Ground Improvement in Soft Clays

Risks and opportunities, an overview of recent developments

Tony O'Brien
Mott MacDonald

Ground improvement techniques

- PVD/Surcharge
- Stone columns and sand compaction piles
- Ultra-lightweight fill (EPS)
- Deep cement mixing (wet and dry)
- Jet grouting

Risks

- Global instability
- Mud waves
- Underestimating settlement and consolidation time

For example - S Korea

- Prediction 72cm + 8months
- Actual 182cm + 31months

- Excessive creep

Opportunities

1

Practical application of Soil Mechanics research

2

More powerful analysis tools

3

“New” ground improvement techniques

4

Digital technology and big data

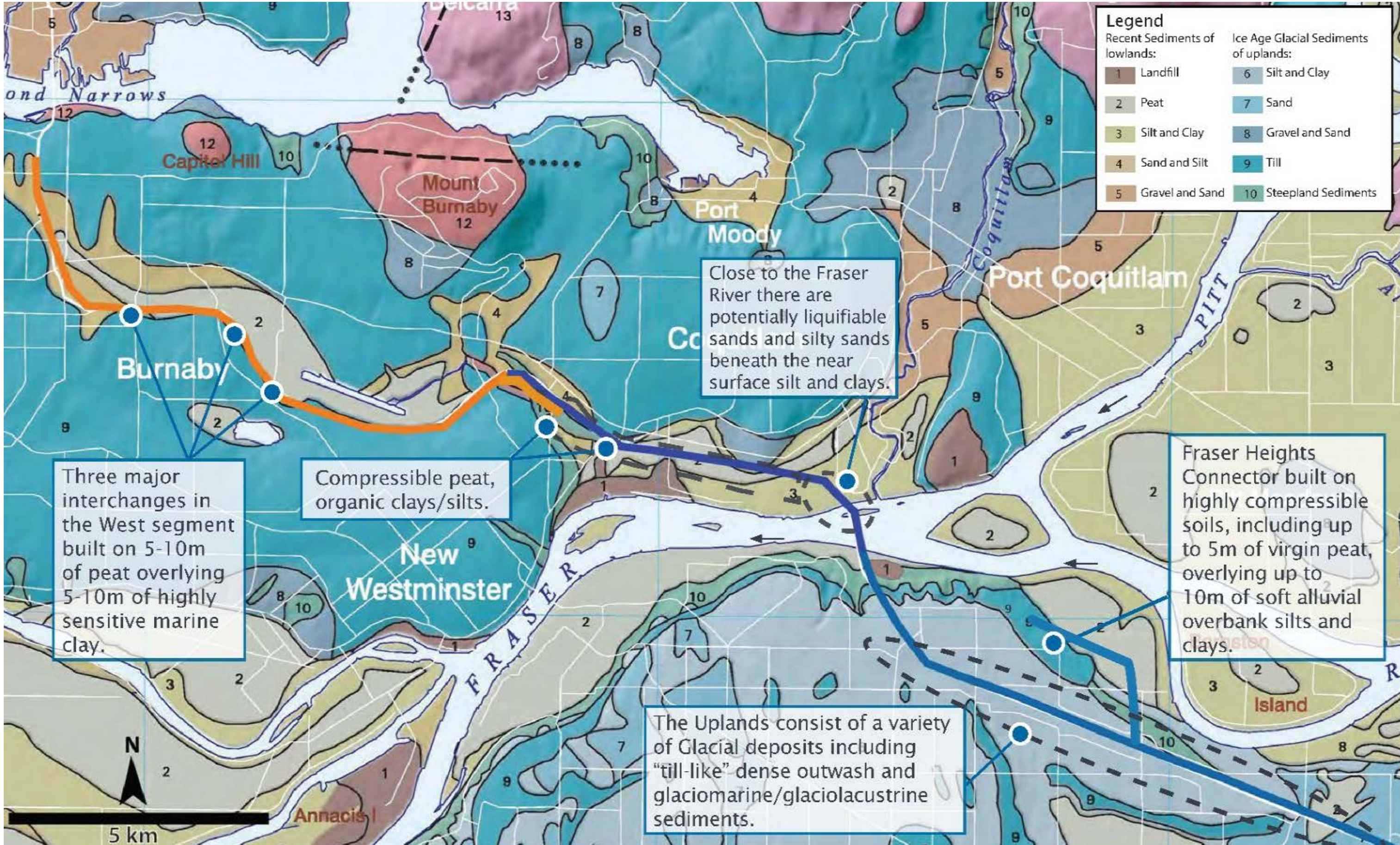
5

Reducing carbon

Port Mann/Highway 1 Improvement, Canada

Geology

- Fill (Hog Fuel!)
- Deltaic Sediments
- Sensitive Marine Clays
- Glacial Deposits
- Seismicity



Port Mann/Highway 1 Improvement, Canada

Pre-load/Surcharge. Ultra lightweight fill. DCM. Jet grouting. Stone columns. LTP

Soft Clays
Fundamentals

Burland Rankine lecture (Geotechnique, 1990)

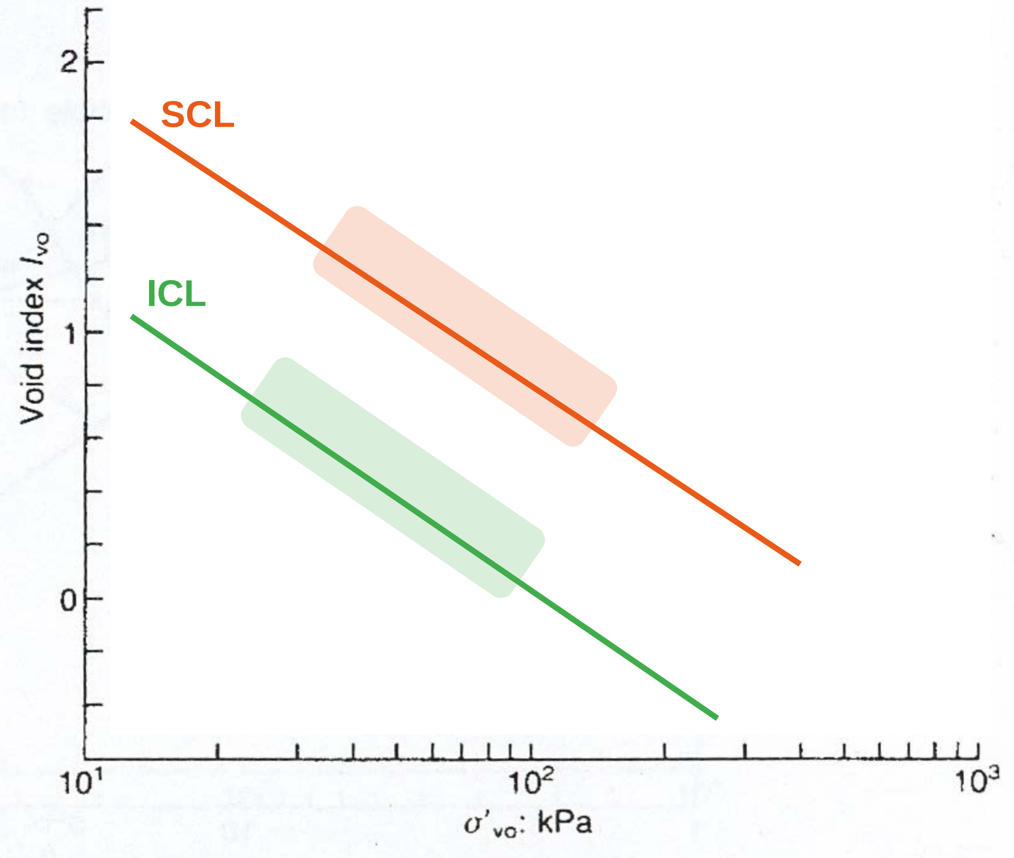
- Void Index vs. σ‘

- ‘Text book’ soft clays – close to ICL

- ‘Sensitive/Structured’ soft clays at or above SCL

often problematic

eg. at 6m, if LI = 1.2 → SCL
if LI = 0.8 → ICL

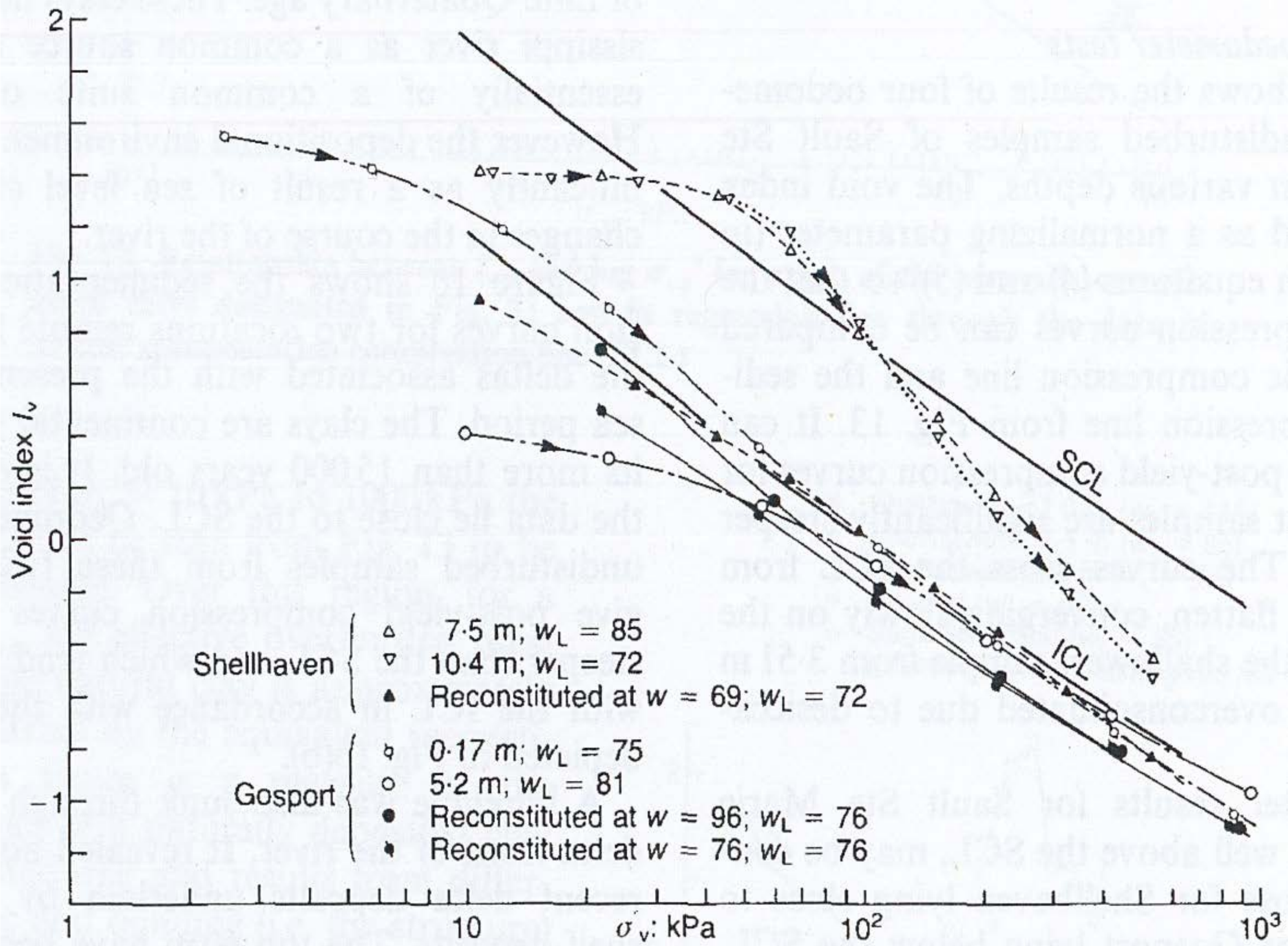


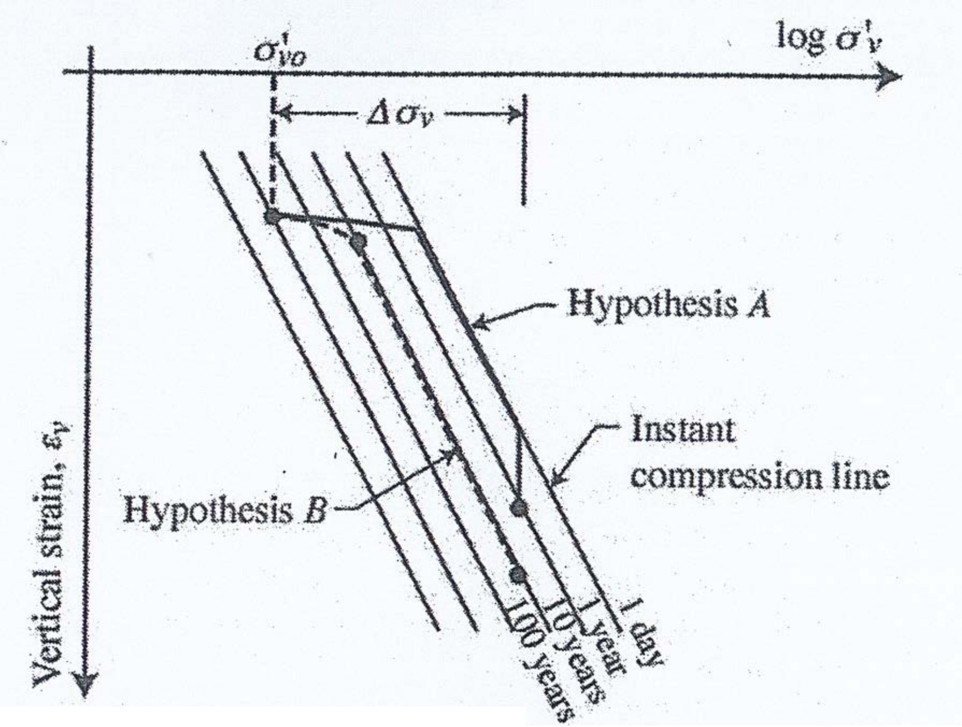
SCL = sedimentary compression line
ICL = Intrinsic compression line
VI = Void index
LI = Liquidity index

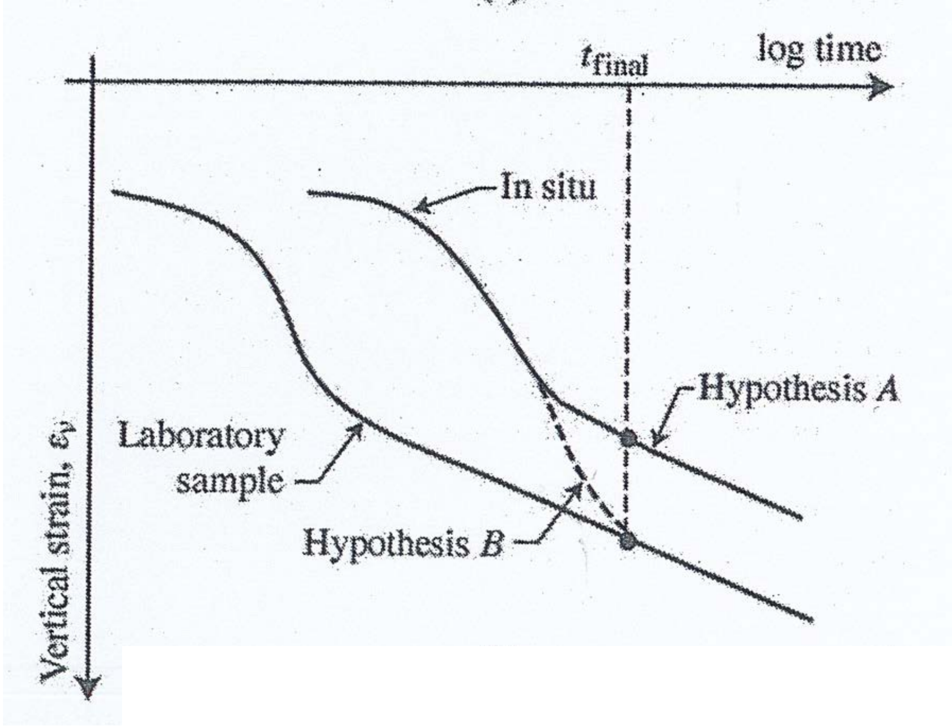
VI ~ 2 (LI) -1

Soft Clays
Fundamentals

- Soils near SCL → very high compressibility post-yield







Hypothesis A – 'Text Book'

