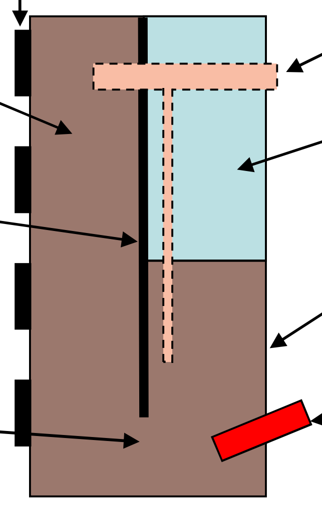

Nick Shirlaw

Ground control for slurry TBM tunnelling
GEO Report 249

Golder Associates

Report 249

GROUND CONTROL FOR
SLURRY TBM TUNNELLING

GEO REPORT No. 249

Golder Associates (HK) Ltd

GEOTECHNICAL ENGINEERING OFFICE
CIVIL ENGINEERING AND DEVELOPMENT DEPARTMENT
THE GOVERNMENT OF THE HONG KONG
SPECIAL ADMINISTRATIVE REGION

Report available on the web since January 2010

Can be downloaded from

http://www.cedd.gov.hk/eng/publications/geo_reports/geo_rpt249.htm

Genesis of Report 249

- An internal report was prepared following the review of submissions for slurry shield tunnelling on KDB 200, part of the Kowloon Southern Link. The review was by Golder Associates (HK) Ltd, under a contract to provide expert advice on tunnel works to GEO
- The internal report was then reviewed by a number of very experienced engineers in Hong Kong, Germany and UK
- The final report has been turned into a GEO Report, made available in order to share technical knowledge with the industry

Contents of Report 249

- Slurry pressure assessment
- Tail void grouting, limiting pressures and volumes
- Excavation management control system (Volume Assessment)
- High risk activities, and discussion of possible control measures
- 60 pages in total, including figures, plates and tables

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Contents of Report 249

- Slurry pressure assessment – the core of the report
  - Factors of safety
  - Effective stress calculations of minimum face pressure at ULS and SLS
  - Total stress calculations of minimum face pressure at ULS and SLS
  - Maximum face pressure
  - Interfaces [between different strata]
  - Variable ground conditions

Contents of Report 249 (Cont.)

- **Slurry pressure assessment – the core of the report (Cont.)**
  - Minimum and maximum acceptable face pressures
  - Compressed air pressures for head access
  - Adjustment of face pressures based on observation
  - Presentation and communication of face pressures
  - Key issues for designers and design checkers

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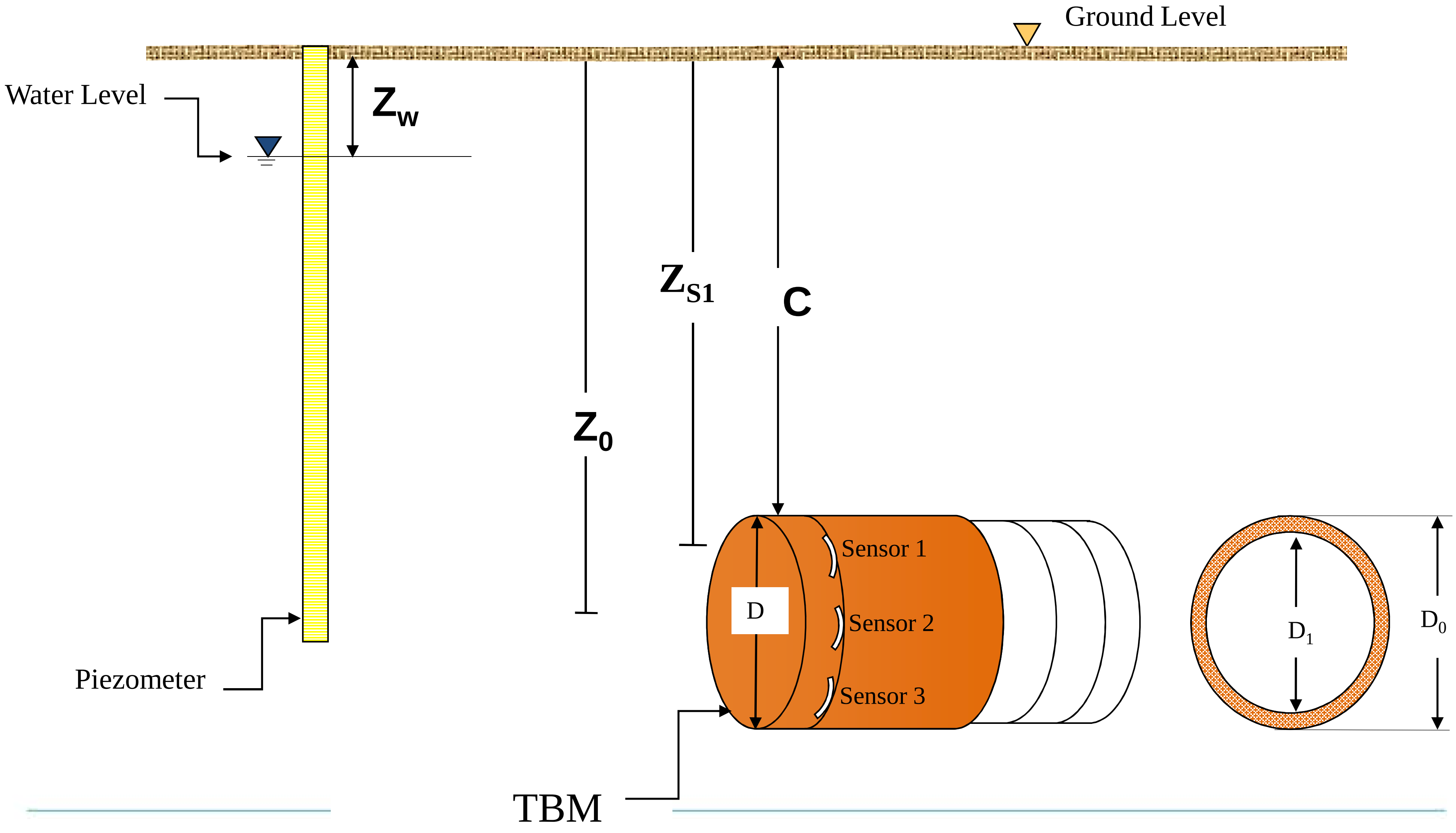
Symbols - TBM



