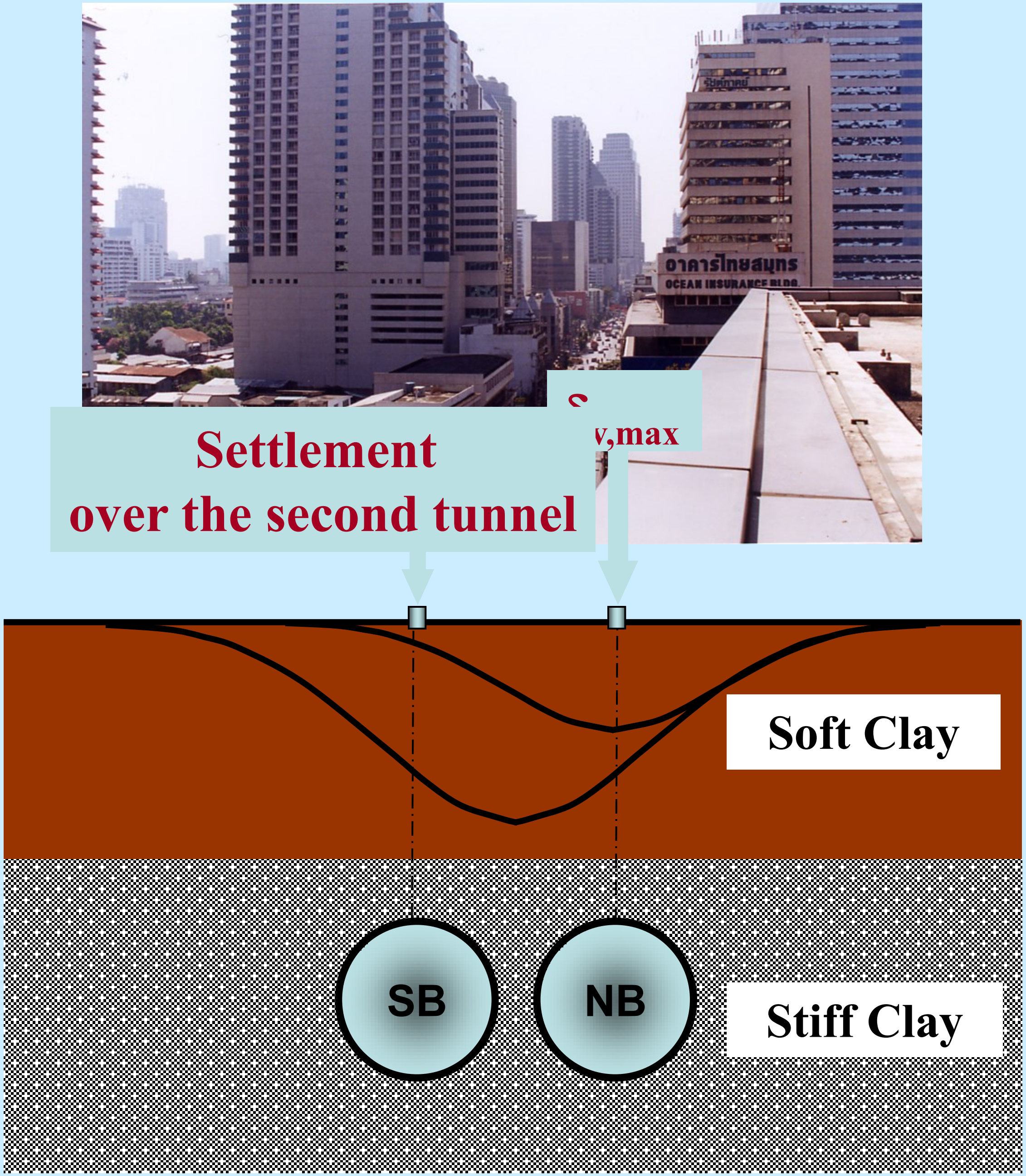
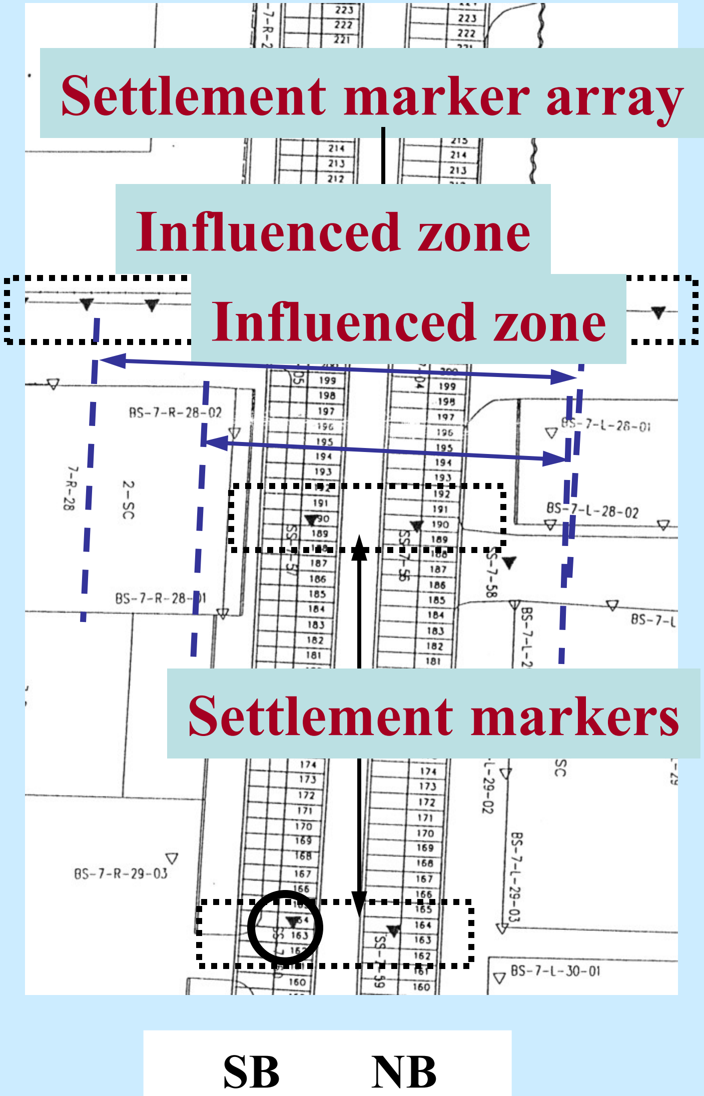
Shield Tunnelling : Soft Ground Movements

Tunnelling in urban area





Classification of Tunnelling Techniques

TUNNELLING TECHNIQUES

NONE
- Roadheader
- Digger type
- Hard rock TBM
- Tunnel reaming machine

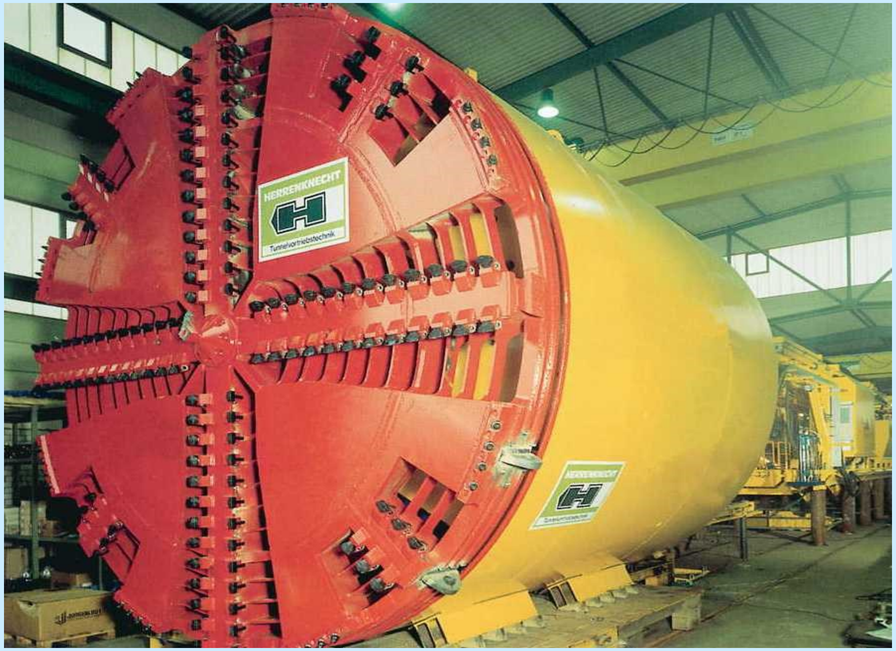
PERIPHERAL
- Gripper shield
- Segmental shield
- Double shield

PERIPHERAL AND FRONTAL
- Mechanical support
- Compressed-air shield
- Slurry shield
- EPB shield
- Mixed face shield

AFTES (2000)

Earth Pressure Balance Shields (EPBS)

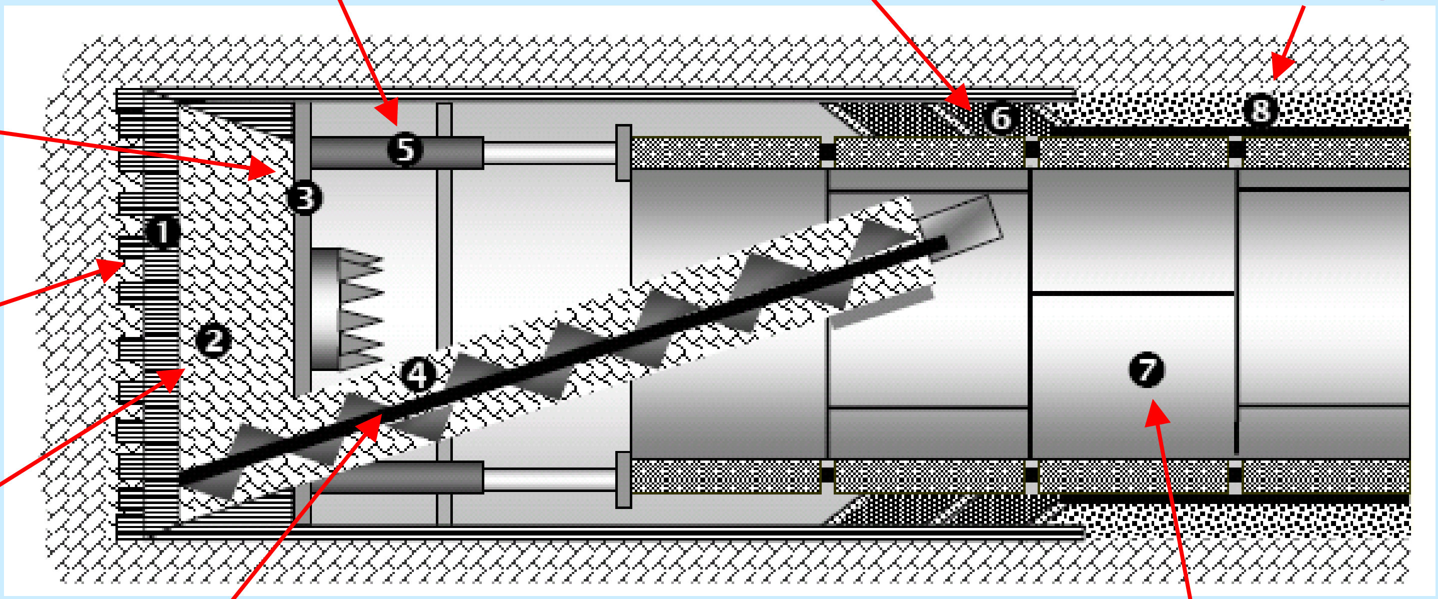
Bangkok MRT Project



Herrenknecht

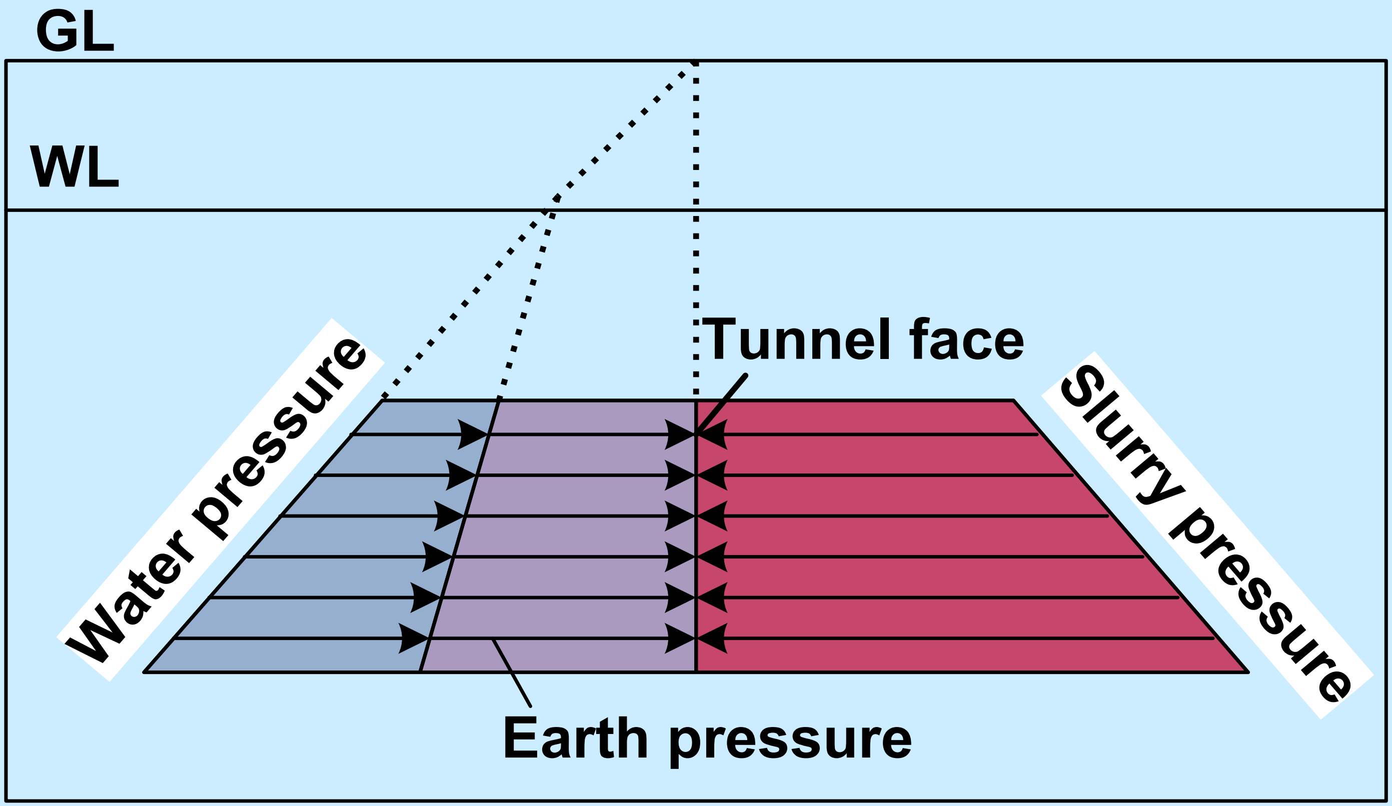
Kawasaki

EPBS

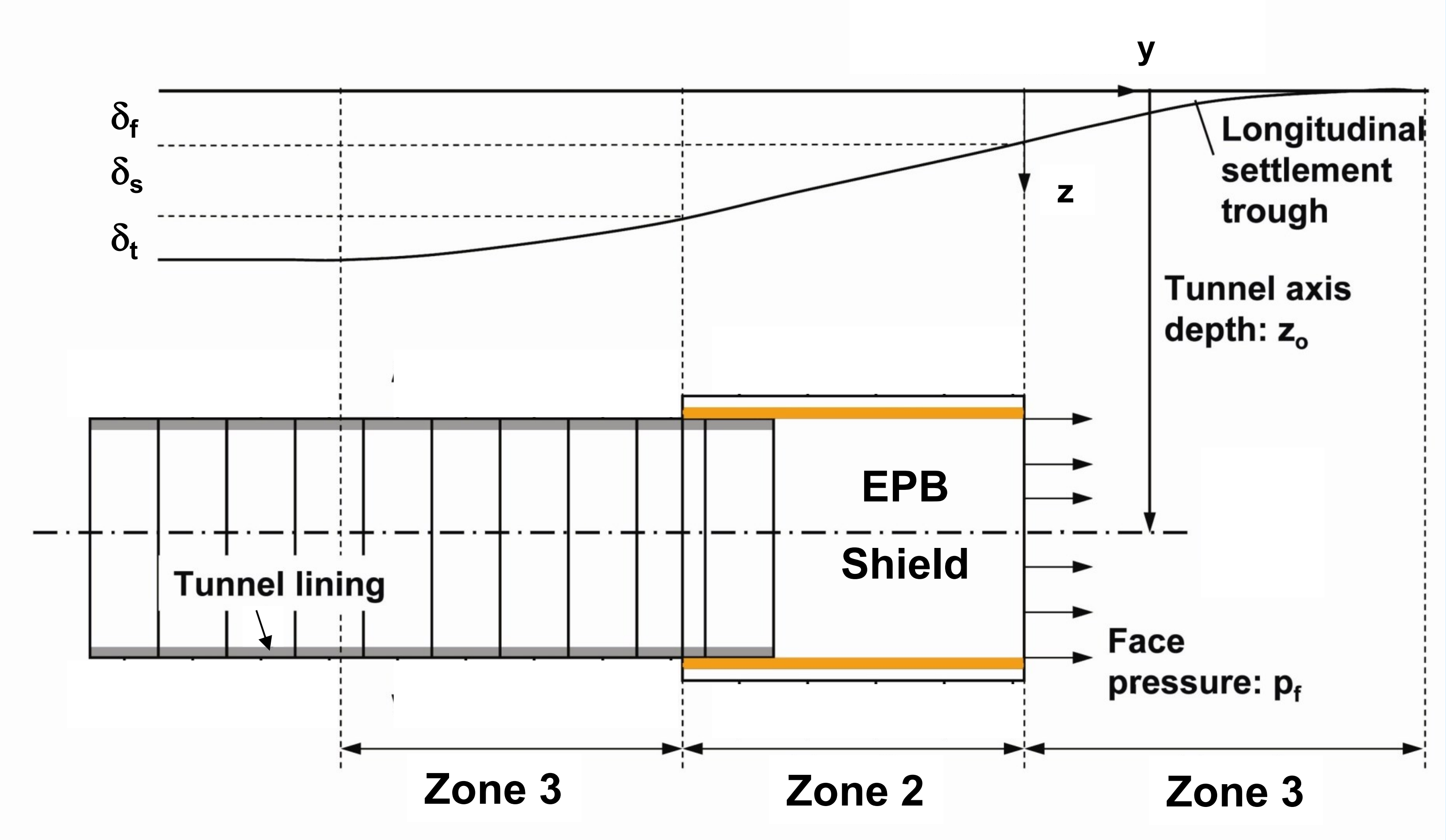


EFNARC (2005)