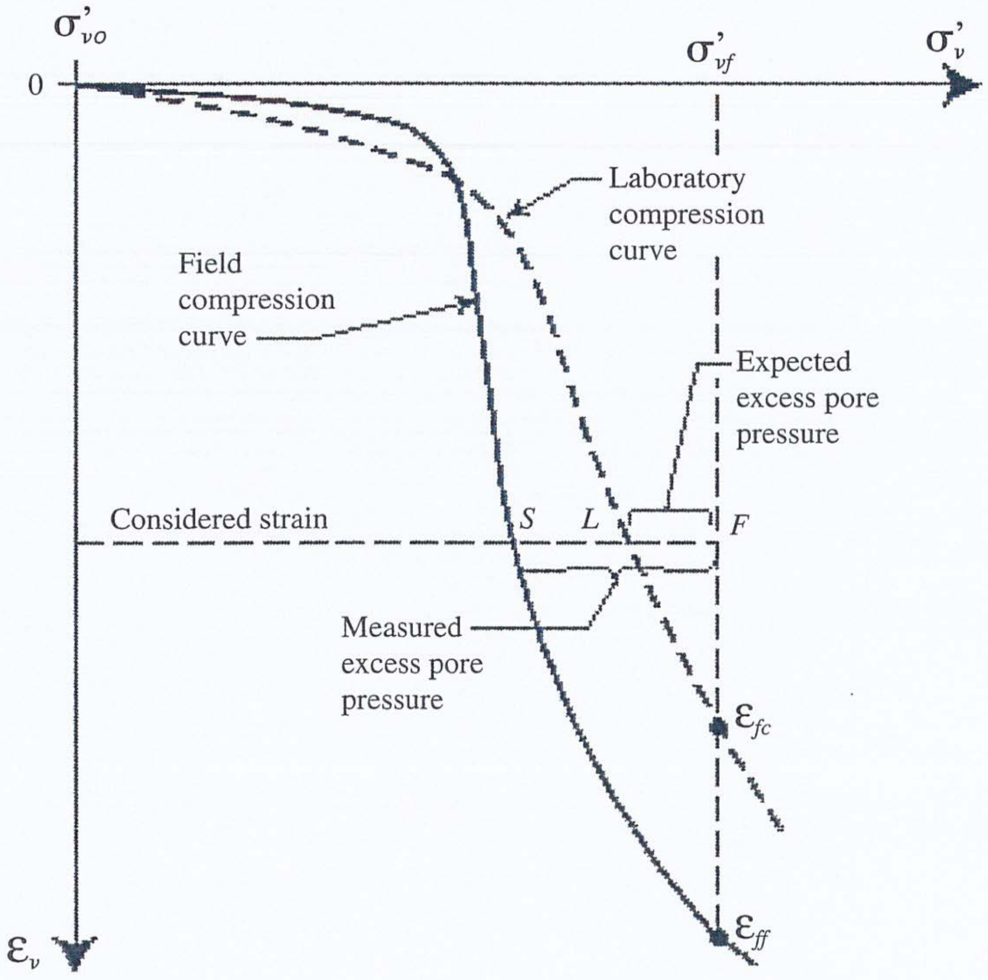
- Primary + secondary consolidation – independent events

Hypothesis B

- Viscous, strain rate effects
- Secondary + primary not independent
- Scale dependent

Hypothesis B
Practical implications

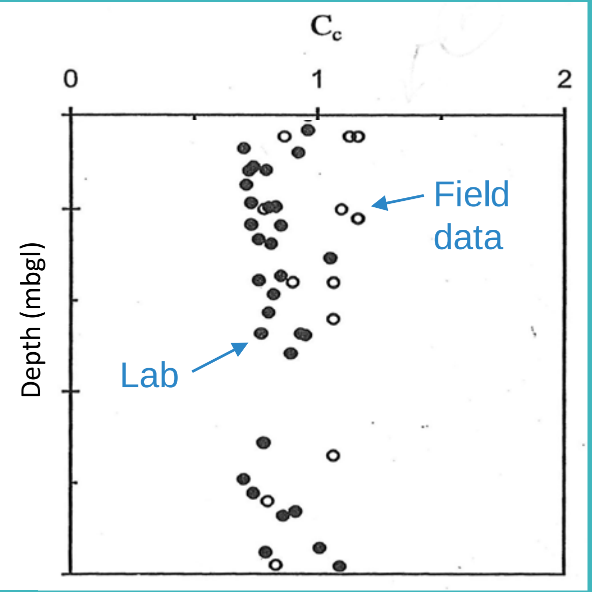
- Insitu stress-strain curve not unique
  - drainage path
  - loading conditions
- Excess pore pressures
  - high + slower to dissipate

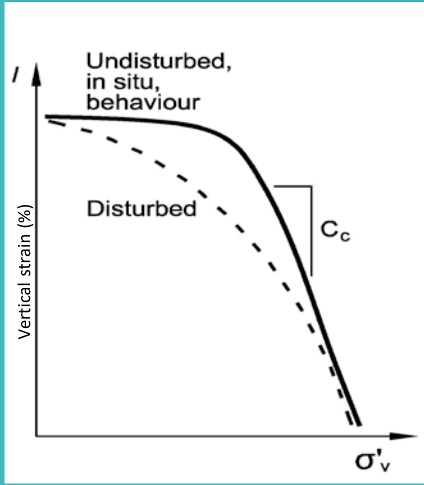


Typical compression curves insitu and in the laboratory

Practical Challenges

Sample disturbance





Soft Clays (SE Asia)

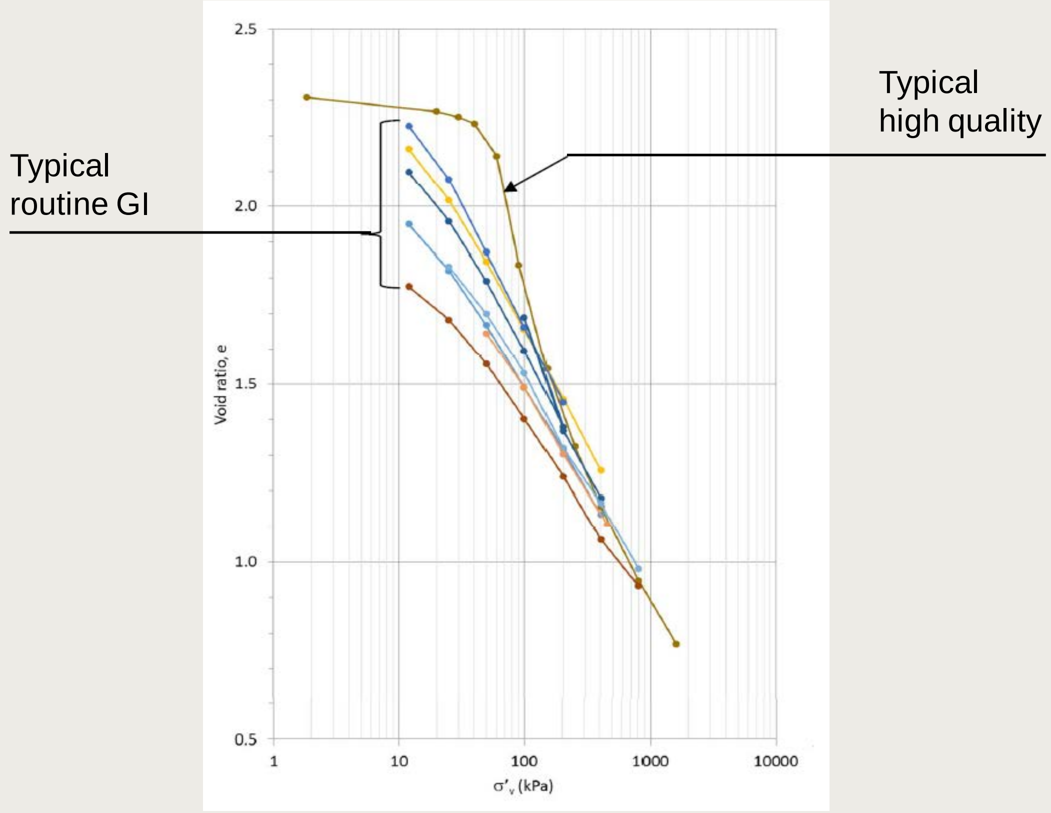
Back analysis of field data, C_c ~ 1.5 x lab C_c

Routine sampling → underestimate compressibility

Settlement

- Larger than expected

Impact of sample and test quality on C_c



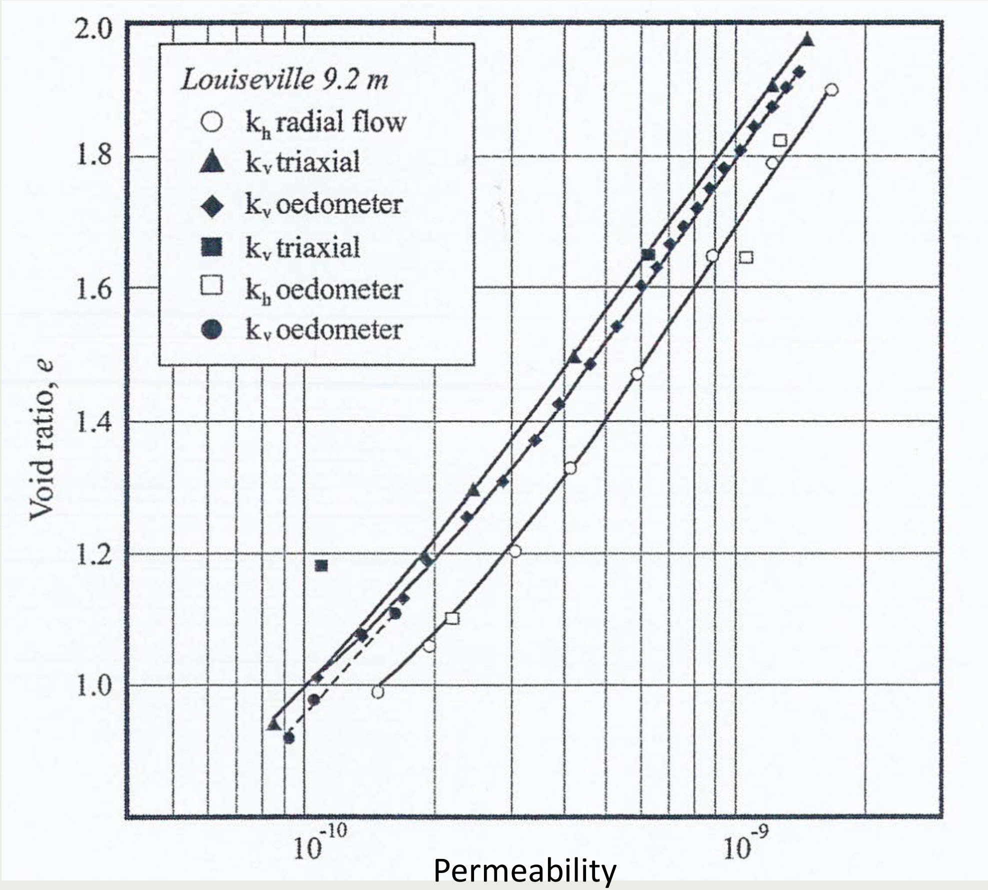
Compression curves

Need high quality to assess C_c

Smaller number of better quality samples

Strength sensitivity: Key consideration when assessing C_c

Permeability + change in permeability (Ck)



Permeability

Permeability + change in permeability (C_k) during consolidation (x10??)

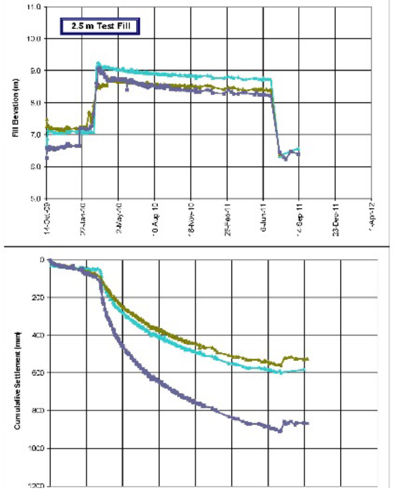
Because of Cc and k change → C_h, C_v may not be constant

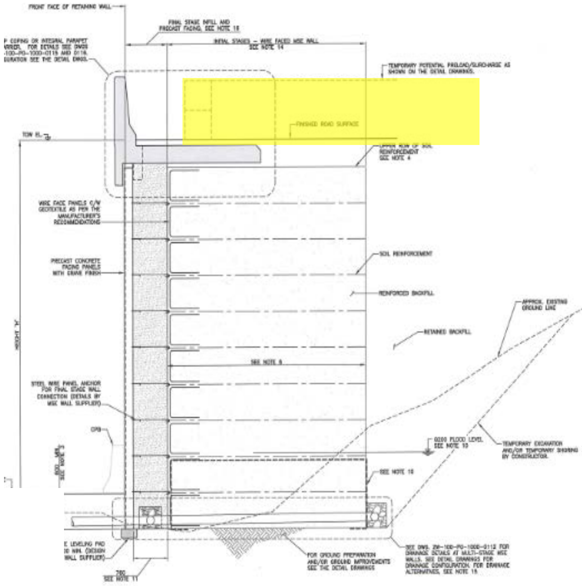
C_k is a key parameter!

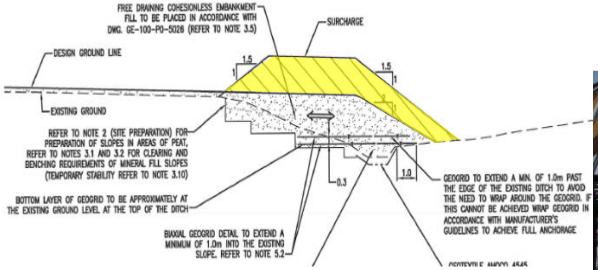
PVD/Surcharge (PMH)

Key considerations

- Surcharge hold duration
  - Schedule Impacts
- Surcharge rate of construction
  - Construction stability
- Geometry and type of approach structure
  - Overbuild of an embankment
  - Restricted space – temp wall requirement
  - Permanent wall solutions – 2 stage MSE walls
- Surcharge height/ratio
  - Material availability







PVD/Surcharge (PMH)

Key considerations

- End performance requirements
  - is ongoing settlement/maintenance acceptable
- Settlement compatibility with existing infrastructure
- Performance uncertainty
  - tests fills
- Potential impacts on adjacent infrastructure
  - Bridge Piles (lateral loading and down drag)
  - Utilities in Soft Ground
  - Damage to adjacent asphalt and drainage impacts
- Staging/detour considerations
  - damage to new construction

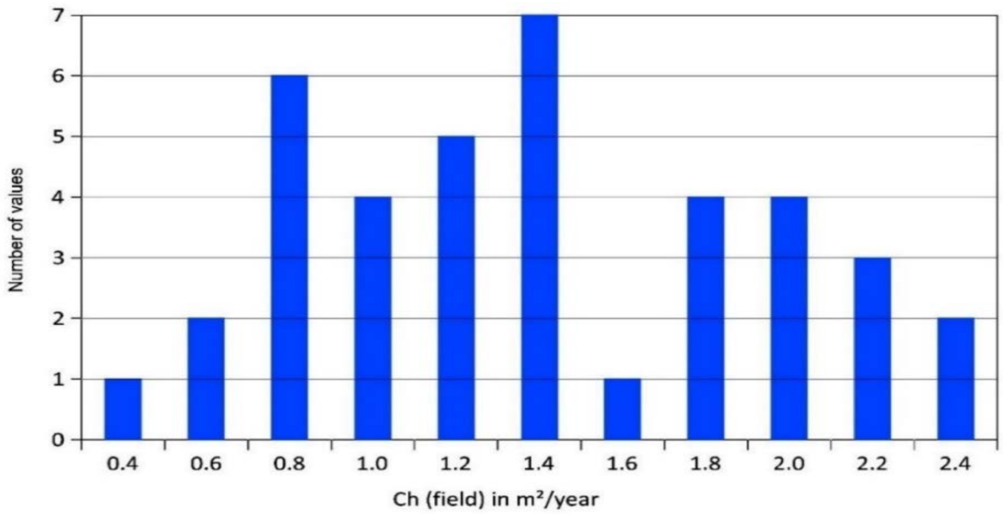
Case history data

C_v $(C_h) = k_v$ $(k_h)/m_v$ (or C_c)

- Intrinsic variability
- Terzaghi theory correct?
- Disturbance of clays (“smear”)
- Poor drain performance
- Poor workmanship
- (mud waves?)

