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EVALUATION OF ROCK OVERSTRESSING IN A DEEP UNDERGROUND EXCAVATION OF PAHANG-SELANGOR RAW WATER TRANSFER TUNNEL

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WATER SUPPLY DIVISION
MINISTRY OF ENVIRONMENT AND WATER

CONTENTS

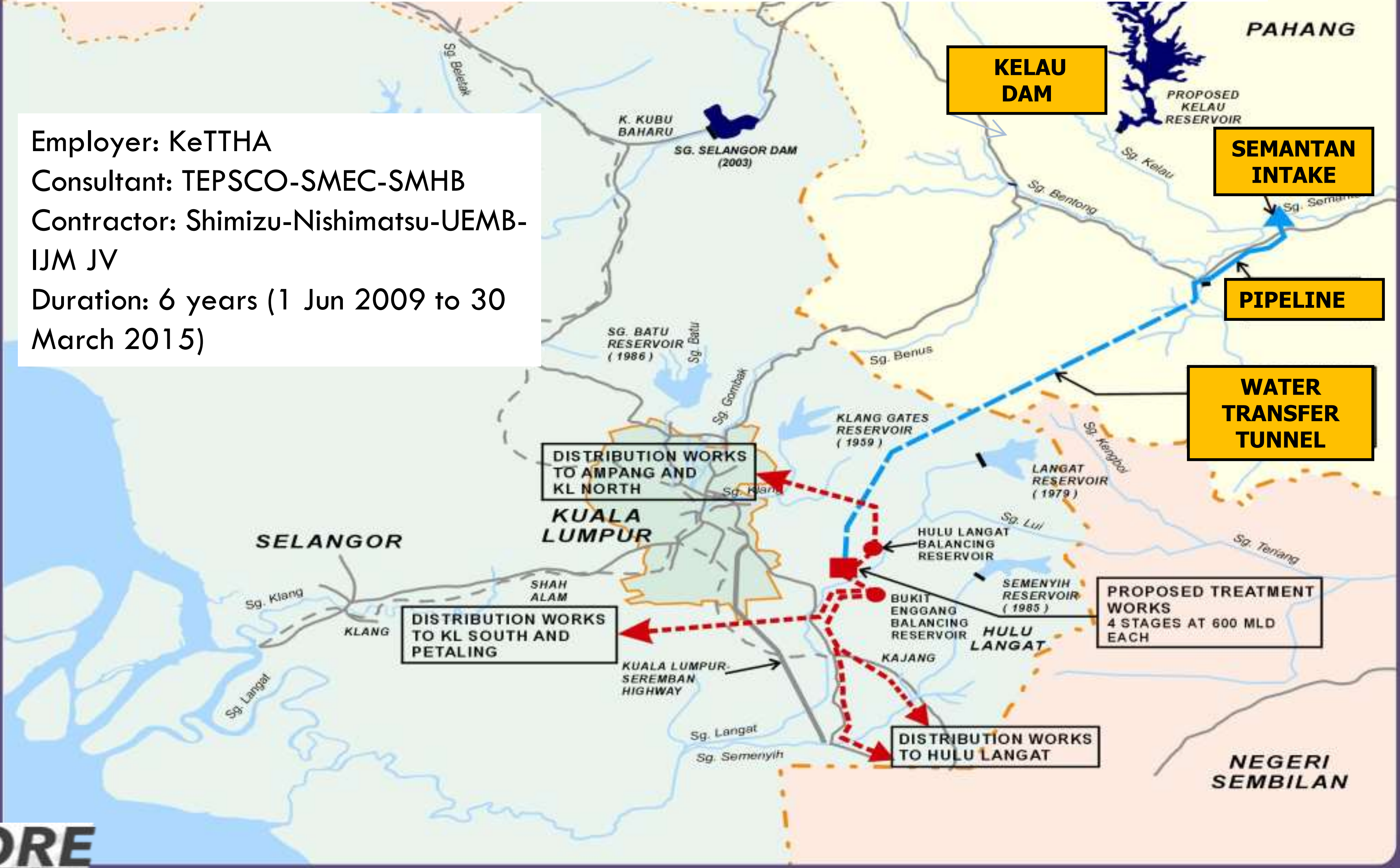
1.0 INTRODUCTION

BACKGROUND OF STUDY AREA

- The objective of the **Pahang-Selangor Raw Water Transfer Project** was to transfer 1890 MLD of raw water from **Pahang** to **Selangor.**
- The tunnel traverses under the **Titiwangsa Main Range** located on the border between Pahang and Selangor States.

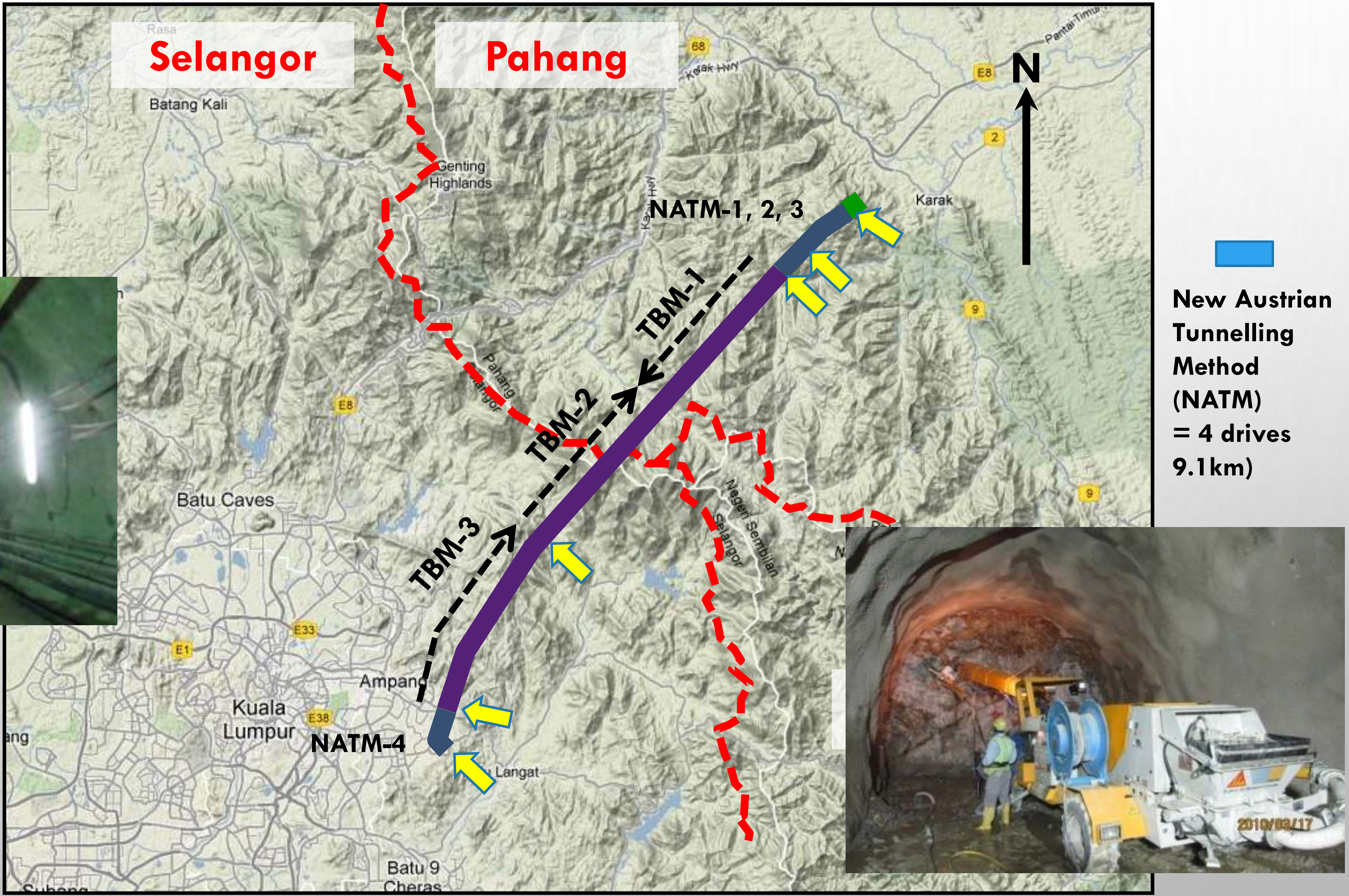
SCHEMATIC DIAGRAM OF RAW WATER TRANSFER PROJECT AND WATER TREATMENT PLANT PROJECT

Employer: KeTTHA
Consultant: TEPSCO-SMEC-SMHB
Contractor: Shimizu-Nishimatsu-UEMB-IJM JV
Duration: 6 years (1 Jun 2009 to 30 March 2015)



PAHANG-SELANGOR RAW WATER TUNNEL EXCAVATION

Tunnel boring machine (TBM) = 3 drives 34.6km



New Austrian Tunnelling Method (NATM) = 4 drives 9.1km)

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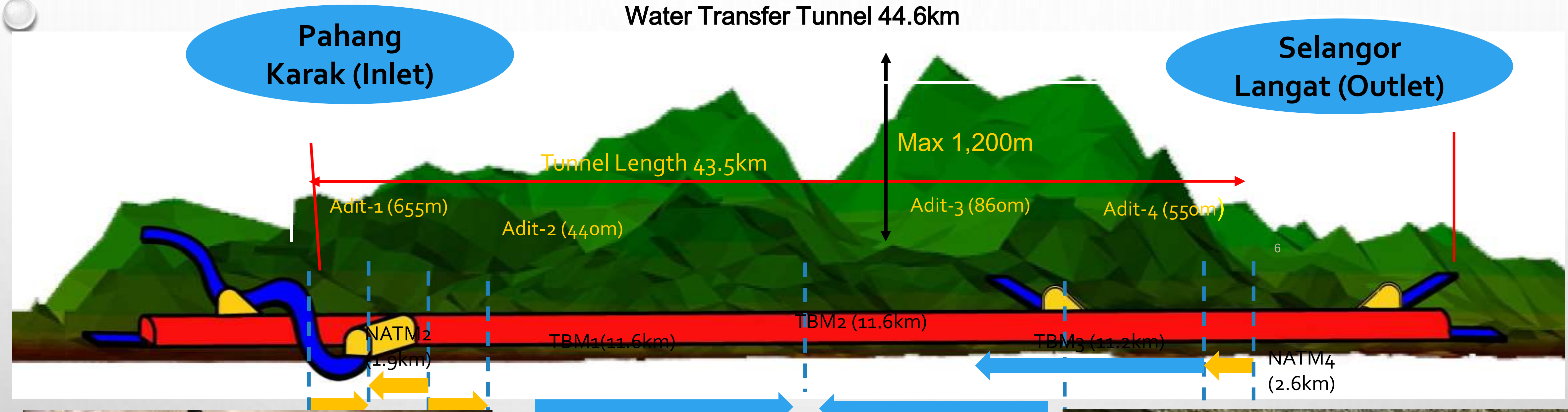
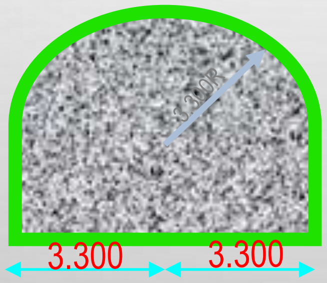
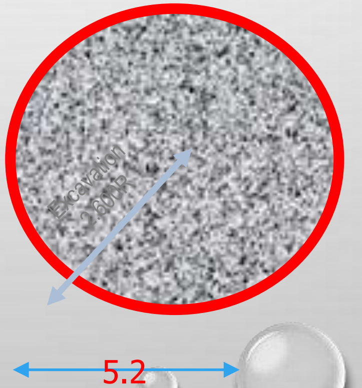
Project Background : Water Transfer Tunnel

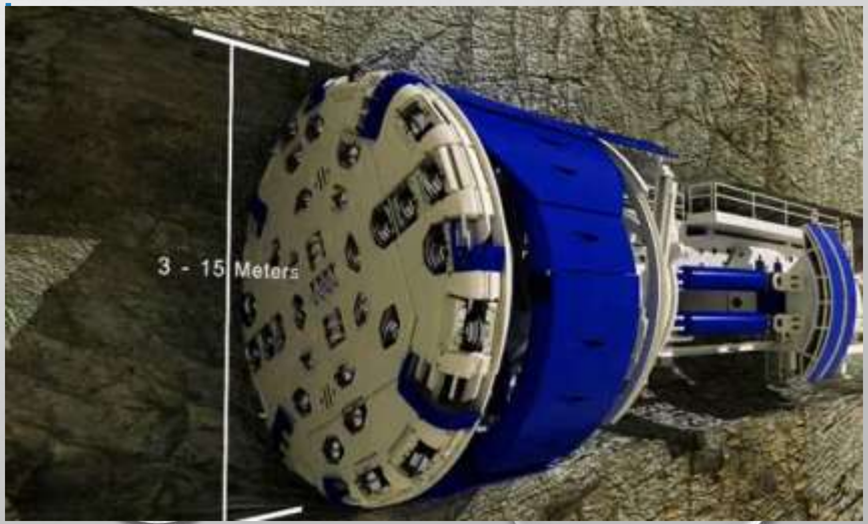




ADIT
(NATM)



MAIN TUNNEL (2)
(TBM)



1.0 INTRODUCTION

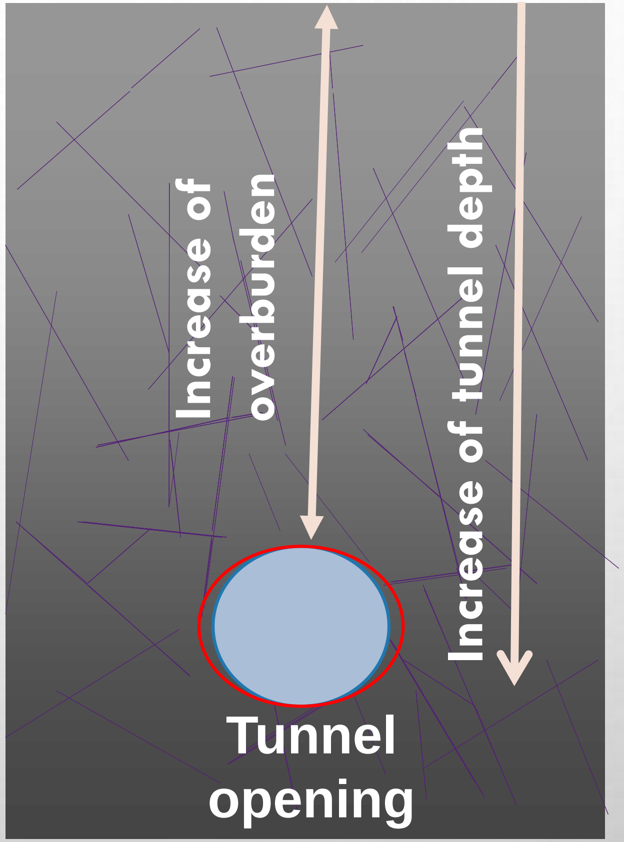
- Time and cost impact for removing rock and backfilling
- Payable under Contract
- Contractor may claim Extension of Time to complete works and costs for physical conditions not foreseeable at time of tender

STRESS-INDUCED PROBLEMS DURING TUNNELING

1.0 INTRODUCTION

- The stability problem because of high overburden stress.
- The addition of induced stress at greater increase the problem related to stress concentrations.
- The distribution of stress leads to stress concentration around the underground opening may cause rock overstressing.