Earth Pressure Balance Technique



Settlement Components



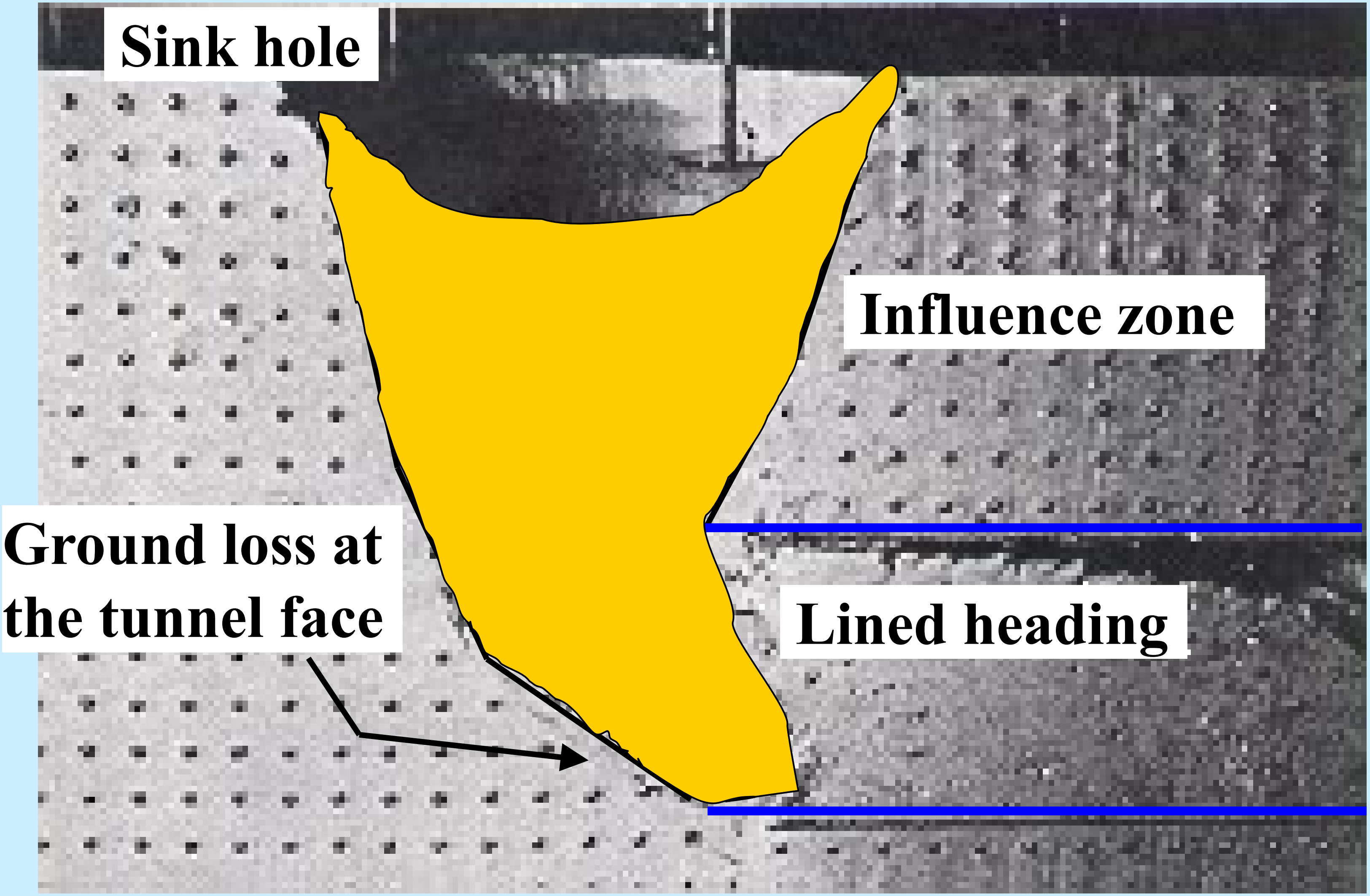
δ_f = Settlement due to face loss

δ_s = Settlement due to shield loss

δ_t = Settlement due to tail loss

Griffith UNIVERSITY

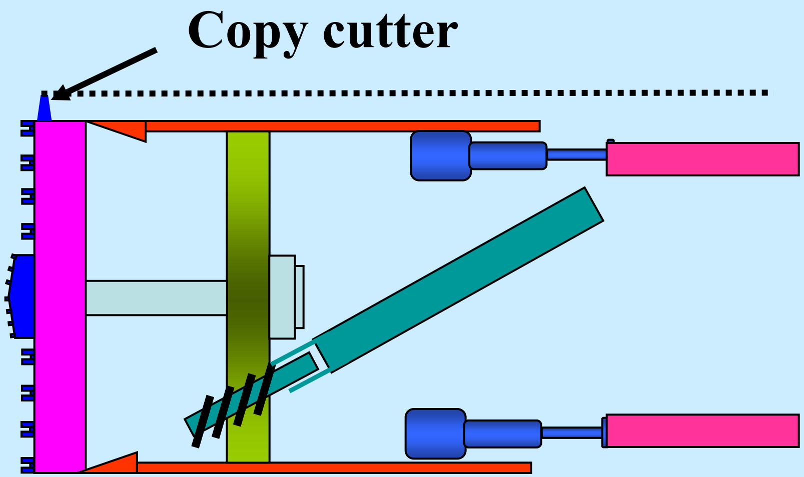
Face Loss



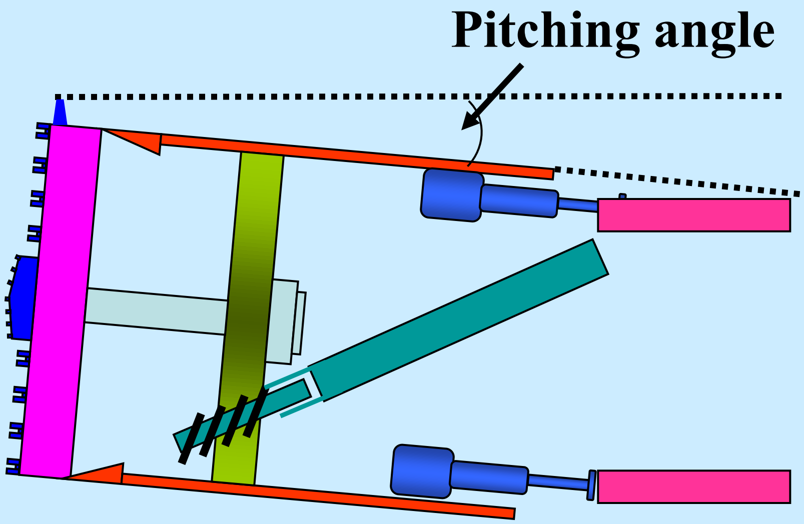
Centrifuge Test (Kimura and Mair, 1981)

Shield Loss

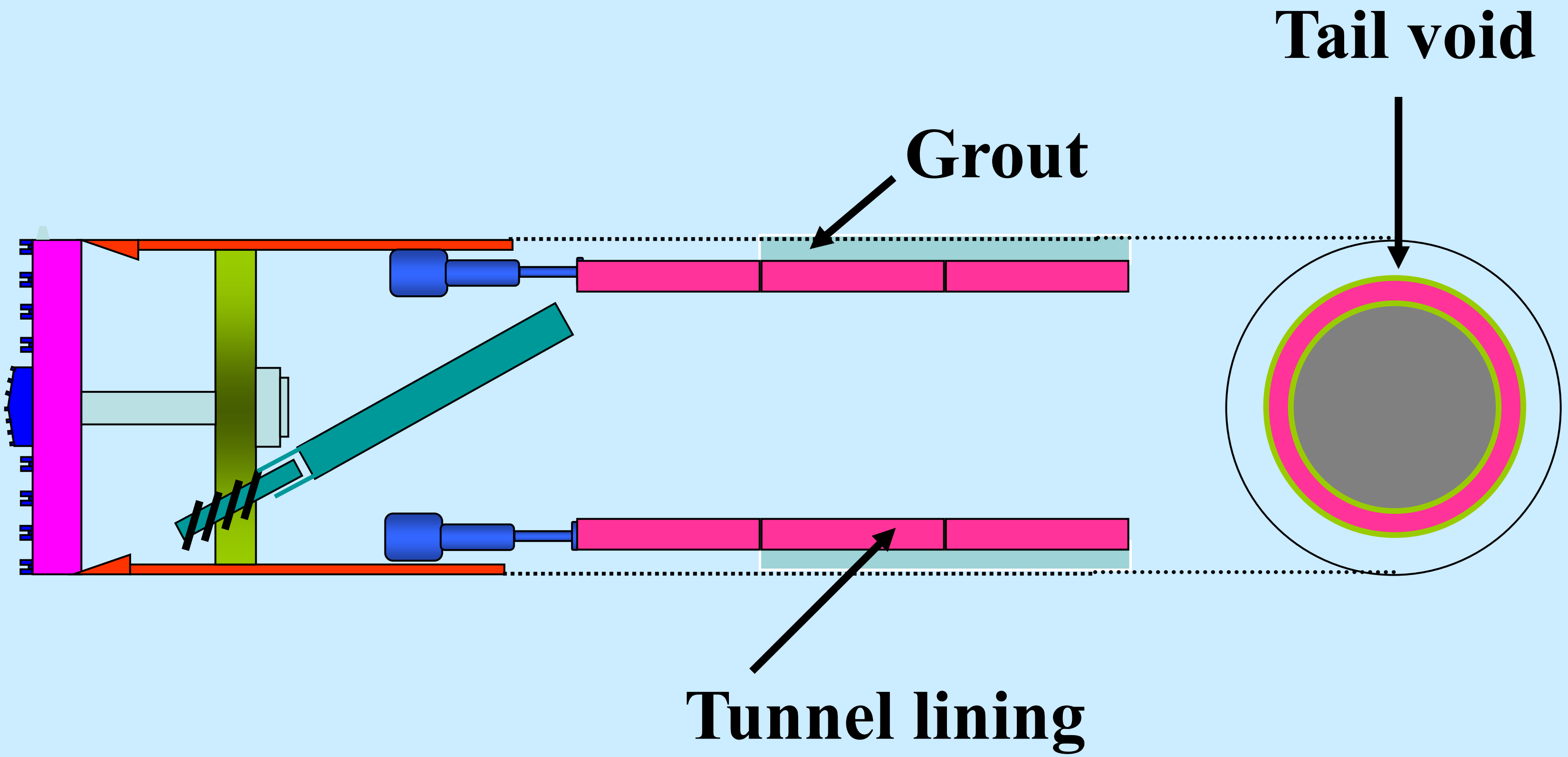
Over-cutting loss



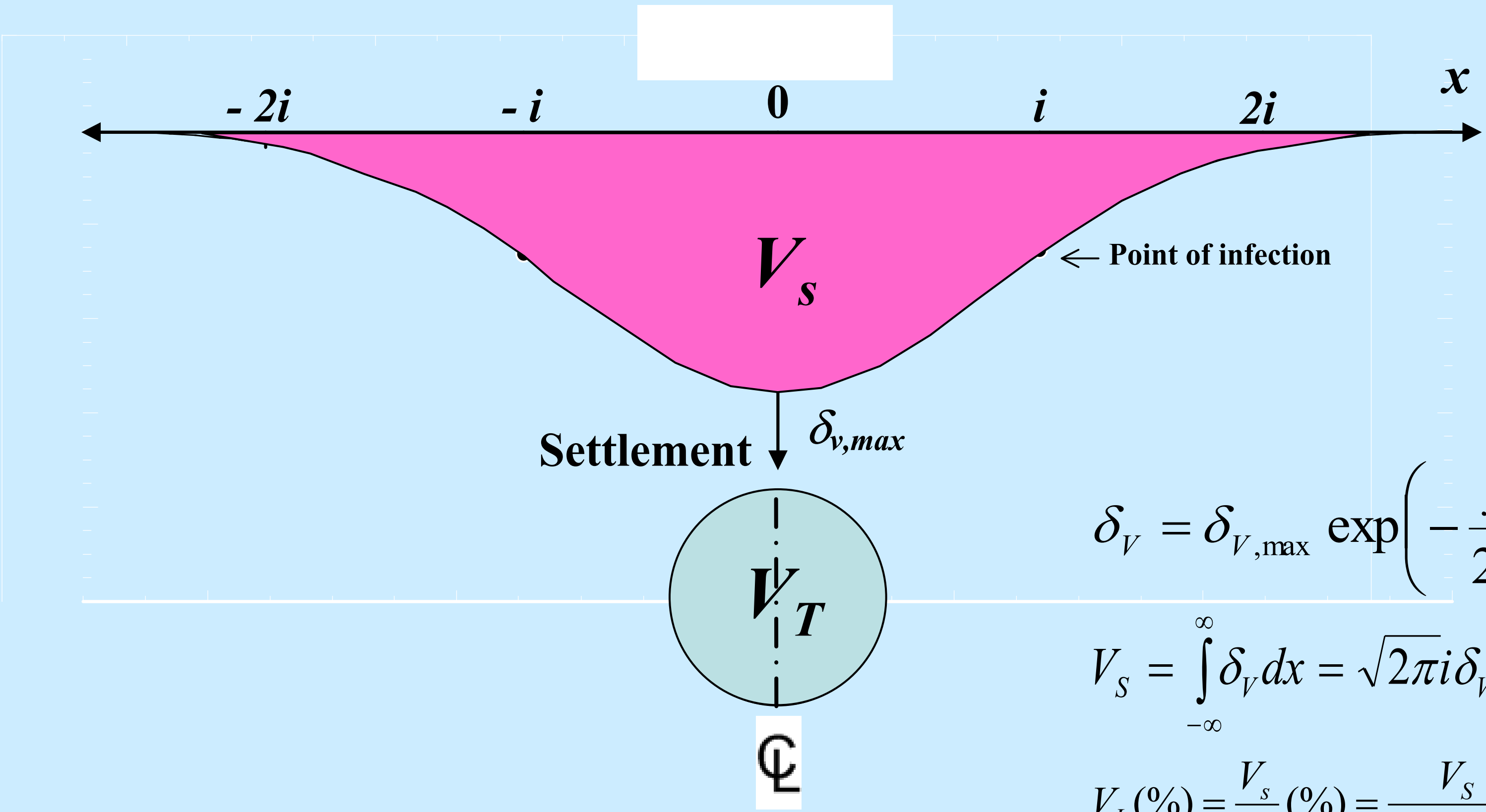
Pitching loss



Tail Loss



Empirical Method by Peck (1969)

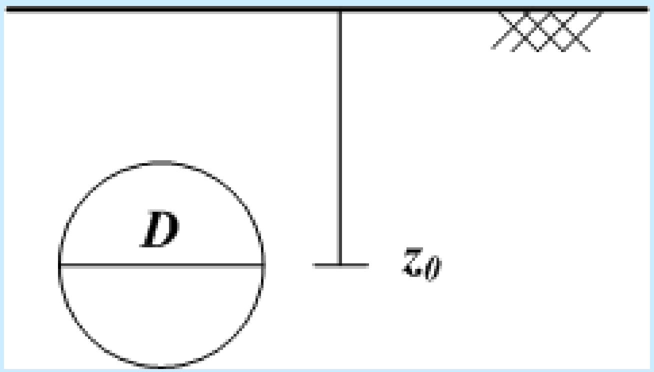


$$\delta_V = \delta_{V,\max} \exp\left(-\frac{x^2}{2i^2}\right)$$

$$V_S = \int_{-\infty}^{\infty} \delta_V dx = \sqrt{2\pi} i \delta_{V,\max} \approx 2.5 i \delta_{V,\max}$$

$$V_L(\%) = \frac{V_s}{V_T}(\%) = \frac{V_S}{0.25\pi D^2} \times 100$$

Parameter (*i*) for Surface Settlement



Attkinson & Potts (1997)

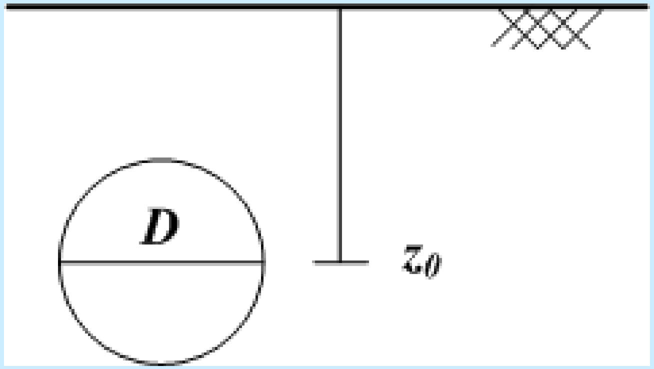
$$i = 0.25(z_0 + 0.5D)$$ (for loose sand)

$$i = 0.25(1.5z_0 + 0.25D)$$ (for dense sand)

Clough & Schmidt (1981)

$$i = \left(\frac{D}{2}\right) \cdot \left(\frac{z_0}{D}\right)^{0.8}$$ (for tunnelling in soft ground)

Parameter (*i*) for Surface Settlement



O'Reilly & New(1982)

$$i = K \cdot z_0$$

(K = 0.4 to 0.7 for stiff clay)

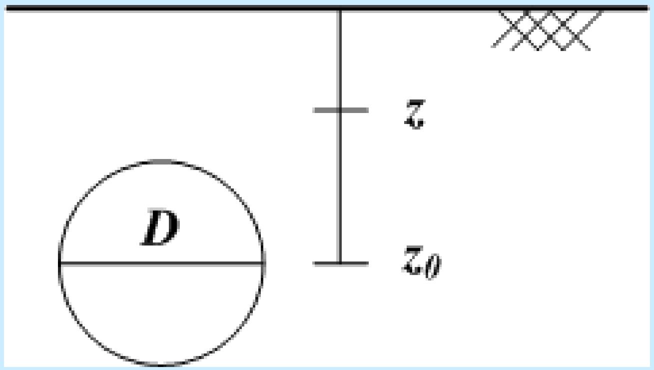
(K = 0.2 to 0.3 for sand)

Logangthan & Poulos (1998)

$$\frac{i}{D} = 0.575\left(\frac{z_0}{D}\right)^{0.9}$$

(for saturated clay)

Parameter (*i*) for Subsurface Settlement



O'Reilly & New(1982)

$$i = K \cdot (z_0 - z)$$

($K = 0.4$ to 0.7 for stiff clay)

($K = 0.2$ to 0.3 for sand)

Mair et al. (1993)

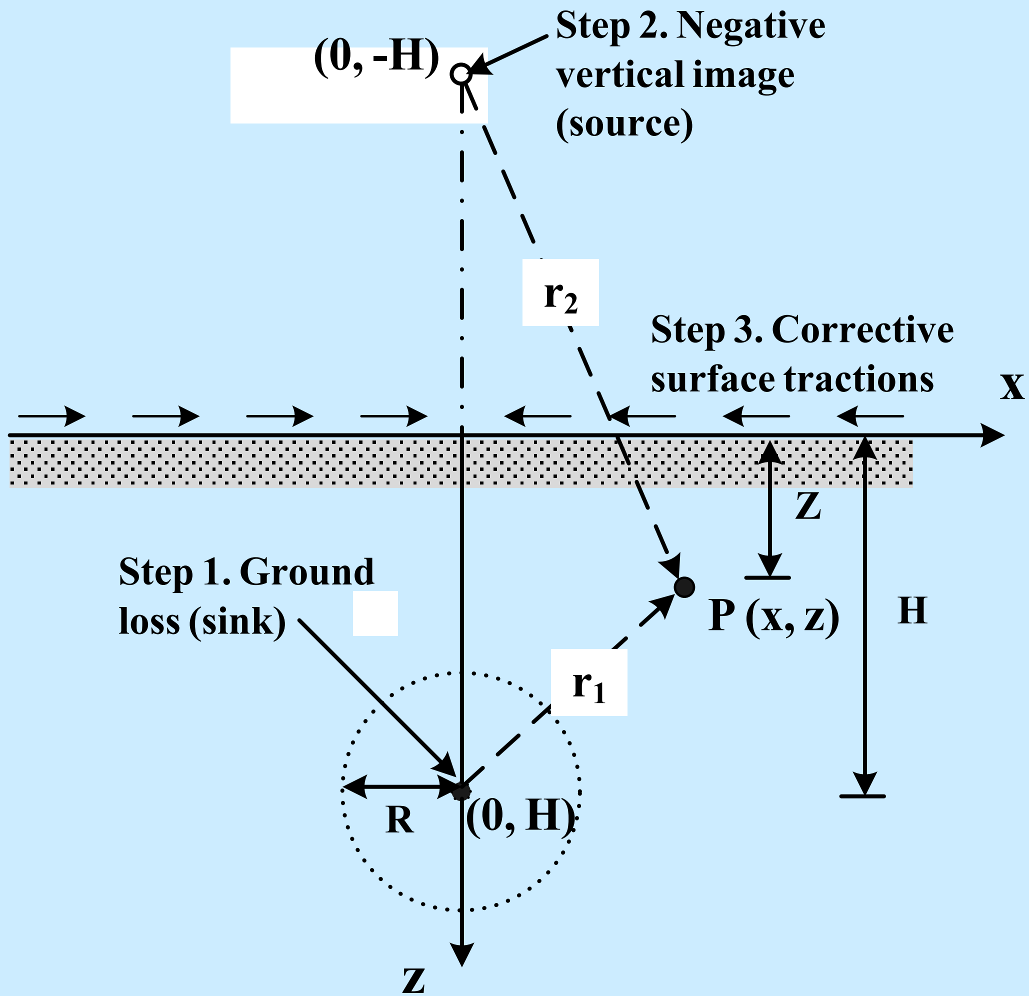
$$i = \frac{0.175 + 0.325\left(1 - \frac{z_0}{z}\right)}{\left(1 - \frac{z_0}{z}\right)} \cdot z_0$$

(for clay)

