Soft ground tunnelling

Nick Shirlaw

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TUNNELMAN'S CLASSIFICATION

Squeezing	Plastic squeeze into tunnel. Soft to medium clays, Stability Number 5 to 9
Flowing	Soil and water flows into the tunnel. Silts and sands below the water table
Running	Dry granular materials run back to angle of repose. Sands above the water table
Ravelling	Chunks of material progressively drop out. Fractured materials, lightly cemented sands.
Swelling	Ground absorbs water, slowly swelling into tunnel. Swelling clays, desiccated soils.
Firm	Ground has sufficient 'stand-up time' to allow heading to be advanced, lining installed

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SQUEEZING BEHAVIOUR - SOFT CLAY

FLOWING BEHAVIOUR, SAND FILL

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FIRM BEHAVIOUR - HARD CLAY

METHODS OF TUNNELLING THROUGH (UNSTABLE) SOFT GROUND

- Use pressurised shield methods: Earth Pressure Balance shield, Slurry shield, plenum shield
- Use other methods to stablise the ground: Compressed air, dewatering, chemical grouting, jet grouting, ground freezing, often in combination with open face shield
- Mixed mode machines becoming available

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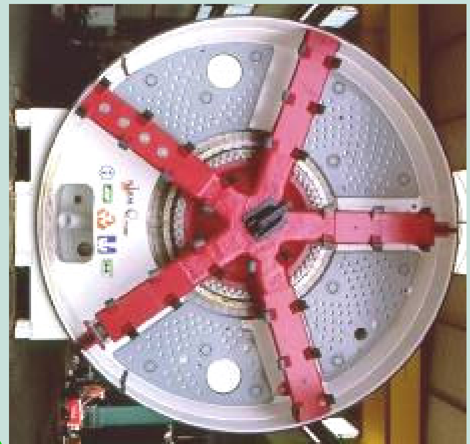
Slurry



Compressed Air

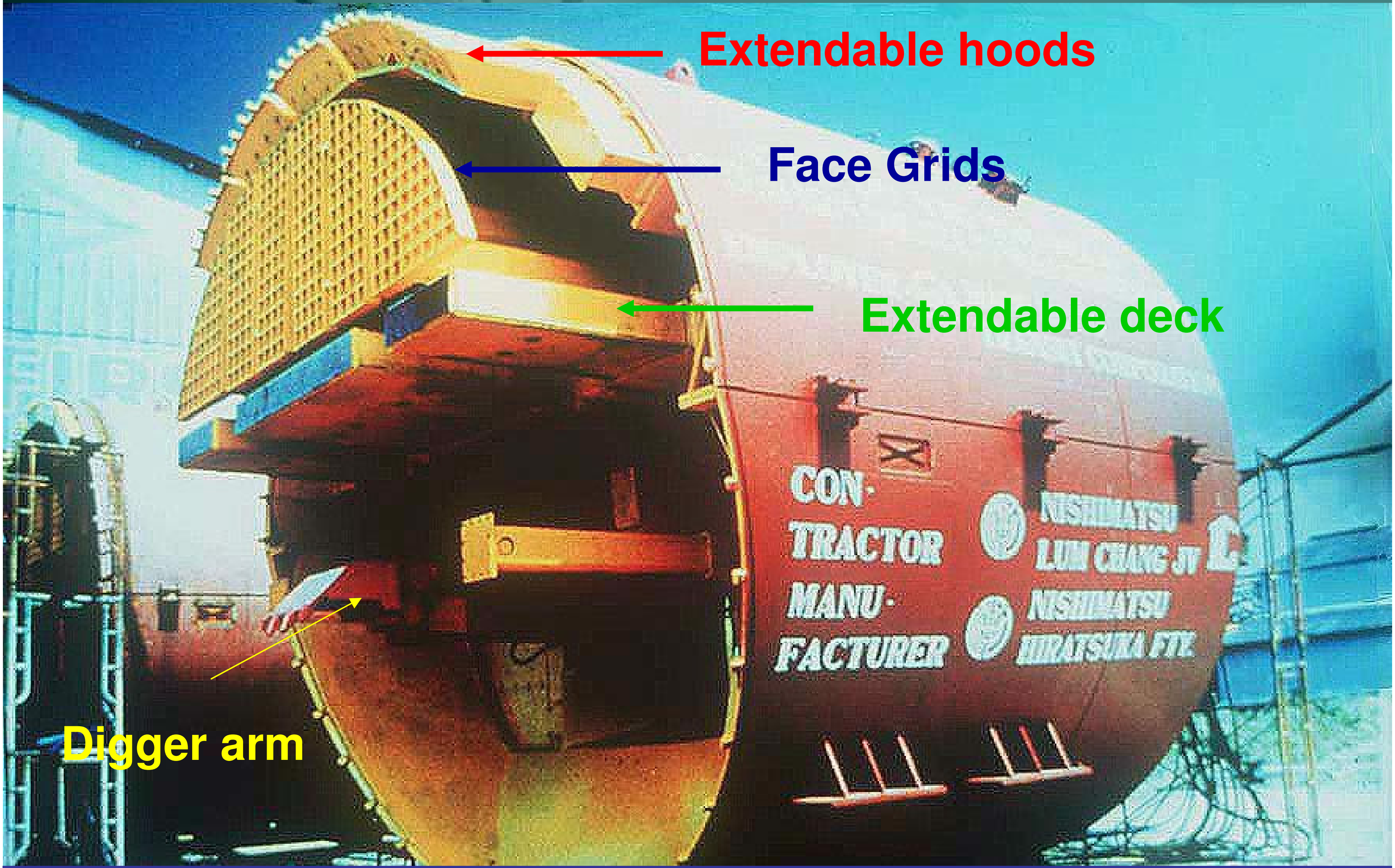
Mode

Mixshield

Hard Rock

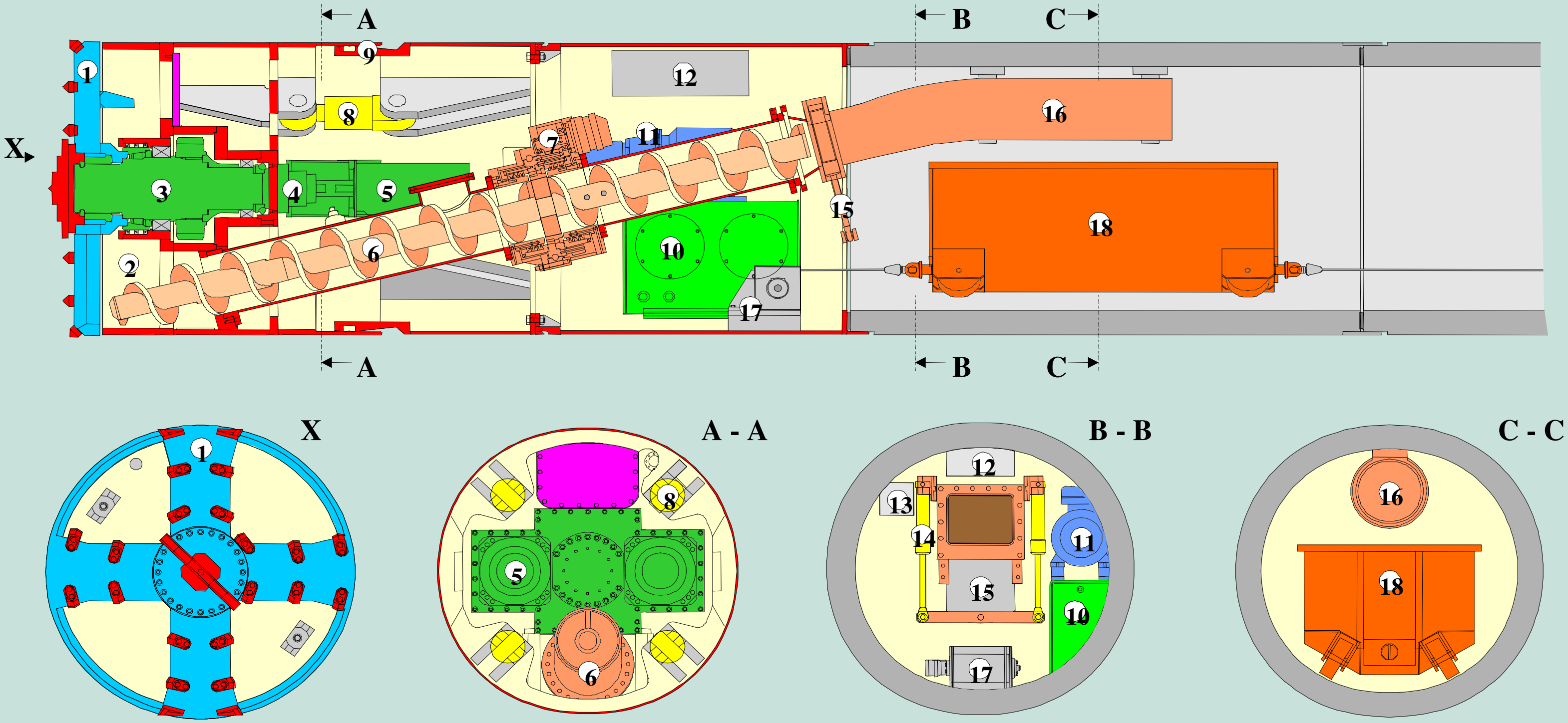
HERRENKNECHT

DIGGER SHIELD, CITY HALL TO BUGIS, 1986

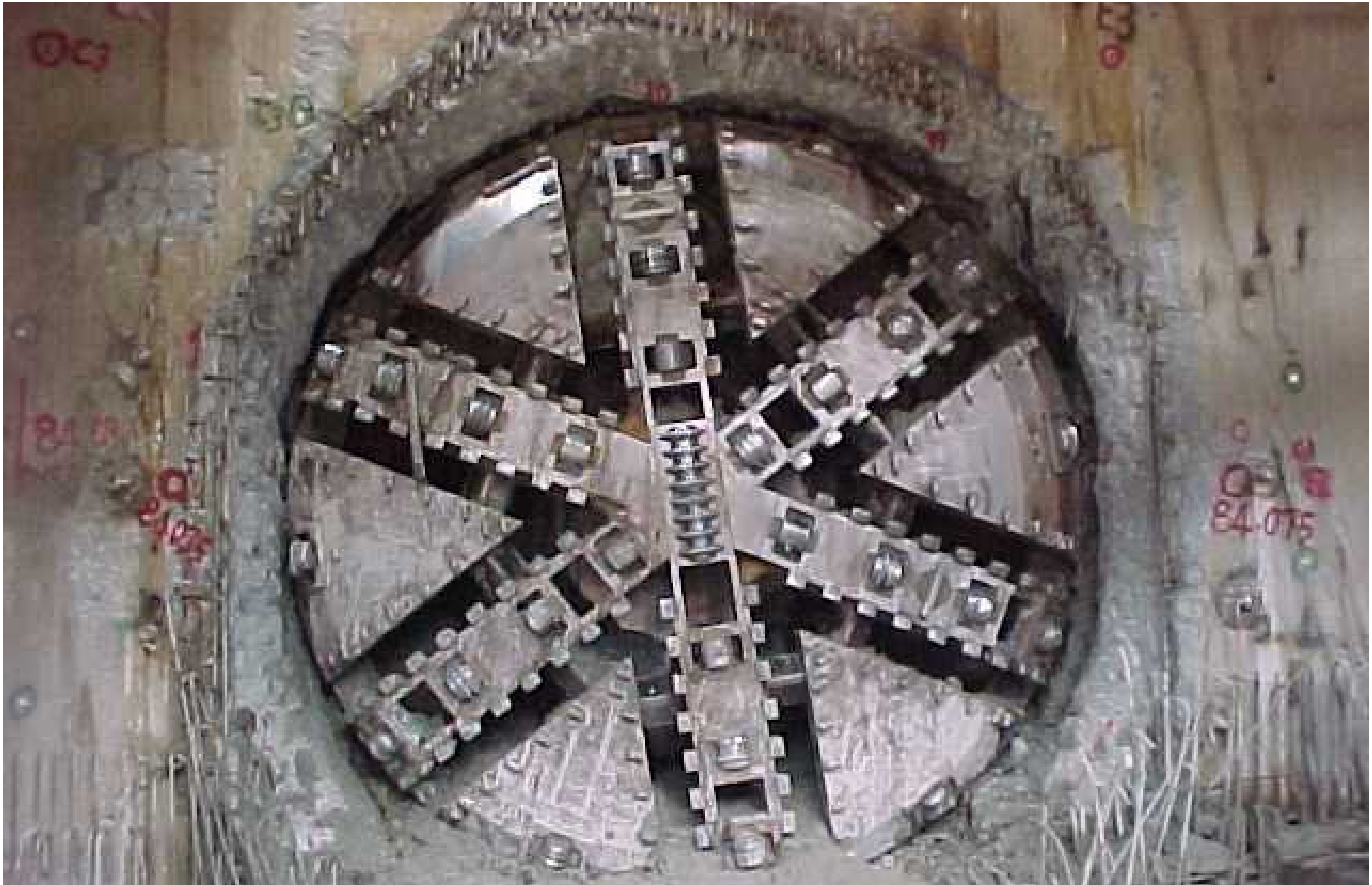


USED WITH COMPRESSED AIR FOR FACE SUPPORT

EPB 1200 - 2600 MUCK SKIP



1	Cutting wheel
2	Excavation chamber
3	Main drive shaft
4	Gearbox assembly
5	Electric drive motor
6	Screw conveyor
7	Screw conveyor drive
8	Steering cylinder
9	Articulation seal
10	Hydraulic tank
11	Electric motor
12	Main electric panel
13	ELS Laser target
14	Telescopic cylinder
15	Gate valve
16	Screw conveyor discharge
17	Hydraulic winch
18	Muck skip



