Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-1257

SPT and CPT based methods to address shear strength of deep mixed soil cement columns

Utilisations de méthodes basées sur l'EPS et l'EPC pour adresser la résistance au cisaillement de piliers en sol-ciment mélangés en grande profondeur

Anand J. Puppala & Venkat Bhadriraju
Department of Civil and Environmental Engineering, The University of Texas at Arlington, Arlington, Texas, USA
Ali Porbaha
Department of Civil Engineering, California State University, Sacramento, California, USA

ABSTRACT
Deep mixing (DM) techniques using cement and lime mixtures have been used to stabilize weak soils, install excavation support, mitigate liquefaction problems and stabilize steep embankments and slopes. Rigorous quality assurance techniques are needed to assess field construction operations since deep mixed soil cement columns in the field are influenced by mixing methods, soil types, constrcution techniques, and mix design methods used in the projects. Current methods of verification of treated soil improvements using field coring and laboratory testing suffer from sampling problems such as rigidity of the sampler, locking of the sampler and rotation of the sampling core with the sampler. Hence, in situ based techniques are often used for strength based quality assessment (QA) studies. As a part of the research study conducted for the National Deep Mixing program, various case studies involving the use of in situ methods for QA studies of treated soil columns across the World are compiled. This data was used to develop different in situ methods based protocols to perform QA investigations. This paper presents two frequently used in situ methods, standard penetration test (SPT) and cone penetration test (CPT) for strength assessments. Several case study results are used to evaluate the use of these test protocols for assessing strength improvements of cement and lime treated soil columns.

RESUME:
L'utilisation de techniques de mélanges en grande profondeur avec des mélanges de chaux et ciment ont déjà été utilisées pour stabiliser les sols faibles, installer des supports d'excavation, atténuer les problèmes de liquéfaction et pour stabiliser les pentes fortes et remblais escarpés. Des techniques d'assurances qualité rigoureuses sont nécessaires pour contrôler les opérations de constructions sur le terrain car des piliers de ciment mélangés en grande profondeur sont influencés par les méthodes de malaxage, les types de sols, les techniques de construction, et des méthodes de conception du mélange utilisées pour les projets. Les méthodes de vérifications courantes pour évaluer l'amélioration des sols traités faisant appelles au carottage en chantier et d'évaluations en laboratoire souffrent de problèmes d'échantillonnages, notamment la rigidité de l'échantillonneur, blocage de l'échantillonneur et rotation de la carotte d'échantillonnage avec l'échantillonneur. D'où les techniques *in situ* sont souvent utilisées dans des études d'évaluation de qualité (EQ) basées sur la résistance. Dans le cadre d'un projet de recherche effectué pour le "National Deep Mixing program", plusieurs études de cas retrouvées à travers le monde ont été compilées traitant des méthodes *in situ* pour des études d'EQ de piliers traités. Cette information a été utilisée pour développer différents protocoles basés sur des méthodes *in situ* pour effectuer des enquêtes d'EQ. Ce rapport présente deux méthodes *in situ* fréquemment utilisées; l'essai de pénétration standard (EPS) et l'essai de pénétration à cône (EPC) pour l'évaluation de la résistance. Les résultats de plusieurs études de cas sont utilisés pour évaluer l'utilisation de ces protocoles d'essais pour évaluer les améliorations en résistance de piliers traités au ciment et à la chaux.

1 INTRODUCTION

Deep mixing is an in situ ground improvement method by blending the native soil with binders, usually cement and lime. The pratice of deep mixing applied to mitigiate liquefaction susceptibility, settlements, improving shear strength and as contaminent barriers is widely prevalent among Europe, Asia and United States. Due to the success of the deep mixing based ground treatment methods, several techniques and installation methods have been developed suiting a variety of field applications for the installation of deep soil mixing columns. As a result, new methods were introduced and labeled with various terminologies. Currently, there are more than eighteen different terminologies used to identify different types of deep soil mixing methods (Porbaha et al. 1999). Irrespective of these terminologies, the stabilization mechanisms are similar and their enhancements to soil strength and compressibility properties are considerable (Puppala, 2003).

