Soil Settlement Due to Underground Tunnelling in Different Soil Types

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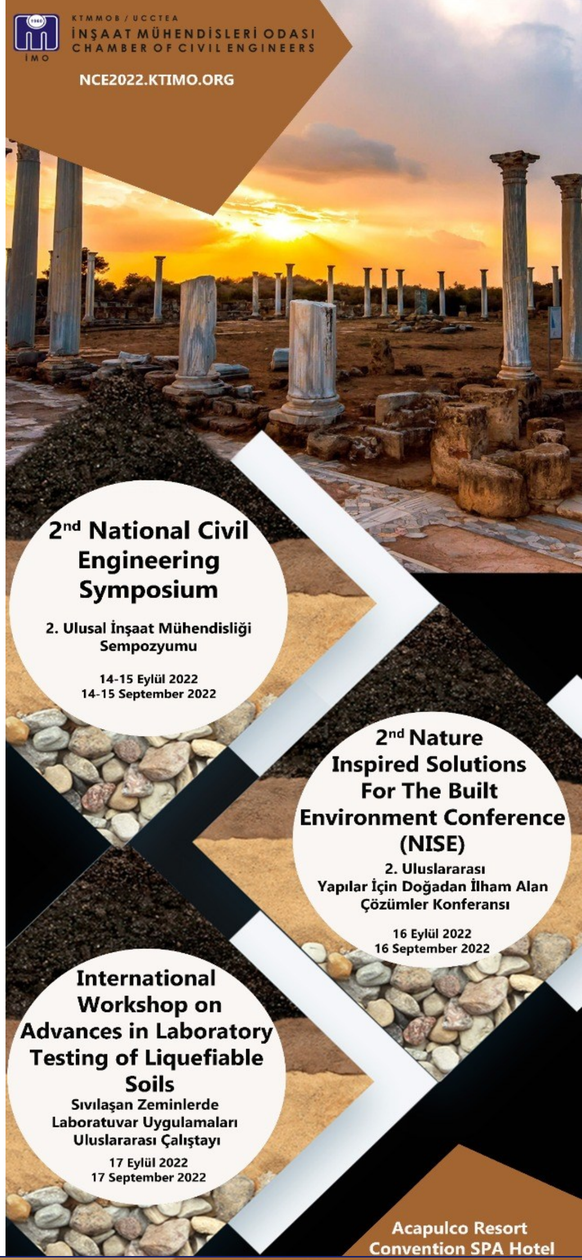


Presentation Overview

1 **Introduction:**
- Brief Introduction
- Literature Survey
- Aim of Research

2 **Research Methodology:**
- Methodology
- Modelling

3 **Results & Discussions**

4 **Conclusion:**
- Concluding Remarks
- Questions & Answers

1. INTRODUCTION

Ground Deformation Due to Underground Tunnelling

i. Construction methods
- NATM
- Bored Tunnels.

ii. Modes of ground deformation.
- Longitudinal Settlements.
- Transverse Settlements.
  - Vertical deformations.
  - Horizontal deformations

iii. Analysis Approach.
- Empirical
- Analytical
- Computer Applications

iv. Tunnel Lining Design Approach
- Forces acting on lining
- Analytical design solution.
- The beam-bedded model.

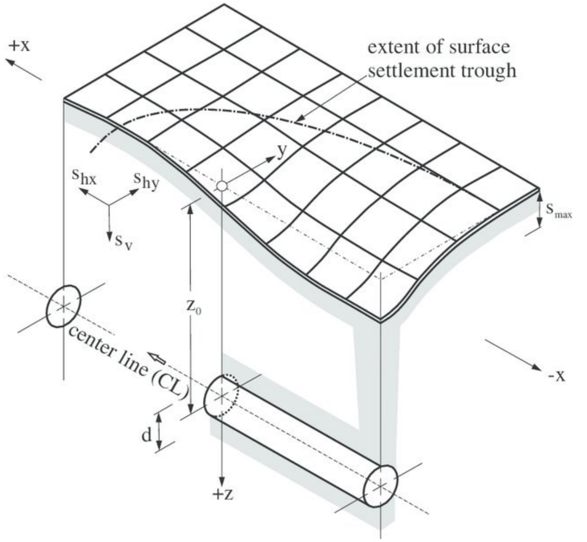


Fig. 1: 3D settlement profile (*Attewell et al. 1986*)

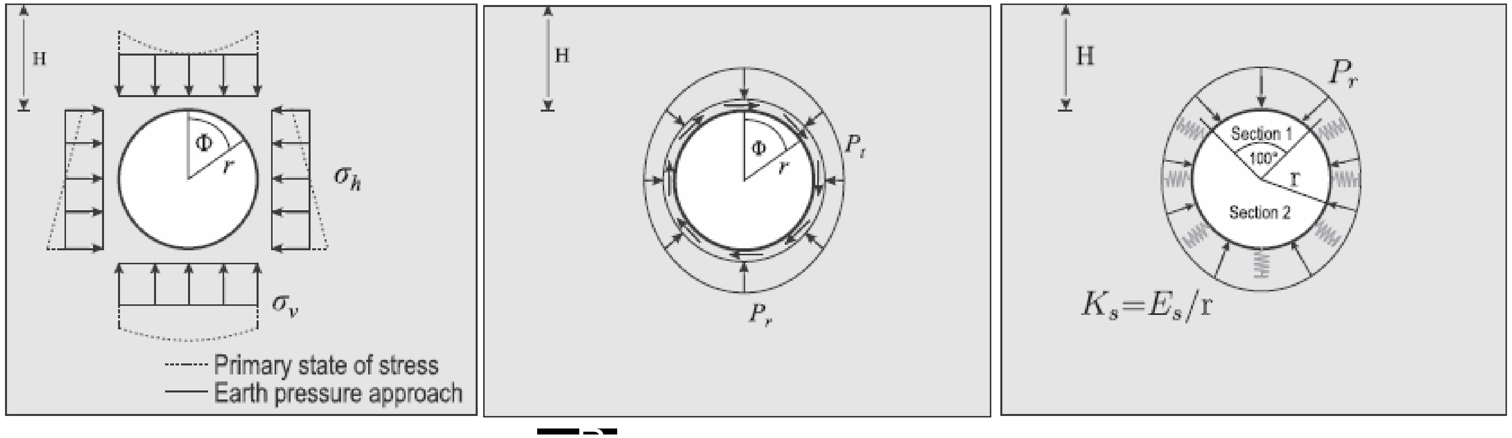


Fig. 2: Schematic illustration of forces acting on tunnel and analytical solutions.

VERTICAL SETTLEMENT

Peck (1969) ---- Gaussian Distribution Curve (***Figure 3)***

$$S_{v(y)} = S_{max} e^{\left(-\frac{x^2}{2i^2}\right)}$$ ***Equation 1***

$$S_{max} = \frac{A_T V_L}{i\sqrt{2\pi}} = 1.252\,\frac{V_L R^2}{i}$$ ***Equation 2***

$S_{v(y)}$ → Vertical settlement at any point

S_{max} → Maximum settlement at tunnel crest

V_L → Volume loss (Ground Loss Ratio)

i → Inflection point

x → Distance from tunnel center line

R → Tunnel radius

A_T → Tunnel Area

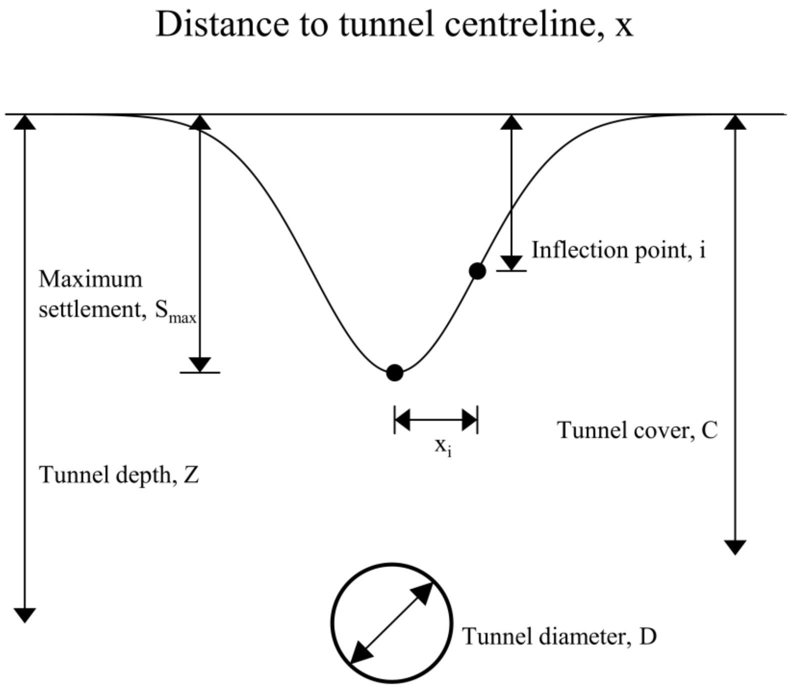


Fig. 3: Gaussian Settlement Curve

VOLUME LOSS:

$$V_L = V_{L,f} + V_{L,s} + V_{L,t} + V_{L,c}$$ *Equation 3*

$V_{L,f}$ → Tunnel face volume loss.

$V_{L,s}$ → Volume loss along the shield.

$V_{L,t}$ → Volume loss at tail.

$V_{L,c}$ → Volume loss due to consolidation.

