GOLDER

AGS (HK)

香港岩土及岩土環境工程專業協會
ASSOCIATION OF GEOTECHNICAL & GEOENVIRONMENTAL SPECIALISTS (HONG KONG)

1-day Seminar on Ground Improvement Organised by AGS (HK)

Practical Design of Deep Cement Mixing

DR SAW AY LEE

GOLDER ASSOCIATES (HK) LIMITED

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AGENDA

1. DCM Application
2. Properties of Cement-treated Soil
3. DCM Key Characteristics
   - ➢ Non-homogenous
   - ➢ Brittleness
4. Summary

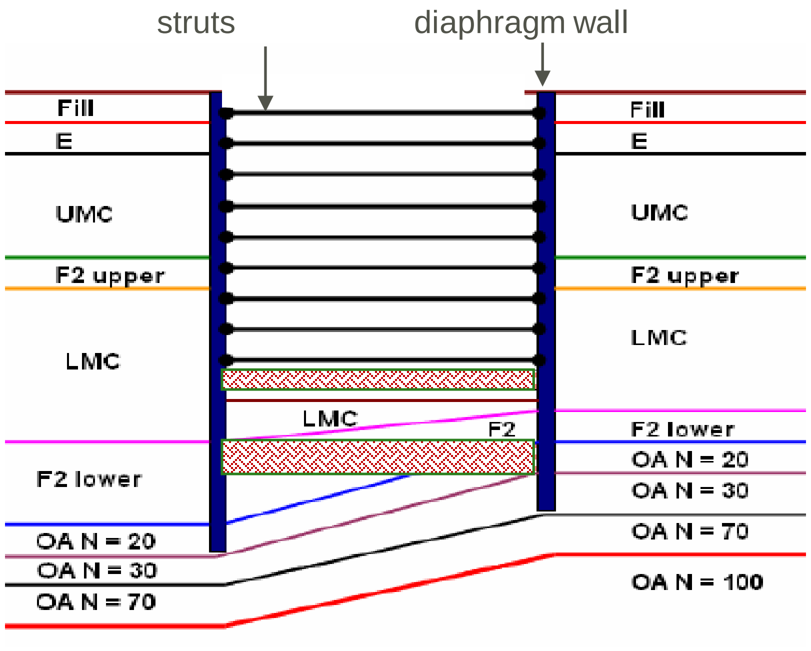
DCM Application

- Deep Cement Mixing (DCM) is categorized as a solidification method which mixes soils with stabilizing agents to improve the strength, stiffness and compressibility of in-situ soils.
- It has been widely used for various construction purposes:
    - Ground Improvement for embankment/reclamation work;
    - Liquefaction mitigation;
    - Support walls/embedded strut for excavation;
    - Eliminate potential future consolidation settlement for tunnel.

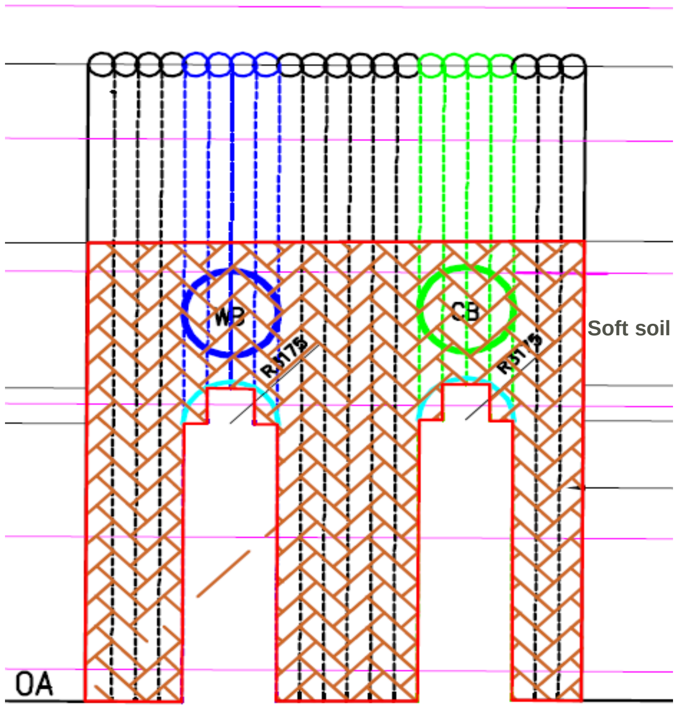
DCM Application

EXAMPLE OF DCM PROJECTS IN SINGAPORE

Embedded strut for deep excavation



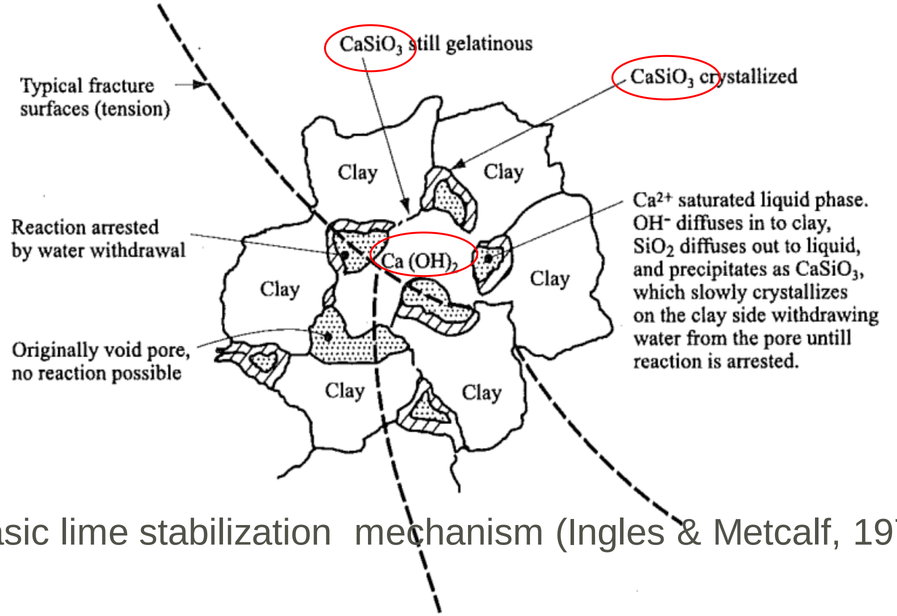
Eliminate potential future consolidation settlement for tunnel



Support wall for excavation

Properties of Cement-treated Soil

- 3 reactions happening in the process of mixing cement with soil:
  i. Hydration   ii. Ion Exchange (Flocculation)   iii. Pozzolanic Reaction
- Thus, the properties of the mixing product are different from the in-situ soil
  1) Physical Properties
  2) Mechanical Properties



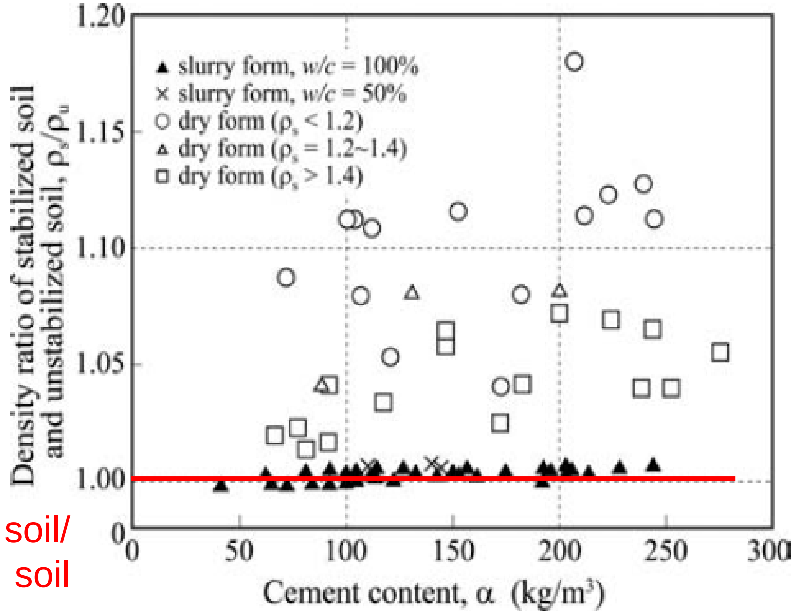
Basic lime stabilization mechanism (Ingles & Metcalf, 1972)

Properties of Cement-treated Soil

PHYSICAL PROPERTIES OF CEMENT-TREATED SOIL

- **Unit Weight**

- The density change due to slurry form treatment is negligible.



Density of stabilized soil/
Density of unstabilized soil

- **Permeability**

$$k_{DCM} \leq k_{in-situ}$$

- The permeability of treated soil decreases with decreasing the water content and with increasing the amount of cement.

