TRAINING MATERIAL

SETTLEMENTS INDUCED BY TUNNELING IN SOFT GROUND

Prepared by WG. 2 “Maintenance and Repair”

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2007

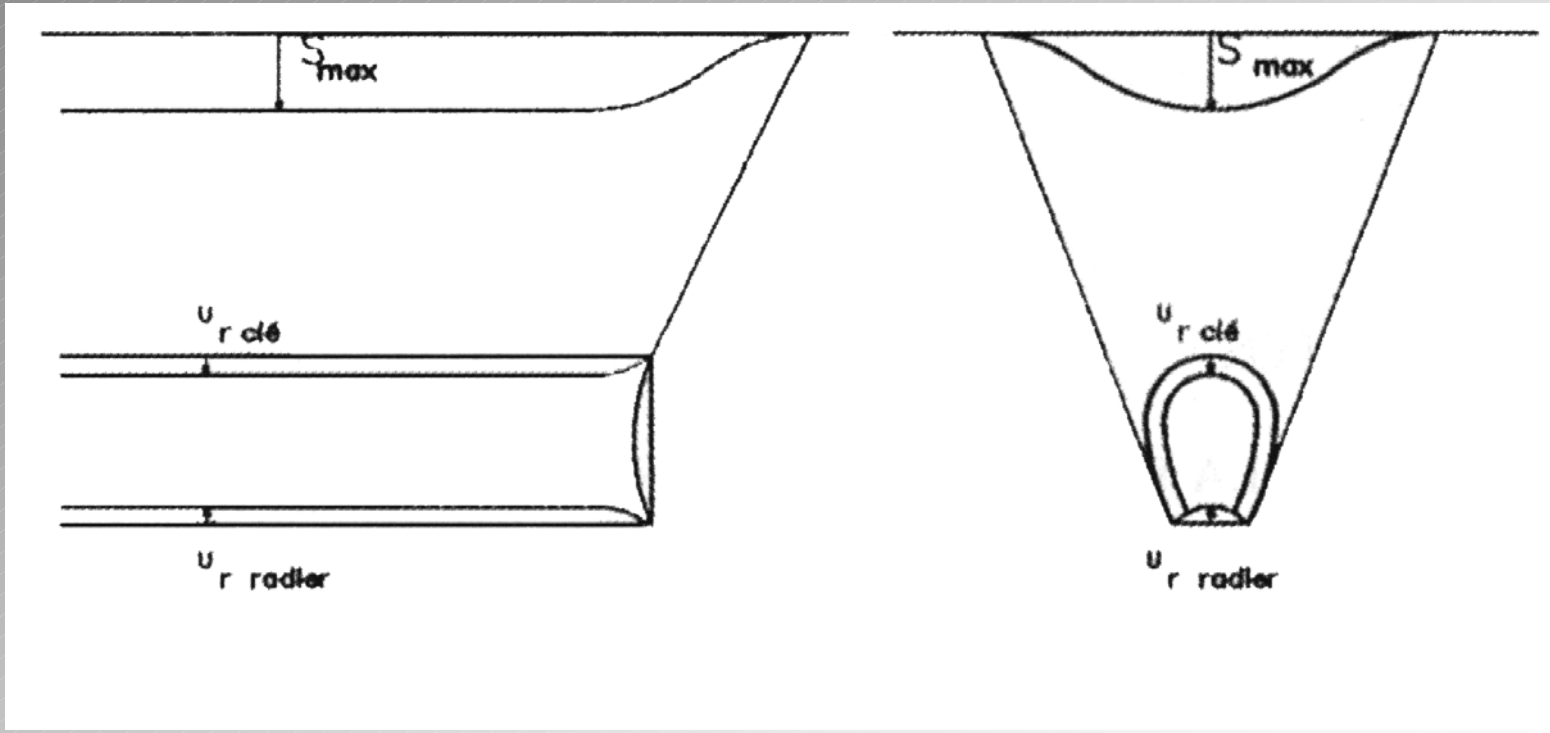
Index

Ground motion induced by tunneling and impact on existing structures

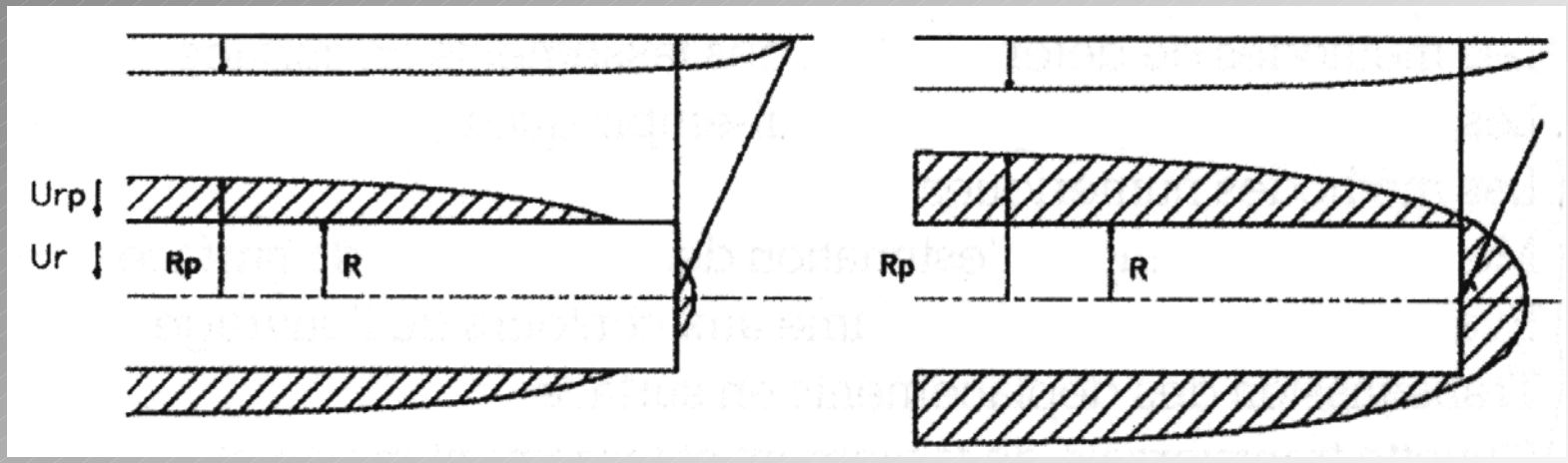
Chapter 1

Tunneling Induced Ground Movements

Displacements of the Excavation Profiles

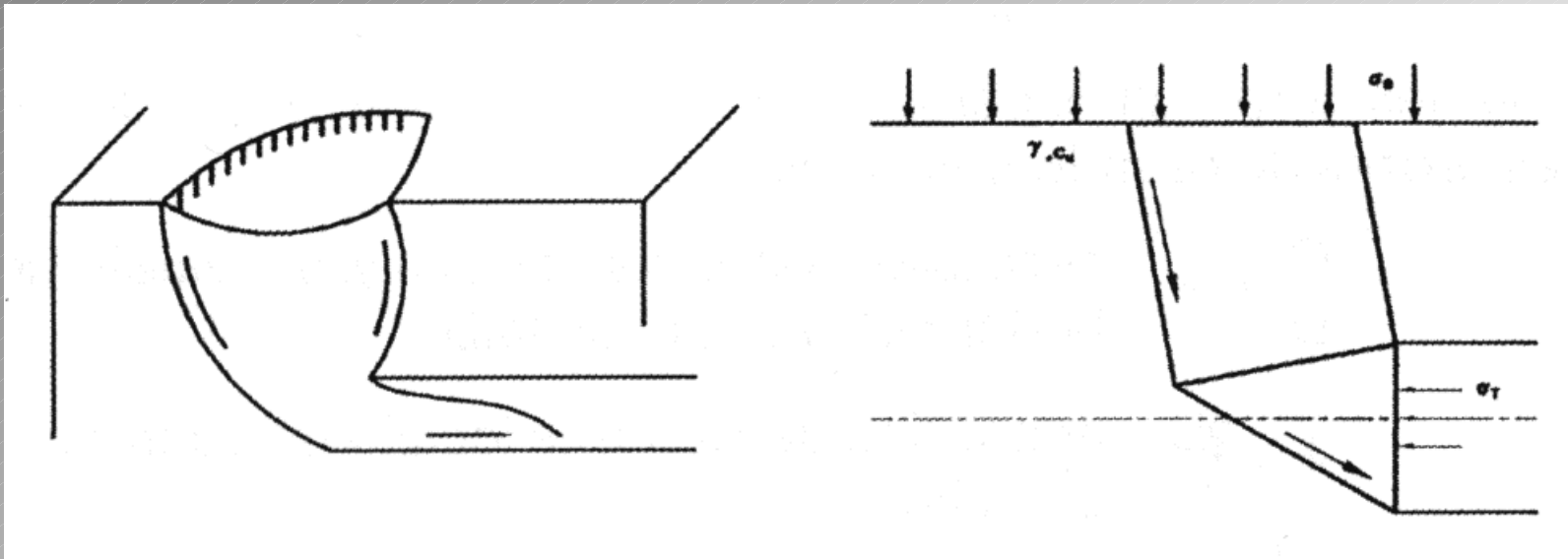


Yielding Zone Around the Opening



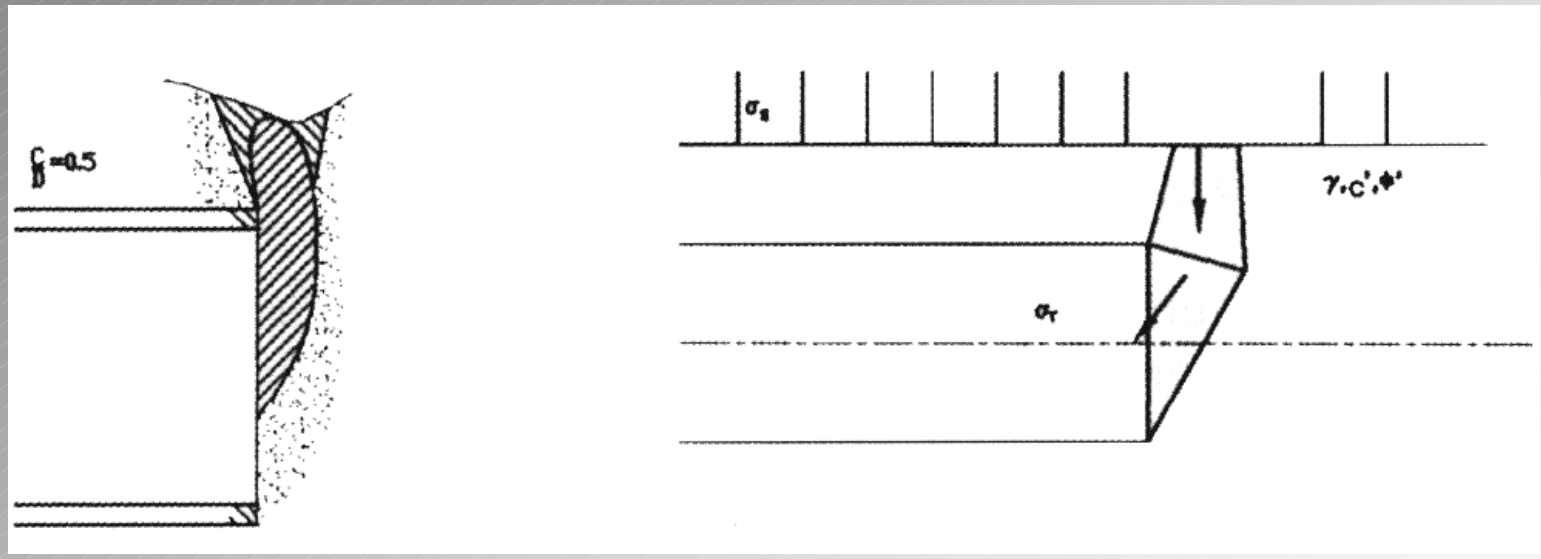
