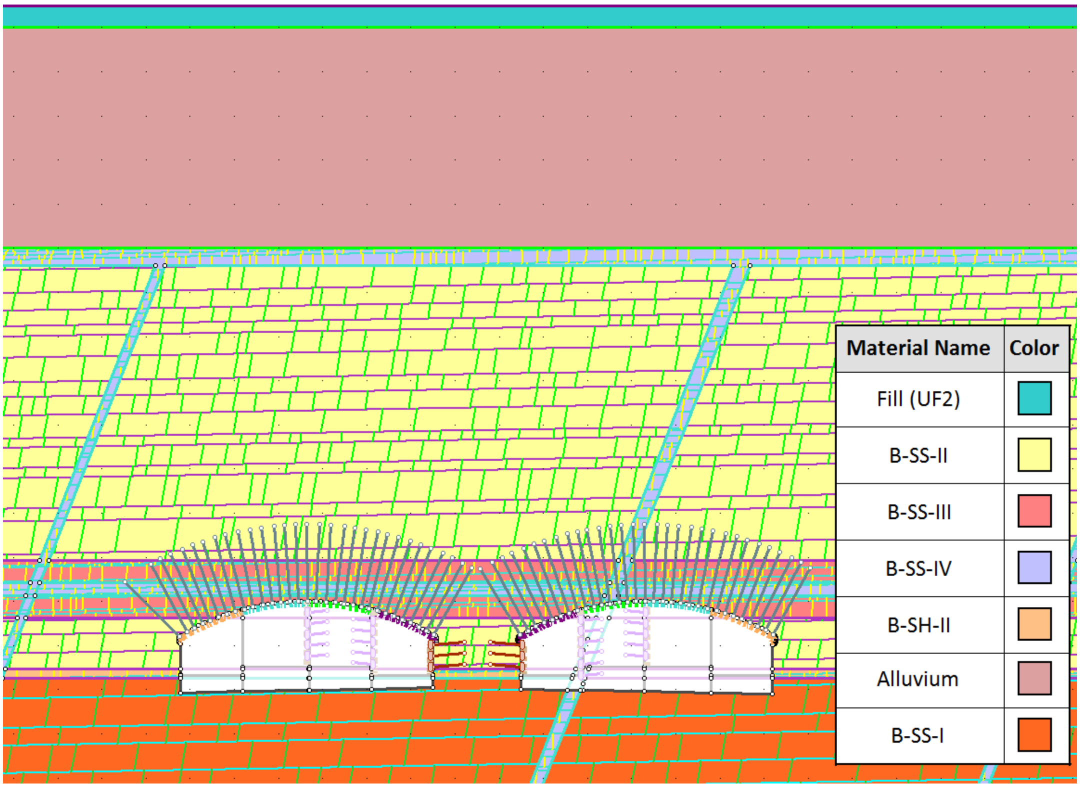

Figure 1.26 FEM model of YJ-HS-TYPE D-W10

1.5 Results

1.5.1 Ground Deformation

1.5.1.1 Tunnel Wall Deformation

Contours of vertical and horizontal displacements around the tunnel openings for the analysed cases are shown in Figure 1.27 to Figure 1.66. A summary of maximum vertical displacement at crown and horizontal displacement at side wall is presented in Table 1.15. The results show that the estimated tunnel convergences vary from 19 mm to 47 mm at tunnel crown and from 15mm to 25mm at side walls of the tunnel. The displacements at tunnel crown are within 0.2% of tunnel span.

Table 1.15 Summary of maximum vertical displacement of crown and maximum horizontal displacement of side wall.

Ground support types	Maximum vertical displacement at crown [mm]	Maximum horizontal displacement at side wall [mm]
YJ-HS-TYPE A-W6	19	15
YJ-HS-TYPE B-W6	28	15
YJ-HS-TYPE C-W6	26	15
YJ-HS-TYPE D-W6	33	15
YJ-HS-TYPE A-W7	21	20
YJ-HS-TYPE B-W7	28	20
YJ-HS-TYPE C-W7	30	20
YJ-HS-TYPE D-W7	35	15
YJ-HS-TYPE A-W8	28	25
YJ-HS-TYPE B-W8	30	20
YJ-HS-TYPE C-W8	40	25
YJ-HS-TYPE D-W8	43	20
YJ-HS-TYPE A-W9	33	25
YJ-HS-TYPE B-W9	35	25
YJ-HS-TYPE C-W9	41	20
YJ-HS-TYPE D-W9	37	20
YJ-HS-TYPE A-W10	35	25
YJ-HS-TYPE B-W10	45	25
YJ-HS-TYPE C-W10	46	20

YJ-HS-TYPE D-W10	47	20

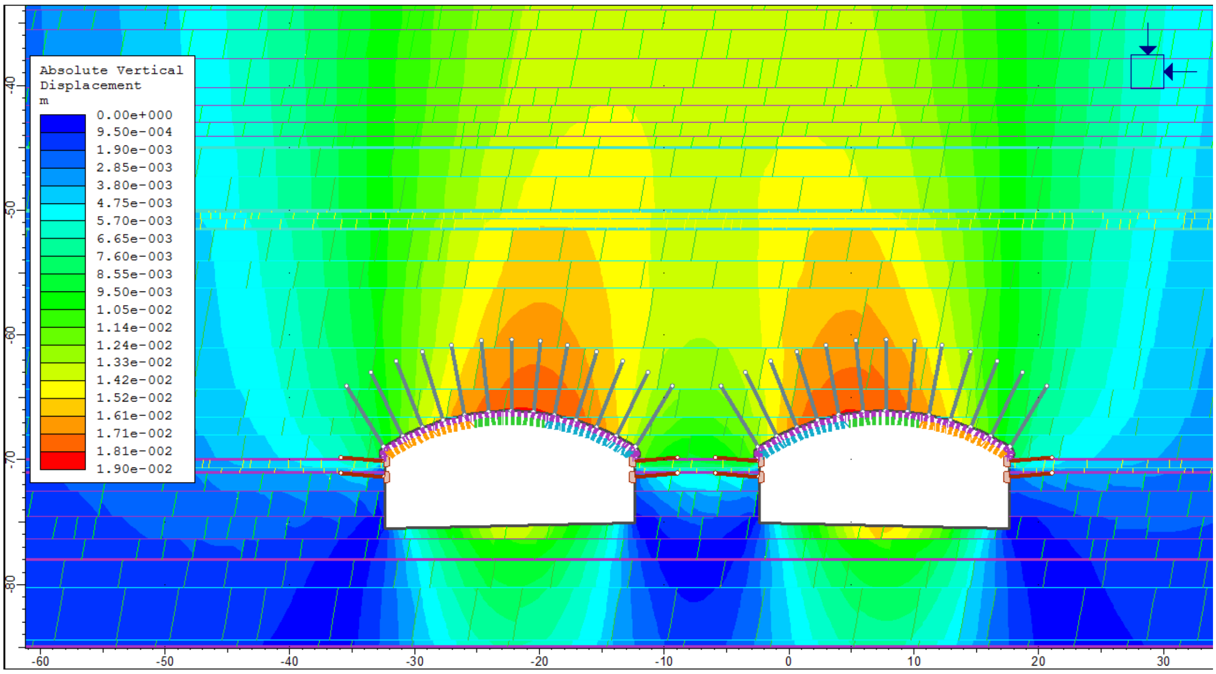

Figure 1.27 Contour of vertical displacements (in m) around tunnel opening for YJ-HS-TYPE A-W6

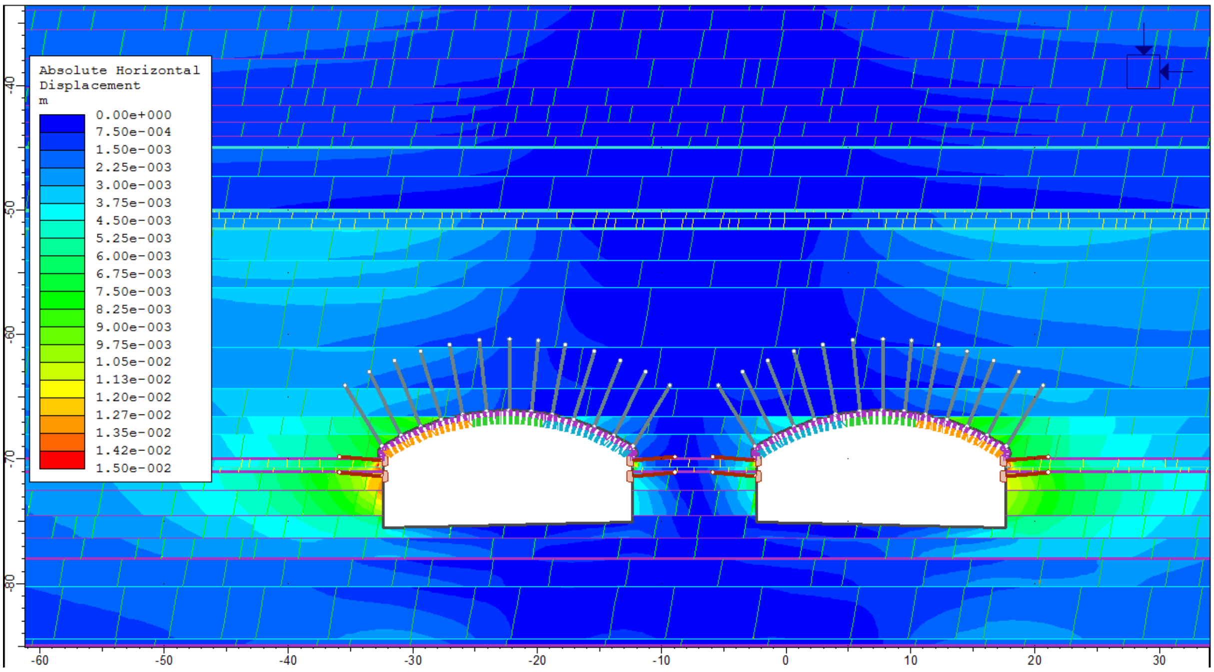

Figure 1.28 Contour of horizontal displacements (in m) around tunnel opening for YJ-HS-TYPE A-W6

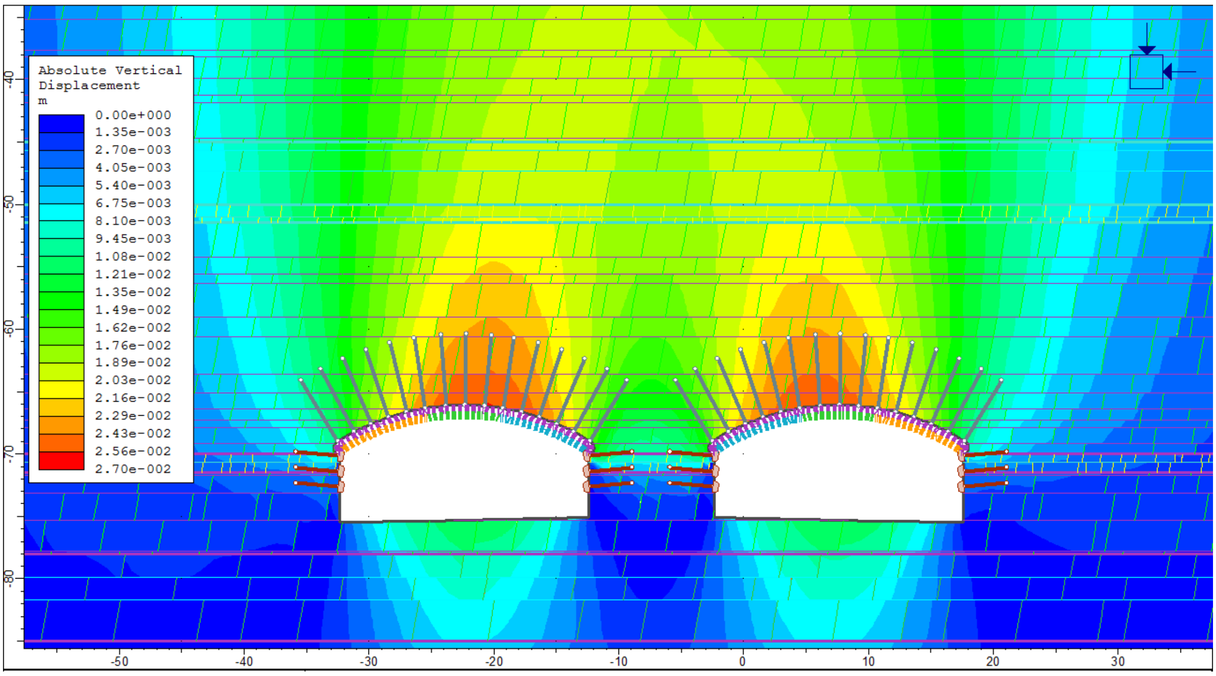

Figure 1.29 Contour of vertical displacements (in m) around tunnel opening for YJ-HS-TYPE B-W6

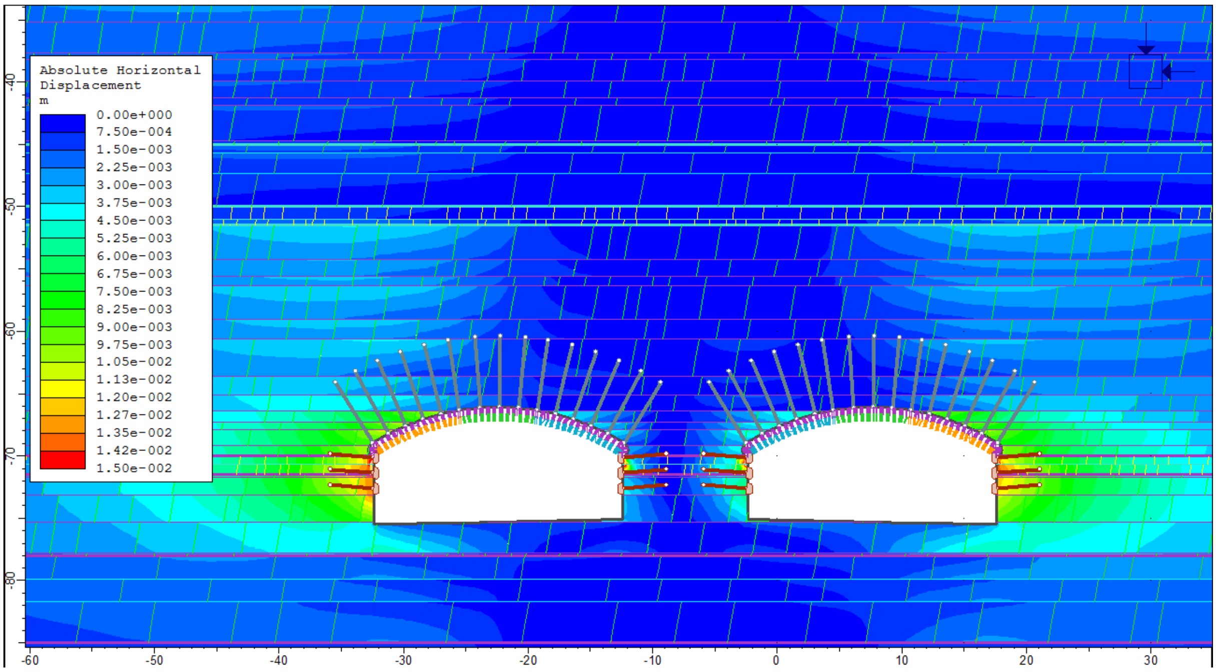

Figure 1.30 Contour of horizontal displacements (in m) around tunnel opening for YJ-HS-TYPE B-W6

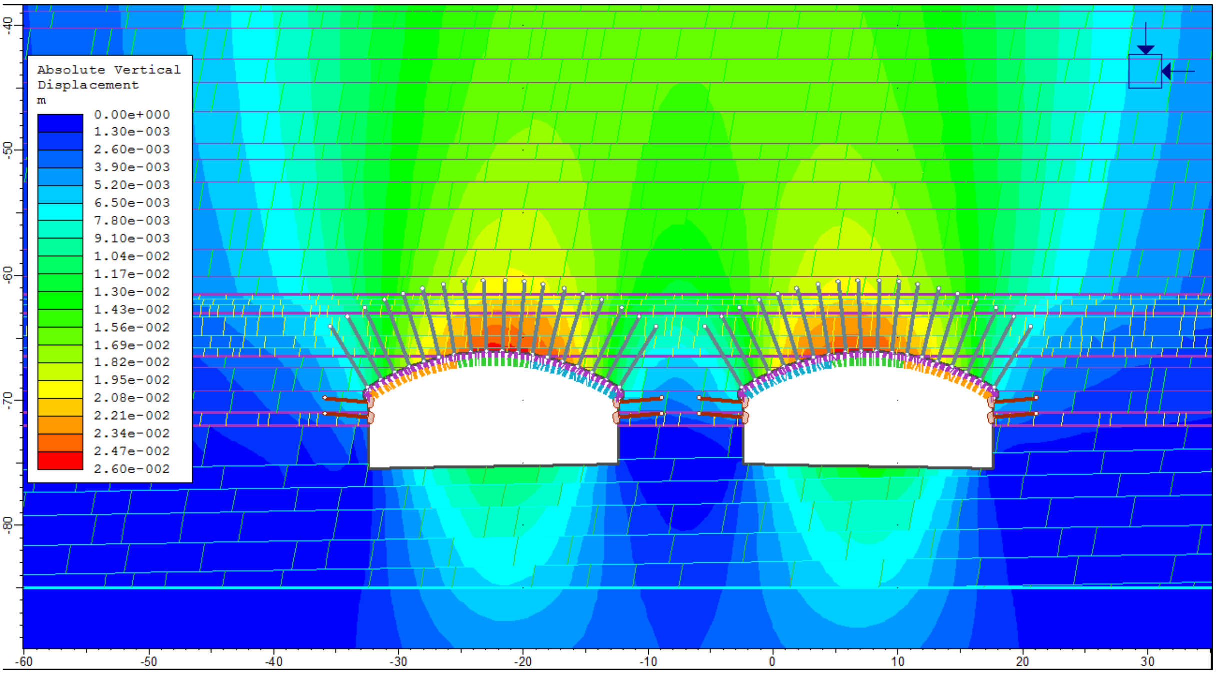

Figure 1.31 Contour of vertical displacements (in m) around tunnel opening for YJ-HS-TYPE C-W6