Test Area	$c_{h\ field}$ (m^2/yr)	Spacing (m)	Length (m)	$c_{h\ field}$ / $c_{v\ lab}$
Sand Drain	0.9 - 1.0	3	7.6	0.7 to 0.8
PVD (Alidrain)	3.1 - 4.2	3	7.8	2.4 to 3.2
PVD (Alidrain)	1.8 - 2.0	1.5	17.8	1.4 to 1.5

CLK Test Embankment $c_{h\ field}$ vs. $c_{v\ lab}$

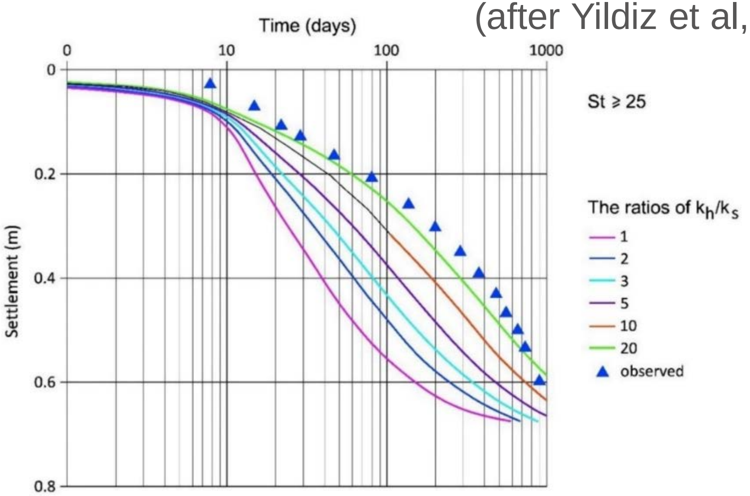


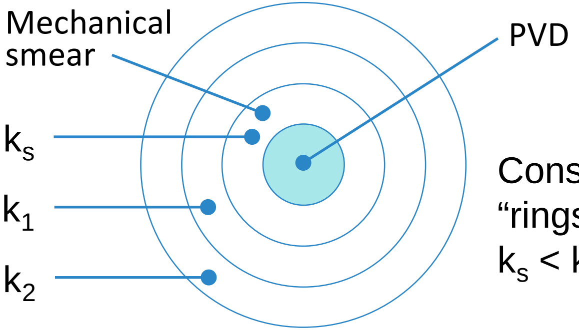
C_h field values back-analysed from settlement data, Siu Ho Wan Depot (after Ng and De Silva, 2007)

Structured sensitive clays, influence of k_h/k_s on rate of settlement

- k_h/k_s = 2 ,typically assumed for soft clays
- Geotechnique, 2017, Zhou and Chai, “equivalent smear due to non-uniform consolidation”
- Equivalent smear = mechanical smear and “smear” due to non-uniform consolidation (function of strain and Ck value, and varies with degree of consolidation, high at low U, reduces at high U)
- Consolidation does not follow Terzaghi theory, if C_c/C_k >1
- k_h/k_s can be >>2 for clays close to SCL!

(after Yildiz et al, 2009)





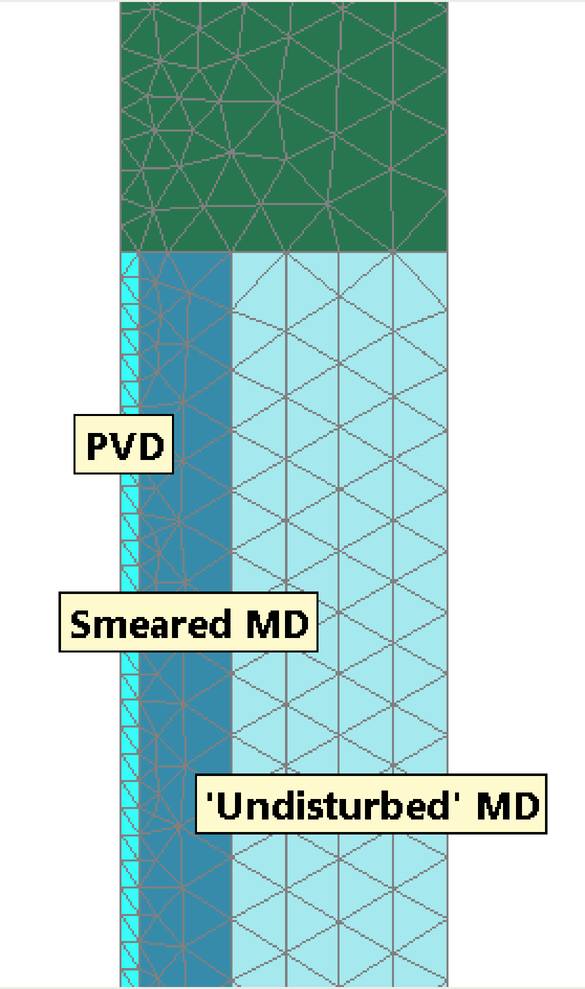
Consolidation “rings” around drain
$k_s < k_1 < k_2$ etc.

Soft clays near SCL

PVD/Surcharge

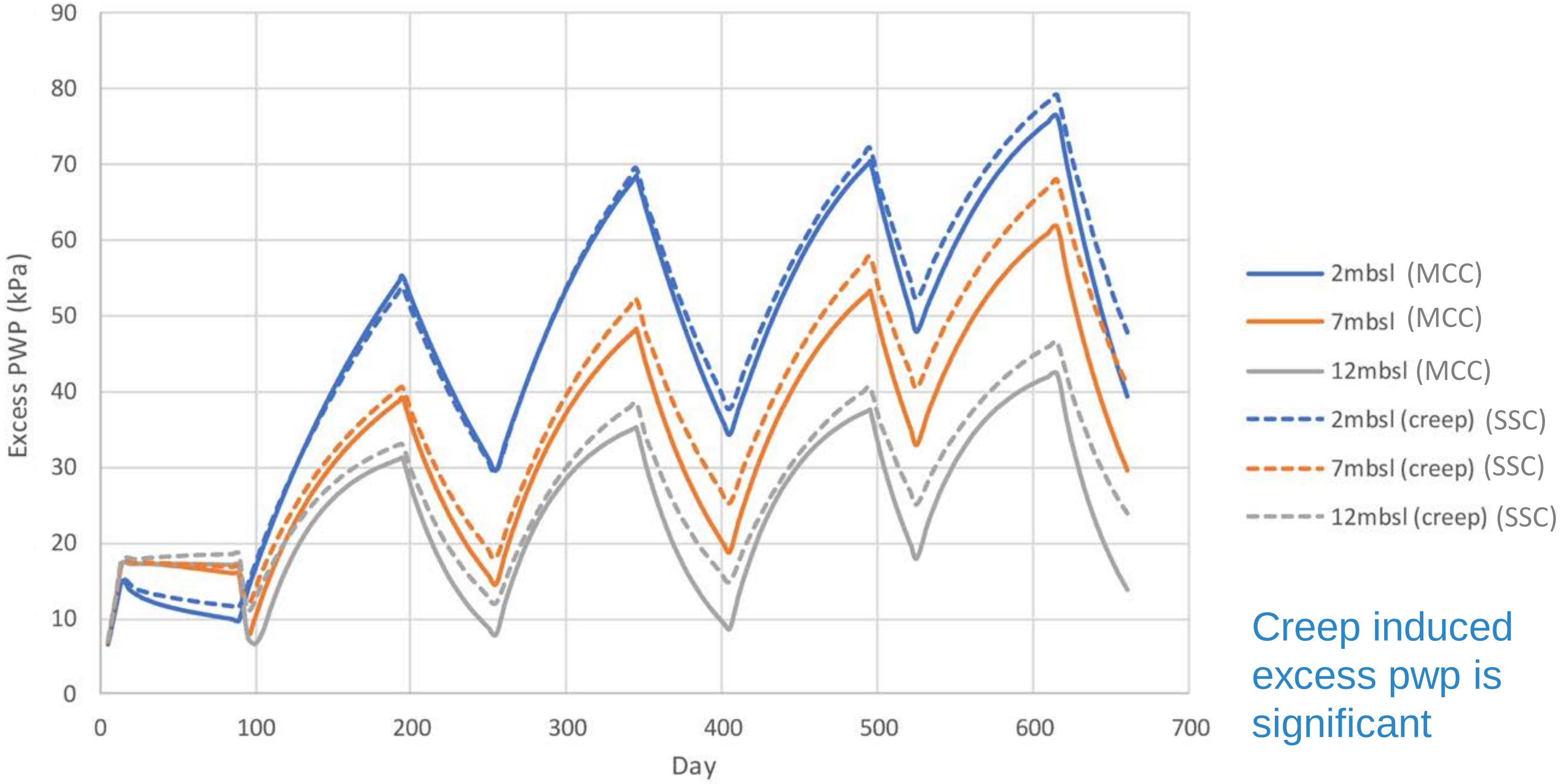
Consolidation analysis

- PVD – use volume elements
- Coupled analysis/updated mesh
- C_c/C_k >1.0 (up to 1.4)
- Soft soil creep model (follows Hypothesis B)
- k_0, C_k, C_c independent variables
- $C_\alpha = 0.04\ C_c$



Soft clays near SCL

Excess pore water pressure (SSC vs. MCC)

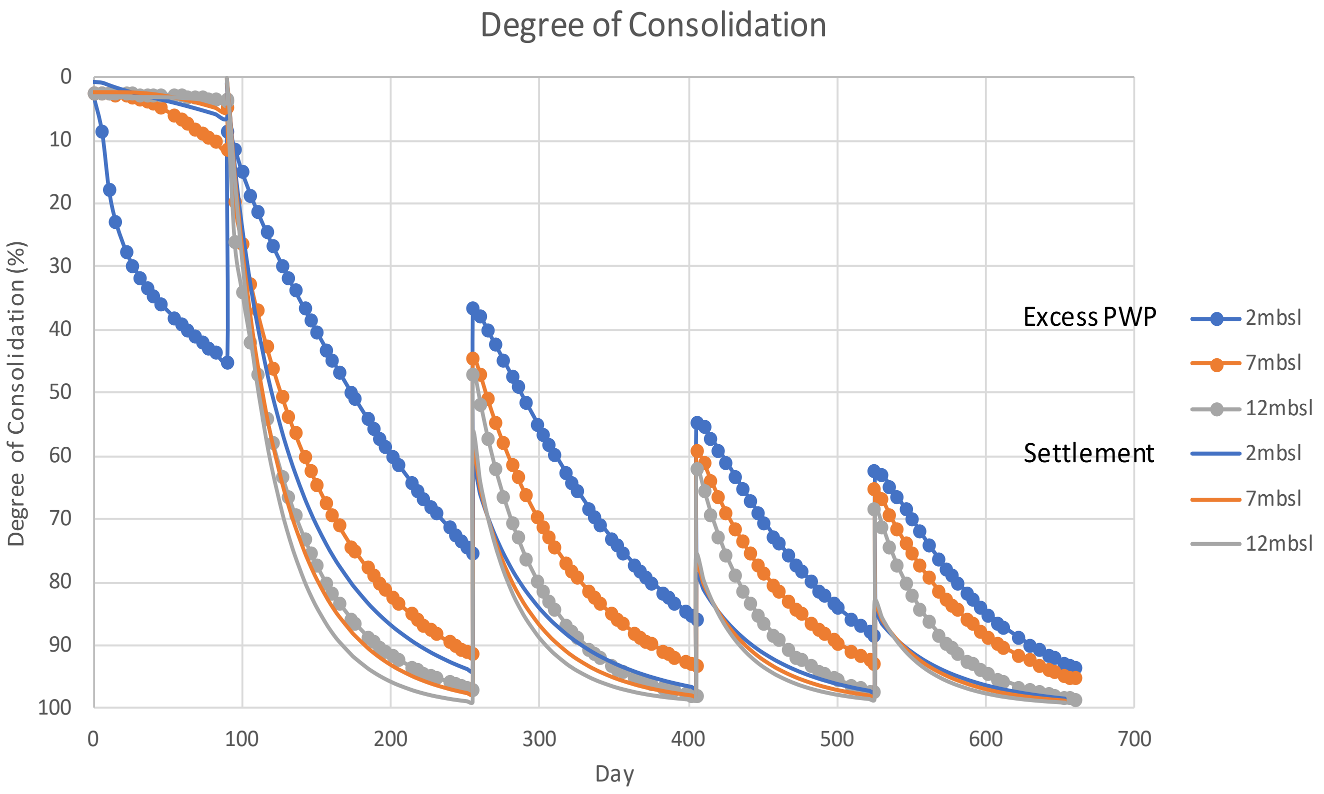


Creep induced excess pwp is significant

Soft clays near SCL

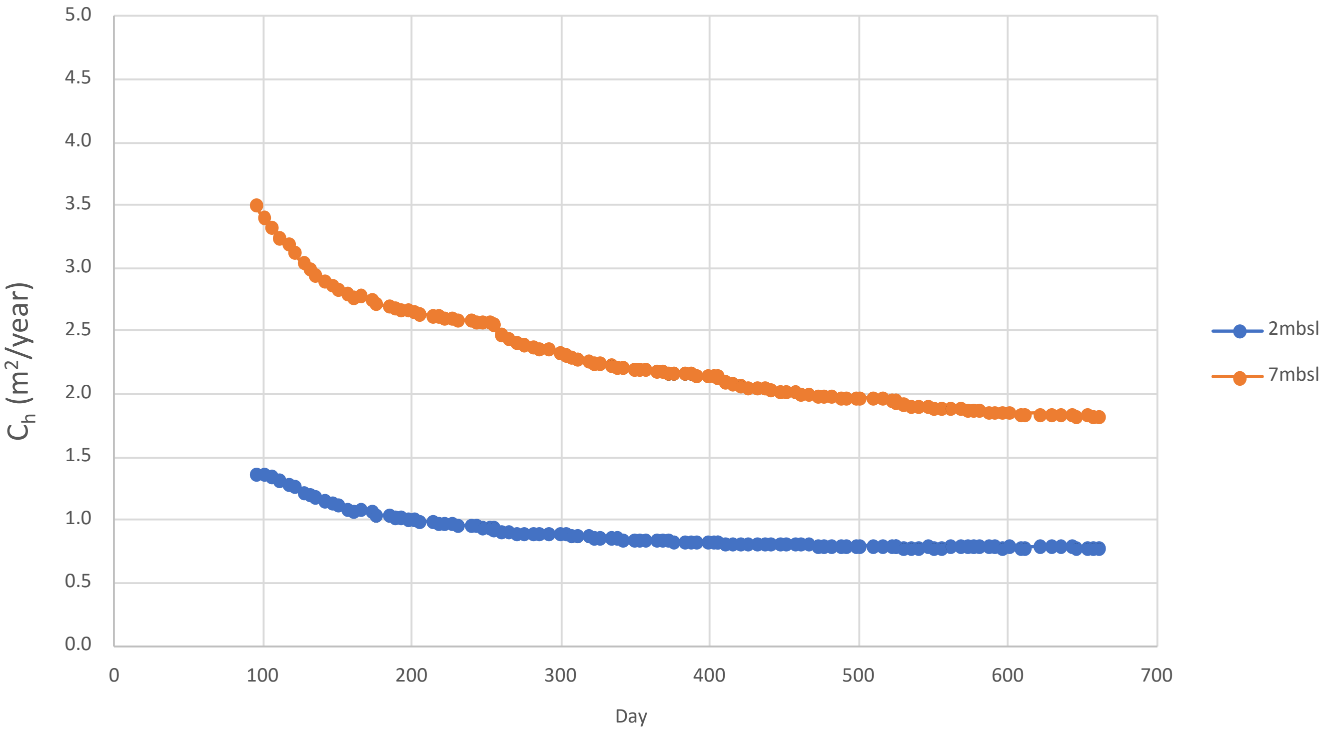
Degree of Consolidation

- U (settlement)
  > U (pwp dissipation)
- U (pwp) varies radially from PVD
- Implication for strength gain



Soft clays near SCL

- C_h reduces during consolidation (consistent with CRS tests)
- C_c/C_k >1.0
- Consolidation does not follow Terzaghi theory!

