Tunnel design – state of the art design examples

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Szerkezetépítési és Geotechnikai tanszék
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Tartalom

- Introduction - K. Glatz
- Basics
- Bergen light rail tram
- Three celled tunnel in a city
- Numerical modelling - T. Megyeri
- Further examples

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Introduction

16 500 employee

Offices in 50 countries, working in 140 countries

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35 employee

Mott MacDonald Hungary

Civil Engineering team

Environmental team

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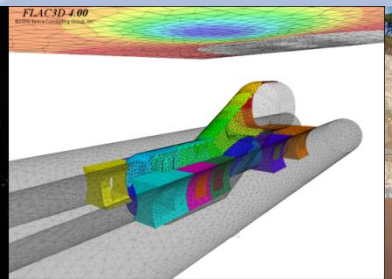
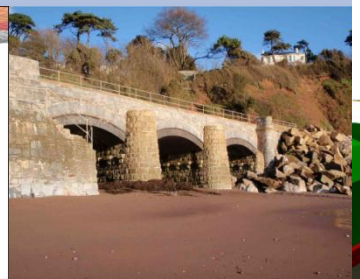
Civil engineering key services

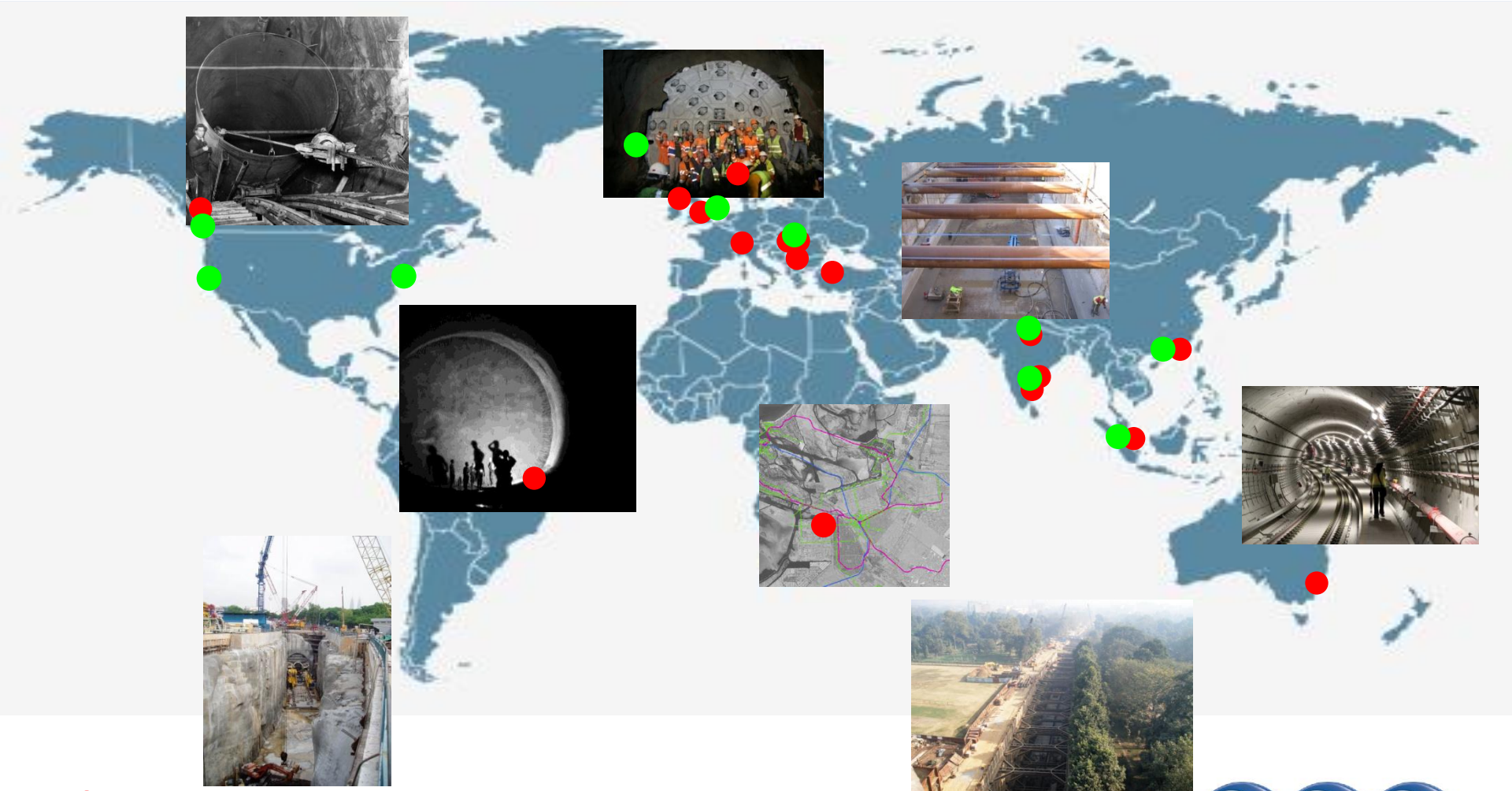
Geotechnics | Tunnelling | Structures | CAD / BIM

- ✓ Engineering Design (from feasibility studies to detailed design)
- ✓ Geotechnics and Rock Mechanics
- ✓ Cut and Cover Structures, Reinforced Concrete and Steel Structures
- ✓ Tunnel Design in Soft Ground and Hard Rock
- ✓ Numerical Modelling (in 2D and 3D)
- ✓ Soil Settlement Analysis, Stability Analysis
- ✓ Instrumentation and Monitoring
- ✓ Retaining Structure Design
- ✓ Foundation Design, Deep Foundation Design, Foundation Strengthening
- ✓ Earthquake engineering
- ✓ CAD 3D
- ✓ Visualisation
- ✓ BIM
- ✓ Design Supervision
- ✓ Construction Supervision
- ✓ Technical audit and compliance test (due diligence)



International Expertise



our project

our engineers

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State of the art tunelling?

- Common sense
- Using tunnelling experts experience
- Literature
- Hand calculation
- Empirical, analytical methods
- Numerical Modelling
- Sanity checks, project reviews
- BIM

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Tunnel design

- Influencing factors in Tunnel design
  - Client expectations
  - Requested geometry
  - Soil parameters
- Design basis
  - Stand up time
  - Arching, Stress changes
  - Soil – lining interaction
  - Four dimensions

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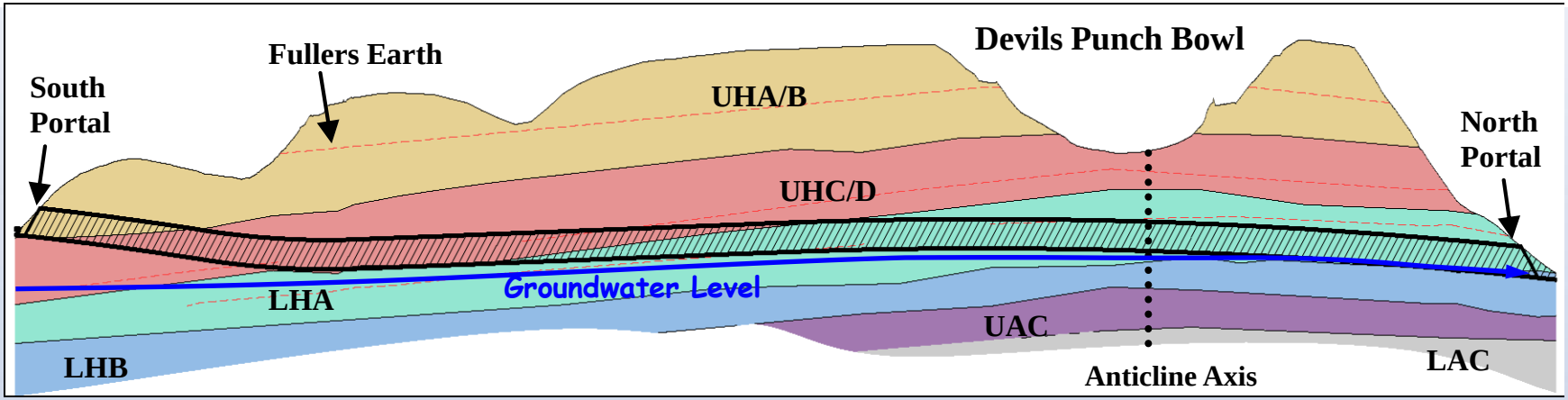
Gelogical long section



The alignment must be set up to minimise the risks and cost

- In the most beneficial soil layer
- Above ground water level, if possible
- At least one diameter cover everywhere

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Geotechnical parametrers

Has affect :

- On design
  - Horisontal and vertical alignment
  - Loads on lining
- Construction technology
  - Excavation method
  - Lining, excavation support
  - Building cost and time

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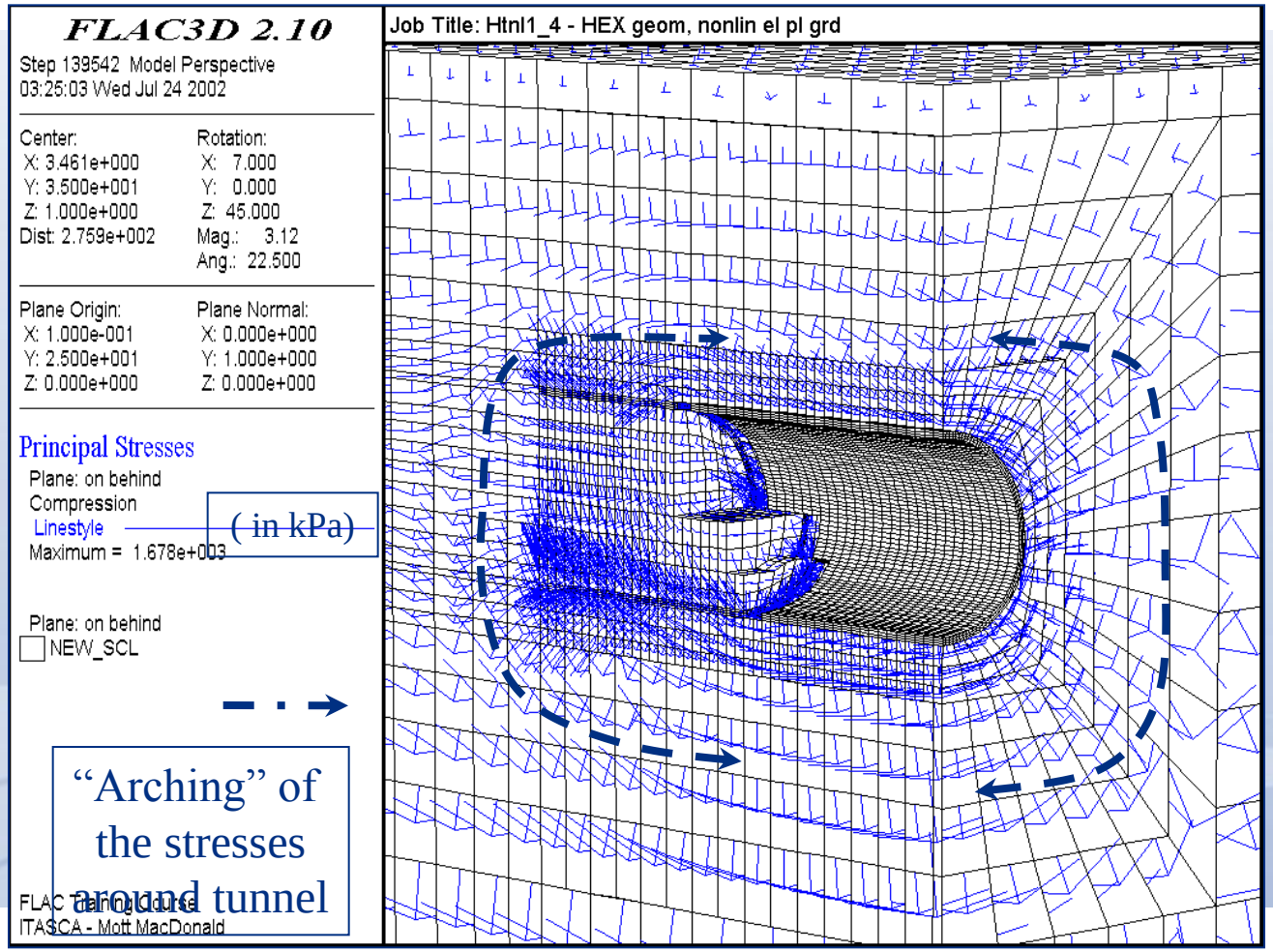
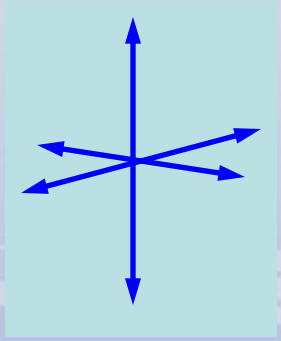
3D arching



Original direction of soil stresses



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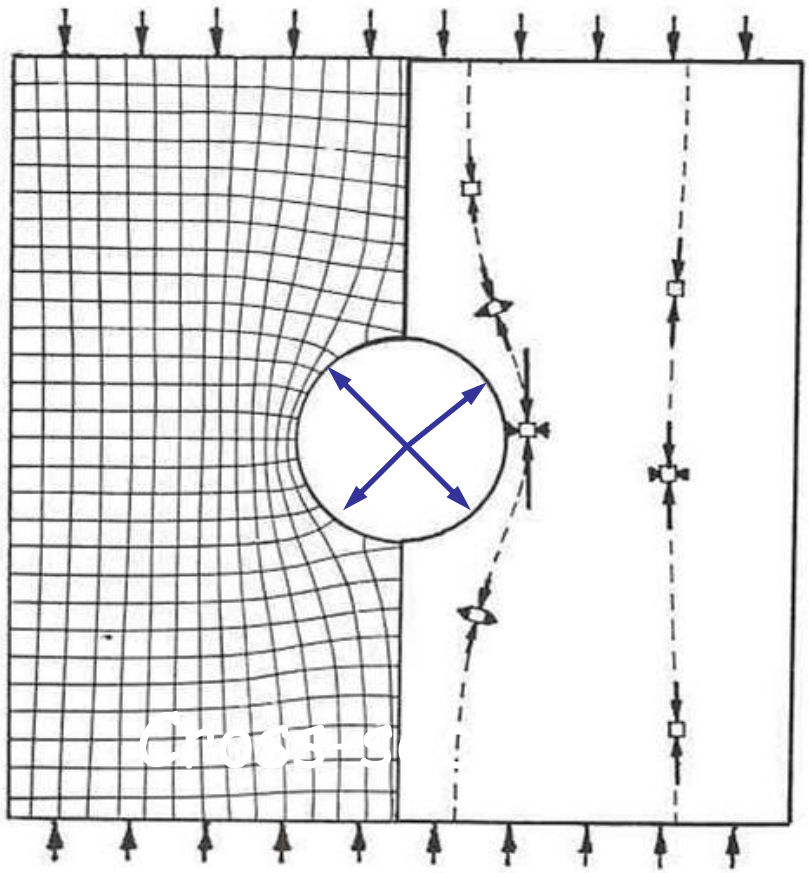
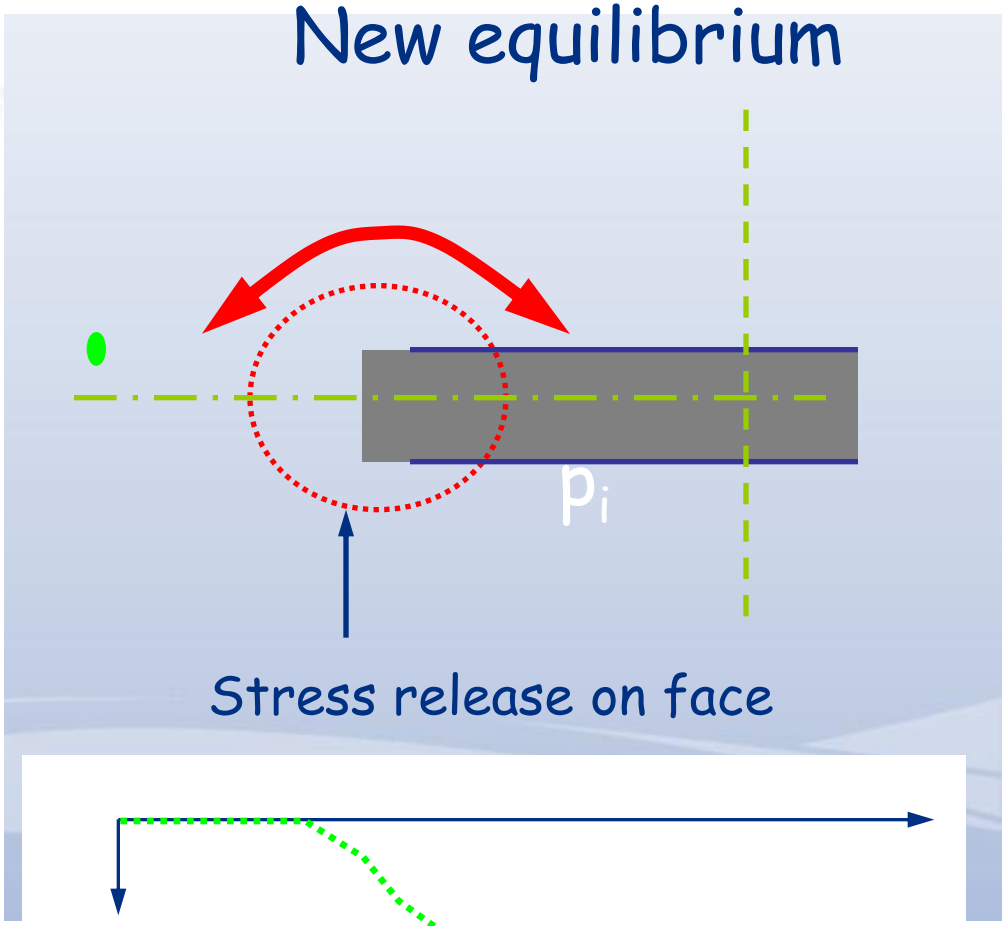
New equilibrium forms