Table 1: Closed face machines volume loss factors (*Ahmed and Iskander, 2011)*

Cases	V_L **(%)**
Good practice in stable ground.	0.5
Usual practice in slowly ravelling ground.	1.0
Poor practice in the poor ravelling ground.	2.0
Poor practice in the poor fast ravelling ground.	3.0
Poor practice with little face control in running ground.	≥ 4.0

$$V_{L,f}(\%) = 0.23\, e^{4.4\, LF}$$

$$LF = \frac{N}{N_C}$$

$$N = \frac{Z\,\gamma_n + \sigma_s - \sigma_T}{c_u}$$

$$N_C = 2 + 2ln\left(\frac{2C}{D} + 1\right) \quad (For\ \ 0 \leq \frac{C}{D} \leq 1)$$

$$N_C = 4ln\left(\frac{2C}{D} + 1\right) \quad (For\ \ 1 \leq \frac{C}{D} \leq 1.8)$$

$$V_{L,s}(\%) = \frac{4\delta}{D}\ \text{x}\ 100$$

$$V_{L,t} = \frac{V_{s,t}}{\pi\left(\frac{D}{2}\right)^2}$$

$$V_{L,t} = \frac{V_{s,t}}{\pi\left(\frac{D}{2}\right)^2}$$

$$V_{cons} = \sum_{j=1}^{n} u_c^j \Delta x$$

DETAILED VOLUME LOSS ANALYSIS

Equations. 4 – 12 (Saeed & Uygar, 2021)

INFLECTION POINT

Inflection Point (Homogenous Ground):

$$i = K\,Z \qquad \textit{Equation 13}$$

K → Trough width parameter.

Z → Depth to tunnel centerline.

Mair and Taylor (1997)

K → 0.4 – 0.6 $K_{mean} = 0.5$

K → 0.25 – 0.45 $K_{mean} = 0.35$

Inflection Point (Layered Ground):

$$i = K_1 Z_1 + K_2 Z_2 \qquad \textbf{\textit{Equation 14}}$$

Table 2: Inflection point estimation equations.

Ground Condition	Equation	Reference	Ground Condition	Equation	Reference
All soil types	$\frac{i}{R} = \left(\frac{Z}{2R}\right)^n \; [n = 0.8 - 1.0]$	*Peck, 1969*	Cohesive soil	$\frac{i}{R} = \left(\frac{Z}{2R}\right)^{0.8}$	*Clough and Schmidt, 1981*
	$\frac{i}{R} = \left(\frac{Z}{2R}\right)$	*Attewell and Farmer, 1974*		$\frac{i}{R} = 1.5\left(\frac{C}{D}\right)^{0.8}$	*Sugiyama et al., 1999*
	$\frac{2i}{D} = \left(\frac{Z}{D}\right)^{0.8}$	*Cording and Hansmire, 1975*		$i = 0.4\,Z + 0.6$	*Arioglu, 1992*
	$i = 0.4\,Z + 1.92$	*Herzog, 1985*		$i = 0.43\,Z + 1.1$	*O'Reilly and New, 1982*
	$i = 0.386\,Z + 2.84$	*Arioglu, 1992*	Cohesionless soil	$i = 0.28\,Z - 0.1$	*O'Reilly and New, 1982*
	$i = 0.5\,Z$	*Kimura and Mair, 1981*		$\frac{i}{R} = \left(\frac{C}{D}\right)^{0.7}$	*Sugiyama et al., 1999*
	$i = 0.9\left(\frac{D}{2}\right)\left(\frac{Z}{D}\right)^{0.88}$	*Arioglu, 1992*	Loose sand	$i = 0.25(Z + 0.5R)$	*Atkinson and Potts, 1977*
			Dense sand	$i = 0.25(1.5Z + 0.5R)$	*Atkinson and Potts, 1977*

2. Methodology

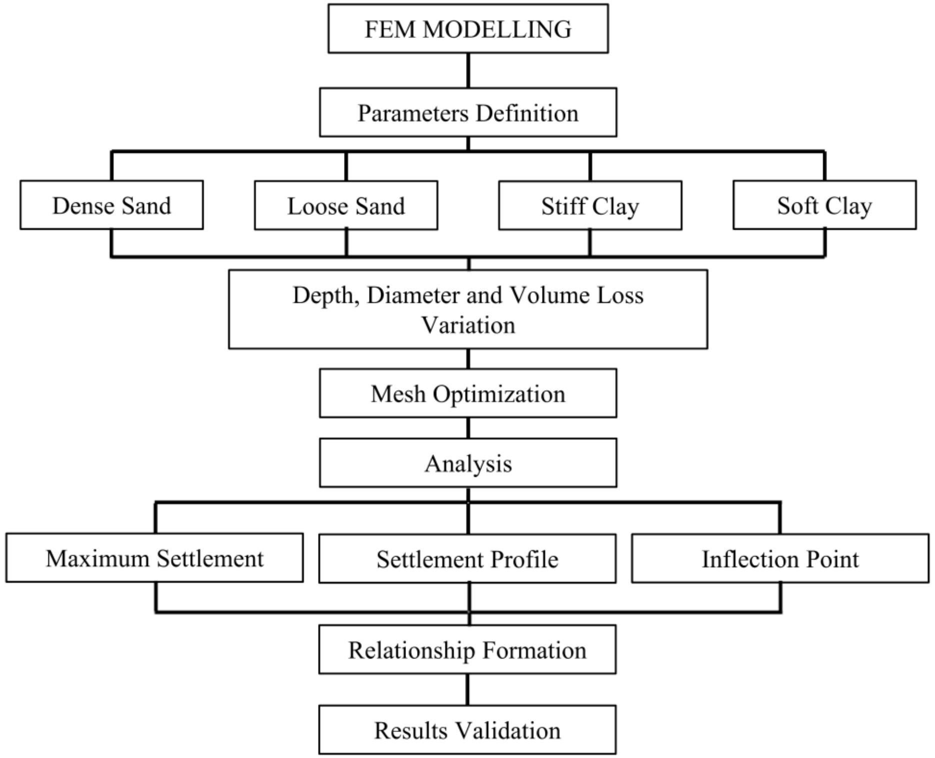


Fig.3 : Research strategy and FEM simulation analysis flowchart

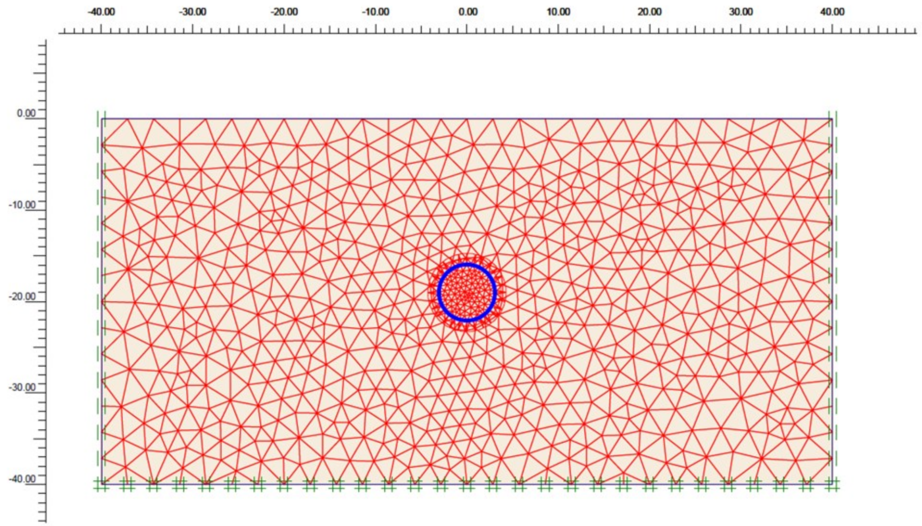


Fig. 4 :Plaxis 2D FEM simulation model.

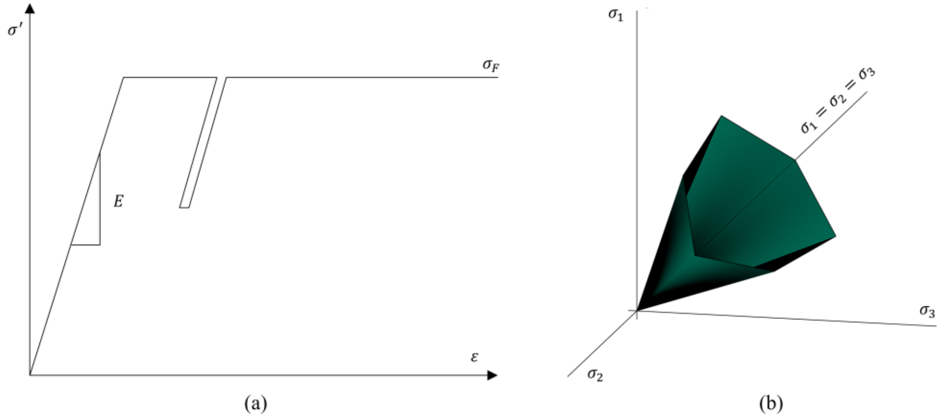


Fig. 5: Mohr-Coulomb model

(a) linear elastic-perfectly plastic materials

(b) principal stress space yield surface for c'=0, ϕ'=30^o

Soil Types: Soft clay, stiff clay, loose sand and dense sand

Table 3: Plaxis 2D input soil material properties data set.

Soil Type	Soft clay	Stiff clay	Loose sand	Dense sand
Saturated unit weight, γ_{sat} (kN/m^3)	16	19	19	20
Cohesion, c' (kPa)	5	25	0.1	0.1
Friction angle, ϕ' (^{o})	22	26	30	35
Modulus of elasticity, E (kPa)	2600	8500	15000	40000
Poisson's ratio, v	0.33	0.20	0.30	0.30
Material behaviour	Undrained	Undrained	Drained	Drained
References	*Wand et al., 2003*	*Likitlersuang, et al., 2014*	*Kanagaraju, et al., 2020*	*Möller, 2006*

Tunnel lining

Table 4: Plaxis 2D input tunnel lining properties data set.

