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Towards a Design Framework for Spatial Variability in Cement Treatment for Underground Construction

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ABSTRACT: The most common form of ground treatment used to facilitate underground construction in Singapore is cement treatment. However, there is currently no indication on how safe and how conservative this adopted strength is since the prescribed strength bears no relationship to the probability of failure or factor of safety. This paper examined several sources leading to non-uniformity and spatial variation in cement-treated soils, including curing time effect, influence of operating parameters on slurry concentration, in-situ water content and column positioning errors. A framework for design and monitoring of ground treatment by cement was proposed.

KEYWORDS: Cement-treated ground; Underground construction; Unconfined compressive strength; Spatial variability

1. INTRODUCTION

Underground development is a matter of strategic importance to Singapore's economic development. This is reflected in the Report of the Economic Strategies Committee (ESC 2010) which states that "..*In the next 10 years, the Government should seek to catalyse the development of underground space as a means to intensify land use*..". It is also embodied in the Land & Liveability National Innovation Challenge (L2NIC 2015) which aims to "…*develop innovative solutions for creating new space cost-effectively and optimising the use of land to sustain Singapore's long-term growth and resilience"*.

Approximately 25% of the land area in Singapore is underlain by soft marine clay of the Kallang Formation (e.g. Tan *et al*. 2003) with undrained shear strength ranging from approximately 15 kPa to 35 kPa. The low strength and stiffness of this clay pose challenges to almost all forms of underground construction including tunnelling and open excavations. Deep excavation and tunnel construction in soft clay may suffer from marginal stability and excessive wall, ground and nearby infrastructural movement. Mined tunnels are particularly affected by soft soil deposits and most mined tunnel constructions cannot proceed without some form of stability intervention. In some areas overlying reclaimed land, the problem is compounded by the continuing settlement of the soft clay, which has persisted for decades and has to be arrested to avoid long-term implications for tunnels.

The most common form of ground treatment used to facilitate underground construction in Singapore is cement treatment. In the Singapore context, cement treatment has several advantages. Firstly, compared to other forms of treatment including lime, strength gain is relatively fast owing to the hydration reaction of cement. Secondly, the cost differential between cement and lime is not as large as it is in other countries; both are imported into Singapore.

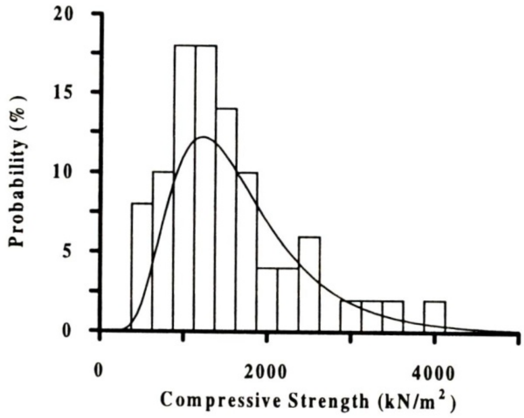
Notwithstanding the fact that it is the most widely soil improvement method for underground construction, the cost of cement-treatment of soft clay has been steadily rising in recent years and is now a significant proportion of the cost of underground construction in soft soil. L2NIC (2015) noted that "*the cost of construction is approximately $130 per m3 for typical developmental designs with good quality rocks and may reach more than $300 per m^3 for complex designs with less favourable rock qualities*".

Over the past 15 years, researchers at the National University of Singapore have been studying various aspect of cement-treated ground with a view to developing appropriate design methodologies for the use of cement-treatment in underground construction. This paper presents some of the developments in characterizing the spatially variability of cement-treated ground and their implications for design. The nature of the variability of the soil is first described using data from various case histories, and their causes examined. The fundamental aspect of this variability is then explored through the use of physical model test data which allow the statistical properties of the variation to be estimated. The impact of this variability on large-scale performance is then studied, leading to a possible design framework which can account for the random spatial variation in strength of the ground. Parts of the material are drawn variously from publications by the Authors and their co-authors. The contribution of this paper is to present an integrated view of the developments to date, which, if viewed separately, may appear to be unrelated and disconnected.

