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Distributed fibre optic sensing of stabilised soil

Détection distribuée par fibre optique d'un sol stabilisé

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ABSTRACT: A frequently adopted method to improve engineering properties of soft soils is the dry deep mixing method, where dry binders like lime and cement are mixed with the soil using a rotating mixing tool. To date, the properties of improved soil are predominantly measured using destructive methods and based on locally constrained methods. Latest sensing technologies such as distributed fibre optic sensing (DFOS) are promising tools to map temporal and spatial changes of geotechnical structures. However, the use of DFOS for stabilised soil has received scant attention. There is a lack of detailed investigations on monitoring curing temperature and detecting weakness zones in stabilised soil using distributed temperature sensing (DTS) and on the strain transfer mechanism between a fibre optical cable and the stabilised soil. This paper experimentally examines DFOS to quantify the integrity and the stress-strain relation of stabilised soil. Samples with layers of stabilised and remoulded clay were instrumented with a loose tube fibre optical cable to monitor changes in the curing temperature. The results indicate that untreated soil layers with a thickness of a few centimetres can effectively be identified when installing a fibre optical cable during the first hours after soil improvement. To address the strain transfer mechanism, composite fibre optical strain cables were directly embedded into stabilised soil samples and tested in unconfined compression tests. The obtained data show that the stiffness differences between the stabilised soil and the fibre optical cable resulted in a complicated strain transfer, which requires further investigation. The findings from this research suggest that DFOS can provide a means of evaluating the engineering performance and safety of stabilised soil.

RÉSUMÉ: Une méthode fréquemment adoptée pour améliorer les propriétés techniques des sols mous est la méthode du mélange sec en profondeur, où des liants secs comme la chaux et le ciment sont mélangés au sol à l'aide d'un outil de mélange rotatif. À ce jour, les propriétés des sols améliorés sont principalement mesurées à l'aide de méthodes destructives et basées sur des méthodes localement contraignantes. Les dernières technologies de détection, telles que la détection par fibre optique distribuée (DFOS), sont des outils prometteurs pour cartographier les changements temporels et spatiaux des structures géotechniques. Cependant, l'utilisation de la DFOS pour les sols stabilisés n'a reçu que peu d'attention. On manque d'études détaillées sur la surveillance de la température de durcissement et la détection des zones de faiblesse dans les sols stabilisés à l'aide de la détection de température distribuée (DTS) et sur le mécanisme de transfert de contrainte entre un câble à fibre optique et le sol stabilisé. Cet article examine expérimentalement la DTS pour quantifier l'intégrité et la relation contrainte-déformation du sol stabilisé. Des échantillons avec des couches d'argile stabilisée et remoulée ont été instrumentés avec un câble à fibre optique à tube lâche pour surveiller les changements de la température de durcissement. Les résultats indiquent que les couches de sol non traitées d'une épaisseur de quelques centimètres peuvent être efficacement identifiées lors de l'installation d'un câble à fibre optique au cours des premières heures suivant l'amélioration du sol. Pour étudier le mécanisme de transfert de contrainte, des câbles composites à fibres optiques ont été directement intégrés dans des échantillons de sol stabilisé et soumis à des essais de compression non confinée. Les données obtenues montrent que les différences de rigidité entre le sol stabilisé et le câble à fibres optiques ont entraîné un transfert de contrainte compliqué, qui nécessite une étude plus approfondie. Les résultats de cette recherche suggèrent que le DFOS peut fournir un moyen d'évaluer la performance technique et la sécurité des sols stabilisés.

Keywords: Distributed fibre optic sensing; ground improvement; deep dry mixing; observational method.

1 INTRODUCTION

The dry deep mixing (DDM) method has been widely employed in countries including Finland, Japan, Norway and Sweden. Traditionally, dry binders such as lime and cement have been mixed with soft soil to obtain stabilised soil columns with improved strength and deformability properties.

Current design procedures weigh the area of the improved and unimproved soil to obtain average strength estimates for the total soil volume (Norsk Geoteknisk Forening, 2012) and to evaluate settlements during loading (e.g., Broms, 1991; Alen et al., 2005; Baker, 2000). In this approach, the spatial variability of both the stabilised and virgin soil is neglected. Likewise, any interaction between the DDM columns and the surrounding clay is ignored. These limitations introduce considerable uncertainties in the design of DDM and often result in conservative estimates.

Field testing and full-scale trials have frequently been employed to improve adopted design solutions. However, traditional field-testing techniques such as sampling of the stabilised soil columns and penetration tests are destructive and often provide only locally constrained data at a specific time after the soil mixing. Reliable data about potential weakness zones in the stabilised soil is often lacking. Monitoring of full-scale field trials typically results in cumulative settlements or settlement data at specific depths. Spatially distributed data about the stress-strain response of stabilised soil remains missing.