Tunnel diameter, D (m)	8.30	6.30	6.13
Tunnel thickness, t (m)	0.35	0.30	0.20
Poisson's ratio, v	0.20	0.15	0.15
Normal stiffness,EA (kN/m)	1.05×10^7	8×10^6	7×10^6
Flexural rigidity,EI (kNm^2/m)	1.07×10^5	5.60×10^4	3.65×10^4
Specific weight, w (kN/m/m)	8.8	7.5	6
Material behaviour	Elastic	Elastic	Elastic
References	*Möller, 2006*	*Likitlersuang, et al., 2014*	*Wand et al., 2003*

SIMULATION STAGES:

3 Staged Analysis

1st Stage → Initial effective stresses.

2nd Stage → Installation of tunnel lining.

3rd Stage → Removal of soil inside tunnel and ***uniform contraction method.***

Initial Conditions:

- Water pressure → Genreal phreatic level (z = 0)
- Effective stress → K_o (*Jáky's* formulation)

$$K_o = 1 - \sin(\phi')$$

- **Volume Loss variation:**

V_L → 0.1, 0.25, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0 (%)

- **Tunnelling depth variation:**

Based on ***D/Z < 1*** (Z = 7, 9, 11, 13, 15, 17, 19, 21, 23, 25, 27, 29, 31 m)

$$Total\ contraction = \frac{Tunnel\ original\ area - Tunnel\ area\ at\ current\ step}{Tunnel\ original\ area}$$

Equation 15

3. Results and Discussions

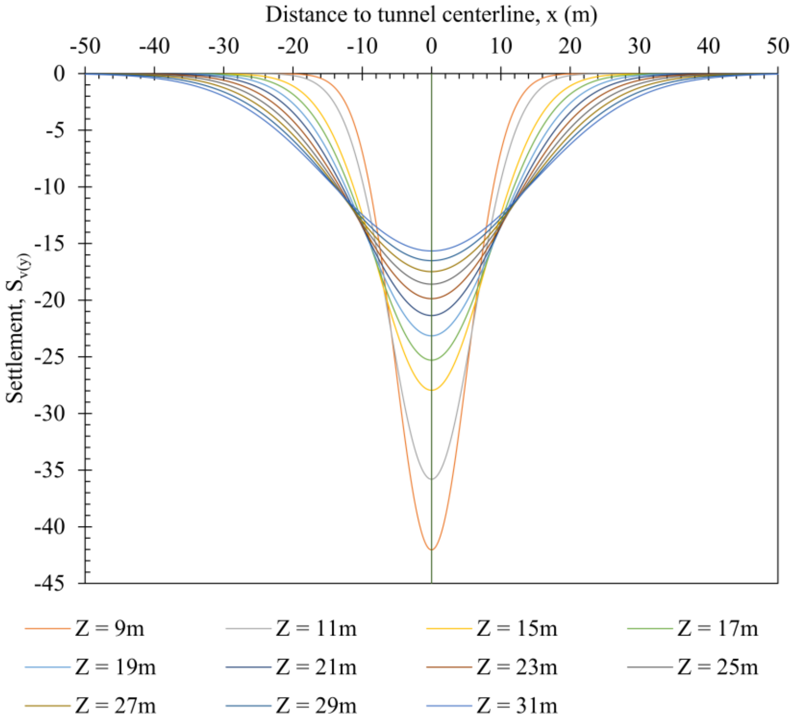


Fig.6: Settlement profile of tunnel at different depths

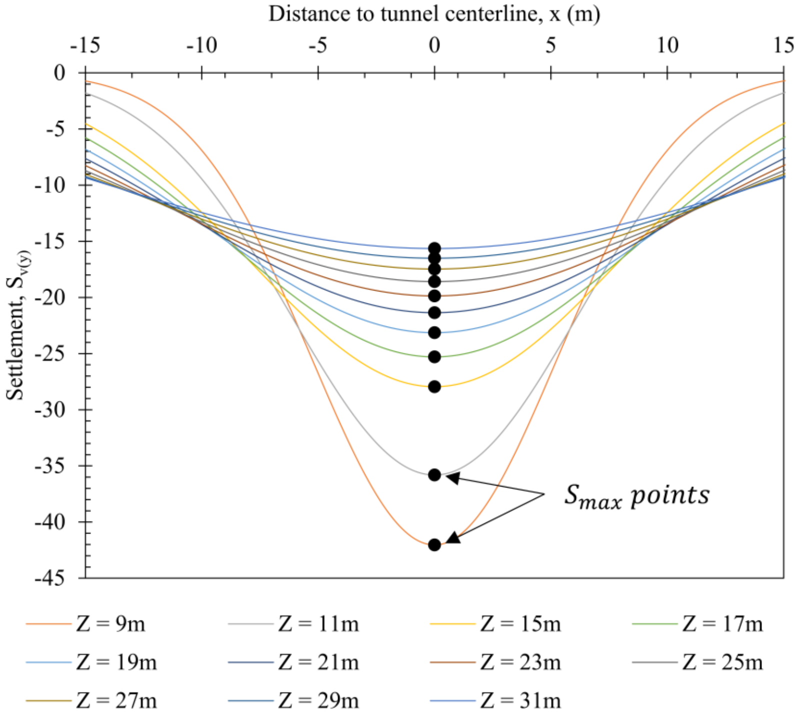


Fig. 7: Maximum settlement at ground surface of tunnel at different depths.

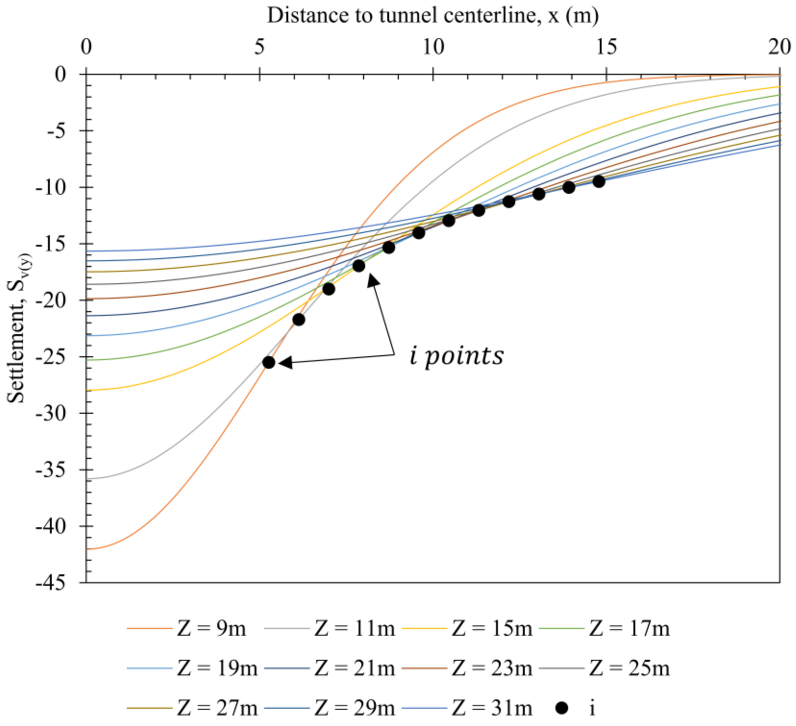


Fig. 8: Inflection point location on settlement profile.

