Mass stabilization quality control methods

Méthodes de contrôle de la qualité de masse stabilization

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ABSTRACT: This article presents applicability of sounding and sampling methods for quality assurance (QA) of mass stabilized soil, and the soil parameters that can be determined using these methods. The target is also to provide recommendations and background information concerning the QA methods utilized for mass stabilized soil. During shallow depth mass stabilization binder is mixed into soft soil using a mixing tool. QC starts during the mass stabilization (deep soil mixing) work process in order to optimize the stabilization work and continues as QA after the stabilization work to verify the strength increase and the homogeneity of stabilized soil. Stabilized soil differs from virgin soil and thus the modified QA sounding methods, large quantity of soundings and statistical analyzing of the results are needed. The QA methods utilized vary according to the site and the construction goals. On the basis of the experience during last decades it can be stated that quite a many QA methods are suitable for investigation of the geotechnical parameters of stabilized soil as discrete tests but only a few of the methods are suitable for day-to-day QA of production mass stabilization.

RÉSUMÉ : Cet article présente des méthodes d'enquête qui ont été utilisés pour le contrôle de la qualité (CQ) du sol masse stabilisé (stabilisation profonde) et quels paramètres peuvent être déterminées par ces méthodes. Elle donne aussi quelques recommandations et des informations générales concernant les méthodes de CQ. En masse stabilisation le liant est mélangé au sol mou avec un outil de mixage. Le sol stabilisé diffère de la terre vierge donc les méthodes de sondage de CQ ont leurs caractéristiques propres. Ces méthodes sont différentes selon le site et le but. Certaines méthodes sont bien établies par exemple dans les pays nordiques, mais sur les continents où la masse stabilisation n'est pas une norme, le CQ peut être réalisé avec des méthodes disponibles appliquées localement. Les exigences et les objectifs pour le liant, les travaux de stabilisation et le sol stabilisé endurci sont définies dans les documents de conception et pour le contrôle de qualité dans le plan de CQ. Le CQ commence pendant les travaux afin d'optimiser le travail de stabilisation et continue après pour vérifier le durcissement de sol stabilisé.

KEYWORDS: mass stabilization, deep soil mixing, quality control (QC), quality assurance (QA), soundings, shear strength, modulus

1 INTRODUCTION

The application of mass stabilization techniques alters the technical and environmental properties of soft soil in such a way that it is possible to construct directly on top of the mass stabilized soil, or to utilize it as filling or construction material. All mass stabilization projects utilize a binder, or chemical stabilizing agent which reacts with the soil mass to change its properties. The primary applications of the method can be divided into two groups - stabilization of soft soils on site (in situ) or stabilization of excavated / dredged sediments off site (ex situ). With the current equipment, the attachment of a mixing unit to an excavator allows for carrying out stabilization to the maximum depth of 6 to 8 meters, providing the conditions are favorable. The soil types which have been mass stabilized include among others peat, mud, clay, silt, or waste materials such as sludge.

The mass stabilization method was developed in Finland in the early 1990s. The past decades have brought fast development of mass stabilization equipment, binders and various new applications (Lahtinen & Niutanen 2009). The method has been implemented in numerous countries, in various infrastructure and environmental engineering applications, proving to be economical and eco-efficient solution. The principles of Finnish mass stabilization method have been presented in the standard EN 14679 (2005) and in the Handbook (Forsman et al. 2015).

2 STAGES OF MASS STABILISATION PROJECT

The main stages of the mass stabilization project implementation in practice can be envisaged as a nine step process as follows: 1. Initial data collection, 2. Preliminary investigations and design, 3. Preliminary stabilization studies, 4. Design, 5. Actual stabilization studies, 6. Competitive bidding, 7. Stabilization contract work, 8. QC and 9. QA studies and reporting. Many of project phases proceed simultaneously and require interaction between engineer and contractor to ensure that stabilization is carried out according to plan. The extent and methods of performance testing of QC/QA shall be defined in the plans and specifications for each individual case. Each mass stabilization project requires a target-specific site organization plan which describes how the contractor should implement stabilization works and perform QC/QA to ensure adherence to design standards. The site organization plan is based on work specifications which can be supplemented by the contractor with such issues as, for instance, the contractor's own QC actions.