Analytical Methods in Analysis

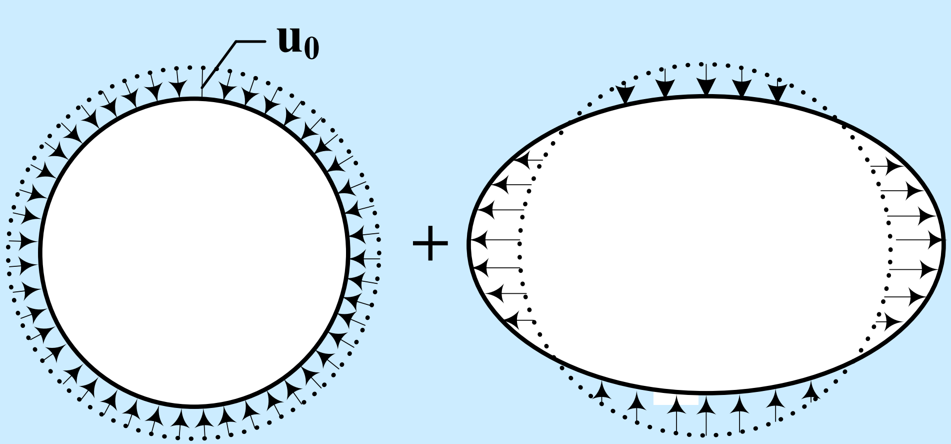
Methods	Sagaseta (1987)	Verruijt & Booker (1996)	Loganathan & Poulos (1998)	Bobet (2001)
Theory	Basic solution			Elasticity
Ground condition	Isotropic-homogeneous-elastic-weightless			Isotropic-homogeneous-elastic
Tunnel condition	Circular			Circular $h/r > 1.5$
Ground property	None	ν	ν	E, ν, γ, K
Liner property	N/A	N/A	N/A	E_s, n_s
Ground loss	Uniform	Uniform	Specified	Uniform

Analytical Method by Sagaseta (1987)



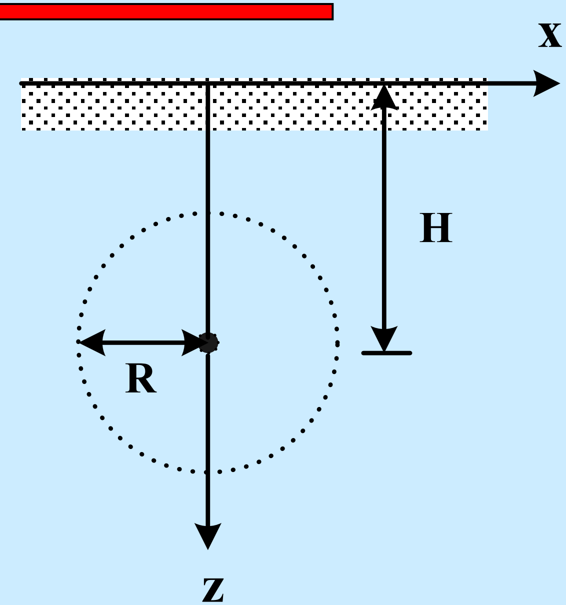
Analytical Method by Verrujit & Booker (1996)

Uniform Radial Ground Loss | **Tunnel Ovalisation**



(a) **(b)**

Short term **Long term**

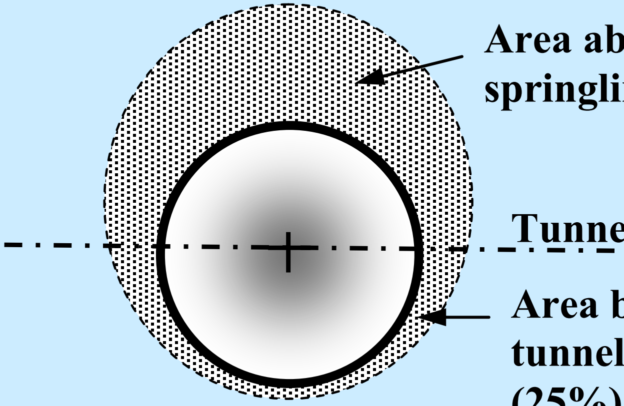


$$u_{z=0} = 2\varepsilon_o R^2 \frac{H}{x^2 + H^2}$$

$$\varepsilon_o = \frac{u_0}{R}$$ **(Ground loss parameter)**

Analytical Method by Loganathan & Poulos (1998)

Oval-Shape Ground Loss



$$\varepsilon_0 = \frac{4gR + g^2}{4R^2}$$

where,

R **= Radius of the tunnel**

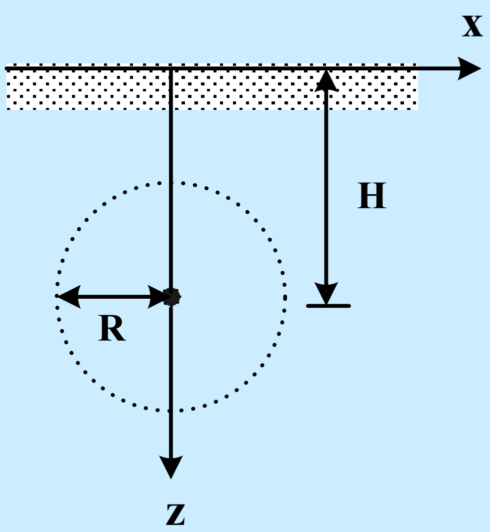
g **= Gap parameter (Lee et.al., 1992)**

Short term

Analytical Method by Loganathan & Poulos (1998)

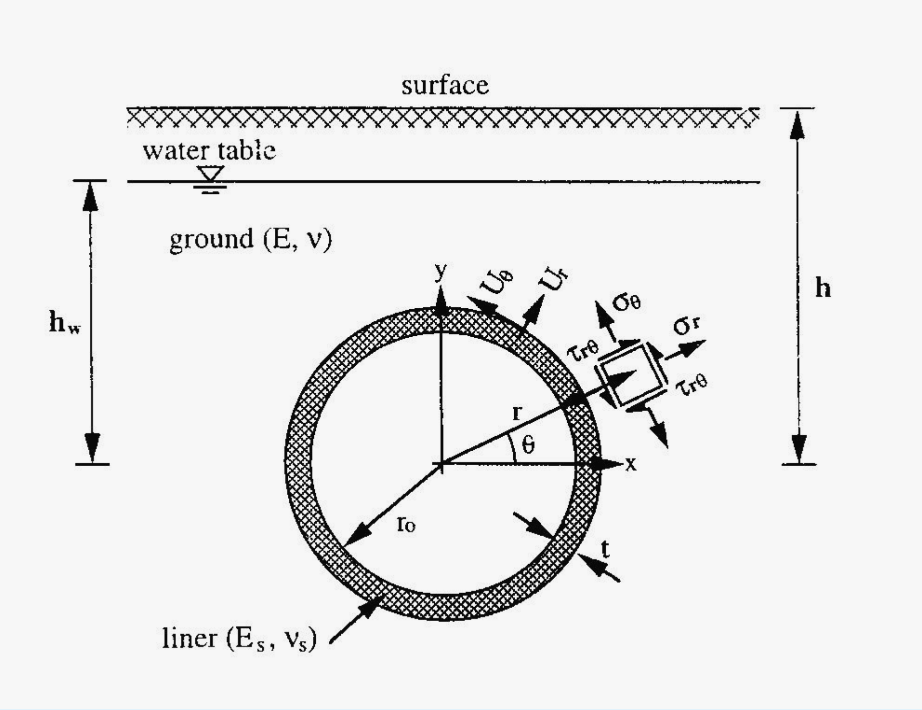
For surface settlement

$$u_{z=0} = 4(1-\nu)R^2 \frac{H}{\left(H^2+x^2\right)} \frac{4gR+g^2}{R^2} \exp\left[-\frac{1.38x^2}{(H+R)^2}\right]$$



where,
g **= Gap parameter (Lee et.al., 1992)**
ν = Poisson's ratio

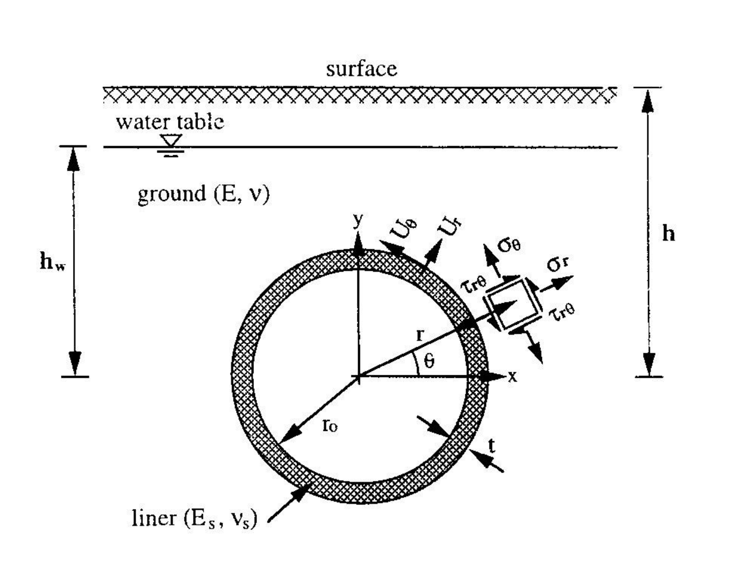
Analytical Method by Bobet (2001)



$$u_r = -\left[\frac{u_o R}{r} + \frac{0.75\gamma R^2}{E_u}\ln r \sin\theta\right]$$

$$u_\theta = -\frac{0.75\gamma R^2}{E_u}\left(1 + \ln r\right)\cos\theta$$

Bobet (2001)



$$u_r = \frac{1+\nu}{E}\left\{-\frac{a_0}{r} + \left[\frac{c'_1}{r^2} + \frac{1}{2}c_1 \ln r\right]\sin\theta + \left[2\frac{a'_2}{r^3} + a\frac{b'_2}{r}\right]\cos 2\theta + \left[3\frac{c'_3}{r^4} + 3\frac{d'_3}{r^2}\right]\sin 3\theta\right\}$$

$$u_\theta = \frac{1+\nu}{E}\left\{-\left[\frac{c'_1}{r^2} + \frac{1}{2}c_1(1+\ln r)\right]\cos\theta + 2\frac{a'_2}{r^3}\sin 2\theta - \left[3\frac{c'_3}{r^4} + 3\frac{d'_3}{r^2}\right]\cos 3\theta\right\}$$

Bobet (2001)

Bobet (2001)

For very flexible and incompressible liner (F = C = 0)

$$u_r = -\left[\frac{u_o R}{r} + \frac{0.75\gamma R^2}{E_u}\ln r \sin\theta\right]$$

$$u_x = u_r \cos\theta - u_\theta \sin\theta = -\left[\frac{u_o R}{r}\cos\theta - \frac{0.75\gamma_t R^2}{E_u}\cos\theta\sin\theta\right]$$

$$u_\theta = -\frac{0.75\gamma R^2}{E_u}\left(1 + \ln r\right)\cos\theta$$

$$u_z = u_r \sin\theta + u_\theta \cos\theta = -\left[\frac{u_o R}{r}\sin\theta + \frac{0.75\gamma_t R^2}{E_u}\left(\ln r + \cos^2\theta\right)\right]$$

where,
u_o = Uniform radial soil deformation
r = Radial distance from the center of the tunnel
γ = Unit weight of ground
E_u = Undrained Young's modulus

Bobet (2001)

Summary of 2D Numerical Analysis

Author(s)	Project	Material	Soil Model	Method of Tunnelling	D (m)	Z_0 (m)	K_0	Program
Rowe et al. (1983)	Thunder Bay sewer tunnel	Isotropic/cross anisotropic	Linear elasto-plastic	EPB shield	2.38	10.5	0.6	EPTUN
Finno and Clough (1985)	N-2 tunnelling project	Isotropic	Modified Cam-Clay	EPB shield	2.9*	11.5*	-	-
Addenbrooke et al. (1997)	Jubilee Line Extension project	Isotropic/ anisotropic	Linear/non-linear elastic perfectly plastic	EPB shield	4.75	10/35	1.5	ICFEP
Karakus and Fowell (2003)	Heathrow Express Trial tunnels	Isotropic	Modified Cam-Clay	NATM	7.9 (h) 9.2 (w)	25	1.15	ABAQUS
Karakus and Fowell (2005)	Heathrow Express Trial tunnels	Isotropic	linear elastic perfectly plastic	NATM	7.9 (h) 9.2 (w)	25	1.15	FLAC

Summary of 3D Numerical Analysis

Author(s)	Material	Method of Tunnelling	D (m)	Z_0 (m)	K_0	Mesh or Grid		Tunnel		Program
						Width (m)	Length (m)	Length (m)	L_{exc} (m)	
Katzenbach and Breth (1981)	Non-linear elastic	NATM	6.7	15.2	0.8	35.0 5.2D	59.0 8.8D	n/a	Varies*	n./a
Desari et al. (1996)	Non-linera elastic perfectly plastic	NATM	8.0	25.0	1.0	40.0 5.0D	50.0 6.3D	40.0 5.0D	2.0*	CRISP
Tang et al. (2000)	Elastic perfectly plastic/Cros s-anisotropy	NATM	8.6	25.0	1.5	80.0 9.5D	95.0 11.1D	67.5* 7.8D	5.0, 10.0	Abaqus
Vermeer et al. (2002)	Elastic perfectly plastic	NATM	8.0	2.0	0.66	55.0 6.9D	100.0 12.5D	80.0 10D	2.0	Plaxis
Lee and Rowe (1991)	Elastic Perfectly Plastic	EPB shield	2.5	8.0	0.85	19.5 7.8D	37.0 15D	20.0 8D	n/a (gap)	FEM3D

Bangkok MRT Projects

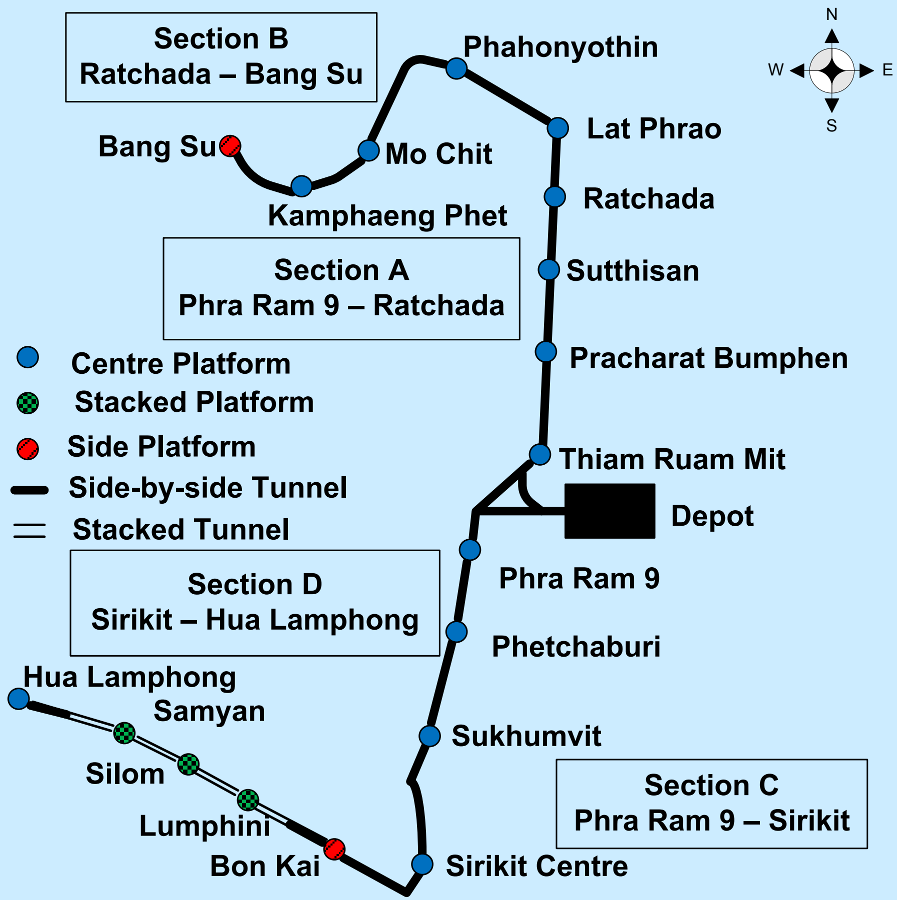
Bangkok MRT Blue Line project (completed route)

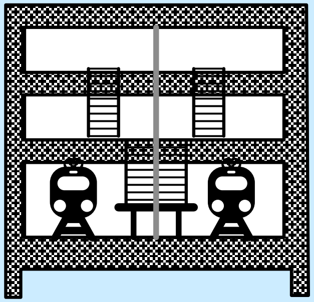
- 22 km of underground twin bored tunnel
- 18 Cut and Cover underground stations
- 6.3 m in outer diameter
- North and South tunnel sections

Bangkok MRT Blue Line Extension project (under design stage)

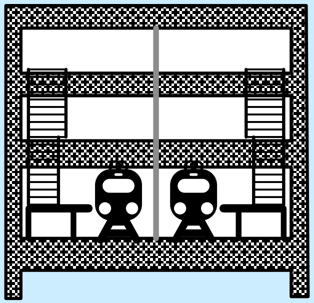
- 5 km of underground twin bored tunnel
- 4 underground stations (2 combined Cut and Cover and NATM, and 2 Cut and Cover stations)

Bangkok MRT Blue Line Project

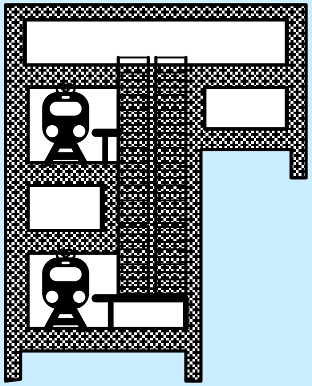




Centre Platform



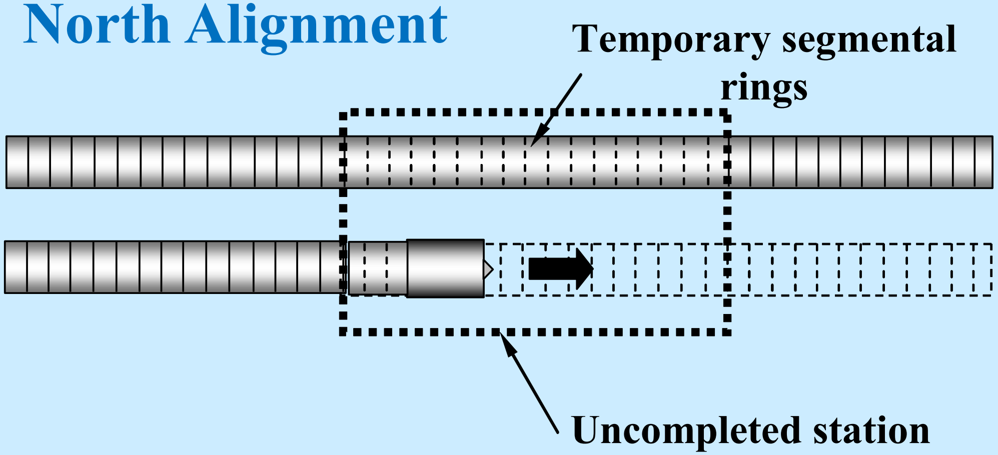
Side Platform



Stacked Platform

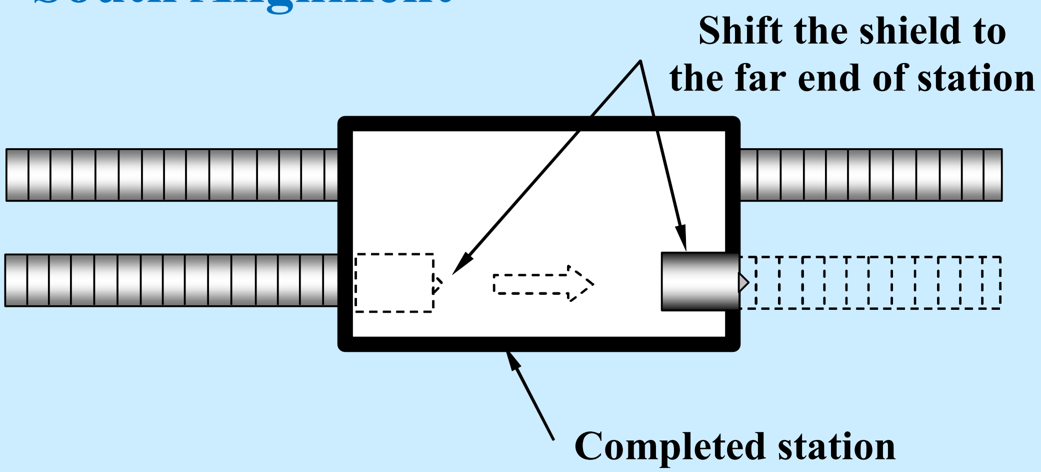
Construction Methods of Underground Stations