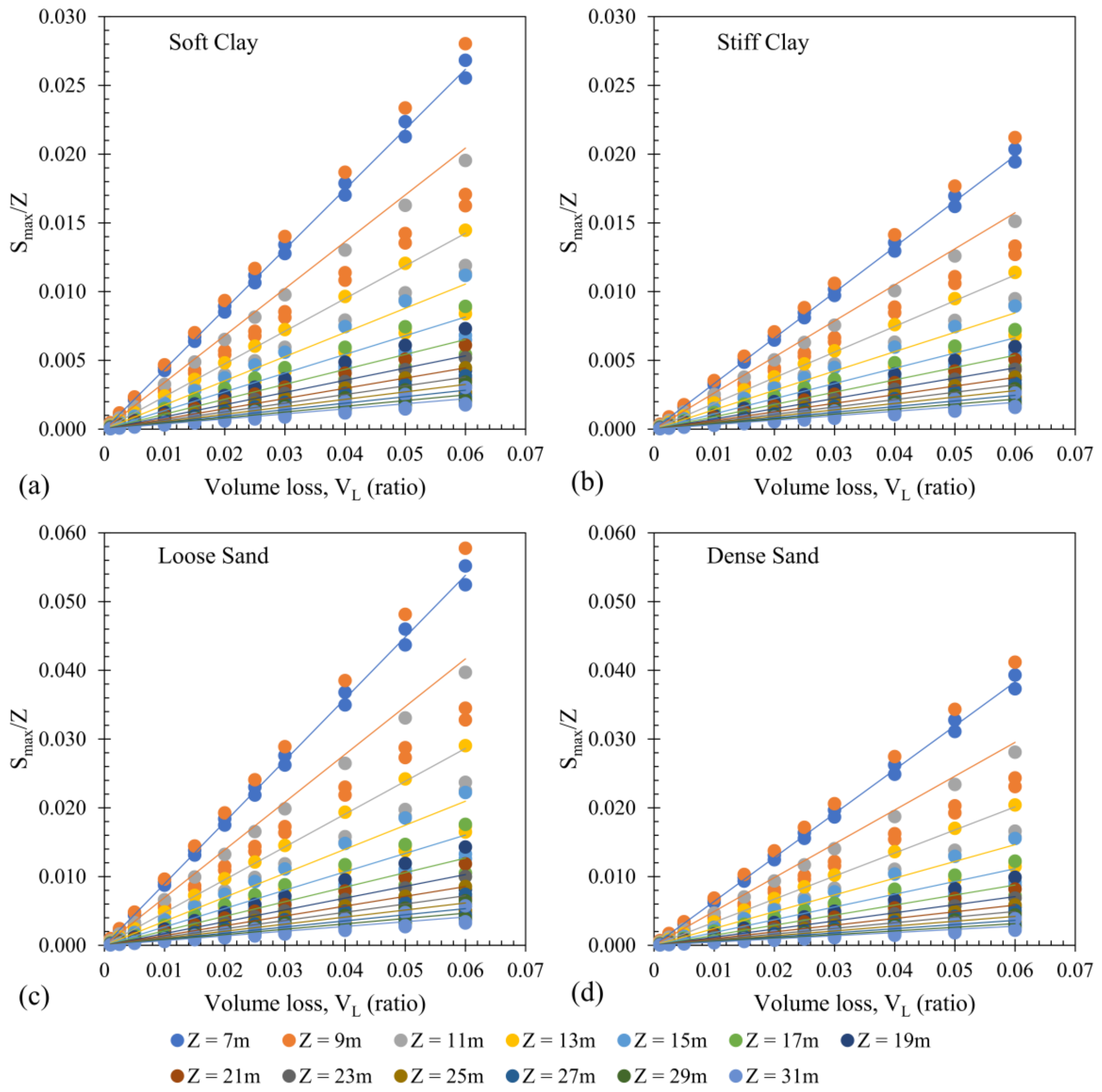


Fig. 9: Volume loss effect on the settlement

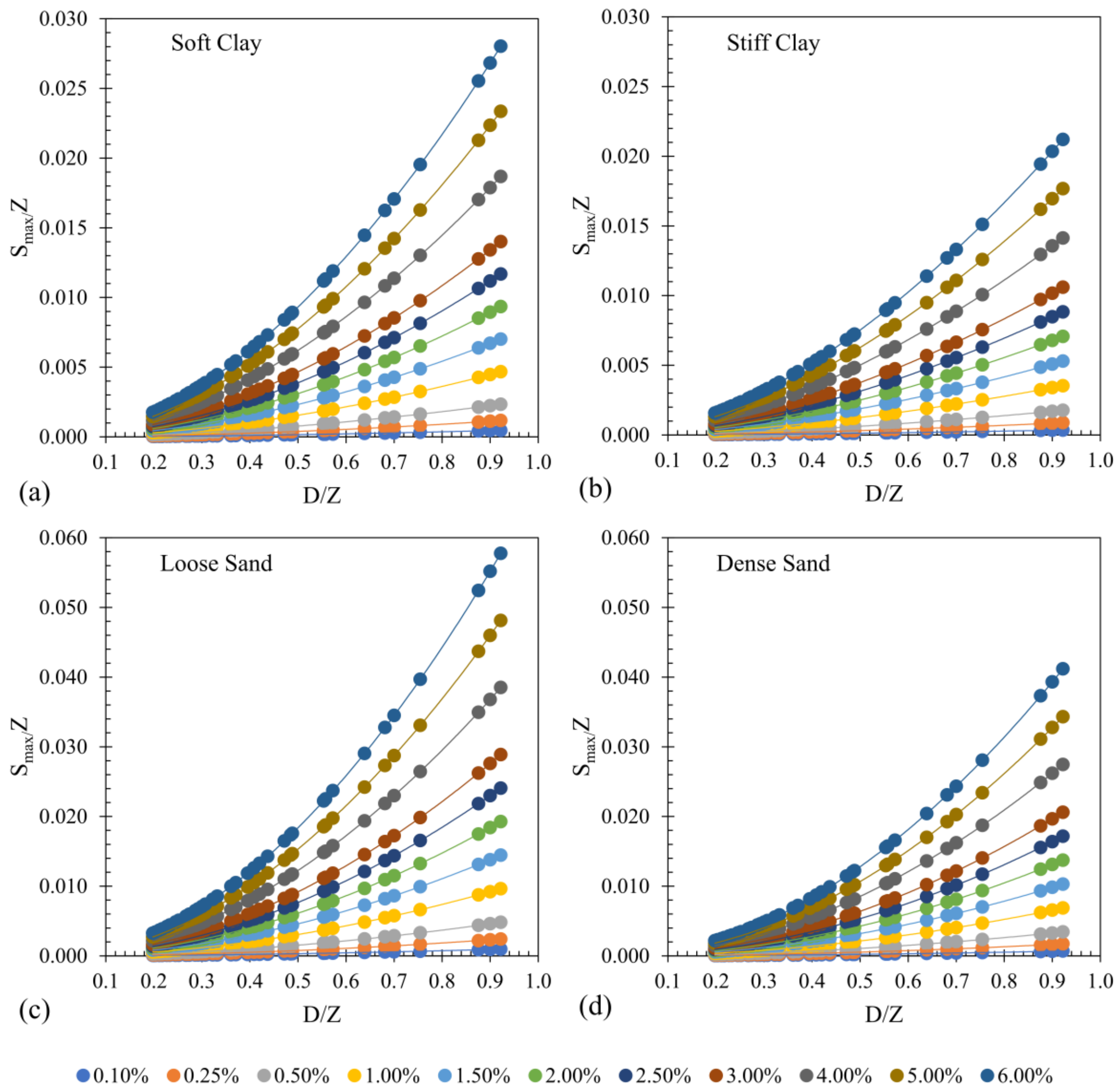


Fig. 10: Variation of settlement with respect to *D/Z*

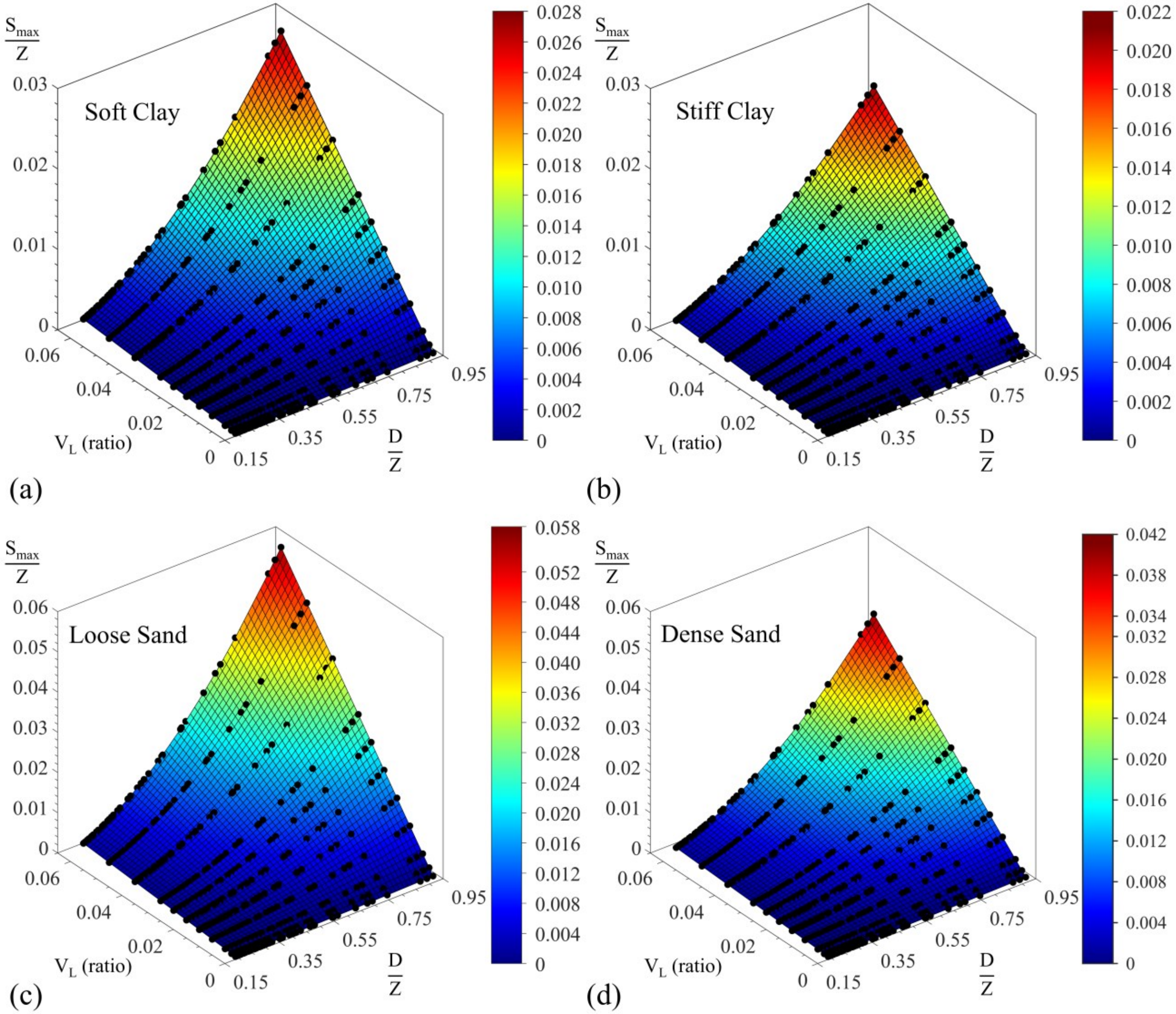


Fig. 11: Normalized multivariable variations for settlement versus volume loss and depth

$$\frac{S_{max}}{Z} = \alpha \, V_L \left(\frac{D}{Z}\right)^{\kappa}$$ ***Equation 16***

Table 5: Equation fitting coefficients

Soil Types	Constant α	Power exponent κ
Dense Sand	0.8011	1.909
Loose Sand	1.1200	1.870
Stiff Clays	0.4052	1.690
Soft Clays	0.5403	1.799