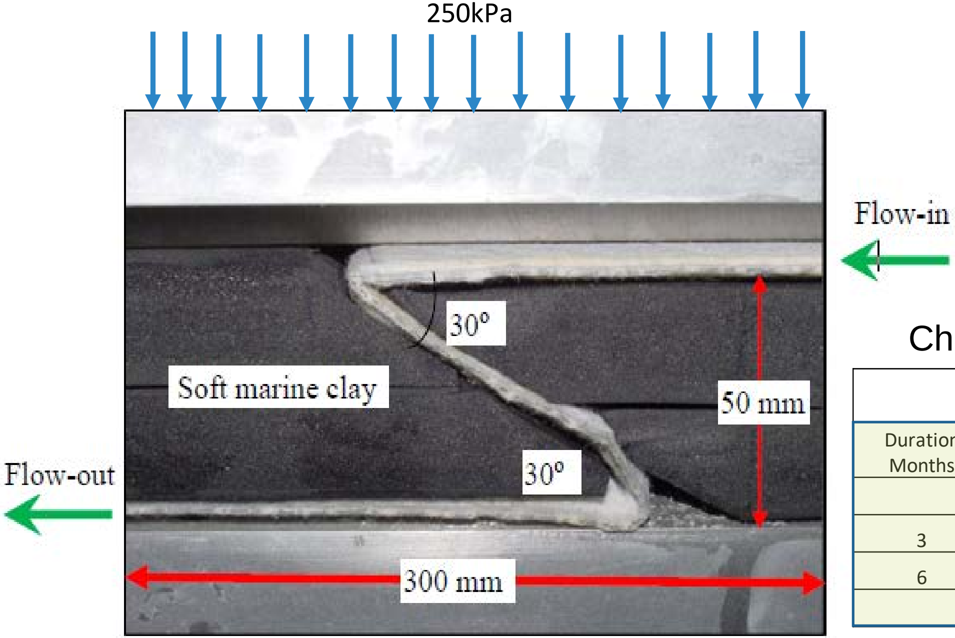


PVD discharge capacity

Time dependent effects that contribute to a reduction in discharge capacity is likely to be due to;

1. Creep of filter into the channels of the PVD core
2. Possible clogging of channels within the core (+ damage during installation?)
3. Distortion of PVD during consolidation

Discharge capacity can reduce by orders of magnitude! (to <10 m^3/yr)



NUS Kinked Drain Tester – Test Arrangement

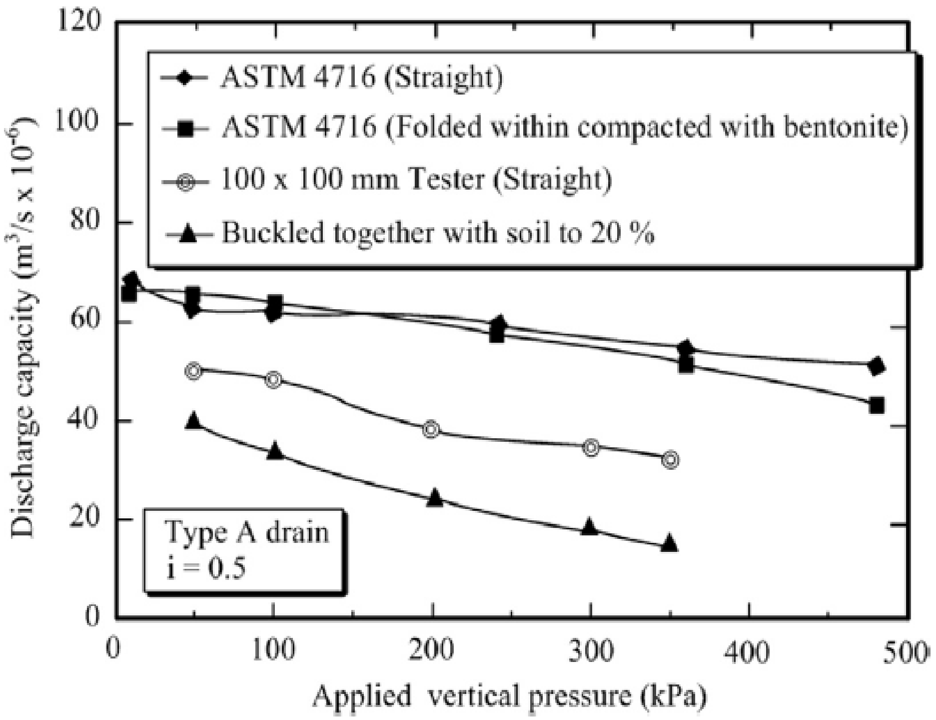
Changi experience

Duration Months	Discharge capacity in Phase IC	
	m^3/s	m^3/year
	2.20E-06	69
3	4.20E-07	13
6	2.20E-07	7
	1.80E-08	1

Duration Months	Discharge capacity in Area A (North)	
	m^3/s	m^3/year
	8.20E-06	259
3	2.50E-07	8
6	2.20E-07	7
	2.10E-08	1

PVD Discharge Capacity

- Influence of test method
- PVD distortion due to large strain
- Discharge capacity - kinked test <1/3 ASTM straight test



Discharge capacity	Brand A	Brand B	Brand C
Straight drain	50	13	65.7
Kinked drain	14.6	5.7	20.9

Impact of PVD Discharge Capacity on Degree of Consolidation

For:

Ch_{lab} = 3m²/year

+

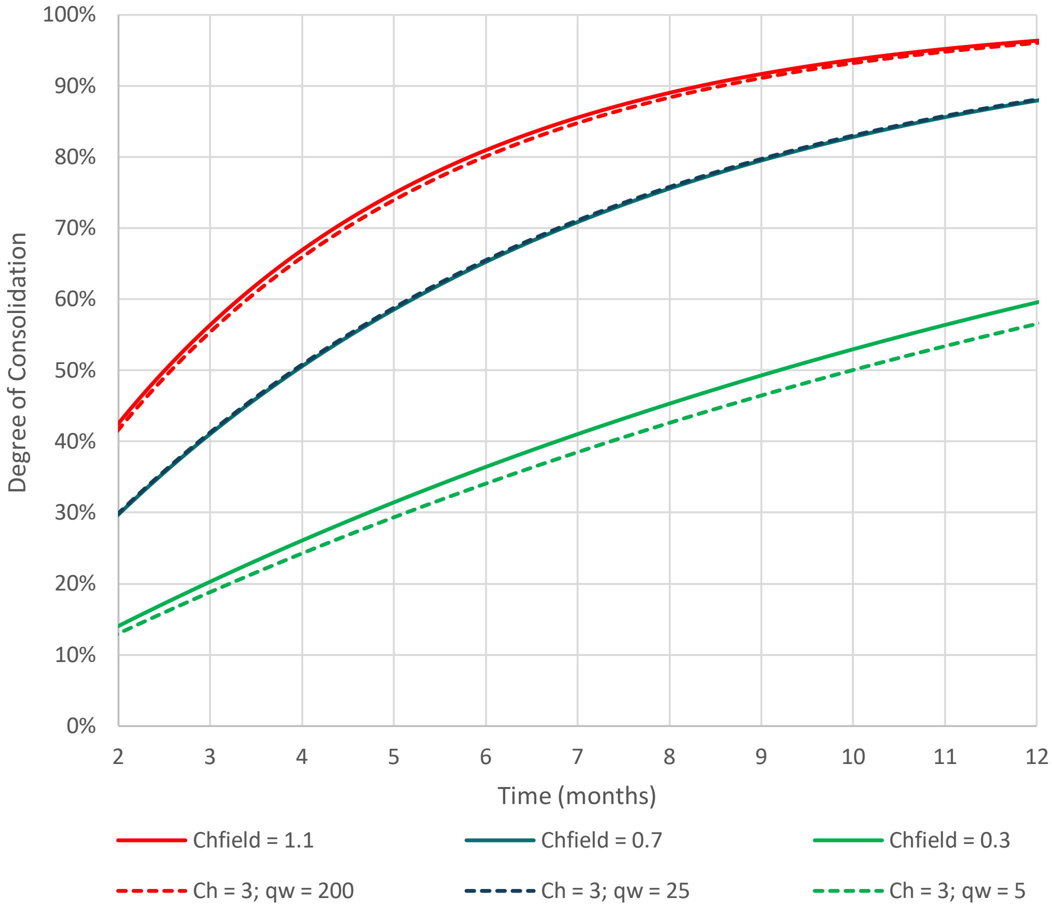
smear

+

low PVD discharge capacity

then

Ch_{field} < 0.5m²/year



Degradation of PVD discharge capacity

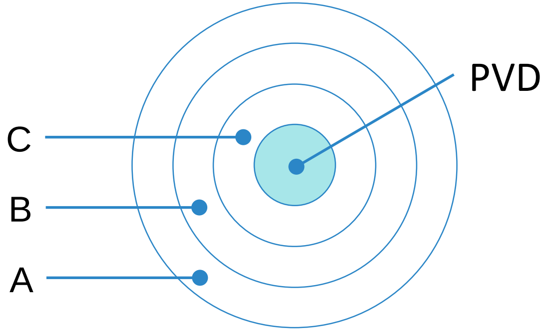
- Key consideration
- Different products perform differently!

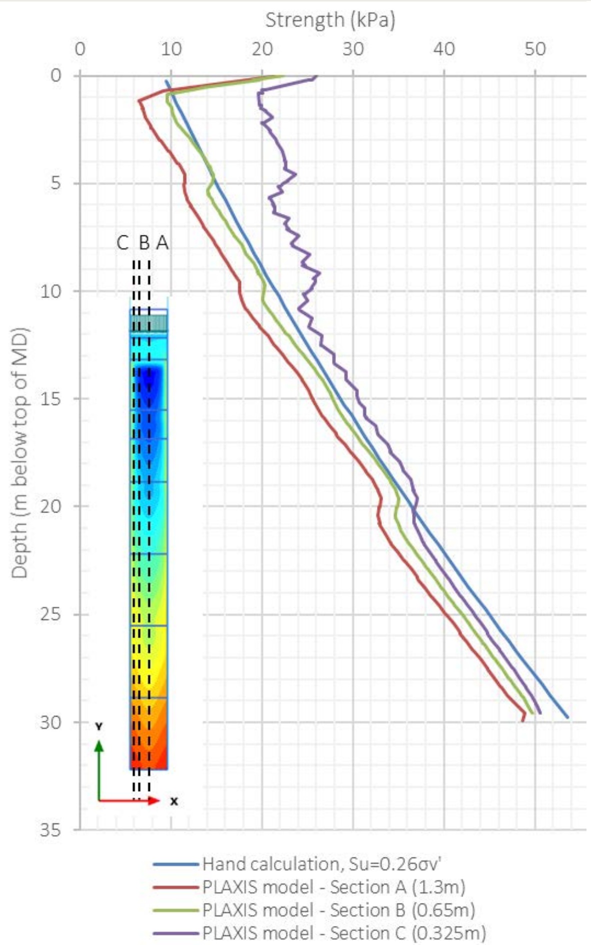
PVD/Surcharge

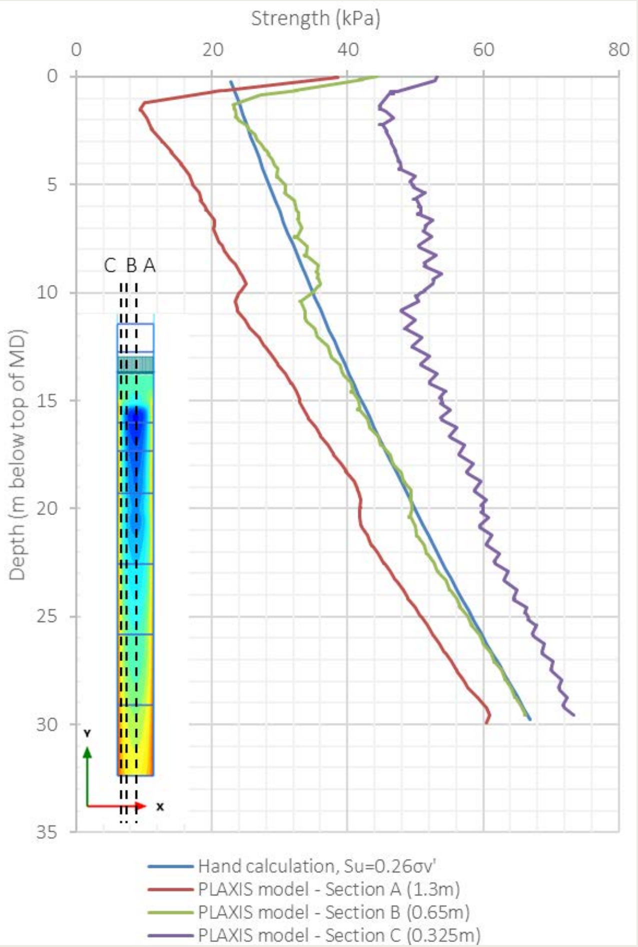
Performance monitoring

Challenging!

- Both strength gain + excess pwp dissipation
  - highly non-uniform vs. PVD location
- Settlement (strain) will be a better “global” indicator







Ultra-lightweight fill – Expanded Polystyrene (EPS)

- EPS is a super lightweight, closed-cell, rigid-plastic, approximately 100 times lighter than soil
- Used in projects for over 40 years
- Grades of EPS differentiated by density; both the strength and cost of EPS is proportional to its density

Applications include:

- Ground conditions too weak to support conventional surcharge
- Insufficient time to adequately preload and surcharge the ground
- Limited space – EPS is a self-supporting material
- EPS used to protect buried utilities
- Limited availability of sand/gravel
- “Competent” ground too deep

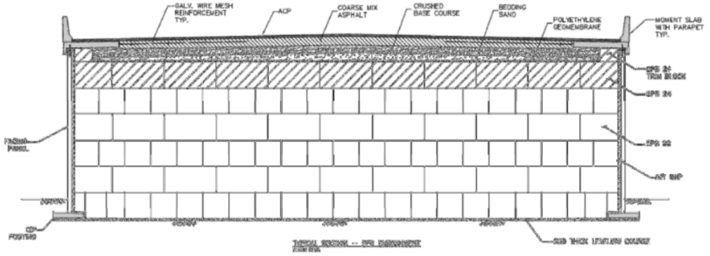
On PMH1 EPS used for:

- 25 embankments and multiple major utility protections
- Tallest embankment 14m, longest embankment 280m, widest embankment 53m
- Over 350,000m^3 used

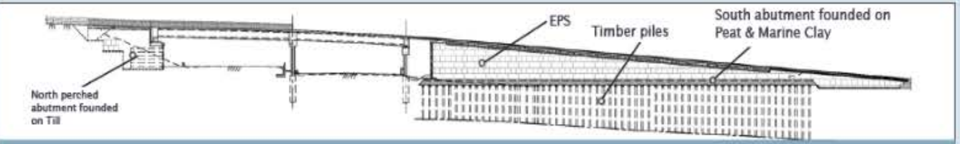
Ultra-lightweight fill – Expanded Polystyrene (EPS)

Typical EPS design considerations

- Protection from hydrocarbons and fire
- Buoyancy
- Reduced surcharge/time to reduce long term settlement
- Modular construction
- Incorporation of street furniture, light signs, drainage etc.



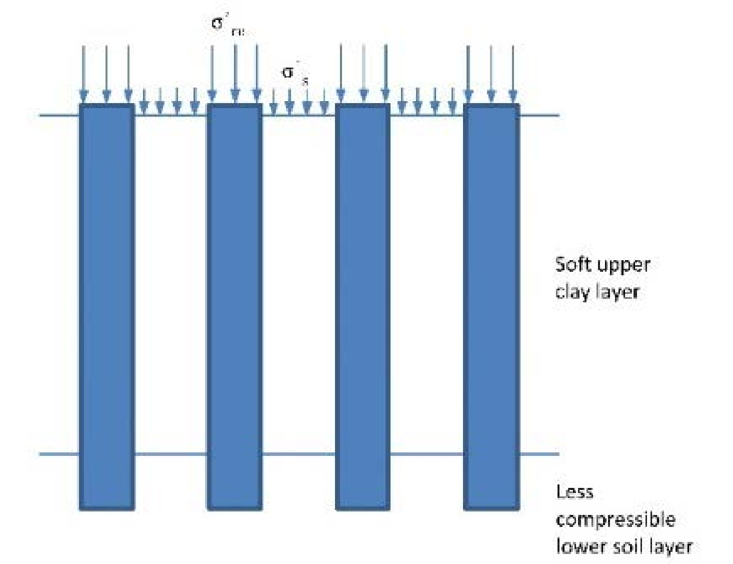
Original 1960's design typically consisted of many bridge spans in areas of compressible soils

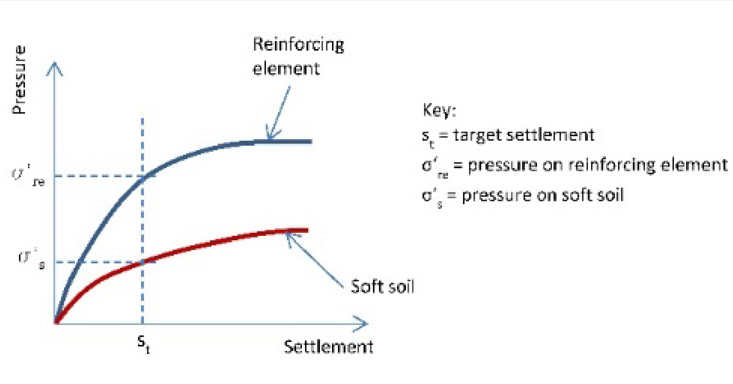


New Sprott Street underpass consists of 2 bridge spans and 1 EPS embankment: 9 meters tall and 100 meters long

