STRENGTH REDUCTION FACTORS ON LIME-CEMENT TREATED RIBS DUE TO RANDOM SPATIAL VARIABILITY AND CONSTRUCTION DEVIATION

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KEYWORDS

cement treated rib; spatial variability; construction deviation; numerical modeling.

ABSTRACT

Lime-cement columns have been widely used as underground struts in deep excavations due to its effectiveness and flexibility. In practical design, a very low design value is usually applied regardless of the average strength of the column, although a much higher average strength from coring samples is available. This is mainly due to great uncertainties in properties of lime-cement treated soils. There are mainly two sources of uncertainties, namely random fluctuation of property, and construction deviation. The former is a result of uneven distribution of binder (lime-cement), in-situ water content and minerals. The latter is due to random tilting in column axes. When both uncertainties are combined, the improved ribs may become defective due to existence of random gaps and spatial variations.

In this study, the impact of construction deviation on the global strength of lime-cement treated ribs will be quantitatively evaluated using numerical methods. Random finite element analysis is used to replicate the random construction deviation. Then the global strength is evaluated based on the statistical results of random finite element method.

1. INTRODUCTION

Lime-cement treated ground has been widely used in many parts of the world to stabilize the ground [1]. The aim of this method is to increase the stiffness and strength of in-situ soil, reduce permeability and remove liquefaction potentials [2]. Common installation methods include jet-grouting and deep mixing.

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Specifically, jet-grouting involves in-situ jetting of high-momentum binders (usually in form of wet cement/lime slurry or dry cement/lime powders), formulating the final mixture in a columnar structure. The final mixture of the binder and in-situ soils will then have hydration and pozzolanic reaction, gaining higher strength and stiffness over time. These columnar structures can be configured into different formations, such as walls, grids, ribs and slabs [3-5], to fulfil different functions. In Nordic practice, the deep mixed lime-cement columns are usually installed in rows of two or more columns (hereafter called ribs) in the to-be-excavated (passive) side of the retaining wall before excavation. The rib works as an in-situ strut to reduce the displacement and increase the resistance in passive zone together with the surrounding soils.

In such cases, the columns are usually idealized as perfectly vertical and cylindrical components. Designs are also done by assuming a lower bound undrained shear strength of around 150-300 kPa, despite the average strength of the cored samples are usually in the range of 800 kPa to several thousand kPa. The main reason of such conservative design is the great uncertainties in the properties of the ground. Although quality control works are usually done for individual columns, e.g. KPS, FOPS, coring. These measures can only show the uncertainties at the point level. The impact of such uncertainties on global performance of the improved ground structure member such as the deep mixed and jet-grouted ribs is largely untouched.

In reality, there are two major sources of uncertainties, i.e. random property fluctuations [6-7], and random construction deviations [4-5, 8]. The former is a result of the uneven distribution of mix ratio (soil solid, water content and stabilizer) [7, 9]. This can be attributed to insufficient mixing within a column (intra-column variation) and original spatial variation of in-situ mineralogy and water content (inter-column variation). This type of variation has been extensively studied in statistical works because the corresponding data retrieval technics are mature and usually required in the quality control phase [6,10]. The latter are usually less considered, although its impact may be more significant than the former [3]. In reality, the construction deviations may lead to continuous gaps in the treated structure [11], and that may greatly reduce the global stiffness and strength, making them less effective in resisting displacement of retaining wall. Pan et al. (2019) [11] quantified the impact of both random fluctuation and construction deviation on the global behavior of a laterally loaded cement treated slab, with a length of 21m, width of 15m and a thickness of 2m. This represents Singapore’s practice, i.e. the whole excavated ground is fully treated. However, these uncertainties are not yet thoroughly considered for Nordic style lime-cement treated ribs, which are much slender and possibly more vulnerable to construction error.

In this study, random finite element method (RFEM) is implemented to consider the effect of construction deviation on the global performance of cement treated ribs.

2. CONSTRUCTION DEVIATION

The construction deviation of a jet-grouted column arises from the random inclination of column axis and the random variation of column diameter over depth [4,5,7], as shown in Figure 1. This random inclination can be divided into two random variables, that is, azimuth α and inclination angle β. The random variation of azimuth is due to the random orientation of the jet-grouting machine shaft and usually has no bias. In case where multiple shaft jet-grouting machine is used, the shafts in the same mixing operation should have strong correlation, because these shafts are oriented at the same direction. In Nordic context, single shaft jet-grouting is more common than multi-shaft jet-grouting. This makes the inclination angle differ from one mixing operation to the other, and the range of the inclination angle depends on the action standard and craftsmanship. Table 1 summarizes action standards in various parts of the world. In addition, the variation of column diameter stems from the vertical variation of soil property [12,13]. A random variable with a marginal normal distribution is used to simulate the diametric variation. The mean value is the target mean diameter of the columns, and the quality is controlled by the coefficient of variation (C.O.V). Previous studies show the C.O.V of jet-grouting's diameter is in the range of 0.05~0.2.