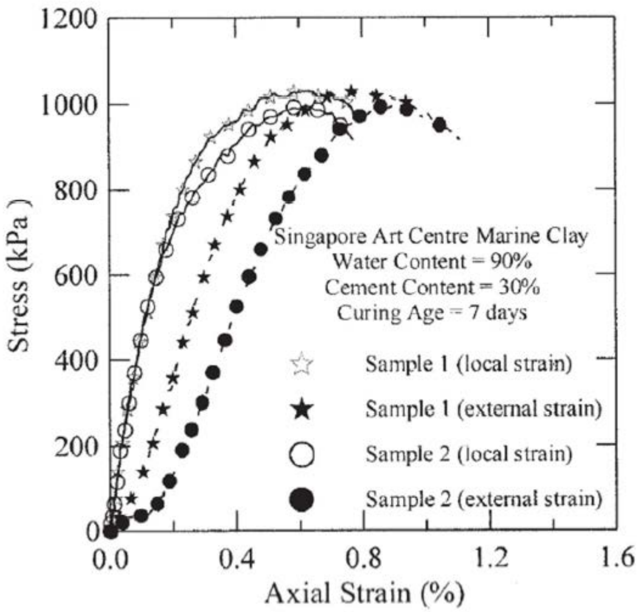
Properties of Cement-treated Soil

MECHANICAL PROPERTIES OF CEMENT-TREATED SOIL

- Stiffness

- Local displacement measurements produce higher value of modulus compared to conventional UCT.

- FHWA recommend to adopt E50 as the effects of higher modulus values at low strains and higher modulus from local strain measurements tend to counteract the effects of long-term creep.



References	E-q_u	In-situ soil type	In-situ improved/ lab improved
Lee et al., 1998	$E_0 = 80 - 200q_u$ #	Marine clay	Lab improved & In-situ improved
Kamruzzaman, 2002	$E_0 = 490q_u$ *	Marine clay	Lab improved
Tan et al., 2002	$E_{50} = 350 - 800q_u$ * $E_{50} = 150 - 400q_u$ #	Marine clay	Lab improved
Lee et al., 2005	$E_0 = 80 - 140q_u$ *	Marine clay	Lab improved
Wen, 2005	$E = 200q_u$	Marine clay	In-situ improved
Wong and Goh, 2006	$E = 100q_u$	Marine clay	In-situ improved
Lorenzo and Bergado, 2006	$E_{50} = 150q_u$	Bangkok Clay	Lab improved

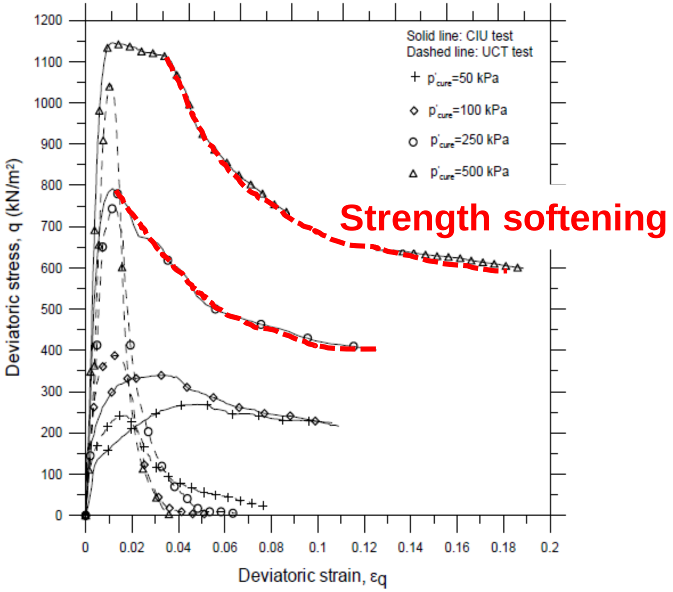
Properties of Cement-treated Soil

MECHANICAL PROPERTIES OF CEMENT-TREATED SOIL

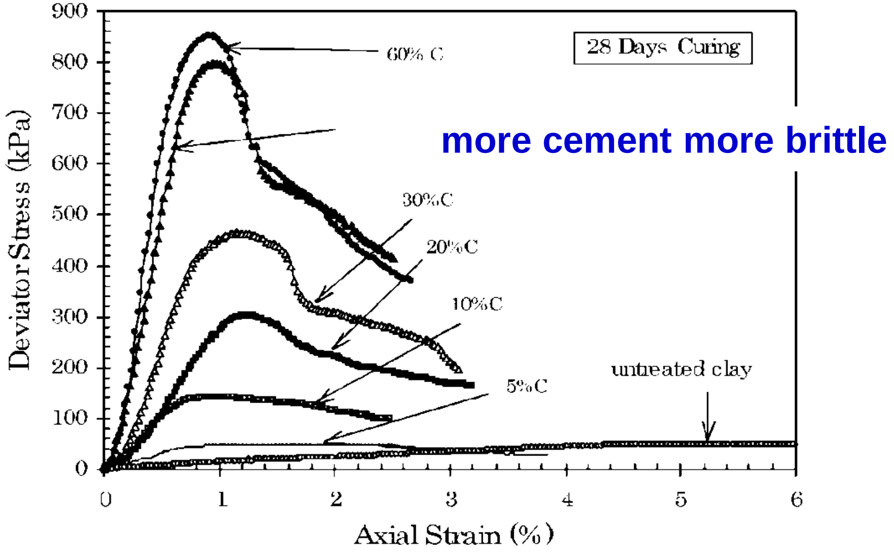
- Compressive Strength

- Compressive stress-strain relationships of cemented soil are well stablished from UCT, CIU and CID tests.

- Compressive strength increases with curing period & cement content



CIU & UCT tests comparison (Chin, 2006)



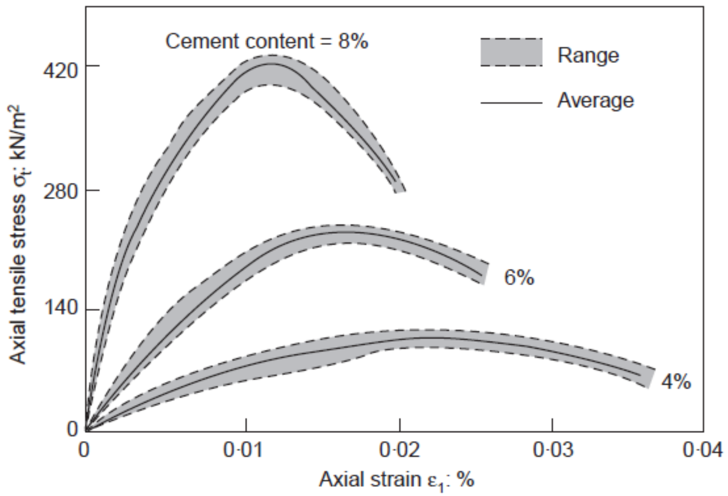
Effect of cement content (Kamruzzaman, 2002)

Properties of Cement-treated Soil

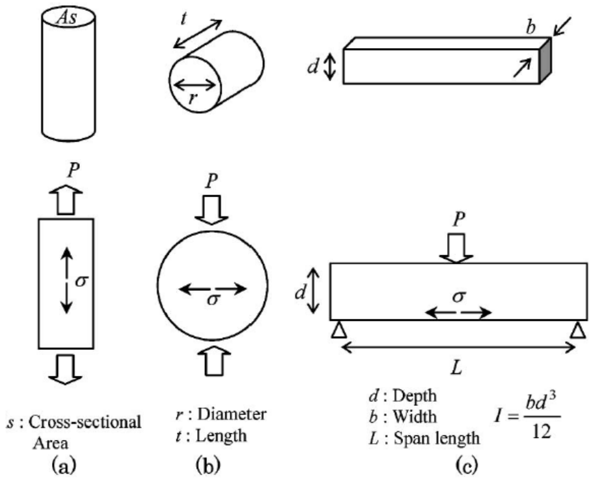
MECHANICAL PROPERTIES OF CEMENT-TREATED SOIL

- Tensile Strength

- Increase in tensile strength - brittle even with small amount of cement; strain softening both in compression and tension.



Direct tension test on cemented sand
(after Das and Dass, 1995)

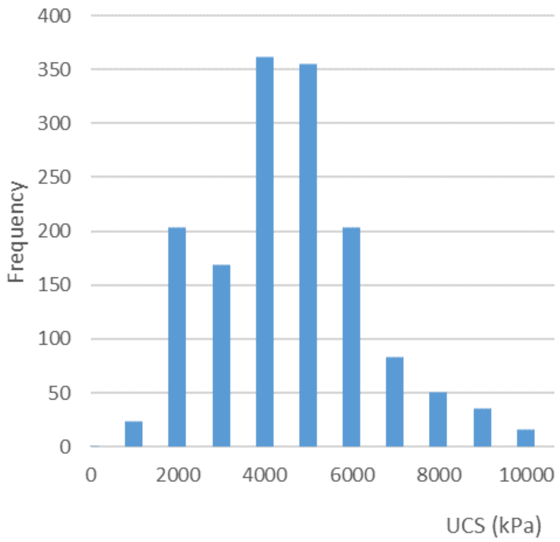


References	Relationship
Porbaha et al., 2000	$\sigma_{st} = 0.1 - 0.15\ q_u$
Saitoh et al., 1996	$\sigma_{dt} = 0.1\ q_u$ $\sigma_{st} = 0.1 - 0.3\ q_u$
Tanaka and Terashi, 1986	$\sigma_t = 0.15\ q_u$
Fang et al., 1994	$\sigma_t = 0.05$ to $0.2\ q_u$
Xiao, 2009	$\sigma_{st} = 0.127\ q_u$

Peak tensile strength is in a range of 0.1 – 0.2*qu

Key Characteristics of DCM

i. Non-homogenous



ii. Brittleness

Key Characteristics of DCM

NON-HOMOGENOUS

It is well documented that the DCM soil has significant heterogeneity in strength

- FHWA – the COV ranged from 0.34 to 0.79 from 10 deep mixing projects in US.
- Kitazume (2013) – the COV in the field strength varied from 0.20 to 0.48 for the marine construction according to the Japanese accumulated data.
- GAHK' experiences – Singapore and HK projects 0.4 to 0.6 but depends on the sample volume

Therefore, it is inevitable to recognize that high variability exists in deep cement mixing soil!