Existing Sprott Street underpass consisted of 8 bridge spans

Ground improvement by reinforcement





Stone columns or DCM columns/panels

Overall behaviour of system: vertical stiffness, and shear resistance

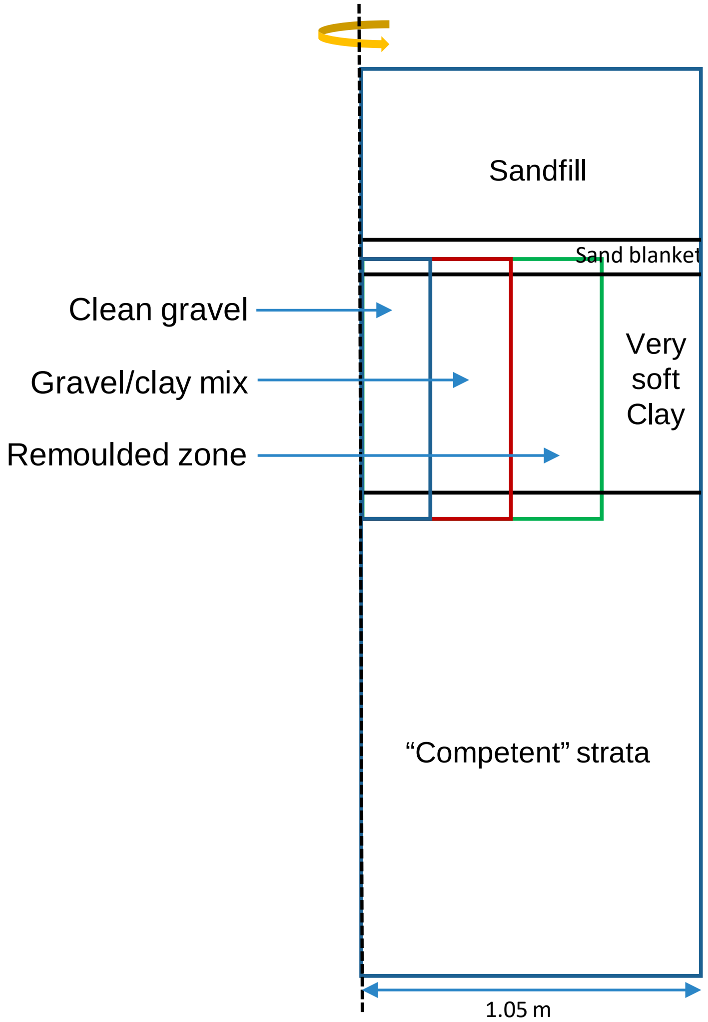
“Stiff” elements within soft clay to reduce settlement

Relative stiffness of reinforcing elements c.f. soft clay

Stone column analysis

- What is load share?
- Plaxis coupled consolidation
- Very soft clay, Su ~ 5 to 15 kPa
- MCC
- Stone column E α p’

NB. Geometry of zones affected by mixing of clay and gravel highly idealised.



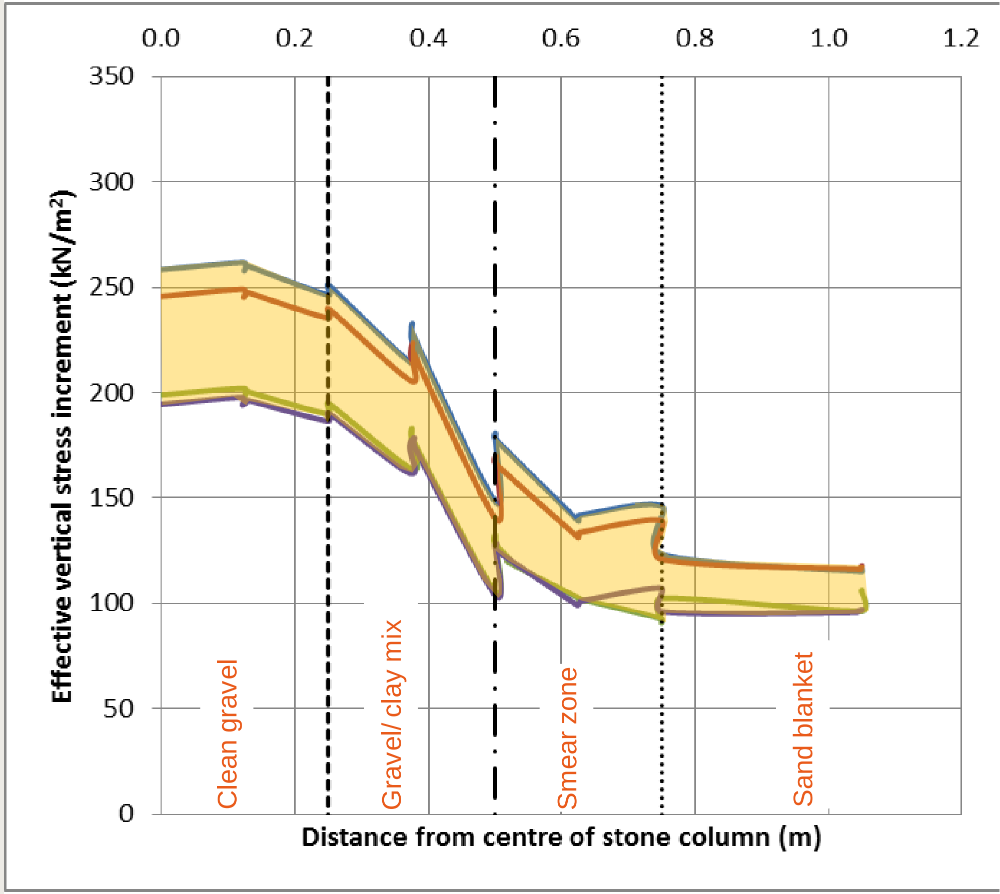
Stone column

Load share under vertical loading

Load share

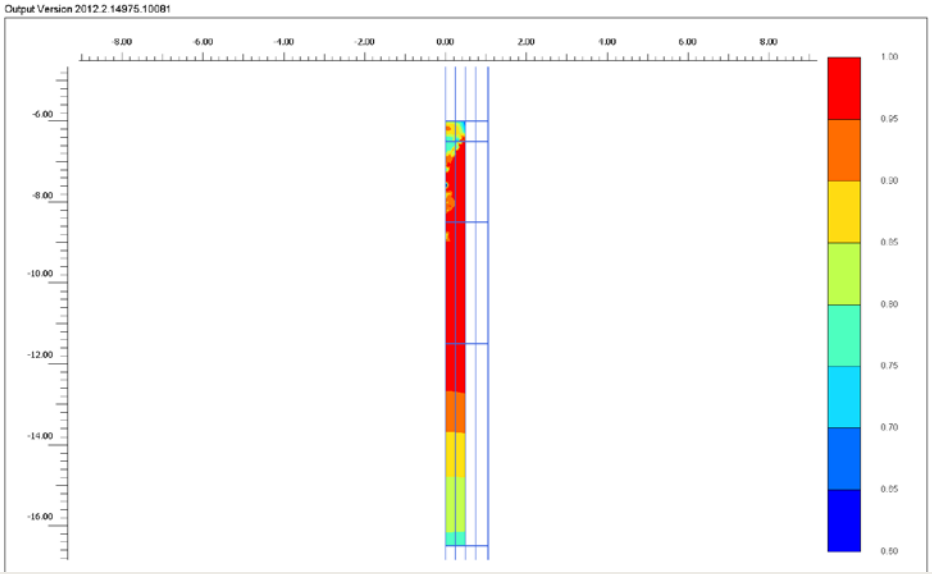
- Varies during consolidation
- Sensitive to “contamination” of stone column
- Stress concentration factor, n varies between 1.6 and 2.5 during consolidation

What is mobilised strength of stone column?

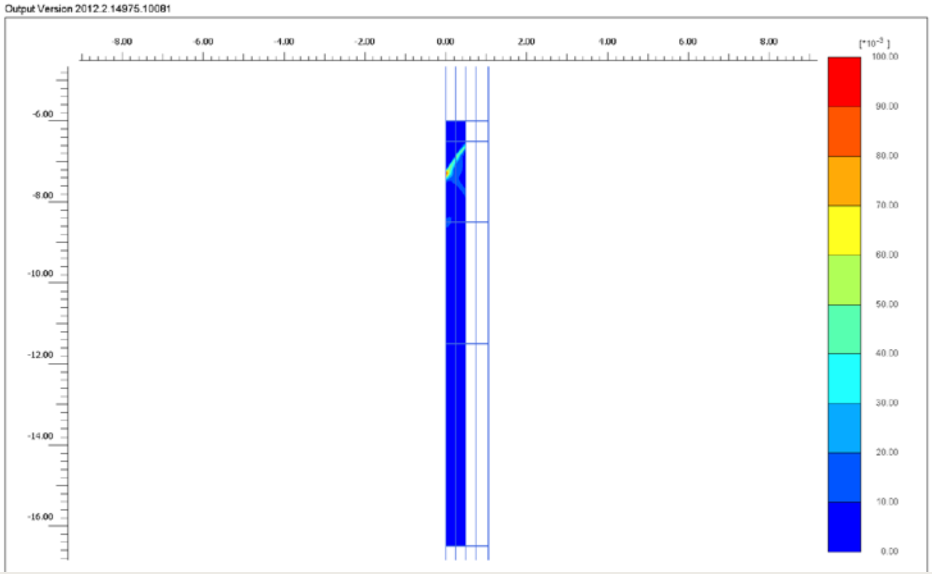


Stone Column – Mobilised Shear Strength/Strain

Relative Shear Stress (-)

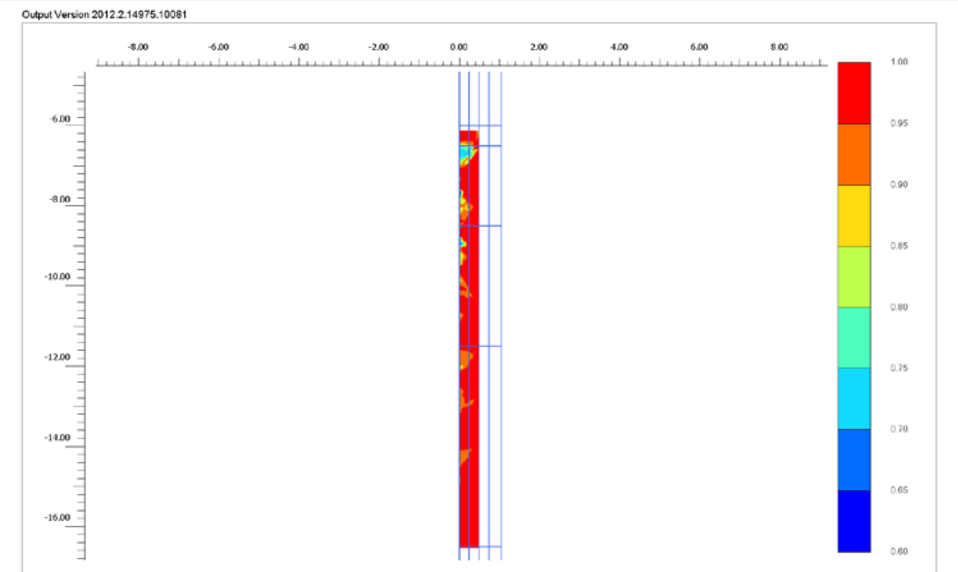


Total Deviatoric Strain (-)

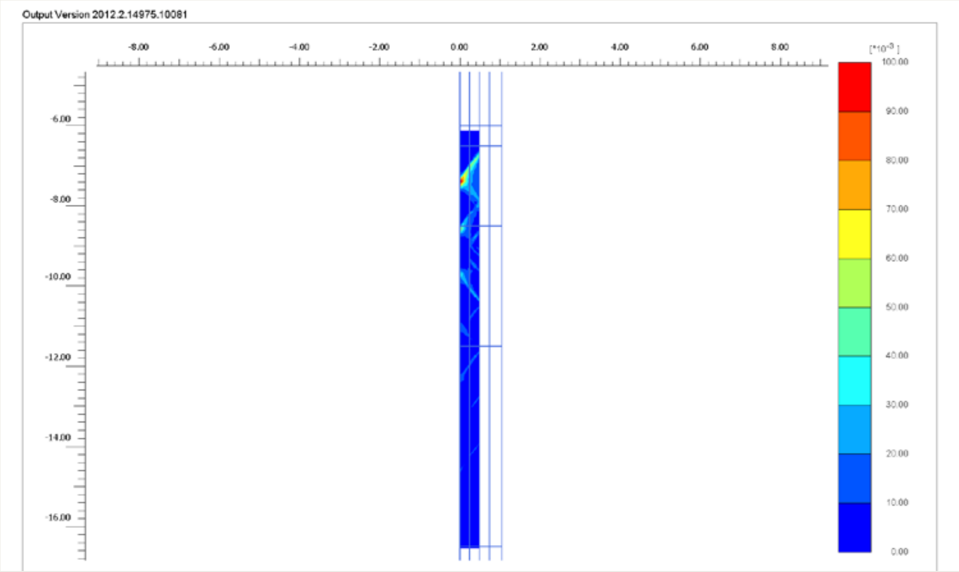


Stone Column – Mobilised Shear Strength/Strain

Relative Shear Stress (-)

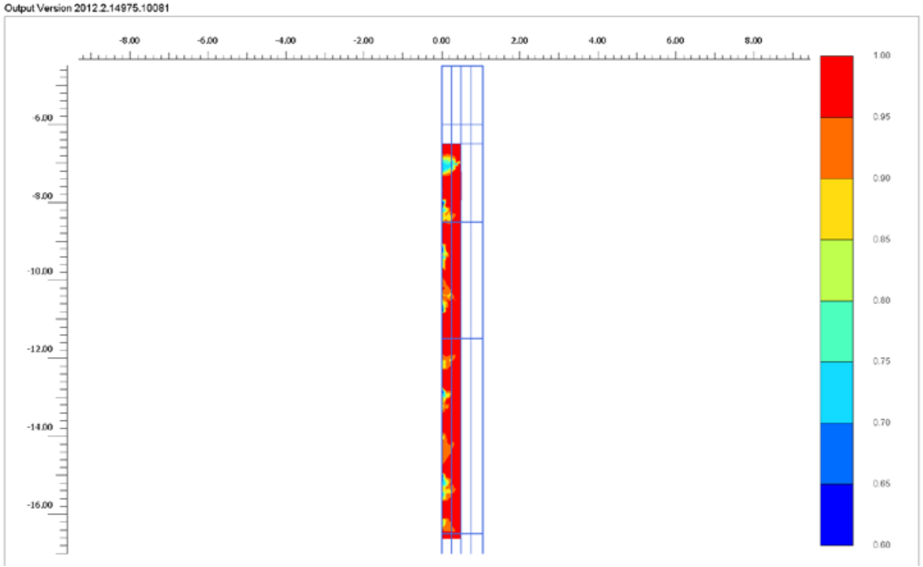


Total Deviatoric Strain (-)

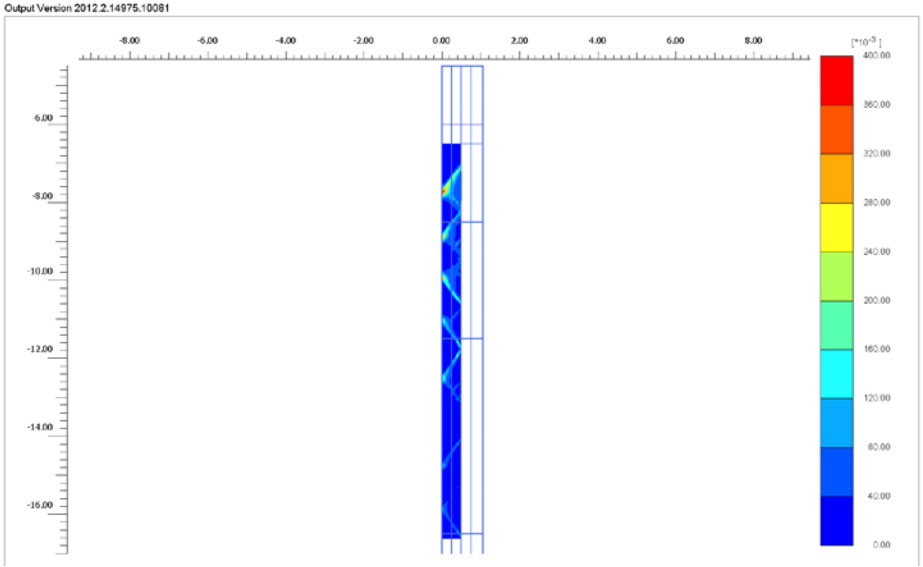


Stone Column – Mobilised Shear Strength/Strain

Relative Shear Stress (-)



Total Deviatoric Strain (-)



Under vertical load, shear strength of column is fully mobilised in upper half of column. Hence, cannot provide any shear strength under out of balance loads, eg. Embankment shoulder or sea wall.

