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MODELLING RANDOM CONSTRUCTION DEVIATION AND SPATIAL VARIABILITY OF LIME-CEMENT TREATED GROUND

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Lime cement columns are widely used to improve unfavorable grounds as they are effective, flexible and versatile. However, this method is usually used with great conservativeness because high uncertainties in both material properties and geometries have significant impact on the global behavior of the treated ground. The material properties vary due to uneven distribution of binder (and therefore local mix ratio). The geometries deviate from the idealized case where the columns are perfectly vertical cylinders due to inevitable inclinations and random variations of diameters. Therefore, a relatively low strength is usually assumed regardless of the average strength. An effective simulation method that quantifies the effect of both uncertainties is highly demanded. The geometric imperfections are tiny as compared to the scale of the whole treated ground, and considering those geometric imperfections in three-dimensional models is very time consuming. In this study, a novel simulation method is proposed to effectively simulate both uncertainties. It saves computation costs and has high potential for further upgrading.

Keywords: spatial variability, geometric imperfection, numerical simulation, random finite element method.

1. Introduction

Cement-based materials are usually used to improve soft soil ground in various parts of the world. They are usually mixed with in-situ soil in the form of deep mixing or jet-grouting, creating arrays of overlapping columns. The improved ground has significantly higher strength and stiffness than in-situ soft soil, and they are used as underground struts in deep excavation, permanent or temporary cut-off walls and foundation for superstructures with massive footprints.

In Nordic countries, dry-mixed lime-cement ribs are usually installed on the passive sideof deep excavation pits to serve as underground horizontal struts. They are pre-installed before excavation by injecting lime-cement binders, and as excavation goes on, the struts begin to transfer load from retaining structures. So far, very low design strength is used worldwide. In Nordic countries, the allowable undrained shear strength is around 150-200 kPa (NGF 2012).Part of the reasons involve great challenges in quality control of improved ground, considering the complexity of both uncertainties and constitutive behaviors.

The uncertainties of improved ground come from two sources, i.e. inherent spatial variability and construction deviation. The former has been extensively studied and widely appreciated. It is due to theuneven distribution of binder and insitu soil properties, creating an uneven distribution of mix proportion (e.g. cement content and water content). The latter means deviations of geometries of improved ground from ideal case (e.g. inclination of column axis and variation in diameters). The existence of such deviation leads to significant defects in the forms of gaps, and may further cause reduction in stiffness, strength and watertightness.

In Nordic countries, quality control is usually done by predrilled column penetration test (FKPS) and reverse column penetration tests (FOPS). Both methods are effective approaches to probe the verticalcontinuity and homogeneity of lime-cement columns. However, for horizontally loadedmembers like lime-cement ribs, the vertical continuity of one single column is not as effective quality indicator, for one single gap in a long ribcould drastically reduce the strength and stiffness. It is, however, not yet developed a horizontal probing method that can quantify the horizontal continuity of lime-cement ribs.

Given the low design values in various codes and standards, practitioners had to provide very conservative designs to minimize risk. This potentially pours more lime and cement into ground than what is needed, and goes against the global goal of reducing carbon emissions, as well as the general public's interest. This is especially true when it comes to massive constructions in public infrastructures.

Is there a hope to quantify those uncertainties? Yes, there is. We can at least bet on numerical modelling to bridge the gap between the uncertainties and the global performance of the defective rib, if we cannot avoid the random occurrence of defects.The aim of this study is to show a framework that can simulate the two uncertainties in the same model. This approach is implemented in Plaxis 3D with coding and can be potentiallyused for optimization of design.

2. Inherent spatial variability and construction deviations of lime cement improved ground

Fig. 1 illustrates the two types of uncertainties of lime cement improved ground.

2.1.Inherent spatial variability

The inherent spatial variability of lime cement improved ground can be described by a random field of unconfined compressive strength (UCS), which is characterized by a marginal distribution and an auto-correlation function.Such UCS is used because it was found to be closely correlated to many other important parameters such as elastic modulus (Lee et al. 2005) and size of yield locus (Pan et al. 2017). The statistical characteristics of lime-cemented soil are summarized in Table 1. The mean value of UCS ranges from 300 kPa to several MPa, depending on the prescribed mix ratio. The COV of UCS varies from 0.3 to 0.6, which is higher than wet mixed cemented soil. The scale of fluctuations (SOF), or alternatively autocorrelation length (not exactly the same in mathematical definition), characterises the texture of spatial distribution of strength. It is loosely defined as a distance within which the correlation is considered significant.Such parameter enables one to consider the effect of correlation and local averaging effect, potentially providing more cutting-edge design. The SOF of Nordic lime-cement soil strength was investigated by hand-operated penetrometer by Larsson et al. (2005). Generally speaking, the SOF is usually smaller than the dimension of a column, making lime-cemented soil a weakly correlated material.