Ground surface



Deep Underground Tunnel

Tunnel Condition

High Rock Cover (Overburden)

High In-Situ Stress

↓

Tunnel Excavation

Stress redistribution

↓

Potential of Overstressing

Rock Burst
Rock Spalling/Slabbing
displacement/deformation

2.0 PROBLEM STATEMENTS

1) Underground excavation **at great depth may cause stress induced failure** such as **rock burst** and **spalling** due to rock overstressing.

4) **Numerical modeling** is a potential tool to evaluate stability and to assist in selection of proper input properties regarding the rock mass.

3) Research on stress induced failure in the deep underground excavation is important **in order to understand the stress state and mechanical behavior of rock masses.**

5) The successful methods in modelling the failure zones around the excavation boundary **has been identified by many researchers** in predicting the stress induced failure.

2) The greatest challenges in deep underground excavation is the in-situ stresses are often not well defined due to **inadequate amount of measured stresses information.**

6) Each method has an assumption behind the parameters assigned to the model which is required **extensive calibration using observed failure zones**.

4) Validation of estimated stresses by **in-situ stress measurement is the most required** factor for any deep underground excavation

8) Understanding **the differences between available material models** may be helpful for the advancement of the science and engineering in underground excavation at great depth.

3.0 LITERATURE REVIEW

Author/yr.	Issues/Gap
(Brox, 2013)	The importance to have an **appropriate amount of rock strength & in-situ stress data** prior to construction from along the tunnel alignment in order to perform a comprehensive evaluation of overstressing.
(Panthi, 2012)	**More cases of tunnel damage should be studied** to verify the applicability of the proposed equations and to establish the approximate range of the horizontal tectonic stress .
(Hoek, 2010)	Rapid evolution of **computer software offers the potential for the calibration** or possible elimination of some of the empirical techniques upon which tunnel designers.
(Panthi, 2012)	More data records representing **different rock formations and locations** should be collected and used to verify and improve the validity of the proposed equations.

4.0 OBJECTIVES

1
- To investigate the **overstressing potential** based on rock mechanical properties and in-situ stress estimation using stress distribution analysis;

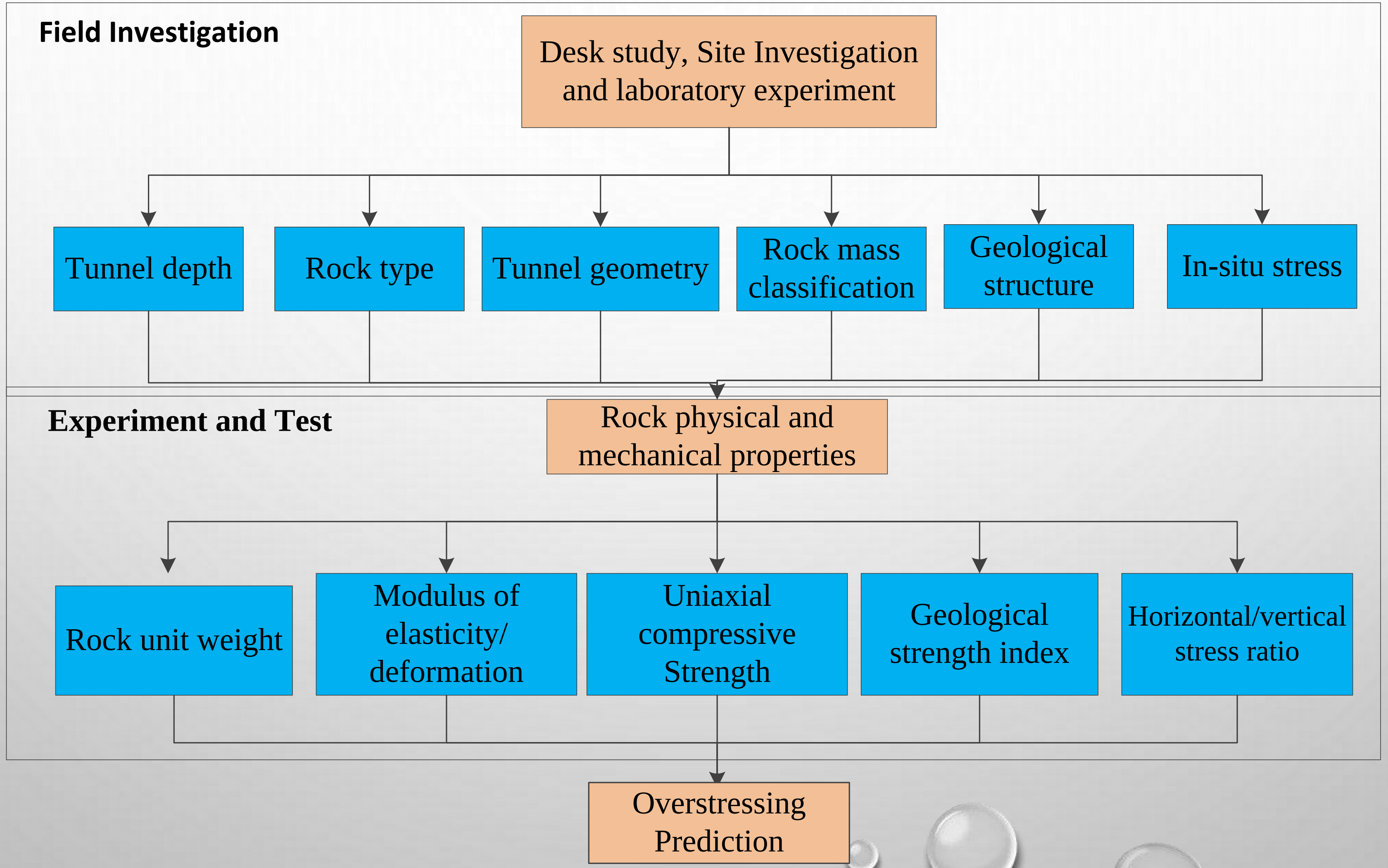
2
- To determine the **stress magnitudes and directions** based on in-situ stress measurement at selected locations for overstressing classification;

3
- To evaluate the Main Range Granite rock mass strength parameters applied in **modified CSFH model** for spalling failure prediction based on Hoek-Brown failure criterion; and

4
- To validate the rock mass strength input parameters and spalling prediction output of the overstressed rock mass to **the real stress induced failures** cases.

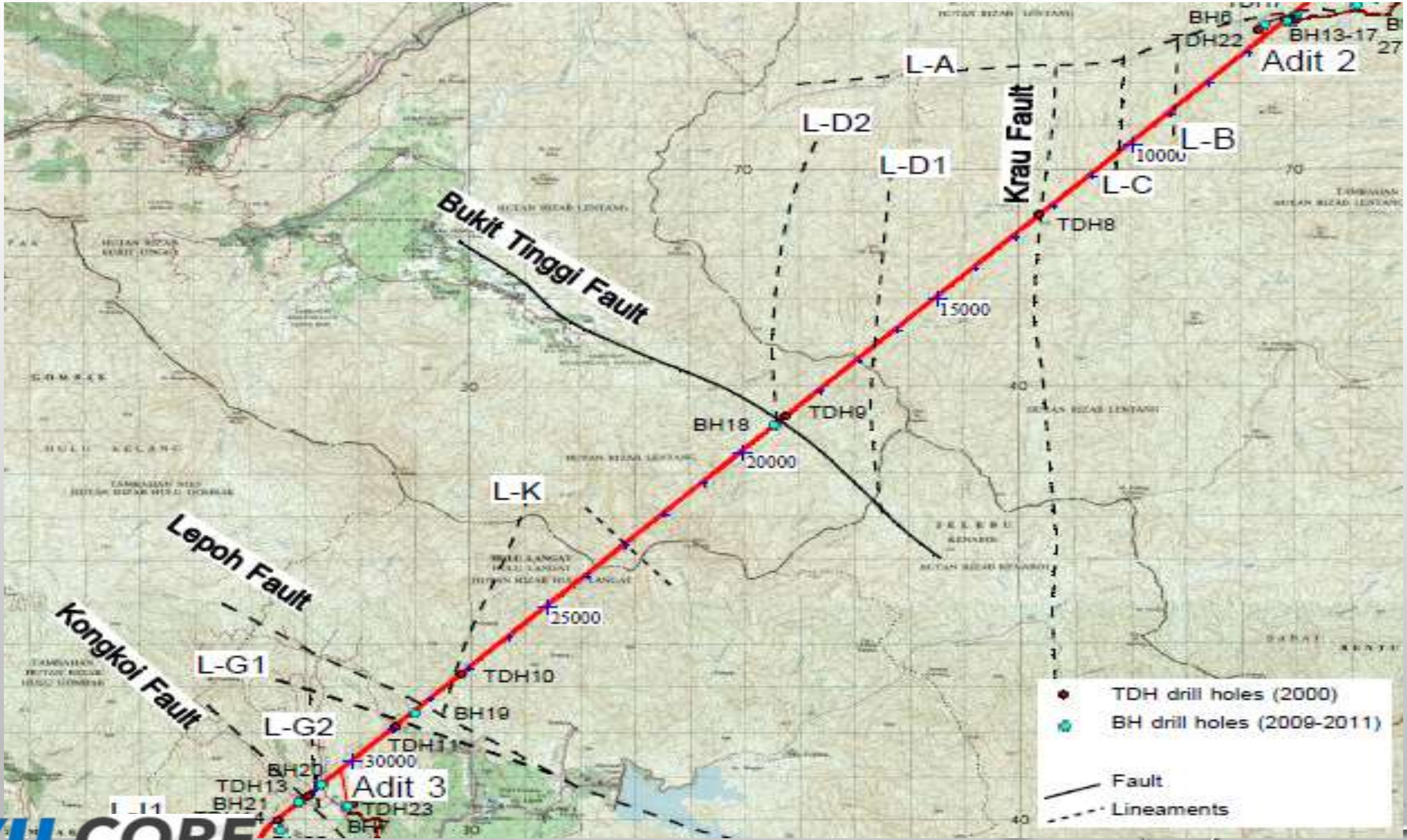
5.0 METHODOLOGY

Objective No. 1: Rock Overstressing Potential -Preliminary Data Collection



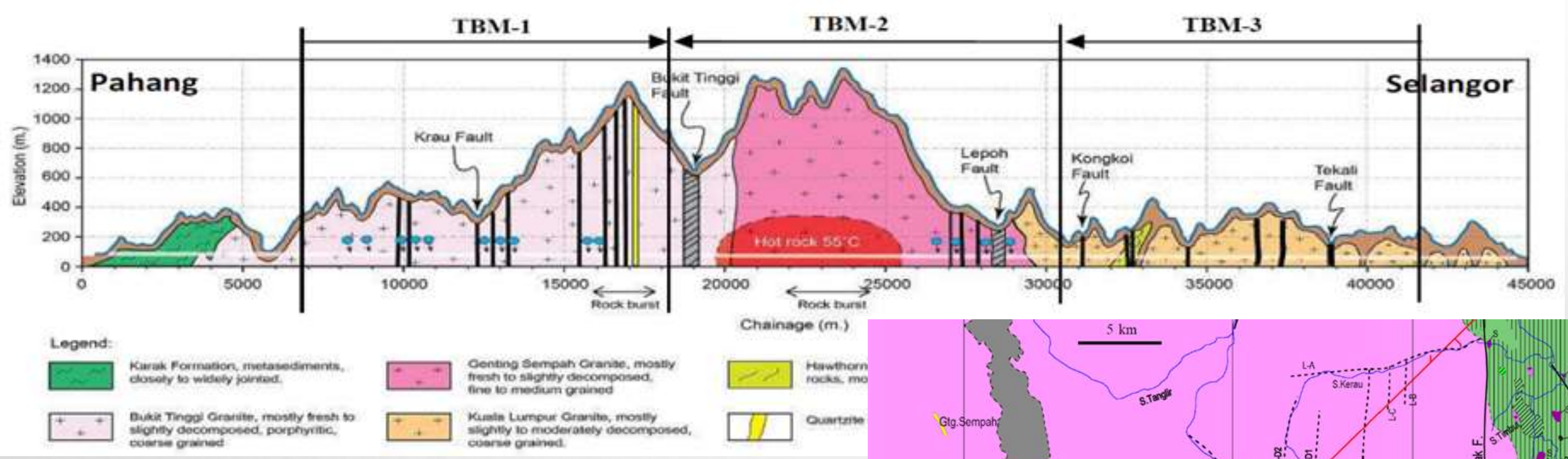
5.0 METHODOLOGY

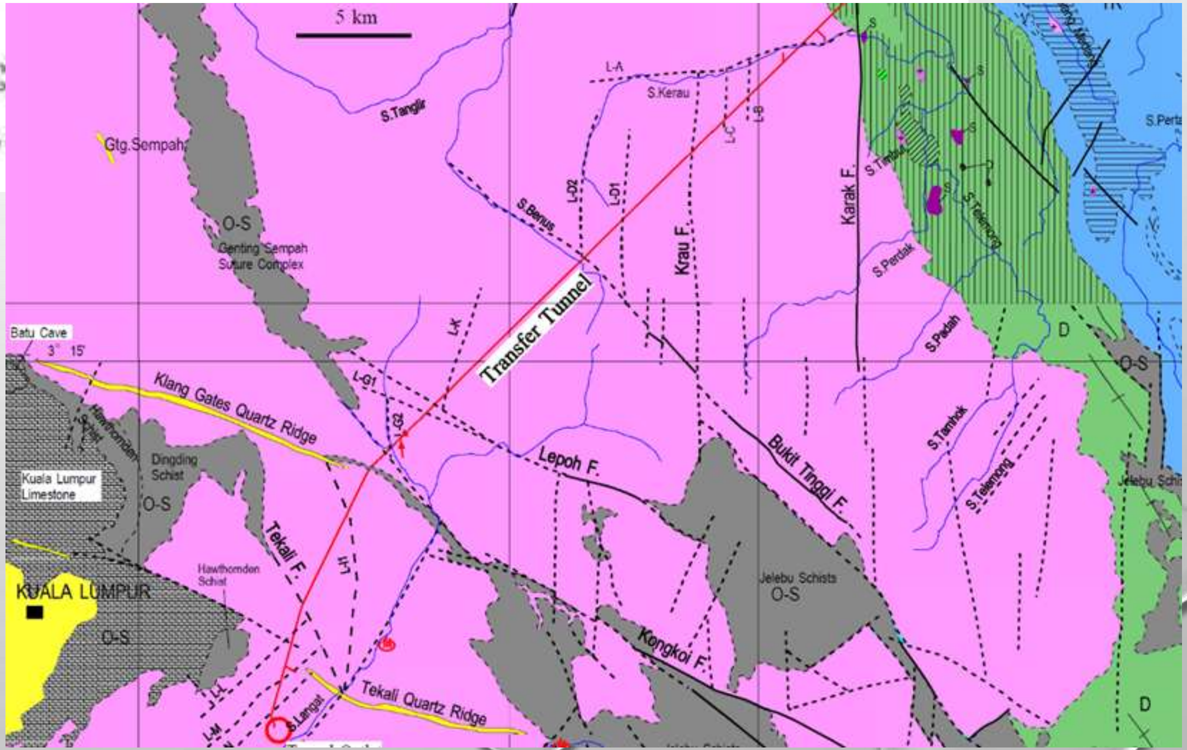
Objective No. 1: Field Investigation Data Collection