The contractor's own QC takes place simultaneously with the progress of mass stabilization works. In practice, this means the surveillance actions concerning the quality of the masses to be stabilized (e.g. water content), observing conditions encountered in the site compared to those described in the plans, monitoring the quality and the quality fluctuations of the stabilized masses, measuring the amount of binder addition, following the progress of hardening process, as well as ensuring the homogeneity and compression strength of the final product. Early results of QC allow the remaining stabilization works to be adjusted to fulfil the design objectives. The QA concentrates on the strength properties and homogeneity of the stabilized soil. Normally an external quality assurance inspector is employed for the duration of the implementation works of QA to ensure independent results. (Forsman et al. 2015; Junnila et al. 2010)

3 QUALITY ASSURANCE METHODS

Various QA methods have been experimented since the first applications of mass stabilization. Many of the methods established in use have been designed fundamentally for the Nordic column stabilization method but have proven to be appropriate for the mass stabilization also. Most of QA methods proposed in literature for determination the quality of stabilized soil are presented in Table 1. Some of these methods are suitable for QA of mass stabilization, but not all. The key elements which differentiate mass stabilized soil from column stabilized soil are the strength and the continuity of the treated soil and the thickness of the stabilized soil layer. Mass stabilized soil is a shallow continuum whereas columns are discrete long and slender elements surrounded by untreated soil; thus, each sounding advanced into mass stabilized soil is performed within the treated soil mass, as opposed to stabilized columns in which the sounding may pass easily out of the column to the untreated soil (this problem is particularly acute in QA of longer columns).

The design shear strength varies normally between 30 and 80 kPa for mass stabilized soil, between 80 and 200 kPa for column stabilized soil in Nordics, and up to 1000 kPa for columns e.g. in Japan. As such, it is clear that the behavior of the stabilized soil with shear strength 30 kPa shall be expected to differ from that of treated soil with strength 300 or 900 kPa. Lower strength of mass stabilized soil is a primary reason why many methods suitable or promising for QA of column stabilized soils are not necessarily applicable for mass stabilized soil.

Heterogeneity is common and typical for mass stabilized soil due to variability in the mixing process and in the soil. Therefore, it is necessary to carry out a sufficient number of QA tests. In order to determine shear strength, a minimum of ≈10 representative soundings (e.g. column penetrometer) should be performed and at least ≈3 vane shear tests should be carried out from a given subarea. At a given subarea the binder recipe is held constant and the size of the area is limited (control includes geology, soil properties, dimensions of stabilized area, etc.). In a larger project there can be dozens of subareas.

Because of heterogeneity of mass stabilized soil, statistical methods should be implemented for evaluation of soil parameters from individual tests. To increase the representativeness and the statistical confidence of the results, the quantity of the soundings has to be increased when the area of the tip is smaller and the quantity can be lower when the area of the tip is larger.

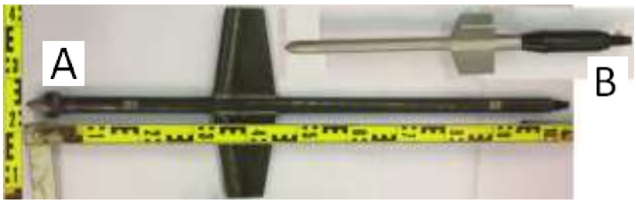

Figure 1. Column (A) and vane penetrometer (B) for columns. The dimensions of the tip A are presented in the standard EN14679 (2005) and in handbook (Forsman et al. 2015) and of tip B in handbook.

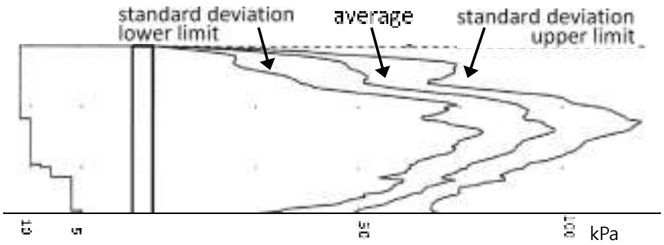

Figure 2. Principle of column penetrometer results from mass stabilized soil layer (z ≈ 2.5 m). On the left is the quantity of the soundings and on the right is presented average shear strength and standard deviation.

