EFFECTIVE SAMPLING, TESTING AND SPECIFICATION APPROACHES FOR DEEP MIXING AT KITIMAT LNG, BC

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ABSTRACT

In-situ wet grab sampling and post-installation coring of soil-cement structures are typically carried out for Quality Control (QC) and Quality Assurance (QA) of deep mixing (DM) schemes. Wet grab sampling and testing is used to provide data to indicate that performance requirements are being met during production, in advance of coring, which typically occurs at 28 days or later, following installation. While unconfined compressive strength (UCS) tests from wet grab samples provide good production indicators, industry practice often requires that acceptance criteria of soil-cement structures be based on UCS results from representative core samples.

This paper outlines the approach adopted for field sampling and QA/QC testing carried out in highly variable subsurface conditions at a site located in northern British Columbia (BC), focusing on post-installation soil-cement coring and strength testing for an extensive deep mixing scheme. A discussion on suitable methods of coring soil-cement structures and appropriate selection of samples for testing that are representative of the in-situ soil-cement structures is provided. This paper also discusses the selection strategy adopted for verification of strength and modulus parameters used for design, providing spatial and time coverage, as well as the acceptance criteria implemented, and provides comparisons with published industry recommendations.

Keywords: deep mixing, unconfined compressive strength, elastic modulus, quality assurance, quality control, technical specifications

BACKGROUND

An extensive deep mixing ground improvement scheme was completed for the development of a Liquefied Natural Gas (LNG) Facility to be located in Bish Cove, BC, Canada. The deep mixing scheme was implemented to treat very weak native deposits in-situ to support two mechanically stabilized earth (MSE) walls up to 20 m (66 ft) high, and their associated bulk earthworks. Within the DM area, the subsurface conditions were highly variable, ranging from deep (up to 21 m (69 ft) thick) deposits of very soft to soft clayey silt to silty clay, overlying layers of dense to very dense gravelly sand to sand and gravel, to compact deposits of silty sand (up to 15 m (49 ft) thick), overlying dense sand and gravel. Bedrock was encountered beneath the granular deposits and generally comprised granodiorite with occasional andesite dykes.

DM panel depths ranged from 5 m (16 ft) to 30 m (98 ft) and were constructed by treating approximately 73,900 m^3 (96,658 yd^3) of soil to meet project-performance requirements. The design of the DM scheme for this project was based on assessment of the stress-deformation response of the ground improvement structure when subjected to static and seismic load conditions. Extensive deep mixing was required to provide foundation support for two MSE walls up to 20 m high; slope stability (for both onshore and nearshore conditions, as the site was located immediately upslope of Bish Cove); liquefaction mitigation; and, lateral confinement of the native weak soils. To meet the design requirements for shear, tensile and compressive stress, as well as the deformation requirements of less than 100 mm (4 in.) at the top of the DM area, DM panels were constructed with average UCS values exceeding 2.5 MPa (363 psi) at 56 days.

Details of the DM design including project constraints; project-specific performance requirements; project background information; design philosophy; analysis results; and final DM arrangement are presented by Li et al. (2014 a and b). Details of the construction aspects of the Kitimat LNG deep mixing including challenges associated with the construction and quality control of a large deep mixing scheme in highly variable subsurface conditions at a remote location with barge-only access are presented by Wilson et al. (2014).

The objectives of this paper are to discuss the strategy adopted at the Bish Cove site for the technical specification of QA/QC sampling and testing to verify that project-specific performance requirements were achieved. The findings from a review of the extensive QA/QC data for the Bish Cove site is compared with published industry guidelines indicating the need for project-specific refinement and enhancement of industry guidelines for the technical specification of QA/QC sampling and testing for deep mixing.

DEEP MIXING TECHNICAL SPECIFICATIONS

The construction of the DM area was based on meeting project-specific performance criteria derived from the detailed design process. Based on the design requirements, the DM area was required to yield a homogeneous mixture of cement and in-situ soils with an area replacement ratio (ARR) of approximately 0.3 and target design UCS values of 1.7 MPa (247 psi) at 28 days and 2.5 MPa (363 psi) at 56 days. Table 1 presents the final DM design configuration and strength requirements for shear, compression and tension.