5.0 METHODOLOGY

Objective No. 1: Field Investigation – Geological Condition



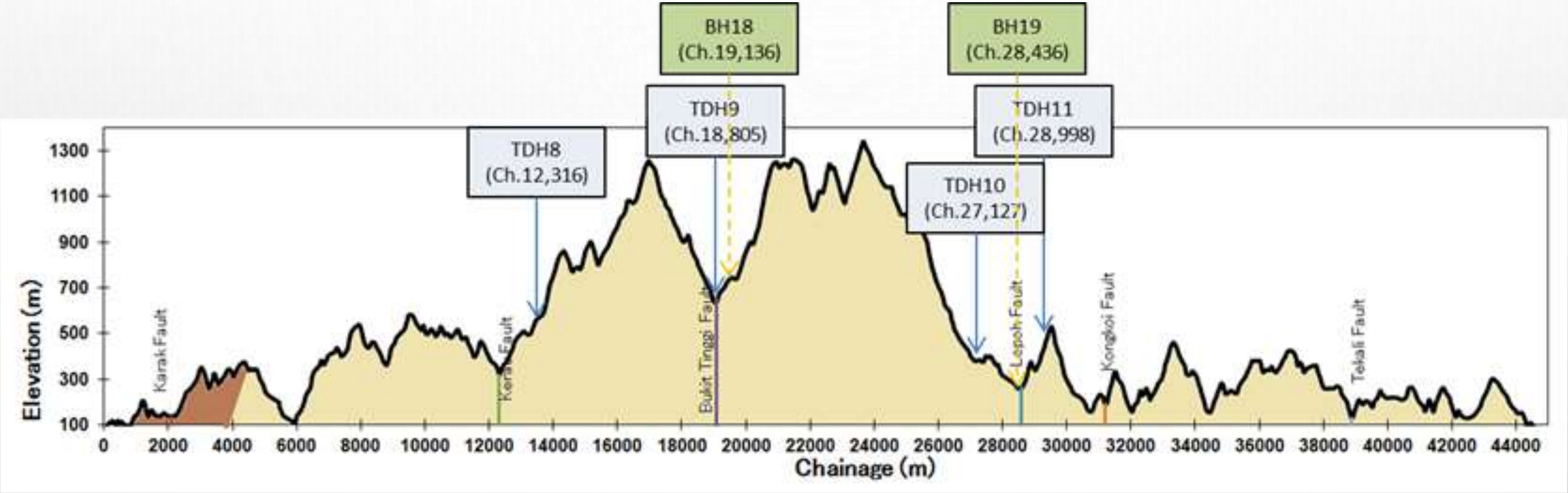


The tunnel section composed of Main Range Granite consist of:

- Bukit tinggi granite (coarse-grained)
- Genting Sempah granite (fine grained)
- Kuala Lumpur granite

5.0 METHODOLOGY

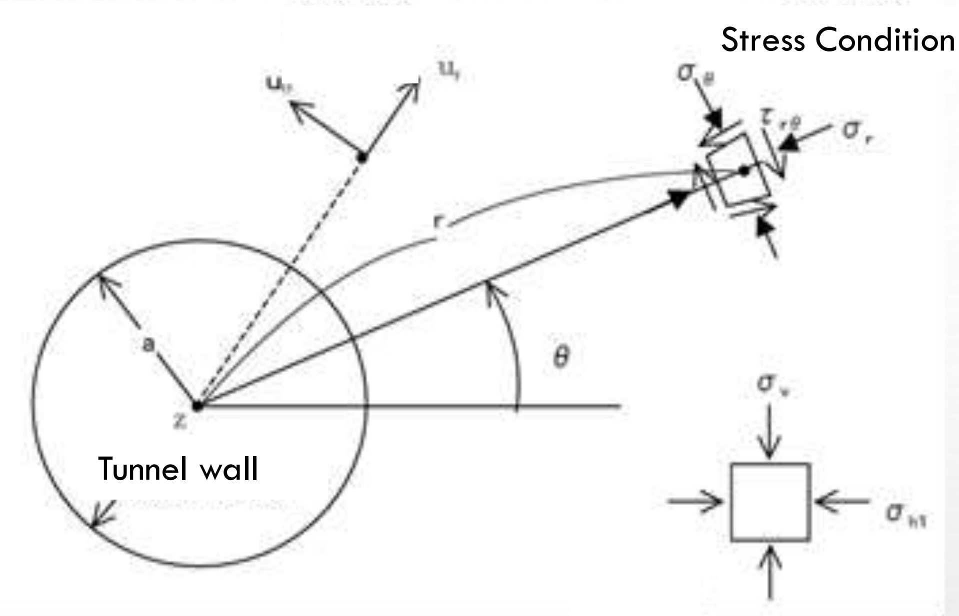
Objective No. 1: Field Investigation Data Collection

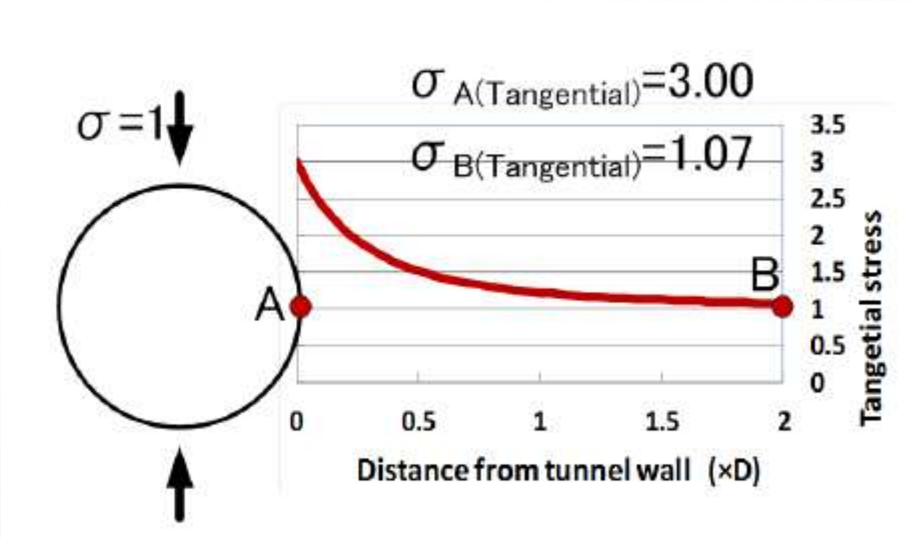


The rock physical and mechanical for deep underground excavations before construction is estimated from boreholes from site investigation (SI).

5.0 METHODOLOGY

Objective No. 1: Stress Distribution Analysis





$$\sigma_r = \frac{P_1 + P_2}{2}\left(1 - \frac{a^2}{r^2}\right) + \frac{P_1 - P_2}{2}\left[1 - \frac{4a^2}{r^2} + \frac{3a^4}{r^4}\right]\cos 2\theta$$

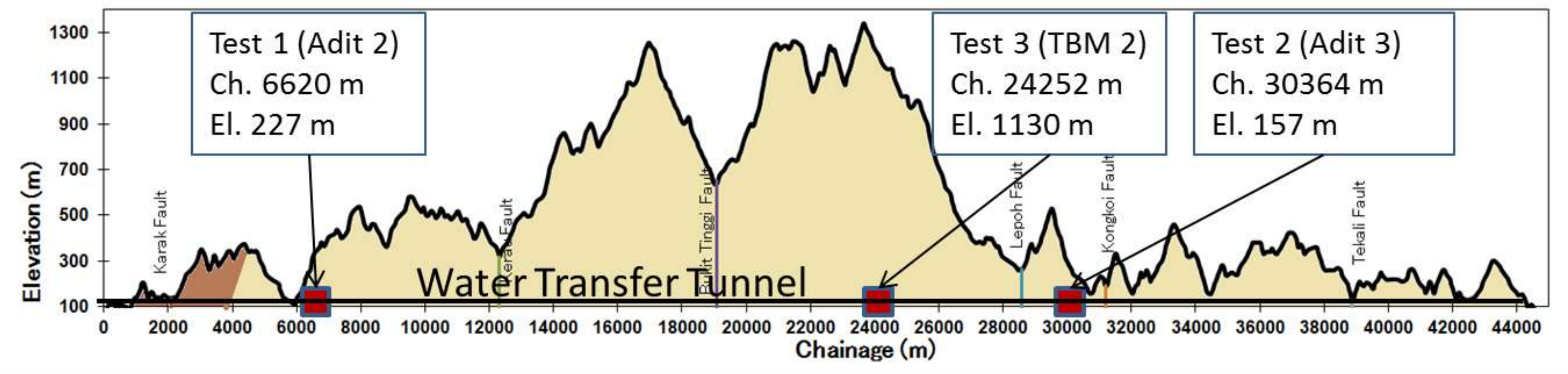
$$\sigma_\theta = \frac{P_1 + P_2}{2}\left(1 + \frac{a^2}{r^2}\right) - \frac{P_1 - P_2}{2}\left[1 + \frac{3a^4}{r^4}\right]\cos 2\theta$$

$$\tau_{r\theta} = \frac{P_1 - P_2}{2}\left(1 + \frac{2a^2}{r^2} - \frac{3a^4}{r^4}\right)\sin 2\theta$$

- Stress state around circular tunnel is calculated from theory of elasticity as follows:
  - Compressional stress σ_A at A point is
    $\sigma_A = 3\,\sigma_{max} - \sigma_{min}$

5.0 METHODOLOGY

Objective No. 2: In-situ stress measurement



Test (Location)	1 (Adit 2)	2 (TBM 2)	3 (Adit 3)
Measurement method	CCBO/hydraulic fracturing	CCBO	CCBO/hydraulic fracturing
Number of times	3/3	3	3/3

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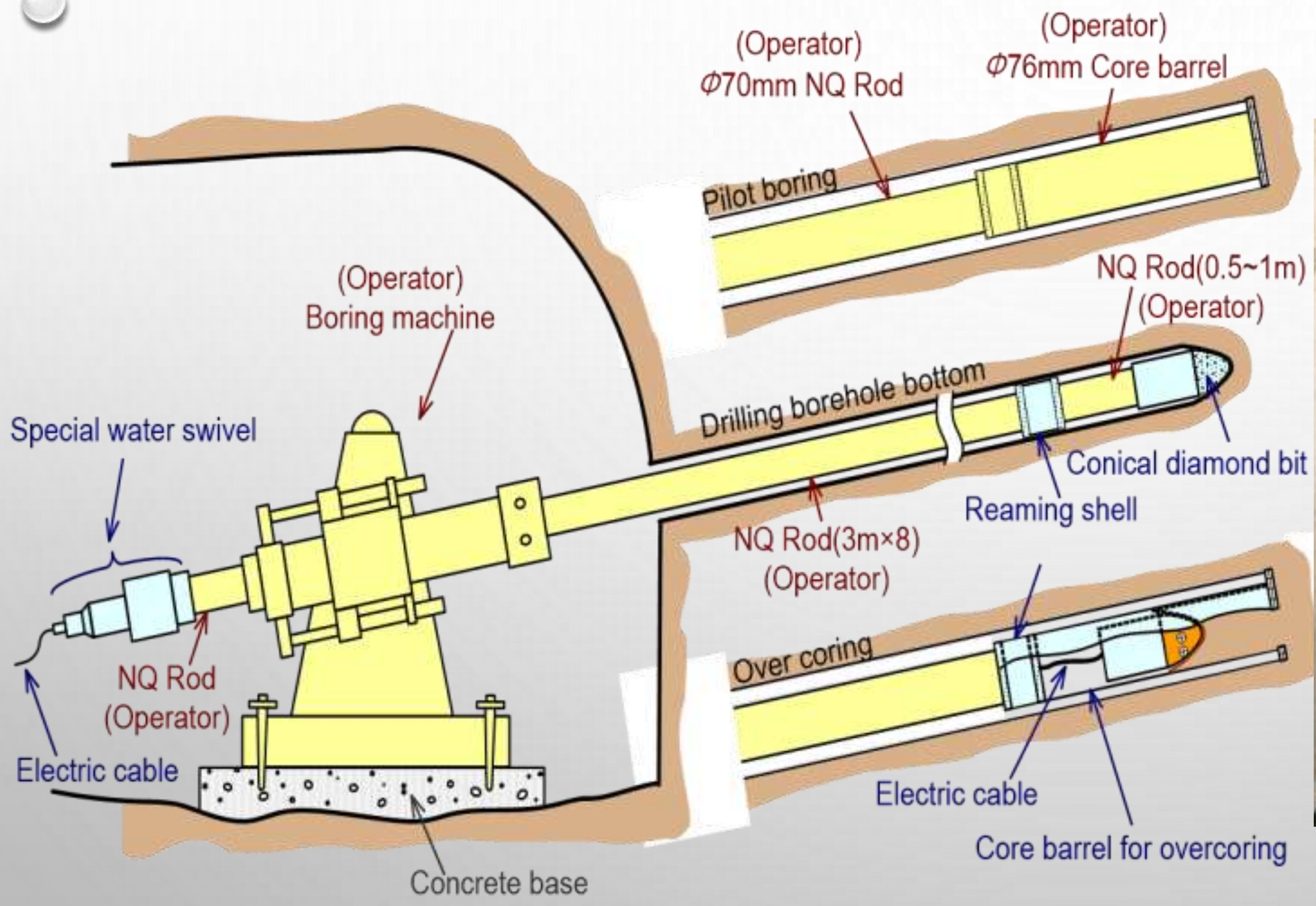
5.0 METHODOLOGY

Objective No. 2: Selection of measurement method



- The compact conical-ended borehole overcoring technique (CCBO)

5.0 METHODOLOGY

Objective No.3: Material Model

Laboratory Testing

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Intact Rock Strength Parameter

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Hoek-Brown Failure Criterion (RocLab)

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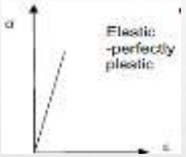
Rock Mass Strength Parameter