A potential technique to obtain high resolution data about the field performance of DDM improved soil is distributed fibre optic sensing (DFOS). Recent research showed the successful application of DFOS in geotechnical engineering (Soga and Luo, 2018). For example, distributed temperature sensing (DTS) was used to quantify the integrity of a cast-in-place concrete pile (Rui et al., 2017). Another study showed that distributed strain sensing (DSS) can provide the full strain profiles of bored concrete piles (Pelecanos et al., 2018). So far, the application of DFOS to DDM has however received scant attention.

The hypothesis of this research is that DFOS can unlock the real performance of DDM improved soil. The specific research objectives were to experimentally investigate if DTS can detect weakness zones in stabilised soil, and if DSS can quantify the stress-strain response of stabilised soil.

2 METHODOLOGY

Two types of laboratory tests were carried out: so-called temperature and strain tests. For each test type, the used soil was a very sensitive clay from Tiller-Flotten, Norway. L'Heureux et al. (2019) provided a detailed description of this clay. The following sections discuss both test types in more detail.

2.1 Temperature tests

The DTS cable was a single-mode optical fibre (PureBandTM-PLUS from SUMITOMO ELECTRIC) within a hydraulic oil (Shell Tellus S3 M 46) filled plastic tube with an internal and external diameter of 2 and 3 mm. The cable was placed at the centre of an isolation box (Figure 1a), which replicated semi-adiabatic conditions (Bache et al., 2022). Two specimens with a diameter of 100 mm and a height of 200 mm with equal parts of stabilised and remoulded clay were prepared.

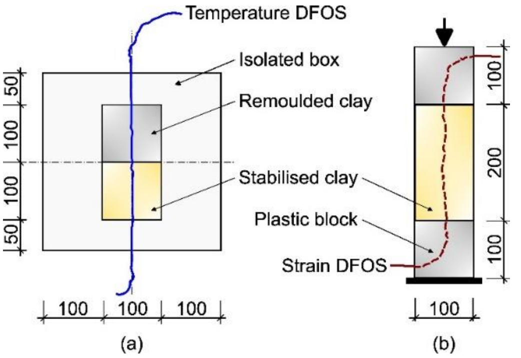

Figure 1. Experimental setups: (a) vertical cross-section of the temperature tests and (b) view of the strain tests. Dimensions in mm.

First, the Tiller-Flotten clay was manually remoulded. Then 50 kg/m^3 of dry burnt lime was added to half of the remoulded clay and mixed. The lime-clay mixture was then added to the isolation box and moulded using a tamping rod. This work was carried out with caution to avoid damage of the DTS cable while minimising the air content of the stabilised clay. The remoulded clay was then poured into the top half of the specimen to replicate a weakness zone in the stabilised soil.

An OBR4600 fibre optic interrogator from Luna Innovations and a spatial resolution of 1 cm was used. A reference measurement was carried out immediately after the sample preparation was finalised. Subsequently, measurements were taken about every 5 minutes until almost 40 hours.

2.2 Strain tests

Three stabilised soil specimens with a diameter of 100 mm and a height of 200 mm were prepared. Similar to the temperature tests, the Tiller-Flotten clay was first remoulded and then mixed with 50 kg/m^3 of dry burnt lime and 50 kg/m^3 of ordinary Portland cement (CEM I 52.5 R). Then, the lime-cement-clay mixture was moulded in a plastic cylinder, in which an EpsilonSensor composite fibre optical core (Nerve-Sensors, 2023) was centrally placed. The EpsilonSensor had a diameter of 3 mm, an elastic modulus of 3 GPa and a strain measurement range of ±4%. The specimens were then wrapped in plastic and cured at room temperature (around 21°C).

After 19 to 27 days the specimens were tested in unconfined compression (UC) tests. Figure 1b shows the experimental setup including purpose-built slotted, rigid plastic blocks to guide the cable from the stabilised soil specimen. This setup ensured that the uniaxial load was only applied to the stabilised soil and not to the fibre optical cable. The UC tests were carried out with displacement rates between 0.2 to 0.4 mm/min and displacement increments between 0.1 to 0.4 mm. Fibre optic strain measurements were obtained before the loading started and after every displacement increment. Again, the OBR4600 with a spatial resolution of 1 cm was used.

3 RESULTS

3.1 Temperature tests

Figure 2 shows the DTS data during the first eight hours of the tests. In the stabilised clay section of the specimens, the measured temperature decreased with the experimental time. This is a result of the reference reading, which was conducted after the peak of the temperature increase had been reached. Consequently, all subsequent readings indicated a temperature reduction compared to the reference reading. By contrast, the temperature transferred to the untreated clay section and caused a temperature increase.

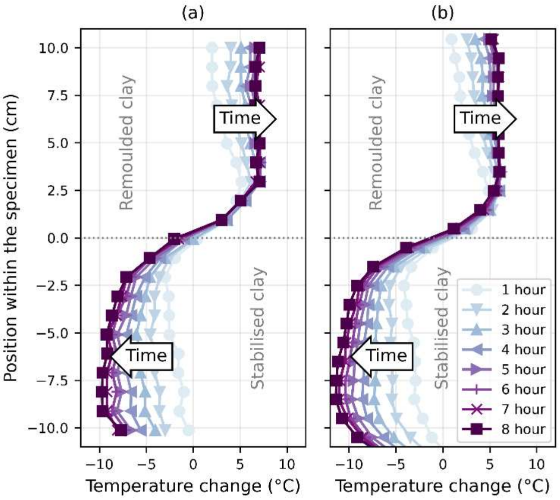

Figure 2. Distributed temperature sensing profiles within the first eight hours of the temperature tests: (a) first specimen and (b) second specimen.