Quality control and quality assessment in deep mixing projects by and large govern the success of the project. The quality control (QC) methods involve monitoring of magnitudes of binders, mixing rate, type of equipment relative to the project requirements and others. In general, the QC steps followed in the field will not always ensure proper soil mixing and uniform stabilization in the field. Typically, the field strengths differ from 20 to 80% of laboratory design strengths. This deviation is expected due to differences in mixing procedures and environmental variables in the laboratory and field conditions. These variations signify the need for quality assurance (QA) methods on DM treated soil columns.

2 SURVEYS ON QA PRACTICES

A wide range of in situ testing techniques including intrusive penetration and geophysical tests are commonly used to assess the extent of improvement and the success of deep mixing projects. As a part of a research study conducted for the National Deep Mixing program, extensive literature reviews and surveys from practitioners across the world were conducted to obtain details about various quality assessment methods used in deep mixing process. A survey questionnaire was hence prepared to collect details about types of QA methods used, sampling types, choice of binders and operational or practical problems experienced during in situ quality assessment tests.

Approximately 54% of the survey respondents have noted that the choice of in situ techniques depends on the type and importance of the construction project and the rest noted different criteria for selection of in situ techniques. An overwhelming majority of respondents, 93%, noted that strength was the main focus of DM projects. Compressibility was chosen by 18% of the respondents and the permeability was mentioned by 4% of the respondents. Approximately 64% of the respondents mentioned a time lag period of 28 days for performing in situ testing of DM columns. One of the common concerns from the majority of the survey responses was the need and the importance of in situ methods for better QA evaluations in the DM projects. A common discrepancy noticed among the survey responses and literature review of several case studies was that there was a lack of agreement among the practices and quality assessment techniques in deep mixing projects. Hence, an attempt was made to develop protocols for better quality assessment of DM columns using in situ methods.

3 DEVELOPMENT OF PROTOCOLS FOR QA

Several protocols were prepared for performing standardized in situ tests on DM columns. As mentioned earlier, the protocol development was based on extensive literature reviews, documented case study information, and surveys with practitioners associated with in situ methods. Currently, the protocols are still under review and should be used with circumspection and engineering judgment as it is difficult to establish universal correlations to predict strength and stiffness properties pertaining to different site conditions. Preliminary investigations of the native soil conditions are necessary to choose the type of binder, equipment and dosage levels. These protocols provide approximate Unconfined Compressive Strength (UCS) values of different site soils stabilized with various binders. In situ tests may then be performed using equipment that is suitable to the treated ground (eg. CPT cones may break when tested on high strength columns).

Typically 1-2% of the columns are randomly selected for performing in situ tests. Empirical relations to obtain strength and stiffness properties of the treated soils are developed based on available case studies involving a wide variety of soil conditions. Comparing laboratory test results on core samples should assess the interpreted properties of treated ground from in situ test methods. Such verifications will help in the modification of current test methods and the developed protocols. A good match enhances the confidence and reliability of the specific test method for conducting quality assessment studies. The following sections briefly discuss the protocols developed for two commonly adopted in situ techniques SPT and CPT.

3.1 *Protocol for SPT method*

The SPT number, N is defined as the number of blows required for a total of 300 mm penetration depth. One of the major limitations of the SPT method is the non-standardization of this test throughout the world. Different types of hammers, extension rods, and other SPT accessories have been used in various countries to drive the sampler. As a result, the energy applied in the SPT method is different in each country, which makes it difficult to generalize any test results or correlations developed. However, by applying energy related correction factor and other correction factors, the SPT number can be normalized to a standard value.

The standardized SPT value (N_{55}) is generally correlated with various soil parameters to characterize sandy and clayey soils (Liu and Hryciw, 2003). A majority of these correlations are empirical in nature and hence engineering judgment is constantly needed to verify their interpretations. The following section presents some guidelines for QA using SPT method.