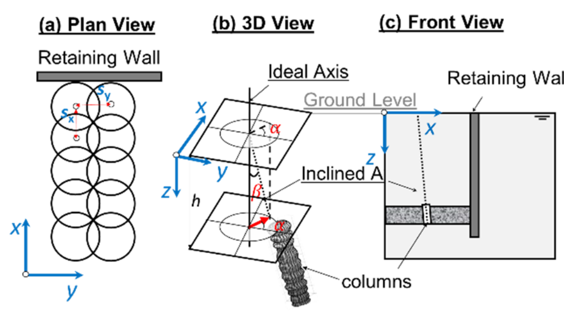

Figure 1 Illustration of construction deviation.

Table 1 Verticality requirements in different standards

Source	Type of technique used	Maximum Deviation from Verticality
ASCE Jet Grouting Guideline (2009)	Jet-grouting	1/100
Christopher and Jasperse (1989)	Deep mixing	1/100
Singapore Standard (2003)	Jet-grouting	1/75
Amos et al. (2008)	Drilled concrete piles	1/200**

Intuitively, this inclination leads to positioning error (deviation distance from the column axis and the ideal center) of the columns, which accumulates over depth. In cases where an action standard of 1/100 is used and the deep mixed ground is 20 m deep, the maximum allowable positioning error is around 0.2 m. When two adjacent columns tilt in opposite directions, the distance between two column centers increases by 0.4 m, which is higher than the preset overlap (0.2-0.3 m) between two adjacent columns. In such a case, untreated gaps will appear among the columns. These untreated gaps are characterized by much lower strength and stiffness than the treated zones, despite some random spillovers of stabilizers.

In this study, the construction deviation is characterized by three random variables, i.e. azimuth, inclination angle and C.O.V of diameter. The azimuth is a uniform distribution between $[0, 2\pi]$, whereas the inclination angle follows a uniform distribution between zero and the maximum allowable inclination, 1/100. An upper bound value of 0.2 is used for diametric C.O.V. Random fluctuation of the property field of treated ground is not considered in this study because the scale of fluctuation of treated column is usually much smaller than the diameter, and significant spatial averaging effect will limit its impact on the global performance.

3. NUMERICAL MODEL

Deep mixed columns with a mean column diameter of 1.0 m are used. A rectangular layout is used, as shown in Figure 1a. The transversal (s_y) and longitudinal (s_x) overlaps are 0.3m and 0.2m respectively. The treated zone consists of 2 rows of columns. The thickness of the treated zone is limited to 2 m due to lack of computational power, though the actual thickness are usually 5 to 10 meters.

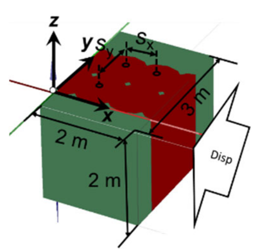

Figure 2 Defective treated ribs with construction deviation (yellow zone means treated, blue zone means untreated.

The FEM calculation zone has a dimension of 3m*2m*2m in *x*- (longitudinal), *y*- direction (transversal) and *z*- (vertical) directions. This covers a rib with 4 by 2 columns (Figure 2). It should be noted that an actual rib could have more than 20 columns. 4 columns are used here due to lack of computational capacity. Given that the ribs are subjected to similar loading conditions, the side boundaries are normally fixed. The bottom boundary is also normally fixed, while the top boundary is free. A longitudinal displacement is exerted in the *x*-max boundary to ramp up the longitudinal load. Only longitudinal load is considered because the rib is usually basically longitudinally loaded when the wall moves inward. It can be expected that the retaining wall may exert an uneven displacement on the *x*-max boundary, and the other side is actually in contact with untreated soils. However, this study is only scoped to the longitudinal capacity of a defective lime-cement treated rib for simplicity. Further study is required for more realistic simulations.

Plaxis 3D ultimate is used for the simulation. A python script is generated to enable randomness simulation. Unlike conventional RFEM analyses which use user-defined material and random field generation at integration point level, this study uses generation of random volumes. Given the random azimuth and inclination angle of a columns, the column axis is determined. By generating cylinders with random diameter along the inclined axes, one can simulate the "calabash" shape of jet-grouted columns. These column volumes are then intersected with the calculation zone using a Boolean operation, and this distinguishes treated zone from untreated zone. One needs to set different models and parameters for both treated and untreated zones. Many advanced models were developed for both treated and untreated soils. However, in this study, an elastic-plastic model with Tresca criterion is used, as it corresponds well with the unconfined compressive test results which are extensively collected. An undrained shear strength of 1000 kPa and 100 kPa are used to represent treated and untreated soils, respectively. The 100 kPa is used to consider possible spillovers of binder [3]. The Elastic moduli is set to be 280 times undrained shear strength, following Lee et al. (2004) [15]. Table 2 summarizes the design configurations of ribs, namely depth of the column top and number of rows. The former is usually the same as the excavation level. The latter is an important parameter for column installations. Lower number of rows saves investment but leads to higher uncertainties. Cases No. 1, 2 and 3 explore the impact of depth, whereas Cases No. 2,4 and 5 aims at quantifying the effect of row numbers.