Key Characteristics of DCM

NON-HOMOGENOUS

When and how to consider DCM strength variation?

Option 1: During design stage?

Apply a strength variation factor, f_r?

Option 2: During construction QA/QC?

Specify acceptance criteria of the field product, e.g 95% confidence level?

Option 3: Adopt variation factor in design and specify the acceptance criteria of the field product

Key Characteristics of DCM

NON-HOMOGENOUS

Ways to determine the design strength of DCM during design stage:

Approach 1: Statistical Calculation

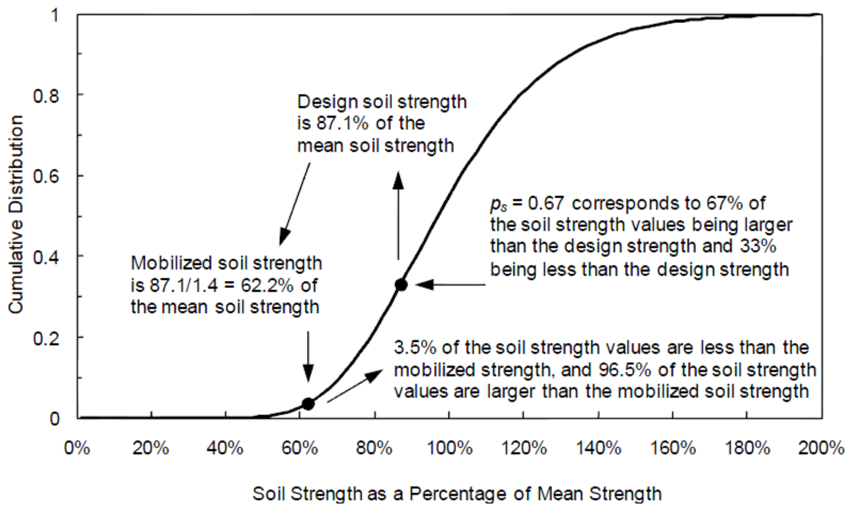
Approach 2: Random Finite Element Analysis

DCM Non-homogenous

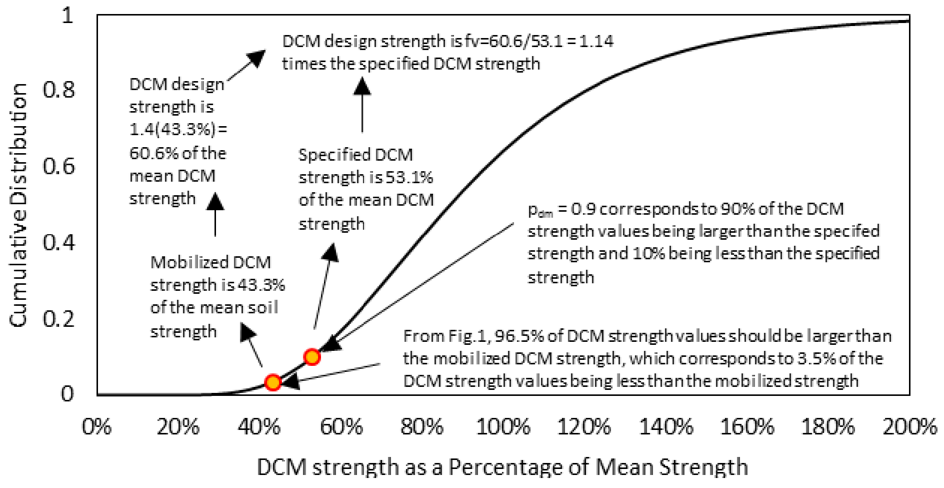
APPROACH 1: STATISTICAL CALCULATION

- Filz and Navin (2010) recommended a methodology to relate a variation factor such that

"the probability that the actual shear strength of the DCM will exceed the actual shear stress in the untreated soil along the potential failure surface in limit equilibrium analyses".



Lognormal distribution of soil strength

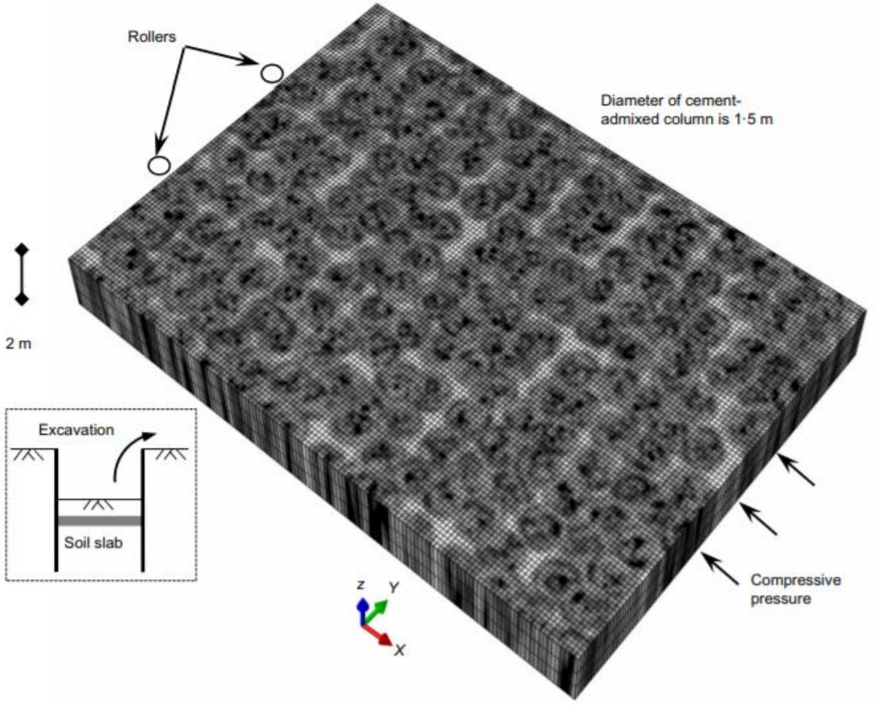


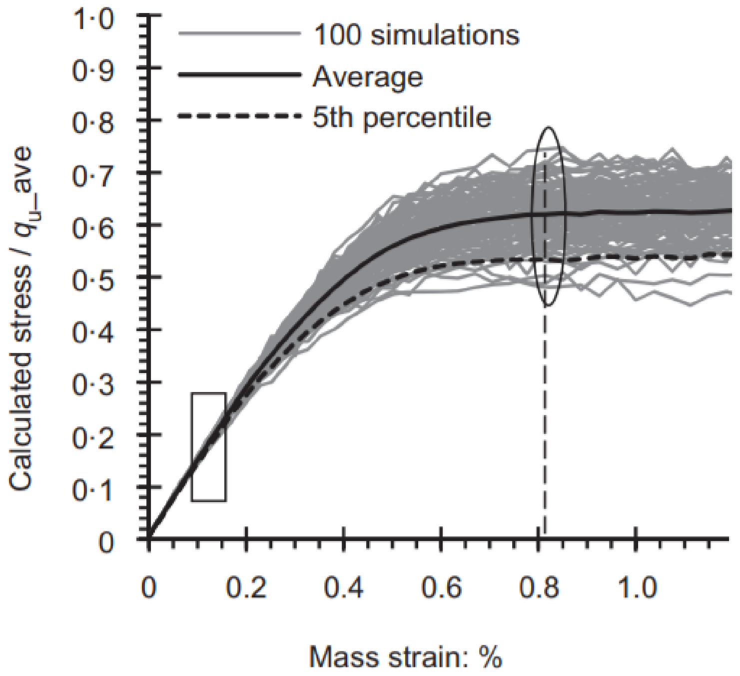
Lognormal distribution of **DCM** strength

DCM Non-homogenous

APPROACH 2: RANDOM FINITE ELEMENT ANALYSIS

- Liu Yong (2015) examined the heterogeneity in strength & stiffness using random FE analyses, and recommended design values of mass modulus and failure stress for a chosen percentile of exceedance.