3.1.1 *Guidelines for Using SPT method for QA*

The range of treated soil strength properties expected from a given project site should be estimated using soil description at the test site, binder detail and approximate time period for QA studies after DM operations. Table 1 could be used as a guide for the selection of strength in terms of UCS properties. Based on the interpreted UCS values of the treated ground, SPT rigs with appropriate efficiencies and rated energies should be selected. However, it is recommended to monitor energy dissipations from driving hammers to the treated soil columns. Approximately, 1 to 2% of the number of columns is generally evaluated for quality assessments of DM operations. Higher numbers are recommended for soft clayey materials and projects of critical importance such as those built for liquefaction resistance. Location of testing on the DM columns plays a vital role in assessing the project. The test is recommended to be performed either on the middle of the column or on the periphery of the column depending on the physical geometry of the column. In the case of overlapped columns, tests should be performed on both overlapped and non-overlapped zones. The SPT method could also be conducted at selected depth locations by performing pre-boring operations to the desired depth intervals.

The SPT results are generally reported as N values corresponding to certain energy configurations. The N values should be corrected for the borehole size, rod length and sampling tubes used during driving. The N_{55} represents the corrected SPT reading with a standard energy ratio of 55% and not corrected for overburden pressure conditions. Based on the magnitudes of the corrected SPT number, strength and stiffness properties of the treated material can be determined either from existing correlations or from charts. Practitioners should be aware of the fact that the correlations developed from different soil types may not necessarily provide accurate interpretations for other soils. Hence, selected and reduced soil sampling and subsequent laboratory testing on cores is recommended to verify the interpreted properties.

Table 1 provides the approximate range of N_{55} values that correspond to the UCS values, compiled from various deep mixing case studies reported in the available literature. These N_{55} values were derived based on the following equations 1 and 2.

Table 1. UCS Results in kPa (SPT N_{55} Values)

Soil Type	Cement	Cement-Lime	Lime
Peat	20-300 (2-30)	20-200 (2-20)	20-200 (2-20)
Organic Clays	20-300 (2-30)	20-200 (2-20)	20-150 (2-15)
Sensitive Clays	50-400 (5-40)	50-300 (5-30)	40-300 (4-30)
Clays	100-1800 (4-72)	50-1600 (2-64)	50-1400 (2-56)
Silty Clay	100-1800 (4-72)	100-1600 (4-64)	50-1600 (2-64)
Clayey Silts	100-2000 (4-80)	100-1800 (4-72)	100-1800 (4-72)
Silts	100-1600 (3-50)	100-1800 (3-54)	100-800 (3-24)
Sands	100-5000 (3-100)	100-1800 (3-54)	100-800 (3-24)

$$q_u = \alpha \times N_{55} \tag{1}$$

Where α = 0.10 for DM treated peats, organic clays, and sensitive clays; α = 0.25 for clays and silty clays; and α = 0.33 for silts and sands. For stiffness properties, the following correlation is recommended.

$$E_{25} = \beta \times q_u \tag{2}$$

Where q_u is the unconfined compression strength and β = 50 to 250 and it depends on the type of treatment. Higher values (close to 250) were recommended for cement treated and lower values (close to 50 to 100) were recommended for lime treated soils.

3.2 *Protocol for CPT method*

Cone penetration test has been increasingly used in geotechnical site characterization studies since the CPT method provides a continuous record of test data. A majority of CPT applications are in the interpretation of properties of untreated soils. Very few applications are however reported in characterizing and interpreting properties of treated soils for QA applications. The following section summarizes the guidelines for interpreting strength properties of treated soil columns using the CPT method.

3.2.1 *Guidelines for Using CPT method for QA*

The approximate strength properties of the treated ground should be established based on the soil profile, binder details and time lag for performing QA studies on columns after installation. Table 1 can be used to select the strength properties in terms of UCS values of the treated soils. The CPT rig and device should be selected as per the expected UCS levels of treated materials. For low, medium and high strength columns choose the corresponding CPT rigs with capacities ranging between 10 to 20 tons, 30 to 40 tons and with capacities above 40 tons respectively. In all cases, it is recommended to use CPTs with inclinometers, which provide the location or position of the cone in the column and to monitor the steering of the cone. The selection of the DM column and CPT test location are similar to those explained in the SPT protocol. For high strength columns, pre-boring operations are required to conduct tests at certain depths.