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Design methods

- Empirical methods ——— For example: Q-method
- Analytical methods ——— For example: anchor design

  Soil response curve calculations
- Numerical methods ——— Discrete element method

  Finite different method

  Finite element method

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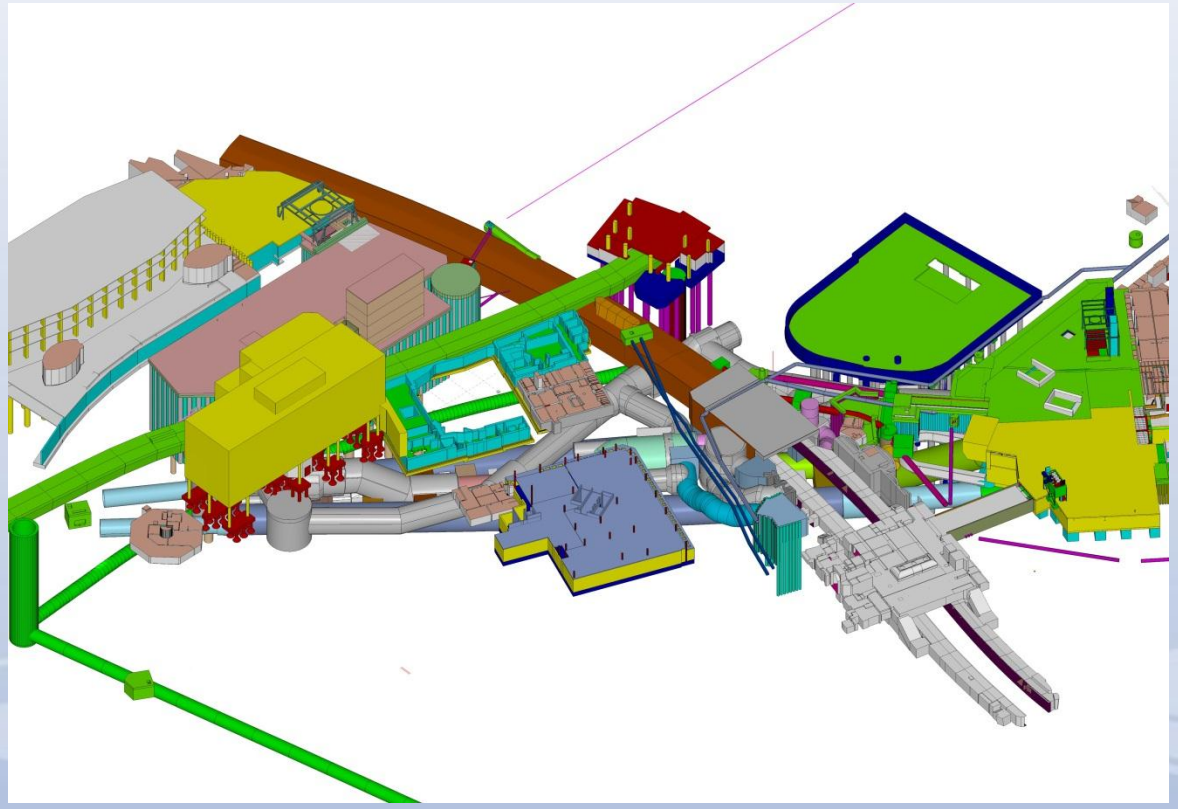
Challenges – Improving techniques

- There is no established code for SCL
- Still young and improving science
- New type of materials
- New excavating techniques
- Quicker advance rates
- Compact sites, denser built-in areas



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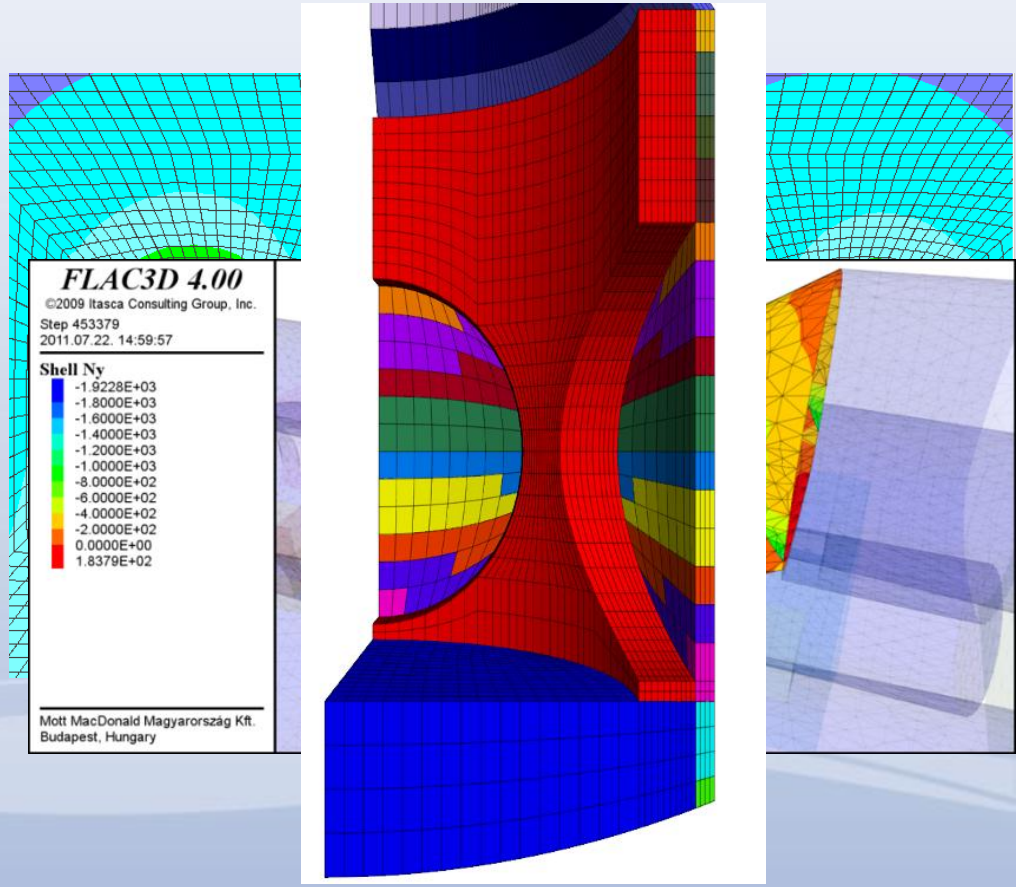
Challenges -Modelling

- Empirical methods are not sufficient anymore
- Clients require Numerical modelling proof for designs
- Complex situations, excavation sequences, shapes and loads
- MM is committed to using Best Practice



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Choosing the design method

1 Identify soil/rock behaviour

2 Choose an excavation method

3 Choose a design method for all element of the tunnel

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Design basics

- Complex soil – lining interactions
- Complex geometry
- Soil/rock behaviour

} 3 D problem

- Material behaviour (Soil/rock & lining)
- Time dependent behaviour (soil/rock & lining)
- Other design criteria- as: endurance, water tightness, etc.

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Tunnel Quality Index (Q), Barton et al 1974

- Rock characteristics and the support systems requirements
- It is based on huge amount of case studies, experience on underground work
- Probably the most frequently used rock classification method these days

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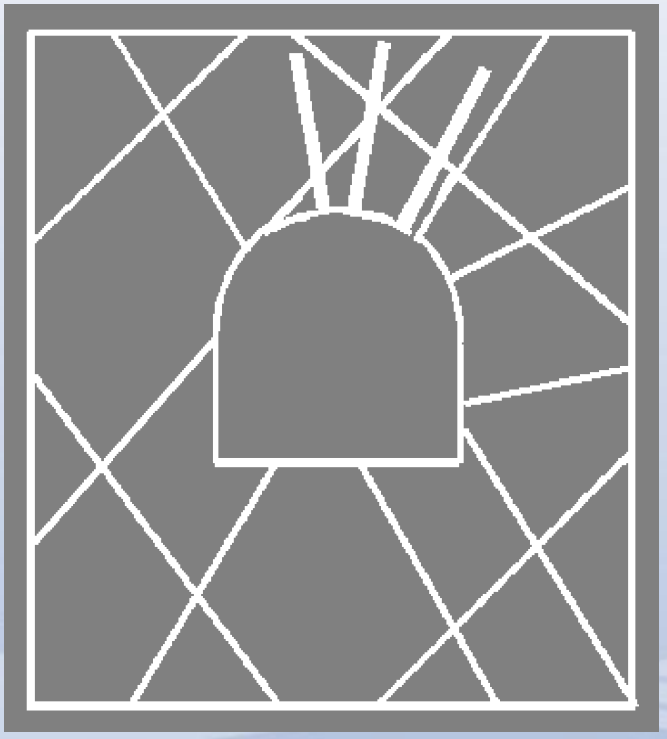
Definition of Quotients

- RQD/J_n — Block size
- J_r/J_a — Shear strength between blocks
- J_w/SRF — Active stress



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Q-system

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}$$

Where:

RQD Rock Quality Designation

J_n number of cracks

J_r crack surface grain

J_a orientation of cracks

J_w water infill of cracks

SRF srtess relief factor

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Q method

- All parameters shall be defined
- The notes to be considered in the table as well
- The Q has to be defined for all structural parts
- The crack arrangement which influence the whole stability shall be checked

JOINT SET	SPACING (mm)	TYPE	DIP/DIRECTION	PLANARITY	ROUGHNESS	APERTURE	INFILLING	WEATHERING	COMMENTS
1	40/100/300	J/B	5H	P	S	T-O(Av. 3mm)*	mid.-light brown silt/ sand size	Fe-Mn stains on more joints.	* up to 10mm
2	50/100/250	J	5V/Strike 020-040	P	S	O(Av. 3mm)*-T	crushed weathered chalk with	"	* up to 15mm
3	40/90/180	J	5V/Strike 290-310	P	S	O(Av. 3mm)*-T	occasional clay.	"	* up to 15mm
4	50/130/260	J	50-70/110-130	P	S/SL.	O(Av. 3mm)*-T	"	"	* J_r(50/mb) 30mm coarse fill.
5	60/150/250.	J	20-30/010-050.	P	S	O(Av. 3mm)*-T	"	"	* up to 10mm

1. QUALITY DESIGNATION — RQD
- A. Very Poor — 0 - 25
- B. Poor — 25 - 50
- C. Fair — 50 - 75
- D. Good — 75 - 90
- 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
- G. Three joint sets plus random — 12
- H. Four or more joint sets, random, heavily jointed "sugar cube", etc — 15
- J. Crushed rock, earthlike — 20

3. JOINT ROUGHNESS NUMBER — J_r
- a. Rock wall contact and
- b. Rock wall contact before 10 cms shear.
- A. Discontinuous joints — 4
- B. Rough or irregular, undulating — 3
- C. Smooth, undulating — 2
- D. Slickensided, undulating — 1.5
- E. Rough or irregular, planar — 1.5
- F. Smooth, planar — 1.0
- G. Slickensided, planar — 0.5
- a. No rock wall contact when sheared
- H. Zone containing clay minerals thick enough to prevent rock wall contact — 1.0
- J. Sandy, gravelly or crushed zone thick enough to prevent rock wall contact — 1.0

4. JOINT ALTERATION NUMBER — J_a
- a. Rock wall contact.
- A. Tightly healed, hard non-softening, impermeable filling — 0.75
- B. Unaltered joint walls, surface staining only — 1.0
- C. Slightly altered joint walls non-softening mineral coatings, sandy particles, clay-free disintegrated rock etc. — 2.0
- D. Silty, or sandy-clay coatings, small clay-fraction (non-softening) — 3.0
- 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, 1-2mm or less in thickness) — 4.0
- b. Rock wall contact before 10 cms shear
- F. Sandy particles, clay-free disintegrated rock etc. — 4.0
- G. Strongly over-consolidated non-softening clay mineral filings (continuous, <5mm thick) — 6.0
- H. Medium or low over-consolidation, softening, clay mineral filings, (continuous, <5mm thick) — 8.0
- J. Swelling clay filings, 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
- a. No rock wall contact when sheared
- K. Zones or bands of disintegrated — 6.0
- L. or crushed rock and clay (see — 8.0
- M. G, H and J for clay conditions) — 8.0 - 12.0
- M. Zones or bands of silty - or sandy clay, small clay fraction, (non-softening) — 5.0

6. STRESS REDUCTION FACTOR
- a. Weakness zones intersecting excavation, which may cause loosening of rock mass when tunnel is excavated.

		SRF
A. Multiple occurrences of weakness zones containing clay or chemically disintegrated rock, very loose surrounding rock (any depth)		10.0
B. Single weakness zones containing clay, or chemically disintegrated rock (excavation depth - 50m)		5.0
C. Single weakness zones containing clay, or chemically disintegrated rock (excavation depth - 50m)		2.5
D. Multiple shear zones in competent rock (clay free) loose surrounding rock (any depth)		7.5
E. Single shear zones in competent rock (clay free) (depth of excavation <50m)		5.0
F. Single shear zones in competent rock (clay free) (depth of excavation > 50m)		2.5
G. Loose open joints, heavily jointed or "sugar cube" (any depth)		5.0
b. Competent rock, more stress problems	σ_c/σ_1	σ_θ/σ_1	SRF
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 for wall stability)	10-5	0.66-0.33	0.5 - 2

5. JOINT WATER REDUCTION FACTOR
- A. Dry excavations or minor inflow, i.e. < 5 l/min. locally — 1
- B. Medium inflow or pressure, prominent outwash of joint filings — 0.66

SUMMARY:-
- RQD = 30
- Jn = 15
- Jr = 1
- Ja = 4
- Jw = 1
- SRF = 5

$$\text{ROCK QUALITY INDEX, } Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} = \frac{30}{15} \times \frac{1}{4} \times \frac{1}{5} = 0.1$$

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Bergen – The gate of fjords

- Bergen: Norwegian city next to the Atlantic ocean
- The largest city of the western part of the country
- It was the most important city of Scandinavia for hundreds of years
- Important port, industrial centre
- „Gateway to the fjords” – dynamically developing tourist centre
- World heritage: remaining buildings of the Hansaeatic city
- International airport: around 50 destinations

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video

Bergen – Climate, surroundings

- Bergen: harbour surrounded by high mountains
- The city itself is on a lower but very variable surface
  - The alignment of the roads and trains usually devious, leads through bridges and tunnels
- Large amount of rainwater 2250 mm
- More than 200 days are rainy
- Mild winter: January average 2,8 °C

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Bergen – LRT project

- Local government initiative: 2000
- Investor – Bergen Bybanen (transportation operator)
- Light Rapid Transit (LRT) between the city centre and the airport
- Connects the city centre, suburbs and important institutes
  - 50% growth in real estate fees after second phase is finished
- 7 km, 7 stations, 6 tunnels, 3 bridges, 8 portal structures, 6 culverts

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Tunnels, portals

- 40% of the 7.1 km length is below ground
- 6 tunnels (lengths: 120-700 m)
- Cross section heights 7,5 m, width: 9,5 m
- 5 tunnels are excavated with drill and blast method (excluded the portals), one is Cut & Cover
- Risks: School, private buildings nearby, shallow tunnels

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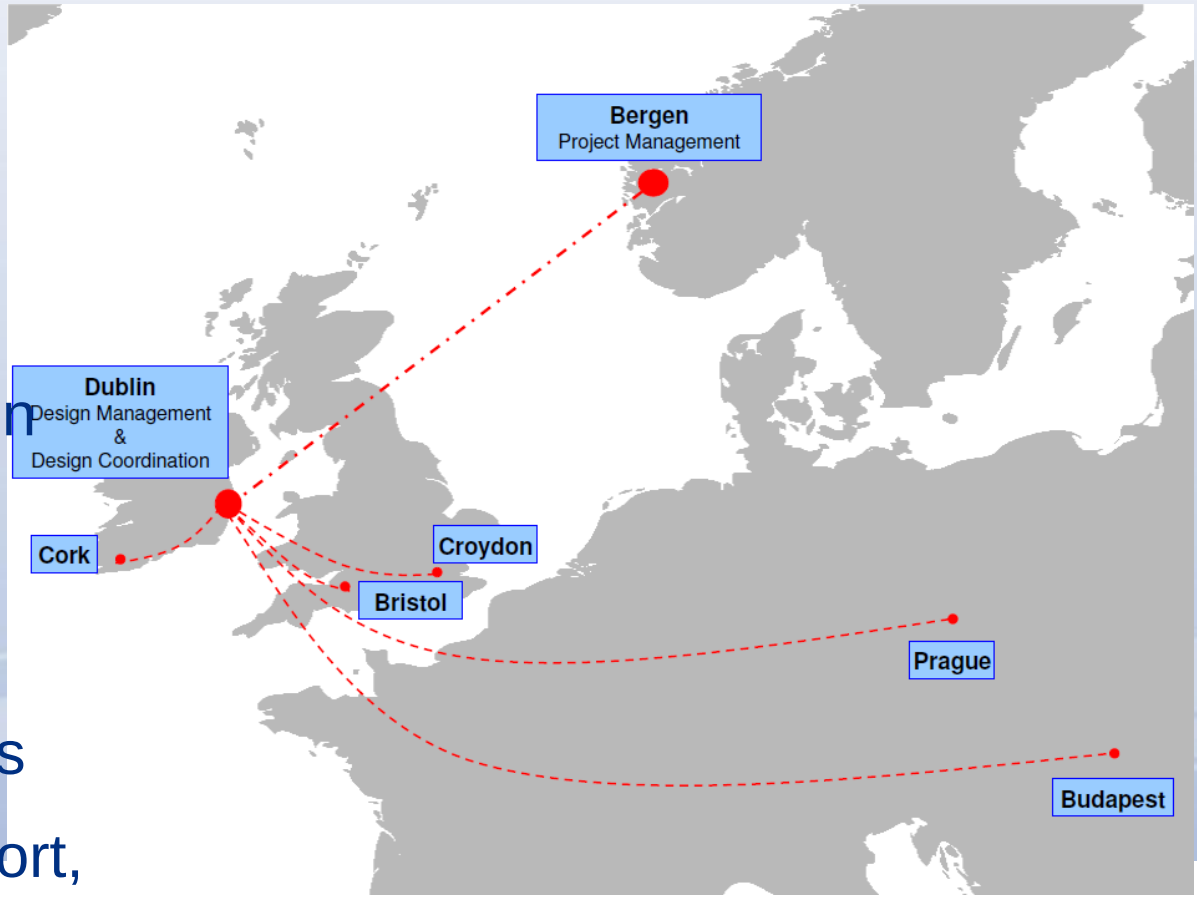
Collaborating offices