EARTH PRESSURE BALANCE SHIELD FOR SOIL AND ROCK

SCREW CONVEYOR

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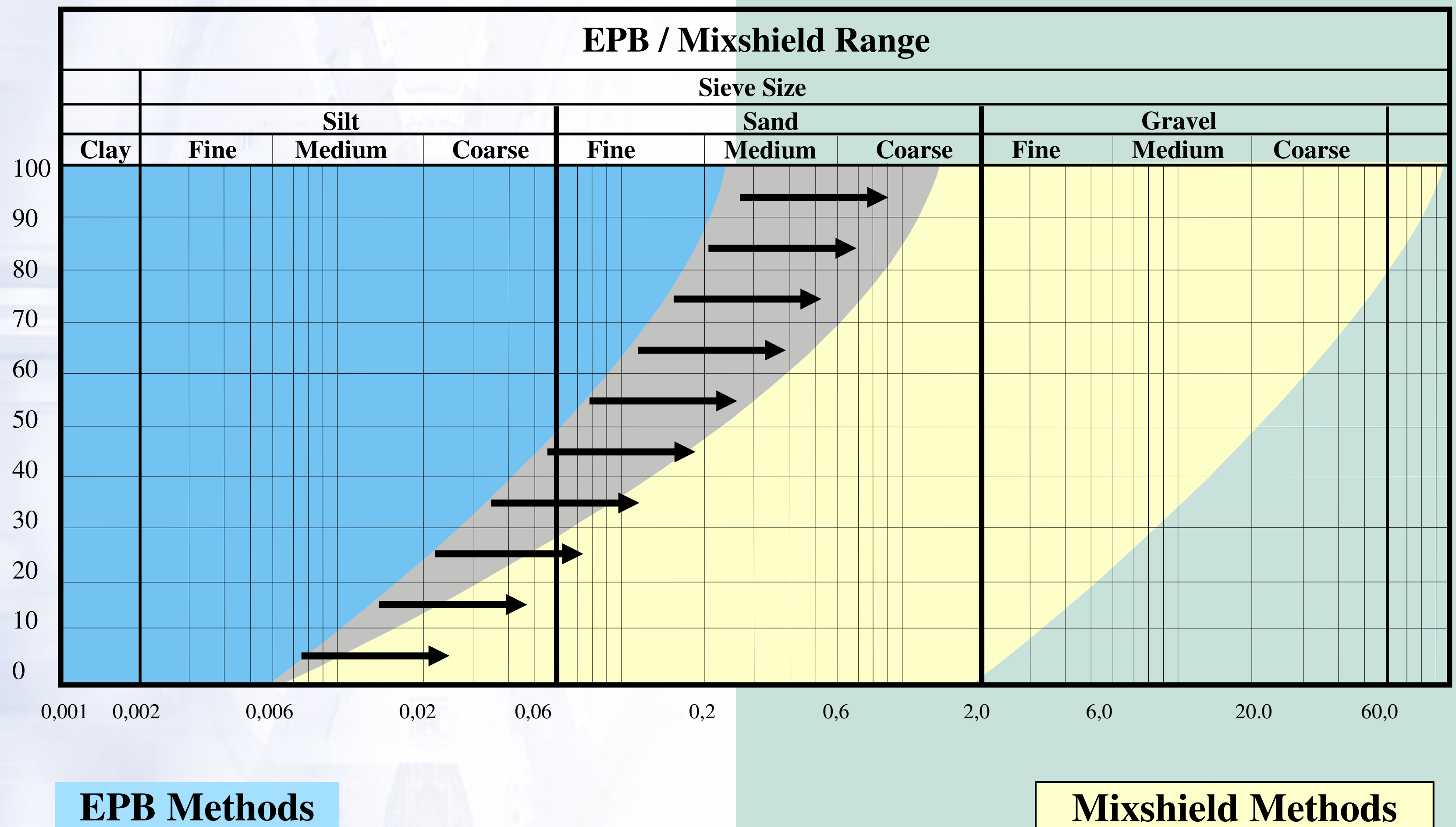
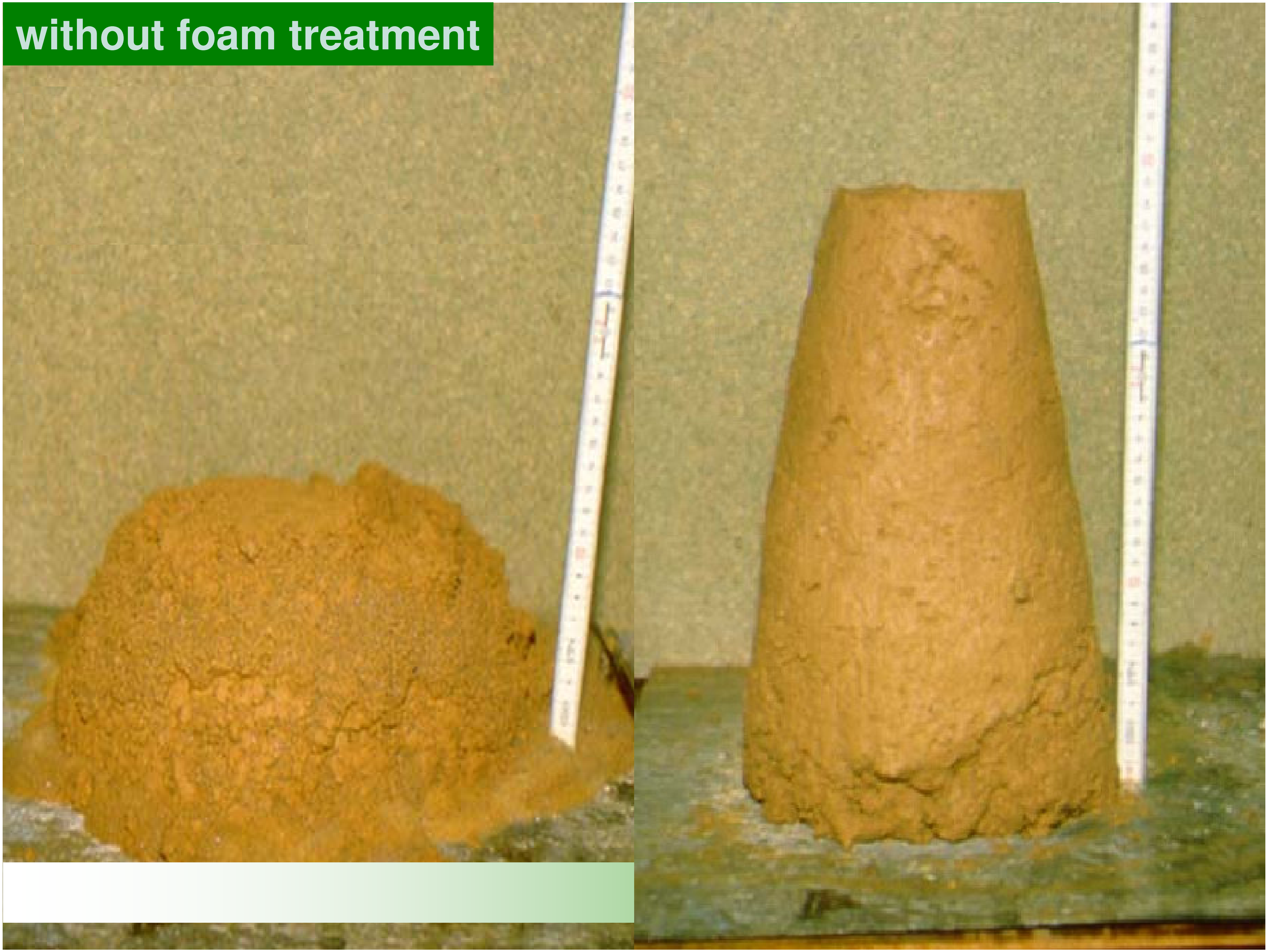
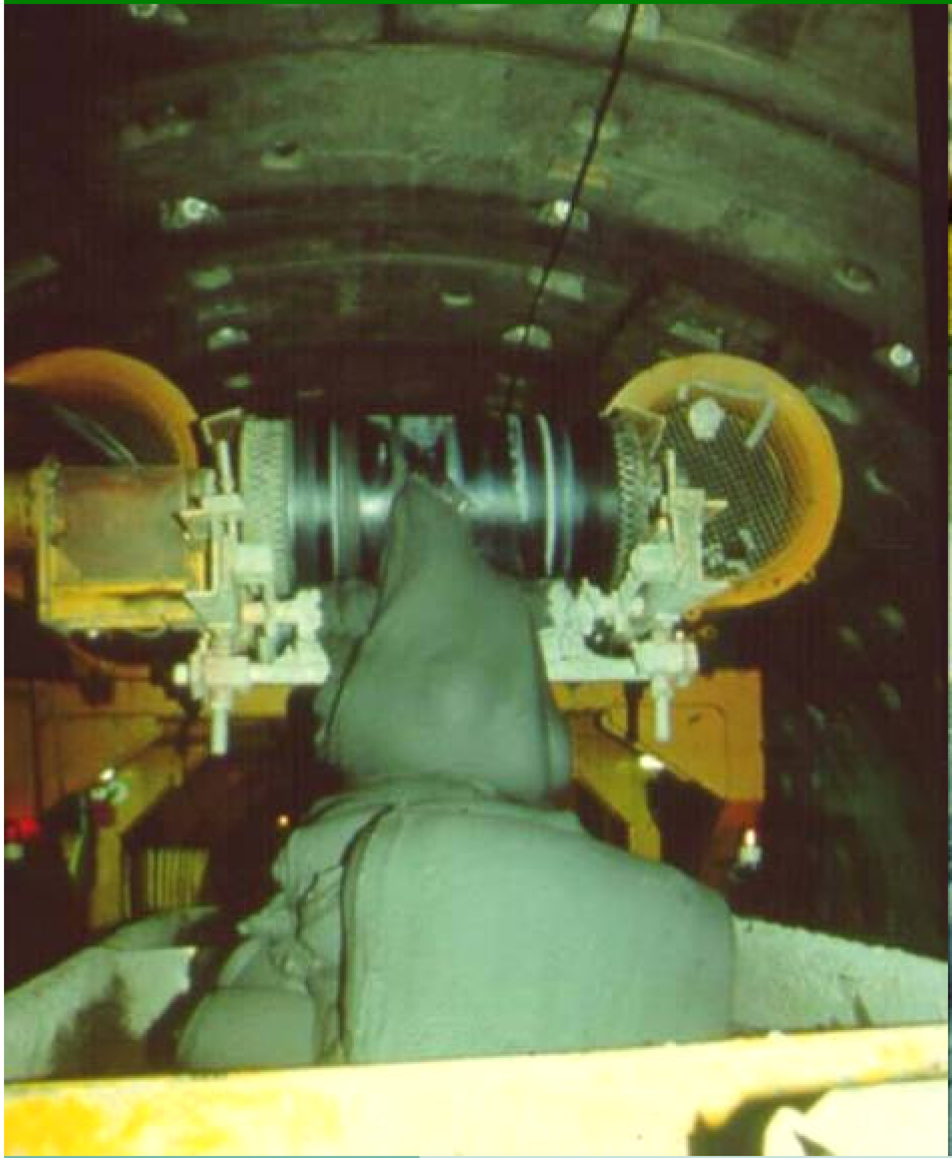
EPB / Mixshield