Table 1. Summary Configuration and Strength Requirements of Deep Mixing Area

Deep Mixing Area	Area Replacement Ratio	Design Unconfined Compressive Strength of DM panels at 56 days, q_{dm} (MPa)	Design Requirements[1]		
			Shear (kPa)	Compression (kPa)	Tension (kPa)
Composite DM zone	0.3	2.5	250	500	50
Longitudinal wall of DM panels	1.0	2.5	600	1,250	50

1 Shear strength, compression and tension values presented are for fine-grained soil-cement.

Details of the DM design including the load-deformation assessment to determine the distribution of the shear, tensile and compressive stress and strains and development of the DM design to accommodate these stresses under static conditions are presented by Li et al. (2015).

Recognizing the variability of the subsurface conditions and therefore, the strength and elastic modulus properties likely achievable for the DM area, the acceptance criteria outlined in Table 2 were defined and specified for the Bish Cove site.

Table 2. Summary Acceptance Criteria for Deep Mixing

Area of UCS Testing	UCS[1] Testing requirements (with axial strain measurement)	Target UCS Values
At each individual DM panel	At least 80% of tested wet grab and at least 80% of tested cored soil-cement samples	1.7 MPa at 28 days and 2.5 MPa at 56 days
All DM areas	Any individual UCS test (absolute minimum)	1.7 MPa at 56 days
Overall Project	At least 90% of tested wet grab and cored soil-cement samples	1.7 MPa at 28 days and 2.5 MPa at 56 days

As the shear, compression and tensile strength properties of the DM panels could be estimated based on the UCS and the elastic modulus values of the DM panels, the design-build team concluded that for ease of mass verification in the field to obtain consistent test results, UCS testing with axial strain measurement be specified for testing and confirmation of acceptance. The sampling and testing requirements specified for the Bish Cove site are presented in Table 3.

Table 3. Summary Deep Mixing Sampling and UCS Testing Requirements

Option[1]	Sample Type	Sampling Frequency	Sampling Depths	UCS Tests (with axial strain measurement)
1	Wet grab soil-cement	At least 1 set[2] of samples from 20% of installed DM panels	Sampling at 5 m depth intervals[3]	A set[2] of UCS tests per sampling depth consisting of: • Two UCS tests at 14 days • Two UCS tests at 28 days • Two UCS tests at 56 days
1	Cored soil-cement	At least 1 continuous core for 1% of installed DM panels	Continuous coring to at least 1.0 m below bottom of DM panels. Sub-sampling of core soil-cement samples from 5 representative depths[4].	Five UCS tests on samples at 28 days or greater
2[5]	Cored soil-cement	At least 1 continuous core for 2% of installed DM panels is required	Continuous coring to at least 1.0 m below bottom of DM panels. Sub-sampling of core soil-cement samples from 5 representative depths[4]	Five UCS tests on samples at 28 days or greater

1 Option 1 or Option 2 could be applied on a parcel by parcel basis or on the basis of the entire project, as indicated in Fig. 1.
2 A sample set consists of at least 6 samples for UCS testing.
3 With 1 sample to be collected within top 6 m (20 ft) and 1 sample within bottom 2 m (7 ft) of DM panels. Remaining samples could be obtained from mid-depth and towards the bottom of the fine-grained soils zone.
4 At varying depths per DM panel.
5 Where the total number of wet grab sampling is less than 20% of installed DM panels, instead of Option 1, where a combination of wet grab sampling and core sampling is required, increased core sampling (i.e. from 1% to 2% of installed DM panels) could be adopted to meet acceptance criteria.

QA/QC SAMPLING AND TESTING

Strategy

To verify that the project-performance requirements had been met in construction, a strategy was developed that would allow sufficient sampling and testing to be completed particularly to assess the following aspects:

1. **Critical areas of DM** design;
2. **Variable subsurface conditions** and therefore the influence on soil-cement structure, e.g., fine-grained deposits, granular deposits, interbedded silt layers, localized organic material, and natural obstructions that included wood and cobbles;
3. **Varying grout mix designs** e.g. changes in water-to-binder ratio, and quantity of binder factor; and,
4. **Changes in construction operation** that may affect the end-product of the soil-cement mixture e.g. CSM operators including batching plant operators, shift changes (day and night shifts and staff rotations), and variations in cutting fluid (water, bentonite or cement slurry) used.