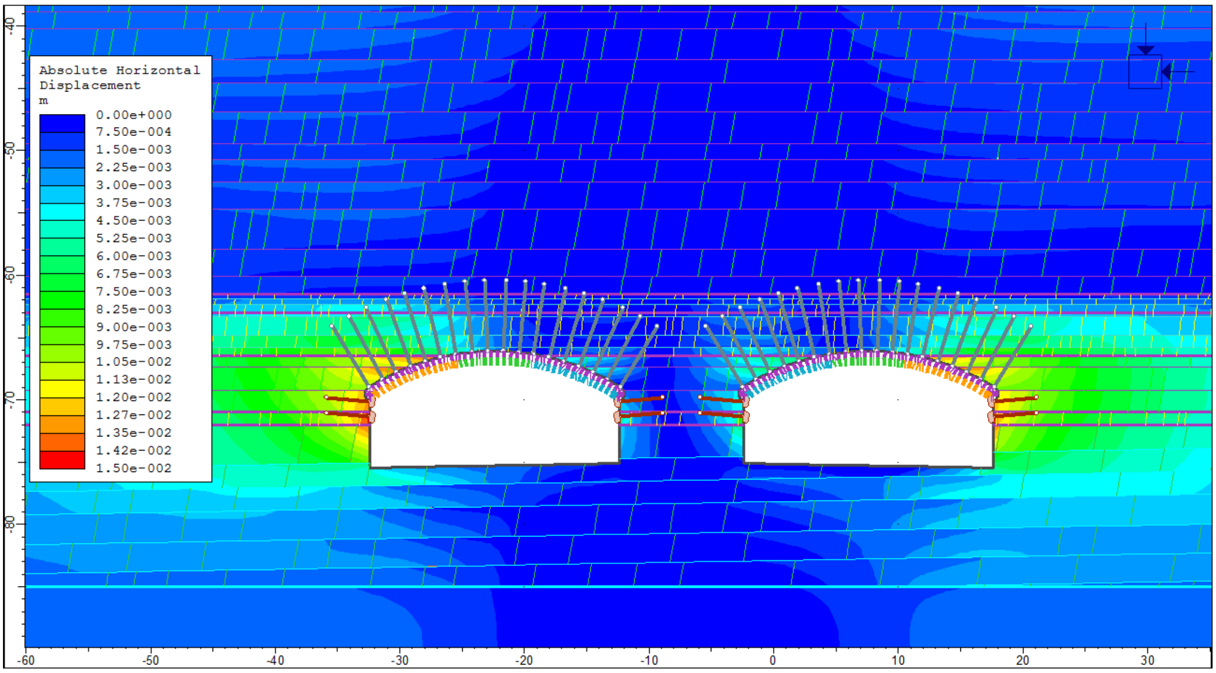

Figure 1.32 Contour of horizontal displacements (in m) around tunnel opening for YJ-HS-TYPE C-W6

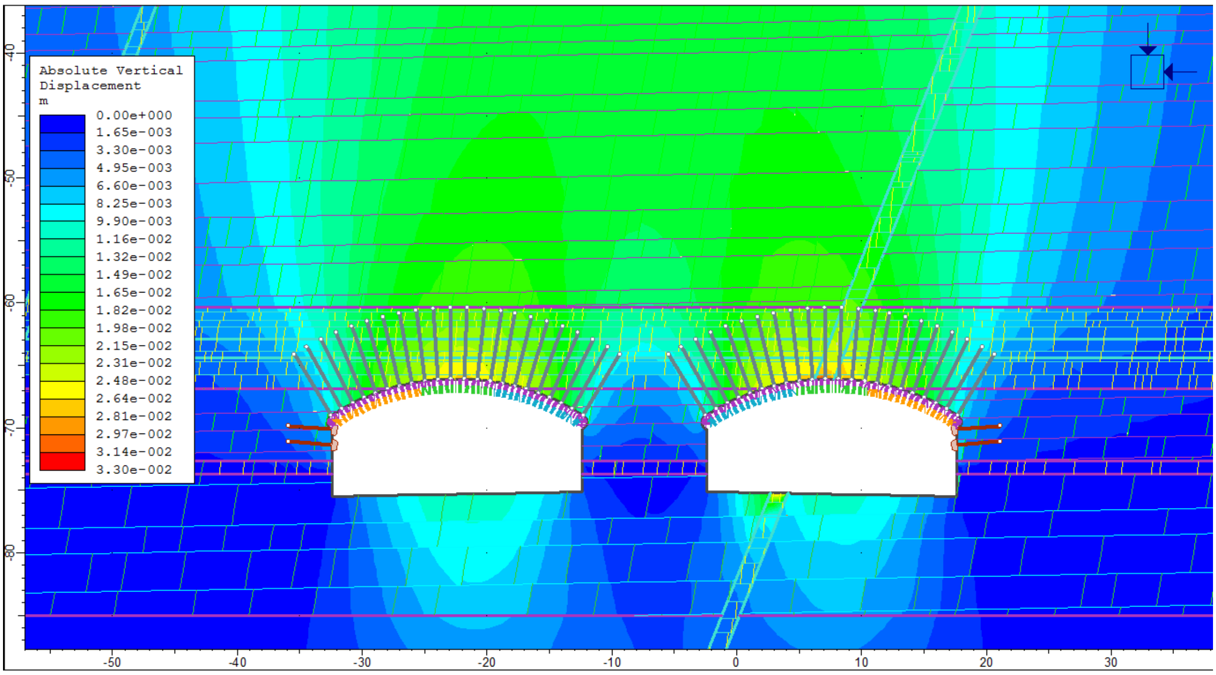

Figure 1.33 Contour of vertical displacements (in m) around tunnel opening for YJ-HS-TYPE D-W6

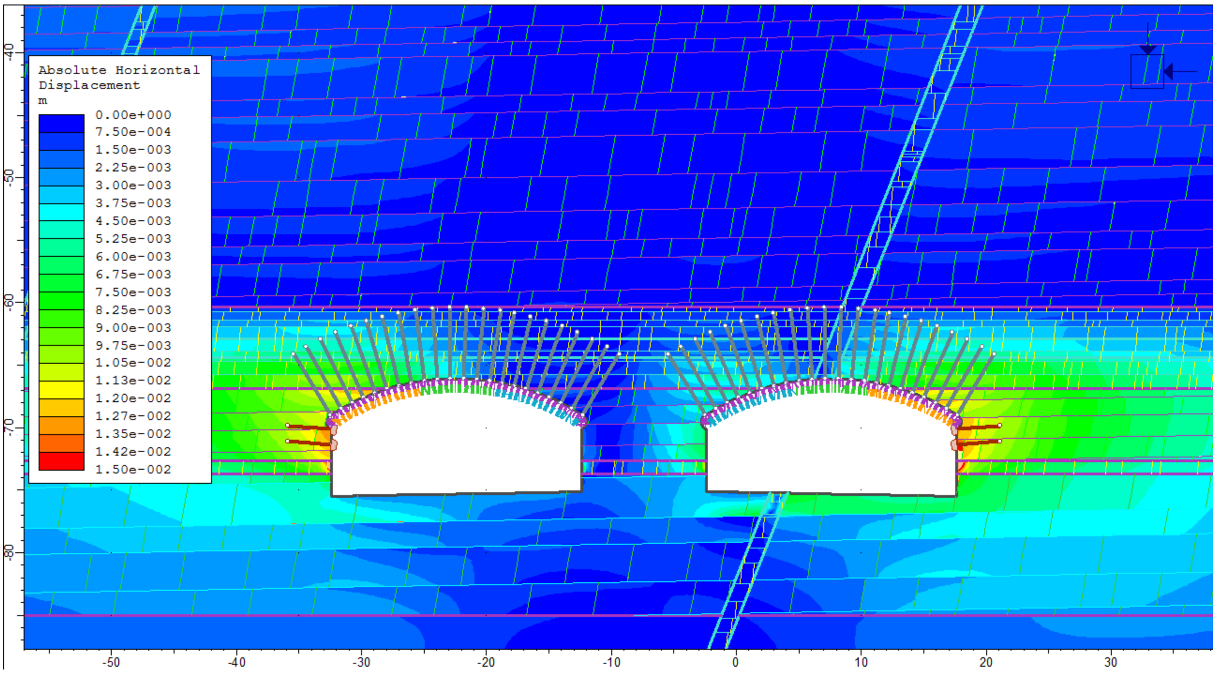

Figure 1.34 Contour of horizontal displacements (in m) around tunnel opening for YJ-HS-TYPE D-W6

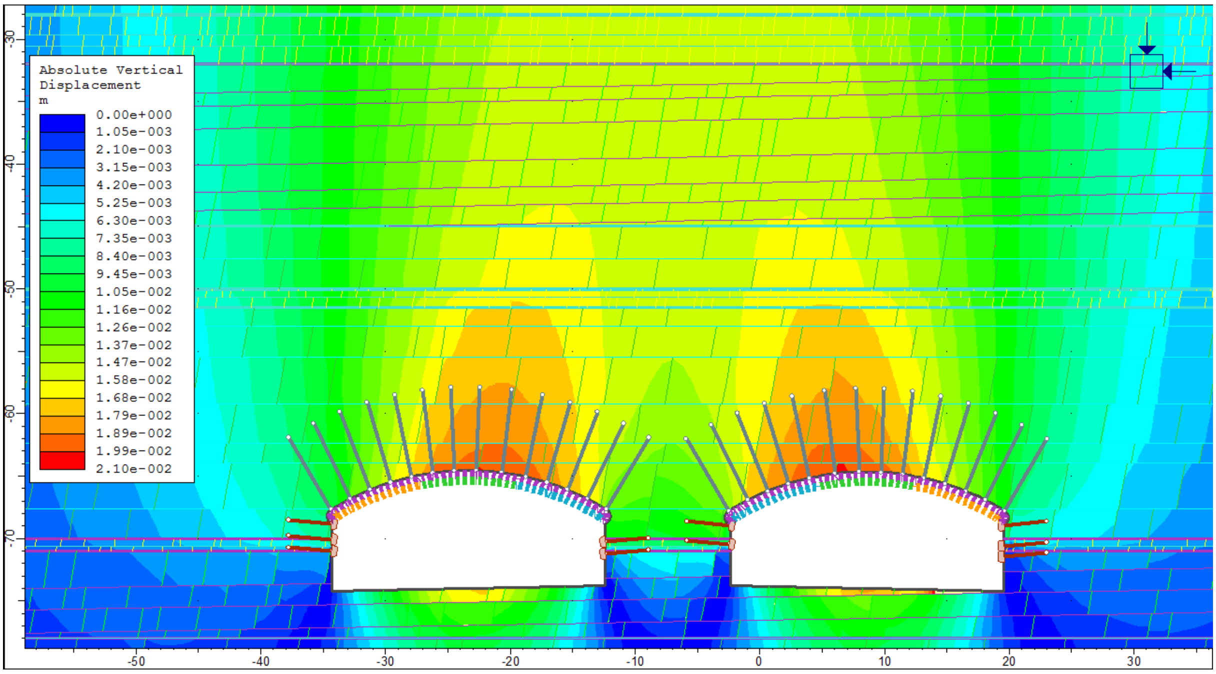

Figure 1.35 Contour of vertical displacements (in m) around tunnel opening for YJ-HS-TYPE A-W7

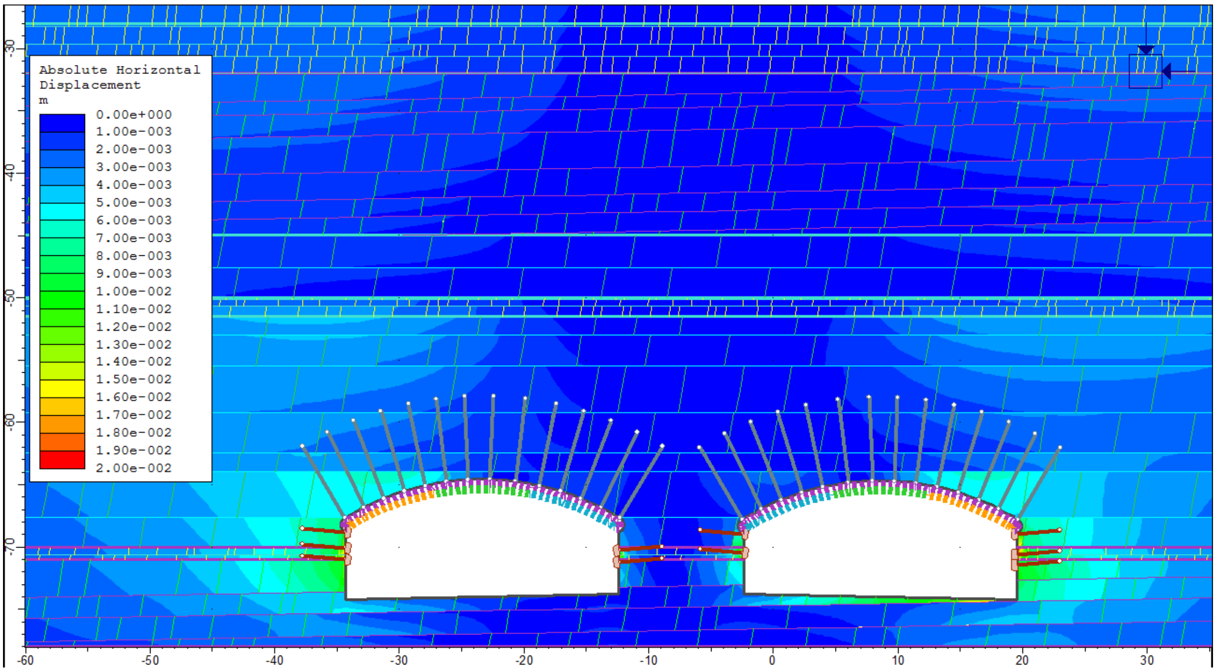

Figure 1.36 Contour of horizontal displacements (in m) around tunnel opening for YJ-HS-TYPE A-W7

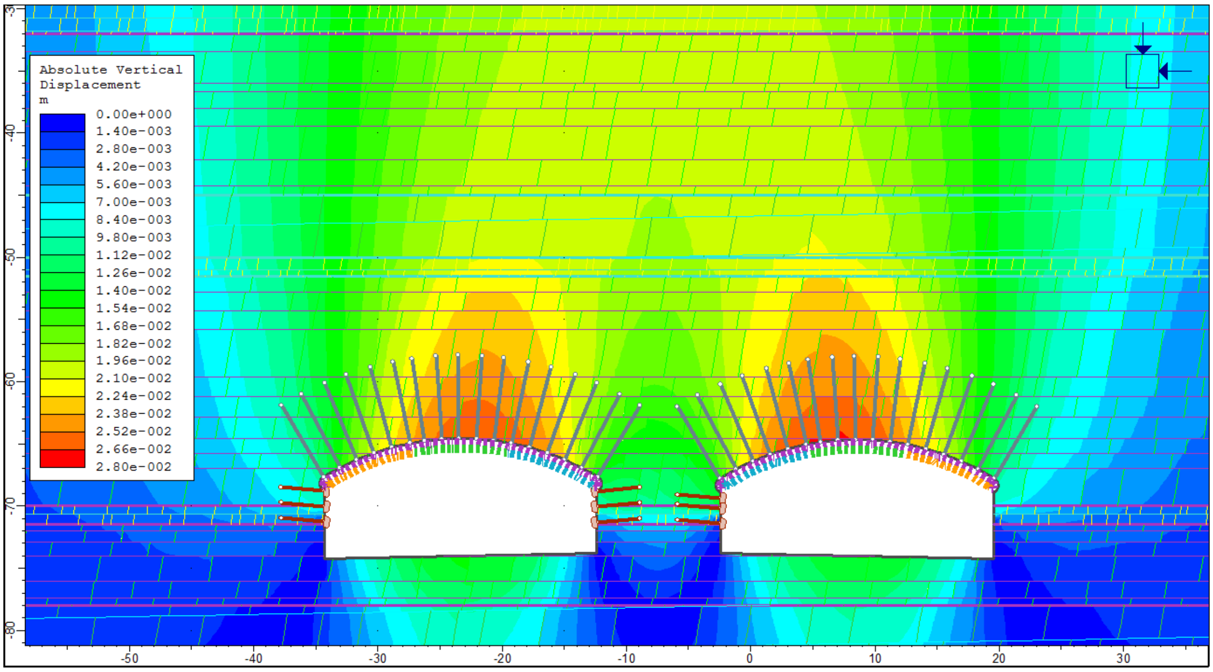

Figure 1.37 Contour of vertical displacements (in m) around tunnel opening for YJ-HS-TYPE B-W7