Table 1. Inherent spatial variability of cemented soils in Nordic countries

References	Test (Result)	COV	Scale of fluctuation (m)	
			Vertical	Horizontal
Hedman and Kuokkanen (2003)	Hand-operated penetrometer test (c_u)	-	0.38-1.12	0.07-0.33[‡]
Larsson et al.(2005)[‡]	Hand-operated penetrometer test (c_u)	<0.60	-	Radial:<0.13 Orthogonal:<0.32[‡]
Larsson and Nilsson (2009)	Cone penetration test (Tip resistance)	0.20-0.60	-	1.8-3.6
Wong et al. (2024)	FKPS	-	0.4-3.5 (average 1.4)	0.4-2.0 (average 0.9)
	FOPS	-	0.3-2.0 (average 0.9)	4.0-11.4 (average 9.1)

[‡] SOF within the column cross-section

2.2 Construction deviations

The construction deviationsdepend on the installation method, action standard and workmanship. The construction deviations are usually described by two sets of parameters, i.e. inclination and diameter, Fig. 1. The random inclination is depicted by azimuth and inclination angle. The former is usually a uniformly distributed random variable between (0, 2À), as the column axis has no preference. The latter is usually normally distributed random variable centred at zero. The standard deviation depends on the action standard, provided the workmanship allows.Table 2 summarizes the allowable (maximum) inclination. A 1/100 allowable inclination corresponds to a standard deviation of 0.3 degree (Pan et al. 2018). The diameter variation is usually considered in jet-grouting. This is because the jet pressure may vary over the depth and the in-situ soil properties also vary over depth. It is very likely to get a "bottle neck" at some specific depth when the soil layer is heavily overconsolidated clay, which is both impermeable and stiff.The diametersof deep mixed columns are more in control.

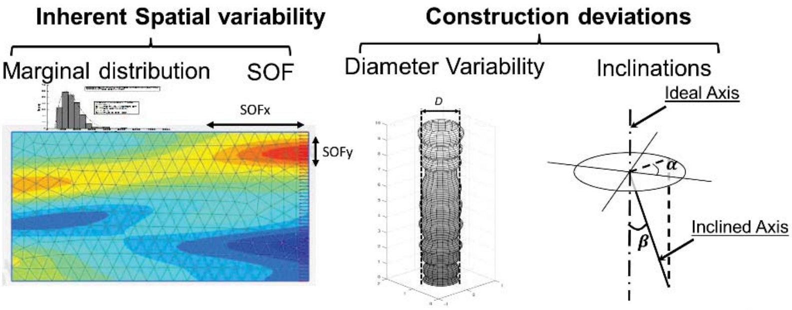


Fig. 1 Uncertainties in lime-cemented ground

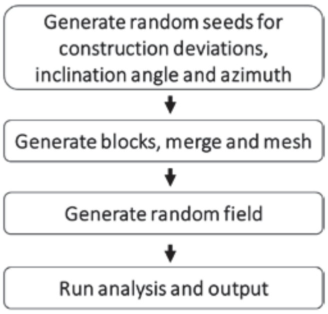


Fig. 2 flowchart of block-level assignment of material

Table 2 Verticality requirements in different standards

Source	Type of technique used	Maximum Deviation from Verticality
NGF (2012)	Deep-mixing	1/100 to 1/50
ASCE Jet Grouting Guideline (2009)	Jet-grouting	1/100
Christopher and Jasperse (1989)	Deep mixing	1/100
Singapore Standard (2003)	Jet-grouting	1/75

3. Simulation in Plaxis 3D

The inherent spatial variability and construction deviation are discussed in 3.1 and 3.2, respectively.

3.1. Inherent spatial variability

Like many existing random finite element method studies, the inherent spatial variability of UCS is simulated using user defined materials. A random field generator algorithm is inserted in an existing user defined material subroutine. In practice, elasto-plastic model with Tresca criterion is usually used to simulate lime-cemented soil because the undrained shear strength is usually constant when effective confining pressure is less than the primary preconsolidation pressure (Xiao et al. 2014). With such method, one can give properties to each integration point, such that a correlation and marginal probabilistic distribution can be replicated.