3.1 *QA sounding methods commonly applied in Nordics*

The most commonly employed sounding method, column penetrometer (Figure 1), enjoys wide and established use in the Nordic countries. The intent in the column penetrometer (Table 1 row 1) is to measure indirectly the shear strength of stabilized soil from penetration resistance. The tip of penetrometer is compressed into the stabilized soil and the force needed to penetrate the soil is measured from the surface-end of the sounding rod. The measurement of static penetration resistance is continuous at 0.04 m intervals. The measured penetration resistance is converted into shear strength by dividing it by the bearing resistance factor N_c=10-15 (Halkola 1999). In very low strength stabilized soil the factor is even larger (Halkola 1982; Melander 2017). When the strength of stabilized soil is excessively high for static penetration (τ > ≈200 kPa), the methodology is shifted to dynamic penetration in which case the blow count per 0.20 m is counted (the process is much like that of the Dynamic Probing or Standard Penetration Test). The resolution of the results is decreased by changing methodology, but under most circumstances the dynamic penetration is rarely needed in the QA of mass stabilization. The principle of the column penetrometer test results are presented in the Figure 2.

Pull out resistance test PORT, utilizing similar tip geometry as that of the column penetrometer, has been used for QA of stabilized columns in Sweden (Table 1 row 2). The advantage of such a method is minor risk of the tip coming out of the column. In mass stabilized soil such risk does not exist and PORT isn't a reasonable method in QA of mass stabilized soil.

The vane penetrometer method is also used to investigate the shear strength of stabilized soil (Table 1 row 3). The tip of the penetrometer is rotated at designated depths at interval 0.5 or 1 m. Torque required to rotate the vane is measured and correlated directly to shear strength assuming vane form cylindrical sliding surface in the ground. The friction between soil and rods is tested by rotating the rods while keeping the vanes stationary.

3.2 *Other sounding methods*

CPT-sounding (Table 1 row 5) has been broadly examined for QA-method of stabilized soil in the 1980's and 1990's by the City of Helsinki and by VTT Technical Research Centre of Finland (Halkola 1999; Laaksonen 1995). The advantage of CPT is measuring force from the tip, and thus the shaft friction is excluded from the results. Additionally, friction between the soil and the tip is measured at the tip of the device, as well as the pore water pressure. The downside of CPT is the sensitivity of the tip. As many parameters are measured using electrical sounding methodology, the tip cannot sustain any dynamic penetration (striking with a hammer) or rocks in the soil. Additionally, the area of the tip is only 10 cm^2 so the representativeness of the results of one CPT sounding is limited.

The combined static-dynamic penetration test with special 50 cm^2 tip is performed the same way as the column penetrometer test, but a constant rotation is applied to the rod (Table 1 row 4). Another difference between the methods is in the tip that is a cylindrical cone with a cross-sectional area of 50 cm^2. The benefits are the reduced shaft friction of the rods and the easy penetration of the aggregate fill layer over mass stabilized soil.

Standard penetration test (SPT, Table 1 row 6) is internationally widely used to examine natural soils. The test is also used for column stabilized soils in Japan but it is not necessarily reliable with mass stabilization. The diameter of the tip is relatively small and the height of the tip is high (≈0.7 m) which means that main part of the measured force is from the shaft friction and minor part is from the bottom of the tip. This may result in uncertainties interpretation of shear strength.

Swedish weight sounding (Table 1 row 7) is used for natural state soils (clay or silt) for many decades in Nordics. However, it is not considered applicable for the mass stabilized soils.

Modified total sounding (Table 1 row 8) has been tested in Sweden. The interpretation of shear strength for medium or very hard column stabilization has been applicable. (Bergman 2012) Method has not been tested for mass stabilized soil.

4 OTHER QUALITY ASSURANCE METHODS

Pressuremeter, screw-plate test and plate load test (Table 1 rows 9, 10 and 11) are suitable methods for determination of deformation parameters (modulus) of stabilized soil but they are comparatively time-consuming and expensive methods giving only discrete results. The plate load test is carried out on surface of stabilized soil and provides no information deeper than the diameter of the loading plate. In practice those methods are not suitable QA methods for production mass stabilization projects.