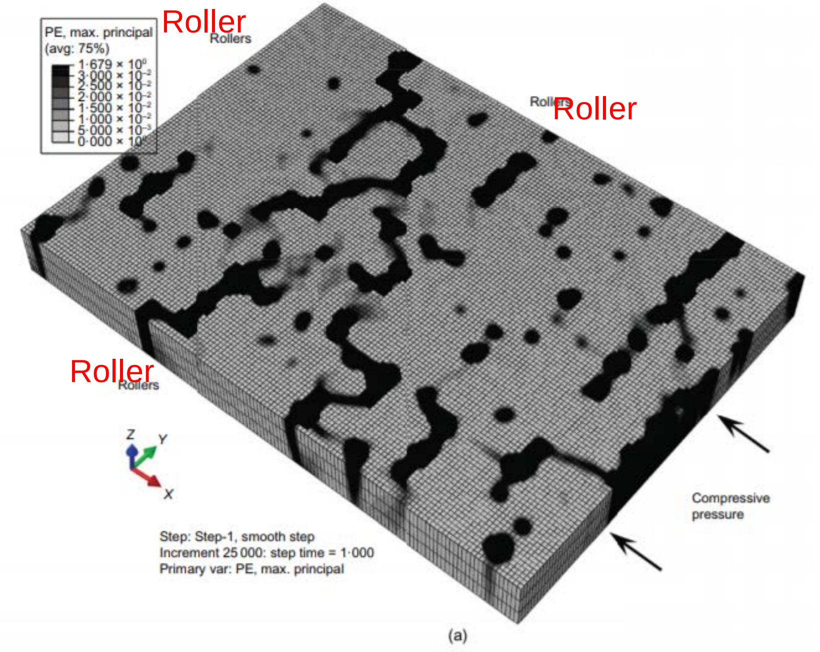




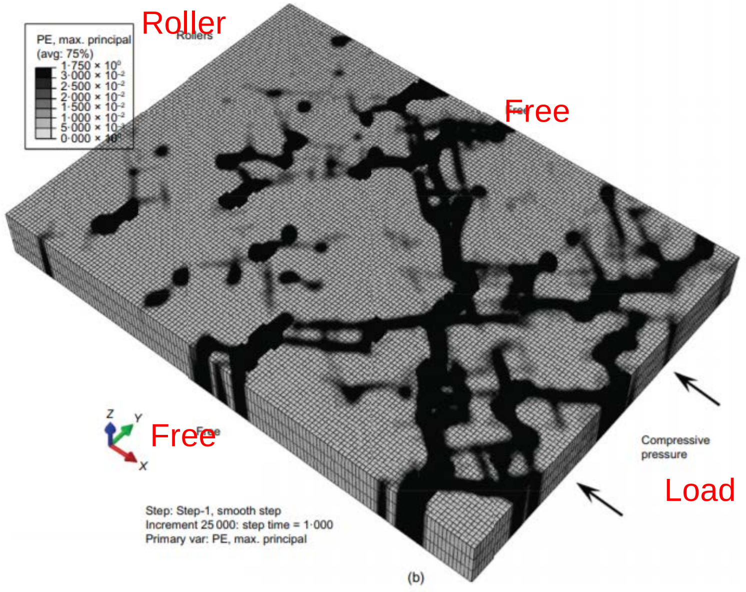
DCM Non-homogenous

APPROACH 2: RANDOM FINITE ELEMENT ANALYSIS

- Failure pattern of confined and unconfined cement-treated soil slab.



Confined Slab

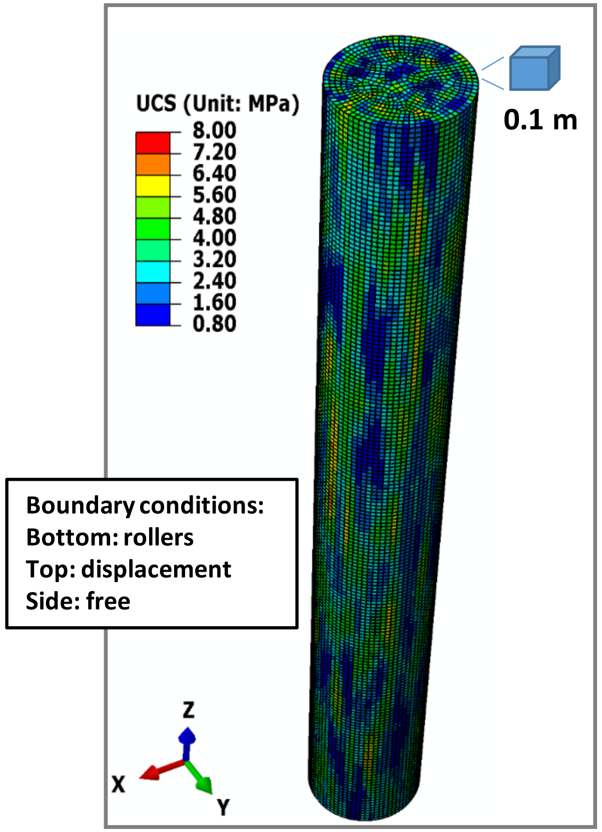


Unconfined Slab

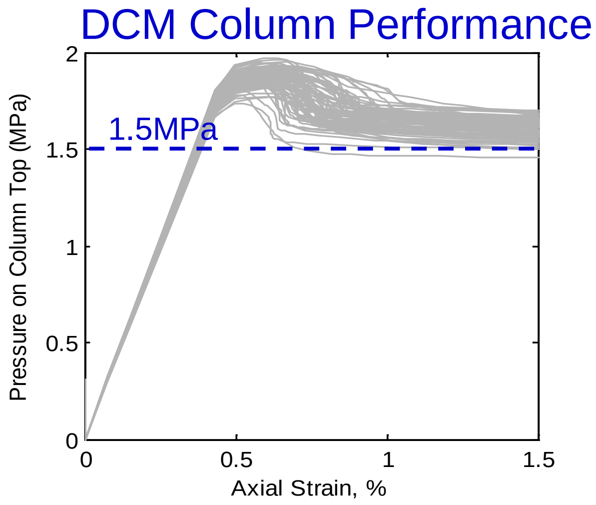
DCM Non-homogenous

APPROACH 2: RANDOM FINITE ELEMENT ANALYSIS

- Unconfined compression behaviour of a 2-m diameter by 20-m high DCM under axial loading.



CoV of core sample = **0.4**, UCS=1MPa
Core sample confidence level = 90%

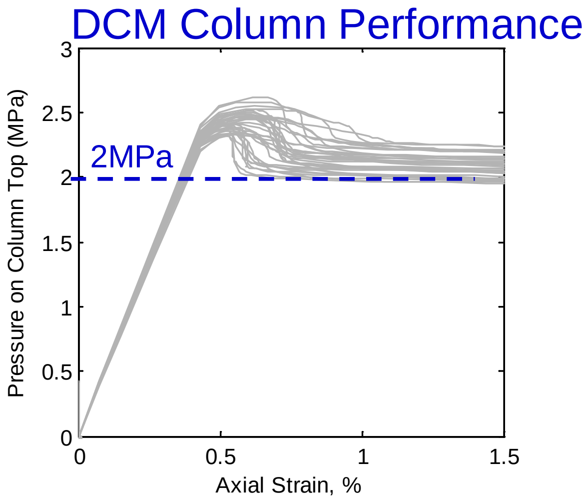


q_{column} > UCS of core samples

$q_{column}/q_{mean\ core\ samples}$

= 1.5/2.07 = 0.72

CoV of core sample = **0.5**, UCS=1MPa
Core sample confidence level = 90%



q_{column} > UCS of core samples

$q_{column}/q_{mean\ core\ samples}$

= 2/2.82 = 0.71

DCM Non-homogenous

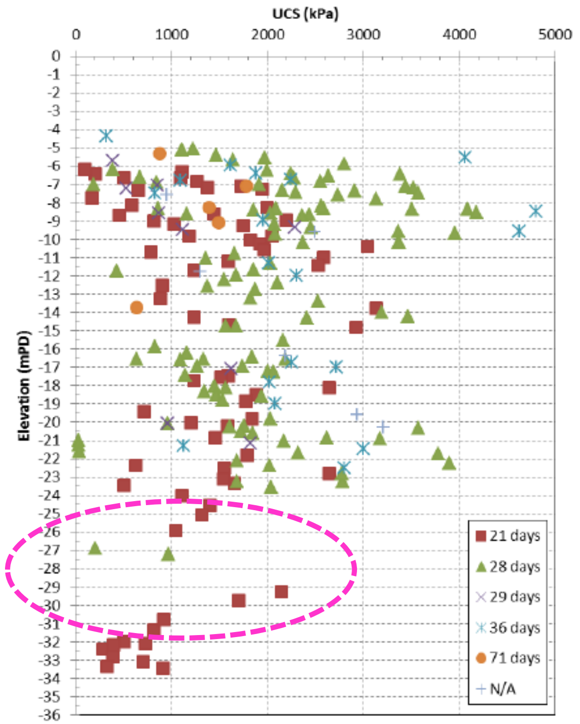
DURING CONSTRUCTION STAGE

Acceptance criteria of the field product

- As part of the QA/QC procedure, the cement mixed soil will need to be investigated and tested to ensure that the continuity, uniformity and strength of the treated soil meet the design requirements.
- Generally, full depth coring using soil investigation borehole and unconfined compression test on the core samples are conducted.
- The number of coring and test sample should depend on the size and/or complexity of the project.
- In general, the acceptance criteria are based on TCS and a specified confidence level of the tested sample results. Anything missing?