- Dublin (IE): Project lead, 3D & CAD, alignment, drainage, railway, environment, costing
- Cork (IE): Structures, roads
- Bristol (UK): Geology
- Croydon (London, UK): Tunnels, ventilation and fire design
- Prague: (CZ): Bridges, C&C tunnel
- Budapest (HU): Tunnels
- Bergen (NO): site support, meetings



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3D modelling and BIM

- First biggest transportation project done in BIM
- Every discipline is responsible for its own 3D model
- Designer meetings, clash detections
- Every 3D object has a Tag which corresponds the costing program's (G-Prog) elements
- G-Prog: is a client requirement, frequently used in Norway
- Usually used in road projects, lacking code for other disciplines work

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Common BIM data environment

- Common Data Environment (CDE)
- ProjectWise based system
  - Connected servers in the interfacing offices
- Created by second largest software company: Bentley
  - MicroStation (DGN), MX (road design), gINT, Staad
- Capable to handle every types of documents
  - Native (without conversation) DWG handling
  - Big 3D files are processed quickly
  - Visualisation in the same software

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PowerRebar V8i (SELECTseries3) [PowerRebar Project: BERGEN_NS-EN ISO 3766] (1)

Rebar Window Help

ProjectWise Explorer V8i (SELECTseries 3)

Datasource Folder Document View Tools Window Help

Search Interface Attributes

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- TFL Projects
- TPN Bank Congestion Relief Project
- TPN Bergen LRT (mottmac\ber64275)
  - Documents
    - Projects
      - Bergen- Depot and Workshop
      - Bergen Light Rail - DEV Phase 1
        - CAD
          - CAD-UserAndIssueGuides
          - Compiled Model-Superceeded
          - IDC_Check
          - Incoming Drawings
          - Outgoing Drawings
          - Resources
          - Working Drawings
            - Contract 00
            - Contract 11
              - (A) Frontpage, Contents, Drawing List
              - (B) Overview Plan. Plan and Profiles
              - (C) Track & Rail Geometry
              - (D) Carriageway
              - (E) Elevation Plans
              - (F) Normal Sections
              - (G) Drainage
              - (H) Private-Public Water & Sewage
              - (I) Cables
              - (J) Construction Technical Details
              - (K) Structure
                - 2D Drawing Sketches
                - 2D Drawings
                - 01_Prelim_(A)
                - 02_Tender_(B)
                - 03_Interim_Const_(Z)
                - 04_Const_(C)
                - 05_AS_Built_(D)
                - Bridges Sources
                - superseded
                - Tender
                - Tunnel Technical Rooms
                - 2D Extractions
                - 3D Models
                - RC Models
                - Reports
                - Schedule

Name	Description
C11-K-14-TG-0070	Folldal Tunnel - Cut and Cover - RC Details - Casting Unit 3 - Sheet 4
C11-K-14-TG-0071	Folldal Tunnel - Cut and Cover - RC Details - Casting Unit 4 - Sheet 1
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C11-K-14-TG-0075	Folldal Tunnel - Cut and Cover - RC Details - Casting Unit 5 - Sheet 1
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C11-K-14-TG-0077	Folldal Tunnel - Cut and Cover - RC Details - Casting Unit 5 - Sheet 3
C11-K-14-TG-0077	Folldal Tunnel - Cut and Cover - RC Details - Casting Unit 5 - Sheet 3
C11-K-14-TG-0120	T K20 Steinsvik Tunnel - East Portal - Reinforcement - Block 1
C11-K-14-TG-0120	T K20 Steinsvik Tunnel - East Portal - Reinforcement - Block 1
C11-K-14-TG-0121	T K20 Steinsvik Tunnel - East Portal - Reinforcement - Block 2-4 - Sheet
C11-K-14-TG-0121	T K20 Steinsvik Tunnel - East Portal - Reinforcement - Block 2-4 - Sheet
C11-K-14-TG-0122	T K20 Steinsvik Tunnel - East Portal - Reinforcement - Block 2-4 - Sheet
C11-K-14-TG-0122	T K20 Steinsvik Tunnel - East Portal - Reinforcement - Block 2-4 - Sheet
C11-K-14-TG-0123	T K20 Steinsvik Tunnel - East Portal - Reinforcement - Block 5-6 - Sheet
C11-K-14-TG-0123	T K20 Steinsvik Tunnel - East Portal - Reinforcement - Block 5-6 - Sheet
C11-K-14-TG-0124	T K20 Steinsvik Tunnel - East Portal - Reinforcement - Block 5-6 - Sheet
C11-K-14-TG-0124	T K20 Steinsvik Tunnel - East Portal - Reinforcement - Block 5-6 - Sheet
C11-K-14-TG-0125	T K20 Steinsvik Tunnel - East Portal - Transition - Reinforcement
C11-K-14-TG-0125	T K20 Steinsvik Tunnel - East Portal - Transition - Reinforcement
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C11-K-14-TG-0140	T K30 Steinsvik Tunnel - West Portal - Reinforcement
C11-K-14-TG-0141	T K30 Steinsvik Tunnel - West Portal - Transition - Reinforcement

Document Properties | Project Properties | Folder Properties | Photo Preview | Access Control | Components

View: <Default>

Property name	Property value
Name	C11-K-14-TG-0123
Folder Name	04_Const_(C)
Environment	Construction Drawing Attributes
File Name	C11-K-14-TG-0123.dgn
Workflow	Drawings

ProjectWise

- File based central data storage system
- Versions
  - WIP – Work In Progress
  - Shared: shared with other disciplines, Clash Detection
  - Other disciplines see the latest version but the previous ones remain as well
  - Issued: issued to the client
  - Final: at the end of the project the client owns the file

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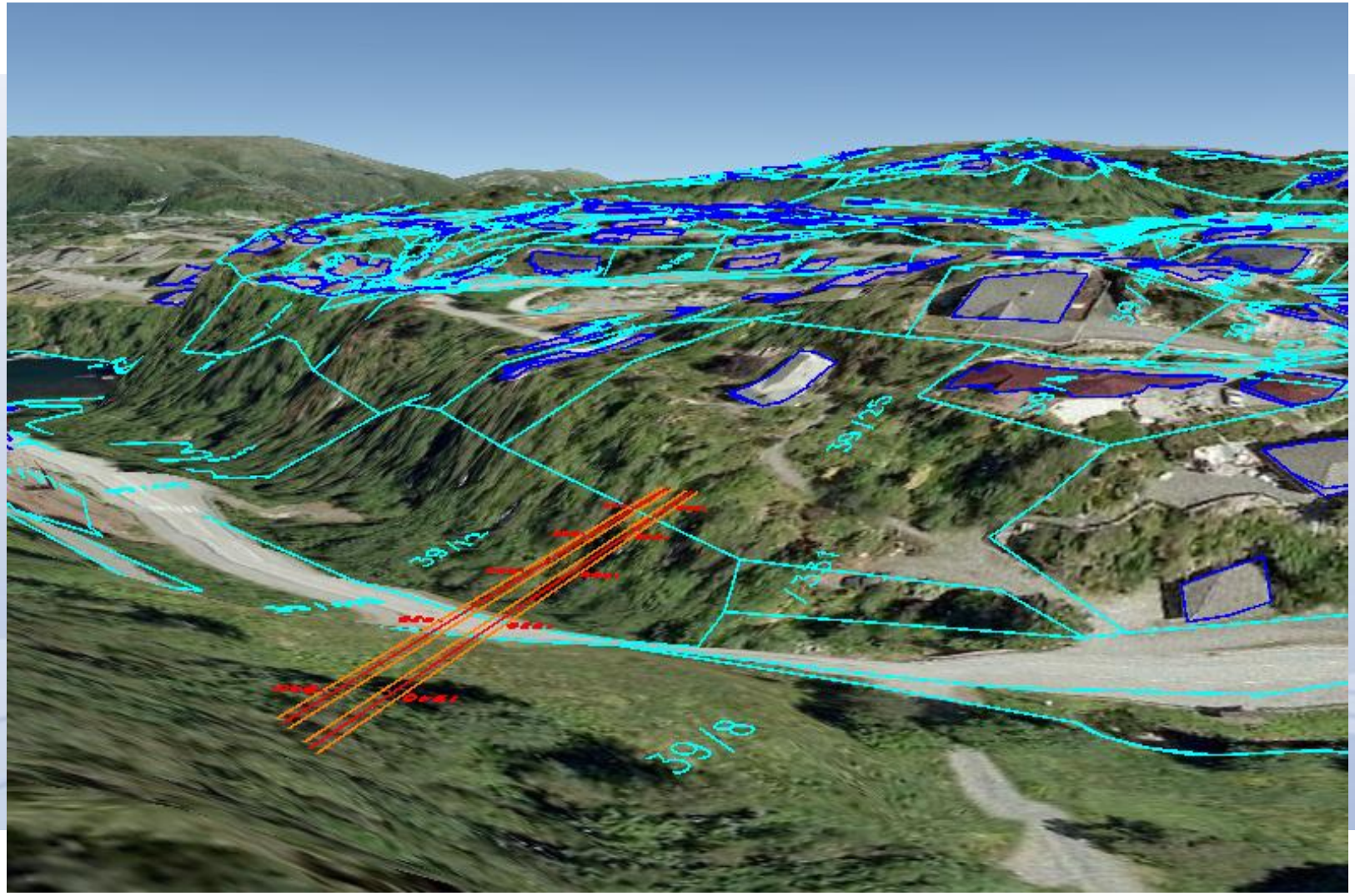
Bergen – soil surface and alignment



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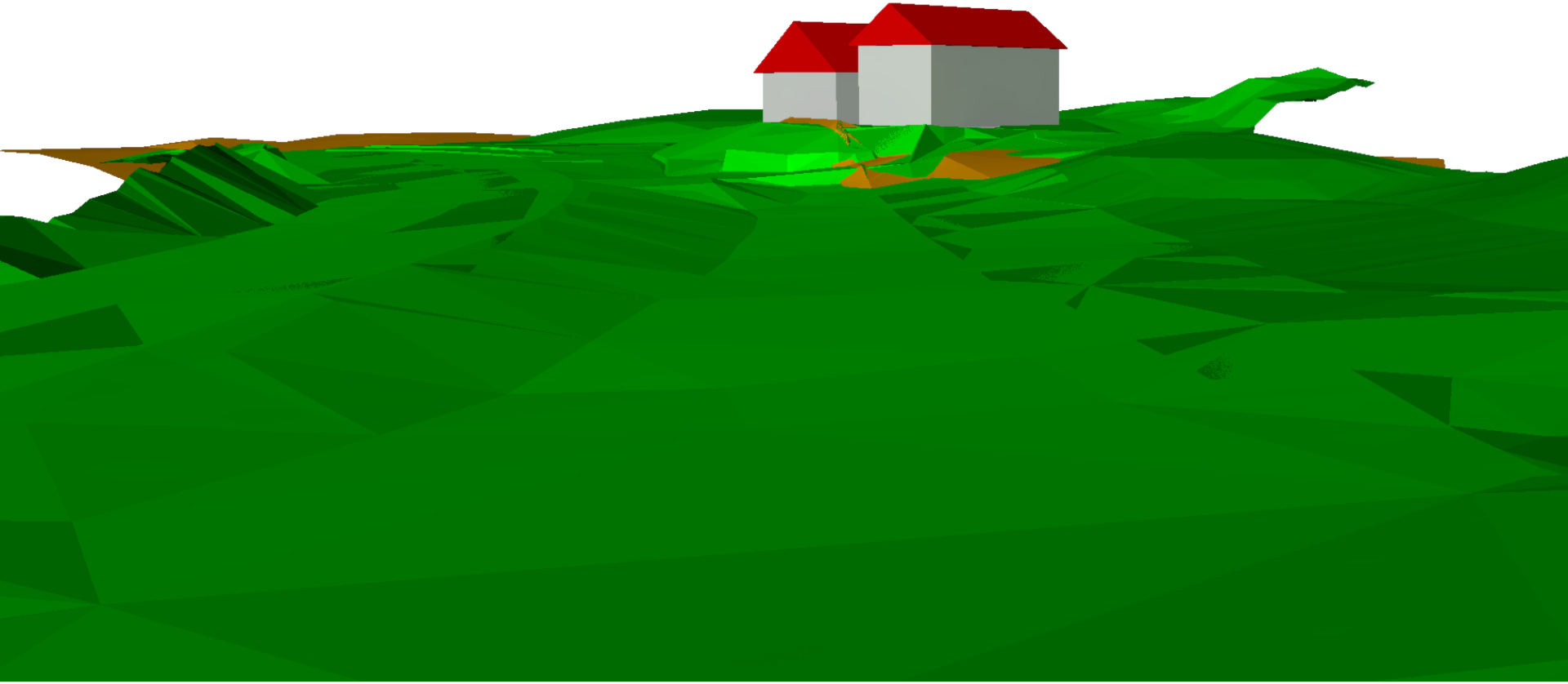

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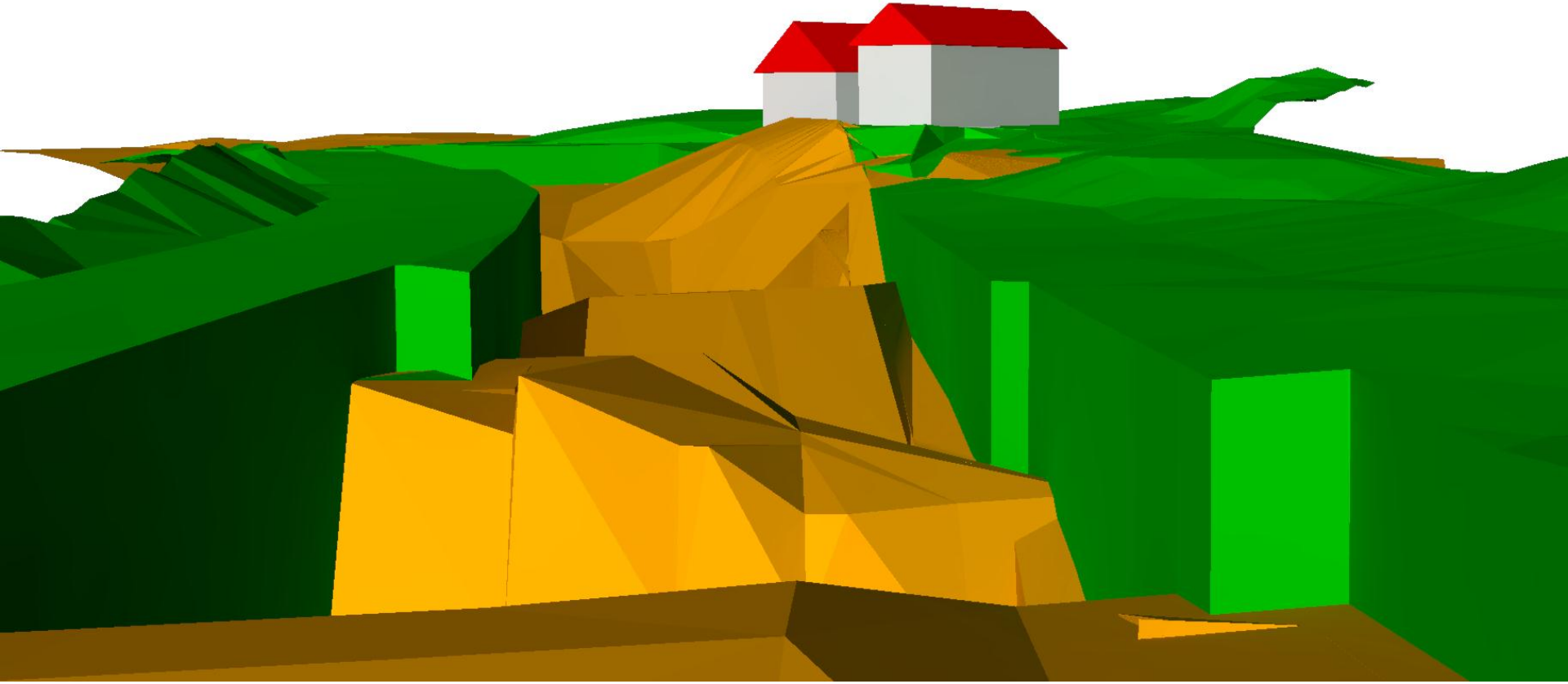