Soundings are the most frequently used QA methods but there are also other methods, e.g. geophysical methods (Table 1 row 12). Different kind of seismic methods have been tested especially in Japan in 90’s for column stabilization but the interpretation of results remains rather difficult and uncertain even for the hard columns. The same conclusion has been presented by Ruotsala (2011) concerning geophysical down hole methods (acoustic, radiometric). It seems that seismic methods are not yet applicable for QC of mass stabilization.

Dynamic compaction assurance method (Table 1 row 13) has been tested 2002 in Finland, but that method has been proven only capable of assessing roughly the homogeneity of mass stabilized soil. Impact acceleration test (Table 1 row 14) is not applicable for QA of mass stabilized soil.

The index properties (w, LOI, pH-value) and binder concentration (amount, distribution) can be measured from disturbed or undisturbed samples (Table 1 rows 16-19) in laboratory. The binder concentration can be measured also with XRF-analyzer on site or in laboratory.

The shear strength of the stabilized soil can be determined from undisturbed samples with uni- or tri-axial compression tests, direct shear test, or fall cone test. E-modulus and settlement parameters can be studied with oedometer or tri-axial tests. Undisturbed samples might be hard to collect from a brittle soil and in some cases the measurement are possible to do from the wall of test pit or from large test pit samples in the bucket of excavator (Table 1 row 18). QA methods suitable for that are miniature or pocket vane penetrometer or miniature penetrometer. Test pit samples can be also studied in laboratory.

Test embankment (Table 1 row 20) is an excellent method for investigating the real behavior of the large scale structure and to get information about the settlement behavior (magnitude, homogeneity, rate), the strength dependence on the loading and long period behavior. One example of test embankment is Veittostensuo test mass stabilization at peat area and test embankment constructed in Finland in 1993. There have been settlement measurements, QA soundings and laboratory tests at time period from 1993 to 2016. (Piispanen et al. 2016)

5 CONCLUSION

The design strength of in situ mass stabilized soil is lower than strength of column stabilized soil. Therefore only some of the commonly employed methods applicable for column stabilized soil QA are recommended for mass stabilized soil QA.

The column penetrometer and vane penetrometer have been used in Finland over three decades and a good statistical correlation has been reached between the sounding results and the shear strength of stabilized soil. Those methods used in conjunction with one another are also quick and easy to perform, thus providing quality data economically. However, these methods are not available at all mass stabilization sites in other regions, so in those circumstances other QA methods are needed.

Some experiences and opinions about the suitability of several other QA methods to the QA of mass stabilized soil have been presented in this paper. The suitability and availability of investigation methods for QA have to be considered site by site in case previous experience with mass stabilized soil QA is limited.

Because of heterogeneity of mass stabilized soil, statistical methods should be implemented for evaluation of soil parameters from individual tests.

6 ACKNOWLEDGEMENTS

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Table 1. Verification techniques proposed in literature for determination the quality of mass and column stabilized (deep mixed) soil. Underlining the raw number means that the method is suitable and used method for QC of production mass stabilization.