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More symbols

P_S **Pressure in the excavation chamber**

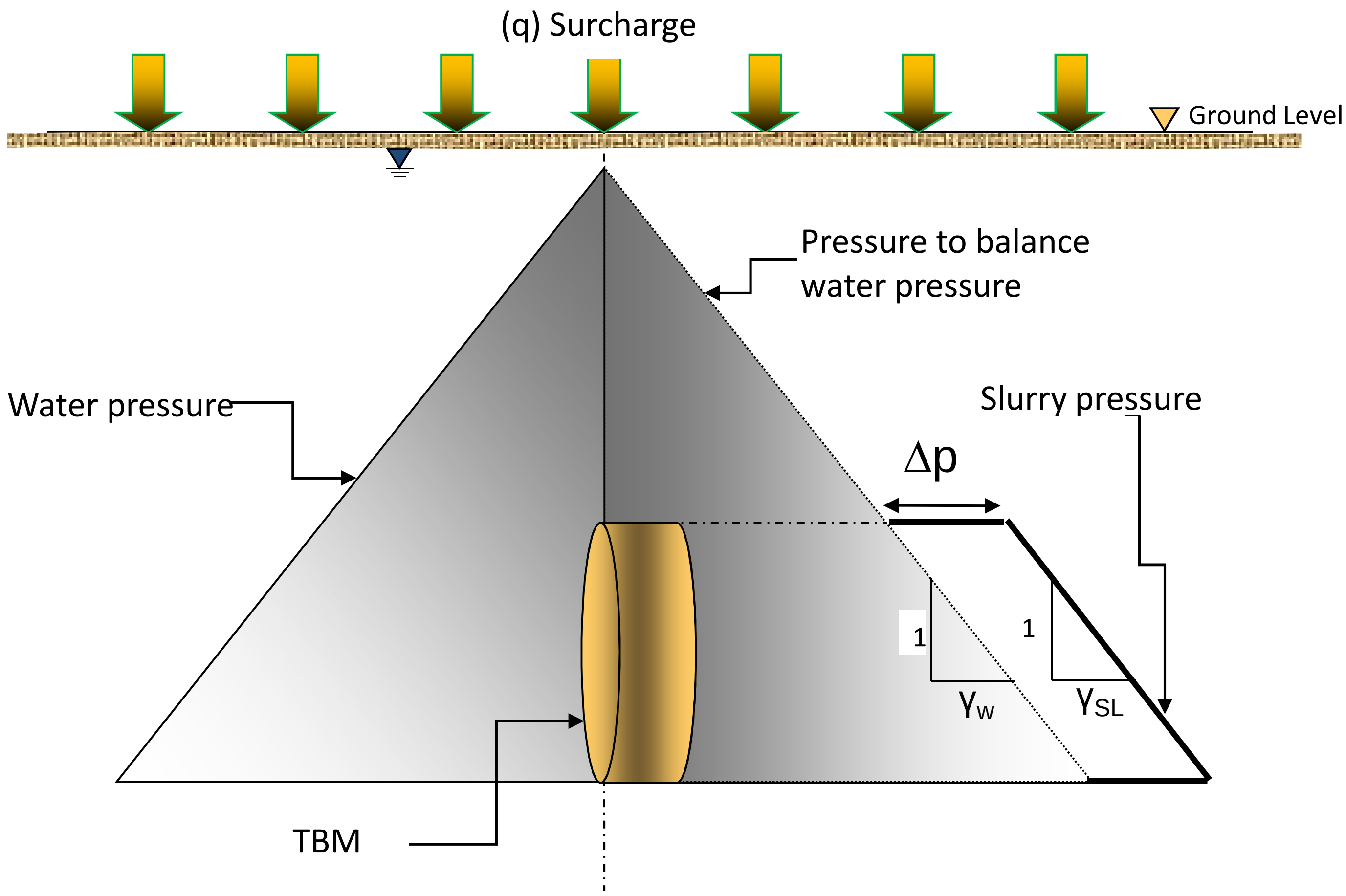
P_{St} **Target pressure in the excavation chamber**

$P_{St(Crown)}$ **Target pressure at the crown of the tunnel**

$P_{St(S1)}$ **Target pressure at sensor 1 (or (S2) for sensor 2, etc.)**

$P_{S(S1)}$ **Slurry pressure measured at sensor 1 (or (S2) for sensor 2, etc.)**

Face pressure – variation with sensor location



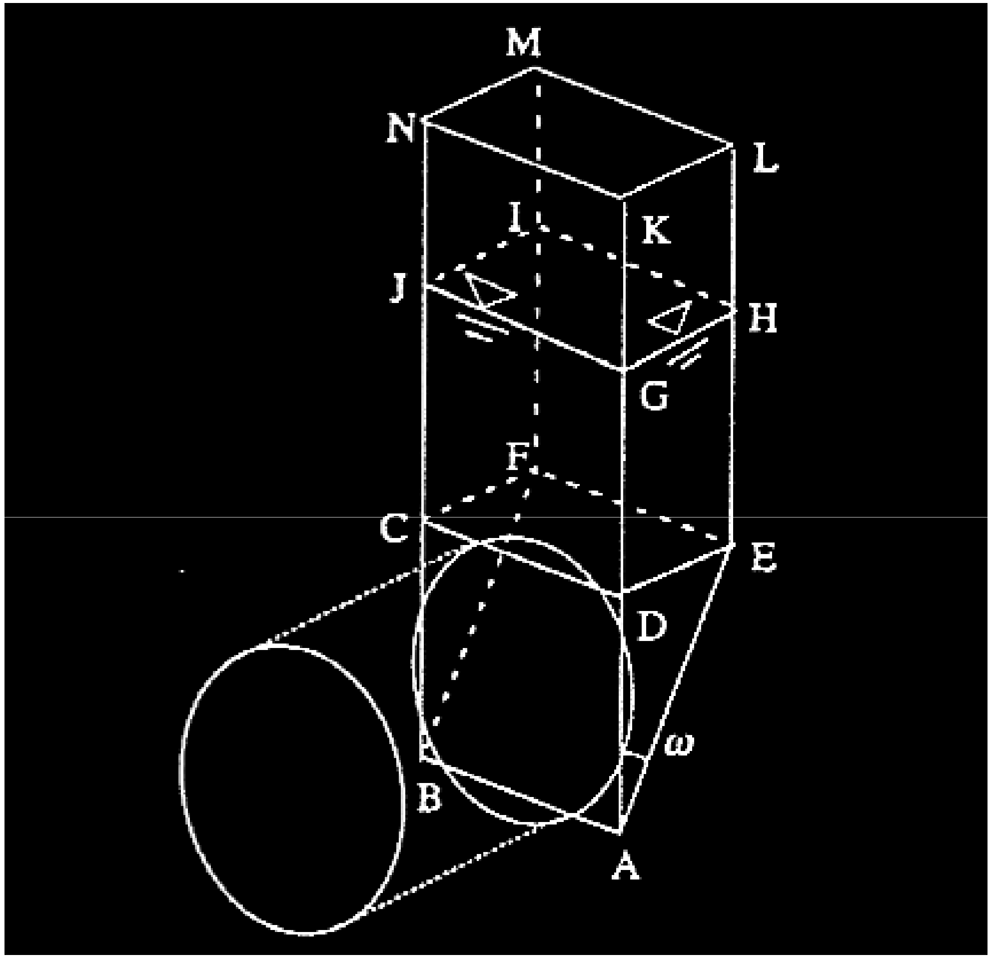
Basis for calculating minimum target face pressures