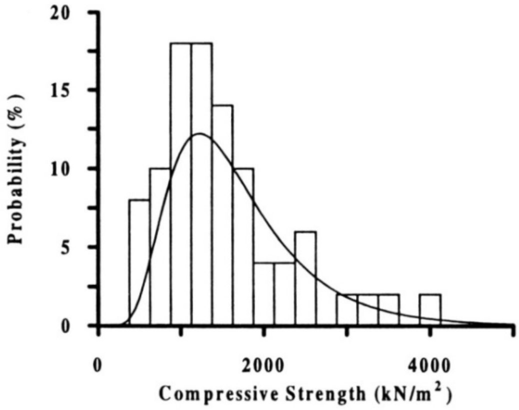
2. POSSIBLE CAUSES OF SPATIAL VARIABILITY

Many instances of spatial variability in the properties of cement-treated soil have been reported. For instance, Chew *et al*. (1997) reported strength distribution in jet-grouted marine clay in the Singapore River Widening Contracts C1 to C3. As Figures 1(a) and 1(b) show, the unconfined compressive strength of the core samples vary from 500 kPa to about 4000 kPa. In deep mixing, Kawasaki *et al*. (1984) also reported variation in direct shear strength of core samples, from about 500 kPa to about 2500 kPa. More recently, Chen *et al*. (2011) also reported variation in unconfined compressive strength of core samples varying from about 1 MPa and 5 MPa.

This variation may be attributed to several possible factors. These include imperfect mixing of cement slurry into the soil, which leads to spot variation in slurry concentration, natural variation of the in-situ soil and variability in the curing parameters. In this paper, three factors will be examined in detail, namely, variation in slurry concentration, natural variation in the water content of in-situ soil and variation in curing time.



(a) Contracts C1 and C2



(b) Contract C3

Figures 1 Distribution of unconfined compressive strength in core samples from Singapore River Widening Contracts C1 to C3 (after Chew *et al*. 1997)

2.1 Curing Time Effect

The most common method of monitoring the quality of cement treatment at present is by core testing. However, there is typically no specification on the time between mixing and testing, hereafter termed as the curing time. Tables 1 and 2 show the distribution of curing time for the Marina Bay Financial Centre (MBFC) and Marina One projects, the sites for both of which are located about 200m apart. As can be seen, the curing time ranges from less than 28 days to more than 150 days.

Table 1 Distribution of curing period for deep cement mixing in the Marina Bay Financial Centre Project

Time between installation and testing	28 – 50 days	50 – 100 days	100 – 150 days	>150 days
Percentage	0.4%	88%	4%	8%
Sample size	1	204	9	18
Total sample size	232			

Table 2 Distribution of curing period for deep cement mixing in the Marina One Project

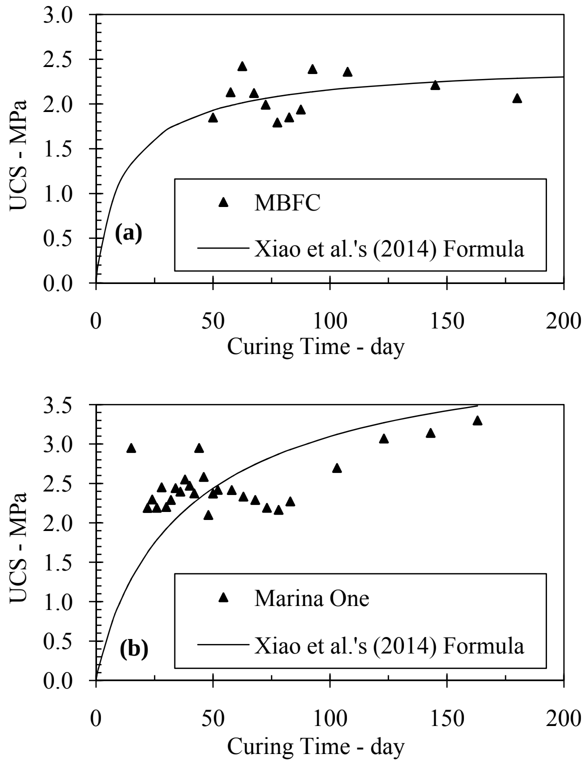
Time between installation and testing	<28 days	28 – 50 days	50 – 100 days	>100 days
Percentage	17%	58%	18%	7%
Sample size	198	665	208	78
Total sample size	1149			