The sampling and testing strategy adopted was based on obtaining a sufficient spatial coverage over the entire DM area, with targeted sampling carried out at critical locations, and reasonable time coverage to enable representative sampling and testing to be carried out over the extent of the construction period. While it may be reasonable to specify sampling and testing at regular intervals to ensure all areas have been assessed, in practice a fixed periodic sampling regime could not be carried out at the Bish Cove site due to operational constraints that included: breakdown of sampling equipment and/or supporting crane; adverse weather conditions affecting sampling ability (i.e., high wind and/or lightning conditions); limitations of equipment (i.e. panel too deep to sample using the available wet grab equipment); and variable quality of samples cast due to unsuitable preparation, curing and/or storage of samples.

In order for the sampling review process to be carried out in a timely manner to optimize the effect of technical support given during construction, post-installation coring locations were selected to supplement areas where insufficient representative wet grab sampling was undertaken. Taking into consideration the variable subsurface conditions, selected areas that included extensive fine-grained deposits were identified for predominantly core sampling, and other areas that included significant granular soils were identified for predominantly wet grab sampling. Based on previous soil-cement drilling experience, HQ sized triple-tube coring through sand and gravel soil-cement mixtures had shown particular difficulty in recovering cores that were representative of the in-situ conditions (i.e. washing out of fine and soft material during drilling and/or significant core loss due to the variable, relatively weak matrix containing soft cement zones and hard, granular zones). Recognizing that the strength of the granular soil-cement mixtures were likely to achieve higher UCS values compared with fine-grained soil-cement mixtures for the same grout mix design, it was considered more suitable for these areas to be sampled using wet grab techniques. As indicated in Fig. 1, the DM area was subdivided to take into consideration sampling constraints and the above listed assessment factors.

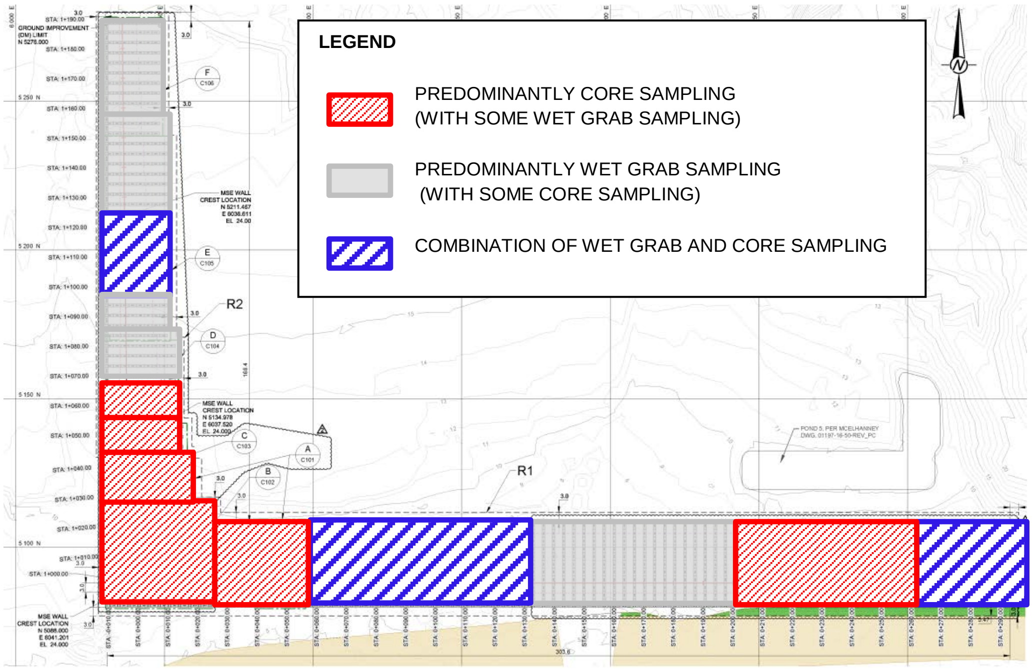


Fig. 1 DM Plan Showing Wet Grab and Core Sampling Locations

Table 4 summarizes the wet grab and core sampling completed on the project including the number of UCS tests completed as part of the QA/QC program.