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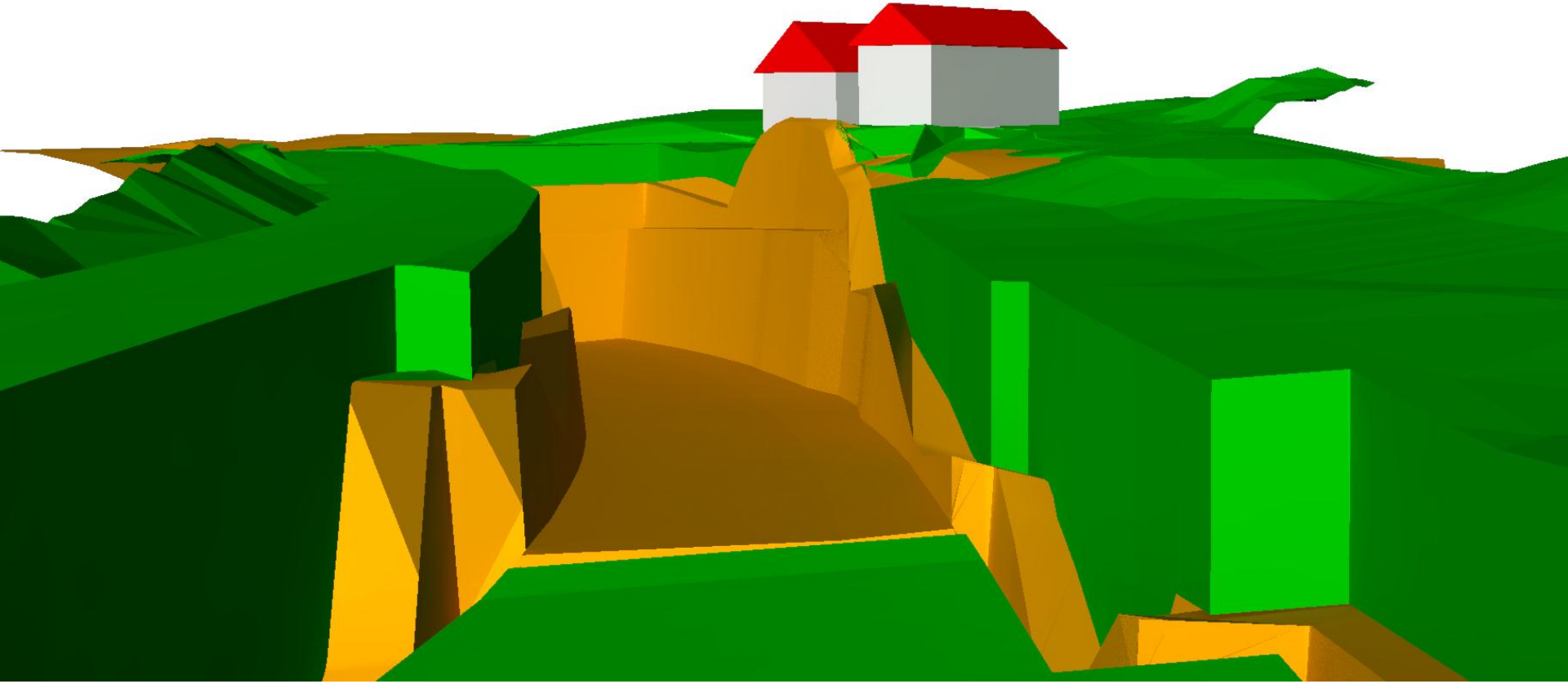

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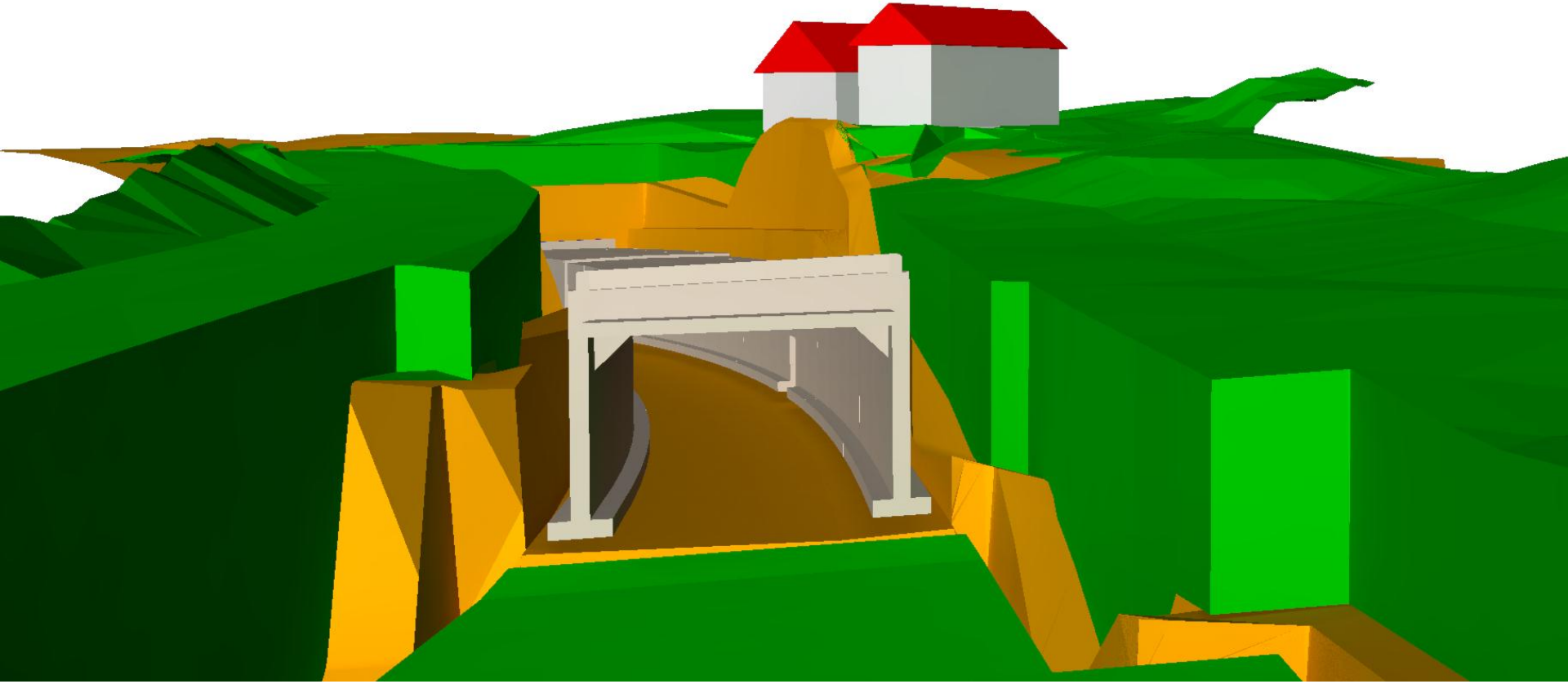

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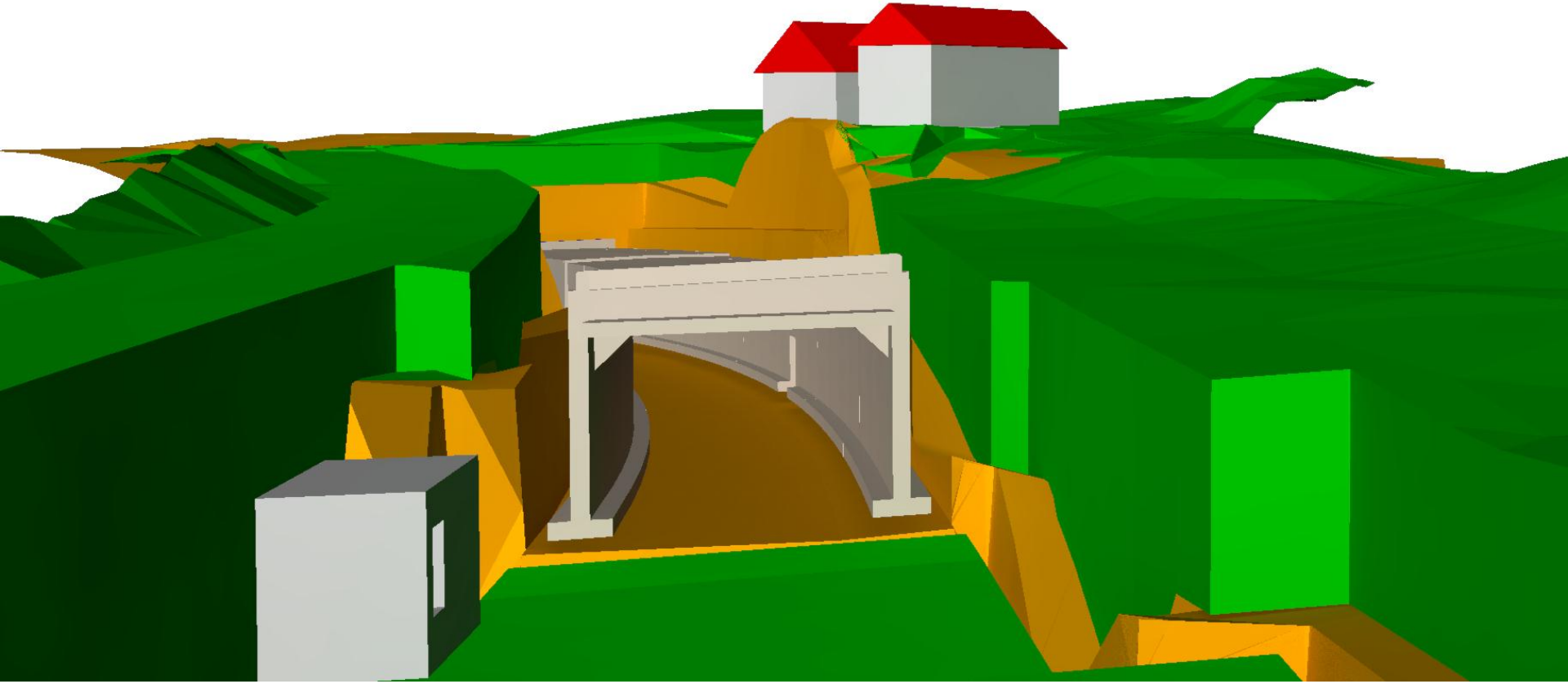

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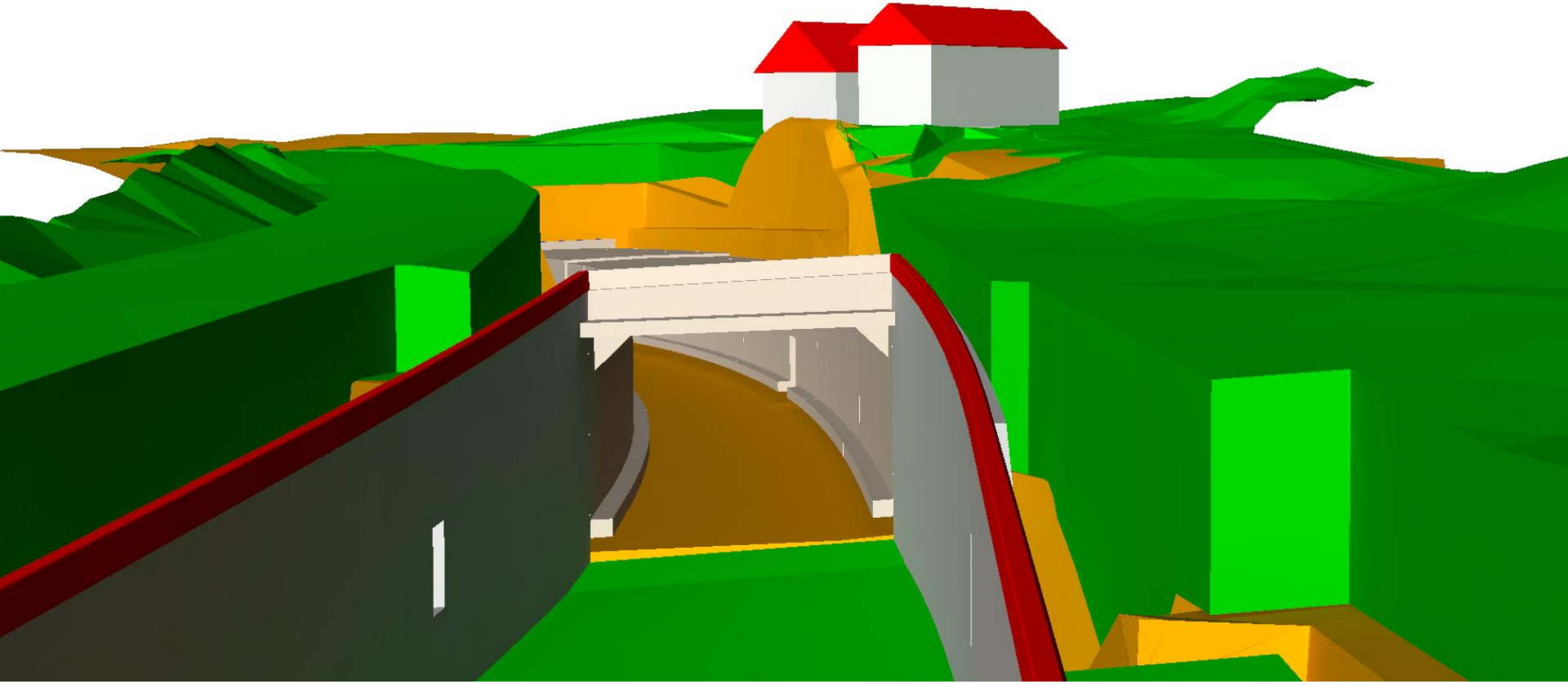

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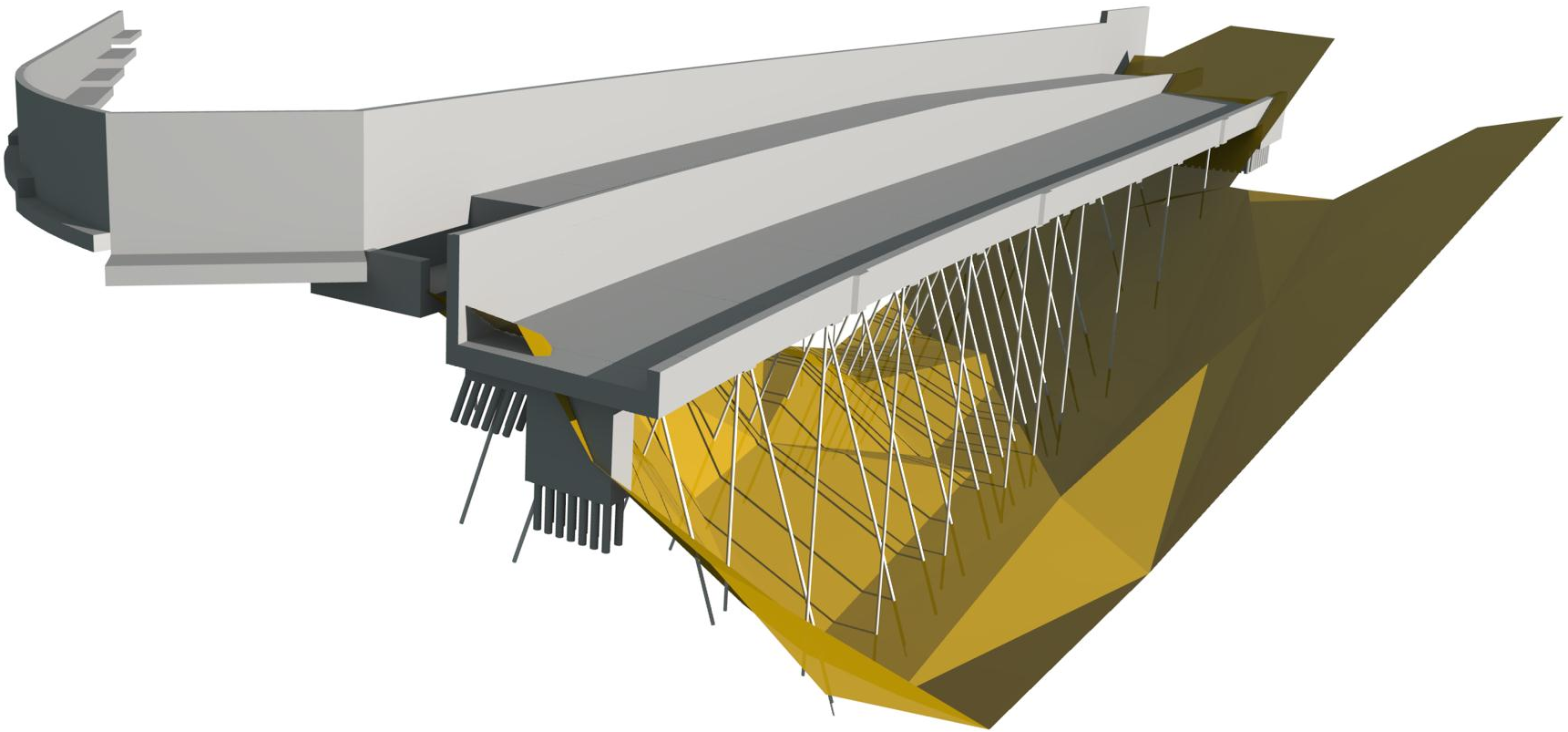

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Tunnel Design- Analytical methods

- Loads
  - Soil interaction curve
  - “closed formulas”
  - Wedge stability
  - Lining design – simple structural calculations

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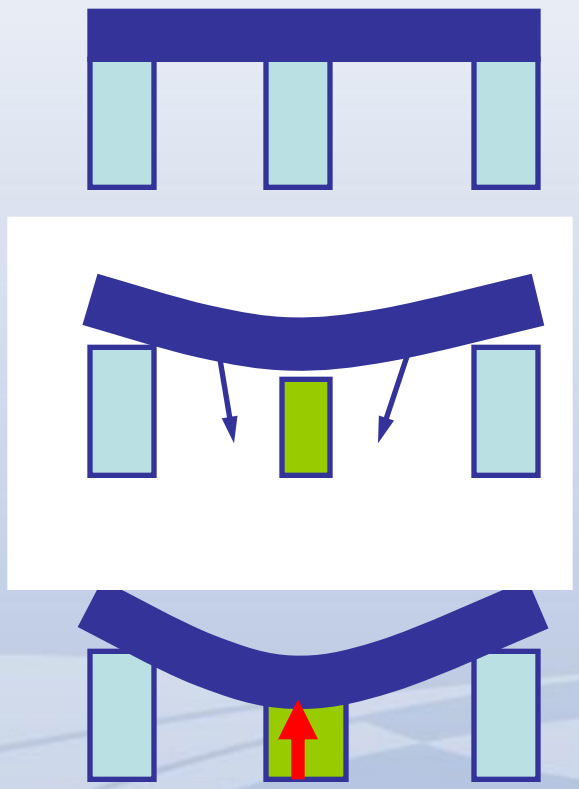
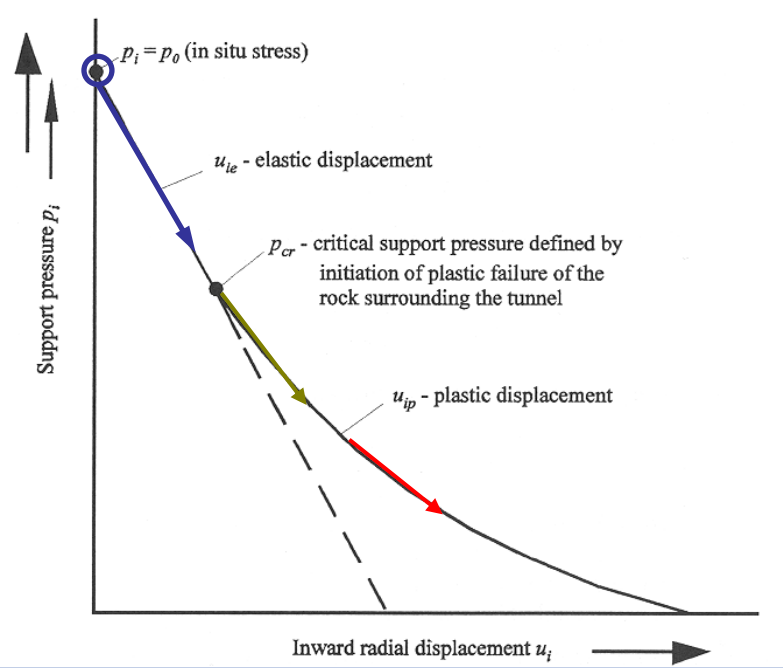
Soil Interaction curve