The strength of cement-treated marine clay increases over a long period of time due to the pozzolanic reaction between the lime released by the hydration reaction and clay minerals (Chew *et al*. 2004). This is particularly where cement with high lime content, such as Portland Blast Furnace Cement for the Marina One project, Figure 2(b). This is because the presence of lime facilitates the long-term pozzolanic reaction between lime and clay minerals, leading to prolonged strength gain over time. Xiao *et al*. (2014) showed that the rate of strength increase in cement-admixed marine clay can be described by a generalized hyperbolic relation of the form

$$q_{ut} = q_{u\infty}\left\{1 - \frac{1}{1+\left(\dfrac{\alpha t}{q_{u\infty}}\right)^r}\right\} \tag{1}$$

in which q_{ut} is the unconfined compressive strength at time t, $q_{u\infty}$ an asymptotic unconfined compressive strength, which can be regarded as a long-term unconfined compressive strength, and α and r are parameters governing the trend of strength gain.

As Figures 2(a) & 2(b) show, the strength gain with time for the two projects are reasonably well-fitted by Eq. (1) with the parameters shown. In both cases, r = 0.9 implies that the curves approximate a conventional hyperbolic curve; in which case α can be regarded as the initial rate of strength gain. The use of Ordinary Portland Cement in MBFC led to more rapid initial strength gain than in Marina One where Portland Blast Furnace Cement was used. However, the final strength gain in Marina One is higher. This may be due partly to the stronger pozzolanic reaction of the Portland Blast Furnace Cement. However, as discussed later, it may also be due to the fact that the water content of the marine clay at the Marina One site is lower than that at MBFC.



Figures 2 Time effect on unconfined compressive strength (UCS) from (a) Marina Bay Financial Centre site and (b) Marina One site

Using Eq. (1), the measured strength q_t at any time t can be converted to an equivalent strength q_{ut1} at a specific time t_1 using the relationship

$$q_{ut1} = q_u\left(1 - \frac{1}{1+\dfrac{\alpha t_1}{q_{u\infty}}}\right) \Bigg/ \left(1 - \frac{1}{1+\dfrac{\alpha t}{q_{u\infty}}}\right) \tag{2}$$

Figures 3(a) & 3(b) show the distribution of strength before and after curing time standardization. Both these cases demonstrate that the strength measured after different curing periods are different. In order to assess the real variation in properties, the strength must be normalized to a fixed curing period.

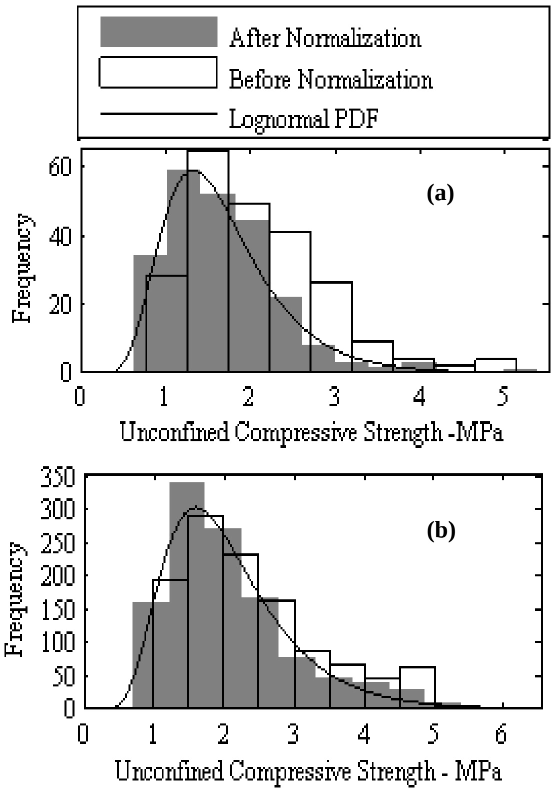


Figure 3 Histograms of unconfined compressive strength from (a) Marina Bay Financial Centre site and (b) Marina One site