The following equation, which was developed based on bearing capacity models, can be used to determine the undrained shear strength of untreated and treated clays.

$$S_u = \frac{q_c - \sigma_v}{N_k} \quad (3)$$

Where q_c is the average cone tip resistance; σ_v is vertical over burden stress determined at the middle of the layer; and N_k is a factor similar to the bearing capacity factor. The N_k factor varies between 8 and 20, with the exact magnitude value depending on the plasticity index of the soil. Typically, N_k values between 15 and 20 are recommended for stiff to soft clays for strength property interpretations. Approximate range of tip resistance values that correspond to undrained strength values based on an assumed N_k value of 18 are reported in Table 2.

4 EVALUATIONS OF CPT AND SPT PROTOCOLS

Several case studies have been reported using the CPT and SPT methods for quality assessments in deep mixing projects. The protocols mentioned in the earlier sections are used in these case studies to interpret the enhanced strength properties of the treated ground and these results are compared with the strength values obtained from laboratory tests on cores or in situ tests.

4.1 *SPT Case Studies*

Three SPT case studies are reported here to illustrate the assessments of strength predictions using CPT protocols. Figure 1 and Table 3 presents comparisons between measured and SPT interpreted strength properties.

Sheills et al (2003) reported results of SPT tests performed on soil-cement columns in highly compressible organic peat. Dry mixing was proposed to support a test embankment near I-95, Virginia. The results indicated an increase in N values ranging from 5 to 20 with in the depths of 0 to 10 m. The approximate UCS values interpolated from Table 2 indicate a strength improvement of 50-200 kPa. UCS results from core samples retrieved from the column range from 0 to 250 kPa that indicate a close match with interpreted values back calculated from the protocols.

Table 2. Cone Tip Resistance and Undrained Shear Strength (from various papers published during 1996-1999 DM conferences)

Average Cone Tip Resistance in MPa	Vertical Stress in kPa (Corresponding to Subgrade Depths)	N_k	Undrained Shear Strength in kPa
1 - 2	100 (< 10 m of unsaturated soil or 20 m of saturated soil)	18	50 -100
1 - 2	300 (< 30 m of unsaturated soil or 60 m of saturated soil)	18	40-94
2 - 5	100 (< 10 m of unsaturated soil or 20 m of saturated soil)	18	100 – 270
2 - 5	300 (< 30 m of unsaturated soil or 60 m of saturated soil)	18	94 – 260
5 – 10	100 (< 10 m of unsaturated soil or 20 m of saturated soil)	18	270 – 550
5 - 10	300 (< 30 m of unsaturated soil or 60 m of saturated soil)	18	260 – 540

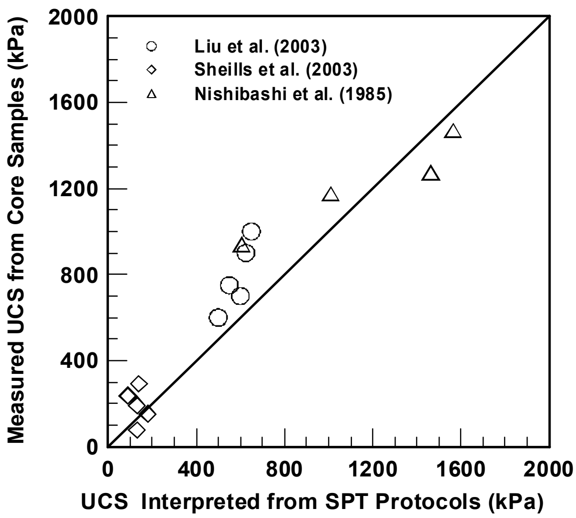

Figure 1: SPT Protocol Validation Studies

Liu et al (2003) discussed results of SPT tests conducted on soil-cement columns formed by dry jet mixing (DJM) in the Lian Yun Gong section of the Lian-Huo Freeway in China. The cement columns were 0.5 m in diameter and 8 to 13 m long corresponding to the typical thickness on an upper soft clay deposit. The interpreted UCS values corresponding to SPT N values of 5-26 are in close proximity to the strength values obtained by performing UCS tests on laboratory cores retrieved from the column.

Nishibashi et al (1985) reported the success of SPT method for quality assessment of DM columns. Similar trend was observed with the measured and present interpreted strength properties of a soil-cement column in sands as can be seen in Table 3. However, in some cases, the range of interpreted values may be higher as it may be difficult to establish correlations for varying site soil conditions.