Table 4. Summary Actual Wet Grab and Core Sampling and UCS Testing

Type of sample	Number of DM panels sampled	UCS tests completed
Wet grab	230 (14% of total DM panels installed)	4,125
Continuous core	49 (3% of total DM panels installed)[1]	617
	Total Number of DM panels sampled = 279 Total Number of DM panels installed = 1,645	

1 Coring, sampling and UCS testing were completed on approximately 3% of the total number of DM panels installed so that the quality of the DM panels were adequately assessed across the project site, as well as assessing specific conditions where obstructions, anomalous conditions and/or inconsistent construction monitoring data were obtained. The criteria for selection of panels for continuous coring are summarized in the section below.

Coring

The criteria for selection of panels for continuous core sampling included one or more of the following conditions:

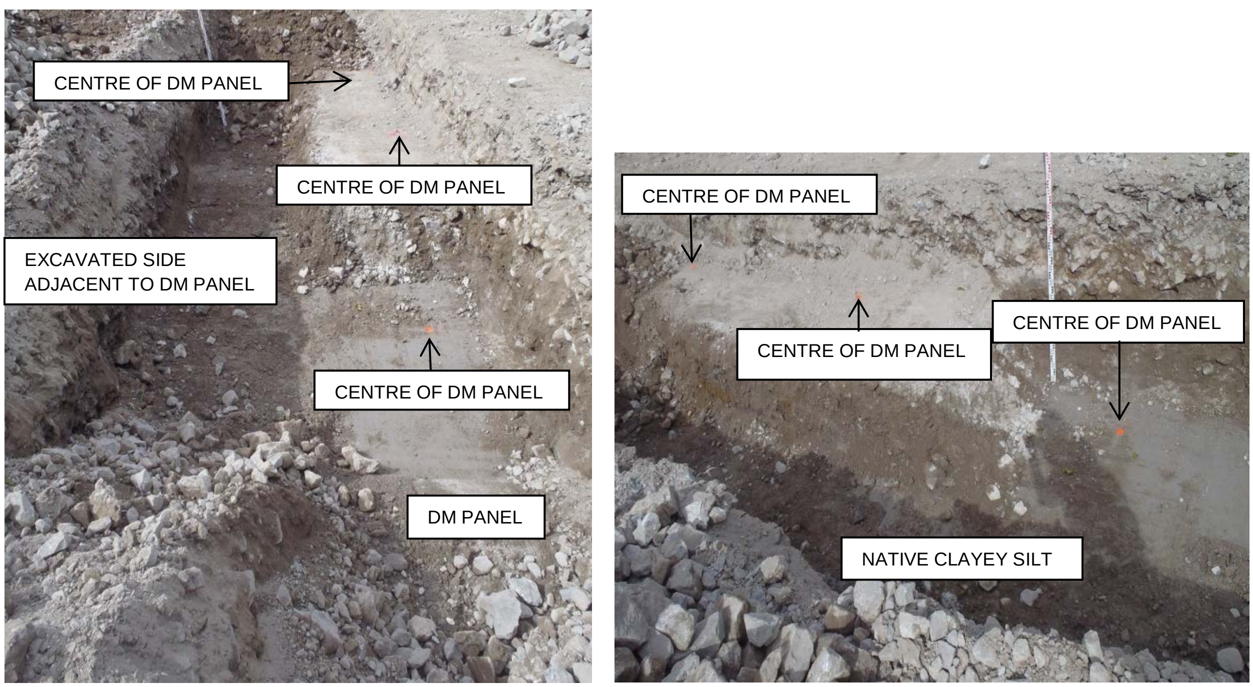
1. DM panel consisting of a significant portion of fine-grained soils;
2. DM panel consisting of highly variable native soils (clayey silt interbedded with silt and sandy silty layers);
3. Adjacent panels that were constructed more than 56 days apart to verify overlap between panels including assessment of potential “cold joint” zones;