2.2 Variation in Slurry Concentration

It has long been recognized that operating parameters can influence the spatial variation in slurry concentration resulting from imperfect mixing (e.g. Porbaha 2000; Porbaha *et al*. 2001 & 2002, Coastal Development Institute of Technology 2002). However, most of the works to date have been qualitative in nature and cannot be used in a quantitative way in design. Using dimensional analysis, Lee *et al.* (2006) showed that centrifuge modelling can be used to study the quality of mixing provided a replacement binder with a viscosity that is scaled-down from that of cement slurry is used. Lee *et al.* (2006, 2008) also showed that the most important operating parameters are the blade rotation number and binder (i.e. cement slurry) density relative to that of the soft soil. Lee *et al*. (2006, 2008) showed that the quality of mixing depends critically upon the density of the binder relative to that of the soil, termed hereafter as density ratio.

Using Lee *et al.*'s (2006, 2008) centrifuge model data and their own data, Chen *et al.* (2016) noted the spot binder concentration in each of the tests is best fitted by a truncated normal distribution. The coefficient of variation of the data can be correlated to the blade rotation number and density ratio by a relation of the form

$$V = A + BT^{-C} \tag{3}$$

In which T is the blade rotation number, expressed in revs/m and A, B and C are parameters which depends upon the density ratio, Figure 4. For a cement slurry with a water-cement ratio of about 0.9, the slurry density is approximately 1.7, giving a density ratio of approximately 1.0. For such a case, the values of A, B and C are 0.102, 0.584 and 0.335, respectively. For slurry with lower water-cement ratio, A will increase whereas B and C will decrease. This leads to larger coefficient of variation for the same blade rotation number, Figure 4.

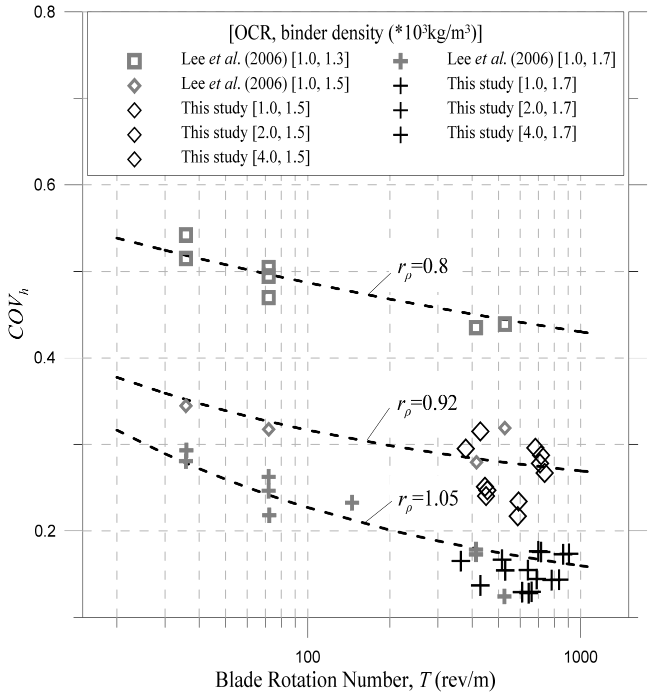


Figure 4 Change in COV with slurry density and blade rotation number (after Chen *et al*. 2016)

By combining the probability distribution function for slurry concentration with Xiao *et al.*'s (2014) relationship between mix ratio and unconfined compressive strength, Chen *et al*. (2016) deduced a relationship which allows probability distribution function of the spatial variation in strength to be evaluated.