a. Limited extension b. Weaker grounds

Tunnel Face Stability



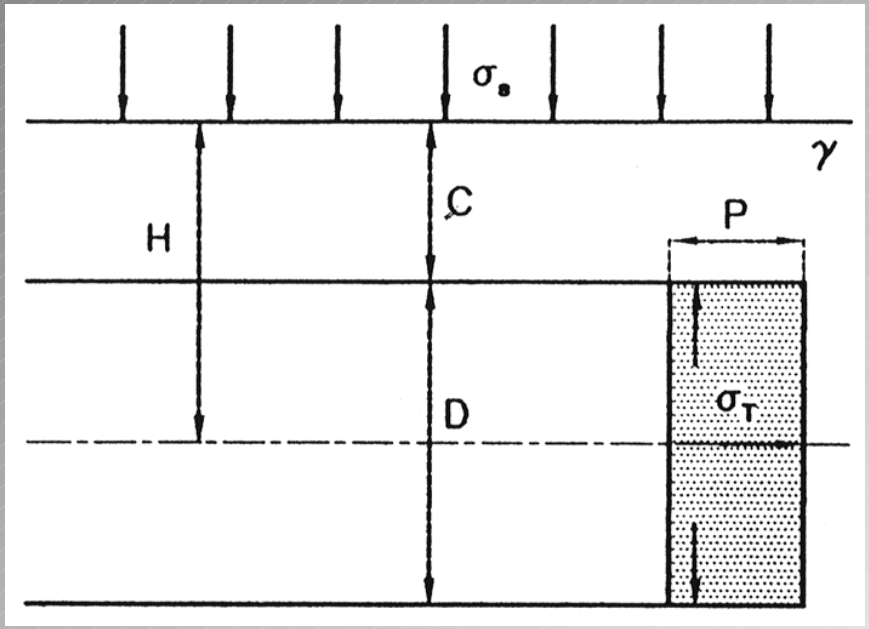
a. Clayey Grounds

Tunnel Face Stability



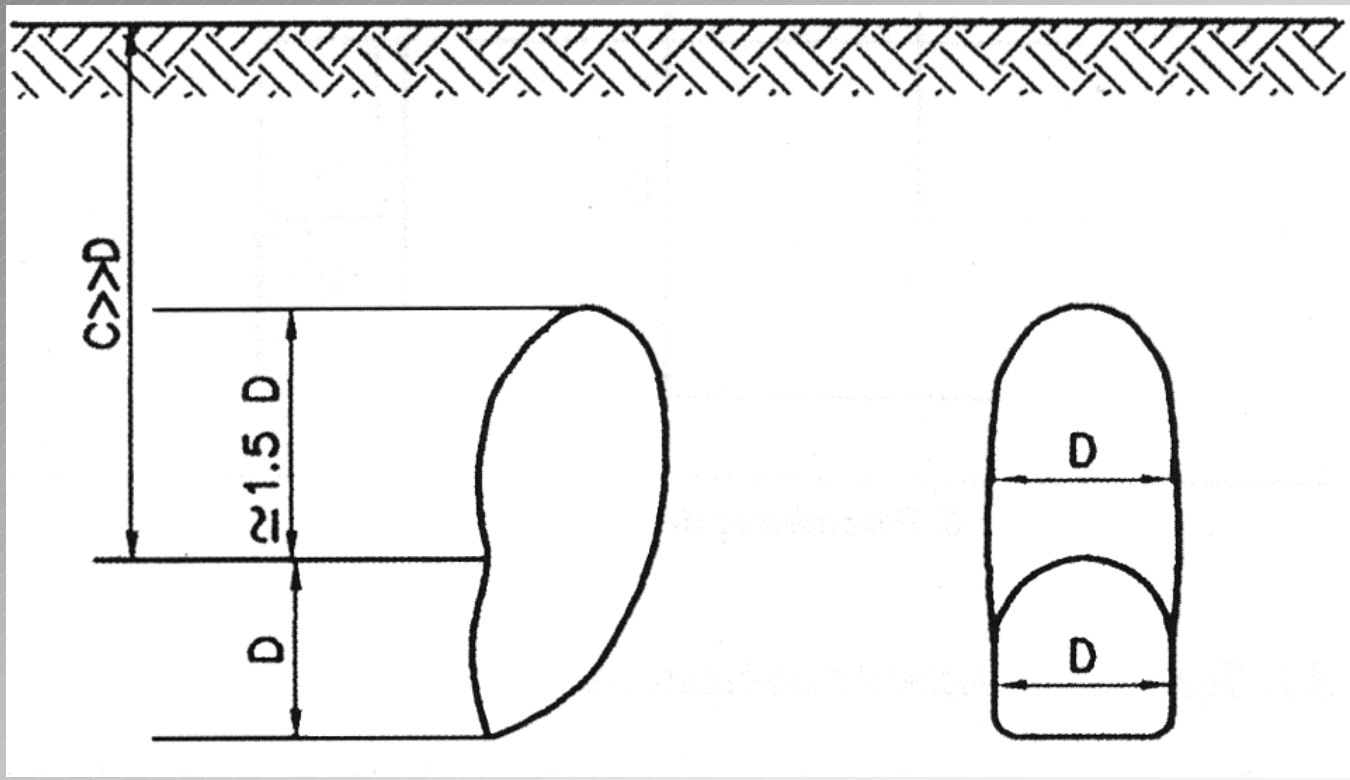
b. Frictional Grounds

Tunnel Face Stability



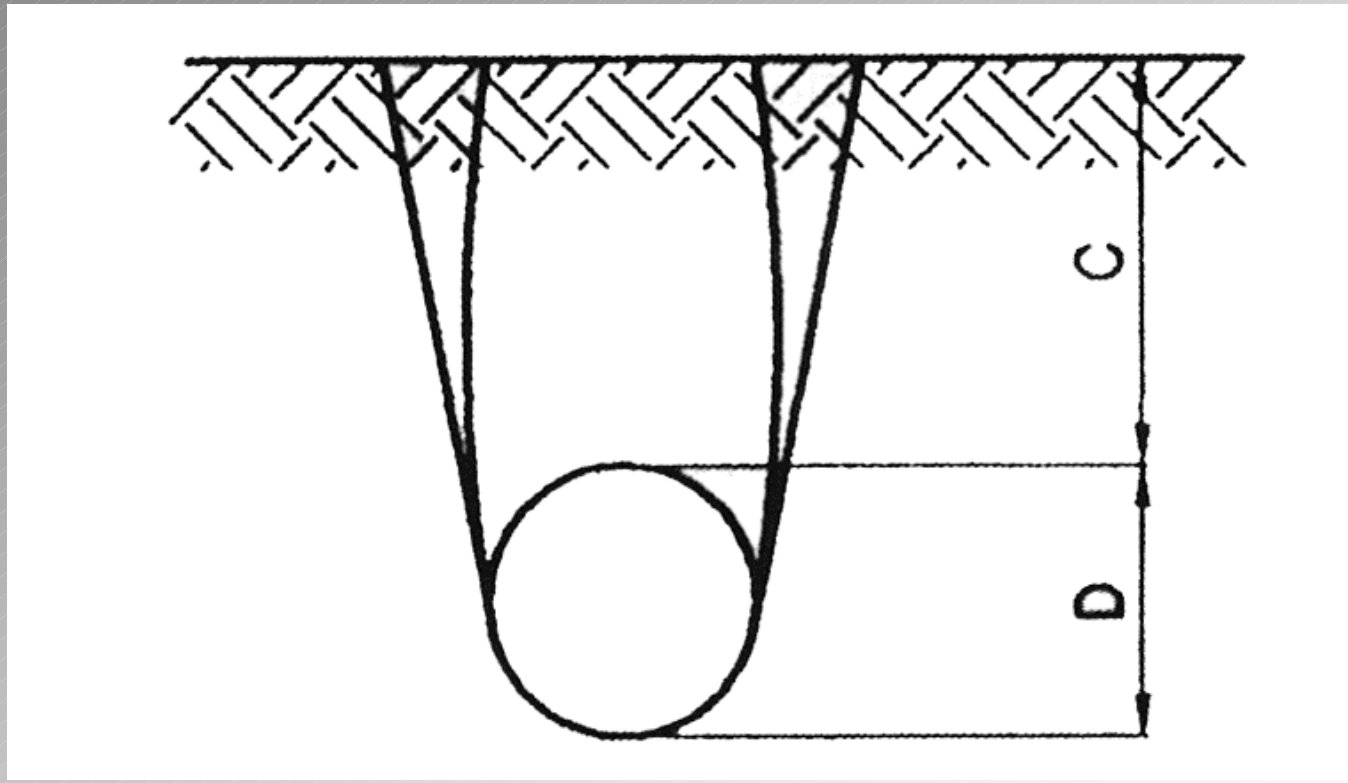
- Clayey Grounds:
  - $N=(\sigma_S+\gamma H-\sigma_T)/S_u$
  - $N<5\text{-}6$
  - U- shear strength: S_u
- Frictional Grounds:
  - σ_S/σ_c, $\gamma D/\sigma_c$, σ_T/σ_c
  - $\sigma_c = 2c' \cos\varphi' /(1-\sin\varphi')$
  - Cohesion: c'
  - Friction angle: φ'