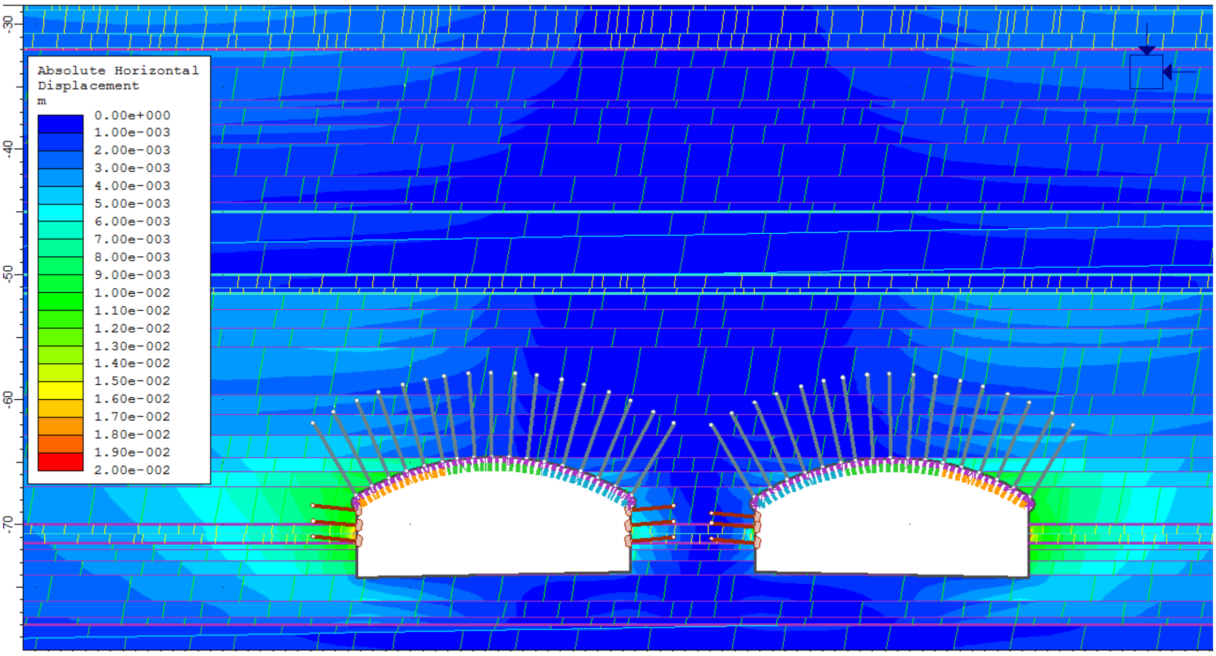

Figure 1.38 Contour of horizontal displacements (in m) around tunnel opening for YJ-HS-TYPE B-W7

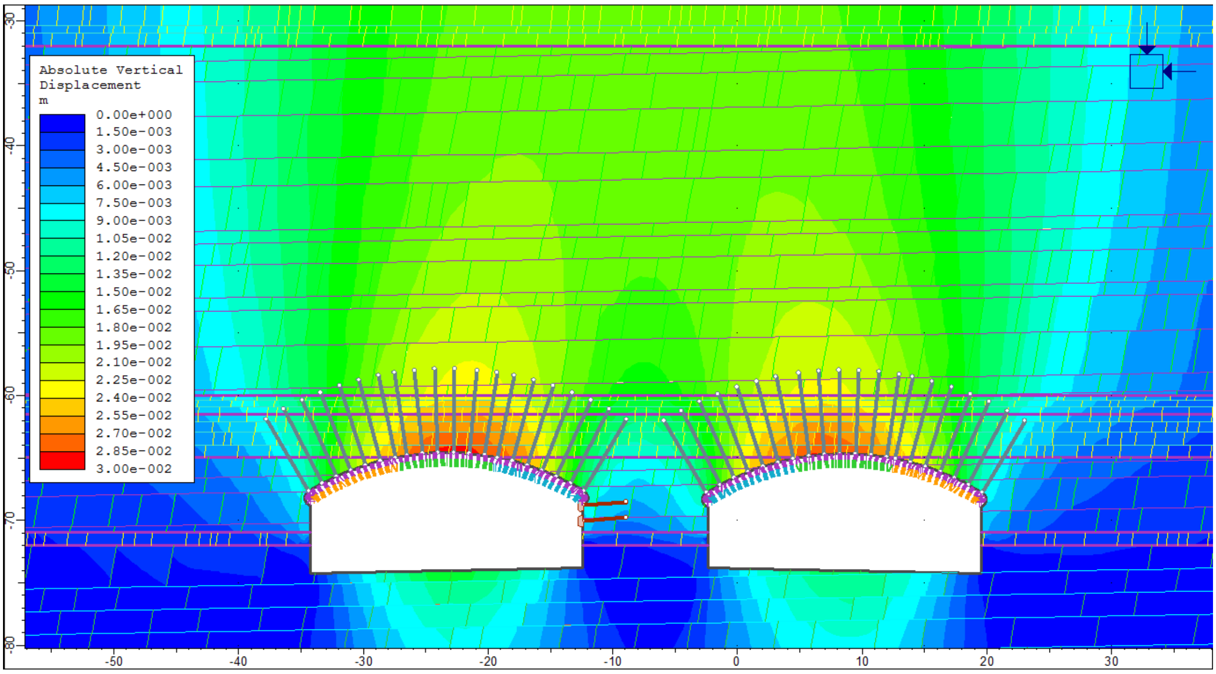

Figure 1.39 Contour of vertical displacements (in m) around tunnel opening for YJ-HS-TYPE C-W7

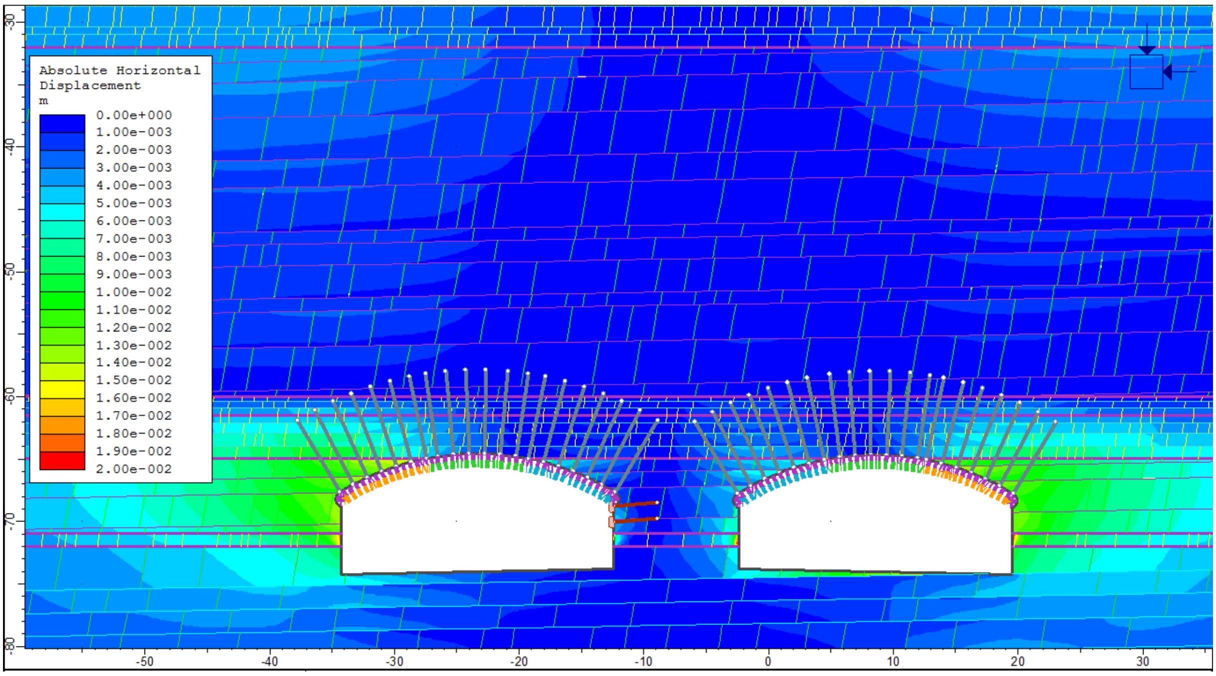

Figure 1.40 Contour of horizontal displacements (in m) around tunnel opening for YJ-HS-TYPE C-W7

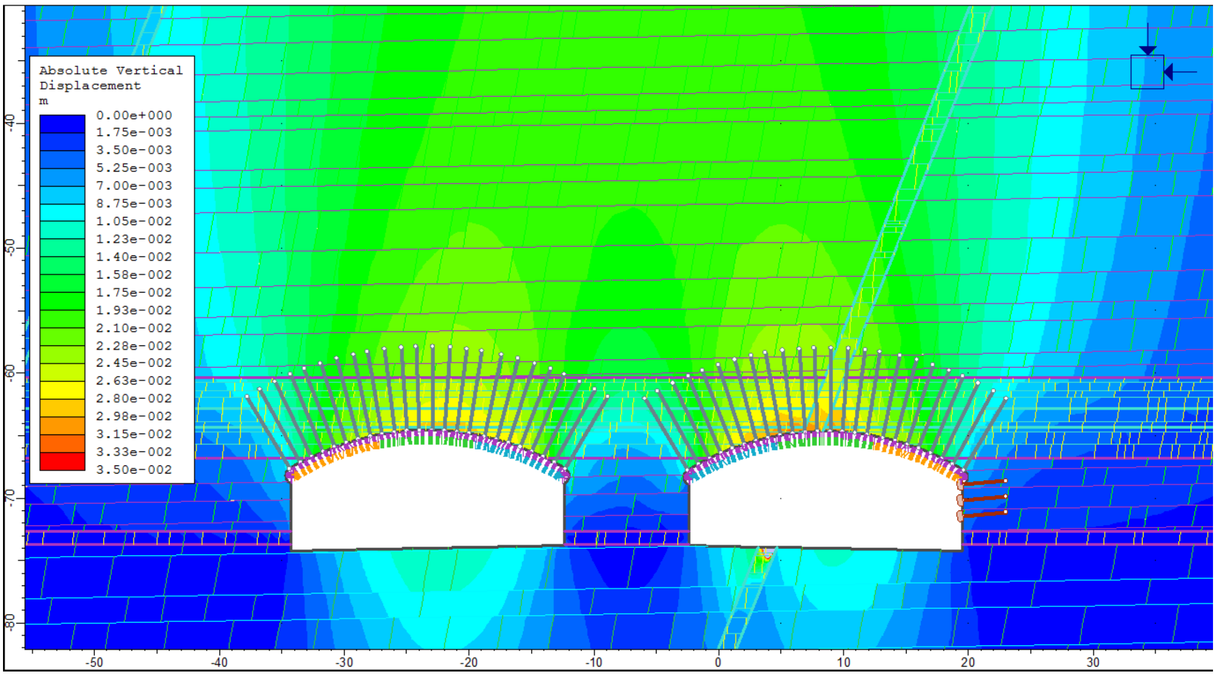

Figure 1.41 Contour of vertical displacements (in m) around tunnel opening for YJ-HS-TYPE D-W7

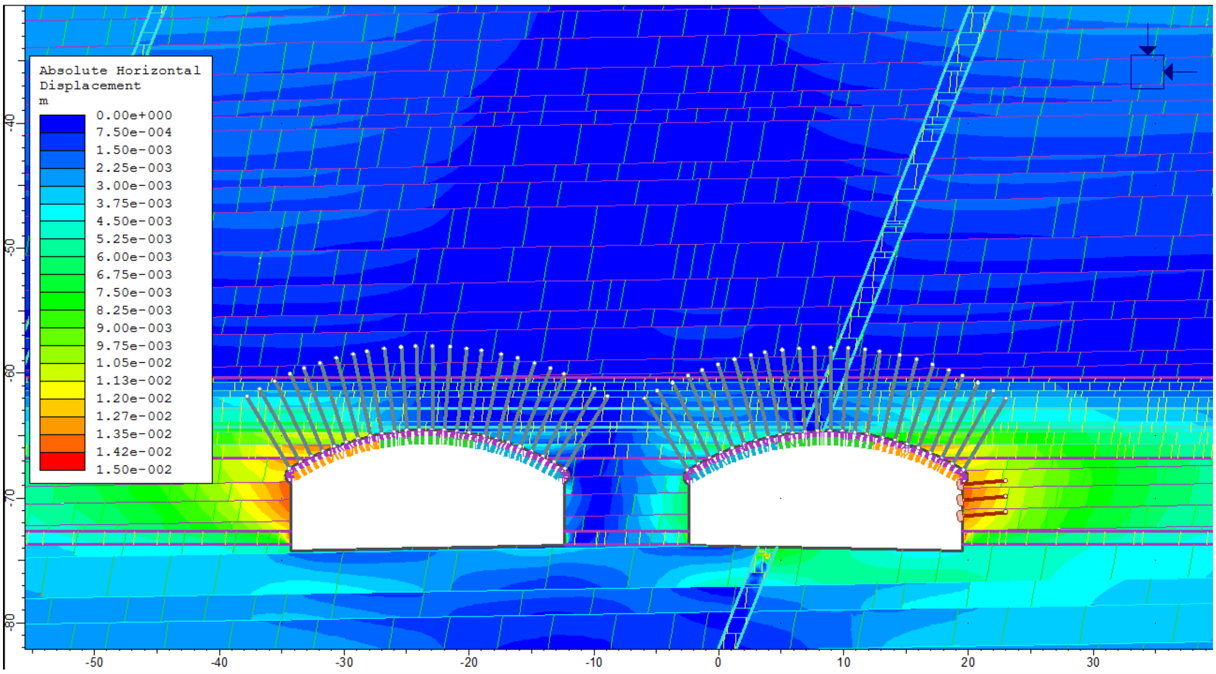

Figure 1.42 Contour of horizontal displacements (in m) around tunnel opening for YJ-HS-TYPE D-W7

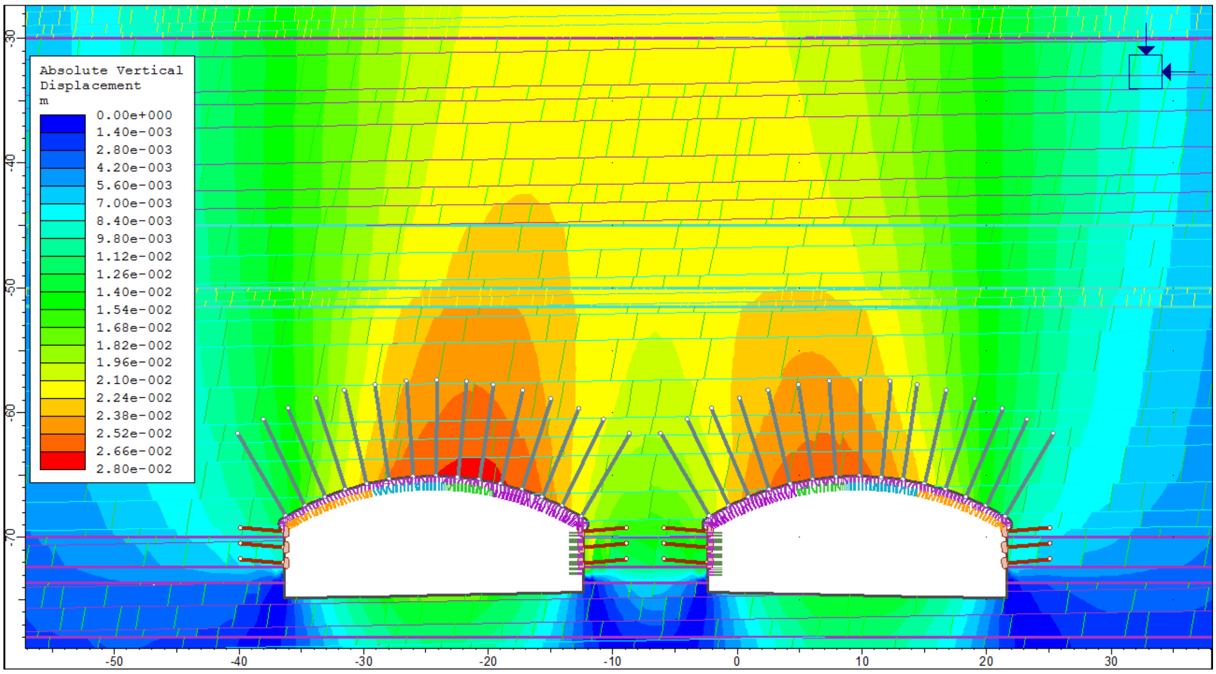

Figure 1.43 Contour of vertical displacements (in m) around tunnel opening for YJ-HS-TYPE A-W8

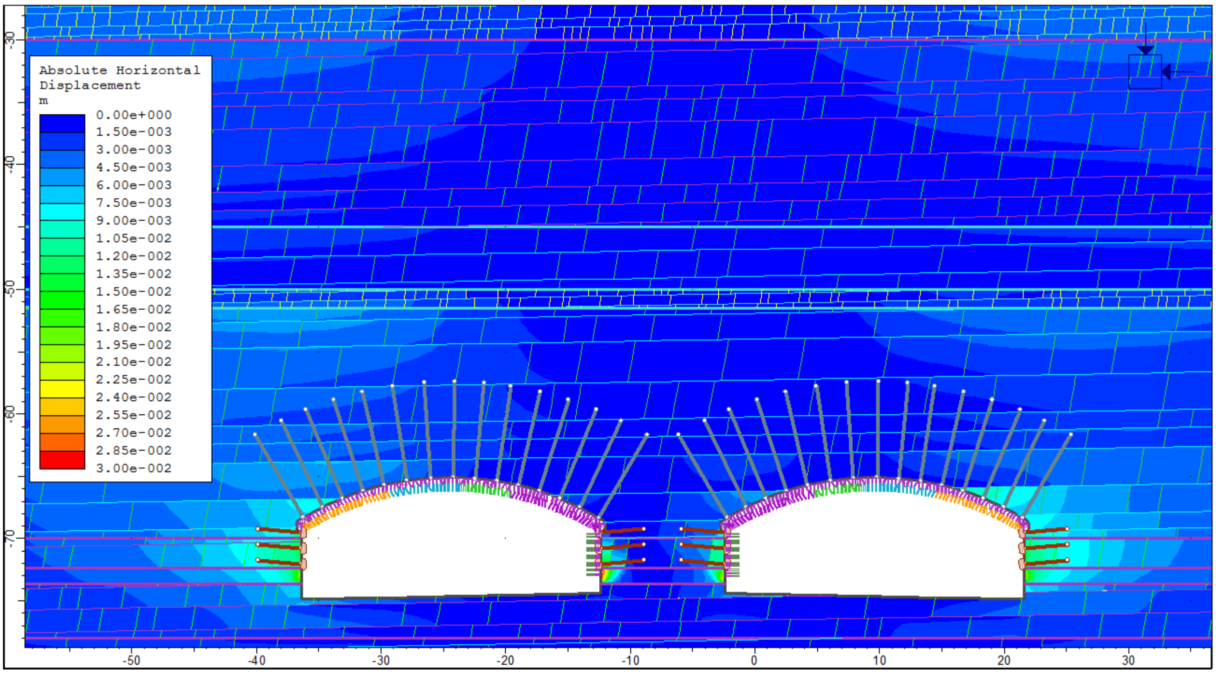

Figure 1.44 Contour of horizontal displacements (in m) around tunnel opening for YJ-HS-TYPE A-W8