2.3 Variation in In-situ Water Content

The strength of cement-soil mix depends on the total amount of water in the mix; this include the water in the cement slurry as well as the in-situ water in the soil. For this reason, one would also expect the in-situ water content of the soil to have an effect on strength of the soil-cement mix. Figure 5 shows the in-situ water content with depth in the MBFC and Marina One sites. Each point represents the average water content from all the boreholes measured in the marine clay at that depth. As Figure 5 shows, the marine clay is found at a larger depth at Marina One. This indicates that the marine clay is sloping downwards from the MBFC site towards the Marina One site. Notwithstanding the difference in depth of the marine clay, there is clear trend of decrease in in-situ water content of the marine clay across both the sites. This is not surprising given that the two sites are in close proximity to each other. Figure 6 shows the core strength of the cement-treated clay from the two sites. As can be seen, not only is the treated strength of the Marina One site higher than that of the MBFC site, but there is also a continuous increase in core strength spanning across the two sites. This suggests that there is a significant correlation between in-situ water content and treated soil strength. This is, again, not surprising. For the same water-cement ratio in the grout and the same weight of cement used per unit volume of ground, a lower in-situ water content will lead to a decrease in overall water content, which would lead to an increase in strength (e.g. Lee *et al*. 2005; Xiao *et al*. 2014). However, much remains unknown about, the quantitative relationship or correlation between the in-situ water content and the strength of the cement-treated soil. It is now being studied by the Authors.

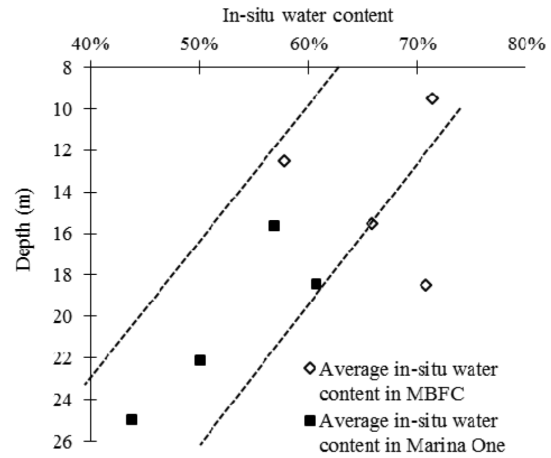


Figure 5 Variation of average in-situ water content with depth in the Marina Bay Financial Centre and Marina One sites

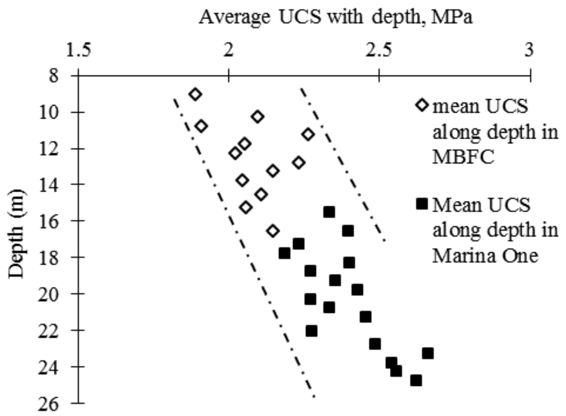


Figure 6 Variation of average unconfined compressive strength (UCS) with depth in the Marina Bay Financial Centre and Marina One sites

3. EFFECT OF VARIABILITY ON LARGE-SCALE PERFORMANCE

As discussed earlier, the heterogeneity in cement-admixed soils show significant point-to-point variation. It is important to note that the non-uniformity may not be completely random. For instance, based on field tests on soil-cement columns, Sakai *et al*. (1994) reported a general trend with regards to strength in the radial direction, the strength being higher in the column's centre and decreasing as one moves to the edges. The columnar structure and non-uniformity have significant effects on the performance partly. There are also some other sources of heterogeneity affecting the uniformity of cement-treated soils. For example, the overlapping columns, which would involve remixing an existing mixed ground, perhaps several times if there are more than two overlapping columns, will have different material properties in the overlapping zones. In addition to the heterogeneity due to mixing, there may also errors arising from positioning errors of the admixed columns which may contribute to the heterogeneity of the treated ground. The difference in column placement is inevitable due to the machinery limitation and workmanship on site. For instance, in Singapore construction practice, an off-vertical tilt of 1-in-75 is often accepted as the tolerance (Singapore Standards, 2003). If the treated soil is located deep in the ground, this tilt can result in large positioning errors. For example, an off-vertical tilt of 1-in-75 will translate to an eccentricity of about 260 mm in the columnar position at 20m depth. In addition, there is no simple method for control of the verticality (Larsson *et al*. 2005). The verticality can only be estimated after installation by measuring the treated area to determine the column position. Therefore, the uncertainty of placing column position needs to be considered when dealing with the variability of cement-treated ground.