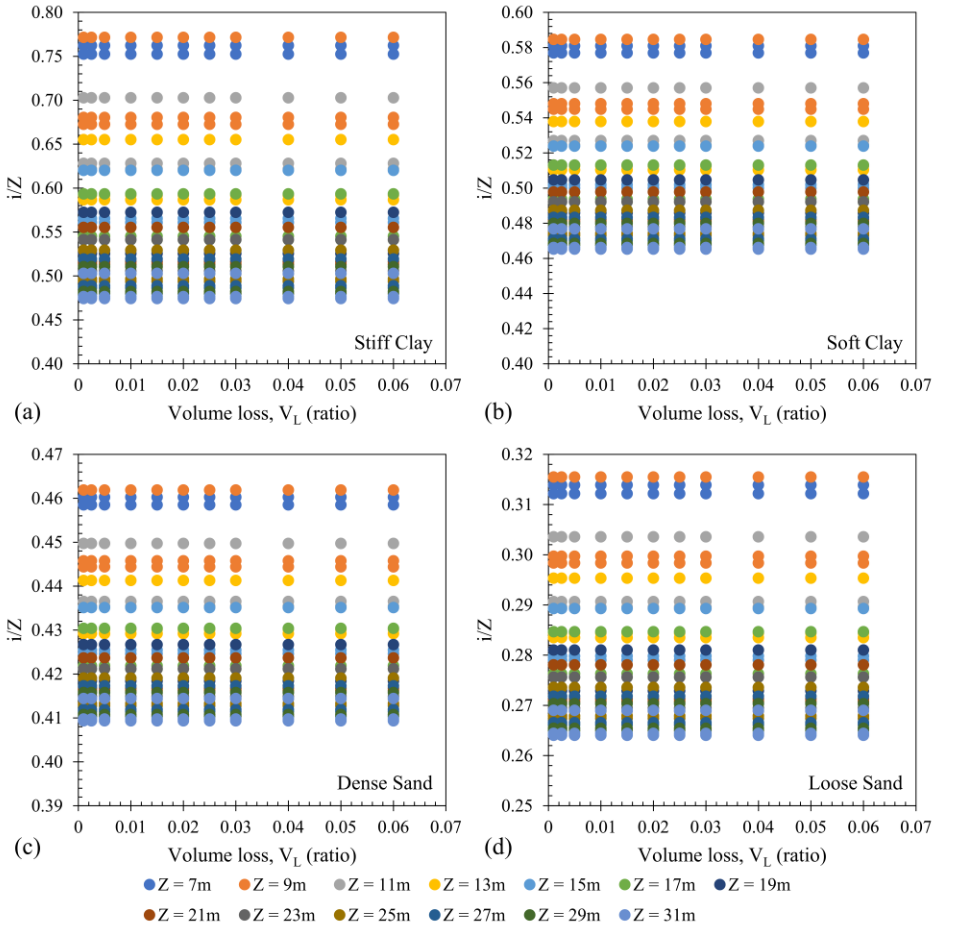


Fig. 12: Effect of volume loss on the inflection point.

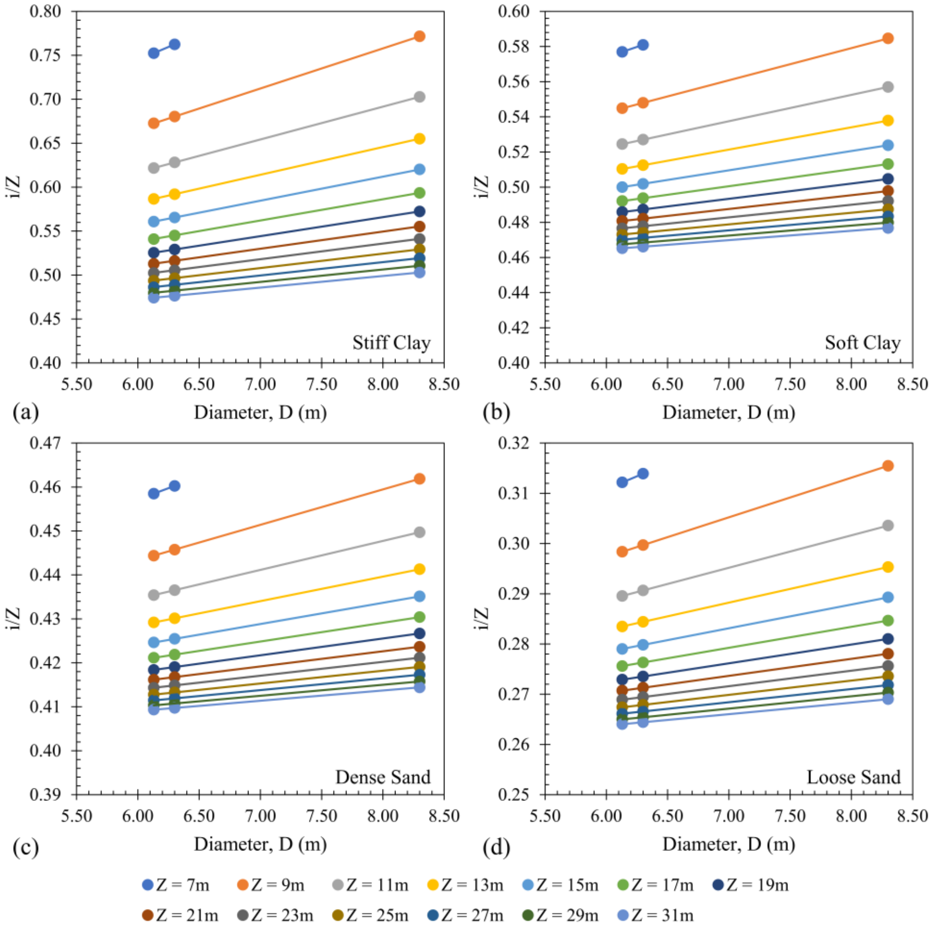


Fig. 13: Effect of diameter on the inflection point

$$\frac{i}{Z} = \beta\left(\frac{D}{Z}\right) + \zeta \qquad \textbf{Equation 17}$$

Table 6.: Fitting coefficients based on the analysis performed.

Soil Types	β	ζ
Dense sand	0.0725	0.3950
Loose sand	0.0710	0.2500
Stiff clay	0.4103	0.3931
Soft clay	0.1647	0.4327

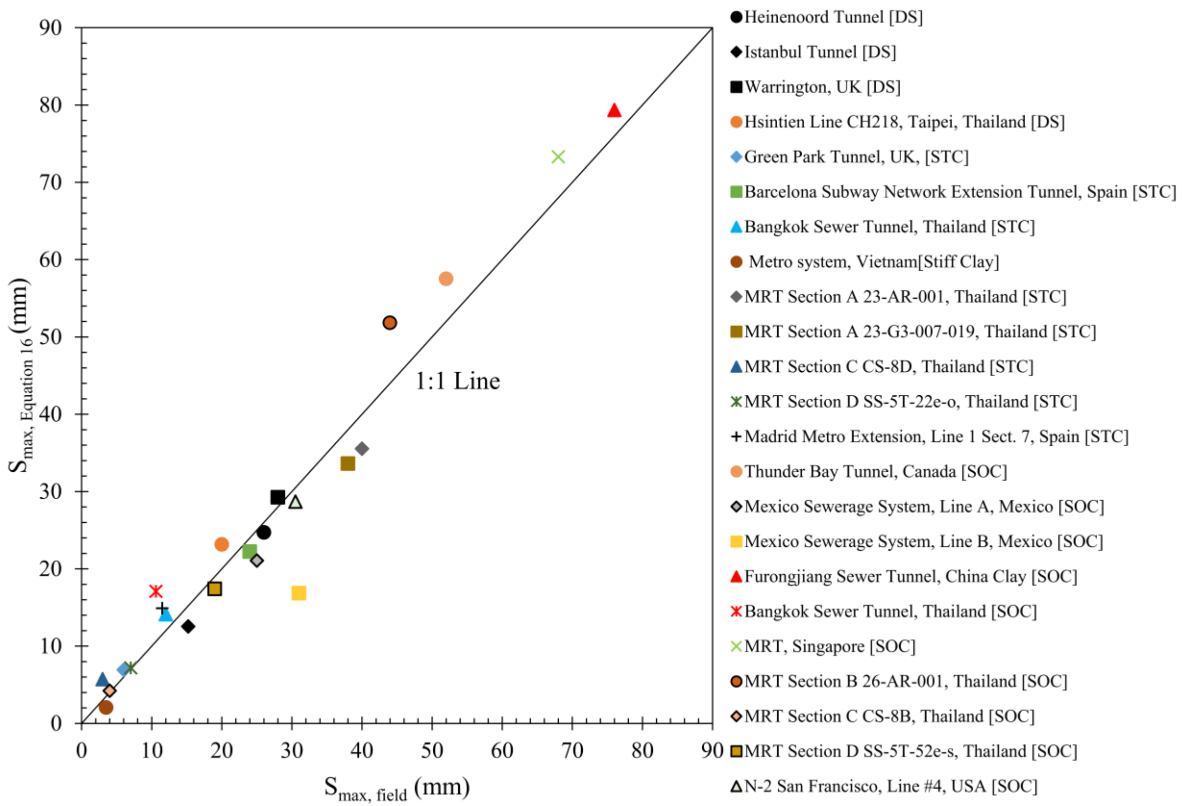


Fig. 15: . S_{max} values comparative validation with $S_{max,field}$

Table 7: Accuracy range of proposed S_{max} equation.