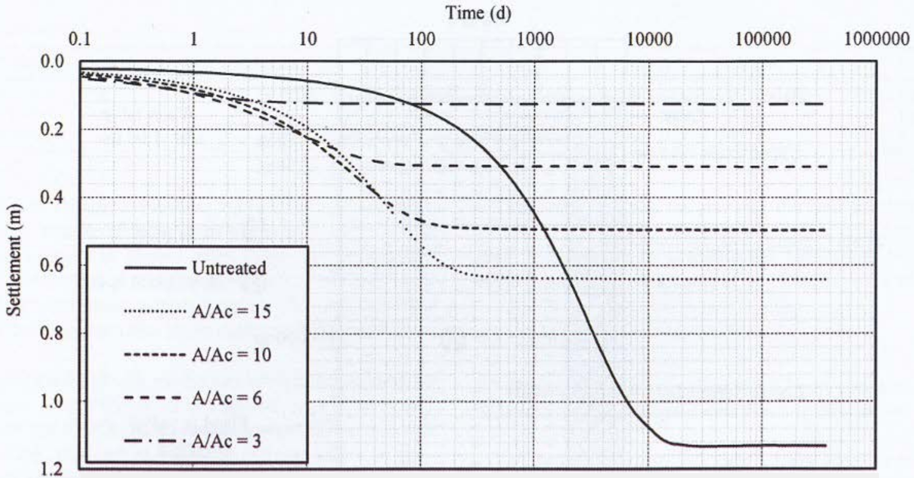
Conventional "weighted average" of shear strength based on area ratio – dangerous for very soft clays!

Stone column

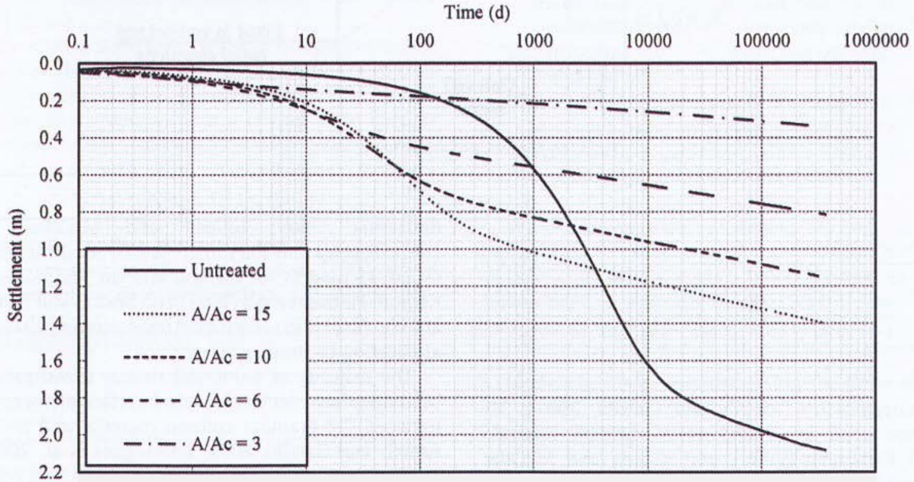
Performance in sensitive clay (at SCL)

Advanced modelling (after Sexton et al, 2016)

- Once clay destructures
  - large long term settlement



No Creep



With Creep

Priebe's method

- Too optimistic for very soft clays at SCL
- Strength sensitivity, S_t is key parameter

NB. S_u ~ 10 to 20 kPa, S_t ~ 9

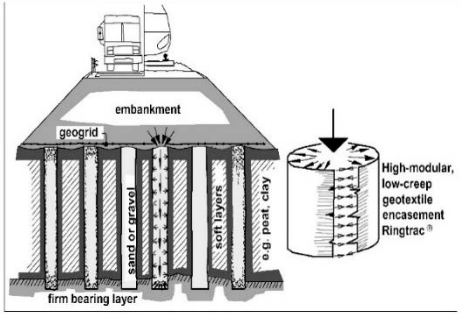
GEC – alternative to SC for very soft clays

GEC

- Use high stiffness seamless geotextile “sock” to provide lateral confinement

- Directly reduces risks
  - poor stone/sand confinement
  - contamination of stone/sand

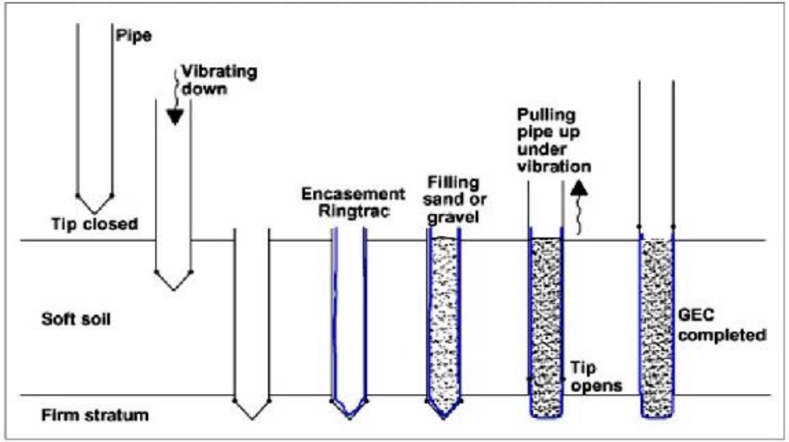
- Highly successful in clays with Su ~ 5 to 10 kPa



GEC – alternative to SC for very soft clays

Installation process

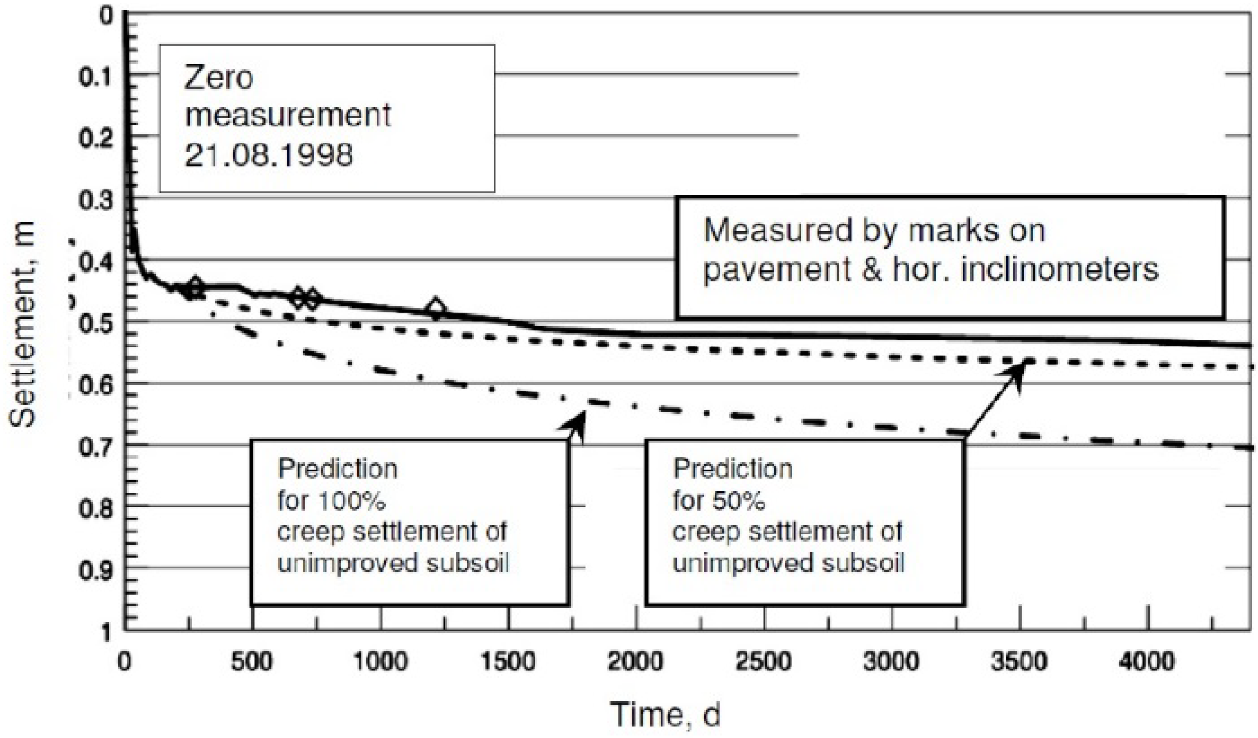
- Modified form of sand compaction pile
- Geotextile sock inserted into steel tube



GEC – long term performance

Low creep

- Due to high stiffness geotextile

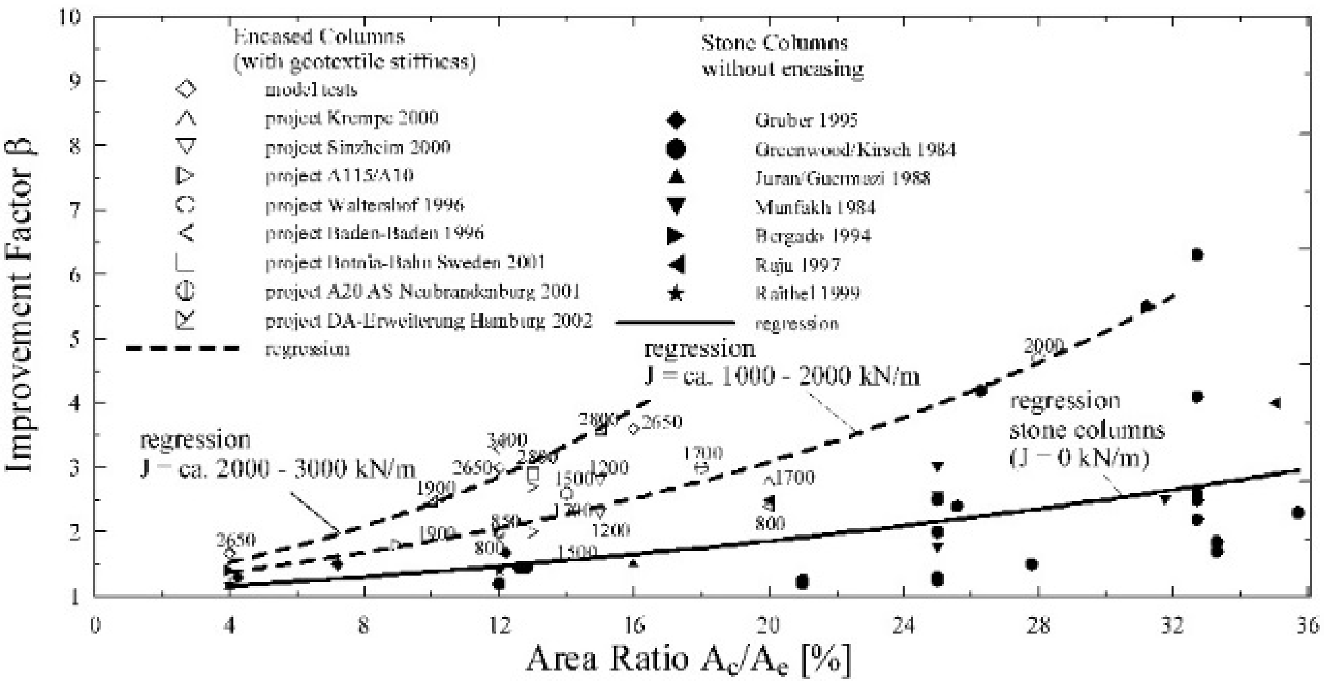


Quality control and stiffness of Geotextile is critical

GEC – Performance vs. Stone Columns

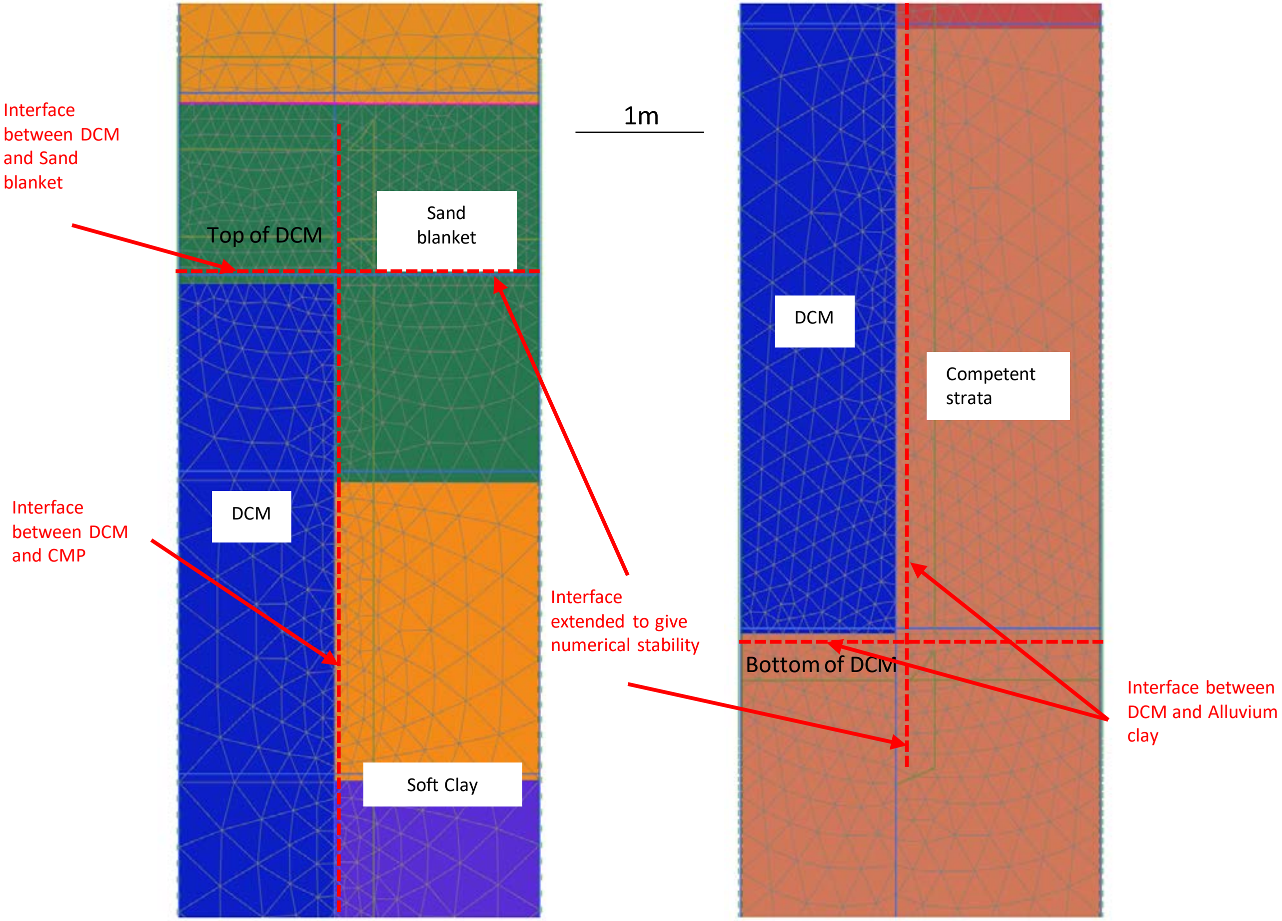
Case history data

- Typically settlement reduction > 3x better than stone columns
- Main experience in Europe, America, Central Asia
- No experience yet in SE Asia



LTP – DCM Soil structure interaction analysis

- Very fine mesh
- Significant stress changes occur across the top of the DCM
- Large strain (updated mesh)
- Interface behaviour
- Coupled analysis

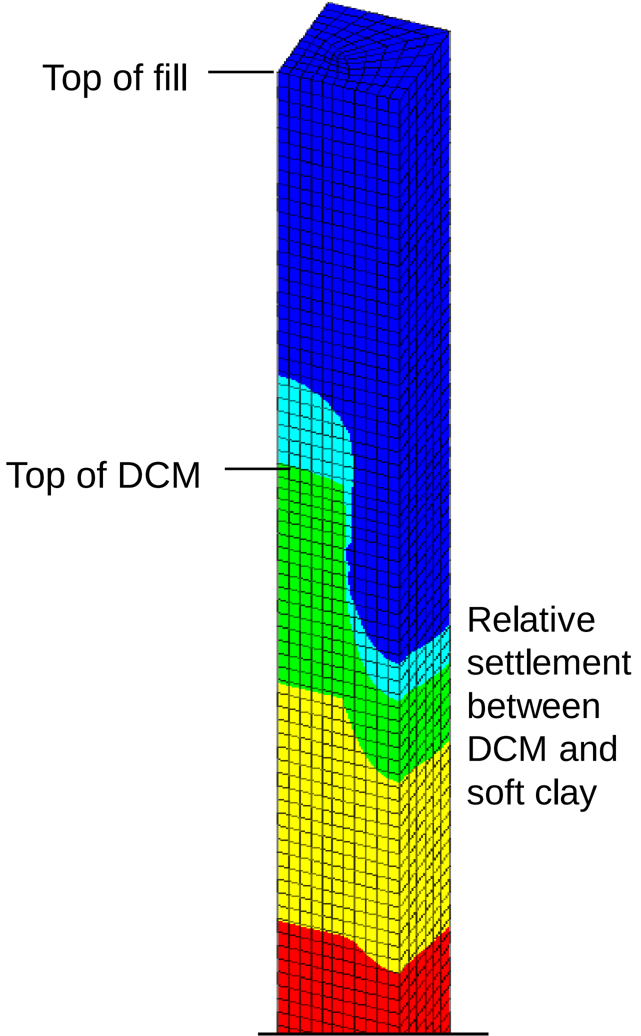


LTP – DCM Soil structure interaction analysis

3D view of typical settlement profile (FLAC 3D)