Table 3. Case studies used in the validation of SPT protocol

Reference	Sheills et al.	Liu and Hryciw	Nishibashi et al
Depth (m)	0-10 m	0-10 m	0 - 6 m
Soil type	Organic clay	Soft clay	Sand/Clayey silt
Stabilizer	Cement	Cement	Cement
Curing time	42 days	60 days	N/A
SPT N	5-20	5-26	1-50
UCS on cores kPa	75-260	250-1000	500-1600

4.2 *CPT Case Studies*

Several DM projects reported both successful and unsuccessful applications of the CPT methods for quality assessment studies. Table 4 and Figure 2 present assessments of CPT results by comparing them with the interpreted results from the present CPT protocol. An N_k value of 18 was used since soils used in the case studies are predominantly soft in nature.

Watn et al (1999) reported results of CPT tests on lime-cement columns used for permanent slope stabilization in Norway. Based on the values from Table 2, assuming a vertical stress of 100 kPa corresponding to a depth of less than 10m and an average cone tip resistance of 1 to 2 MPa, the undrained shear strength computed from Equation 3 varies from 60 to 120 kPa. These interpreted values are in agreement with measured undrained shear strength values.

Table 4. Case studies used in the validation of CPT protocol

Reference	Watn et al.	Forsman et al.	Hansson et al.
Depth (m)	0-10 m	0-12 m	0-2 m
Soil type	Organic clay	Soft clay	Peat
Stabilizer	Cement/Lime	Cement/Slag	Cement
Curing time	40 days	N/A	N/A
Cone resistance	1-2 MPa	0-4 MPa	1-5 MPa
Vertical stress	100 kPa	300 kPa	100 kPa
N_k	18	18	18
Laboratory S_u	60-120 kPa	0-400 kPa	100-220 kPa

Forsman et al. (1999) and Hansson et al. (2001) conducted CPT studies on two different types of DM treated soils. Interpretations of present CPT methods indicate a good match between the laboratory undrained shear strength (S_u) values and interpreted strength properties as shown in Table 4 and Figure 2. The CPT interpretations are slightly closer to strength measurements than the SPT interpretations, indicating the importance of semi-empirical methods over the empirical correlations for strength property interpretations.

5 SUMMARY AND CONCLUSIONS

This paper summarizes two in situ test protocols for conducting quality assessment of deep mixing columns. As a part of the development of test protocols, surveys were first conducted worldwide. The responses from practitioners and researchers show considerable differences in quality assessment methods in various intrusive in situ penetration tests. These results along with the DM test database were used to develop SPT and CPT protocols. The interpretations of the test protocols were evaluated by researching three case DM studies each for SPT and CPT methods. There was a close match between measured and interpreted values for both methods. Slightly better match was obtained in CPT evaluations indicating the importance of semi-empirical methods in the predictions. Due to the scatter in the comparisons, it is always prudent to conduct a limited number of laboratory tests on cores to verify the interpretations. Such verification studies will expand the database and will provide better refinements of the cone penetration test protocols for future deep mixing QA studies.

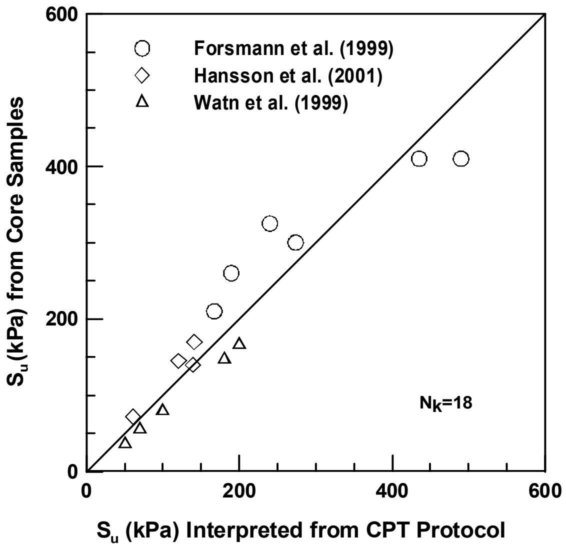

Figure 2: CPT Protocol Validation Studies

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