Propagation of Movements Towards the Surface



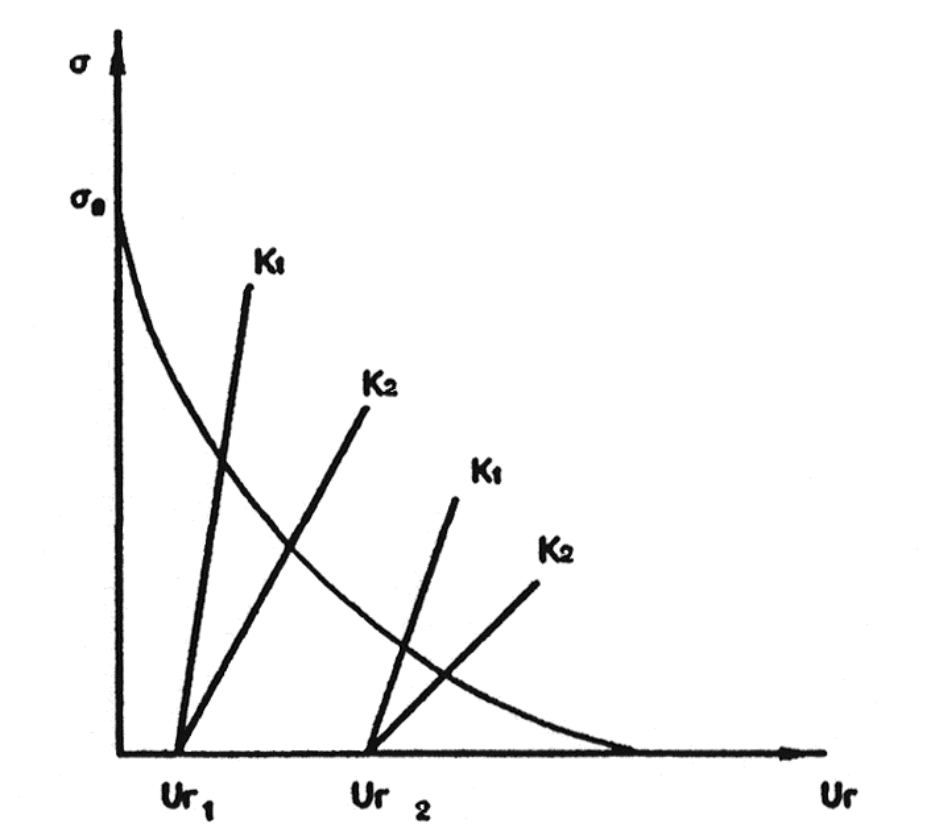
a. Deeper Tunnel

Propagation of Movements Towards the Surface



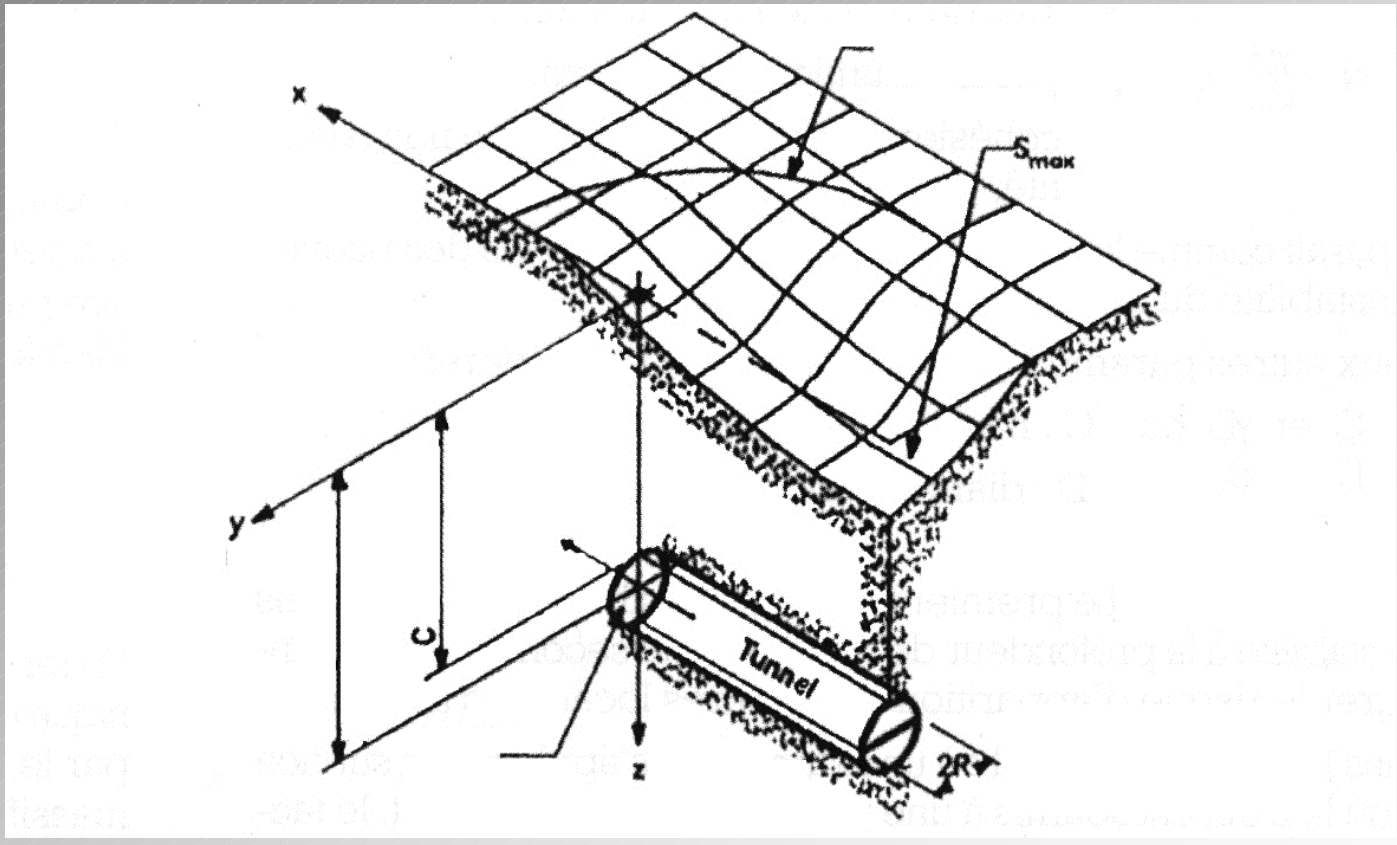
b. Shallow Tunnel

Influence of Support Conditions



- Support stiffness
- Installation timeframe

Surface Settlement Trough

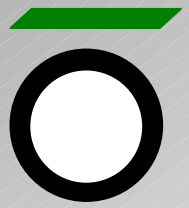


Chapter 2

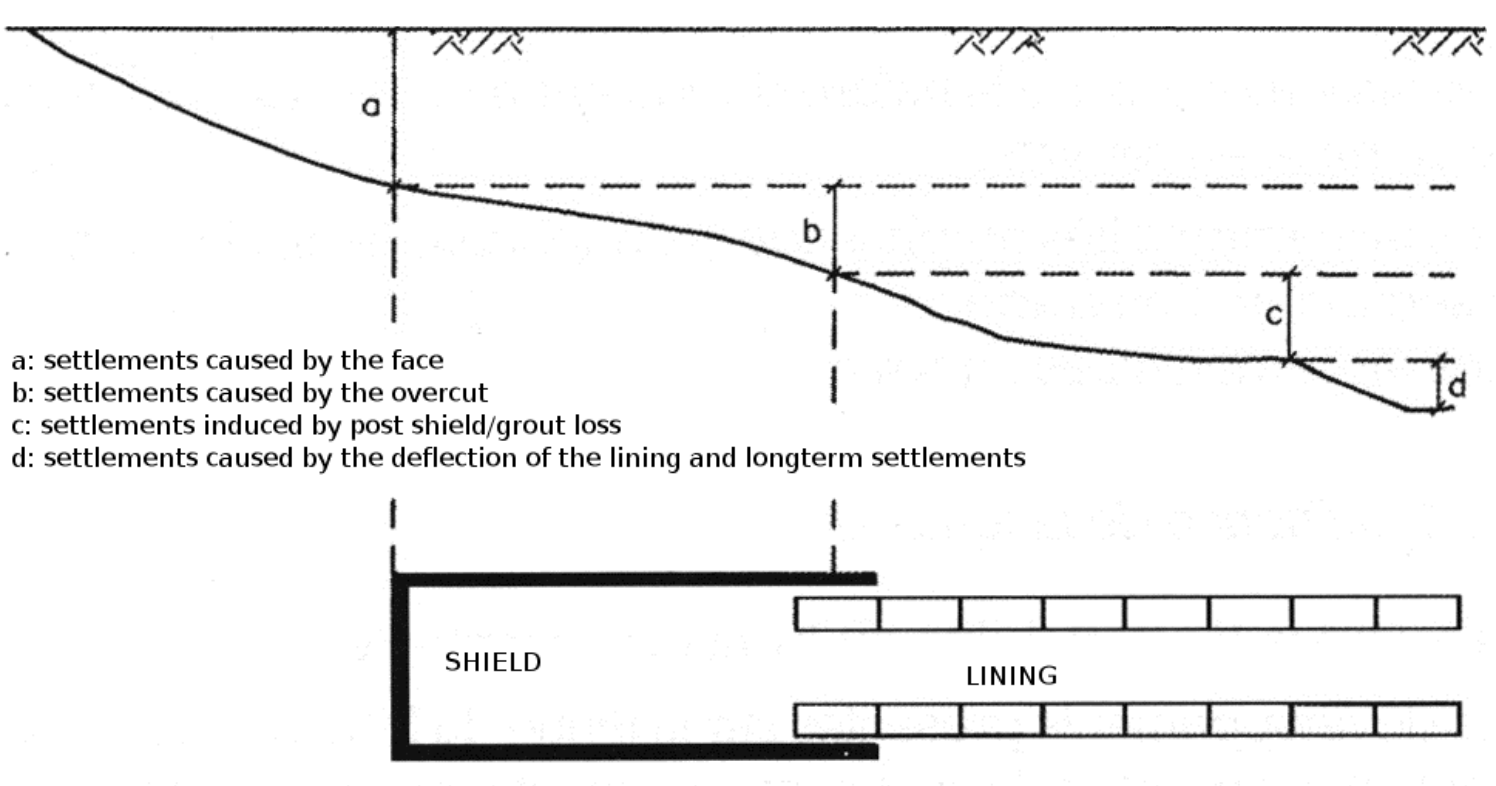
Causes For Construction Induced Settlements

