SPATIAL VARIABILITY IN LIME-CEMENT MIXED CLAY AT MULTIPLE LENGTH SCALES

Vijayshree Sadasivan[1*], Dawn Wong[1], Jonatan Isaksson[1,2], Jelke Dijkstra[1]

Keywords

Lime cement columns, variability, soil stabilisation, scale of fluctuation

ABSTRACT

Lime-cement columns, widely used for soil improvement in Nordic countries, exhibit heterogeneous strength and stiffness. Characterising this variability is crucial to optimise their performance. This paper introduces an integrated approach to characterise strength and stiffness variability across various scales in lime-cement columns in natural sensitive clay at the Centralen project site in Gothenburg, Sweden, using laboratory-based methods and field measurements. The aim is to uncover diverse variability estimates, providing valuable insights into the challenges associated with characterising lime-cement mixed soils.

1. INTRODUCTION

In Sweden, lime-cement columns (LCC) are commonly used to improve the engineering properties of soft soils. However, lime-cement mixed clay in the columns is highly heterogeneous in strength and stiffness. Factors such as type of binder [1], non-uniform mixing of lime and cement [2,3], variations in soil composition and moisture content [4], and heterogeneous distribution of in-situ stresses [5,6] contribute to the complex spatial variability observed in these stabilised soil systems.

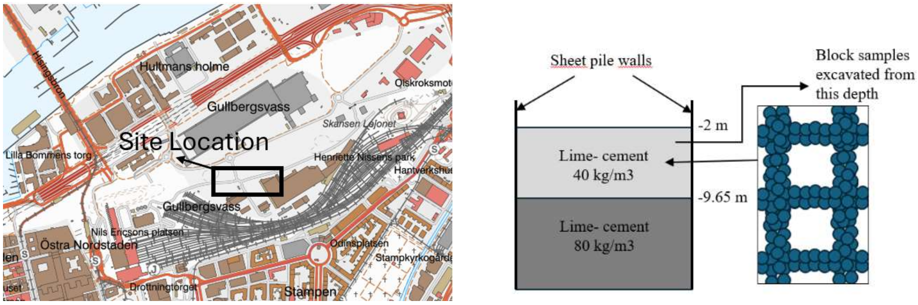
[1] Department of Architecture and Civil engineering, Chalmers University of Technology, SE 41296 Gothenburg, Sweden (*corresponding author, email: vijsad@chalmers.se)

[2] NCC Infrastructure, NCC Sverige AB, Drakegatan 10, SE 412 50 Gothenburg, Sweden

This paper outlines an integrated method for analysing spatial variability in both field and laboratory scale, using field mixed samples and quality control data from a Gothenburg excavation site. The results provide valuable insight into the spatial variability of lime-cement mixed clay at different scales, and highlight the challenges involved in characterising this variability.

2. TEST SITE

The data presented in this study was obtained from an excavation site (E02 Centralen, West Link railway project) located in Gothenburg (Figure 1a). The site was a 200m excavation supported by sheet pile walls of length 22m, struts and lime cement columns [7,8].



a) *b)*

Figure 1; a) Location of the site b) Cross-section of the excavation.

3. METHODOLOGY

Laboratory study

Block samples of the lime-cement columns were obtained from the excavated material (Low binder content of 40kg/m^3, Figure 1b). The curing period of the samples was approximately 1 year at the time of testing. Two types of testing were conducted: Unconfined compressive strength (UCS) test with local strain measurements, and UCS tests with coupled Digital Image Correlation (DIC) measurements.

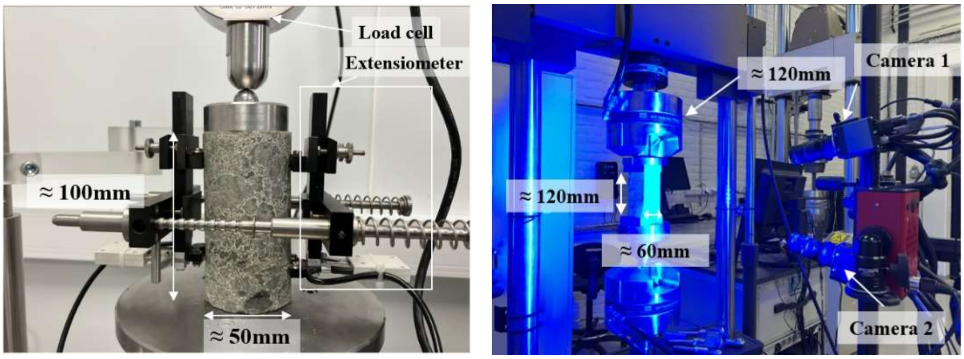
UCS tests

The UCS tests utilised a GDS loading system equipped with a 10kN load cell to monitor the axial load on cylindrical samples (Figure 2a). Tests were performed on six samples (with loading rates of 0.01%/min and 0.1%/min). Four samples were instrumented with a pair of extensometers with a precision of 1µm to measure the local strains at the midsection of the specimen.