4. Obstruction(s) encountered during panel construction, restricting termination depth;
5. Anomalous conditions that could affect long-term performance of DM panel meeting project requirements e.g. inconsistent cutting/filling slurry consumed, and highly variable in-situ moisture content of native soils that could affect water-to-binder ratio; and,
6. Inconsistent construction monitoring data from DM operation (e.g., loss of drill rig monitoring data such as volume of filling slurry consumed, rotational speed of cutter wheel data, etc.)

Continuous core sampling carried out at the Bish Cove site consisted of HQ sized cores drilled in run lengths of 0.5 m (2 ft) to 1.5 m (5 ft) using mud or polymer-based drilling fluids. The cores were drilled from the existing working platform elevation and extending to at least 1.0 m (3.3 ft) below the bottom of the DM panels.

Generally, it was observed that the quality of the uppermost core run typically resulted in less than 80% of core recovery with highly fractured core runs resulting in soil-cement samples that were unsuitable for UCS testing, i.e. less than the standard 2 length (L):1 diameter (D) ratio. Initially this gave rise to questions as to the technical compliance of the upper portion of the DM panels.

To more readily assess the surface conditions of the top of the DM panels, the approach summarized below was consequently adopted for all cored DM panels i.e., 49 DM panels (3% of total DM panels installed). In addition, six barrettes were partially exposed i.e., at least three to four panels within a barrette were exposed consistent with the approach presented below and shown in Fig. 2.



Top of Panel in North-South direction

Top of Panel in East-West direction

Fig. 2 Exposed Top of DM Panels

a) Mechanically excavate the bulk of the existing working platform material to uncover the top of the selected panel;
b) Within approximately 0.5 m (1.6 ft) from the top of the DM panel, hand dig to expose the top of the DM panel;
c) Expose the top of the DM panel in plan including partially exposing adjacent overlapping panels;
d) Expose along one side of the DM panel to at least 1.0 m (3.3 ft) below the top of the panel;
e) Using the excavator fitted with a ditching bucket, mechanically scrape the top of panel removing all native and soft soil-cement material until panel becomes difficult to expose (i.e. high-pitched scraping sounds and small chippings breaking off from the panel);
f) Visually inspect the top of the DM panel and locally probe the upper 0.3 m (1 ft) of the panel for soft spots; and,
g) Backfill the top and the side of the DM panel with fine to medium coarse sand.

Based on experience from previous projects and initial coring efforts at this site, a variable rate of coring was adopted and modified for each coring location. Coring rates were adjusted relative to the anticipated matrix of the soil-cement to maximize recovery of continuous cores; to reduce the amount of mechanical breaks to the soil-cement cores; limit "washing out" of fine-grained material within the soil-cement cores; and reduce potential damage to the DM panels. Table 5 presents the rate of coring applied for coring HQ sized soil-cement containing fine-grained deposits to granular native soils with UCS values ranging from approximately 1.9 MPa (275 psi) to 10.0 MPa (1,450 psi) (excluding outlier values) with an average UCS value of 4.5 MPa (653 psi).

The quality of coring was highly dependent on the experience and judgment of the driller, particularly in timely identification of changes in soil-cement strength and consistency, indicating modifications required to the core sampling process. Modification to the coring process included adjustment to the applied coring pressures, coring rate, consistency and type of drilling fluids, and core run lengths. Where evidence of gravel was found trapped in the drill bit, core run lengths were reduced to minimize core loss. As indicated in Table 5, the rate of drilling is dependent on the relative strength and consistency of the soil-cement. The core box photographs presented in Figs. 3A and 3B are examples of poor and good core recovery, respectively.