Load share

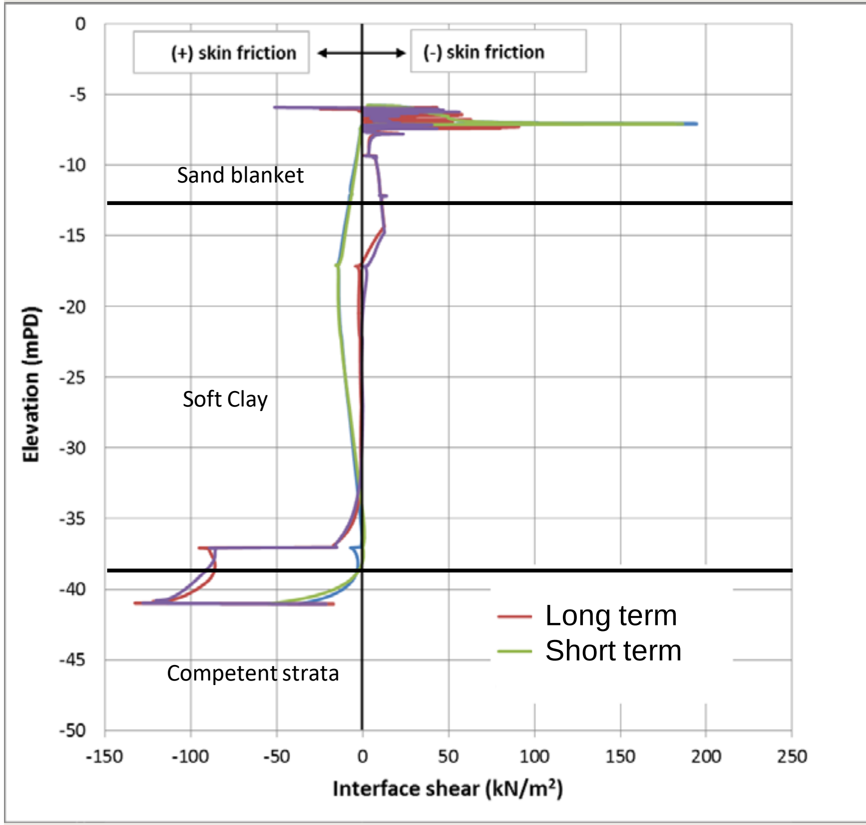
- Short term ~ 80% on DCM columns
- Long term ~ 90% to 95% on DCM columns



LTP – DCM Soil structure interaction

Interface shear stress

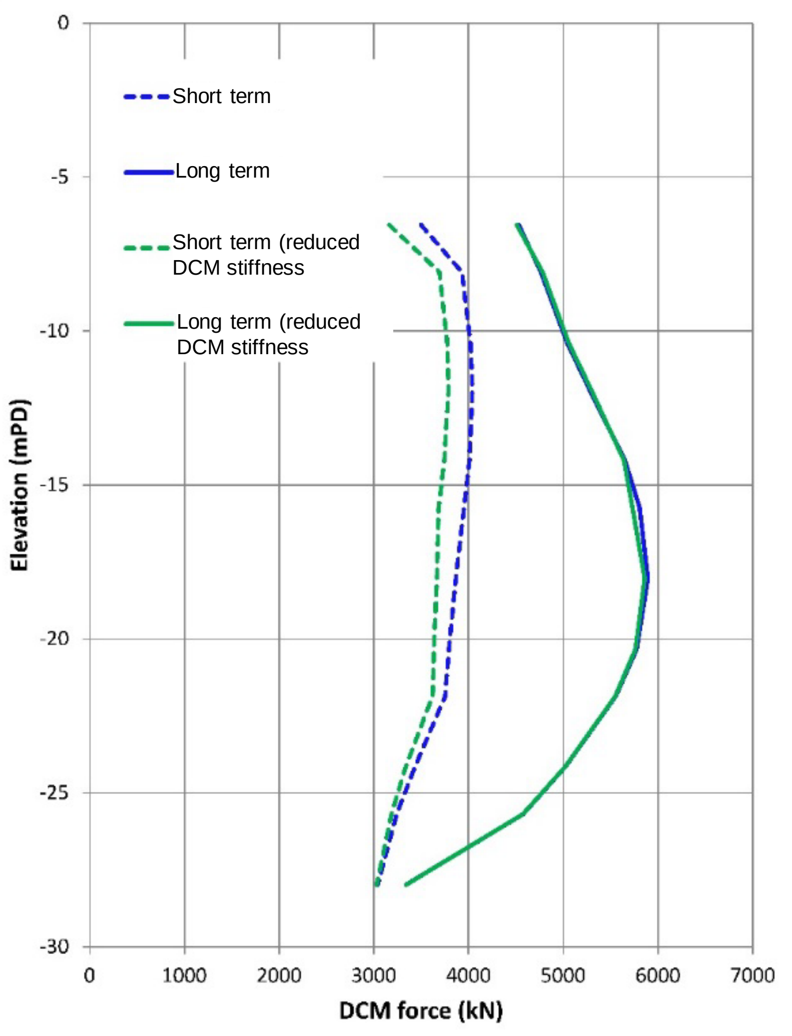
- Mobilised shear stress between DCM and soil
- Complex interaction
- Changes in relative movement and stiffness, during consolidation
- As NSF increases DCM settlement increases (then NSF/PSF reaches equilibrium)



LTP – DCM Soil structure interaction

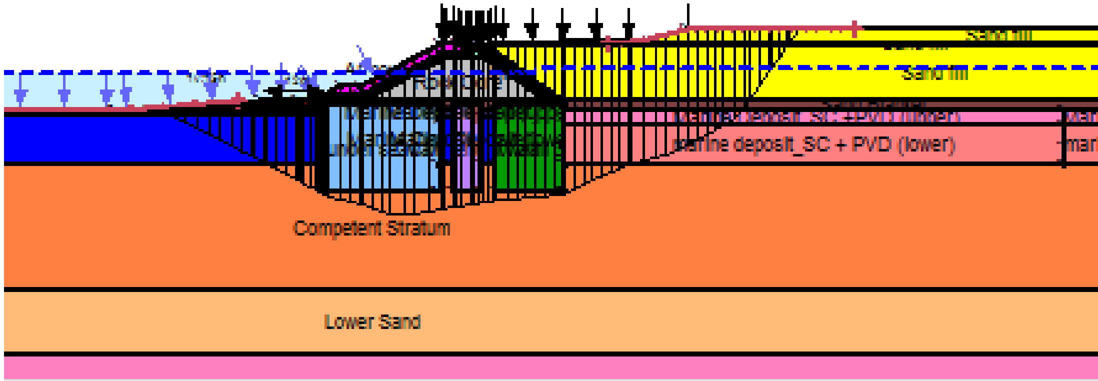
Influence of DCM stiffness

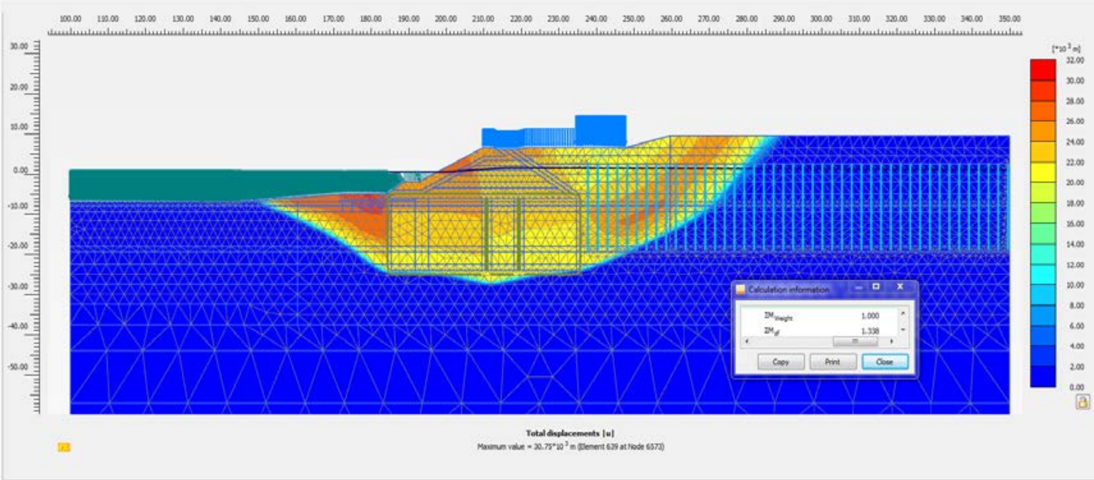
- Stress in DCM column, increases with time
- Strength + stiffness of DCM is increasing with time
- Sensitivity studies are important



DCM – Shear panels
Global stability

- Many potential failure mechanisms
- FHWA, good summary
- Filz, 2013. Compares limit equilibrium with numerical modelling
- Slope/W vs. PLAXIS (?)
- PLAXIS use of calibrated SHANSEP model can be helpful

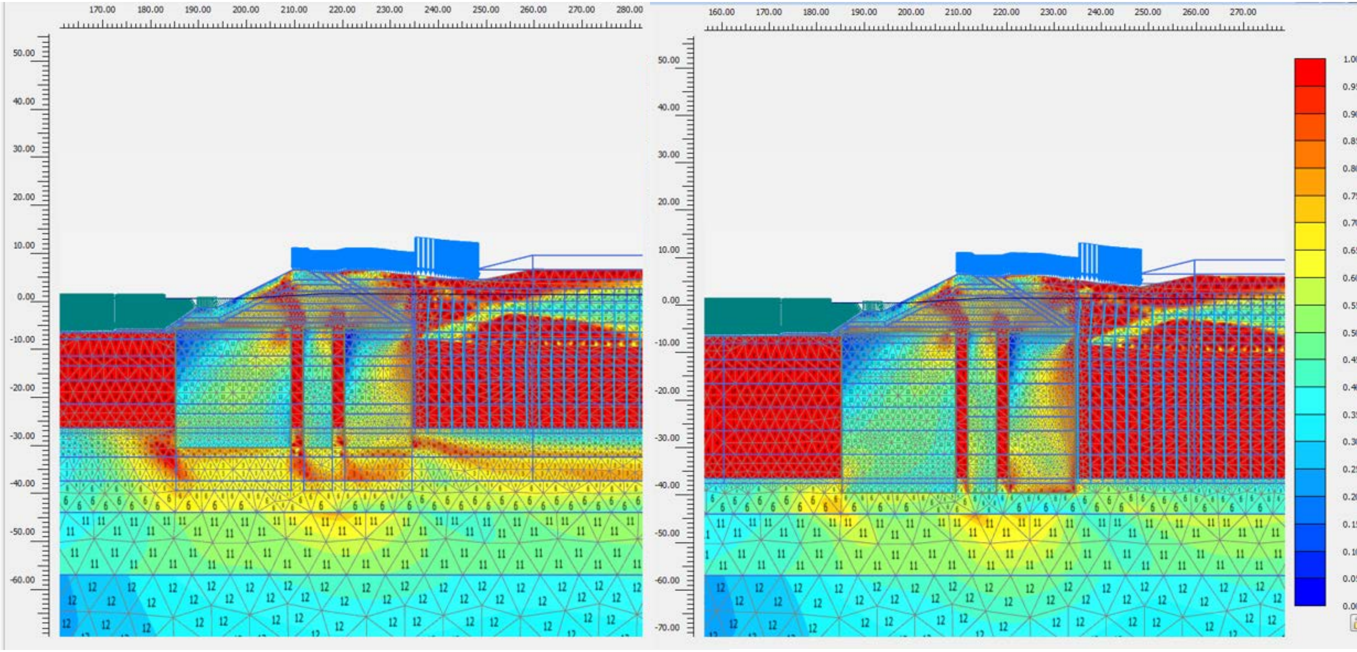




DCM – Shear panels

Induced shear in panels

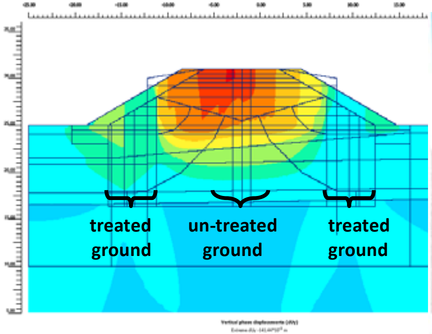
- Sensitive to sequence and strength gain
- Relative stiffness and strength of DCM and bearing strata
- Geometry of problem, panel aspect ratio, etc.

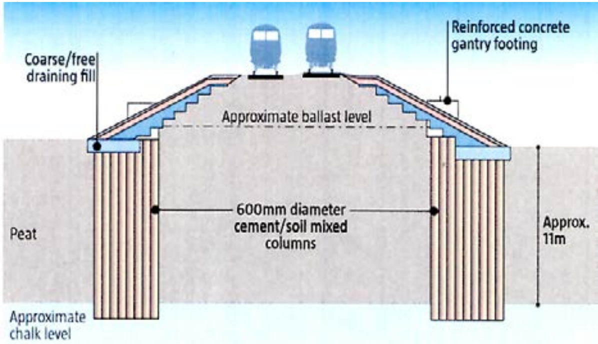


Use of dry soil mixing to stabilise existing infrastructure

Original design

- Used tied sheet pile walls
- alternative solution used DCM with dry mix
- safety – smaller plant working further from the tracks
- specialist skills available in market place
- possessions – all works in traffic hours
- technically greater lateral stiffness to embankment core
- re-use of material
- only 40% of cost





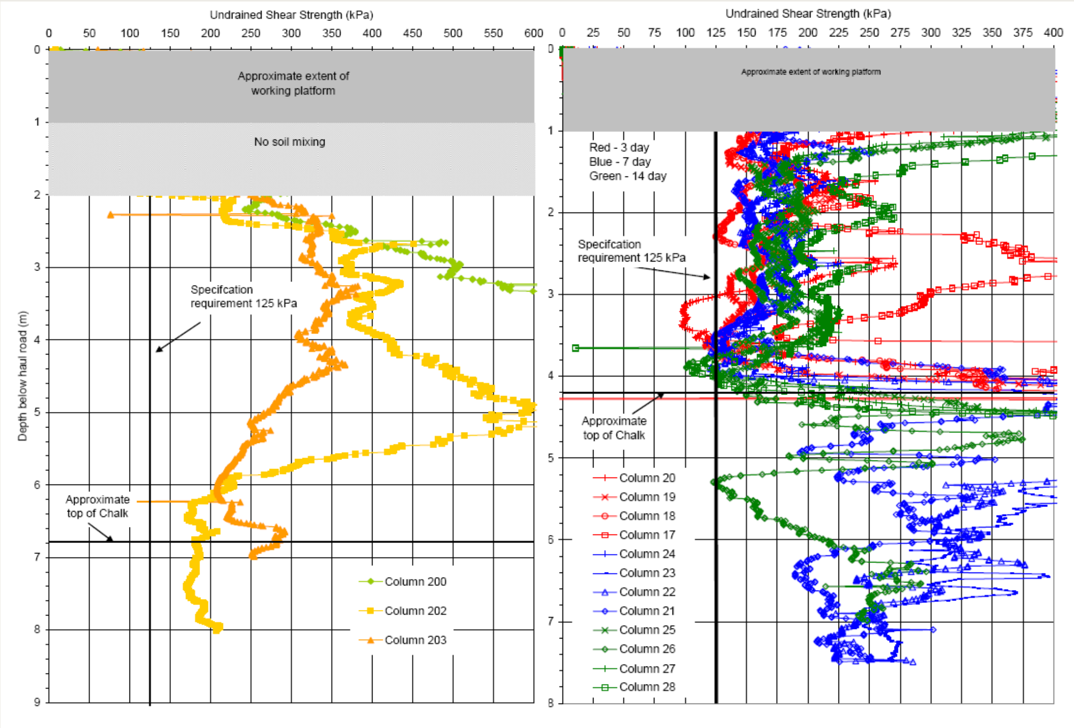
Use of dry soil mixing to stabilise existing infrastructure