North Alignment



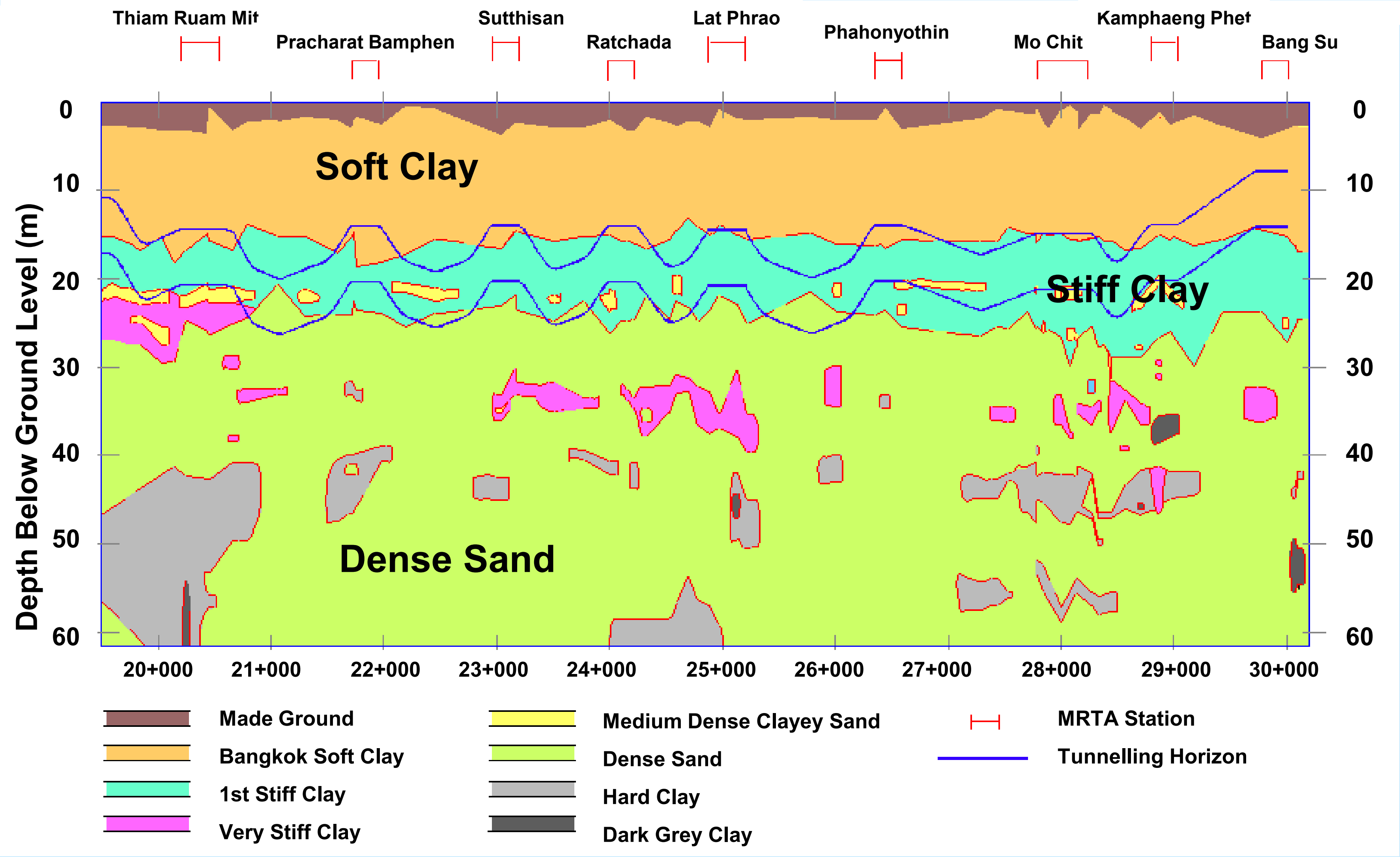
Tunnel constructed through the uncompleted station box

South Alignment

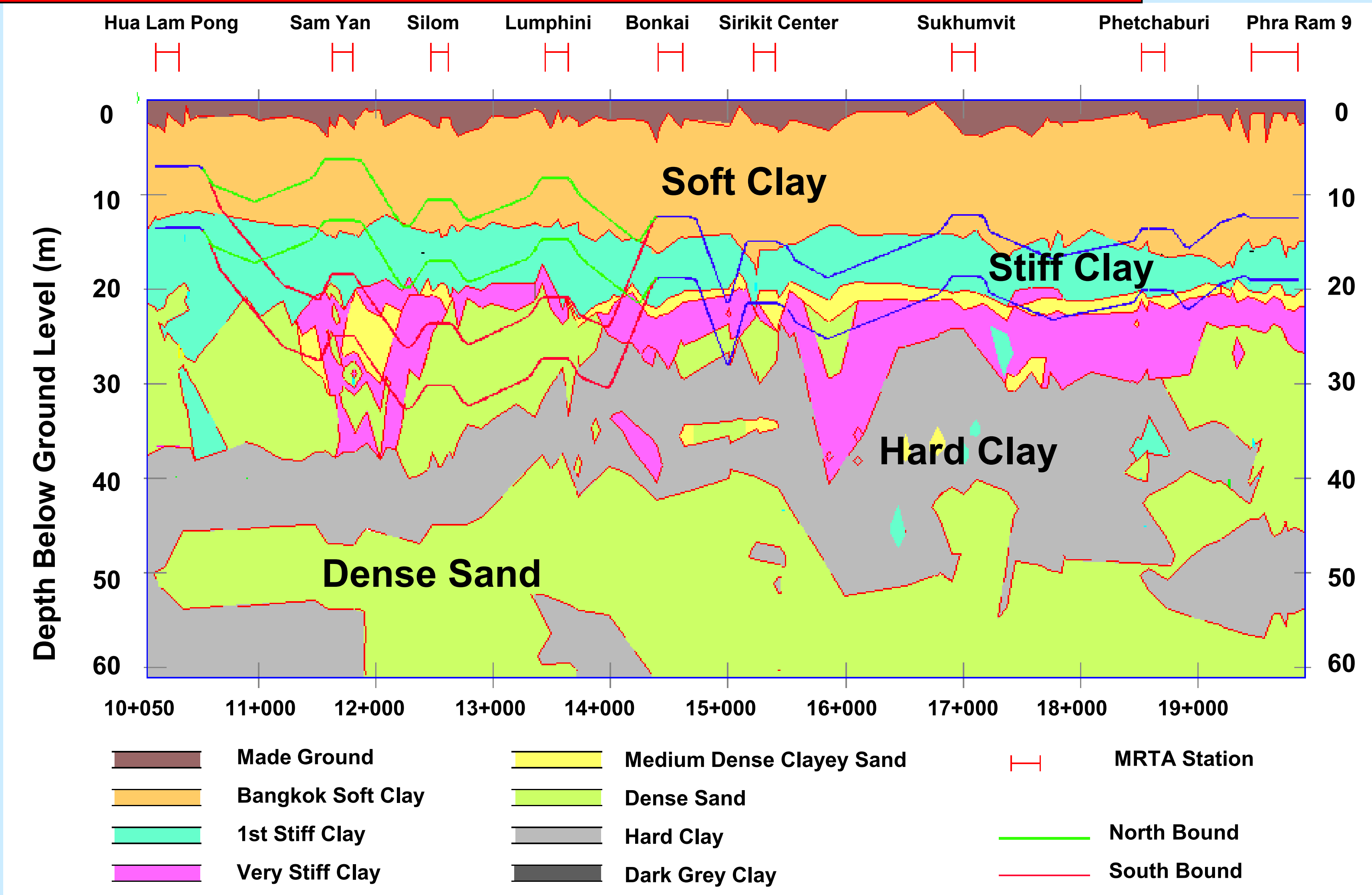


Station box constructed prior to tunnelling process

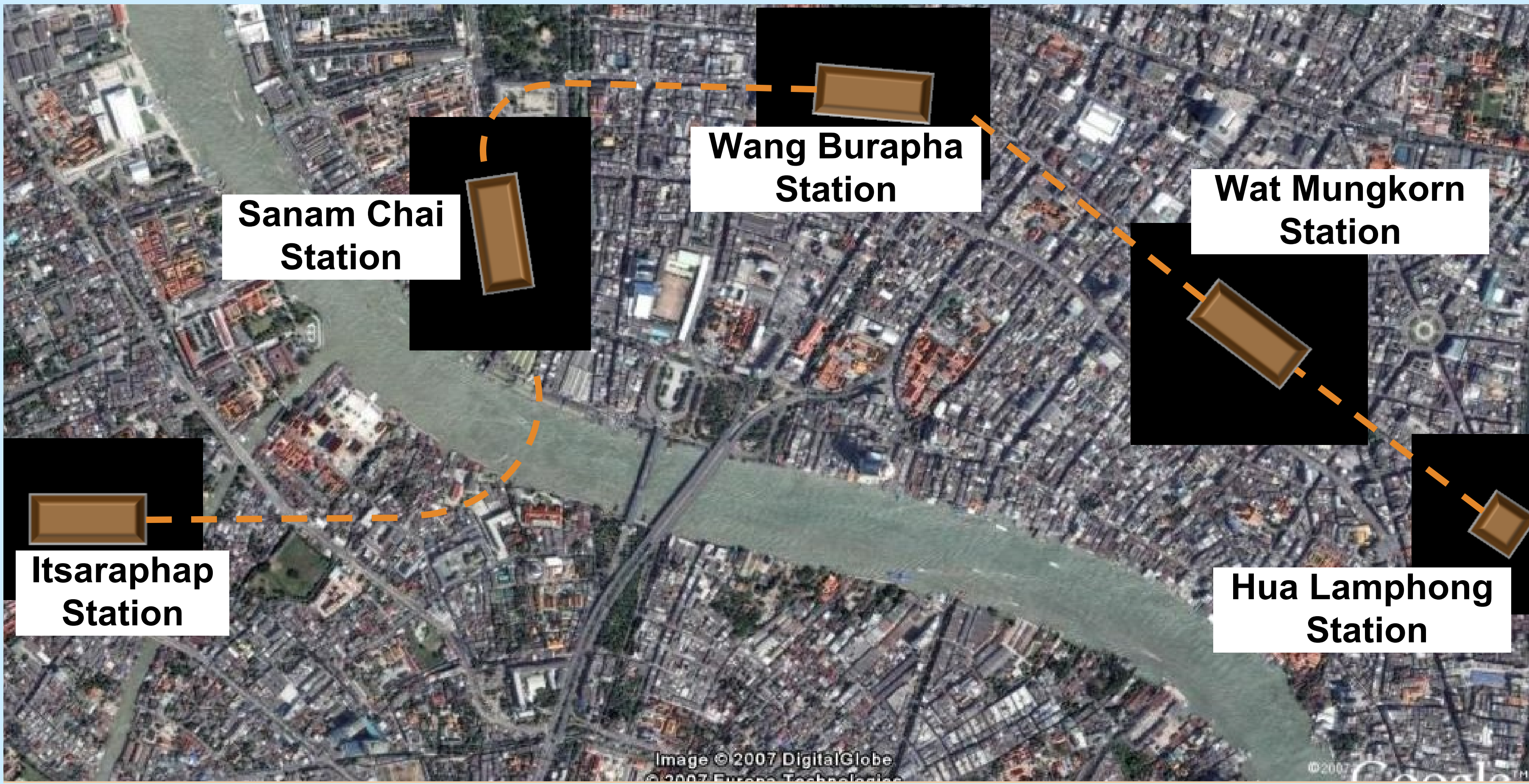
North Alignment Subsoil Condition



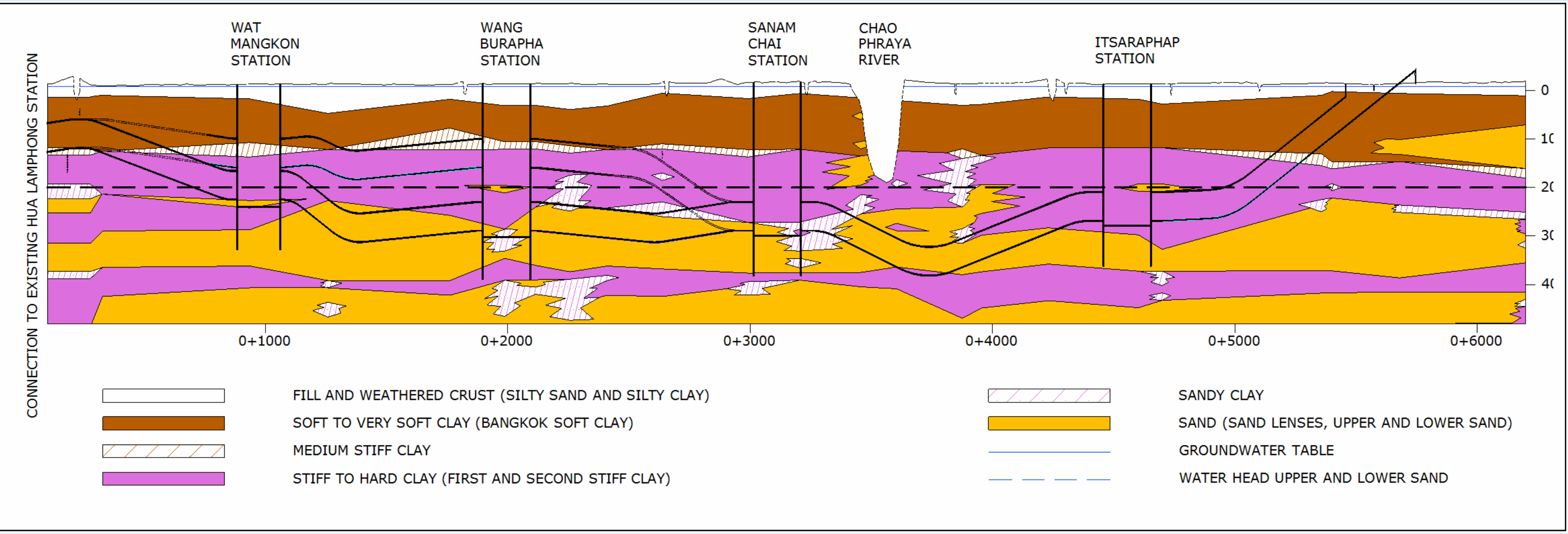
South Alignment Subsoil Condition



Blue Line Extension Project



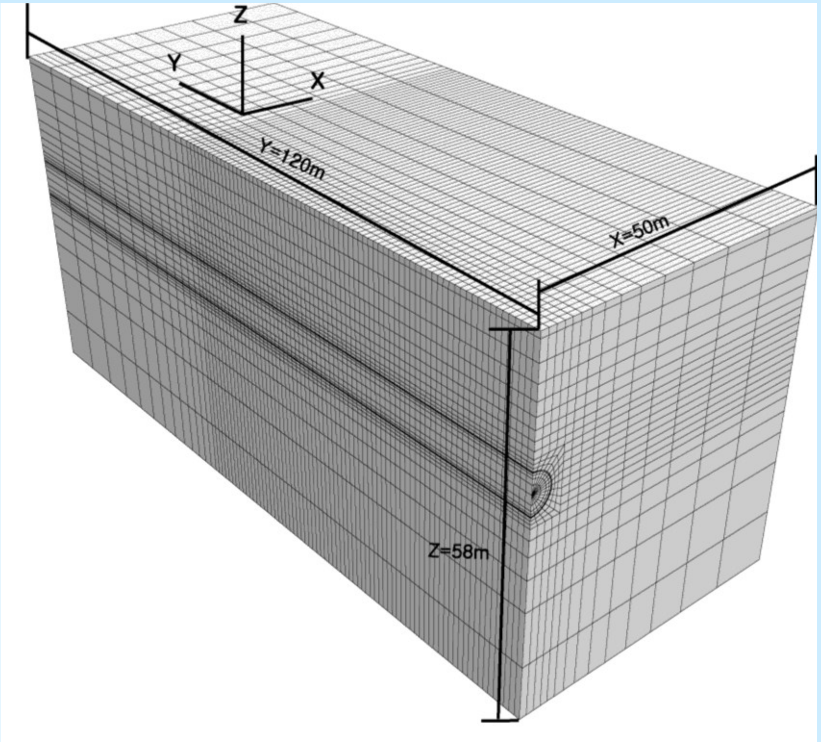
Blue Line Extension Subsoil Condition



2D Numerical Analysis

Author	Main Findings
Chanchaya (2000) *(Plaxis 2D)*	▪Back calculation using 2D FE analysis has been conducted. ▪The parameters Eu/Su from back calculations suitable for soft and first stiff Bangkok clays layers are 240 and 480, respectively and these values are comparable to the pressuremeter test results from Teparaksa (1999)
Timpong (2002) *(Flac 2D)*	▪Reasonable agreement between 2D FD analysis and field observations can be obtained if an appropriated ground loss expressed in percent relaxation is adopted. ▪The values of percent relaxation are ranging from 30 to 80 percent.
Du (2003) *(Plaxis 2D)*	▪Plaxis interface element is used to simulate the redial contraction between the shield and surrounding soil. ▪The reduction factor (R) for interface element property varies from 0.5-0.9 with the average of 0.7.
Tavaranum (2004) *(Plaxis 2D)*	▪Back calculated percentage ground loss from Plaxis analysis and analytical solution by Loganathan and Poulos (1998) are compared. ▪Generally, good agreements are obtained from the two method with the values varying from 0.3-2.9%

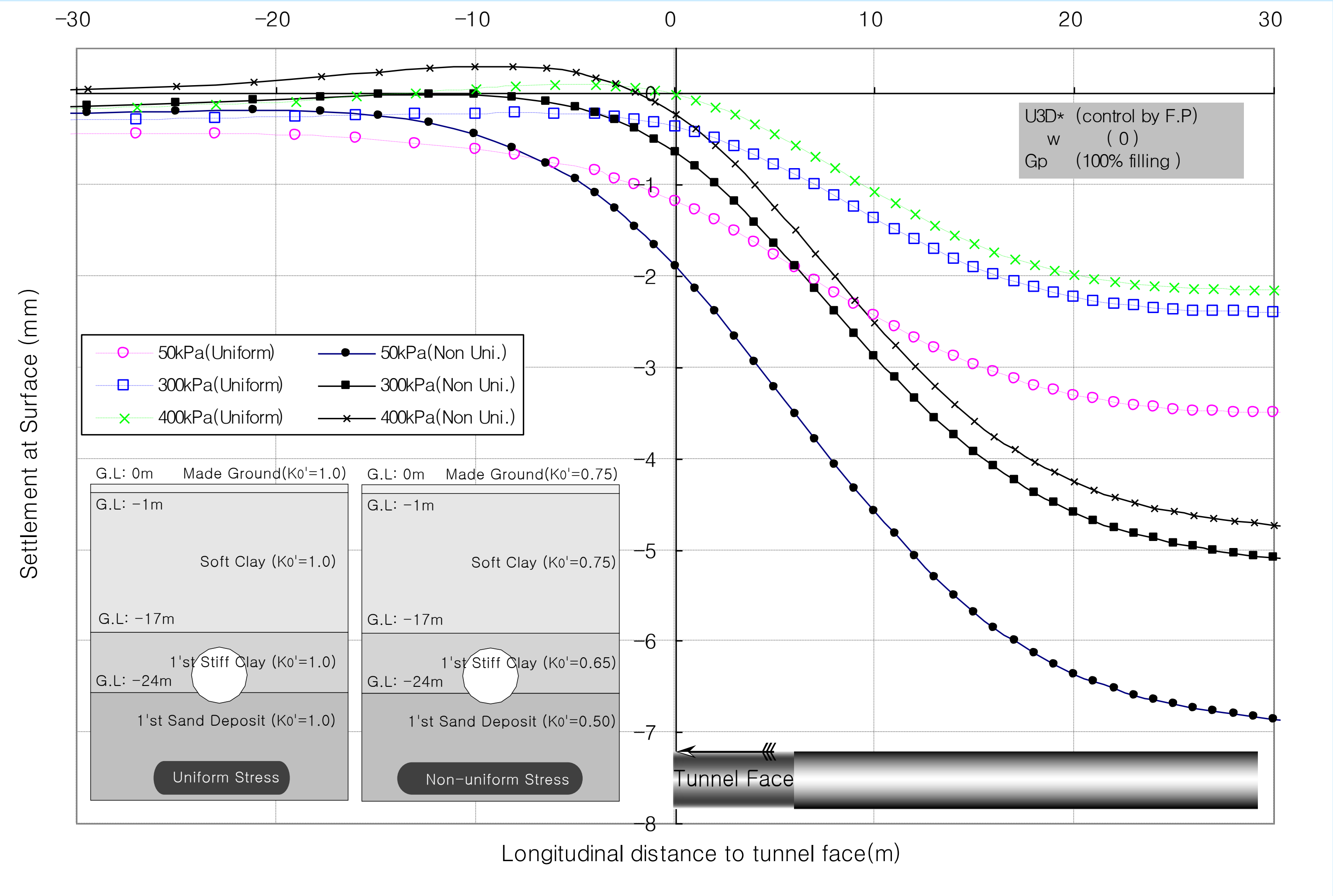
3D Numerical Analysis Literatures on Bangkok MRT Project