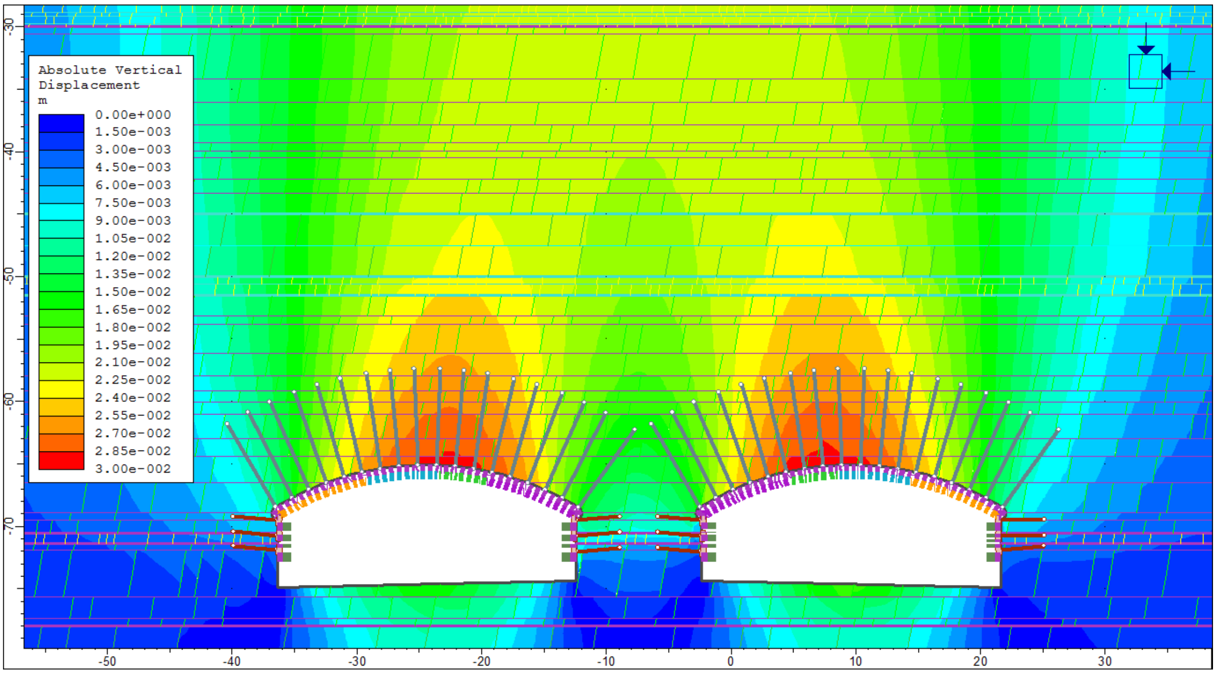

Figure 1.45 Contour of vertical displacements (in m) around tunnel opening for YJ-HS-TYPE B-W8

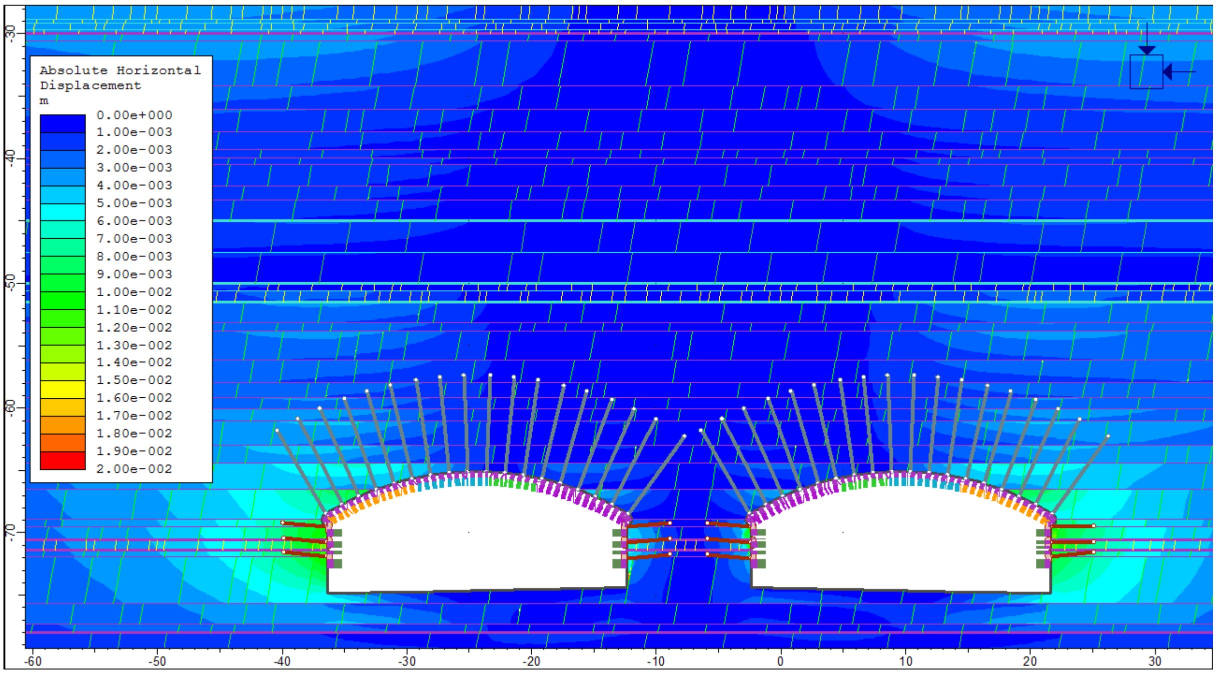

Figure 1.46 Contour of horizontal displacements (in m) around tunnel opening for YJ-HS-TYPE B-W8

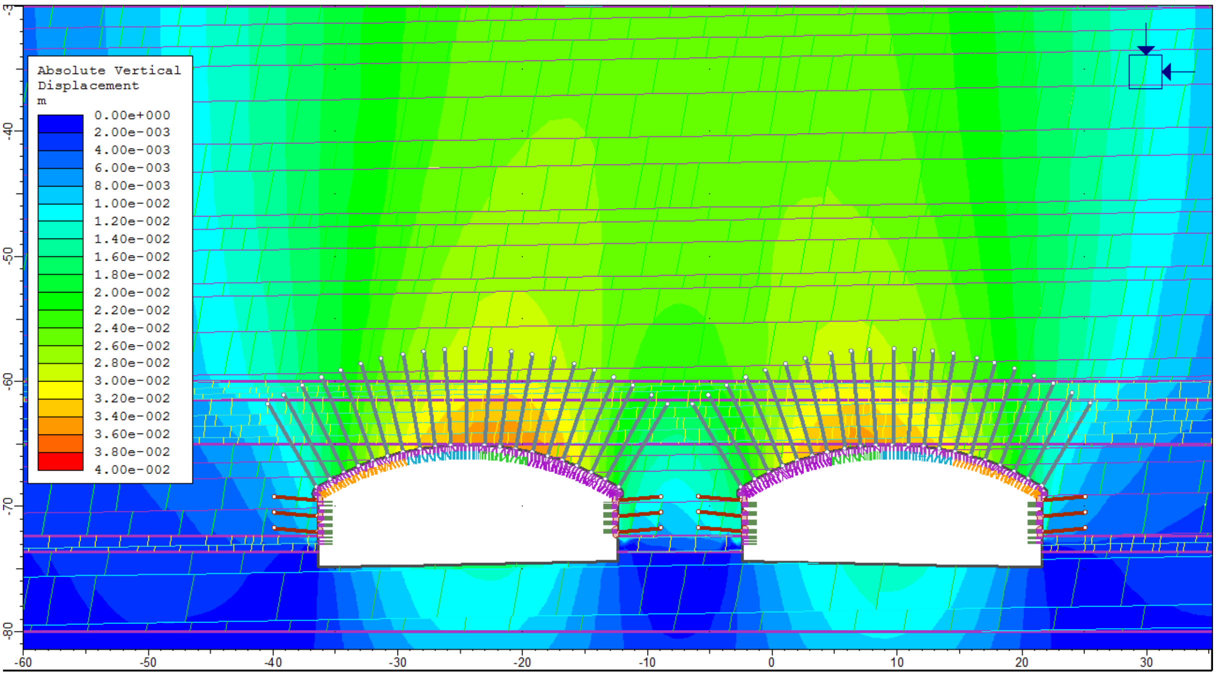

Figure 1.47 Contour of vertical displacements (in m) around tunnel opening for YJ-HS-TYPE C-W8

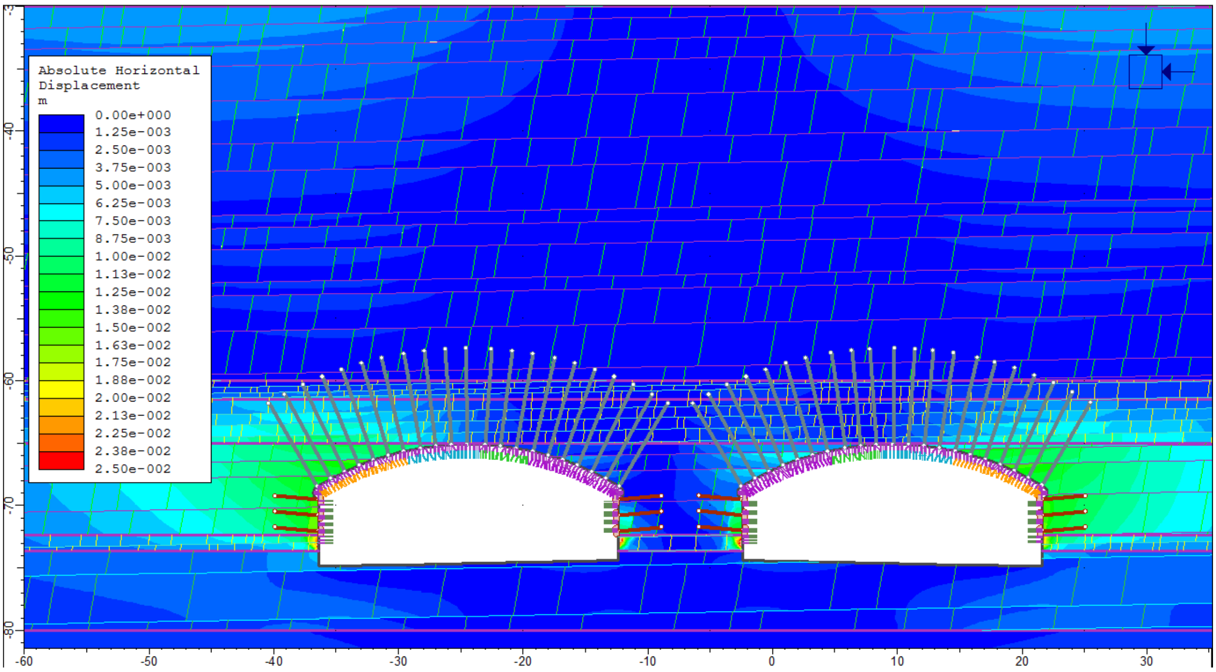

Figure 1.48 Contour of horizontal displacements (in m) around tunnel opening for YJ-HS-TYPE C-W8

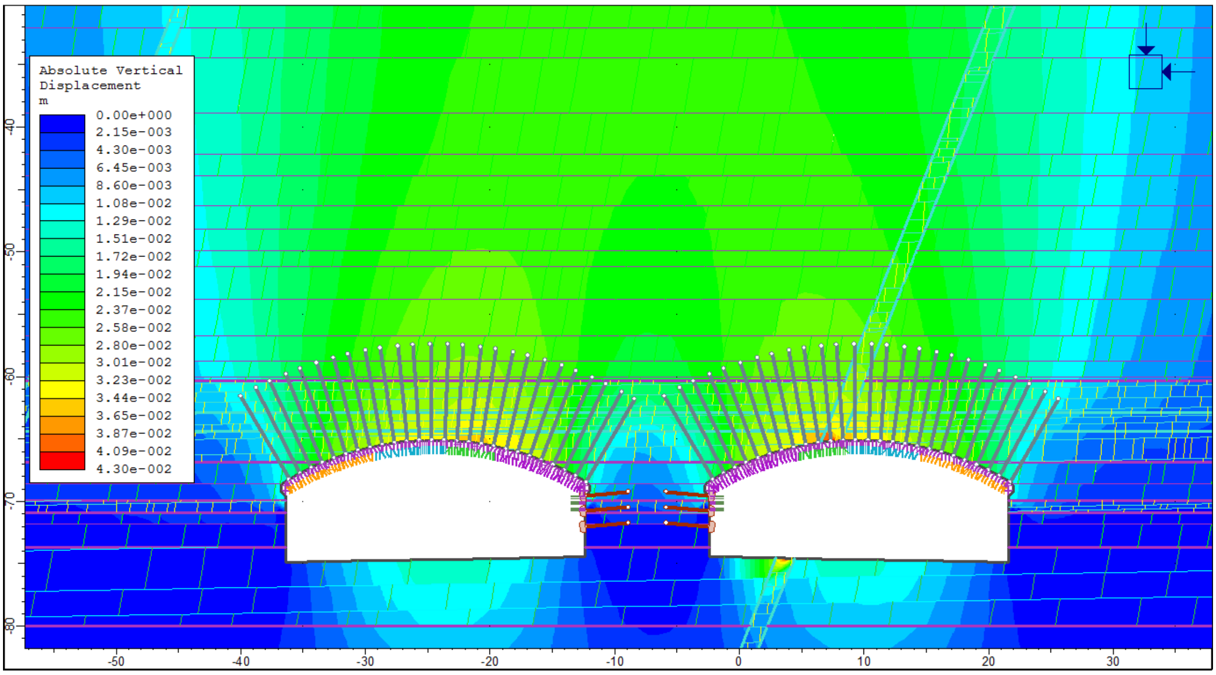

Figure 1.49 Contour of vertical displacements (in m) around tunnel opening for YJ-HS-TYPE D-W8

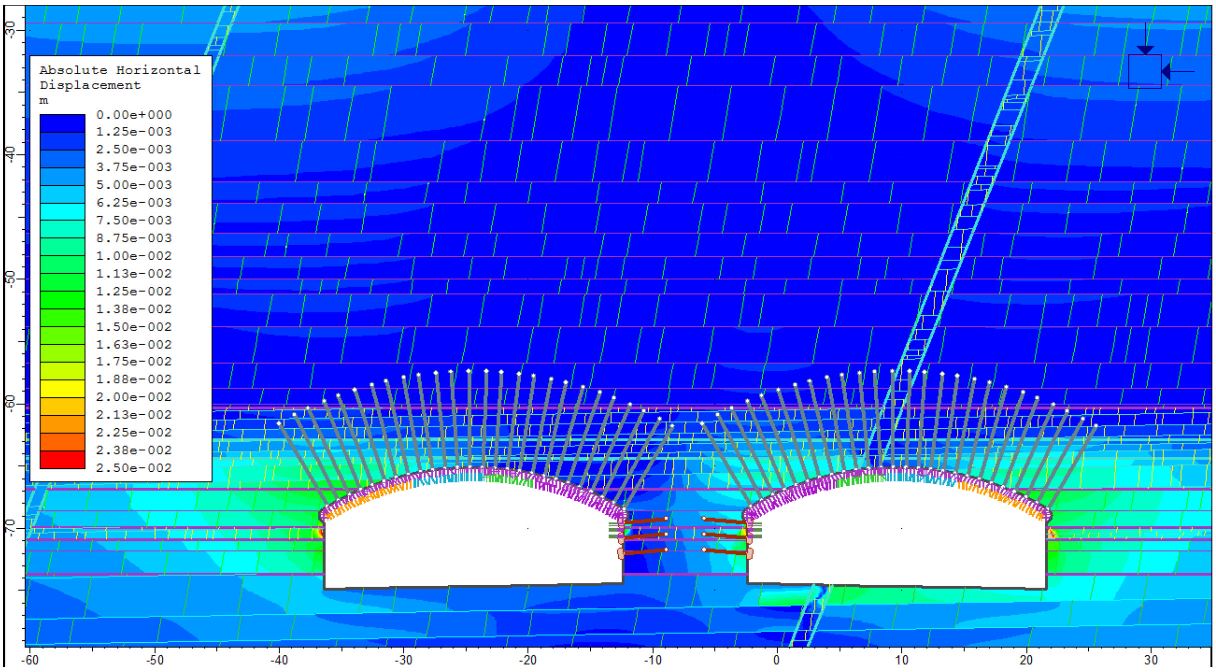

Figure 1.50 Contour of horizontal displacements (in m) around tunnel opening for YJ-HS-TYPE D-W8