DCM Non-homogenous

ACCEPTANCE CRITERIA OF THE FIELD PRODUCT



No UCS tests have been taken

- A specified logging terminology for cement treated soil should be established and it can serve as the primary assessment of the improvement status of the full-depth treated column.

DCM Non-homogenous

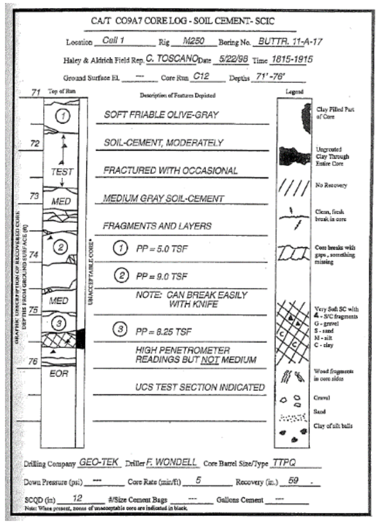
ACCEPTANCE CRITERIA OF THE FIELD PRODUCT

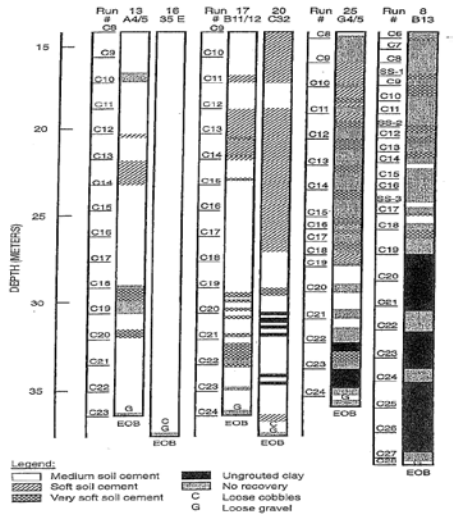
Case Study: Boston’s CA/T Project (James R.L and Scott N., 2003)

- The cement-treated soil was classified using 3 categories. Field identification by the inspector using the scratch-test was the principle means of delineating core strength categories.
- In core log, both written and sketched visual descriptions of the core was included.
- A standardized legend was created for a summary visual presentation.

Table 1: Cement treated soil field classification system used in Boston's CA/T Project

Class	Field test strength
Medium	Can only be scratched with a knife, to maximum 1.5mm depth. Penetrometer readings in this material are greater than 1350kPa.
Soft	Can be relatively easily scratched with a knife to a depth of 3mm to 6mm. The core samples can be imprinted under thumb pressure applied to the cored surface. At the lower end of the “soft” strength range, pocket penetrometer readings were on the order of 450kPa to 700kPa and brittle failure with some spalling was still commonly observed.
Very Soft	Can be easily craved with a knife, and the knife could be readily penetrated through the core. Penetrometer readings in this material were commonly in the range of 25kPa to 400kPa.





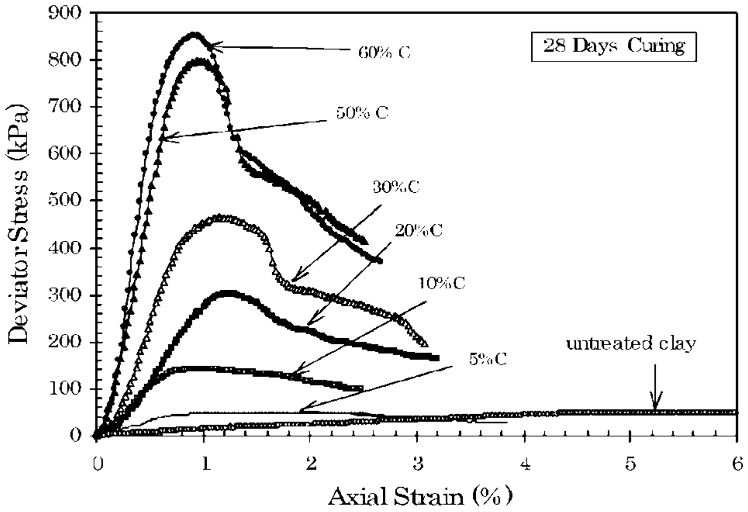
Key Characteristics of DCM

BRITTLENESS

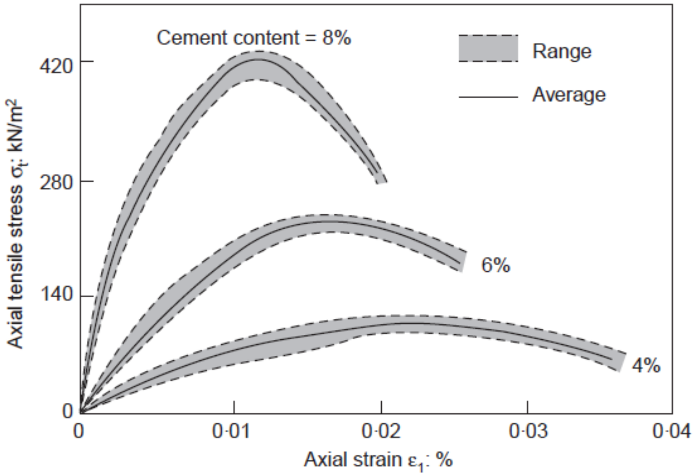
A material is brittle if, when subjected to stress, it breaks without significant plastic deformation. Brittle materials absorb relatively little energy prior to fracture, even those of high strength.

more cement more brittle

UCT Stress-Strain



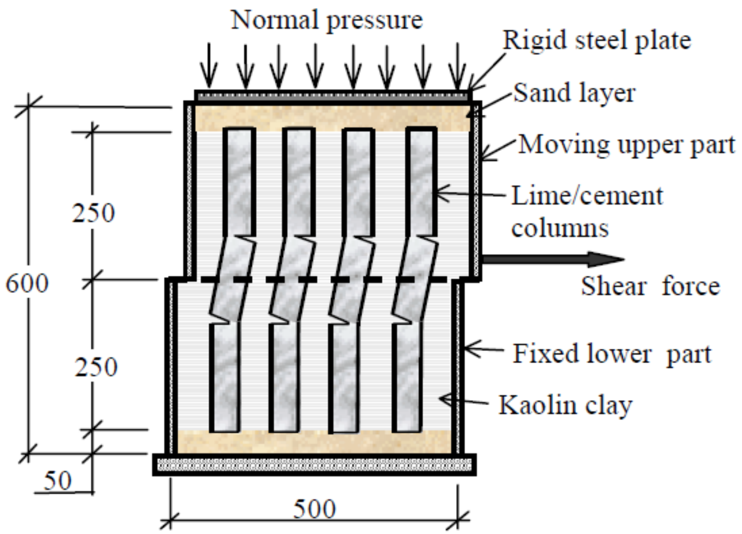
Direct Tension Test Stress-Strain



Key Characteristics of DCM

BRITTLENESS

- Study showed that the ave. fracture energy for the shear failure is 15 times higher than the tensile failure – columns fail easier in tension than shear mode.
- Larsson (1999) found that for a shear box test, the individual lime-cement columns failed in bending mode and not in shear mode.
- The DCM bending capacity is about 0.15*qu



Key Characteristics of DCM

BRITTLENESS

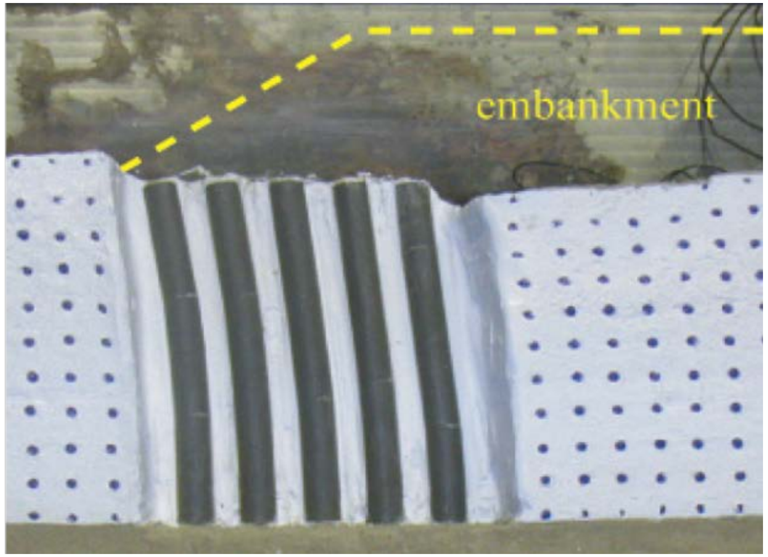
When and how to consider DCM brittleness?