UCS with DIC analysis

DIC analysis was performed using a GOM DIC stereoscopic setup with two cameras on samples (Figure 2b). The test setup consisted of an MTS series 300 loading frame with a loading capacity of 100 kN. The cameras with a resolution of 3000 x 4000 pixels captured images at 6 frames per second at one side of the cubic sample. These images were processed using GOM Correlate software for subsequent analysis.

Strain distribution was determined from these images using SPAM Python package's DIC scripts [9]. Computed strains were utilised to derive local stiffness across the sample's height. Symmetry was assumed for calculating the average stress at a specific height in the sample from the axial load. The approach used to derive the scale of fluctuation of the stiffnesses along the height of the samples is outlined in detail by Wong et al. [8].



a) *b)*

Figure 2: Setup of a) UCS test with local strain measurements b) UCS test with DIC measurements.

Field study

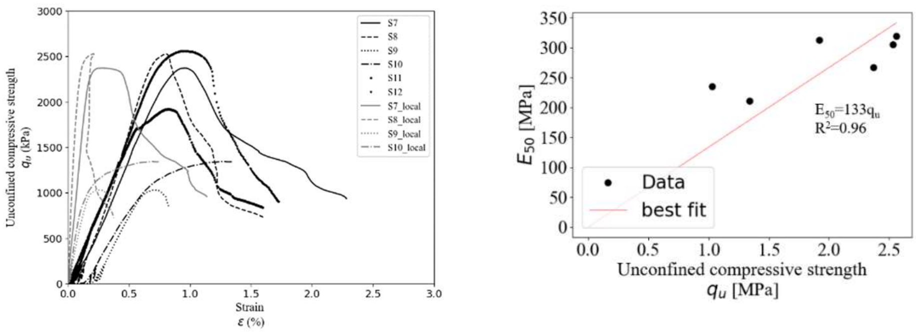
Results from predrilled column penetration tests (FKPS) and reverse column penetration tests (FOPS) conducted 1 to 5 days after construction were utilised to evaluate spatial variability in lime-cement columns at the field scale. Following [8], FKPS data points within the range of 2 to 8 m depth were selected to determine the SOF as the FKPS test is most reliable near the surface. Conversely, FOPS, being a bottom-up technique, offered a reliable dataset within the depth range of 10 to 18 m.

4. RESULTS AND DISCUSSION

In the following section only selected findings are presented, for complete set of results refer to [8].

Unconfined compressive strength

The variation of unconfined compressive strength q_u with axial strain ε and average local axial strain (ε_{local}) is depicted in Figure 3a. The q_u ranged from 1.03 to 2.56 MPa (mean value = 1.96 MPa, standard deviation = 0.65 MPa). The variability in q_u values at failure is attributed to inherent variability in the field-mixed samples. Young's modulus E for the tested samples ranged from 199 to 398 MPa (mean value = 286.20 MPa, standard deviation = 67.95 MPa). E_{local} ranged from 589 MPa to 3122 MPa (mean value = 1640 MPa, standard deviation = 921 MPa), averaged approximately 6 times E, indicating its greater representation of small-strain material stiffness. This observation is supported by subsequent DIC measurements of local stiffness values. A E_{50}/q_u ratio of 133 was determined which is in good agreement with the literature of cemented clays [10,11] as seen in Figure 3b.



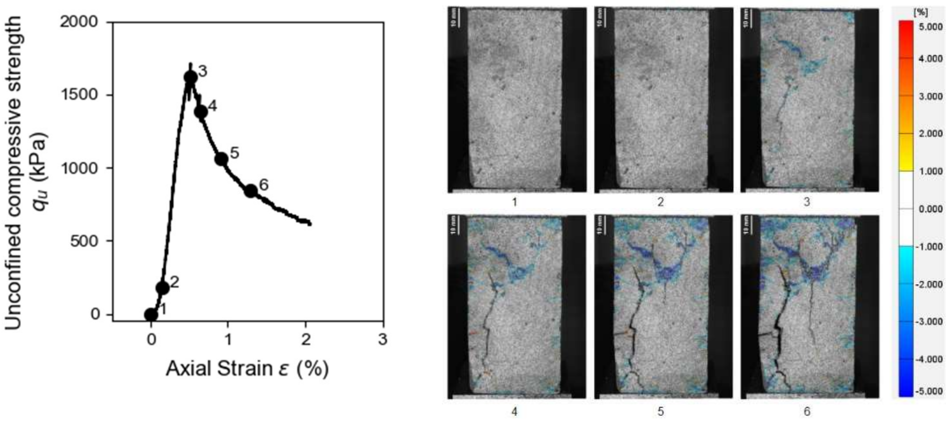
(a) *(b)*

Figure 3: a) q_u vs ε and b) E50 vs q_u from UCS tests.