- For slurry shields face pressure is generally based on effective stress. Need to check that total stress calculations do not govern where tunnel is in fine-grained soils
- Need to check for both ULS and SLS conditions
- Minimum Partial Factors of Safety required:

	ULS	SLS
γ,γ’	1.0	1.0
c’, tanϕ’	1.2	1.0
S_U	1.5	1.0
q	1.5	1.0

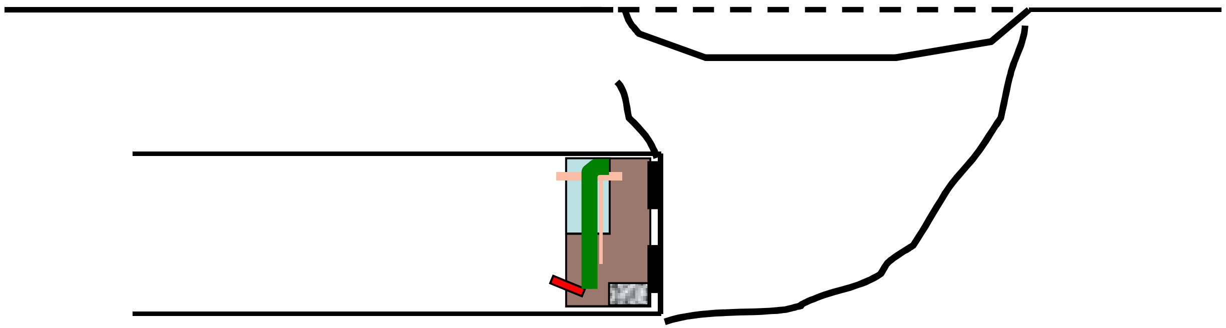
For water pressure, use most onerous likely pressure, and partial factor of 1.0

Failure surface – tunnel in sand, after Horn (1961)

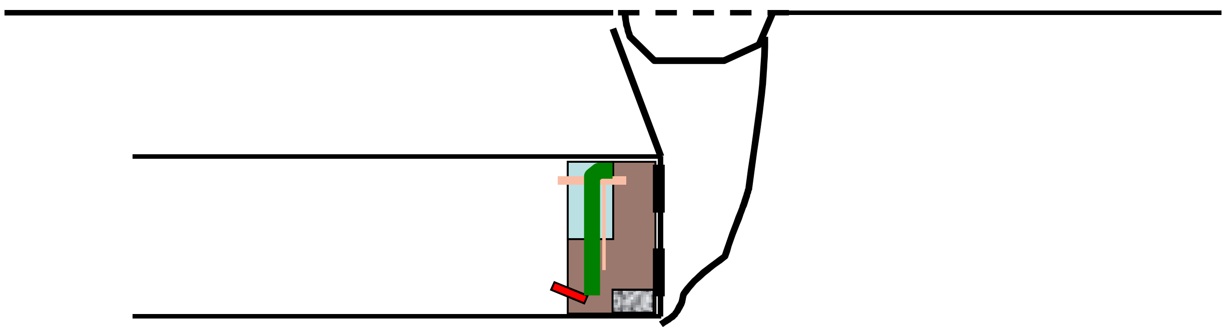


Used in subsequent work by Anagnostou and Kovari (1996)

Failure Mechanisms based on Centrifuge Model Tests (Mair, 1979)



Clays



Sands

The Horn model is reasonable for sands, but not for clay

Effective support pressure needed

Anagnostou and Kovari (1996):

$s' = F_O\gamma'D – F_1c' + F_2\gamma'\Delta h - F_3c'\Delta h /D$

where F_O to F_3 are dimensionless coefficients, Δh is the difference between the original piezometric head at tunnel level (h_o) and that in the chamber (h_f). If the chamber pressure exceeds the water pressure, then:

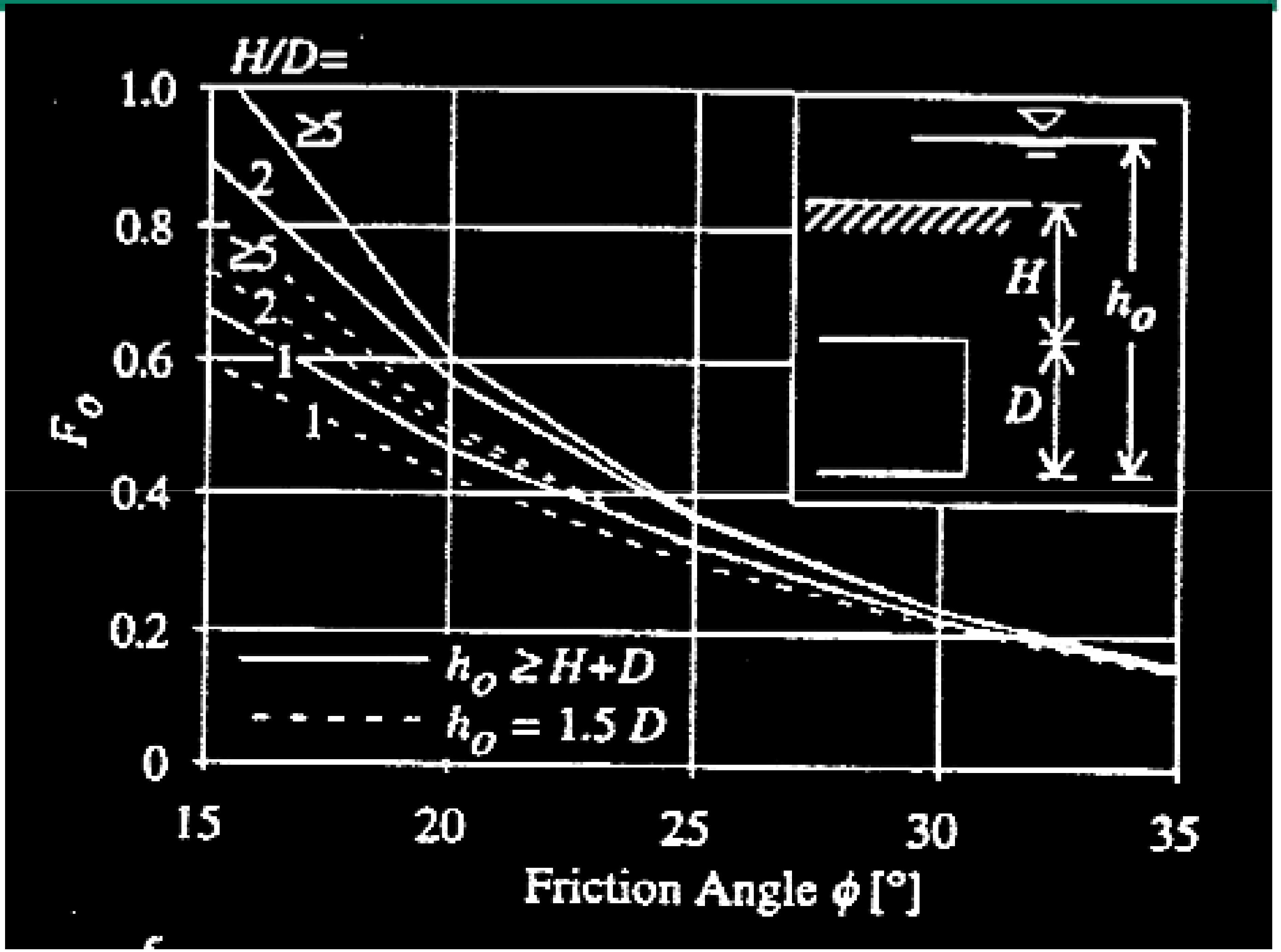
$s' = F_O\gamma'D – F_1c'$,

and if $c' = 0$ then:

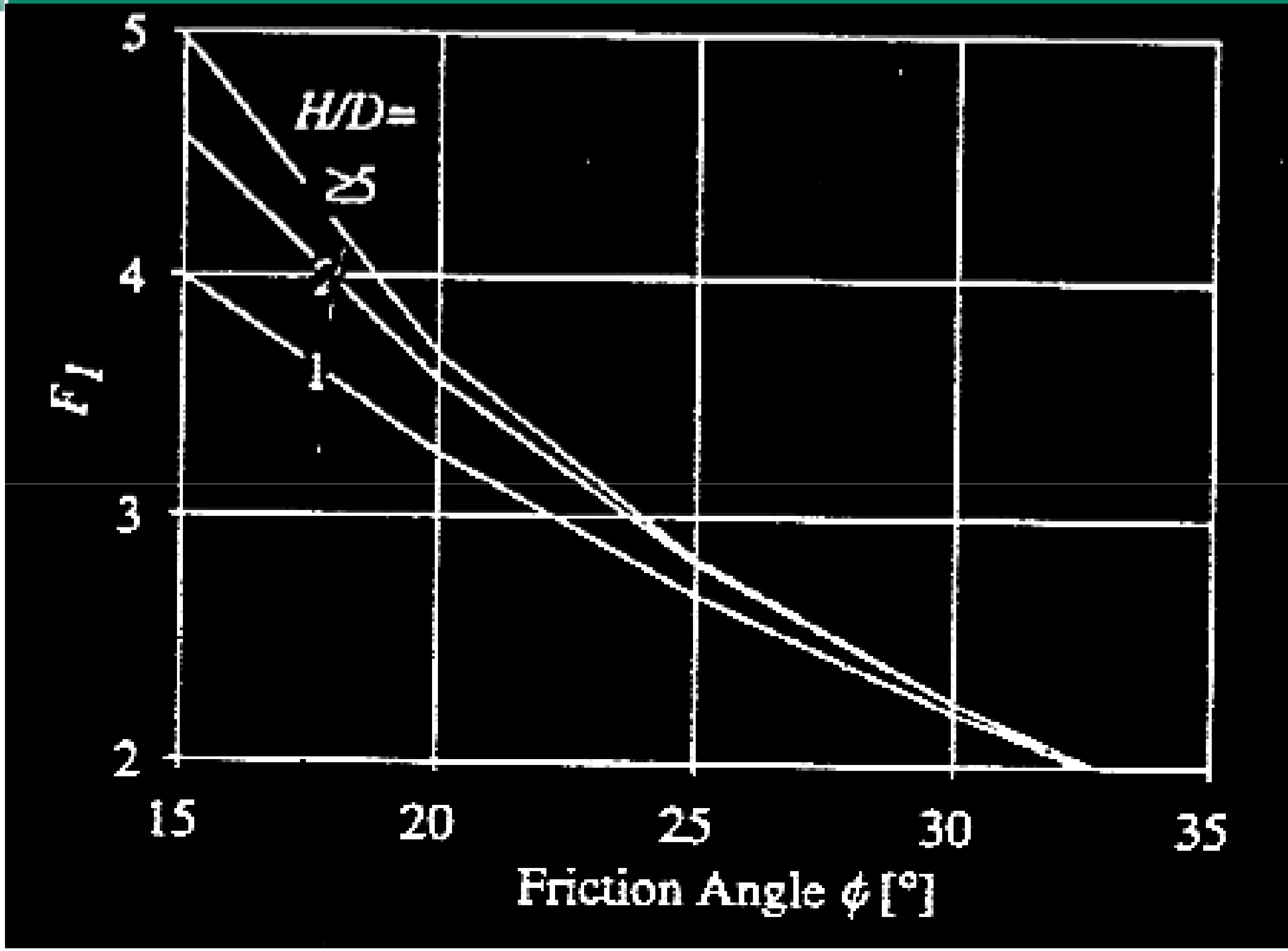
$s' = F_O\gamma'D$ [the pressure to support the soil skeleton, the water pressure needs to be added to obtain total pressure]

F_O – from Anagnostou and Kovari

For H/D =2,
Factored tanΦ'
F_O =
0.20 for dense sand
0.25 for medium sand
0.31 for loose sand