When?

- When DCM columns subjected to lateral loading

How?

- Avoid the potential bending mode
- Use the appropriate analysis tool to design



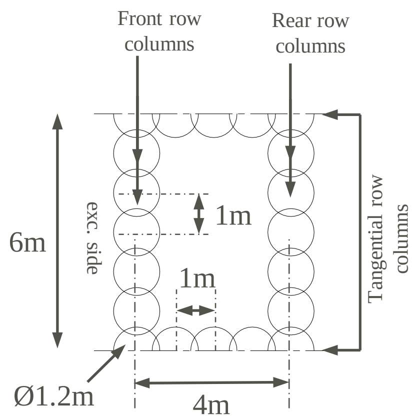
Bending failure mode in centrifuge test by Kitazume

DCM Brittleness

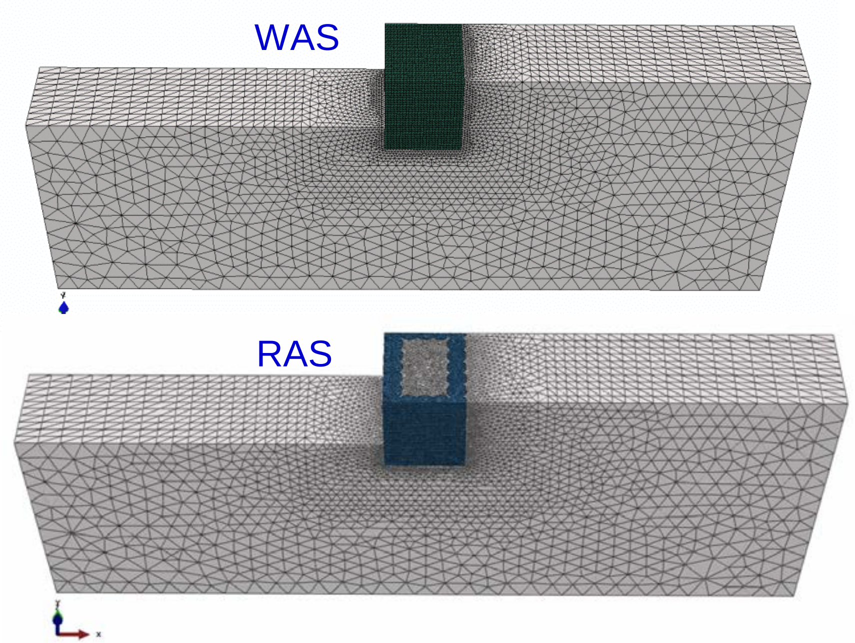
COMMON NUMERICAL SIMULATION OF CEMENT-TREATED SOIL

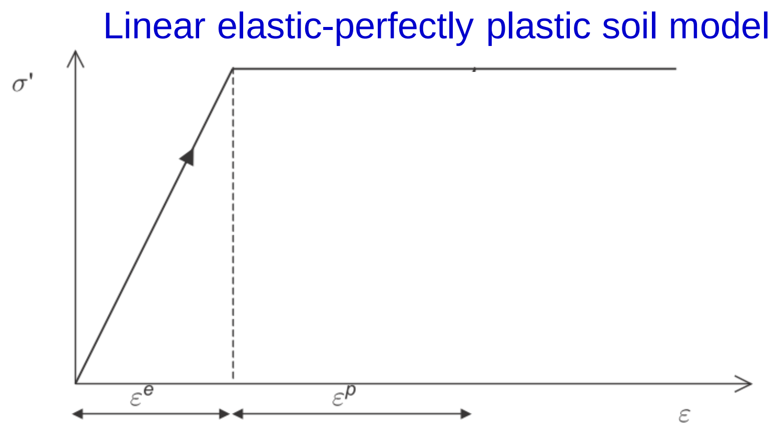
1) Weight average simulation (WAS) approach in 2D analysis or real allocation simulation (RAS) approach in 3D analysis.

2) Linear elastic-perfectly plastic, Mohr Coulomb model is used to simulate the cement-treated soil behaviour due to its simplicity & fewer parameters needed.



Grid Pattern Improvement Plan View

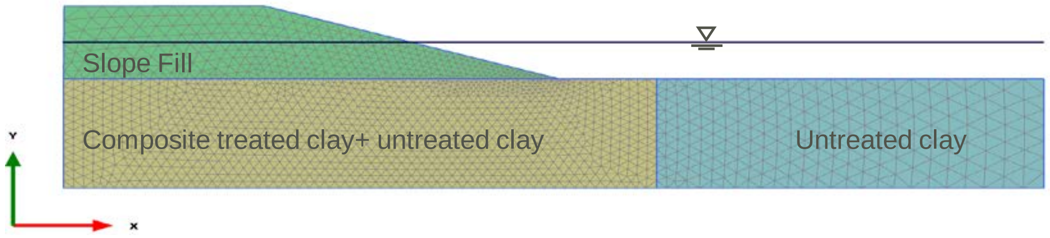




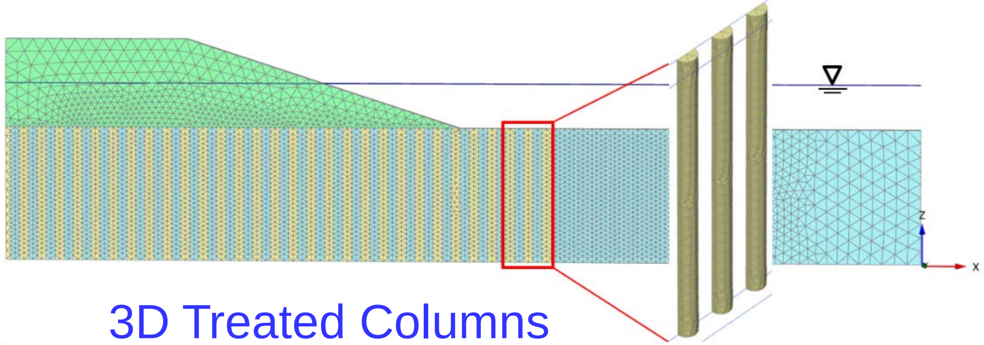
DCM Brittleness

COMMON NUMERICAL SIMULATION OF CEMENT-TREATED SOIL

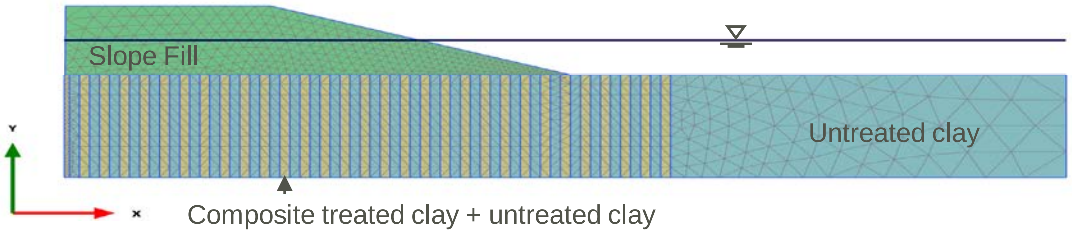
- Analysed using Plaxis 2D and Plaxis 3D
- Modelled with Mohr Coulomb with tension cut-off = 0kPa
- FoS obtained using Phi/C reduction approach in Plaxis