Liu *et al*. (2015) simulated a cement-treated soil slab with random finite-element method, where three sources of heterogeneity were considered; that is, a radial trend, stochastic fluctuation about the trend and positioning errors. This is a common stability enhancement measure in deep excavations in soft clay in Singapore where the soil slab serves as a lateral supporting structure in a deep excavation. A section of the slab consisting around 160 columns was modelled as illustrated in Figure 7. As can be seen, the columnar structure and positioning error can be well simulated with the random finite-element method. Table 3 listed the parameters used for the analysis, where the Poisson's ratio of 0.49 is adopted to reflect the "incompressibility" of the saturated improved soil under undrained loading.

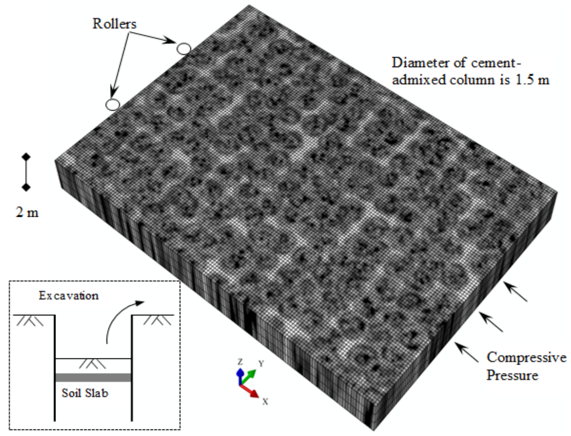


Figure 7 Geometric and mesh sizes of model in finite-element analysis (after Liu *et al*. 2015)

Table 3 Deterministic and statistical parameters in reference case (source Liu *et al*. 2015)

Parameter	Value or choice for reference case
(a) *Deterministic parameters*	
Size (length × width × depth)	21 m × 15 m × 2 m
Radius of column, R	1.5 m
Layout of columns	Rectangular arrangement
Centre to centre distance	1.7R
E / c_u (improved soils)	280 on average
E / c_u (natural soils)	200
c_u (natural soils)	73 kPa*
Poisson's ratio (all soils), ν	0.49
Density (all soils)	1700 kg/m^3
Friction angle (all soils)	0°
Dilation angle (all soils)	0°
Element type (all soils)	8-noded brick with reduced integration
(b) *Statistical parameter: unconfined compressive strength of cement-admixed soils*	
Mean value	2.15 MPa
Resultant coefficient of variation	0.47
Cross-correlation between E and c_u (improved soils)	0.85
Scale of fluctuation	
Circumferential direction	π/4
Radial direction	R/3
Depth direction	5R
Strength ratio, R_{cp}	2 (inner-stiffer)
Amount of positioning error	D/4 (drilling depth ~25 m)
Correlation lengths of positioning error	Transverse to pressure: 3R Longitudinal to pressure: 1R

Notes: R = columns radius; E = Young's modulus; c_u = undrained shear strength. * The value of c_u for natural soil is set relatively large to account for potential penetration of cement slurry into surrounding soils during deep mixing.

Figure 8 shows the spread of mass stress-strain curve for 100 random simulations of the model. The mass strain is defined as the compressive strain of the slab. The mass stress and strength were inferred by dividing the total force and ultimate total force, respectively, acting across one of the loaded sides by its area. For the unconfined slab, a representative Young's modulus, termed herein as the mass modulus, can be deduced from the initial linear portion of the mass stress-strain curve. On the contrary, a common method to determine a design value is to adopt a conservative strength that can be exceeded by most, if not all, of the tested core samples. For example, in most deep excavation projects in Singapore, the design UCS is about 700kPa (e.g. COI 2004; Chen *et al*. 2011). This is equivalent to factoring the mean UCS commonly produced by deep-mixing (e.g. Chen *et al*. 2011) down by a strength factor of about 3 to 3.5 times. As Figure 8 shows, even when a relatively low strength factor of about 2.5 times is used, the results from the equivalent homogeneous slab mostly fall well below the spread of the mass stress-strain curves from the random analyses. This is not surprising since the mass properties evaluated from the random finite element computation have near-normal distributions with relatively low coefficient of variations, implying that the mass behaviour tends to be narrowly dispersed around the average behaviour. The use of a strength factor without considering the distribution of mass performance cannot account for the effect of spatial variation in soil property on mass behaviour.