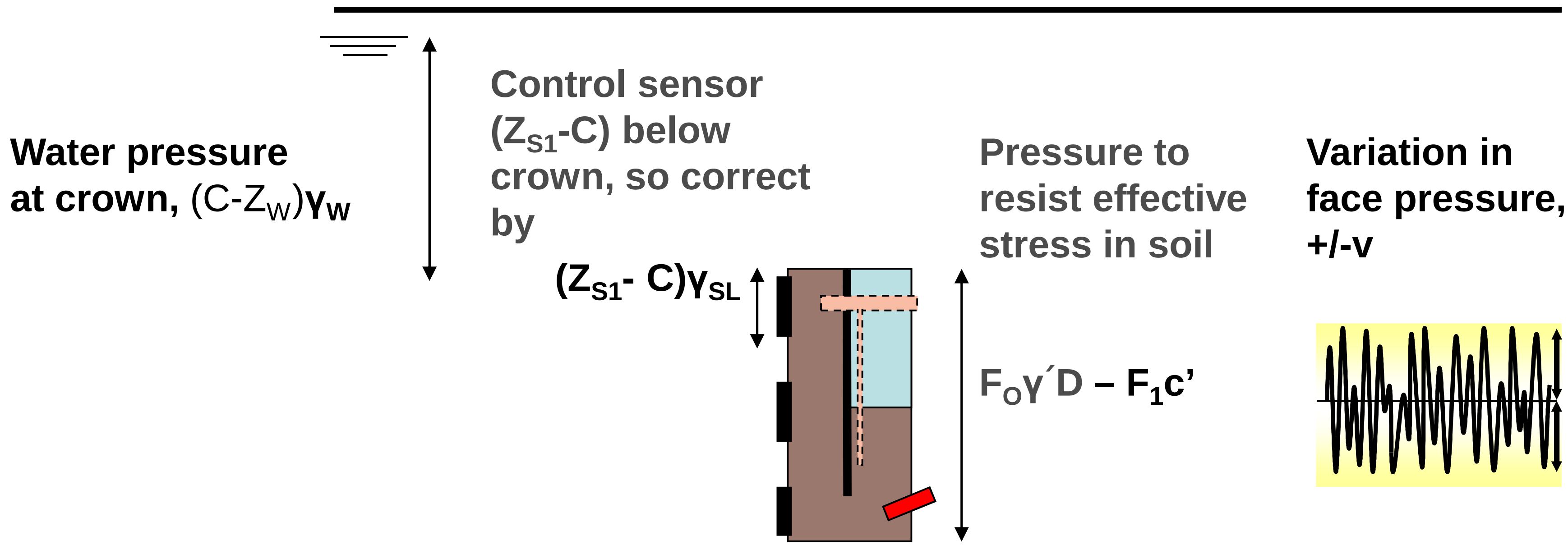
F_1 – from Anagnostou and Kovari



Basis for calculating target face pressures at ULS

- Effective stress calculations at ULS based on Anagnostou and Kovari (1996). If the face pressure exceeds the water pressure, and a filter cake is formed:

$$P_{target} = (C-Z_W)\gamma_W + (Z_{S1} - C)\gamma_{SL} + F_O\gamma'D - F_1c' + \text{variation}$$



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Example for calculating target face pressure at ULS in medium sand

- Example of calculation with axis level 31.85m below ground level, C = 28.5m, D = 6.7m, Z_W = 1.5m:

$$P_{target} = (C-Z_W)\gamma_W + (Z_{S1} - C)\gamma_{SL} + F_O\gamma' D - F_1 c' + v$$

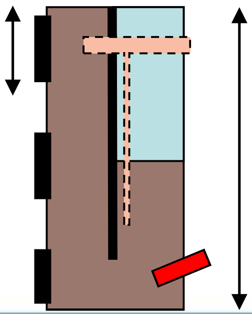
$$P_{target} = 27 \times 10 + 1 \times 11.5 + 0.25 \times 10 \times 6.7 + 20 \text{ kPa}$$

$$P_{target} = 270 + 11.5 + 16.75 + 20 = 318.25 \text{ kPa} = 3.2 \text{ bars}$$

Water pressure at crown, $(C-Z_W)\gamma_W$

Control sensor 1m below crown, so correct by

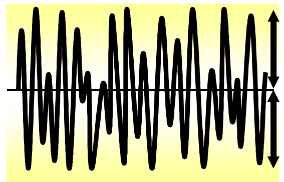
1 x γ_{SL}



Pressure to resist effective stress in soil

$F_O\gamma' D - F_1 c'$

Variation in face pressure, +/-v



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Effective stress calculations - SLS Case

- Limited theoretical basis
- By comparing pressures with design pressures on rigid tunnel linings:

$$P_{St(S1)} = F\gamma' D + \gamma_w (C - Z_w) + \gamma_{SL}(Z_{S1} - C) + v$$

where:

F = 0.25 for Dense Saprolite (SPT >30)

F = 0.40 for Medium Saprolite or Residual Soil (SPT 10-30)

F = 0.55 for Loose Granular Superficial Deposit (SPT <10)

To target 1% Volume Loss

Example for calculating target face pressure at SLS in medium saprolite

- Example of calculation with axis level 31.85m below ground level, C = 28.5m, D = 6.7m, Z_W = 1.5m:

$$P_{target} = P_{target} = (C\text{-}Z_W)\gamma_W + (Z_{S1} - C)\gamma_{SL} + F_O\gamma' D - F_1 c' + v$$

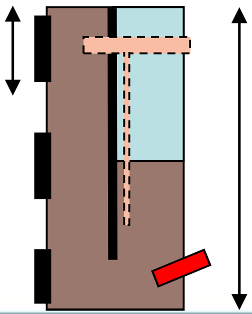
$$P_{target} = 27 \times 10 + 1 \times 11.5 + 0.4 \times 10 \times 6.7 + 20 \text{ kPa}$$