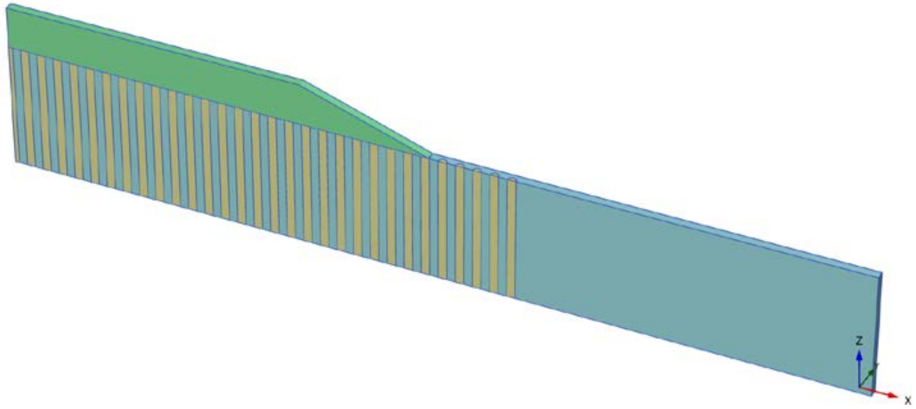
2D Plane Strain: Composite Block



3D Treated Columns

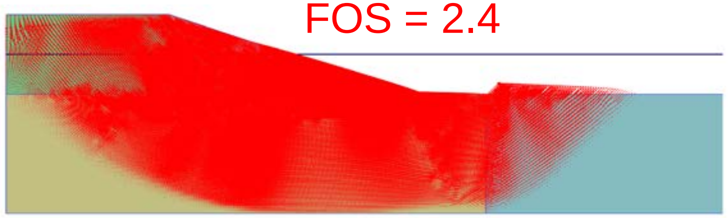


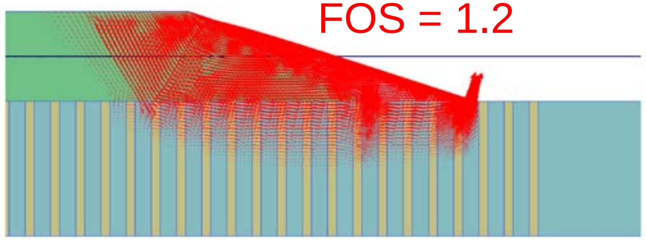
2D Plane Strain: Composite Strip Walls

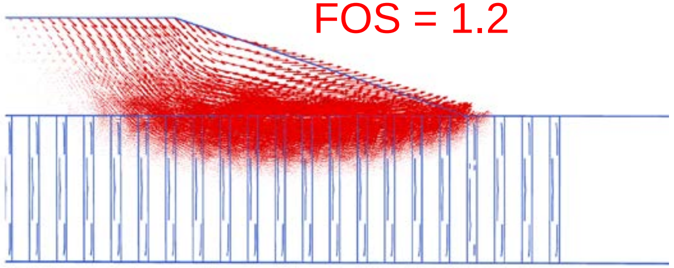


DCM Brittleness

COMMON NUMERICAL SIMULATION OF CEMENT-TREATED SOIL







ϕ' and Cu, C'

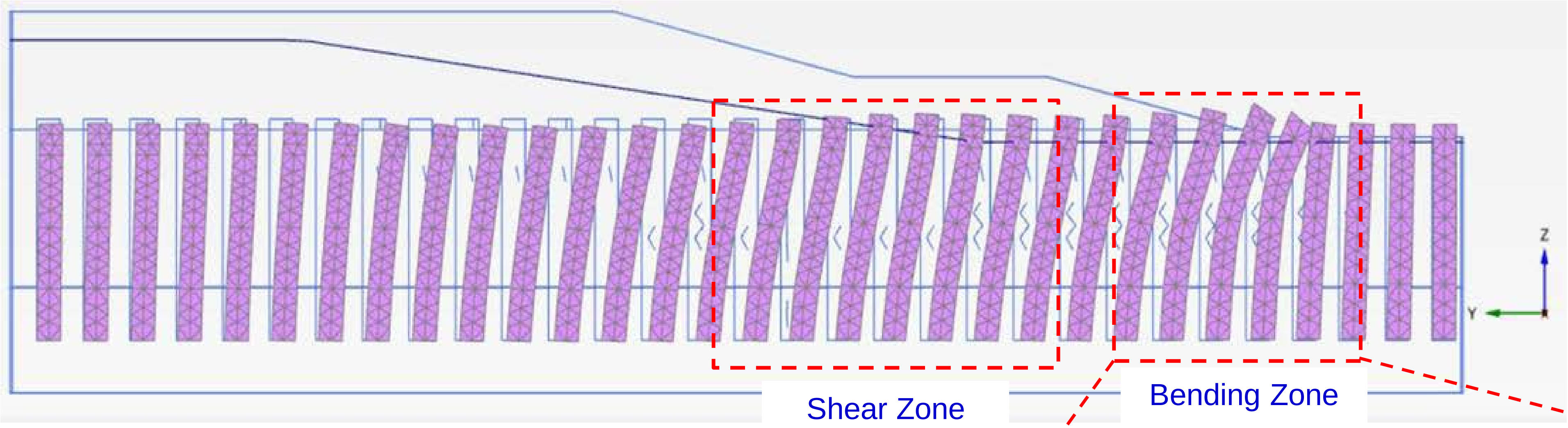
FoS = Available Strength / Strength at Failure = ΣMsf

Is this FoS reliable? What about internal stability?

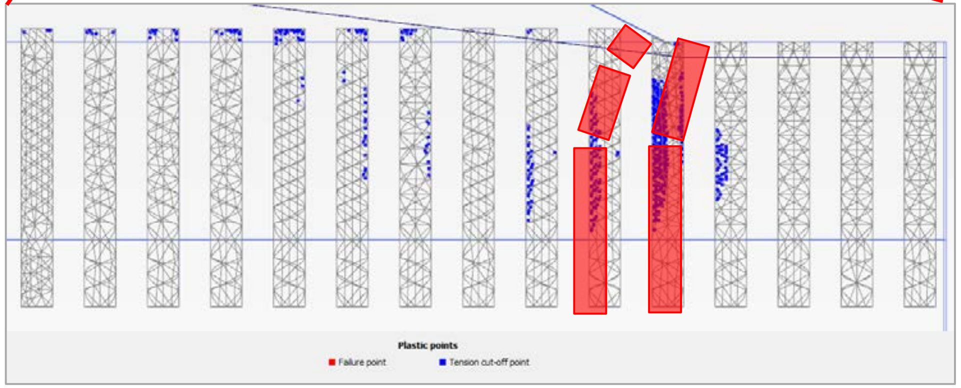
Brittleness and tensile behaviours of the treated columns are not considered!

DCM Brittleness

COMMON NUMERICAL SIMULATION OF CEMENT-TREATED SOIL



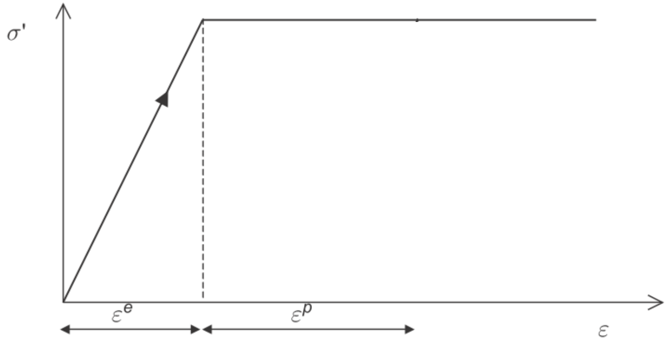
- MC with tension cut-off cannot capture the tension softening behaviour.
- Design to satisfy serviceability limit state (SLS) criterion, i.e. limit strain and tension point failure

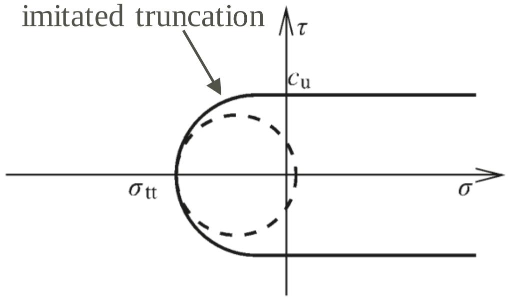


DCM Brittleness

CONSTITUTIVE SOIL MODEL

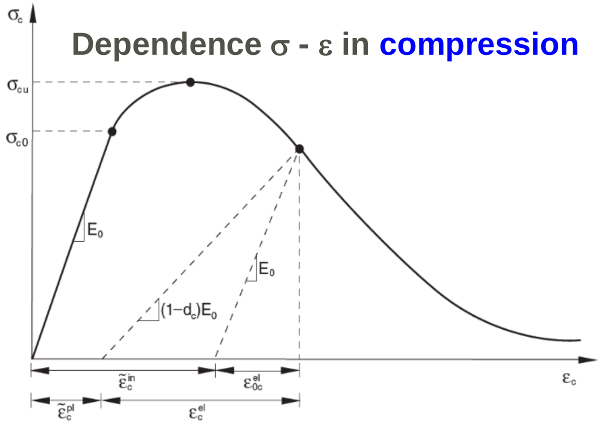
i. Linear elastic-perfectly plastic, Mohr Coulomb