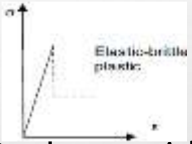
↓

Material Model

↓



Mohr-Coulomn



Mohr-Coulomn with CSFH

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Parametric Analysis

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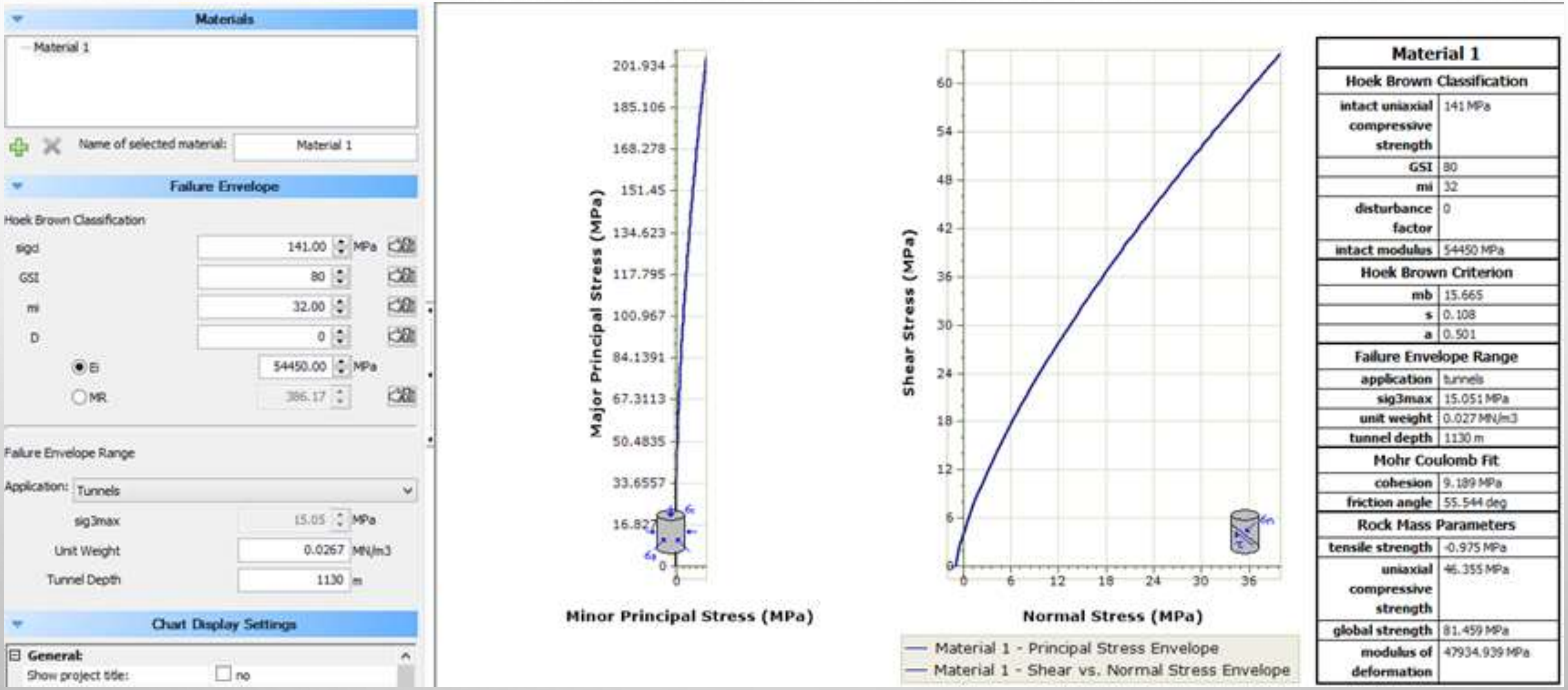
Modified Cohesion Softening Friction Hardening

↓

Input Data for Numerical Simulation

5.0 METHODOLOGY

Objective No. 3: Rock Mass Strength Estimation



RocLab software's user interface

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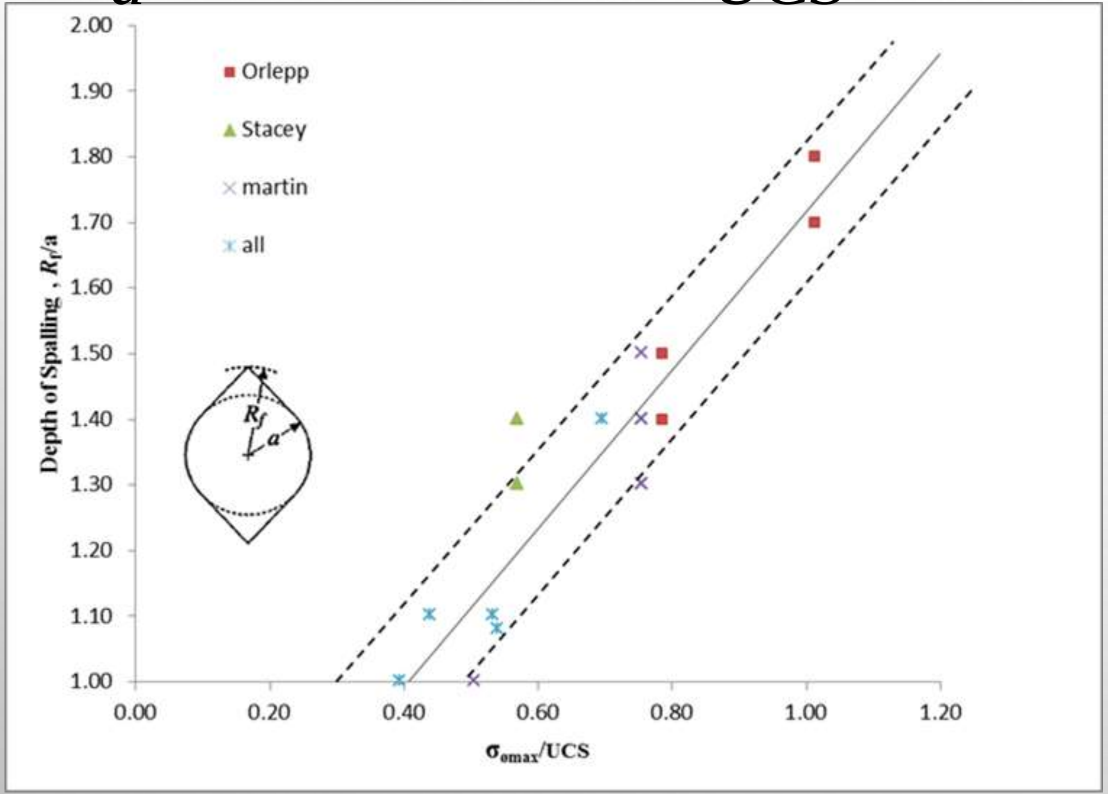
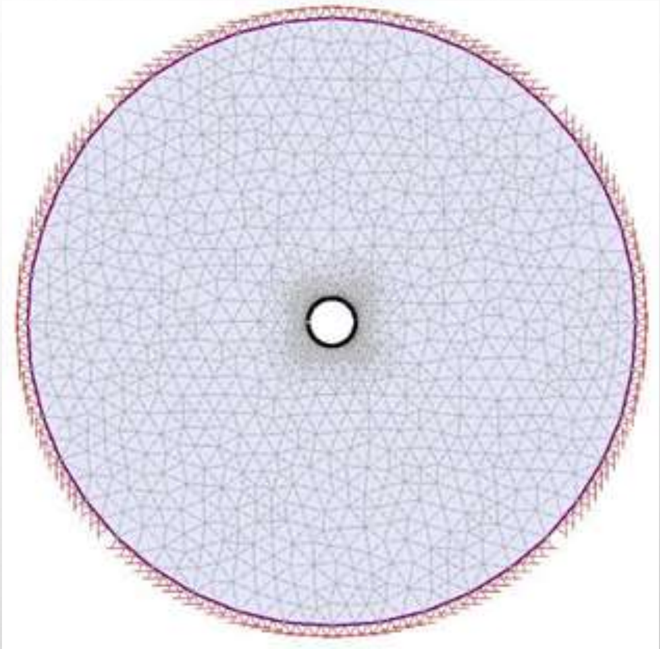
5.0 METHODOLOGY

Objective No. 3: Empirical and Numerical Spalling Depth Prediction

$$\frac{R_f}{a} = 0.49(\pm 0.1) + 1.25\frac{\sigma_{\theta\,\max}}{UCS}$$



Empirical spalling depth modified by Martin et al. (1999)



FEM discretization of circle domain into triangular elements by RS2 9.0 (RocScience Software) elasto-plastic finite element stress analysis program,

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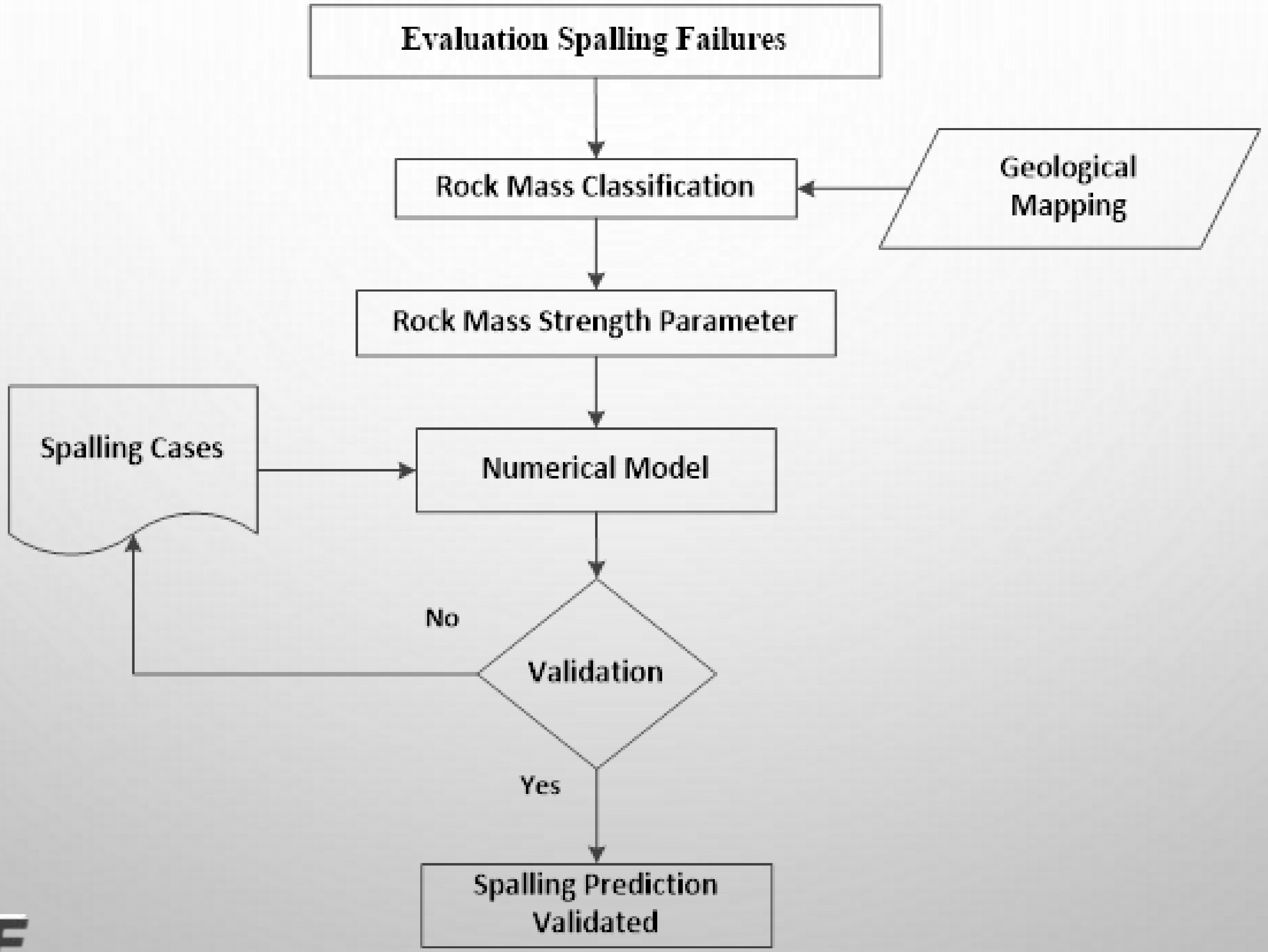
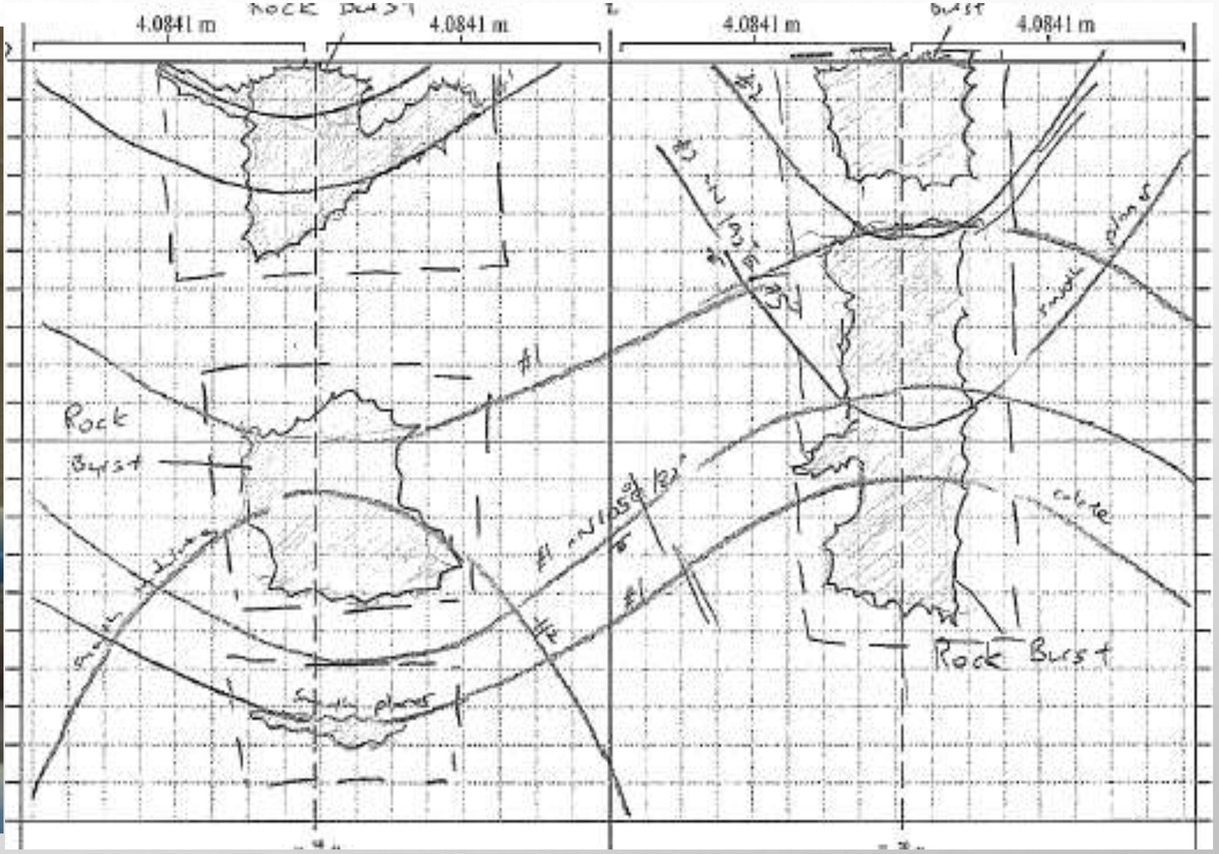
5.0 METHODOLOGY

