Settlement, sinkholes and control

Nick Shirlaw

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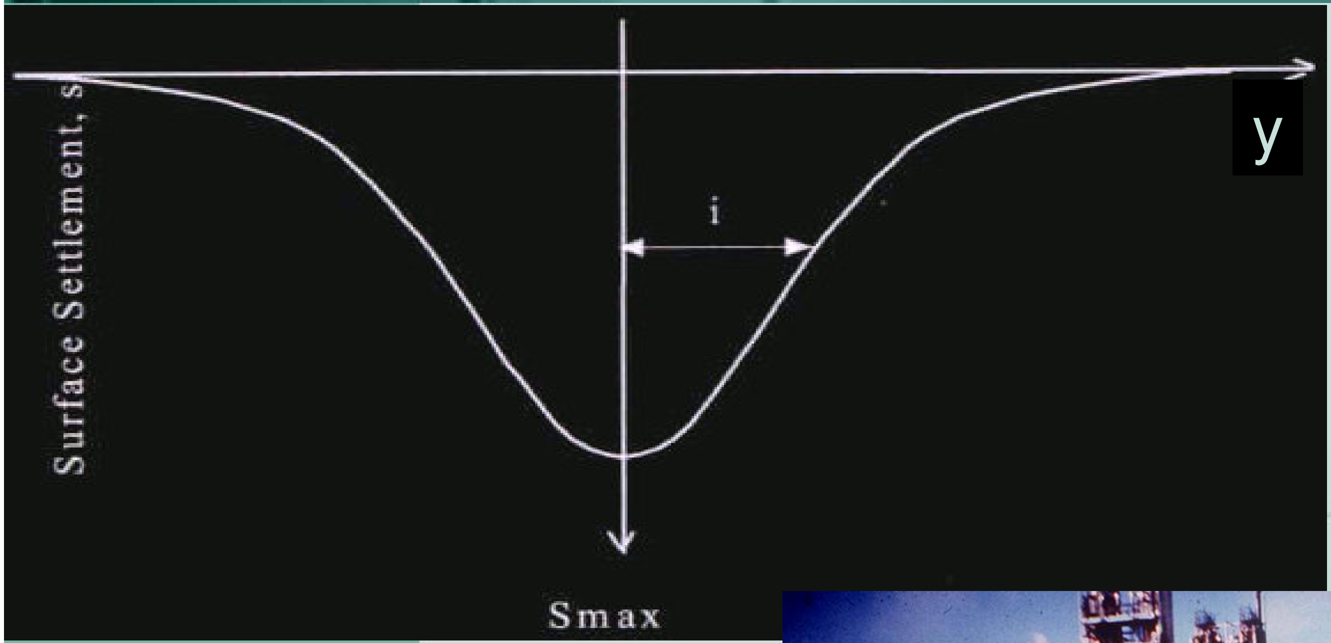
SETTLEMENT TROUGH



$$s(y) = s_{max}\, e^{(-y^2/2i^2)}$$

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'ERROR FUNCTION' CURVE

$$s(y) = smax\ e^{(-y^2/2i^2)}$$

- When y = i, $s(y) = s_{max} \cdot e^{(-1/2)} = 0.606 s_{max}$
- When y = 2i, $s(y) = s_{max} \cdot e^{(-2)} = 0.135 s_{max}$
- When y = 3i, $s(y) = s_{max} \cdot e^{(-4.5)} = 0.011 s_{max}$

VOLUME LOSS

- Volume Loss = Volume surface settlement trough (per m)/Volume of excavated tunnel (per m)
- Unit Volume = 2.5 i $S_{max.}$
- Expressed a a percentage
- Typical design figures in range 1% to 3%
- Governed by maximum surface settlement

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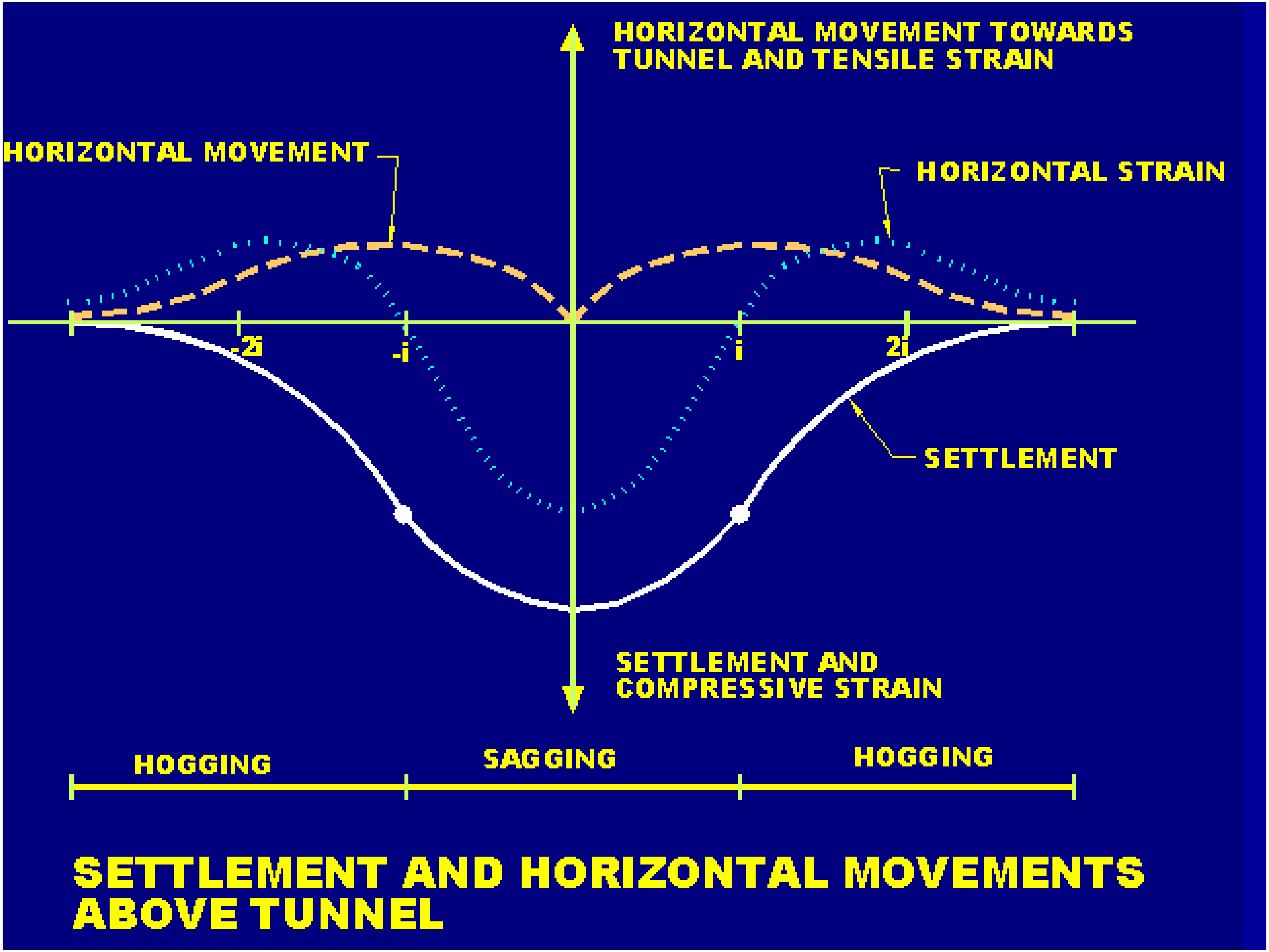
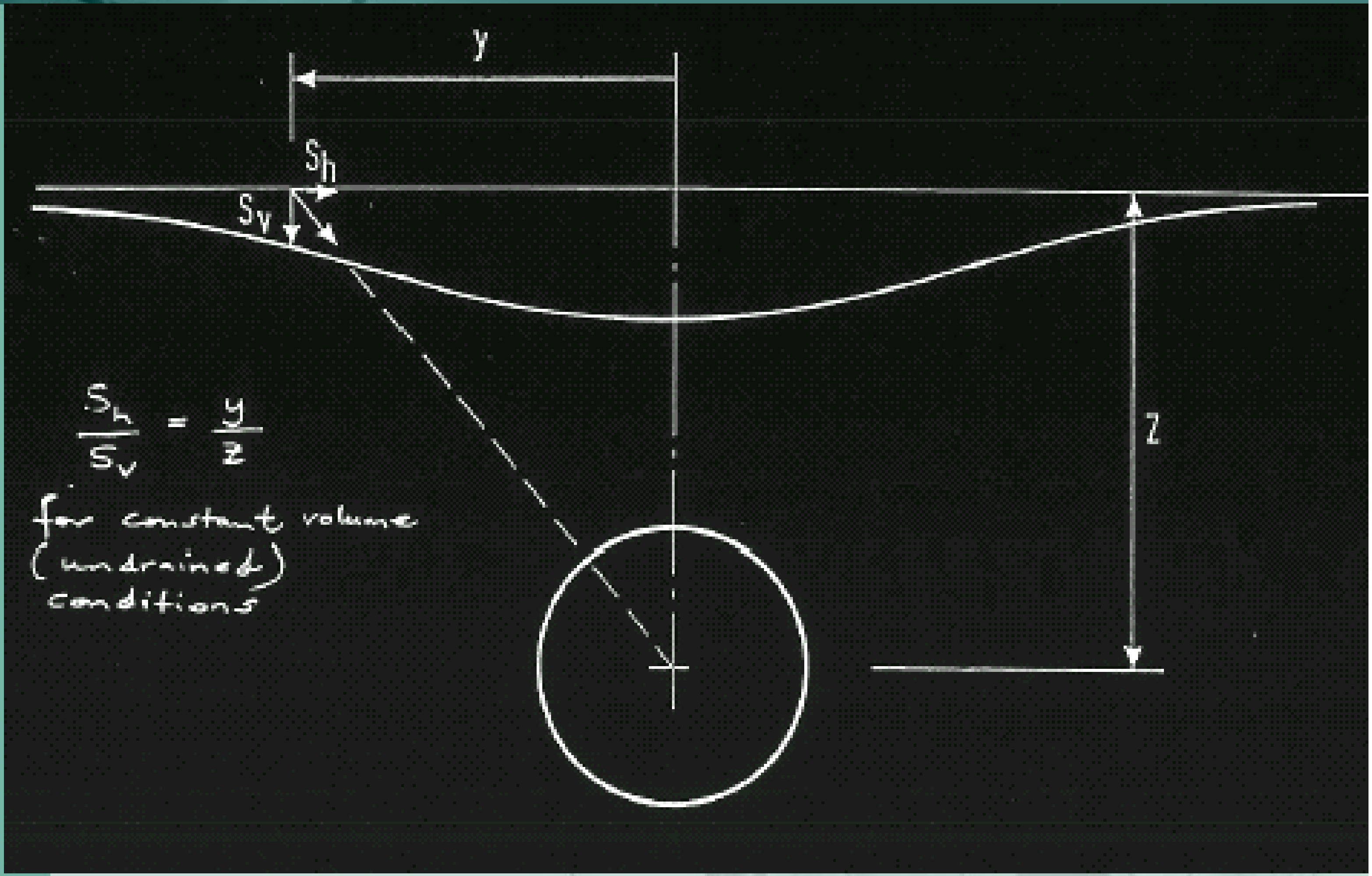
CALCULATING S_{MAX}

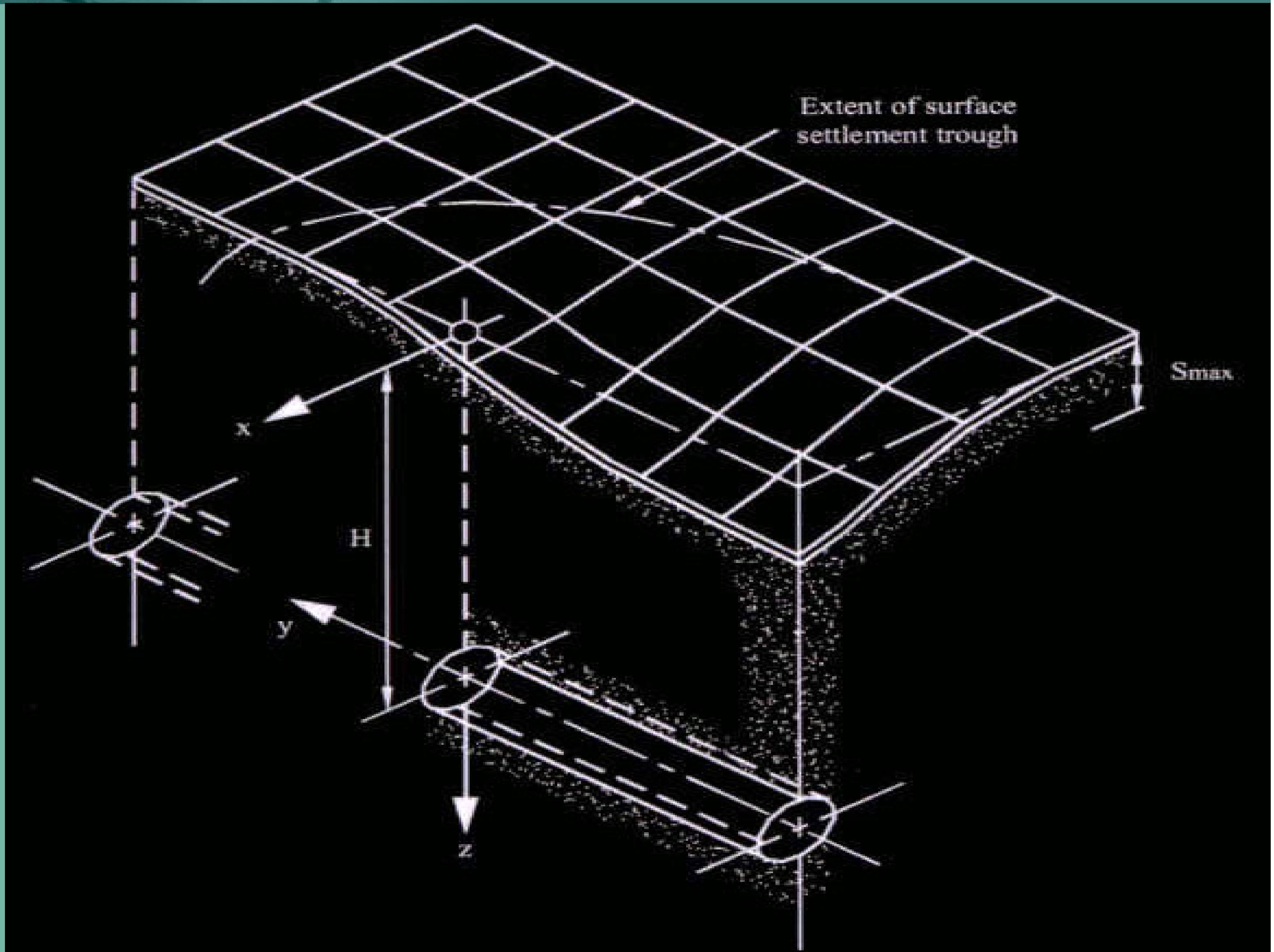
- V_t is unit volume of tunnel, V_l is volume loss in %, V_{SS} is actual unit volume of surface settlement trough
- $V_l = V_{SS} \cdot 100 / V_t$ (percent)
- $V_{SS} = 2.5 \cdot i \cdot S_{max} \times 1m$ (m^3)


HORIZONTAL MOVEMENT TOWARDS
TUNNEL AND TENSILE STRAIN
HORIZONTAL MOVEMENT
HORIZONTAL STRAIN
-2i
-i
i
2i
SETTLEMENT
SETTLEMENT AND
COMPRESSIVE STRAIN
HOGGING
SAGGING
HOGGING
SETTLEMENT AND HORIZONTAL MOVEMENTS
ABOVE TUNNEL