HERRENKNECHT

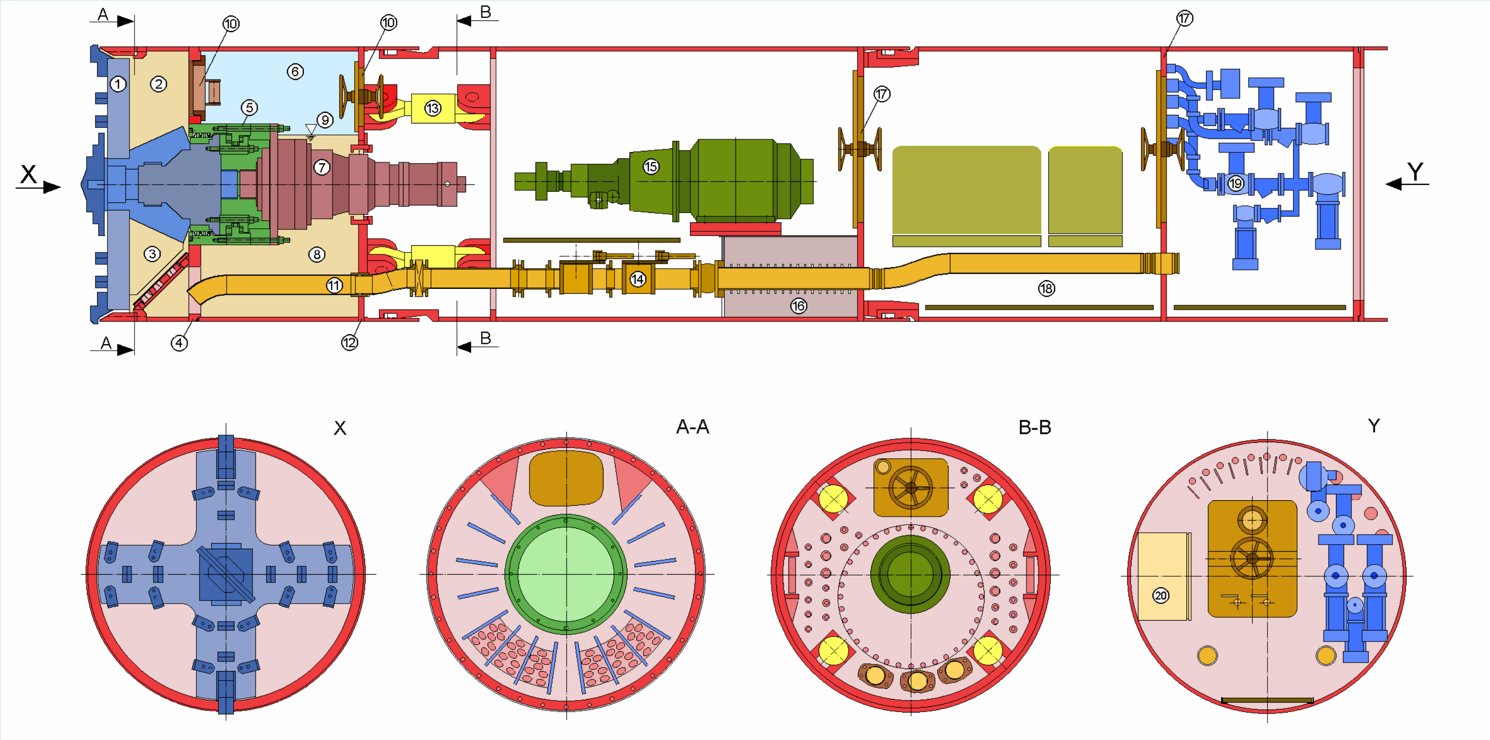

without foam treatment

EBP-Shield Taipai (Ø 6.26 m) , belt conveyor outlet

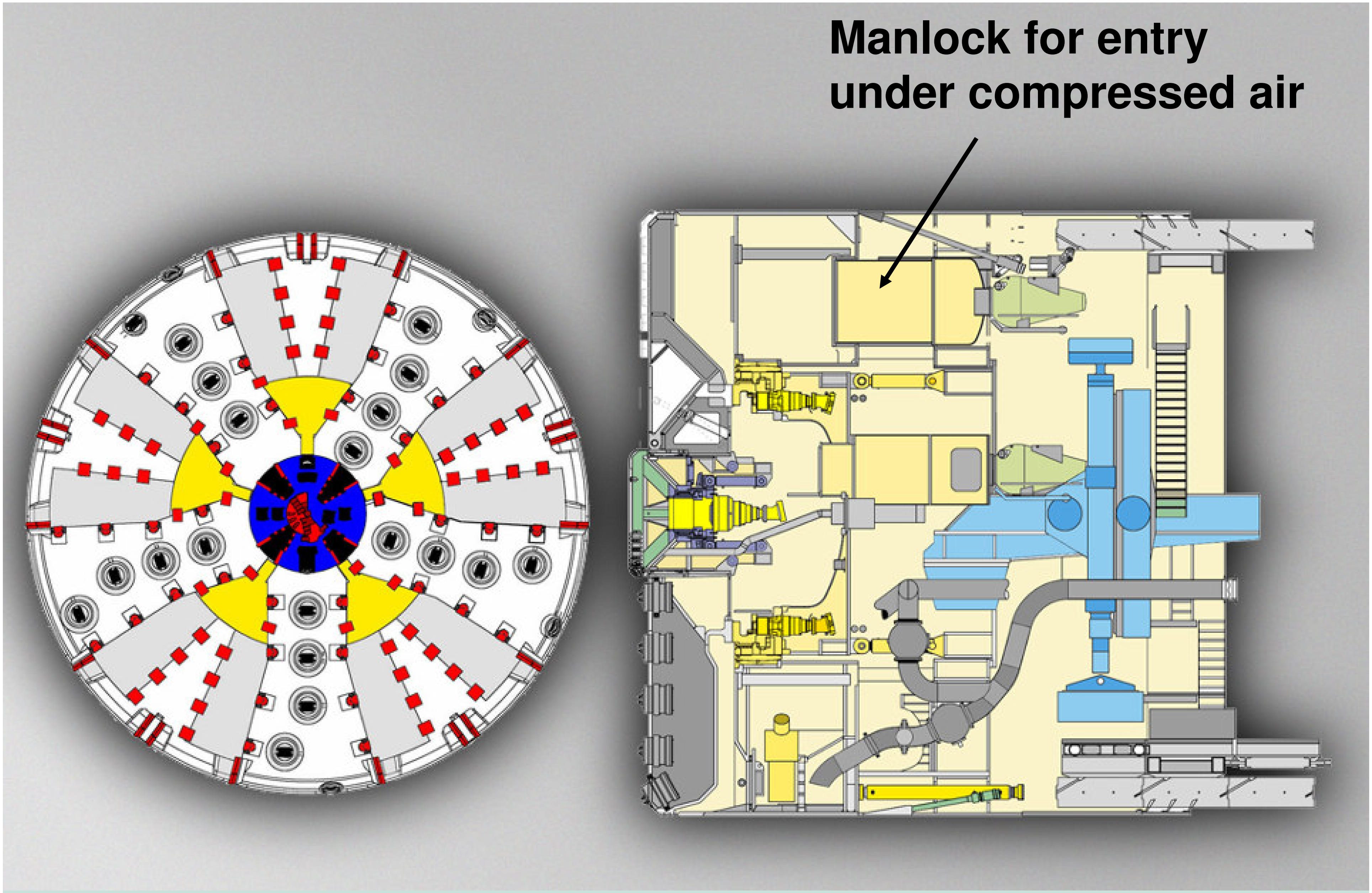


POOR GROUND CONDITIONING – SPOIL NOT PLASTIC

SECTION THROUGH AVN D-SERIES



1	Cutting wheel	6	Air pressure cushion	11	Slurry discharge line	16	Hydraulic oil tank
2	Excavation chamber	7	Motor gearbox assembly	12	Pressure bulkhead	17	Airlock bulkhead
3	Crusher chamber	8	Bentonite	13	Steering cylinder	18	Airlock
4	Submerged wall	9	Bentonite level indicator	14	Bypass assembly	19	Air pressure regulation equipment
5	Main bearing	10	Face access hatch	15	Drive motor	20	Electric cabinet


Manlock for entry
under compressed air

SLURRY TREATMENT PLANT

HAND MINING THROUGH DEWATERED GROUND

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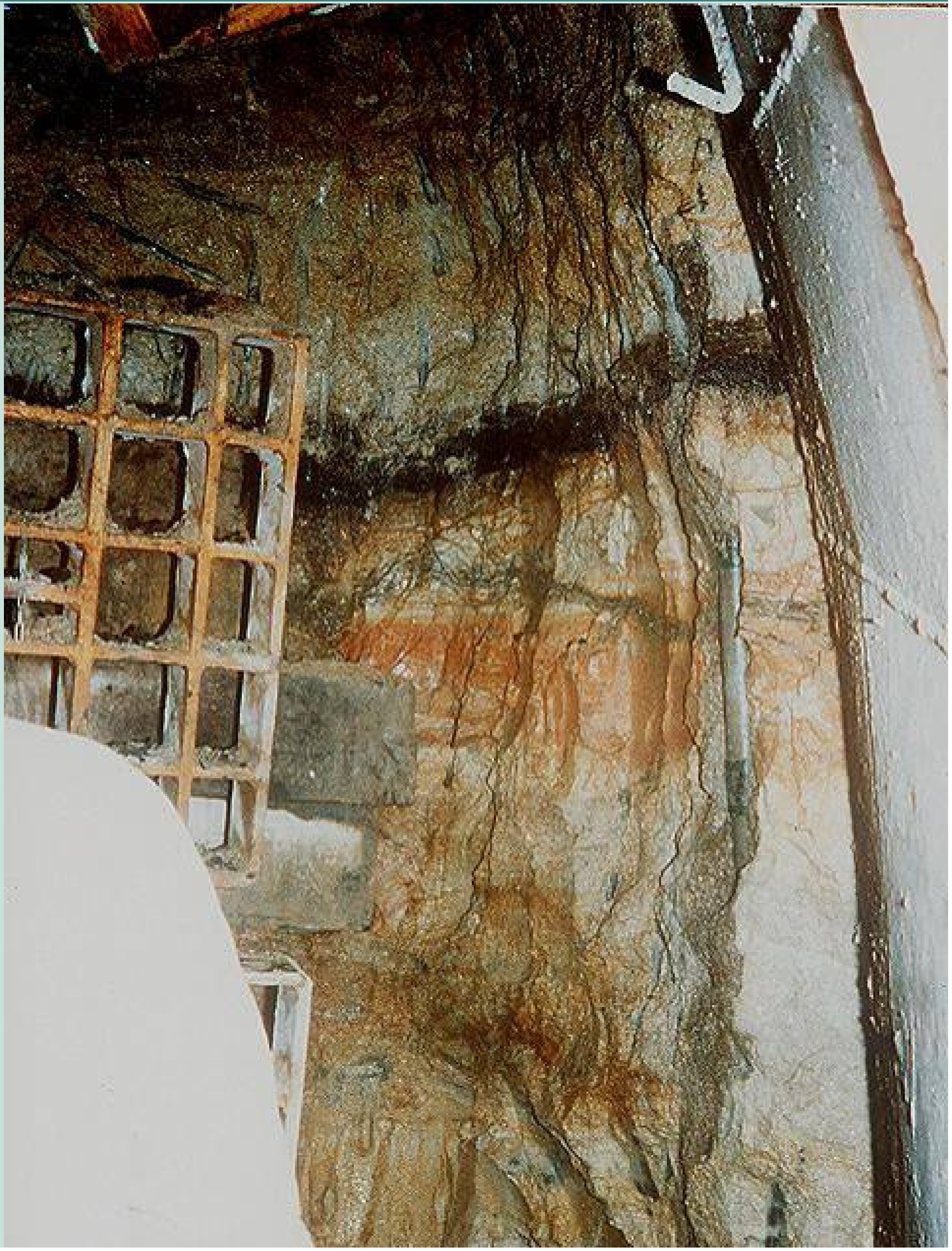
CHEMICAL GROUTING

OPEN FACE SHIELD TUNNELLING THROUGH CHEMICALLY TREATED SOFT GROUND



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GROUND FREEZING - SINGAPORE

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ASSESSING THE FACE PRESSURE

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FACE PRESSURE

- Theoretical – based on limit equilibrium methods and/ or centrifuge testing
- Relationship between face pressure and settlement - examples
- Review of theory against field data

HEADING GEOMETRY

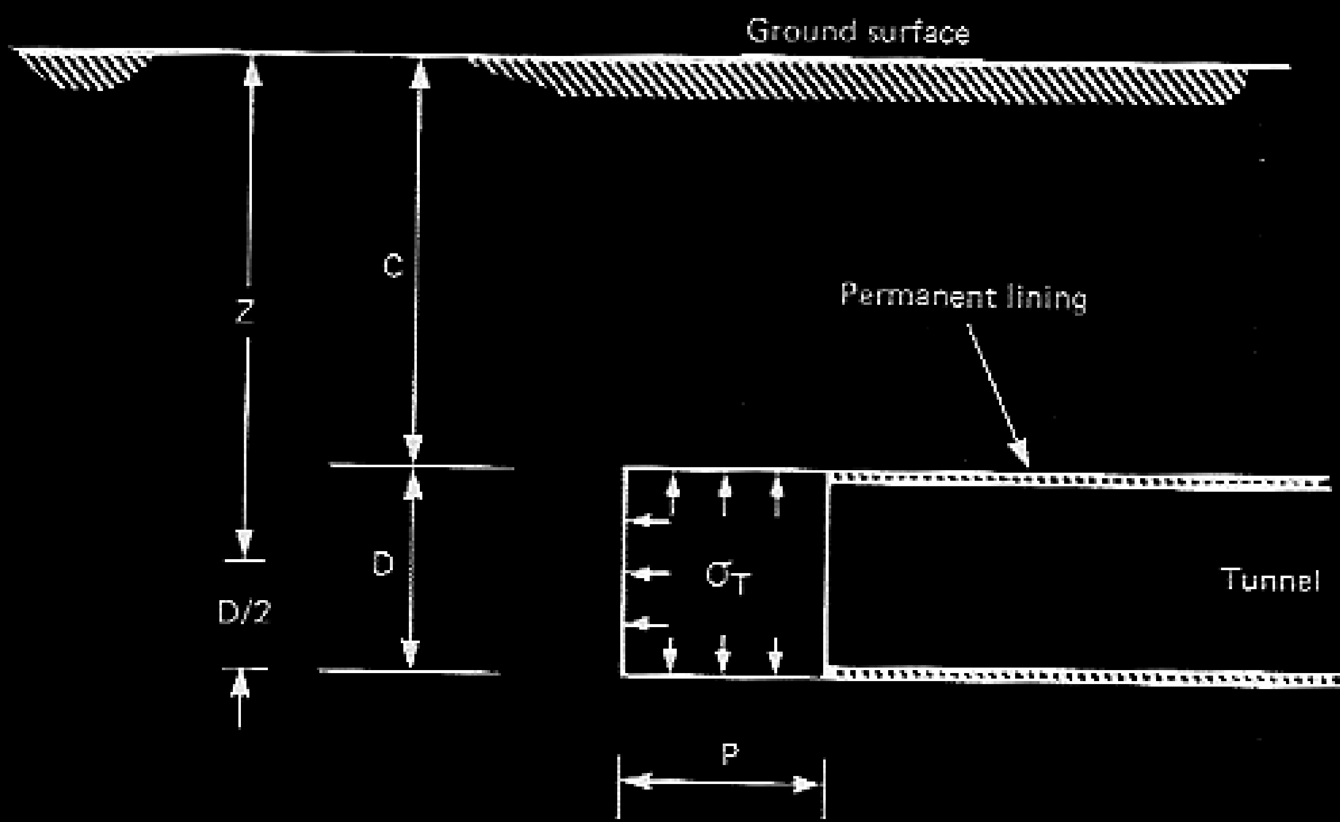
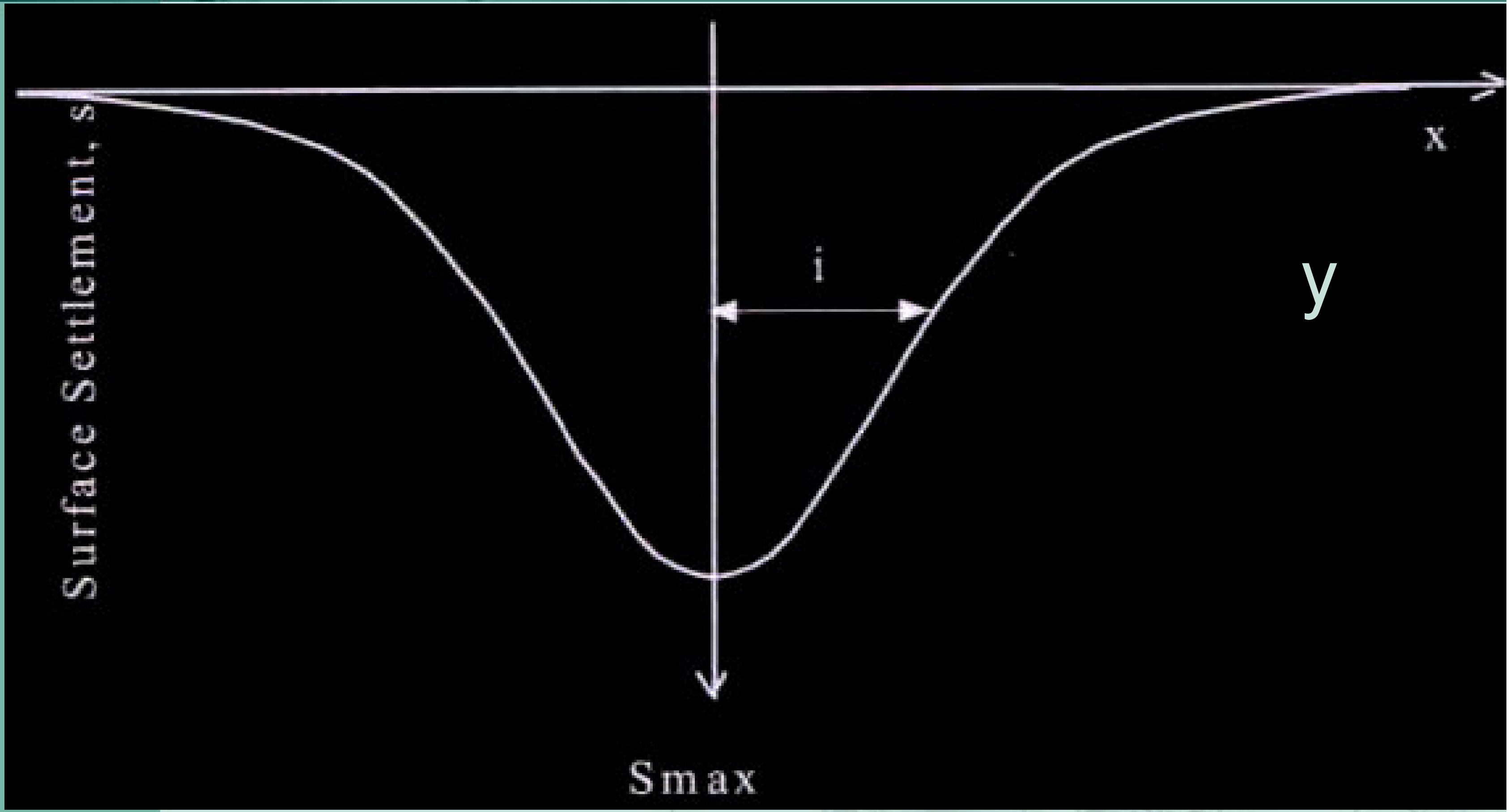


Fig. 2 Geometry of tunnel heading

SETTLEMENT TROUGH – IMMEDIATE SETTLEMENT



$$s(x) = s_{max} \exp(-x^2/2i^2)\text{ , Volume under curve} = 2.5\ i\ s_{max}$$

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VOLUME LOSS

- **Volume Loss = Volume surface settlement trough (per m)/Volume of excavated tunnel (per m)**
- **Unit Volume = 2.5 i $S_{max.}$**
- **Expressed as a percentage**

CLAYS

- Practical experience led to the concept of the ‘stability number’ N
- Centrifuge testing allowed the refinement of the calculations so that the depth, size and construction sequence of the tunnel could be taken into account. Also allowed face pressure to be linked to volume loss (from which settlement can be derived)

STABILITY NUMBER

$$N = \frac{\text{Overburden pressure} - \text{Tunnel support pressure}}{\text{Undrained shear strength}}$$

$$N = (\gamma Z + q - P_t)/C_U$$

Initial assessment suggested the tunnels would fail at a stability number of about 6. This was refined using centrifuge tests on model tunnels. Scanned figures below are derived from Kimura and Mair, 1982.