Objective No.4: Evaluation of Rock Overstressing of Pahang-Selangor Tunnel



5.0 METHODOLOGY

Objective No. 4: Evaluation of Rock Overstressing of Pahang-Selangor Tunnel



Spalling simulation for real case of spalling failure at Pahang-Selangor tunnel

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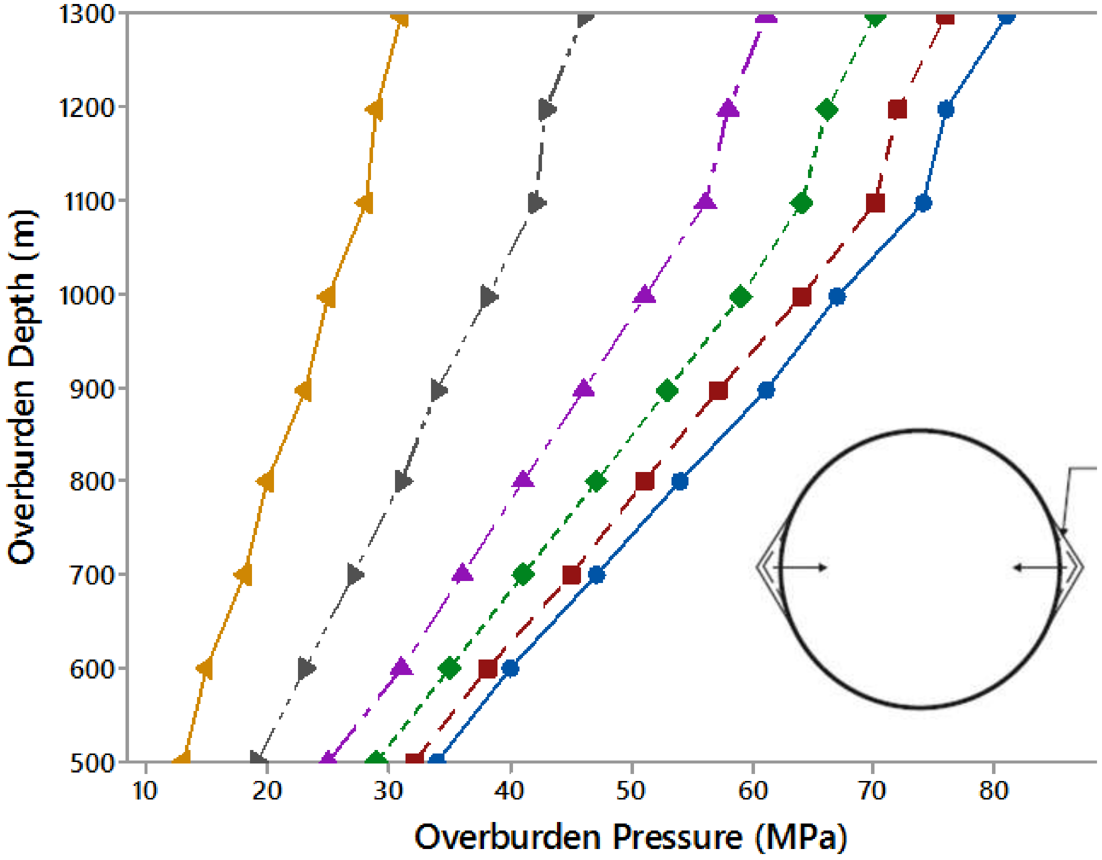
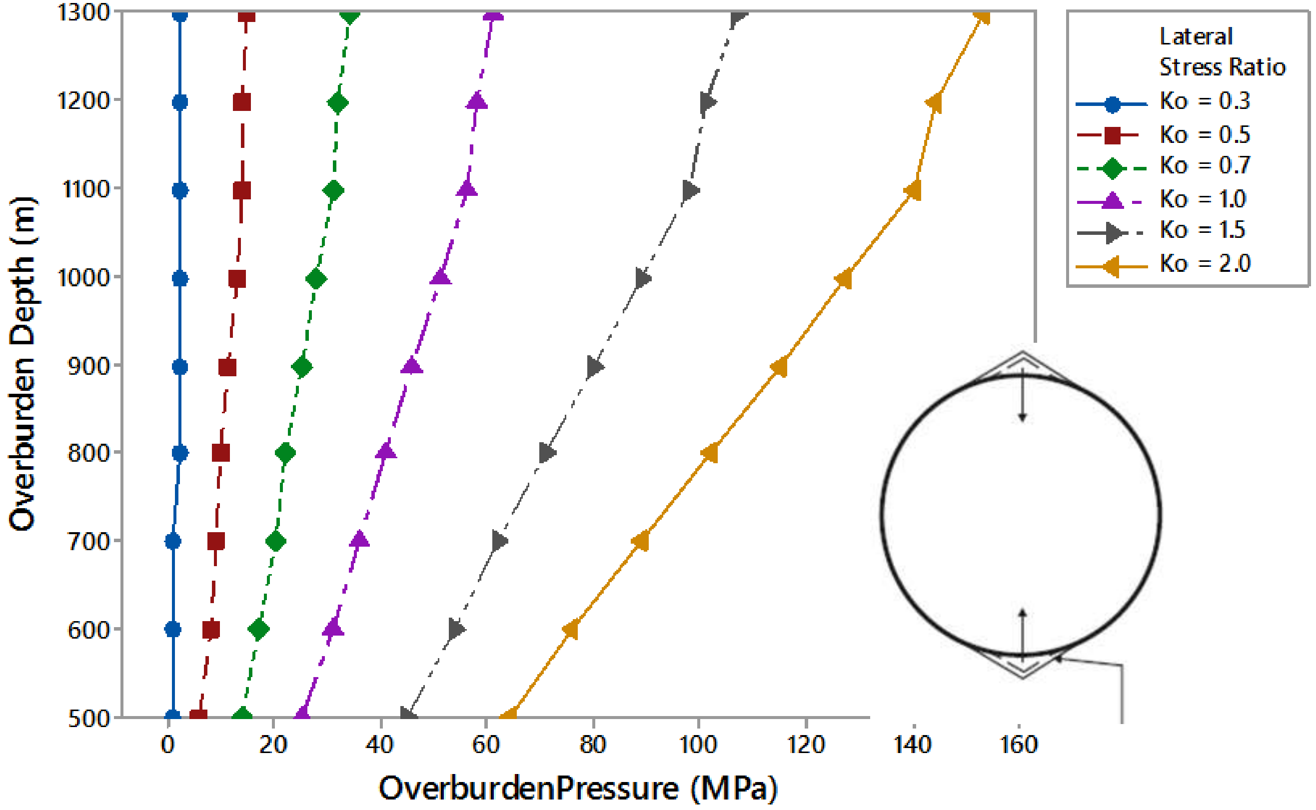
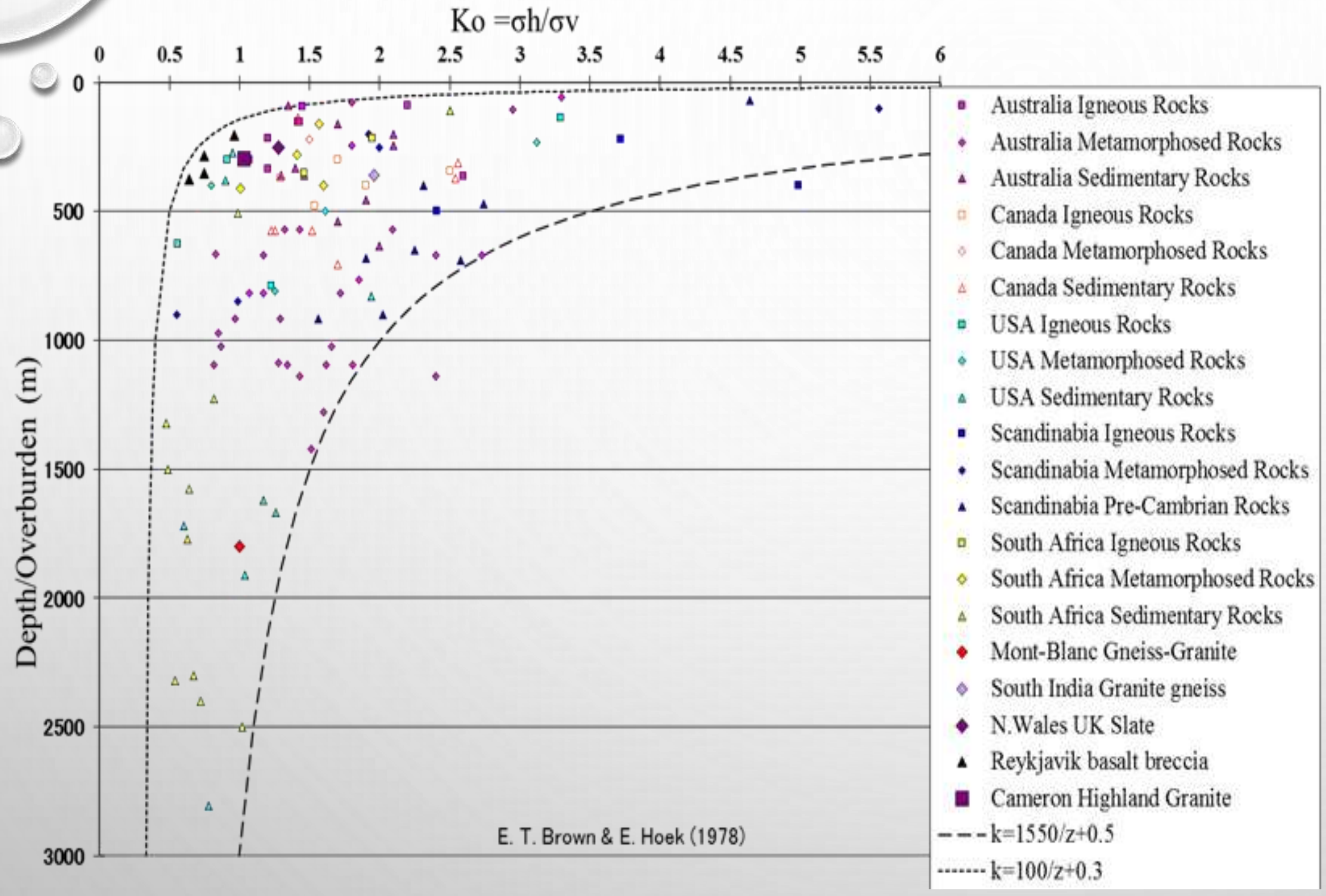
6.0 RESULTS AND DISCUSSIONS

Objective No. 1: Stresses distribution with variations of Coefficient of Lateral Stress (Ko).





6.0 RESULTS AND DISCUSSIONS



Average lateral stress ratio and overburden by Hoek and Brown (1978).

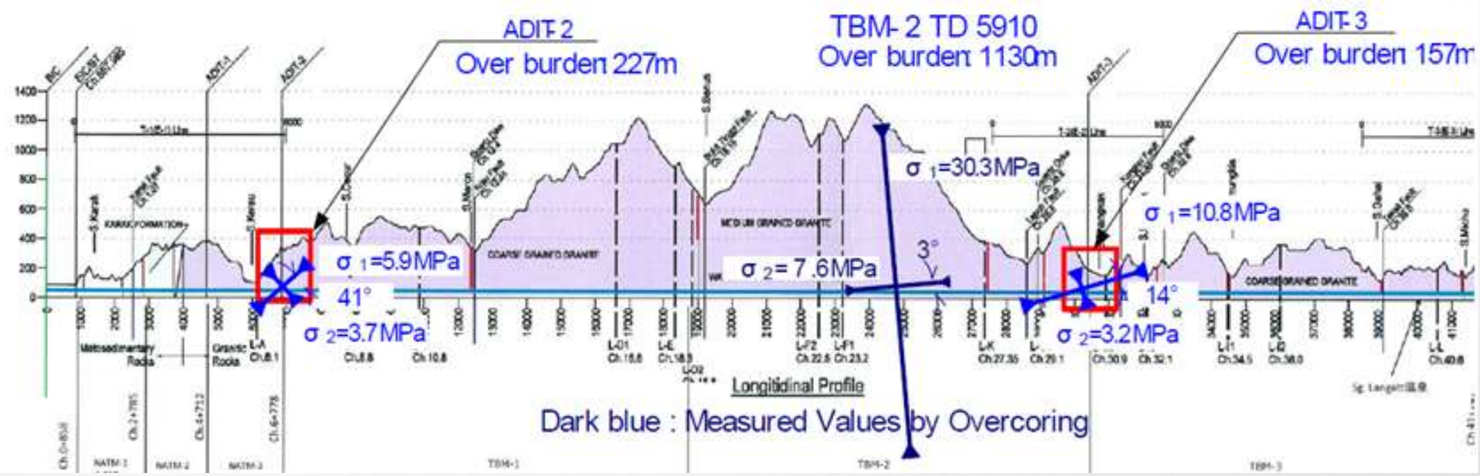
Overburden (m)	Tangential Stress (MPa)			
	K_o = 0.3	K_o = 0.5	K_o = 0.7	K_o = 1.0
500	34	32	29	25
600	41	38	35	31
700	48	45	41	36
800	55	51	47	41
900	62	57	53	46
1000	69	64	59	51
1100	76	70	64	56
1130	78	72	66	58
1200	**85**	**80**	**75**	**63**

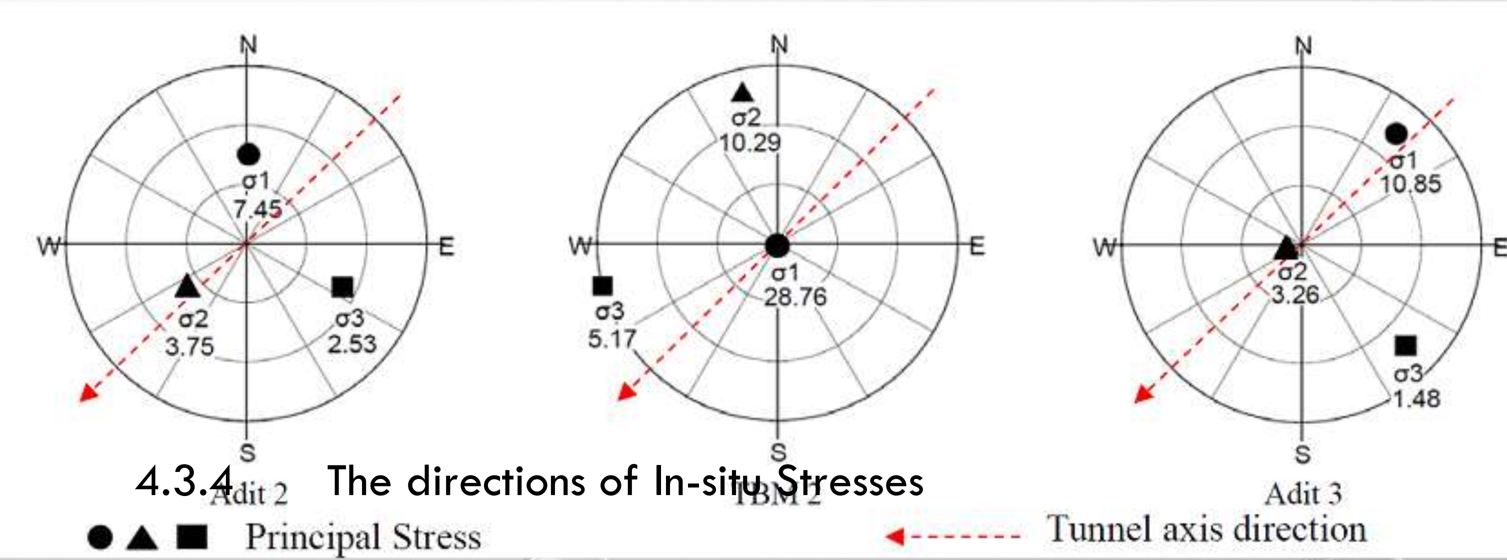
Tangential stress around circular tunnel by coefficients of lateral stress.