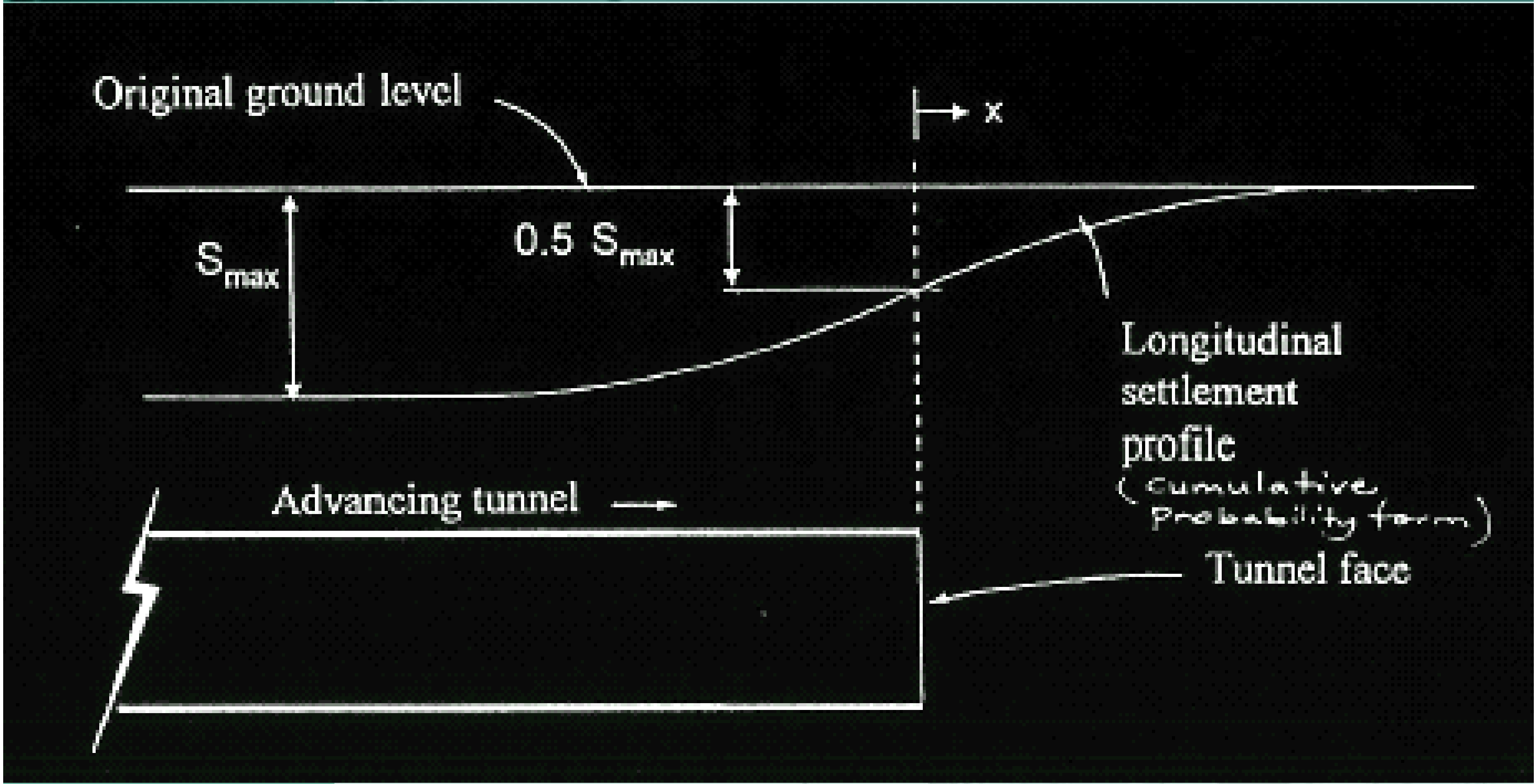
HORIZONTAL MOVEMENT



DISTRIBUTION OF TUNNELLING INDUCED SETTLEMENTS



SETTLEMENT TROUGH – OPEN FACE SHIELDS



NOT APPLICABLE TO PRESSURISED FACE SHIELDS, WHERE
SETTLEMENT OCCURS AS /AFTER FACE PASSES

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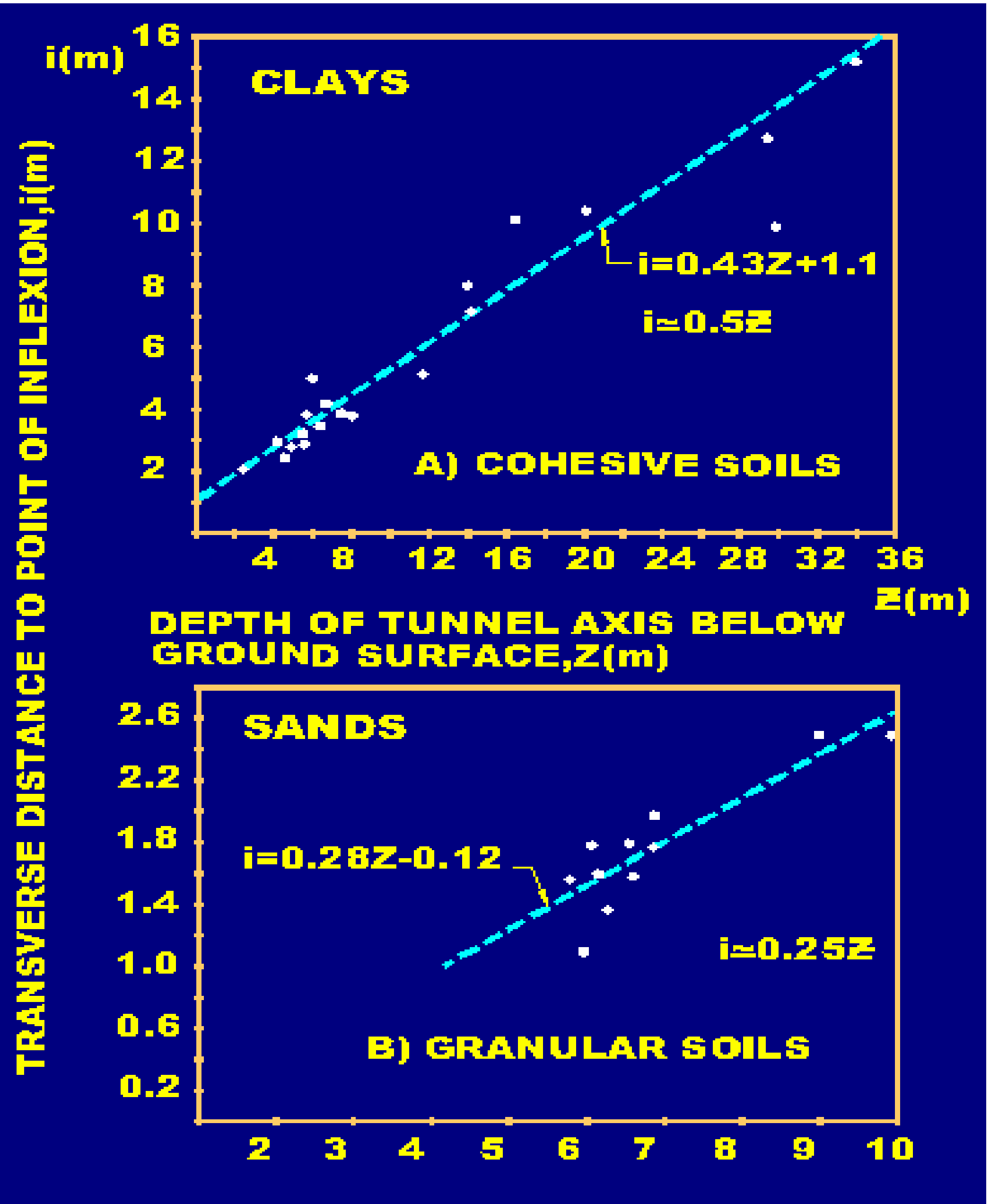
VALUES FOR 'i'

(FROM O'REILLY AND NEW, 1982)



VARIATION OF TROUGH WIDTH PARAMETER,i,WITH TUNNEL DEPTH AFTER O'REILLY & NEW (1982)

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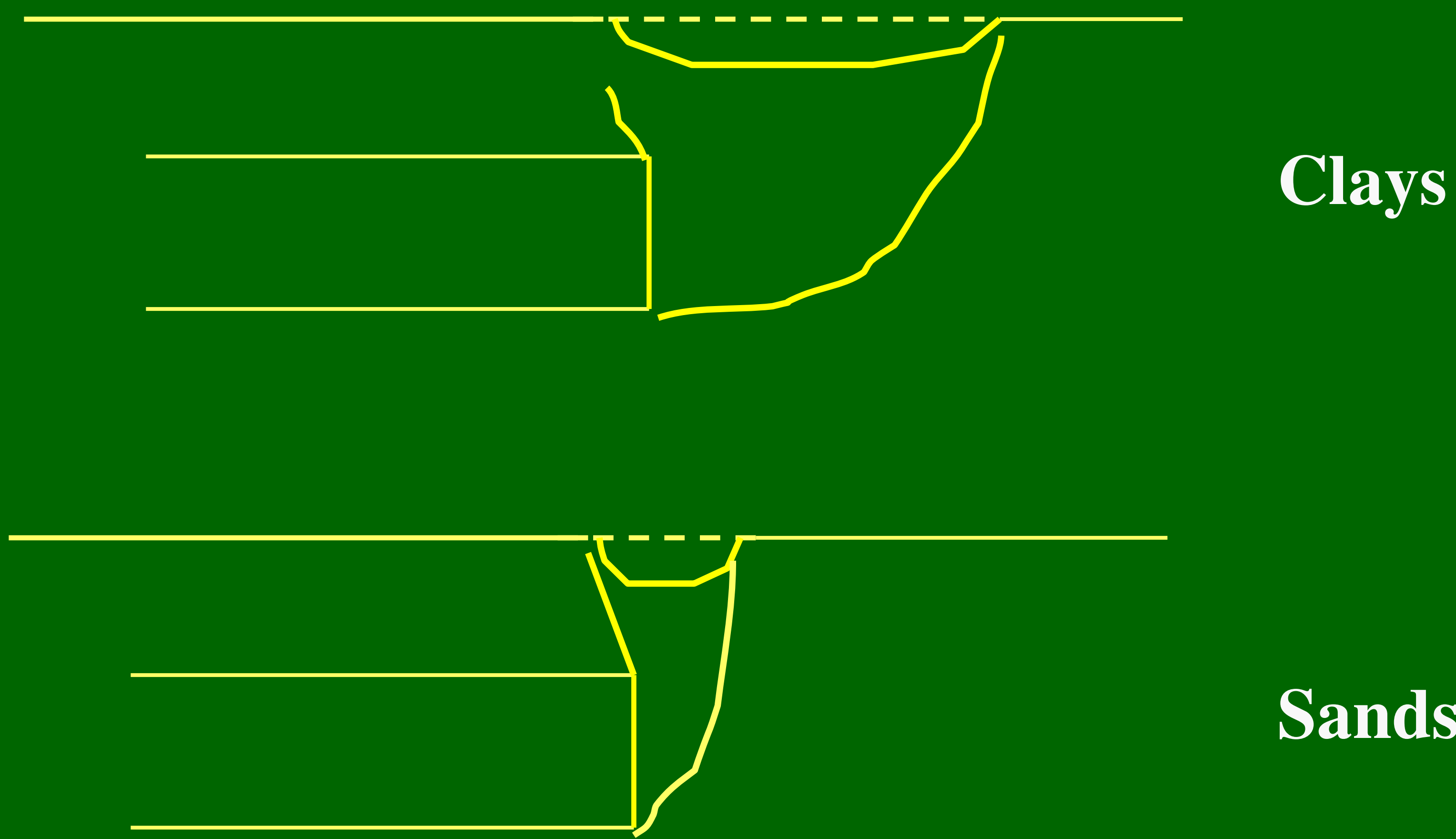
VALUES FOR ‘i’ (Mair 1998)

For clays, use i = 0.5Z
For sands, use i = 0.35Z

FAILURE MECHANISM BASED ON CENTRIFUGE MODEL TEST (MAIR, 1979)



SURFACE SETTLEMENT VS VOLUME LOSS

- **For 6m diameter tunnel at 20 m depth in clay:**

  1% Volume Loss ~ 11mm settlement

  3% Volume Loss ~ 34 mm settlement

Trough extending to 30m from tunnel

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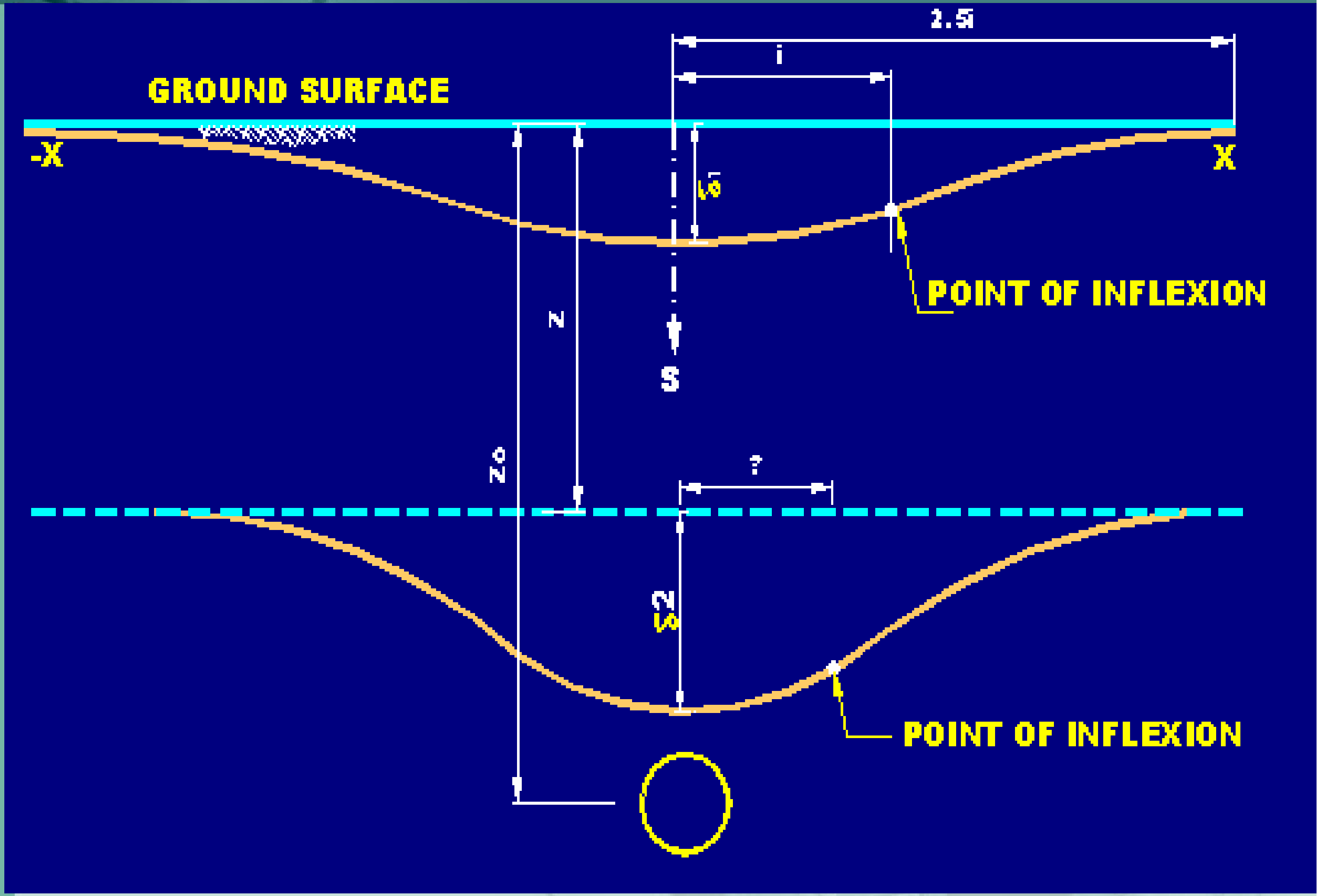
SUBSURFACE SETTLEMENT



SUBSURFACE SETTLEMENT PROFILES IN CLAY

- Ignoring consolidation, can assume deformation at constant volume
- Volume loss at hypothetical subsurface boundary is the same at the surface
- Trough width parameter needs to be adjusted compared with the surface settlement trough