Main Sources For Settlements (sequential construction)

- Face intake/instability
- Impact of characteristics and installation conditions of temporary support
- Staging of the excavation works (cross-section
- Final liner installation and response



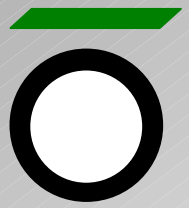
Settlements Along a Shield Driven Tunnel



Settlements Induced by Tunneling in Soft Ground

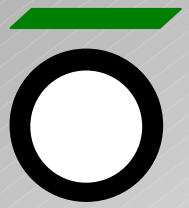
Typical Contributions to Shield Tunneling Induced Settlements

- Face intake: 10-20%
- Along the shield: 40-50%
- Tail skin: 30-40%



Sources For Additional Settlements

- Effect of groundwater
  - During construction
    - drawdown of ground water table
    - Seepage towards the tunnel face
  - In the long term (consolidation)
- Effect of worksite conditions
  - e.g. impact of vibrations of weaker grounds

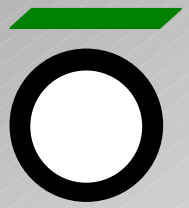


Chapter 3

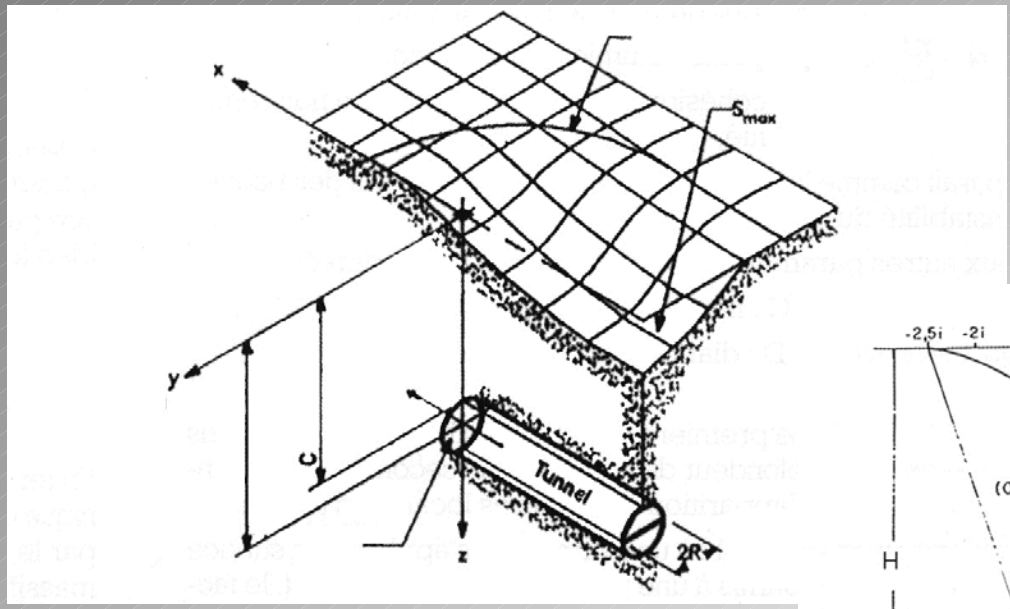
Evaluation of Ground Movements

Settlement Evaluation Methods

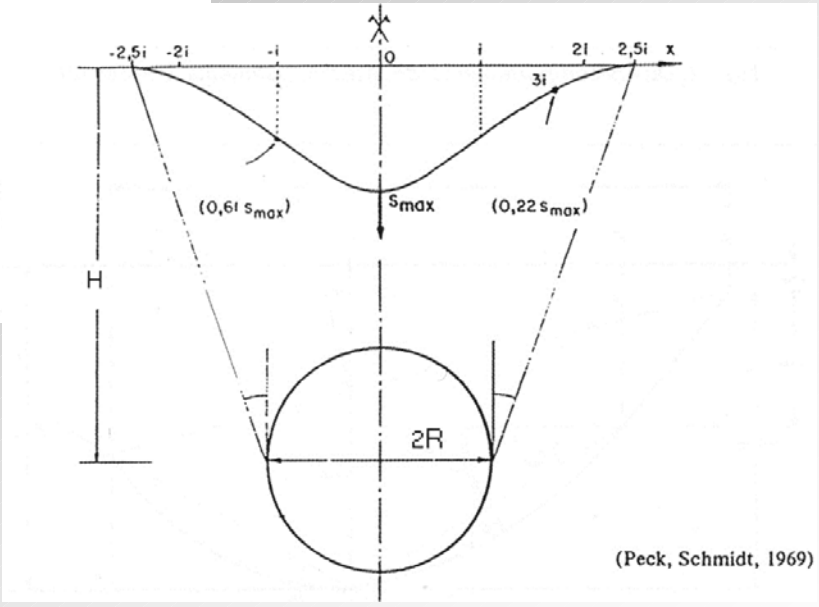
- Empirical and Semi-empirical
  - Analytical
  - Observational
- Numerical