6.0 RESULTS AND DISCUSSIONS

Result of Overcoring (CCBO)

Adit 2	**TBM 2**	**Adit 3**
Stress (MPa)	**Stress (MPa)**	**Stress (MPa)**
$\sigma_{Hmax} = 6.13$	$\sigma_{Hmax} = 10.83$	$\sigma_{Hmax} = 10.40$
$\sigma_{Hmin} = 2.94$	$\sigma_{Hmin} = 5.17$	$\sigma_{Hmin} = 1.60$
$\sigma_{Have} = 4.54$	$\sigma_{Have} = 8$	$\sigma_{Have} = 6$
$\sigma_{v} = 4.67$	$\sigma_{v} = 28.8$	$\sigma_{v} = 3.6$
K (σ_H/σ_v) =1.31	**K (σ_H/σ_v) = 0.38**	**K (σ_H/σ_v) = 2.89**

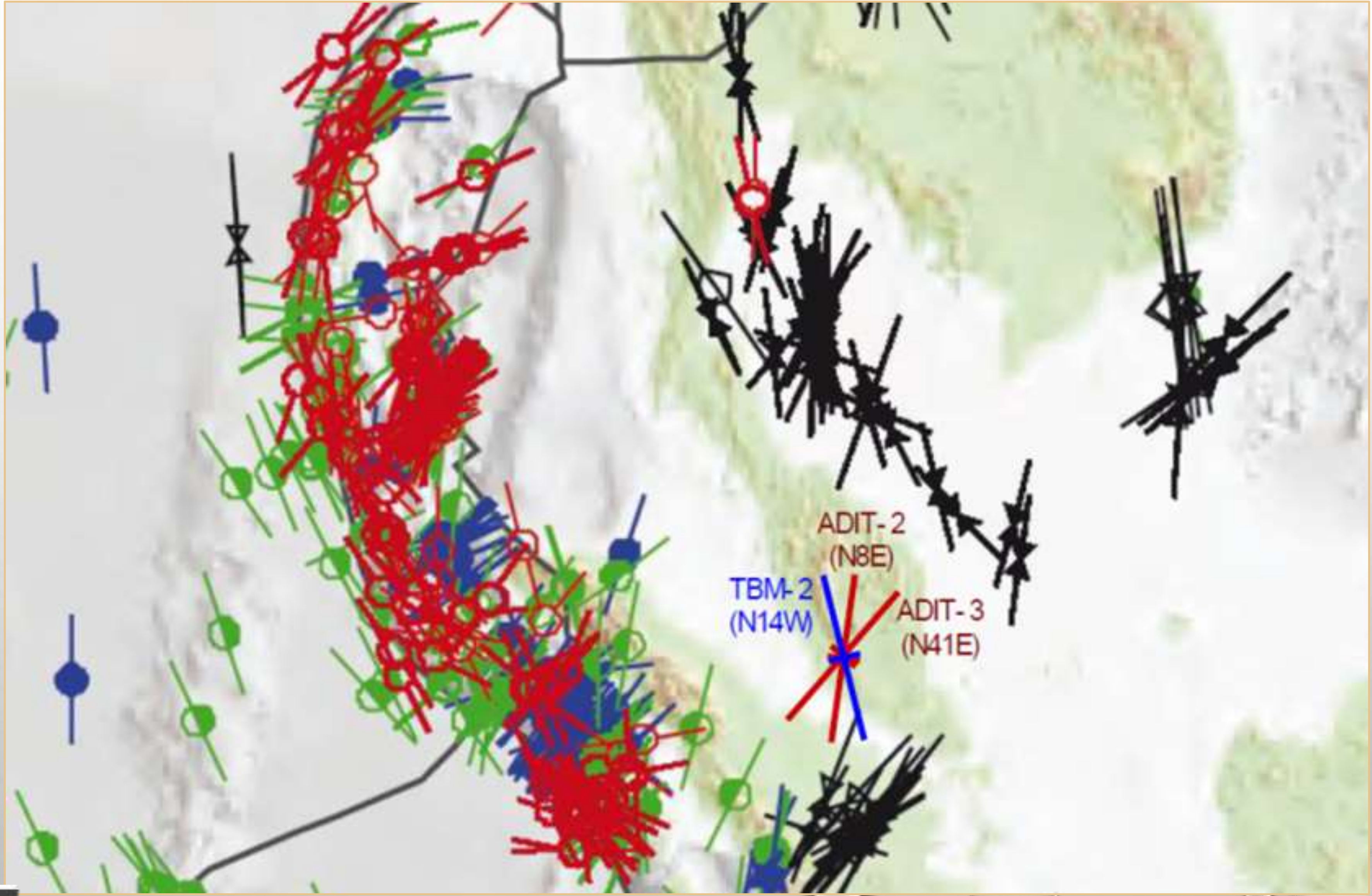




4.3.4 The directions of In-situ Stresses

6.0 RESULTS AND DISCUSSIONS

Comparison of test Results to Regional Stress Map



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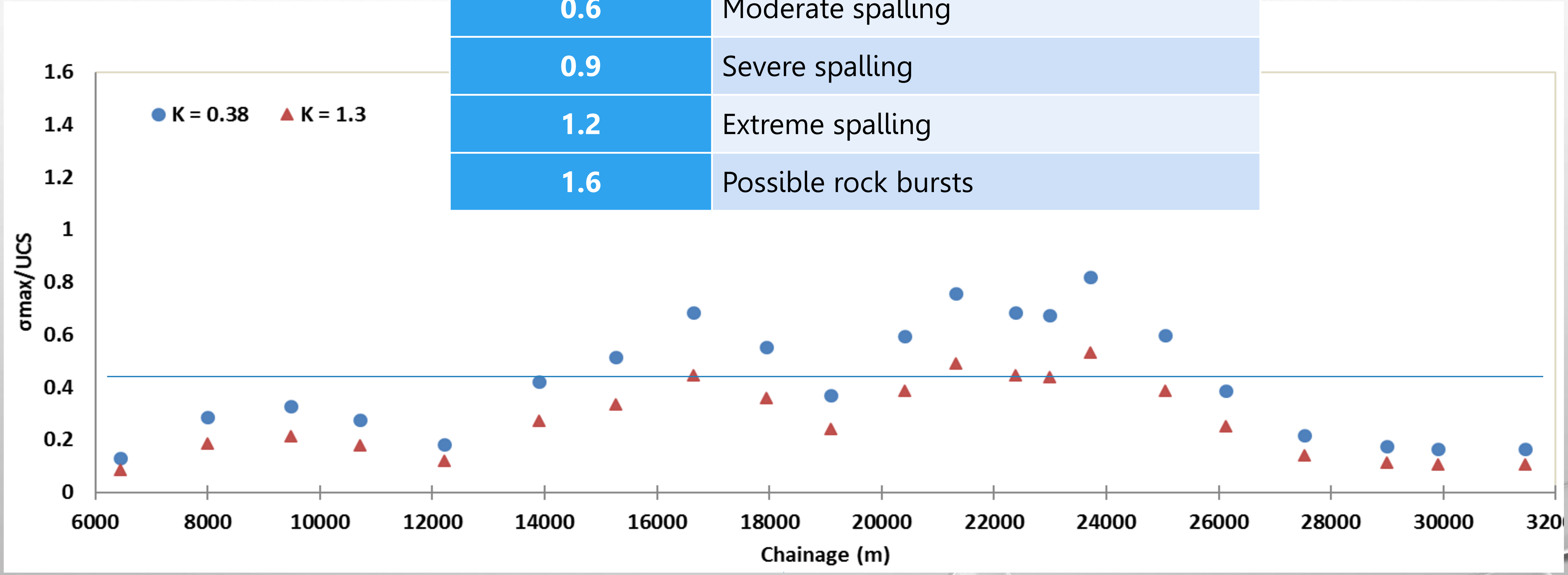
6.0 RESULTS AND DISCUSSIONS

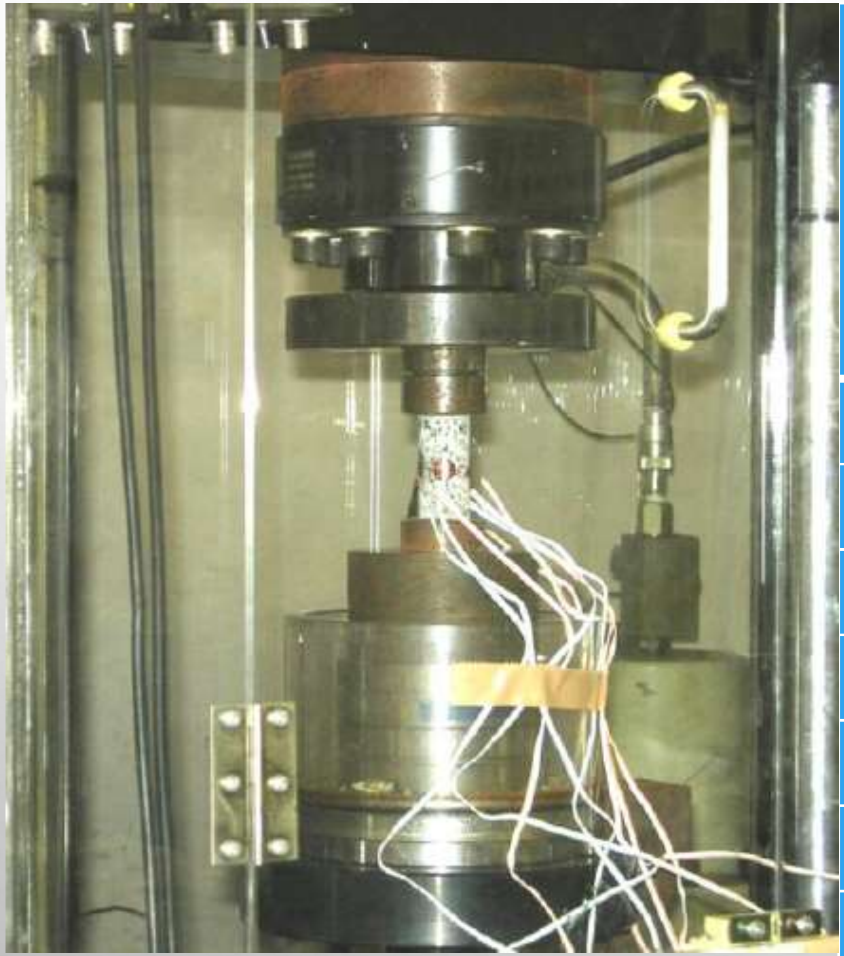
Objective No. 2: Rock Overstressing Classification (Hoek and Marinos 2009)

($\sigma_{\theta max}$/UCS)	Overstressing class
0.45	Minor spalling
0.6	Moderate spalling
0.9	Severe spalling
1.2	Extreme spalling
1.6	Possible rock bursts



6.0 RESULTS AND DISCUSSIONS

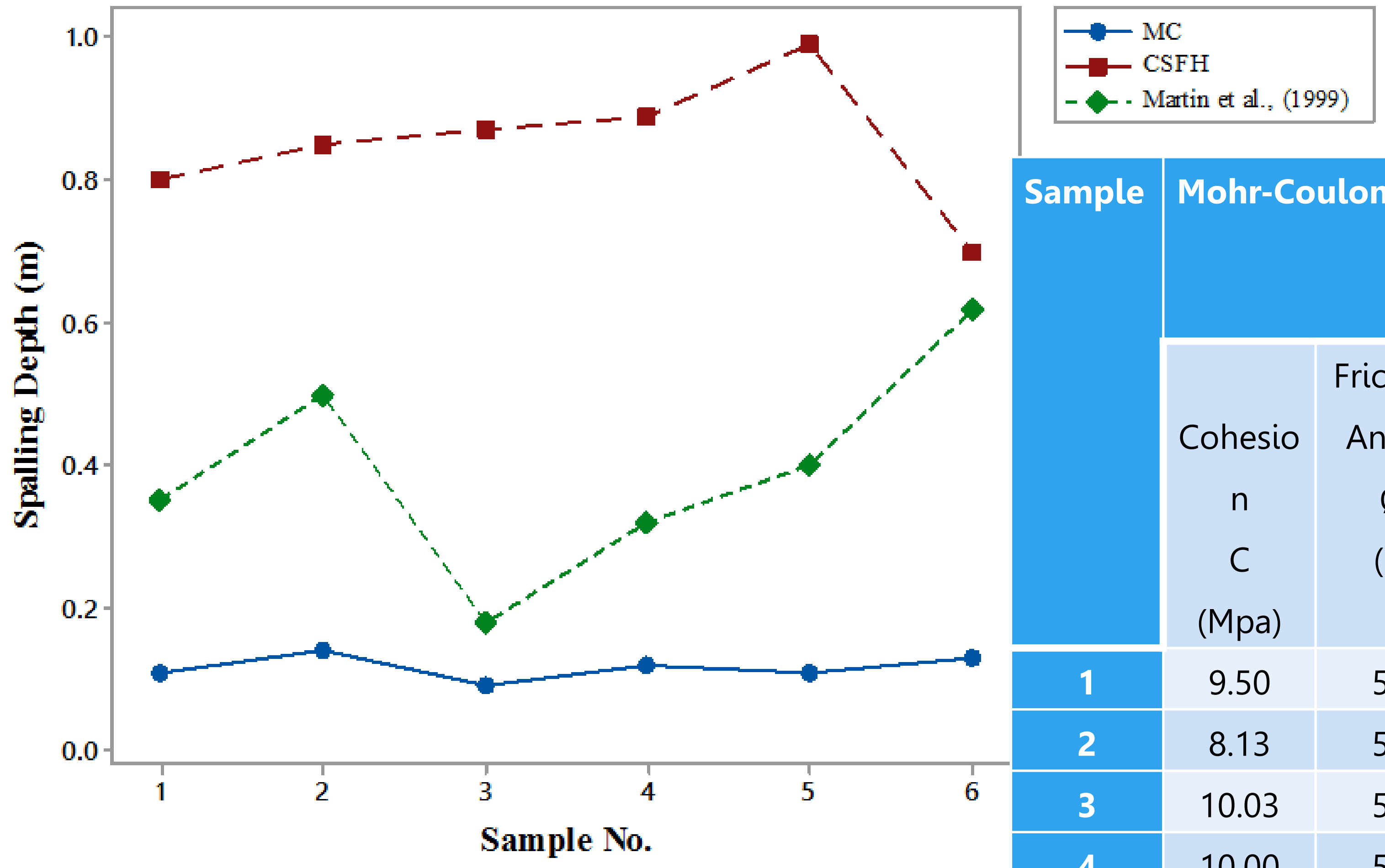
Objective No.3: Intact Rock Strength Parameters - Rock Mass Strength Parameters



Sample no.	Density ρ (g/cm^3)	Uniaxial Compressive Strength UCS(MPa)	Young's Modulus E(MPa)	Poisson's Ratio v
1	2.66	149	56000	0.22
2	2.64	108	49800	0.20
3	2.67	166	61000	0.22
4	2.65	152	50100	0.17
5	2.68	145	61900	0.25
6	2.67	128	48600	0.13
Average	2.67	141	54000	0.20