Table 5. Summary Coring Rates

DM matrix	Rate of Coring (min/1.5 m) [average]	Coring Techniques	Observations (per 1.5 m run)
Fine-grained soil-cement (clayey silt to silty clay and silt)	16 to 30 [20]	Low pressures applied to advance coring	• <50% core recovery • Predominantly within initial 1.5 m of coring
	16 to 20 [18]	Low pressures applied to advance coring	• 80% to 100% core recovery • For relatively "soft to firm" soil-cement mixture
	11 to 15 [13]	Medium pressures applied to advance coring	• 80% to 100% core recovery • For relatively "hard" soil-cement mixture
Granular soil-cement (sandy silt to sand and gravel)	8 to 15 [11]	Medium to high pressures applied to advance coring	• 90% to 100% core recovery

Core Test Sample Selection

Initial visual inspections of core samples were undertaken by the QA representative, ignoring assessment of the top 1.5 m of core, which was investigated as described above. The selection of samples for UCS testing relied heavily on the experience and judgment of the QA representative. Adequate training and experience is necessary to ensure consistency in visual inspection of core boxes and selection of representative core samples. For the Bish Cove DM project, the critical areas for strength verification were generally within the top 5 m (16 ft) of the DM panels, and within the fine-grained portion of the DM panel, where typically strengths will be lower. Higher strength soil-cement is more readily achieved within the granular portion of the DM for a consistent cement-slurry content. The selection of representative soil-cement samples considered approximately 80% of the UCS testing being predominantly undertaken on the fine-grained portion of the DM panels (up to 20 m depth), with the remaining 20% of the UCS testing completed on the granular portion of the DM panels (generally bottom 2 m (7 ft) to 3 m (10 ft) of panels).

Fig. 3A Core Box Photographs showing poor quality cores recovered at approximately 1.5 m (5.0 ft) runs

Fig. 3B Core Box Photographs showing good quality cores recovered at approximately 1.5 m (5.0 ft) runs

Selection of core test samples was generally evenly distributed with depth, with staggering of sampling depths to provide improved depth coverage over the DM area. The criteria for selection of samples for UCS testing included: soil-cement that was representative of the as-built conditions of DM panels (i.e. not consistently assessing the "weakest" or "strongest" zones for testing); reasonable quality samples (i.e. at least met, or exceeded the aspect ratio of 2(L):1(D)); no micro-fractures or mechanical breaks; no large voids or surface pitting due to loss of granular component; and no large solid components such as gravel and cobble fragments. The use of Rock Quality Designation (RQD) and fracture indices (FI) were not considered appropriate as part of the qualitative assessment of the soil-cement core samples as often the initial RQD and FI values could provide non-representative indications of the quality of the soil-cement core samples for weak soil-cement (i.e. soil-cement with UCS values of less than 3 MPa (435 psi) to 4 MPa (580 psi), considered as hard soil or very weak rock). The initial RQD value could be significantly lower and the FI value could be significantly higher if mechanical fractures were taken into consideration. The RQD and FI values also do not take into consideration the presence of microfractures and imperfections that could impact on UCS testing.

At select locations where core recovery was generally less than 80% per 1.5 m (5 ft) core run and/or the quality of core samples was deemed unsuitable for UCS testing, video logging to assess the side walls of the cored hole was undertaken. The ability to undertake video logging of cored holes throughout the depth of the DM panel has proven to be useful in assisting with the assessment of the quality of DM panels. Particularly for instances where coring and sampling has provided inconclusive results of the quality of the DM panel (i.e., poor core recovery and/or poor quality of core samples recovered; or inconsistent observations noted during drilling such as fast drilling through particular depths. For the Bish Cove site, video logging was successfully applied at selected DM panel locations to verify the quality of the panels (i.e., in one instance the quality of the soil-cement matrix within the mid-depth, fine-grained zone of a DM panel was confirmed to be of poor quality and remedial works were carried out; another instance verified that the quality of the DM panel within the bottom 5 m (16 ft) of the DM panel, within the granular zone was sound and poor core recovery was likely due to the presence of gravel and cobble fragments within the soil-cement matrix, which would have impacted the ability to obtain good quality HQ sized core samples). The cost of video logging is relatively inexpensive compared with replacement coring, and therefore, video logging is recommended to be considered as an additional quality assessment tool, particularly for large-scale projects.