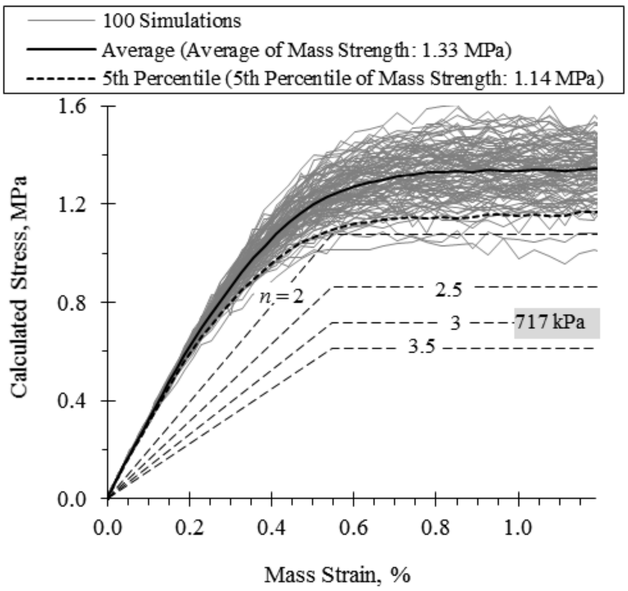


Figure 8 Random finite element analysis results and results with strength factor *n* (after Liu *et al*. 2015)

Based on the random finite-element analysis results, a representative strength (Q_d) of a soil slab could be determined as

$$Q_d = q_{u\_ave} - \alpha_Q \cdot \sigma_{q_u} \tag{4}$$

where q_{u_ave} is the volume-averaged strength; σ_{qu} is the standard deviation in strength; α_Q is a strength reduce factor, which depends on positioning error and probability of failure. As a result of an extensive series of parametric studies, the strength reduce factor α_Q under different combination of positioning error and probability of failure are tabulated in Figure 9.

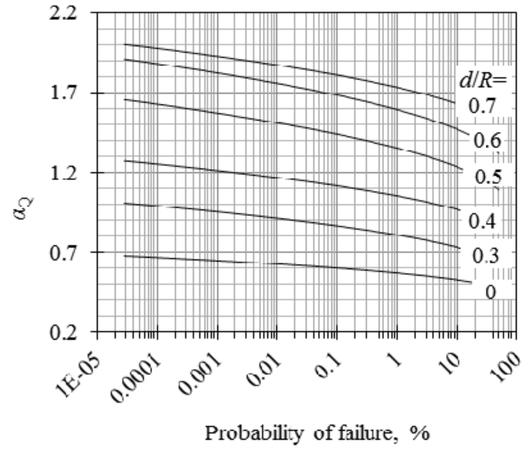


Figure 9 Evaluation of strength reduce factor
(*d*: maximum deviation in positioning error; *R*: column radius)
(after Liu *et al*. 2015)

4. TOWARDS A RATIONAL DESIGN METHODOLOGY

At present, there is no internationally accepted or rational design methodology for cement treatment works pertaining to underground construction. Although there is a general recognition that the treated ground is spatial variable, there is no method of design which takes the statistical properties of the ground into consideration.