- FDA using FLAC 3D
- MC model was adopted
- Parametric study has been conducted on shield face pressure, effective coefficient of earth pressure at rest , soil types, initial ground pore pressure and soil strength parameters

Hong (2005); Phien-wej et al. (2006)

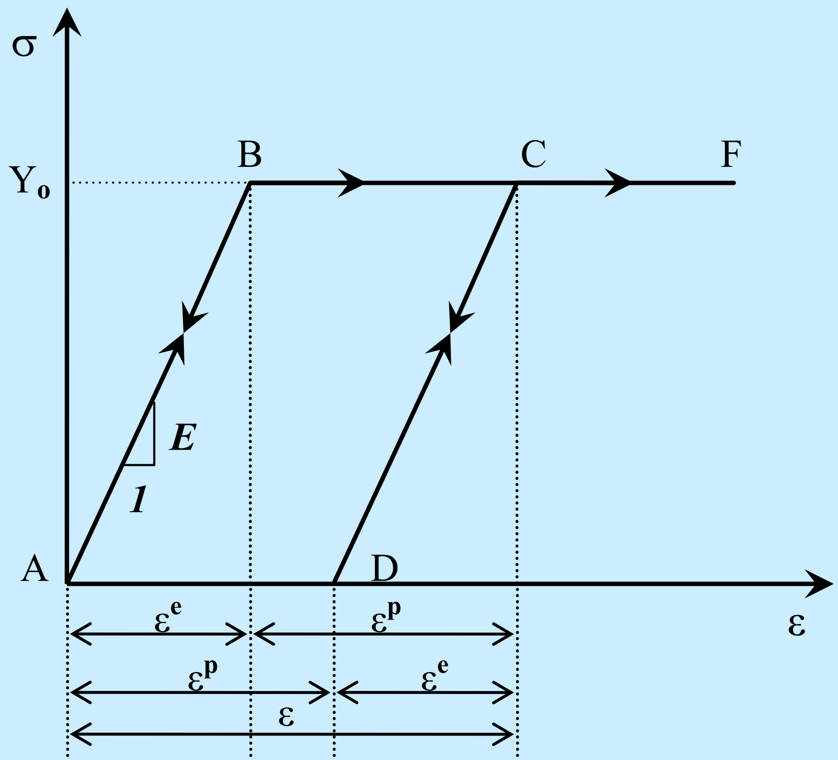
3D Numerical Analysis on Bangkok MRT Project



Soil Models

- Linear-elastic perfectly plastic Mohr-Coulomb (MC) soil model
- Non-linear elastroplastic Hardening Soil (HS) soil model

Mohr-Coulomb Soil Model



- Assume elastic behaviour in initial elastic range
- Perfectly plastic behaviour after yield point is reached
- Young's modulus (E) is governing both loading and unloading behaviours

Parameters for MC Model

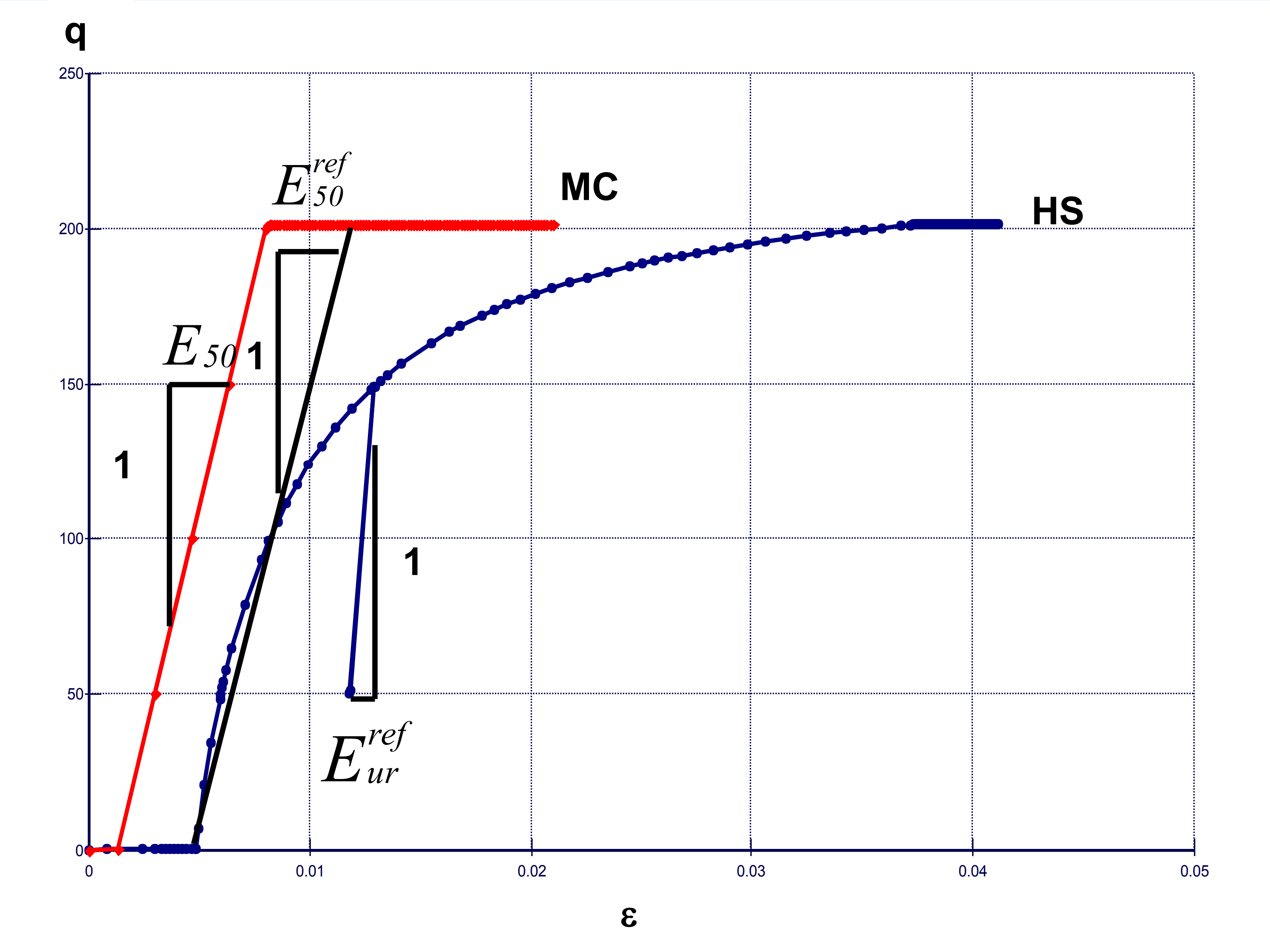
E	Young's modulus	[kN/m^2]
ν	Poisson's ratio	[-]
c'	(effective) cohesion	[kN/m^2]
φ'	(effective) friction angle	[º]
ψ	Dilatancy angle	[º]

Hardening Soil Model

Soil behaviour includes:

- Difference in behaviour for primary loading - reloading/unloading
- Nonlinear behaviour well below failure conditions
- Stress dependent stiffness
- Small strain stiffness (at very low strains and upon stress reversal)
- Influence of density on strength and stiffness

Hardening Soil Model



Parameters for HS Model

φ' friction angle
c' cohesion
ψ' dilatancy angle

E_{50}^{ref} **secant modulus from triaxial test** (controls deviatoric hardening)

E_{oed}^{ref} **tangential modulus from oedometer test**
(controls volumetric hardening)

E_{ur}^{ref} **unloading / reloading modulus**

m **power for stress dependency of stiffness**

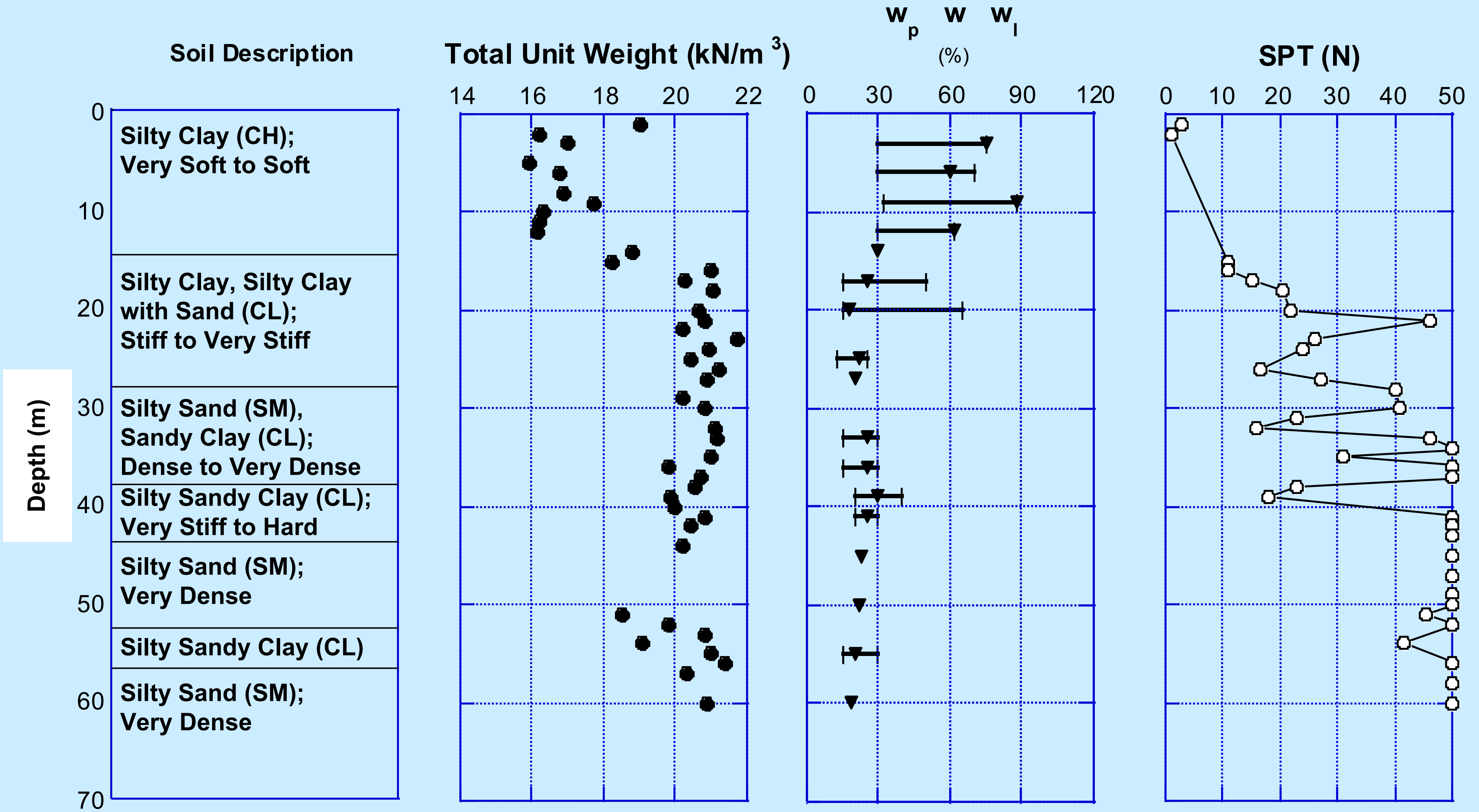
Parameters for HS Model

ν_{ur}	**Poisson ratio for unloading / reloading** (default ν_{ur} = 0.2)
p^{ref}	**reference stress** (default p^{ref} = 100 stress units)
K_0^{nc}	**K_0-value for normal consolidation** (default = 1-sinφ) (controls volumetric hardening)

Results

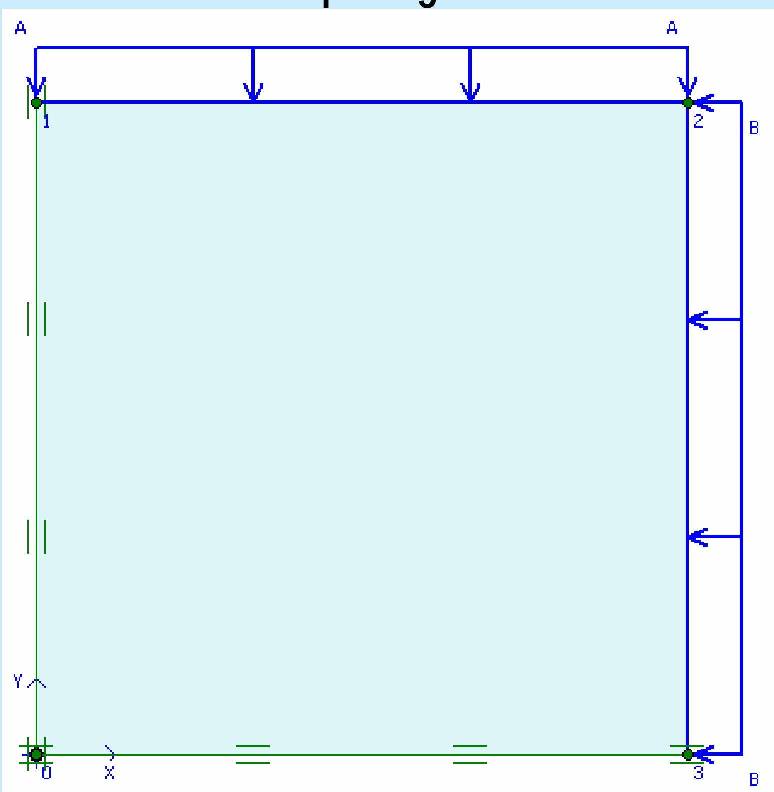
- Laboratory and field test data interpretations
- Predictions of ground movements by analytical methods
- Superposition technique to estimate volume loss
- Contraction method for 2D FE analysis

Laboratory and Field Test Data Interpretations



Unconsolidated Undrained Triaxial Test Back-Calculation

$\sigma_1 - \sigma_3$

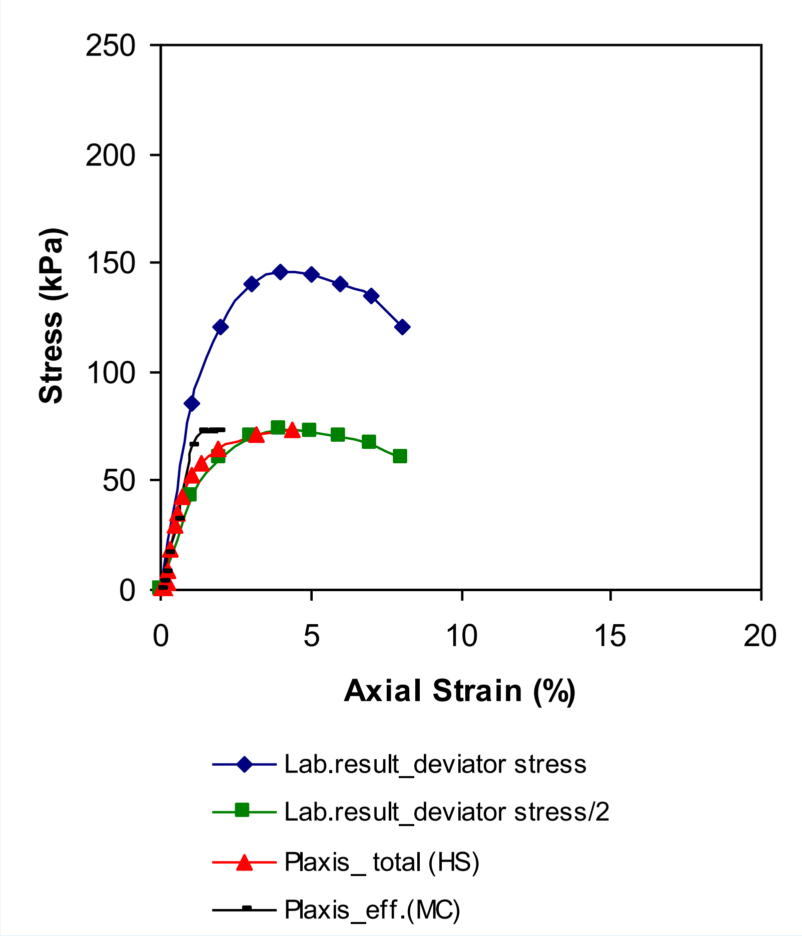


σ_3

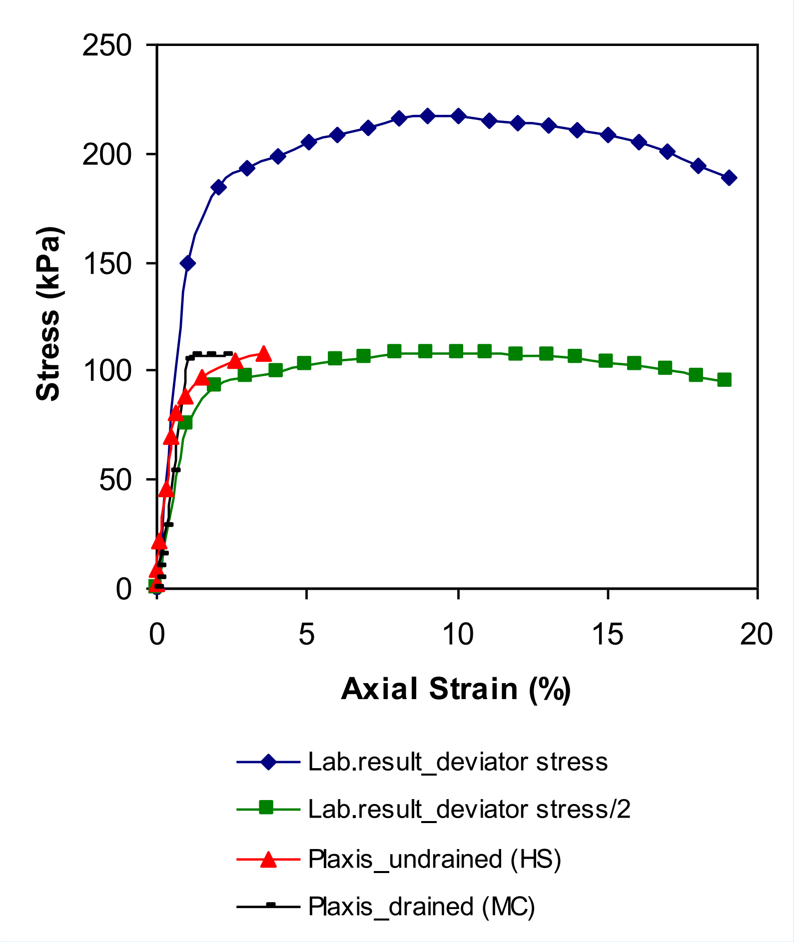
- Axisymetric model of 1x1 m
- HS model is adopted for back-caluating undrained parameters
- MC model is adopted for drained parameters