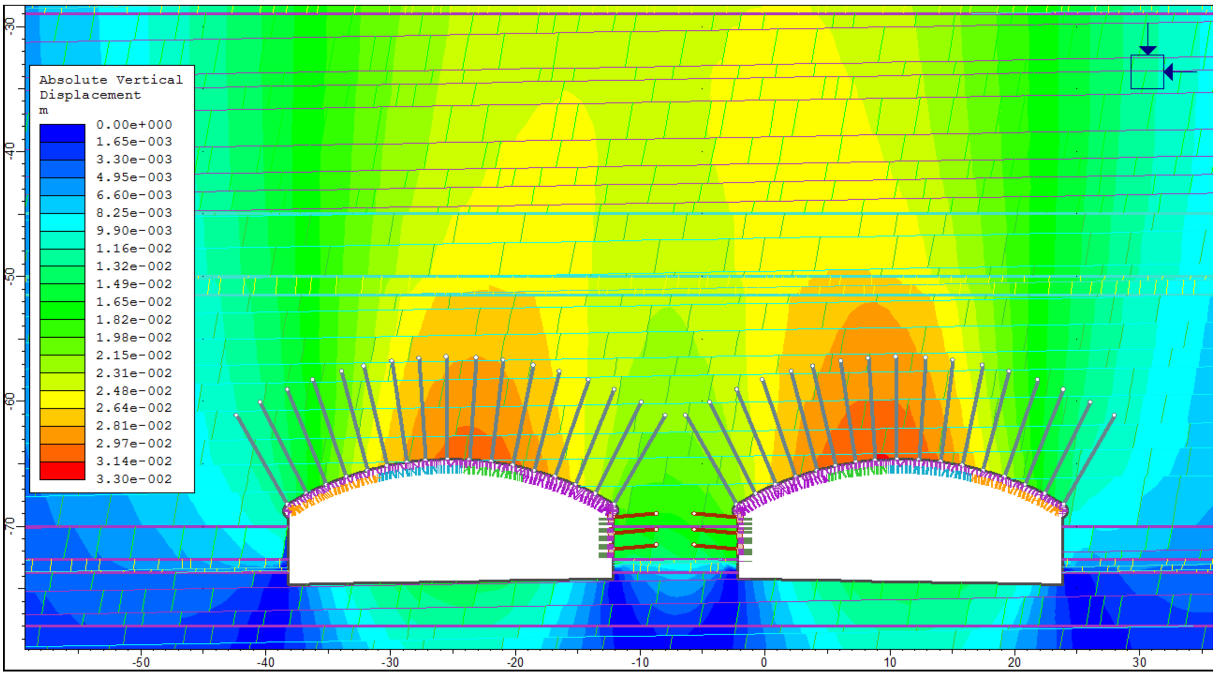

Figure 1.51 Contour of vertical displacements (in m) around tunnel opening for YJ-HS-TYPE A-W9

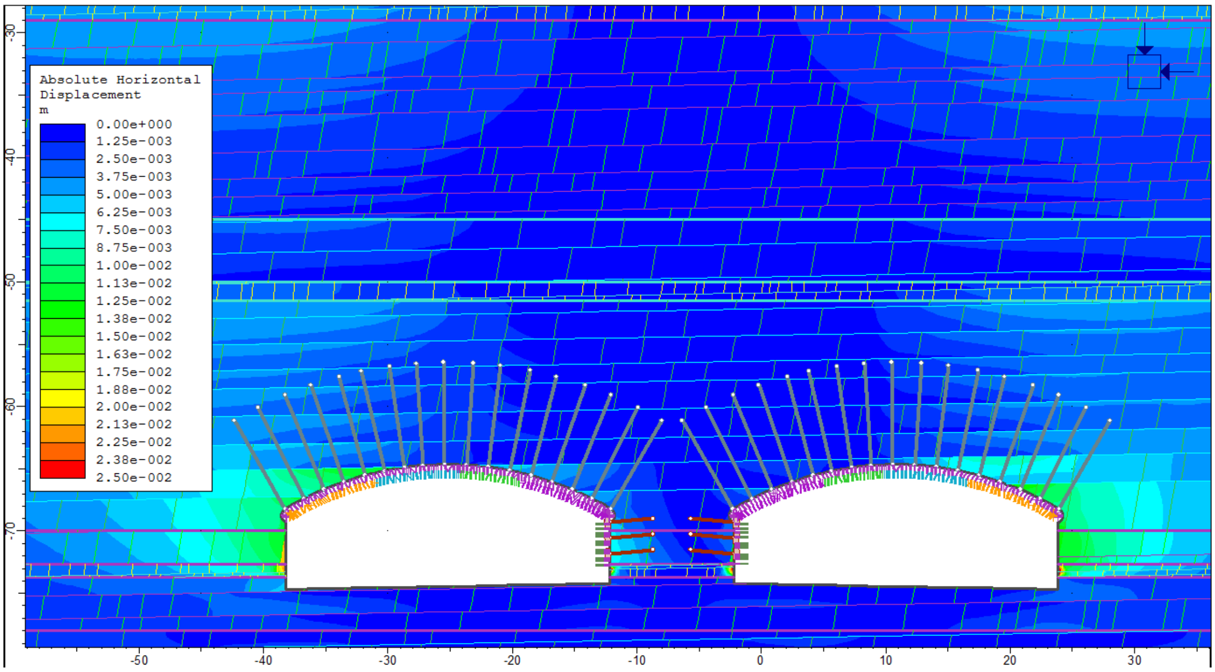

Figure 1.52 Contour of horizontal displacements (in m) around tunnel opening for YJ-HS-TYPE A-W9

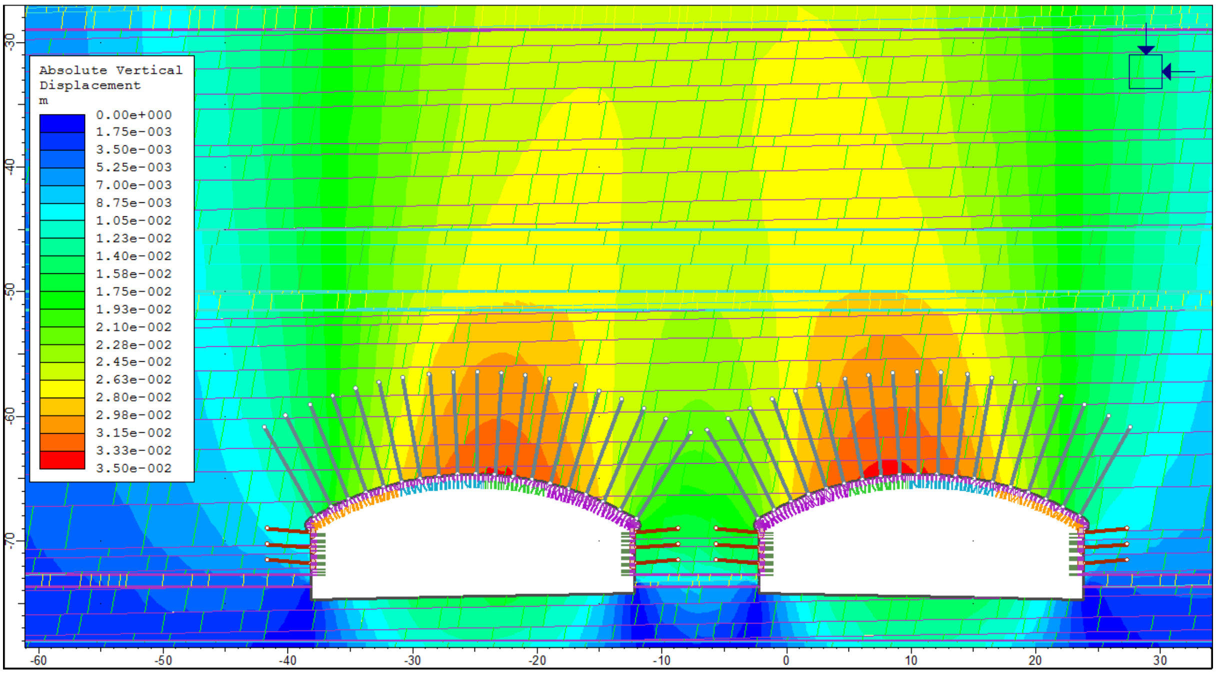

Figure 1.53 Contour of vertical displacements (in m) around tunnel opening for YJ-HS-TYPE B-W9

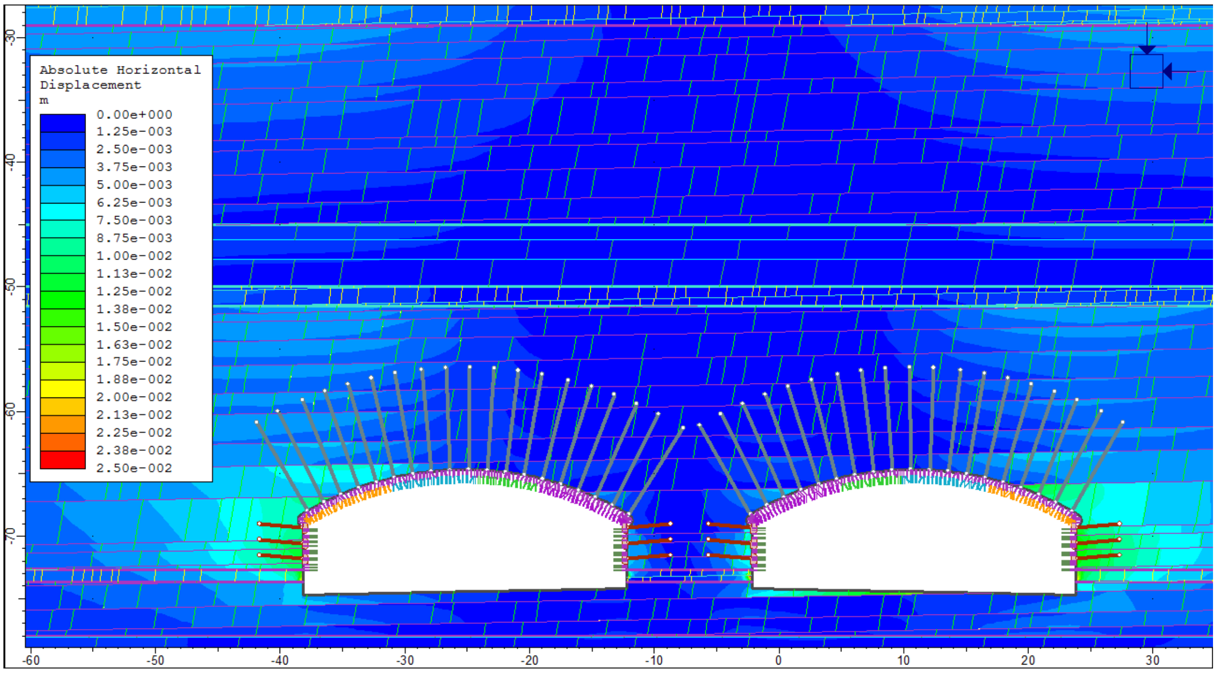

Figure 1.54 Contour of horizontal displacements (in m) around tunnel opening for YJ-HS-TYPE B-W9

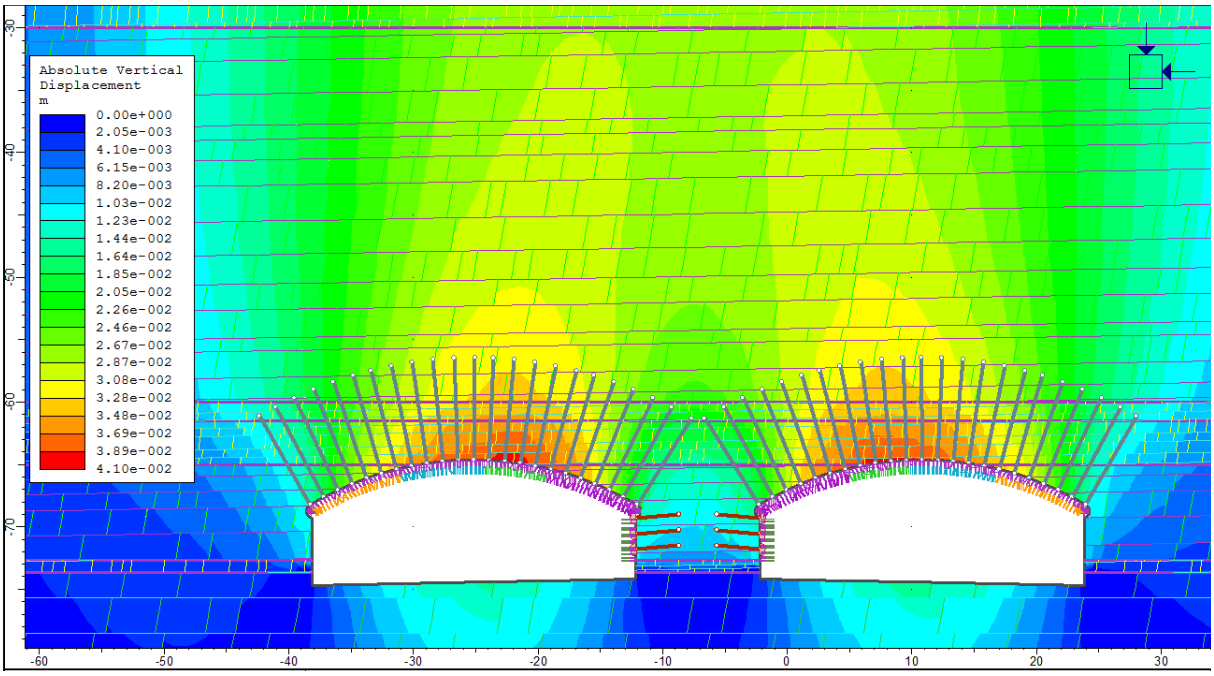

Figure 1.55 Contour of vertical displacements (in m) around tunnel opening for YJ-HS-TYPE C-W9

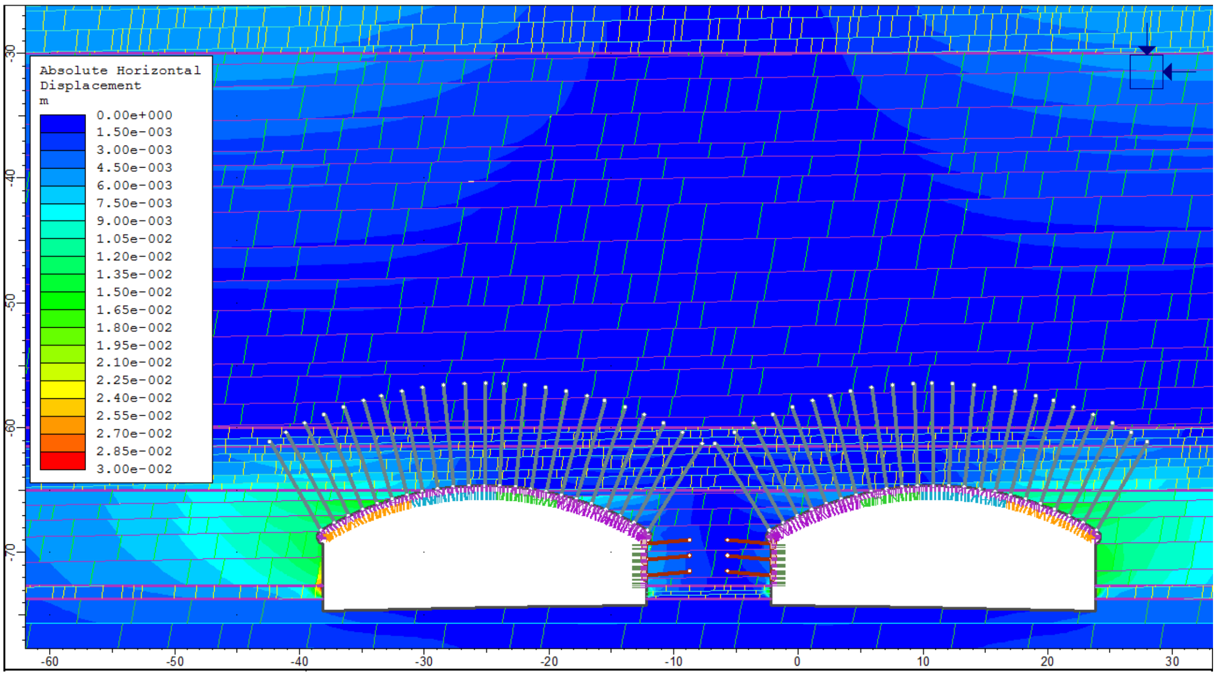

Figure 1.56 Contour of horizontal displacements (in m) around tunnel opening for YJ-HS-TYPE C-W9

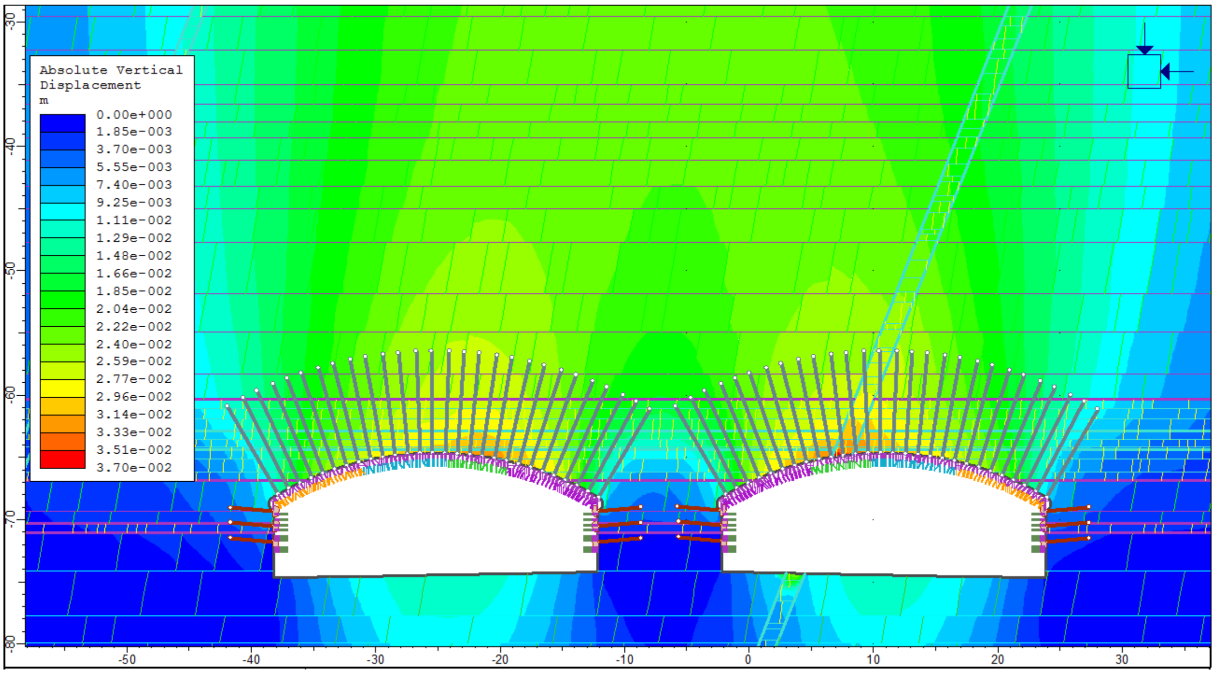

Figure 1.57 Contour of vertical displacements (in m) around tunnel opening for YJ-HS-TYPE D-W9