The DTS data exhibited a signature temperature profile at the transition zone between the stabilised and untreated soil, see Figure 2. This suggests that zones with lower binder content in DDM can be detected using DTS. The data further indicate that notable temperature changes were obtained for the first five hours. This suggests that in the field a DTS cable should be installed directly after a DDM column is installed and immediate measurements should be taken.

3.2 Strain results

The three strain tests resulted in UC strength and stiffness values between 524 to 674 kPa and 27 to 54 MPa, respectively. These values agree with typical strength and stiffness values of laboratory improved soils (e.g., Hov and Larsson, 2023).

Figure 3 shows strain profiles obtained for the three different tests. Each strain profile relates to a specific axial strain, $\varepsilon_{UC,}$ applied on the stabilised soil specimen. Interestingly, the strain data show a maximum strain value in the centre region of the specimens which differs from the theoretical axial strain profile of UC tests. The disagreement may be due to stiffness differences between the DSS cable and the stabilised soil affecting the associated strain transfer mechanism. Similar observations about complex strain transfer were reported when embedding DSS cables in both granular (Zhang et al., 2020) and cementitious material (Zhang et al., 2022).

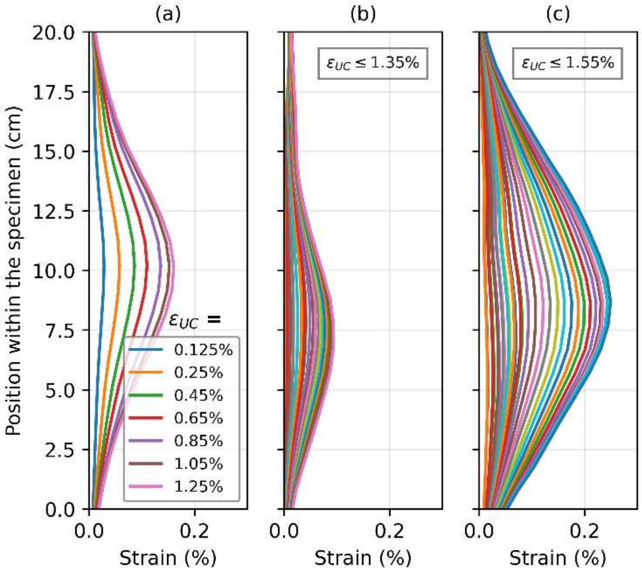

Figure 3. Distributed strain sensing profiles for the three tested specimens before the fibre optical cable noticeably slipped. For test (a), the applied axial strain in the unconfined compression test, ε_{UC}, are indicated. For tests (b) and (c), each strain profile corresponds to ε_{UC} increments of 0.05%.

In addition to the different strain profiles, the magnitude of the strains measured by the DFOS was considerably lower than the applied strain (compare measured strains with applied ε_{UC} in Figure 3). This observation indicates that the entire strain could not be transferred from the stabilised soil to the DSS cable. Again, this inconsistency may be due to the notable stiffness differences between the stabilised clay and the DSS cable and partial slippage. In addition, the length of the DSS cable was most likely too short to transfer the entire applied strain to the DSS cable.

The differences between the three strain tests are likely a result of how well the stabilised soil could be compacted in the vicinity of the DSS cable. Although great care was taken while preparing these specimens, good bond between the DSS and cable and the stabilised soil was difficult to achieve. This is especially true for the top of test (b) as can be seen from Figure 3b.

4 CONCLUSIONS

The objectives of this research were to examine if DTS can reveal anomalies in stabilised soil, and if DSS can quantify the stress-strain response of stabilised soil. This study can draw the following conclusions:

- During the first hours after mixing clay with lime, DTS exhibited a signature temperature profile at the interface between the stabilised and untreated soil. This implies that DTS may locate weakness zones with lower binder content of only a few centimetres in stabilised soil.
- DSS data resulted in notably different strain magnitudes and profiles compared to the axial strains in UC tests. The obtained disagreement could be attributed to stiffness differences between the stabilised clay and the fibre optical cable and the small length of the DSS cable in the stabilised soil specimen causing a complex strain transfer mechanism. This finding indicates that caution must be applied when interpreting the strain data from a DSS cable embedded in stabilised soil.

The obtained results support the hypothesis that DFOS can provide novel insight into the properties and performance of DDM improved soil. However, future studies are required to explore the interface behaviour between DSS cables and stabilised soil to better understand the associated strain transfer. In addition, full-scale tests are needed to study the installation of fibre optical cables in stabilised soil.

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