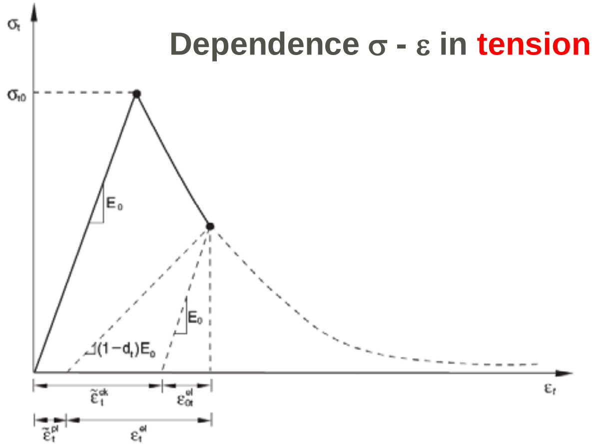




Tension truncated Tresca

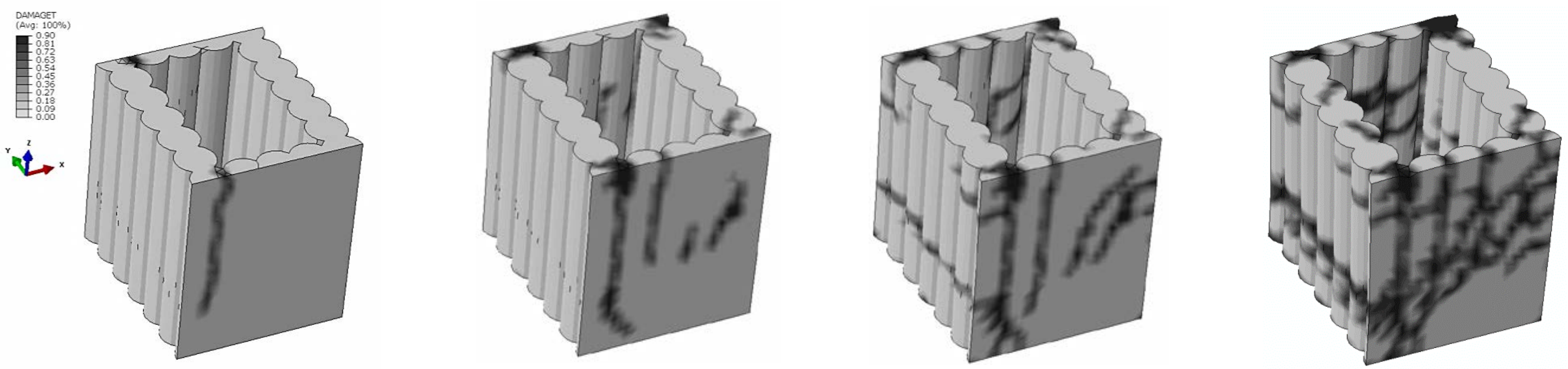
ii. Concrete Damage Plasticity (CDP)

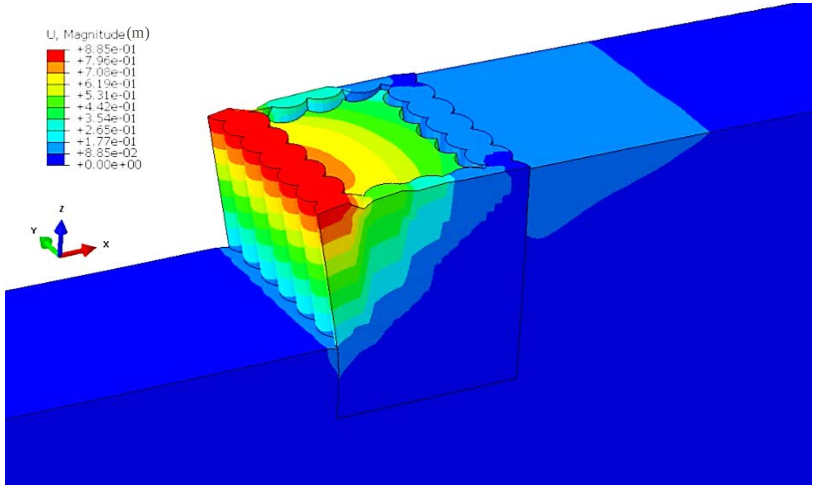




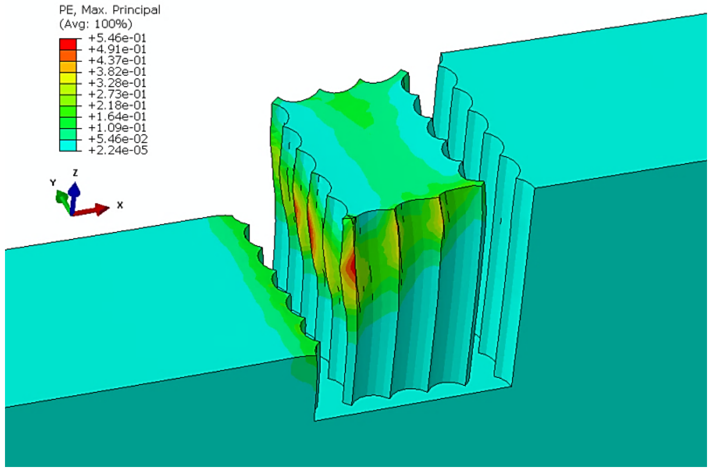
DCM Brittleness

PROGRESSIVE TENSILE CRACK DEVELOPMENT IN TREATED SOIL COLUMNS





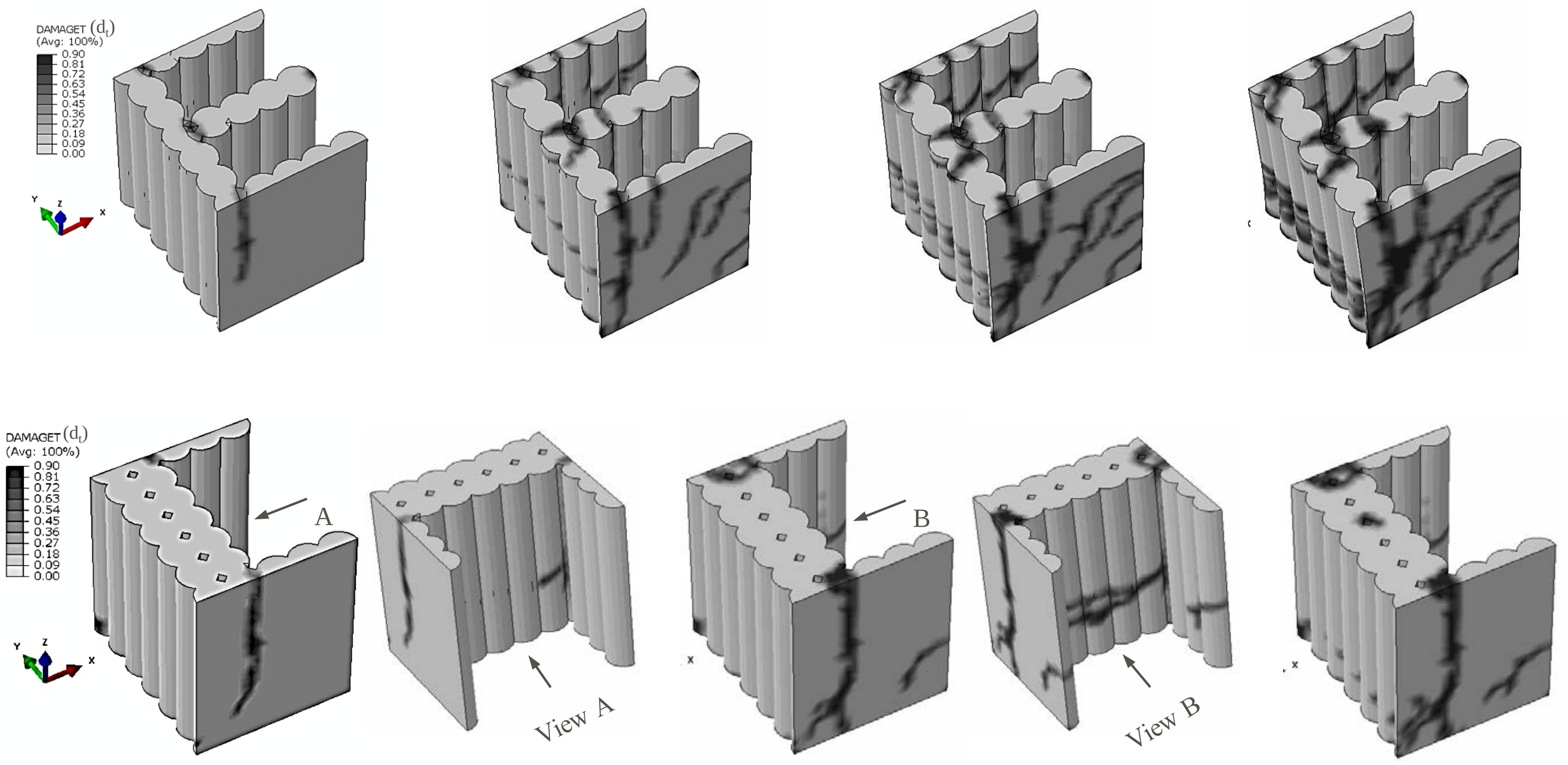
Ground Response



Plastic strain developed in soil

DCM Brittleness

PROGRESSIVE TENSILE CRACK DEVELOPMENT IN TREATED SOIL COLUMNS



Summary

- It is essential to acknowledge that high variability exists in cemented soil. This factor should be taken care of during design stage and field acceptance criteria.
- A specified logging terminology for cement treated soil should be established.
- DCM is brittle and breaks without significant plastic deformation when subjected to tensile stress.
- FoS predicted by the phi/c reduction in Plaxis for individual cemented soil columns must be considered carefully as it does not consider the internal stability.
- Tension capacity simulated by MC in Plaxis assumes the material to ultimately sustain at ultimate tensile stresses – unsafe as the tension-softening (crack propagation) is not captured.

Thank You