Soil Type	Mean Absolute Percent Error MAPE	Determination coefficient R^2	Correlation coefficient R
Dense sand	10.00	0.8778	0.9340
Stiff clay	25.02	0.9797	0.9898
Soft clay	18.31	0.9444	0.9718
Overall	17.98	0.9517	0.9756

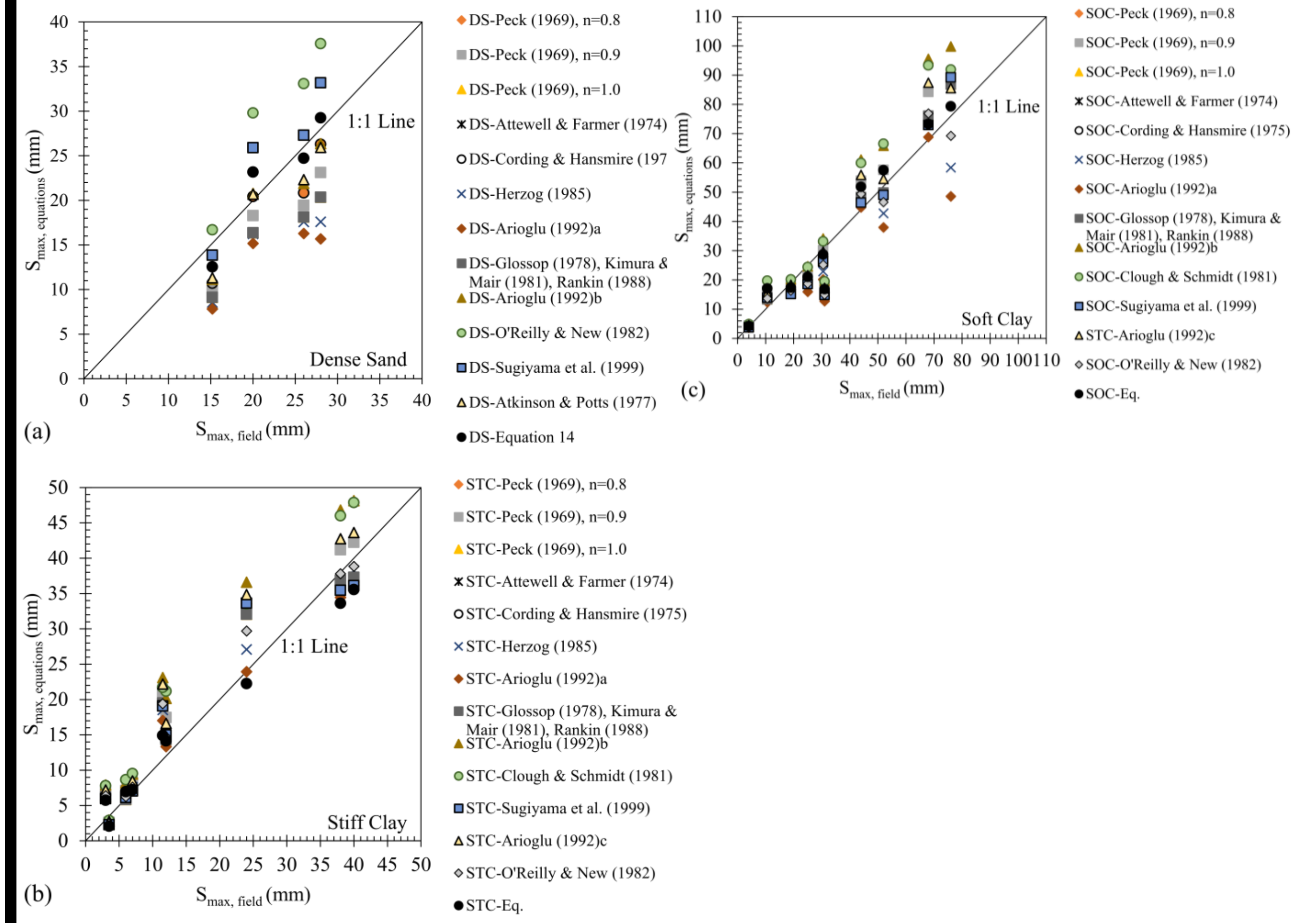


Fig. 15: . S_{max} *Table 2* equations comparative validation with $S_{max,field}$

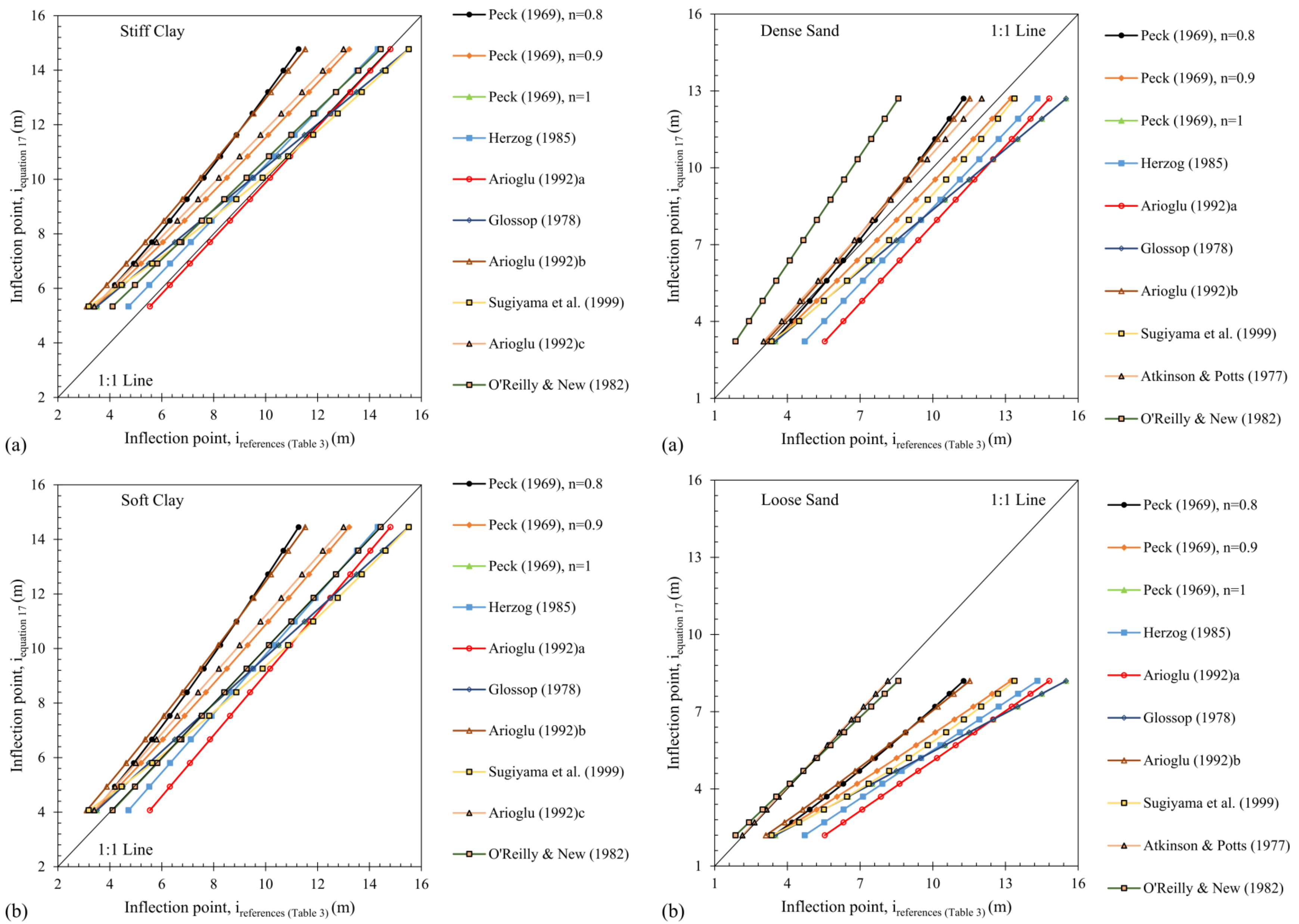


Fig. 16: Comparison between FEM and ***Table 2*** inflection points equations

T#		VL-refs.	Eq. 16	Peck (1969), n=0.8	Peck (1969), n=0.9	Peck (1969), n=1.0	Attewell & Farmer (1974)	Cording & Hansmire (1975)	Herzog (1985)	Arioglu (1992)[a]	Glossop (1978)	Arioglu (1992)[b]	O'Reilly & New (1982)	Sugiyama et al. (1999)	Atkinson & Potts (1977)
1	Dense Sand	0.7	0.74 ≈	0.87 ↑	0.94 ↑	1 ↑	1 ↑	0.87 ↑	1.03 ↑	1.12 ↑	1 ↑	0.83 ↑	0.55 ↓	0.67 ≈	0.82 ↑
2	Dense Sand	0.5	0.61 ↑	0.71 ↑	0.77 ↑	0.83 ↑	0.83 ↑	0.71 ↑	0.89 ↑	0.97 ↑	0.83 ↑	0.68 ↑	0.46 ≈	0.55 ≈	0.67 ↑
3	Dense Sand	3.9	3.73 ≈	4.15 ≈	4.72 ↑	5.37 ↑	5.37 ↑	4.15 ≈	6.2 ↑	6.97 ↑	5.37 ↑	4.14 ≈	2.91 ↓	3.29 ↓	4.21 ≈
4	Dense Sand	1.3	1.12 ↓	1.27 ≈	1.42 ≈	1.59 ↑	1.59 ↑	1.27 ≈	1.6 ↑	1.71 ↑	1.59 ↑	1.25 ≈	0.87 ↓	1 ↓	1.26 ≈
Overall			≈	≈	↑	↑	↑	≈	↑	↑	↑	≈	↓	↓	≈