	Quality assurance methods	Method description	Area and type of the tip	Measured parameter	max. Shear strength	Usage
<u>1</u>	Column penetrometer	Static / dynamic penetration	A=100 cm^2, ϕ= 375 mm (wings) *	Force or blows => Shear strength	Static < 0.2, Dyn. < 1 MPa	Nordics since 1980, * other A + ϕ in EN14679
2	Pull out resistance test (PORT)	Static uplifting (penetration)	A=100 cm^2, ϕ= 375 mm (wings) *	Force => Shear strength	< 600 kPa	For column stabilization since 1990's in Sweden
<u>3</u>	Vane penetrometer	Vane rotation	ϕ=130 or 160, H=0.5×ϕ	Torque => Shear strength	< 200 kPa	In Finland since beginning of 1980's
<u>4</u>	Combined static-dynamic penetration test	Static / dynamic penetration with rotation	A= 50 cm^2 for stab. soil and 16 cm^2 for very hard stab. soil	Force or blows => Shear strength	< 2000 kPa	Nordic countries from 80's
<u>5</u>	CPT-sounding	Static penetration	ϕ≈36 mm, A=10 cm^2	Force+frict. in tip => Shear strength	< 1000 kPa	e.g. Finland in 80's and 90's
6	Standard penetration test, SPT	Dynamic penetration	ϕ=51 mm, A≈20 cm^2, H_{tip}≈700 mm	Force => Shear strength	(?)	used or tested in Japan
7	Swedish weight sounding test	Static penetration with rotation	ϕ=35 mm, screw shaped point	Force & rotations => Shear strength	(?)	Tested in Sweden and Finland in 70's, used or tested in Japan
8	Modified total sounding	Static penetration with rotation	ϕ=57 mm	Force and friction => Shear strength	no	Tested in Sweden for stabilized columns
9	Pressuremeter	Preboring of a hole for pressuremeter	ϕ = 44 / 60 mm	G_{pr} => E_{pr} -modulus	no (?)	No experience in mass stabilization QC (?)
10	Screw-plate test	Gradual loading of soil in various depths	ϕ 160 mm	Force => E-modulus	(?)	Tested in Finland and Sweden at 80's for columns
11	Plate load test	Gradual loading of surface	ϕ 300 mm (or wider)	E-modulus of the surface	no	Results only from the surface to depth ≈ ϕ_{plate}
12	Geophysical methods	Various non-destructive test methods	Various	e.g. S-wave veloc. => Shear strength	no (?)	Methods mainly in research stage
13	Dynamic compaction control method	Accelometer measuring of the response	Vibratory roller	Relative homogeneity of mass stab.	no	Tested in Finland 2002
14	Impact acceleration test (DYLA)	Dropping weight to top of stabilized soil	Equipment like in pda-measures	Compressive strength, integrity	≥ 500 kPa (Japan)	Tested in Finland at 90's for columns τ<<500 kPa
<u>15</u>	Undisturbed samples	Tube sampler, excavator, large scale bore samples	ϕ 60-200 mm	Shear strength, E-mod., water perm.	no	Not possible with very brittle stabilized soil
<u>16</u>	Disturbed samples	Sampling	Variable	Binder amount and variation	no	Almost all methods suit in non-cohesive soils
<u>17</u>	Wet grab sampling	Excavator etc. => placing in mold, curing and testing	Variable	Shear strength, E-modulus, water permeability	no	Not used in Nordic mass stabilization, but have been used in USA
<u>18</u>	Test pit	Excavation and sampling	Variable	Visual, disturbed or undisturbed samples	no	Excavator needed, used everywhere
19	Uplift of column	Uplifting whole column with steel pipe	$\phi_{pipe} > \phi_{column}$	undisturb. samples, ϕ_{column}, homogeneity	no	Maybe could be used with mass stabilization
20	Test embankment	Loading embankment, settlement plates	Variable	Settlement, E-modulus	no	Full scale test method, long-term measurements

1 Halkola 1982 & 1999; EN14679:2005; Kitazume&Terachi 2013; Forsman et al. 2015
2 Halkola 1999; Kitazume&Terachi 2013; ESS 2002
3 Halkola 1982 & 1999; Kitazume&Terachi 2013; Forsman et al. 2015
4 Halkola 1999; EN14679:2005; Kitazume&Terachi 2013; ESS 2002, Vähäaho 2009
5 Halkola 1982 &1999; EN14679:2005; Kitazume&Terachi 2013; ESS2002; Laaksonen 1995; Bergman 2012; EN ISO 22476
6 Halkola 1999; Kitazume&Terachi 2013; EN ISO 22476
7 Kitazume&Terachi 2013; ESS 2002; EN ISO 22476
8 Bergman 2012; EN ISO 22476
9 EN14679:2005; Kitazume&Terachi 2013; EN ISO 22476
10 Halkola 1982 & 1999
11 Halkola 1982; Kitazume&Terachi 2013
12 Halkola 1999; Kitazume&Terachi 2013
13 Korkiala-Tanttu & Törnqvist 2003
14 Forsman et al. 1999; Kitazume&Terachi 2013
15 Halkola 1982; EN14679:2005; Kitazume&Terachi 2013
16 Halkola 1999; Forsman et al. 2015
17 EN14679:2005; Kitazume&Terachi 2013
18 Piispanen et al. 2016; Forsman et al. 2015
19 Halkola 1982; Vähäaho 2009
20 Piispanen et al. 2016; Forsman et al. 2015