The displacements happen in a finite period of time

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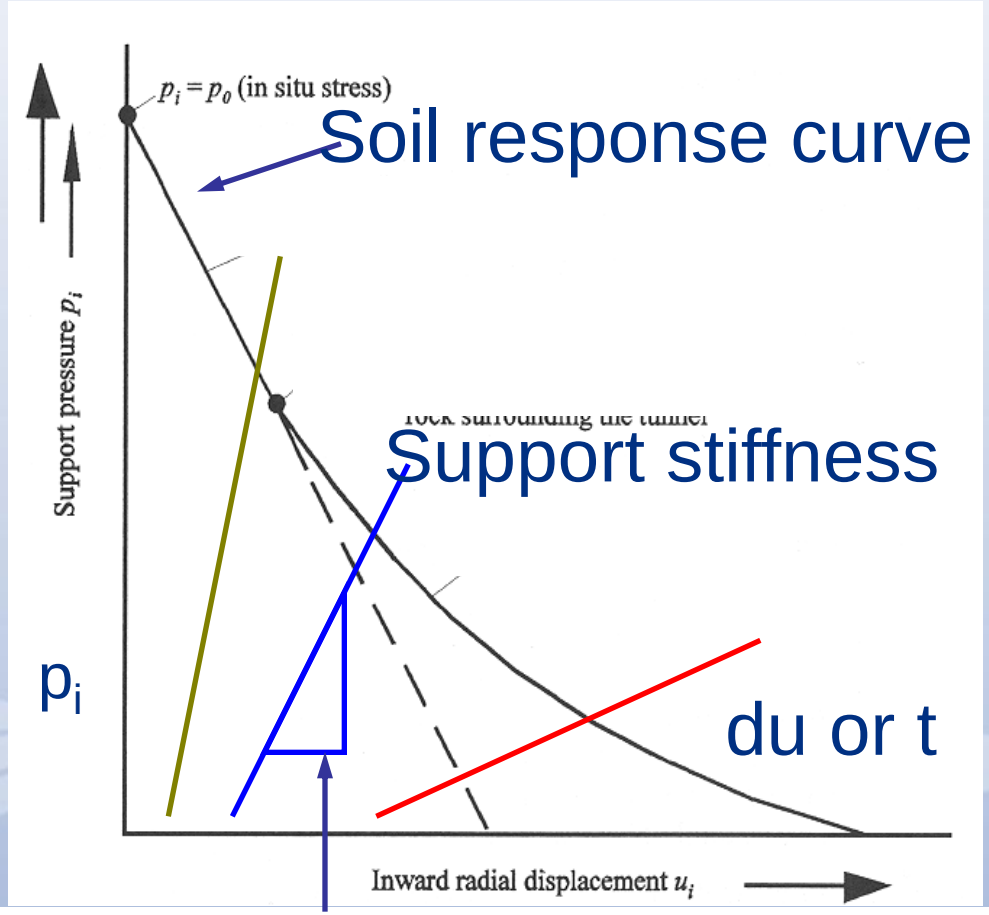
Timing & Support stiffness

Load on the support



displacement

p/u = E stiffness

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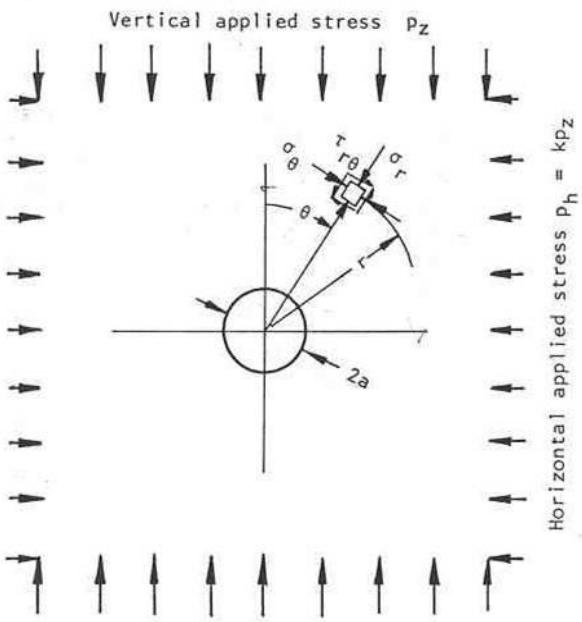
Hole in the elastic continuum

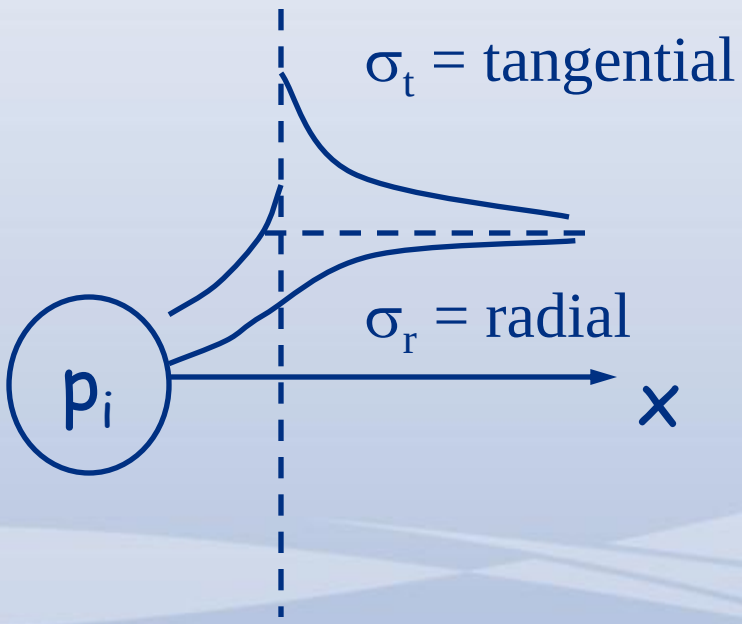


STRESS COMPONENTS AT POINT (r, θ)

Radial $\sigma_r = \frac{1}{2}p_z\left((1+k)(1-a^2/r^2) + (1-k)(1-4a^2/r^2+3a^4/r^4)\cos 2\theta\right)$

Tangential $\sigma_\theta = \frac{1}{2}p_z\left((1+k)(1+a^2/r^2) - (1-k)(1+3a^4/r^4)\cos 2\theta\right)$

Shear $\tau_{r\theta} = \frac{1}{2}p_z\left(-(1-k)(1+2a^2/r^2-3a^4/r^4)\sin 2\theta\right)$



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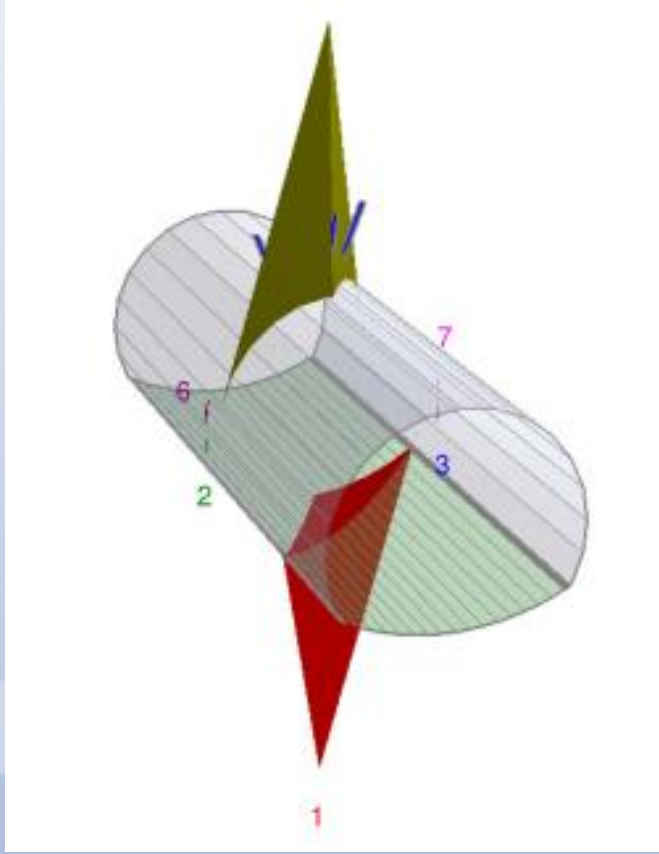
Analytical methods

- Face or wedge stability

Input data:

- Strength
- Stiffness
- In situ stress
- Crack orientation, density



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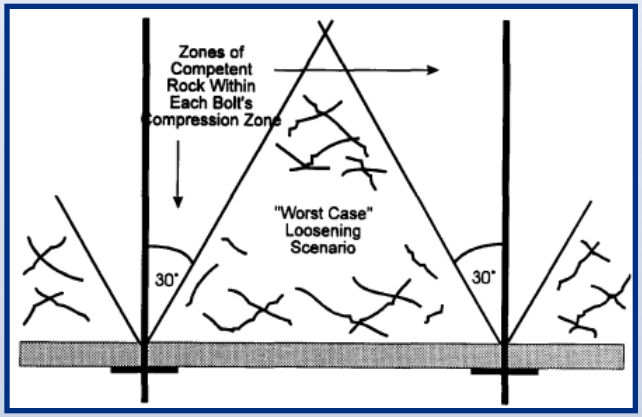
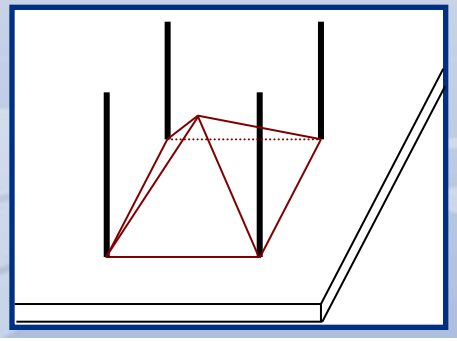
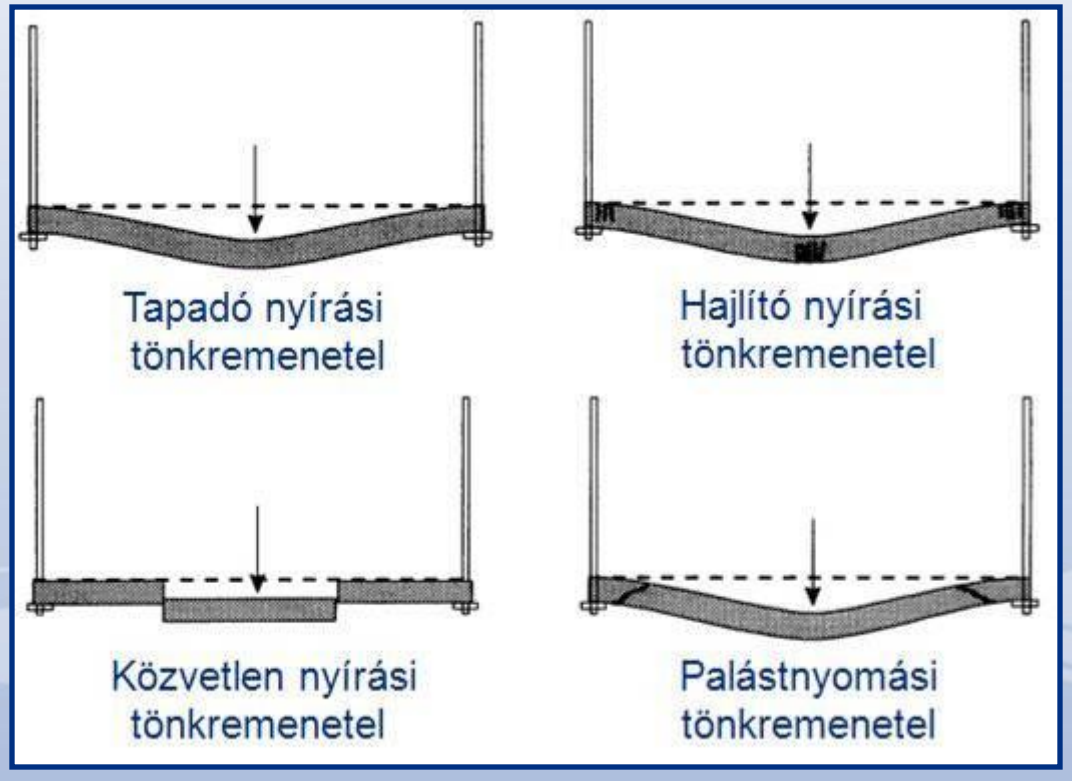
Analytical methods

- Barrett&McCreath (1995) calculation (small block rock)







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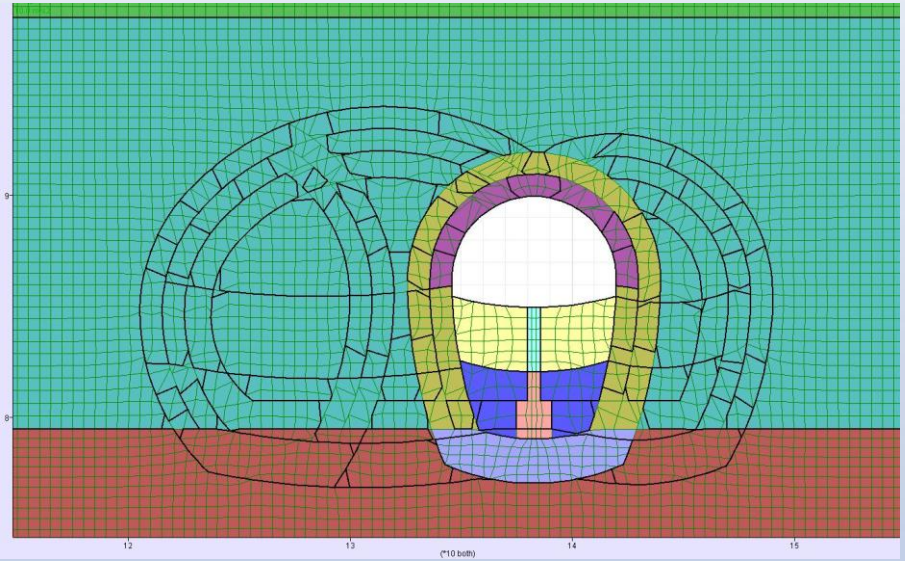
Numerical analysis

- 2D Numerical analysis
- 3D Numerical analysis
- Discrete element method
- Finite different method
- Finite element method



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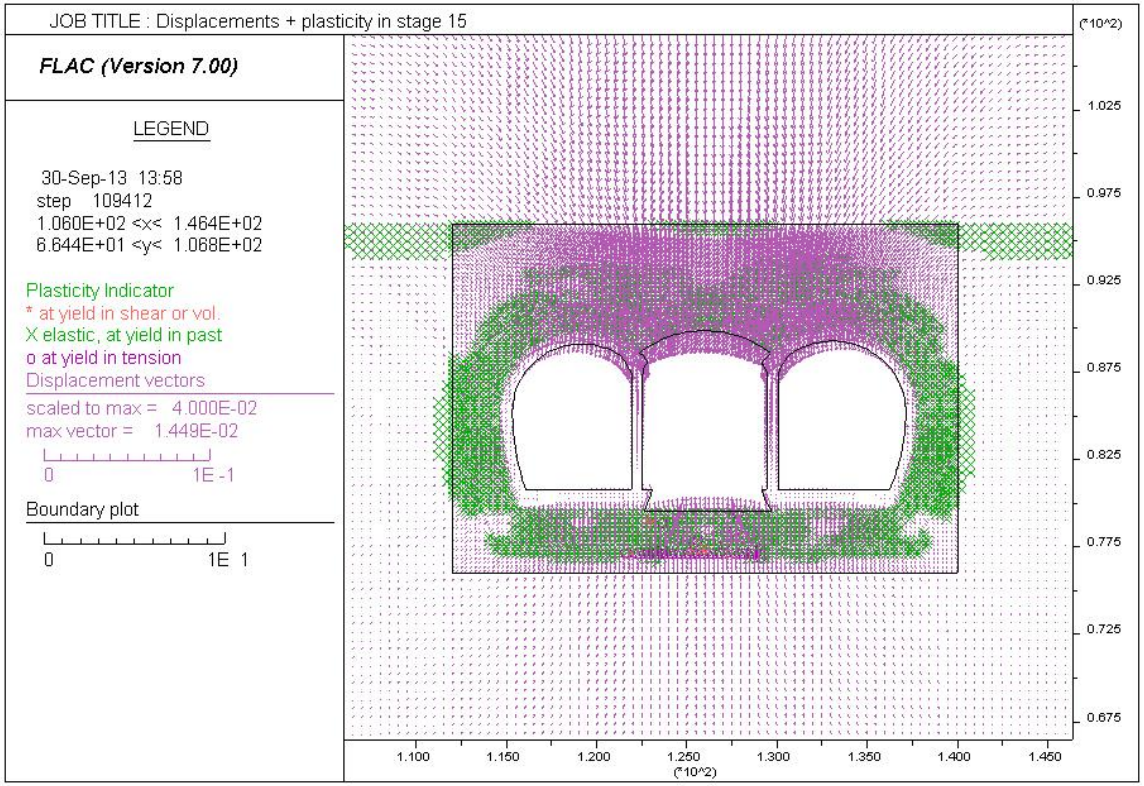
Three celled tunell project