T#		VL-refs	Eq. 16	Peck (1969), n=0.8	Peck (1969), n=0.9	Peck (1969), n=1.0	Attewell & Farmer (1974)	Cording & Hansmire (1975)	Herzog (1985)	Arioglu (1992)[a]	Glossop (1978)	Arioglu (1992)[b]	Clough & Schmidt (1981)	Sugiyama et al. (1999)	Arioglu (1992)[c]	O'Reilly & New (1982)
5	Stiff Clay	**1.6**	1.4 ↓	1.1 ↓	1.4 ↓	1.6 ≈	1.6 ≈	1.1 ↓	1.5 ≈	1.6 ≈	1.6 ≈	1.2 ↓	1.1 ↓	1.6 ≈	1.4 ↓	1.5 ≈
6	Stiff Clay	**0.8**	0.9 ↑	0.6 ↓	0.6 ↓	0.6 ↓	0.6 ↓	0.6 ↓	0.7 ↓	0.8 ≈	0.6 ↓	0.5 ↓	0.6 ↓	0.6 ↓	0.6 ↓	0.6 ↓
7	Stiff Clay	**6**	4.2 ↓	3.4 ↓	4.1 ↓	5 ↓	5 ↓	3.4 ↓	5 ↓	5.4 ↓	5 ↓	3.6 ↓	3.4 ↓	4.8 ↓	4.3 ↓	4.9 ↓
8	Stiff Clay	**0.15**	0.25 ↑	0.18 ↑	0.2 ↑	0.22 ↑	0.22 ↑	0.18 ↑	0.23 ↑	0.24 ↑	0.22 ↑	0.18 ↑	0.18 ↑	0.23 ↑	0.19 ↑	0.22 ↑
9	Stiff Clay	**3.3**	3.7 ↑	2.8 ↓	3.1 ≈	3.5 ≈	3.5 ≈	2.8 ↓	3.5 ↑	3.6 ↑	3.5 ↑	2.7 ↓	2.8 ↓	3.7 ↑	3 ↓	3.4 ≈
10	Stiff Clay	**2.82**	3.1 ↑	2.33 ↓	2.6 ≈	2.9 ≈	2.9 ≈	2.33 ↓	2.91 ↑	3.11 ↑	2.91 ≈	2.29 ↓	2.33 ↓	3.02 ↑	2.51 ↓	2.84 ≈
11	Stiff Clay	**0.5**	0.3 ↓	0.2 ↓	0.2 ↓	0.2 ↓	0.2 ↓	0.2 ↓	0.2 ↓	0.3 ↓	0.2 ↓	0.2 ↓	0.2 ↓	0.3 ↓	0.2 ↓	0.2 ↓
12	Stiff Clay	**0.75**	0.72 ≈	0.55 ↓	0.64 ↓	0.73 ≈	0.73 ≈	0.55 ↓	0.69 ≈	0.73 ≈	0.73 ≈	0.56 ↓	0.55 ↓	0.74 ≈	0.62 ↓	0.69 ≈
13	Stiff Clay	**0.6**	0.5 ≈	0.3 ↓	0.3 ↓	0.4 ↓	0.4 ↓	0.3 ↓	0.4 ↓	0.4 ↓	0.4 ↓	0.3 ↓	0.3 ↓	0.4 ↓	0.3 ↓	0.4 ↓
Overall			≈	↓	↓	≈	≈	↓	≈	≈	≈	↓	↓	≈	↓	≈

T#		VL-refs	Eq. 16	Peck (1969), n=0.8	Peck (1969), n=0.9	Peck (1969), n=1.0	Attewell & Farmer (1974)	Cording & Hansmire (1975)	Herzog (1985)	Arioglu (1992)[a]	Glossop (1978)	Arioglu (1992)[b]	Clough & Schmidt (1981)	Sugiyama et al. (1999)	Arioglu (1992)[c]	O'Reilly & New (1982)
14	Soft Clay	13.7	12.4 ↓	10.7 ↓	12.4 ↓	14.3 ≈	14.3 ≈	10.7 ↓	16.7 ↑	18.8 ↑	14.3 ≈	10.8 ↓	10.7 ↓	14.5 ↑	13.1 ≈	15.3 ↑
15	Soft Clay	2.5	3 ↑	2.6 ≈	2.9 ↑	3.2 ↑	3.2 ↑	2.6 ≈	3.6 ↑	3.9 ↑	3.2 ↑	2.5 ↑	2.6 ≈	3.4 ↑	2.9 ↑	3.3 ↑
16	Soft Clay	2	3.7 ↑	3.2 ↑	3.6 ↑	4 ↑	4 ↑	3.2 ↑	4.4 ↑	4.9 ↑	4 ↑	3.1 ↑	3.2 ↑	4.2 ↑	3.6 ↑	4.1 ↑
17	Soft Clay	4.4	4.2 ≈	3.6 ↓	3.7 ↓	3.9 ↓	3.9 ↓	3.6 ↓	5.7 ↑	6.9 ↑	3.9 ↓	3.4 ↓	3.6 ↓	3.7 ↓	3.9 ↓	4.8 ↑
18	Soft Clay	5.6	3.5 ↓	3 ↓	3.6 ↓	4.4 ↓	4.4 ↓	3 ↓	4.5 ↓	4.8 ↓	4.4 ↓	3.2 ↓	3 ↓	4.2 ↓	3.8 ↓	4.3 ↓
19	Soft Clay	5.5	4.6 ↓	4 ↓	4.4 ↓	4.9 ↓	4.9 ↓	4 ↓	5 ↓	5.4 ≈	4.9 ↓	3.9 ↓	4 ↓	5.1 ≈	4.3 ↓	4.9 ↓
20	Soft Clay	3.6	3.1 ↓	2.6 ↓	2.9 ↓	3.3 ≈	3.3 ≈	2.6 ↓	3.3 ≈	3.5 ≈	3.3 ≈	2.6 ↓	2.6 ↓	3.4 ≈	2.8 ↓	3.2 ↓
21	Soft Clay	0.3	0.3 ≈	0.2 ↓	0.3 ≈	0.3 ≈	0.3 ≈	0.2 ↓	0.3 ≈	0.3 ≈	0.3 ≈	0.2 ↓	0.2 ↓	0.3 ≈	0.3 ≈	0.3 ≈
22	Soft Clay	1.4	1.5 ≈	1.3 ↓	1.5 ≈	1.7 ↑	1.7 ↑	1.3 ↓	1.7 ↑	1.7 ↑	1.7 ↑	1.3 ↓	1.3 ↓	1.8 ↑	1.4 ≈	1.6 ↑
23	Soft Clay	3.1	3.3 ≈	2.8 ↓	3.1 ≈	3.5 ↑	3.5 ↑	2.8 ↓	4.1 ↑	4.7 ↑	3.5 ↑	2.8 ↓	2.8 ↓	3.6 ↑	3.2 ≈	3.8 ↑
Overall			≈	↓	≈	≈	≈	↓	↑	↑	≈	↓	↓	↑	≈	↑

↓ ≈ ↑

Lower V_L Required **V_L Reference** **Higher V_L Required**

Fig. 17: Back analysis for volume loss required to match S_{max}

TUNNEL LINING FORCES

Basic assumptions:

1. Cross-section in plane strain condition.
2. Cross-section is circular
3. Soil stresses are assumed as equivalent to initial stresses.
4. Bond between tunnel lining and ground.
5. Elastic behaviour of material (soil and lining).

Basic Model (*Bakker, 2003*)	Initial soil stresses considered.	Does not account soil structure interaction
Analytical Method (*Schulze and Duddek, 1964*)	The bedding model with complete and closed solution	
Continuum Model (*Ahrens et al. 1982*)	Complete solution	

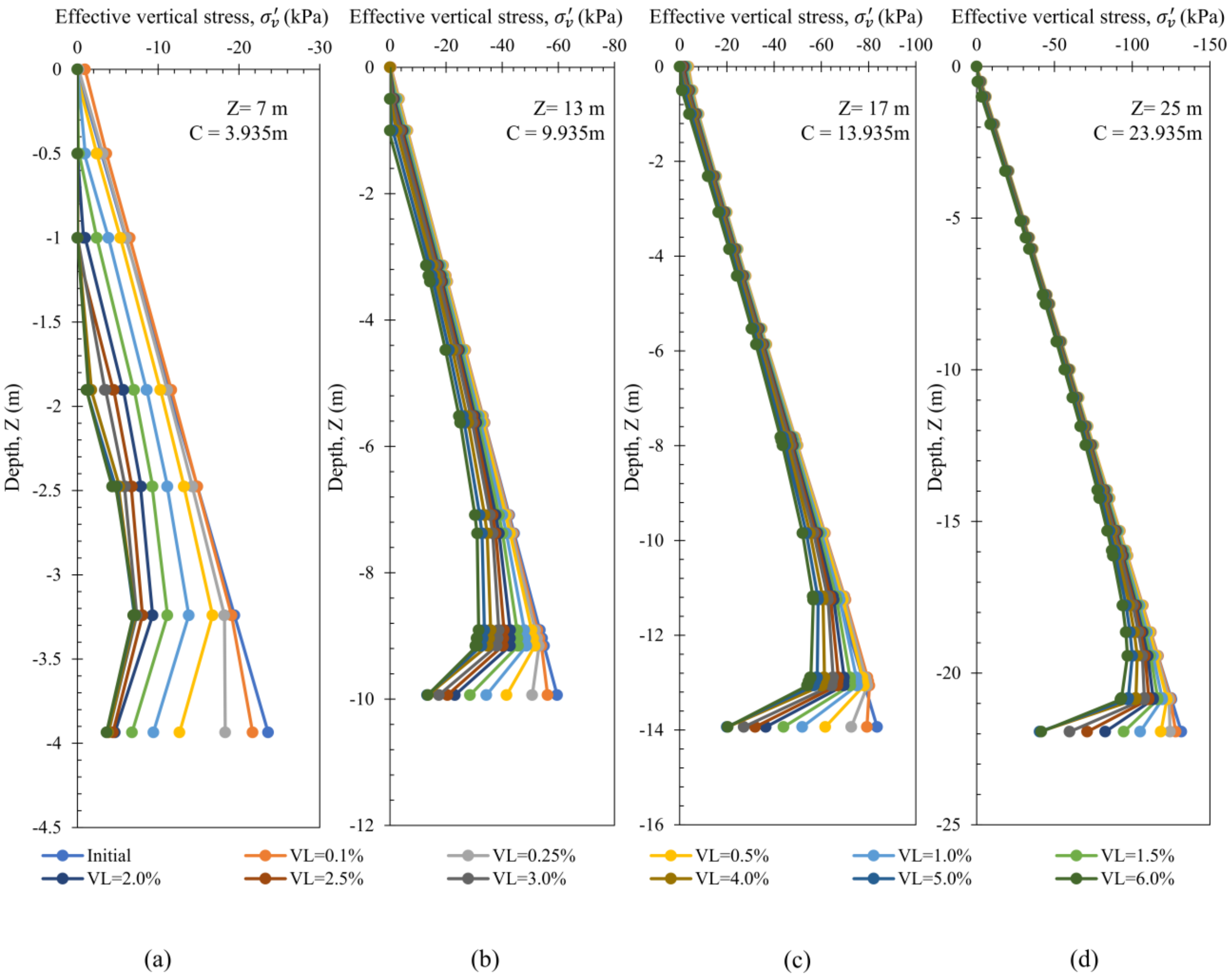


Fig. 17: Comparison of stress-relieve at tunnel crown (C) in correspondence with V_L