Typical Results from Back-Calculation

BS9/18 m



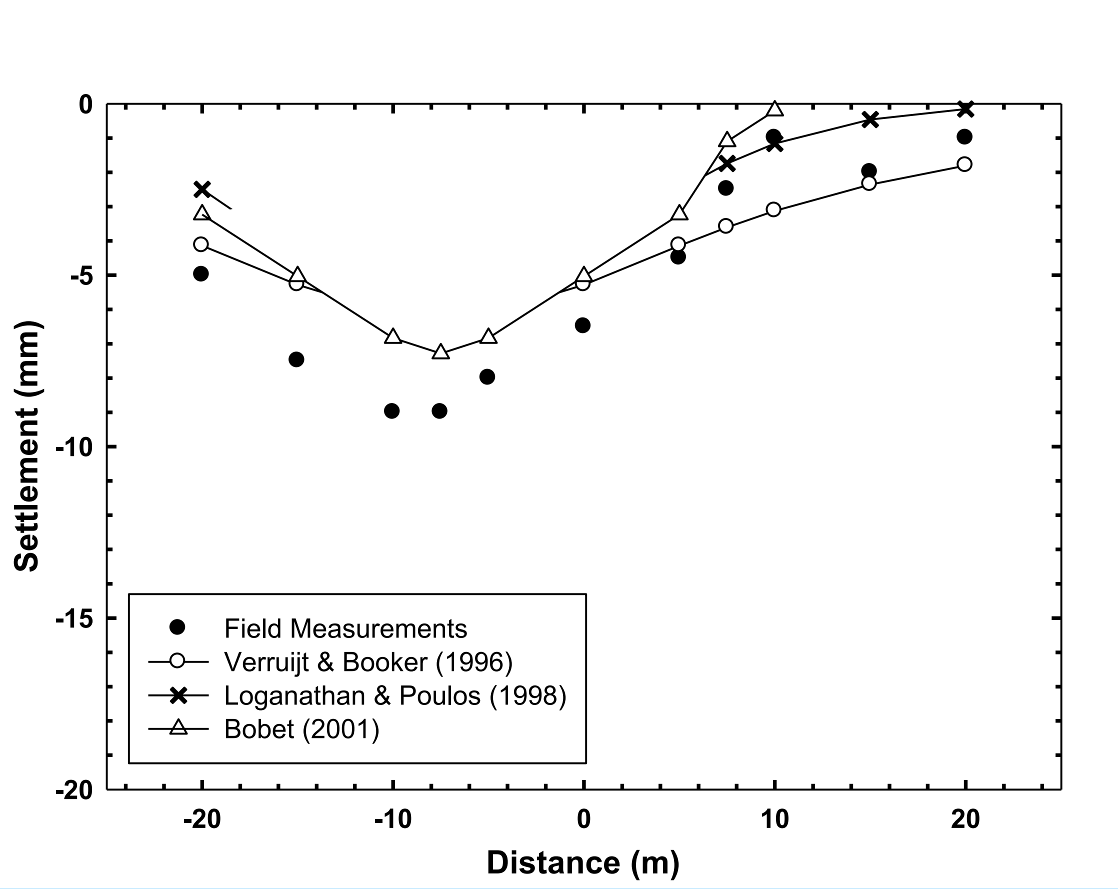
BS9/39 m



Typical Results from Back-Calculation

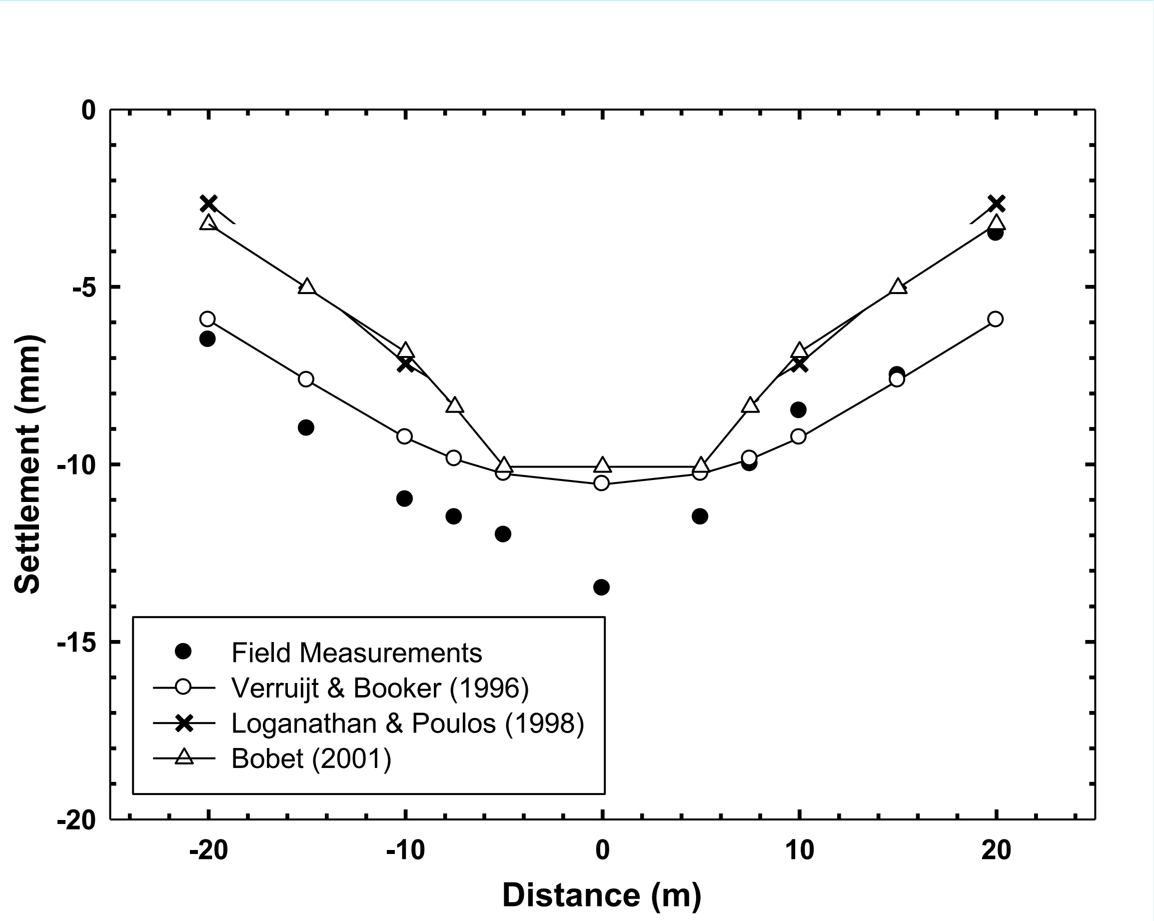
Bore Log	Depth (m)	HS Model Back-Calculation			MC Fitting Process		
		C_u (kPa)	E_{u50} (kPa)	E_{u50}/C_u	E'_{50} (kPa)	c' (kPa)	φ' (^{o})
BS-08.1	24.0	247.3	21000	85	15000	150	26
BS-08.2	37.5	1.8.1	21620	200	1700	65	23
BS-09.1	18.0	73.0	14600	200	12000	45	26
BS-09.2	39.0	109.0	21800	200	20000	71	23

Analytical Methods (Single Tunnel)



- *Verruijt & Booker (1996)*
- *Loganathan & Poulos (1998)*
- *Bobet (2001)*

Analytical Methods (Twin Tunnels)

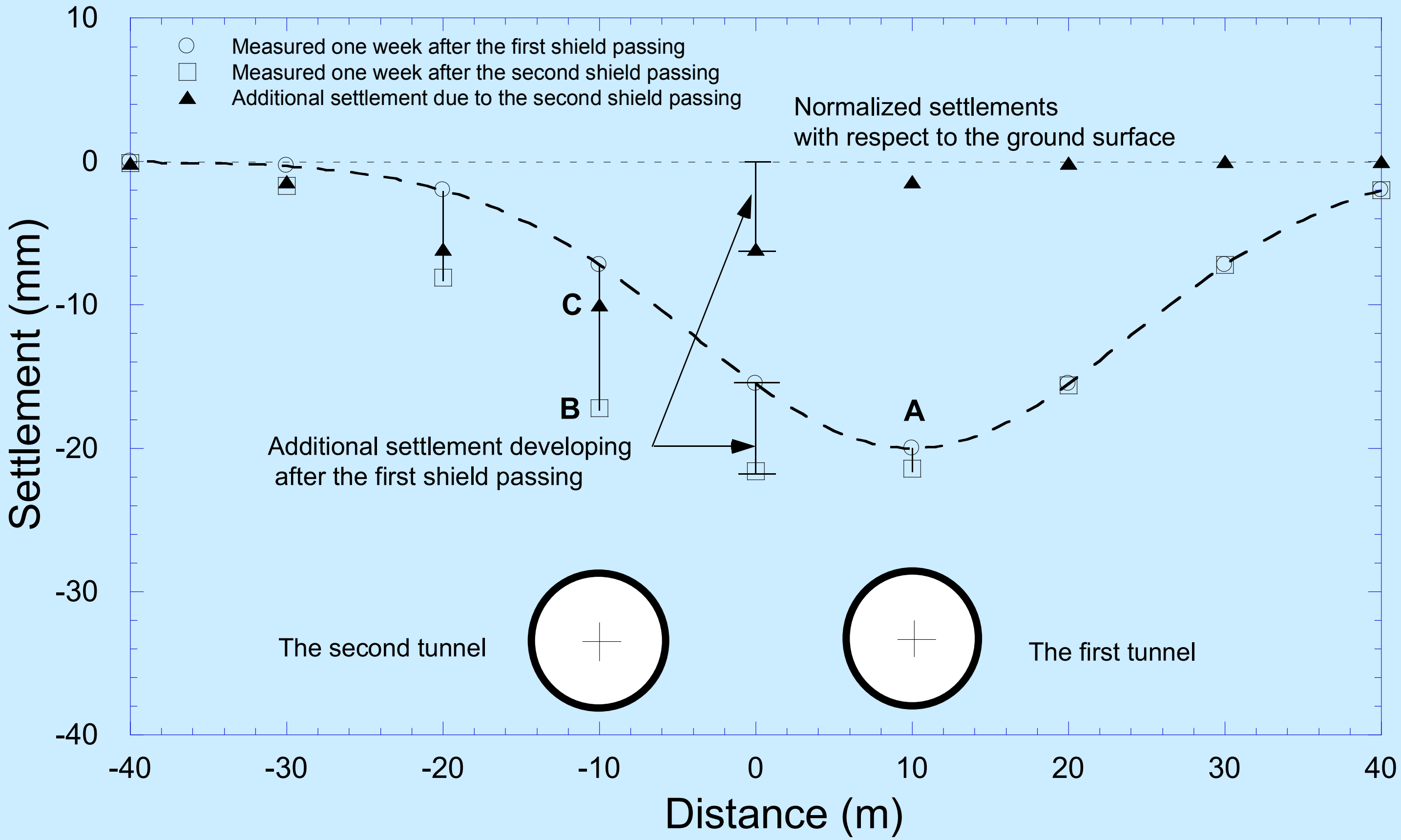


Verruijt & Booker (1996)

Loganathan & Poulos (1998)

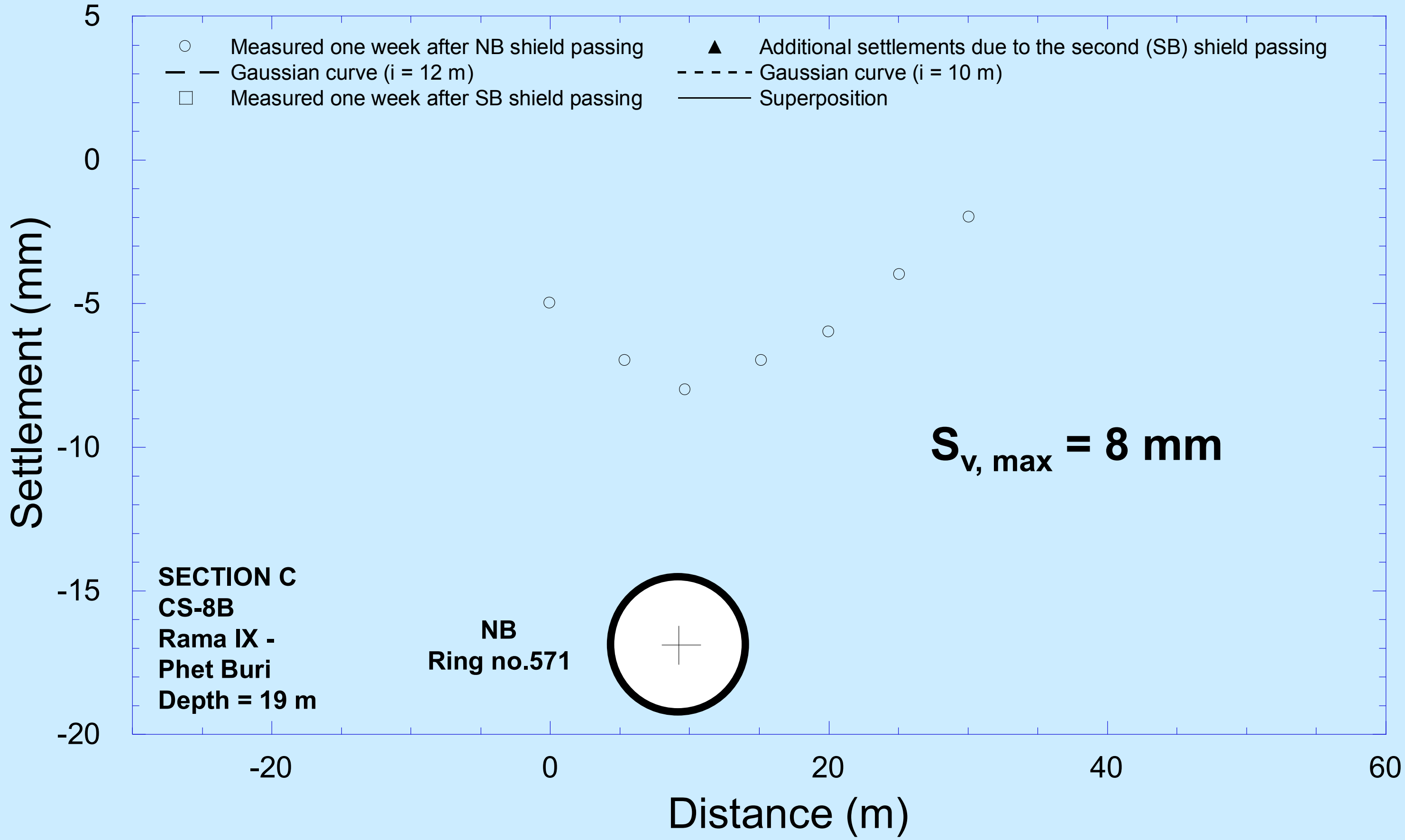
Bobet (2001)

Superposition Technique

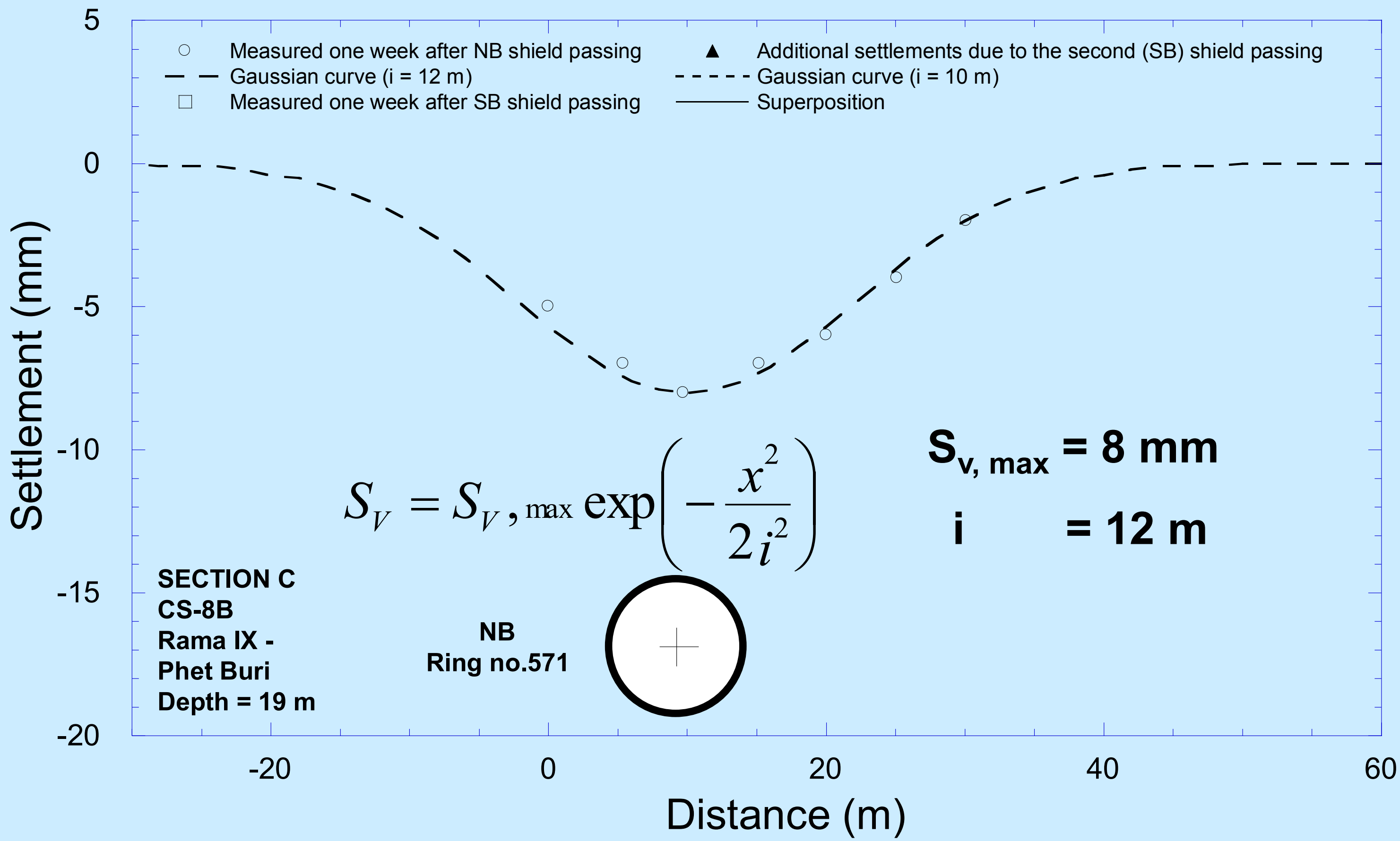


(Suwansawat & Einstein, 2007)

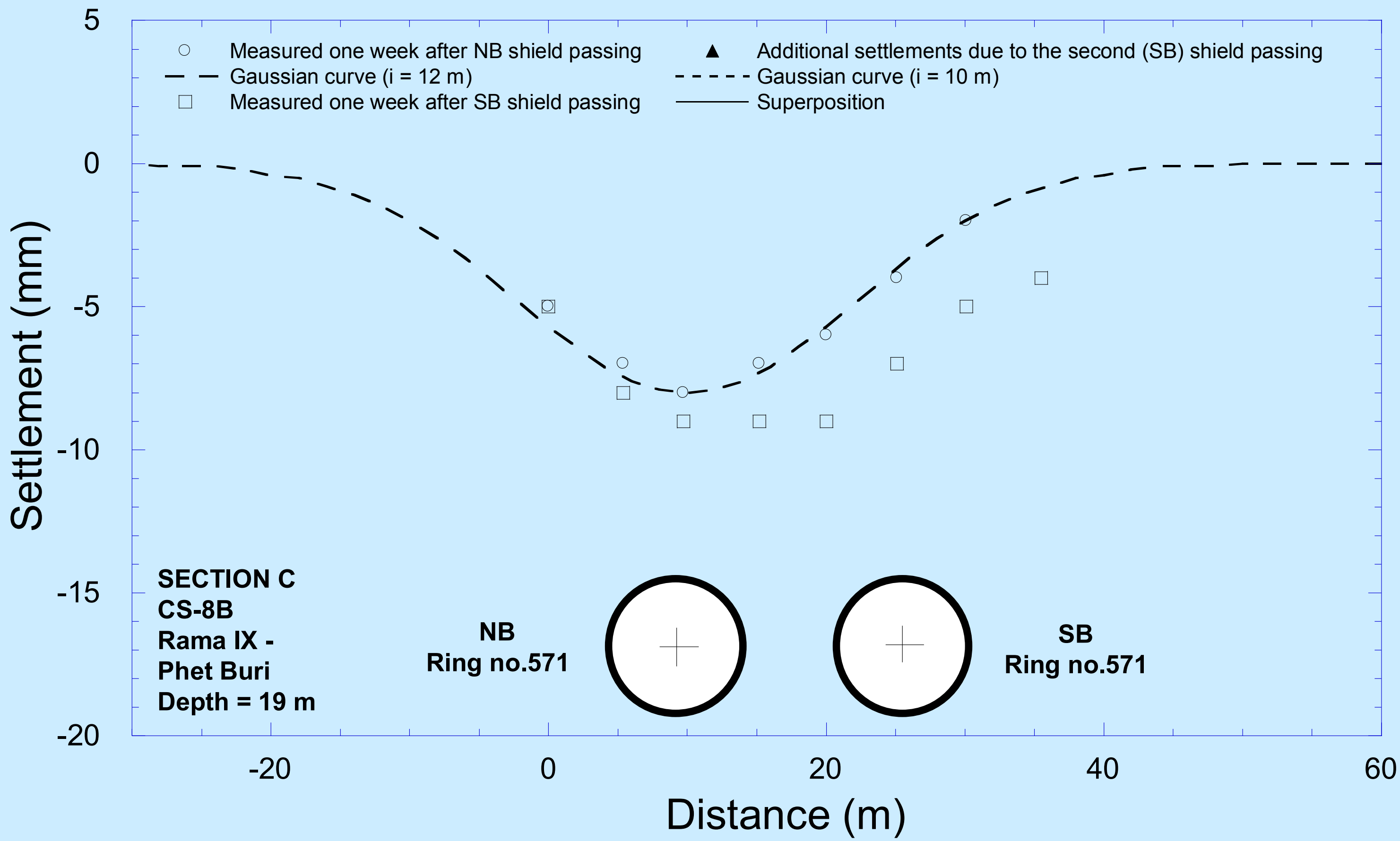
Back-Calculation of Twin Tunnels Volume Loss