Settlement Trough Characterization

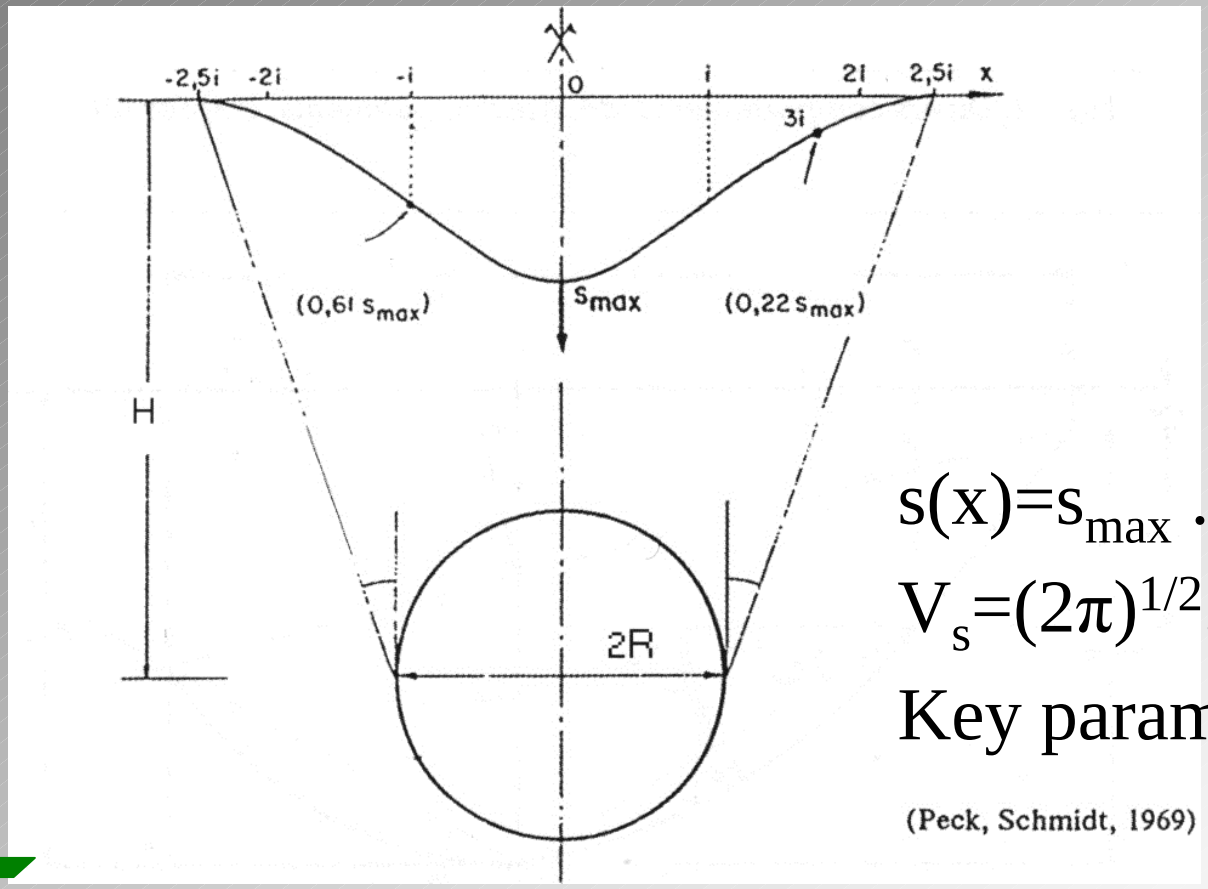


3D Distribution



Cross-section

Settlement Trough Characterization



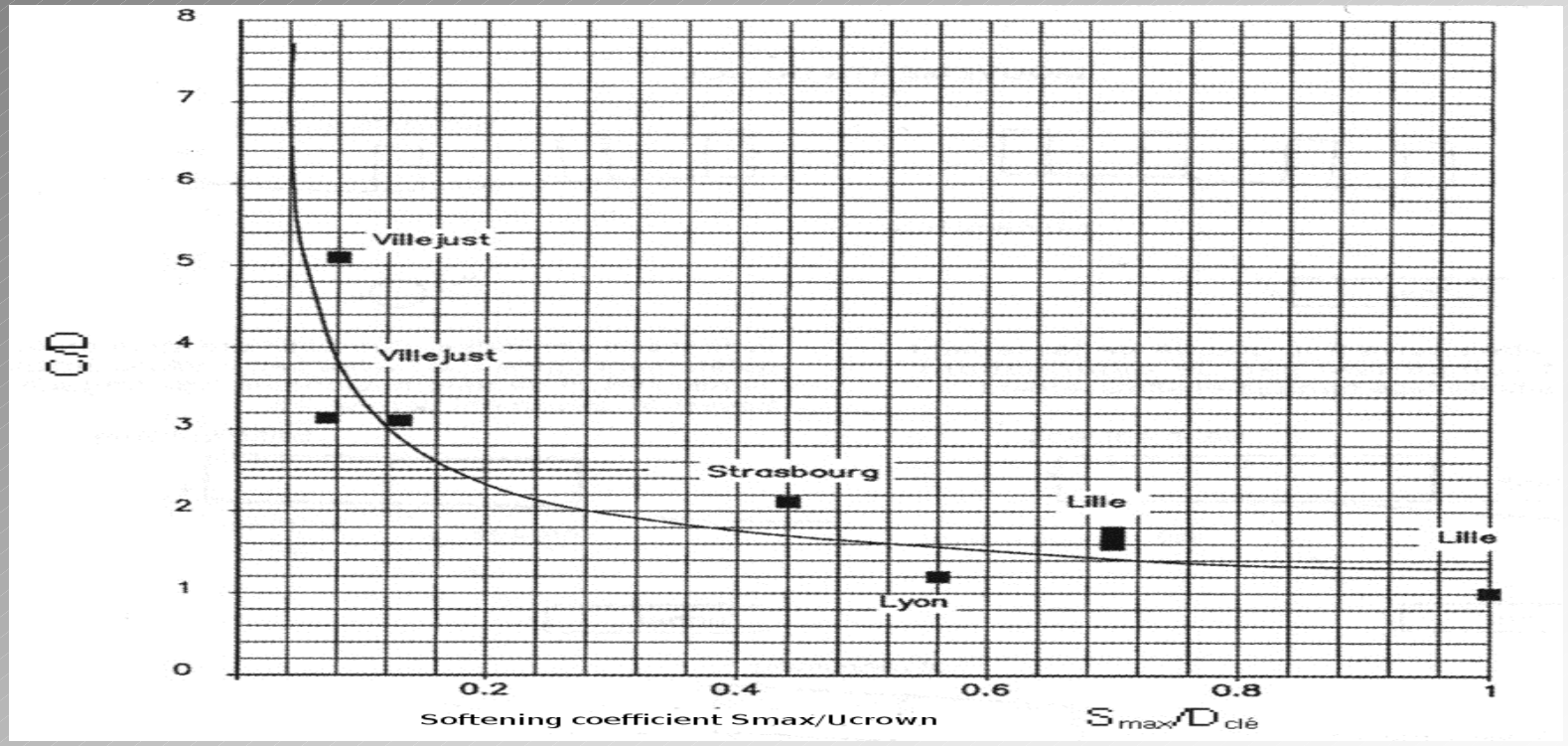
$s(x)=s_{max}.\exp(-x^2/2i^2)$

$V_s=(2\pi)^{1/2}.i.s_{max}$

Key parameters: s_{max}, i

(Peck, Schmidt, 1969)

Dampening Effect

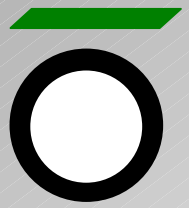


- V_l = Volume loss at the opening
- V_s = Volume loss at ground level

Ground Movements at Depth

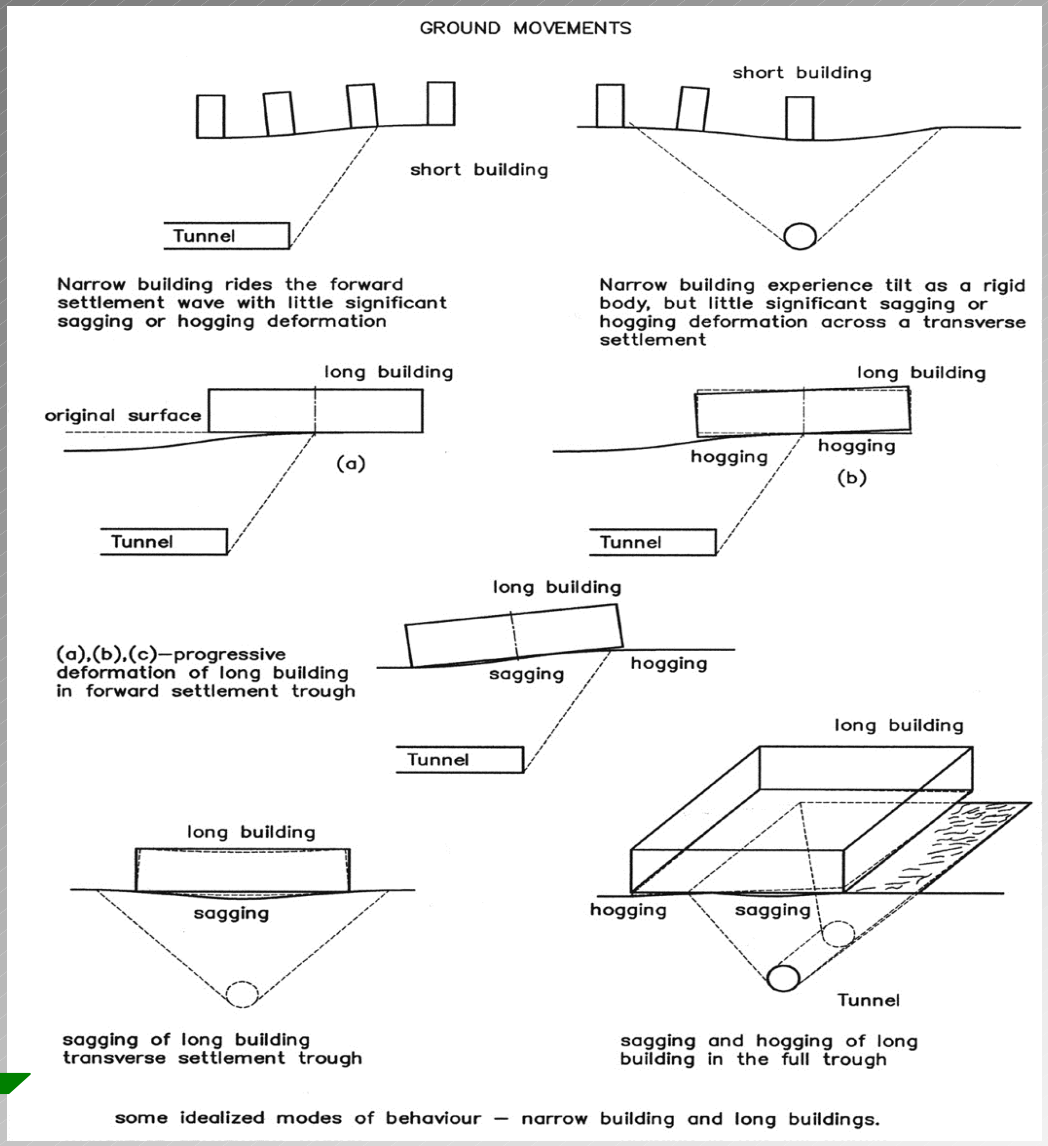
- $S(x,z)=s_{max}(z).\exp(-x^2/2(Kz)^2)$
- $H(x,z)=S(x,z).x/z$
- $V_s(z)=(2\pi)^{1/2}.Kz.s_{max}(z)$
- K = empirical coefficient
  - (varies typically from 0.5 for stiff clay and sandy clay to 0.25 to softer sands and gravels)

(after O'Reilly & New, 1982)



Chapter 4

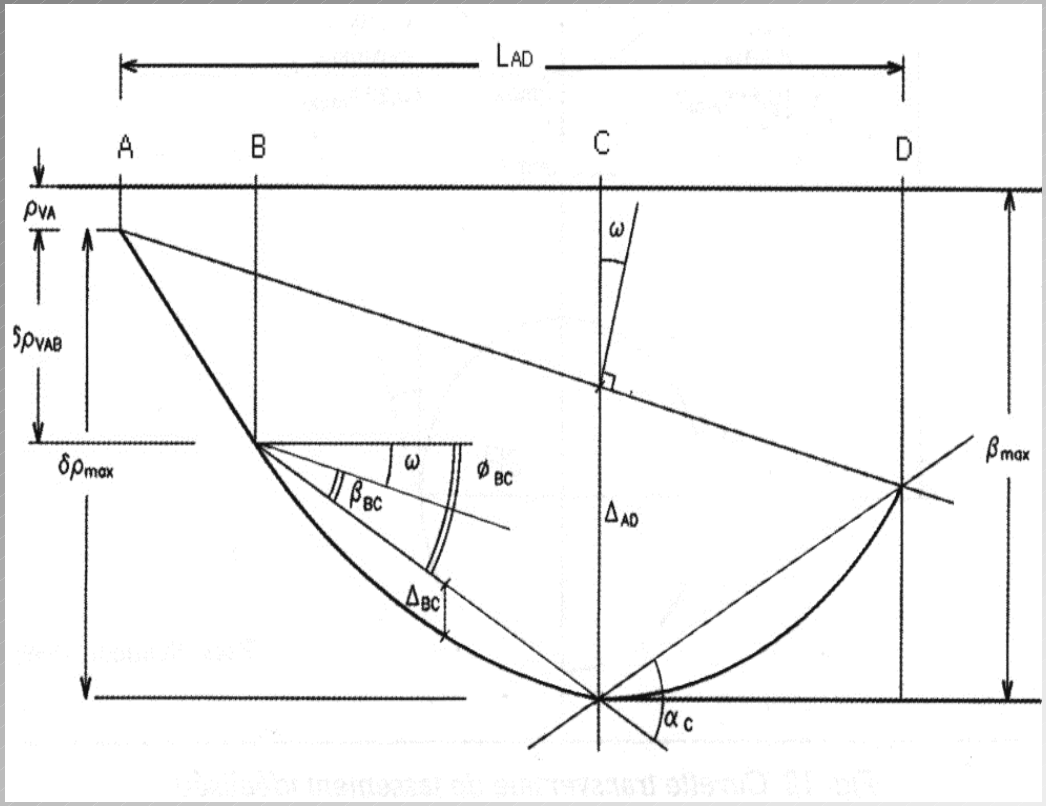
Incidence of Ground Displacements on Existing Structures



Typical Idealized Building Response to Ground Motion

(after Attewell et al, 1986)