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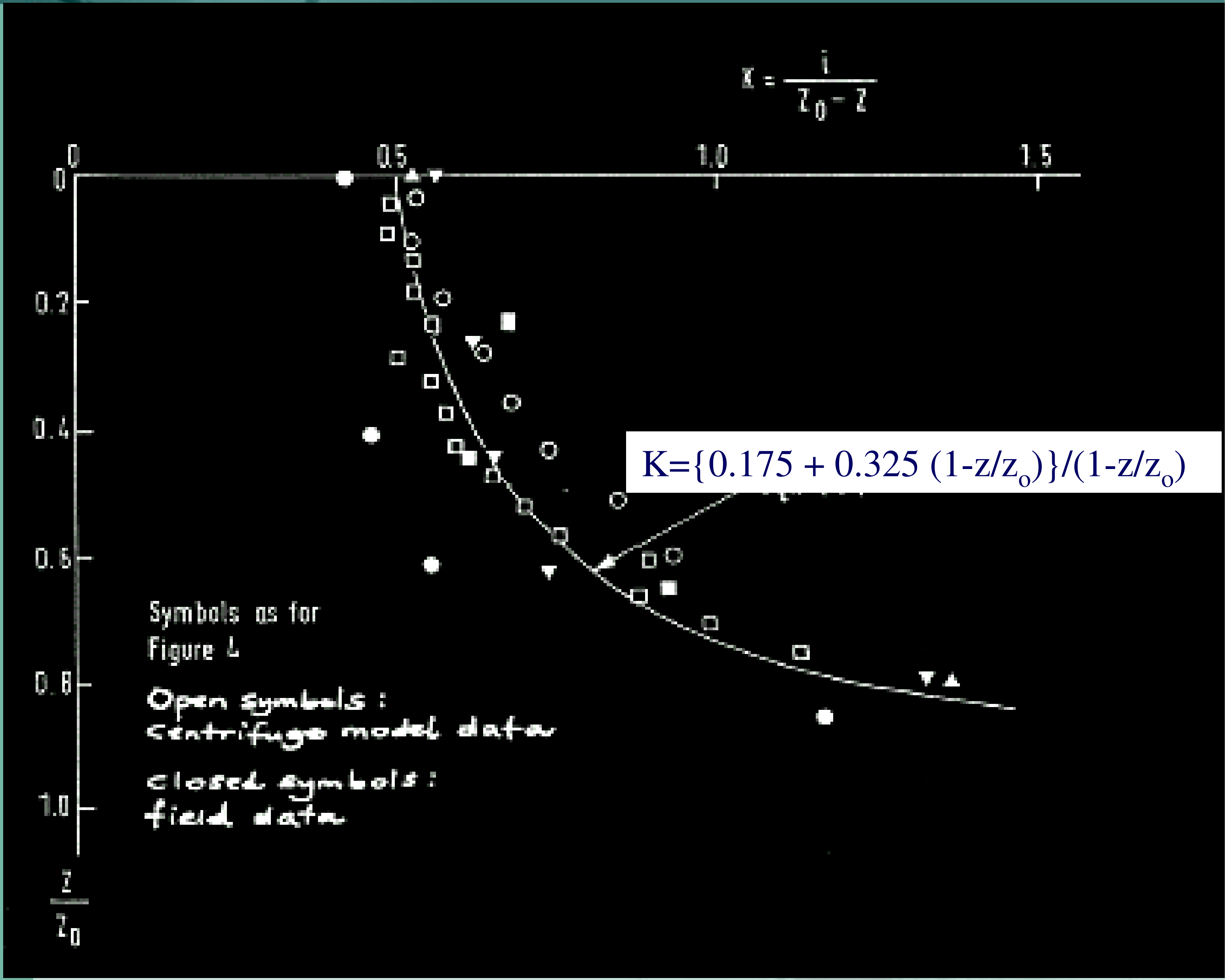
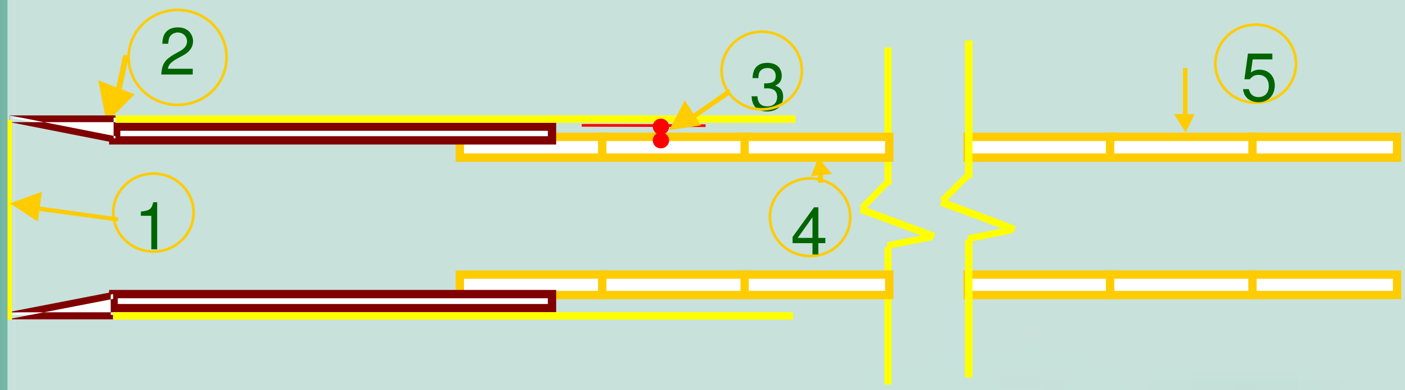
SUBSURFACE SETTLEMENT - CLAY



K={0.175 + 0.325 (1-z/z$_o$)}/(1-z/z$_o$)

SOURCES OF VOLUME LOSS

SOURCE OF MOVEMENT FOR TBM TUNNELLING



1. **Elastic or plastic deformation (stress relief)**
2. **Over cutting, negotiating curves, shield inclination**
3. **Tail void**
4. **Lining deformation**
5. **Consolidation**

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DIMENSIONS – USED IN EXAMPLES

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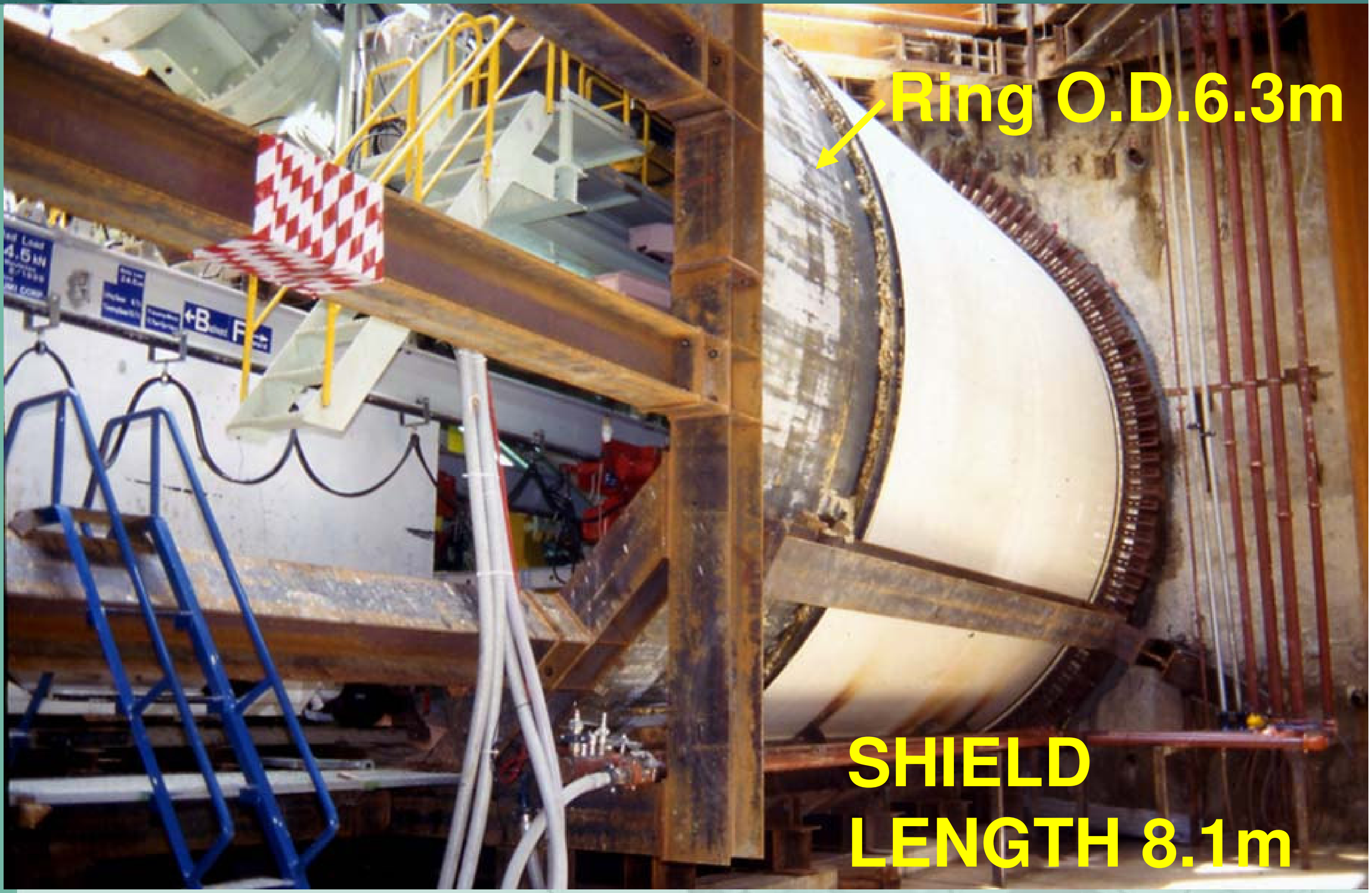
DIMENSIONS – USED IN EXAMPLES



VOLUMES – MINIMUM & MAXIMUM OVERCUT

- **Minimum overcut:**

$$\frac{(3.23^2 \times \Pi) - (3.22^2 \times \Pi)}{(3.23^2 \times \Pi)} = 0.6\%$$

- **Maximum overcut (say 70mm):**

$$\frac{(3.30^2 \times \Pi) - (3.22^2 \times \Pi)}{(3.23^2 \times \Pi)} = 5.00\%$$

- **Overcut will close in soft clay but may stay open long enough to grout in stiffer soils**

VOLUME LOSS DUE TO CURVATURE

$$Vc = \frac{\sqrt{(R+rs)^2 + \left(\frac{L_s}{2}\right)^2} - (R+rs)}{2 \cdot rs}$$

Vc	Volume loss due to curvature
Ls	Rigid shield length
rs	Shield radius
R	Radius of alignment curve

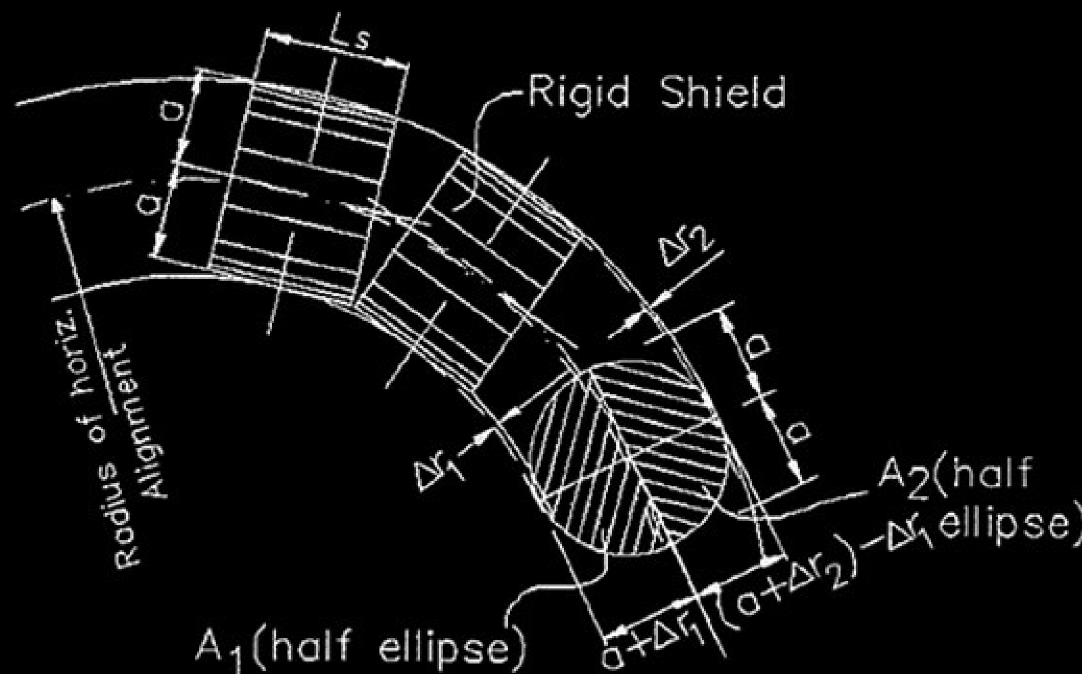


Figure 5 Geometrical Situation for Calculation of Curvature Loss

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POTENTIAL VOID DUE TO CURVATURE

- 200m curve:

$$\frac{[(R+r_s)^2 + (L_S/2)^2]^{½} - (R+r_s)}{2r_s} \times 100$$

$$= \frac{[(200 + 3.23)^2 + (8.1/2)^2]^{½} - (R+r_s)}{2r_s} \times 100$$

$$= 0.62\%$$

- Void due to curve acts like an overcut, but is not additive (use larger of two)

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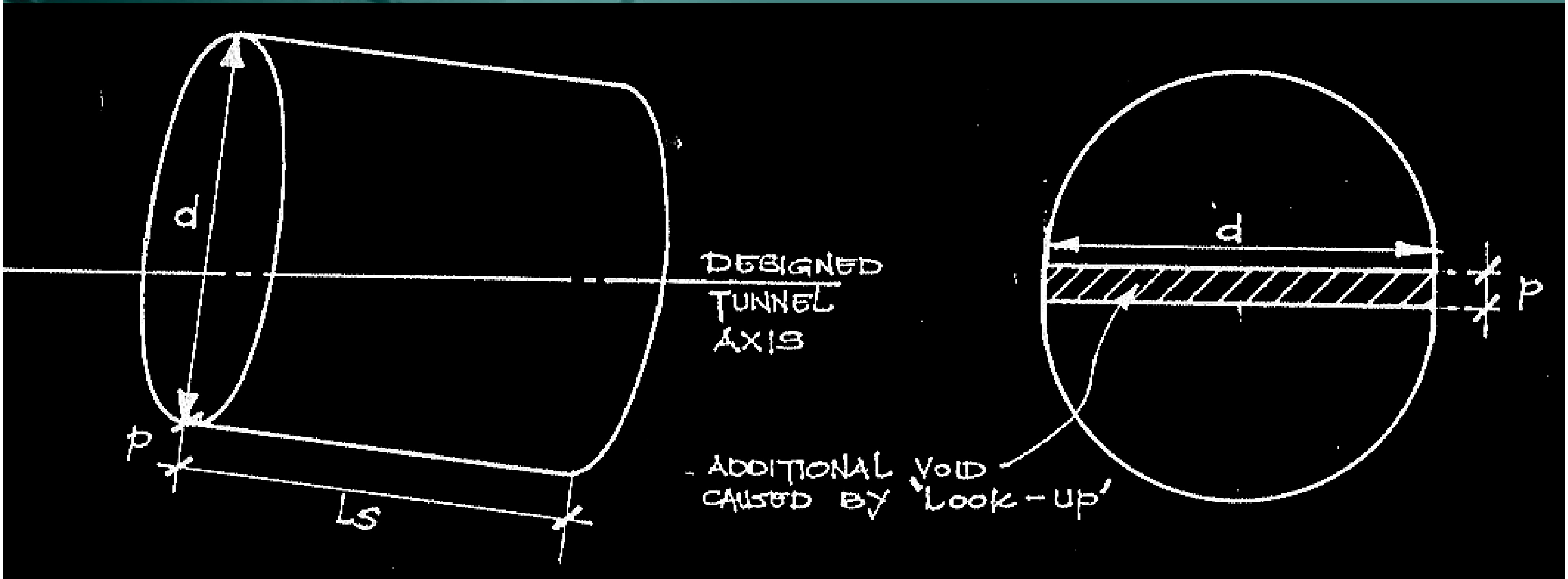
OVERHANG OR 'LOOK UP'



1.Overhang used when invert in hard soil or rock, crown in soft clay

2.'Look up' used to counter effect of weight of head causing shield to dive in soft clay

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POTENTIAL VOID DUE TO INCLINATION

- **50mm ‘look-up’ (example):**
- **Potential $V_I = \frac{O_h \times L_s \times 100}{\Pi r^2}$**
- **Where O_h is the overhang or look up.**
- **Potential $V_I = \frac{0.05 \times 8.1 \times 100}{\Pi \times 3.23^2}$**

  $= 1.24\%$
- **Void due to inclination acts like an overcut, but is not additive (use larger of two)**

VOLUME – TAIL VOID

- Tail void =

$$\frac{(3.22^2 \times \Pi) - (3.15^2 \times \Pi)}{(3.23^2 \times \Pi)} = 4.27\%$$

- In soft clay with conventional grouting through the rings, the tail void closes
- Simultaneous tail void grouting helps to reduce the closure at the tail void