In Singapore, the undrained strength of the improved ground is commonly prescribed at the outset, in the range of 350 kPa to 400 kPa. This implies an unconfined compressive strength of about 700 kPa to 800 kPa, which is well below the mean strength typically measured in the field. While this implicitly recognizes the spatial variability of the ground, there is currently no indication on how safe and how conservative this adopted strength is since the prescribed strength bears no relationship to the probability of failure or factor of safety. Moreover, it is also a "one-strength-fits-all" approach, which took no account of the actual quality of mixing or the workmanship of the ground improvement work. In terms of core strength monitoring, a common requirement is to stipulate that all of the core strength must exceed the prescribed design value. This approach of using the sample minima is very sensitive to outlier data points and took no account of the overall statistical distribution of the spatial variation. Furthermore, there is no guideline on how re-design should proceed in the event that some of the cores fall below the prescribed design and no means of analysing how that would impact the safety of the structure.

The above findings indicate that a more holistic and rational design and monitoring approach may be feasible. The schema of this approach is encapsulated in Figure 10. In this framework, the first step is to estimate the statistical parameters for the strength distribution in the ground using the model proposed by Chen *et al*. (2016), based on operating parameters indicated by the ground improvement contractor. Based on the resulting mean strength and coefficient of variation, as well as an estimated or allowable positioning error and an agreed probability of failure, a strength which represents that of an equivalent uniform treated slab is deduced which can be used in conventional finite element or similar analysis. This equivalent strength takes into account the variability of the ground together with an explicit probability of failure which is accepted by the regulatory authorities and all the parties involved in the construction.

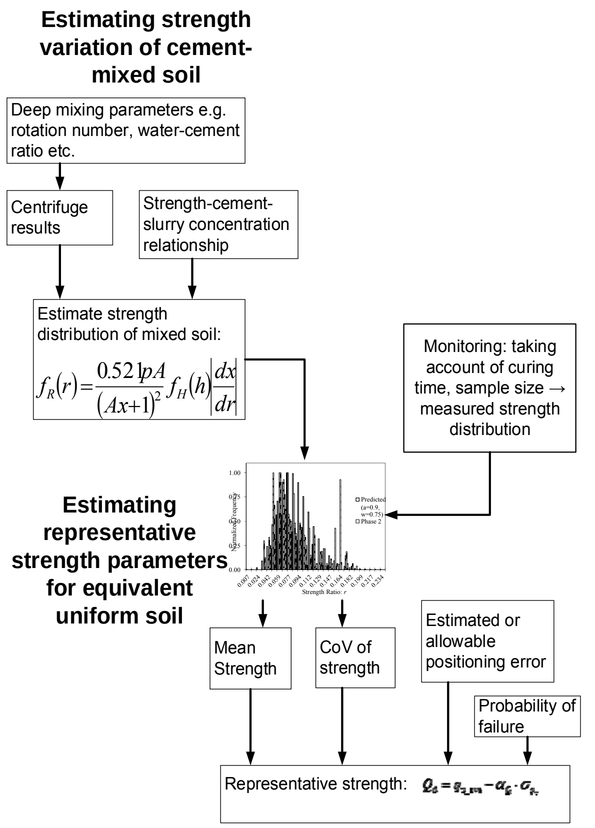


Figure 10 A proposed framework for the design and monitoring of ground treatment by cement

In the quality control process, the presence of curing time effect means that either the time between installation and testing should be fixed or else the strength should be normalized to an equivalent strength at a given fixed time. One way of normalizing is to use Eq. 2. However, it is unnecessary to stipulate a standard curing time of, say, 28 days. This can be a matter of negotiation between the various parties involved in the construction. This should yield a set of statistical parameters which are more representative of that in the actual treated ground. Based on the actual measurement, the representative strength of the equivalent uniform ground can be refined and, if necessary, would allow re-design to proceed. This proposed framework has a number of advantages over the current framework. Firstly, instead of a prescribed value, it allows the representative strength to be deduced through an engineering process, based on the mixing parameters and the effect of the spatial variation on overall behaviour. Secondly, if necessary, re-design can proceed on a rational basis, taking into account the measured statistical parameters of the treated ground.

Certain elements of the framework are still being developed at the time of writing this paper. For instance, a model which allows the influence of in-situ variation of the water content on the strength of the treated soil to be considered is still being developed. In addition, the effect of spatial variation on other types of construction, apart from a treated soil slab, is still being studied. As findings are progressively obtained, they will help to refine and add substance to the framework.

5. ACKNOWLEDGEMENT

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