$$P_{target} = 270 + 11.5 + 26.8 + 20 = 328.3 \text{ kPa} = 3.3 \text{ bars}$$

Water pressure at crown, $(C\text{-}Z_W)\gamma_W$

Control sensor 1m below crown, so correct by

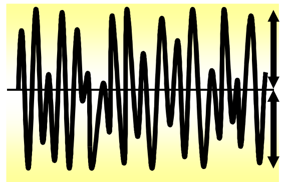
1 x γ_{SL}



Pressure to resist effective stress in soil

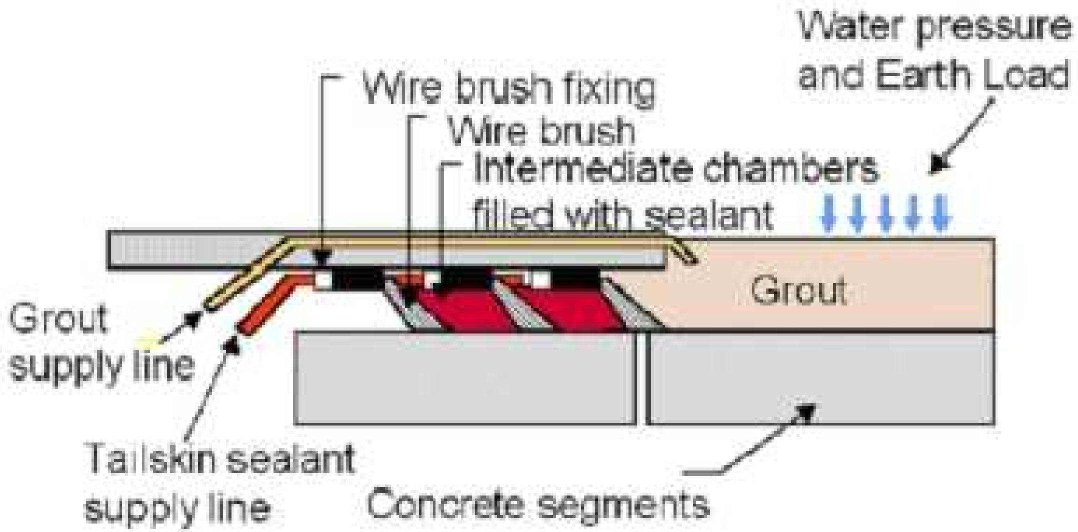
$F_O\gamma' D - F_1 c'$

Variation in face pressure, +/-v



Losses at tail void

- Face pressure not the only factor in settlement – need to consider loss at tail void
- With good grouting typically about 15% to 20% of theoretical volume of the tail void will close in soft or loose soils
- Figure may reduce with improved technology



Other issues – heave and/or loss of of slurry

- Need to consider maximum allowable face pressure – excessive heave is a ULS case
- Need to check the presence of unfilled boreholes

Loss of slurry onto road

Leakage of air into the excavation chamber led to an ‘airlift’ effect up an old borehole

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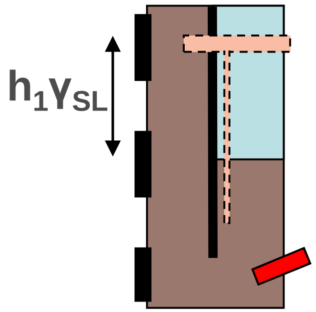
Basis for calculating target face pressures – Total stress

- Total stress calculations can be based on data from model tunnels tested in a geotechnical centrifuge
- Minimum pressure to achieve ULS:

$$P_{target} = (\gamma Z_O + q) - h_1\gamma_{SL} - N_C S_U/F_S + v$$

Total overburden pressure and surcharge, γZ_O + q

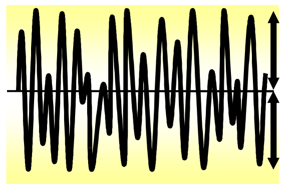
Control sensor 2.35m above axis, so correct by



Effect of shear strength

$N_C S_U/F_S$

Variation in face pressure, +/-v



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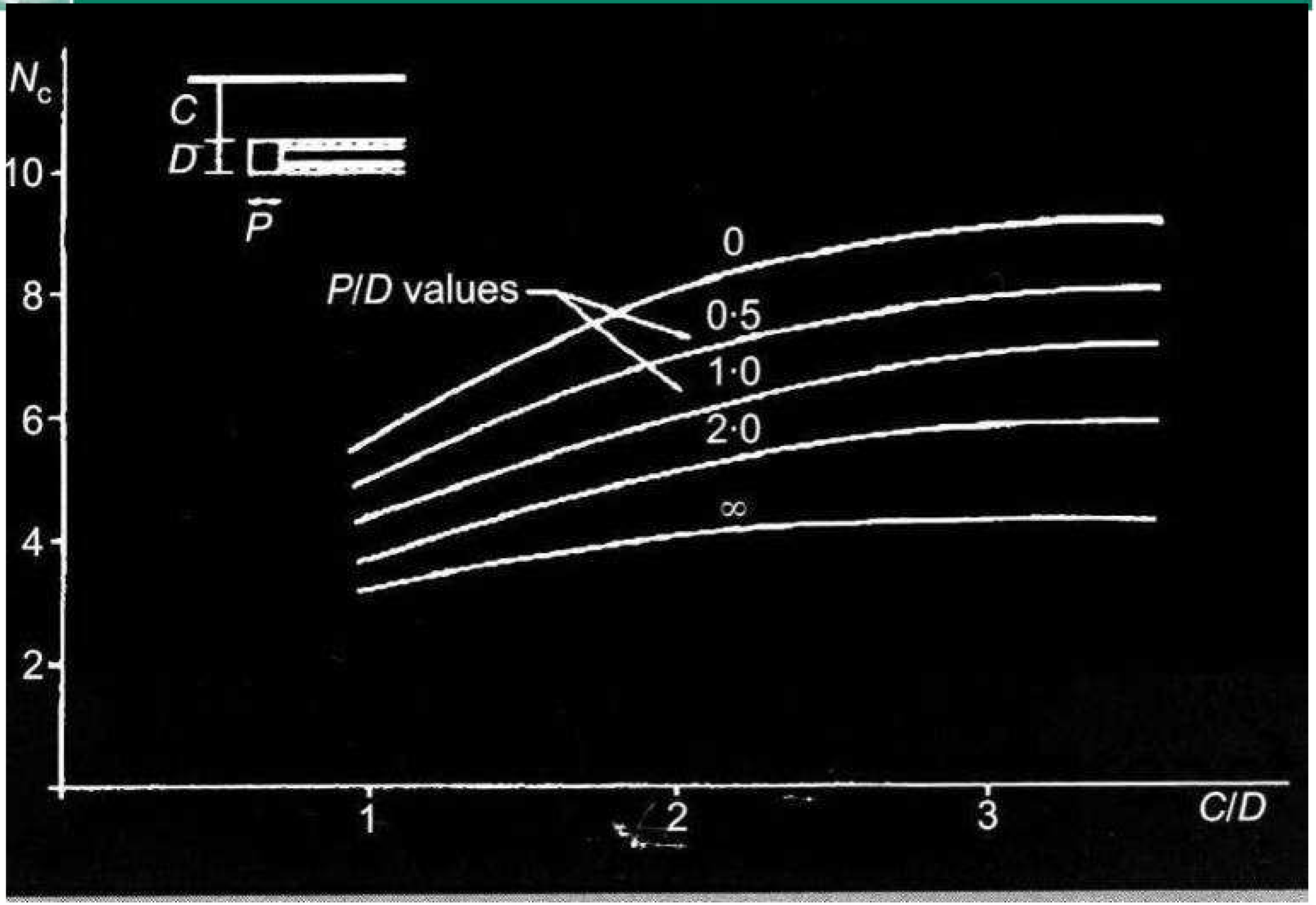
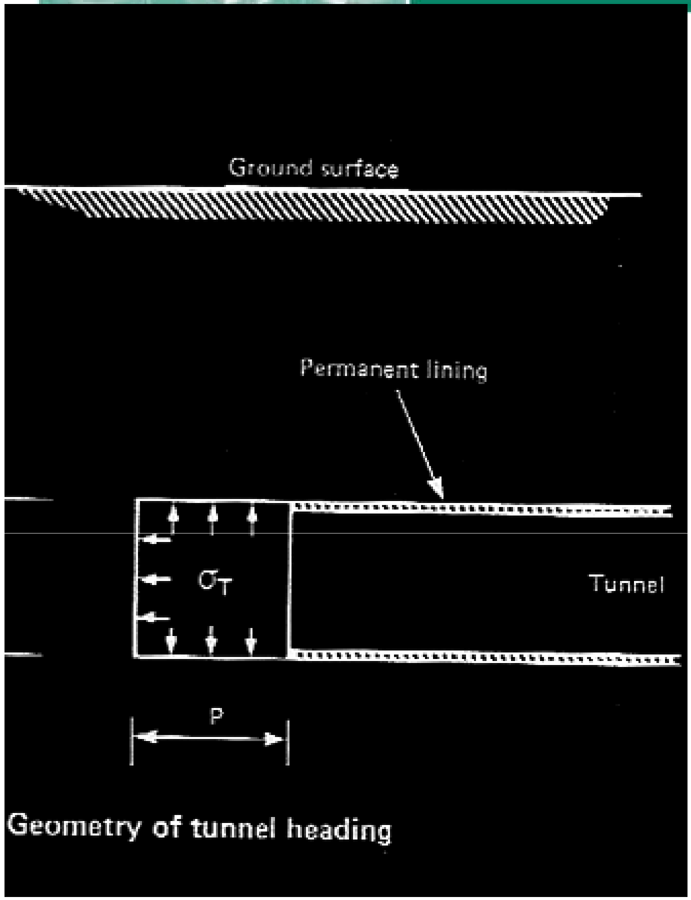
Influence of heading geometry on stability number at collapse