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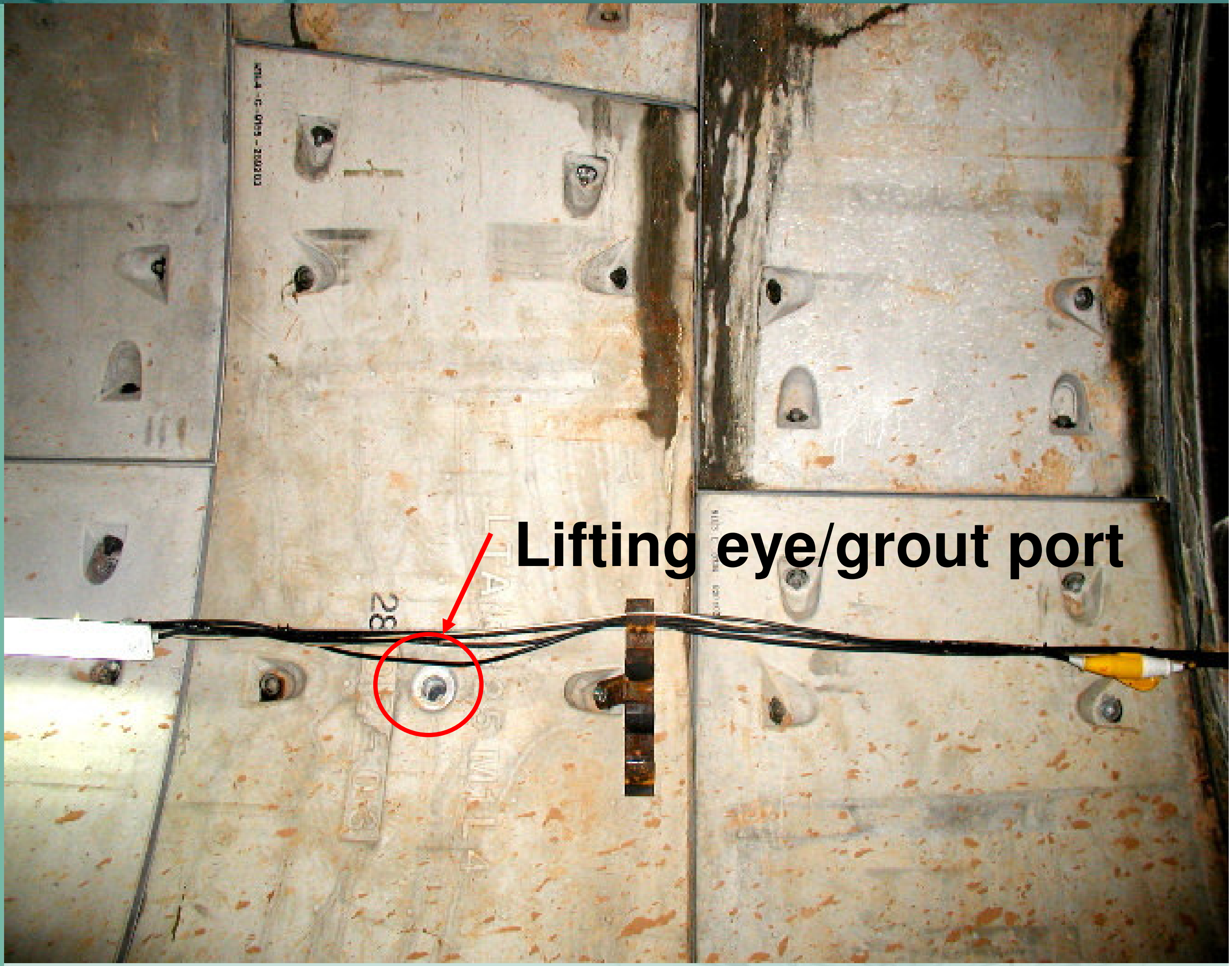
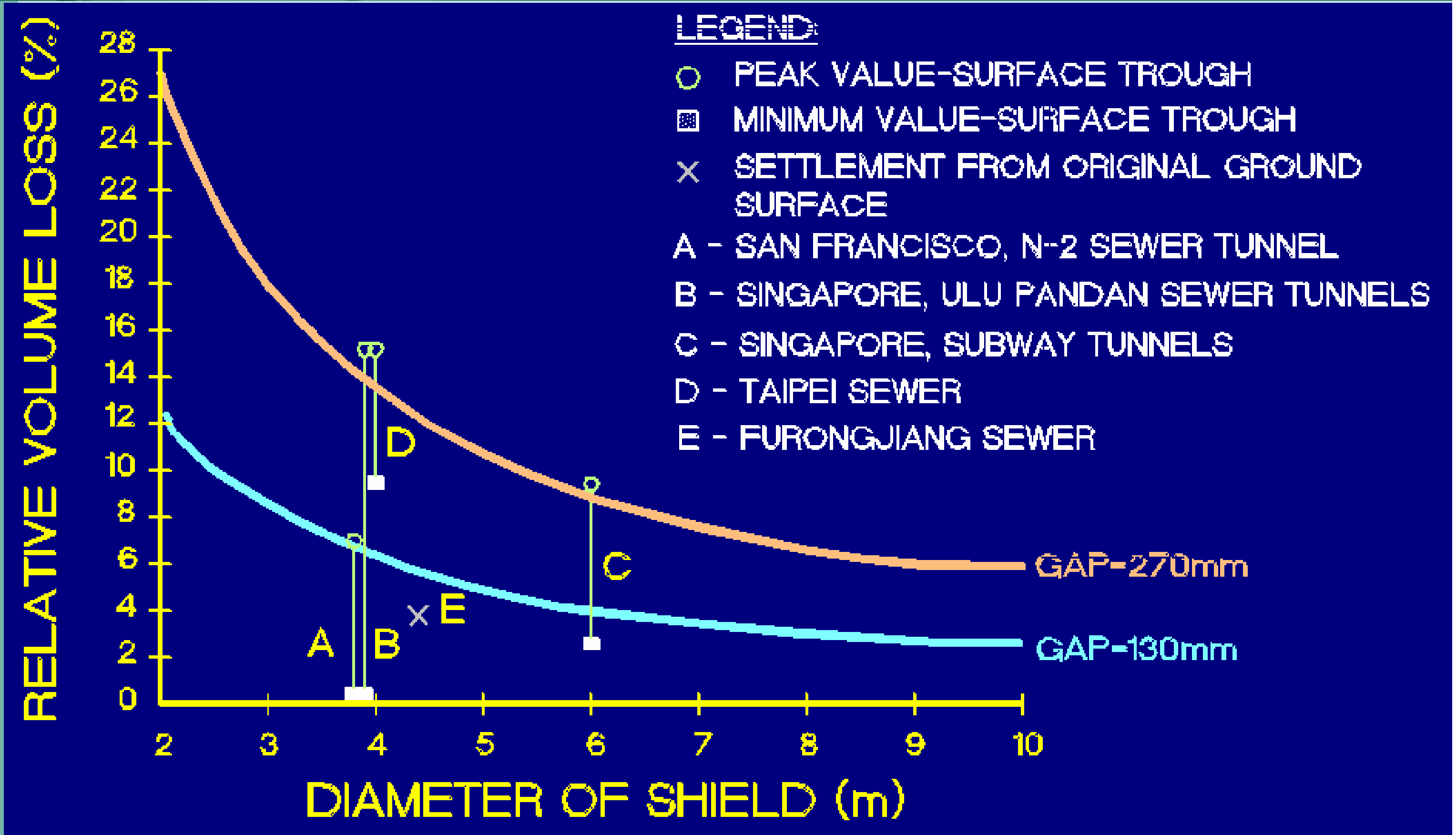
SETTLEMENT

- Actual settlement will be due to the sum of volume losses from:
- Face
- Overcutting or steering (whichever is larger) minus any effects of grouting
- Tail void minus any effects of grouting
- Lining deflection (v.small for segmental lining)
- Use field data to assess some of these effects

PORT FOR GROUTING THROUGH RINGS



EPB SHIELD, CONVENTIONAL GROUTING



EPB TUNNELLING IN SOFT CLAY, CONVENTIONAL GROUTING

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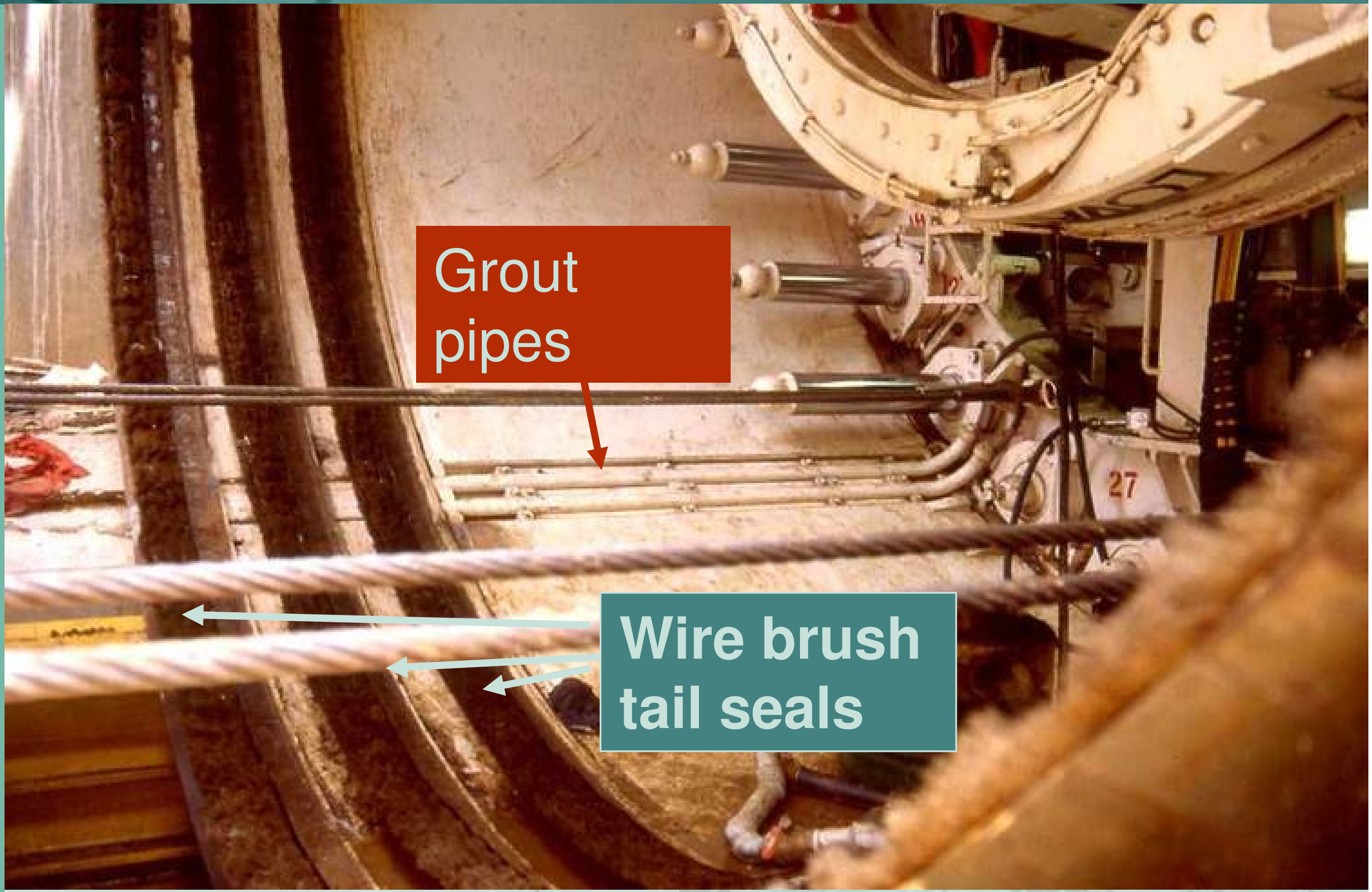
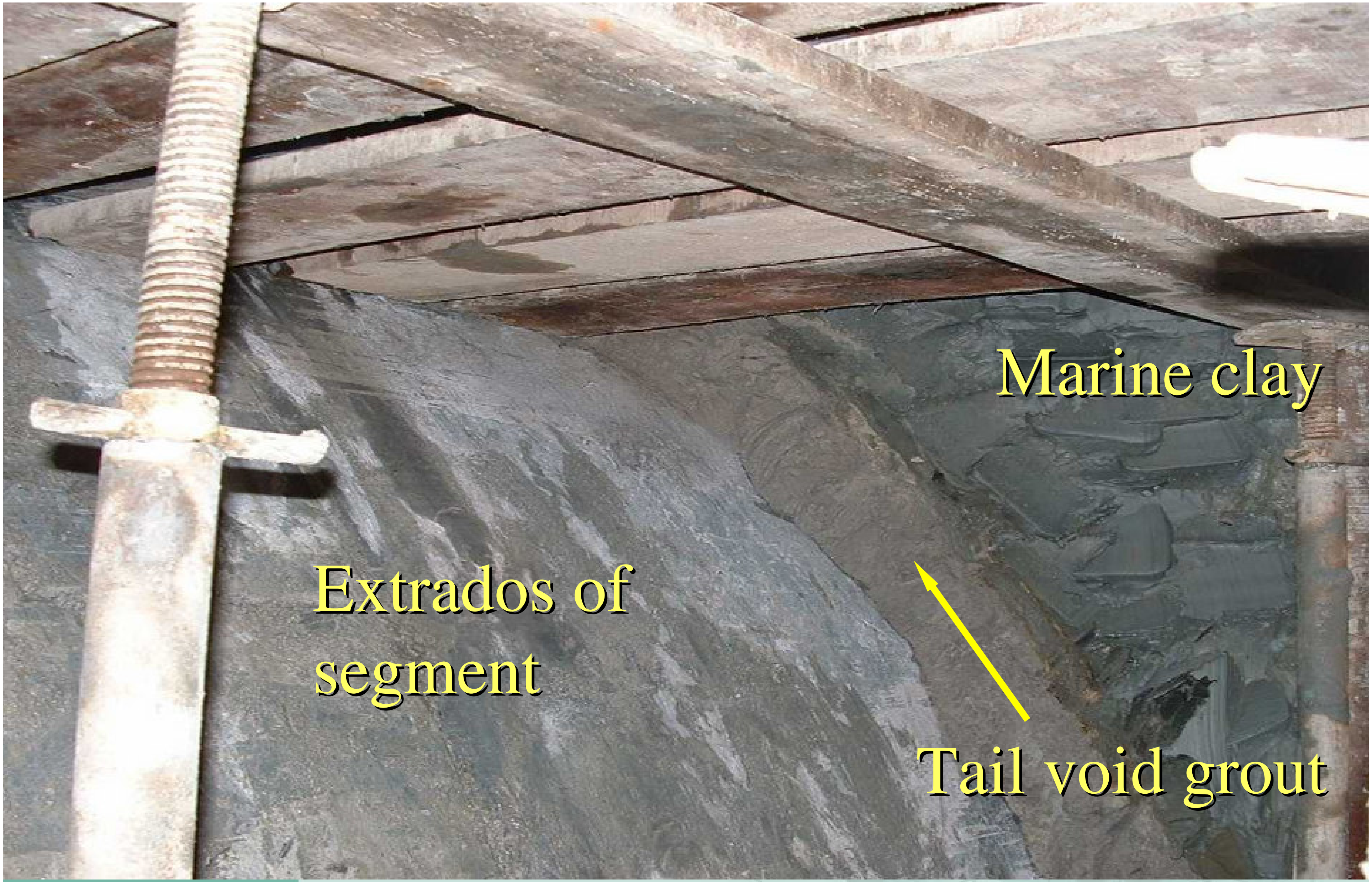
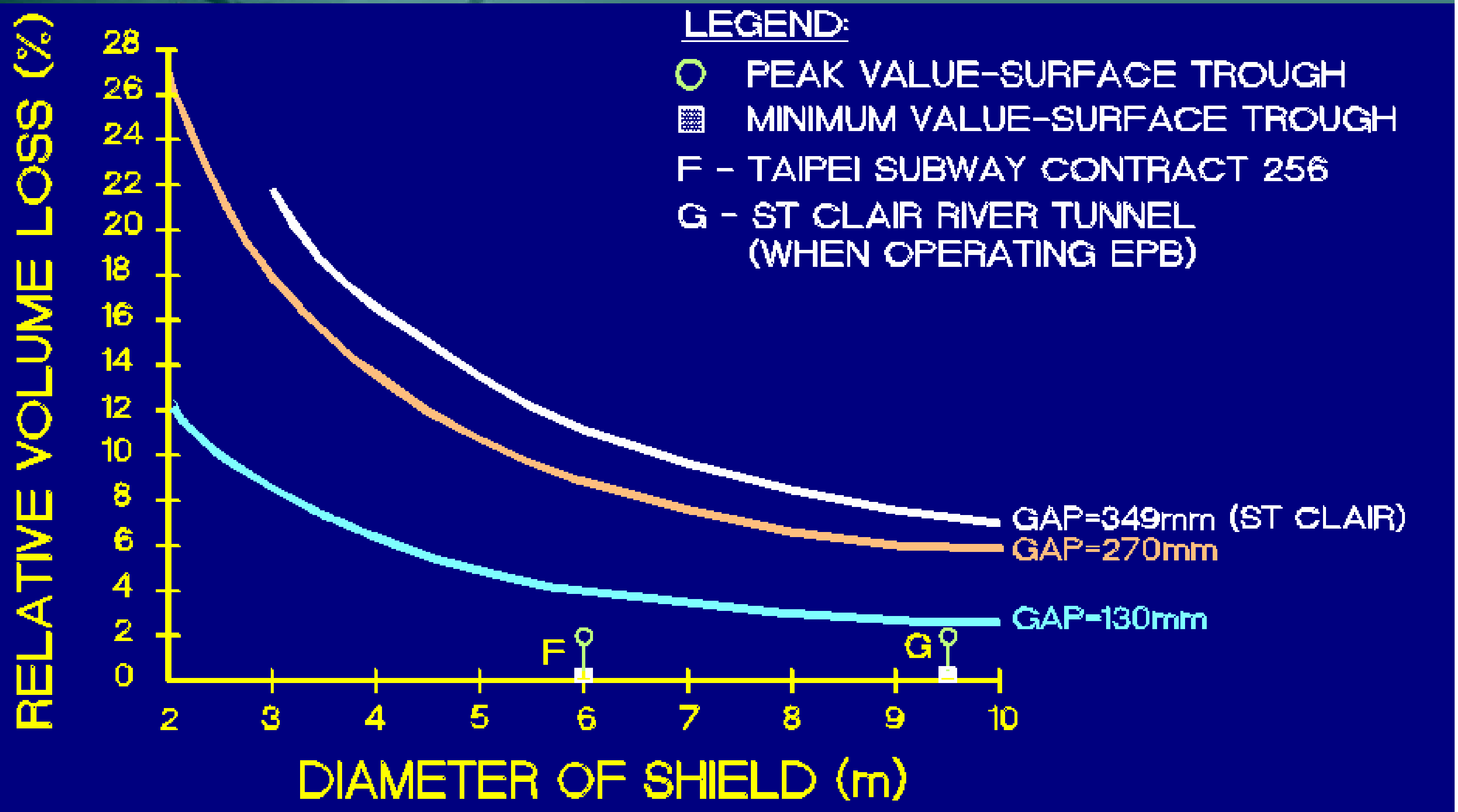
PIPES FOR SIMULTANEOUS TAIL VOID GROUTING