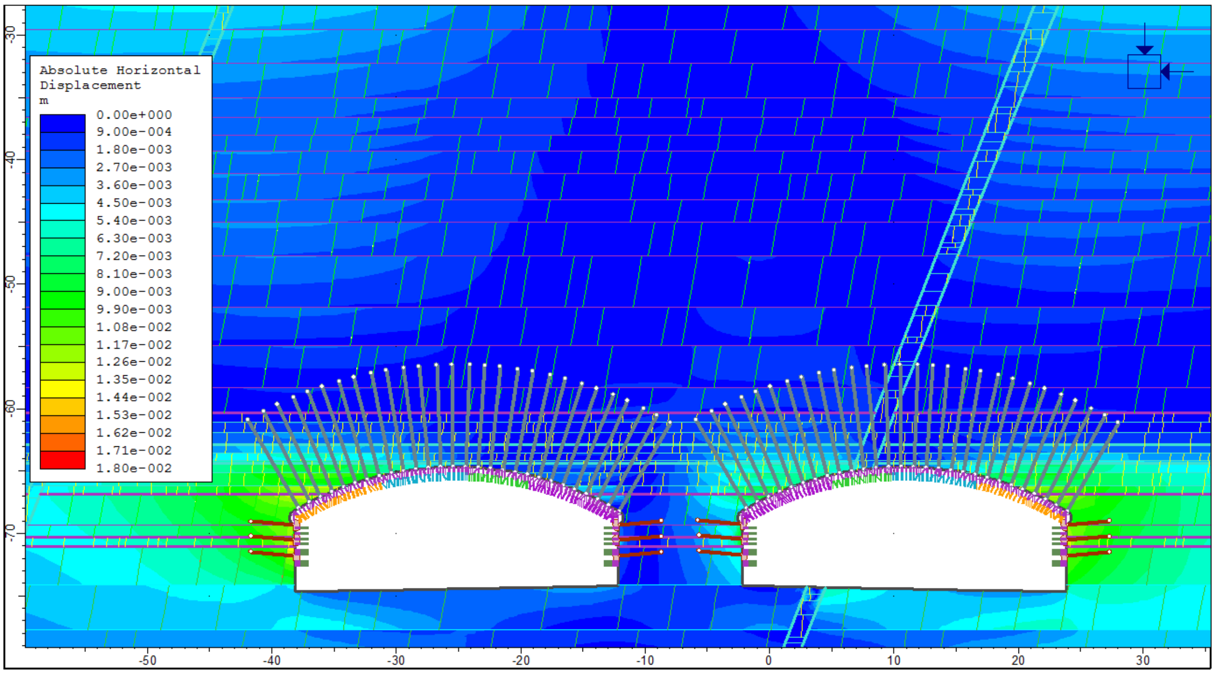

Figure 1.58 Contour of horizontal displacements (in m) around tunnel opening for YJ-HS-TYPE D-W9

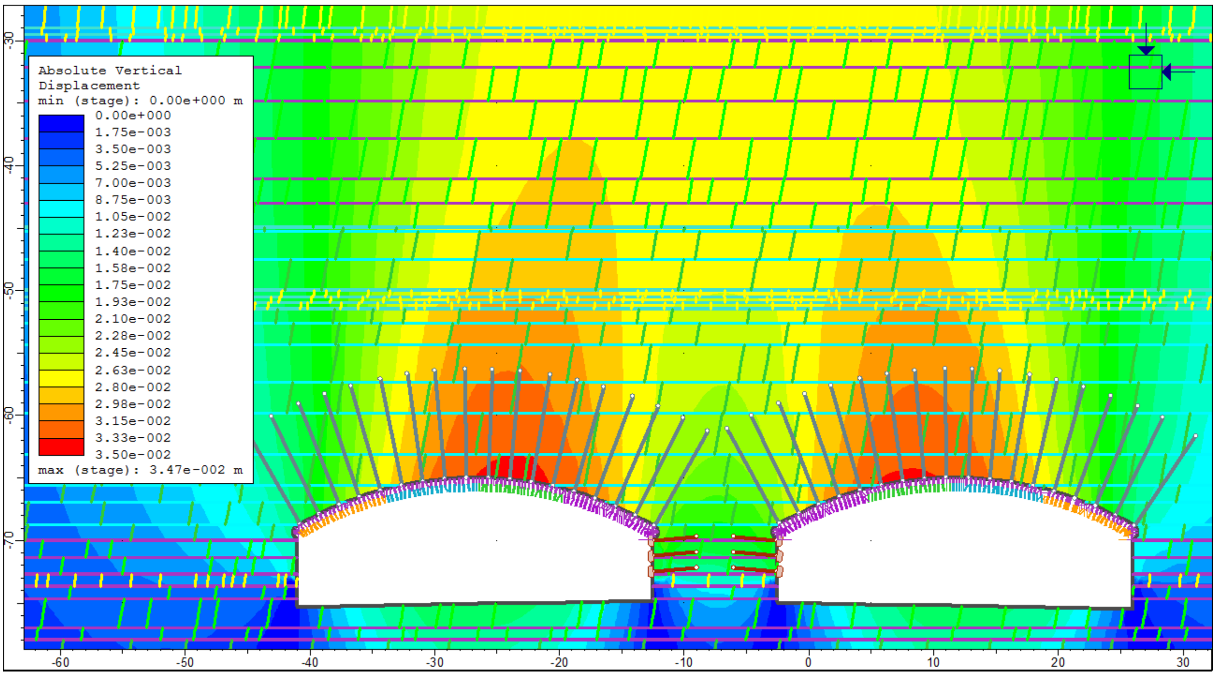

Figure 1.59 Contour of vertical displacements (in m) around tunnel opening for YJ-HS-TYPE A-W10

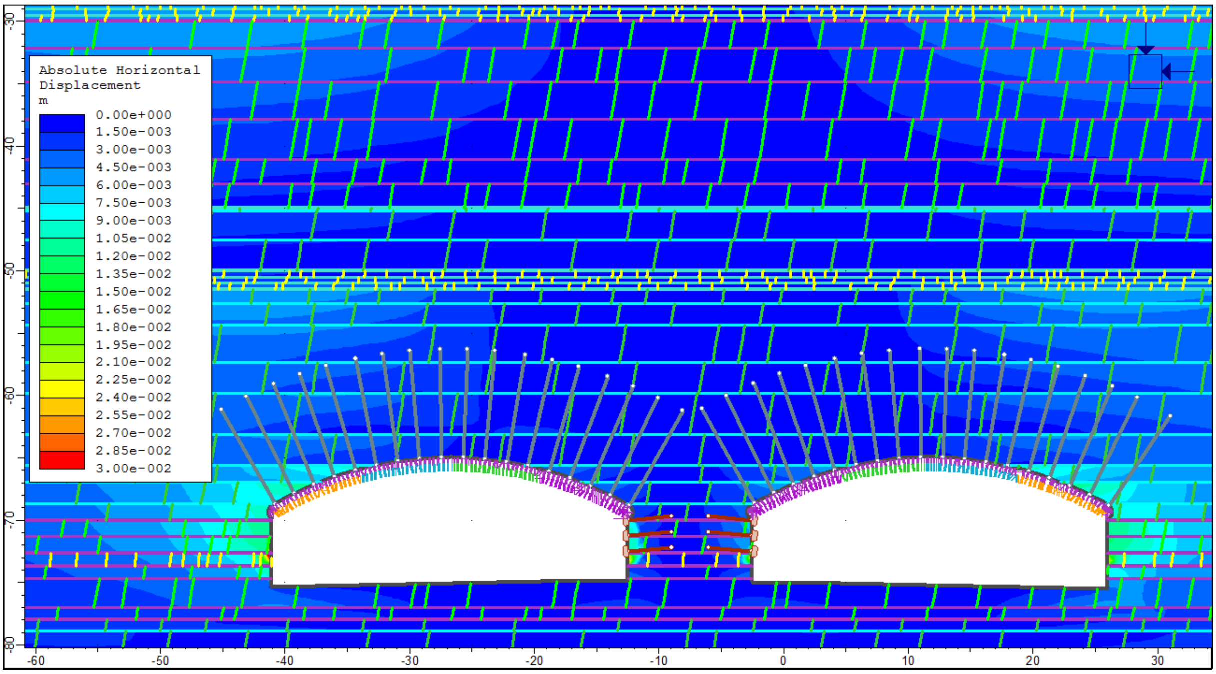

Figure 1.60 Contour of horizontal displacements (in m) around tunnel opening for YJ-HS-TYPE A-W10

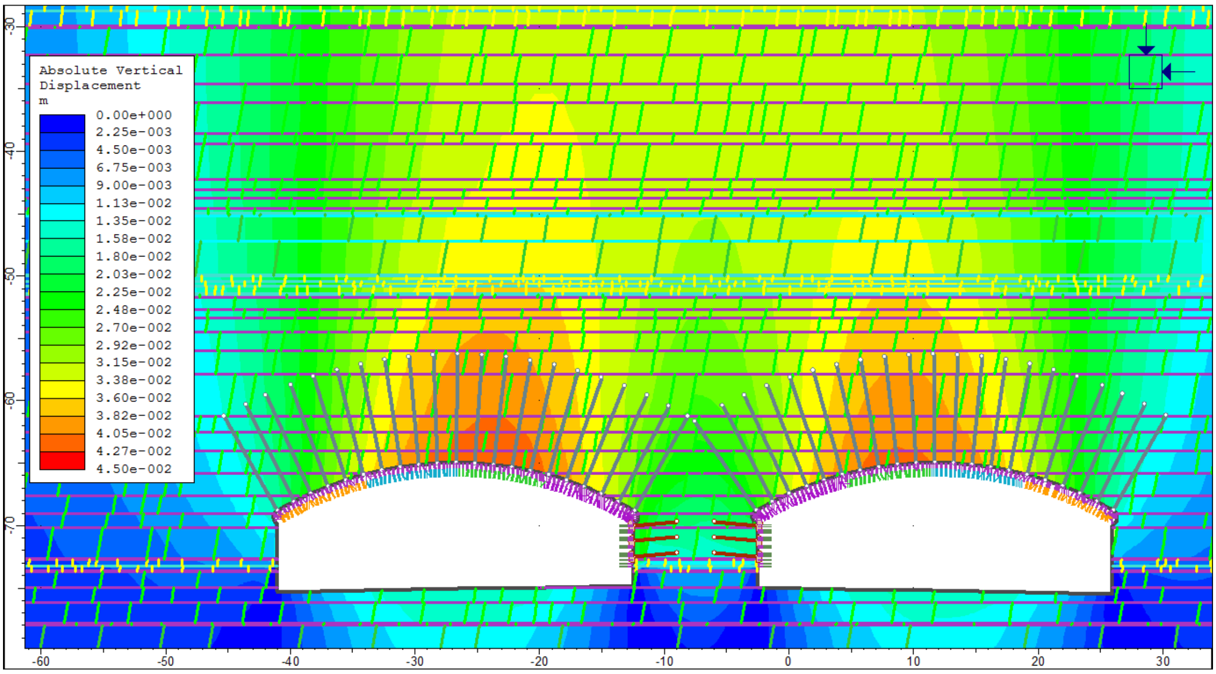

Figure 1.61 Contour of vertical displacements (in m) around tunnel opening for YJ-HS-TYPE B-W10

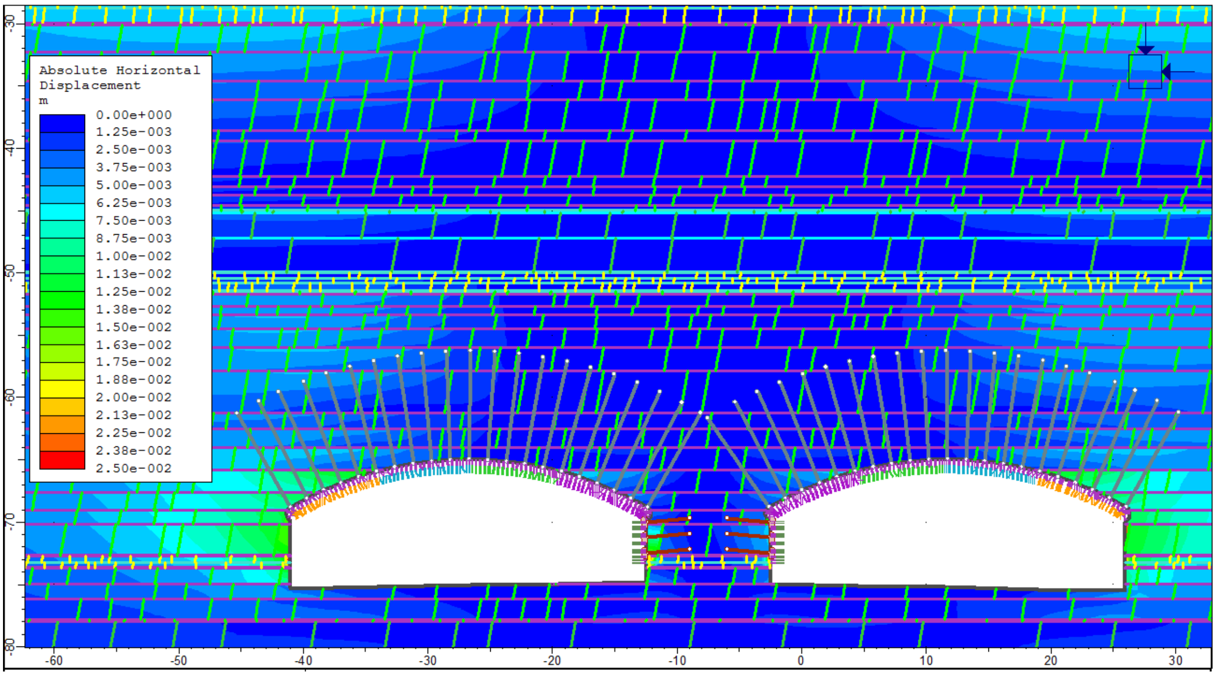

Figure 1.62 Contour of horizontal displacements (in m) around tunnel opening for YJ-HS-TYPE B-W10

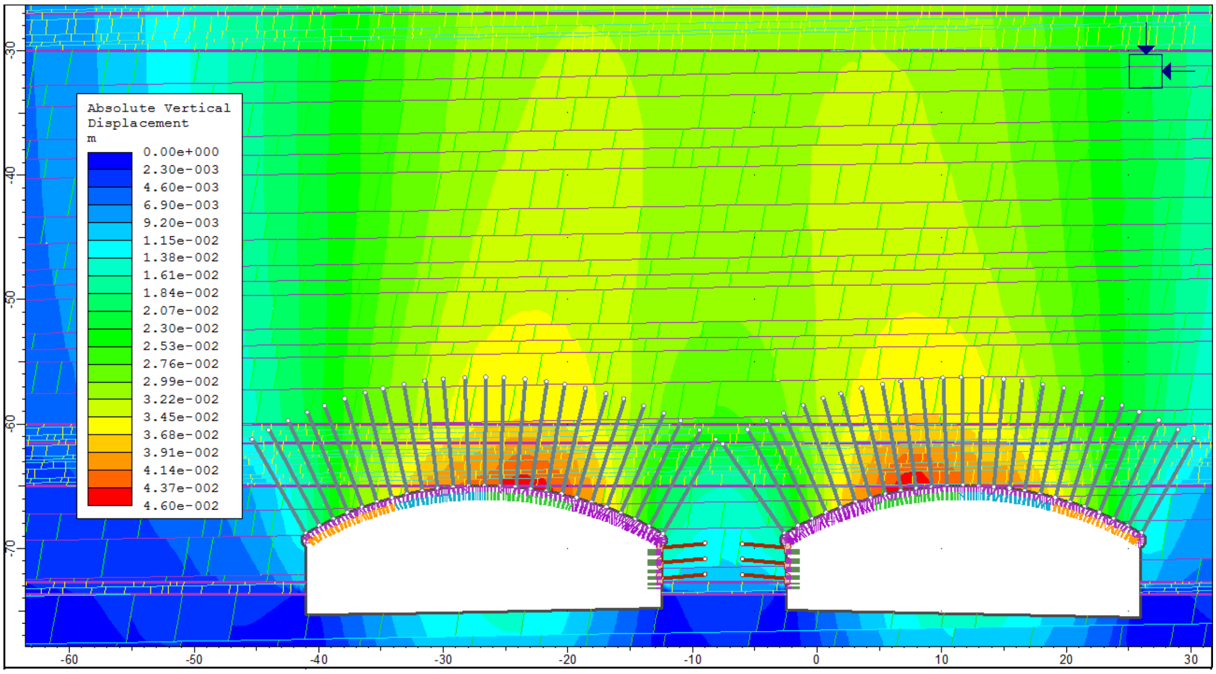

Figure 1.63 Contour of vertical displacements (in m) around tunnel opening for YJ-HS-TYPE C-W10