Uniaxial compression tests with DIC

The stiffness values obtained from the measured axial load and external Linear Variable Differential Transformer (LVDT) measurements for the two cubic samples tested was 229 MPa and 319 MPa. The globally measured stiffness does not provide information on the variability within the specimens. Visual examination reveals distinct areas of cemented and uncemented material, prompting further investigation with simultaneous surface DIC.

Figure 4a shows the strain distributions on the front surface of sample S14 obtained from DIC corresponding the linear region of loading curve (Figure 4b). A noticeable non-uniform distribution of strains with localisation on areas of uncemented clay is observed. The variation in local stiffness across the height of the samples S13 and S14, estimated from DIC strain measurements, is shown in Figure 5. The stiffnesses obtained from this analysis was in the similar range to those obtained from local transducers (Figure 3a). The mean stiffness was 1028 MPa and the standard deviation was 792 MPa. Following the approach outlined in [8, the vertical scale of fluctuation (SOF_y) for the two samples are summarised in Table 1.



a) b)

Figure 4: a) q_u vs ε for S14 b) Vertical strain field for S14.

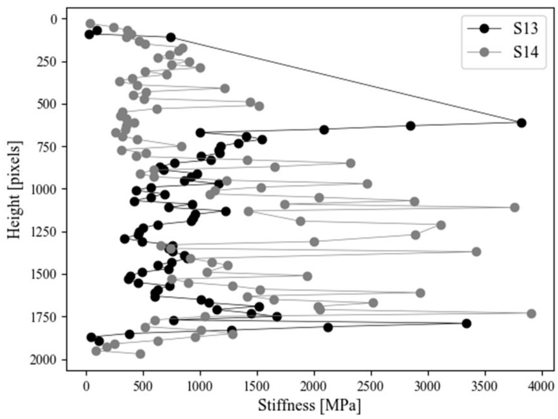


Figure 5: Stiffness distribution along the height of the sample determined using DIC.

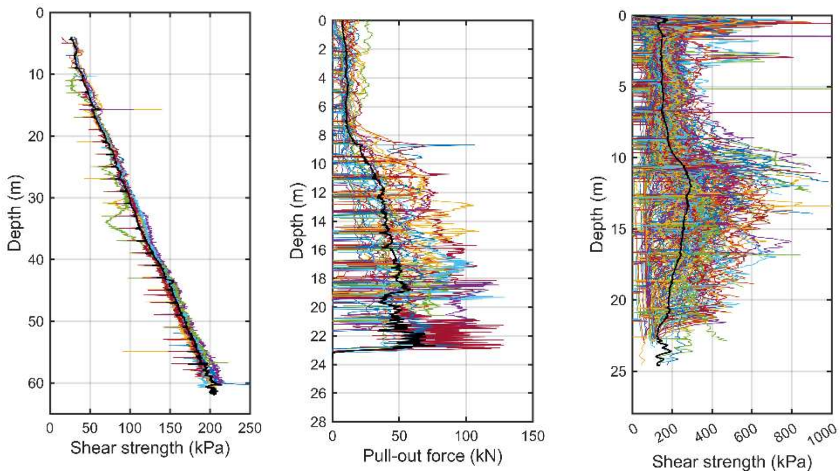
Field scale

Natural clay

Figure 6a shows the variation in shear strength with depth of the original clay deposit (as derived from nine sets of cone penetration test (CPT) data prior to construction).

Lime cement column

Figure 6b shows the variation of shear strength with depth obtained from FKPS (202 data sets). Figure 6c shows the corresponding plot for pull-out force obtained from FOPS (29 data sets). The mean of both data sets is shown by the solid black line. The vertical scale of fluctuation for the natural clay and the lime-cement columns, estimated following the procedure outlined in [7] using the data shown in Figure 6, is summarised in Table 1.



a) *b)* *c)*

Figure 6: a) CPT data from the in-situ clay deposit b) FOPS data tests from LCC (c) FKPS data from LCC.

Table 1. Summary of SOF_y from different test methods for LCC and the in-situ clay

Test type	**Material**	**SOF_y**
Laboratory DIC	LCC (S13)	5.4 mm
	LCC (S14)	13.0 mm
FKPS	LCC	0.4 m to 3.5 m, 1.4 m (average)
FOPS	LCC	0.3 m to 2.0 m, 0.9 m (average)
CPT	in-situ clay deposit	2.7 m to 6.3 m, 4.1 m (average)

5. CONCLUSION

In this paper, various techniques are proposed to characterise the spatial variability of lime-cement mixed clay at the laboratory scale and at the field scale. The key finding is that different magnitudes of SOF exist for lime-cement mixed clay at the laboratory scale and at the field scale, this provides a more nuanced picture on the inherent variability of lime cement columns.

A key challenge is understanding the relationship between the SOF measured at different length scales. However, bridging the results from these tests can be challenging due to differences in timing and conditions. Field tests on lime-cement columns are typically conducted shortly after construction, while laboratory tests involve excavating samples after a 1-year curing period. Nevertheless, the results shed light on the extent of inherent spatial variability in LCC and highlights the challenges in accurately characterising this variability.

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