Tail Void Grout between Extrados of Segment Lining and Ground

EPB SHIELDS, SIMULTANEOUS GROUTING



EPB TUNNELLING IN SOFT CLAY, SIMULTANEOUS GROUTING

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SPRAYED CONCRETE TUNNELS (NATM)

Face Loss: P typically
1m in soft ground
No steering, overcut, tail void losses
Larger movements of lining

In stable ground, Volume Loss often smaller, more consistent, than shield

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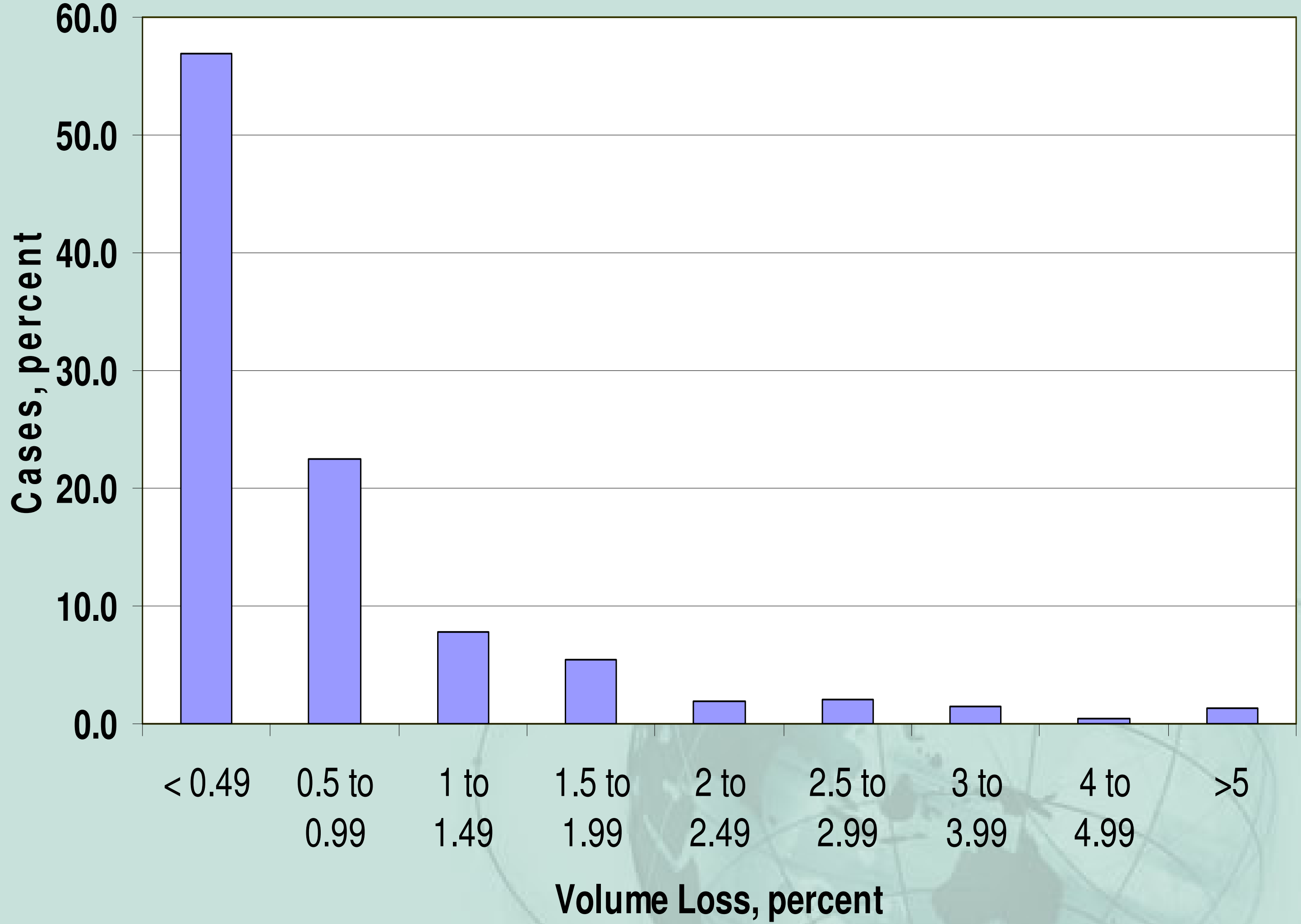
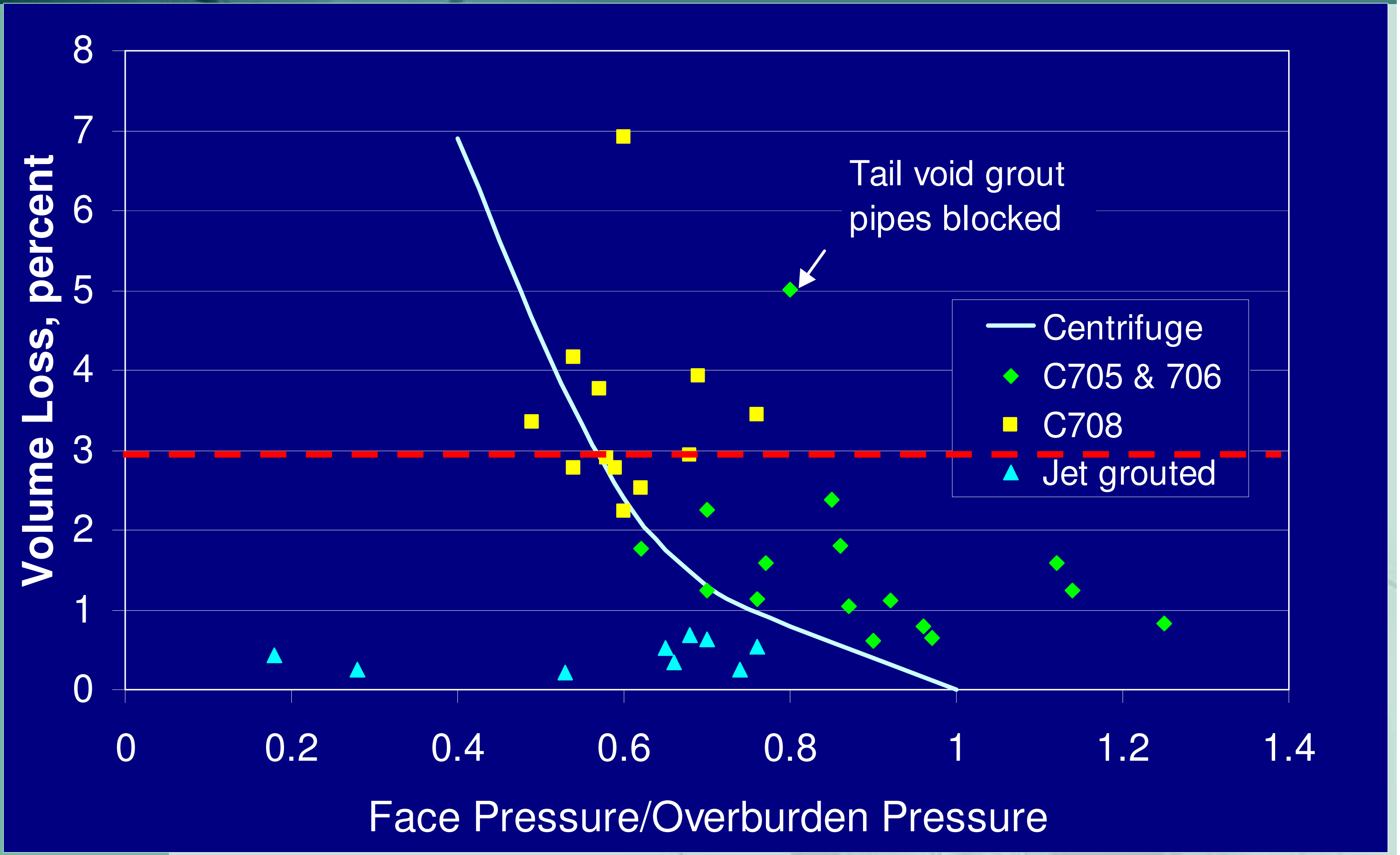
OVERALL RESULTS - NEL



RESULTS FROM 20KM OF EPB TUNNELLING, SINGAPORE, CONDITIONS VARYING FROM SOFT CLAY TO WEATHERED ROCK

MARINE CLAY



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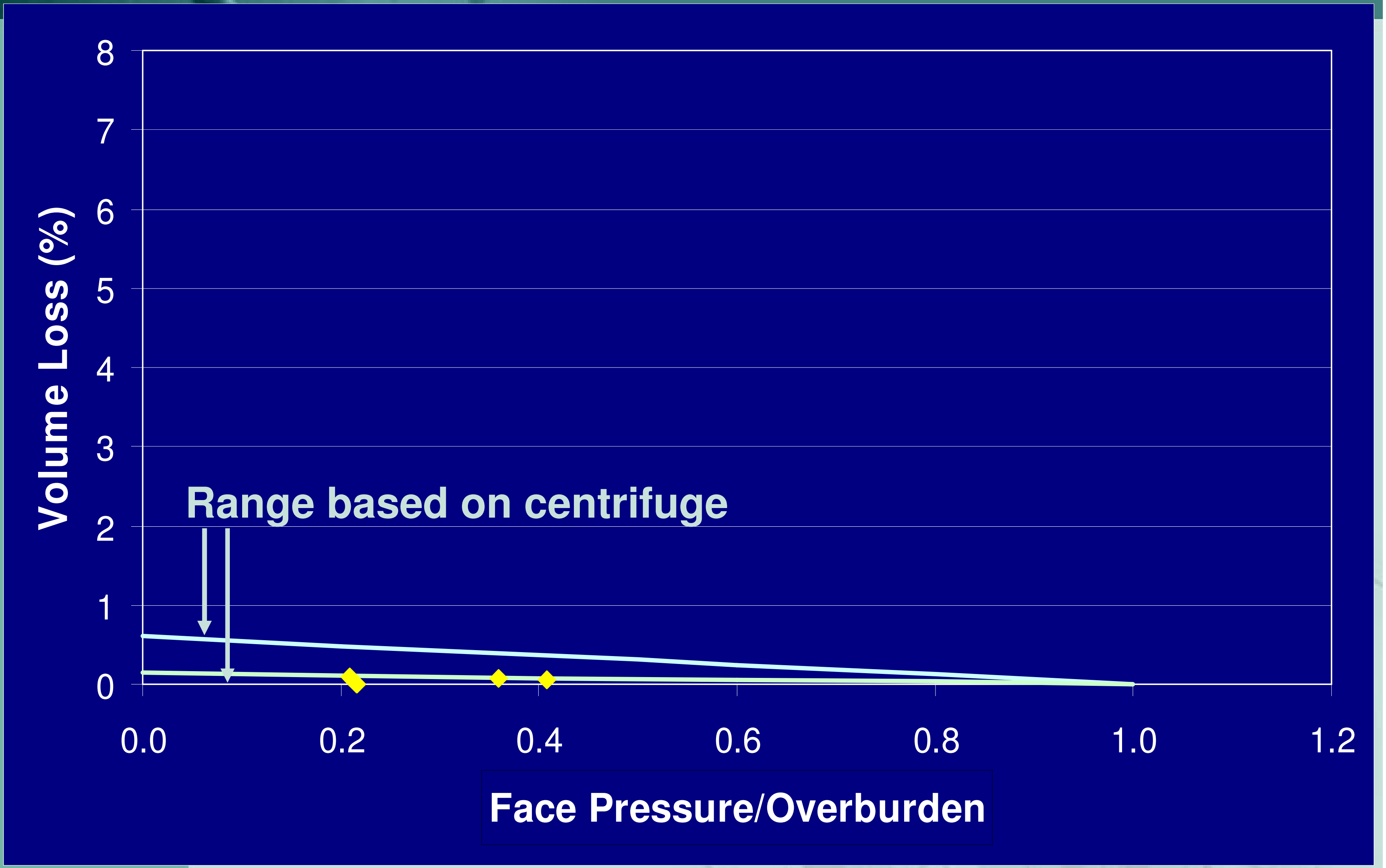
KALLANG FORMATION

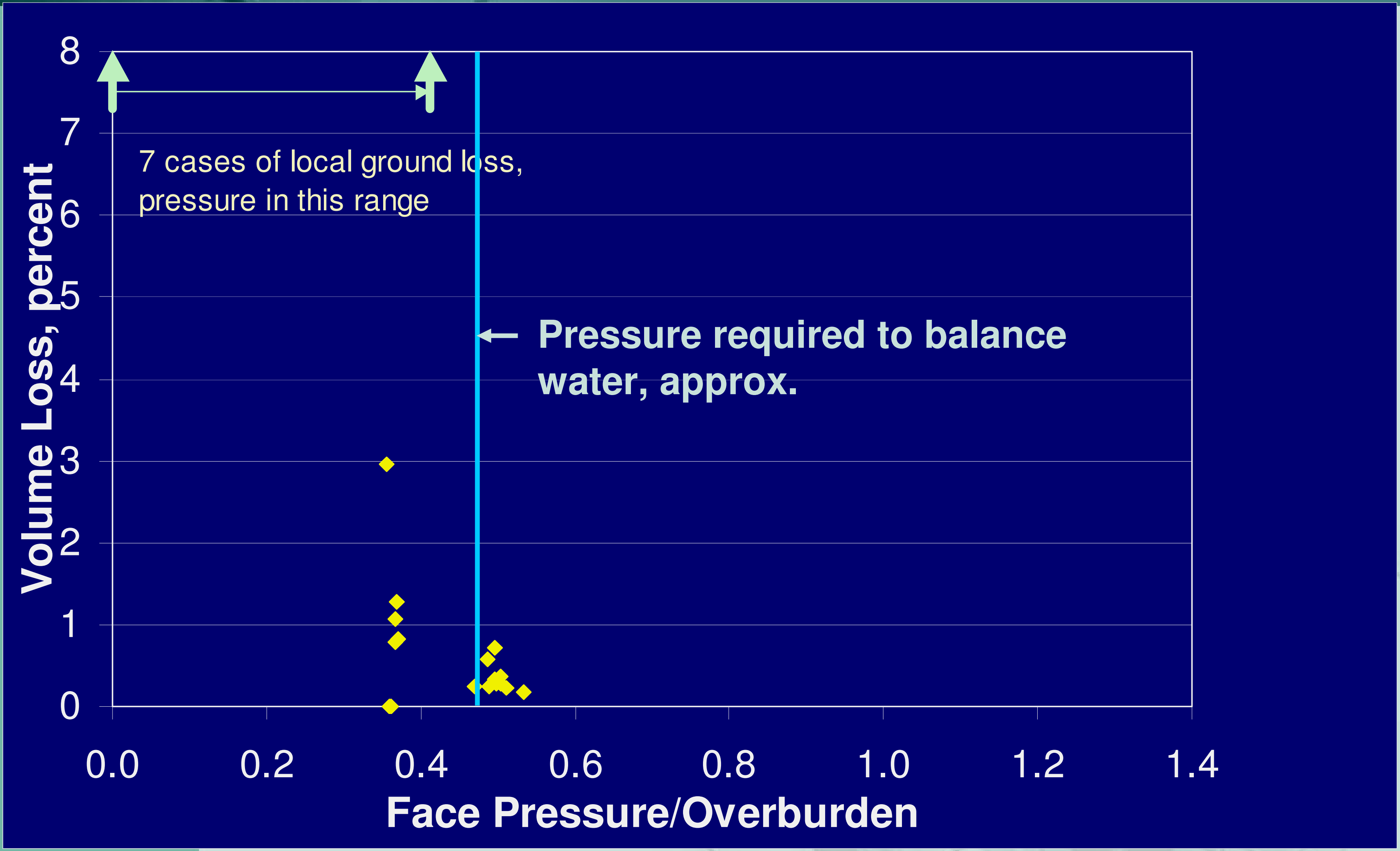
- Where simultaneous tail void grouting is used, total volume loss is typically:

Loss at face + 1 to 2% for other factors

FORT CANNING BOULDER BED (HARD CLAY WITH BOULDERS



MIXED GRADES (II TO V) OF GRANITE



Granular behaviour

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PREDICTION OF SETTLEMENTS

- Predictions' for settlement over tunnels are based on what is reasonably achievable, provided that good control is exercised over face pressure and grouting
- Actual settlements will (hopefully) generally be smaller than predicted, but occasionally will be higher

FACE PRESSURES

- In soft clay, maintain between 0.9 and 1.2 x total overburden for <2% Volume Loss
- In granular soils need to balance water pressure plus a margin
- In heavily over-consolidated clay, some face pressure will help to minimise settlement

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LOCAL, LARGE SETTLEMENT DUE TO TUNNELLING

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SINKHOLE DUE TO TUNNELLING

DTSS – FARRER ROAD

CIRCLE LINE

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SHEPPARD SUBWAY, CANADA

ST CLAIR RIVER TUNNEL, CANADA

SINKHOLES OR SETTLEMENTS> 150mm, EPB TUNNELLING

Tunnel	Year	Length	Incidents	No./km	Strata
Phase 2 (MRT)	1986-1987	1.6	0	0	Soft Clay
St Clair River	1993-1994	1.9	3	1.6	Soft Clay (Till)
Allen Sewer	1994	1.1	1	0.9	Glacial sand
Sheppard Subway	1997-1998	6.4	15	2.3	Tills
Changi Line	1998-1999	7	1	0.1	Old Alluvium
North East Line	1998-2000	20	16	0.8	Incidents mainly in w. rock
Deep Sewer System	1999-2005	48	23	0.48	Incidents mainly in w. rock

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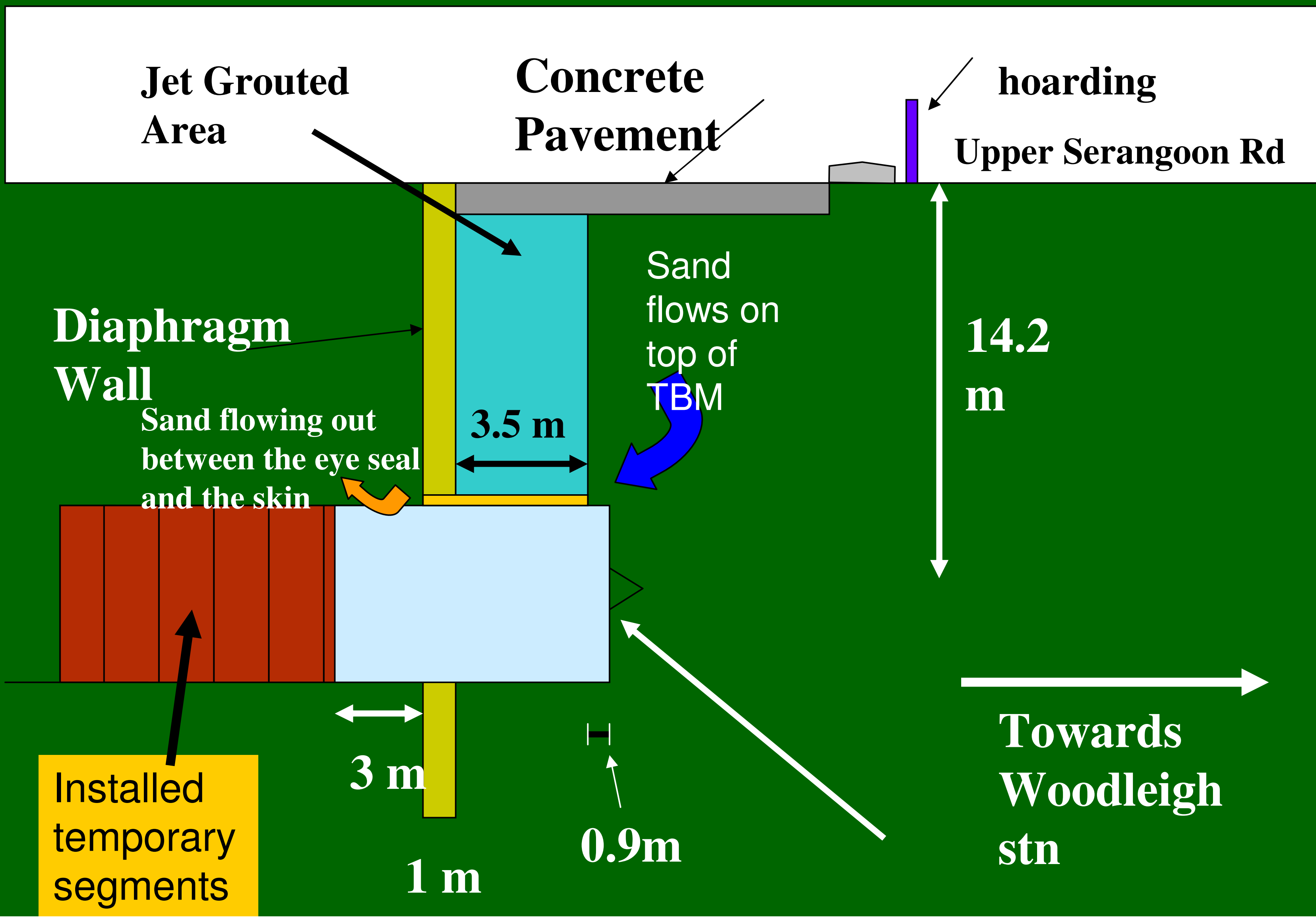
HIGH RISK AREAS - 56 CASES

- Launching the shield [9]
- Breaking into shafts or excavations [3]
- Interfaces between strong, stable soils and weak soils [6]
- Mixed faces of rock or hard till and soil [15]
- Head access for maintenance [13]
- Mechanical Failures, often associated with long drives in abrasive ground [6]
- Others [4]

LAUNCHING PROBLEM



SHIELD LAUNCH

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SINK HOLE DUE TO FLUVIAL SANDS FLOWING INTO LAUNCHING SHAFT

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EXCEPTIONAL SETTLEMENTS OR SINKHOLES

- Generally due to large losses at the face of the tunnel
- Either due to poor planning of face pressures (interfaces) or due to inability to maintain desired face pressures

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CONSOLIDATION SETTLEMENTS OVER TUNNELS

Why do they occur?

- **Occur due to pore pressure changes induced by tunnelling. The reduction in pore pressures causes consolidation**
- **If water drains towards the tunnel ⟶ pore pressure reduction**
- **If stress changes during tunnelling cause positive excess pore pressures, then consolidation occurs as those excess pore pressures dissipate**

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CONSOLIDATION SETTLEMENTS OVER TUNNELS

- Can be as much as 30% to 90% of the total settlement over the tunnel, if no measures are taken to control them
- 30% to 90% is based on tunnelling for N-S and E-W MRT lines, Singapore, in areas of marine or estuarine clay (soft clay)
- Significant consolidation settlements have also been measured over tunnels in London Clay (stiff to very stiff clay)

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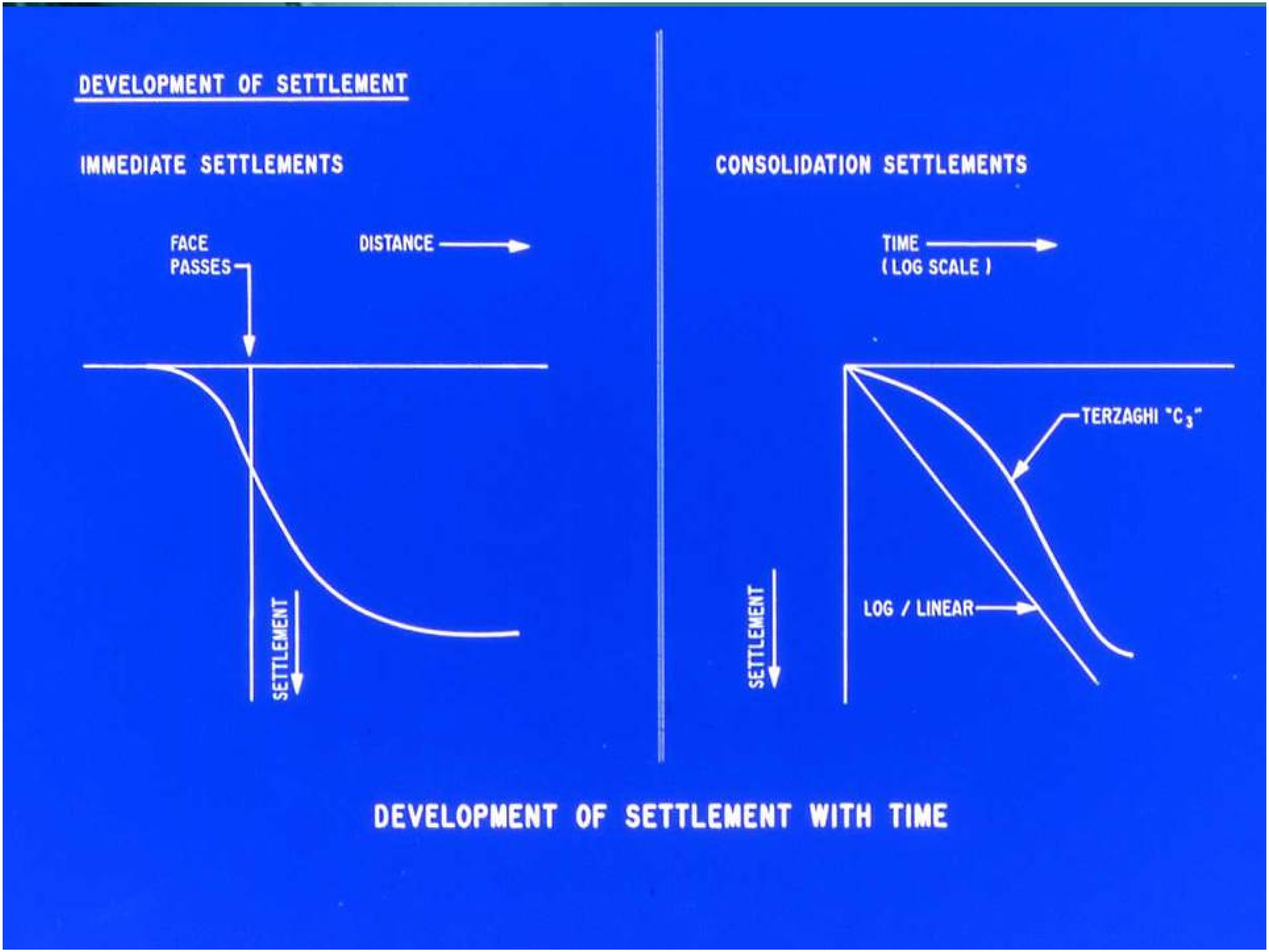
CONSOLIDATION SETTLEMENTS OVER TUNNELS

How to identify them?

- **Marine clay in Singapore is a perfect medium for studying consolidation settlements**
- **The clay is of such low permeability that consolidation settlements occur slowly**
- **'Immediate' settlements occur in an 'S' curve, as the face passes under the settlement point**
- **Consolidation settlements in marine clay develop slowly with time, and follow Terzaghi's one dimensional consolidation model**

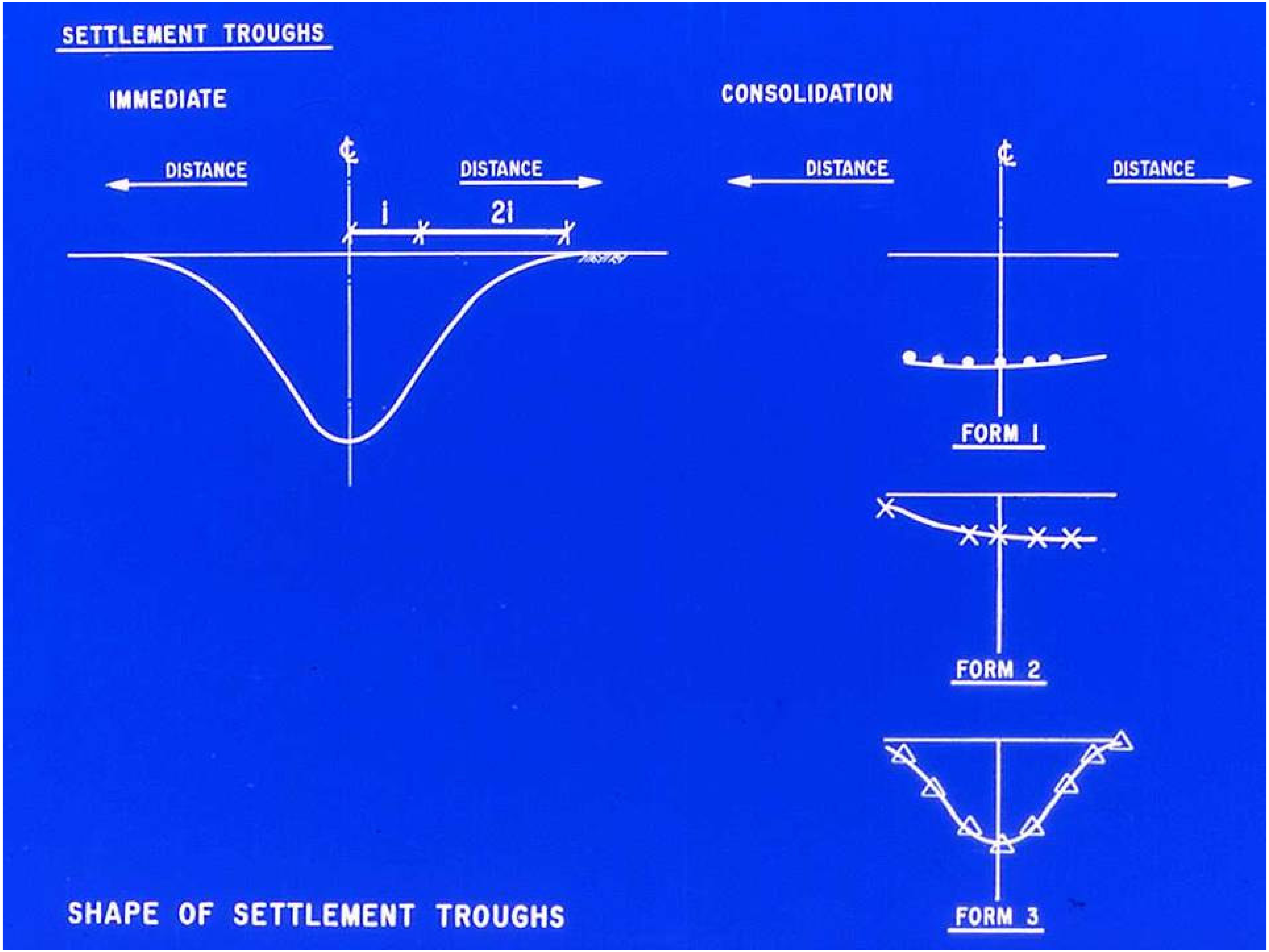

DEVELOPMENT OF SETTLEMENT
IMMEDIATE SETTLEMENTS
FACE PASSES
DISTANCE
SETTLEMENT
CONSOLIDATION SETTLEMENTS
TIME (LOG SCALE)
TERZAGHI "C3"
LOG / LINEAR
SETTLEMENT
DEVELOPMENT OF SETTLEMENT WITH TIME