Table 2 Parametric study

Case No.	Depth	Number of rows	Max. Inclination Angle	C.O.V of diameter	Normalized Global Peak Strength (Q)		
					Average	C.O.V.	5% fractile
1	**5**	2	0.01	0.2	0.92	0.07	0.82
2*	**10**	**2**	0.01	0.2	0.88	0.08	0.77
3	**20**	2	0.01	0.2	0.75	0.16	0.56
4	10	**3**	0.01	0.2	0.92	0.06	0.82
5	10	**4**	0.01	0.2	0.93	0.06	0.83

*reference case to be compared with other case studies

Given the reference configuration, a typical realization of lime-cement-treated rib is shown in Figure 3a. As can be observed, significant gaps are observed between the two highlighted columns.

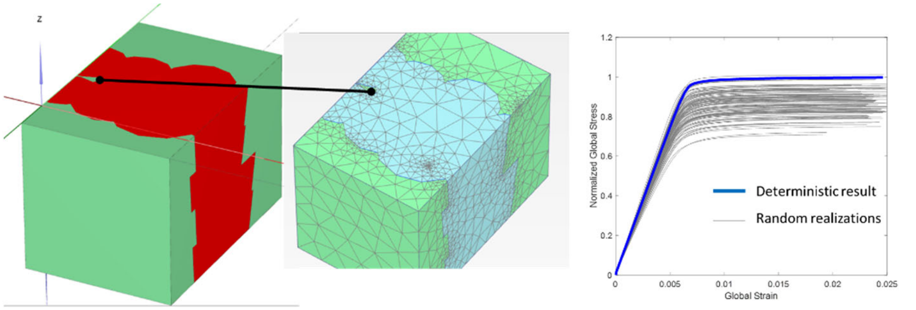

Figure 3 (a) a typical random realization and mesh; (b) Normalized global stress strain curves.

4. IMPACT OF RANDOM CONSTRUCTION DEVIATION ON GLOBAL PERFORMANCE

Deterministic analysis

The deterministic analysis is performed with zero inclination angle. In such case, the columns are perfectly overlapped. The normalized global stress-strain curve is plotted as the thick blue curve in Figure 3. The global stress is defined as the reaction force in x-direction divided by the cross-sectional area in the x-max boundary, whereas the global strain is the x-displacement of the x-max boundary divided by the longitudinal length of the rib. The global stress of the treated rib is normalized by the average strength of the rib, which is the weighted average undrained shear strength. This value is used because the global performance of a cement-treated rib is usually estimated using such weighted average value. In this case, the weighted average unconfined compressive strength (two times undrained shear strength) is calculated as (1.7 m*2000 kPa + 1.3m*200 kPa)/3m=1167 kPa. The normalized global stress (Q) reaches its peak at approximately 1.0 in deterministic case, indicating that the weighted average unconfined compressive strength is a good indicator of the global performance of the longitudinal capacity. This is rational because the rib is surrounded by much softer clays in transversal direction (y-direction), which can be easily displaced when the failure mechanism is formed. This would render the treated rib in an approximately unconfined case.

Random realizations

100 Monte Carlo simulations are done to evaluate for each case in Table 2. The random realizations are plotted as grey curves in Figure 3b. Most of the calculated 100 random realizations have lower peak strengths and stiffness than the deterministic counterpart. When the maximum inclination angle is set 1/100, the average normalized peak strength is around 0.88 and coefficient of variation is around 0.08. This average value is higher than the normalized global peak strength (0.62) of a wide cement treated slab [11], despite the latter has a more significant local averaging effect. This is because the rib is not

long enough, in cases there are more columns along the longitudinal directions. Higher possibility of untreated gaps is expected which leads to lower normalized global strength and higher Coefficient of variation. In addition, this simulation is based on Tresca criteria which does not account of strain softening.

Parametric study (Table 2) shows a clear reduction of average Q with increasing depth. With more rows in a rib, the uncertainty is reduced and a higher average and 5% fractile can be obtained. The 5% fractile can reach as low as 0.56 of the mean value when the depth reaches 20 m. This amounts an undrained shear strength of 560 kPa, which is still much higher than most practical design guidelines. However, given the limited number of columns simulated in this study, it is highly possible that a lower peak strength could be reached somewhere in a longer rib.

5. CONCLUSIONS AND LIMITATIONS

In this study, random finite element analysis on cement treated rib is used to quantify the impact of pure construction deviation on the global strength a cement treated rib. The result shows that the construction deviation makes the ribs defective and reduces the global strength to around 50% of its average strength. However, the current study is only limited to a small-scale numerical model on limited case studies. Further study is required to have a more comprehensive parametric study with more realistic dimensions of the ribs and strain-softening effect. Both factors would lead to a lower normalized global strength.

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