Kimura and Mair (1981)

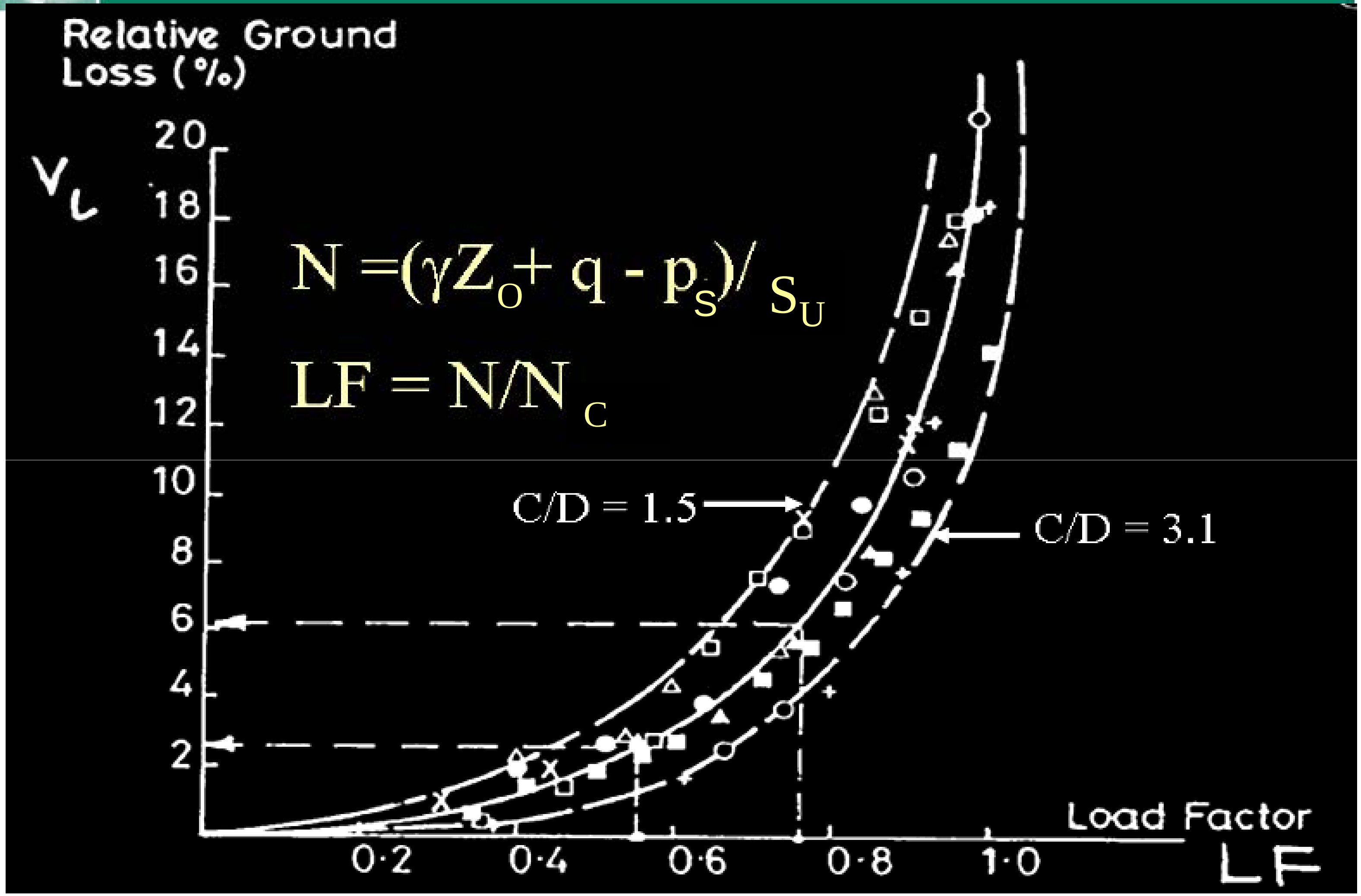
Heading geometry - P



Heading geometry - P

Type of shield	ULS Calculation	SLS calculation
Slurry	P=0	P=L
EPB	P=0	P=0, but add V_l due to overcut closure
EPB with slurry injection around skin, pressure = face pressure	P=0	P=L

Basis for total stress calculation at SLS



Kimura and Mair (1981)