- Usage of several design methods



Strata

Formation	Strata
Fill	Fill
Kallang Formation	Estaurine Clay
	Fluvial Sand
	Fluvial Clay
Bukit Timah Granite	Residual Soil
	Completely Weathered Granite
	Highly Weathered Granite
	Moderately Weathered Granite
	Slightly Weathered Granite
	Fresh Granite

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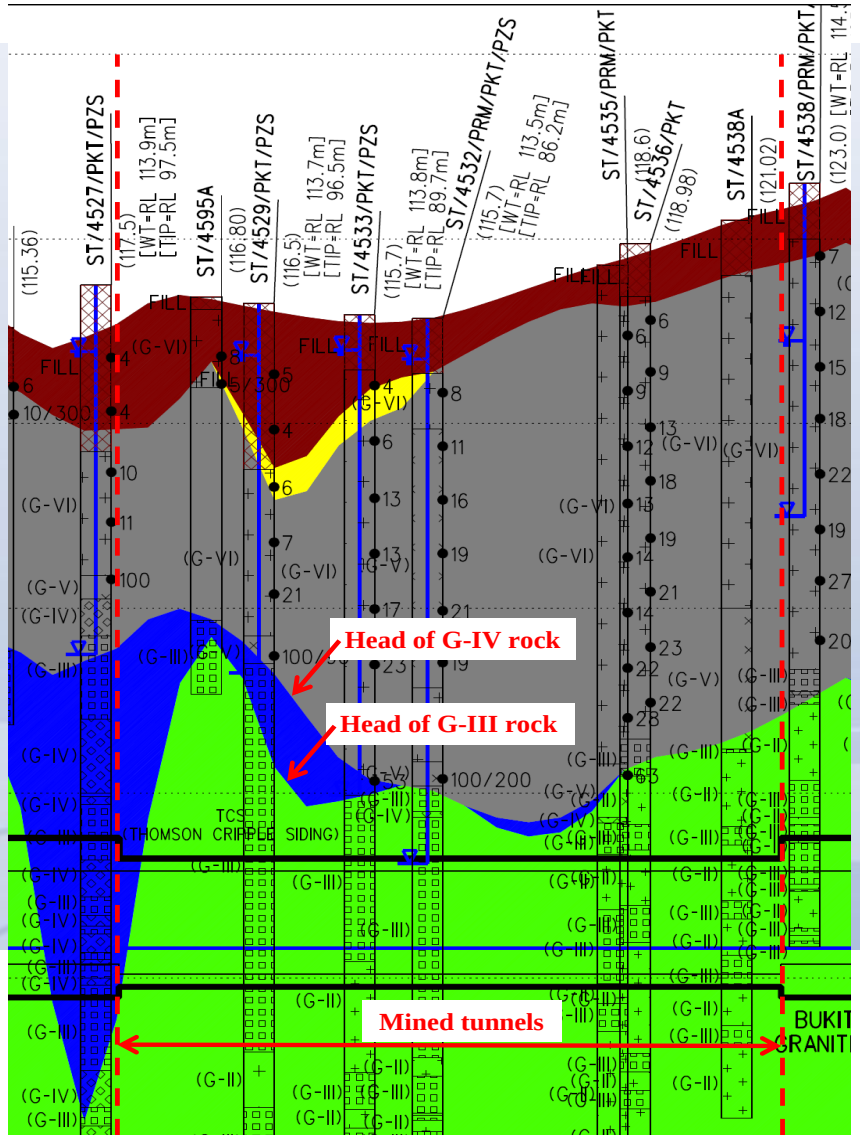
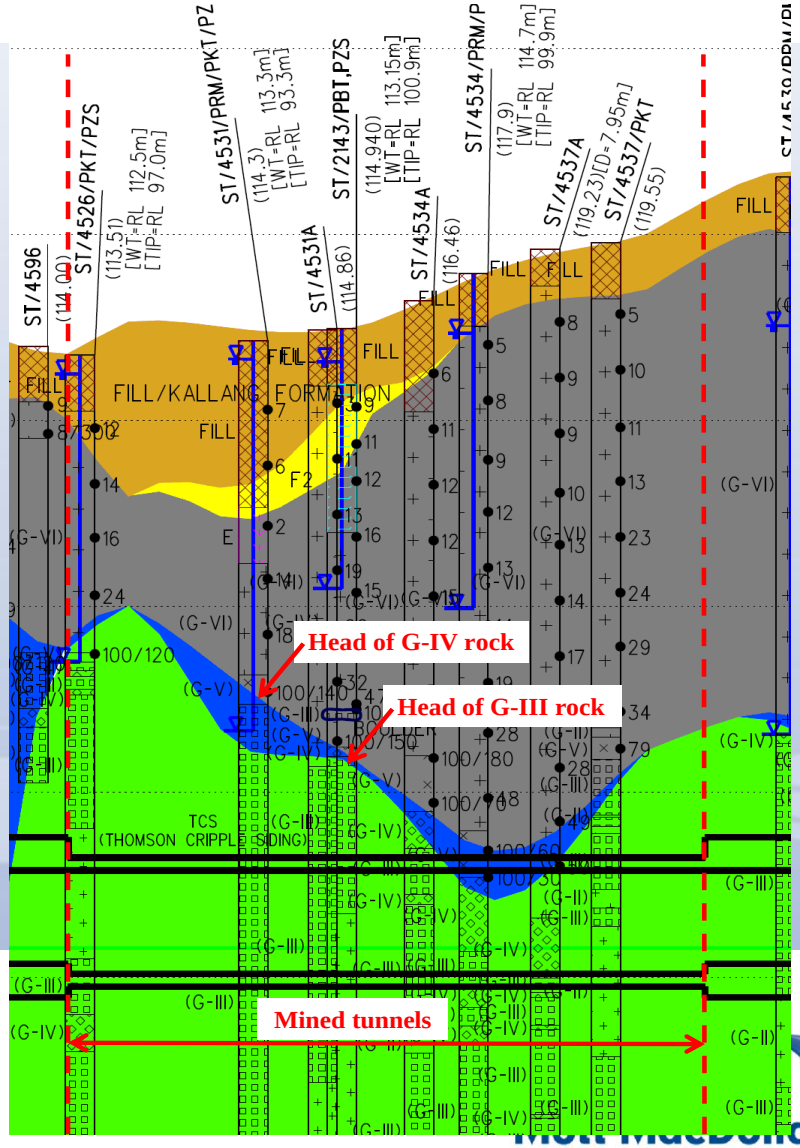
Geological profile along the NB Track



Geological profile along the SB Track



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Input data

- Parametres (too conservative)

Stratum	SPT value, N (-)	Unit weight, γ (kg/m³)	Undrained shear strength, c_u (kPa)	Effective cohesion, c' (kPa)	Effective friction angle, Φ' (°)	Undrained elastic modulus, E_u (MPa)	Drained elastic modulus, E' (MPa)	Coefficient of earth pressure at rest, K_0 (-)	Coefficient of permeability, k (m/s)
Fill	-	19	30	0	30	10	10	0.5	1.0×10^{-6}
E	-	15	20	0	25	6	5	1.0	1.0×10^{-6}
F1	-	20	-	0	30	-	10	0.7	1.0×10^{-6}
F2	N≤4	17	25	5	25	7.5	6	1.0	1.0×10^{-6}
	N>4	19	50	5	25	15	12	1.0	1.0×10^{-6}
G-VI	N≤15	19	5.0 × N	5	32	2.5 × N	2.0 × N	0.8	2.0×10^{-7}
	N>15	19	5.0 × N	10	32	2.5 × N	2.0 × N	0.8	2.0×10^{-7}
G-V	N≤50	20	5.0 × N	12	32	2.5 × N	2.0 × N	0.8	2.0×10^{-7}
	50<N≤100	20	250	20	32	2.5 × N	2.0 × N	0.8	2.0×10^{-7}
	N>100	20	250	25	32	2.5 × N	2.0 × N	0.8	2.0×10^{-7}
G-IV	-	24	500	40	40	500	500	0.8	1.0×10^{-6}
G-III	-	25	1000	90	45	2000	2000	0.8	3.0×10^{-7}
G-II	-	26	1000	250	45	5000	5000	0.8	5.0×10^{-8}
G-I	-	26	1000	250	45	5000	5000	0.8	5.0×10^{-8}

- Failure criteria (Mohr-Coulomb instead of Hoek-Brown)

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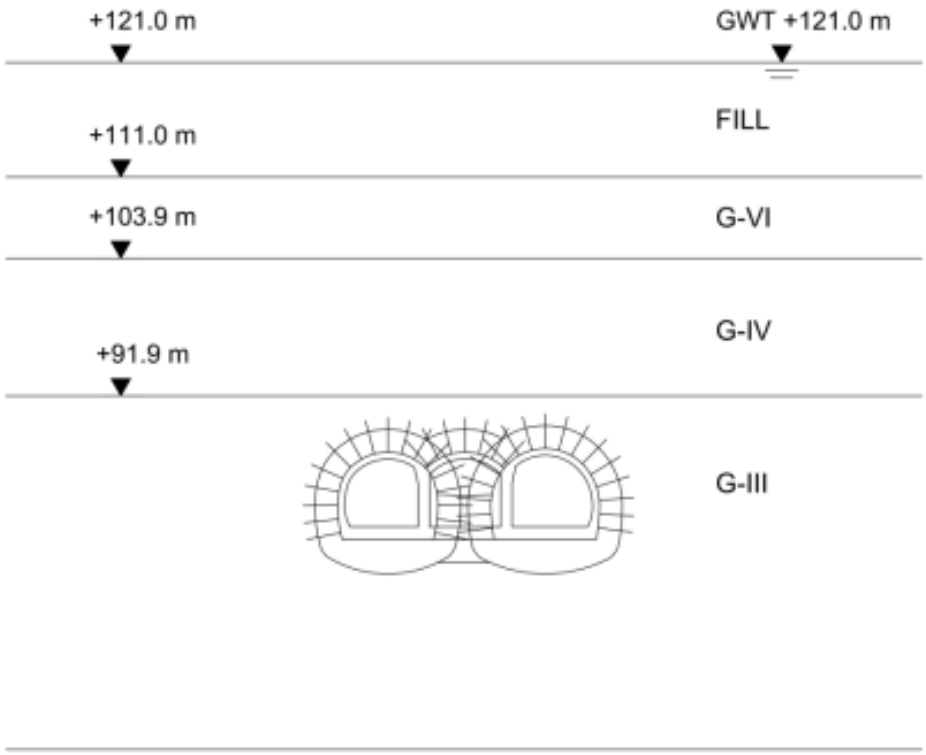
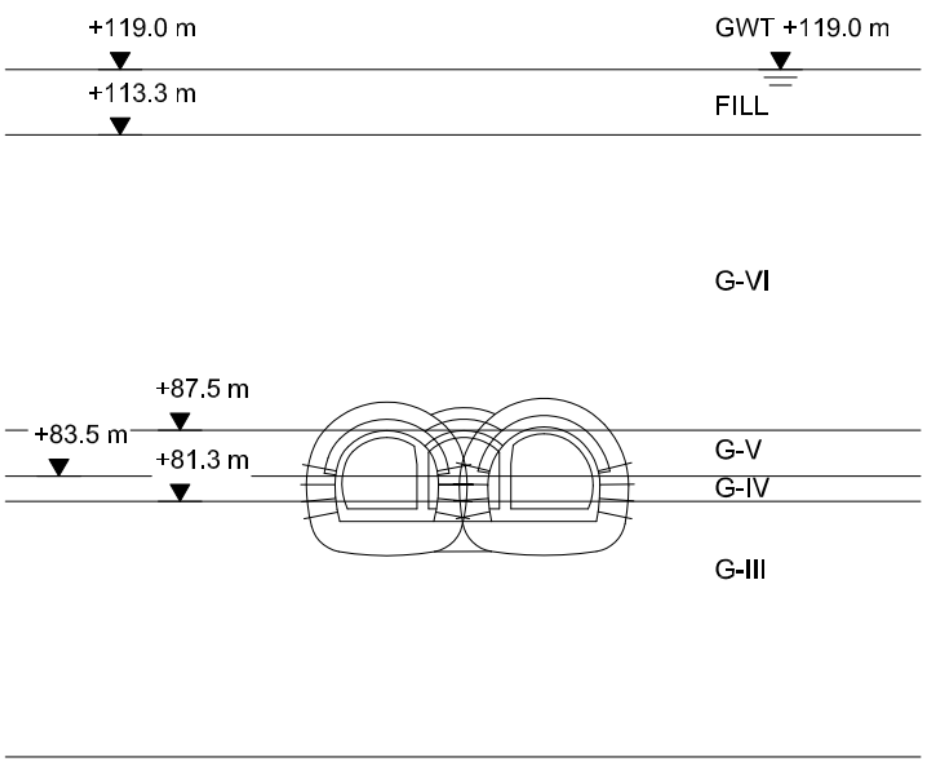
Strata – excavation support

Proposed stratification for Type A analysis



Proposed stratification for Type B analysis



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Soil parametres – Type A and B

Table 3.3: Geotechnical properties for the analysis of section Type A (Model 01)
Source: GIBR for Contract T213 [R15]

Stratum	Average SPT value, N (-)	Unit weight, γ (kg/m³)	Undrained shear strength, c_u (kPa)	Effective cohesion, c' (kPa)	Effective friction angle, Φ' (°)	Undrained elastic modulus, E_u (MPa)	Drained elastic modulus, E' (MPa)	Coefficient of earth pressure at rest, K_0 (-)	Coefficient of permeability, k (m/s)
Fill	-	19	30	0	30	10	10	0.5	1.0×10^{-6}
G-VI	26	19	130	10	32	65	52	0.8	2.0×10^{-7}
G-V	26	20	130	12	32	65	52	0.8	2.0×10^{-7}
G-IV	-	24	500	40	40	500	500	0.8	1.0×10^{-6}
G-III	-	25	1000	90	45	2000	2000	0.8	3.0×10^{-7}

Table 3.4: Geotechnical properties for the analysis section Type B (Model 02)
Source: GIBR for Contract T213 [R15]

Stratum	Average SPT value, N (-)	Unit weight, γ (kg/m³)	Undrained shear strength, c_u (kPa)	Effective cohesion, c' (kPa)	Effective friction angle, Φ' (°)	Undrained elastic modulus, E_u (MPa)	Drained elastic modulus, E' (MPa)	Coefficient of earth pressure at rest, K_0 (-)	Coefficient of permeability, k (m/s)
Fill	-	19	30	0	30	10	10	0.5	1.0×10^{-6}
G-VI	26	19	130	10	32	65	52	0.8	2.0×10^{-7}
G-IV	-	24	500	40	40	500	500	0.8	1.0×10^{-6}
G-III	-	25	1000	90	45	2000	2000	0.8	3.0×10^{-7}

Groundwater conditions

- Groundwater table is at ground level
- Groundwater table is 5m below ground level

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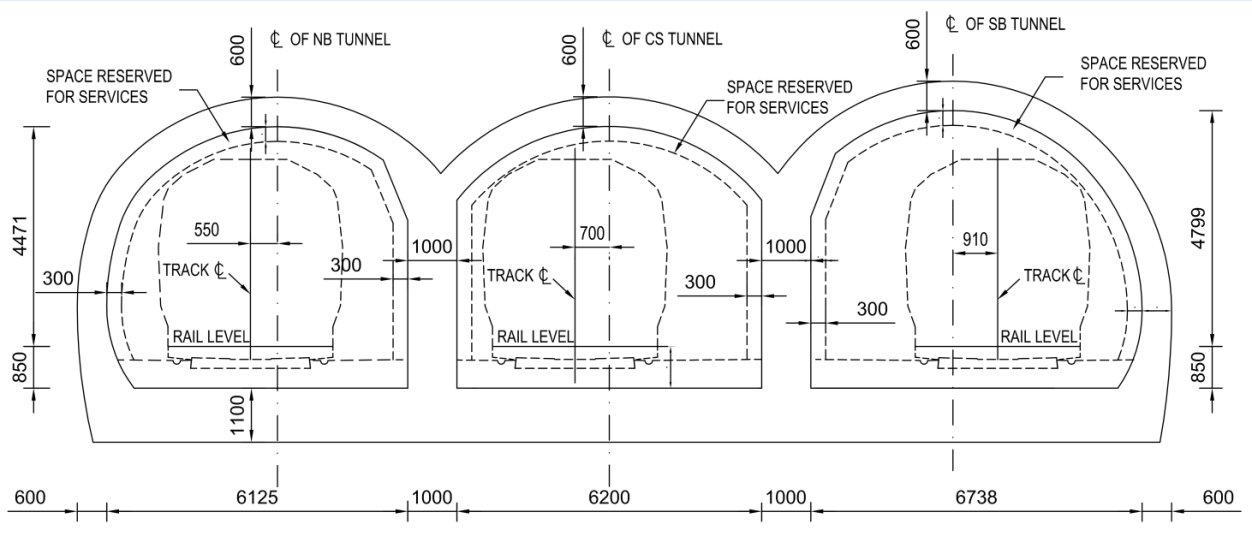
Designed structure