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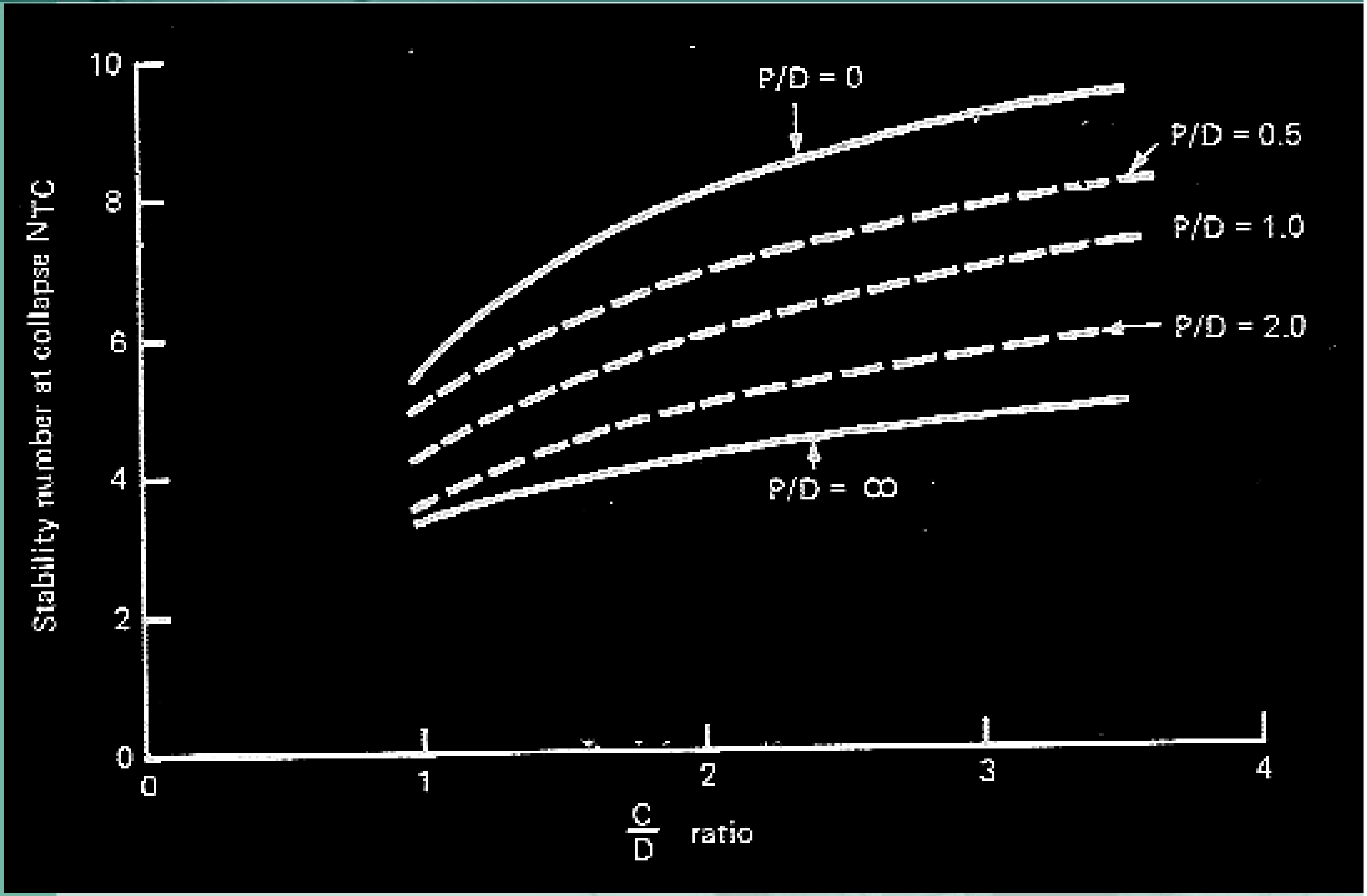
LOAD FACTOR

Load factor = Stability number
Stability number at collapse

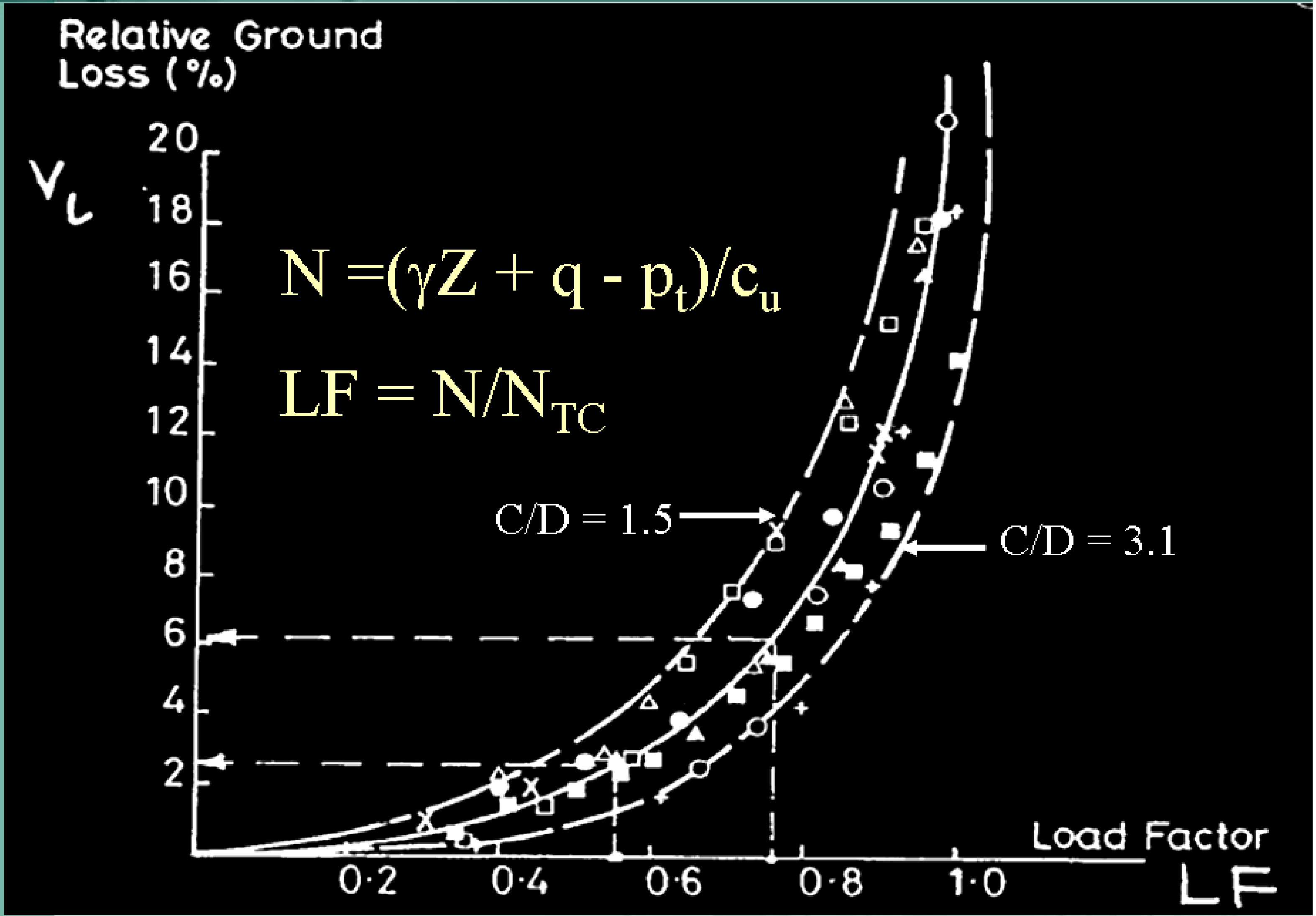
$LF = N/N_{TC}$

(also based on Kimura and Mair,1982)

INFLUENCE OF HEADING GEOMETRY ON STABILITY NUMBER AT COLLAPSE



VOLUME LOSS VS LOAD FACTOR



FACE PRESSURE IN CLAY

- If settlement not an issue use a load factor of 0.67 or less (equivalent to FoS of 1.5)
- To control settlement due to face to below 2%, use load factor of 0.4 to 0.6.
- In very settlement sensitive areas may need to use close to full overburden pressure (LF = 0 to 0.3)
- For large, shallow tunnels need to check that the pressure in the crown < overburden pressure ignoring surcharge, due to risk of blow-out

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SANDS

- Pressure in sand commonly based on limit equilibrium methods developed by Anagnostu and Kovari (1996)
- Scanned figures in following slides are from Anagnostu and Kovari (1996)
- Limit equilibrium methods give pressure required to avoid failure, not to control settlement. Need higher pressure to control settlement.

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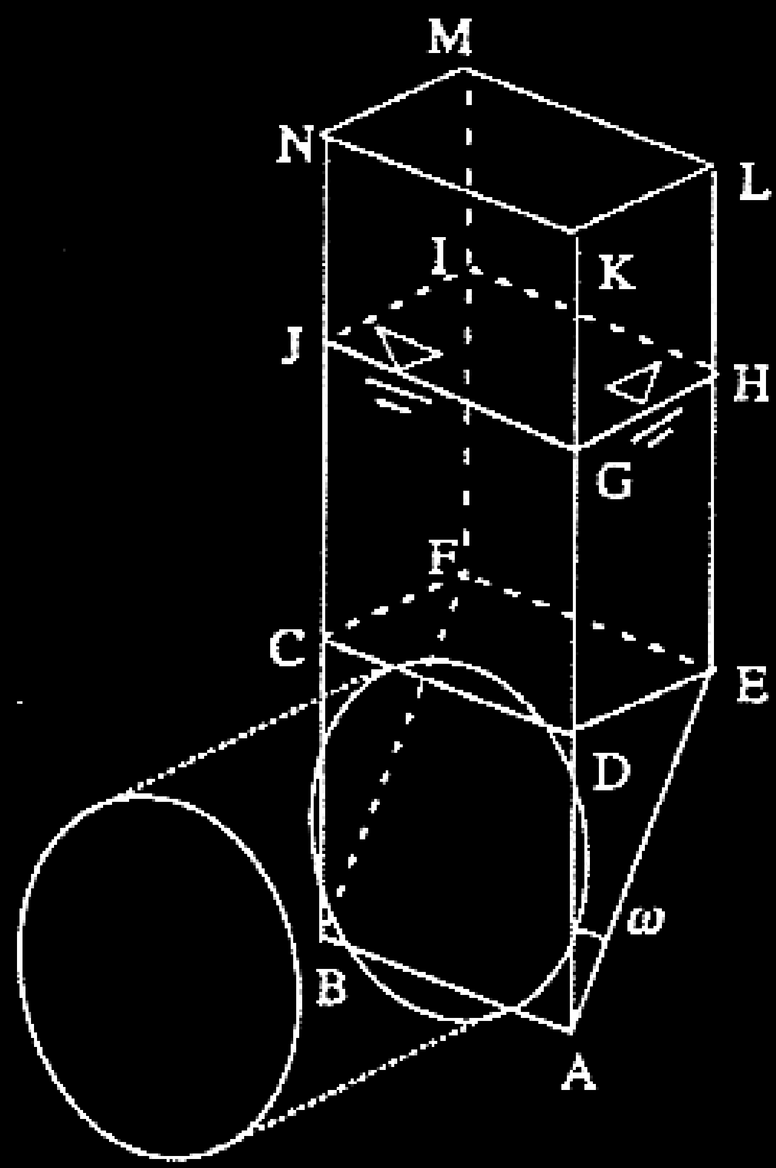
ASSUMED FAILURE SURFACE - SANDS