6.0 RESULTS AND DISCUSSIONS

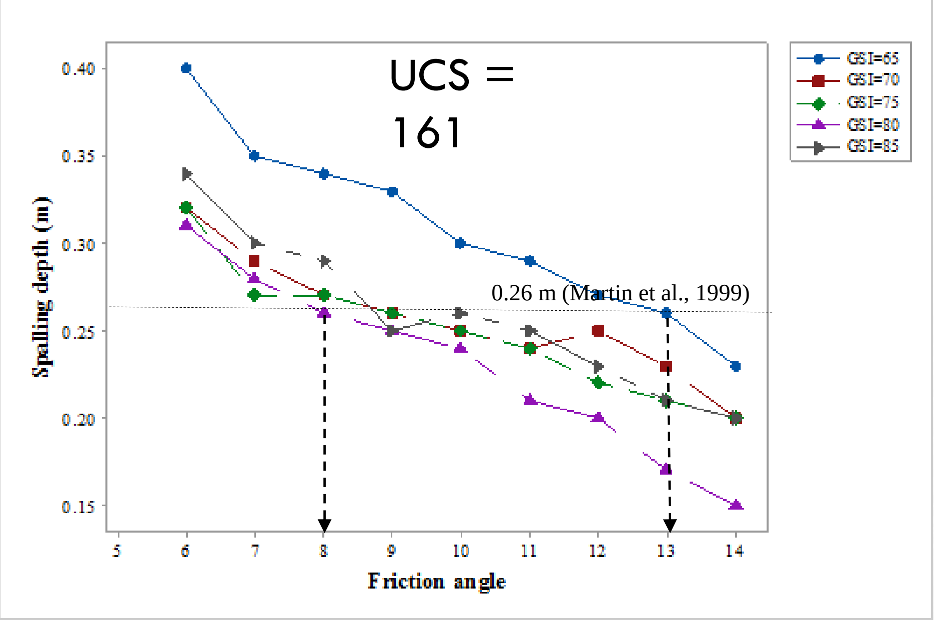
Material Model of the Main Range Granite for Spalling Prediction

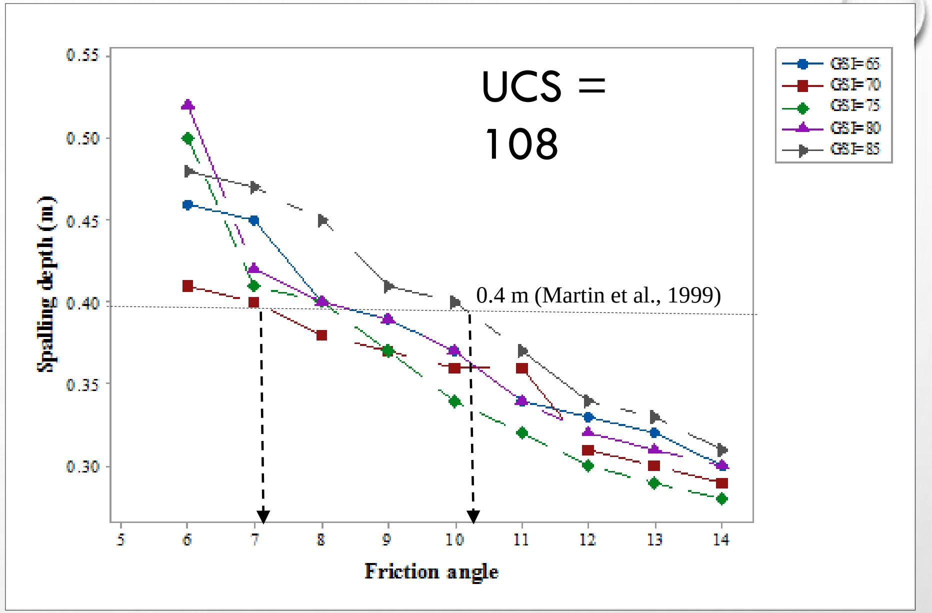


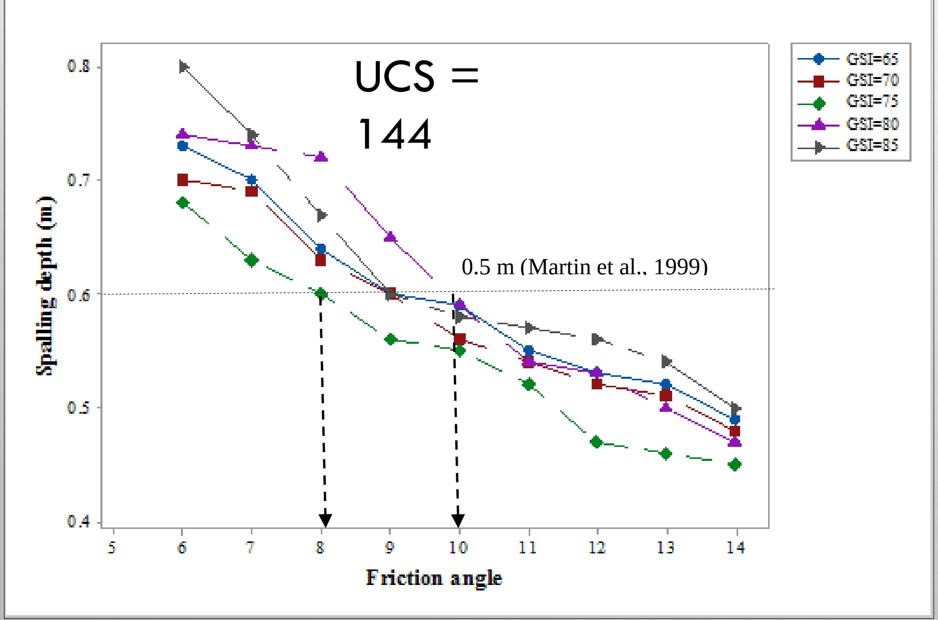
Sample	Mohr-Coulomb		Cohesion Softening Friction Hardening (CSFH)			
	Cohesion C (Mpa)	Friction Angle ∅ (°)	Peak Friction Angle $\emptyset_{peak}$ (°)	Residual Friction Angle $\emptyset_{res}$ (°)	Peak Cohesion, C_{peak} (Mpa)	Residual Cohesion, C_{res} (Mpa)
1	9.50	56	10	56	22.90	2.85
2	8.13	54	10	54	17.70	2.44
3	10.03	57	10	57	24.96	3.01
4	10.00	56	10	56	23.26	3.00
5	9.37	56	10	56	22.41	2.81
6	8.81	55	10	55	20.28	2.65

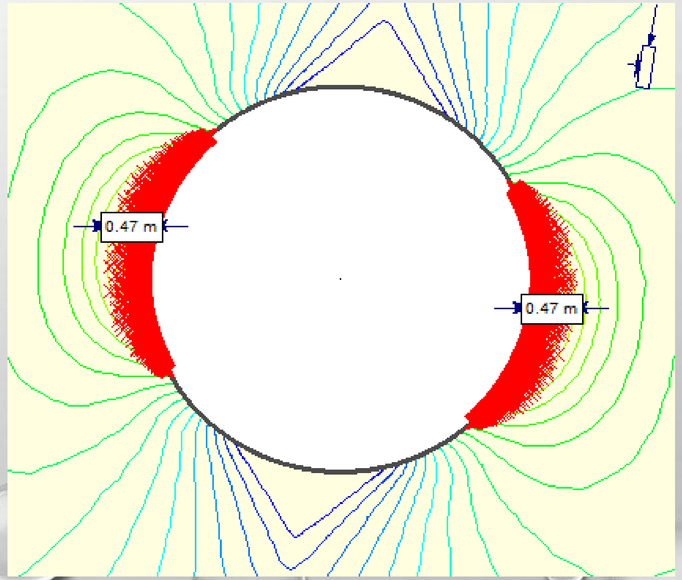
6.0 RESULTS AND DISCUSSIONS

Parametric Study – Peak and Residual Cohesion for the CSFH model



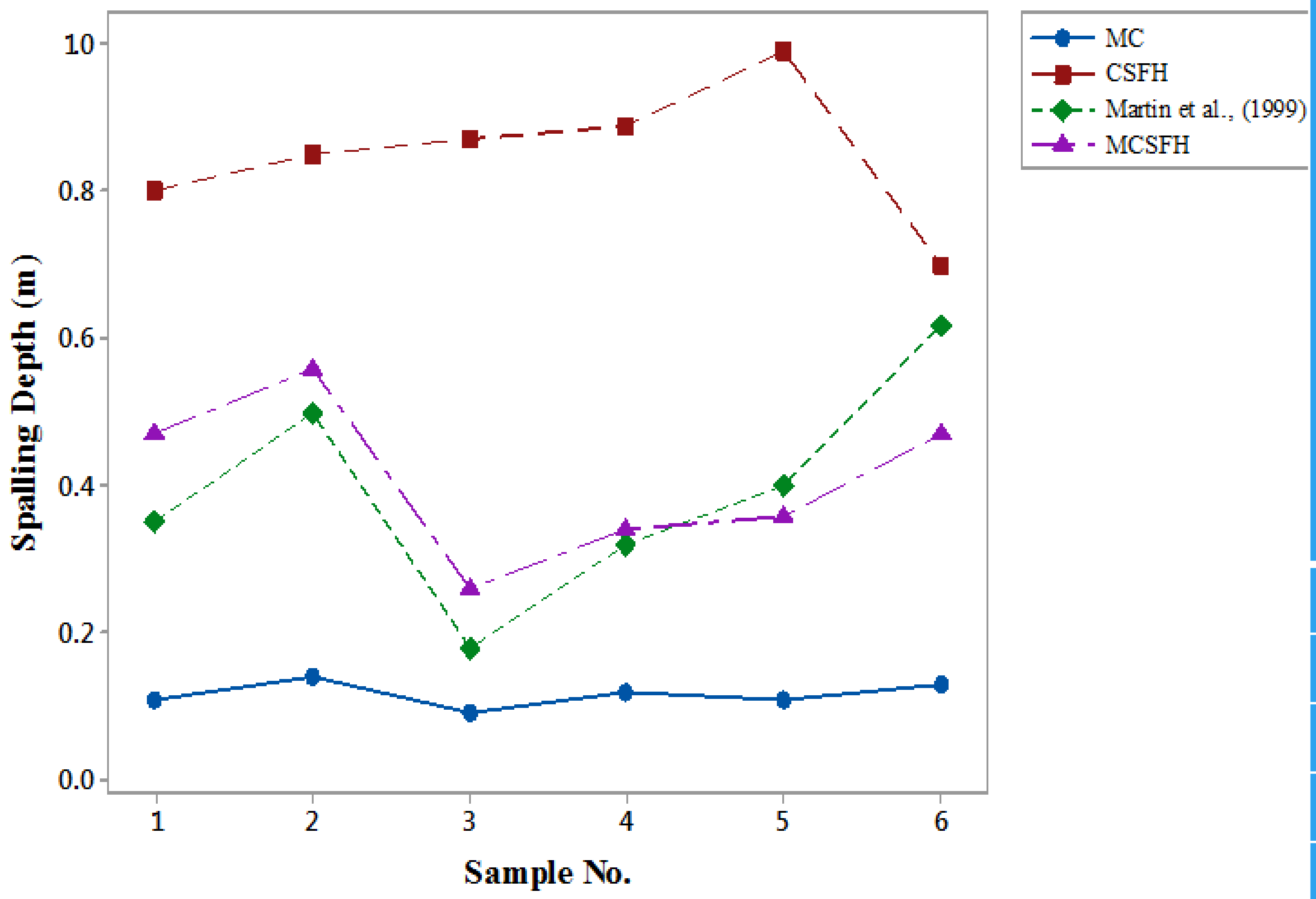






6.0 RESULTS AND DISCUSSIONS

Modified CSFH Material Model for Spalling Prediction



Sample	Modified Cohesion Softening Friction Hardening (CSFH)			
	Peak Friction Angle $\varnothing_{peak}$ (°)	Residual Friction Angle $\varnothing_{res}$ (°)	Peak Cohesion, C_{peak} (Mpa)	Residual Cohesion, C_{res} (Mpa)
1	10	56	22.90	9.50
2	10	54	17.70	8.13
3	10	57	24.96	10.03
4	10	56	23.26	10.00
5	10	56	22.41	9.37
6	10	55	20.28	8.81

