Some issues in core strength measurement in cement-soil treatment for deep excavation
– Field data study

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ABSTRACT

Deep mixing and jet grouting with cement are widely used to improve soft clayey soils as part of stability intervention in deep excavation and tunnelling. The quality of the improvement is often evaluated by measuring the strength of cored samples after the installation of deep mixing or jet grout columns. Although the spatial variability in the strength of cement-treated soil in such operations has been reported, this variability, as well as its influence on design and construction control, has still not been well-characterized. Using data from two field cases, this paper examines two issues associated with strength measurement and its usage in design. The two field cases are the ground treatment works for Marine Bay Financial Centre and the Marina One projects, which lie in the same locality, overlying thick layers of soft marine clay. The first issue examined is the time interval between ground treatment and core testing. The effect of this parameter on the measured strength and its implications on ground treatment construction control are discussed. The second issue relates to the specification of design strength, which takes into account the strength variability of the ground. The robustness of several criteria with respect to sample sizes is examined using the data from these sites, leading to recommendations for design strength and control measures.

Keywords: cement-admixed soil, unconfined compressive strength, time effect, robustness, probability density function

1 INTRODUCTION

Deep mixing and jet grouting with cement are widely used to improve soft clayey soils as part of stability intervention in deep excavation and tunnelling. It is well-known that significant heterogeneity can be induced into the improved ground in the process of chemical improvement. For instance, Larsson et al. (2001, 2005) showed that significant point-to-point variation occurred when using dry lime improvement method. In a similar way, significant non-uniformities can result from chemical improvement using cement slurry (e.g. Lee et al. 2005, 2006, 2008). Chen et al. (2011) also reported that the unconfined compressive strength (UCS) of core samples varies from about 700 kPa to about 5 MPa for the deep mixing work at the Marina Bay Financial Centre (MBFC) project in Singapore.

Due to the heterogeneity and spatial variation, the strength of cement-admixed soil adopted in design is often several times lower than the laboratory-measured strength using the same mix proportion (e.g. Chew et al. 2004), and also different criteria in determining the design strength from core sample data can be found in literature or practice. Currently, public agencies in Singapore often require that the strength of all of the cores tested must not be lower than the design strength (e.g. LTA 2010). Alternatively, the design strength is determined as a low-value percentile, typically 5% to 10%, of all the core sample data (e.g. Kasama et al. 2012). This is equivalent to accepting a percentage of sub-standard cores. Finally, a design strength may also be determined from the core sample data by subtracting a multiple of the standard deviation from the mean strength. This is the criterion adopted by Eurocode 7 (CEN 2002) to determine the characteristic value of a material property with spatial variation. The second criterion is actually an alternative form of the third criterion, in that tolerable percentage in the former can be expressed in the form of the latter by adjusting the coefficient. Both the second and third criteria can be also unified in the framework of reliability-based design with the concept of reliability index (e.g. Liu et al. 2007, 2008; Sivakumar Babu et al. 2011).

In this paper, two deep mixing cases in Singapore marine clay were considered; namely, the MBFC and Marina One projects. The UCS was measured from more than 1350 core samples taken from these two

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Wide disparities in the curing time for these core samples were noted. The time effect on strength was discussed in this paper, which points the way to a method of normalizing the strength to a 28-day value. Based on the converted core sample data, the robustness of the different criteria for prescribing design strength was compared.

2 UNCONFINED COMPRESSIVE STRENGTH AND TIME EFFECT

The MBFC and Marina One sites are located in land reclaimed in the 1970’s in the Marina South district of Singapore. To facilitate deep basement construction, the soft marine clay underlying the sandfill was improved using deep-cement mixed columns from 8 m to 25 m depth. The strength of the improved ground was assessed by coring samples for UCS test. The MBFC and Marina One projects contributed 232 and 1149 UCS data points, respectively. As Fig. 1 shows, the curing times of the samples vary considerably from 20 days to 180 days. Such disparities probably contributed to the observed variation in UCS. Xiao et al. (2014) proposed that the curing time \( t \) can be related with UCS \( q_u \) via

\[
q_u = q_\infty \left[ 1 - \frac{1}{1 + \left( \frac{\alpha}{q_\infty} \right) \left( \frac{w}{c} \right)^m} \right]^{\frac{1}{n}}
\]

in which \( q_\infty \) is the long-term value of UCS; \( \alpha \) and \( r \) are experimentally fitted parameters; \( m \) and \( n \) can be taken as 0.3 and 2.92, respectively; \( s/c \) and \( w/c \) are the soil-cement and water-cement ratios, respectively. For MBFC and Marina One projects, the fitted parameters are listed in Table 1 and the fitted curves are illustrated in Fig. 1.