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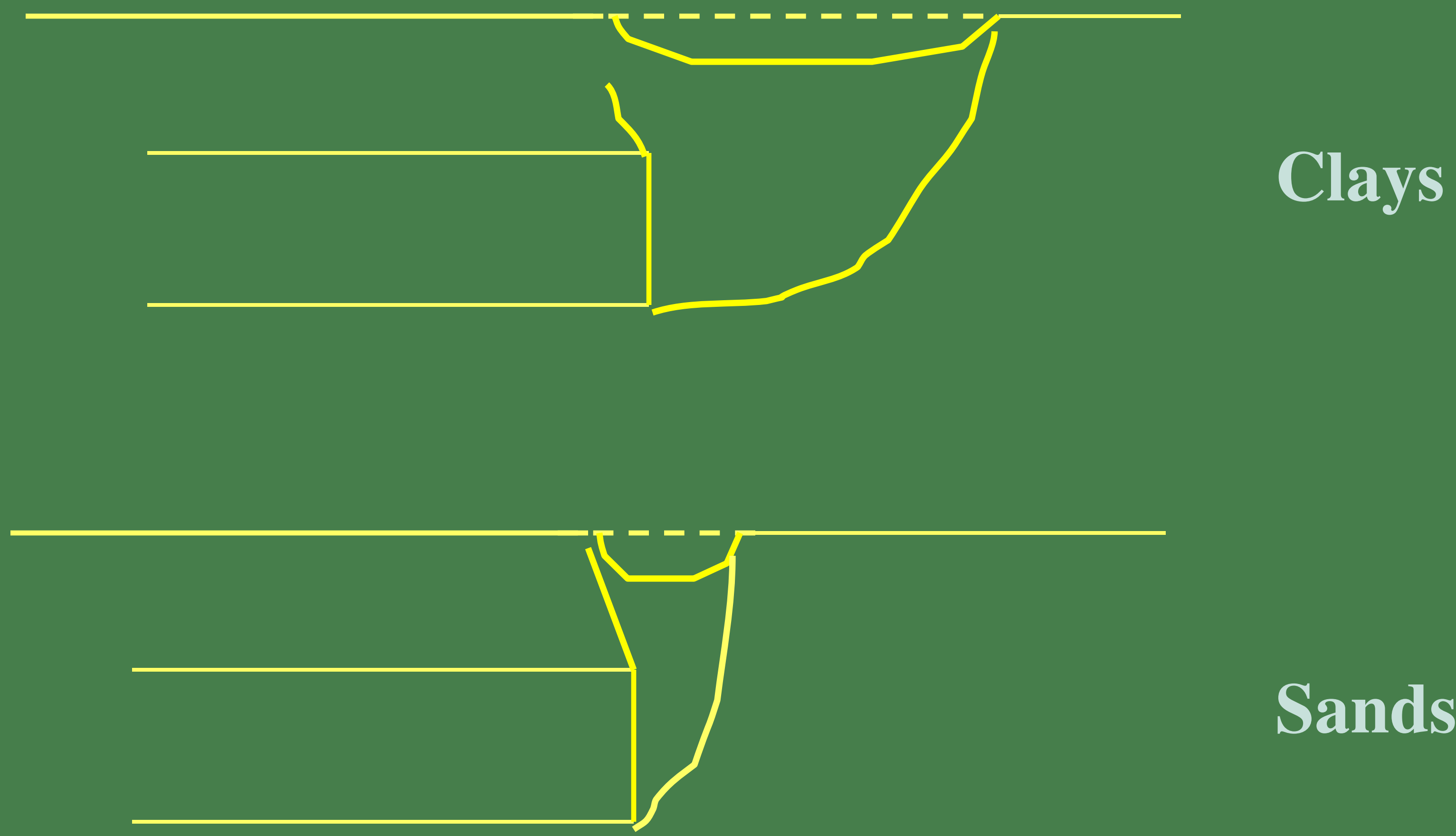
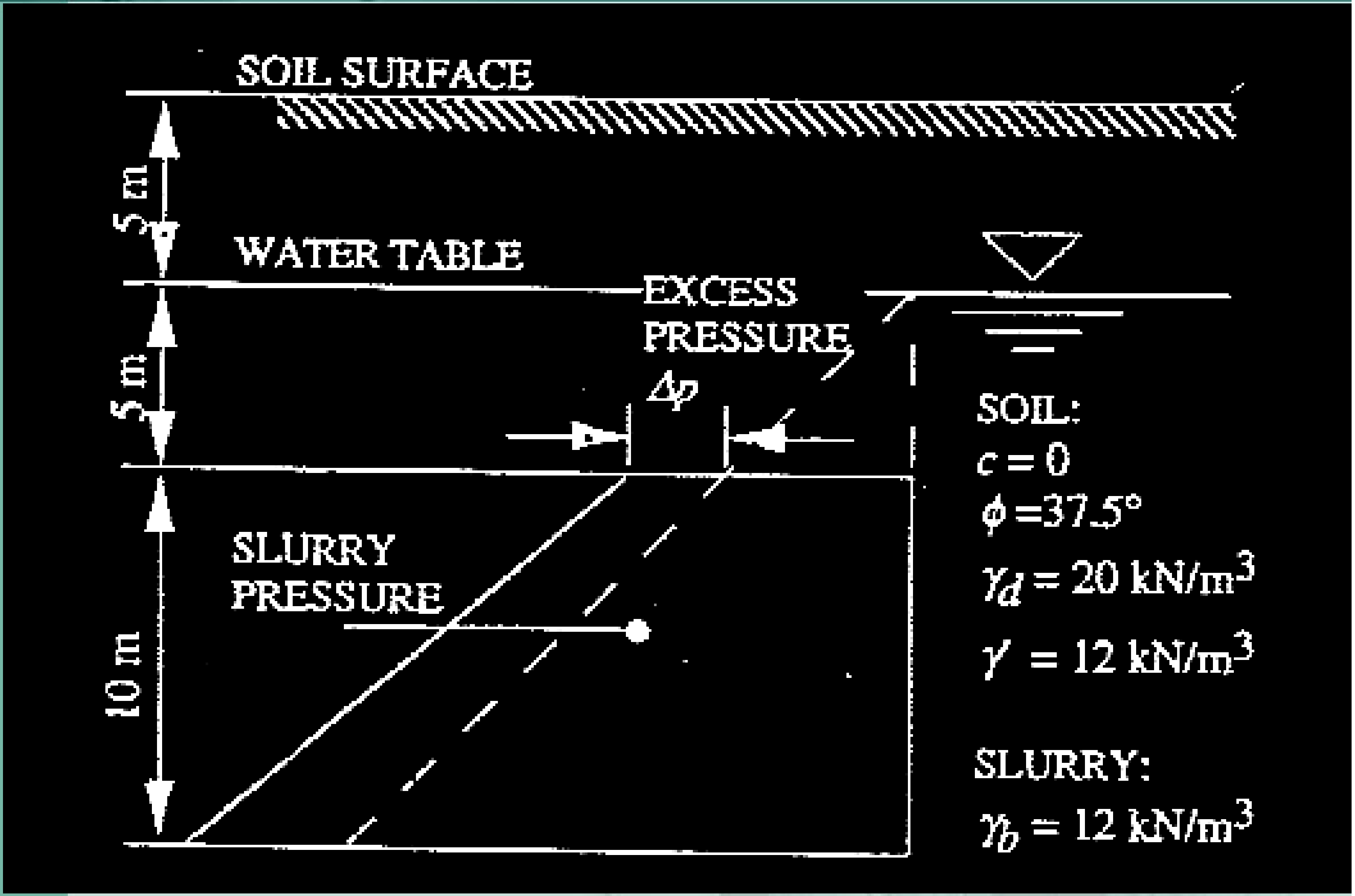


Failure Mechanism Based on Centrifuge Model Test (Mair, 1979)

SLURRY SUPPORT, SAND



PENETRATION OF SLURRY INTO THE FACE

- In fine and medium sand the excess pressure causes water to bleed out of the slurry at the face, forming a filter cake (like a membrane)
- In coarser ground the slurry penetrates into the ground. The penetration distance e_{max} can be calculated from
- $$e_{max} = \frac{\Delta p.\ d_{10}}{2\ \tau_f}$$
- The greater the penetration the lower the factor of safety

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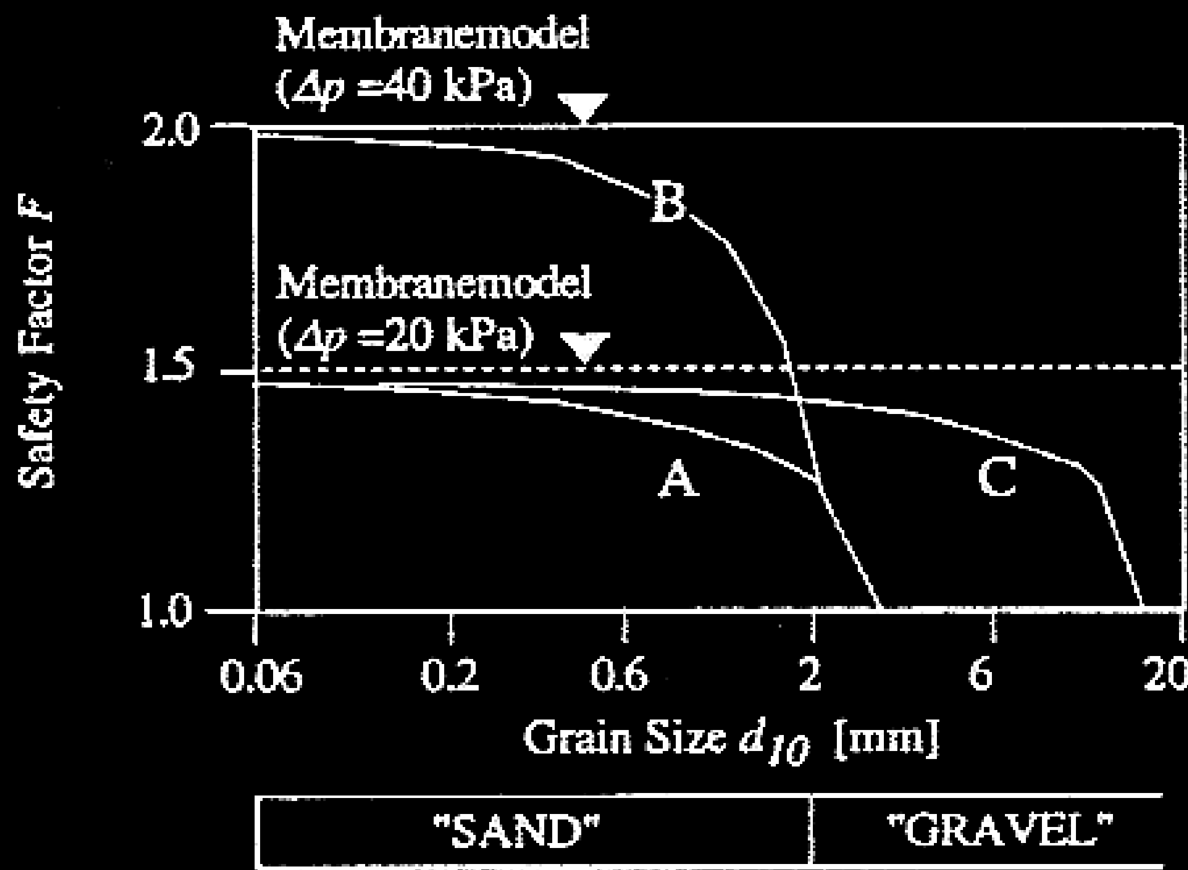
EFFECT OF GRAIN SIZE ON SAFETY FACTOR



A: Δp = 20 kPa, 4% bentonite (τ_f=15 Pa)

B: Δp = 40 kPa, 4% bentonite (τ_f=15 Pa)

C: Δp = 20 kPa, 7% bentonite (τ_f=80 Pa)

Fig. 4. Safety factor as a function of characteristic grain size

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EFFECT OF TIME

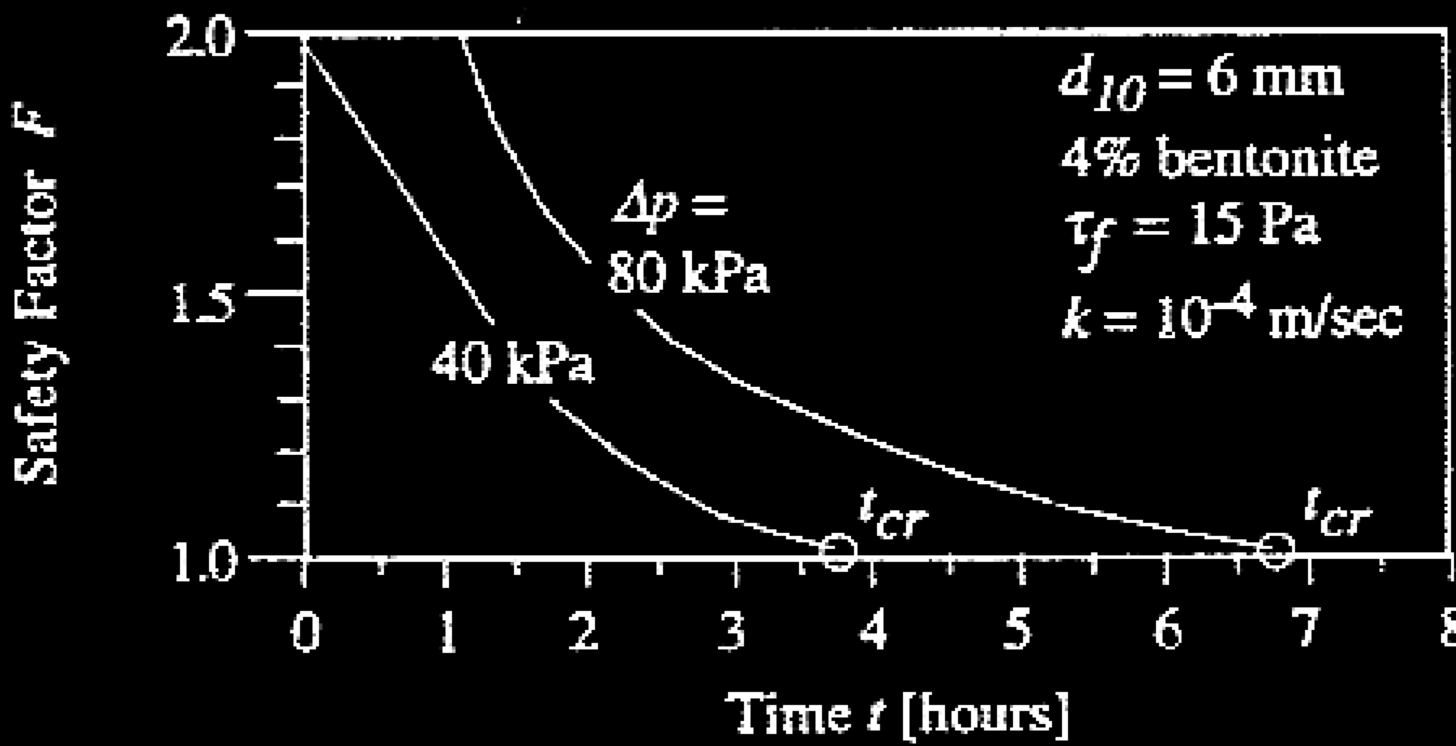

Fig. 5. Safety factor as a function of time

EFFECT OF SLURRY

- Below a d_{10} of about 0.6mm treat as membrane
- Above a d_{10} of about 0.6mm, slurry penetrates into ground and factor of safety reduces
- Can: increase face pressure, use thicker bentonite mix (both limited value), speed up tunnelling (? certainty?), use additives to improve filter cake formation