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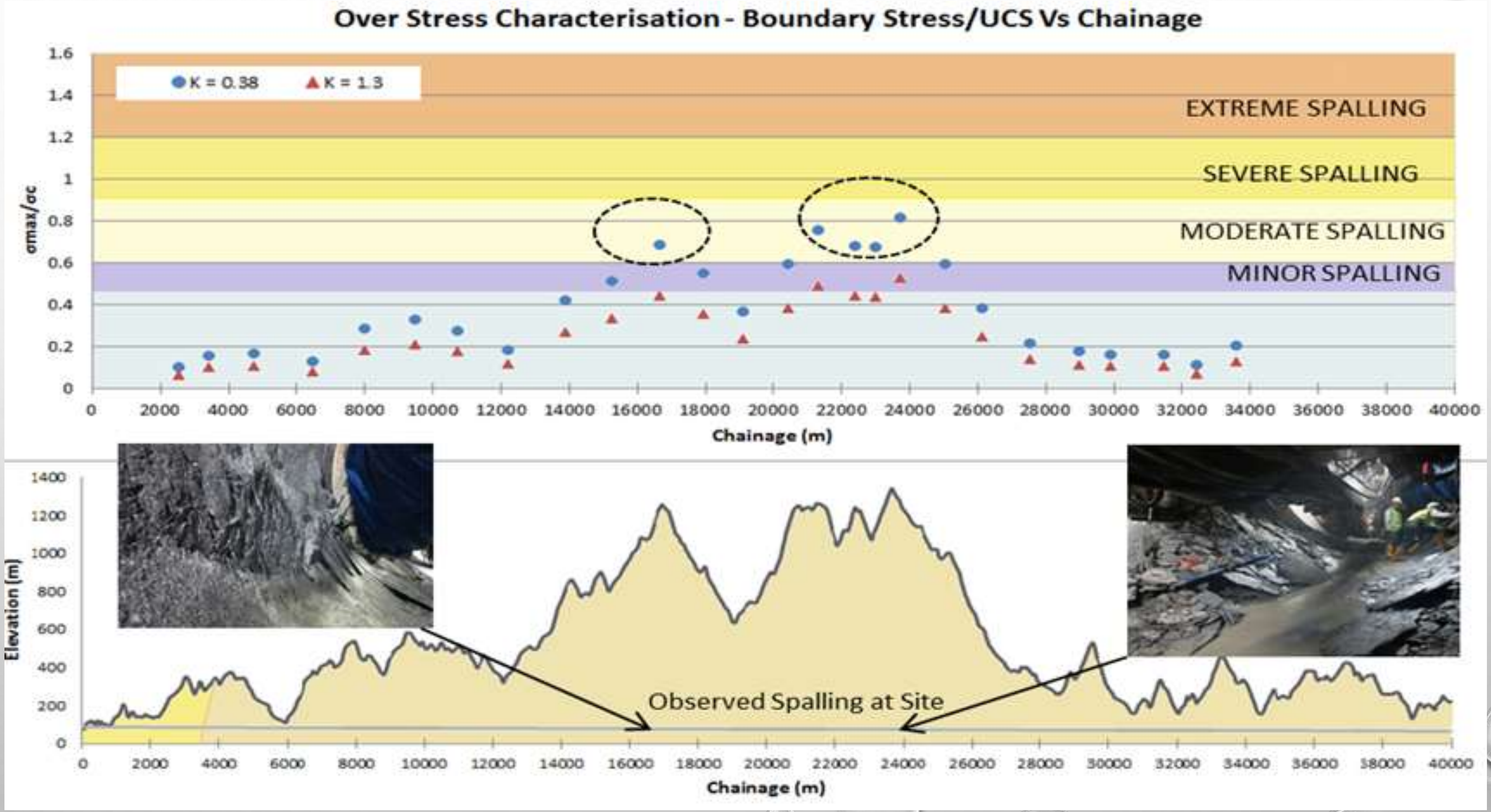
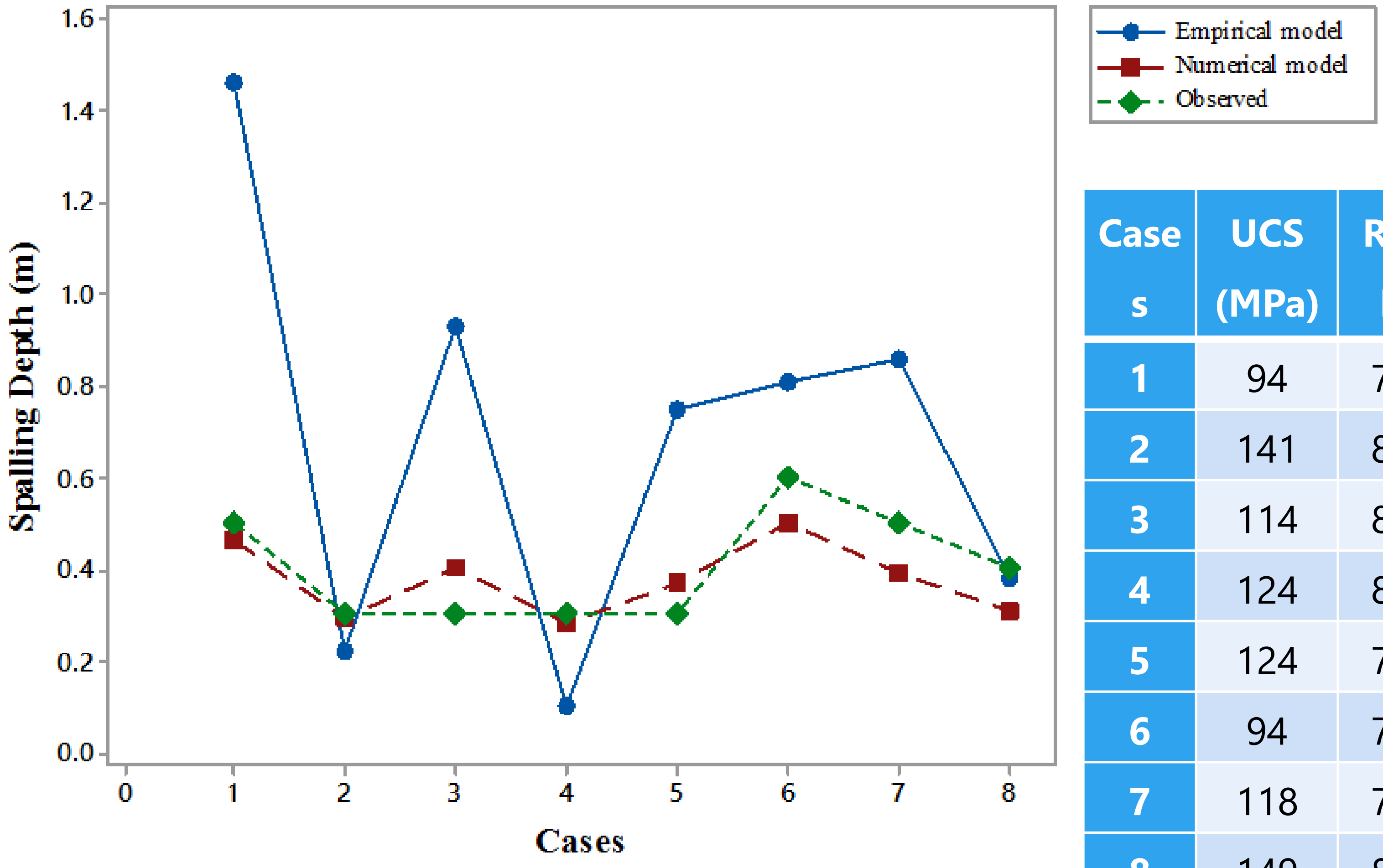
6.0 RESULTS AND DISCUSSIONS

Objetive No. 4: Evaluation of Overstressing Potential and Spalling Failures



6.0 RESULTS AND DISCUSSIONS

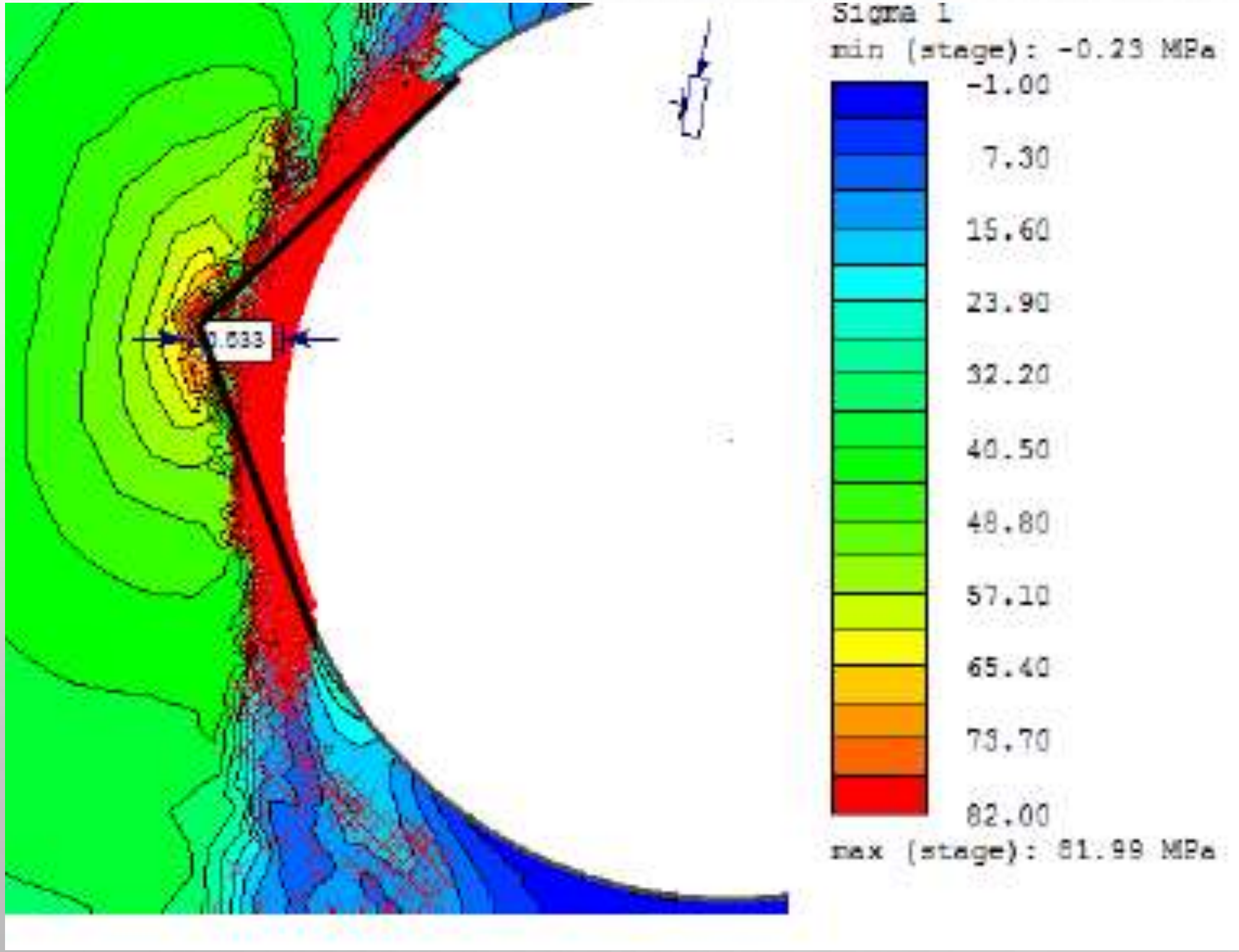
Evaluation of Overstressing Potential and Spalling Failures



Cases	UCS (MPa)	RMR	$Jcon_{89}$	GSI	Hoek-Brown Criterion		
					m_b	s	a
1	94	75	20	70	2.865	0.021	0.502
2	141	82	23	77	3.305	0.032	0.501
3	114	88	23	83	3.245	0.035	0.501
4	124	89	19	84	4.137	0.011	0.503
5	124	79	16	74	2.153	0.008	0.504
6	94	75	16	70	1.866	0.005	0.505
7	118	75	16	70	1.934	0.006	0.504
8	149	81	16	76	2.574	0.015	0.502

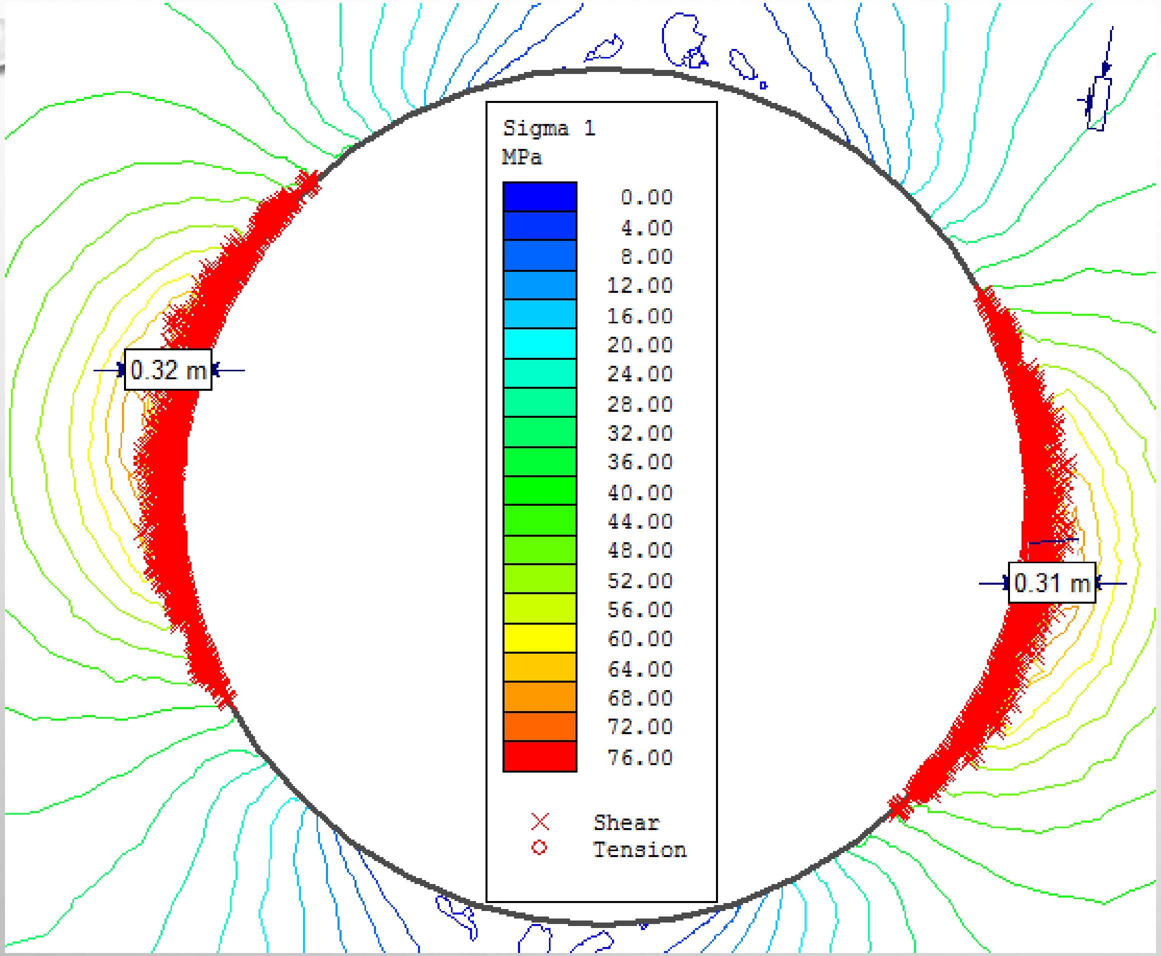
6.0 RESULTS AND DISCUSSIONS

Evaluation of Overstressing Potential and Spalling Failures



6.0 RESULTS AND DISCUSSIONS

Evaluation of Overstressing Potential and Spalling Failures



7.0 CONCLUSIONS

- The vertical stress dominates in deeper part of the Main Range in Malaysia, the coefficient of lateral stress (K_o) is estimated to be less than one ($K_o<1$).

- From the measurement of in situ stress at the critical section of Pahang-Selangor Tunnel, the K_o value was found to be 0.38, this has been validated that the vertical stress dominant of in-situ stress in Peninsular Malaysia.

- The parametric analysis had identified that the peak friction angle of 10^o and residual cohesion is equal to rock mass cohesion, which are suitable for determining the size of spalling depth.

- The validation of numerical analysis had shown that the modified CSFH is suitable for spalling failure prediction with respect to location, depth and shape.

LIST OF PUBLICATIONS (Journals)

- **Azit, R.,** Ismail, M. A. M., Thang, Y.J., (2017). Evaluation of Spalling Fallout on Excavation Disturbed Zone under Deep Hard Rock Tunnel. IOP Conference Series: Materials Science and Engineering. Vol. 226. (Scopus).

  Azit, R., Ismail, M. A. M., (2016). In-situ Stress Measurement by Overcoring and Hydraulic Fracturing of Pahang-Selangor Raw Water Transfer Project. Jurnal Teknologi. Vol 78, no. 8-6. (Scopus)

  Azit, R., Ismail, M. A. M., Zainal, S.F.F.S., and Mahmood, N. (2015). Rock Overstressing in Deep Tunnel Excavation of Pahang-Selangor Raw Water Transfer Project, Journal of Applied Mechanics and Materials, Vol. 802, pp. 16-21.

  Azit, R., Ismail, M. A. M., (2016). Analysis of rock burst event in deep TBM excavation of Pahang-Selangor raw water transfer tunnel. The Malaysian Construction Research Journal. Vol 20 pp. 1-13. (Scopus).

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LIST OF PUBLICATIONS (Conference proceedings)

Azit, R. and Ismail, M.A.M. 2016 Modeling Stress-Induced Failure for the Deep Tunnel Excavation of Pahang-Selangor Raw Water Transfer Project ISRM International Symposium- 9th Asian Rock Mechanics Symposium, 18-22 October 2016, Bali, Indonesia

Ismail, M.A.M., **Azit, R**., Mahmood, N., and Narita, N. 2014. Evaluation of Rock Overstressing in the Excavation of Pahang-Selangor Raw Water transfer Tunnel Project, 2014 ISRM International Symposium- 8th Asian Rock Mechanics Symposium, 14-16 October 2014, Sapporo, Japan International Society of Rock Mechanics Publishing (Published)

Ismail, M.A.M., and **Azit, R**. 2013. Rock Mass Classification System Used for Pahang-Selangor Raw Water Transfer Tunnel, 2013 Proceedings of the International Civil and Infrastructure Engineering Conference 2013, Kuching Sarawak, Malaysia
Springer International Publishing (Published)

Thank you for your attention

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