QA/QC DATA REVIEW

Review of the UCS test data was also undertaken by experienced QA/QC representatives, knowledgeable in the technical aspects of the project. Initially, assessment of the soil-cement samples, to confirm that they were representative of the as-built DM panel conditions, was undertaken. The detailed review of the soil samples included: description of sample; aspect ratio; moisture content; densities; stress versus axial strain response; and failure mode. Where UCS values fell below the target values presented in Table 1, further assessment was undertaken. Investigative measures included: visual assessment and selection of samples within the immediate vicinity of non-compliant UCS results; coring of adjacent DM panels and UCS testing; and review of the recorded video logging of the cored hole.

From the QA/QC data obtained from UCS testing with axial strain measurement on a total of 1,443 soil-cement samples at 28 days and greater, consisting of 878 samples of clayey silt to silty clay soil-cement mix (539 wet grab samples and 339 cored samples), 518 samples of sandy silt to silty sand soil-cement mix (471 wet grab samples and 47 cored samples), and 47 samples of sand and gravel soil-cement mix (30 wet grab samples and 17 cored samples), the ratio of the elastic modulus E_{50} to UCS value of the DM, q_u, was assessed (Li et al., 2015). The summary E_{50} to q_u values for fine-grained soil-cement and granular soil-cement mixes are presented in Figs. 4 and 5, respectively.