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STAND-UP TIME RELATED TO GROUND PERMEABILITY

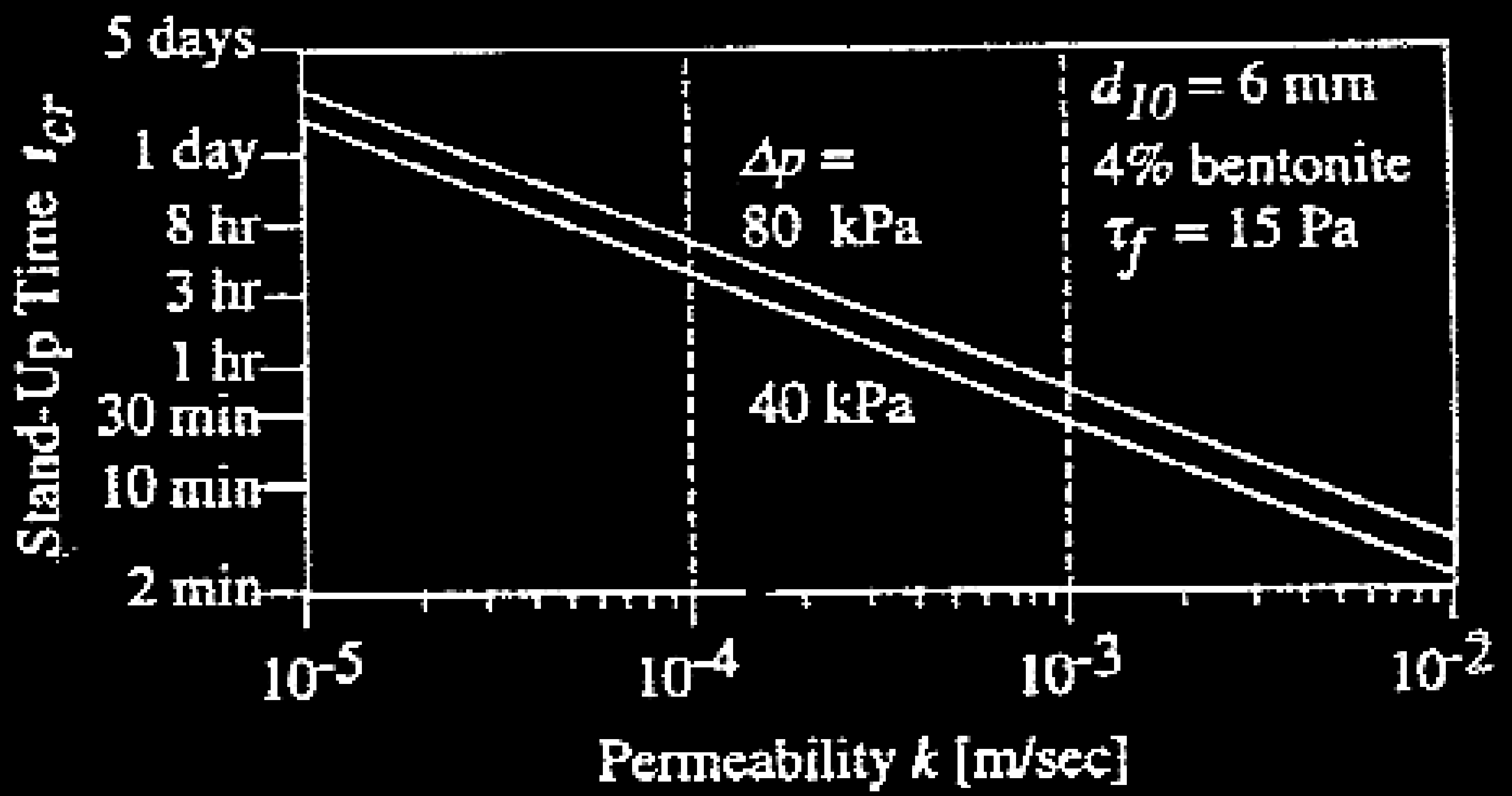


Fig. 6. Stand-Up Time as a function of permeability

EFFECT OF ADVANCE RATE

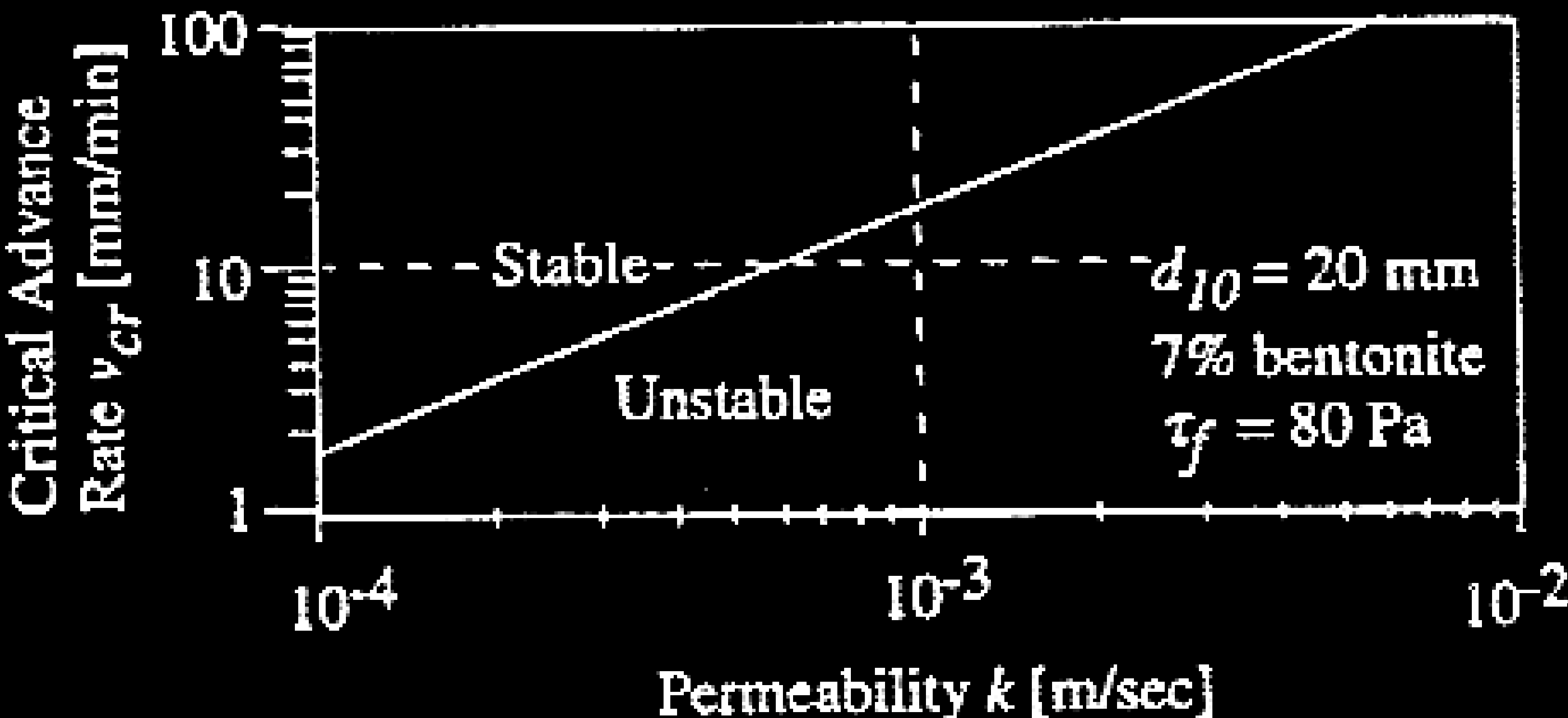


Fig. 7. Critical advance rate as a function of permeability

EFFECTIVE SUPPORT PRESSURE – EPB SHIELDS

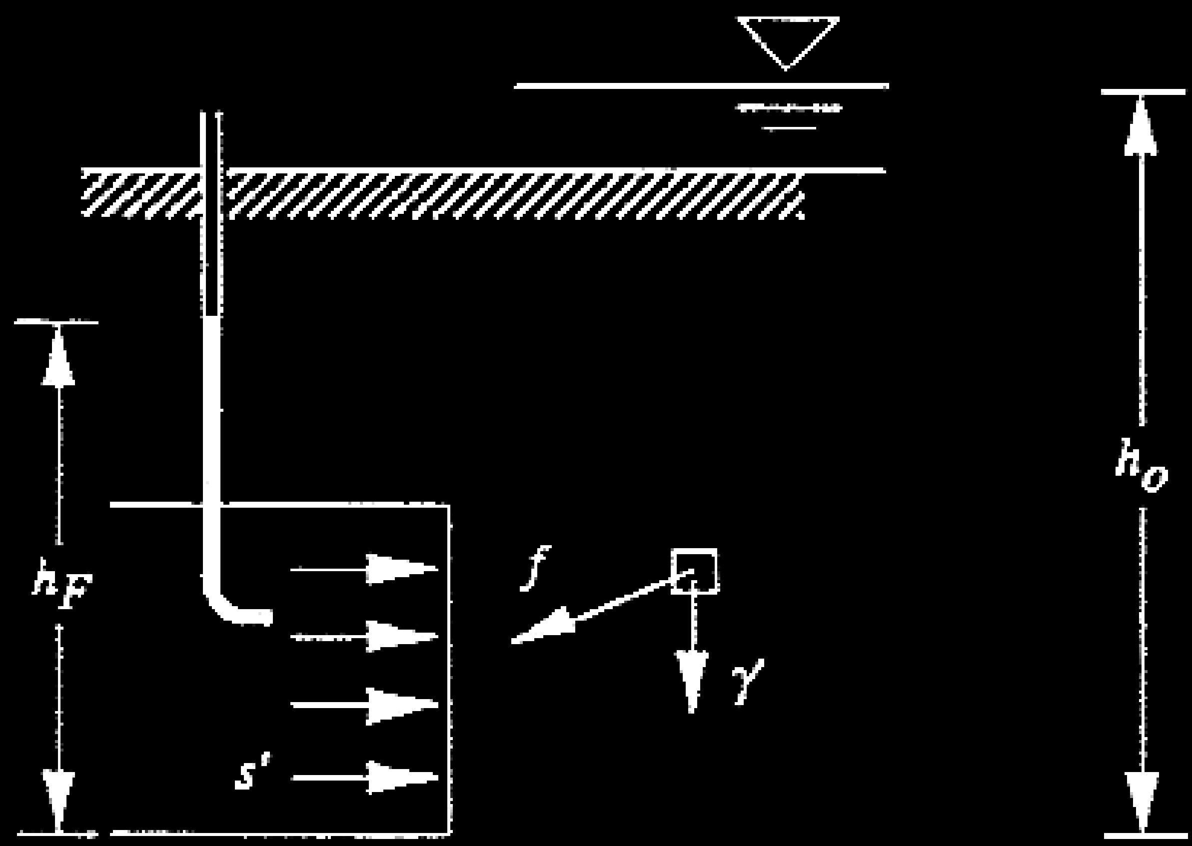


Fig. 8. Seepage force *f* and effective support pressure *s'*

SEEPAGE FORCES

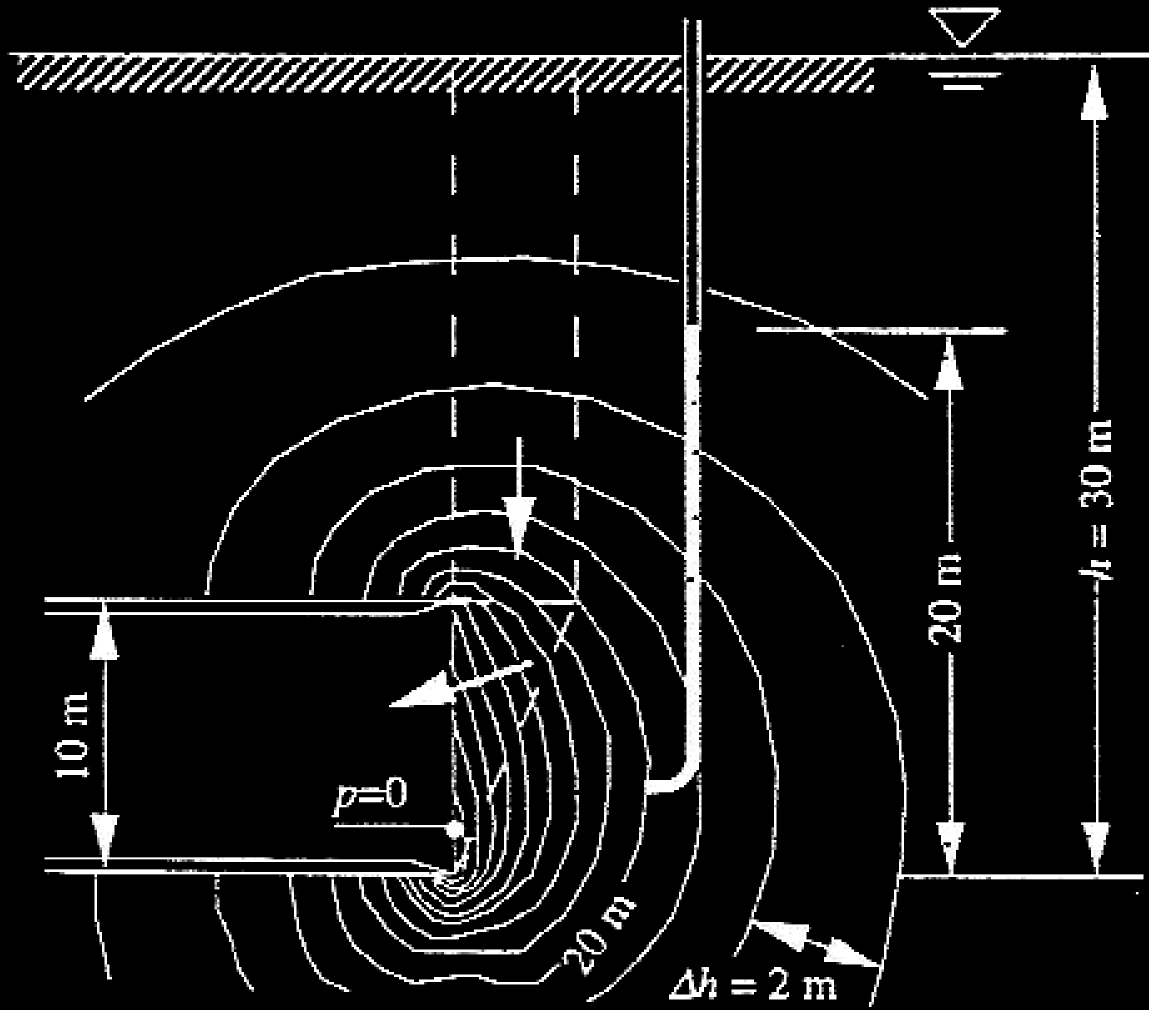


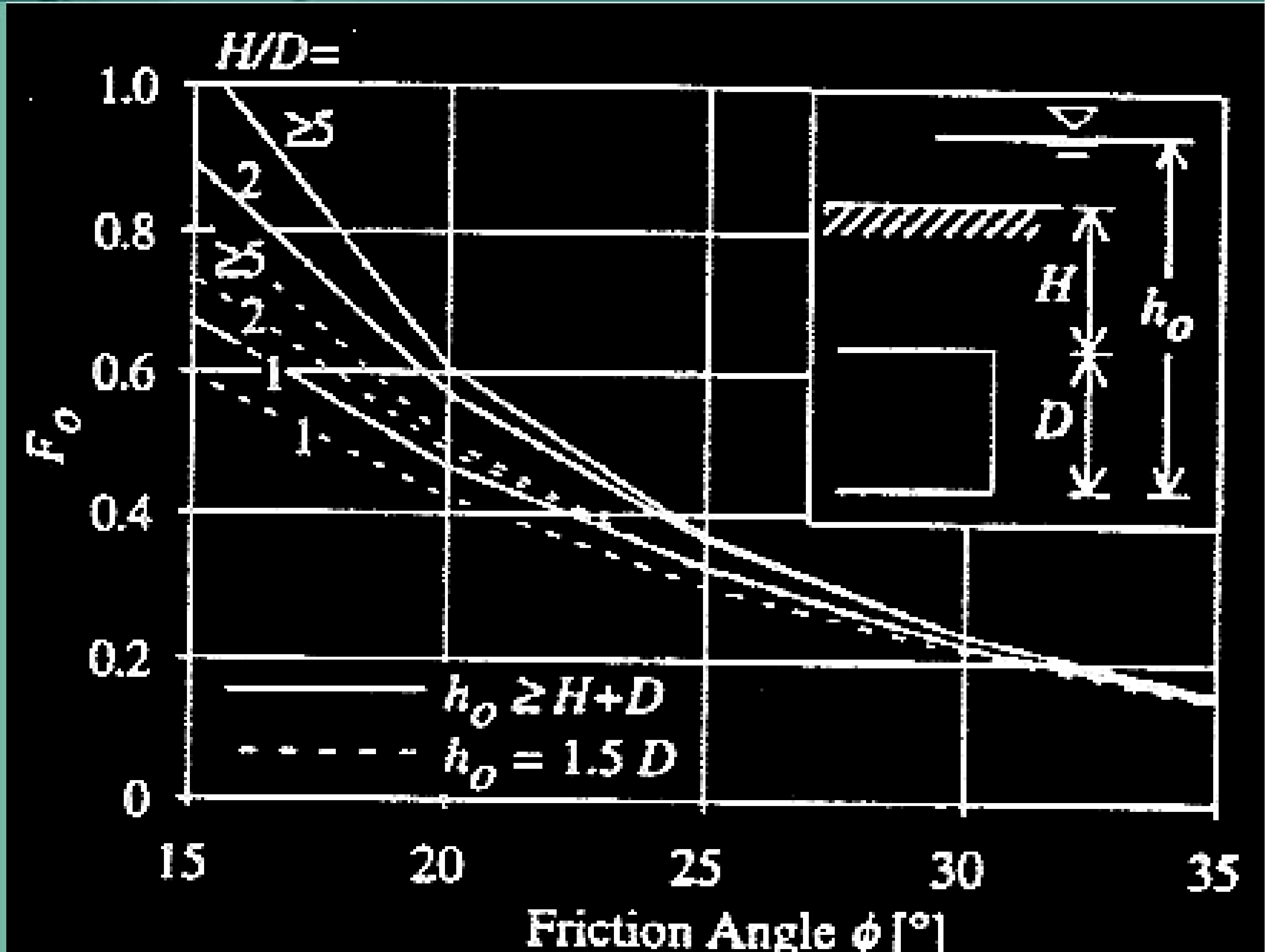
Fig. 9. Numerically computed contourlines of piezometric head