Induced Vertical Movements



ρ_{vA}= settlement at A

δ_{vAB}= differential settlement b/w A-B

ω = tilt

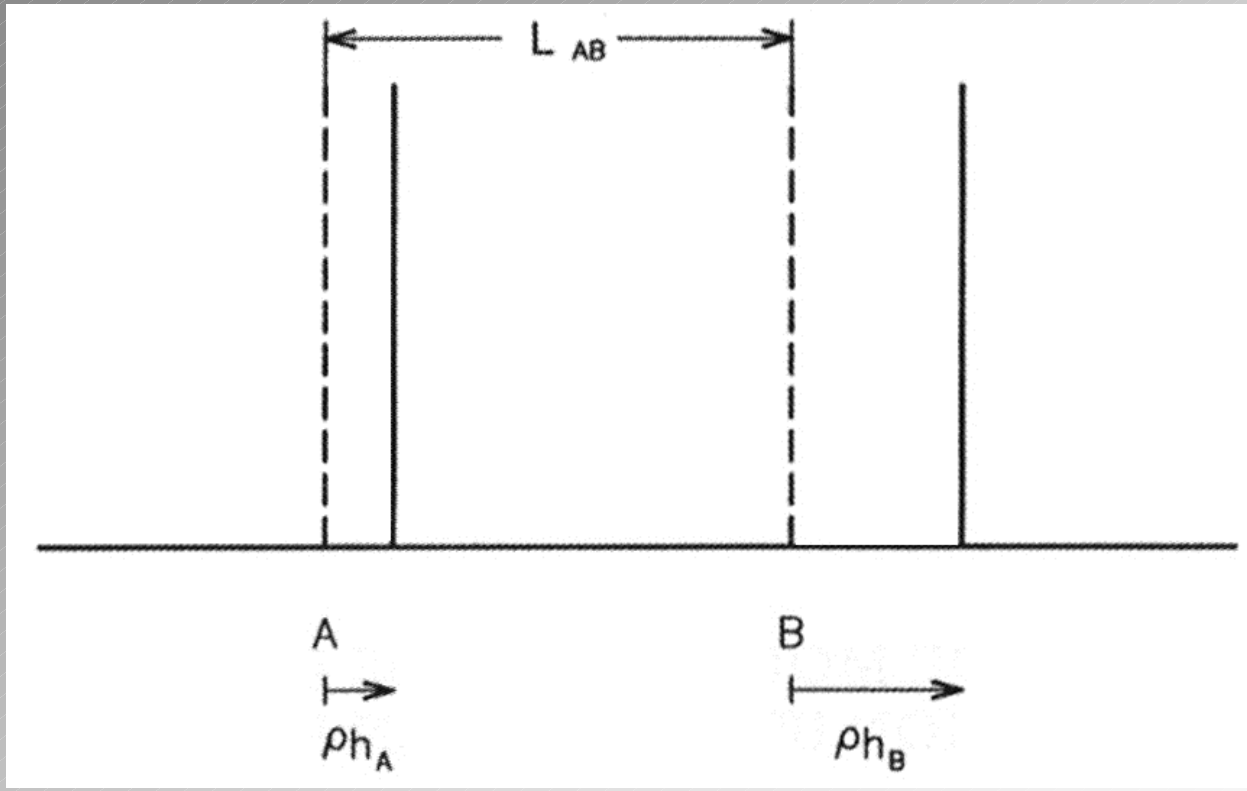
β_{BC}= relative rotation b/w B-C

α_C= angular deformation at C

Δ_{AD}= relative deflection b/w A-D

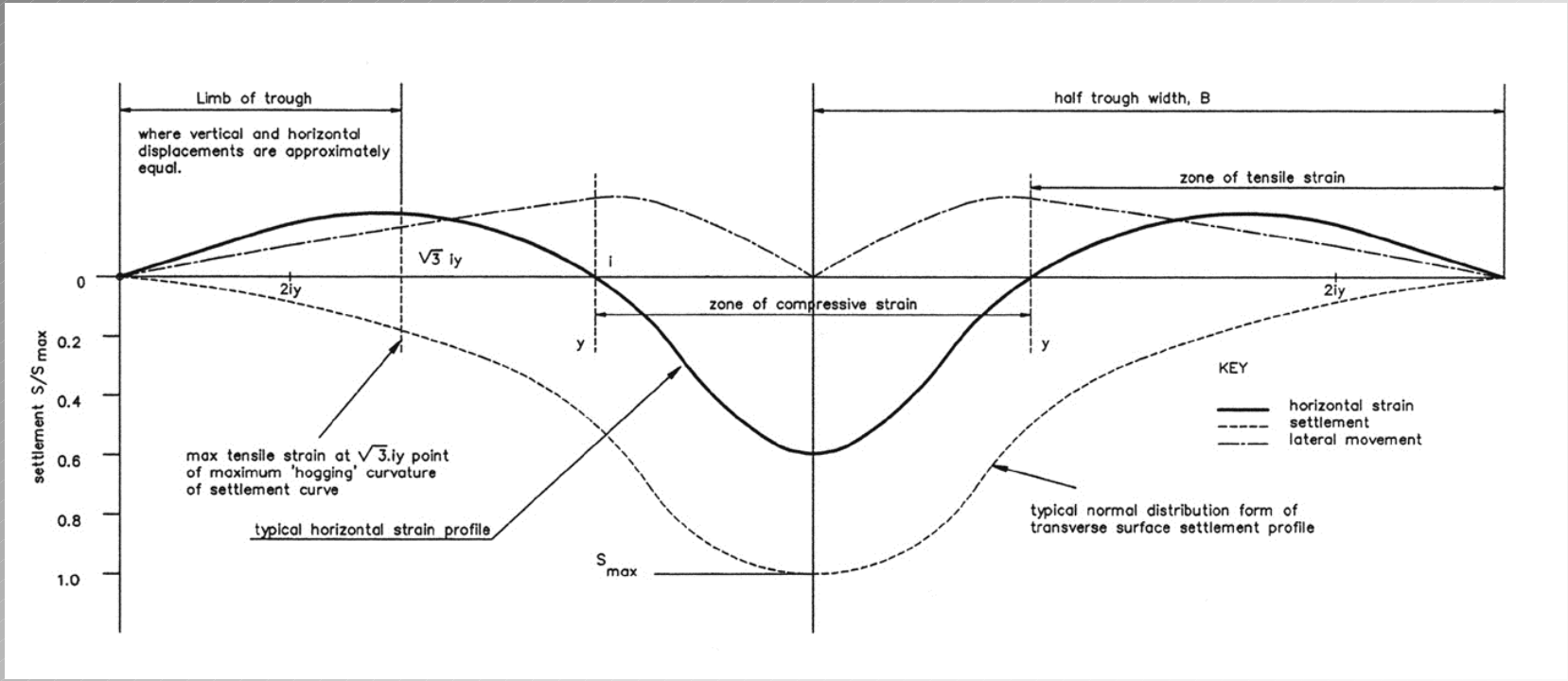
Δ_{AD}/L_{AD}= deflection rate

Induced Horizontal Movements



$$\varepsilon_{hAB}=(\rho_{hA}-\rho_{hB})/L_{AB}$$

Induced Horizontal Deformations



Damage Classification

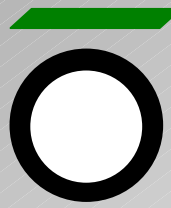
Damage Type	Damage Degree	Damage Description	Crack width (mm)
0	Negligible	Micro-cracks	<0.1
1	Very slight	Architectural	<1
2	Slight	Archit. - to treat	<5
3	Moderate	Functional	5-15 or sev.>3
4	Severe	Structural	15-25 (number)
5	Very severe	Structural	>25 (number)

(after Burland et al, 1977; Burland, 1995; Mair et al, 1996)

Relationship Between Critical Extension and Cracking

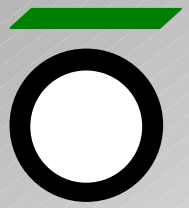
Damage Type	0	1	2	3	4&5
ε_{crit} (%)	≤0.050	0.050< ≤0.075	0.075< ≤0.150	0.150< ≤0.300	0.300<

(after Boscardin & Cording, 1989)



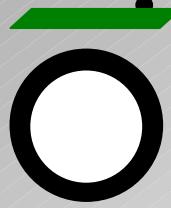
Range of Serviceability Limit State For Standard Structures

Damage Type	Average Slope of Settlement Trough Under Structure (%)	Maximum Settlement of the Structure (mm)
1	< 2	< 10
2	2 < < 4	10 < < 20



Design Methodology

- Phase 1: Investigation of Existing Buildings
- Phase 2: Information Summary
- Phase 3: Selection of Damage Criteria
- Phase 4: Modeling (after Burland, 1995; Mair et al, 1996)
  - Preliminary Assessment
  - Second Stage Assessment
  - Detailed Evaluation
- Phase 5: Determination of Allowable Thresholds
- Phase 6: Back-analysis & Calibration of Models

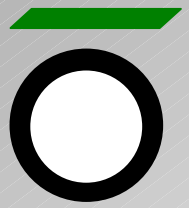


Chapter 5

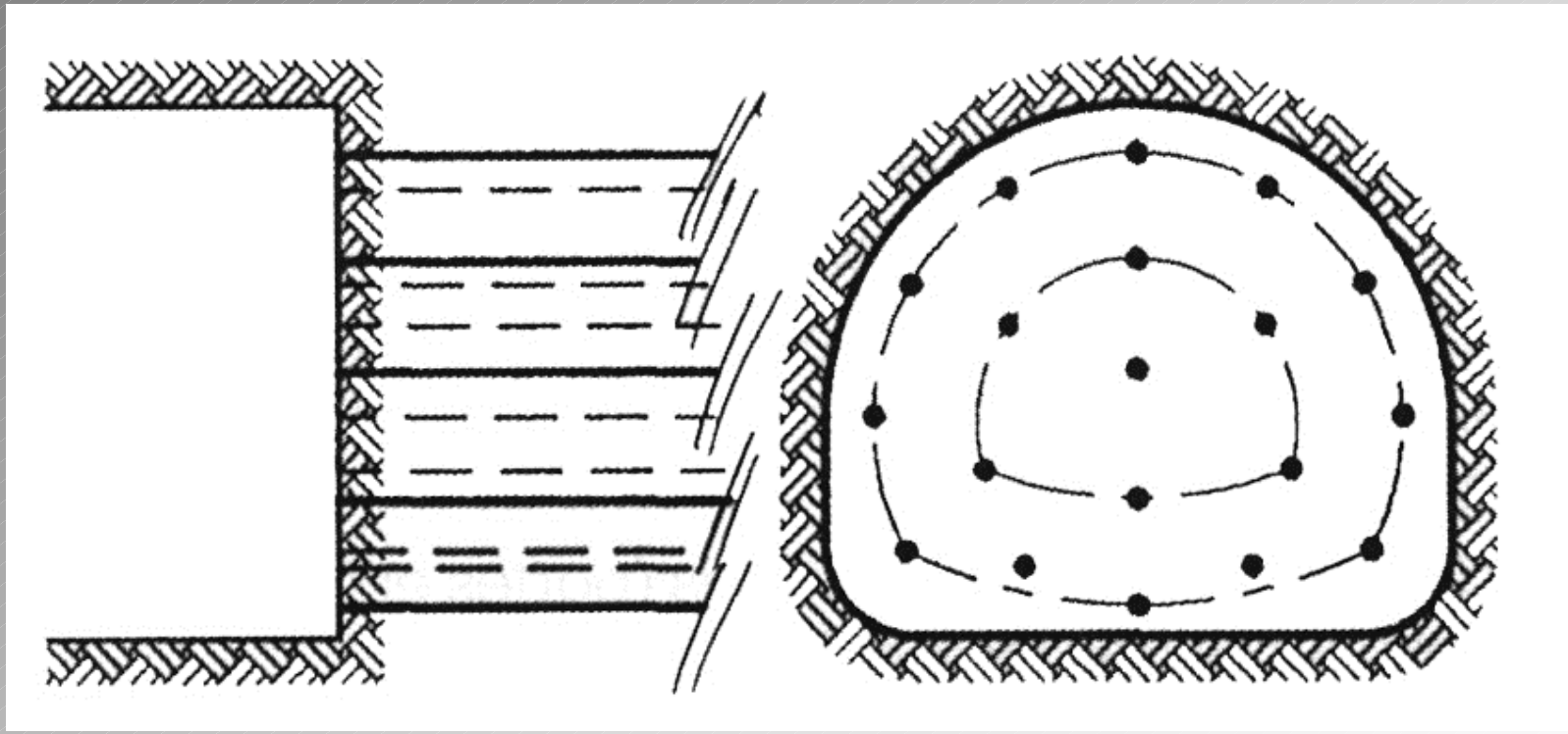
Settlement Control

Preventive & Remedial Approaches

1. Improvement of Overall Project Conditions
   - Aim at larger depth of cover
   - Look for ground layers of good mechanical properties
   - Minimize excavated cross-section
   - Aim at straight alignments
2. Improvement of Ground Characteristics
3. Structural Improvement of Building
4. Improvement During Construction
   a. Sequential/Conventional
   b. Shield Tunneling