3.2. Construction deviation

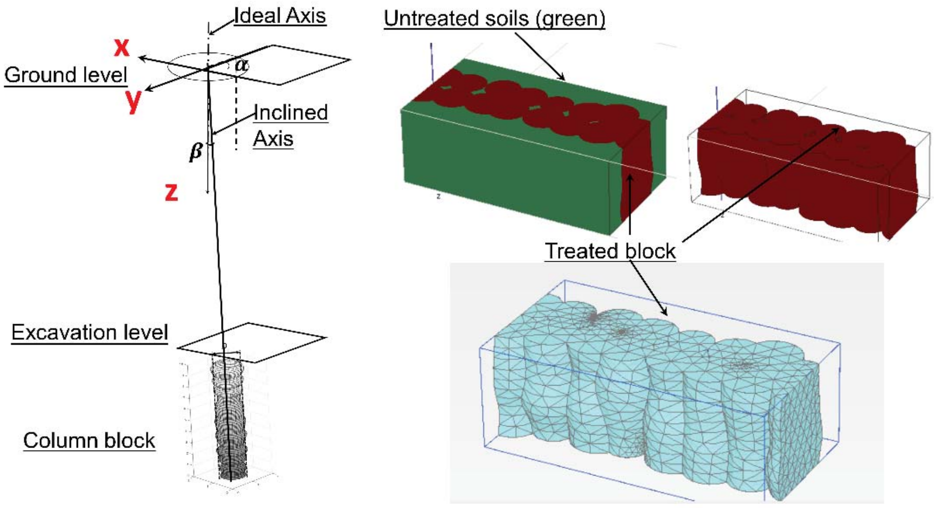
Simulation of inherent spatial variability involves generation of random fields with mature algorithms, such as spectral representation method (Shinozuka and Deodatis 1991). In such simulations, the property varies gradually over space, as prescribed by COV and SOF. Simulation of construction deviation involves more drastic property change over short distance and cannot be readily represented by simple random fields. There are threeapproaches to consider such construction deviations in an FEM program. They can be categorized into three levels, i.e. 1) integration point level, 2) element level and 3) block level.

1) integration point level. This is similar as simulating random field in 3.1, except that one should limit the scope of the columns on top of the random field generator. This method has been used in Liu et al. (2015) and Pan et al. (2019ab). This method is easy to implement in FEM. However, it requires one to use the same constitutive model for both treated and untreated materials. At boundaries of treated and untreated zones, one element could have both treated and untreated integration points.This would smear the difference when constructing element stiffness matrix, which potentially increase the strength of the weak part.

2) element level. One may also choose to simply determine if the geometric centre of one element is within a treated or untreated zone (Liu et al. 2017). This avoid having treated and untreated integration points in one element and it enables the user to assign different material type for treated and untreated materials.However, this requires additional efforts to prescribe material for specific elements when commercial software is used, because material assignments are usually done at block level. It also creates pixeled boundaries between treated and untreated zones.

3) block level. In many commercial FEM software, soil blocks are usually defined before meshing. One can create small blocks and then assign material properties. However, this is usually limited by the maximum allowable number of blocks. An alternative is that one generatesa several blocks and merge them to before meshing, flowchart shown in Fig. 2. This approach has several advantages over other existing methods. 1) it has

smoother boundaries than other approaches. 2) it allows assignment of different constitutive models for treated and untreated zones. 3) it enables a decoupled analysis of inherent spatial variability and construction deviations. 4) it does not require a refined homogeneous structured mesh. Fig. 3 shows the generation of one column (Fig. 3a), multiple columns and mesh (Fig. 3b). Basic assumptions: 1) the maximum inclination is set to be 1/100.2) The top of the columns is 20 m under the ground level.3) The overlaps among adjacent columns are set to be 200 mm, which is consistent with the industrial practice. 4) The diameter is simulated as a random process with a mean value of 1m, coefficient of variation of 0.1, scale of fluctuation of 0.5m, following Pan et al. (2019a). The boundary between treated and untreated zones are clearly delineated using such approach. Clear untreated gaps can be observed in the upper subplot of Fig. 3b.

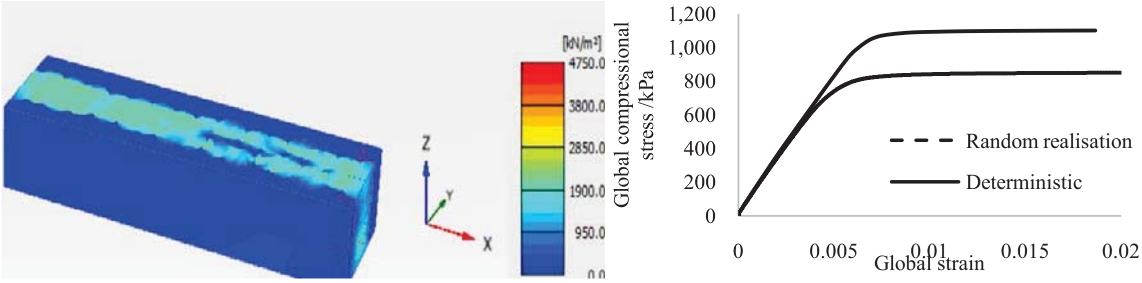


(a) (b)