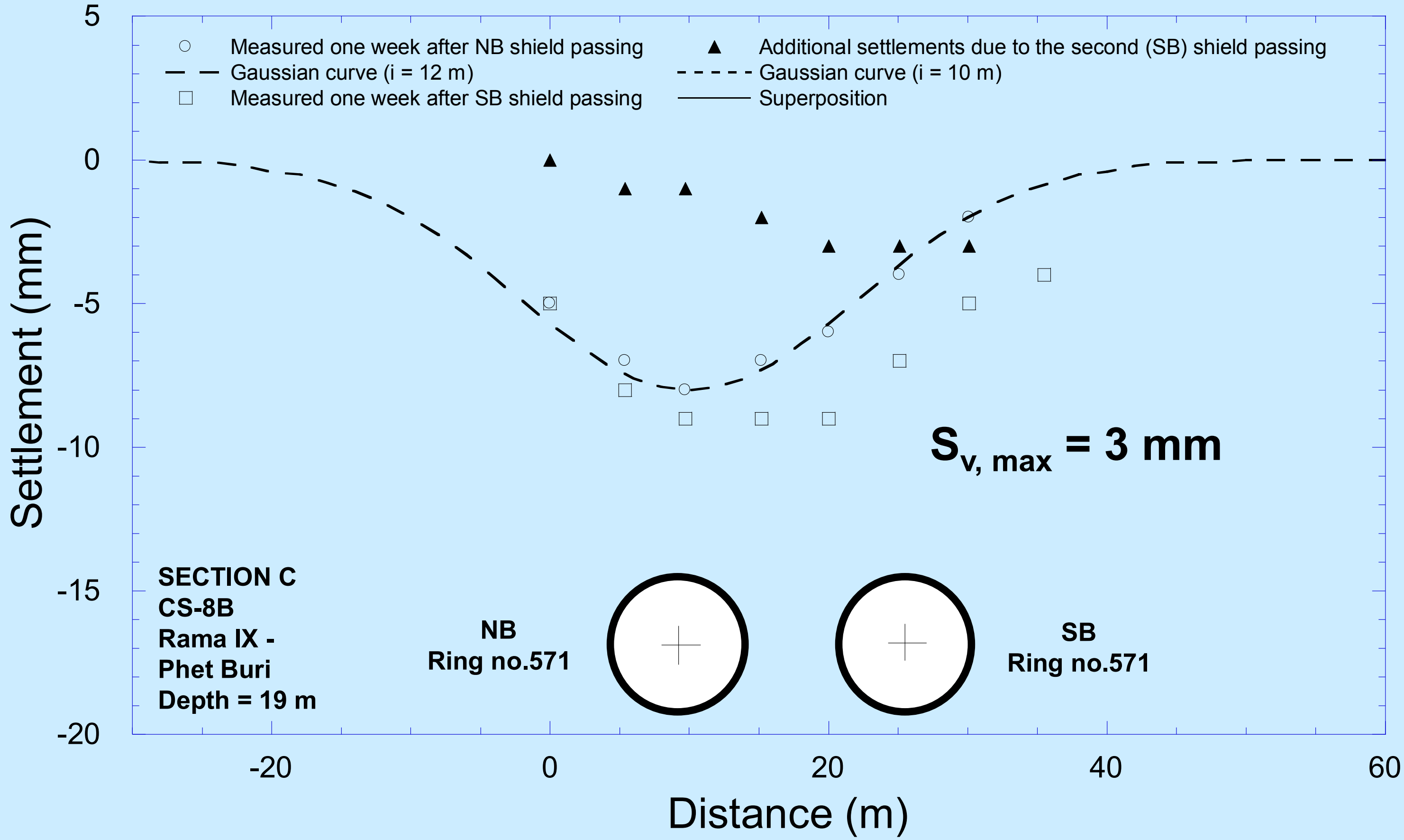
Back-Calculation of Twin Tunnels Volume Loss



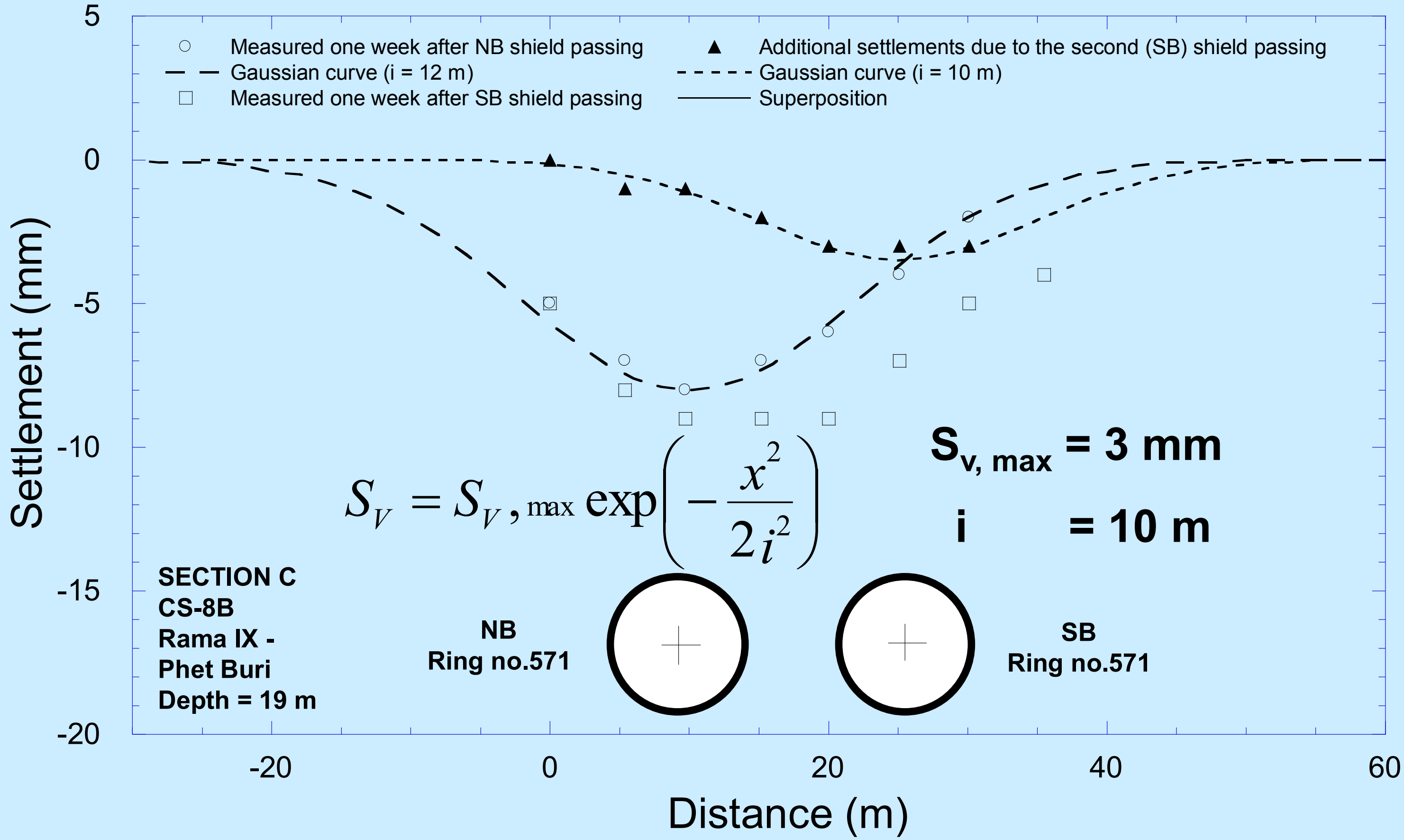
Back-Calculation of Twin Tunnels Volume Loss



Back-Calculation of Twin Tunnels Volume Loss



Back-Calculation of Twin Tunnels Volume Loss



$$S_V = S_{V,\max} \exp\left(-\frac{x^2}{2i^2}\right)$$

$S_{v,\max}$ = 3 mm

i = 10 m

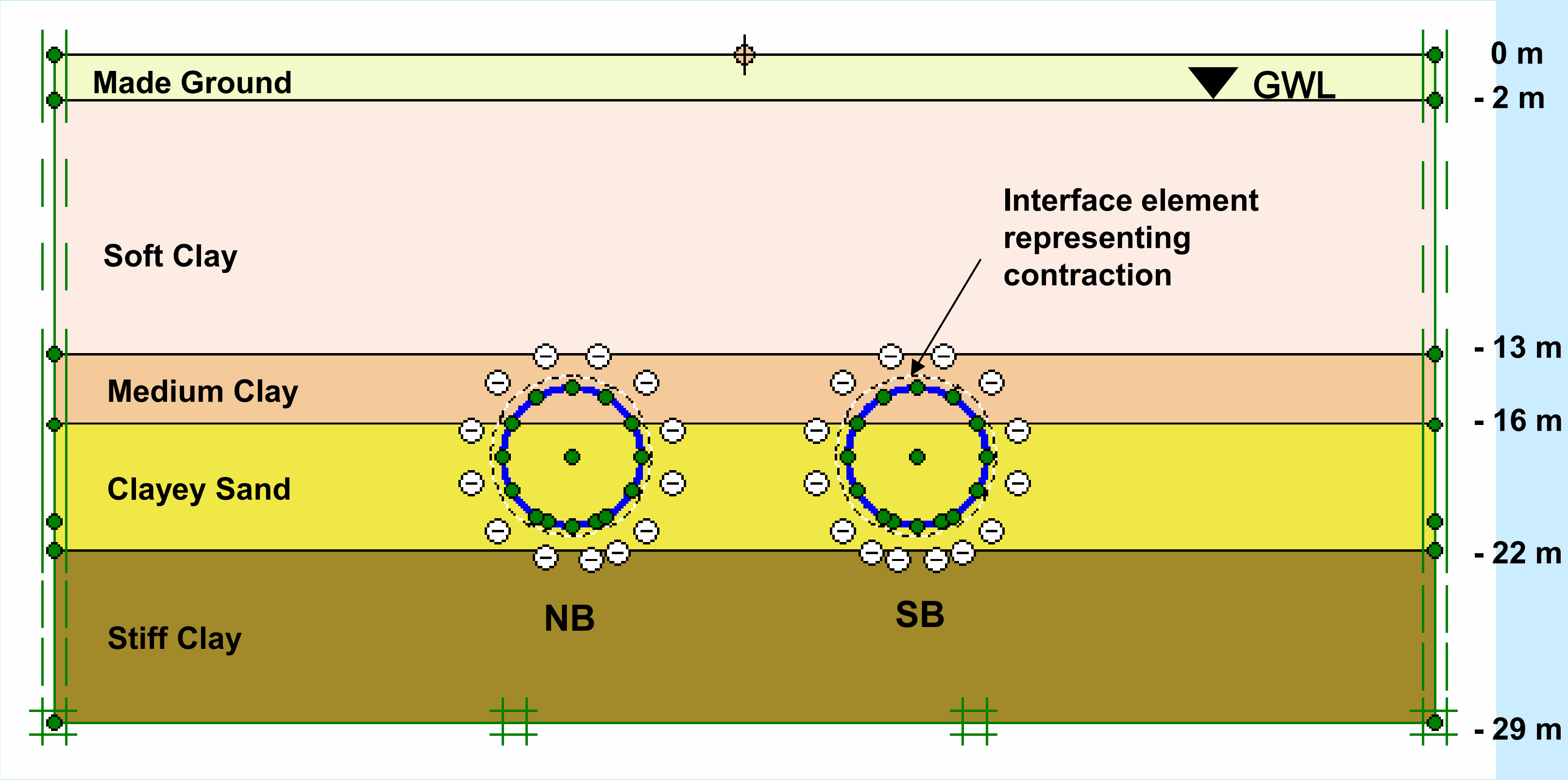
Back-Calculation of Twin Tunnels Volume Loss

	i (m)	$S_{v,(max)}$ (m)	D (m)	V_s (m^2)	V_L (%)
NB (1st pass)	12	0.08	6.43	0.241	0.78
SB (2nd pass)	10	0.03	6.43	0.075	0.23

$$V_S = \int_{-\infty}^{\infty} S_V \, dv = \sqrt{2\pi} i S_{V,\max} \approx 2.5 i S_{V,\max}$$

$$V_L = \frac{V_S}{0.25 \pi D^2}$$

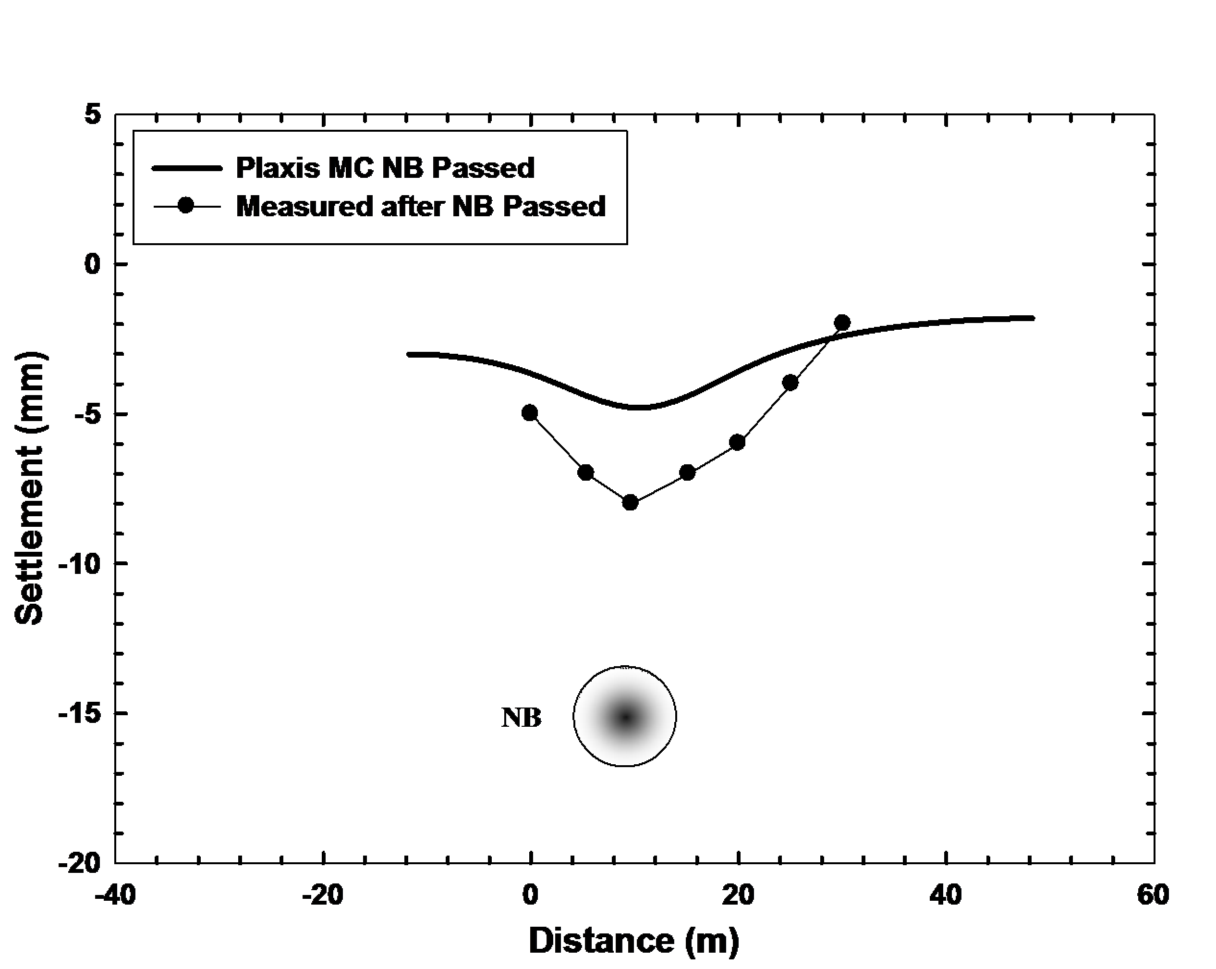
Contraction Methods for 2D Finite Element Analysis



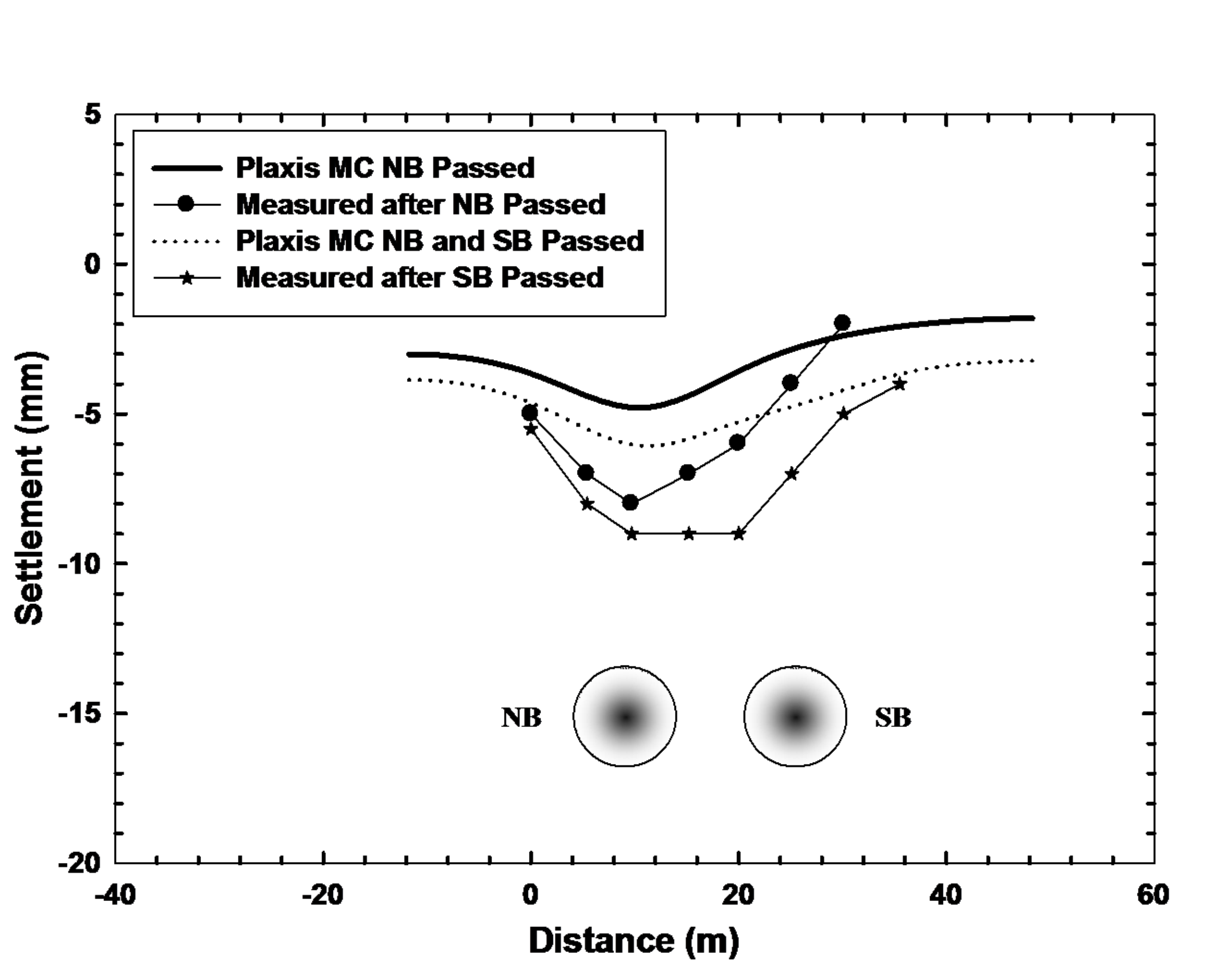
Soil Parameter in Plaxis MC Analysis

Parameter	Name	Made Ground	Soft Clay	Medium Clay	Clayey Sand	Stiff Clay	Unit
Material Model	*Model*	MC	MC	MC	MC	MC	-
Material Behaviour	*Type*	Undrained	Undrained	Undrained	Undrained	Undrained	-
Unsaturated Unit Weight	γ_{unsat}	18	16.5	17.5	17	17	kN/m^3
Saturated Unit Weight	γ_{sat}	18	20	17.5	20	20	kN/m^3
Young's Modulus	E_{ref}	10800	5000	15400	52800	52800	kN/m^2
Poisson's Ratio	υ	0.3	0.33	0.3	0.33	0.3	-
Cohesion	c_{ref}	1	1	1	1	1	kN/m^2
Friction Angle	φ	25	23	23	27	23	Degree
Dilatancy Angle	ψ	0	0	0	0	0	Degree
Interface Strength	R_{inter}	1	1	0.7	0.7	0.7	-