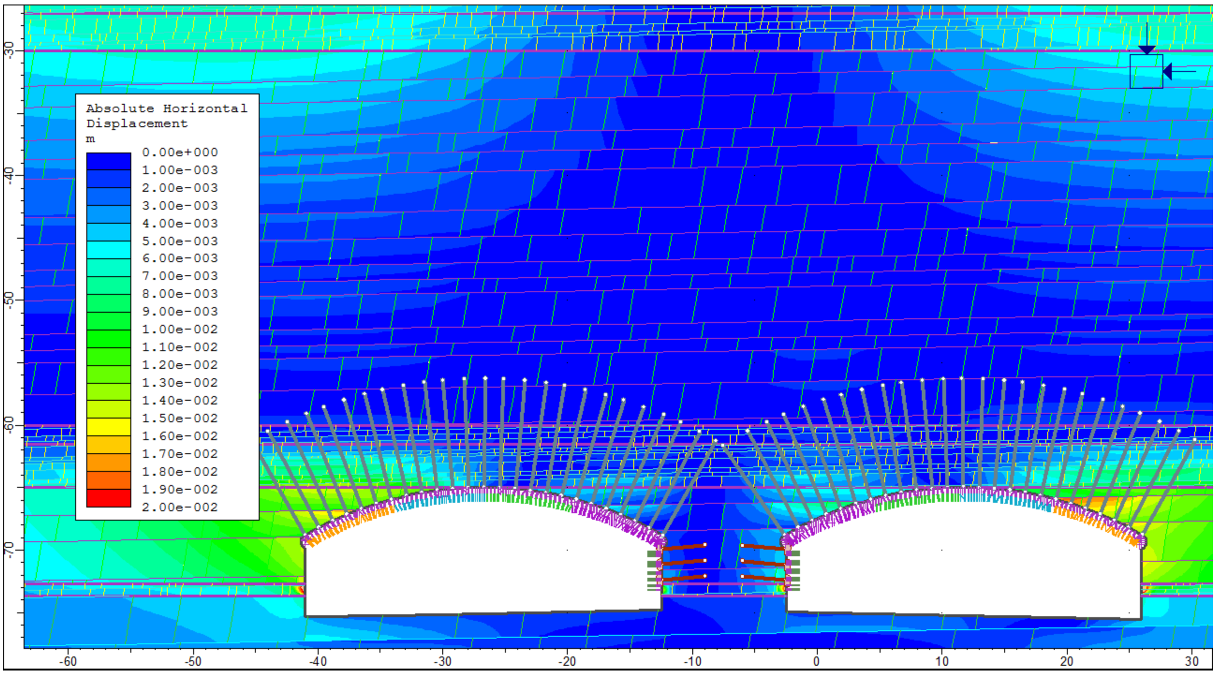

Figure 1.64 Contour of horizontal displacements (in m) around tunnel opening for YJ-HS-TYPE C-W10

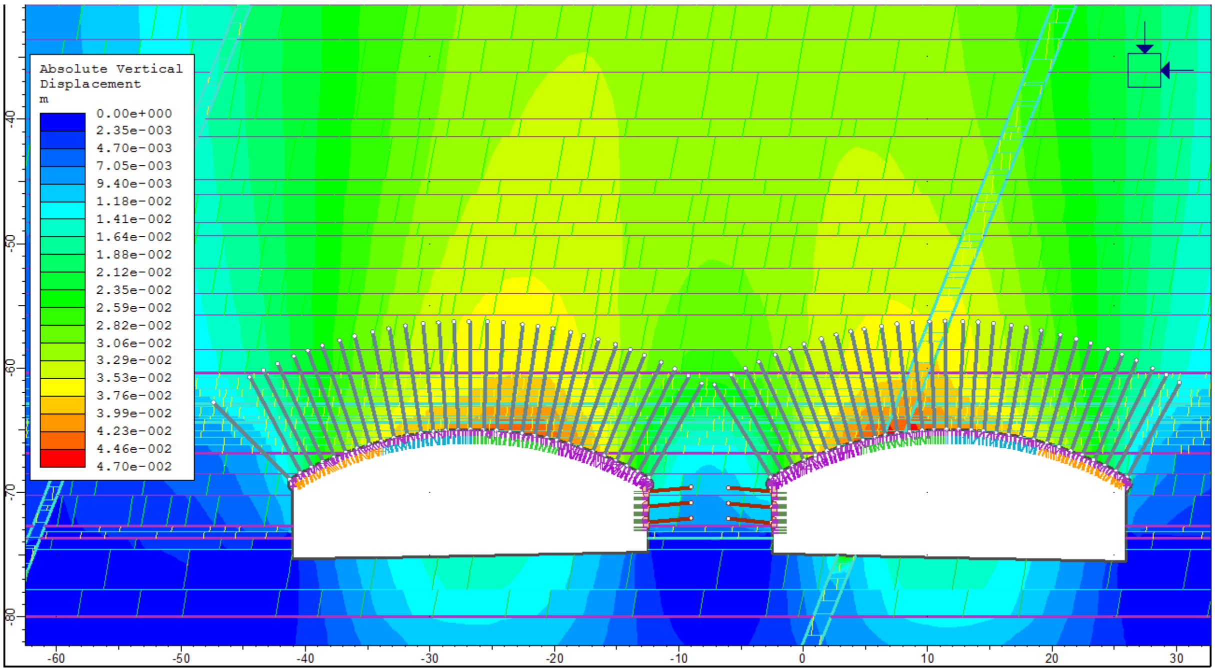

Figure 1.65 Contour of vertical displacements (in m) around tunnel opening for YJ-HS-TYPE D-W10

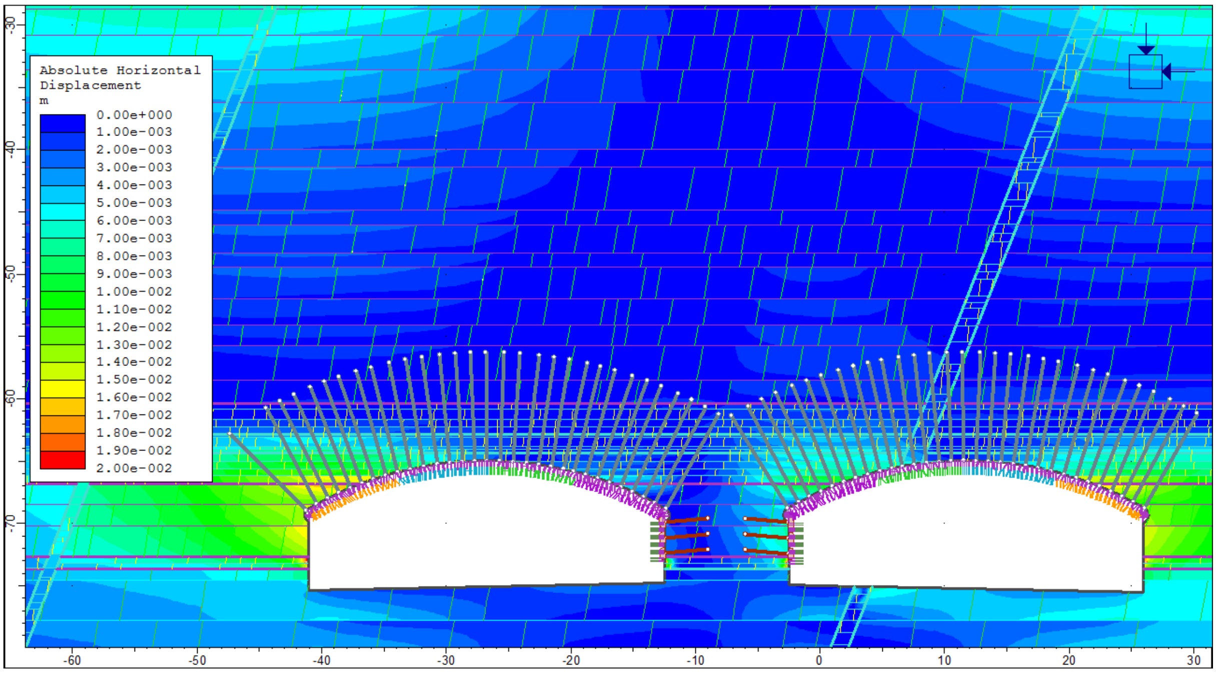

Figure 1.66 Contour of horizontal displacements (in m) around tunnel opening for YJ-HS-TYPE D-W10

1.5.1.2 Surface Settlement

Figure 1.67 to Figure 1.71 show the ground surface settlements due to tunnelling excluding the settlement induced by groundwater drawdown. As expected, the estimated ground surface settlement increases with increasing of tunnel span. For example, maximum ground surface settlement of 29mm was estimated for the tunnel cavern with the span of approximately 28.5m. The estimated ground surface settlements at the Arncliffe caverns vary from 12mm to 29mm.

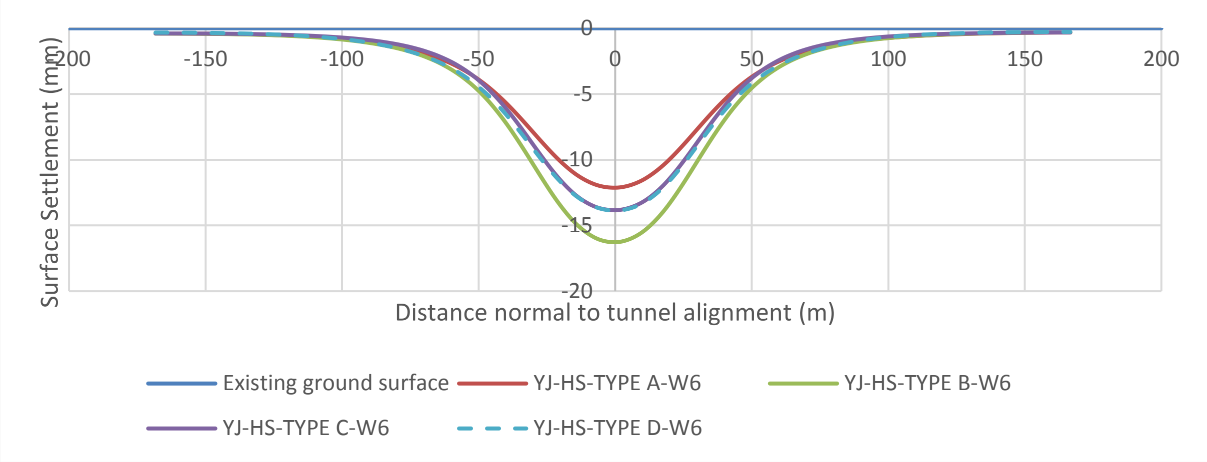

Figure 1.67 Ground surface settlement due to tunnelling (not included settlement induced by water drawdown) for the cavern span W6

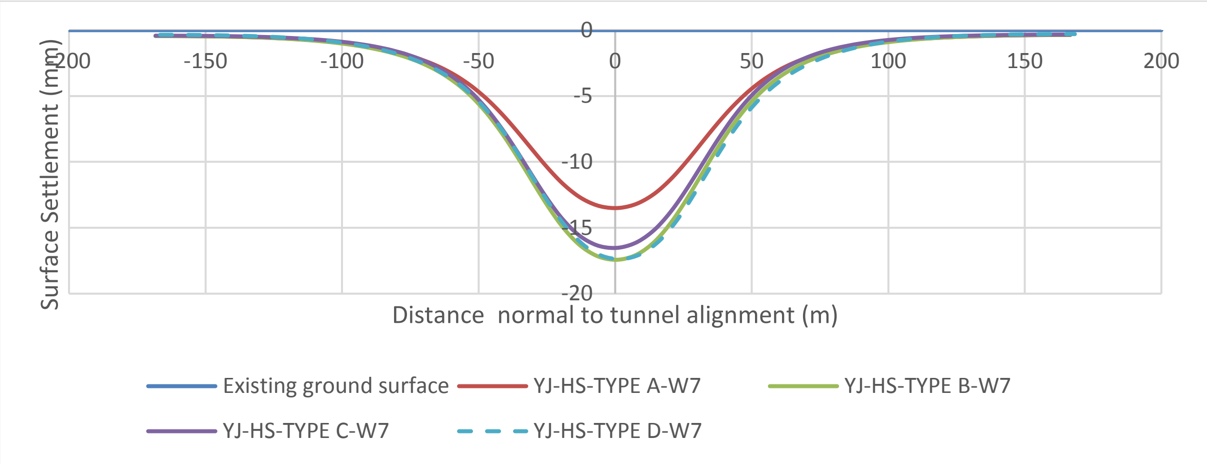

Figure 1.68 Ground surface settlement due to tunnelling (not included settlement induced by water drawdown) for the cavern span W7

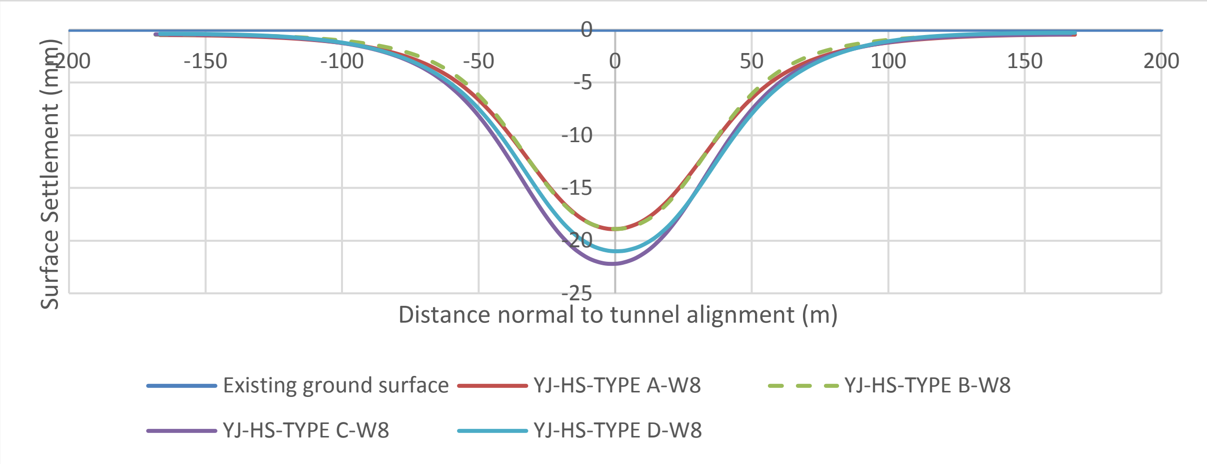

Figure 1.69 **Ground surface settlement due to tunnelling (not included settlement induced by water drawdown) for the cavern span W8**

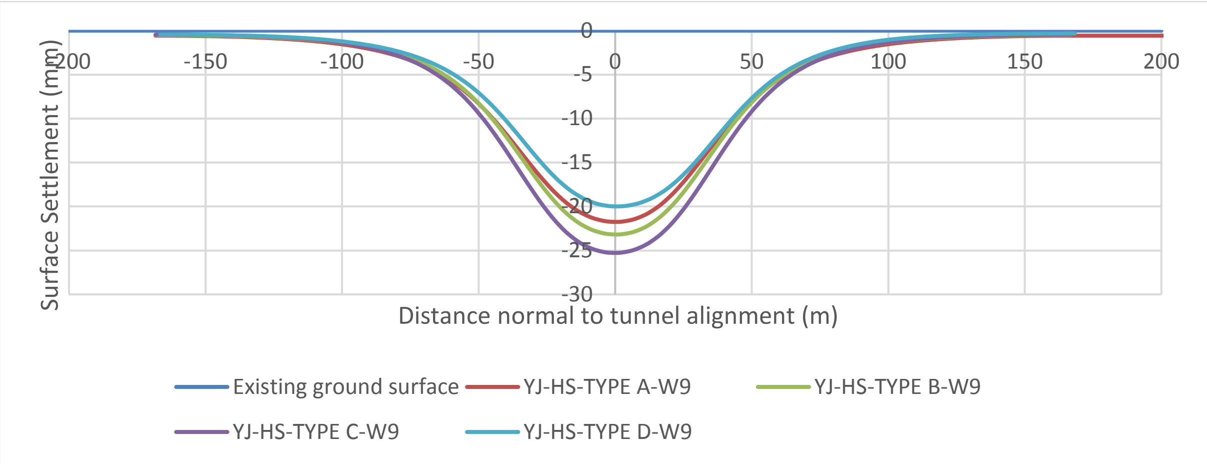

Figure 1.70 **Ground surface settlement due to tunnelling (not included settlement induced by water drawdown) for the cavern span W9**

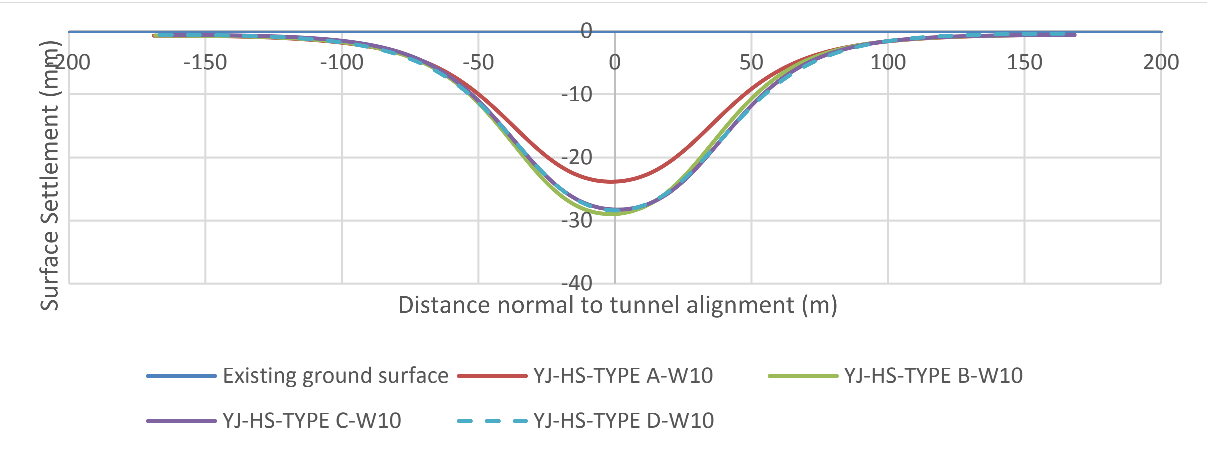

Figure 1.71 **Ground surface settlement due to tunnelling (not included settlement induced by water drawdown) for the cavern span W10**

1.5.2 Cable bolt performance

Factored axial loads acting on rock cable bolt obtained from numerical analysis are shown in Figure 1.72, Figure 1.73, Figure 1.74, Figure 1.75, and Figure 1.76 and Table 1.16. The maximum factored axial loads developed in rock cable bolts are in range of 370-480kN which are not exceeded the design ultimate tensile capacity of proposed cable bolt type (480kN).