SETTLEMENT / LOG TIME,
EPB TUNNELLING IN SINGAPORE

CONSOLIDATION SETTLEMENTS OVER TUNNELS

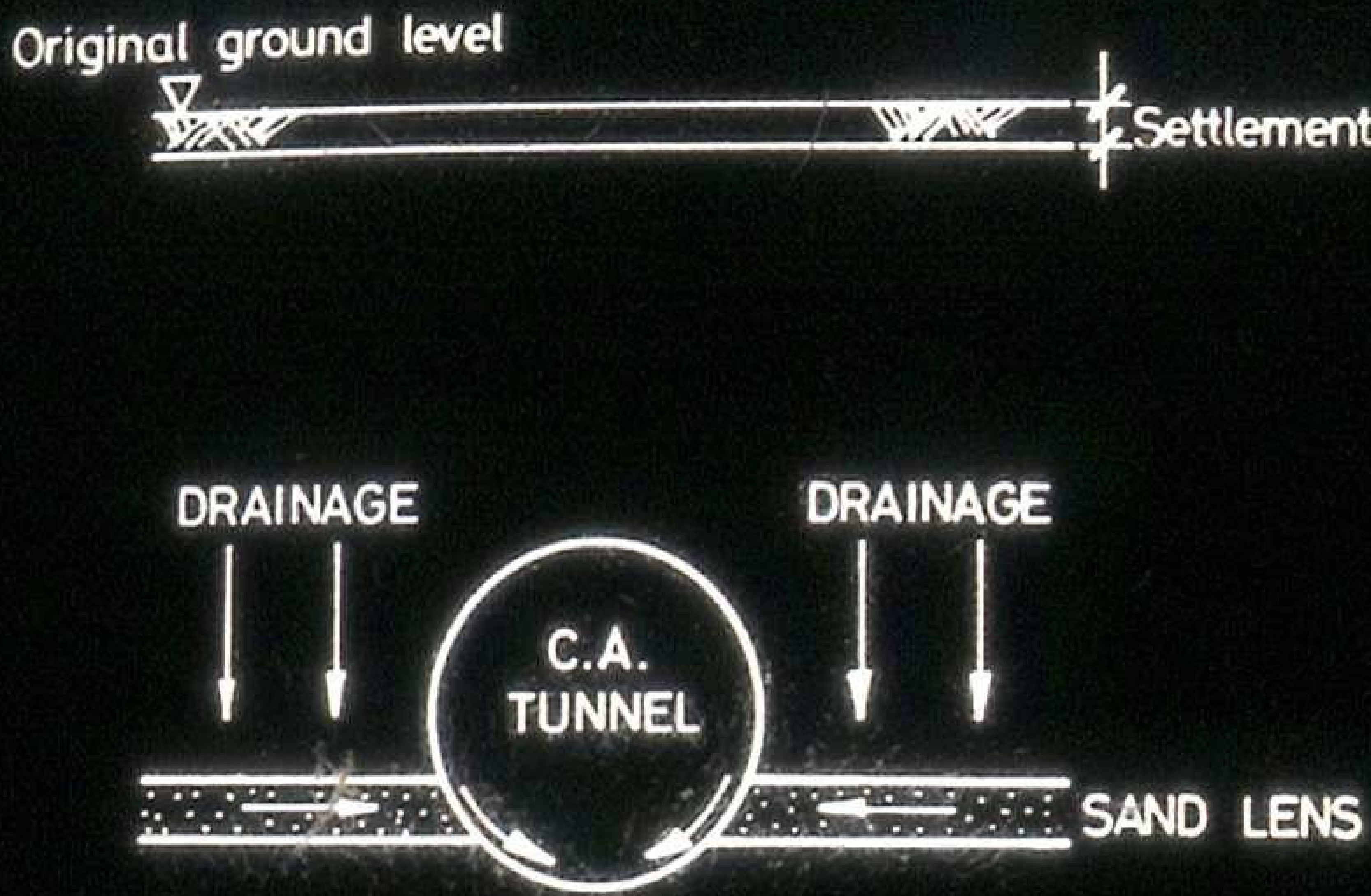
What from do they take?

- Two (possibly three) general forms of consolidation settlement over tunnels have been identified.
- This is unlike 'immediate' settlements, where the 'error function' trough is constant in width for a particular ground condition



SETTLEMENT TROUGHS
IMMEDIATE
CONSOLIDATION
DISTANCE
DISTANCE
DISTANCE
DISTANCE
i
2i
FORM 1
FORM 2
FORM 3
SHAPE OF SETTLEMENT TROUGHS

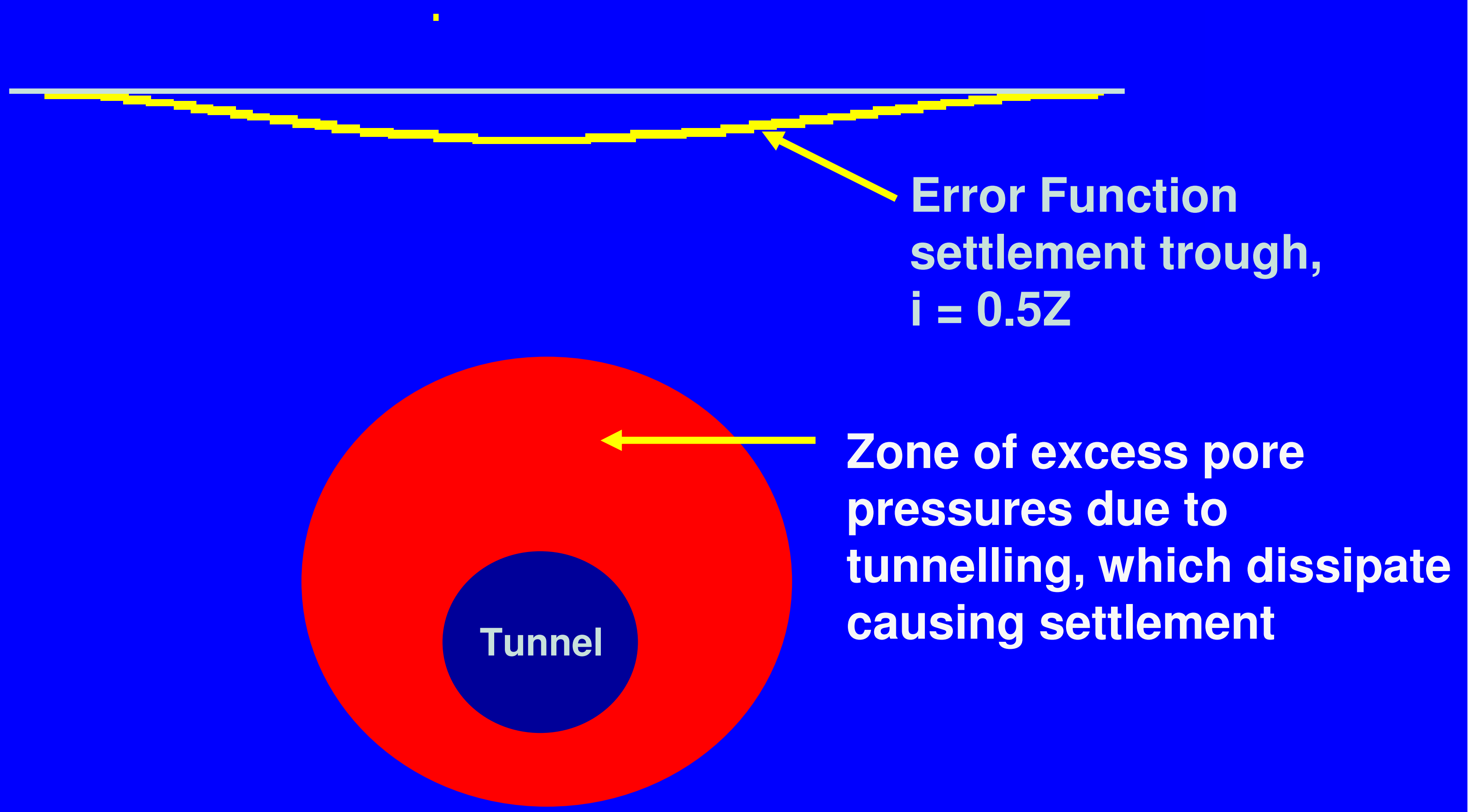
FORM 1



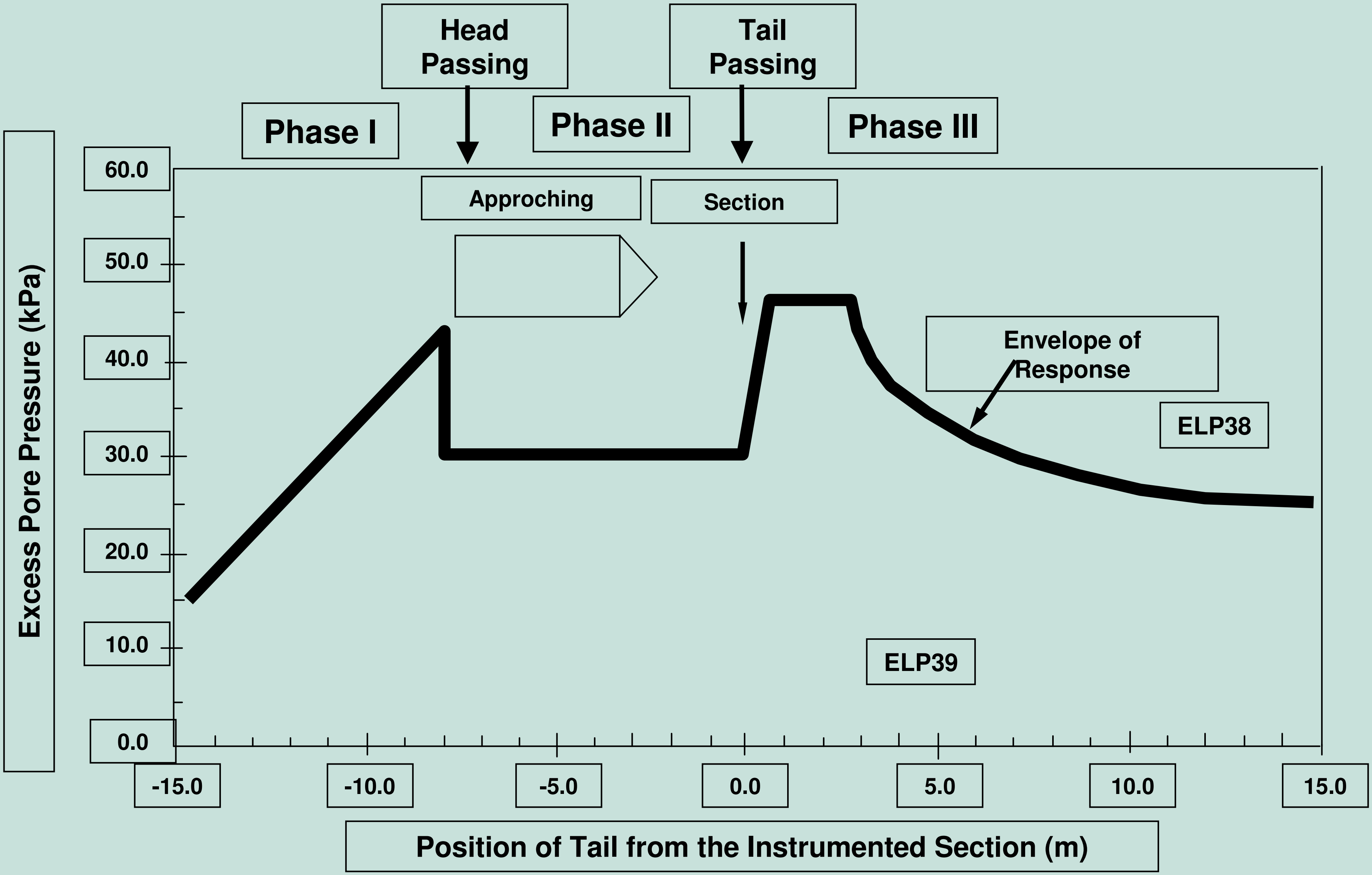
Original ground level
Settlement
DRAINAGE
DRAINAGE
C.A.
TUNNEL
SAND LENS

FORM 3

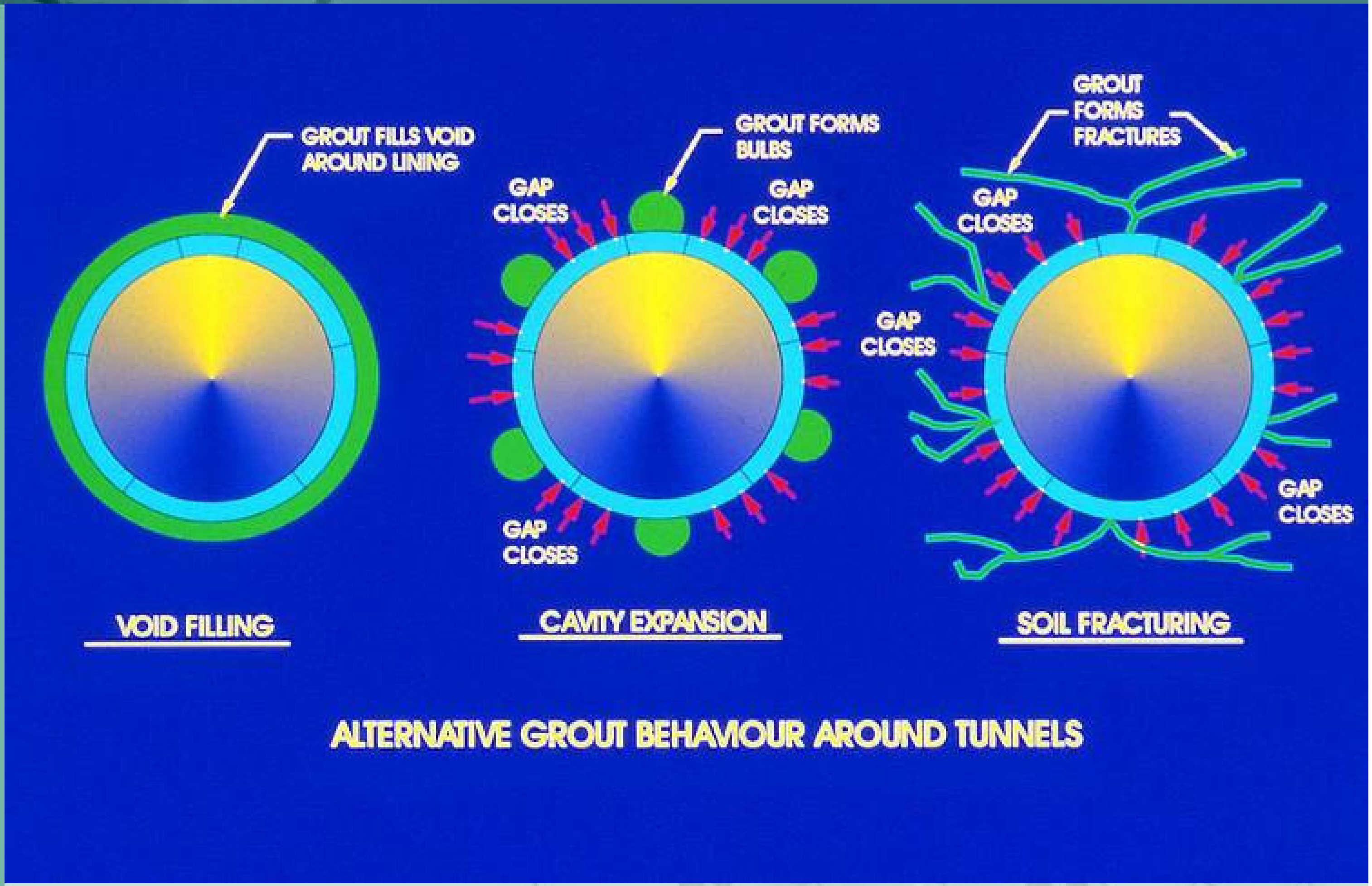
TUNNEL DRIVEN AT EXCESS PRESSURE



PORE PRESSURE MEASUREMENTS, TAIPEI



GROUT BEHAVIOUR IN TAIL VOID



MINIMISING CONSOLIDATION SETTLEMENTS OVER TUNNELS

- **Minimise stress changes during tunnelling in soft clay. Keep face pressure at close to overburden pressure and use simultaneous tail void grouting**
- **Minimise seepage into the tunnel**
- **Where there are soft clays over the tunnel, can use recharge wells, particularly where buildings on mixed foundations or varied founding conditions occur near tunnels not driven by pressurised TBM**