- Three celled tunnel



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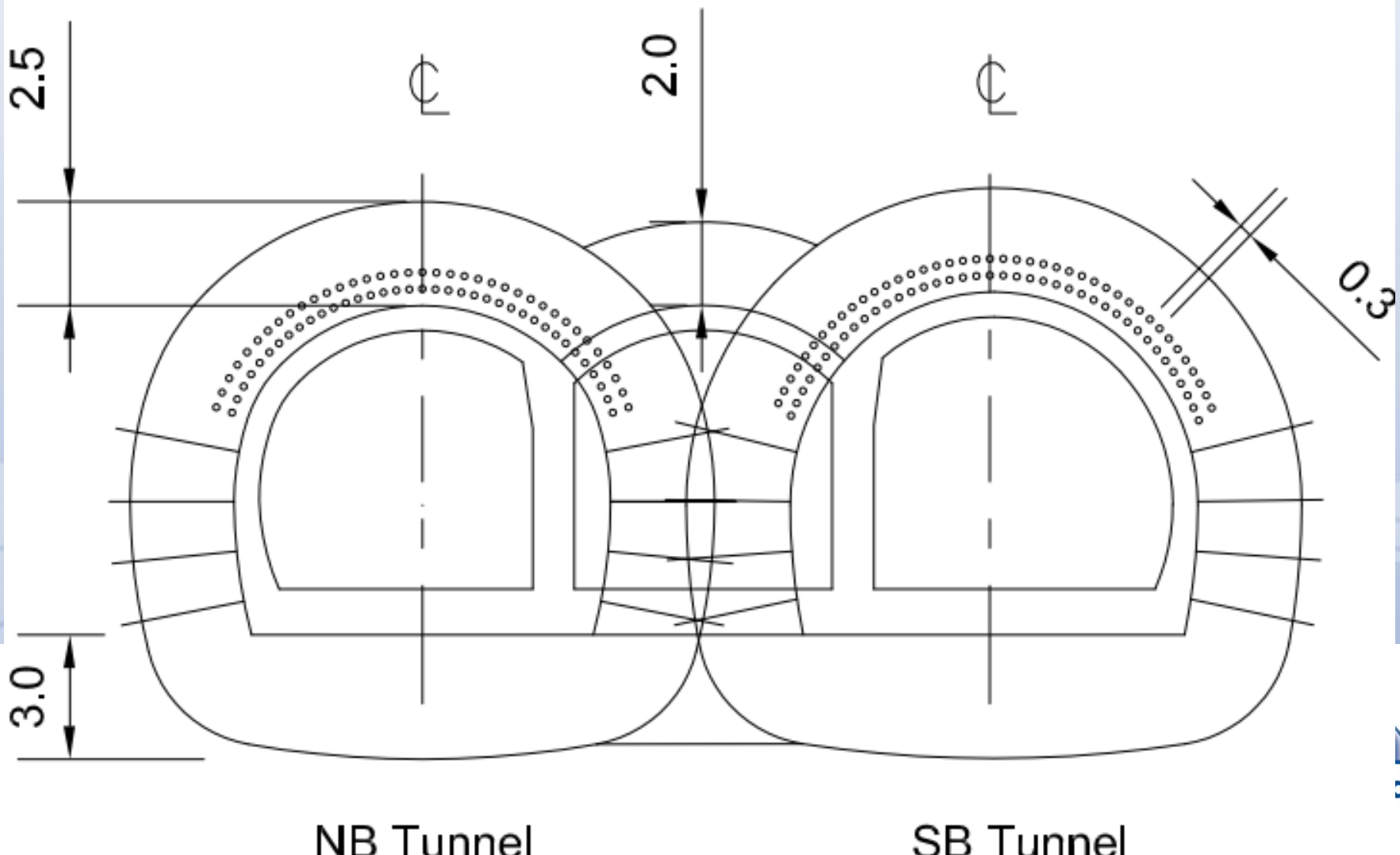
Soil strengthening around the tunnels

Layout of grouting and forepoles around tunnels (type B)



Empirical methods

- Rock classification methods:
  - Q,
  - RMR,
  - GSI
- The benefits of Q methods
  - More detailed method applicable for tunnel design, supports standardised design
  - Very effective in preliminary design

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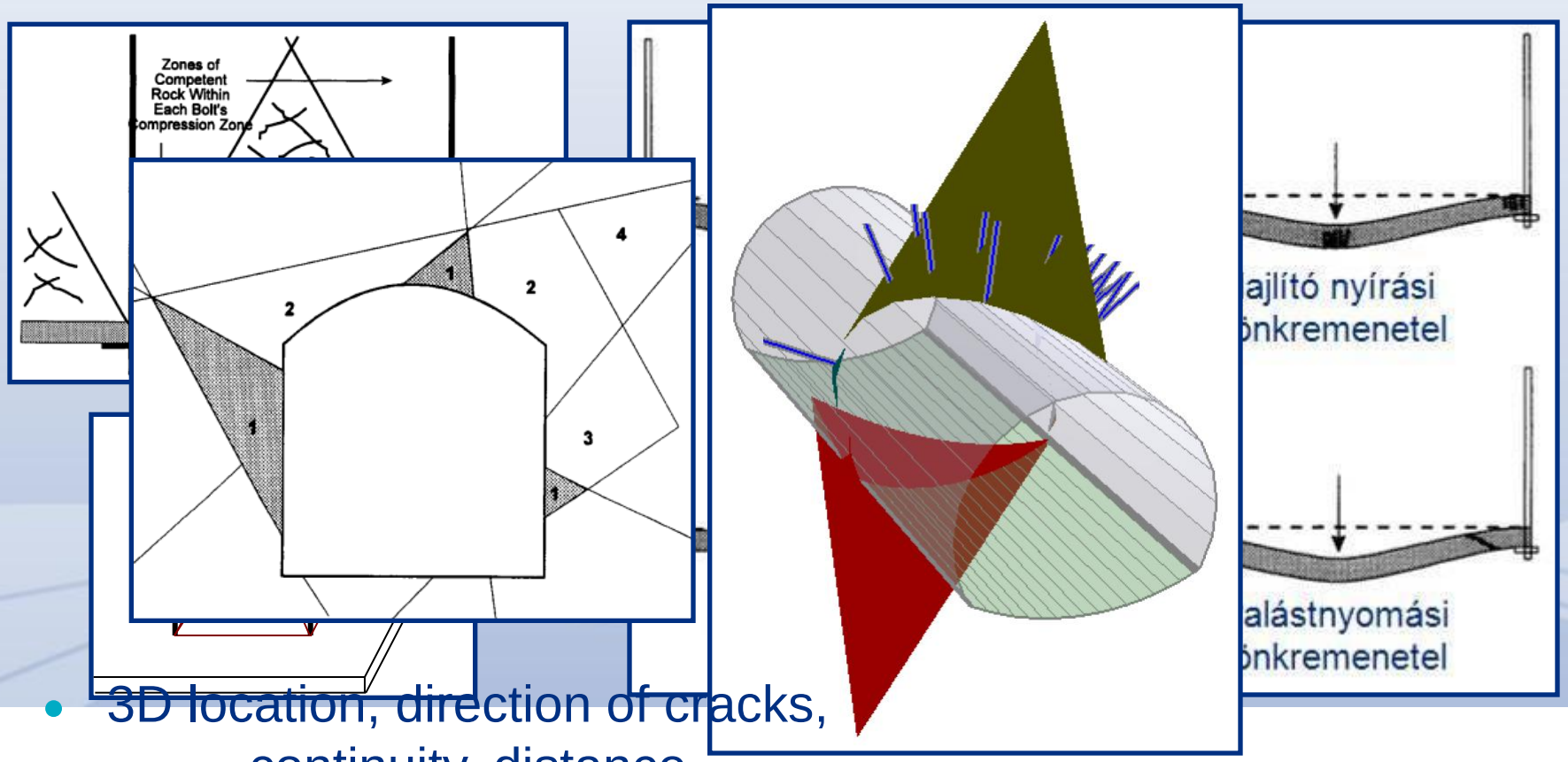
Analitical methods

- UnWedge software /large blocked rock/
- Barrett&McCreath (1995) calculation



- 3D location, direction of cracks, continuity, distance

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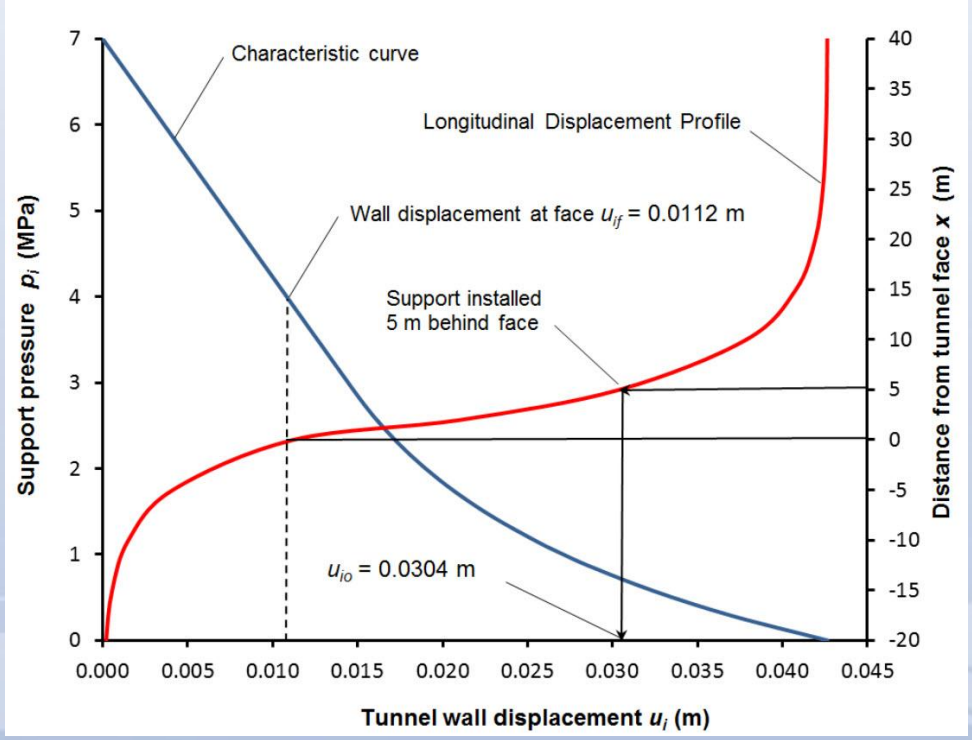
Example for input data

- In situ stresses
- + Estimated excavation support elements
- +Estimated excavation sequence



- Relaxation (support effect of the face)

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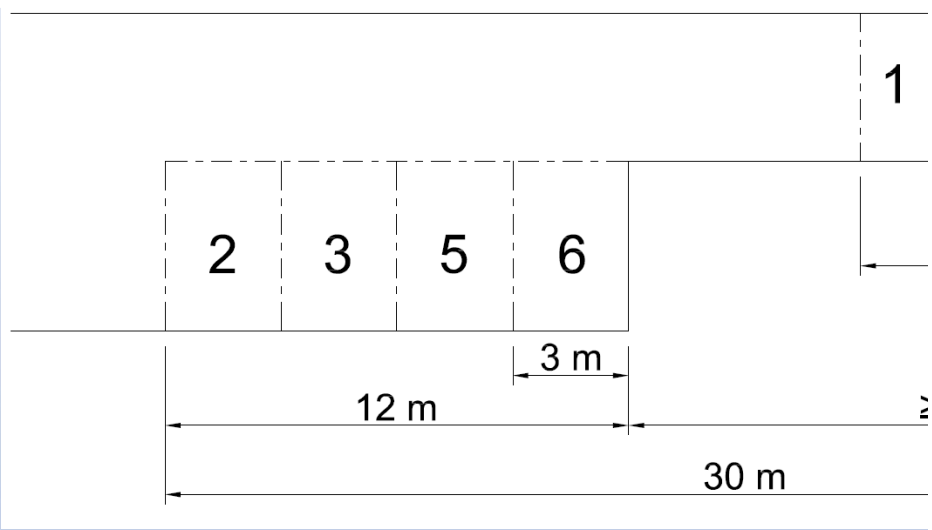
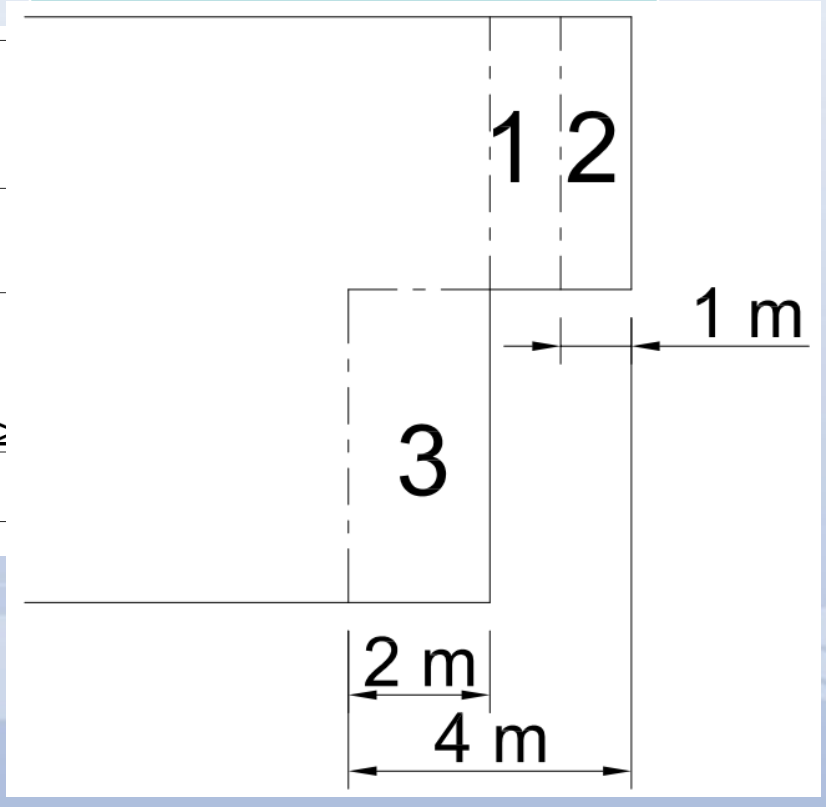
Steps of excavation

An example on the excavation sequence for section type A



Excavation sequence for section type B



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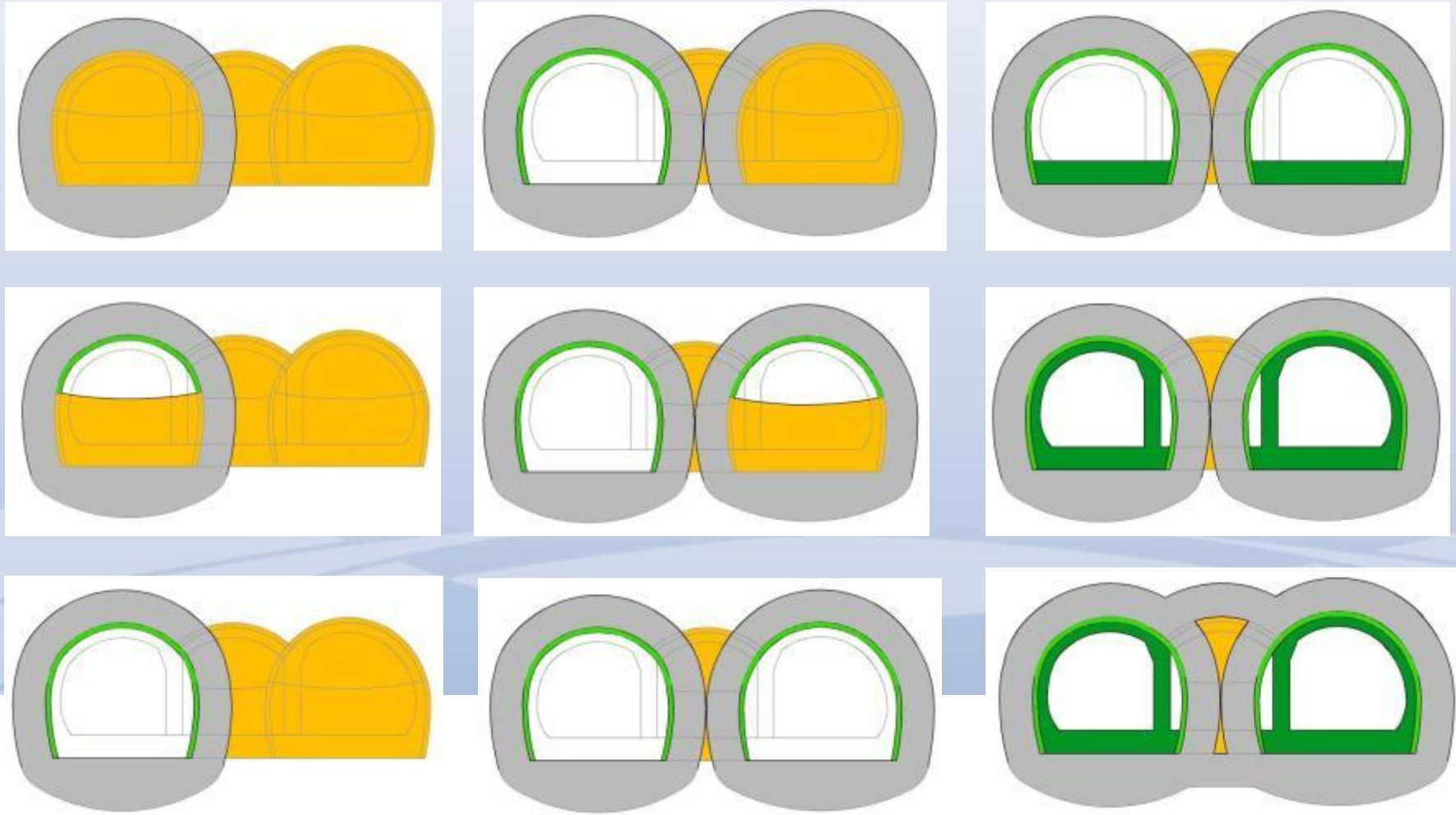
Steps of excavation (type A)