Volume loss vs load factor

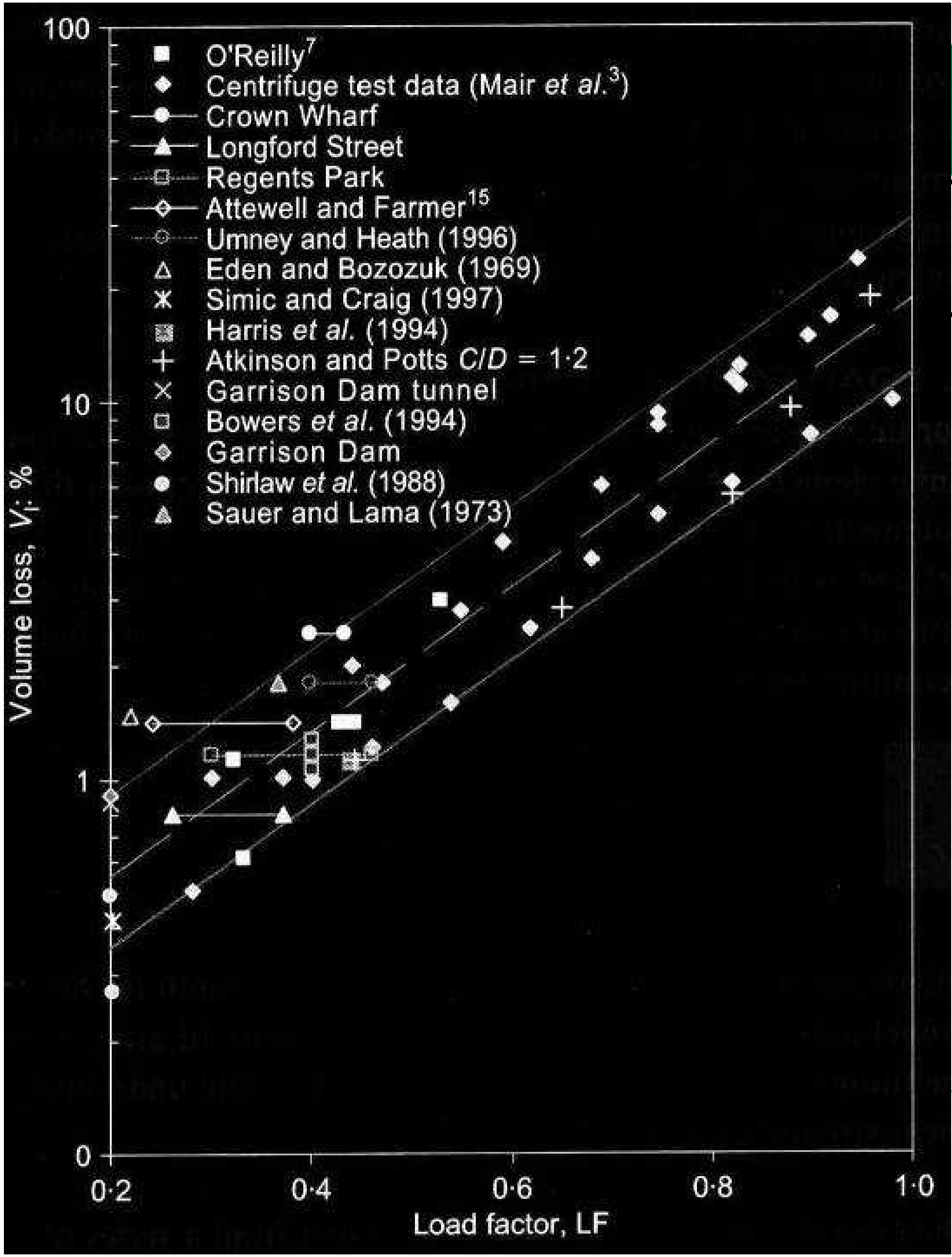


Figure from Dimmock and Mair (2007)

$$V_l = 0.23\ e^{4.4(LF)}$$

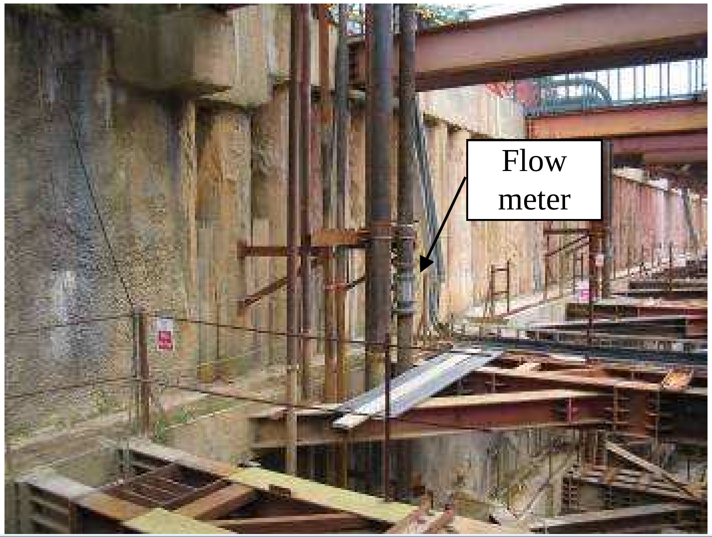
for LF > 0.2

At ULS (LF = 0.67)

V_l = 4.39% + closure of gaps around skin, at tail void

Excavation Management Control (EMC)

- Establish net dry weight of soil removed and compare with theoretical dry weight
- Accuracy typically +/- 5 to 10% [can be even worse]
- Not accurate enough to control SLS case, but gives warning of possible ULS (very large settlement or sinkhole)
- Face pressure is the primary control, EMC is a valuable back-up control



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Very large, localised settlements, generally because of over-excavation, inadequate face pressure

SOUTH CHINA MORNING POST MONDAY, JUNE 4, 2007

Section of Salisbury Road subsides, causing gas leak, closure of lanes

KCR tunnelling suspected in TST cave-in

Over 100 incidents worldwide in last 10 years over EPB and slurry shield drives

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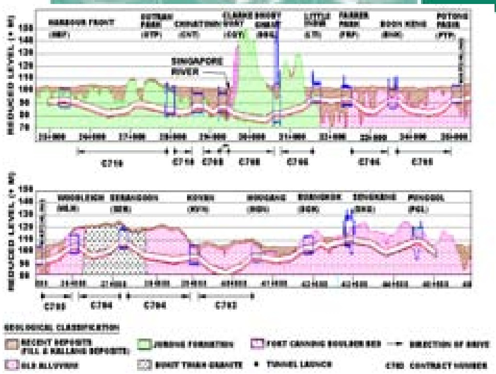
Risk areas for large settlements or sinkholes

- Launching
- Break-through
- Interfaces, between strata of contrasting strength
- **Mixed face of rock and soil**
- **Head access (interventions)**
- **Mechanical problems (particularly for long drives in abrasive soil or rock)**
- Extended periods of flushing

Circle Line work causes cave-in off Holland Road

Examples of risk mitigation measures are given in the report

Practical basis and use of Report 249



Calibrated against results of 20 EPB drives, North East Line, Singapore

Developed from assessment of face pressures for 2 x slurry and 2 x EPB drives in Singapore, and 2 x slurry drives in Hong Kong

Used for target face pressures for EPB driven sewer tunnel in Melbourne

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Questions?