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SETTLEMENTS OVER TUNNELS

- Prediction is an important part of tunnel design in urban areas
- Important to know why settlements occur (components of settlement), and how they can be controlled

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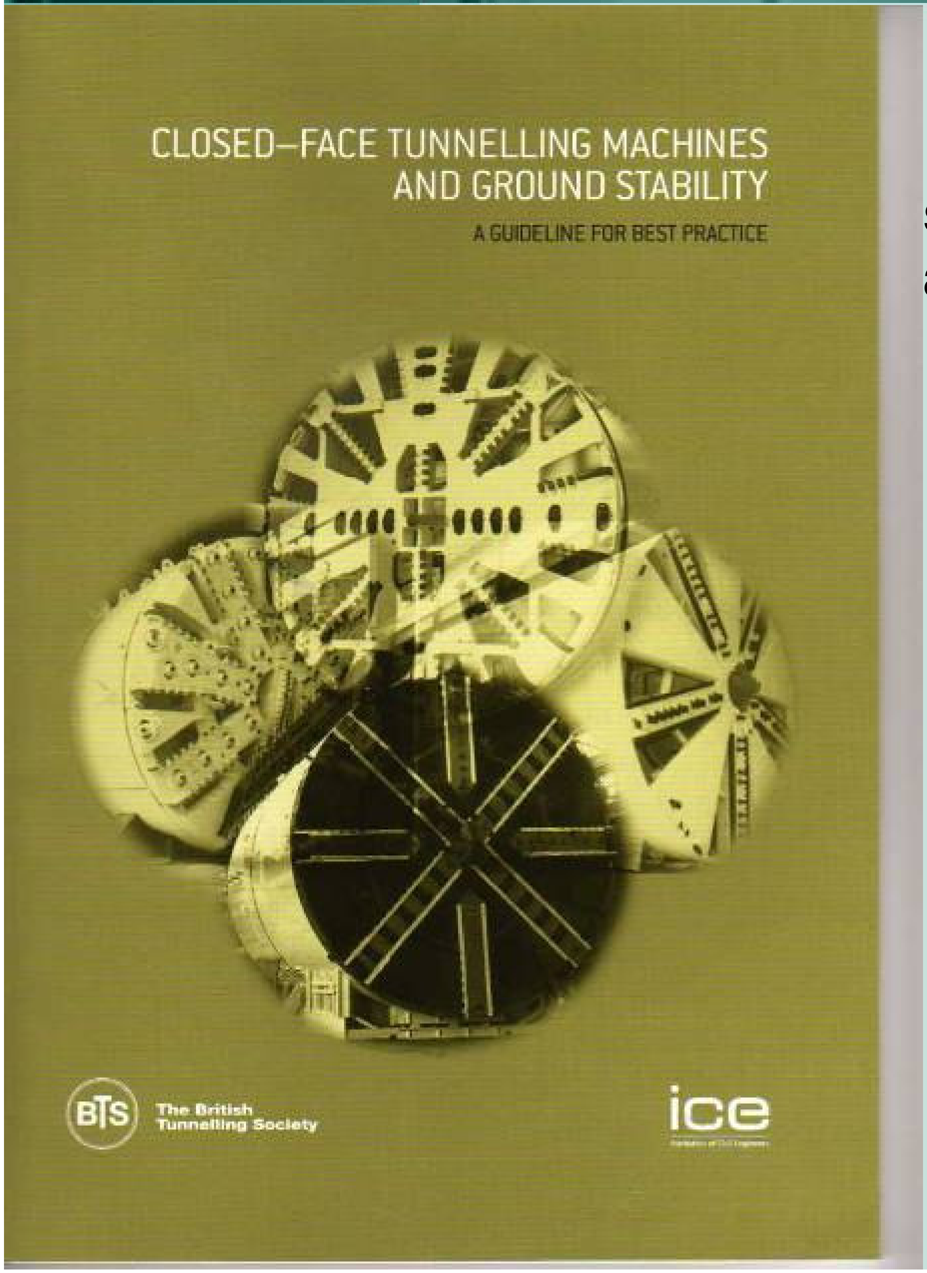
PUBLISHED 2005

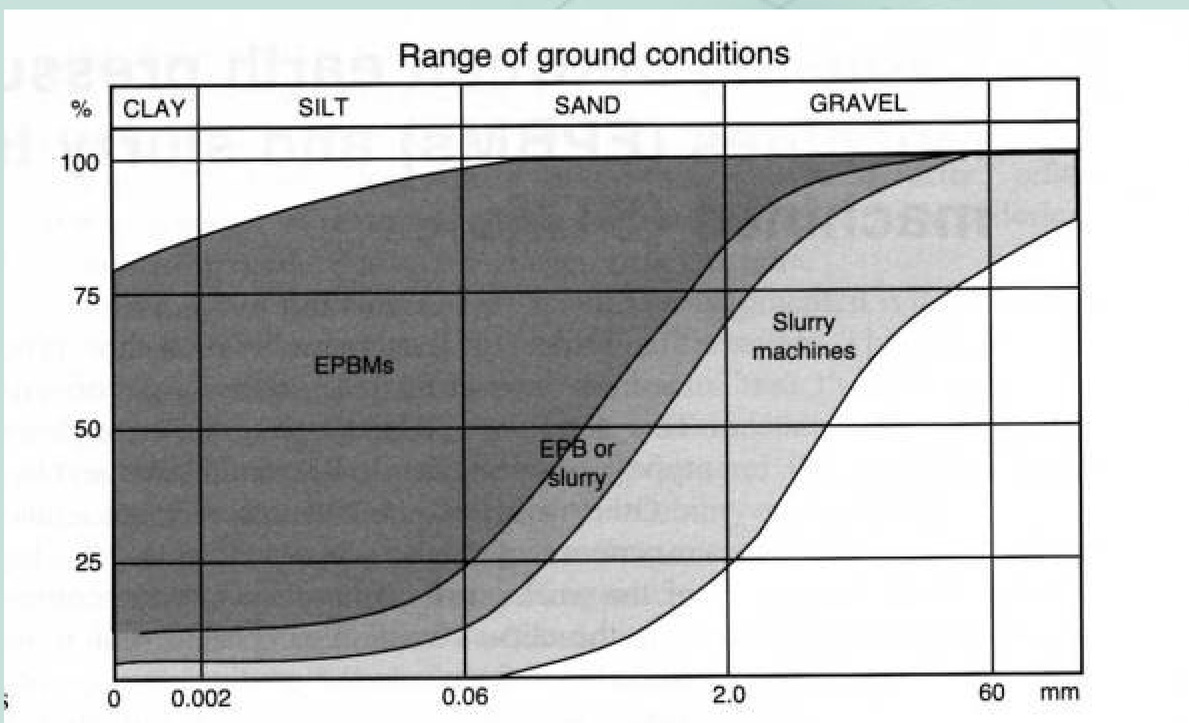


Resulted from the Lavender Street sinkhole in London, but took into account over 100 incidents worldwide

RECOMMENDATIONS IN BTS GUIDELINE

On choice of shield type (EPB or Slurry). Base on:

- **Gradings of ground anticipated**
- **Soil permeability**
- **Hydrostatic head at tunnel horizon**



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RECOMMENDATIONS IN BTS GUIDELINE

Operating pressure:

- **Keep operating pressure > hydrostatic pressure and sufficient to ensure chamber is full**
- **Operating pressure < pressure to heave the ground surface**
- **Plan and justify operating pressures**
- **Minimum three pressure cells in plenum chamber, one near top**

COMMENTS ON BTS GUIDELINE

Using a face pressure over the hydrostatic pressure is a good basis for avoiding major loss of ground

- Using a high face pressure in abrasive ground exacerbates wear – excessive wear can lead to ground losses

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RECOMMENDATIONS IN BTS GUIDELINE

Setting operating parameters; provide ‘drive sheet with targets for:

- Operating pressures
- Grouting parameters
- Thrust forces
- Cutterhead torque
- Excavation quantities
- Foam/slurry parameters
- Alignment

- Provide operator with information on geology, groundwater and structures

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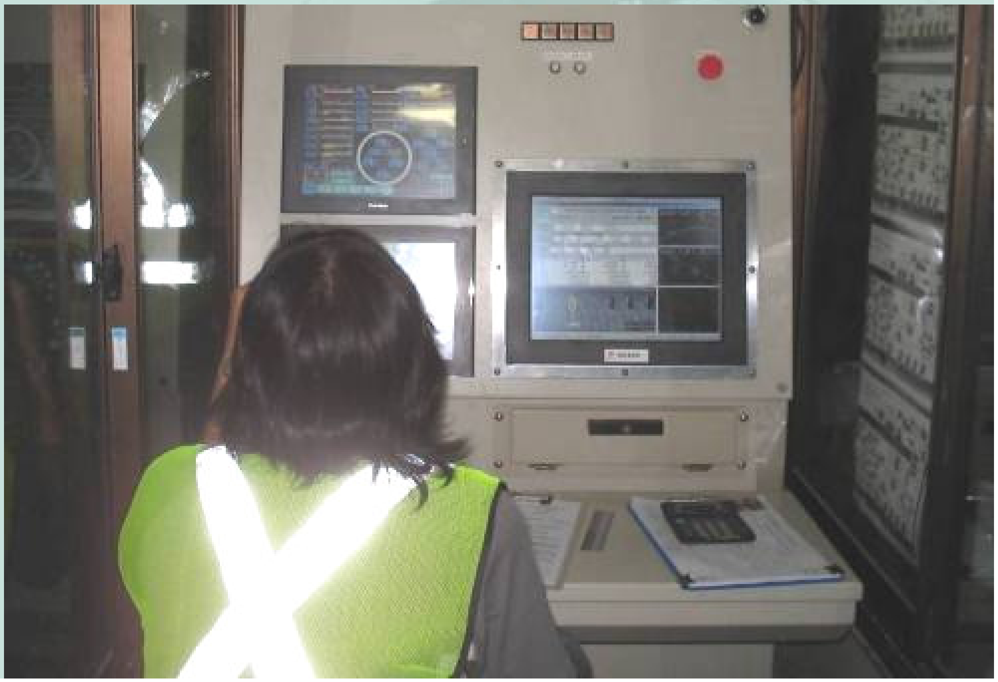
COMMENTS ON BTS GUIDELINE

Setting operating parameters; provide 'drive sheet'

- Can operator of shield practically assess all data and adjust operation continuously when tunnelling through highly variable conditions?
- Team approach required?



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RECOMMENDATIONS IN BTS GUIDELINE

Measure excavation quantity:

For slurry shields:

- Monitor flow and density of slurry in in-bound and out-bound lines

For EPB shields:

- Use at least 3 belt weighers
- Count muck skips
- Consider laser profiler

General:

- Provide audible and visible alarm of excessive excavation
- Monitor for each ring of advance

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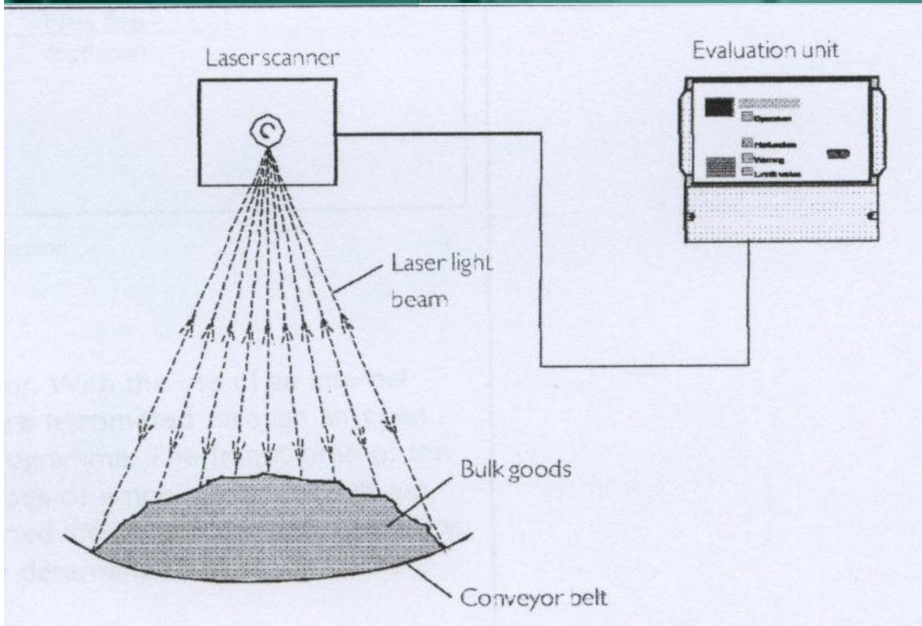
LASER BELT SCANNER - Circle Line



COMMENTS ON BTS GUIDELINE

Measure excavation quantity:

- Singapore experience is that it is necessary to check at least every 200mm of advance
- Very wet muck will slide/spray off belt

RECOMMENDATIONS IN BTS GUIDELINE

Spoil conditioning:

For slurry shields:

- Use slurry with polymer

For EPB shields:

- 1 cutterhead injection point/metre of diameter
- Continuous record of quantities injected
- Test foams for the anticipated ground conditions, under pressure

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RECOMMENDATIONS IN BTS GUIDELINE

Tail void grouting.

For TBMs > 5m diameter: Grouting through pipes along tailskin (also for smaller shields in critical areas)

- Minimum of four ports, double grout lines at each port
- Accurately measure volume and pressure at each port
- Control by pressure primarily, check volume
- Recommends two part, accelerated grouts

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RECOMMENDATIONS IN BTS GUIDELINE

Risk Management:

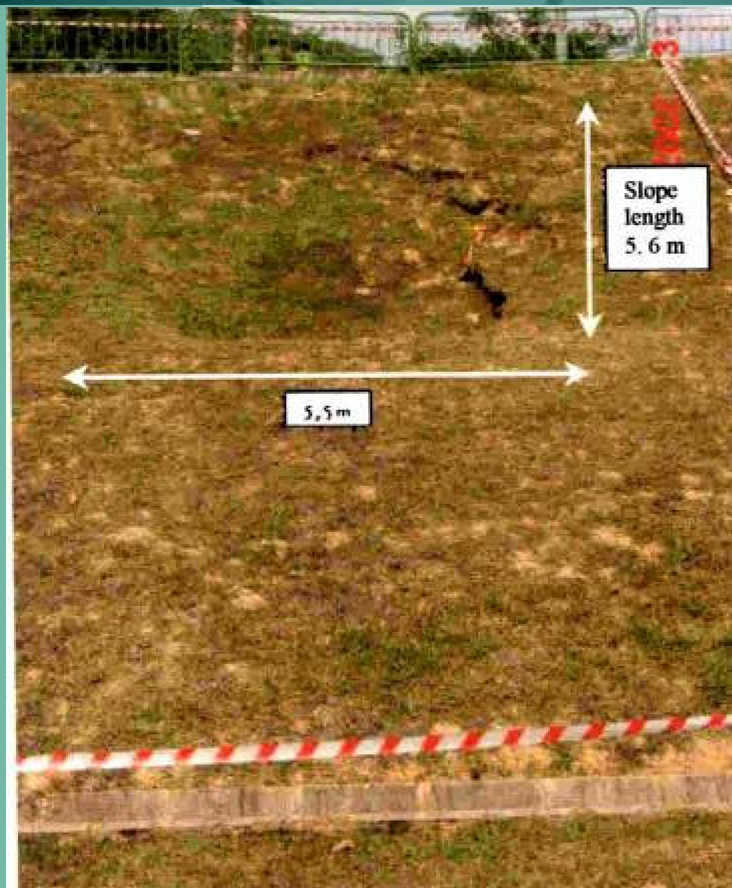
- Four stages of risk management (identification, assessment, response, and embed and review)
- Aim for risk reduction/elimination
- Correct choice of equipment, including TBM
- Risk register by each main party to contract

RECOMMENDATIONS IN BTS GUIDELINE

Staff and personnel:

- **Minimum criteria for experience of key staff**
- **Training of new operatives**

HOWEVER…..



Risk assessment – experienced contractor, trained staff, specially Selected EPB TBMs, therefore negligible risk of excessive settlement

Result: 7 sinkholes in first 500m of tunnelling

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RECOMMENDATIONS IN BTS GUIDELINE

Site investigation:

- **Three phase investigation; desk study and reconnaissance, detailed investigation, construction review**
- **Intrusive investigation (boreholes) and geophysics, before tunnelling**
- **Further information obtained during tunnelling**