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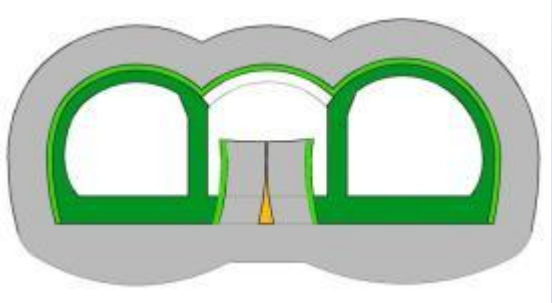
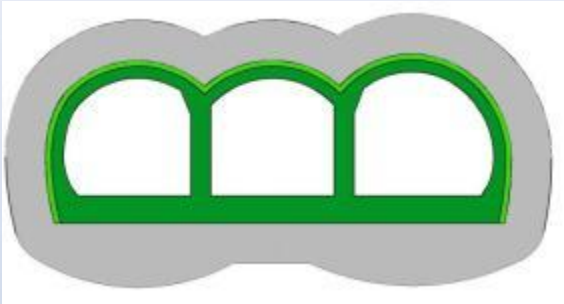
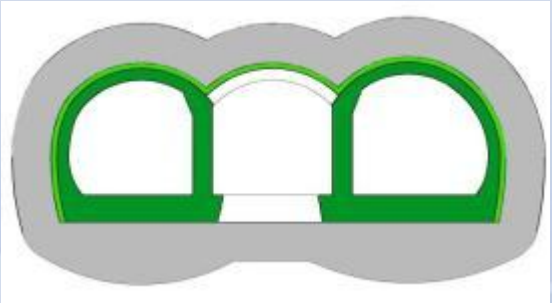
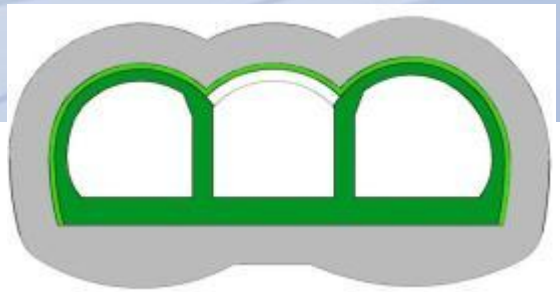
Steps of excavation (type A)









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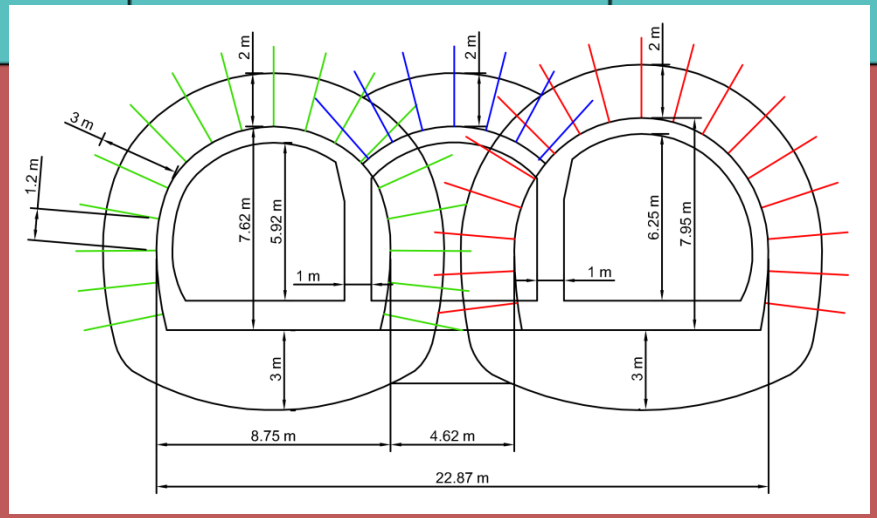
Temporary support design



User-defined Groups
- Soil:Fill
- Bukit Timah Granite:G-VI
- Bukit Timah Granite:G-IV
- Bukit Timah Granite:G-III

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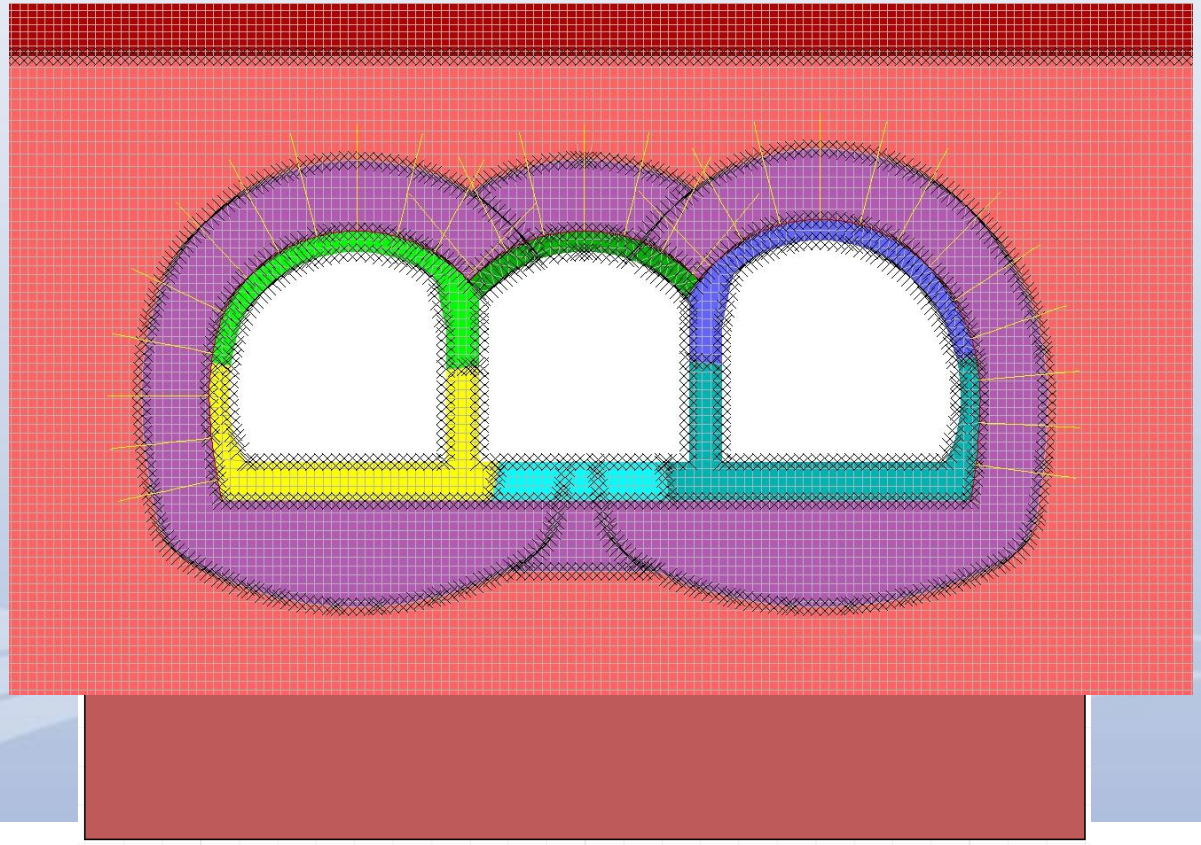
Numerical modelling

2D models for different excavation systems



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Lining parameters

Model	Temporary lining thickness (mm)	Rockbolt length (m)	Longitudinal rockbolt spacing (m)	Lateral rockbolt spacing (m)
01 (section Type A)	150	3.0	1.0	1.2
02 (section Type B)	300	3.0	1.0	1.2

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Capacity check of the support system

Project				
T213 Construction Singapore				
Calculations for:	**Divn/Dept:**	**EDE**	**Job No./File No.:**	328619
Bending moment - Axial force capacity check	**Calculated by:**	**VJ**	**Date:** 2014.04.29	Sheet No.
	Checked by:	**CG**	**Date:** 2014.05.05	1

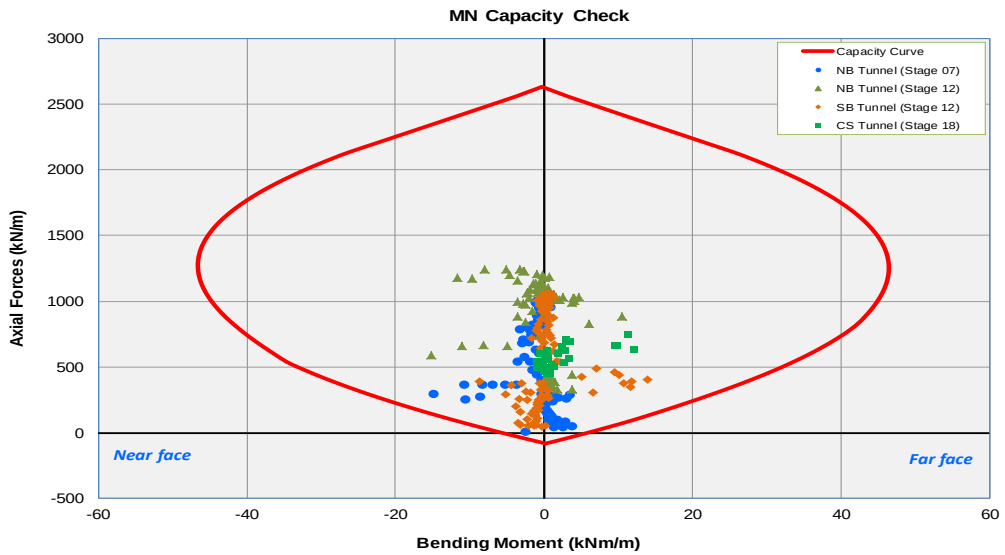
Section Data				
Concrete Grade (f_{ck})	30	MPa	Fibres ?	No
Steel (f_y)	500	MPa	*[Yes / No]*	
Steel Elastic Modulus (E_s)	205	GPa		
Design Flexural Tensile Strength ($f_{ctd,fl}$)	0.00	MPa	RILEM Values	
Tensile σ_1	0.00			
Maximum residual σ_2	0.000			
Minimum residual σ_3	0.000			
Effective Tensile Strain Limit if Unreinforced	-0.50%		Material factors	
Factored Yield Stress	434.78		SFRC	1.5
Width of section (b)	1000	mm	Conc	1.5
Depth (h)	150	mm	Steel	1.15
Reinforcement	Diameter	Spacing	Cover to bar	
Tension Bar 1	0	150	50	mm
Tension Bar 2	0	150	76	mm
d-1	100	mm		
d-2	74	mm		
Ast1	0	mm^2		
Ast2	0	mm^2		
Compression Bar 1	6	150	75	mm
Compression Bar 2	0	150	76	mm
d'-1	78	mm		
d'-2	76	mm		
Asc1	188	mm^2		
Asc2	0	mm^2		
Section Effective depth d	150	mm		
Tension Steel Ratios – Actual	0.00%	Section classed as unreinforced, capacity calculated to Section 12.6		
Tension Steel Ratios – Minimum for Reinforced	0.15%			

Concrete grade
C30/37.5 D 2.5 S 0
after BS EN 14487-1

κ_h = 0.97
$f_{R.k1}$ = 1.26 MPa
$f_{R.k4}$ = 0.98 MPa

(closest to the surface)

N.B. Cover-to-bar is to the tension or compression bar itself, not just the specified minimum cover to rebar generally.



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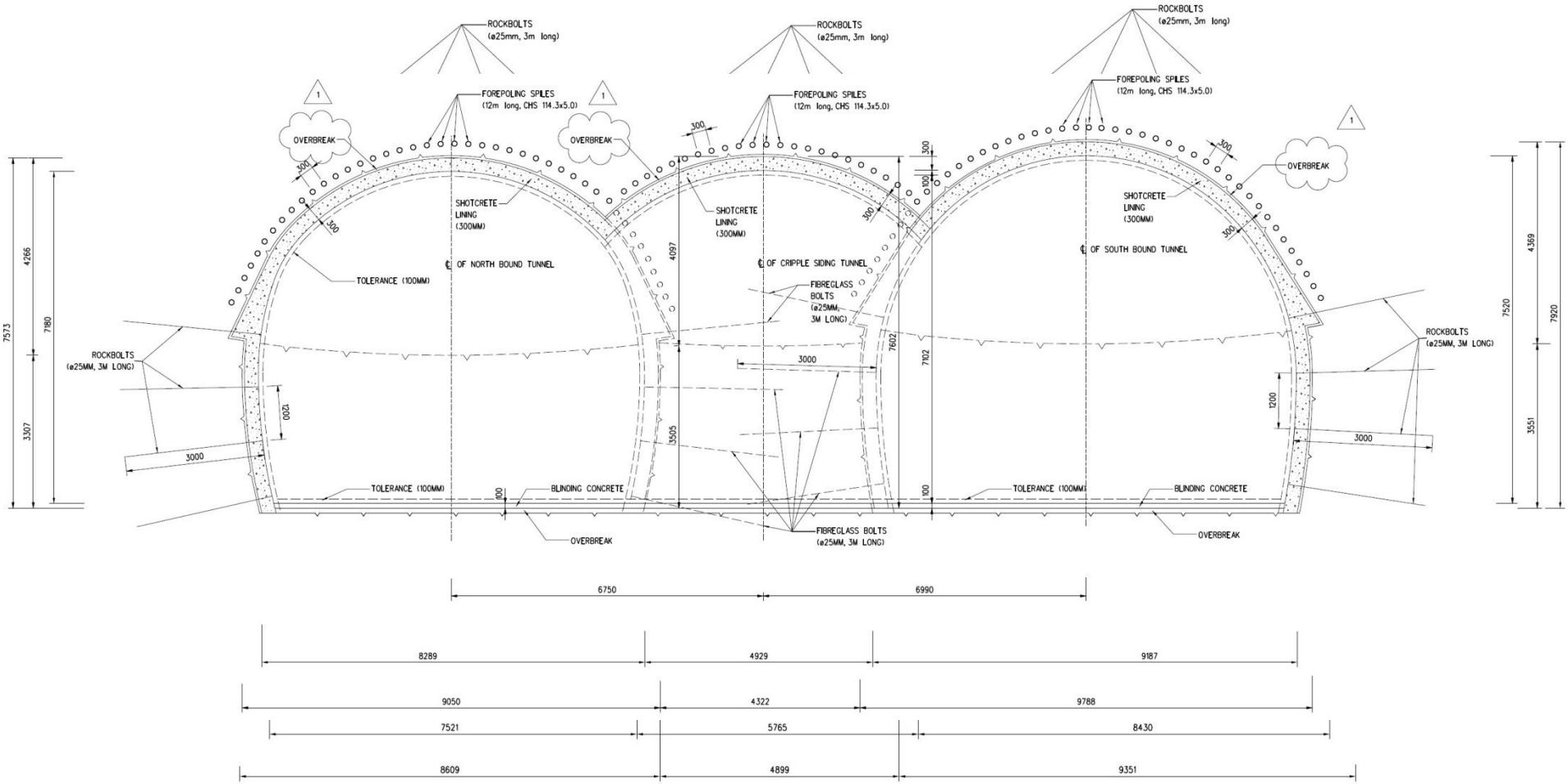
Standardised drawings – excavation support



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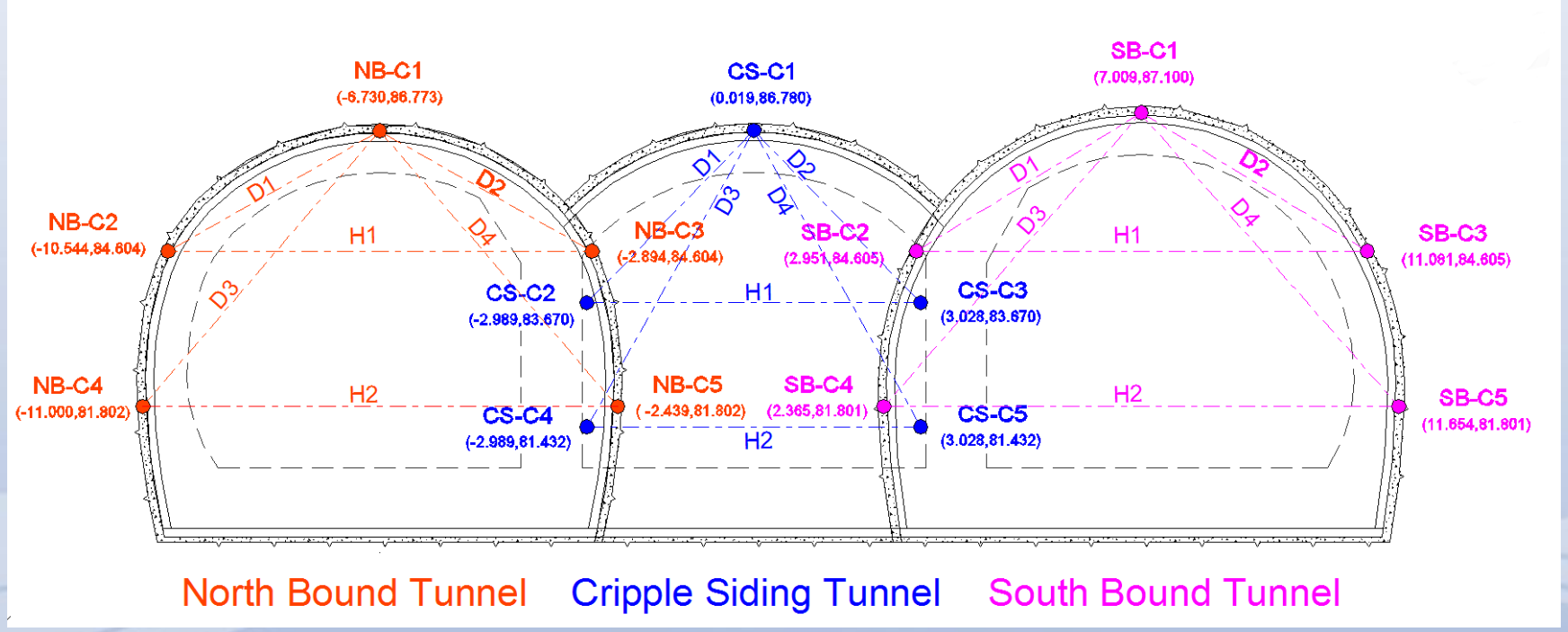
Monitoring design



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Designer support on site

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