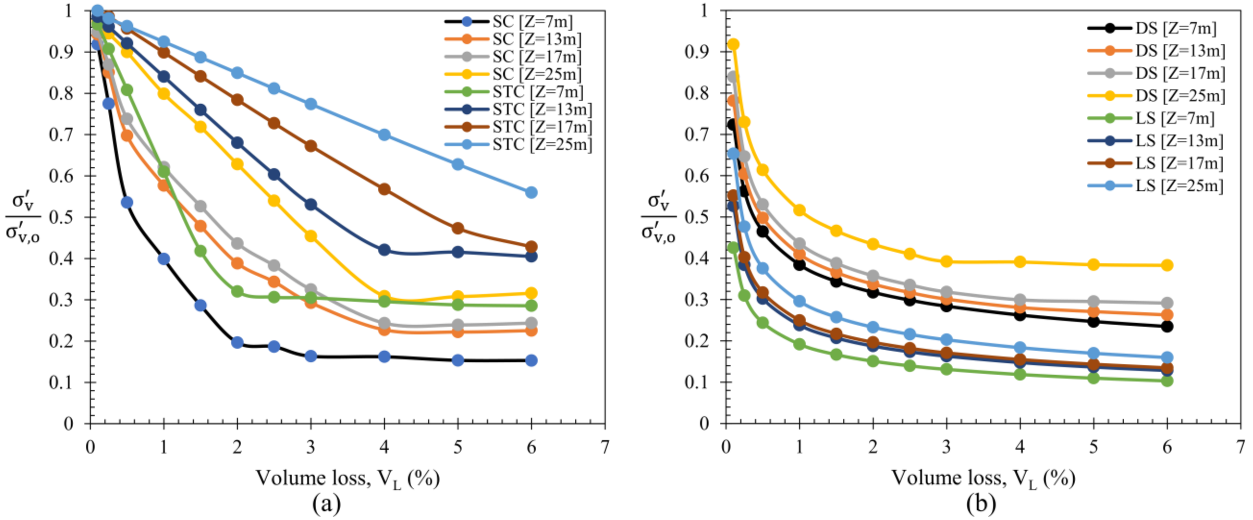


Fig. 18: Variation of σ'_v/σ'_o with V_L

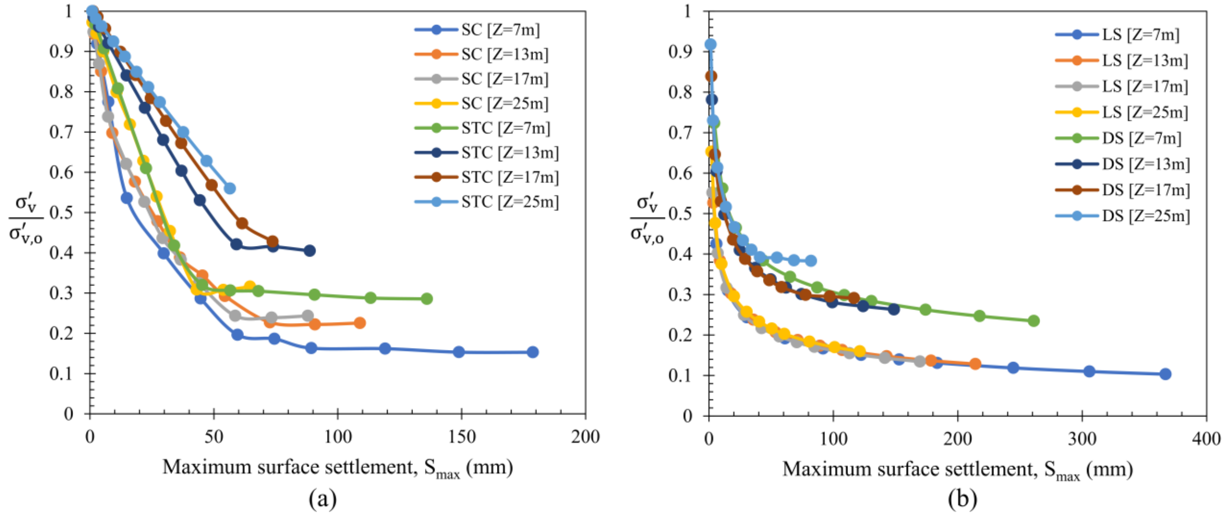
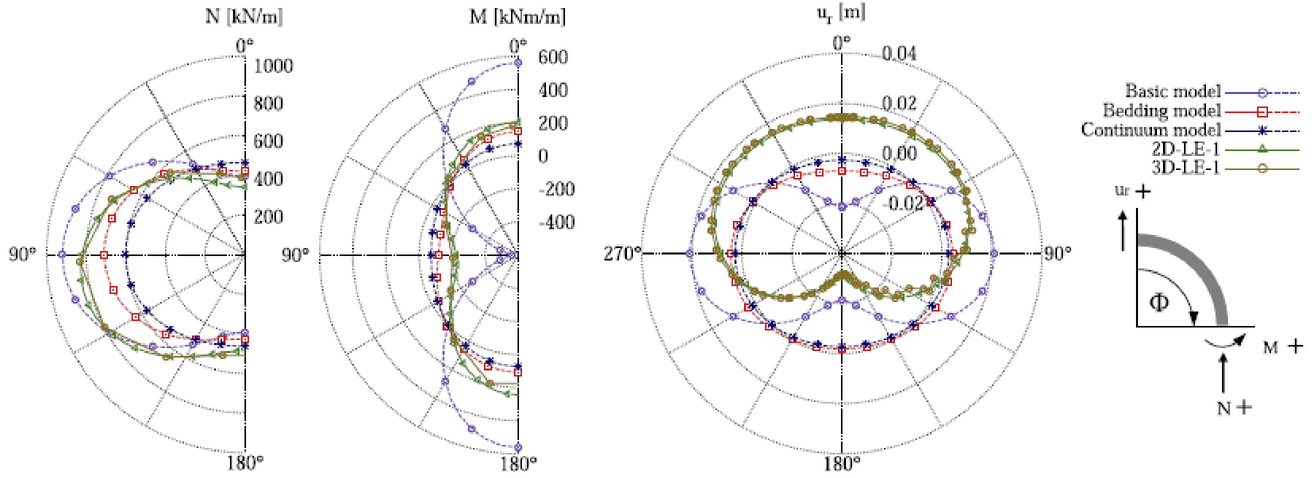


Fig. 19: Variation of σ'_v/σ'_o with S_{max}

Shallow Tunnels



Deep Tunnels

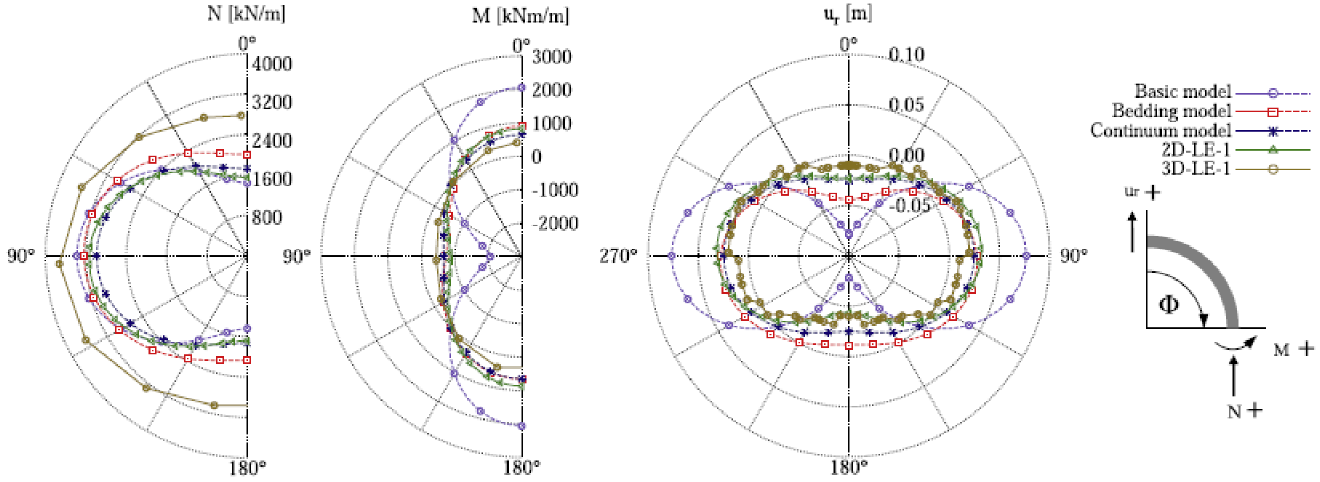


Fig. 20: Analytical and Numerical models comparison for lining forces (*Zhao et al., 2017*).

4. Conclusions

- The proposed maximum settlement equation was developed based on the FEM simulation by selecting parametric studies' material and tunnel lining properties.
- The accuracy of the proposed maximum settlement prediction equation was validated using data from the literature on tunnelling in different soil types.
- The tunnel diameter was observed to be effective only at shallow depths, and the volume loss indicated no significant correlation with the location of the inflection point.
- The stress-relaxation and lining forces plays a crucial role in the final design of tunnel linings.

THANK YOU!