As seen in Table 1.16, the maximum shear displacements experienced by the rock cable bolts are in the range of 2-10mm in which rock cable bolts are expected to have adequate shear capacity to provide the permanent support for tunnel. However, instrumented cables are proposed to monitor bedding shear displacement in Arncliffe caverns. If the bedding shear displacement exceeds 12 mm, re-bolting is recommended in support drawings.

Table 1.16 Cable bolt performance for the proposed support types

Ground support type	Estimated maximum axial force in cable bolts [kN]	Maximum shear displacements experienced by discontinuity [mm]
YJ-HS-TYPE A-W6	370	5
YJ-HS-TYPE B-W6	460	6
YJ-HS-TYPE C-W6	480	5
YJ-HS-TYPE D-W6	480	2
YJ-HS-TYPE A-W7	370	4
YJ-HS-TYPE B-W7	470	5
YJ-HS-TYPE C-W7	480	7
YJ-HS-TYPE D-W7	480	3
YJ-HS-TYPE A-W8	380	7
YJ-HS-TYPE B-W8	430	4
YJ-HS-TYPE C-W8	480	4
YJ-HS-TYPE D-W8	480	4
YJ-HS-TYPE A-W9	415	9
YJ-HS-TYPE B-W9	440	6
YJ-HS-TYPE C-W9	480	5
YJ-HS-TYPE D-W9	430	3
YJ-HS-TYPE A-W10	450	8
YJ-HS-TYPE B-W10	480	10

Ground support type	Estimated maximum axial force in cable bolts [kN]	Maximum shear displacements experienced by discontinuity [mm]
YJ-HS-TYPE C-W10	480	7
YJ-HS-TYPE D-W10	480	4

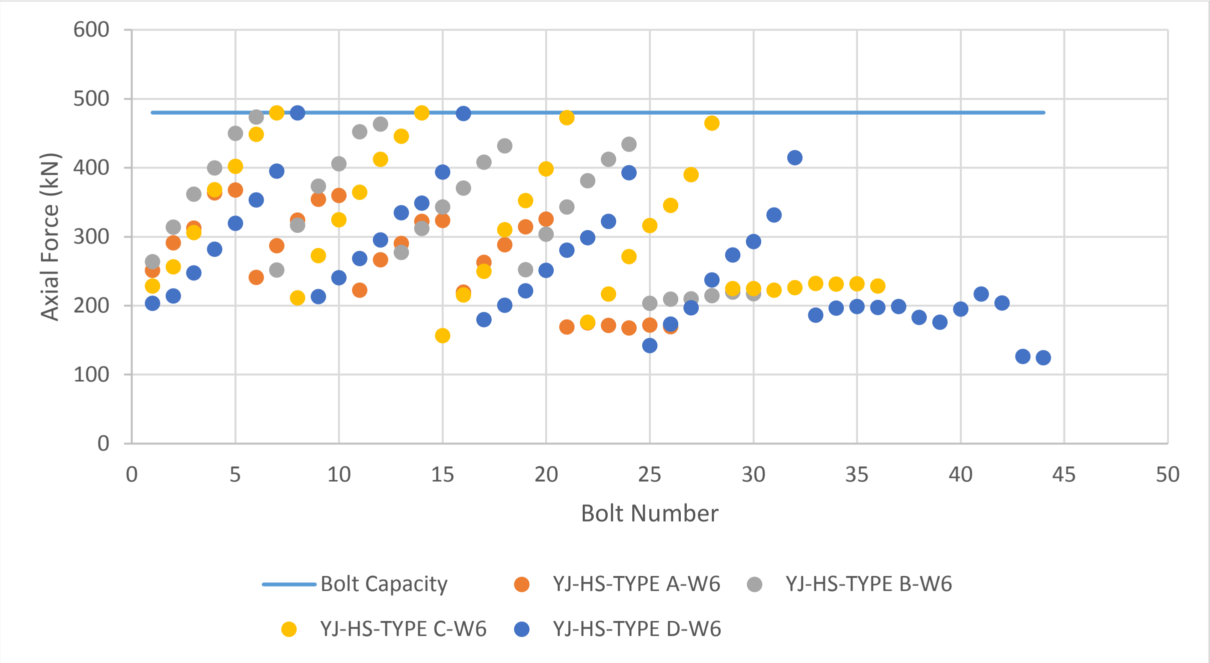

Figure 1.72 Cable bolt capacity check for YJ-HS-TYPE A/B/C/D-W6

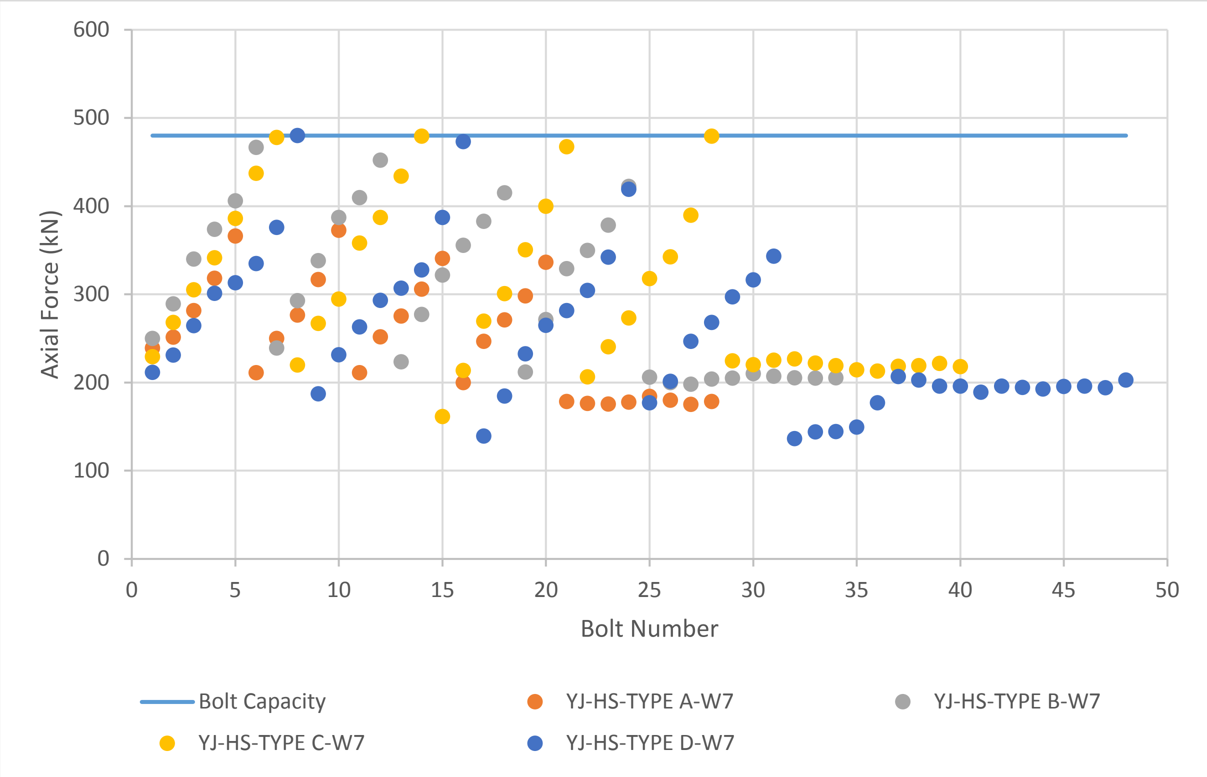

Figure 1.73 Cable bolt capacity check for YJ-HS-TYPE A/B/C/D-W7

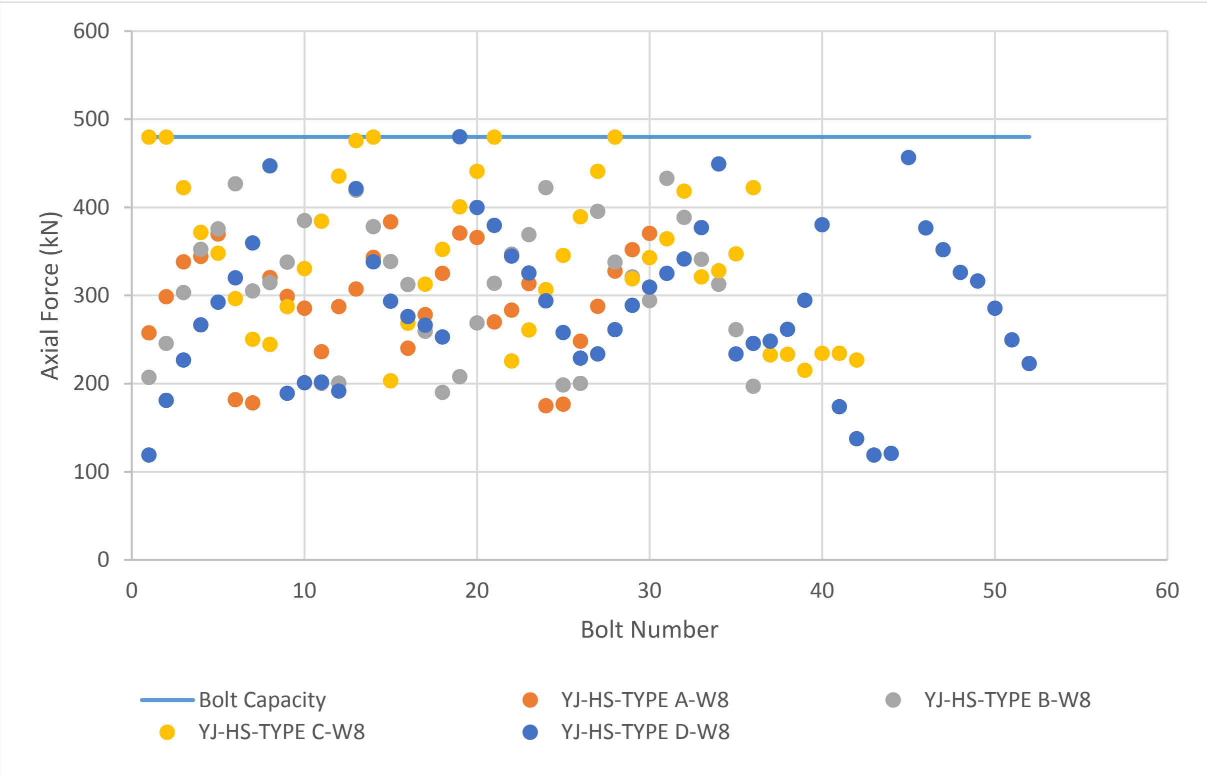

Figure 1.74 Cable bolt capacity check for YJ-HS-TYPE A/B/C/D-W8

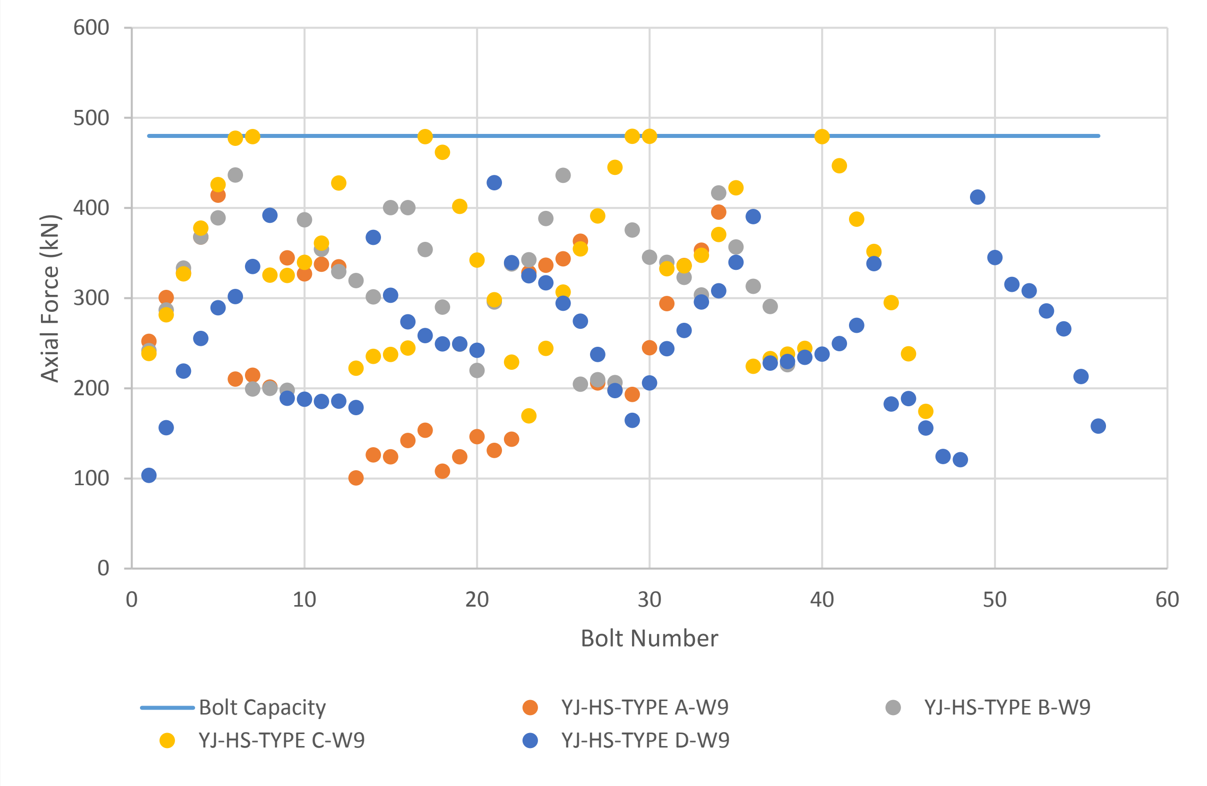

Figure 1.75 Cable bolt capacity check for YJ-HS-TYPE A/B/C/D-W9

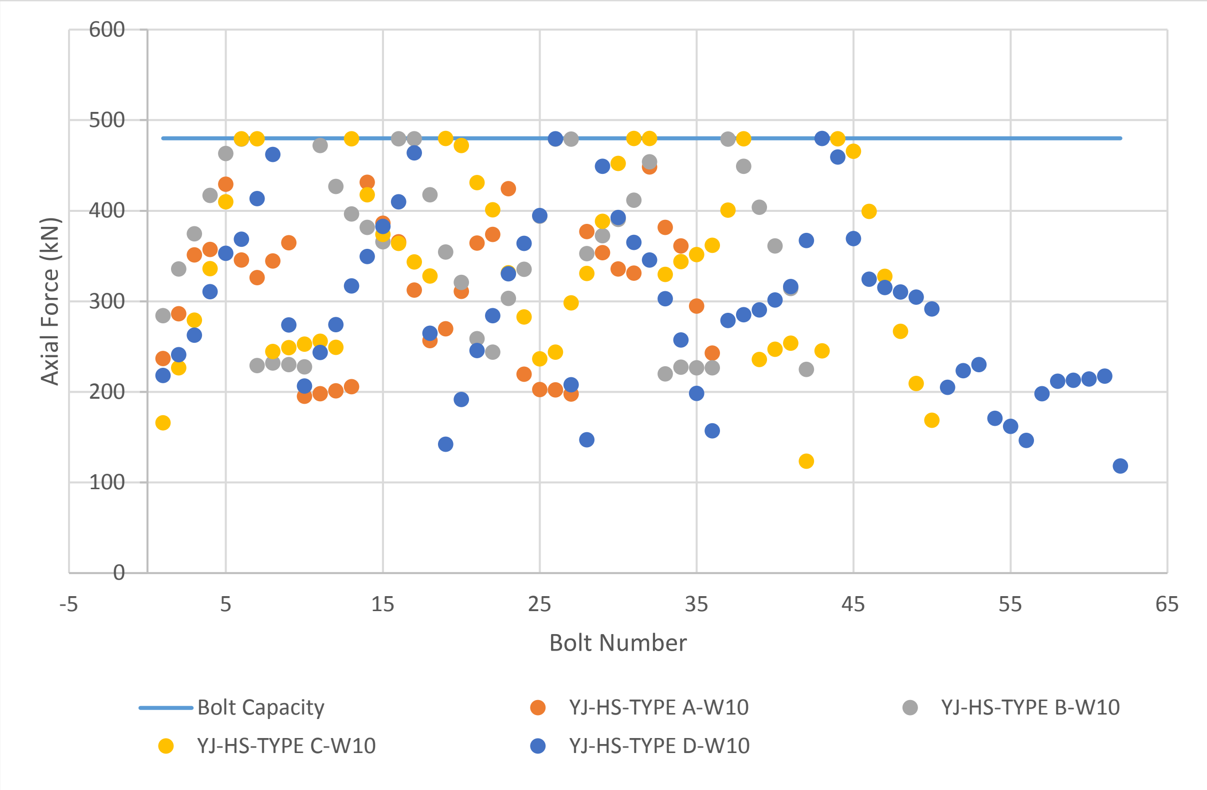

Figure 1.76 Cable bolt capacity check for YJ-HS-TYPE A/B/C/D-W10

1.5.3 Shotcrete performance

For proposed support types YJ-HS-TYPE A/B/C/D-W6, YJ-HS-TYPE A/B/C/D-W7, YJ-HS-TYPE A/B/C/D-W8, YJ-HS-TYPE A/B/C/D-W9, and YJ-HS-TYPE A/B/C/D-W10, the rock cable bolts and rock bolts are the primary means of ground support and the primary shotcrete lining is only designed to provide support for potentially unstable blocks between bolts. In other words, the shotcrete is not designed as a full structural lining and the interaction capacity diagram, therefore it considered relevant for the assessment. If some load points exceed the bending capacity, this would result in cracking of the shotcrete which would trigger a residual strength. This residual strength is the value adopted for the design of the shotcrete spanning between rock bolts with the Barret and McCreath method.

1.6 References

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