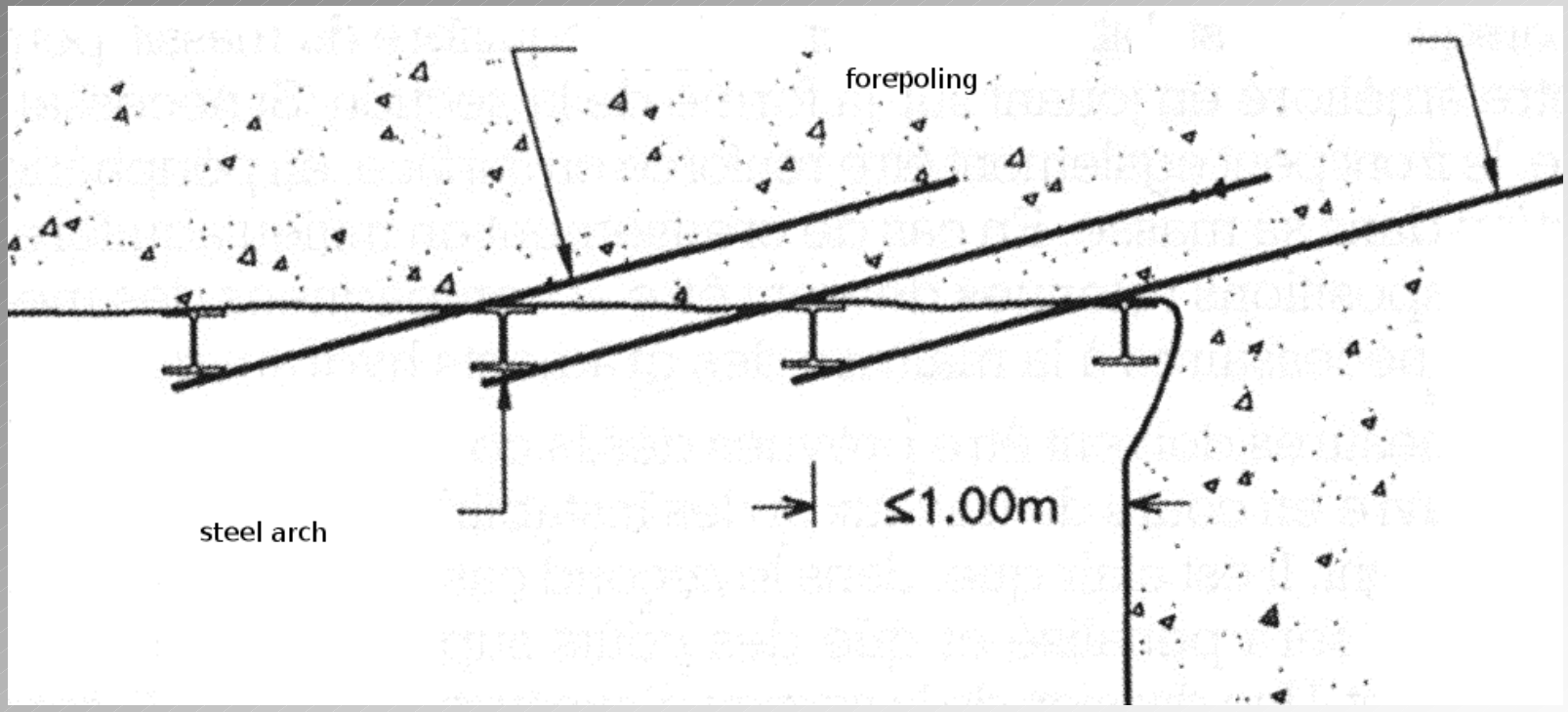


Pre-support



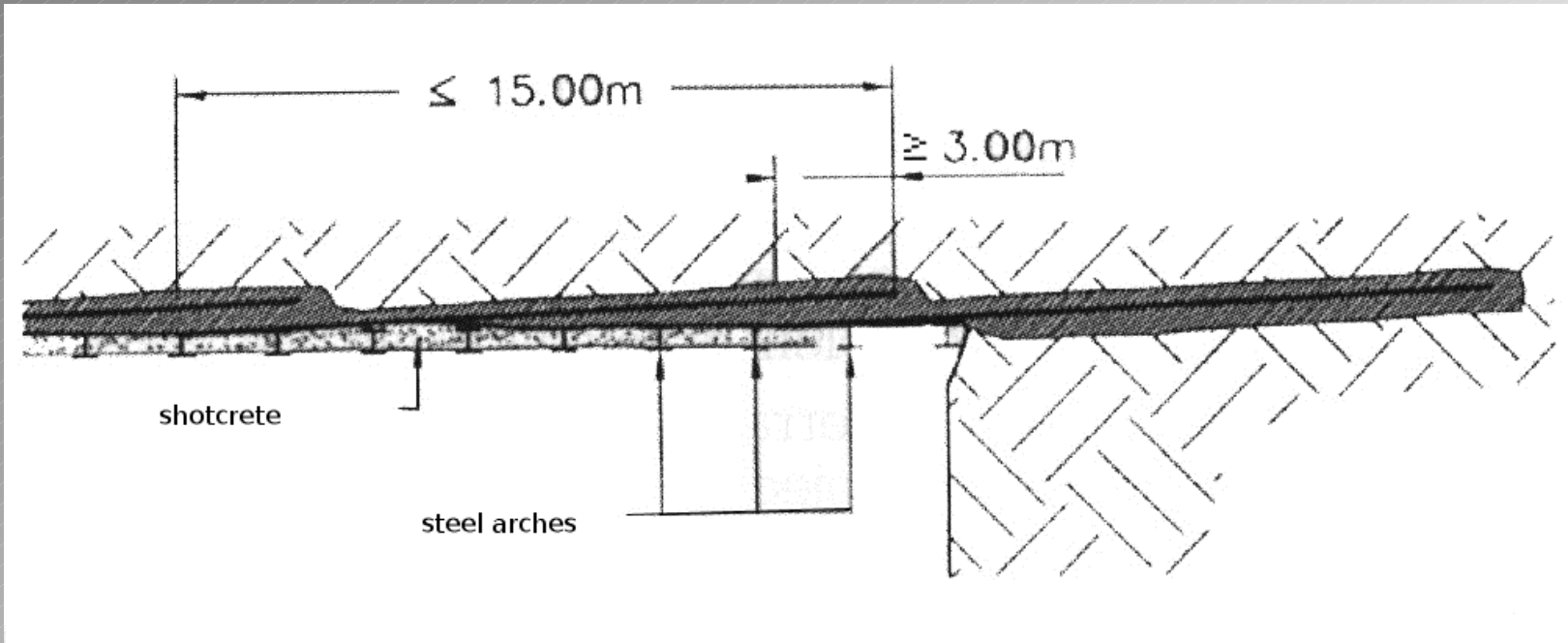
Face Bolting

Pre-support



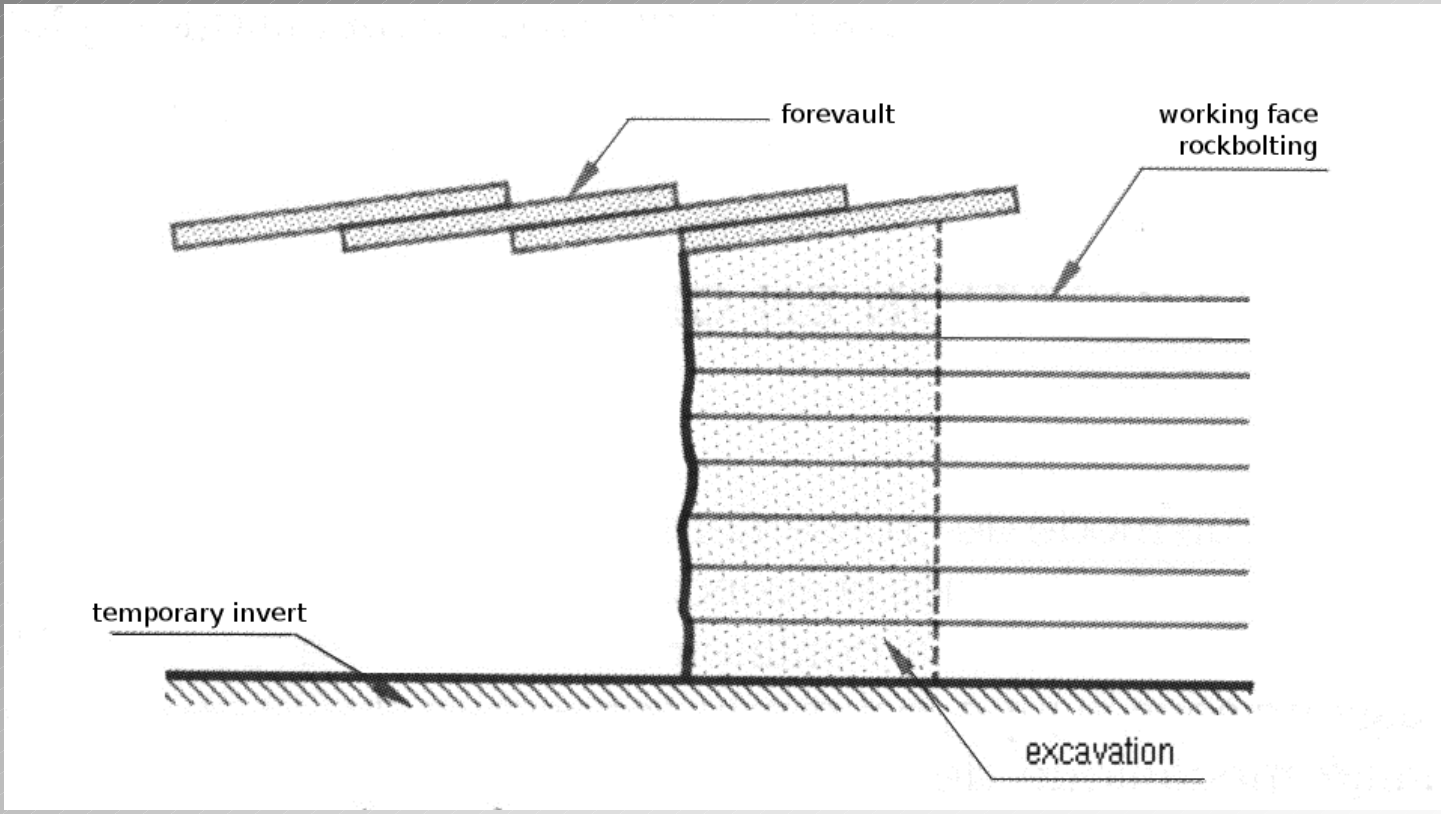
Fore-poling

Pre-support



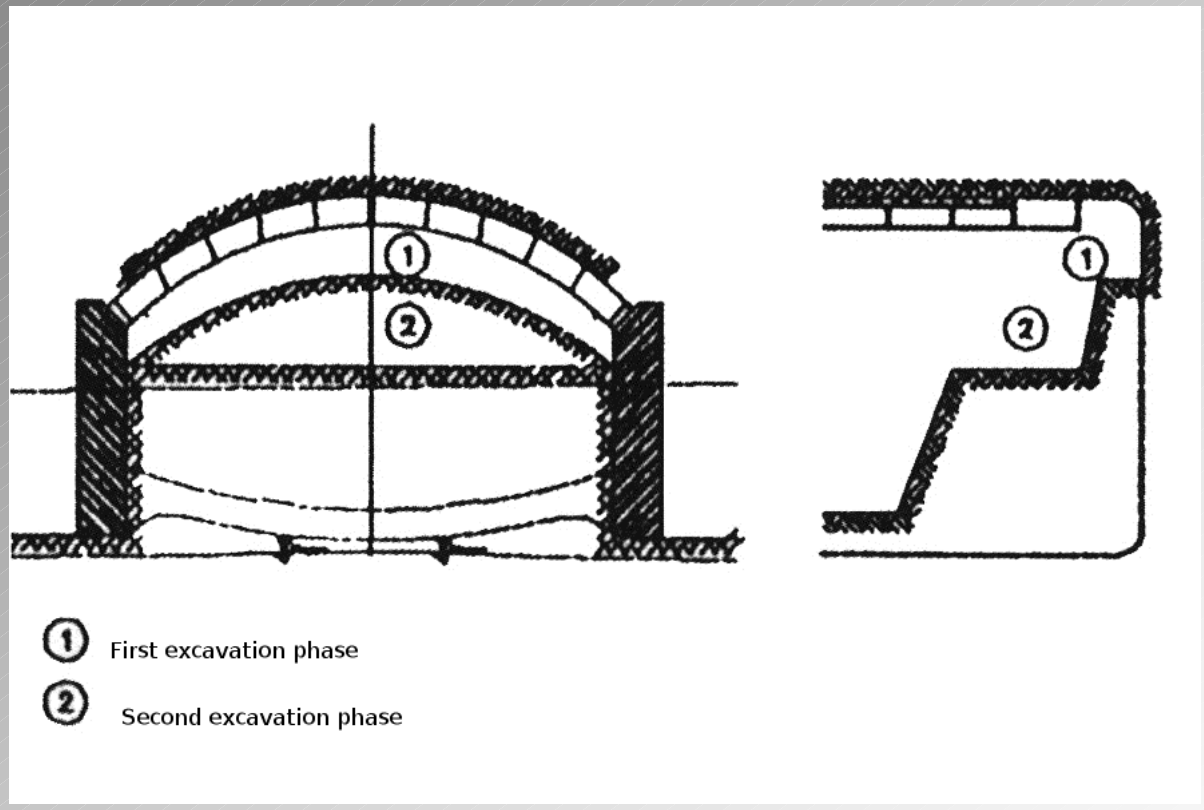
Umbrella Vault

Pre-support



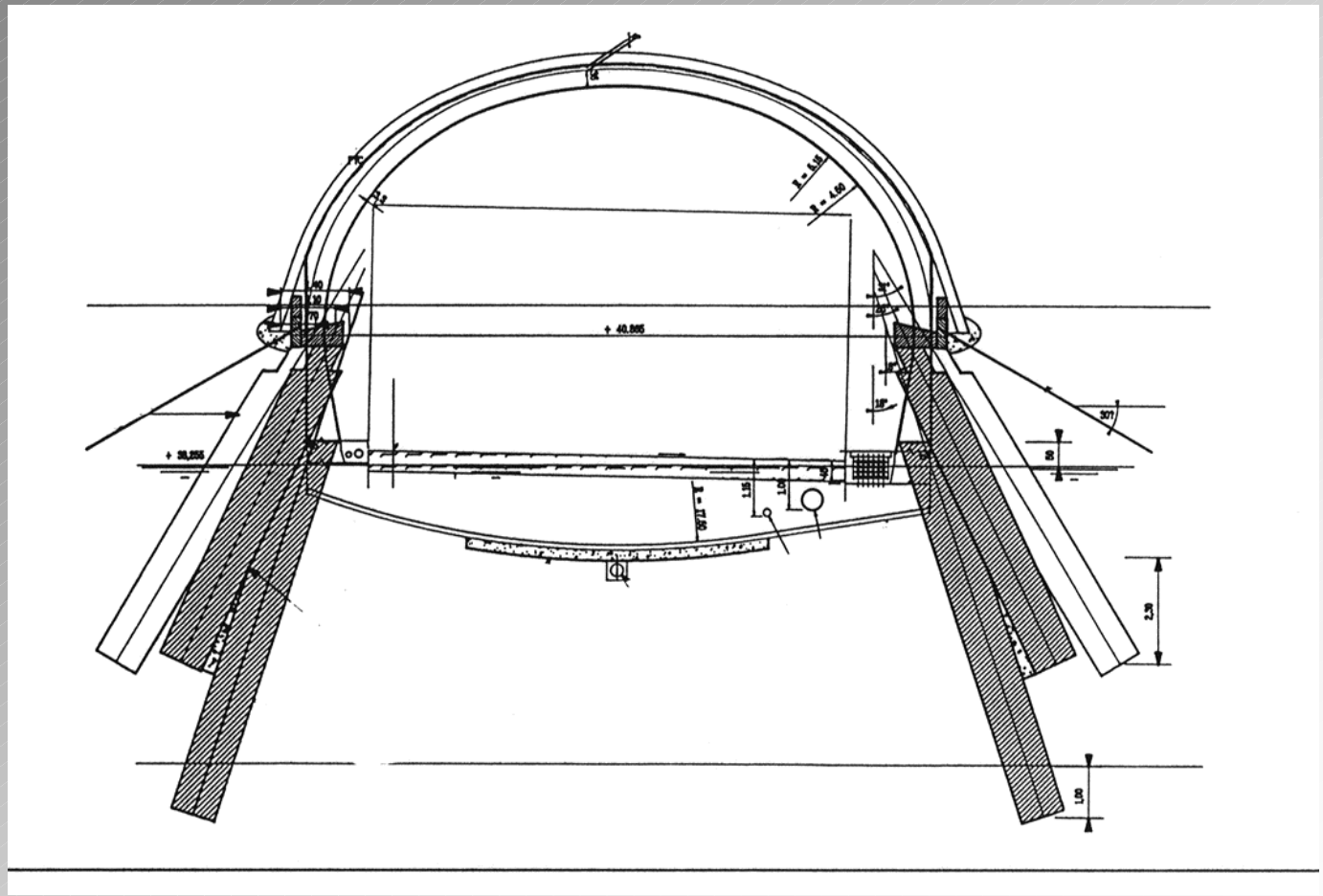
Pre-vault

Crown Support



Expanded Concrete Segment Vault

Underpinning

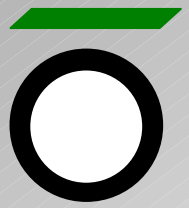


Chapter 6

Observation and Monitoring of Ground Response

Observation & Monitoring

- Inspection
- Instrumentation
  - Monitoring of existing structures
  - Ground measurements
- Monitoring Program

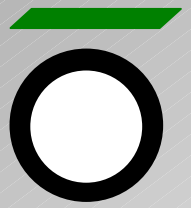


Chapter 7

Contractual Aspects

Contractual Aspects

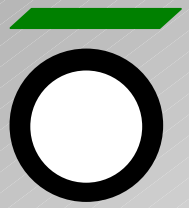
- Usual contractual clauses
- Position of the different players
  - The Owner
  - The Engineer
  - The Contractor



Further Developments and References

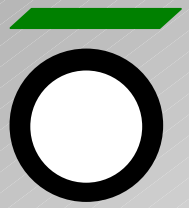
Recommendations and Possible Ways of Improvement

- At Owner – and Engineer - Level
  - Organize preliminary inspections & studies
  - Commission a comprehensive program of studies
  - Set appropriate settlement limits
  - Provide available information at tender stage
- At Contractor's Level
  - Provide assistance required during construction
  - Set accountabilities
- Possible contribution of Insurance Companies
  - Obtain greater technical clarity when defending cases
  - Require risk analyses prior to finalizing binding agreements
  - Exercise greater diligence when reviewing litigious situations



References

- AITES-ITA, Working Group 2: Leca, E. & New, B., “Settlements induced by tunneling in Soft Ground”, Tunnelling and Underground Space Technology (TUST) 2007, 22, Nr. 2, 119-149.
- AFTES, Groupe de Travail n°16 : Leblais, Y., André, D., Dubois, P., Gigan, J.P., Guillaume, J., Leca, E., Pantet, A., Riondy, G., 1994, « Tassements liés au creusement d’ouvrages souterrains », Tunnels et Ouvrages Souterrains (TOS), 132.
- Additional references quoted in WG2 document (TUST, 22)



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