MC Model Prediction after 1st Shield Passed



MC Model Prediction after 2nd Shield Passed



Converting MC Model Parameters to HS Model Parameters

$$E_{50} = E_{50}^{ref}\left(\frac{c\cos\varphi - \sigma_3'\sin\varphi}{c\cos\varphi + p^{ref}\sin\varphi}\right)^m$$

$$E_{50}^{ref} = E_{oed}^{ref}$$

$$E_{ur}^{ref} = 10 \cdot E_{oed}^{ref} / K_0$$ for normally consolidated clay

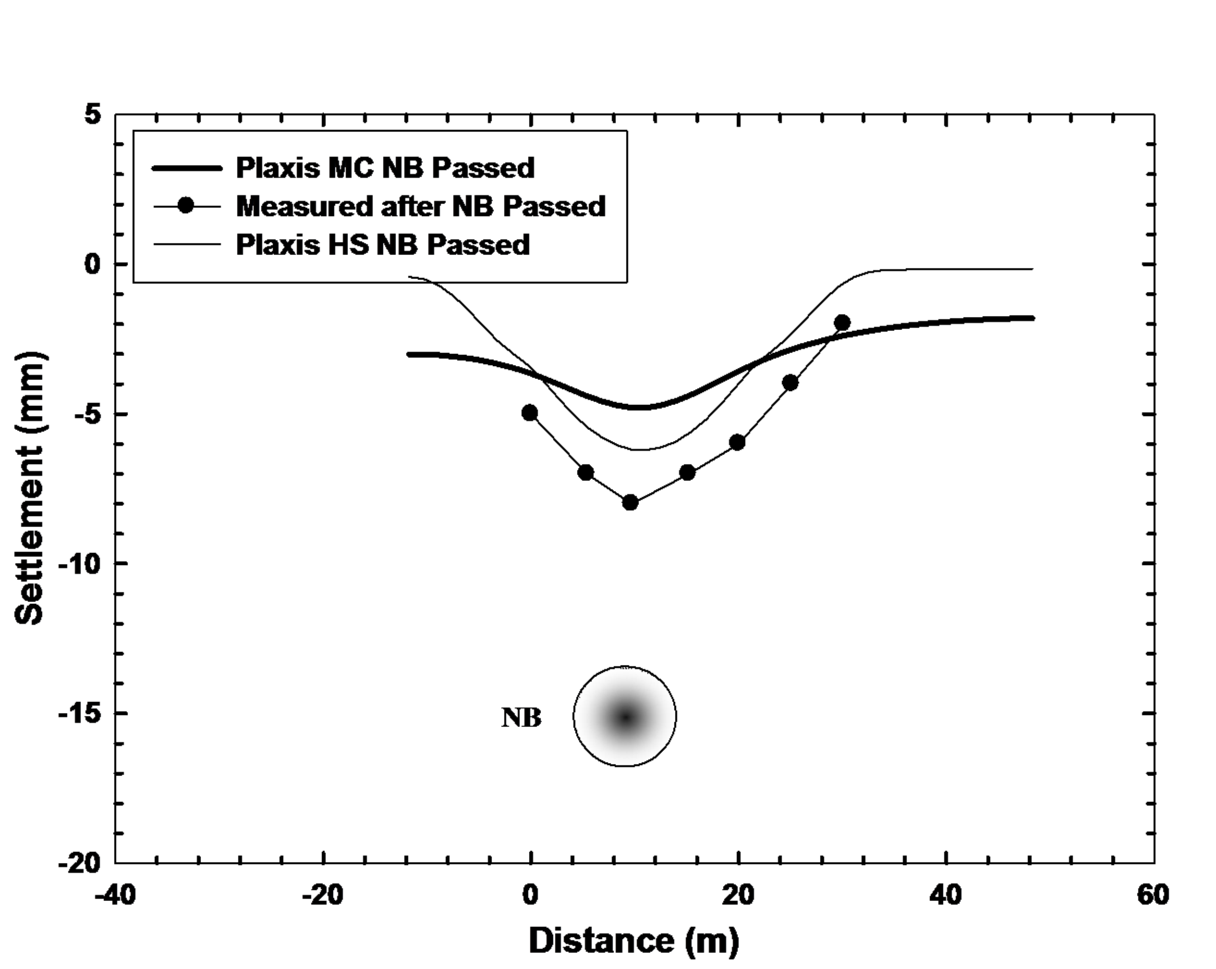
Smoltczyk (2002)

$$E_{ur}^{ref} = 3 \cdot E_{oed}^{ref} / \sqrt{K_0}$$ for normally consolidated sand

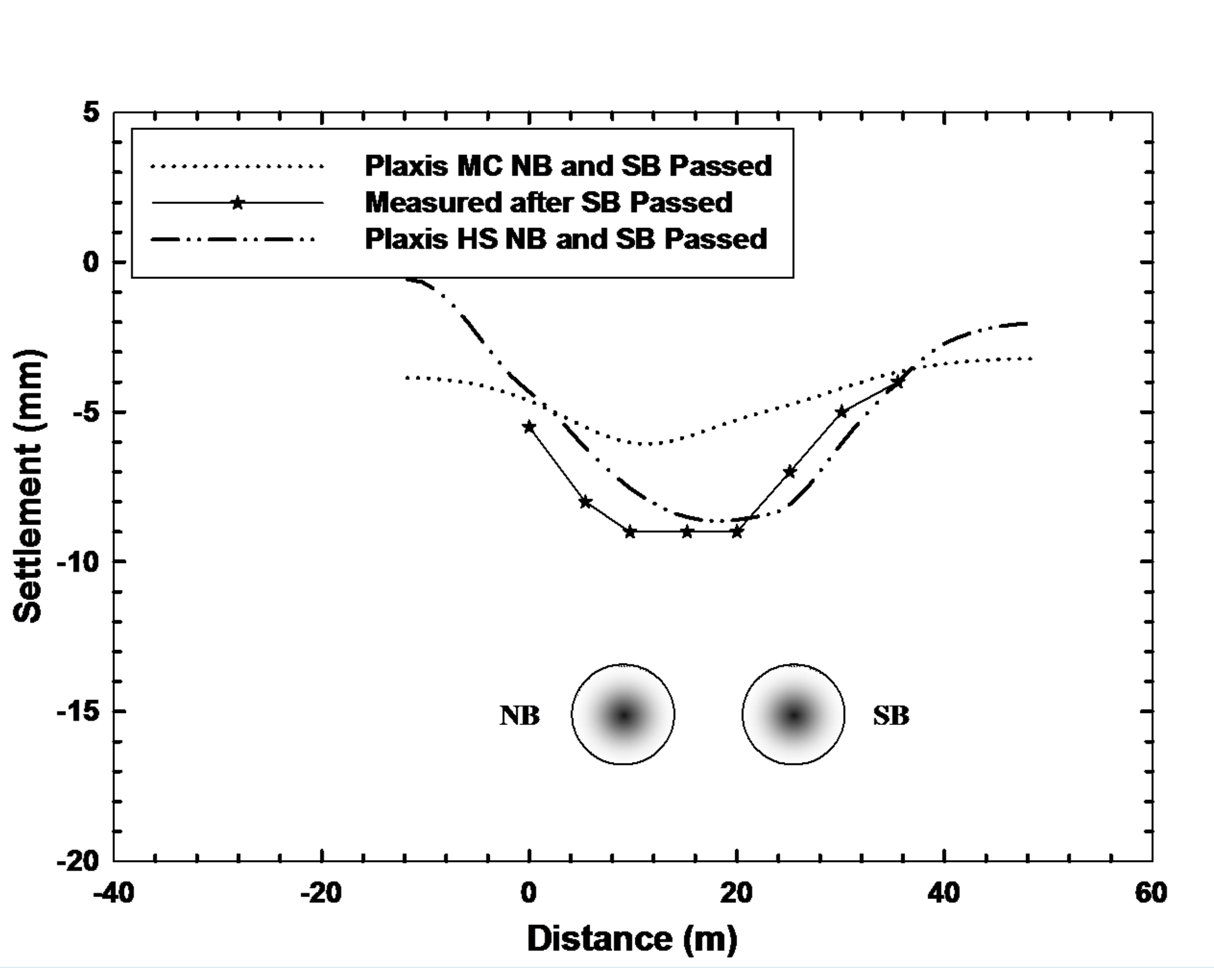
Parameters in HS Model Analysis

Parameter	Name	Made Ground	Soft Clay	Medium Clay	Clayey Sand	Stiff Clay	Unit
Material Model	*Model*	HS	HS	HS	HS	HS	-
Primary Loading Modulus	E_{50}^{ref}	15431	8380	16122	120005	55278	kN/m^2
Oedometer Modulus	E_{oed}^{ref}	15431	8380	16122	120005	55278	kN/m^2
Unloading/ Reloading Modulus	E_{ur}^{ref}	46293	134088	257964	276012	884448	kN/m^2

HS Model Prediction after 1st Shield Passed



HS Model Prediction after 2nd Shield Passed

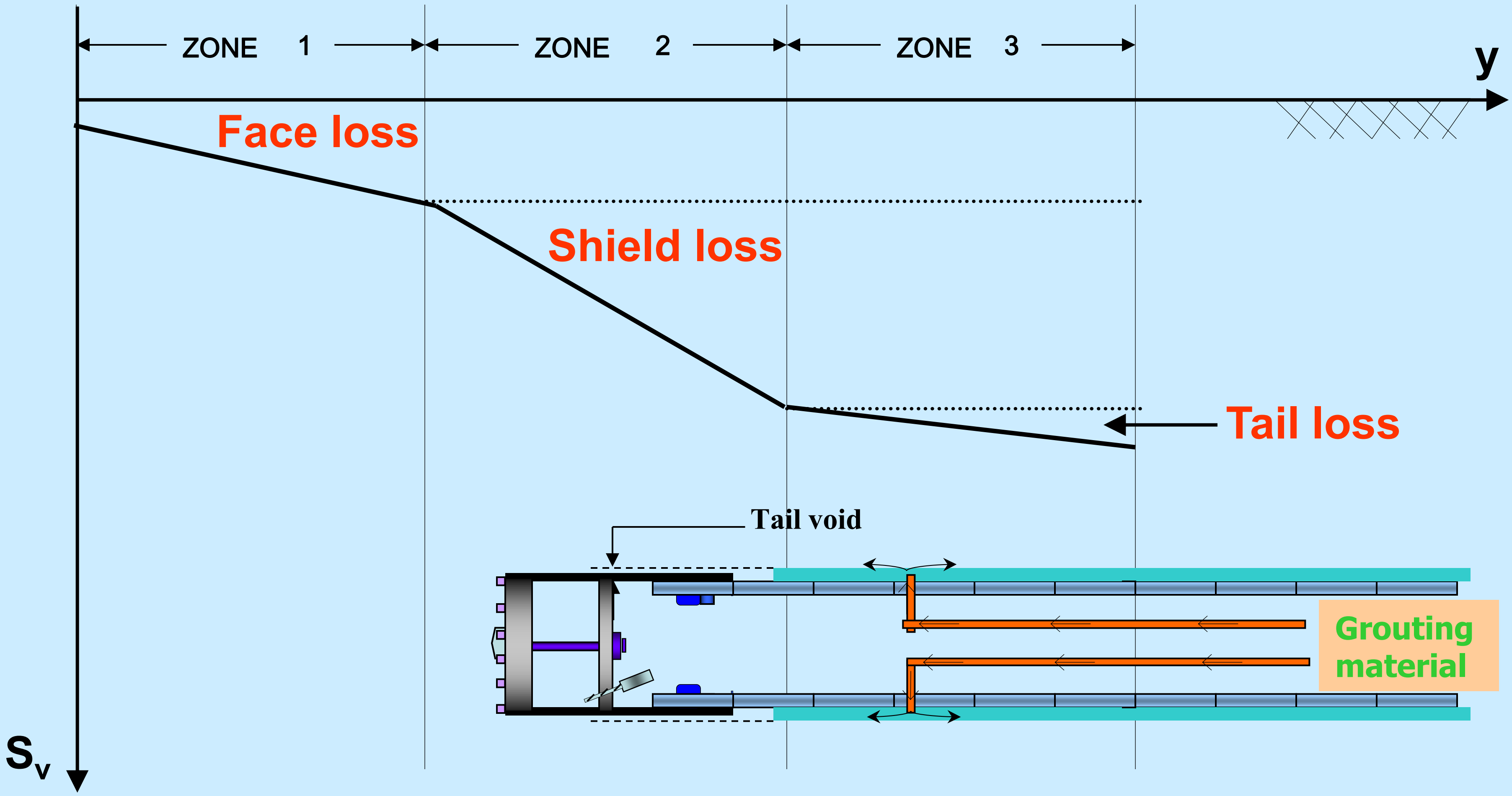


Conclusions from MC and HS Models Analyses

Similar conclusions as presented in literatures (Addenbrooke et al, 1997; Franzius, 2003) can be drawn as follows:

- The linear-elastic perfectly plastic model (MC) gives an under-estimate settlement profile, especially in Greenfield condition
- By using non-linear model (HS) itself without adjusting soil parameters, the settlement profile prediction can be improved

Components of Ground Loss



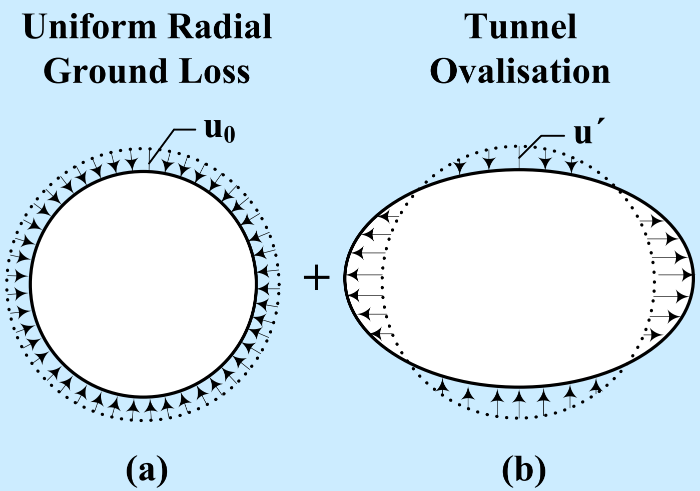
Empirical Parameter (*i*)

Surface Settlement		
Authors	***Formula***	***Remarks***
Atkinson and Potts (1997)	$i_o = 0.25\left(z_0 + 0.5D\right)$	**Loose sand with surcharge**
Atkinson and Potts (1997)	$i_o = 0.25\left(1.5z_0 + 0.25D\right)$	**Dense sands and OC clays without surcharge**
Clough and Schmidt (1981)	$i_o = \left(\frac{D}{2}\right) \cdot \left(\frac{z_0}{D}\right)^{0.8}$	**Tunnelling in soft ground**
O'Reilly and New (1982)	$i_o = K \cdot z_0$	K **0.4 – 0.7 for stiff – soft, stiff clay** **0.2 – 0.3 for granular materials**
Loganathan and Poulos (1998)	$\frac{i_o}{D} = 0.575\left(\frac{z_0}{D}\right)^{0.9}$	**Saturated clays**

2D Numerical Analysis

Author	Main Findings
Chanchaya (2000) *(Plaxis 2D)*	▪Back calculation using 2D FE analysis has been conducted. ▪The parameters Eu/Su from back calculations suitable for soft and first stiff Bangkok clays layers are 240 and 480, respectively and these values are comparable to the pressuremeter test results from Teparaksa (1999)
Timpong (2002) *(Flac 2D)*	▪Reasonable agreement between 2D FD analysis and field observations can be obtained if an appropriated ground loss expressed in percent relaxation is adopted. ▪The values of percent relaxation are ranging from 30 to 80 percent.
Du (2003) *(Plaxis 2D)*	▪Plaxis interface element is used to simulate the redial contraction between the shield and surrounding soil. ▪The reduction factor (R) for interface element property varies from 0.5-0.9 with the average of 0.7.
Tavaranum (2004) *(Plaxis 2D)*	▪Back calculated percentage ground loss from Plaxis analysis and analytical solution by Loganathan and Poulos (1998) are compared. ▪Generally, good agreements are obtained from the two method with the values varying from 0.3-2.9%

Verrujit & Booker (1996)



$$u_x = -\varepsilon_o R^2 x \left\{ \frac{1}{x^2 + (H-z)^2} + \frac{1}{x^2 + (H+z)^2} - \frac{4z(z+H)}{\left[x^2 + (H+z)^2\right]^2} \right\}$$

$$u_z = \varepsilon_o R^2 \left\{ -\frac{z-H}{x^2 + (z-H)^2} + \frac{z+H}{x^2 + (z+H)^2} - \frac{2z\left[x^2 - (z+H)^2\right]}{\left[x^2 + (z+H)^2\right]^2} \right\}$$

Verrujit & Booker (1996)

For surface settlement

$$u_{z=0} = 2\varepsilon_o R^2 \frac{H}{x^2 + H^2}$$

where

ε_o = Uniform radial ground loss parameter

H = Depth of the tunnel axis from ground surface

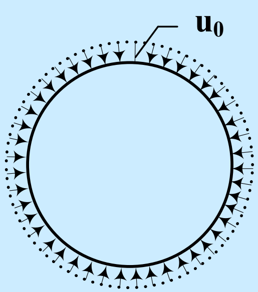
R = Radius of the tunnel

z = Depth measured from ground surface

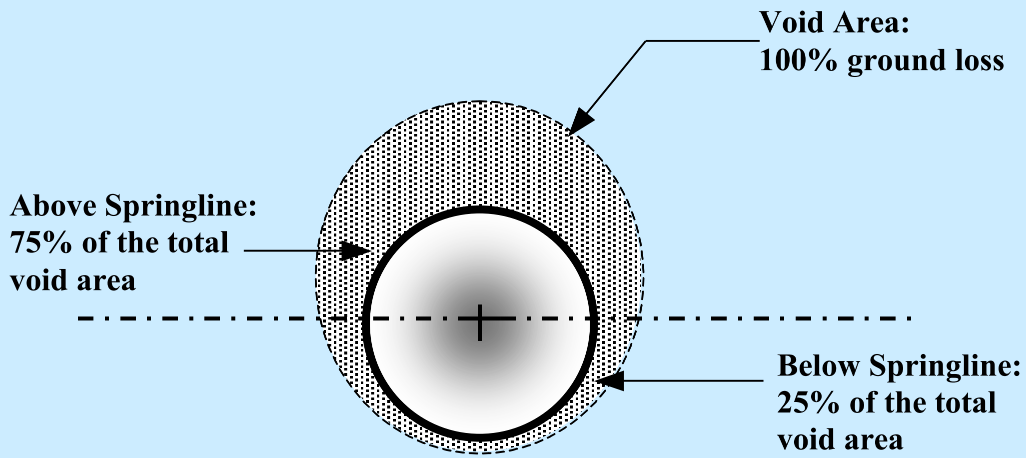
x = Lateral distance from tunnel center line

Loganathan & Poulos (1998)

Uniform Radial Ground Loss



$$\varepsilon_0 = \frac{u_0}{R}$$



$$\varepsilon_0 = \frac{4gR + g^2}{4R^2}$$

$$U_{z=0} = 4(1-\nu)R^2 \frac{H}{\left(H^2 + x^2\right)} \frac{4gR + g^2}{R^2} \exp\left[-\frac{1.38x^2}{(H+R)^2}\right]$$

where,
H = Depth of the tunnel axis from ground su
R = Radius of the tunnel
g = Gap parameter (Lee et.al., 1992)
z = Depth measured from ground surface
x = Lateral distance from tunnel center line

Loganathan and Poulos (1998)

Earth Pressure Balance Shields (EPBS)

Singapore MRT Project

Bangkok MRT Project