EFFECTIVE SUPPORT PRESSURE NEEDED

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

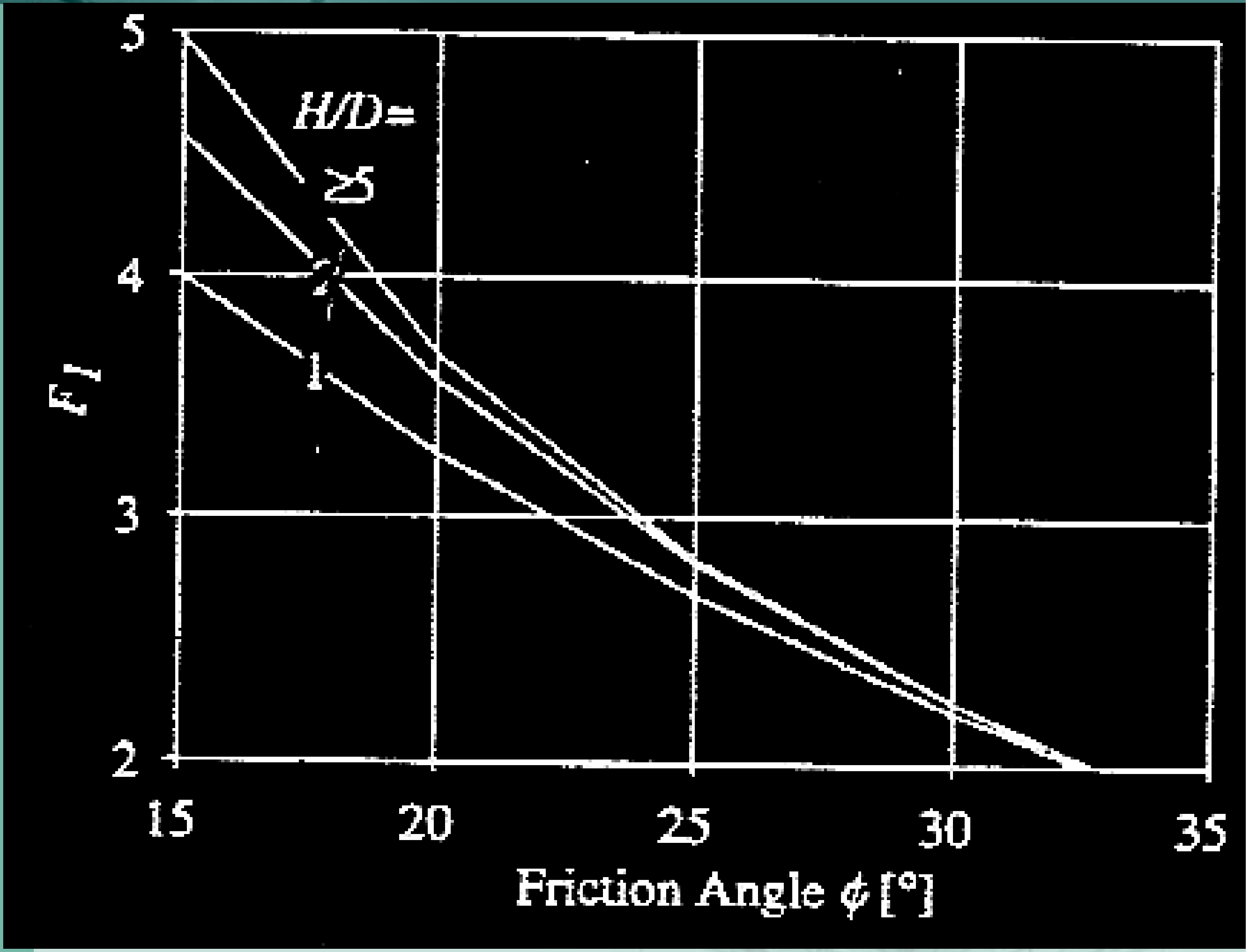
where F_O to F_3 are dimensionless coefficients, Δh is the difference between the original piezometric head at tunnel level (h_o) and that in the chamber (h_f)

F_O



H/D=
1.0
0.8
0.6
0.4
0.2
0
≥5
2
≥5
2
1
1
F_o
H
D
h_o
$h_o \geq H+D$
$h_o = 1.5\ D$
15
20
25
30
35
Friction Angle φ [°]

F_1



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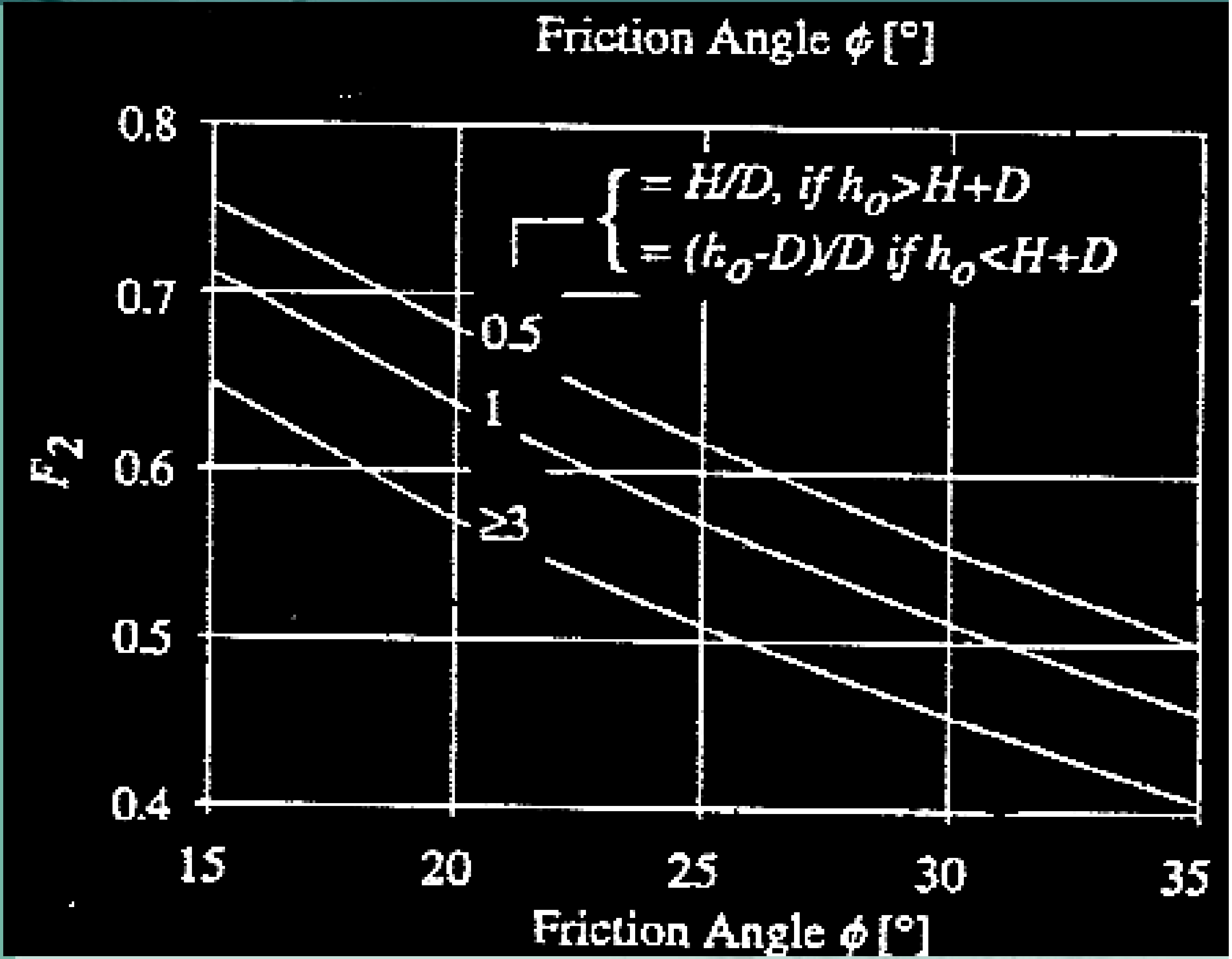
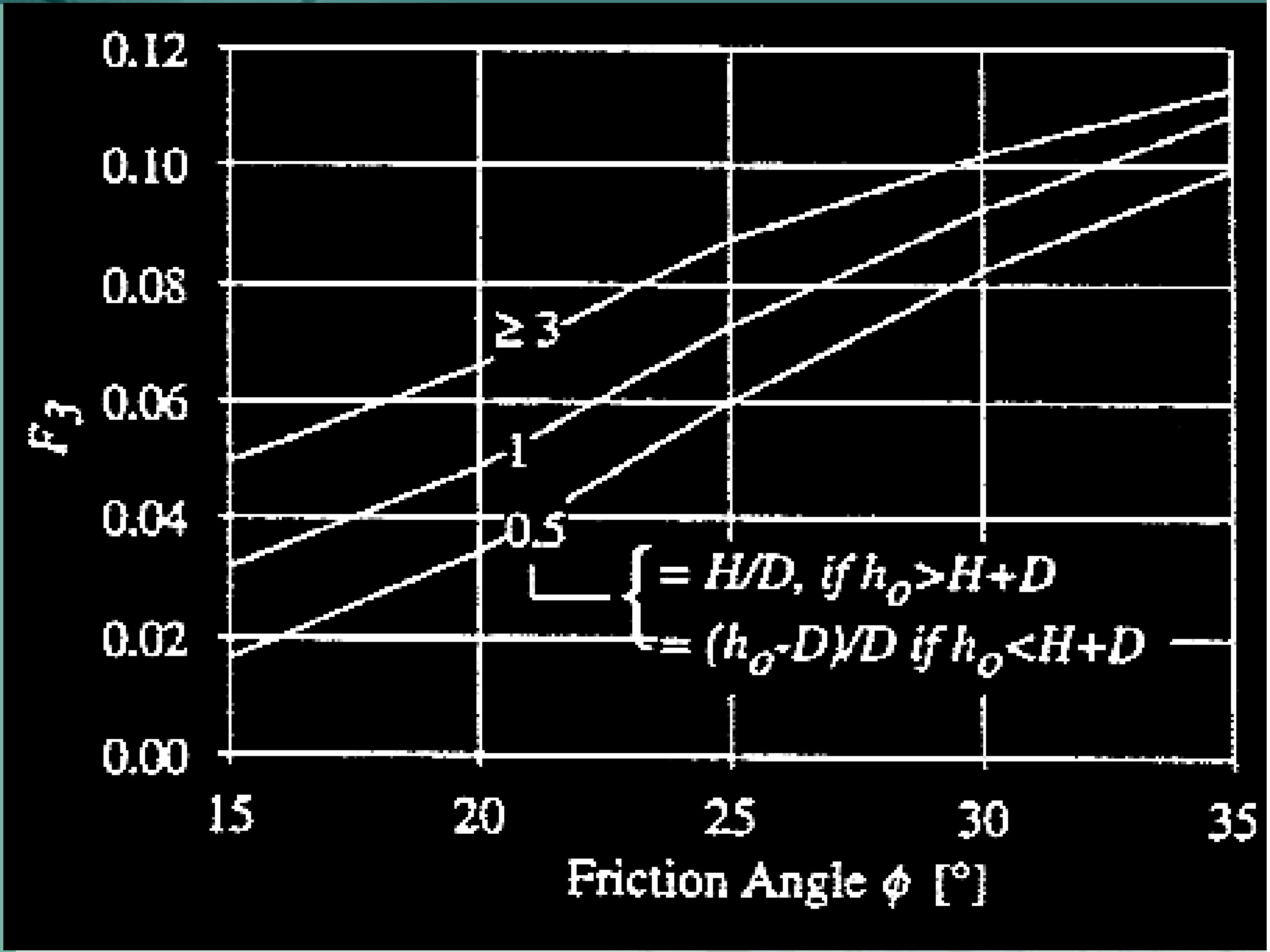
F_2



Friction Angle ϕ [°]
0.8
0.7
0.6
0.5
0.4
F2
= H/D, if ho>H+D
= (ho-D)/D if ho<H+D
0.5
1
≥3
15
20
25
30
35
Friction Angle ϕ [°]

F_3



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TOTAL FACE PRESSURE

Total face pressure, $s = s' + h_f$

In practice, unless the sand has significant cementation, additives have to be used to reduce the permeability of the sand, such that h_f is close to h_o

TOTAL FACE PRESSURE

Total face pressure, $s = s' + h_O$

Then $s = F_O\gamma'D - F_1c' + h_{O,}$

i.e. a small margin over the original water pressure. However, note that this is the pressure to avoid failure, not to control settlement.

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MARINE CLAY EXAMPLE

- 6m diameter tunnel @20m depth (Z = 20, C=17)
- C_U = 30kPa, γ = 16kPa, q=10kPa
- EPB Tunnel, look at face support only, take P=0
- P/D = 0, C/D = 2.83
- From chart N_{TC} = 9
- Overburden + surcharge = 20 x 16 + 10 = 330kPa

VOLUME LOSS DUE TO FACE – MARINE CLAY

Face pressure	N	LF	Volume Loss
0	11	1.22	Collapse
50	9.33	1.037	Collapse
100	7.67	0.85	7%
150	6.0	0.67	3.7%
200	4.33	0.48	1.2%
250	2.67	0.30	0.5%
300	1	0.11	0.20%
330	0	0	0%

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Note: settl ... ther factors

MARINE CLAY EXAMPLE

- Need to use a face pressure of 70% to 80% of overburden pressure, as a minimum, to control settlement to a low value.
- Total collapse will occur at about 30% of total overburden pressure

WEATHERED GRANITE IN SINGAPORE

- Use same tunnel dimensions as for clay
- Water (h_o) typically Z-1.5m in Singapore
- Friction angle – typically 34^o
- F_O = 0.18
- F_1 = about 2
- c’ = 0 to 1000kPa for weathered rocks
- γ = 20 to 26 for weathered rocks

GRADE V WEATHERED GRANITE

- $s = F_O \gamma' D - F_1 c' + Ho$
- s = 0.18 x 10.19 x 6 – 2 x 5 + 18.5 x 9.81
- s = 11 – 10 + 181.48 = 182.48 kPa
- 46% of total overburden pressure required to avoid collapse
- Calculation uses depth to axis of tunnel to calculate pressure. Anagnostu and Kovari use depth to invert. Pressure needed depends on where the pressure sensor is – calculation assumes at axis level.