Delivering sustainability

	embodied energy (GJ)	embodied CO_2 (kg)
Tubular steel piles	256,585	17,594,400
	embodied energy (GJ)	embodied CO_2 (kg)
Dry soil mixing	43,087 (<20%)	5,430,092 (30%)

Soil mixing trial

- Lab tests - unsuccessful
- Field tests - successful
- Peat layers - lower strength
- Organic content - key parameter



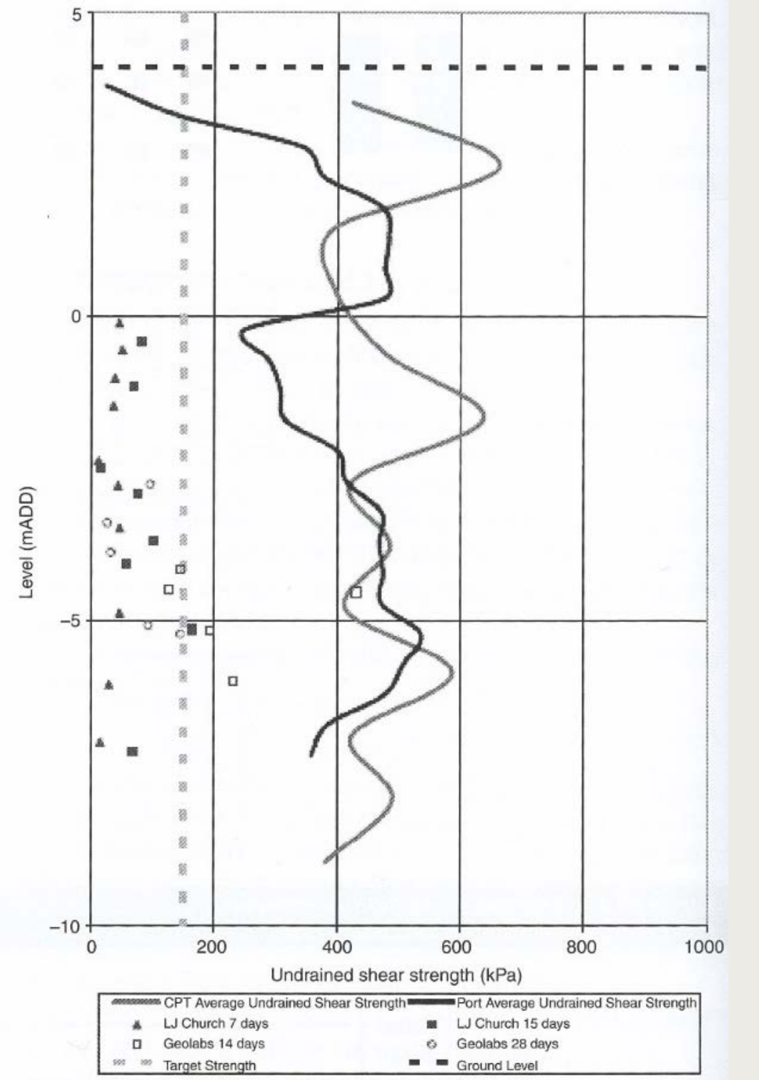
Undrained shear strengths for **CLAY** for 200kg/m^3 calculated from Col PT results.

Undrained shear strengths for **PEAT** for 275kg/m^3 calculated from Col PT results.

DCM Strength verification

Holistic approach

- (c.f. GI in weak rock!)
- Logging system, overall DCM quality
- Both field and lab tests
- Coring is always challenging
- UCS may be misleading
- Consider triaxial tests

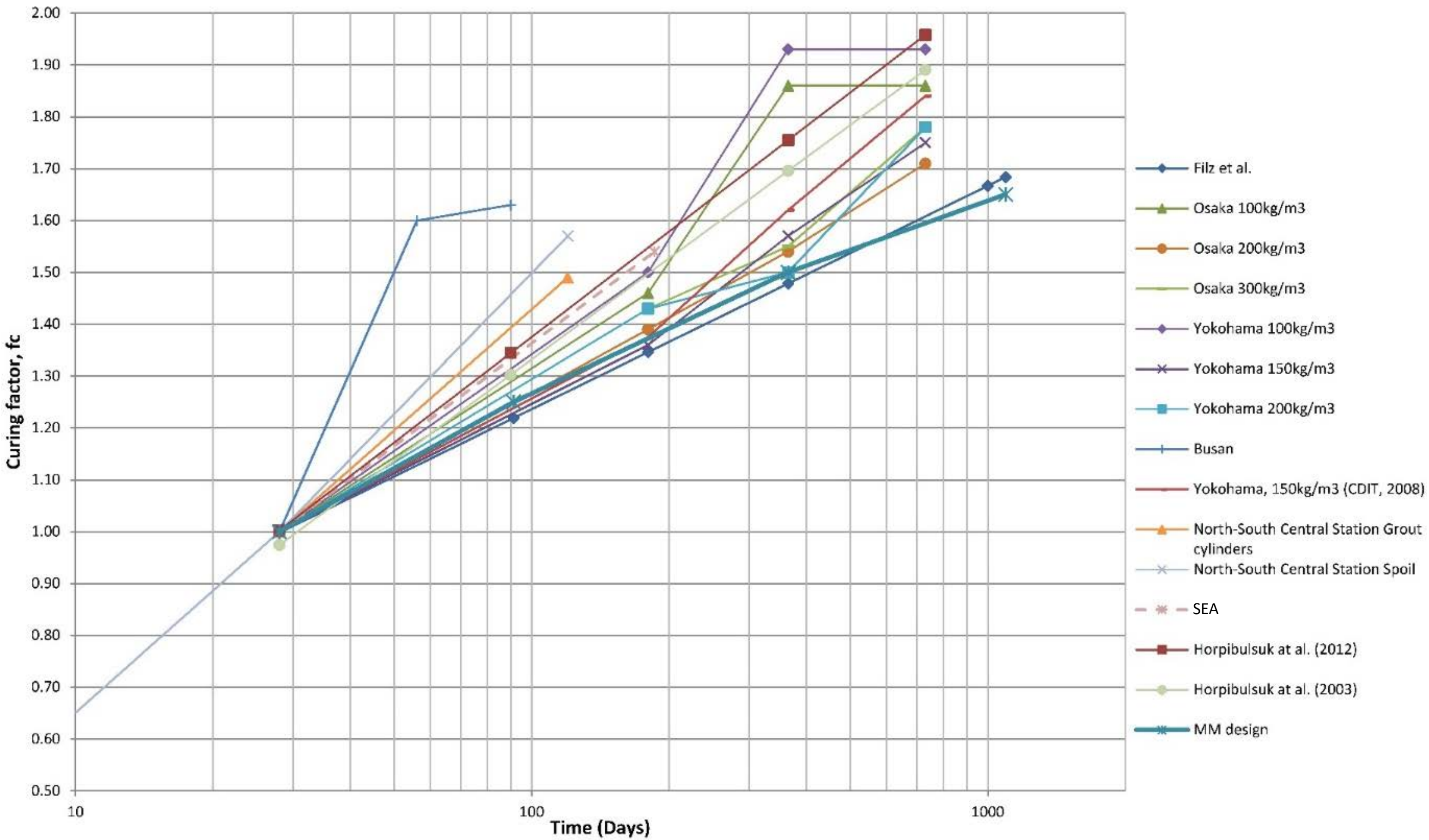


Design strength

- FHWA definition - conservative
- New EC7 – potential for more economy/ lower carbon
- Consider – brittleness, DCM uniformity + scale of potential failure mechanism

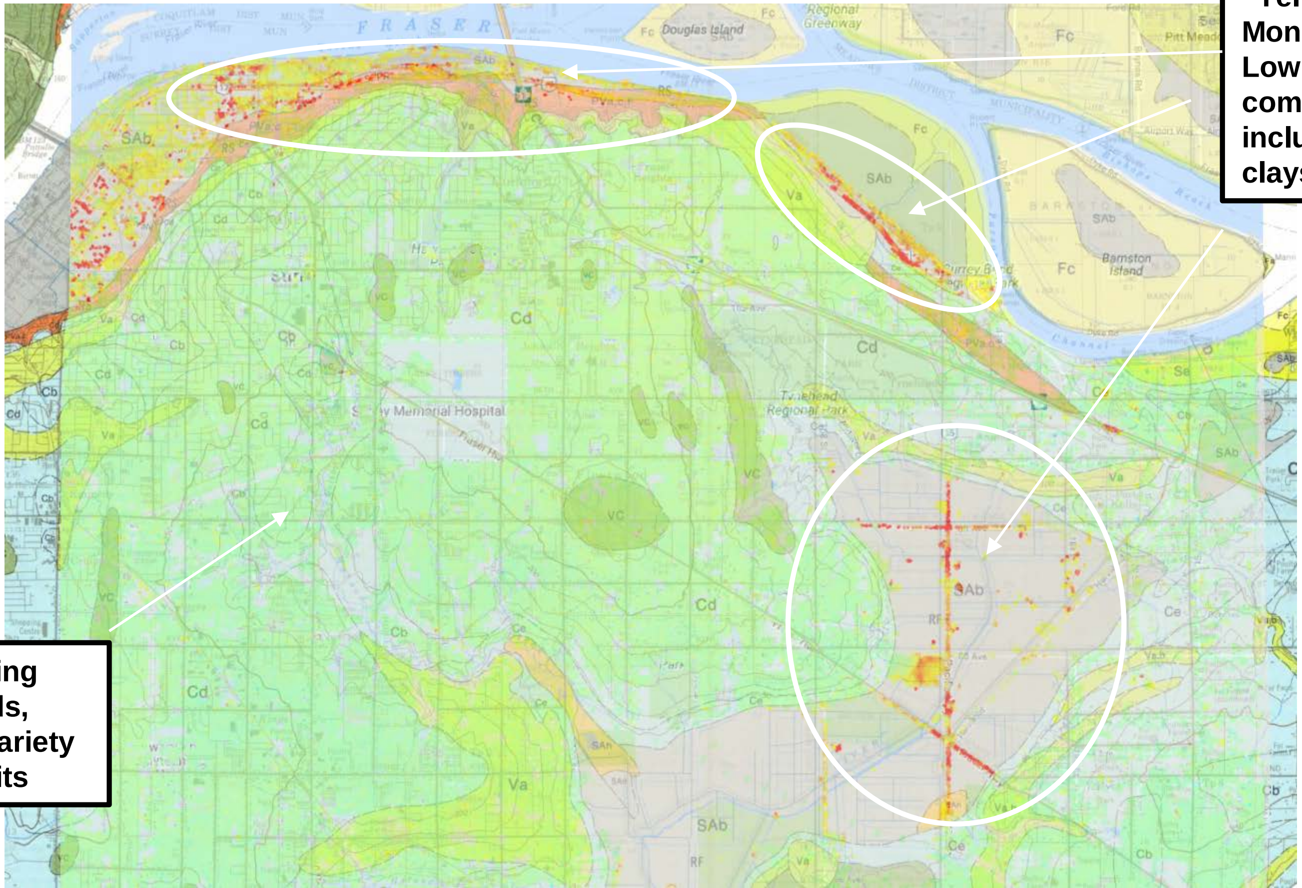
DCM – Strength gain with time

Longer term – DCM is much stronger!



New technology, assessing long-term settlement

Insar monitoring overlaid on geology, Vancouver



“Yellow to Red” Monitoring points on Lowlands – compressible soils including peat and soft clays

“Green” Monitoring points on Uplands, consisting of a variety of Glacial Deposits

Insar monitoring

Ongoing movement on Bridge Deck

Negligible over 24months

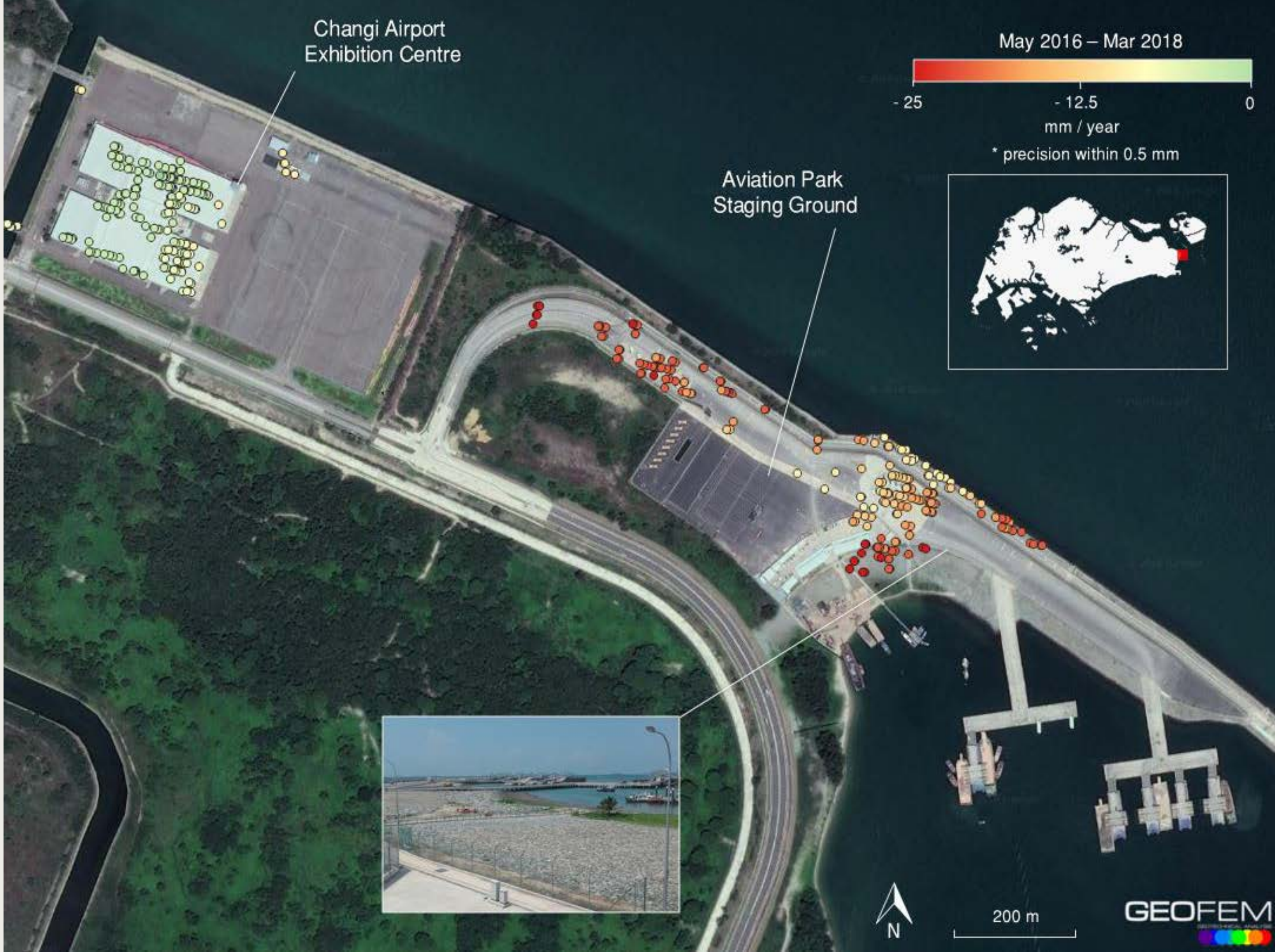
Insar monitoring

Ongoing movement away from Abutment (no EPS)

Approximately 100mm over 24months

Insar Monitoring

Changi, Singapore



GEOFEM Contact
andrew.lees@geofem.com

Concluding thoughts

1. Clay close to SCL – “non-text book” behaviour
2. High quality sampling/testing, plus advanced analysis – insights into stability, deformation and soil-structure interaction
3. PVD/Surcharge – PVD discharge capacity is critical
   - test methods appropriate?
   - 2 PVD rounds to reduce risks
4. LTP stone columns
   - Caution required if clay close to SCL
   - Install after PVD + strength gain to reduce risks?
   - Column strength – mobilisation just under vertical load?
5. GEC as alternative to stone columns
6. LTP – DCM. Load share varies during consolidation
7. DCM – Global stability
   - Many potential failure mechanisms, FHWA/Filz
   - Limit equilibrium, necessary but not sufficient
8. DCM – Strength verification
   - Always difficult
   - “Borrow” from rock mechanics best practice
   - Strength definitions
9. Insar monitoring – new opportunities to assess long term settlement of soft clay