Using Eq. 1, core sample data with different curing time can be normalized to a strength at a “standard” time so that the time effect can be eliminated from the data sets. Fig. 2 illustrates the histograms of core sample data before and after normalizing the strengths to 28-day values. As can be seen, the “spread” of the distribution is reduced after normalization. This underscores the importance of curing period normalization in real UCS data collected over widely disparate curing periods.

| Parameters | MBFC | Marina One | Unit |
|------------|------|------------|------|
| \( q_\infty \) | 40   | 72         | MPa  |
| \( \alpha \) | 3.1  | 1.8        | MPa/day |
| \( r \)     | 0.9  | 0.9        | -    |

Fig. 1. Time effect on unconfined compressive strength (UCS).

Fig. 2. Histograms of unconfined compressive strength and fitted probability density functions (PDF). COV = coefficient of variation. Fittings were based on histogram after normalization.
For both data sets, the lognormal and beta distributions (Liu et al. 2006) fit better than the normal distribution, since the latter predicts negative strengths which is counterintuitive. In this paper, only the beta distribution for the Marina One project was considered, where the lower bound of UCS was chosen as 80 kPa to represent the strength of natural soil. The upper bound of UCS was chosen as 8 MPa which was taken from the core sample data.

3 ROBUSTNESS OF CRITERIA IN EVALUATING DESIGN STRENGTH

As discussed earlier, there are two main criteria in determining the design strength, which can be mathematically expressed as two variables, namely \( y \), being the minimum of all the samples and

\[
z = \mu - h \cdot S
\]

in which \( \mu \) and \( S \) are the mean and standard deviation of the sample, respectively and \( h \) is a constant. In this section, the coefficients of variation (COV) of \( y \) and \( z \) are examined, thereby enabling an assessment of the robustness of these two criteria for prescribing design strength.

**Variable \( y \)**

The minimum value, \( y \), of a sample with size \( n \) has the following cumulative distribution function (CDF) (Ang and Tang 1975):

\[
F_Y(y) = 1 - \left[1 - F_X(y)\right]^n
\]

in which \( F_Y \) and \( F_X \) are the CDFs of the minimum value of the sample and the sample itself, respectively. The expectation and variance of the minimum value \( y \) can be respectively calculated by definition:

\[
\mu_y = \int_{-\infty}^{\infty} y dF_Y(y)
\]

\[
Var(y) = \int_{-\infty}^{\infty} (y - \mu_y)^2 dF_Y(y)
\]

in which \( Var(*) \) denotes the variance.

**Variable \( z \)**

The mean and variance of Variable \( z \) can be respectively estimated as:

\[
\mu_z = \mu - h \cdot \sigma
\]

\[
Var(z) = Var(\mu - h \cdot S)
\]

in which \( \bar{\mu} \) and \( \sigma \) are the population expectation and standard deviation, respectively. Assuming the sample mean and sample standard deviation are uncorrelated, which is usually the case (Vlad and Badea 2008), yields:

\[
Var(z) = \frac{\sigma^2}{n} + h^2 \cdot Var(S)
\]

On the other hand, the variance of \( S^2 \) is (Ang and Tang 1975):

\[
Var(S^2) = \frac{\sigma^4}{4n} \left(\kappa - \frac{n-3}{n-1}\right)
\]

in which \( \kappa \) is the kurtosis of the distribution \( F_X \) in Eq. 3 (e.g. the kurtosis for the normal distribution is 3). Thus, the variance of \( S \) can be evaluated from the variance of \( S^2 \) by the Taylor expansion. The second-order approximation of the variance of \( S \) is:

\[
Var(S) = \frac{\sigma^2}{4n} \left(\kappa - \frac{n-3}{n-1}\right)
\]

Eq. 8 can be rewritten as

\[
Var(z) = \frac{\sigma^2}{n} + h^2 \cdot \frac{\sigma^2}{4n} \left(\kappa - \frac{n-3}{n-1}\right)
\]

As Fig. 3 shows, the COV of \( y \) is generally greater than that of \( z \). Furthermore, to assess how \( y \) and \( z \) would converge with different sample sizes, samples with different number of data points were randomly sampled from the data set. As Table 2 shows, the required sample sizes to achieve a specified COV for \( y \) is consistently larger than that required to achieve the same COV for \( z \).

![Fig. 3. Coefficient of variation (COV) of different criteria in evaluating design strength. (\( \mu \) and \( S \) are sample average and standard deviation, respectively)](image-url)
4 CONCLUSIONS

This paper examines two issues often encountered in deep-cement mixing works, the effect of curing period on strength variation and the criterion for prescribing a design strength, taking into account the variation in the deep-mixed soil. The foregoing discussion shows that the spread of the distribution can be reduced by converting the curing time to 28-day values; this allows the real variation to be reflected.

Comparison of the two different criteria also shows that, compared to sample-minimum type of criterion, a mean-standard deviation type of criterion would require a smaller sample size to achieve the same coefficient of variation. This indicates that the latter criterion is likely to converge to a stable value faster than the former. Sample sizes required to achieve a specified coefficient of variation are also shown. These may be useful for estimating the number of cores needed for reliability-based design.

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