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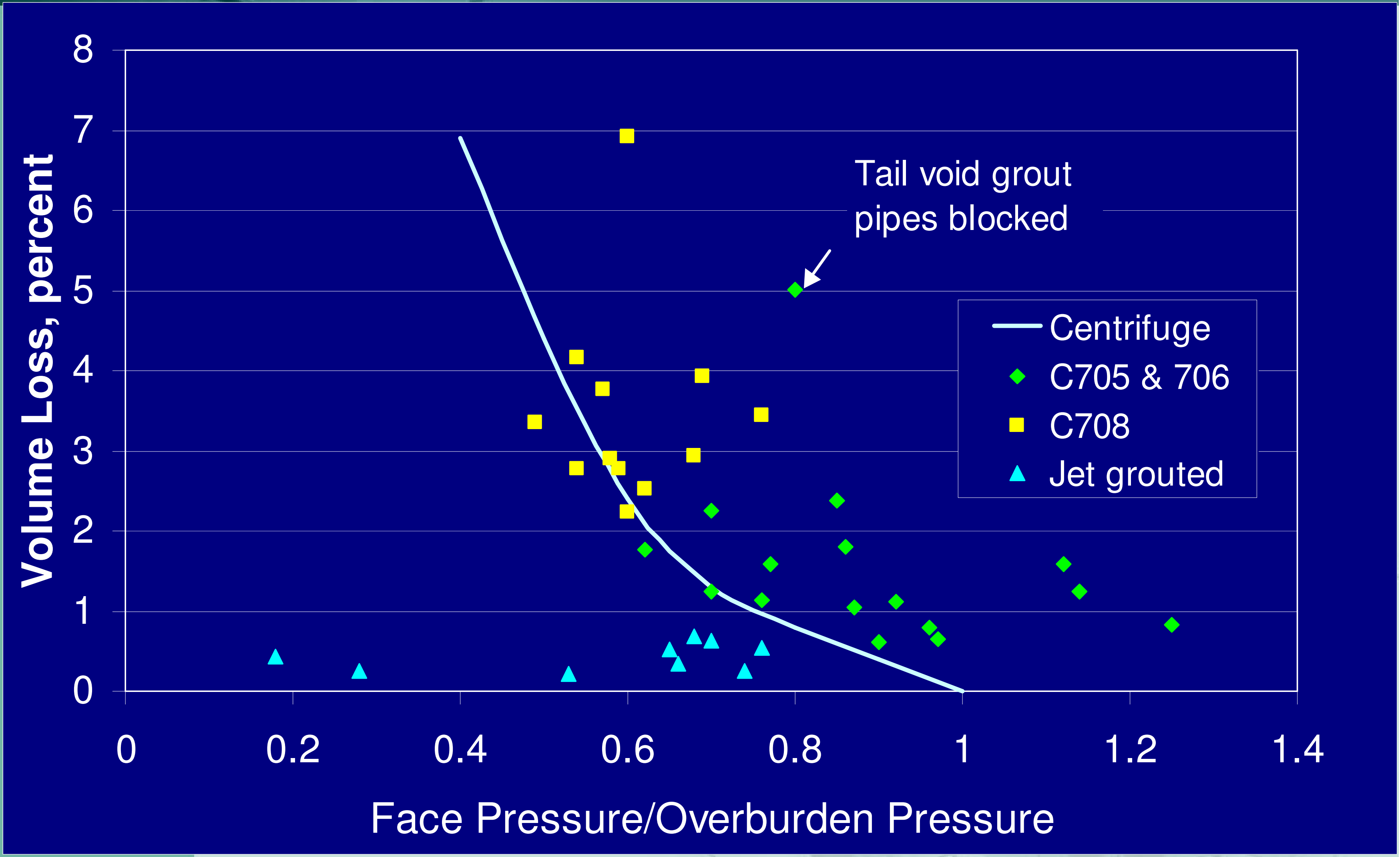
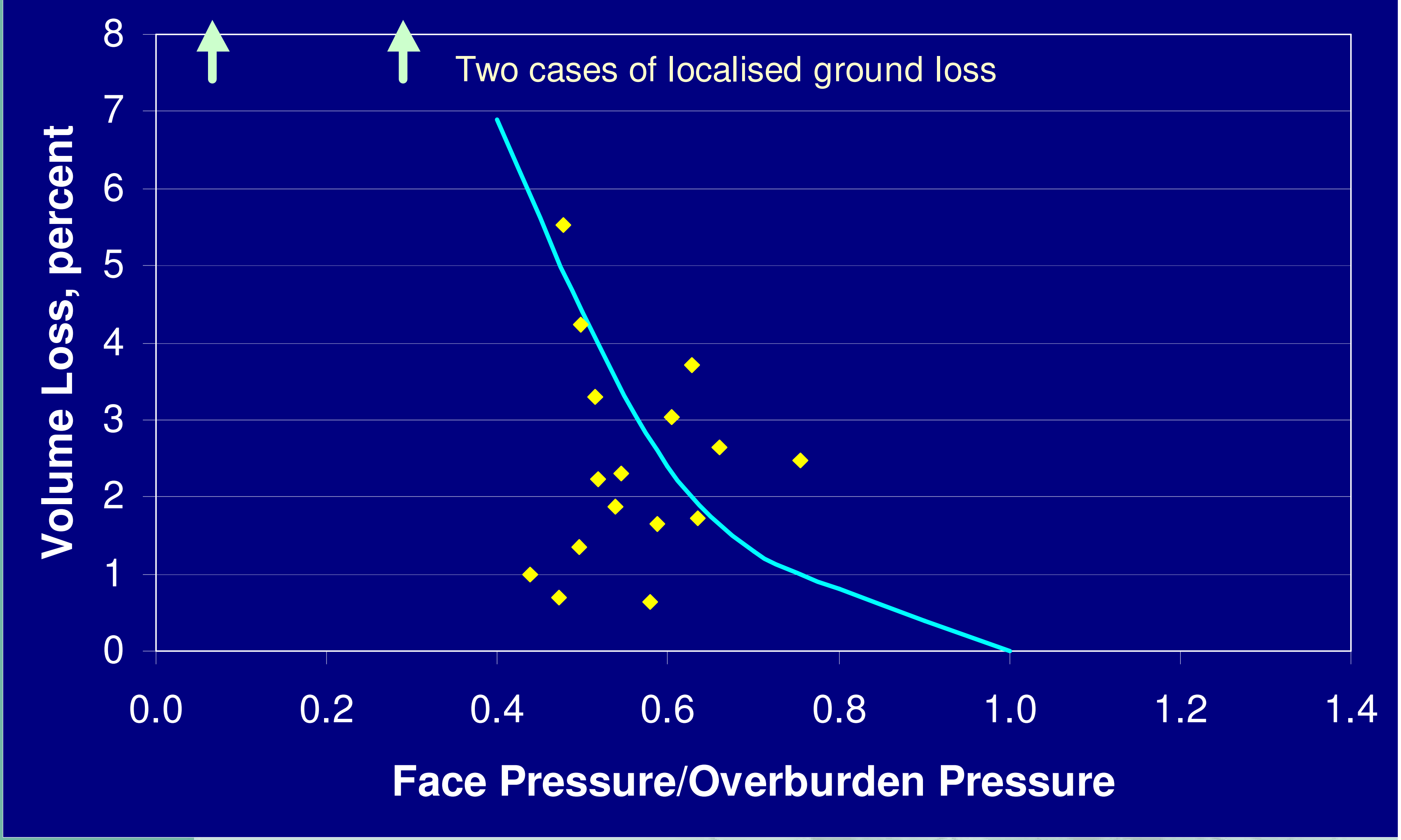
EPB TUNNELLING IN MARINE CLAY



MARINE CLAY/SEDIMENTARY ROCK INTERFACE



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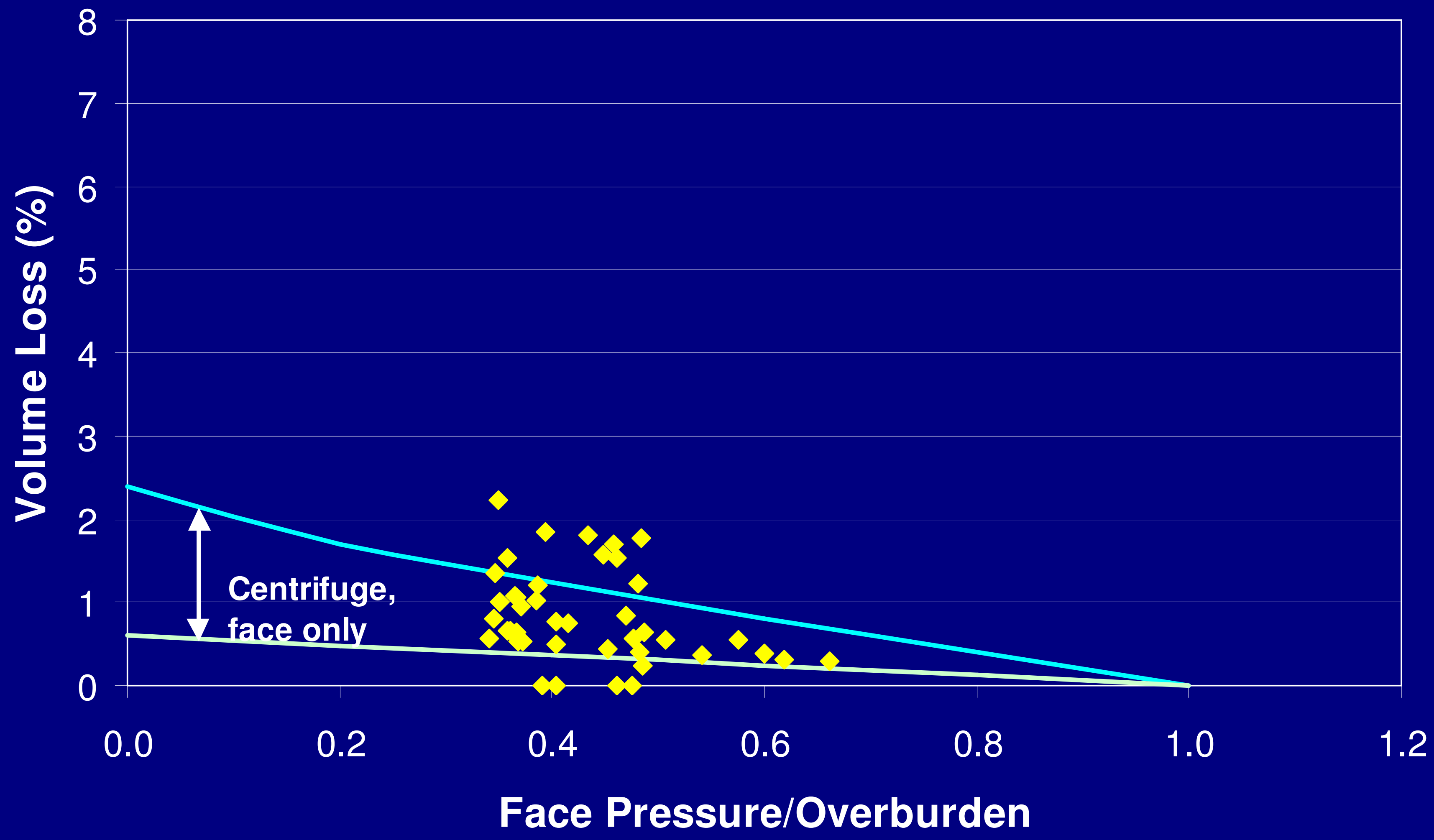
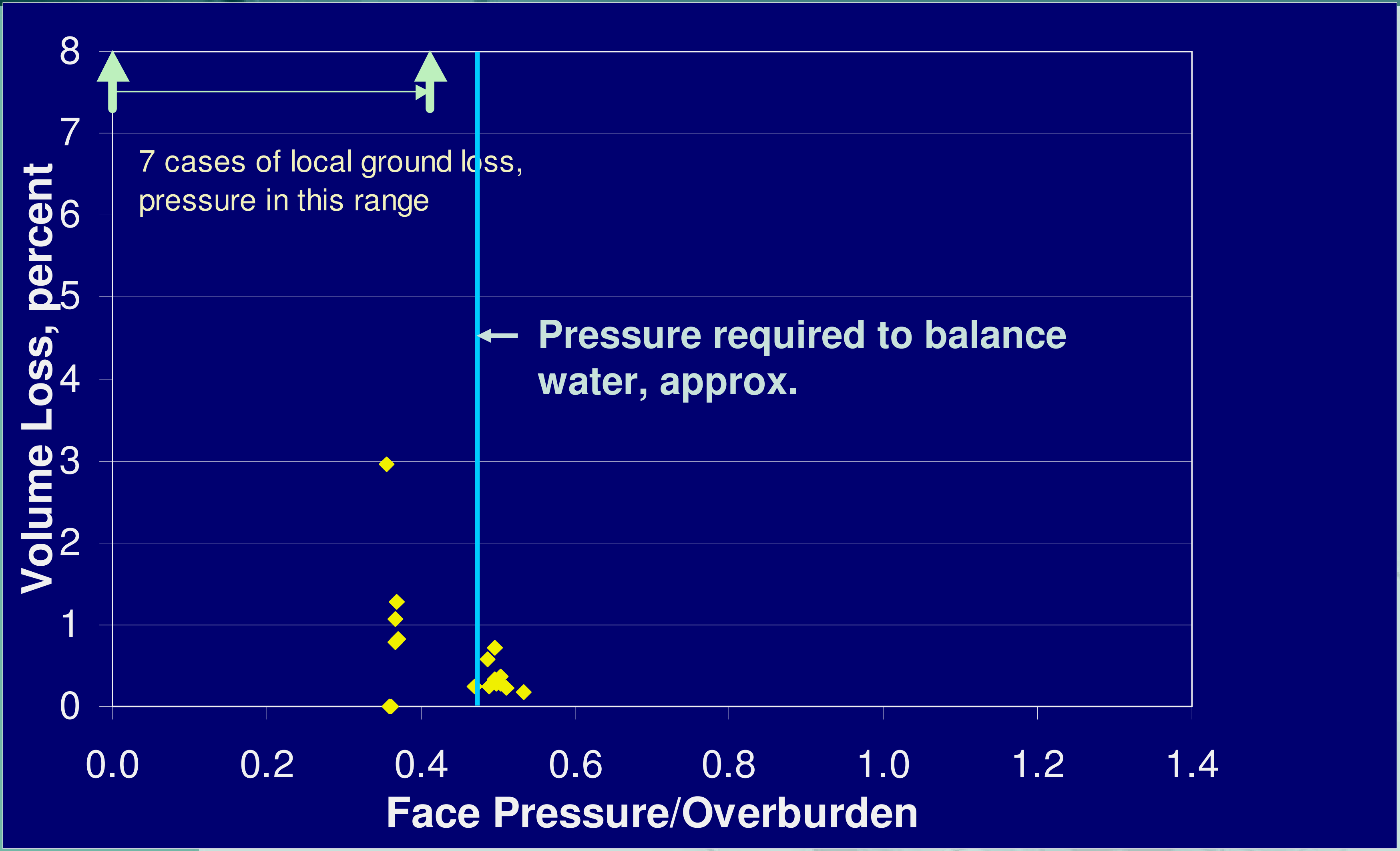
SINKHOLE DUE TO INADEQUATE FACE PRESSURE

RESIDUAL SOIL (GRADE VI GRANITE)



STIFF CLAY BEHAVIOUR

MIXED GRADES (II TO V) OF GRANITE



Granular behaviour

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CONCLUSIONS

- The use of centrifuge data in clay and the methods of Anagnostu and Kovari can give reasonable guidance as to the face pressure required for tunnelling in clay and sand, respectively