Fig. 3 One realisation illustration (a) single column block (b) laterally-loaded lime-cement strut with construction deviation (upper subplots: column volumes, lower subplot: meshed columns)

4. Preliminary results

Figure 4a shows the preliminary result of one random realization with assumptions in 3.2. Inherent spatial variability has not yet been implemented. It can be readily done by assigning treated zone with a user-defined material with incorporated random field generator. It should be noted that the aim of this study is to show the possibility of simulating two variabilities in the same model. Given that inherent spatial variability are successfully simulated in many studies and there is still on-going work, implementation of random field is not shown here. The deviator stress contour shows a clear stress concentration around the columns, as the strength (q_u= 1000 kPa) and stiffness are significantly higher than the untreated clay (q_u= 100 kPa).The gaps lead to even higher deviator stress level in the vicinity, as the effective load transfer width is bottle-necked. The global stress strain curves of the strip (Fig. 4b) show significantly lower global strength than deterministic results (without deviation).



(a) (b)

Fig. 4 (a) deviator stress contour of one realization with random construction deviation (b) comparison between deterministic and random results

5. Conclusion and future work

The block-level simulation of construction deviation is proved to be a good approach and was realized using python coding. It does not require unified refined structured mesh and potentially saves computational costs. It can be further coupled with random field which simulates random spatial variability.

Further studies are required to explore the effect of mesh size and production runs with multiple parameters can be done to consider the effect of both inherent spatial variability and construction deviations. provide a quantified basis for design optimisation.

References

Larsson, S., Stille, H., & Olsson, L. (2005). On horizontal variability in lime-cement columns in deep mixing. Geotechnique, 55(1), 33-44.

Lee, F. H., Lee, Y., Chew, S. H., & Yong, K. Y. (2005). Strength and modulus of marine clay-cement mixes. Journal of geotechnical and geoenvironmental engineering, 131(2), 178-186.

Liu, Y., Lee, F. H., Quek, S. T., Chen, E. J., & Yi, J. T. (2015). Effect of spatial variation of strength and modulus on the lateral compression response of cement-admixed clay slab. Géotechnique, 65(10), 851-865.

Liu, Y., Pan, Y., Sun, M., Hu, J., & Yao, K. (2017). Lateral compression response of overlapping jet-grout columns with geometric imperfections in radius and position. Canadian Geotechnical Journal, (doi: 10.1139/cgj-2017-0280).

Pan, Y., Liu, Y., Hu, J., Sun, M., & Wang, W. (2017). Probabilistic investigations on the water-tightness of jet-grouted ground considering geometric imperfections in diameter and position. Canadian Geotechnical Journal, Canadian Geotechnical Journal, 54(10): 1447-1459.

Pan, Y., Liu, Y., Xiao, H., Lee, F. H., & Phoon, K. K. (2018). Effect of spatial variability on short-and long-term behaviour of axially-loaded cement-admixed marine clay column. Computers and Geotechnics, 94, 150-168.

Pan, Y., Liu, Y., Lee, F. H., & Phoon, K. K. (2019a). Analysis of cement-treated soil slab for deep excavation support–a rational approach. Géotechnique, 69(10), 888-905.

Pan, Y., Liu, Y., & Chen, E. J. (2019b). Probabilistic investigation on defective jet-grouted cut-off wall with random geometric imperfections. Géotechnique, 69(5), 420-433.

Pan, Y., Liu, Y., Tyagi, A., Lee, F. H., & Li, D. Q. (2021a). Model-independent strength-reduction factor for effect of spatial variability on tunnel with improved soil surrounds. Géotechnique, 71(5), 406-422.

Al-Naqshabandy, M. S., Bergman, N. S. & Larsson, S. (2012). Strength variability in lime-cement columns based on CPT data. Ground Improvement 165, No. 1, 15-30.

Xiao, H., Lee, F.H. and Chin, K.G., 2014. Yielding of cement-treated marine clay. Soils and Foundations, 54(3), pp.488-501.

Wong, D. Y. C., Sadasivan, V., Isaksson, J., Karlsson, A., & Dijkstra, J. (2024). Trans-scale spatial variability of lime-cement mixed columns. Construction and Building Materials, 417, 135394.

Hedman P and Kuokkanen M (2003) Strength Distribution in Lime-cement Columns - Field Tests at Strängnäs. MSc thesis 03/06, RoyalInstitute of Technology. Slockholm, pp. 47-59 (in Swedish).