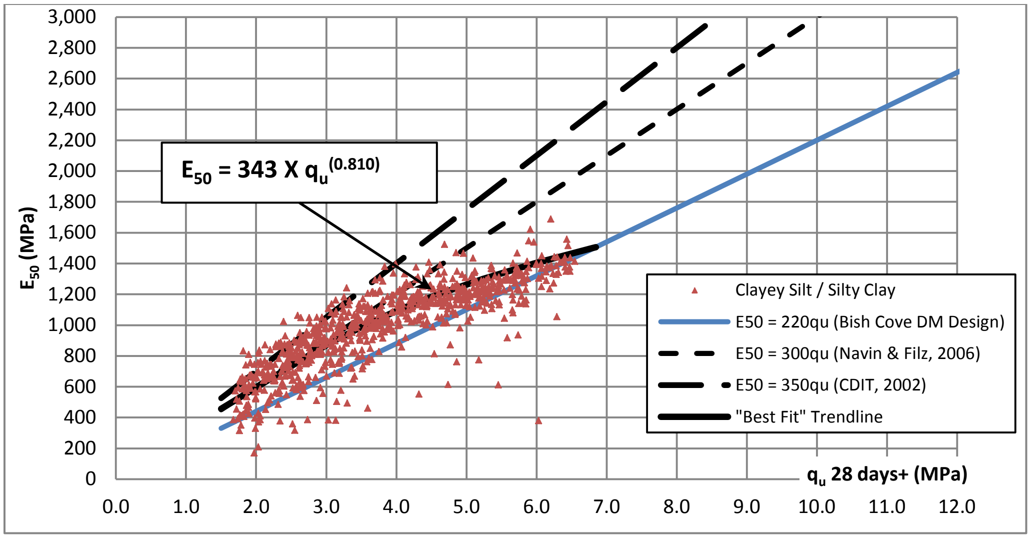


Fig. 4 Elastic Modulus derived from UCS data for fine-grained soil-cement mix

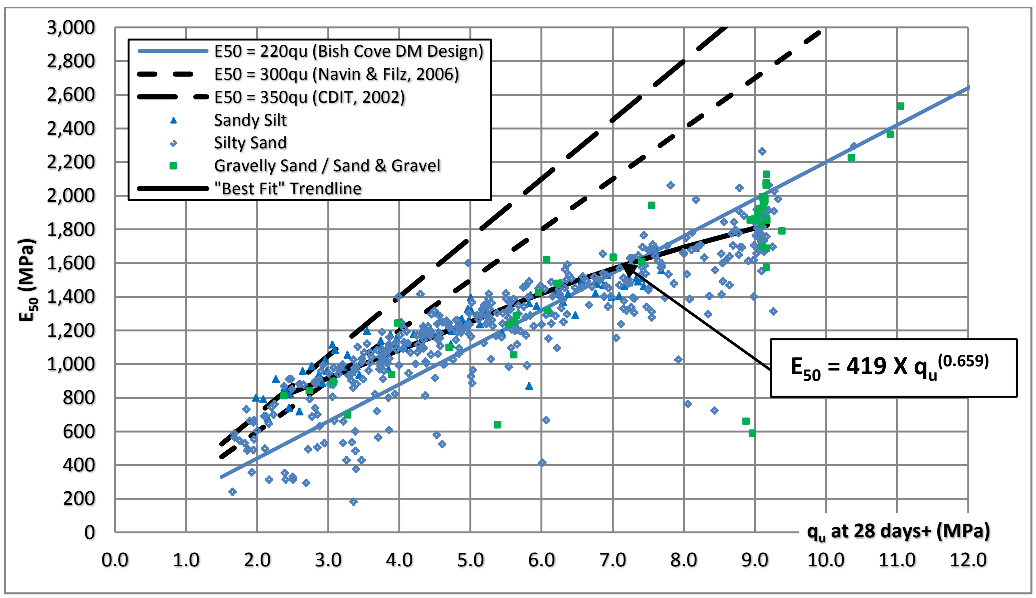


Fig. 5 Elastic Modulus derived from UCS data for granular soil-cement mix

CONCLUSIONS

Industry guidelines for deep mixing (Bruce et al., 2013), provide a good basis for technical specification of projects. Consideration should however be given to additional detailed specification, beyond published industry guidelines (Bruce et al., 2013) for sampling and testing requirements for complex projects or sites with challenging subsurface conditions and/or stringent project-specific performance requirements. Project and site-specific requirements that should be considered include: targeted sampling frequencies and testing for spatial coverage; targeted sampling frequencies and testing for variable native soils present; and prescriptive measures for sampling and testing for acceptance.

Strategies for sampling and testing including appropriate criteria for acceptance are recommended. Consideration should be given to the variability of the subsurface conditions; gradation of the native soils;

method of mixing; and availability of supporting QA/QC data for review, including real time construction monitoring data. Combined with a suitable strategy, experienced and knowledgeable field representatives are required to undertake the QA/QC tasks. Suitable training and monitoring for consistency in engineering assessment and judgment is also recommended.

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REFERENCES

Bruce, M.E.C., Berg, R.R., Collin, J.G., Filz, G.M., Terashi, M. and Yang D.S. 2013 Federal Highway Administration Design Manual: Deep Mixing for Embankment and Foundation Support. Report No. FHWA-HRT-13-046. Contract/Grant No. DTFH61-06-C-00039.

Li, M.S.W., Olivera, R.R., Williams, R.R. and Wilson, B.W. 2014a. Deep mixing ground improvement design to support large MSE walls for Kitimat LNG, BC, Deep Foundations Institute, 39th Annual Conference on Deep Foundations, Atlanta, GA.

Li, M.S.W., Olivera, R.R., Williams, R.R., Atukorala, U.D. and Wilson, B.W. 2014b. Design of a deep soil mixing ground improvement program to support large MSE walls for Kitimat LNG at Bish Cove, British Columbia, Canadian Geotechnical Society, Vancouver Geotechnical Society 22nd Symposium on Foreshore Engineering, Vancouver, BC.

Li, M.S.W., Williams, R.R., Wilson, B.W., Filz, G.M. and Bruce, D.A. 2015. Load-Deformation based design of deep mixing for supporting MSE walls at Kitimat LNG, BC, Deep Foundations Institute, Deep Mixing Conference, San Francisco, CA.

Wilson, B.W., Coull, J.A. and Siddle, D.J., 2014. Construction of a ground improvement scheme to support large mechanically stabilized earth (MSE) walls in Kitimat, B.C. – using Cutter Soil Mixing, Deep Foundations Institute, 39th Annual Conference on Deep Foundations, Atlanta, GA.